Understanding Quantum Technologies

Ninth edition – 2026

Part 5/5 – Ecosystem

Olivier Ezratty

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Ninth edition - 2026 - Version 9.0

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Olivier Ezratty is an author, academic, teacher and advisor on quantum technologies. He started this endeavour in 2018.

He is the author of the reference book "Understanding Quantum Technologies" (September 2021, 2022, 2023, 2024, 2025 and 2026) following three previous editions in French in 2018, 2019 and 2020. The 2025 edition is also available in paperback version on Amazon. This 2026 edition's Amazon print version will be available before the end of 2026.

Since 2021, he has been teaching quantum technologies at EPITA, an IT engineering school in France, at Ecole Normale Supérieure Paris-Saclay since 2024 and CentraleSupelec since 2005. He's affiliated with the EPITA Research lab for his various research writings.

He is a cofounder of the Quantum Energy Initiative in 2022 with Alexia Auffèves (CNRS MajuLab Singapore), Robert Whitney (CNRS LPMMC) and Janine Splettstoesser (Chalmers University, Sweden), and member of its scientific board.

He acts as an independent expert for Bpifrance and at the Agence Nationale de Recherche (ANR) to evaluate quantum R&D projects, as a member of the European Quantum Computing Advisory Board (Q-CAB) since April 2026, and of the Inria expert group for the selection of risky research projects (Programme PIQ) since June 2024.

Since 2018, he has spoken in a large number of quantum technology events such as the Q2B Paris and Santa Clara organized by QC Ware, France Quantum, Lindau Nobel Laureate meeting, DPG, Q-Expo and other events, on top of presentations at Société Générale, BNPParibas, Crédit Agricole, Michelin, Adéo, L'Oréal, FIECC, IHEDN, Business France, CentraleSupelec, Avolta Partners, IHEDN, etc.

He coproduces two series of podcasts on quantum technologies along with Fanny Bouton (in French): a monthly "Quantum " on tech news (since September 2019) and Decode Quantum (2020-2026), with entrepreneurs and researchers, with a total of about 170 episodes as of September 2026.

He also lectures or lectured in various universities such as CentraleSupelec, ENSTA, Telecom Paristech, Les Gobelins, HEC, Neoma Rouen and SciencePo, on artificial intelligence, entrepreneurship and product management (until 2020) and on quantum technologies (since 2018), in French and English as needed. He is also the author of many open-source ebooks in French on entrepreneurship (2006-2019), the CES of Las Vegas yearly report (2006-2020) and on artificial intelligence (2016-2021).

Beforehand, Olivier Ezratty was specialized in many other topics since 2005, like digital television, internet of things and artificial intelligence. As such, he carried out various strategic advisory missions, conferences, or training assignments in different verticals and domains such as media and telecoms, finance and insurance, industry and services and the public sector.

Olivier Ezratty started in 1985 at Sogitec, a subsidiary of the Dassault group, where he was successively Software Engineer, then Head of the Research Department in the Communication Division. He initiated developments under Windows 1.0 in the field of editorial computing as well as on SGML, the ancestor of HTML and XML. Joining Microsoft France in 1990, he gained an extensive experience in many areas of the marketing mix: products, channels, markets and communication. He launched in France the first version of Visual Basic in 1991 and Windows NT in 1993. In 1998, he became Marketing and Communication Director of Microsoft France and in 2001, of the Developer Division, which he created in France to launch the .NET platform and promote it to developers, higher education and research, as well as to startups. Olivier Ezratty is a software engineer from Centrale Paris (1985), which became CentraleSupelec in 2015.

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Foreword

The birth of the second quantum revolution may be reasonably settled to 1982, with two celebrated articles: "Experimental Test of Bell's Inequalities Using Time-Varying Analyzers" by Alain Aspect and colleagues, and the famous theoretical paper "Simulating Physics with Computers" by Richard Feynman. They were quickly followed in 1985 by David Deutsch's "Quantum theory, the Church–Turing principle and the universal quantum computer", providing the birth certificate of what is known now as quantum computing. Incidentally, I got a position at CNRS also in 1982, a good spot to witness these developments. However these subjects, including the surprising quantum key distribution scheme proposed by Charlie Bennett and Gilles Brassard in 1984, were still quite confidential at that time. It took ten more years for the topic to attract broad international attention, with the articles "Algorithms for quantum computation: Discrete logarithms and factoring" (1994) and "Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer", both by Peter Shor.

This started an explosive development, which has not stopped since then. The big impact of Shor's algorithm is that it may break cryptographic codes that were considered fully secure at that time, and are still broadly used on internet - so each layman gets concerned. This, and other reasons, triggered a huge international effort to build a quantum computer. Since it was clear that such a computer was still far away, this effort was mostly academic during the next 20 years. But another earthquake happened in 2014, when large US companies, Google and IBM as the most visible ones, decided to get into the race. They set up heavily funded research programs, focused on a specific technology, superconducting quantum bits. This move stimulated a high level of private investment, leading to the creation of a flurry of dedicated companies, initially startups, but then quite respectable enterprises in terms of funding. They were not limited to superconductors, but included all quantum objects likely to become a quantum bit, a qubit : ions, atoms, photons, and even more exotic ones. One must honestly say that, from this time, the language used in this research field changed significantly: the way to speak with investors is not the same as the way to publish articles in reputable scientific journals. The result was a mixture of authentic scientific and technological progress, coming together with hype and overselling. This may be seen either as an unavoidable evil, or as the appropriate way to communicate in an extremely competitive high-tech environment.

A good example is the way to name the "ultimate goal", the point where a quantum computer can really achieve a useful task that no classical computer can do in any reasonable time. The first name that popped up was "quantum supremacy", but it did not make it, both for technical and political reasons. The next one was "quantum advantage", more politically correct, but still difficult to warrant. The next one is "quantum utility", clearly more modest, but more likely to be reached in a reasonable time span. In the current language, "utility" is used as a step towards "advantage", with some possible oscillations between the two due to progress in classical computing.

Then a question arises : given the very fast progress of the devices, their technical complexity, and the strange mixture of science and publicity used by companies to communicate their results, how to find one's way in the jungle, without getting lost or eaten ? One would need somebody with good scientific and technological knowledge, but also a huge talent for global accounts, given the many facets of these developments, involving physics, hardware, software, middleware, logistics, and finance. We are lucky enough that this person exists, his name is Olivier Ezratty, and you hold his book in your hands or on your computer screen. This is not a modest enterprise, and ≈1,822 pages carefully written in LaTeX is a minimal container. Go for it, it's free ! But how to approach such a monument ? Fortunately there is a reading guide in the first pages, able to orient you depending on your background and interests. It includes also an illustrated "Pandora's box", listing the main high level topics (physics, mathematics, human sciences, engineering, computer science, geopolitics), together with their inner content, opening doors towards many stimulating questions for science, technology, and society.

So where do we stand now, already 44 years after the baby was born ? The general idea is that the real stuff, the one needed for supremacy / advantage / utility for practical problems of industrial interest, requires what is called now "Fault Tolerant Quantum Computing" (FTQC), in the line of Deutsch's ideas; this is quite attractive for computer scientists, but very hard to achieve. Physicists tend to prefer quantum simulators, in line with Feynman's ideas, potentially useful for more fundamental physics problems. Myself, as a physicist, will go for the second trail, because one should not dismiss fundamental physics problems: it is by solving them that science made progress, and not necessarily by jumping right now into the market. Actually, it is not clear that all fundamental questions to be answered before being able to implement quantum computing have been solved, as summarized in the old joke : "Where is quantum computing? Somewhere between cold fusion and hot fusion", a physicist's warning that nature's laws are not to be fooled around.

Anyway, as we say in French, "*on ne discute pas des goûts et des couleurs*" (there's no accounting for tastes): whatever your personal interest is - physicist, computer scientist, or investor -, and wherever you may want to look at - computing, communications, sensors or metrology - the development of quantum technologies is a fascinating arena where much more is expected to come.

I cannot close this foreword without a few words about another ongoing revolution, artificial intelligence and large language models generative artificial intelligence (simplified as "LLM"). The most straightforward step forward, taking place currently in all domains of scientific and technical activities, is to use LLM as super-efficient assisting tools; their progress during the 2 or 3 last years has been astonishing, and it cannot be listed here. Another more speculative idea is to think about a "quantum AI", an AI running on a quantum computer. The mismatch between the current performances of quantum computers, and what is used now on supercomputers running AI, makes this objective extremely far-fetched. Still, blue-sky thinking about what might be achieved by such machines - and even the question of whether they will still be "machines", is attracting attention by some quantum theoreticians. Where will these revolutions lead humanity ? Only time will tell.

Philippe Grangier

Director of Research emeritus at CNRS, Institut d'Optique Graduate School (IOGS), and incoming President of the French Optical Society (SFO).

September 2026

Contents

This is **Part 5/5** – **Ecosystem** of the book "Understanding Quantum Technologies 2026", which is also downloadable using this link.

The downloadable PDFs are available in a single A4 and Letter version, containing the five parts in sequential order. You can also download compressed PDFs for the five parts in A4 and Letter formats. Their size fits the constraints of ebook readers like the Kindle from Amazon.

The e-reader and printed version of the book separates parts 1, 2, 3, 4 and 5.

- The **first part** contains a history of quantum physics, some quantum physics 101 and everything about quantum computing basics and engineering including quantum error correction, the energetics of quantum computing, a view on pessimism and optimism with regard to the advent of scalable and useful quantum computers, as well as some economic considerations.
- This **second part** contains the sections dedicated to quantum computing hardware with all types of qubits and their related industry vendors, enabling technologies, and unconventional computing solutions which are potential alternate routes between classical and quantum computing.
- The **third part** contains the sections dedicated to algorithms, software tools, and applications across multiple markets. It also contains an inventory of quantum computing software and service vendors.
- The **fourth part** covers quantum communications, quantum cryptography, post-quantum cryptography and quantum sensing.
- The **fifth part** describes the quantum ecosystem at the entrepreneurial level, the country level, on various societal topics, corporate adoption methodologies, quantum pseudosciences. It ends with a glossary, and book bibliography.

The book is split into five parts to make its printing easier, some online printing services including Amazon being limited to a maximum of 600 pages.

You can order the printed version of this book in five parts on all Amazon sites by searching for the book title, edition 2026, when it is released around October-November 2026.

1 Quantum ecosystems around the world

Quantum technologies in the broadest sense became a strategic technology domain for various reasons. In cybersecurity, state sovereignty is at stake with the protection of sensitive communications. Quantum computing has critical applications that may extend the scope of digital computing beyond what is feasible today, particularly in the fields of material design, life sciences, and the environment. Quantum sensing is also strategic due to its dual-use applications. This part of the book describes the various quantum ecosystems per category: investors, startups, research and government bodies, and then per country, but also look at topics like patents and export controls. In the latter case, it is sometimes based on my own visits to national ecosystems over the last few years (USA, Canada, Germany, the Netherlands, Denmark, Finland, Austria, Israel, Slovenia, Slovakia, Taiwan) on top of my home country (France).

1.1 Quantum ecosystems

Let's start with defining what is a quantum ecosystem (Figure 1). The definitions are about the same for all technology sectors. An ecosystem consolidates all the stakeholders in the creation and adoption of a given science and technology domain. It can be AI, healthcare, or whatever.

What is different in the case of quantum science and technology? Maybe its long-term aspect, which reinforces the role of government and public organizations in funding a long-term effort, which is generally not done by the private sector entirely. The dual usage of quantum technology is there but not much different from many technologies like AI, even when considering the role of Shor's algorithm on cybersecurity.

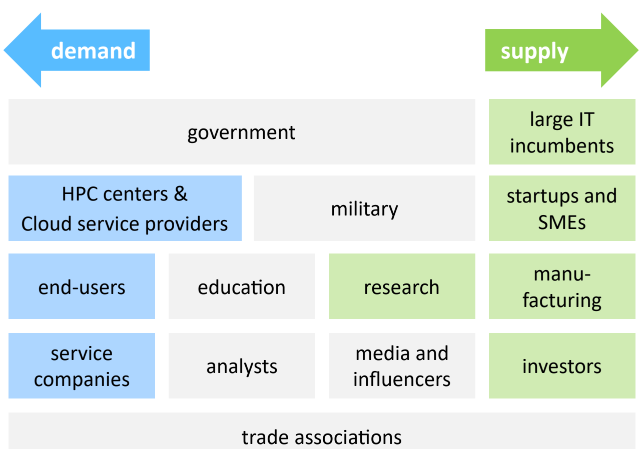


Figure 1: Simple quantum ecosystem map with all potential stakeholders, from demand (usage) to supply (creating the technology). © Olivier Ezratty, September 2025.

So here are the key stakeholders to consider.

Education. This covers initial education up to master's degree level, both in scientific degrees and non scientific degrees like in business management (MBAs), legal training and sales/marketing. There are few such education courses available that specifically cover quantum science and technologies. *Key metrics*: number of people trained per year and per degree.

Academic research. This covers investments in academic research, which includes the training of PhD students and their related infrastructure. *Key metrics*: number of existing and additional PhDs per year and per domain (fundamental science, computing, sensing, communications, others), same for post-docs, number of full-time research positions created, additional infrastructure budget (instrumentation, clean rooms, etc.), then papers published, researchers' h-index or equivalent, new patents.

Governments. They fund part of education and most of academic research, depending on the country. They launch their "National quantum strategy initiatives" with specific global funding. They fund public research datacenter capabilities. They define tax and other incentives favoring investment in R&D and innovation. They play a role in regulation. See the 2025 policy report from the OECD which makes a good inventory of government practices [1]. *Key metrics*: their National Quantum Strategy Initiative funding, per year and with clearly distinguishing between legacy and incremental investments. The rest is about the decomposition of this funding. Some other more generic metrics cover innovation favorability indexes.

Military. Defense departments cofund research in dual-use technology with specific programs. The most famous examples are DARPA (QBI program), AFRL and IARPA related investments in the USA, and their equivalent from DSTL in the UK, DGA in France with the ProQCima program in quantum computing, and the Diana program at NATO. Disclosed investments in military, related programs, and share of military investment in the global government investment can be larger in some countries like China and Russia. One working hypothesis is that a higher share of military spending in GDP goes with a higher military quantum budget, but the share of military spending alone does not establish quantum expenditure and this should be tested against comparable budget data before being relied upon.

Public supercomputing. In many countries like in the European Union, research funding covers supercomputing infrastructures. They are the first natural customers of quantum computers. They test their installation in traditional data centers. They focus their efforts on "hybrid classical-quantum computing". Quantum processors depend on classical control and are generally embedded in classical workflows, and many near-term applications also use iterative hybrid algorithms, but not every quantum algorithm is intrinsically hybrid. One key such program is the EU-funded EuroHPC JU which funds exaflops HPC deployments as well as QPU acquisitions. *Key metrics*: official acquisition costs of QPUs, provided QPU performance (number of qubits, of supported gates, etc.).

Investors. These are the organizations or individuals who invest in startups. It includes family offices of wealthy people, venture capital early-stage and later-stage investors, sometimes public banks (EIB in Europe, Bpifrance in France, etc.) and some large user organizations (for example SK Telecom and Hyundai who invested in IonQ, CMA CGM who invested in Pasqal, Airbus Ventures who invested in IonQ, Q-CTRL and QC Ware, Bosch Ventures who also invested in IonQ, and created a deep tech fund of $280M in 2025). Foundations can also invest in the quantum space, particularly to fund research programs like Novo Nordisk in Denmark, Wallenberg Foundation in Sweden, and the Simons Foundation and the Templeton Foundation in the US. *Key metrics*: investment per year in these various categories of companies. Number of exits.

Incumbent IT hardware companies. These are the large established information technology companies who invest their own R&D efforts in quantum science and technologies. This includes for example IBM, Google, Microsoft, Amazon/AWS, Intel, Nvidia and Cisco. They are mainly US companies, creating a significant gap with other regions like the European Union. *Key metrics*: their own investment per year, which is unfortunately never public data and can only be inferred using some fuzzy metrics like their headcount dedicated to quantum, their patents data, their revenue in quantum when disclosed.

Startups and small businesses. They are in communications, sensing and computing. They create hardware and/or software and also enabling technologies, manufacturing capabilities and new materials. *Key metrics*: number of existing companies, number of startups created per year, amounts raised, their revenue.

Manufacturing. All eyes are currently on TSMC due to its current dominance in the manufacturing of high-density chips, with about two thirds of the pure-play semiconductor foundry revenue market as of 2025. It exemplifies the importance of having some manufacturing capabilities for key components used in quantum technologies. Like superconducting qubits, nanophotonics, regular electronics, lasers and cryogenic systems. It explains why both the EU and the USA allocated part of their "Chips Act" programs to quantum technologies. *Key metrics*: in which domain is a given country autonomous for the manufacturing of key components.

IT services providers. These are the IT service companies of all sizes, up to large companies like Capgemini and Accenture. They do consulting, project management and software development, infrastructure deployments, etc. It also includes cybersecurity services companies. *Key metrics*: team sizes, projects, published case studies.

Cloud services providers. These are the cloud service vendors like the large hyperscalers (AWS, Microsoft, Google) and the smaller players like OVHcloud (France) or Ionos (Germany). They provide QCaaS (quantum computing as a service), providing access to quantum computer emulators or real QPUs, which are usually still running from the vendor's location. *Key metrics*: number of emulators, number of quantum computer vendors and quantum computers available, number of active customers.

User organizations. These are the organizations testing or using quantum technologies, in various verticals (financial services, life sciences and healthcare, transportation and logistics, manufacturing, etc.). *Key metrics*: number of users per vertical and per project maturity stage. Penetration rate in verticals.

Analysts. These are the McKinsey, BCG, IDC and others who produce qualitative or quantitative reports, market trends, and also do strategic consulting. They are strong influencers, and their published forecasts should be read alongside the commercial relationships they disclose, since several of them also sell consulting services to the vendors they cover. *Key metrics*: the metrics in their own forecasts that can later be compared with actual data.

Trade associations and consortia that specialize in quantum. You have for example the QED-C for the USA and the QuIC consortium for Europe. Other non specialized trade associations in various verticals play a key influential role. *Key metrics*: is there at least one such dedicated quantum organization in a given country, members representative of the entire value chain, organized events for scientific and business audiences (audience including share of international audience).

Standardization bodies. This concerns the country role in international standardization efforts and influence. *Key metrics*: number of standards working groups where the country is involved.

Media and influencers which include media, podcasters, youtubers, scientists doing scientific intermediation and outreach. *Key metrics*: papers, videos and podcasts published, audiences.

When analyzing quantum ecosystems, you can try to figure out whether they are focused on the supply or demand side. Small countries tend toward the demand side while larger countries focus first on the supply side.

Their demand side also grows naturally, particularly if the country has a good "innovation spirit". Also, even on the supply side, there can be some bias between hardware and software, software investment being easier for smaller areas since it is less capital intensive.

Reports are published from time to time to benchmark quantum ecosystems like the MIT Quantum Index created by the MIT Sloan Management School [2] using some of the aforementioned metrics.

The usual question is: which are the best ecosystems? What are the metrics to gauge them? The simplest answer is to rank them relative to GDP, and you get it easily: USA and China. Patents and scientific publications are another usual simplistic way to evaluate academic research output. Then the number of companies created, the investment in these companies, the government investment (to be normalized on a similar number of years, and deduplicating some announcements). You can also normalize these numbers relative to country size.

In terms of domain maturity, post-quantum cryptography and quantum cryptography must be assessed separately. PQC is classical cryptography designed to resist known quantum attacks, and it is the field where standards are now published and deployment has started, following the NIST FIPS 203, 204 and 205 standards of August 2024. Quantum cryptography relies on quantum physical systems, mostly QKD, and has a distinct and narrower deployment path with its own hardware, certification and key-management constraints. Both have fewer scientific unknowns than scalable quantum computing, but their readiness levels are not comparable.

Quantum computing is much less mature. The feasibility of commercial and useful quantum computers remains an open question both in the NISQ and FTQC regimes. There are significant technological challenges to overcome, including the issue of qubits quality at scale, quantum error correction overhead, and how to scale the number of physical qubits by several orders of magnitude. So, quantum computing is full of scientific and technological uncertainties even before being full of economic and market ones. How countries deal with that is a good indicator of their innovation and forward-looking culture.

The quantum computing software industry is in its infancy. The major players and startups creating quantum computers have all invested in the software arena, starting with the low-level supporting tools and sometimes, for developing quantum or quantum inspired applications.

Some QPUs are already available in the cloud, directly or through cloud services providers like AWS, Microsoft, Google and OVHcloud. Most of these players also sell cloud access to classical quantum emulators. In 2019, **Yuri Alexeev** from the DoE Argonne National Laboratory drew a parallel between the history of AI and quantum computing. He anticipated two quantum winters, the first which occurred in the late 1990s, the second in 2020 and the next around 2030 [3] (Figure 2). Well, it has not happened yet: as of September 2026, practical industry-grade applications are still not there.

Since this excitement is hard to measure directly, the metaphor does not carry much analytical weight. Measurable indicators are more useful: funds raised per year, public budgets actually disbursed, vendor revenue, QPU procurement, and headcount. One quantum winter could still show up if NISQ systems don't deliver business value. It could slow down investments in various parts of the ecosystem, from public funding of academic research to investments in startups and with end-user corporations. Hardware startups will have a hard time delivering useful machines, while software startups will not have a large enough addressable market due to the lack of hardware. But this will not prevent public research laboratories and large tech companies from doing fundamental and applied research. In a sense, the strength of a quantum ecosystem, to be measured a posteriori, would be its resilience to any form of potential quantum winter.

1.2 Quantum computing startups and SMEs

Mapping these vendors is a bit easier than in other deep techs like in artificial intelligence because there are not so many. There are many methods to inventory worldwide quantum startups and small businesses. My own database contains over 970 such companies worldwide. There are many such inconsistent inventories available all over the place. The discrepancy comes from the way enabling technologies companies are accounted for. I put them in my database provided that they enable "second quantum revolution" solutions. As a consequence, metal cutting lasers and classical telecommunications photonics are out!

This ecosystem began to take shape even before quantum computers were working on a small scale. It is fascinating to discover startups that make long-term bets, particularly with hardware. Software startups rely on a still limited hardware infrastructure but often reduce their risks by also supporting traditional computing architectures like Nvidia GPGPUs in machine learning and promoting so-called quantum inspired classical solutions. Their customers are large companies who test algorithms on a small scale to get their hands on quantum programming. To date, no serious application seems to be deployed in production. We are in the field of applied research and small scale prototyping within client companies. The software ecosystem is to be monitored closely. It will probably expand once hardware works on a larger scale, particularly with NISQ computers and quantum simulators [4].

For their part, quantum cryptography systems are operational and correspond to a very separate market, just

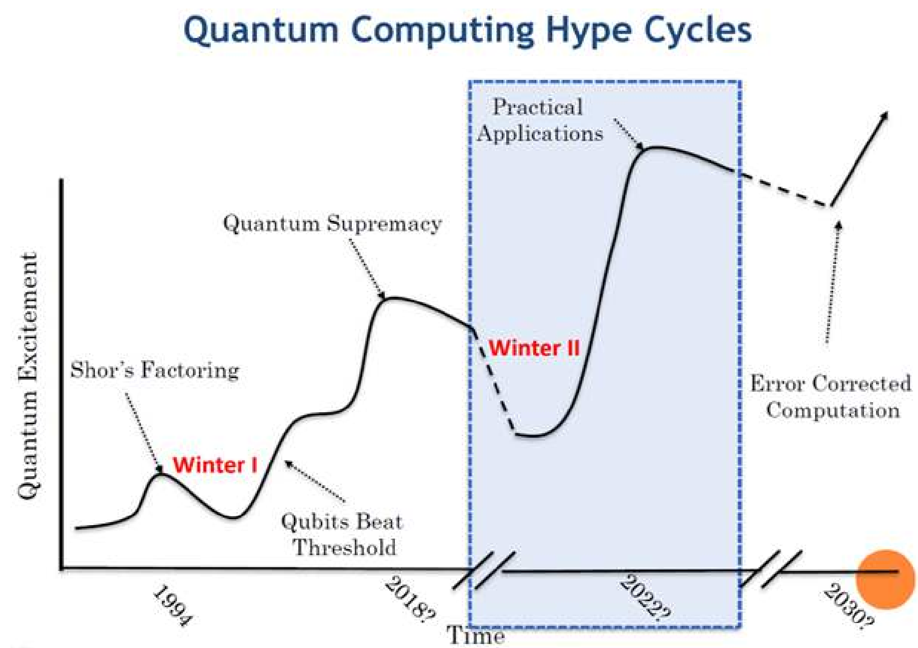


Figure 2: One view of the quantum computing hype cycle from 2019. There was no winter between 2019 and 2022 and we don't yet have truly practical applications. Source: [3].

like the quantum sensing market that is more mature technologically but still in its infancy.

The stakes for many startups in this field are common with those of deep techs: how to develop real products with economies of scale, how to expand internationally rapidly, how to avoid falling into models that are too "service-oriented" and at last, how to resist a potential quantum winter or simpler investment winters not specifically related to quantum. Enabling technologies niche companies (photon sources, cryostats, ultra-vacuum, various sensors, electronics) can do well by reaching out diversified markets, notably targeting several different branches of research, telecommunications, defense and aerospace applications.

1.2.1 Investors

Quantum technologies investments may be impressive for the large rounds like those from PsiQuantum and IonQ and the associated "FOMO" factor ("*fear of missing out*"). But it is still small in volume in the technology sphere. The first investment funds more or less specialized in quantum technologies have already emerged with the following ones, a few of them being shown in Figure 3:

- **Quantonation** is a French seed fund created by Charles Beigbeder, Christophe Jurczak and Olivier Tonneau. Christophe Jurczak who is the managing partner of Quantonation is a physicist who obtained his PhD with Alain Aspect [5]. They invested in over 40 startups [6], with a total of $310M raised across two funds, which makes it one of the largest funds dedicated exclusively to quantum technologies. Rankings of this kind depend on whether capital raised, capital committed or assets under management is used as the metric, and on the snapshot date. Quantonation was also behind the launch of **Le Lab Quantique**, which was jointly created with **Bpifrance** and many industry vendors and users. Quantonation have many limited-partner investors, including Temasek (Singapore), Novo Holdings, Planet First Partners, Toshiba and the European Investment Fund (EIF) who invested in their second fund, Quantonation II which as of Mid-2026 had gathered €220M of funds.
- **Quantum Valley Investments** (QVI), a $100M Canadian investment fund, raised in 2013, dedicated to quantum technologies. Their founders invested in 1984 in Blackberry / RIM. They do not disclose their investments, except in ISARA Corporation, part of which are spin-offs from the Canadian research laboratory Institute for Quantum Computing at the University of Waterloo in Ontario.
- **Quantum Exponential** (UK) invested £450K in May 2022 in Universal Quantum who plans to build a million qubit quantum computer. It also invested in Arqit, Siloton, Aegiq and Delta G (UK) which develops gravity sensors.
- **Quantum Ventures** is a quantum investment company launched in 2016. Its "Quantum Revolution Fund" is managed from London and Switzerland. It aims to raise €100M.
- **Quantum 1 Group** is an American investment fund specializing in quantum technologies since 2015.
- **Quantum Coast Capital** (USA) is an early-stage investment fund dedicated to quantum technolo-

gies that was created in March 2024 in Florida by Matthew Cimaglia. It has no public investment yet.

- **Summer Capital** is a Dutch investment fund specialized in quantum technologies, data and finance. Their investments include Horizon Quantum Computing, Rigetti and Turing.
- **Parkwalk Advisors** is a British deep tech fund. As of 2025, they have invested in Phasecraft, Quantum Motion, Riverlane, Nu Quantum, Nu Nano, OQC and Crypto Quantique. This fund has been part of IP Group Plc since December 2016.
- **Runa Capital**, created by Serguei Beloussov (Russian with a Singapore nationality, founder of Acronis) is an investor in many deep tech startups, including IDQ, Qnami, Qu&Co, Pasqal and Welinq. And no new investments since about 2023.
- **Phystech Ventures**, previously Quantum Wave Fund, created by Russians in the Silicon Valley, including Serguei Beloussov, and having already invested in the IDQ and Nano-Meta Technologies. Their fund is not 100% specialized in quantum. They also invest in robotics, drones, sensors and connected objects.
- **Machine Capital**, a UK fund focused on quantum and AI, which has so far invested in **QuantumX Incubator,** an incubator for quantum software projects launched jointly with Cambridge **Quantum** Computing (now in Quantinuum), with a 20-week incubation period.
- **SpeedInvest** is an Austrian investment fund specializing in deep tech start-ups, which invests among others in quantum technologies. They invest in seed stage with up to €1M. They have invested in QphoX and Kets.
- **QAI Ventures** is a quantum-focused investment fund and a startup accelerator which is part of QuantumBasel in Switzerland. Their first accelerated startups include Anaqor, Kipu Quantum, Miraex, Moonlight AI and QDC.ai. They are partnering with Redstone VC. It established an office in Calgary, Canada, in April 2024 and one in Singapore in October 2025.
- **Redstone VC** launched in September 2023 a €52M dedicated seed fund to quantum technologies.
- **IQ Capital** is a deep-tech UK fund that raised $400M in 2023. Out of its 48 investments, its only investment in the quantum space is Nu Quantum (entangled based QKD).
- **Qbit Capital** is another early stage investment fund based in Switzerland and dedicated to Swiss startups.
- **Quantacet** is a small early stage $20M investment fund from Québec in Canada. They invested in Nord Quantique, Phantom Photonics, Quminex, and Silq Connect.
- **Airbus Ventures** is an investment fund, headquartered in Silicon Valley, that operates independently from the Airbus Group which is one of its limited partners among several others. They invested in QCWare, IonQ, Q-CTRL, C12 and Qunnect.
- **2xN** (UK) launched in August 2022 is a dedicated $120M fund focused on quantum computing startups with $3M to $5M pre-seed to Series A tickets. It was created by Lars Fjeldsoe-Nielsen and Niels Nielsen. Limited partners include the Danish Growth Fund and some family offices. They invested in QuantrolOx and Sparrow Quantum.
- **Quantum Italia** is an investment fund created in 2023 by Scientifica Venture Capital, with some partnering with the Unitary Fund (new Unitary Foundation).
- **VanEck** (USA) launched a quantum ETF in May 2025. It is an Exchange-Traded Fund that focuses on investing in early-stage or newly public companies.
- **QBeat Venture** is an Israeli early-stage venture fund specialized in quantum technologies. They already invested in Classiq and Quamcore in Israel, and in Orange Quantum Systems in the Netherlands.
- **55 North** is a pure play quantum VC fund created in 2025 and headquartered in Copenhagen. They invested in IQM and Kiutra. Their initial funding was €134M as of October 2025 with the goal to reach €300M.
- **Ground State Ventures**, formerly QDNL Participations, is an $88M quantum fund as of April 2026. They invested in QuantWare, Qblox, QphoX, QT Sense, Q*Bird, Orange Quantum Systems and Quantamap.
- **Deep33** is an Israeli-US fund launched in 2026 with $150M initially. It funds quantum computing and other deep-tech startups. Their first funded quantum startup is QuamCore (Israel).
- **Firgun Ventures** is a UK $250M fund specialized in quantum scale-ups. They invested in Photonic Inc (Canada), Quantum Motion (UK), SQC (Australia), OQC (UK), Quantum Elements (USA), and ZuriQ (Switzerland).
- **Propagator Ventures** (Norway) is invested in Universal Quantum and Zapata Quantum and other deep tech startups.

You then have generalist funds who invested in one or two startups, like the Canadian pension fund **PSP Investments** that invested in D-Wave with seats in the board, **UVC Partners** who invested in HQS in Germany, **Supernova Invest**, **Elaia Partners** and **Breega Capital** in Alice & Bob in France, **Omnes** and **Serena Capital** in Quandela, again in France. And

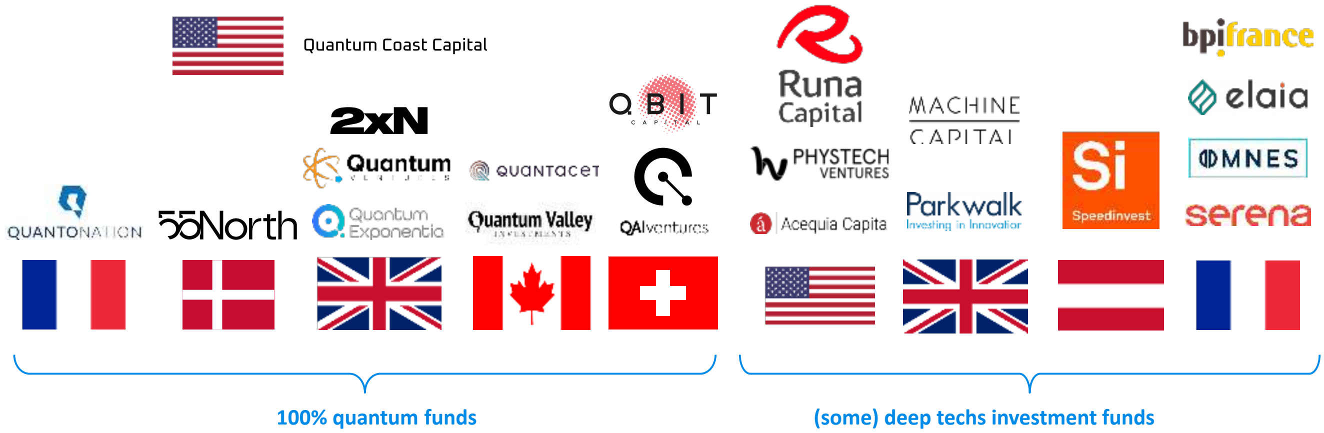


Figure 3: A few of the key investors in quantum technologies. © Olivier Ezratty, 2021-2025.

of course, corporate venture funds like **TotalEnergies Ventures** and **Tencent Investments**.

We must also describe the **SPAC** funding mechanism that was used by IonQ, Rigetti, D-Wave, Arqit, Xanadu, Horizon Quantum, IQM, and Infleqtion, and is in motion with Pasqal, Quantum Art and Classiq. A SPAC is a shell company that raises money and lists on a stock exchange first, before it has identified a target [7]. It then looks for one operating company to combine with. In the business combination, the private company merges into the already listed SPAC and takes over its listing, usually with additional money from PIPE investors such as corporate venture funds, and the combined entity is then traded under the operating company's name. Once listed, the company can raise further capital separately, for example through an at-the-market (ATM) offering, which sells new shares progressively at prevailing market prices rather than at a fixed negotiated price. This mechanism has been used by D-Wave (4 times for $725M), Rigetti (2 times for $450M) and IonQ (one time, for $375M) as of September 2025, with much larger amounts raised since then (see Table 1).

The process is a bit complicated. The SPAC business model is unbalanced. The SPAC fund takes a significant cut of the deal and has a significant upside when the company IPO takes place, whatever the subsequent outcome in the stock market. There were hundreds of SPACs until 2022, but the phenomenon then dried up, particularly with asset reallocations by investors as inflation popped up after the start of the war in Ukraine [8]. Compared to a traditional IPO, a SPAC-driven IPO is simpler, but at the expense of relinquishing more control to the investors [9]. The only recent traditional IPO was Quantinuum's, on June 4, 2026, which raised $1.68B gross at $60 per share, valuing the company at about $15.6B [10].

IonQ and Rigetti's stock value trended down after their IPO, due to significant overpromises in their investor pitch decks. D-Wave's IPO in August went well but things went awry starting in November 2022 and the company faced delisting for a while until June 2023 [13].

First, we had a sluggish start for 2022 with large fund rounds [14]. Then, the post-pandemic market downturn and the tighter financing conditions that followed the start of the war in Ukraine drove asset reallocations unfavorable to long-term risky investments [15]. This explains indirectly why governments and their aggressive national quantum plans find workarounds to fund their local startups, notably through public procurement of experimental quantum hardware, where delivery and performance should be assessed against the contractual milestones of each program rather than against commercial availability.

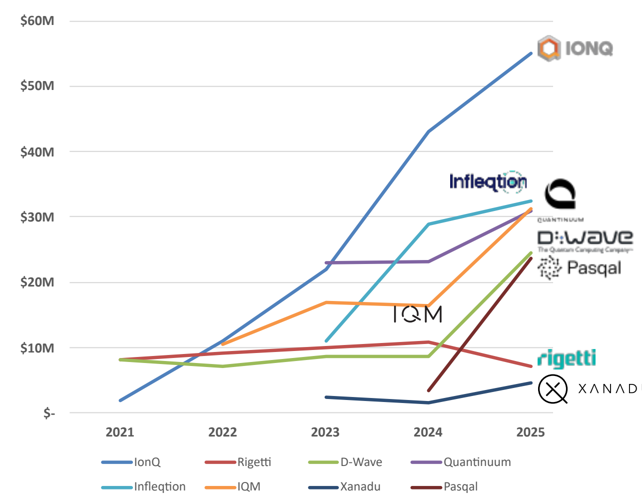


Figure 4: Traded quantum computing startup revenue per year. Source: Data sources for IonQ given the chart only accounts for quantum computing revenues [16–20], Quantinuum [21–24], D-Wave [25], Rigetti [26], Infleqtion [27–29], IQM [30–33], Xanadu [34–36], and Pasqal [37, 38]. © Olivier Ezratty, September 2026.

Company	Private/VC	Listing	Post-listing	Total gross	Cash
IonQ (IONQ)	84	636	3,373	**4,093**	3,000
Quantinuum (QNT)	1,225	1,710	0	**2,935**	2,107
D-Wave (QBTS)	250–300	49	1,078	**1,400**	546
Rigetti (RGTI)	190–200	262	485	**942**	541
Xanadu (XNDU)	250	302	67	**619**	313
Total	**2,030**	**2,959**	**5,003**	**9,990**	**6,507**

Table 1: Decomposition of the funding of the quantum computing hardware traded companies separating their pre-IPO, IPO and post-IPO funding, in US $M. Cash as of June 30, 2026. The $3,000M shown for IonQ is its reported cash at that date, before the SkyWater transaction, announced at a value of about $1.8B in stock consideration and closed on July 31, 2026, which leaves a pro forma cash position of about $2,000M [11] and Quantinuum as reported at June 30, 2026 [12]. Listing events: IonQ SPAC October 2021, Rigetti SPAC March 2022, D-Wave SPAC August 2022, Xanadu SPAC March 2026, Quantinuum IPO June 2026. Excluded: debt (Xanadu $30M, D-Wave $50M PSP term loan) and non-dilutive government funding (Xanadu up to CAD$390M under Project OPTIMISM plus CAD$40M SIF, Rigetti up to $100M Department of Commerce LOI). © Olivier Ezratty, September 2026.

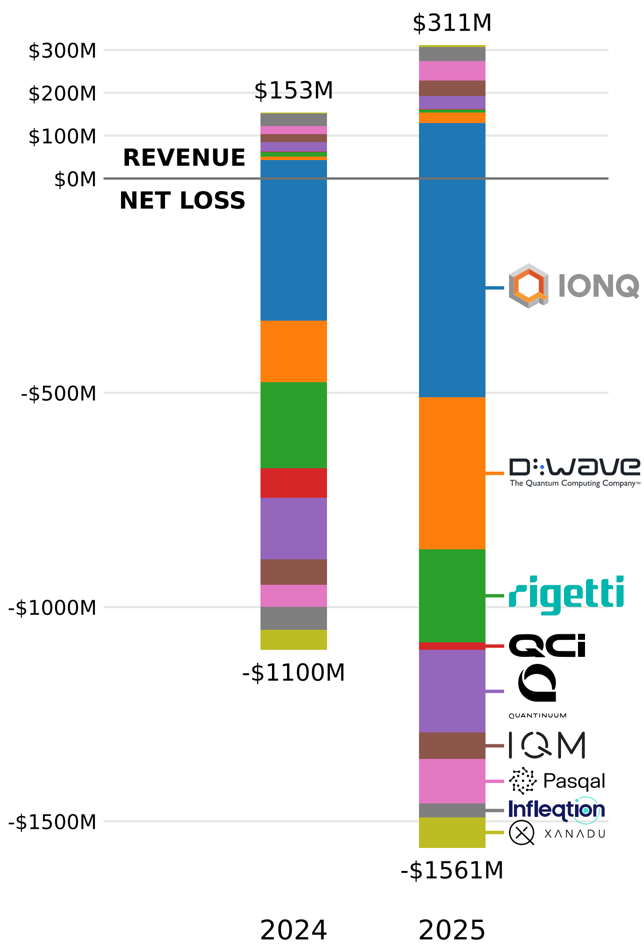


Figure 5: Traded quantum computing startups cumulative revenue and cumulative net loss per year, in US $M, obtained by summing the yearly reported figures of each company over the period shown. Source: IonQ [16–20], Quantinuum [21–24], D-Wave [25], Rigetti [26], Inflection [27–29], IQM [30–33], Xanadu [34–36], and Pasqal [37, 38]. © Olivier Ezratty, September 2026.

Now, looking at the current revenue streams of the traded hardware companies, you find out that they have rather modest revenues, coming from QPU sales, cloud revenue either directly or through cloud vendors like AWS, Microsoft and Google and some services (Figure 4). Their cash burn rate is in the tens of million $ per year which corresponds to between 2 and 6 years of "air supply" for Rigetti and IonQ (see their available cash in Table 1) and cash burn in Figure 5.

The investment trend in quantum startups in amount slowly decreased in 2022 compared to 2021 which was itself a performance compared to other sectors. The global VC investment was about $450B in 2025, $337B in 2024, $312B in 2023, $432B in 2022 and $618B in 2021 [39]! In 2023, the amount raised by quantum startups was halved while the number of deals still increased. Things are tougher for some startups in their various rounds of investment, particularly in series B and C. The winning startups who are escaping the startup funding crisis have good fundamentals: excellent teams, respected roadmap milestones, good competitive positioning, some IP and preferably some orders and/or revenue. However, investments in quantum startups grew in 2025, benefiting from large funding rounds from QuEra, Quantum Machines, Classiq and Alice & Bob with a total of about $1.8B in Q1 2025 alone.

1.2.2 Industry vendors maps

Since 2018, I have been consolidating many resources to build my own database of quantum industry vendors, starting with startups and then expanding it to small businesses and large established companies having a foothold in quantum technologies. Many other such databases are published or sold by various consulting or analyst firms and their content is very variable.

They sometimes integrate companies that are not really in the "second quantum revolution" value chain, like the vendors selling metal cutting lasers. As of September 2026, my database had over 850 companies including 21 large established companies (IBM, Google, Microsoft, Intel, NEC, Hitachi, Toshiba, Fujitsu, Baidu, Huawei, Alibaba, ...), 539 companies created between 2018 and September 2026, and 154 between 2014 and 2017.

Many of the startups inventoried here are not yet in the "pure" form of the startupian model, i.e., they are far from having a scalable model or even just a product. They are often fundamental or applied research labs on wheels funded by VC and government subsidies, with a very high scientific and technological uncertainty. They sometimes fund themselves with contract research, various consulting services for large companies or public institutions, or with businesses not related to quantum technologies, like in the artificial intelligence field for software vendors.

Some startups broadcast so little information about them that one may wonder if they are not scams. This lack of communication may be simply due to many creators being uncommunicative researchers, them being poorly funded, and their projects having too remote business prospects. Also, many times, they are so early-stage that they can't talk about anything that would drive interest, such as "*I have two operational qubits*".

I rely a lot on public information available on the Internet to describe what these startups do in the various parts of this book. One way to find out what they do is to identify their founders, if they are researchers, and find their original laboratories, their past scientific publications, and their PhD thesis if it is available. Finally, search for possible patents filed by the startups. This is technology intelligence using open-sourced information (OSINT). Of course, you can also meet with entrepreneurs, live or distantly.

Here are some charts extracted from my database of startups and SMBs. Figure 7 shows an indication of the number of startup creations per year and a breakdown of companies per country, with an interesting uptick in 2024. Figure 8 shows a different breakdown by country that highlights the largest funding. As usual, we see a significant funding gap between North America and Europe, but the share of funding of the European Union startups grew from 12.7% to 17% in one year thanks to the latest funding rounds from Alice & Bob and IQM but then decreased to 14% after the surge of IPO-led funding of North-American companies (see Table 1). One of the reasons is that European startups were created later or are more traditional small businesses which don't rely on venture capital for their development [40, 41]. The other is of course different access to capital and markets. The US market size has always been an advantage for US-born companies although it doesn't prevent some worldwide leaders to emerge elsewhere in the world like ASML or SAP.

Another chart, in Figure 6, that you will not find in any analyst report, shows how many quantum companies include a q at the beginning or within their name. Easy, you replace any c or k by a q and it's done! If you avoid this, you are really creative! How about two Qs in the company name? There is one case with UK's QinetiQ defense service contractor.

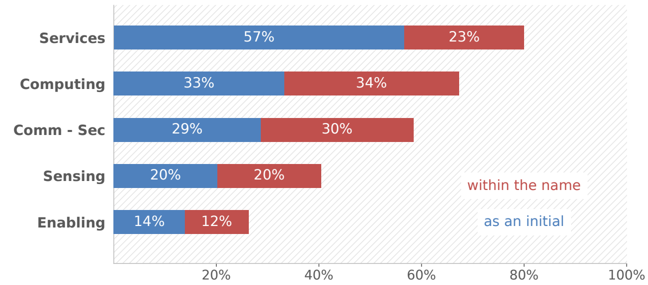


Figure 6: Fun fact: in some fields like computing, telecommunications, cryptography and services, quantum startups branding shows a lack of creativity with many names containing a Q. The percentage is slightly increasing every year.

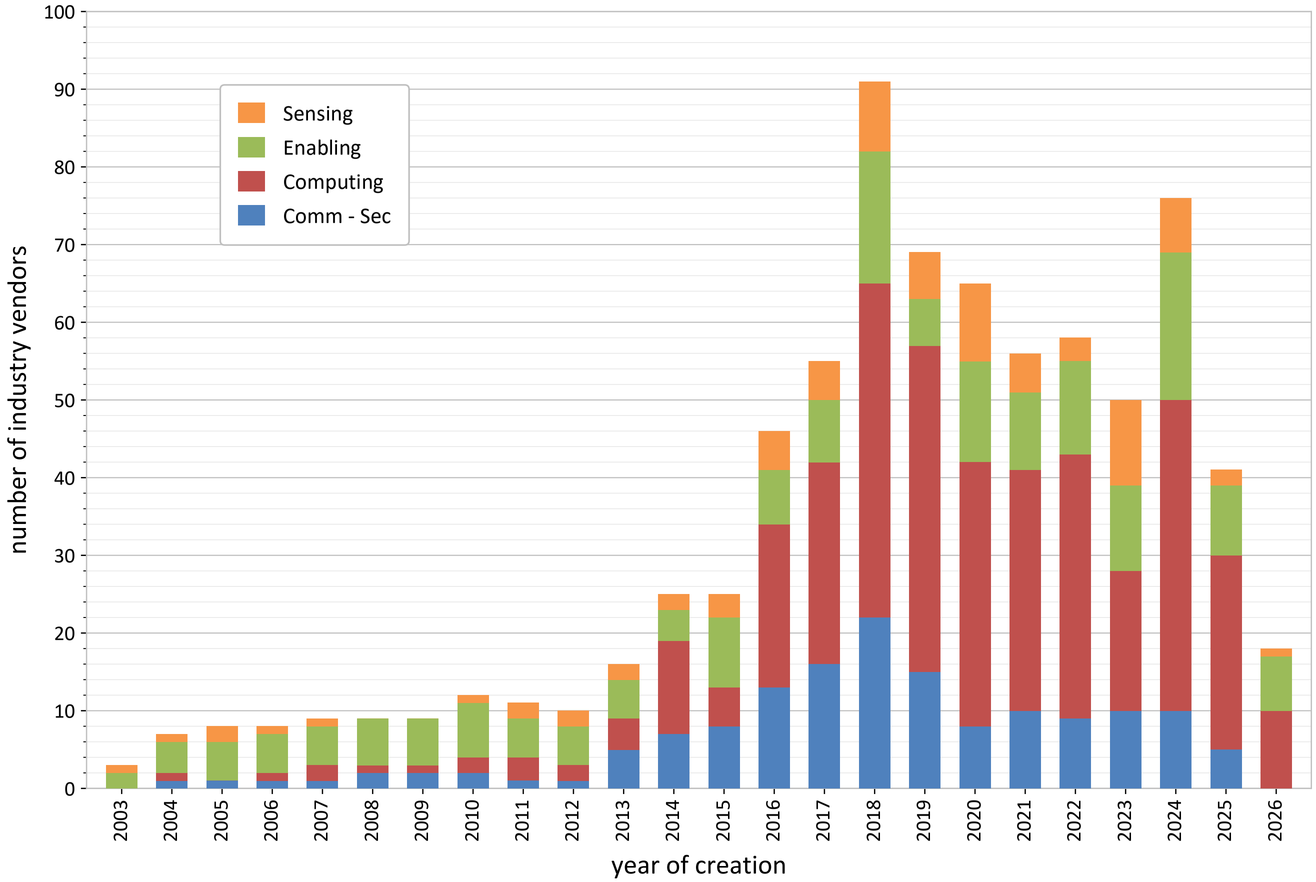
As of September 2024, 56% of worldwide startups funding went to the top 10 startups: IonQ, PsiQuantum, Rigetti, D-Wave, Xanadu, Quantinuum all from the North America, Arqit from the UK, IQM from Finland, Origin Quantum from China and Pasqal from France, while Europe has an equivalent number of companies compared to North America. These charts miss the undisclosed amounts raised by many startups, particularly from China.

If there are as many quantum startups and small businesses in mainland Europe as in North America, their visible equity funding represents only 12.5% of worldwide funding while North American companies got a hefty 60.7% as of September 2024, but it was 5% in September 2021. This doesn't include the investments from large IT corporations like IBM, Amazon, Microsoft, Google and Intel.

1.2.3 Quantum Startup incubation and acceleration

There are already a few incubation and acceleration programs for deep tech startups which host quantum startups in the world. One of the most famous is the **Creative Destruction Lab**, based in Toronto and other cities in Canada. **Xanadu** and **Nord Quantique** came out of it. Similarly, **Unit DX** is a deep tech incubator based in Bristol, UK, which started in the biotech industry and also helped some quantum startups [42]. **Duality** is a quantum dedicated startup accelerator in the USA with a sponsorship from Amazon. **Quantum Startup Foundry** is the University of Maryland accelerator which was completed in 2022 by **Q-Cat** (Quantum Catalyzer), a startup studio. **Spectral Capital Corporation** is an accelerator based in Seattle, USA, specialized in "quantum as a service" software startups.

In France, the **HEC Challenge+** program and the **Deeptech Founder** program created by the team behind the deep tech Hello Tomorrow event, accelerated a big share of France's quantum startups like Quandela, Pasqal and Alice & Bob. The Quantum Launchpad



Country	Computing	Enabling	Sensing	Comm - Sec	Total
USA	87	61	24	42	214
Germany	32	28	9	9	78
UK	21	23	10	22	76
France	22	35	9	8	74
Canada	30	13	6	19	68
China	19	9	6	11	45
India	22	5	2	4	33
Japan	16	13		4	33
the Netherlands	9	11	3	5	28
Switzerland	6	14	1	4	25
Australia	7	5	7	2	21
Israel	10	2	2	4	18
Italy	5	6	2	4	17
Denmark	5	6	3	2	16
Finland	6	7		3	16
Spain	9	3	1	3	16
Sweden	3	11	2		16
South-Korea	9	2		3	14
Singapore	8	2	1	2	13
Austria	4			4	8
Poland	4	2		2	8
Russia	1	2		4	7
Taiwan	1	2		2	5
Belgium	1	2			3
Chile	1			2	3
Estonia	2			1	3
Slovenia	1	1		1	3
UAE	2			1	3
Bulgaria	1			1	2
Czechia				2	2
Greece	2				2
Hong-Kong	2				2
Turkey		1	1		2
Brazil	1				1
Columbia	1				1
Libya	1				1
Lithuania				1	1
Luxembourg		1			1
Romania				1	1
Sri Lanka	1				1
Ukraine	1				1
Uruguay	1				1
Total	**354**	**267**	**89**	**173**	**883**

Figure 7: Chart of the creation year of small businesses and startups in "second revolution" quantum technologies. It also includes large corporations creation such technologies like Google, IBM, Microsoft and others. It doesn't include pure service companies which are often one-person shops. Notice the surge in startup creation in 2024. This sort of inventory is never complete. For example, it may miss a large number of stealth startups created in China.

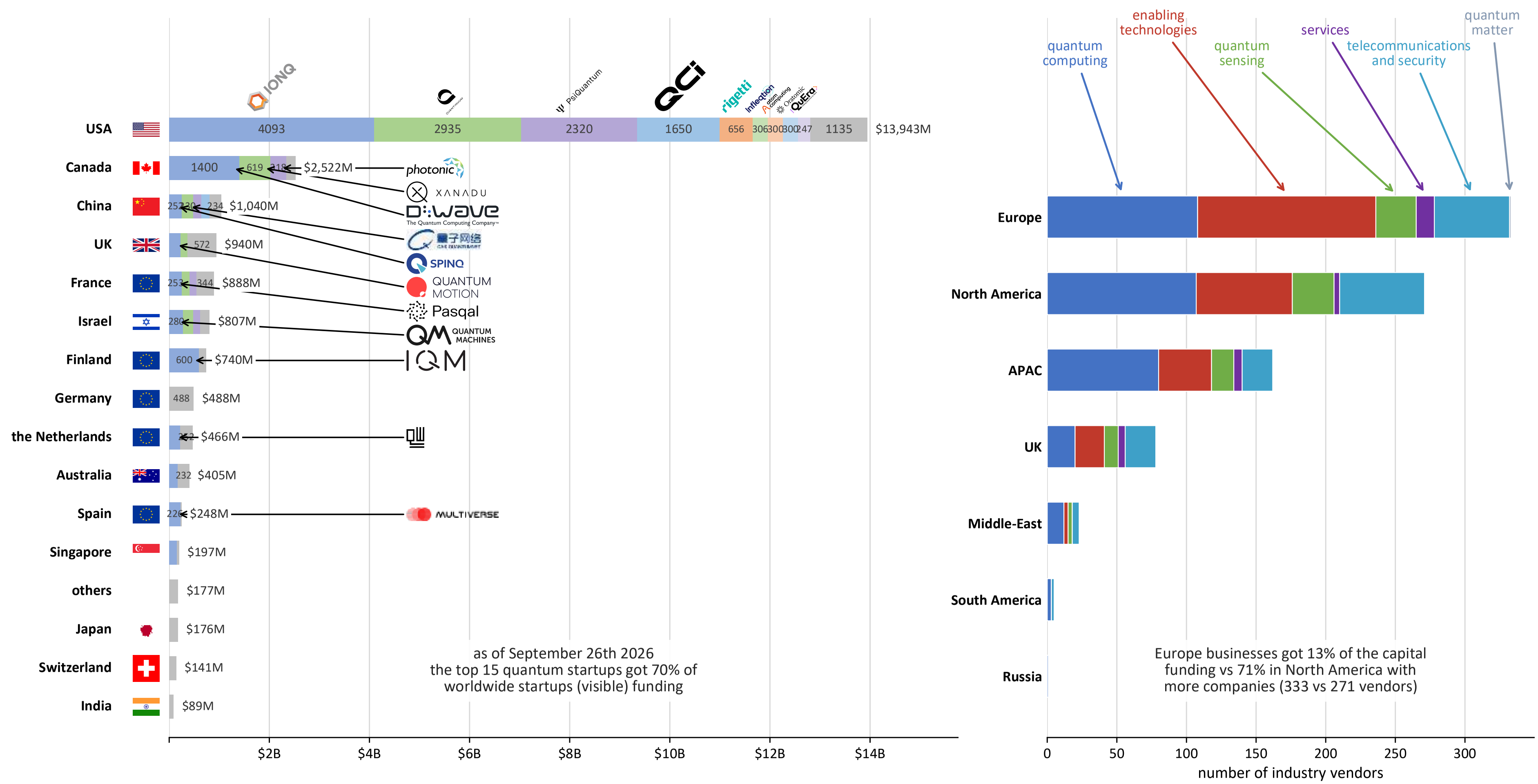


Figure 8: Chart showing where the investment money went by country and its concentration. North America concentrates about two thirds of the recorded amounts. The mechanisms that European startups face are measurable ones: access to later-stage capital, acquisition by US buyers, and relocation of headquarters. My startup database may miss some funding data from China. © Olivier Ezratty, 2021-September 2026.

startup studio followed-on, launched by Quantonation and Zaz Venture.

To create such acceleration programs, you need to be close to a critical mass pool of talents, such as a dynamic academic and research zone. In Germany, the Quantum Entrepreneurship Lab (QEL) created by the Technical University of Munich (TUM) is a one-semester course that bridges the gap between academic researchers and business students for the creation industry oriented ventures in the quantum software sector [43].

The most common scenario with startup creation starts with public academic institutions scientists who have an idea for a product based on their research. Academic labs are usually not the right place to build a product. Indeed, it requires a lot of engineering and creating relatively large teams with various backgrounds, and for a longer term work than the usual PhD and postdoc roles in research. Creating a startup is also a way to get better funding than through most of the public research calls. Still, particularly with quantum computing hardware, quantum startups are sorts of private R&D organizations, geared for the long term. They are sitting on the edge between hard tech and deep tech. Deep tech is about creating a product out of some established research. Hard tech is when science is not settled yet. Most of the time, quantum hardware startups are still doing scientific research on top of technology development and engineering. Their scientific uncertainty remains quite high. Like: how far can we go with entangling a large number of qubits? How can we fight noise to be 10 times below quantum error correction thresholds to make it possible?

Scientists turned into entrepreneurs then learn and adopt the codes of business in the startup scene. They create an investor presentation deck with the usual tricks: market problem, solution, market potential, competitive position, revenue growth forecasts, funding need and the like. They define their mission and a tagline. Value conflicts quickly arise. How to keep a scientifically ethical position while conveying some dream? When looking at many investor decks from startups who made their IPOs through a SPAC, and how they communicate, you can observe the shift toward clear overselling (see a couple examples in Figure 9).

During their first one to three years of existence, many startups are stealth and don't communicate much about what they do. Then, after a first significant funding round, they start to disclose more. They explain what they do, with variable levels of detail. Sometimes, the market codes they adopt are so ill-conceived that when looking at their website, you can't figure out what product they are designing. One reason is the influence of various entrepreneurial training. Some of them are pushing for the selling of some "business value" without even defining what the product does. This is nonsense and should be avoided. You can do it all: define the product, the market and the business value. One shouldn't be done at the expense of the other.

Then, another very weird phenomenon happens. Since investors are keen to invest in startups already having customers, quantum computing hardware startups find customers with whom they design case studies which usually run on either an emulator or with early prototypes with a couple qubits. These don't provide any quantum advantage, but they are presented as "industry case studies". Some startups even tend to present these as deployed solutions, which, as of September 2026, is not the case. The gap between the described maturity and the documented experiment then widens, and it is a non-virtuous cycle. The problem is that this consumes a significant bandwidth for the startup which should be focused on creating its hardware and middleware. Hopefully, some startups I have seen (EeroQ, Equal1) don't play this game and focus on their R&D cycles.

When a market is not there yet, a way to do "business development" is to announce various strategic partnerships with other vendors [44]. Translation: some enabling technology vendor sold some stuff to another vendor which may not have real customers but is well funded.

I will not delve here into all the steps quantum startup entrepreneurs are going through. Some media and other organizations publish various guides on this topic [45, 46].

1.2.4 Disappeared startups

How about startups who disappeared? You would guess that there are many given the technological immaturity of the sector. Well, there aren't so many out of the 300 to 400 and so created so far.

- **SeQureNet** (2008-2017, France) was a spin-off of Telecom ParisTech specialized in the distribution of long distance CV-QKDs. It had been funded within the framework of the European research project SECOQC (secure communication based on quantum cryptography). The startup was based on work done by Romain Alléaume from Telecom ParisTech, Philippe Grangier's research team at the Institute of Optics, and the Thales TRT laboratory in Palaiseau. The company closed down in 2017. It had been launched a little too early compared to the QKD market maturity [47].
- **Quantum Factory** (2018-2021, Germany) was building trapped ions computers. **NextGenQ** (2019-2021, France) was pursuing the same goal with a founder with no quantum physics skills nor any funding.
- **Black Brane Systems** (2016-2023, Canada) was a startup focused on the development of quantum machine learning solutions. The startup started as a very "stealthy" company, got some undisclosed funding in 2018 and then closed its business.
- **AppliedQubit** (2019-2021, UK) was a publisher of "quantum software for businesses".

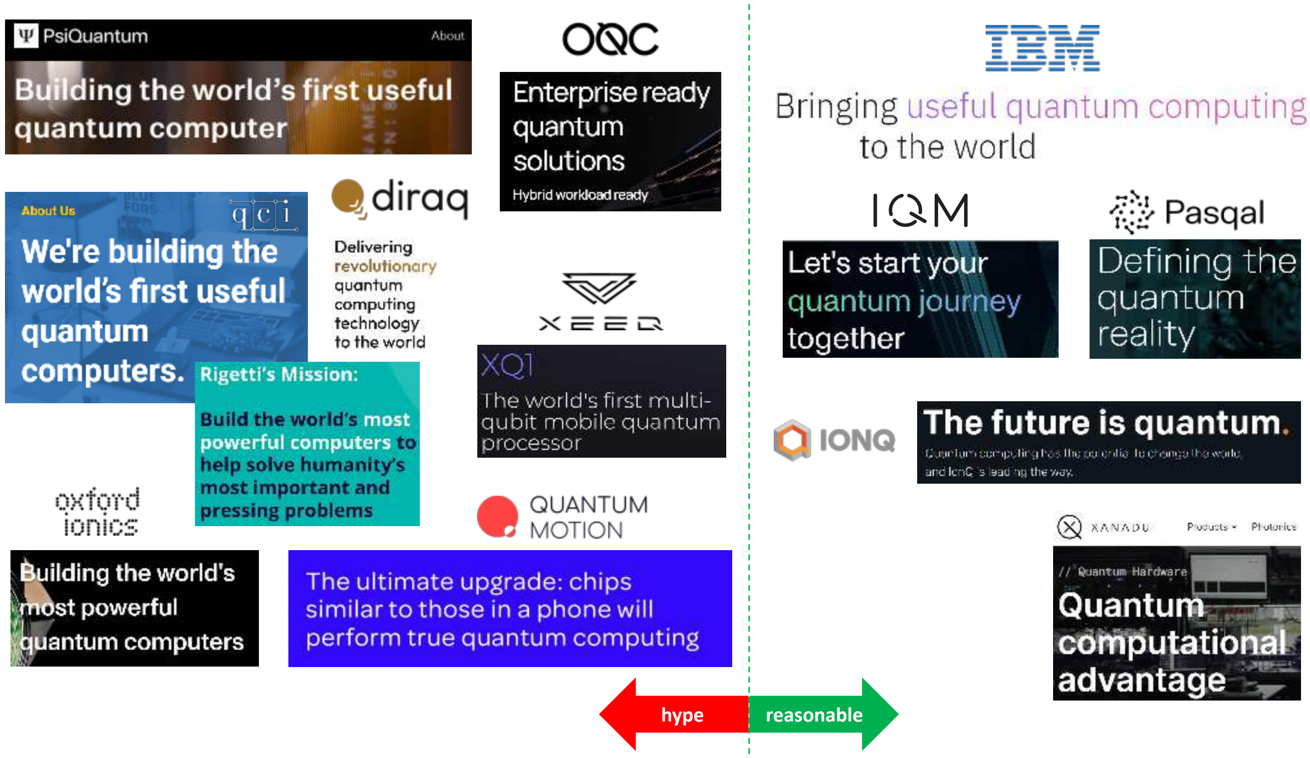


Figure 9: Compilation of various industry vendors taglines. Compilation by Olivier Ezratty, July 2024.

- **Bleximo** (2017-2023, USA) ceased operations in October 2023. **Atomtronics** (2015, Italy), **D Slit Technologies** (2018, Japan), **Xofia** (2019, USA) and **NQCG** (2024, Norway) also ceased operations. Also, many small software startups silently disappeared a couple years after being created or pivoted toward classical computing, and particularly AI.
- **CryoConcept** (2001, France) was acquired in 2020 by Air Liquide but its activity was discontinued in 2025.
- **Q-Lion** (2019, Spain) disappeared in 2024.
- **HaQien** (2019, India) disappeared around 2024/2025.
- **M Squared** (2006, UK) went bankrupt in 2025.

We also have acquired startups like **CQC** (2015, by Quantinuum in 2021), **Labber Technology** (2016, USA, by Keysight in 2020) and **Quantum Benchmark** (2017, Canada, by Keysight in 2021), **Muquans** (2011, France, by ixBlue in 2021, now Exail), **QxBranch** (2014, USA, by Rigetti in 2019), **Qu&Co** (2016, the Netherlands, merged with Pasqal in 2022), **Super.tech** (2020, USA, by ColdQuanta in 2022, now Infleqtion), **QDevil** (2016, Denmark, by Quantum Machines in 2022), **Orolia** (2005, France, by Safran in 2022), **Syrlinks** (2011, France, by Safran in 2022) and **Qubitekk** (2012, USA, by IonQ in 2024), **ID Quantique**, **Lightsynq**, **Capella Space**, **Oxford Ionics** and **Vector Atomic** (by IonQ in 2025), **Nucrypt** (by Quantum Computing Inc. in 2026) and **Quantum Circuits** (2015, USA, by D-Wave in January 2026 for $550M) [48]. So far, no quantum startup was acquired by a large IT vendor like IBM, Google and Microsoft. But to some extent, the investment of **SandboxAQ**, a spin-off from Alphabet, in August 2022, is a first [49].

1.3 Intellectual property

As quantum technologies are the focus of hundreds of startups and many large information technology vendors like IBM, Google, Microsoft, and others, patents are becoming increasingly important to safeguard businesses and even national quantum strategies and sovereignty [50]. Patents always play an offensive role and a defensive one. The defensive one enables research and industry vendors to extract commercial value from their work without being disrupted by competitors. The offensive one usually plays a role later, when the market really grows up and when royalties can be obtained from licensing your technology and contribute to growing your revenue base and to fund your own R&D efforts.

On a worldwide scale, many sorts of know-how can be patented: architectures, protocols, processes, materials, tools, algorithms and even business processes (particularly in the USA). Patent applications must demonstrate novelty, non-obviousness, usefulness, and applicability, and should be clearly described to enable replication. Applicants must disclose enough for a skilled reader to reproduce the invention, and a common practice consists of claiming broadly while describing no more than what enablement requires, which leaves the practical reproducibility of a given filing variable. Where an invention cannot be easily reverse engineered, organizations often prefer trade secret protection, which is a different regime and involves no disclosure at all. All these phenomena are amplified in the complicated field of quantum technologies, as we have seen elsewhere in this book about some Huawei and AMD patents with unusually broad claims. The complexity of the field also drives speculative projections from IP specialists on the impact of quantum computing in copyright law [51].

As they are created, quantum startups start to understand the need to get a maximum number of patents. It creates a business safety belt. It can help get good pre-money value for the company while getting term sheets from investors. Still, this work usually starts earlier, as technologies usually see the light of day in public research laboratories [52, 53]. They are also incentivized to patent their own innovation. First, to get some economic reward and second, to best protect the startups that spin out of their labs.

Patent data are being used to rank countries and companies and quantum technologies are not an exception. Published rankings usually showcase the usual dominance of the USA and China. They have their many shortcomings given it is difficult to build well-crafted database requests in the USPTO and other patent databases due to the complex lingua of quantum technologies, and sometimes, to various abuse by patent applicants.

For example, in some patent reports, China's large number of patents granted in the quantum space seems due to the abundance of patents related to spectroscopy, something that doesn't really belong to the "second quantum revolution", which should be a beacon to identify relevant patents. It may explain why China accounts for above half of all the applications in various patent jurisdictions for quantum technologies [54]. But the explanation may be elsewhere.

China is investing a lot in patenting its R&D efforts in quantum technologies, and particularly in quantum sensing and quantum communication. In that latter case, they are very active in their research labs like in Hefei, and with their first startups in the field. In the quantum computing realm, the USA seems to dominate the field. IBM, Google, D-Wave, Northrop Grumman, Microsoft and Intel are the first applicants [55].

2023 charts like the one in Figure 10 from Michel Kurek shows an uptick with China companies like Origin Quantum and Baidu who, together, have more patents than IBM. It is quite surprising since both companies are not as advanced as IBM in their superconducting qubits R&D. Another report, from the EPO (European Patents Office) shows that patents related to physical realizations of quantum computers come mainly from US vendors [56]. All this is consistent with another report coming from China's IPRdaily [57, 58]. There are also some correlations with the number of peer-reviewed scientific publications as shown in Figure 11. An OECD and PTO report from December 2025 provide more recent charts on quantum patents, but with similar phenomena [59].

While it shows that quantum computing patent applications submitted by companies in China went from 137 in September 2020 to 804 in October 2022, US companies still largely leading the field. Another 2024 report shows the trends in patents per qubit modality [60].

Europe is relatively absent from these charts. It contrasts with its significant activity in scientific publications, showing the unpreparedness of its startup ecosystem and the relative absence of large IT players in the field [61]. This was still visible in a 2025 report on quantum patents from QuIC [62]. The lack of sufficient government incentives may be at play here, but the lack of large players may be a more important explanation since these are the most active patent holders, whatever the business [63].

1.4 Government investments

What about government investments in quantum computing? A 2015 McKinsey study provided an overview of investments that likely compiled public research budgets [64]. At that time there were 1,500 researchers worldwide with a total budget of $1.5B. This number has since then increased dramatically. The USA and China are obviously leading that space. But the distribution of these investments, which probably includes both quantum cryptography and quantum computers, is intriguing for other countries. As usual, Europe was fragmented with Germany, France, the Netherlands, Finland, Italy, Spain, the United Kingdom (then, in the European Union) and Switzerland (geographically in Europe). And we have strong quantum countries in other regions like Canada, Japan, Singapore and Australia.

Quantum technologies became a geopolitical issue, with national portfolios treated as defensive and bargaining assets [65]. Governments are motivated to invest in quantum for strategic reasons: both in the idea of being able to decrypt existing or past telecommunications in the context of the activities of their intelligence services and to protect their own via quantum or post-quantum cryptography [66]. More than almost any other digital technology, quantum is therefore becoming a strategic sovereignty tool for developed countries [67]. The public authorities in these different countries have been mobilized in very different manners around quantum science and technology. Most developed country governments coordinate efforts in the quantum field. Plans with up to $4B over 5 or 10 years periods have been announced here and there (Figure 12).

It is still quite difficult to compare these investments between countries and for a couple of reasons:

- What is the **existing run-rate investment**? It is sometimes not easy to capture this data, particularly

Figure 10: Quantum computing patents view per holder, comparing the situation between 2020 and 2023. Source: Michel Kurek. March 2023.

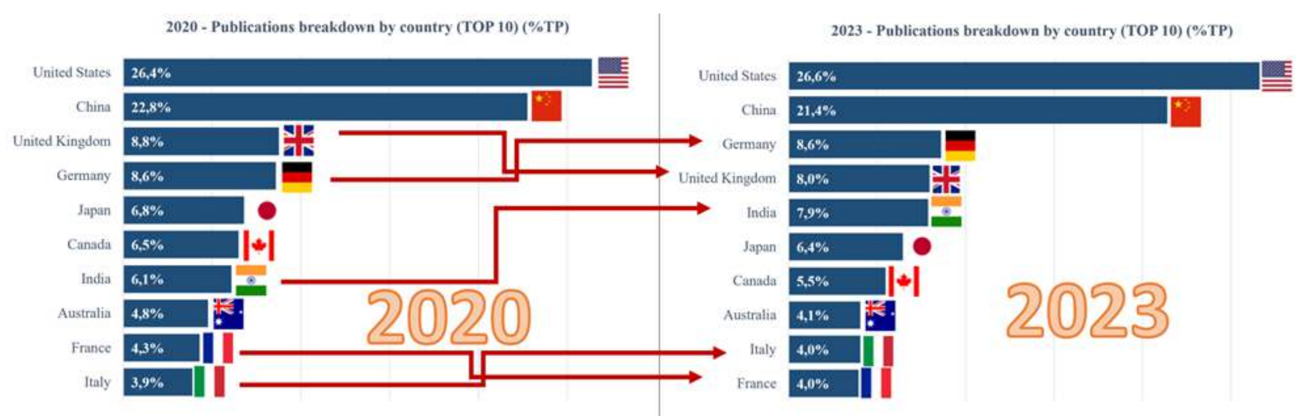


Figure 11: Comparison between 2020 and 2023 of peer-reviewed scientific publications on (quantum comput*). Source: Michel Kurek, 2024.

with highly decentralized research like in the USA and most European countries.

- What are the **undisclosed investments** in military and intelligence? It may be high in the USA and Russia. But lower in Europe, given these countries don't allocate a great share of their GDP to military expenses.

- Is the publicized funding **incremental** or does it include existing investments? You can easily embellish things with the latter accounting method or create misleading rankings of country investments like when McKinsey did showcase a chart with Germany investing more than the USA which was not true at all [68].
- Are there any **double bookings** in the showcase investments? This can easily generate misleading information.
- Are some countries **overinflating** their investment? This is a hypothesis for China's investments which have been highly confusing. We provide as accurate data as possible here.
- You can also use various metrics like **investment per GDP**, which has to be normalized over a given period of time [69].

Where's government money (your taxes) going? It usually funds the following in these various national quantum initiatives:

- Incremental **public research** funding efforts. This comes from both the country governments and sometimes, from local governments, like in Germany or Canada. It is always a good practice to support long-term research.
- Growing the **education effort** and addressing the skills shortage. This is particularly important as it deals with highly skilled roles, with a strong scientific background.
- Creating **quantum hubs** that consolidate quantum research and sometimes startup creation. These are handled within universities or public labs (like the DoE in the USA) and regions (like in Munich in Germany or Chicago in the USA) or across several of them in a thematic way (UK). This may involve some real estate and building construction. Every country wants to consolidate their quantum ecosystems. What is a quantum ecosystem? Well, like with other technology ecosystems, it contains a mix of education, academia, public research labs, industry vendors of all sizes (large, small businesses and startups; hardware, software, telecommunications and cloud, services, including enabling technologies), and users [70].
- Create **hybrid quantum-classical supercomputing centers**, based on existing supercomputing capacities, which is being done nearly everywhere, in the USA, in Europe, etc.
- Create a **quantum technologies industry** with both encouraging startup creation and encouraging existing industries to adopt quantum technologies, like in the sensing domain or just, in software development. This goes with putting in place public/private funding mechanisms for long-term investments.
- Handle **procurement** with local startups with countries indirectly funding their local quantum computing startups champions through local procurement like in Finland with IQM, Australia with Quantum Brilliance, the USA AFRL with IonQ [71], the UK with Orca and OQC, or France with Pasqal. This is often related to the hybrid quantum-classical centers already mentioned. It can also come from universities procurement like in China. Defense procurements are also being put in place like the ProQCima program in France and DARPA Quantum Benchmark Initiative in the USA, both launched in 2024. They fund the development of early stage FTQC QPUs with funding it step-by-step, planning to select fewer vendors progressively. The ProQCima program started with 5 French vendors announced in March 2024 while DARPA QBI selected 16 vendors in April 2025, all coming from 5-eyes countries (USA, UK, Canada, Australia) and one from Europe (Alice & Bob from France). In phase 2 of the program announced in November 2025, 11 vendors were kept (Atom Computing, Diraq, IBM, IonQ, Nord Quantique, Photonic, Quantinuum, Quantum Motion, QuEra, Silicon Quantum Computing and Xanadu) and the four Stage A participants that did not advance were all superconducting qubit players (Alice & Bob, Google, HPE/Qolab and Rigetti) [72].
- Foster **global partnerships** that are different in nature, between research laboratories within countries (as in the UK hubs), between particular labs across various countries, and between public and private research within the same country (CEA and Atos) or between different countries (Intel with QuTech). The raison d'être of all these partnerships can be identified: quantum computing is a complex scientific subject that cannot be mastered by a single laboratory or company. Collaboration is necessary to bring together talent from different specialties, between condensed matter physics, sensors, and control technologies, optronics, cryogenics, semiconductor production, algorithmics and software development.
- Launch **bilateral partnerships between countries** like the USA with Nordic countries, Switzerland, the UK and Australia, or France with the Netherlands, and Singapore with Finland.

An interesting phenomenon is at play in these plans. The overall scientific and vendor community has a tendency to oversell the present and future capabilities of quantum technologies and particularly quantum computing. Since one of the key motivations of governments is to improve their country's economic competitiveness, they are keener to listen to messages about growing the economy, startup and employment creation. They listen to the gospel from analysts about quantum technology market value creation which is evaluated in trillion dollars. They compute their share of this value which lands in dozens of billion dollars for individual countries if not US states or regions in other parts of the world. It

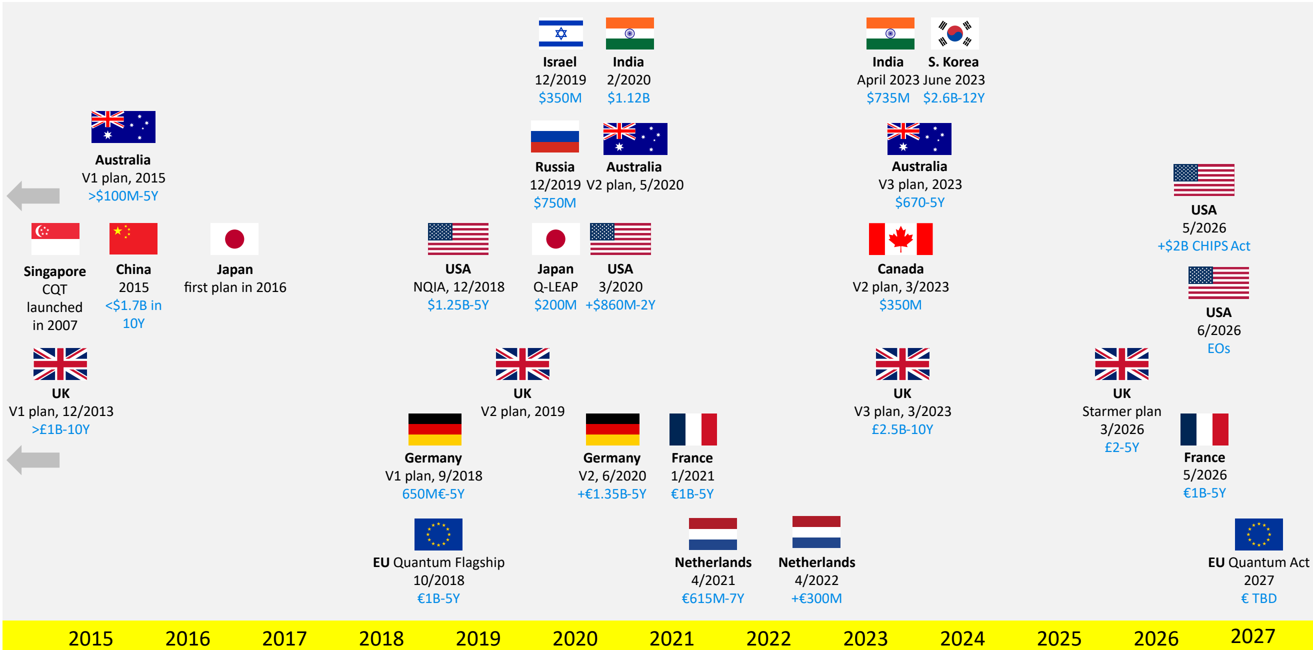


Figure 12: Main national quantum initiative plans across the years including only public funding. Some countries may be missing, particularly when they merge AI and quantum plans and don't disclose the investments specifically dedicated to quantum science and technologies. This happens for example with Japan, China and in 2026 with Canada. EO = executive order from the president. © Olivier Ezratty, 2023. Updated in September 2026.

happened in Australia in 2024 to justify the country's investment in PsiQuantum and also in one state of India in 2025 which believes quantum technologies will create a $20B economy around Bengaluru [73].

Figure 13 consolidates a more global view with public and industry investments per country or region. This is based on some guesstimates for large industry vendors in the USA (IBM, Microsoft, Google, Intel) but the public investment data is rather safe. What this shows is counter-intuitive: the first region in public investment is the European Union! It is investing more than the USA and even China. Still, the USA leads the international pack thanks to their industry investments, both from large IT vendors and from VCs in startups.

Europe's Achille's heel is not having these large IT vendors on one hand and investing less in startups in proportion to GDP. The result is some pressure put on European startups who have to find ways to get bigger fundings in Series B, C and beyond with investment sources outside the EU like the USA, Asia or even the Middle East oil countries.

This chart was created after seeing so many analysts providing wrong or outdated numbers on countries and regional public investments in quantum technologies. A BCG 2022 report 2022 tried to compare of investments across the EU, the USA and China. Their data was probably wrong. Like many, in page 14, they overestimated China's investment (at $10B when it is probably lower) and underestimated USA's which is about $5B as of mid-2025 for 5 years instead of the mentioned $2.9B [74, 75]. They also showcased a $700M plan from France in 2019 that never existed. This is puzzling. But they showcased the harsh reality of a much smaller investment in startups in the EU compared with the USA, Canada and the UK. Similar reports from the **World Economic Forum** contains the same wrong data on the USA, China, and also Japan [76]. A 2026 similar inventory by Qureca [77] contains multiple errors for Japan ($9.34B, which includes their classical semiconductor plans), the EU (€1.16B instead of 2), Sweden (with $1.45B which doesn't make much sense), Spain (with $1.28B which don't exist) and Russia (with $1.95B, which were never announced) and so on. These numbers are wrong as their aggregate. They are then used by startups in their investor presentation decks. What happens is that the most authoritative sources like McKinsey are the worse in reliability. Only a few sources provide the right numbers but don't convey the same clout [78].

An evaluation of scientific publications in quantum computing done by **Insead students** in 2018 did show, with no big surprise, that the USA, Canada and China are the first countries to publish [79].

The significant investments made by developed countries in quantum technologies raise fears that computing power could end up being concentrated in the hands of a few or even a single country or company. I don't believe this, at least not in the initial phase of development of these technologies. Knowledge of the subject is highly distributed, as are enabling technologies and strategic materials. I would rather situate the risk of concentration in a second phase of the maturation of this market, one that will see a market that was initially

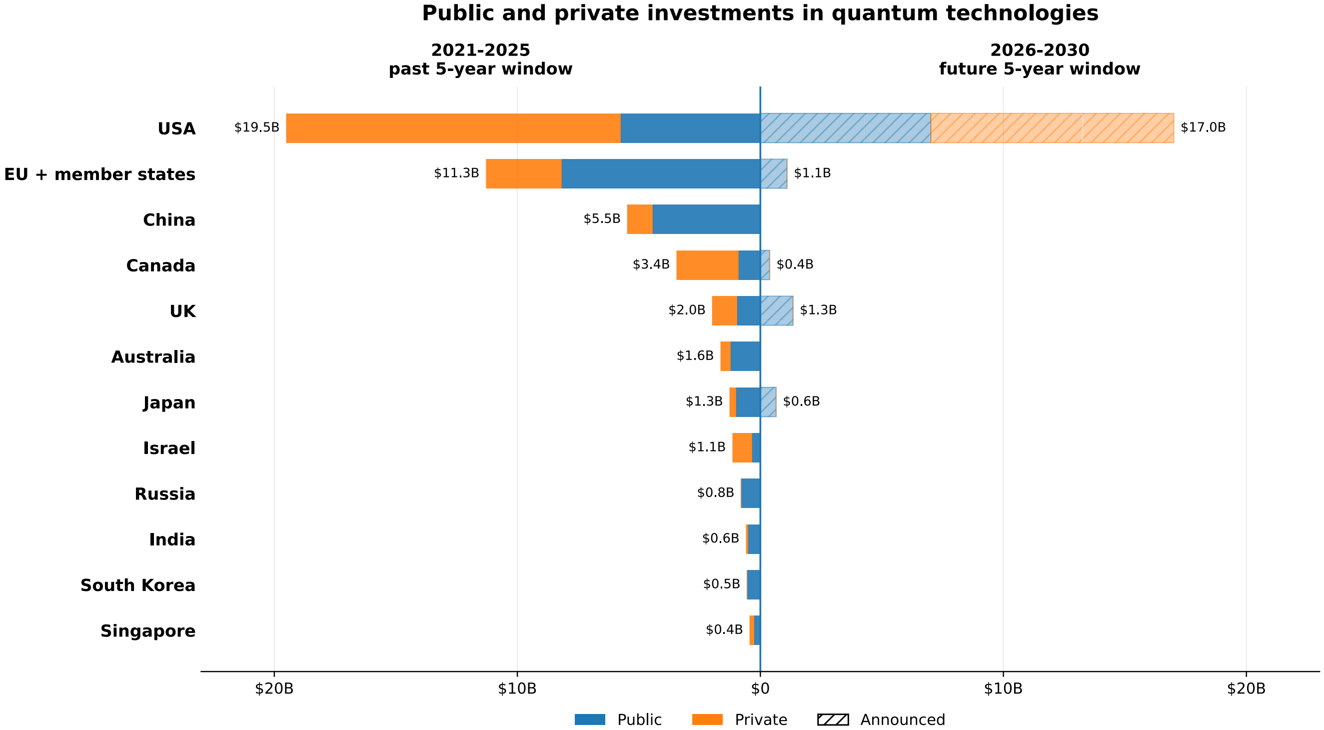


Figure 13: Consolidation of quantum technologies public and private investments with some raw estimated for large IT vendors, normalized over 5 years given some countries announce plans for 4, 5, 6, 10 and 12 years. The chart has two parts. The left side consolidate past investments that were showing up in the 2025 version of this chart, with updated numbers for startup investments, which grew significantly, particularly in the USA. The right side corresponds to new announcements and commitments for the future. It includes the $10B announcement from IBM, the $2B CHIPSACT announcement from the US Department of Commerce, plus some additional announcements for France (in the EU bar), Canada, the UK and China. Many numbers are missing here which are related to ongoing investments. Also, several countries like China and Japan are making investments embedding quantum technologies in broader deep tech categories which also contain AI, semiconductors and sometimes, even life sciences. The decomposition being undisclosed, you can't integrate any quantum specific data. Private investments on the left side include all life-to-date investments in startups. It creates a very different picture than what is commonly thought about the place of China and Europe. This data consolidation is subject to caution. Some governments announced investments that were consolidating quantum and other technologies and the chart excludes what is not quantum based on raw estimates. Accounting for variations in currency exchange rates adds some fuzziness in the comparison. China's public investment varies from $750M to $3B per year according to various estimates. I also added estimates of undisclosed defense related funding for the USA and China. © Olivier Ezratty, Updated in September 2026.

fragmented with many players concentrating through consolidation.

It will probably do so for reasons that are more macro-economic than scientific or technological, through economies of scale and the platforming of offers. This explains why it is necessary to simultaneously keep an eye on the hardware, development tools and software applications of quantum computing.

Once the main scientific and technological uncertainties are lifted, the success of each company and country will depend on the classic key success factors of technology ecosystems: execution speed, team quality, funding levels, communication, marketing, sales, the ability to promote technology platforms to a maximum number of players and on a global scale.

This is where sovereignist approaches combining protectionism of key players while ensuring maximum trade openness to the world to enable them to achieve economies of scale will have to be carefully adopted.

We will go through the details, country by country, continent by continent. With one exception, Africa, where my database records almost no supply-side activity apart from South Africa, which has an established academic presence [80]. This is a limitation of the dataset, which is built from company and public-budget disclosures, as much as it is a statement about the continent.

Figure 14 shows which country best masters quantum computing technology per qubit type. All in all, we have a good balance between the USA and the European Union, although the USA has the benefit from having large IT vendors invested in the field in superconducting (Google, IBM), silicon (Intel), trapped ions (Honeywell, IonQ) and topological qubits (Microsoft). China and Japan are less represented here, despite some interesting research, mostly since they only have a few quantum computing hardware startups.

What are the key indicators of success for countries investing in the quantum race? We'll probably have some analyst shops create their own quantum sort-of Shanghai

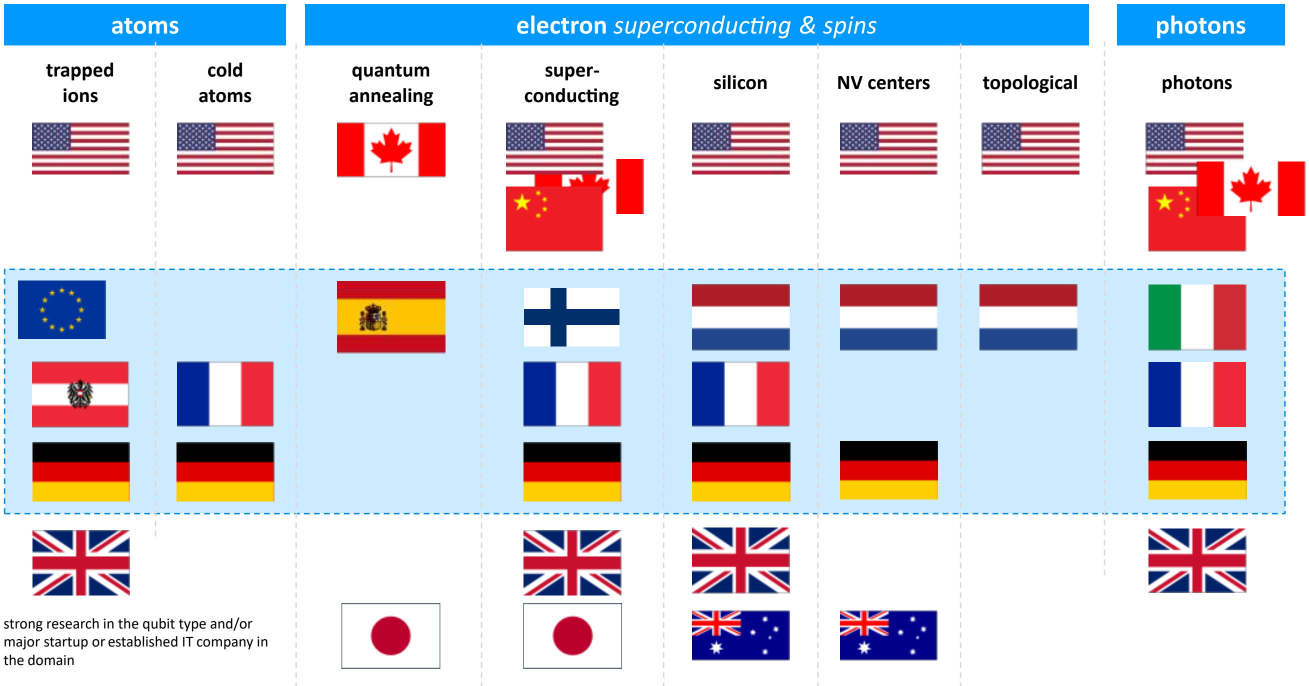


Figure 14: Key quantum computing technologies per qubit type and country of origin. © Olivier Ezratty, 2022-2023.

ranking using composite metrics: public funding, scientific publications, patents and the like, entrepreneurship spirit, number of startups, startups funding, large companies' investments, corporate adoption, skilled workforce and others. Guess what? US and China will probably rank first there, and smaller countries behind in some variable order. But what if Europe was consolidated? It would probably fare better.

1.5 Export controls

Starting in 2021, as quantum technologies were starting to mature, the US Commerce Department started to enact export restriction rules related to quantum technologies. It even listed specific China government and academic entities to which some quantum-related technologies could not be sold.

These rules have evolved over time and extended to several technologies. And not only the US is applying these rules but many other countries, mostly from the Western world, like Canada, France, the Netherlands, and Japan. One general rule here is that participating countries should not contribute to the creation by specific countries of capabilities like scalable quantum computers able to break RSA-keys or quantum sensors with some military value.

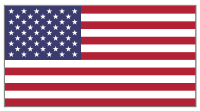
In September 2024, the U.S. Department of Commerce's Bureau of Industry and Security (BIS) published an interim final rule describing these export controls restrictions on various emerging technologies, including quantum computing [81]. These are implemented through a License Exception Implemented Export Controls (IEC). Practically, industry vendors from the participating countries will have to obtain an export authorization from their government authorities before exporting specific hardware and software products to any country.

Some entrepreneurs are showing discontent on these rules like in the UK and Australia [82]. The covered products and features are the same across the participating countries and are also publicly described by the UK [83], Canadian [84], French [85], the Netherlands and Japan governments [86]. It describes a series of quantum computer scales starting with 34 to 100 physical qubits with CNOT gate error rates below 10^{-4}, then 100 to 200 physical qubits with error rates below 10^{-3}, and so on with 1,100 to 2,000 physical qubits with CNOT error rates below $6{\times}10^{-3}$. Whether a given machine falls within these thresholds has to be assessed product by product against the exact ECCN wording of the applicable September 2024 interim final rule, which defines the qubit metric it controls and attaches notes and license requirements, and which has been revised since. The rationale behind these technological thresholds is that, if available to these countries, the related quantum computers would enable them to scale it to create quantum computers that would endanger national security. There are also restrictions on enabling technologies like cryostats with 600 μW of cooling power at below 100 mK as well as cryogenic wafer probers. In September 2025, these rules were generalized at the European Union level [87]. It "*brings the list in line with decisions taken in the multilateral Export Control Regime's Wassenaar Arrangement (WA), Missile Technology Control Regime (MTCR), Australia Group (AG) and Nuclear Supplier Group (NSG) in 2024. It also includes commitments that Member States have accepted, as members of* *the Wassenaar Arrangement, to control additional items uniformly*".

In some cases, agreements between countries will relax this process, like within the AUKUS pact connecting the USA, UK and Australia [88]. European Union member states do not have to follow this process either when selling products within the EU. It is probable that these rules will change over time as technology progresses.

1.6 North America

1.6.1 USA



The USA is leading the world in quantum technologies with four dimensions that are unique.

These are a powerful Federal government investing significant amounts in fundamental and applied research, large and well-funded Universities, giant IT companies investing a lot as well in research and industrialization, and a healthy well-funded dense startup ecosystem.

Early Quantum Coordination

The coordination of research in the different branches of quantum physics started in October 2014, when the Obama White House produced two reports [89]. Quantum technologies were split into four categories with quantum communication, sensing, computing and simulation. In 2017, industry and research lobbying started to push the federal government to launch a national quantum plan, with the U.S. House of Representatives organizing a hearing in October 2017 (video). The Democrats were concerned about the Trump administration's proposed cuts in funding for civilian research in favor of defense budget increases and tax cuts. But the US Congress increased federal research budgets for FY2018 and beyond [90].

This is one of the few cases where the Republican-controlled Congress opposed the Trump administration. This happened consistently throughout all fiscal years of the Trump administration.

The National Quantum Initiative Act was then first proposed on June 26, 2018 by the House of Representatives Science Committee (H.R. 6227, 25 pages) with an equivalent proposal coming from the Senate on the same day. This project was the result of a proposal, the National Quantum Initiative-Action Plan [91], prepared by public and private research stakeholders including IBM, Google, and Rigetti.

Quantum Lobbying

An intense lobbying campaign was carried out by several professional associations [92], with the **National Photonics Initiative** (NPI), a professional association bringing together photonics physicists and industrialists in the sector, accompanied by the lobbying firm **BGR Group**. This association, which wanted to make photonics a priority, was launched in 2012. It is sponsored by other entities: The Optical Society (now named Optica), SPIE (The International Society for Optics and Photonics), American Physical Society (APS), IEEE Photonics Society, LIA (Laser Institute of America) and many other professional associations. The lobbying was also pushed by **Jonathan Dowling** (1955-2020, American), professor of physics at Louisiana State University and a photonics specialist. He was warning about the risk to see China lead the quantum technology race. If the USA were not investing more: "*The future of the quantum Internet is in photons and the short circuiting of the development of optical quantum information processors in the United States means that the future quantum Internet will have 'Made in China' stamped all over it.*" [93].

Various quantum industry consortiums also played a role in lobbying the US government. The **Quantum Industry Coalition** brings together generalist vendors such as IBM, D-Wave, Intel, as well as some startups [94]. The founder of the Quantum Industry Coalition is Paul Stimers [95], then, a partner of K&L Gates, a US law and lobbying firm ranked as the 41st largest law firm in the world making $1B annually, and since 2023, at Holland & Knight LLP, another large US law firm. The **Quantum Alliance Initiative** launched in 2018 by the Hudson Institute, a conservative think tank, creates proposed standards for QKD and QRNG and of course advocates for the development of this industrial sector in the USA. **NIST** had also created with **SRI International** the **Quantum Economic Development Consortium** (QED-C) to develop the American quantum industry [96, 97]. It is run by Celia Merzbacher, a semiconductor industry lobbyist who worked in the White House during the Bush 43 administration. It publishes an aggregate data report on the state of the worldwide quantum ecosystems (see the 2025 edition in [98]).

National Quantum Initiative Act

In 2018, the National Quantum Initiative Act proposed the allocation of $1.275B over five years to fund civil quantum R&D, divided among the Department of Energy ($625M), NSF ($250M) and NIST which is focused on cryptography issues ($400M). It also proposed the creation of a National Quantum Coordination Office within the White House Office of Science and Technology Policy. It asked the President of the United States to create a 10-year quantum plan, the first step being a five-year plan to be delivered one year after the passage of the law. This bill was pushed by elected officials fearing that China will take over the quantum space, especially in computer security [99–102]. In September 2018, the White House published the National Strategic Overview for Quantum Information Science that included the terms of the congressional proposal [103].

They emphasized research, training of scientists and international collaboration. The bill was voted by the House in September and then by the Senate in December 2018 [104]. At last, Donald Trump signed this law on December 21, 2018.

In December 2019, the **Quantum Information Edge** alliance was created, bringing together Lawrence Berkeley National Laboratory and Sandia Labs of the Department of Energy, the University of Maryland, Duke University (North Carolina), the University of Colorado at Boulder, Harvard, Caltech, MIT and the University of New Mexico [105]. The **NPI** embarked on a new lobbying campaign at the end of 2019 and early 2020 to increase once again the federal funds allocated to research in quantum technologies [106]. In 2022, the campaign was still going on with pushes for more Federal investments in quantum technologies procurement [107].

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In February 2020, the White House published a memo from the National Quantum Coordination Office recommending the development of quantum networks [108]. In March 2020 at the beginning of the Covid pandemic, it proposed a new increase in quantum research budgets for the years 2020/2021 [109]. It included $450M for the Department of Energy, $330M for the NSF and $80M for the NIST. In August 2020, the White House announced a 30% increase in the quantum and AI budgets for fiscal year 2021. In their yearly report since then, the NQI discloses actual spending related to these plans on top of legacy investments, as shown in Figure 15, Figure 16 and Figure 17.

The US NQI (National Quantum Initiative) is run by the **National Quantum Coordination Office** (NQCO), hosted by the White House Office of Science and Technology Policy (OSTP). The first director of NQCO was Charles Tahan, who left this role to join Microsoft in 2024. The second Director is Gretchen K. Campbell.

If you wonder about the bureaucracy in your own country, here you are also with several related committees: the **National Science and Technology Council** (NSTC) Subcommittee on Quantum Information Science (SCQIS) that coordinates Federal R&D in quantum technologies, the **National Science and Technology Council** (NSTC) Subcommittee on the Economic and Security Implications of Quantum Science (ESIX) that handles economic and security implications across federal agencies [110] and the **National Quantum Initiative Advisory Committee** (NQIAC) that advises the President, the Secretary of Energy and the NSTC Subcommittee on quantum information science [111].

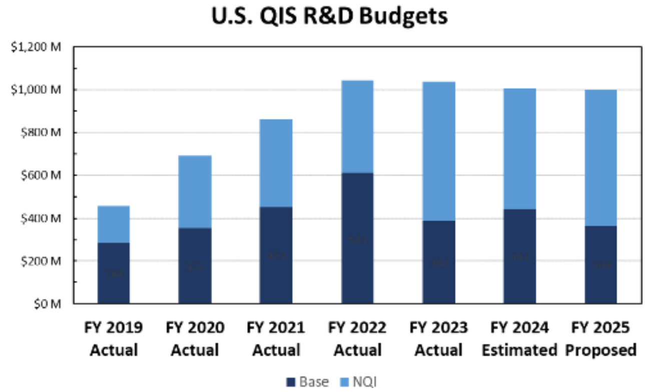


Figure 15: The most accurate Federal investment report on quantum technologies. It shows a regular funding of about a billion dollars per year. Source: [112].

In April 2021, Congress made the **Quantum for Universal Advancement in Nationwide Technology Use and Modernization** (QUANTUM) for National Security Act of 2021 proposal, which didn't directly turn into law [113]. Two Senators introduced two bills to "*better position the United States to be globally competitive in quantum information science*". It was focused on developing Department of Defense quantum networking and telecommunications use cases and workforce developments. This bill appeared as a direct response to China's massive investments in quantum telecommunications infrastructures.

It was kind of a military grade version of the National Quantum Initiative Act launched in 2018 that had mostly a civilian face despite the significant DoE funding it did incorporate [114].

In February 2022, the NQI released a report on the development of quantum technologies workforce in the USA [115]. It includes exposing the public to educational content about quantum technologies and to ensure quantum technologies are as inclusive as possible.

The USA is concerned about managing its talent pool efficiently with, simultaneously caring about its national security. It is a concern fueled by a simple fact: a significant share of the quantum research talent pool in the USA are first generation immigrants. So, they need to attract more of them.

This talent pool is largely international, and the NQI workforce reports document the dependency without inferring anything about individuals. Names do not establish nationality, citizenship or affiliation, so the only reportable data here are verified institutional affiliations and declared funding sources.

In May 2022, President Biden signed two Presidential directives [116]. The first was an Executive order enhancing the governance of the NQI with the creation of an Advisory Committee. The second was a National Security Memorandum describing how the Federal government will prepare for the adoption of PQC cybersecurity to protect it from future quantum computing cryptology threats, in line with the four algorithms that NIST se-

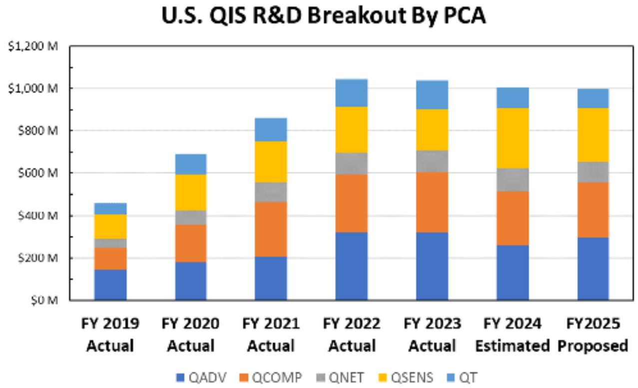


Figure 16: Split of the US federal budget per domain as of late 2024 (advanced quantum, computing, networking, sensing, technologies). Source: [112].

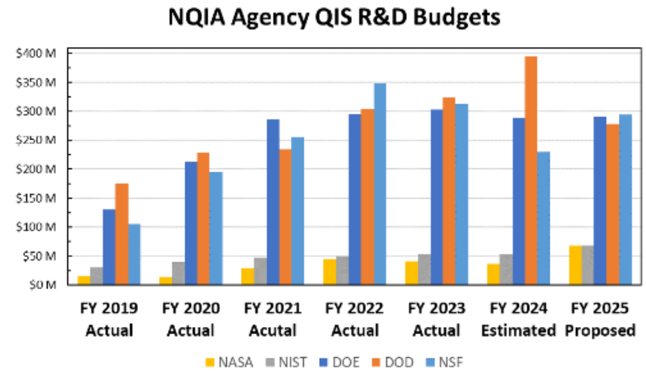


Figure 17: Split of the US federal budget per agencies, including the DoD, which consumes a significant part of this budget, roughly $280M out of $1B per year. Source: [112].

lected for standardization in July 2022, the first three of which were published as the FIPS 203, 204 and 205 standards in August 2024. The NIST is tasked with running a PQC migration project for the Federal government at the National Cybersecurity Center of Excellence and for the industry. The NSM also mandates new protections against IP theft and abuse. It led to the **Quantum Computing Cybersecurity Preparedness Act** that was signed into law in December 2022 [117].

In August 2022, the CHIPS Act was signed by POTUS with additional Federal funding of $152M per year for quantum technologies for the 2023-2027 period, going to NIST, the DoE and the NSF as usual. Consequently, it adds about $760M to the 5-year $4B run-rate of quantum federal research expenditures [118].

In a Defense bill signed by Joe Biden in 2023, Congress pushed for the prototyping of useful quantum computing applications in the NISQ realm in less than 24 months, showing a sense of impatience [119, 120]!

In a similar fashion, and a bit naively, an Iowa congressman is advocating for the inclusion of agriculture use cases in future funding appropriations for the NQIA, like for creating fertilizers [121]. More realistic work comes from a US quantum technology roadmap proposal, the **Quantum Technology Demonstration Projects** (QTDPs) [122].

International partnerships

At the international scale, the USA has signed various bilateral partnership agreement framework on quantum technologies with the UK, Australia, Switzerland, Finland, Sweden, Denmark, France, Japan, India, South Korea and still counting [123].

Export restrictions

In November 2021, the USA decided to restrict exports of quantum technology goods to China. The US Commerce Department added the Hefei National Laboratory for Physical Sciences at Microscale and QuantumCTek to the Entity List for acquiring and attempting to acquire US made items in support of military applications. The goal is to prevent China from developing counter-stealth technology like advanced radars and counter-submarine sensors. In its own stated rationale, BIS also targets US technology that would support cryptanalytic quantum computing or the development of post-quantum cryptography, which is designed to resist known quantum attacks rather than to be unbreakable [124]. Indirectly, this will impact exports from other countries related to the US, mainly from NATO. There are few dissenting voices on this exacerbated fight, that slows down international collaboration for the democratization of quantum technologies [125]. In 2023, the Biden administration enacted an executive order to forbid American investments in China in sensitive sectors, including quantum technologies [126].

Meanwhile, the Subcommittee on Quantum Information Science from the National Science & Technology Council recommended that international partnerships get some long-term funding, under the coordination of the State Department and with better interagency coordination, covering both quantum technologies and enabling technologies [127].

NQIA renewal

Discussions started in 2023 to renew the NQIA with a second 5-year round plan [128]. Interestingly, the NQIAC is advocating for removing a lot of red tape from the federal administration to accelerate projects funding [129]. Late 2023, the US Congress proposed the National Quantum Initiative Reauthorization Act to renew the NQIA with a $3,657M funding proposal from 2024 to 2028 [130]. As of July 2024, it was not yet enacted as law. It proposed a few additions to the initial 2018 NQIA like adding NASA as a funded federal agency for the creation of a Quantum Institute focused on space and aeronautics applications, an expansion of international cooperation, more emphasis on real world use cases and commercialization, funding for new quantum centers and institutes including the creation of Quantum Testbeds, and a new Quantum Instrumentation and Foundry Program, and workforce training. In August 2024, there was even a Congress bipartisan proposal to fund specifically quantum research at the DoE for $2.5B and 5 years [131]. In November, many Congress proposals where seemingly consolidated in the National Quantum Initiative Reauthorization Act with the aim of providing a $1.8B funding over 5 years, covering civil federal agencies needs (NSF, DoE, NIST, NASA) [130]. This must be added to legacy regular funding for these agencies that the NQCO is reporting every year.

Then came the new Trump administration in January 2025, sending mixed signals. Industry lobbying pushed the new administration to quickly extend NQIA funding and even to name a "quantum czar", who actually already exists at the White House [132]. The Governor of Colorado warned that the US risked falling behind the quantum race in April 2025 [133]. The Business Software Alliance urged Congress to renew the NQIA in May 2025 [134]. Meanwhile, the Trump administration froze funding for several universities including Harvard, and fired NSF employees in February 2025. As a side effect, significant civil funding for quantum research was stalled but there's no public numbers about it. In April 2025, Senator Marsha Blackburn introduced three bipartisan bills to fund the NQIA with the Defense Quantum Acceleration Act, the Quantum Sandbox for Near-Term Applications Act and the Advancing Quantum Manufacturing Act. It was just one of many such proposals coming from Congress since mid-2024. In May 2025, the White House published its FY2026 budget proposal which kept funding stable for quantum research.

One key question remains about USA's investments in quantum related to quantum communications. The country focuses on PQC with the key driving role of NIST, while the NSA's reluctance to consider QKD with a favorable eye did cast a shadow on the investments in quantum communications. As we saw in the related part of this book, it didn't prevent private and academic projects from deploying pilot QKD networks, like the Gotham project in New York with the participation of Qunnect or academic networks in various places (Boston, etc.). DARPA's focus is to develop quantum networks for applications, mainly for quantum computing and sensing interconnect. The NQCO produced a guidelines memo going in that direction in September 2024 at the end of the Biden administration [135].

2026 Executive orders. In June 2026, the Trump administration published two Executive Orders on quantum technologies. The first one *Ushering in the Next Frontier of Quantum Innovation* [136] focused on accelerating domestic quantum research, manufacturing, and commercialization. It directed key federal agencies to collaborate on developing specifications for a large-scale quantum computer and mandated an update to the National Quantum Strategy to prioritize private-sector partnerships. It also asked federal agencies to present a 5-year plan for deploying quantum sensors and networking infrastructure while expanding workforce recruitment and intelligence efforts to protect intellectual property. The second one *Securing the Nation Against Advanced Cryptographic Attacks* [137], accelerated the timeline for the federal government and its contractors to transition to PQC, with new deadlines with PQC keys to be deployed by 2030 and digital signatures by 2031. The day after, the DoE announced its Quantum Genesis plan (see below).

Military and intelligence federal agencies

Public laboratories investing in quantum computing cut across much of the federal military-industrial complex with internal research or external research funded through calls for proposals or joint laboratories with universities:

DARPA funds several programs in quantum technologies. It started with long-distance quantum communications, quantum metrology applied to imaging, neurological trauma diagnosis and PTSD. Funding goes to projects led by universities, startups and established companies [138]. In 2020, they launched a NISQ computation challenge which led to the selection of 7 research teams as part of the ONISQ program [139] and QAFS, a program on quantum annealing involving among others the Lincoln Lab from the MIT. In 2020, DARPA awarded ColdQuanta (now Infleqtion) with a $7.5M project to build a neutral atom based quantum computer. In 2023, it selected Microsoft, Atom Computing and PsiQuantum for the first phase of the Underexplored Systems for Utility-Scale Quantum Computing (US2QC) program which focused on underexplored approaches to quantum computing which could enable utility-scale operations [140, 141]. In February 2025, PsiQuantum and Microsoft were selected for the second phase of US2QC. Their stage seems to indicate that they are more advanced than the regular participants to the QBI program selected in 2024 and 2025. It is probably not the case, at least for Microsoft.

Launched in 2024, the Quantum Benchmark Initiative is a plan to determine whether a utility-grade scalable quantum computer can be manufactured and bring value exceeding costs. It is run in three phases with a plausibility stage or phase 1 (with $1M funding, 6 months), an R&D plan or phase 2 (up to $15M, 12-months) and a validation and co-design stage (up to $300M) or phase 3 [142].

In April 2025, 16 vendors were selected for the first phase of QBI across 7 different qubit modalities [143] (Figure 18). All but one (Alice & Bob) vendors came from so-called "five eyes" countries (USA, Canada, Australia, UK). HPE is the coordinator of the superconducting qubit project led by Qolab. As already said before, 11 were selected for QBI phase 2 in November 2025. Quandela was added in phase 1 in June 2026.

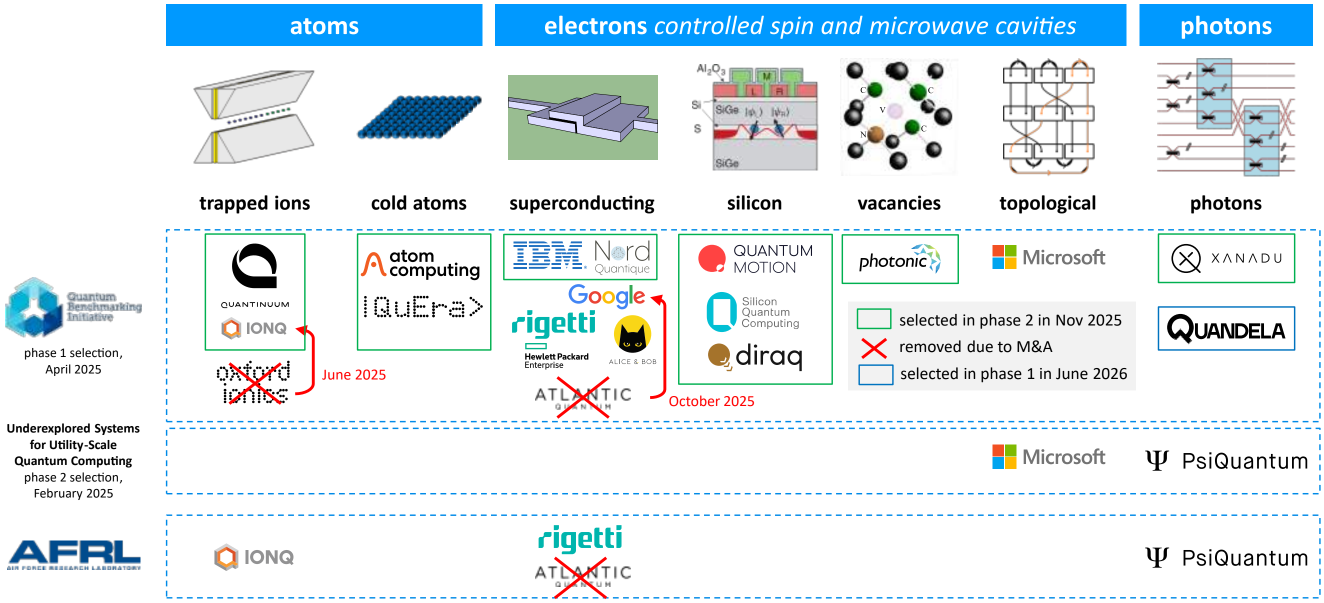


Figure 18: DARPA QBI first and second phase, US2QC second phase and AFRL selected industry vendors. Google was added in September 2025. Industry merger and acquisitions changed the landscape with Oxford Ionics being acquired by IonQ in June 2025 and Atlantic Quantum by Google in October 2025. In the phase 2 selection announced in November 2025, 11 players were kept, leaving aside for the moment Alice & Bob, Google, HPE/Qolab and Rigetti. They may be added in a subsequent selection. Quandela was selected in phase 1 in June 2026. Consolidation: Olivier Ezratty, September 2025-September 2026.

In June 2025, DARPA launched the OASIC program (Optical-Atomic System Integration & Calibration) to support industry vendors in creating chip-scale atomic testbeds focused on computing (QuEra, Harvard, MIT, University of Montana) quantum sensing (Rydberg Technologies, University of Michigan, and Purdue University), and atomic clocks (Vector Atomic and the University of Colorado).

In August 2025, DARPA launched the 4-year HARQ project (Heterogeneous Architectures for Quantum) to combine multiple qubit types in interconnected and heterogeneous quantum computing systems [144].

Air Force Research Laboratory (AFRL) is a key player at the DoD, both in quantum computing with its Quantum Information and Sciences Laboratory and quantum communications with its Quantum Communications lab. The AFRL announced in December 2020 that it planned to work with the Office of Naval Research to test quantum technologies with the "Five Eyes" countries (USA, Canada, Australia, New Zealand and UK) for a Naval exercise. The Quantum Information and Sciences Laboratory does applied research in superconducting qubits, photonic qubits, trapped ions qubits, quantum algorithms and quantum sensing. They even deployed their own superconducting qubits system prototype, created with the MIT. AFRL awarded PsiQuantum with a $22.5M contract to build a photonic quantum computer in October 2022, then, in 2023, another contract of the like, of $1.25M to Atlantic Quantum, a 5-year fab contract with Rigetti and then a $25.5M contract with IonQ in September 2023, completed by a $54.4M 4-year contract with them to study QPU interconnection and deployments aspects. In April 2023, AFRL also announced a 5-year $500M funding in quantum information science covering quantum computing and quantum interconnect. It then seems that AFRL became the quantum computing "funding by procurement" arm of the DoD, a bit like DLR in Germany.

Army Research Office also has its own quantum research program covering the entire spectrum from sensing to quantum computing, cryptography and quantum communications. The Stevens Institute of Technology in New Jersey got a $15M funding from the US Army in February 2024 for the development of some hybrid classical-quantum neural network computing system, under the leadership from Yuping Huang [145, 146]. In June 2026, alongside the Laboratory for Physical Sciences from the NSA and Maryland University, the US Army DEVCOM launched the QuantumEAGLe initiative to strengthen the US FTQC quantum computing ecosystem and accelerate commercial and research progress [147]. It seems to mix fundamental physics/hardware and applications-oriented research.

Office of Naval Research (ONR) is working on the use cases of QKDs for the Navy and on using quantum algorithms related to the Navy operational needs.

NSA is investing heavily in quantum technologies, both in the race to implement Shor's algorithm for breaking RSA-based public-key protected communications and for protecting sensitive communications with quantum keys and cryptography. This work is obviously not public. The NSA subcontracts some of its research to private companies such as Lockheed-Martin. It is also part of a joint laboratory with NIST and the University of Maryland, QuICS, which was launched in 2014.

IARPA (Intelligence Advanced Research Projects Agency) funds third-party projects on quantum computing and quantum algorithms. They run several quantum programs that happen to involve academics outside the USA. **LogiQ**'s goal is to improve the quality of qubits and involves TU Delft (the Netherlands), the University of Innsbruck, Duke University and IBM. As part of the **ELQ** (Entangled Logical Qubits) project that seeks to demonstrate high-fidelity entanglement between two error-corrected logical qubits in a fault tolerant manner, SuperMOOSE is led by ETH Zurich (Andreas Wallraff) with superconducting qubits. and **MODULARIS** led by the University of Innsbruck along with Cornelius Hempel from PSI and Jonathan Home from ETH Zurich is based on trapped ions. IARPA also funds programs conducted by third parties. It is a small agency that employs fewer than a hundred people.

Defense Innovation Unit (DIU) is another DoD branch that helps the US military make faster use of emerging commercial technologies, probably with higher TRLs than what is funded by DARPA. It currently funds a Transition of Quantum Sensors (TQS) program to drive in a multi-year program the adoption of advanced quantum sensors, particularly inertial quantum sensors [148].

Department of Defense. The above organizations are all part of the US DoD. Seemingly, there was not much coordination of the DoD quantum strategy and operations across its different branches. At the beginning of 2024, calls for a better integration of the DoD quantum efforts started to become visible [149]. Then, in April, Elise Stefanik, a GOP House member, and Marsha Blackburn, a GOP member of the Senate, introduced the "Defense Quantum Acceleration Act" proposal that proposed the creation of a DoD Principal Quantum Adviser and the creation of a "National defense quantum information science joint center of excellence" at the Pentagon [150]. It also calls for a strengthening of the efforts as part of the USA/UK/Australia AUKUS deal from 2021. Stefanik had in sight the potential benefits of such an initiative for her own county in Upstate New York but, hopefully, for the whole USA as well [151].

A little after, the QED-C organized a quantum showcase in Congress to raise awareness on the domain [152]. As of July 2024, the law was not yet enacted.

Federal civil agencies

In quantum science and technologies, the key Federal civil agencies are the Department of Energy, the NIST, the NSF and NASA.

Department of Energy (DoE) is doing research in all fields of quantum technologies: computing, sensing and communications [153]. It has many research laboratories that are big consumers of supercomputing capacities like in the Oak Ridge (Tennessee), Argonne Labs (Chicago), the Los Alamos National Laboratory (LANL) and its Quantum Institute (QI) launched in 2002 that also invests in quantum computing and cryptography and Sandia National Laboratories (New Mexico), which conducts applied research in all areas of quantum physics. They fund research at UNSW (Australia) as well as in Maryland. The DoE launched a call for proposals to award 158 grants totaling $32M to 118 SMEs through the SBIR program. The grants are delivered in two phases, a first phase of $200K followed by a second phase of $1.1M for the best projects, spread over a period of two and a half years.

The DoE initiated in August 2020 the funding of five research centers in quantum technologies, all led by its own national laboratories, with a total of $625M coming from the DoE and the rest from relevant institutions and the industry (IBM, Microsoft, Intel, Lockheed Martin) [154]. These new research centers are **Q-NEXT** (Next Generation Quantum Science and Engineering Center, David Awschalom) led by Argonne National Laboratory which focuses on the industrialization of quantum hardware, **C^{2}QA** (Co-design Center for Quantum Advantage, Steve Girvin) led by the DoE Brookhaven National Laboratory which will focus on ways to achieve quantum advantage in scientific applications, the **SQMS** (Superconducting Quantum Materials and Systems Center, Anna Grassellino) led by the Fermi National Accelerator Laboratory which will focus on superconducting qubits, the **QSA** (Quantum Systems Accelerator Center, Irfan Siddiqi) led by the Lawrence Berkeley National Laboratory which works on quantum computing hardware and software along with 250 experts from 14 other US and Canada research institutions [155] and the **QSC** (Quantum Science Center, David Dean) led by the Oak Ridge National Laboratory which will focus on quantum computing scalability issues. In 2026, Los Alamos National Laboratory created its own quantum computing research center, whose scientific program is coordinated by Carleton Coffrin [156].

The DoE then launched a $30M program in March 2021 on nanoscale matter and their use case in energy applications. It did fund the five existing DoE Nanoscale Science Research Centers and their research partners over 3 years. The awards size is between $1M and $2.5M [157]. It also launched a $25M program in April 2021 on Quantum Internet including quantum repeaters, quantum memory and quantum communication protocols, opened to the 17 DoE labs. In January 2025, the DoE also announced a funding of $71M for 25 high-energy physics (HEP) projects using quantum information science.

In 2026, the DoE launched first an RFI for a "Scientifically Relevant Fault-Tolerant Quantum Computing Systems" supporting a minimum of 150 to 250 logical qubits and a universal gate set, 10^5 T or Toffoli gates, and a logical error rate of 10^{-8} per operation before 2028 [158]. The request for information was published on May 12^{th} with a response due date for June 10^{th}.

They were in a hurry to announce the Quantum Genesis program on June 23rd after the two POTUS Executive Orders [159]. The Quantum Genesis program's goal is to deliver what was in the RFI questions as part of the DOE Q Competition and create a system for a future National Quantum Supercomputing User Facility dedicated to scientific computing. It was also aligned with the report commissioned in April 2026 and published in September 2026 by the SCAC subcommittee [160]. In September 2026, the DoE also formally launched a competition to build an FTQC quantum system with up to $215M of funding, and spread over two phases, and for the delivering of a 150 to 200 logical qubits system [161]. Compared to the DARPA QBI competition, this competition targets short term goals (2028) while DARPA is focused on longer term for an utility grade system in 2033.

Alongside this hardware bet, the DoE is also funding research for the development of quantum applications. The related budget was not made public although, the applications goal was already part of a $293M plan announced in February 2026 for the funding of AI and quantum application research [162]. Behind this story is Dario Gil, the Undersecretary of Science for the DoE since September 2025, formerly the director of research at IBM, replaced since then by Jay Gambetta. It means the responses to the RFI from some vendors were positive. Based on published roadmaps, you can guess that it came at least from some cold atoms and trapped ion vendors.

NSF funds various research projects [163]. In 2019, it launched a call for **Quantum Leap Challenge Institutes**, to fund research institutes conducting interdisciplinary research projects advancing the state of the art in quantum technologies [164]. Their format is reminiscent of the UK quantum program hubs. Three hubs were selected in July 2020 for a total of $75M spread over five years: a first dedicated to quantum sensing led by the University of Colorado, a second dedicated to quantum computing led by the University of Illinois-Urbana-Champaign and a third also on quantum computing and rather software side led by the University of Berkeley [165]. These three hubs bring together 16 academic institutions, 8 national laboratories and 22 industrial partners. In August 2026, the NSF added a 5-year $290M funding for 8 Quantum Leap Challenge Institutes, each getting $28M to $37M [166],, including the existing 5 and 3 new ones.

On top of that, the NSF is also funding the consolidation of other initiatives like the one around Purdue University in Indiana, which launched in July 2021 a new Center for Quantum Technologies funded by the NSF with an established team of 50 quantum scientists and engineers coming from various research institutions in Indiana working on many quantum fields (atomic and molecular optics, solid state quantum systems, quantum nanophotonics, quantum information and communication).

NIST is a federal research institute within the Department of Commerce. Its historical role is sensing and the definition of weights and measures. Its work on atomic clocks naturally led it to look after quantum technologies. It has an annual budget of $1.2B and employs 3,400 people in two campuses, one in Boulder, Colorado and another one in Maryland, next door to the University of Maryland and north of Washington DC. Several of its research groups are dedicated to quantum technologies with the Quantum Processing Group for quantum computing, another for spintronics, one for quantum sensing and another for superconducting electronics. On top of this, the Computer Security Division of the Information Technology Laboratory (ITL) manages the call for tenders on the standardization of PQC (Post-Quantum Cryptography) [167]. NIST's PQC standardization strategy has wide implications. It will sediment the market around a dozen standards that will be royalty-free. This may favor large cybersecurity vendors instead of enabling new players to disrupt the market.

NIST is also a stakeholder in and a cofounder of three joint laboratories with major universities, each located near its own campuses in the states of Colorado and Maryland, the JQI, QuICS with the NSA and JILA with the University of Colorado.

The University of Maryland's **Joint Quantum Institute** (JQI), established in 2006 is a fundamental quantum physics laboratory. It is a joint NIST/University of Maryland laboratory. NIST's most famous alumnus in this domain is David Wineland, a long-time specialist in ion control by laser cooling, who worked at the NIST Boulder campus and won the Nobel prize in Physics in 2012 along with Serge Haroche. It is in this laboratory that the IonQ was launched in 2015 out of Christopher Monroe's team. Many alumni from this lab also joined Honeywell's quantum team in Denver, Colorado. This laboratory employs 35 permanent researchers, 55 postdocs and 85 PhD students with an annual budget of $6M supplemented by various external funding. NIST employs a fourth Nobel Prize winner in physics, William D. Phillips for his work on the laser cooling and trapping of atoms, including the Zeeman slower, awarded in 1997.

The **Joint Center for Quantum Information and Computer Science** (QuICS) at the University of Maryland (UMD) launched in 2014 in partnership with NSA's research directorate that focuses on quantum computing architectures, algorithms and complexity theories to complement the JQI.

The **JILA** at the University of Colorado at Boulder which is dedicated to sensing technologies. It was created in 1962 as the Joint Institute for Laboratory Astrophysics but they now use only the acronym without this meaning given their extended activities beyond astrophysics. It is home to two Nobel Prize winners: Eric Cornell (in 2001, for his work on Bose-Einstein condensates) and John Hall (in 2005, for his work on laser frequency combs).

In May 2026, the Department of Commerce and NIST signed nine letters of intent totaling $2,013M for quantum chips manufacturing as part of the CHIPS and Science Act voted during the Biden administration [168]. Half of this ($1B) is a grant for the creation of Anderon, a standalone pure-play 300 mm quantum wafer foundry subsidiary of IBM based in Albany, New York State, IBM matching it with $1B of its own cash. The rest is made of equity funding in exchange for minority non-controlling stakes, with $375M for GlobalFoundries to set up a multi-modality quantum foundry covering superconducting, trapped-ion, photonic, topological and silicon-spin architectures, then $100M each for Atom Computing, D-Wave, Infleqtion, PsiQuantum, Quantinuum and Rigetti, and $38M for Diraq. Missing in this game are IonQ (self-sufficient with SkyWater) and Google (who explicitly declared its willingness to keep things simple and avoid this sort of deal, plus, they're not short in cash)

In June 2026, NIST announced the creation of the Quantum Manufacturing Engineering Center (QMEC) to accelerate manufacturing of quantum sensors, to be operated by SRI.

NASA created in 2013 the Quantum Artificial Intelligence Laboratory (QuAIL) jointly with Google, located at the Ames Research Center near the Google's headquarters in Mountain View to explore the field of quantum algorithms, in particular on a D-Wave quantum annealer they acquired and installed there.

Department of Commerce. In October 2023, the DoC Economic Development Administration (EDA) designated 31 Tech Hubs in regions across the country, with two focused on quantum information science, Elevate Quantum Tech Hub across Colorado and New Mexico [169] and the Bloch Tech Hub in Chicago [170]. Elevate Quantum Tech Hub received a total of federal $41M funding for the buildup of quantum labs and fabs, and workforce training efforts [171]. The promise is to create 10,000 quantum jobs and activate over $2B of private funding in quantum technologies by 2030 on top of establishing "world-class open-access quantum facilities" for hardware and fabrication. These are akin to the overpromises made to politicians all over the world. If you added them all, it would make trillions of dollars.

USA regional quantum ecosystems

The main geographical quantum hubs in the USA combine a mix of national labs like those from the DoE or NIST, Universities and industry vendors. State governments are investing in the development of their quantum ecosystems and the competition is strong within the USA to capture the attention, the talents and the companies. So here we are:

- **California** with the Silicon Valley and in the Los Angeles area, with Stanford, UCLA (which got a $5M grant from Boeing to support the Center for Quantum Science and Engineering in May 2022), Caltech (with the creation in 2022 of the "Dr. Allen and Charlotte Ginsburg Center for Quantum Precision Measurement" thanks to a donation), UCSB, plus the labs from Google, Microsoft and Amazon, and also Rigetti. The Los Angeles area seems on par with the Silicon Valley which is not at all the case in classical computing.
- **Massachusetts** with the MIT, Harvard, UMass Amherst, Atlantic Quantum and QuEra [172]. In May 2026, the state government funded the creation of the MIT Quantum Systems Laboratory with $25M. The lab will host the MIT Quantum Initiative (or QMIT) launched in December 2025, and is an addition to the MIT.nano and MIT Lincoln Laboratory's SQUILL foundries, the last one being cofunded by DARPA and the Laboratory for Physical Sciences from NSA.
- **Colorado** at Boulder, with Quantinuum, NIST and the University of Colorado Boulder (which created the Qubit Quantum Initiative to foster interdisciplinary quantum research in a 4-floor building) and the Elevate Quantum Tech Hub we just mentioned above. The Colorado governor even signed a quantum industry bill, that added a $74M state funding for the Elevate Quantum Tech Hub [173, 174], in the form of $44M refundable tax credits and $30M loan loss reserve to improve access to funding for small and medium quantum companies. In 2026, Google created a lab in Boulder, with the team of Adam Kaufman from JILA and CU Boulder.
- **Connecticut** with its very influential Yale University in New Haven, particularly in the superconducting qubit domain, and Quantum Circuits Inc. (QCI), a spin-out from Yale created in 2015 by Robert Schoelkopf, Michel Devoret and Luigi Frunzio, which was acquired by D-Wave in January 2026 for $550M [48]. Yale and the University of Connecticut want to establish a quantum hub in the state with the help of NSF funding, starting with an initial grant of $1M.
- **Illinois/Chicago** with two DoE labs (Fermilab [175] and Argonne), several universities and the Chicago Quantum Exchange ecosystem which regroups these labs, the University of Chicago, the University of Illinois, the University of Wisconsin and Northwestern University [176, 177]. The University of Chicago Polsky Center and the Chicago Quantum Exchange launched the first national quantum startups accelerator program in April 2021. In September 2022, the NRF (National Research Foundation of South Korea) awarded $1M (over 5 years) to David Awschalom and Liang Jiang from the University of Chicago to create a joint lab, "The Center for Quantum Error Correction". The University is also partnering with IBM and Google as part of a partnership announced in May 2023 with the University of Tokyo with the goal to create a superconducting QPU with 100,000 qubits. In neighboring Michigan, the University of Michigan

announced in May 2023 an investment of $55M in its new Quantum Research Institute, starting with 8 new principal investigators. In 2024, the Bloch Quantum Tech Hub was launched with yet to be announced funding by the Department of Commerce EDA [178]. This launch took place with some empathetic support from the Illinois governor, promising the creation of 30,000 jobs in the state [179]. In May 2024, there were even unconfirmed rumors about the launch of a sort of Quantum Manhattan project with the creation of a $20B campus and with a $60B economic impact by 2035 [180, 181]. This was seemingly part of an effort from PsiQuantum to get some funding from the state, and to even build a $300M facility [182]. The governor even committed a funding of $500M for quantum. Guess what? Australia bought first PsiQuantum exaggerated promises and their project in Chicago seems less funded. At last, in July 2024, DARPA funded the creation of a quantum-testing facility in Chicago, with a funding of $140M matched by a similar amount from Illinois state [183]. All of this will take place at the Illinois Quantum & Microelectronics Park (IQMP), including the National Quantum Facility (NQF) which will provide cryogenic services with up to 20 traditional cryostats for IBM, Pasqal, Infleqtion, Diraq and potential other vendors, the PsiQuantum datacenter which will host a prototype and three final FTQC systems [184] and the National Quantum Algorithm Center (NQAC).

- **New York State** with Cornell, Columbia, the Flatiron Institute, IBM, GlobalFoundries and SEEQC (Princeton sits just across the state line, in New Jersey). In 2026, the state opened a $60M RFP to fund up to four quantum technology hubs.

- **Maryland** with the University of Maryland, IonQ, NIST, NSA, the Quantum Catalyzer quantum startups accelerator (Q-CAT) launched by Ronald Walsworth that creates quantum startups from scratch and the National Quantum Laboratory Qlab from the University of Maryland, established in partnership with IonQ. In January 2025, the governor of Maryland launched a five-year $1B investment plan for quantum in his state [185]. Looking at the details, the real secured budget was $27.5M. There was also $58M private investments and $185.4M state funding for the creation of a quantum lab on the University of Maryland campus, where two third of the funding goes to some construction research lab that is not related to quantum technologies. After being reluctant, they also funded IonQ for about $10M. Most of the funding is supposed to come from private investors and companies. UMD (University of Maryland) also launched the Maryland Institute for Quantum Applications, a research center for defense and intelligence related use cases, in relation to the Applied Research Laboratory for Intelligence and Security (ARLIS). Also, in September 2025, Microsoft announced the creation of a quantum R&D center in Maryland. It looks that this is more a technical center to support the adoption of Microsoft technologies than a real R&D center [186].

- **Tennessee** and **New Mexico** host three DoE labs and their quantum research centers. New Mexico is part of the Elevate Quantum Tech Hub funded by the Department of Commerce EDA. In 2026, Tennessee launched a $24M plan to support the Tennessee Quantum Initiative, focused on workforce training.

- **Washington State** with the University of Washington and the Pacific NorthWestern DoE lab, given Microsoft and Amazon HQ are there but their quantum teams mostly sit in part in Santa Barbara, in Southern California.

- **South Carolina** which modestly provided $15M of funding in 2024 to the South Carolina Quantum Association to provide quantum computer access to students [187]. It created the Qllianse coalition with to build "south-east" quantum ecosystem. Participating vendors include IonQ, QuEra, Xanadu and Pasqal. A report published in February 2025 by an economist from the University of South Carolina forecasted that quantum technologies would create $8.5B of economic value and 20K new jobs statewide [188]. This is as far-fetched as McKinsey and BCG economic value forecasts.

- Lesser developed ecosystems in **Pennsylvania** (PennState, Pittsburgh University with its Western Pennsylvania Quantum Information Core - WPQIC, launched in May 2023 [189]), **Texas** (with the University of Texas Austin [190], the sponsoring of the Lindau Nobel laureates meeting in July 2024, and the passing of a Texas Quantum Initiative act in the state House in June 2025), **Indiana** (Purdue University, Midwest Quantum Collaboratory, a joint lab between Purdue University, Michigan State University and University of Michigan), **Virginia** (Virginia Tech), **Georgia** (GeorgiaTech), **Florida** (Florida State University, IonQ with the acquisition of SkyWater and D-Wave).

The map in Figure 20 showcases this geographical distribution of USA's quantum technology R&D areas. The distribution is more even than in classical digital technologies, which are more concentrated on the country's West Coast and particularly in the Silicon Valley.

Finally, let us recall a market reality that echoes economist **Maria Mazzucato**'s thesis on the public origin of technological innovations: the major American players are sourcing at different levels and throughout the USA and the world to advance their quantum technologies. Figure 21 is a good illustration of this phenomenon, showing how large IT players like IBM, Google, Intel, Microsoft, Amazon, Honeywell and even IonQ, surf on the work of publicly funded research labs not only in the USA but throughout the world. The last example being the creation of a Google AI lab in

Australia in partnership with UNSW, the University of Sydney, Macquarie University and UTS, for the development of quantum applications.

1.6.2 Canada

In Canada, a parallel can be drawn between artificial intelligence and quantum technologies.

In both cases, the country's influence is far greater than its economic weight, at the basic research level, with a healthy startup ecosystem and best-in-class investment per capita. This is due to constant and early-stage investments in research by government and universities and to a certain entrepreneurial dynamism.

Canada has two great quantum stars in research with **Gilles Brassard** from the University of Montreal, who is, along with **Charles Bennett** of IBM Research, the co-inventor of QKD's BB84 protocol, and also **Alexandre Blais** from Sherbrooke University, who co-created cQED at Yale University.

Research

Canada is distinguished by a strong investment in basic research in quantum computing, including more than $1B of public investment over a decade, mainly in three institutions [191]. Let's look at the Canadian ecosystem from East to West (Figure 22).

In **Québec**, the quantum ecosystem is spread over at least four places, Montreal, Bromont, Sherbrooke and the city of Québec. Polytechnique Montréal is home to the quantum INTRIQ laboratory, specializing in quantum photonics. Bromont is a skills and infrastructure center in semiconductors assembly and testing with the C2MI (Miqro Innovation Collaborative Center), which partners with an IBM assembly line that is next-door. IBM installed one of its quantum computers there as part of a regional investment of CAN $68M and CAN $62M from IBM. The ibm-quebec 127 qubit QPU was inaugurated in September 2023. PINQ² (Platform for Digital and Quantum Innovation of Quebec) will facilitate the access to the 127-qubit IBM QPU to researchers and other users. In Sherbrooke, the University is the home of 3IT (Institut interdisciplinaire d'innovation technologique) which runs a small superconducting component fab.

The University of Sherbrooke Quantum Institute, near Montreal hosts researchers like Alexandre Blais and startups.

Figure 19: Institut Quantique in Sherbrooke, which hosted among other things the startup Nord Quantique (as of 2023). Photo: Olivier Ezratty, May 2023.

SBTech (metrology), Nord Quantique (GKP bosonic qubits based quantum computing) and Quantic (sensing) came out of there. In February 2022, the Québec Region announced an impressive plan of public/private investment of C$435M (about US $350M) in the Sherbrooke region. It includes C$131M to create "Sherbrooke Quantique" coming from the region and the rest from industry investors including IBM. As part of this program, the DistriQ Espace quantique 1 opened in fall 2023 with 5,000 m^2 of facilities (offices, conference rooms, coworking spaces, a quantum studio built with Quantonation, assembly zones, hosting quantum computer dilution fridges, datacenters). It will host teams from 1Qbit, Multiverse and Pasqal. Pasqal has a subsidiary there which includes a QPU assembly line and a future cloud data center covering the North American market. The rest of the region's investments (about $62M) covers various research funding and real-estate investments, including the innovation platform PINQ^2. 1QBit, Pasqal and Eidos-Sherbrooke installment in Sherbrooke will represent an investment of C$205M over 5 years. Eidos-Sherbrooke is a video games studio that is planning to use quantum computing.

A region funding of CAN $3.6M out of a total of CAN $8.1M is allocated to setting up a collaborative platform on quantum software design with CMC Microsystems who also manufactures some electronic components (CMOS down to 22 nm density, III-V, Si Photonics, superconducting).

In November 2023, the Québec region announced a CAN $65.3M funding for five projects at DistriQ, including a loan of $11M to Pasqal for the establishment of their assembly line there [192, 193].

In **Ontario**, the quantum ecosystem is centered around Toronto and Waterloo.

The University of Waterloo hosts its Institute for Quantum Computing, near Toronto.

It obtained $120M in 2017 to fund its various quantum research institutes, complemented by $53M in Australian funding from UNSW, the operator Telstra and the Commonwealth Bank of Australia. The IQC does

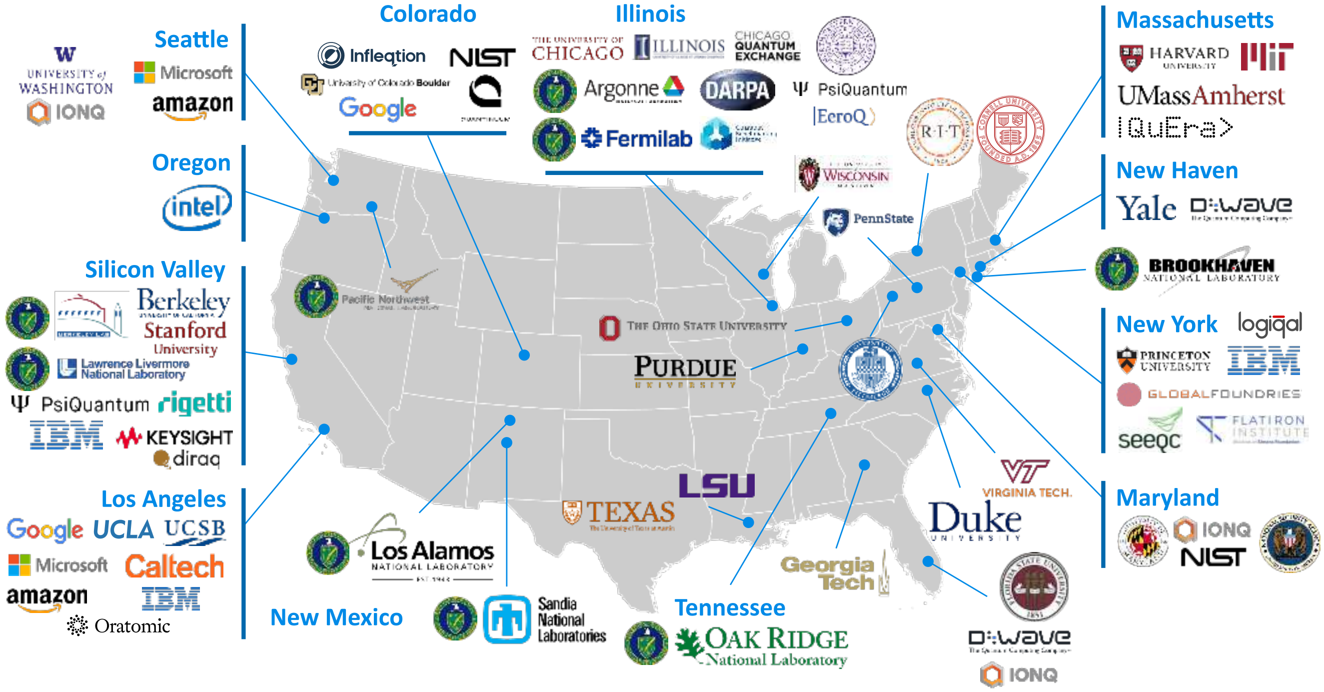


Figure 20: Map of the USA quantum ecosystem. © Olivier Ezratty, 2022-September 2026.

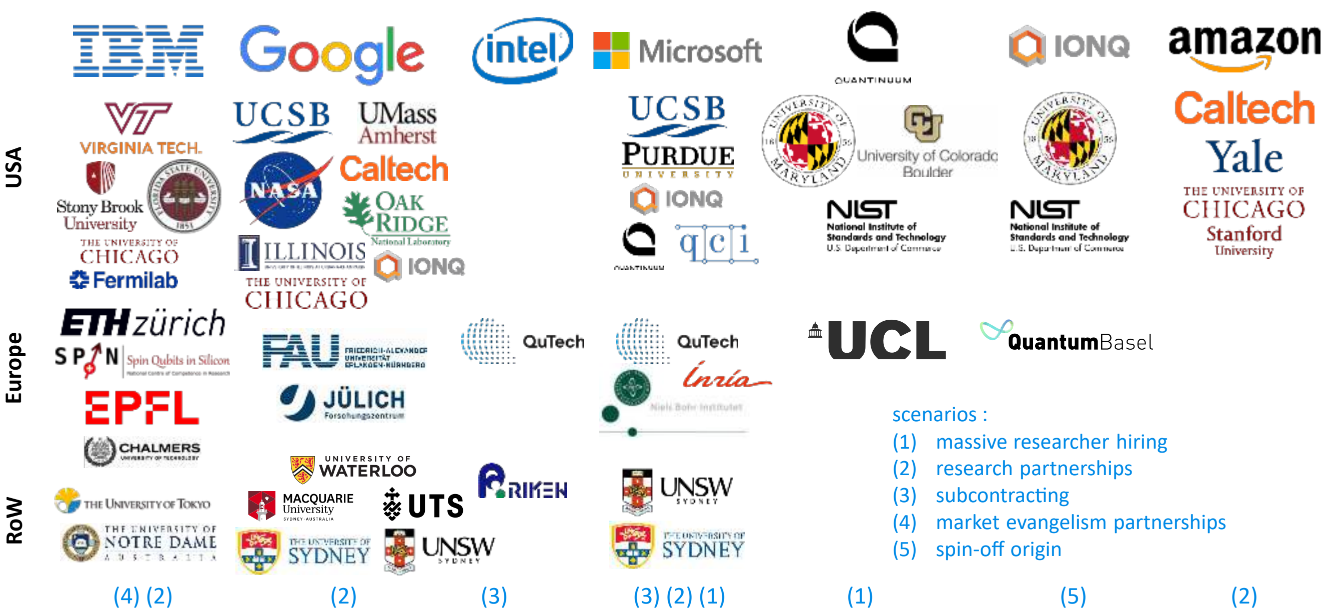


Figure 21: Large IT vendors are reusing a lot of research and talent from universities both in the USA and in the rest of the world. Here's a map of who works with whom. © Olivier Ezratty, 2021-2024.

both research and teaching. They offer short courses of one to two weeks in the summer on quantum cryptography and quantum computing. The IQC was directed by Raymond Laflamme, one of the fathers of QEC. They cover all aspects of quantum technologies with about thirty teams of theorists and experimentalists, about fifty post-docs and 125 PhD students. A dozen startups have been created since 2002. The IQC is leading the Transformative Quantum Technologies (TQT), a seven-year research commercialization program funded by the Canadian government and its First Research Excellence Funds to the tune of $76M.

In January 2020, TQT launched the Quantum Alliance, an umbrella for IQC and TQT to link them to their Canadian and international ecosystem, including the fabric of quantum startups. The University of Waterloo also runs its Quantum-Nano Fabrication and Characterization Facility (QNFCF) with cleanrooms located in the Lazaridis Quantum-Nano Centre. Among others, it builds the superconducting qubit chips for Anyon Systems (Montréal). In 2024, the region announced a funding of $14.9M for both research and applications developments [194]. The Waterloo quantum ecosystem

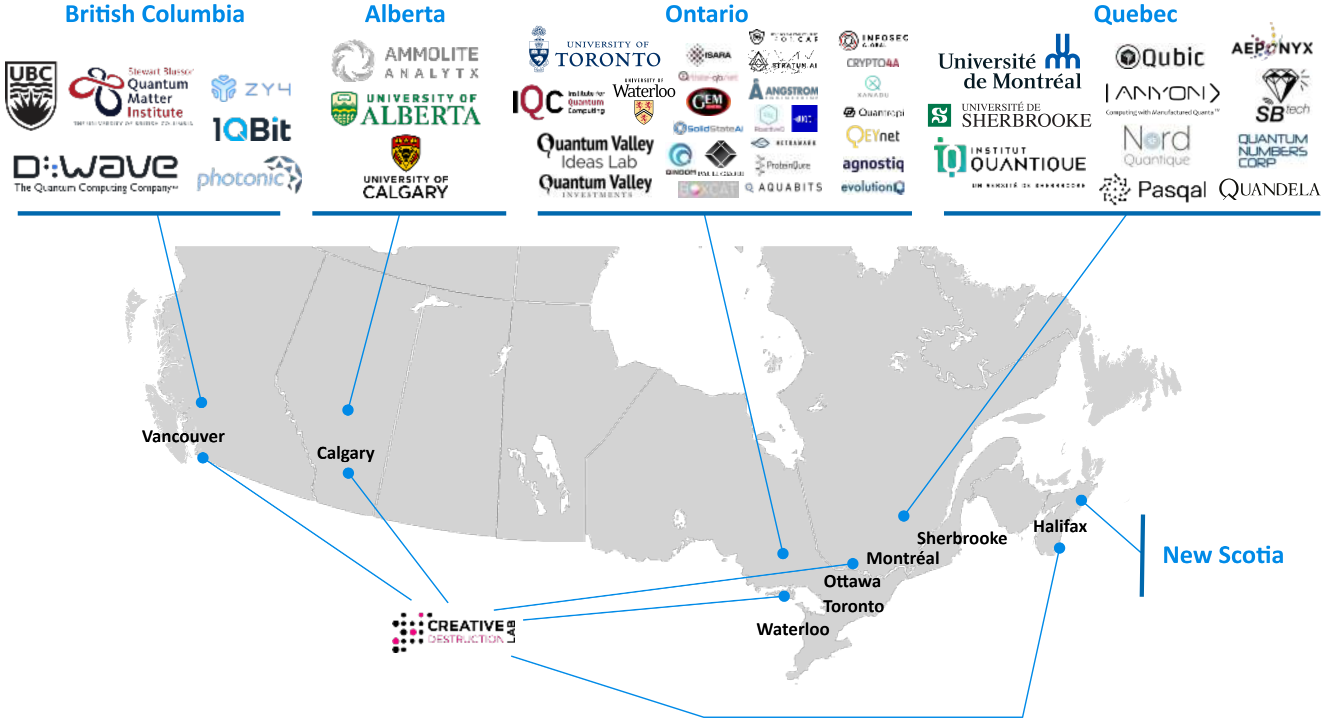


Figure 22: Map of Canada's quantum ecosystem from East to West where you see a startup concentration in Ontario. Ⓒ Olivier Ezratty, 2022-October 2024.

also hosts the Research Accelerator Center of Quantum Technologies.

In **Alberta**, the University of Calgary is working on quantum communications and has deployed an experimental QKD network of a few tens of kilometers. The University of Alberta in Edmonton, north of Calgary, is also involved in this work [195]. In 2020, the government of Alberta dedicated $11.8M to the creation of an international hub for quantum computing, $3M of which will fund quantum research. In October 2024, the Government of Canada added $8.4M of funding spread over the University of Calgary, the University of Alberta and Zero Point Cryogenics.

In **British Columbia**, the region launched its own quantum initiative in December 2022 with CAN $14M funding over six years, focused on business and on the commercialization of quantum products.

The region ecosystem key research player is the UBC (University of British Columbia) with its Quantum Matter Institute (QMI), located primarily in Vancouver.

Then, you have of course D-Wave and 1Qbit. In 2024, the region announced a CAN $11M funding for 1QBit ($3.4M) for the development of its Topological Quantum Architecture Design (TopQAD), for Simon Fraser University ($4.3M) to create the Quantum Manufacturing Centre at its 4D LABS facility for the University of British Columbia to increase its capacity to commercialize quantum technologies at the Stewart Blusson Quantum Matter Institute (>$3.2M) [196].

Government funding

As in most countries, the government is funding quantum research and the industry.

The Canadian government invested over CAN $1B in quantum research and education between 2009 and 2020. In March 2021, it announced a public funding of $40M for D-Wave [197]. In April 2021, it launched its National Quantum Strategy with a CAN $360M (US $300M) plan spread over 7 years [198]. All this was packaged with highly optimistic business forecasts.

The National Research Council of Canada (NRC) estimated that quantum technologies would generate CAN $139B turnaround and create 209,000 employments in Canada by 2045 [199]. It is even larger than the most bullish worldwide forecasts! In January 2023, the Canada federal government announced, again, its National Quantum Strategy with more details on the CAN $360M funding allocation spread on research ($141M), education and talent development ($45M) and applied solutions development ($169M). They target both applied quantum computing and a quantum Internet of thing dimension (with CAN $50M funding) [200]. It contains also a specific investment in defense quantum technologies (quantum-enhanced radar, quantum-enhanced light detection and ranging (LiDAR), quantum algorithms for defense and security and quantum networking) [201].

In October 2022, the EU and Canada announced three joint quantum technology fundamental research project funded as part of the EU Quantum Flagship: MIRAQLS for image quantum sensing, FoQaCiA for quantum computing algorithms and HYPERSPACE for quantum communications with CAN $5M each [202]. Various other international partnership exists like the CAFQA (Canada-France Quantum Alliance) with France led there by CNRS [203].

In March 2026, the Canadian government announced a CAN $900M (US $ 648M) investment in defense technologies, part of which being allocated to quantum computing, sensing and communications over an unspecified duration. The announcement was ambiguous [204, 205]. It covers all defense technologies in their Defence Industrial Strategy. In August 2026, Canada also awarded Xanadu about CAN $195M to build a photonic quantum chip manufacturing plant in Toronto, on top of the up to CAN $390M of the Project OPTIMISM funding [206]. Indeed, the "Security, Sovereignty and Prosperity:CANADA'S Defence Industrial Strategy" document also mentions included AI, critical minerals, munitions, space systems, aerospace, and shipbuilding [207].

Quantum industry

In the industry side, you can't escape **D-Wave** and the quantum software specialist **1QBit**. With about 60 quantum startups and SMEs, they are the third largest ecosystem in the world in this respect after the USA and UK, mapped in Figure 23.

Private funding includes donations from Michael Lazaridis, one of the RIM BlackBerry cofounders, with $75M to the **Institute for Quantum Computing** at the University of Waterloo and $128M in 1999 to the **Perimeter Institute for Theoretical Physics** also located in Waterloo. Together with Doug Fregin, also cofounder of RIM, they also created the **Quantum Valley Investment Fund** with a total of $100M in funding and the **Quantum Valley Ideas Lab**.

Let us also note the existence of the **Creative Destruction Lab**, a deep-tech startup acceleration structure with a specialty in quantum technologies. They are in Canada (Toronto, Montreal, Vancouver, Calgary, Halifax), in the USA (Atlanta) as well as in Oxford and Paris.

In 2020, of group of industry vendors created **Quantum Industry Canada** (QIC), an association promoting the Canadian quantum industry. It includes D-Wave, 1Qbit, Xanadu, Zapata Computing (now Zapata AI) and ISARA.

In April 2023, **Ericsson** announced that it would invest in quantum technologies R&D in Canada as part of a multi-domain investment of CAN $470M [208]. Quantum R&D will probably represent a small share of this investment. Indeed, Ericsson already employs 3,100 people in Canada and invested CAN $7.6B in telecommunications R&D. This quantum investment will probably in the $1M-$2M range per year. In November 2024, Ericsson said its total investment in telecom and quantum technologies would reach US $453M.

1.7 South America

On top of Brazil and Chile, Panama and Colombia also announced their entry in the world of quantum computing with the acquisition of a SpinQ Gemini Mini Pro with two NMR qubits from China. That is the bare minimum one country can do.

1.7.1 Brazil

Brazil has many academic institutions operating in various fields of quantum physics and technologies, including software engineering [209].

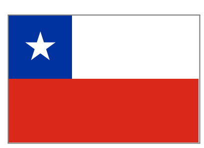
It was consolidated in December 2022 in a national quantum initiative funded through EMBRAPII (a sort of governmental innovation agency). $11M will fund the creation of a Competence Center in Quantum Technologies driving the creation of startups.

The main academic groups in quantum are **ISP-SC** (University of Sao Paolo São Carlos Institute of Physics) with its Group of Quantum Information (GIQ) and Group of Theoretical Physics (FT-FCI), **UFABC** (Federal University of ABC) where the Quantum Information Science & Technology group works in spin qubits (NMR), photonic qubit and atomic (trapped ions) qubit labs, **UFSC** (Federal University of Santa Catarina) with its Southern Quantum Information Group and **Unicamp** (State University of Campinas) with it Quantum Information Theory group. The **Brazil Quantum** community launched in 2020.

In 2021, Atos/Eviden (now Bull) and **SENAI CIMATEC**, which hosts a supercomputer center, launched the creation of a Center of Excellence in Quantum Computing. It hosts an Atos QLM simulation appliance, nicked-named CIMATEC KUATOMU.

In Spring 2026, the state of Paraíba announced the acquisition of two superconducting qubit quantum computers with 20 and 100 qubits from CETC (China) for about $10m, to be installed "early 2026" at the Paraíba International Quantum Computing Center (CIQuanta).

1.7.2 Chile



Chile hosts several University groups focused on quantum physics and quantum information.

It included the Quantum Computing Group from Pontificia Universidad Catolica de Chile and the Department of Physics of CEDENNA, Universidad de Santiago de Chile (USACH), where they work on DAQC, on condensed matter physics, skyrmions, cQED and quantum optics and quantum information.

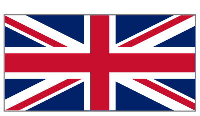
Figure 23: The Canadian industry ecosystem by product category. 🅭 Olivier Ezratty, 2023-2024.

You also have the Millennium Nucleus Physics of Active Matter of the University of Chile. The startup scene comprises **SeQure Quantum** and **GoQuantum**, two companies specialized in PQC.

1.8 Europe

Just making things clear, we're dealing here with geographical Europe, including European Union member states, the UK and Switzerland!

1.8.1 United Kingdom



UK had its quantum physics precursors and founders, followed by a new generation of scientists in the second half of the 20$^{\text{th}}$ century.

Let's mention **Thomas Young** (1773-1829), **Ernest Rutherford** (1871-1937), **Joseph John Thomson** (1856-1940), **James Chadwick** (1891-1974), **Paul Dirac** (1902-1984), **Brian Josephson** (1940), **David Deutsch** (1953), **Andrew Steane** (1965) and even the creators of the QML language, **Thorsten Altenkirch** and **Jonathan Grattage**.

Research

In the UK, the main quantum research laboratories are located in the Universities throughout the country. All of these have one or several quantum physics laboratories. Their main specialties are found later in the UK quantum plan rollout with a lot of advanced photonics (Bristol, Oxford), electron spin (UCL), telecommunication and cryptography (nearly all of them), sensing (same) and the like. See the list of UK Universities in the UK map in a forthcoming page.

Government funding

At the instigation of the physicist Sir **Peter Knight** (1947), the **UK** was the first large country to launch a quantum technology structured plan, the **UK National Quantum Technologies Programme**, announced in November 2013. It had an initial funding of £270M over five years [210, 211].

This represented a much larger amount of funding than for previous initiatives in innovative materials or robotics. The plan did not start from scratch. It was built on an existing ecosystem of university research laboratories in quantum physics.

The plan was and remains coordinated by the **EPSRC** (Engineering and Physical Sciences Research Council), a non-governmental organization funded and supervised by the government. The plan involves **Innovate UK** (commercialization and innovation support, as distinct from the EPSRC research funding above), the **Department for Business, Energy and Industrial Strategy**, the **NPL** (National Physical laboratory, where Peter Knight had been Chief Science Advisor, it is UK's metrology lab), **GCHQ** (their NSA) and **dstl** (army research) (Figure 24).

In a conventional way, the UK plan targeted all the usual quantum fields: computing, security, and sensing with a strong focus on medical imaging. Funding was based on thematic hubs bringing together universities and selected by call for projects (£124M), training, technology transfer and industrialization (Figure 25). From the outset, the plan showed a strong commitment to creating business and attracting private capital. The original

Figure 24: Key public stakeholders of the UK quantum plan. 🅭 Olivier Ezratty, 2021.

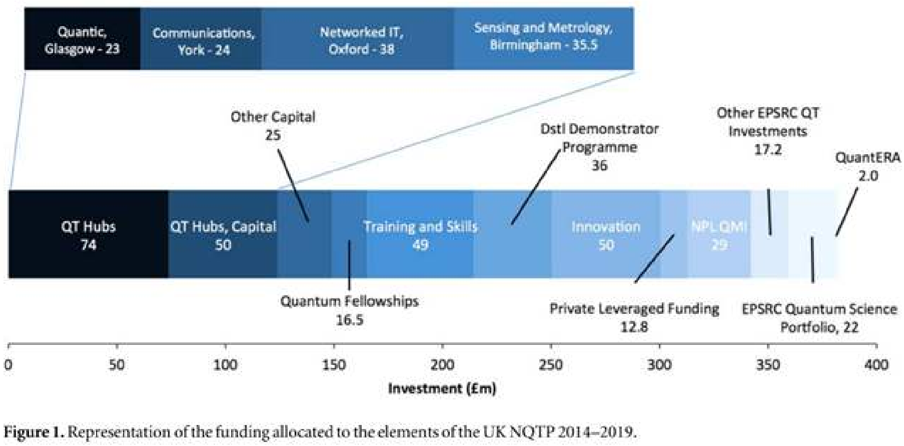


Figure 25: UK's investments in quantum technologies in the first phase of their plan from 2014 to 2019. Source: [212].

plan was to move research into startups as quickly as possible.

Four quantum hubs were created that covered the major fields of quantum technologies and brought together teams spread over the territory in some thirty universities. All the hubs' managers are scientists, supplemented by a business development director and a board of 8 people including industry vendors CTOs. The four hubs were the UK Quantum Technology Hub Sensors and Timing, the Quantic on quantum imaging, the Quantum Computing & Simulation Hub and the Quantum Communications Hub, which created a quantum communication network between Bristol, Cambridge and Ipswich via the UK National Dark Fibre Infrastructure Service launched by the EPSRC (also linking Southampton and UCL in London) (Figure 26).

This did not prevent the government security agency (GCHQ) from expressing skepticism about the suitability of QKD in a four-page white paper published in April 2020 [213].

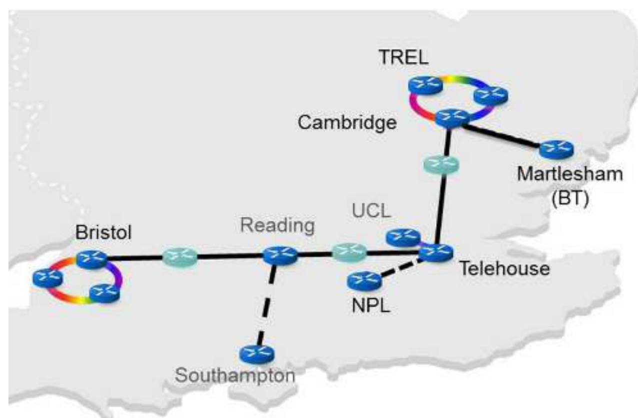


Figure 26: UK National Dark Fibre Infrastructure Service. Source: The Quantum Communications Hub, 2016 (11 slides).

These hubs are very multipolar, bringing together universities that are involved in several different hubs, according to the map in Figure 27 [214]. As we will see later, these hubs had a duration of 5 years and were then renewed twice with different names and participants. This creates a lot of confusion from the branding perspective.

In August 2022, as part of the NQTP, the EPSRC launched a new "Materials for Quantum Network" program led by Peter Haynes (Imperial College London) and Richard Curry (University of Manchester) to focus on quantum matter research. It seems that this topic will soon complement the usual computing/sensing/communications trio of all national quantum plans.

A progress report was published in 2015 by the EPSRC and Innovate UK followed by another interim report, the Quantum Age-Blackett review in 2016 investment launched in 2014 and extending the effort to the algorithmic and software part, in particular in liaison with the **Alan Turing Institute** and the **Heilbronn Institute for Mathematical Research** to propose case studies of computational problems to be solved [215, 216].

This was followed by a parliamentary report published in November 2018 which supported the continuation of the plan, the launch of a second phase of £350M over the period 2019-2024 and some fine tuning on the coordination between the different stakeholders (hubs, innovation centers, companies) [217].

This led to the official announcement of Phase 2 in June 2019, following the recommendations of the House of Commons [218]. With the expected private sector investments, the total of the two phases of the UK Quantum Plan was estimated at $1.227B. Phase 2 funding renewed funding for hubs (£94M over 5 years), industrialization projects (£153M from the Industrial Strategy Challenge Fund, over 6 years, the Industrial Strategy Challenge Fund (ISCF) was a multi-domains initiative of £2.6B backed by £3B of private investments, created to invest in challenges having a strong economical and societal impact. A dedicated Commercialising Quantum Technologies Challenge was then launched in two stages, first in 2018 with £20M and second with £153M completed by £205M from the private sector, in July 2019. In 2021, over 40 such projects were funded), training (£25M over 5 years).

It added the launch of the **NQCC (**National Quantum Computing Centre**)** for the development of quantum computing solutions, with £93M over 5 years [219]. The NQCC building construction started in September 2021 and it was inaugurated in October 2024. It now hosts or will host about 10 QPUs.

The first "UK" quantum computer was to be built by Rigetti (US). How can this be? It is linked to Rigetti having acquired a local startup, QxBranch and to its various connections with the local ecosystem and universities. But Oxford Quantum Circuits announced the launch of its cloud based superconducting qubits based computer in July 2021. All in all, the UK government has invested £100M per year in quantum technologies between 2014 and 2022.

The bulk of Phase 2 was the creation of the NQCC, which is led by **UKRI**, the **EPSRC** and the **STFC** (Science and Technology Facilities Council), a government agency that conducts research in physics and astronomy and manages the country's major scientific instruments (particle accelerators, lasers, space engineering, etc.). UKRI (UK Research and Innovation) is an autonomous non-governmental organization created in April 2018 with an annual budget of £7B which consolidates seven former research councils including the EPSRC and STFC, Innovate UK and Research England. NQCC is tasked to create NISQ and then LSQ computing demonstrators, develop quantum algorithms and software and their uses, and build a community of users around them. The center became fully operational in 2022. It planned to deploy up to ten NISQ quantum computers. In 2020, the preferred technologies were superconducting and trapped-ions qubits.

In May 2022, NQCC launched its SparQ Applications Discovery Programme and a collaboration with OQC. SparQ is a sort of directory aimed at UK-based companies and researchers who are looking for case studies of quantum computing [220, 221]. In November 2023, NQCC announced a partnership with IBM which will provide UK researchers with access to its online QPUs.

The UK had recovered approximately 14% of the budgets for the first wave of European Quantum Flagship projects by October 2018. Despite the Brexit, the country will continue to benefit from it, as the collaboration with Europe on research survives the Brexit. For example, John Morton's UCL laboratory is part of the flagship project QLSI on silicon qubits driven by CEA-Leti and awarded in March 2020.

In November 2021, the UK signed a partnership agreement with the USA [222], the first of a long list of USA bilateral partnerships later signed with Australia, all Nordic countries and Switzerland.

In March 2023, the UK government announced its Phase 3 wave of quantum investments with a new round of investment of £2.5B over the 2024-2033 period, doubling current public investments [223]. The plan was motivated by the increased investments from countries like Germany and France, but also, the perceived threat coming from China. The plan KPIs (key performance indicators) are to generate an additional £1B of private investment, train 1,000 postgraduate research students, launch bilateral arrangements with 5 countries, increase the share of worldwide investments in startups from 12% to 15%, and grow quantum technologies market share from 9% to 15%, plus drive 75% large accounts adoption of quantum technologies, influence international standards developments, launch new research hubs, accelerators and establish the Office for Quantum in the Department for Science, Innovation and Technology (DSIT). This new investment is part of the UK Science and Technology Framework that focuses the UK on five technologies: artificial intelligence, quantum, telecommunications, semiconductors and biology [224].

The political switch to Labor in July 2024 created some uncertainty on this plan. The new government was said to be considering a withdrawal of £1.3B out of this 10-year commitment, driving an obvious push-back from the UK quantum industry [225, 226]. Finally, in June 2025, a £670M plan for quantum computing was announced. This is not in addition to the £2.5B plan announced in 2023 but part of it [227].

In May 2023 was launched the University of Edinburgh Quantum Software Lab, led by Elham Kashefi who was

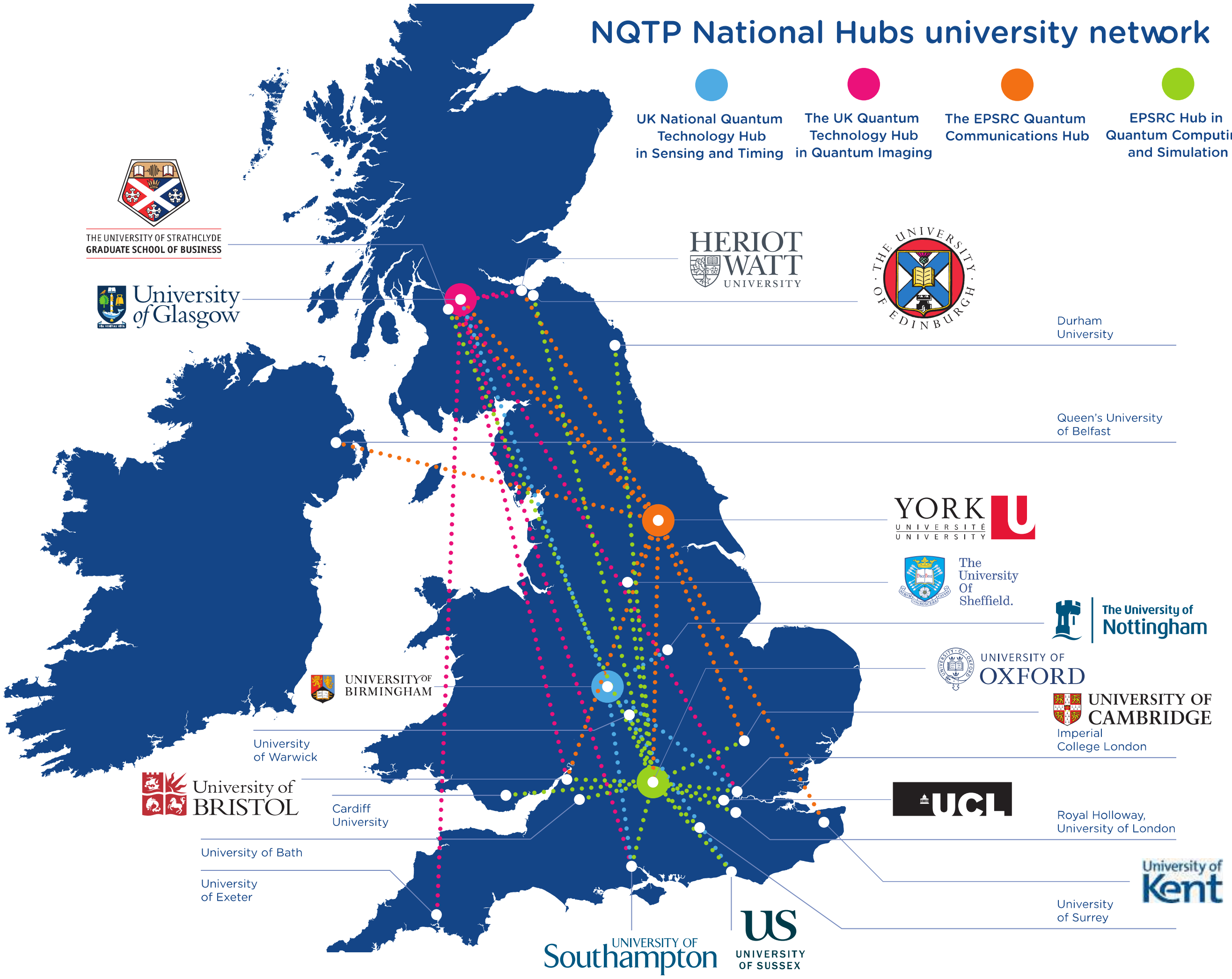


Figure 27: UK universities map. Source: UK National Quantum Technologies Plan Strategic Intent, 2020 (38 pages). I added some of the large university logos. Olivier Ezratty, 2021.

also named as the chief scientist of the National Quantum Computing Centre (NQCC) in November 2022 [228, 229]. It strengthens UK's investments in quantum algorithms and software engineering [230]. Late 2023, the then conservative UK government published a roadmap for quantum computing in line with many vendor roadmaps. The goals are in QOPS, with 10 million QOPS by 2028, 10 billion by 2032 and 10 trillion by 2035 (so in powers of 10, respectively 10^7, 10^{10} and 10^{13}) [231]. All these require FTQC.

In a June 2024 report, the Royal Academy of Engineering made recommendations on the establishment of a clean room nanofabrication infrastructure for quantum technologies and with other enabling technologies like EDAs (electronic design automation software) [232].

Considering the potential shift in government, which happened in July 2024, the UKQuantum industry association preempted it with publishing a Manifesto in June with a set of general recommendations [233].

Namely, the quantum industry asked for stable policies, clarity and consistency in export controls like in cryogenics [234] and on securing the quantum supply chain, train people, improve seed funding for startups, develop international partnerships, favor the codevelopment of regulations [235], and plan for the deployment of quantum-resistant cryptography (quantum or classical).

UKRI launched five new quantum technology hubs in August 2024, with a public investment of £106M complemented by £54M of industry investment [236]. These are replacing the previous hubs.

- **QEPNT** (Quantum Enabled Position, Navigation and Timing) led by the University of Glasgow, which focuses on quantum LiDAR sensors, atomic clocks and submarine positioning systems.
- **QCI3** (Quantum Computing via Integrated and Interconnected Implementations), hosted by the University of Oxford. It is dedicated to quantum computing applications in materials design, chemistry, machine learning, and fluid simulation techniques.
- **IQN** (Integrated Quantum Networks) led by Heriot-Watt University in Edinburgh, is working on the

creation of a quantum internet, distributed quantum sensing applications, secure quantum communications.

- **QuSIT** (Quantum Technology Hub in Sensing, Imaging and Timing) which is hosted by the University of Birmingham, works on quantum brain scanners, quantum microscopy, quantum clocks, quantum cameras, quantum magnetic and gravity sensors.

- **Q-BIOMED** led by the University of Cambridge and UCL, is working on early disease diagnosis with quantum sensors working at the molecule and cells level and also on magnetoencephalography and quantum-enhanced blood tests (no Theranos promise, please).

In May 2025, the UK was back in the EU. Sort of! It can now access Horizon Europe funding as part of the 2025 Horizon Europe Work Programme published in April 2025 [237]!

In November 2025, the Tony Blair Institute for Global Change proposed a quantum plan for the UK [238]. Like most countries in Europe, it puts forward the excellence of local research and weak capacity to turn it into commercial success. The secret sauce? Creating a "Quantum Translational Research Group" to improve the link between research and technology development, focus on software, revive corporate venture, government-driven procurement competitions, strategic alliances and PQC readiness.

In March 2026, the Starmer government announced its "Quantum Leap" plan with up to £2B of government investment to turn the UK into a world leader in quantum technologies. They plan to be the first to deploy quantum computers at scale by the early 2030s, with about half of the envelope going to the procurement of large-scale quantum computers through the ProQure program, more than what the Blair foundation proposed. The rest funds quantum companies, sensing and navigation, networking and the five national research hubs, which got an immediate £13.8M top-up. They ambition to add £200B to the economy by 2045. The promise is to "*deliver better drugs and treatments, greener energy, and protect people's finances and national security*" [239]. The economic impact number comes from a survey by the analyst company Oxford Economics which plans that quantum technologies will increase productivity by 7% in the UK in 2045 and 8.3% in 2055 [240]. This is hype to the max.

Quantum industry

On the entrepreneurial side, as of July 2025, I have identified 80 quantum technologies startups and small businesses in the UK with a good balance by category (Figure 29). It is the second country in the world in terms of the number of startups, behind the USA. In October 2022 was created **UKQuantum**, a quantum industry association with Kets, Orca Computing, Arqit, Nu Quantum, Riverlane and Oxford Instruments among its funding members.

The intellectual property management company **IP Group**, launched in August 2020 a £12M fund to fund startups, these being selected by the independent agency **UKRI**. Projects funding range from £125K to £2M. Let's also mention the **Quantum Technology Enterprise Centre** from the University of Bristol which was a sort of startups incubator and training program for quantum startup founders. The QTEC incubation program offered a 12-months salaried fellowship to quantum scientists during the build-up of their startup and business skills training.

Since 2016, QTEC helped the creation of 31 startups including KETS, QLM, Nu Quantum, Quantum Dice and Vector Photonics. The program funding ended in 2021 and QTEC is looking for funding to launch a new "cohort" of quantum entrepreneurs.

Notable players are **Oxford Instruments** (cryogenics), **Oxford Quantum Circuits** (superconducting qubits [241]), **Quantum Motion** (silicon qubits), **Cambridge Quantum Computing** (operating system, software, services, which merged with Honeywell Quantum Systems in 2021 to become later Quantinuum), **TundraSystems** (photonic qubits), **Oxford Ionics** and **Universal Quantum** (both with trapped ions qubits), **Orca Computing** (photonic qubits and memories), **Riverlane** (quantum error correction) and **NuQuantum** (quantum memories for quantum communications). On the other hand, no major company in the country seems to be particularly invested in quantum computing, except perhaps in telecommunications.

In 2025, Quantum Zeitgeist published a post on the so-called "Quantum British Invasion" [242] (Figure 28). The British startup ecosystem is indeed strong but its size is still quite small in funding and influence compared to the USA and the EU. According to an analyst report published in February 2025 by Oxford Economics [243], there were 947 employees in quantum computing in the UK. And it includes the local branches of US companies like Quantinuum, Rigetti and SEEQC Figure 30.

Figure 28: This Quantum Zeitgeist title is a little preposterous. Nobody feels invaded by British quantum at this stage.

Let's mention here PentaBridge, a non-profit organization based in the UK created by Connor Teague, Kris Kaczmarek and Niels Nielsen that supports the acceleration and growth of the quantum economy. It provides a network for quantum hubs to showcase their startups, find investment, engage with end users and

Figure 29: The UK startup scene is one of the most active in Europe (the old Europe, with them, before Brexit...). 🅭 Olivier Ezratty, 2022-2025.

Fig. 4: UK quantum computing sector, quantum only firms OXFORD ECONOMICS

	Number of active firms	Age (years)			Number of UK employees			
		Youngest	Median	Oldest	Total	Lowest	Median	Highest
Hardware	16	0	5	10	578	1	16	127
Software	36	0	4	27	369	1	5	91

Figure 30: UK quantum computing sector employment as of February 2025. Source: [243].

government entities, and collaborate with academics. They also have a team of advisors and supporters, including Freeke Hiejman-Te Paske, Katya Almasque and Lars Frolund.

1.8.2 Germany

Germany is a land of dense basic research in quantum technologies.

It builds on a strong history of the many German founders of quantum physics with **Max Planck**, **Albert Einstein**, **Werner Heisenberg** and many others [244]. It also has a strong ecosystem of industry vendors, particularly in quantum enabling technologies.

Research

The main research organizations and laboratories involved in quantum technologies are shown in Figure 31 and described below:

Max Planck Institute for Quantum Optics (MPQ), based in Munich, is one of the 84 MPIs and their 24,000 employees. It was the home of Theodor Hänsch, Nobel prize in physics in 2005 for laser-based precision spectroscopy and the optical frequency comb, and hosts Ignacio Cirac's theory division. Klaus von Klitzing, who discovered the quantum Hall effect in 1980 and got the Nobel prize in physics in 1985, belongs to another Max Planck Institute, the one for Solid State Research in Stuttgart.

They specialize in cold atom-based qubits in particular. This MPI is associated with the International Max Planck Research School also based in Munich. Two other MPIs are dedicated to information technology, but do not seem to be invested in quantum.

Munich Center for Quantum Science and Technology (MCQST) in Munich was launched in 2019 and brings together Munich's quantum research centers: the MPQ, the Walther-Meißner-Institute for Low Temperature Research (WMI) and the city's two leading scientific universities: Ludwig-Maximilians-Universität München and Technical University of Munich (TUM). It covers all quantum technologies (simulation, computing, communication, sensors). The whole with a budget of €31M over five years and about 55 permanent researchers. In February 2022, the Bavaria region announced an additional funding of €300M for the Munich quantum valley supplemented by €80M of federal funding. Among other things, the funding helped build the upcoming Center for Quantum Computing and Quantum Technologies (ZQQ), a center that will provide access to superconducting, trapped-ions and cold atom qubits quantum computers. Meanwhile, in January 2022, a D-Wave Advantage was installed at Jülich in the JUNIQ (Jülich UNified Infrastructure for Quantum computing) that was created in 2019.

Fraunhofer Institutes for Applied and Partnership Research with its 72 institutes and 26,600 people. They comprise several institutes specializing in quantum physics: the **IAF** (Institute for Applied Solid State Physics) in Freiburg, the **IOF** (Institute for Applied Optics and Precision Engineering) in Jena, the **ILT** (Institut for Laser Technology) in Aachen, **FOKUS** (Open Communication Systems) in Berlin, **SCAI** and **IAIS** (quantum machine learning) in Sankt Augustin and **ITWM** (quantum HPC) in Kaiserslautern. On top of that must be accounted for cleanrooms from **IPM** in Freiburg and **IPMS** near Dresden. EIN Quantum NRW was launched in March 2022, a competence network for photonics-based quantum technologies in the North Rhine-Westphalia (NRW) lander, involving the Fraunhofer Institutes **FHR** (High Frequency Physics and Radar) and **IAIS** (Intelligent Analysis & Information).

Helmholtz Association groups 18 Research Centers that conduct basic research in response to major societal challenges, with a total of 40,000 people. It includes the Quantum Laboratory of the **Jülich Forschungszentrum** (*aka* Jülich FZ or Jülich Research Center, which started in 1956 as a nuclear research center and is located between Aachen and Cologne). It hosts the Jülich Supercomputing Center (JSC) where Kristel Michielsen leads the HPC for Quantum Systems division. Jülich FZ also hosts Tommaso Calarco who coordinates the European Quantum Flagship. He is associated with the University of Aachen in the **JARA Institute Quantum Information** (IQI). The Helmholtz Network also includes the **Institute of Photonics and Quantum Electronics at the** Karlsruhe Institute of Technology (KIT).

Leibniz Association with its community of 96 centers conducting basic research includes the Institute for Solid State and Materials Research (IFW) in Dresden, Germany, which focuses on superconductivity and magnetism, the Institute of Photonic Technology (IPHT) in Jena, Germany, the Max-Born-Institute for Nonlinear Optics and Short Pulse Spectroscopy (MBI) in Berlin, Germany, and the Paul Drude Institute for Solid State Electronics (PDI) in Berlin, Germany.

Institute for Complex Quantum Systems at the University of Ulm between Stuttgart and Munich.

PTB (Physikalisch-Technische Bundesanstalt) is Germany's national metrology institute, the counterpart of the NIST, and invests in quantum sensing and quantum metrology.

BSI is the federal office for information technology security. Its report which was updated in 2025 provided an update on quantum computing, focusing in particular on cybersecurity issues [245]. This is a very good overview of global quantum computing research. It provided a surprisingly accurate inventory of efforts in the field, particularly in US public research.

At last, let's mention here the **Quantum Alliance** which regroups the German clusters of excellence and research centers working in quantum science and technology.

Germany is like the USA, a federal nation with many regions, called Länder. In the quantum ecosystem, the most vibrant one seems to be Bavaria, around Munich. You then have North-Rhine Westphalia with the Jülich research center and RWTH Aachen, Saxony with the Dresden ecosystem with semiconductor manufacturing (which launched SAX-QT, its quantum network, in December 2025), Hamburg, of course Berlin, and all the other länders [246].

In 2025 was launched the INTERREG trinational UpQuantVal associating France (East region), Germany (Baden-Württemberg) and Switzerland (Northwestern region) with €2.3M of EU FEDER funding and a total funding of €5.1M, spanning 2025 to 2027. It is coordinated by the University of Strasbourg and focused on cold atom technologies.

Government funding

In September 2018, the German Federal Research Ministry announced €650M in funding for quantum technologies over four years (2018 to 2022) [247, 248]. Like all such plans, it funds projects in quantum computing, quantum communication and quantum metrology. In September 2019, IBM announced that it would join this plan and install a quantum computer in Germany addressing researchers and cloud usages. It is not certain that this is the best approach to develop a German and European quantum industry, at least on the hardware side. The IBM computer was launched early in 2021 in the Stuttgart region in an IBM facility. It led to misleading information regarding a supposed investment of the German government in IBM of $717M corresponding to these €650M. At best, only a small share of these €650M were dedicated to cofund the IBM initiative in Germany. Looking at what was done in 2022 in Canada, you can guess that the German government participation was around 40-€60M [249].

In June 2020, the German government more than doubled its efforts by announcing a seemingly incremental €2B in funding for its quantum plan, including investment in two quantum computers [250]. This €2B included the initial €650M of the 2018 plan. The German government put in place a scientific and industry experts board of 16 members to propose a roadmap and funding

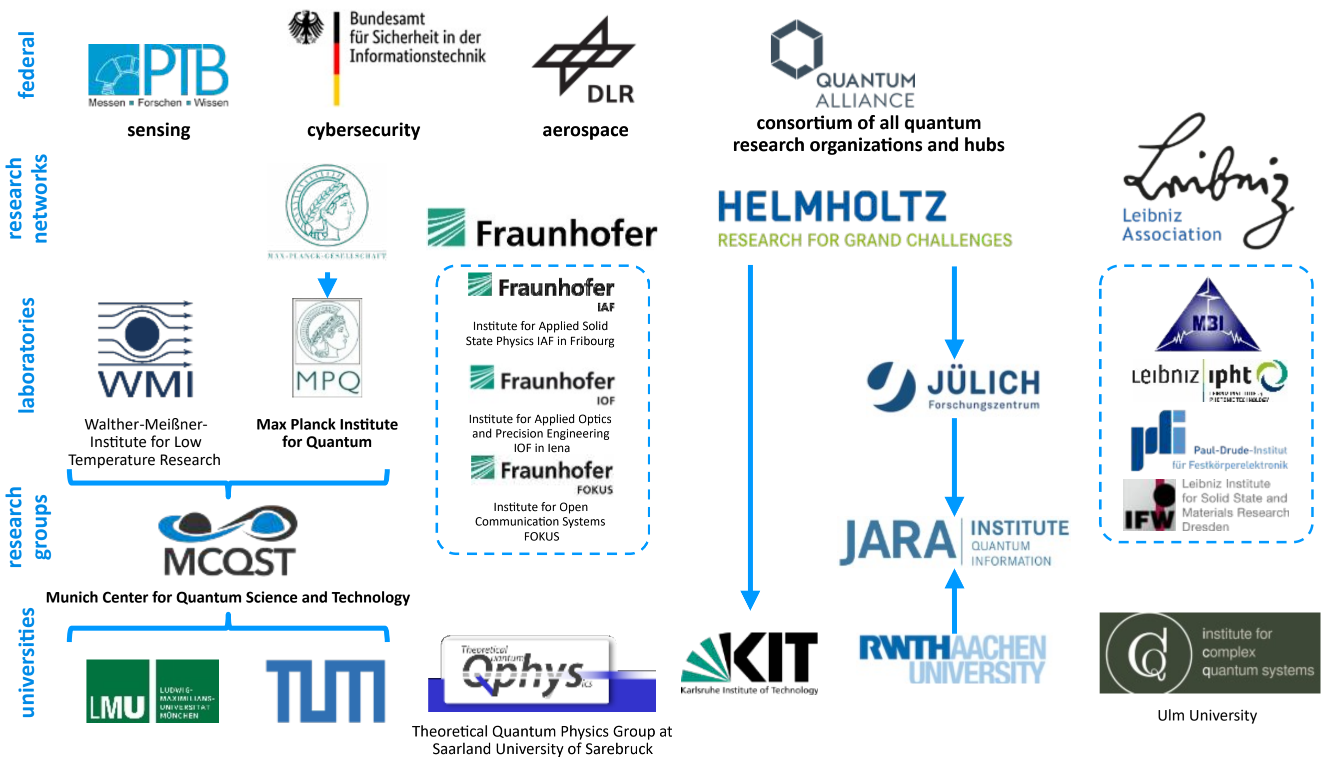


Figure 31: Understanding the research ecosystem in Germany. © Olivier Ezratty, 2022.

allocation with a Joint presidency of a scientist (Stefan Filipp from TU Munich) and an industry member (Peter Leibinger from Trumpf). It made some proposals in December 2020 including creating an independent coordination body, Deutschen Quantengemeinschaft (DQG). In January 2021, the BMWi disagreed with some of these proposals, estimating that too much funding was directed to fundamental research at the expense of startups.

In May 2021, the plan was split in two parts with €1.1B managed by the Federal Ministry of Education and Research (BMBF) and €878M by the Federal Ministry of Economic Affairs and Energy (BMWi), focused on applications developments.

One key showcased goal for this plan is to build two national quantum computers with 24, then 100 and later 500 functional (physical) qubits. DLR (Germany's Aerospace Center) was to receive the bulk of this funding (€740M) to work with small, mid-sized and large companies and create two related consortia. In 2022, DLR awarded QuiX (the Netherlands) a €14M contract to build a photonic quantum computer and Universal Quantum (UK) a €67M contract to build two trapped ions-based quantum computers to be installed in Hamburg. Their investment in trapped-ions caps €208M also involves EleQtron (Germany) and Universal Quantum (UK). Planqc also got a €29M contract for a cold atom QPU. They even have the COMIQC project for the creation of 10 qubits made of organic molecular crystals, with a very low TRL [251]. DLR deals with startups outside Germany provided they install a significant part of their R&D and/or manufacturing in Germany.

In May 2023, the German federal government "revealed" a €3B plan to build a quantum computer by 2026 with from 100 to 500 physical qubits, the same goals as before [252]. The funding is split between €2.2B including €1.37B to the research ministry and €800M for the National research institutes [253]. It seems that this amount was a repackaging of the €2B plan announced in 2020 with some additional funding. It also covered quantum sensing and quantum cryptography/communications. But how about the missing €800M? Is it including the Lander existing funding which is about €750M? It seemed according to various sources that the spent amount in the end was about €1.4 B.

In September 2024, Germany's Cyber Agency (Agentur für Innovation in der Cybersicherheit) awarded three contracts totaling €35M of funding for the creation of a portable quantum computer. One went to Quantum Brilliance and ParityQC (by 2027), the second to Infineon and Oxford Ionics and the last one to neQxt (trapped ions) [254]. They may be a little optimistic or do not care much about their utility.

The Federal government is indeed not the only public body funding quantum research. The Länder added these €750M including €300M from the Bavarian region (probably with half of it coming from the Länd and the rest from industry). How is that possible? The German Länder have a very large budget independent from the Federal government (in a 42%/58% ratio). Bavaria being a large Länd, it has the means to invest significantly in research. For example, it cofunded two quantum research projects, NeQuS (quantum networks between quantum computers) and IQ-Sense (quantum sensing) for a total of €3.5M in August 2022.

Like with each country, the German quantum plan covers quantum computing, communications and sensing. In 2024, there was a cut in the German quantum budget of an unspecified amount after a decision from the Constitutional Court [255].

A false number on German public investment circulated with a hefty €4,456M from Interference Advisors. This report is amazingly entirely wrong, making double bookings of the 2018 and 2020 announcements, using unsafe press reference ($717M allocated to IBM's effort...) and double-accounting subsequent quantum projects which were already part of the €2B 2020 announcement. So if you bump on some public investment reports showing that Germany leads the USA, you know that it is wrong.

Let's list some identified projects funded by the German government.

GeQCoS (German Quantum Computer based on Superconducting Qubits) with €14.3M BMBF funding, involving Fraunhofer IAF in Freiburg and Infineon). It was launched in February 2021 and will seemingly use German originated quantum technologies. The ambition is modest with a goal of 50 qubits.

QSolid is another superconducting qubit computer that would be tied to a HPC from the Jülich Supercomputing Centre, including optimized firmware and software. The 2021-2026 project budget is €76.3M with 89.8% being funded by the BMBF over five years starting in January 2022. On top of Julich, it involves Fraunhofer IPMS and Fraunhofer IZM-ASSID, Karlsruhe Institute of Technology (KIT), Leibniz IPHT in Jena and the PTB. The project is driven by Frank Wilhelm-Mauch. The first 10-qubit system was delivered mid-2024 with plans to expand it to 30 qubits by 2026. The team is also working on a qubit control cryo-CMOS chip manufactured by Global Foundries in Dresden.

DAQC is a project launched in February 2021 which got €12.4M from BMBF. It is coordinated by IQM Germany and involves Jülich, Infineon and ParityQC from Austria as well as the Leibniz Computing Center and Free University of Berlin. It will create a digital-analog superconducting qubits system using IQM's architecture. This project is related to the Quantum Flagship OpenSuperQ project.

MANIQU is a project running from 2021 to 2023 related to the usage of NISQ hardware to undertake quantum simulations to simulate new materials. The participants are HQS, Bosch, BASF, the Friedrich-Alexander University in Erlangen, and the Heinrich-Heine University in Düsseldorf.

Q-Exa is yet another superconducting qubit project announced in November 2021, involving IQM. Their systems will be integrated with HPCs. The project funding is €45.3M. It seems to be a follow-up project to DAQC.

PhotonQ is a photonic quantum computer project launched with a funding of €16M and led by the University of Stuttgart with participations from the Universities of Würzburg, Mainz and Ulm, TU Munich, the Institute of Microelectronics Stuttgart and Vanguard Automation GmbH. The four-year project first goal is to create a demonstrator of 8 qubits using MBQC and deterministic photon sources, silicon photonics circuits and new single-photon detectors.

PhoQuant is another photonic quantum computer project with a funding of €50 M, led by Q.ANT, a subsidiary of Trumpf, with the notable participation of Christine Silberhorn's Paderborn University lab and many others (Universities of Münster, Jena, Ulm, Humboldt Berlin, Fraunhofer IOF and IPM, HQS, Swabian Instruments, TEM Messtechnik, ficonTEC Service and MenloSystems). It led in October 2024 to the creation of the Paderborn Quantum Sampler (PaQS), a German GBS (Gaussian Boson sampler), implemented by Q.ANT [256].

ATIQ is a trapped ions computing project. The German government is funding 81.1% of the €44.5M project that will last from 2021 to 2026. Participants include Toptica (lasers). The project is coordinated by the Leibniz University Hannover with participations from Johannes Gutenberg University Mainz, University of Siegen, TU Braunschweig, RWTH Aachen, Physikalisch-Technische Bundesanstalt, Fraunhofer-Gesellschaft, AMO, AKKA Industry Consulting, Black Semiconductor, eleQtron, FiberBridge Photonics, Infineon, JoS QUANTUM, LPKF Laser & Electronics, ParityQC, QUARTIQ, Qubig, AQT, Boehringer Ingelheim, Covestro, DLR-SI, Volkswagen and QUDORA Technologies.

QUASAR is a semiconductor-based project using shuttling electrons with a QuBus, a quantum bus to transport electrons and their quantum information over distances of 10 μm. The partners are Infineon, HQS, Fraunhofer (IAF, IPMS), Leibnitz Association (IHP, IKZ) and the Universities of Regensburg and Konstanz. The project will run until 2025 to create 25 coupled qubits.

The resulting computer is to be deployed at JUNIQ. Jülich is also participating in the European Flagship QLSI project driven by CEA-Leti in France. QUASAR got a €7.5M funding from BMBF [257].

QuaST is an enabling technologies project (Quantum-enabling Services and Tools for Industrial Applications) that will develop high-level libraries automatically decomposing and optimizes a solution into classical and quantum parts. The project is run by the Fraunhofer Institute for Cognitive Systems IKS with other Fraunhofer Institutes (AISEC, IIS, IISB), the Leibniz Supercomputing Center, and the TUM, plus DATEV, Infineon, IQM and ParityQC. The project sponsor is German Aerospace Center (DLR). The project will last 4 years and got a funding of €7.7M.

QLindA is a quantum machine learning project led by Siemens with participations from Fraunhofer IIS, IQM and others.

We also have three enabling technologies projects: **QuMIC** (Qubits Control by Microwave Integrated Circuits, €6.3M, 2021-2024), **qBriqs** (€2M, 2021-2024, compact cryogenic connectors, qubit readouts TWPA and HEMT amplifiers, filters and attenuators, DACs and ADCs and DC flux current generators) and **HIQuP** (2021-2024, €2.2M, superconducting and cryogenic qubit control electronic circuits).

Germany also launched the creation of two QKD-based telecommunications networks, both funded by BMBF:

QuNET (€165M) which uses a standard QKD associated with terrestrial and satellite links. The project involves several Fraunhofer Institutes including the Heinrich Hertz Institute (HHI), the Max Planck Institute for the Physics of Light and the German Aerospace Center (DLR) [258–260]. The project launched in November 2019 was scheduled to last seven years and aims to create a communications protection infrastructure for the German government. This should lead to the creation of a secure European network. The private sector is also involved with Deutsche Telekom, ADVA Optical Networking and Tesat-Spacecom. Test sites were planned in Bavaria, Saxony and Thuringia.

Q.Link.X (€14.8M) for the creation of a terrestrial network in optical fiber and QKD-based on quantum repeaters, managed by the Fraunhofer HHI [261].

Germany leads or participates to various European Flagship programs: **MetaboliQs** (NV center based medical imaging), **UNIQORN** (photon qubits chips), **S2QUIP** (hybrid photonic chips), **QRANGE** (QRNGs).

At last, the German national plan is funding three other initiatives associating research labs and industry vendors: **BrainQSens** (medical imaging with NV centers, €2.8M), **Opticlock** (compact optical clock to synchronize communication networks, €6M) and **QUBE** (space QKD with Cube-Sats, €3.12M).

Germany is part of the "trilateral" agreement with France and the Netherlands leading, among other things, to the joint funding of industry-research collaborative projects across the three countries. In March 2024, it signed a scientific partnership agreement with the UK [262]. In May 2024, Germany and the USA signed a Joint Statement on Cooperation in Quantum Information Science and Technology (QIST) like the same agreement signed with nearly half of European countries on top of Australia and other "western" countries [263].

In April 2025, Germany announced its new "High-Tech Agenda Germany" prioritizing six key technology sectors, including artificial intelligence, quantum technologies, microelectronics, biotechnology, fusion energy, climate-neutral energy and mobility. The total plan will be funded with up to €5.5B but the share allocated to quantum technologies was not yet public as of September 2025. In May 2026, they published milestones including two error-corrected quantum computers by 2030 and the first logical qubits by 2028.

Quantum industry

On the private sector side shown in Figure 32 and in the map in Figure 33, Germany has a various set of quantum startups including **PlanQc**, **neQxt**, **Qudora**, **Eleqtron**, **Quantum Brilliance**, **SaxonQ**, **XeedQ**, **Peak Quantum**, and **ARQUE** in quantum computing, **Avanetix** (hybrid algorithms), **InfiniQuant** (CV-QKD cryptography), **PicoQuant** (photon counters), **Kiutra** (magnetic cryogenics), **HQS Quantum Simulations** (algorithms), **JoS Quantum** (software in finance), **QuantiCor Security, QuBalt** (both in post-quantum cryptography) and **QuTools** (sensing).

Only a few quantum computing hardware startups have been created like **eleQtron** (trapped ions), **ARQUE** (silicon spins), **XeedQ** and **SaxonQ** (NV centers), **Planqc** (cold atoms).

Many of the country's major industrial companies are also interested in quantum applications, particularly in chemistry (**BASF**), health (**Merck),** telecommunications (**Deutsche Telekom)**, components and automotive (**Bosch**, **Daimler**).

PlanQK (Platform and Ecosystem for Quantum-Assisted Artificial Intelligence) is a project to build a marketplace of quantum assisted artificial intelligence components, with first, quantum inspired algorithms. It gathers scientists from various universities (Stuttgart, Berlin, Munich) on top of Accenture, HQS, Deutsche Bahn, Deutsche Telekom and many other corporations and mittelstands. It is supported by BMWi with a total funding of €19M. In 2023, it turned into the company **Anaqor** and in 2024, it was acquired by Kipu Quantum (Berlin).

In June 2021, ten German companies created **QUTAC** (Quantum Technology and Application Consortium).

It fosters the development of quantum computing usable industrial applications in the technology, chemical and pharmaceutical, insurance and automotive industries. The consortium was launched by BASF, BMW Group, Boehringer Ingelheim, Bosch, Infineon, Merck, Munich Re, SAP, Siemens, and Volkswagen. One of its goals is to create a cross-industry application portfolio.

QuCUN (Quantum Computing User Network) also comprises SAP and BASF as partners.

It is supported by the German Federal Ministry of Education and Research (BMBF). The QuCUN platform launched in 2022 is "*designed to give potential quantum computing users – from SMEs to industrial giants – a*

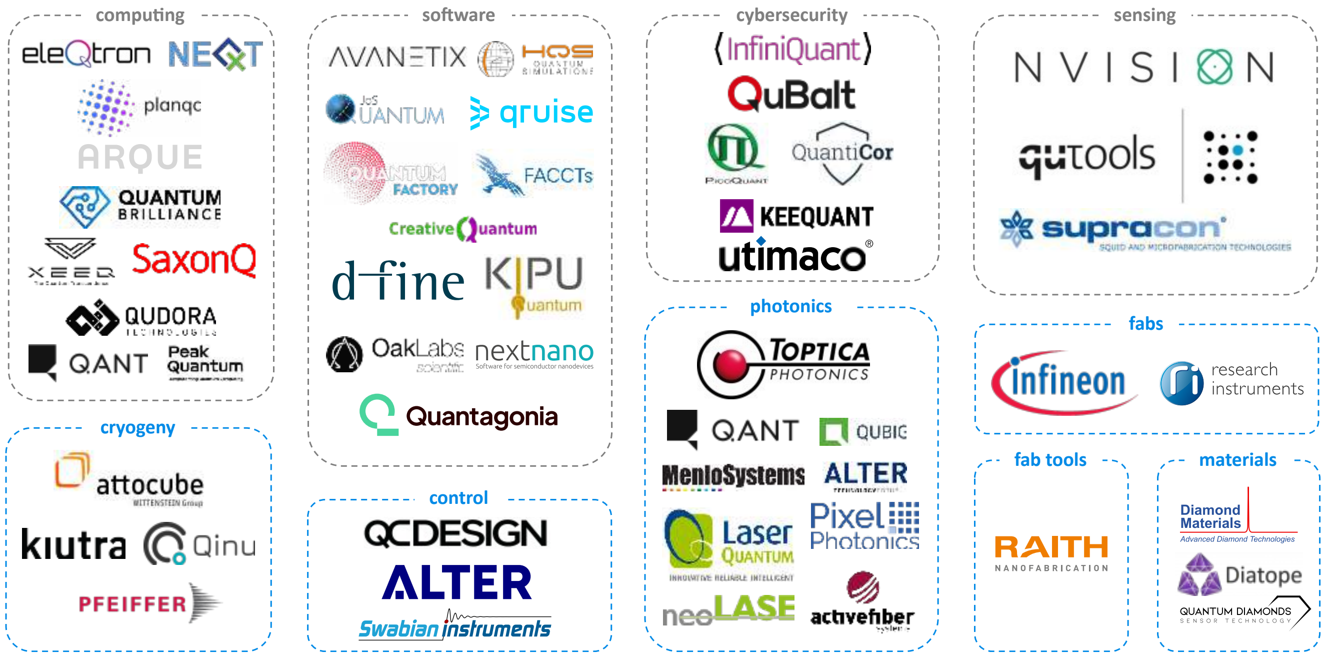


Figure 32: The German quantum industry. 🅭 Olivier Ezratty, 2023-November 2024.

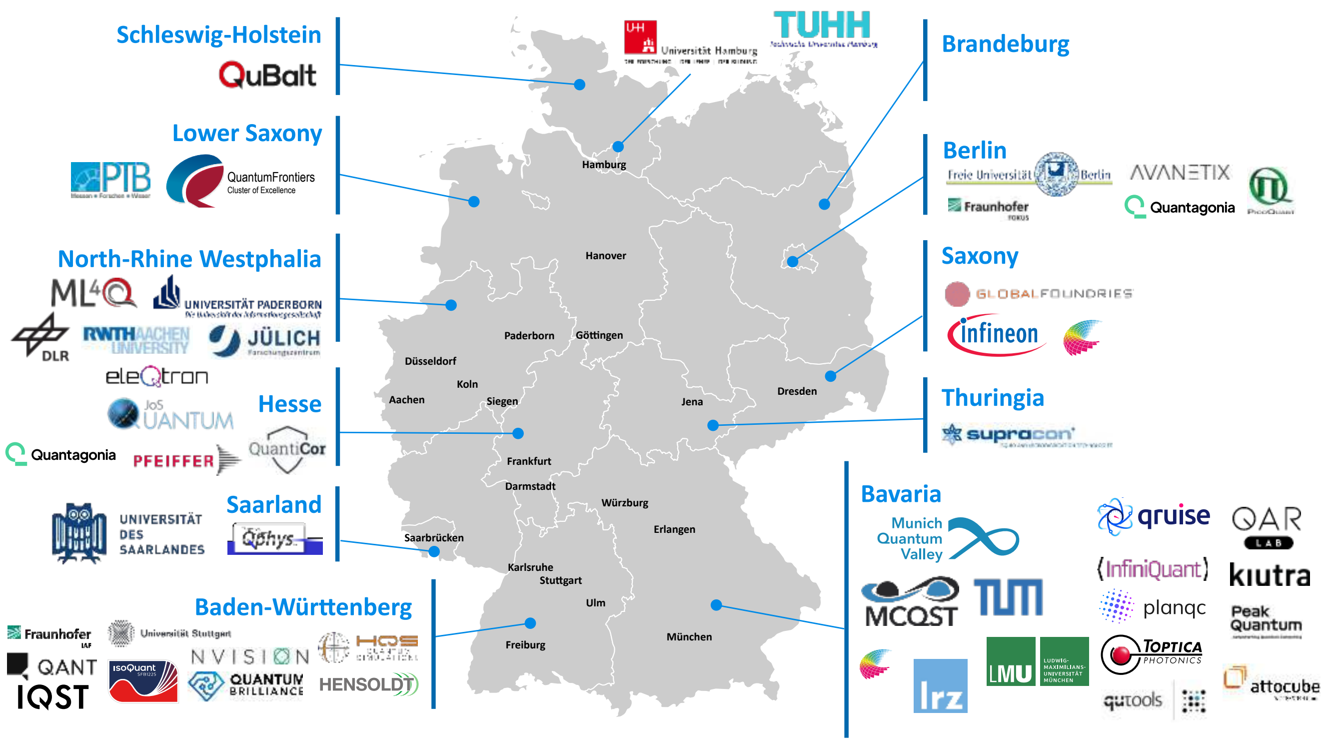


Figure 33: Map of Germany's quantum ecosystem. 🅭 Olivier Ezratty, 2023-2025.

central point of entry". Does it mean that QUTAC is peripheral?

Let's also mention **PushQuantum**, a student initiative born in Munich that organizes lectures, workshops and entrepreneurship labs for wannabe quantum entrepreneurs.

1.8.3 Austria

Austria is one of the key European countries in quantum history and scientific development.

It started with Ludwig Boltzmann, Paul Ehrenfest, Wolfgang Pauli and Erwin Schrödinger. Then, you can count on key scientists like Anton Zeilinger (2022 laureate of the Nobel prize in physics), Rainer Blatt, Peter Zoller, Tracy Northup, and Markus Aspelmeyer. Ignacio Cirac and Peter Zoller proposed the first practical scheme for a trapped-ion quantum computer in 1995 [264]. The first two-qubit entangling gate was demonstrated the same year by David Wineland's NIST team [265], while Rainer Blatt's Innsbruck group implemented the Cirac-Zoller gate itself in 2003 [266].

Austria's investment in quantum computing is concentrated in the **IQOQI**, the Institut für Quantenoptik und Quanteninformation in Innsbruck and Vienna.

It focuses in particular on the design of trapped ions qubits, but also on cold atoms computing and interconnect, and quantum communications. This led to the start-up **Alpine Quantum Technologies (AQT)**, founded by Rainer Blatt and Thomas Monz from IQOQI. It received €12.3M in public funding and competes with **IonQ** and **Quantinuum**. One other notable Austrian startup is **ParityQC** which develops ParityOS and a related architecture to codevelop quantum hardware and software platforms.

The Vienna Center for Quantum Science and Technology (**VCQ**) is a partnership between the University of Vienna, Vienna University of Technology and the Austrian Academy of Sciences.

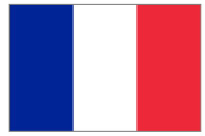
It brings together a critical mass of about 20 quantum physics research laboratories.

Austria is also invested in quantum cryptography and is associated with China, with whom it has conducted experiments in sending quantum keys via the Micius satellite to set up secure video communication. One key reason is that Jian-Wei Pan is a former PhD student of Anton Zeilinger.

IQOQI is also collaborating with the **Grenoble University Space Center** (CSUG) in the development of a CubeSat-type quantum key relay satellite, similar to the one in Singapore, in the **Nanobob** project [267].

The Austrian government announced a formal quantum plan in June 2021 with €107M over 2022-2026 covering research and quantum technology developments. Quantum Austria is part of the Austrian 10 years Research Technology and Innovation strategy 2030 launched in 2020, in a country that spends over 3.18% of its GDP in R&D. Part of the funding comes from the European Resilience and Recovery Facility (NextGenerationEU). The plan is managed with RFPs from the Austrian Research Promotion Agency (FFG) and the Austrian Science Fund (FWF).

1.8.4 France



France has a good breadth of research and industry activities in quantum technologies.

Let's first mention its greatest scientists with **Henri Poincaré** (1854-1912), **Louis de Broglie** (1892-1987, Nobel prize in physics in 1929), **Alfred Kastler** (1902-1984, Nobel prize in physics in 1966), and **Claude Cohen-Tannoudji** (1934, Nobel prize in physics in 1997).

Serge Haroche (1944, Nobel prize in Physics in 2012) is a pioneer in cavity quantum electrodynamics and on the interaction between photons in a superconducting cavity and Rydberg atoms passing through the cavity). **Alain Aspect** (1946, Nobel prize in physics in 2022) demonstrated in 1982 the violation of Bell's inequalities and confirmed the nonlocal correlations of entangled photons, a cornerstone of the second quantum revolution. Other domains worth mentioning are in quantum photonics with **Pascale Senellart**, neutral atoms physics with **Jean Dalibard** and **Antoine Browaeys**, silicon spin qubits with **Maud Vinet**, **Tristan Meunier** and **Silvano de Franceschi**, quantum cryptography and telecommunications with **Philippe Grangier**, **Frédéric Grosshans** and **Eleni Diamanti** and PQC with various cryptographers like **Damien Stehlé**.

Research

Public research is organized around three national research organizations: **CNRS**, **CEA** and **Inria**. The first is involved in fundamental research in physics, mathematics, and algorithms. The second also does fundamental research in physics, particularly on superconducting qubits, and applied research on electron spins qubits as well as on photonics. Finally, Inria is doing research in computer science, and for quantum technologies, on quantum error correction, cryptography, and quantum algorithms. Many laboratories are joint research units ("Unités Mixtes de Recherche" in French) between Universities, these national organizations and sometimes industry vendors like Thales.

These research laboratories are mainly located in Ile de France and in Grenoble, but other regional locations are active such as Toulouse, Montpellier, Marseille, Lyon, Bordeaux, Besançon and Lille as shown in Figure 34. Like many large countries, French laboratories are exploring many qubit tracks: superconducting, cold atoms, electron spins, photons and topological matter.

Public sector researchers get projects funding by answering various countries and European RFPs. Some researchers obtain ERC Grants (European Research Council): Synergy Grants for a few handfuls of teams (up to €14M over 6 years), and more often Starting (young researchers, up to €1.5M), Consolidators (experi-

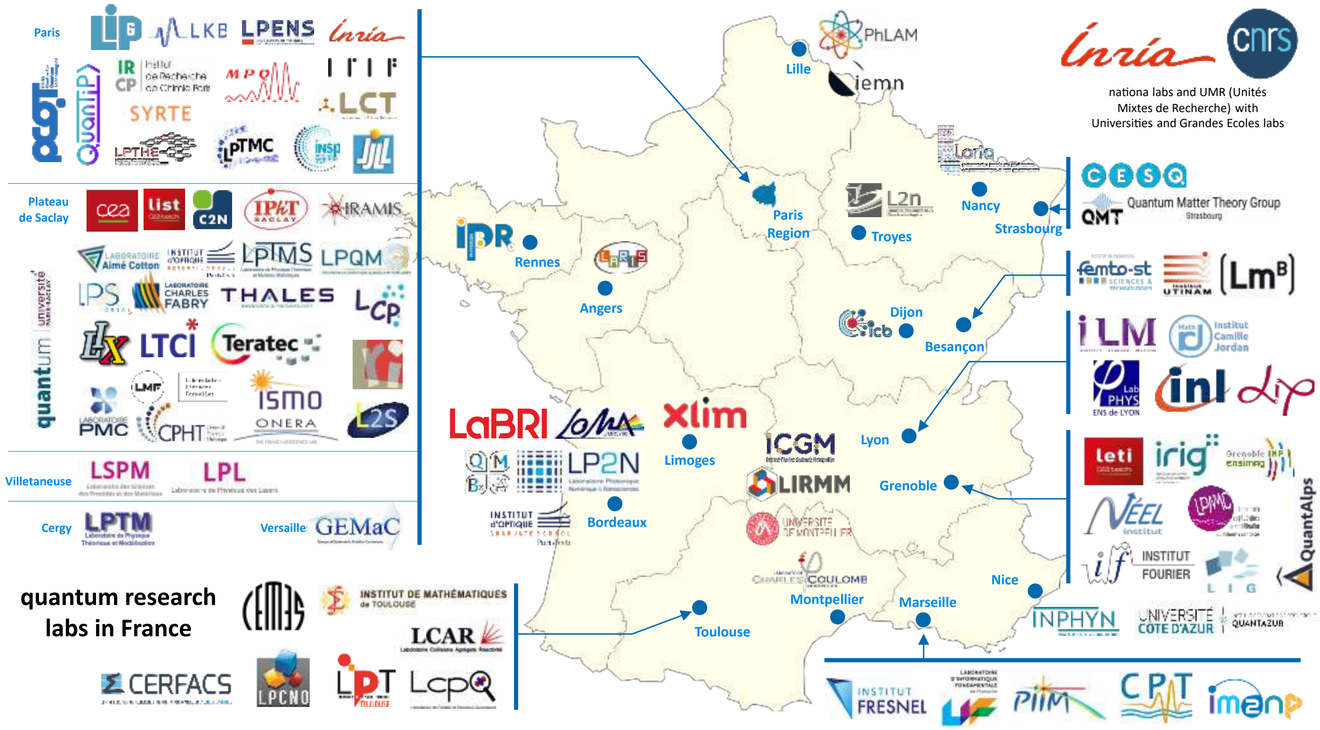


Figure 34: Map of France's quantum related research labs. © Olivier Ezratty, 2021-September 2025.

enced researchers, up to €2M) and Advanced (emeritus researchers, up to €2.5M spread over 5 years). Then European FET funding, funding via the European Quantum Flagship, or finally through various calls for projects at the national level.

Paris region The Paris Region (aka "Ile de France") is home to a good half of the country's research laboratories devoted to quantum technologies. Let's start with the laboratories that are located within Paris.

Inria's efforts in the Paris region are concentrated over nearly 10 teams.

in the Quantic (Quantum Information Circuits) team of Pierre Rouchon, Mazyar Mirrahimi, Zaki Leghtas and Alain Sarlette, which is a joint venture between the CNRS, ENS and the Ecole des Mines de Paris.

They work on mathematical models of superconducting qubits, on quantum error correction (including cat-qubits), on proof of superiority of quantum algorithms and on cryptographic issues. The COSMIQ team led by Anne Canteaut, works on cryptographic algorithms, and David Pointcheval's CASCADE team, works in cryptography and PQC. Inria also jointly runs many other teams with various labs from CNRS.

Other Inria teams are dedicated to quantum science and technology: IQA (LTCI, Saclay) is working on networking aspects in quantum computing, cryptography and photonics and quantum machine learning, QI with LIP6, MOCQUA with LORIA, QAT on quantum computing architectures, algorithms, applications and their theory jointly with ENS Paris, QInfo (LIG, Grenoble, ENS Lyon) on quantum information science, quantum foundations and quantum combinatorial games, AlgoComp with IRIF, MC2 with LIP Lyon and PACAP with IRISA and Inria Rennes working on mapping quantum circuits to particular architectures, QuACS on quantum algorithms in Saclay, PhiQus on quantum information science including distributed quantum computing, and Quriosity which associates Telecom Paris and LCTI, led by Romain Alléaume, are all in the Saclay area.

LIP6 hosts several specialists in quantum cryptography, telecommunications (QKD) and computing (Laboratoire d'Informatique de Paris 6).

Eleni Diamanti was awarded an ERC Synergy Grant for her work in the QUSCO (Quantum Superiority with Coherent State) project. Elham Kashefi is cofounder of the VeriQloud startup. She is also working on verified quantum computing, secure multiparty quantum computing, and features to achieve quantum advantages.

LPENS (Laboratoire de Physique de l'Ecole Normale Supérieure) merged in 2019 several ENS Paris physics laboratories.

It's including the former **LPA** (Laboratoire Pierre Aigrain), which specialized in nanotechnology and photonics. Its researchers are working on numerous nanotechnologies used for the creation of qubits and the transport of quantum information: superconducting thin films, superconducting and microwave circuits for their control, two-dimensional electron gases with very high mobility, semiconductor quantum boxes, qubits based on carbon nanotubes.

Taki Kontos and Audrey Cottet's teams are at the origin of the creation of carbon nanotubes used as electron traps potentially usable in electron spin qubits, which led to the creation of the **C12** startup, already mentioned. The lab is also a participant on the work on cat-qubits related to the startup Alice & Bob.

The **LKB** (Laboratoire Kastler Brossel) is a laboratory of quantum physics from ENS Paris.

It focuses on quantum information and photonics, interactions between light and matter (Nicolas Treps and Valentina Parigi), quantum simulation and precision sensing with cold atoms (Christophe Salomon). Thibault Jacqmin is working on microwave photon generation with NEMS (nano MEMS).

IRIF (Institut de Recherche en Informatique Fondamentale) from CNRS and the University Paris Diderot is led by Frédéric Magniez.

It also hosts Iordanis Kerenidis, Sophie Laplante and two Inria teams. It works in quantum computing, cryptography and communications.

The **MPQ** laboratory (Materials and Quantum Physics) is part of the University Paris Cité.

It is particularly interested in trapped ions in the Quantum Physics and Devices (QUAD) and QITE (Quantum Information and Technologies) groups. But also, to the generation of entangled photon pairs (Sara Ducci).

The **LPTHE** (Laboratoire de Physique Théorique et Hautes Energies) is part of the University Paris Sorbonne.

It works in condensed matter and statistical physics with applications in superconducting qubits.

The **INSP** (Institut des Nanosciences de Paris) is part of Paris-Sorbonne University. It is a generalist laboratory specialized on nanosciences and in different branches of photonics including NV and SiC color centers.

They also work on spin and magnetism, and on photonics components in III-V materials.

The **IRCP** (Institut de Recherche de Chimie Paris) associated with the Ecole Nationale Supérieure de Chimie ParisTech.

It conducts research in innovative materials. Philippe Goldner is working on the creation of qubits based on nanocrystals doped with rare earth ions such as europium or erbium, and is involved in the SQUARE project of the European Quantum Flagship, coordinated by the Karlsruhe Institute of Technology and also involving Thales. The laboratory is also involved in the European Quantum Flagship **ASTERIQS** project which is working on NV-based qubits in diamonds.

The **LPEM** (Laboratory of Physics and Study of Materials) of the ESPCI and Sorbonne Université (formerly UPMC) works in particular in superconductivity as well as on Majorana fermions.

The **LPTMC** (Laboratoire de Physique Théorique de la Matière Condensée) is part of the University Paris-Sorbonne.

It contains teams working on condensed matter physics like Jean-Noël Fuchs and Julien Vidal on topological insulators and Majorana fermions and Rémy Mosseri working on quantum information with topological qubits.

SYRTE (Laboratoire Systèmes de Référence Temps-Espace) is located at Paris Observatory.

It works in quantum sensing, in particular gravimetry, quantum gyroscopes and on time measurement with atomic and optical clocks. They are partnering with NIST. The quantum gravimeter and interferometry team is led by Franck Pereira dos Santos. SYRTE is led by Arnaud Landragin.

The **Laboratoire Jacques Louis Lions** (LJLL) specializes in applied mathematics. It focuses on the analysis, modeling and high-performance scientific computation of phenomena represented by partial differential equations.

Mario Sigalotti and Ugo Boscain, who specialize in the control of quantum systems and are also members of Inria, are among others.

The **Laboratory of Theoretical Chemistry** at Sorbonne University is directed by Jean-Philippe Piquemal (cofounder of Qubit Pharma).

It is interested in computational chemistry, including quantum.

In September 2020, the **Quantum Innovation Center Sorbonne** (QICS) was inaugurated, a collaborative research structure associating LIP6, the LKB of the ENS and Inria.

The **Saclay plateau** has an even higher density of laboratories, located south-west of the Paris region. Most of these entities are consolidated in **Université Paris Saclay**.

At the **CEA**, the Quantronics team at the Iramis laboratory in Saclay has been working on superconducting qubits for over 30 years.

The lab was led by Daniel Esteve and is now managed by Hugues Pothier.

IphT (Institut de Physique Théorique de Saclay) associates CEA and CNRS.

It works on the physics of condensed matter, including high-temperature superconductors, and on Majorana fermions. But their main focus seems to be mainly astrophysics. The laboratory has also a team working on quantum information.

The **LAC** (Laboratoire Aimé Cotton) is located at the ENS Saclay.

It also works on cold atoms and interactions between atoms and light. In particular, they create qubits by combining an optically active erbium ion and a nuclear spin of yttrium.

The **C2N** (Centre des Nanosciences et des Nanotechnologies) of CNRS and Université Paris Saclay is a key quantum photonics laboratory. It is the home to Pascale Senellart and Jaqueline Bloch's labs.

They work in particular on light-matter coupling in semiconductors. It also hosts quantum electronics teams (Frédéric Pierre).

The **LPS** (Laboratoire de Physique des Solides) works on magnetism, Josephson junction superconductors, thermodynamics, superconducting spintronics and quantum dynamics.

They also develop codes for quantum and semi-classical dynamics and quantum control with applications in quantum information.

The **LPTMS** (Laboratoire de Physique Théorique et de Modèles Statistiques) works on various fundamental quantum physics domains.

The **LCP** (Laboratoire de Chimie Physique) works on superconductors and on the dynamics and control of trapped ions controlled by laser pulses.

They develop hybrid computational models of quantum chemistry (quantum+traditional) using MCTDH (Multi-configuration time-dependent Hartree) which solves the Schrödinger equation for the simulation of interactions between atoms in molecules. On their agenda: condensed matter physics, modeling of classical and quantum systems via statistical physics, quantum chaos, number theory and quantum chaos, theoretical aspects of quantum information; cold atoms, quantum integrable systems, quantum groups, etc.

Télécom Paris's **LTCI** (Laboratoire Traitement et Communication de l'Information) is an industry laboratory operating with partnerships with the private sector and via chairs.

Its "Quantum Information and Applications" (QIA) team specializes in the theoretical and experimental aspects of quantum communications.

They develop hybrid CV-QKD-based quantum cryptography protocols compatible with telecom operators' fiber networks and QKD repeaters. They are a contributor, founding member and reporter to the ETSI QKD-ISG on the QKD standardization processor. The team is led by Isabelle Zaquine and includes Romain Alléaume. Another team led by Frédéric Grillot works on quantum information.

ISMO (Institut des Sciences Moléculaires d'Orsay) works on quantum dynamics, interactions between heavy particles and electrons at low temperature, light/matter coupling and on software for the simulation of quantum physics.

The **CPht** (Centre de Physique Théorique de Polytechnique) is specialized among other things in the physics of condensed matter.

But not to the point of creating superconducting qubits! We find there Karyn Le Hur's group, who is specialized in condensed matter physics and Laurent Sanchez-Palencia's Quantum Matter Group.

The **Charles Fabry Laboratory** of the Institute of Optics Graduate school (IOGS) is specialized in lasers and quantum optics.

It is home to Alain Aspect, Philippe Grangier as well as Antoine Browaeys, cofounder of the startup Pasqal and its laser-controlled cold atom qubits.

The **LIX** (Laboratoire d'Informatique de l'Ecole Polytechnique) is particularly active in post-quantum cryptography algorithms.

The **PMC** (Laboratoire de Physique de la Matière Condensée) is another laboratory of the Ecole Polytechnique. They work in particular on spin dynamics in semiconductors and magnetic thin films.

The **L2S** (Signals and Systems Laboratory) of CentraleSupelec is active in quantum systems research. Here, Zeno Toffano is focused on quantum states measurement and quantum logic.

The **LPQM** (Laboratory of Quantum and Molecular Photonics) associates ENS Paris Saclay and CentraleSupelec.

Their domains or expertise are coherence and quantum correlations.

The **LRI** (Laboratoire de Recherche en Informatique) located at CentraleSupélec is managed by Benoît Valiron. He teaches and conducts research in quantum computing.

The **LMF** (Formal Methods Laboratory) was created in 2021 as a joint research center of University Paris-Saclay, CNRS, ENS Paris-Saclay, Inria, and CentraleSupelec with a focus on formal methods.

It combines 100 members from the former Laboratoire Spécification et Vérification (LSV) and the VALS team of Laboratoire de Recherche en Informatique (LRI). They target computational paradigms ranging from classical to emerging ones such as biological and quantum computing.

Thales **RT** (Thales Research and Technology) carries out R&D to create industrialized quantum sensing solutions.

In particular, they have developed expertise in diamond NV centers.

Onera studies quantum optics in its Palaiseau site.

It is in this capacity that it coordinates the ASTERIQS project of the European Quantum Flagship, "Advancing Science and Technology through diamond Quantum Sensing".

They also have teams of researchers in photonics, in III-V semiconductor materials (gallium, ...) with a prototype manufacturing unit located in their premises in Palaiseau, in metrology (gravimeter, atomic clock, accelerometer) and in QKD.

Let's move on to other parts of the Ile de France: Cergy-Pontoise, Villetaneuse and Versailles.

The **LPTM** (Laboratoire de Physique Théorique et Modélisation) of the University of Cergy-Pontoise is interested in cold atoms, in liaison with the Institut Francilien de Recherche sur les Atomes Froids (IFRAF).

They also study graphene, electronic quantum transport, topological phases and entanglement.

The **LSPM** (Laboratoire des Sciences des Procédés et des Matériaux) of the University of Paris 13 in Villetaneuse is working on the manufacturing processes of NV centers, carbon nanotubes and graphene centers and associated applications.

The **LPL** (Laboratoire de Physique des Lasers) of the University Paris 13 in Villetaneuse works in photonics and cold atoms, their traps and on quantum metrology.

It is the laboratory of Hélène Perrin, already mentioned, who is its Deputy Director.

The **GEMaC** (Groupe d'Etude de la Matière Condensée) of Versailles operates in the field of diamonds and graphene, on spin electronics and magnetism.

It also works on QKD and photonic quantum memory.

QuanTiP (Quantum Technologies in Paris Region) is a community that groups research laboratories in the Paris Region that are focused on all quantum sciences and technologies.

According to them, there are 650 quantum researchers in the Ile-de-France region in all (physics, algorithms, telecommunications, cryptography) spread over 100 teams in 30 research laboratories. It followed-on SIRTEQ in 2022, that was created in 2017.

Launched in 2014, the Paris Center for Quantum Computing (PCQC) which was later rebranded into Paris Center for Quantum Technologies (PCQT) brings together several dozen researchers from various laboratories in Paris.

The high-performance computing cluster **Teratec** is very active to promote quantum computing.

It brings together about 80 private and public HPC players including Atos, CEA, CERFACS (European Center for Advanced Research and Training in Scientific Computing), Dassault-Aviation, EDF, IFPEN, PCQC (Paris Centre for Quantum Computing), Total and the University of Reims. It aims to develop quantum algorithms, hybrid development methods, use cases, and to inform, train and animate a community. They benefit from an Atos QLM simulator installed at the CRTT (Centre de Calcul, Recherche et Technologie) of the CEA in Bruyères-le-Châtel.

Grenoble The Grenoble quantum ecosystem is the second densest in France after the Paris region. It is well-organized and very focused on the creation of qubits based on electron spins but also on superconductors, all with good skills in photonics. It is probably the place where coordination between research teams works best, particularly by integrating the key stages of industrialization. Quantum research in Grenoble is led by different branches of the CEA (Leti in nanoelectronics and IRIG in fundamental physics), the CNRS with Institut Néel, LPMMC and two joint CNRS and CEA teams: NPSC (NanoPhysics and Semiconductors) focused on quantum sensing, quantum photonics, quantum thermodynamics and quantum foundations.

Institut Néel is a CNRS laboratory launched in 2007 that is specialized in condensed matter physics with a critical mass of researchers in quantum physics.

Its researchers are exploring the possibilities of electron spin qubits (Tristan Meunier), superconducting qubits (Nicolas Roch), topological matter (Adolfo Grushin) and photonics. It also works on cryogenics (Sébastien Triqueneaux) and quantum foundations (Cyril Branciard).

The institute was named after Louis Néel (1904-2000, French), a physicist born in Lyon who was awarded the Nobel prize in physics in 1970 for his studies on magnetism and the discovery of antiferromagnetism. He is at the origin of the creation of the Polygone Scientifique de Grenoble, which brings together numerous research institutes and companies in the peninsula between the Isère and Drac rivers. The place hosted the first CEA site outside the Paris region in 1956, launched by Louis Néel. The CNRS established a foothold there in 1962, and in 1967 CEA-Leti was created. CEA-Leti is one of the world's largest civilian laboratories for applied research in nanoelectronics and nanotechnology. The Grenoble Science Park is also home to several international research organizations, the Institut Laue-Langevin, the European Synchrotron Radiation Facility and one of the branches of the European Molecular Biology Laboratory. In 2005 the CEA-Liten was created, a branch of the DRT specialized in new energies (photovoltaic solar, batteries, fuel cells, complete management of the carbon cycle, mixed energy management, innovative materials). In 2006, Minatec was launched, a nanotechnology commercial development center, later complemented by the Minalogic competitiveness cluster. In 2012, the Clinatec research center, founded by Alim-Louis Benabid, was launched, which is at the origin of the first complete exoskeleton for tetraplegics.

CEA-Leti (Electronics and Information Technology Laboratory) in Grenoble is the CEA's micro and nanoelectronics laboratory. It is at the origin of the SOI wafer technology that led to the creation of SOITEC.

In the quantum space, Leti is focused on CMOS electron spin qubit engineering and also on quantum photonics. It is also involved in the SUPREME EU project to create manufacturing capacities for superconducting technologies in computing, control electronics, and sensing.

CEA IRIG (Grenoble Institute for Interdisciplinary Research) is the counterpart of Institut Néel in fundamental research at CEA.

It includes the Laboratory PHotonique ELectronique et Ingénierie QuantiqueS (PHELIQS), which works on the physics of condensed matter including silicon spin qubits, topological qubits and unique photon sources.

LPMMC (Physics of Condensed Matter) of the University Grenoble Alpes is a CNRS UMR focused on the theoretical physics of condensed matter and quantum physics.

It works on many-body quantum interactions, superconductivity and superfluidity, and on the temporal evolution of quantum systems under the effect of magnetic and electric fields. It hosts researchers like Anna Minguzzi and Robert Whitney.

The **IJF** (Institut Joseph Fourier) of the University of Grenoble is working on quantum dynamics and in particular on issues of decoherence and thermal quantum noise.

The **LIG** (Laboratoire d'Informatique de Grenoble) is interested in quantum algorithms in general. One of its researchers is Mehdi Mhalla, who works on the quantum resolution of graph problems.

Research in quantum computing in Grenoble is currently federated by **QuantAlps**.

It has been organizing the QuantAlps Days every year in Fall since 2022. Anna Minguzzi is the Director of QuantAlps. Beforehand, QuEnG (Quantum Engineering Grenoble) was federating the same research ecosystem, from 2017 to 2022.

Lyon Research in Lyon is well balanced between the physical part and the mathematical and software part of quantum.

The **Physics Laboratory of ENS Lyon** studies condensed matter. The Quantum Circuit Group of Benjamin Huard is working on superconducting qubits and their error correction codes.

He was notably joined by Audrey Bienfait in 2019, who works on electron spin resonance and its applications in quantum sensing. It was also there that Théau Peronnin finalized his thesis in 2020 while creating the startup Alice & Bob with Raphaël Lescanne.

The **iLM** (Institut Lumière Matière) of Lyon is specialized as its name says in photonics.

The **INL** (Lyon Nanotechnology Institute) is located at Centrale Lyon (Ecully).

They work on semiconductors and photonics. They have a technological platform for component prototyping, particularly in photonics.

The **Camille Jordan Institute** in Lyon is a research laboratory in mathematics that works in particular on quantum probabilities.

It is distributed on several sites: Villeurbanne, Saint-Étienne and on the Centrale Lyon campus in Écully.

The **LIP** (Laboratoire de l'Informatique du Parallélisme) of ENS Lyon associates CNRS, Inria and Claude Bernard Lyon 1 University.

Its MC2 team works on theoretical computer science and complexity theory. It includes Omar Fawzi, CNRS 2019 bronze medalist and specialist in quantum information theory.

Occitanie The Occitanie region hosts 100 researchers in quantum science (as of April 2025). It is spread over Toulouse, Montpellier and Perpignan. Quantum research in Toulouse is very focused on fundamental physics and quite far from quantum computing with the exception of **LPTT**. Two key quantum laboratories are in Montpellier: Laboratoire Charles Coulomb and LIRMM from the University of Montpellier.

The **Institute for Quantum Technologies in Occitanie** was created in January 2021 to consolidate all the Occitan research and industry organizations, including the research labs below from Toulouse and Montpellier.

CEMES (Centre d'Élaboration de Matériaux et d'Etudes Structurales) in Toulouse is specialized in physics and optronics. It works on light-matter coupling at scale and the creation of sensors oriented more towards connected objects than quantum applications.

LCAR (Laboratoire Collisions-Agrégats-Réactivité) of the Paul Sabatier University of Toulouse works on Rydberg atoms.

It is in the team of Juliette Billy and David Guéry-Odelin.

The **IMT** (Institut de Mathématiques de Toulouse) of the University of Toulouse studies statistical and quantum physics.

Here, Clément Pellegrini is studying quantum information theory and quantum state measurement.

The **LPCNO** (Laboratory of Physics and Chemistry of Nano-objects) of INSA Toulouse is specialized in photonics and quantum electronics.

They study electron and nucleus spins, quasiparticles and quantum dots. They aim at applications in quantum computing. Their research is looking at applications in the health sector.

The **LPTT** (Laboratoire de Physique Théorique de Toulouse) works on superconductors and SQUIDs.

The **LCPQ** (Laboratory of Quantum Chemistry and Physics) of the Paul Sabatier University of Toulouse develops generalist quantum chemistry codes, contributing to molecular simulation efforts.

The University of Montpellier has several labs with quantum scientists, like the LIRMM and L2C, but also the Institut des Données (data science).

The **L2C** (Charles Coulomb Laboratory) of the University of Montpellier is working on quantum metrology, spin dynamics and graphene, with applications in magnetic microscopy.

This is the home of Vincent Jacques and Anais Dréau's labs which study the use of NV centers for sensing and silicon-vacancy (SiV) centers for communications applications and quantum sensing.

The **LIRMM** (Montpellier Laboratory of Computer Science, Robotics and Microelectronics) focuses on the creation of quantum algorithms.

It hosts Éric Bourreau, who is specialized in operational research and works on quantum versions of operations research algorithms.

iCGM (Institut Charles Gerhardt Montpellier) hosts Bruno Senjean who works on quantum computing in quantum chemistry.

Nouvelle Aquitaine The Nouvelle Aquitaine ecosystem is specialized in sensing and enabling technologies like lasers, with its industry ecosystem comprising **Exail** (which absorbed Muquans and iXblue) and **Azurlight Systems**. Since March 2021, this ecosystem is federated under the umbrella **Naquidis**, as part of the AlphaLRH cluster and with the support of the Region.

Besides the local branch of IOGS (Institut d'Optique Graduate School), there are two quantum research labs in the region.

The **LP2N** (Laboratoire Photonique, Numérique et Nanosciences) of the Institut d'Optique de Bordeaux does research in photonics and metrology based on cold atoms (microgravitometry).

This is where the startup Muquans started.

QMBx (Quantum Matter Bordeaux) from the University of Bordeaux is a laboratory created in 2019 that gathers researchers in quantum science and quantum technologies.

It is specialized in quantum matter and particularly on nano-optomechanical systems, on quantum transduction, on topological matter and quantum simulators.

The **LOMA** (Laboratoire Ondes et Matières) from CNRS works on quantum matter and is investigating, among other things, nanomechanical qubits based on carbon nanotubes.

LABRI (Laboratoire Bordelais de Recherche en Informatique) has a Quantum Information and Computation research group.

XLIM (Limoges) conducts research in photonics. They are notably partners with Thales TRT.

They are working on applications in polariton metrology, in particular SPR (Surface Plasmon Resonance).

Sud There are also a few quantum physics laboratories in Marseille, three of which are directly related to the needs of quantum computing. And one laboratory in Nice.

QuantAzur is a quantum research institute federating the Université Côte d'Azur (Nice) labs working on quantum photonics, quantum information science, maths, material sciences and enabling technologies.

INPHYNI (Institut de Physique de Nice) of the Université Nice Côte d'Azur is interested in cold atoms, wave transport, interactions between light and atoms.

It deploys a QKD test network between Nice in Sophia-Antipolis since 2019 in partnership with Orange. The quantum laboratory is directed by Sébastien Tanzilli.

CRHEA (Research Center for Heteroepitaxy and its Applications) is a CNRS/Université Côte d'Azur research laboratory specializing in material science.

It develops wide bandgap III/V semiconductor materials epitaxy and the growth of 2D materials (graphene, transition metal dichalcogenides) in its own cleanroom.

CPT of the Universities of Marseille and Toulon is working on quantum dynamics and wave diffusion in optical fibers and light guides.

They are partners of various foreign universities: Aalborg University (Denmark), Pontificia Universidad Catolica de Chile, Karlsruhe Institute of Technology (Germany), Kyoto Institute of Technology and the Moscow Institute of Physics and Technology.

The **Fresnel Institute of Marseille** is involved in photonics, so inevitably, it can contribute to advances in photon-based qubit management and QKD-based quantum cryptography.

IM2NP (Institut Matériaux Microélectronique Nanosciences de Provence. Magnétisme) is working on high-temperature superconducting materials and on modeling various nanostructures and quantum materials.

The **PIIM** (Physique des Interactions Ioniques et Moléculaires) laboratory at the University of Marseille does research in plasmas, more related to the ITER nuclear fusion project than to quantum computing.

The **Laboratoire d'Informatique Fondamentale de Marseille** is particularly interested in quantum computing. Their Discrete Time Quantum Simulator project was launched in 2018.

They are working on Quantum Walks and the Quantum Cellular Automata.

Burgundy Franche-Comté Besançon is home to three quantum laboratories and Dijon to a fourth.

The **LmB** (Laboratoire de Mathématiques de Besançon) of the Université Bourgogne Franche-Comté studies quantum groups and probabilities.

The **UTINAM** Institute of the University of Besançon studies quantum decoherence, control, diagnosis, processing and transport of quantum information in the field of quantum sensing.

Femto-St is a research institute in Besançon focused on nanosciences, optics and optoelectronics.

They work on optical telecommunications, nonlinear optics, optics-based Ising machines and quantum imaging.

Icb (Interdisciplinary Carnot of Burgundy) of the University of Burgundy, based in Dijon, includes a team studying quantum and nonlinear dynamics (DQNL).

Great East The region includes three quantum laboratories located in Strasbourg, Nancy and Troyes.

CESQ (Centre européen de sciences quantiques) is a multi-domain quantum research center inaugurated in 2023 in Strasbourg, in partnership with the Karlsruhe Institute of Technology.

It hosts 80 people from 7 labs and 20 projects in a new 2600 m^2 building.

The **Quantum Matter Theory Group** from the University of Strasbourg is involved in condensed matter physics and also works on the interactions between light and matter, with Rydberg atoms.

Run by Shannon Whitlock, the lab is developing cold atom-based quantum systems. It is part of CESQ.

The **L2n** (Lumière Nanomatériaux Nanotechnologies) of the Université de Technologie de Troyes is specialized in optoelectronics and photon sources and is run by Christophe Couteau.

It has a fab of 700 m^2 that manufactures and characterizes these components.

The **Loria** (Lorraine Laboratory for Research in Computer Science and its Applications) is based in Nancy.

Two teacher-researchers are interested in quantum computing and algorithms: Simon Perdrix and Emmanuel Jeandel. The first is one of the main contributors of ZX-Calculus. Since 2021, Simon Perdrix has been a PI at Inria Nancy.

Elsewhere in France And finally, here are a few quantum physics laboratories located in other regions, in Rennes, Lille, Bordeaux and Limoges, but with no apparent direct link to quantum computing.

The **IPR** (Institut de Physique de Rennes) is attached to the University of Rennes. They are interested in quantum dynamics, the evolution of quantum states over time.

The **LARIS** (Laboratoire Angevin de Recherche en Ingénierie des Systèmes) based in Angers deals with various IT domains.

Within it, François Chapeau-Blondeau and Etienne Belin are interested in the impact of noise on quantum algorithms.

The **PhLAM** (Laboratoire de Physique des Lasers Atomes et Molécules) in Lille is interested in photonics and cold atoms.

The **IEMN** (Institute of Electronics, Microelectronics and Nanotechnology) is a laboratory located on four sites in Lille, Villeneuve d'Ascq and Valenciennes.

They specialize in the design of quantum nanostructures.

International collaborations International partnerships are very common in research. Many of the works of French researchers are carried out with researchers from other countries, including the USA, the UK, Austria, the Netherlands and Germany, Japan and Singapore, with joint international units of the CNRS JFLI in Japan, MajuLab in Singapore and another one in Canada in Sherbrooke.

CEA-Leti is a partner of **IMEC,** its counterpart in Belgium, based in Leuven, covering AI and quantum computing [268]. Like CEA-Leti in Grenoble, they have a clean room for etching up to 28 nm on 30-cm wafers and another on 20-cm wafers for MEMS.

Since 2017, the **Grenoble University Space Center** has been collaborating with the Austrian **IQOQI** on sending quantum keys via satellite in the Nanobob project.

And there is another international collaboration on quantum involving France, the Netherlands (QuSoft) and Latvia.

Government funding

After Atos launched in 2015/2016 its venture in quantum computing emulation, the French government started to look at the opportunity to launch a quantum plan. Back then, it was involved in the European Quantum Flagship which was announced in October 2018.

Things really started with the creation of a parliamentary investigation commissioned by the Prime Minister in March/April 2019 and led by MP **Paula Forteza**, accompanied by **Iordanis Kerenidis** (CNRS researcher specialized in quantum machine learning) and **Jean-Paul Herteman** (former CEO of Safran). The parliamentary mission submitted its report on January 9, 2020, titled "Quantum: the technology disruption that France will not miss". The report made fifty proposals, 37 of which were made public. The government then created a national quantum strategy that included some but not all the parliamentary mission's proposals. All this during the early stages of the covid pandemic. It was finally announced a bit late, in January 2021, but by President Emmanuel Macron, a premiere in the western world.

The ambitions of the strategy and its roadmap revolved around rather classical themes: NISQ quantum computing, Fault Tolerant Quantum Computing, algorithms and software, quantum telecommunications overall (including quantum cryptography and distributed quantum computing), quantum sensing, and finally, enabling technologies. This includes cryogenics, cabling, control electronics, vacuum control, lasers and photon sources. The plan was spread over 5 years from 2021 to 2025 with €1B public funding and an additional €850M funding expected from European Union funds and the private sector (industry R&D and startups funding) [269, 270].

In 2021 and 2022, many components of this quantum strategy were launched. There was an incremental €150M research program handled by CNRS, CEA and Inria announced in September 2021 and launched in 2022. Then, the HQI (Hybrid HPC Quantum Infrastructure) program, a hybrid classical/quantum platform announced in January 2022, which is located at the TGCC supercomputing center handled by CEA, hosting the Joliot-Curie supercomputer in association with an Eviden Qaptiva classical server for emulation and QPU drive, and a Pasqal analog quantum simulator that was inaugurated in November 2025 along with the Lucy quantum computer from Quandela. This project was partly funded by the EU HPC-QS and EuroHPC programs. On top of this, a €65M education program was launched with 21 universities to expand quantum training from the bachelor's and master's levels through the PhD. Other programs were launched for FTQC-related enabling technologies, for the incubation and acceleration of quantum startups, for cryogenics and for the deployment of PQC systems.

Many of France's National Quantum Strategy's accomplishments and related projects are described in its Annual Report published in March 2023 [271].

In March 2024, the ProQCima was announced by the Minister of Defense. It is a €500M procurement program modeled on DARPA-style challenges. It selected 5 local startups (Alice & Bob, C12, Pasqal, Quandela and Quobly) for a three-stage program whose stated target is a fault-tolerant machine with 128 logical qubits by 2032. This is a selection target rather than a demonstrated result, and the published wording does not define the logical error rate, the supported logical operations or the class of problems the machine would address. In the end, only 2 startups will be retained for the last stage [272]. The program has some similarities with what the AFRL is doing in the USA and DLR in Germany.

At the regional level in the Paris region, the Pack Quantique program funds collaborative projects on quantum case studies between industry vendors, mostly startups, and end-user customers [273].

In December 2022, France and the USA signed a joint statement to enhance cooperation on quantum technologies, like the USA are doing bilaterally with so many countries as you'll see afterwards.

In May 2026, the second phase of the French quantum strategy was launched, and again, by President Macron. The public investment is of €1B like in 2021, but this time, all being incremental instead of $2/3^{rd}$ in 2021. The plan budget split is €130M for research on computing and sensing in collaboration with the industry, €50M for training and standardization, €470M for research and development including €300M for the remainder of the ProQCima program, €190M for middleware and software and €160M for joint European projects.

Quantum industry

On the industry vendors scene mapped in Figure 35, France has a handful of ventures on the quantum computing hardware front with **Alice & Bob** (cat-qubits), **C12** (electron-spin qubits in carbon nanotubes), **Pasqal** (cold atoms qubits), **Quandela (**single photon sources and photonic qubits), **Quobly** (silicon quantum dots spin qubits) and **Crystal Quantum Computing** (using trapped ions in Rydberg states).

On the software side, we have **Qubit Pharmaceuticals** (healthcare), **QuantFi** (finance), **MolKet** (chemistry), **ColibriTD** (multisector), **QbitSoft** (logistics and retail), **QPerfect** (emulation), **Aqemia** (biotech), **VeriQloud** (quantum telecommunications) plus a bunch of companies specialized in cryptography, mostly PQC with **CryptoNext**, **CryptoExperts**, **Ravel**, **QuRisk** and **Secure-IC**.

In quantum sensing, we can count on **Muquans** (microgravimeters, acquired by **iXblue** in 2021, becoming **Exail** in 2022), **Chipiron** (magnetic imaging), **KwanTek** (NV-center imaging), **Mag4Health** (imaging) and **Thales** (NV centers, SQUIDs and cold atoms sensing, lightweight cryogeny).

In addition to **Bpifrance** and the investment fund **Quantonation**, the **Deep Tech Founders** trains entrepreneurs/researchers in deep-tech companies. It is an international program created by the Hello Tomorrow team. All these organizations are behind the creation of a structure to support the quantum ecosystem in partnership, the **Lab Quantique**, launched officially in April 2020. The Lab Quantique is a think tank for the development of talent, particularly at the crossroads between science and entrepreneurship. From a practical point of view, le Lab Quantique organizes regular meetings that bring together mainly quantum technology entrepreneurs from France and abroad.

These meetings took place in the form of videoconferences on Zoom during the covid-19 pandemic period in 2020 and 2021. Its objectives are to connect industry players, startups and researchers, to build bridges with the international community, to launch a program to accelerate quantum startups and to organize a major annual high-level conference bringing together all the stakeholders in the ecosystem, as well as an International Prize (attracting talent). It takes the form of a trade association mixing the quantum industry (large organizations, small businesses and startups) and its users (mainly, large companies like EDF, Airbus and the like).

One distinctive feature of France in Europe is the number of its large corporations directly invested in quantum technologies and quantum enabling technologies : **Bull** (formerly Atos and Eviden, software, emulators, quantum accelerators), **Thales** (sensors), **Air Liquide** (cryogenics), **Orano** (isotope production, such as silicon-28), and small/medium businesses like **Radiall** (connectors, cabling, switches, attenuators, couplers, optical links), **ATEM** (cabling) and many in photonics (like **Exail, Azurlight Systems, Aurea Technology, Lumibird** and **Cailabs**) and even semiconductor manufacturing machines with **Plassys Bestek** and **Riber**. We can also add **OVHcloud**, a European cloud services vendor, which launched in 2022 its first quantum offerings, in partnership with Bull (Eviden) (emulation), Pasqal (quantum simulation), Quandela (QRNG with a first QPU) and C12 (emulation).

1.8.5 The Netherlands

The Netherlands is one of the most active European countries in quantum technologies research and development, mainly around the University of Delft (**TU Delft**) and its **QuTech** branch.

Dutch physicists have for a long time been at the core of Europe's quantum forefront.

Historical Dutch researchers are **Hendrik Antoon Lorentz** (1853-1928), **Heike Kamerlingh Onnes** (1853-1926), **George Uhlenbeck** (1900-1988), **Hendrick Casimir** (1909-2000) and **Samuel Goudsmit** (1902-1978).

Research

QuTech is TU Delft's quantum research center launched in 2014. As of late 2022, QuTech employed 330 people, of which only 44% are Dutch. QuTech is also associated with **Intel** and **Microsoft**. QuTech has received $50M in funding in 2015 from Intel as part of a partnership on their superconducting and electron spin qubits. Mi-

Figure 35: France's quantum industry ecosystem. Ⓒ Olivier Ezratty, 2021-September 2026.

crosoft has also been a partner of QuTech since 2010 and hired **Leo Kouwenhoven** into its Microsoft Research laboratory, located on site and working on topological quantum computing and Majorana zero modes in liaison with a QuTech team on the same subject. Kouwenhoven left Microsoft in 2022 and came back as a researcher at TU Delft.

Collaborative research approaches are making good progress, particularly with a view to recovering European funding. In October 2017, QuTech launched a partnership with the Institute of Photonic Sciences, the University of Innsbruck in Austria and the Paris Centre for Quantum Computer. QuTech is also a partner of the University of Aachen in the CMOS qubit. The University of Delft has also obtained for the European part of the QuNET project mentioned about Germany an ERC of €1.5M with a launch in November 2019 and an end planned for October 2024 [274].

Other initiatives whose scope and governance are not publicly documented have been launched, such as **Quantum Helix**, funded under the European Quantum Flagship Program and Horizon 2020.

Government funding

In 2015, the Dutch government launched a 10-year, €135M plan to create a quantum computer [275]. The investment was made in **QuTech**, with a 10-year budget of €145M, half of which comes from TU Delft University and the other half from the NWO, the national funding agency [276].

In 2021, the Dutch government then announced a 7 years €615M plan, complemented by a €228M extension in 2022 [277]. Relative to GDP, this is among the largest announced public commitments in Europe, bearing in mind that it is an announced multi-year allocation and not realized annual spending, so it is not directly comparable with the run-rate figures reported by other countries.

This public funding was supposed to drive private sector investments of €3.6B, a very ambitious goal in comparison with the similar €565M expected in France as part of its 5-year plan announced in 2021. The country planned to create 30,000 high-tech jobs and create a cumulative economic impact of at least €5B with quantum technologies. The country plan is organized around the creation of three technology demonstrators, four generic action lines and shared cleanroom facilities. In July 2024, QDNL got an additional funding of €273M in funding for the third phase of their expansion [278].

The Dutch quantum plan is managed by the non-profit foundation **QDNL** that was created in 2020 [279, 280], formerly Quantum Delta the Netherlands. DELTA did stand for Delft, Eindhoven, Leiden, Twente and Amsterdam, the five locations in the country with a significant quantum ecosystem in either research and/or industry vendors (Figure 36). In 2024, Philippe Bouyer, a French scientist already involved in the Dutch quantum ecosystem as a researcher, became the chairman of Quantum Delta.

QDNL

Key components of their activities are:

- **House of Quantum**, a startup ecosystem facility which opened in 2023 in Delft, with a budget of

Figure 36: Map of the Netherlands research ecosystem. Source: Venturing into Quantum Technology in the Netherlands by Deep Tech Fund and Invest-NL, October 2023.

€182M. It should accelerate part of the 100 startups the country wants to consolidate by 2027, probably quite an optimistic goal (like in many other countries). It opened a second building in May 2024, hosting several local and foreign quantum startups like Q*Bird, Equal1, Xairos, and Qblox [281]. They already hosted Single Quantum, Orange Quantum Systems, and QuantrolOx. TNO expanded in 2025 its presence at the House of Quantum with a new quantum testing hub.

- Within this house, the **Living Lab QT** focuses on ethical, legal and societal aspects of quantum technology with research collaborations between universities, the public and private sector, with a funding of €20M. They opened two related interdisciplinary university positions, created a desk and a toolkit for responsible innovation and entrepreneurship and a covenant to be signed by private and public stakeholders promoting sustainable and safe use of quantum technologies.

- **Quantum Inspire**, their cloud superconducting computer service that is already available and got €90M of funding. They are working on setting up a hybrid HPC/QPU infrastructure [282].

- **Quantum Network** project on quantum telecommunications and cryptography, connected to the related European projects, with a funding of €62M. They expect to quantumly connect three quantum computers by 2023 and five by 2026.

- **LightSpeed** is a program connecting startups with investment funds. It is overselling a bit its value touting access to €13.6B in investment capital, representing the totality of the various funds managed by these investors. The 2022 funding extension added €15M for a startup seed fund. It was completed by the startup **Infinity** support program [283].

- They also planned to invest €150M in the 5 cleanrooms from **NanoLabNL**, have a quantum sensors plan with €23M funding and a training program that should create 2000 PhDs and engineers by 2027 with a funding of €41M.

The **Quantum Software Consortium** runs for 10 years from 2017 and has received €18.8M in public funding from the country's Gravitation Program. It brings together various Dutch laboratories: **TU Delft**, **QuTech** (part of the latter), **QuSoft** (a research laboratory dedicated to quantum software, launched by CWI, UvA and VU in 2015), **CWI** (Centrum Wiskunde & Informatica), the **University of Leiden, UvA (**University of Amsterdam) and **VU** (Free University of Amsterdam) to conduct research in quantum software and cryptography.

The Netherlands and France signed in September 2021 a Memorandum of Understanding to expand collaborations in quantum technologies. The bilateral collaboration includes research partnerships in silicon qubits as part of the European flagship project QLSI, research-industry collaboration involving companies like Atos, the creation of a joint portal listing job opportunities in France and the Netherlands (www.quantumjobs.fr and quantumjobs.nl) and collaboration to increase EU venture capital in the domain (involving Quantonation). Then, in November 2022, Quantum Delta « raised » an additional €60.2M from its government National Growth Fund as part of a joint partnership with France and Germany [284].

Quantum industry

The country startup ecosystem includes **QuantWare** (superconducting qubits chips), **Delft Circuits** (flexible cabling), **Qblox** (electronics for controlling superconducting qubits), **Groove Quantum** (silicon-germanium spin qubits), **Single Quantum** (single photon detectors), **QuiX** (photonic processor, a subsidiary of Lionix, a foundry capable of producing photonics wafers in silicon nitride on SiO_2), **QuSoft** (quantum software), **QPhoX** (quantum computer interconnection), **ipCLock** (quantum clock) and **Leiden Cryogenics** (high-power dilution cryostats). As in most non-US countries, the local ecosystem is striving to get enough funding for its startups and calling for more private equity investments [285].

In December 2020, the Dutch quantum industry created the **IMPAQT** consortium. The first members were Orange QS, Qblox, Delft Circuits, and QuantWare. Their goal was to improve the coordination of how they are creating quantum computer enabling technologies.

In 2024, QDNL launched the consortium **Hecto-Qubit/2** (HQ/2) combining academic research labs and industry vendors with the goal to build a superconducting 100-qubit QPU. It associates Leonardo DiCarlo from TU Delft, QuTech, TNO, QuantWare, Delft Circuits, Orange Quantum Systems, and Qblox [286]. In May 2025, as part of the HQ/2 project, QuTech, TNO, and four Dutch startups launched the Tuna-5 system on the Quantum Inspire public cloud, with a 5-qubit chip from QuantWare, control electronics from Qblox, operating system from Orange Quantum Systems, and cabling for future prototypes by Delft Circuits. The QPU is a testbed for the integration of enabling technologies, mostly coming from the Netherlands [287]. The Dutch startup ecosystem also benefits from the services from **Techleap**, a deeptech startups community.

In 2024, **Fujitsu** established an Advanced Computing Lab at TU Delft to accelerate its R&D in the field of NV-center quantum computing [288].

A January 2026 report created by the Dutch financial newspaper Het Financieele Dagblad stated that the country startup ecosystem needed €9B to fill the funding gap with the rest of the world [289]. You can wonder about the comparables and rationales. In my startup database, I have €2.8B invested in all EU startups "life to date". So three times this amount would be needed for a single country?

1.8.6 Belgium

Belgium is the host of the famous Solvay conferences created in the early 20th by Ernest Solvay.

Their presence in the quantum science and technology scene is exemplified by **IMEC**, the international semiconductor and nanotechnologies research center based in Leuven, an equivalent to CEA-Leti in France, with 4,000 employees.

IMEC's quantum technology activities are centered on producing superconducting and electron spin qubits on behalf of various laboratories and vendors as well as some cryoelectronics systems. Among other projects, they participate to the European Quantum Flagship QLSI project that is coordinated by CEA-Leti. They announced in August 2021 a partnership with **Xanadu**, for the development of fault-tolerant photonic qubits chips based on silicon-nitride.

Let's also mention the **Centre for Quantum Information and Communication** (QuIC) from the Université libre de Bruxelles (ULB). It works on quantum measurement, quantum entanglement, quantum communication, quantum cryptography and quantum algorithms. It has also worked on continuous-variable quantum cryptographic protocols and developed quantum adiabatic algorithms.

In the vendor space, I have identified a company that was already mentioned, **QBee.eu**, a quantum accelerator and incubator created by Koen Bertels, who led the Quantum Computer Architectures Lab at TU Delft and QuTech before moving to Ghent University.

1.8.7 Luxembourg

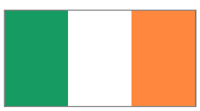
Luxembourg has a couple academic quantum groups like the Quantum Information Theory and the Quantum Science and Technology groups from the University of Luxembourg.

The Luxembourg Institute of Science and Technology (LIST) hosts the new group of Florian Kaiser to develop materials for quantum computing.

LIST obtained a funding of €4M as part of the PEARL program for the project AQuaTSiC (Advanced Quantum Technologies with Silicon Carbide) which works on creating materials for cavities-based quantum computing.

The country is also active in the field of QKD, including the involvement of ESA (European Space Agency), and a partnership with SK Telecom [290] and another one with Belgium for the creation of a terrestrial cross-border QKD connection within the framework of the national initiatives LuxQCI [291] and BeQCI, both part of the EuroQCI European initiative [292, 293].

1.8.8 Ireland



In Ireland, a first quantum computing initiative (QCoIr) was launched in 2020 with a funding of $11M.

It included global companies like IBM and Mastercard, plus the Tyndall National Institute in Cork. It established a Quantum Center of Excellence.

In May 2023, the **Trinity Quantum Alliance** (TQA) was launched to build a local quantum ecosystem, starting with establishing a custom space in Trinity East, a new zone of Trinity College in Dublin. It is associated with several foreign quantum industry vendors who have a foothold in Ireland like Microsoft, IBM, Horizon Quantum Computing, Algorithmiq and Moody's Analytics and will rely on Trinity College's quantum Master of Science.

In November 2023, Ireland published its national quantum strategy dubbed Quantum 2030 organized along five typical pillars (research, education, entrepreneurship, international collaboration, public awareness), but with no announced budgeting [294]. ICHEC's Quantum Programming Ireland (QPI) Initiative has a group working on quantum computing.

In June 2026, the government funded the creation of Rinn Quantum, a research and innovation center in quantum information science and technology with about €40M.

Its vendor ecosystem contains **equal1**, an Irish/US quantum computing company.

1.8.9 Finland

Finland has a couple very interesting assets in quantum technology including a worldwide leader, with Bluefors, which leads the low-temperature dilutions market.

It also has IQM, so far, the best funded quantum computing company in Europe. It also has strong academics groups in various domains. I visited the Finnish quantum ecosystem in April 2024.

Research

In research you can count with Aalto University, the University of Helsinki, Tampere University and VTT Technical Research Centre of Finland.

VTT is a public RTO (Research and Technology Organization) with a total of over 2200 employees. Its quantum team gathered 50 people as of mid-2024. They work on quantum materials, superconducting qubits including 50/54 qubits chips codeveloped with IQM, parametric amplifiers and TWPAs, photon detectors (SNSPDs and others), SQUID magnetometers, graphene based superconducting materials, optical conversion for signals multiplexing, and even do some design of SFQ superconducting electronics. They also have Micronova, a 150 and 200 mm clean room manufacturing various chips, from superconducting to silicon qubits which will be complemented by Kvanttinova, an upcoming 300 mm cleanroom, with an investment of €500M.

The Finnish Quantum Institute federates the efforts of Aalto University, the University of Helsinki and VTT. It is an organization fostering collaborative research (ResQ) and education particularly with public broad audiences (EduQ) and business adoption of quantum technologies within Finland (BusinessQ).

In January 2022, Finland and VTT launched **QuTI** with €10M to pool the expertise and resources of four research and eight industry partners over a three year period. It is centered around enabling technologies for quantum computing (materials, cryogeny, electronics, software, systems architecture). The program industry partners are Afore, Bluefors, IQM, Quantastica, Saab, Vexlum, and for companies outside Finland, Picosun and Rockley Photonics.

The **CSC** computing center hosts the LUMI supercomputer and will put in place a hybrid quantum/classical computing architecture with IQM as part of the EuroHPC HPCQS (High Performance Computer – Quantum Simulator hybrid) program.

In September 2026, VTT, Tampere University and Aalto University launched the 3-year QScale project, to develop technologies aimed at improving the energy efficiency and scalability of quantum computers with a funding of about €6.9M including €5.5M from Business Finland. It involves integrated optics, optoelectronics, semiconductor electronics and superconducting electronics with new electrical cooling methods [295].

Government funding

In April 2022, Finland and the USA signed a Joint Statement on Cooperation in Quantum Information Science and Technology very similar to the ones signed with Australia, Sweden, Denmark, Switzerland, Singapore and the UK in 2021/2022, and Germany in 2024.

In December 2022, the EU awarded a €19M Specific Grant Agreement (SGA) funding for the project Qu-Pilot to upgrade the existing European micro, nano and quantum technology manufacturing infrastructures, mostly in superconducting chips. It is led by VTT with 24 member organizations from 9 EU countries (Finland, the Netherlands, Germany, Belgium, France, Austria, Italy, Spain and Czech Republic). VTT got $3.8M of this funding.

In September 2022, the Finnish quantum community formed a working group which published in February 2023 a list of recommendations for the development of quantum technologies in the country. It included a better coordinated research and innovation program, long term investments, education investments and the support for national and international cooperation [296]. It estimated the ongoing R&D effort at $45M per year including the Swedish Wallenberg Foundation investment of €130M for 12 years starting in 2018. In January 2024, the Research Council of Finland awarded a 5-year €13M funding to the new Finnish Quantum Flagship project covering funding for various research organizations including VTT, Aalto University, the University of Helsinki, and Tampere University.

In April 2025, Finland finally published its 10-year national quantum technology strategy containing eight measures covering quantum computing, sensing, and communications, in a 55-page document [297]. These cover the creation of a quantum competence center covering a master-doctoral path and continuing education, the development of a 1,000 logical qubits QPU by 2035, investment in R&D infrastructure including chip manufacturing, PQC deployments, long-term research efforts, fuel commercial developments with a mix of public and private funding, international collaboration and national coordination. By the way, the document estimated that Finland public research investments were of $52M in 2023, the bulk going to Aalto University and VTT. It didn't provide any new funding data.

In June 2025, Finland said it will lead a new EU defense initiative named Quest (Quantum Enablers for Strategic Advantage). It will explore the potential of military applications of quantum computing, sensing and communications. Quest is one of the 11 projects of the EU's PESCO (Permanent Structured Cooperation) framework. It involves Germany, Denmark, Latvia, and Italy. Envisioned used cases are PNT (positioning in GPS-denied areas), hypersonic missile defense and cryptanalysis.

Quantum industry

On the industry side, **Bluefors** is the worldwide leader in low temperature cryogeny used with superconducting and silicon spin qubits quantum computers. **IQM** is by far the largest and best funded superconducting qubits quantum computing startup. Other Finnish startups are **SemiQon** (silicon qubits), **Algorithmiq**, **Ampliconyx**, **Kronus**, **Qplaylearn**, **Quanscient**, **Quantastica**, **SSH Communications Security**, **Unitary Zero Space** and **Vexlum**.

1.8.10 Sweden

On the **Swedish** side, there is mainly the WACQT (Wallenberg Centre for Quantum Technology) which is part of the **Chalmers University** of Gothenburg and is co-funded by the Wallenberg Foundation.

The WACQT has been funded under a 12-year plan with over $100M. As in all countries, the center targets all quantum technologies domains (computing, communications and sensing). They are invested in superconducting qubits as well as in continuous variable qubits. They plan to create a 100 qubits superconducting computer. WACQT is also working on Rydberg atom qubits, named after the Swedish physicist Johannes Rydberg. It has also launched a "Women in WACQT" initiative to develop gender diversity in quantum science.

In March 2021, the Wallenberg budget nearly doubled to $9M per year, allowing the hiring of 40 more researchers. In April 2022, Sweden and the USA announced a partnership on quantum technology similar to the ones with the UK, Finland, Denmark, Australia, Switzerland and France.

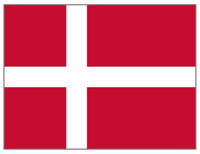
Vinnova (Sweden Innovation Agency) with RISE (Research Institutes of Sweden), Swelife (life sciences community), The Swedish Research Council and Chalmers-WACQT published in March 2023 a position paper calling for a Swedish quantum agenda [298]. It remains to be launched by the Swedish government.

In January 2023, WACQT announced it would deliver a 25-qubit quantum computer to the country ecosystem in academia and industry, with a funding of $9.5M coming from the Knut and Alice Wallenberg Foundation. They later plan to upgrade the system to 40 and then 100 qubits. In 2025, Sweden entered into a partnership with the Singapore quantum ecosystem.

Let's remind a key influence from Sweden in quantum physics. Its Royal Academy of Science is awarding every year the Nobel prize in physics!

The country industry vendors ecosystem comprises **Altitun** (lasers), **Atlantic Quantum** (fluxonium qubits, US-based with Swedish roots, acquired by Google in October 2025), **Beamfox** (EBL correction software), **ConScience** (fab), **Intermodulation Products** (microwave generation), **Low Noise Factory** (cryoelectronics), **Phase Space Computing** (quantum computing training), **Quantum Technologies AB** (services) and **Scalinq** (superconducting chips packaging).

1.8.11 Denmark



Quantum research in **Denmark** is spread over multiple sites. One is the Center for Quantum Devices (**QDev)** at the **Niels Bohr Institute** (NBI) at the University of Copenhagen.

There is also **DTU** (Technical University of Denmark) with a QuantumDTU Center for Quantum Technologies. NBI is focused on various fields in condensed matter physics.

In a visit to DTU and NBI in December 2023, I had a chance to discover part of the breadth of academic work on cold atoms experiments, nanomechanical oscillators, and color center based magnetometry (Eugene Polzik, NBI), crystal photonic sources (Nika Akopian at DTU), continuous variable photon squeezed light both for QKD and for quantum computing (Ulrik L. Andersen and Jonas S. Neergaard-Nielsen at DTU), quantum gravimetry (Rene Forsberg at DTU), quantum dots operating in the telecom wavelengths (Leif Oxenløwe at DTU), creating micropillar quantum dots operating in the 1,550 nm telecom band (Niels Gregersen, DTU), phononic based memories (Albert Schliesser, NBI) and nanofabrication at Nanolab (Jörg Hubner). They also study fluxonium qubits [299].

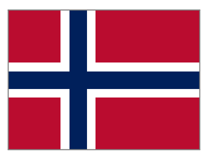
The Danish government invested $12M on quantum research between 2017 and 2019. In June 2023, the Danish government announced a formal National Strategy for Quantum Technology in two parts. Part 1 corresponds to $140M of funding focused on research with an eye on use cases in healthcare, green transition and cyber security over the 2024-2027 period ($35M per year). Part 2 is focused on commercializing quantum technologies in Denmark ($7M per year) for the same period [300].

This was completed in September 2022 by the launch of a $200M initiative by the **Novo Nordisk Foundation**, the largest in the world, to build a generic quantum computer in 2034, most of the funding going to NBI as part of the Novo Nordisk Foundation Quantum Computing Programme (NQCP), led by Peter Krogstrup. In February 2024, the foundation committed $29M in funding for the development of quantum sensors in healthcare. In May 2024, **Novo Holdings** added €188M to fund the expansion of the Danish quantum computing and sensing startup ecosystem [301]. The foundation expects to spur the creation of a fully functional quantum computer by 2034 able to solve real problems like in life sciences, of course. In July 2025, the Novo Nordisk Foundation and EIFO, the export and investment fund of Denmark, announced an investment of €80M for the creation of QuNorth, a quantum data center that will host an Atom Computing QPU nicknamed Magne, built with software support from Microsoft. The vendors describe a logical-qubit target for the system, which should be quoted with its date and with the encoding and error rates it assumes, since delivering the hardware does not by itself establish fault-tolerant logical performance.

In April 2022, NATO announced the setup of a NATO Accelerator for Quantum Technologies in Denmark. This innovation accelerator is installed at NBI [302]. This was completed in June 2022 by the announcement of a global quantum partnership with the USA.

From an industry perspective, Denmark hosts about a dozen quantum companies, mostly in enabling technologies, like **QDevil** (filters, acquired by Quantum Machines), **Sparrow Quantum** (single photon sources) and **Cryptomathic** (cryptographic software and PQC), **ATLANT-3D** (ALD manufacturing), **Type one systems** (sensing) and **QPurpose** (algorithms). In 2024, the Danish Quantum Community published a white paper with 16 quantum use cases, including 7 in quantum computing, all realized with local software players [303].

1.8.12 Norway



Norway feared in 2018-2019 to miss the second quantum revolution.

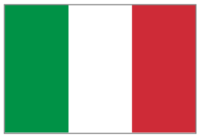
In 2020, it created a Gemini-center on quantum computing with SINTEF, the University of Oslo, NTNU, and in 2021, Simula Research Laboratory, a fundamental research organization belonging to the Norwegian Ministry of Education and Research, where Shaukat Ali leads research in quantum software engineering (among other things) [304]. The project was led by Franz Georg Fuchs from SINTEF, an independent research organization with the goal to make Norway "quantum ready". Later in 2021, the Norwegian Quantum Computing Centre was created consolidating research from 13 scientists from three partner institutions (SINTEF, the Norwegian University of Science and Technology *aka* NTNU and the University of Oslo) including Jeroen Danon from the Center for Quantum Spintronics at NTNU [305].

In June 2023, the QCNorway consortium published a white paper calling for a national quantum initiative, like in many other countries [306]. In October 2024, the government launched a quantum initiative with an annual funding of $6.6M.

In 2024, the Gemini Center scope was expanded to quantum sensors and materials, and quantum communication and security so that all quantum technologies are covered.

In June 2026, IQT Nordics was organized in Oslo, gathering speakers from the Nordic countries and a couple others like France (including me, Quobly and Sealsq), UK (Orca Computing), Israel (Quantum Machines), Portugal (Yasser Omar), Germany (Jörg Wrachtrup) and the Netherlands (Eindhoven University).

1.8.13 Italy



Italy has very active research in place in various technologies in quantum computing. Photonic qubits are explored by **Fabio Sciarrino** at Università La Sapienza in Rome.

He is a European pioneer of boson sampling experiments and wants to make it programmable. The **Università di Padova** launched its own Quantum Technologies Research Center working on trapped ions computing.

Francesco Tafuri from the Università Federico II in Naples works on superconducting qubits. The Italian National Institute for Nuclear Physics (INFN) is also working with the US DoE on superconducting quantum materials at the FermiLab in Chicago, which happens to be run by Anna Grassellino, an Italian.

In the quantum communication realm, **Paolo Villoresi** from the University of Padova pioneered photons polarization encoding with a satellite in 2015. Italy also deployed its **Italian Quantum Backbone** (IQB) with a total of 1,850 km fiber link based on commercial fibers. It connects INRIM's premises in Turin to Milan, Bologna, Firenze, Rome, Napoli, Pozzuoli and Matera. From Turin, a 150 km fiber reaches Modane in France, and connects to Grenoble, Lyon and Paris, then Europe. Federica Mantegazzini's team from the **Fondazione Bruno Kessler** in Trento develops superconducting components for various use cases (qubits, TWPAs [307], high-kinetic inductances [308] and quantum sensors [309]).

The public supercomputing center **CINECA** entertains a quantum computing lab. It tests the capacities of various quantum computers, develops quantum algorithms and hybrid solutions associating classical supercomputers and quantum accelerators. It hosts a Pasqal analog simulator and an IQM 54-qubit system. The University of Torino deployed an IQM Spark 5-qubit system in 2026 as well, named Lagrange [310].

Italy has comparatively few industry vendors and startups engaged in quantum technologies relative to its research output, with 16 companies in my database and a visible cumulative funding below €15M. It led in 2023 to the creation of **Quantum Italia**, an investment vehicle dedicated to quantum technologies and created by Scientifica Venture Capital and with additional funding from Quantonation in March 2024. They partner with the Unitary Fund to support the open-source quantum ecosystem in Italy, as well as with Quantonation.

As part of its recovery plan announced in April 2021, the Italian government allocated a budget of €1.6B to fund 7 new research organizations, one of these being focused on quantum technologies [311].

It led in 2023 to the formal creation of **NQSTI**, the National Quantum Science and Technology Institute [312].

This virtual institute gathers 20 academic institutions spread throughout Italy, with a hub center in Rome, and a single vendor, Thales Alenia Space. It gathers 322 researchers and got €115M of funding coming from the National Recovery and Resilience Plan (NRRP) and EU's NextGenerationEU program, covering the period from December 2022 to November 2025, plus open calls with €23M of funding. Like quantum plans from every country, NQSTI covers the entire innovation chain from low-TRL research, to prototyping and industry developments and startups creation.

The project is organized in 9 "spokes" with information processing and communication (including quantum nonlinear dynamics, advanced quantum algorithms and protocols, AI against quantum noise, storage/processing quantum information), driven-dissipative and complex many-body systems (including quantum matter, quantum networks, quantum thermodynamics for the production, storage and transfer of energy, energy consumption in quantum information processing, quantum sensing, quantum control), atomic and molecular quantum technologies (including hybrid atomic systems, interferometry, quantum optical fields and macroscopic atomic ensemble interfacing), photonic platforms (sources, manipulation, detectors and interfaces), electrons (hybrid material systems), integration (atomic circuits, photonic devices, electronic quantum devices, inter-platform quantum devices, TWPAs, quantum radars), complete quantum systems (imaging, sensing, QKD communication and IoT, simulation systems), technology transfer and finally, education and outreach.

In total, Italy was investing €227M in quantum science over 5 years.

In September 2023, **SISTEQ** (Società Italiana di Scienze e Tecnologie Quantistiche) was created. It is an academic and industry group involving all the Italian quantum ecosystem.

In March 2025, Italy launched its National Quantum Strategy creation process, with a 65-page report and first draft submitted to comments [313], prepared by over 30 quantum scientists [314]. The report proposes to create national quantum labs, develop workforce training, and develop the local industry with better private funding with typical incentives (funding, tax credits, public-private partnerships) and push large Italian players in finance, energy, and manufacturing to go the quantum route. The measurable gap it has to close is the one recorded above: 16 companies and a visible cumulative funding below €15M. Like most national plans, the report targets all three domains at once (computing, sensing, communications) without stating how the effort is prioritized between them.

1.8.14 Slovenia

Slovenia is a small EU country with 2.1 million inhabitants. I had a chance to visit its quantum ecosystem in April 2024.

I visited 14 research teams and met with 3 startups. The quantum research scene is concentrated in the JSI (Jožef Stefan Institute), FMF (Faculty of mathematics and physics from the University of Ljubljana) and FE (Faculty of electroengineering also from the University of Ljubljana). Notable researchers include **Dragan Mihailović** (JSI, Nanocenter) who does research in material science with use cases in superconducting qubit improvements, metastable states, and self-assembly of electrons. He worked on a nonvolatile memory with a switching energy on the order of a femtojoule per bit and a switching time on the order of a picosecond, under the measurement conditions reported in the cited papers which could enable doing QEC at low temperatures, using charge density wave (CDW) which is hard to manufacture [315–317]. His team is also working on using D-Wave quantum annealers [318] and on spin liquids [319]. Teaming with his lab, **Google** is establishing a research laboratory in Slovenia on superconducting qubits.

Denis Arčon (JSI, FMF) is a solid state experimenter working on NV centers and endohedral fullerenes ($N@C_{60}$, a nitrogen atom trapped inside a C_{60} cage) which behaves like a qubit and has long coherence times, and on various high T_c superconducting materials [320–322]. He also observes how biological cells decide to eat diamonds. **Jure Brence** and **Sašo Džeroski** (JSI) work on machine learning research, on interpretable and explainable AI with 50 people and 40 FTE. They are interested in the use of AI in science, including in physics and environmental topics [323]. **Andrej Zorko** works on quantum materials at JSI, using electron paramagnetic resonance (EPR) using μ-SR (muon spectroscopy) and various other quantum matter domains. **Matjaž Gomilšek** also studies quantum effects with muons and nucleus [324].

Zala Lenarčič is a JSI theoretician working on solving many-body quantum systems problems with quantum computing [325]. **Martin Klanjšek** (JSI) works on quantum spin liquids and topological matter using ruthenium trichloride in honeycomb lattices [326]. **Rainer Kaltenbaek** (FMF) works on quantum optics experimenting entanglement based QKD. **Rok Zitko** (JSI) is a theoretician working on various quantum and superconducting materials [327]. **Janez Krč** (FE) works on the automatic characterization of silicon nitride photonic circuits.

On the startup scene, Slovenia has **Beyond Semiconductor**, a security RF transceiver company which now designs and manufactures 1U QKD receivers as part of the SiQUID EuroQCI QKD project, **AtomQL**, which designs a cold-atom processing unit and whose architecture, in particular whether it uses neutral atoms or trapped ions and which species and trapping method, should be confirmed with the company and **Aresis** which sells a tweezer system to control cold atoms.

In October 2025, Slovenia announced its formal quantum strategy with a total funding of about €45M, including EU funds.

1.8.15 Slovakia

Slovakia is an EU country with 5 million inhabitants having borders with Austria, Hungary, Czechia, Poland and Ukraine.

I had a chance to visit its quantum ecosystem in July 2025.

The QUTE Institute in Bratislava focuses on Quantum Information Science (QIS) and Quantum Key Distribution (QKD), with initiatives like netQUTE contributing to the EuroQCI project for secure communication. Training and education are also highlighted by eduQUTE, a quantum training program focused on QKD.

The institute has its own dedicated "QUTE pavilion" and also functions as the association for quantum technology in Slovakia.

QUTE acquired a Gemini Mini Pro from SpinQ for learning quantum computing. It is developing dete-QUTE quantum detectors, including SNSPDs (Superconducting Nanowire Single-Photon Detectors) from Single Quantum that are tested in a Leiden cryostat with a cryocooler from Sumitomo and Helium-3 sorption for cooling. QUTE is associated with various academic labs in Slovakia: Institute of Electrical Engineering, Institute of Experimental Physics, Institute of Physics, International Laser Center of SCSTI, Mathematical Institute, Faculty of Electrical Engineering and Information Technology STU Bratislava, Faculty of Informatics and Information Technologies STU Bratislava (run by Ivan Kotuliak), Faculty of Materials Science and Technology in Trnava, Faculty of Mathematics, Physics and Informatics, and Faculty of Science UPJŠ.

The Quantum Communication Infrastructure (QCI) project in Bratislava is utilizing entanglement sources from Vienna-based spin-off ZeroThird. This project aims for a meshed network, theoretically exploring GHZ states. The team led by Dejeylan Atkas acquired a quantum memory from Welinq. The ambition is to build a full mesh network enabling many-to-many quantum connections, with a quantum entanglement lab focused on a quantum correlation layer. They are working on multiplexing technologies, initially exploring 12 wavelengths and reducing to 6 channels to facilitate this connectivity.

ARICOMA is an IT shop starting to learn and prototype quantum computing projects and PQC. They organized a Summer School in Vienna in August 2025. They purchased a quED demonstrator from qutools (Germany). Professor Vladimir Buzek from the Slovak Academy of Science worked on the no-cloning theorem and quantum copying [328].

I met other researchers who work on MPS, complexity theory, on the development of 3D tensors to be used for quantum chemistry.

1.8.16 Romania

Romania planned in May 2026 to install its first quantum computer late in the year with a total investment of €100M.

This investment is not for the quantum computer alone, but for all the facility and the FreeYaMind Campus ecosystem with its laboratories, workspaces and startup infrastructure. IBM will be the provider of this quantum computer.

1.8.17 Spain

Spain's quantum academic efforts are spread in various places like in Madrid, Barcelona and in Bizkaia.

Research. The leading academic institutions in Spain are **ICFO** (Institut de Ciències Fotòniques) of Barcelona which is mainly specialized in photonics, the Quantum Information and Computation Laboratory (GIC-UB) of the **University of Barcelona** as well as the **Autonomous University of Barcelona** [329], **IFAE QCT**, the Quantum Technology Group from the IFAE (Institut de Fisica d'Altes Energies) from the Autonomous University of Barcelona opened its new lab and fab in October 2020.

Partnerships. The Basque country led by the **Provincial Council of Bizkaia** is also fostering the adoption of quantum computing in the industry. Participating members are Tecnalia (again), IBM, Telefónica, Accenture, the Bilbao City Council, Gaia, Silicon Europe, the UPV/EHU (the University of the Basque Country), the University of Deusto in San Sebastián and Mondragon Unibertsitatea (east of Bilbao). The region established a partnership with IBM to deploy one QPU in San Sebastian in Spain [330]. In March 2025, IBM and the Basque government announced that a System Two would be installed by the end of 2025, which was done in October [331].

Quantum communications. Spain is invested in testing and deploying quantum networks. The **MadQ-CM** (Madrid Quantum-CM) project is about building a quantum communications ecosystem in Spain involving various regions (Galicia, Basque Country, Castilla y León, Cataluña and Valencia). It involves the Polytechnic University of Madrid, the Autonomous University of Madrid (UAM), Complutense University of Madrid (UCM), IMDEA Software Foundation (IMDEA SW), IMDEA Networks Foundation (IMDEA NW), National Institute of Aerospace Technology (INTA), the Spanish Metrology Center (CEM), the Vithas Foundation (FV), Telefónica and RedImadrid (Madrid city infrastructure project). It will support the **MadQCI** project (Madrid Quantum Communications Infrastructure), which will link the area of Madrid with other European quantum communications network as part of the EU EuroQCI project, and within a radius of 30 km.

Startups. On the startup scene, **Multiverse** is a software player focused on quantum inspired algorithms and quantum annealing, operating in the financial and other verticals. **Qilimanjaro** develops a cloud-based quantum software platform and a superconducting quantum annealer. **Entanglement Partners** is a service provider that is clearly succeeding in selling quantum-related cybersecurity services. **aQuantum** creates development tools facilitating quantum programming, particularly for quantum annealing.

In February 2022, UMIQ aQuantum-UEx was created, a Joint Quantum Software Research Unit between the Spanish quantum software and engineering company aQuantum and the University of Extremadura (UEx) consolidating a partnership that started in March 2020. They are collaborating on software research projects including the "QHealth: Quantum Pharmacogenetics Applied to Aging" project. Seven Spanish quantum companies (Amatech, BBVA, DAS Photonics, GMV, Multiverse Computing, Qilimanjaro Quantum Tech and Repsol), five research centers (BSC, CSIC, DIPC, ICFO and Tecnalia) and the Universitat Politècnica de València launched in 2022 the **CUCO Project** to foster quantum computing research and development in Spain, particularly in the industry.

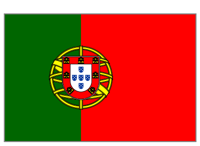
National strategy. In 2023, **Ametic**, the digital trade association in Spain, published a position paper on quantum technologies in Spain [332]. It looked like a call to action for the government to launch a strategic quantum initiative like the ones that exist in many other countries, particularly in the EU. It led to the launch of Quantum Spain initiative in 2023 which plans to build the first local quantum computer at the Barcelona Supercomputing Center in a project led by Qilimanjaro with the help from IQM.

And then, in April 2025 came a full-blown national quantum strategy with an official budget of €808 M over 5 years documented in a 110-page document in Spanish [333]. When looking at the details, only about €43 M are really committed by the government for academic research, the rest coming from EU funding, particularly in quantum communications (€125 M), and a provision of generic startup funding of about €600 M, one third being allocated to enabling technologies startups. In January 2026, the Spanish government invested €9.75M in Nu Quantum (UK) to fund the launch of their Spanish subsidiary.

In 2026, as part of the EuroHPC JU, a Qilimanjaro 10-qubit analog system was installed next to the MareNostrum 5 supercomputer, advertised for "*optimization, molecular simulations and AI workloads*" [334]. These are the vendor's stated target workloads. At 10 analog qubits, the system has no published application benchmark and its problem-encoding capacity is very limited. The installation sits in a former chapel of the building (Figure 37).

Figure 37: The Marenostrum Qilimanjaro quantum computer with 10 qubits, to be upgraded later with more qubits. It sits in a chapel at the Barcelona Supercomputing Center. Source: Qilimanjaro [334].

1.8.18 Portugal



Portugal's key investment in quantum technologies sits with **QuantaLab**, a collaborative research center launched by **International Iberian Nanotechnology Laboratory** (INL) and the **Universidade do Minho**, both in Braga, Portugal.

It focuses on quantum materials and quantum technologies. Portugal is also participating in European quantum projects including the QCI (Quantum Communication Infrastructure).

Launched in 2022, **PQI** (Portuguese Quantum Institute) consolidates research in quantum science. Led by Yasser Omar, it has 13 principal investigators. The Institute is involved in various EU funded projects like IPAS (Quantum Information in Malta), DigiQ (EU masters program), EuRyQa (infrastructure for neutral atoms quantum computing) and QuantHEP (quantum computing for high-energy physics).

1.8.19 Poland

Poland launched its National Quantum Information Centre in Gdansk (KCIK) in 2007 with 9 research institutions.

Other interesting labs are the Quantum Physics Research Center focused on quantum cryptography and the International Center of Theory of Quantum Technologies (ICTQT).

The University of Warsaw is also very involved in quantum research, particularly in photonics with the Center of Quantum Optical Technologies (QOT), led by Konrad Banaszek [335, 336].

The Polish National Science Centre also coordinates the international research network **QuantERA,** itself funded by the European Union's Europe 2020 budgets. It does this in coordination with the French ANR. The countries involved, in addition to those of the European Union, are Switzerland, Israel (Bar-Ilan University) and Turkey. About thirty research projects had been funded after a call for proposals in 2017, some of which were subsequently funded in the European Quantum Flagship, such as SQUARE. They are all quantum physics projects (photonics, cold atoms, ...).

Some other Polish quantum research groups worth mentioning are The Quantum Research Group from the Polish Academy of Sciences which works on quantum computing, qubit measurement, error mitigation and software engineering and the Quantum Resources Group from the Jagiellonian University in Kraków that was created in 2020 and works on quantum information science.

In the ecosystem, The Quantum AI Foundation was created in 2019 by Paweł Gora. It organizes meetings of the Warsaw Quantum Computing Group (WQCG) and hackathons.

In January 2025, Poland communicated on the creation of MIKOK, a prototype military QPU, which could be completed by the end of the year [337, 338]. It is handled by a consortium led by the Warsaw University of Technology (WUT). The machine is presented as intended for cryptanalysis applications. A prototype at this scale could not run cryptographically relevant instances of Shor's algorithm, and the intended research task should be specified. The QPU uses trapped calcium ions ($^{40}Ca^{+}$), which are controlled entirely optically by lasers and in 1D with Paul traps. The consortium includes the Military University of Technology, the Military Institute of Armament Technology, the Silesian University of Technology, and the engineering company Sonovero R&D. The consortium mainly developed laser control electronics and ion traps that could support up to 100 ions in 1D. This is in connection with the Sinara project and the ARTIQ operating system of Creotech, a Polish company competing with Quantum Machines. This project involves Grzegorz Kasprowicz who also worked at CERN on the control electronics of the AEgIS experiment at the Antimatter Factory [339]. It also involves Krzysztof Poźniak, a researcher who is developing electronics to control the CBM (Compressed Baryonic Matter) experiment that is being set up for the FAIR (Facility for Antiproton and Ion Research), an international laboratory for the exploration of baryon particle physics under construction in Darmstadt, Germany. Polish electronic control modules are already in use at NIST, various American universities (Maryland, Oregon, Duke), Oxford and Oxford Ionics, Innsbruck and AQT, as well as CERN [340].

In June 2025, the 20-qubit trapped-ion PIAST-Q QPU built by AQT (Austria) and funded by the EuroHPC JU was inaugurated in the Poznań Supercomputing and Networking Center. It was ordered in July 2024.

1.8.20 Hungary

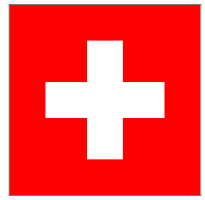
Hungary launched in 2018 its quantum plan with a funding of about $11M, consolidated in a new consortium named HunQuTech.

The participants are the Wigner Research Centre for Physics, the Institute of Physics the Faculty of Electrical Engineering and Informatics of the Budapest University of Technology and Economics, the Institute of Physics of the Eötvös Loránd University, completed by industry partners (Bonn Hungary Electronics, Ericsson Hungary, Nokia-Bell Labs, and Femtonics). The plan goals were to work on single photon sources for quantum telecommunications, pairs of entangled photons at telecom wavelength, free-space QKD systems, quantum memories, qubits and quantum gates and new quantum algorithms. Researchers also work on QRNG and PQC. In total, Hungarian researchers got 4 ERC from the EU in quantum physics and information science.

In 2022, the country launched the Quantum Information National Laboratory initiative that consolidates quantum research covering quantum computing and quantum telecommunications. Hungary also participates to the EuroQCI project since 2019 with its QCIHungary program. The country seems to have several intra-European partnerships like with Germany and the Netherlands.

In 2022, the Faculties of Science and of Informatics of the Eötvös Loránd University selected QuiX as a vendor for a photonic circuit to build their own research photonic quantum computer.

1.8.21 Switzerland



Switzerland is mobilized on quantum technologies, particularly at **ETH Zurich**, which is collaborating with IBM and especially on quantum cryptography

It also hosts one of the oldest quantum startups, **IDQ**, which is a leader in quantum random numbers generation used in quantum cryptography and elsewhere and with the Lausanne's **EPFL**. Other ecosystems are very active like in Geneva and Basel.

The **Swiss Quantum Initiative** (SQI) funded by the government is coordinated and led by the Swiss Quantum Commission (SQC), a group of experts (Figure 38). It is hosted by the Swiss Academy of Sciences SCNAT, mandated by the Swiss Confederation. The initiative got a funding of €18.4M for 2023/24 with additional pending funding for 2025-2028.

The **Quantum Science and Technology** initiative (QSIT), a National Centre of Competence in Research (NCCR) that ran from 2011 to 2022 as a joint initiative of ETH Zurich and the University of Basel, which also involves the University of Geneva and EPFL Lausanne, has 34 faculty members and 300 students. It was funded with about $120M over that period. It covers all the usual fields of quantum with, with a particular effort in quantum telecommunications. In August 2021, the EPFL launched its own multidisciplinary Quantum Science and Engineering Center consolidating its research and academic efforts in all branches of quantum technologies.

The **Swiss Quantum Investor Club** was created in 2020 to link investors and quantum entrepreneurs and organize events in Geneva, Lausanne and Zurich, as well as the **Swiss Quantum Hub,** a think tank and accelerator for quantum startups [342], and the Quantum Computing Garage, a permanent hackathon.

In November 2020, Martin Haefner, an alum from ETH Zurich donated $44M to the ETH Foundation to have them build a quantum research facility. We could wish more wealthy people would make such long-term investments for their community! In another similar initiative, ETH Zurich and the **Paul Scherrer Institute** (PSI, which has its own proton accelerator and an electron synchrotron, the Swiss Light Source, that is equivalent to SOLEIL in France) created the Quantum Computing Hub in 2021, a joint quantum computing research center, focused on trapped ions and superconducting qubits with the goal to host 30 researchers. ETH Zurich invested $36M there [343].

In October 2022, Switzerland and the **USA** signed yet another bilateral quantum cooperation agreement [344]. ETH Zurich is participating in two quantum error correction projects funded by the US IARPA, with $40M.

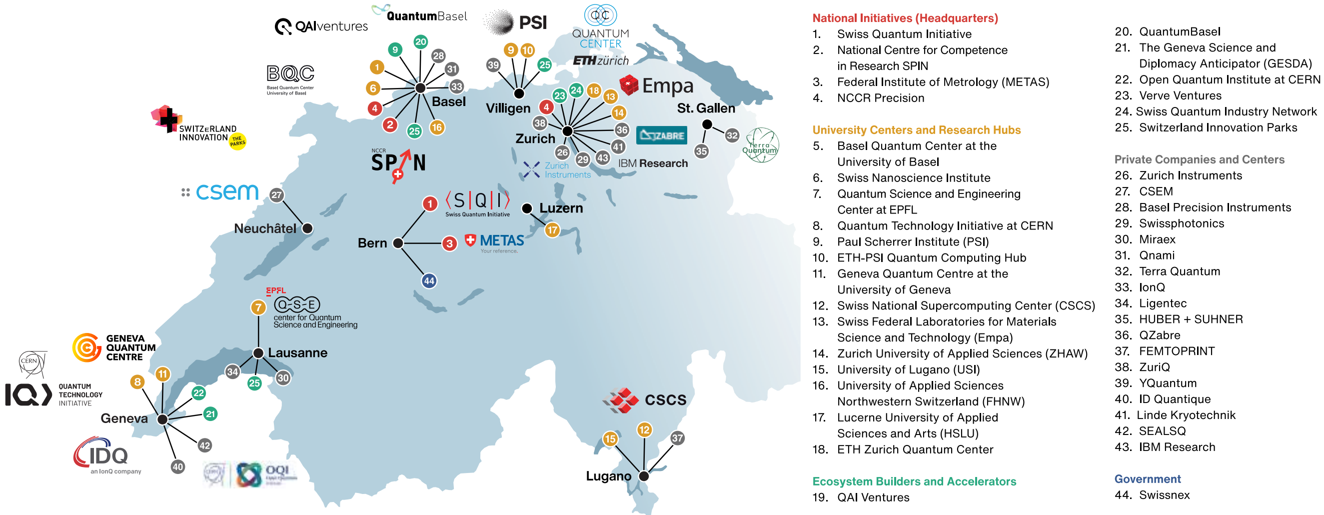


Figure 38: The Swiss quantum ecosystem in 2026. You can notice that some of these companies were acquired by US vendors: Qnami and ID Quantique. Source: [341].

The SuperMOOSE project is led by Andreas Wallraff (ETH Zurich) focuses on superconducting qubits, and the MODULARIS project coordinated by the University of Innsbruck in Austria involves Jonathan Home's ETH Zurich group and is working on trapped ions.

The Basel quantum ecosystem is structured around **QuantumBasel**, its Center of Competence for Quantum and Artificial Intelligence whose CEO is Damir Bogdan. It belongs to uptownBasel Infinity which is itself a subsidiary of the uptownBasel Group, an international competence center for Industry 4.0 and which opened a first building in use by Bouygues and Vinci (Axians and Actemium) and is planned to host 50 to 100 companies with up to 2,500 jobs (not just in quantum technologies). QuantumBasel has several quantum computing partnerships in place, with D-Wave (December 2022, which announced the opening of their European headquarters in Basel in October 2023), IBM (December 2022) and IonQ (June 2023 with the upcoming installment of an IonQ QPU with 35 qubits, the first outside the USA). Located in Basel, **QAI Ventures** is an accelerator and seed investment fund for the quantum ecosystem.

1.8.22 European Union

The **European Union** has a lot of programs operating in the quantum technologies field and is the leading region for public investments in the domain.

You have for example: European Quantum Flagship, EuroHPC, EuroQCI, ERC, QuantEra, Chips Act, COST, …) totaling about €4.5B of funding over 10 years and €1.9B over the last 5 years. These various programs are funded through Horizon Europe and Digital Europe.

European Quantum Flagship

The European Quantum Flagship was formally launched in October 2018. It funds collaborative research on all aspects of quantum information: sensing, communications, computing and simulation [345]. It was endowed with €1B over a 10-year period with over 20 programs described below. It is one of the three European "flagships" that aim to place Europe at the forefront of major technological breakthroughs with strong community investment in research, the two other flagships being the "Human Brain Project" which was initiated by Henry Markram [346] and the Graphene project in nanotechnologies. The first phase of the Flagship included €132M spread onto 20 projects selected out of 140 applicants and for a period of three years. 130 additional projects will be later selected [347–349] (Figure 39). The flagship projects involve an average of at least half a dozen countries, even partner countries like Switzerland and Israel. As of 2025, over half of the €1B had been engaged or committed, the remainder corresponding to the 3 years left, with a focus on technology industrialization. It now belongs to the Quantum Act to follow-up.

It starts with three side projects related to quantum computing:

- **AQTION** (Austria, €9.57M) is trapped ions qubit computer project, planning to reach 50 qubits. Austria has a long history here and is quite legitimate. Atos is participating in this project.
- **MicroQC** (Bulgaria, €2.36M) plans to create another trapped ion computer.
- **OpenSuperQPlus** (Germany, €20M) is a follow-up to the OpenSuperQ project launched in 2018 with teams from Spain, Sweden, Switzerland and Finland and a total of 10 research laboratories. Its ambition was to create a 100-qubit system. The 7-year project led by Forschungszentrum Jülich was

shooting for 1,000 qubits, with an intermediate 100 useful NISQ qubit stage (which will require very high-quality qubits). It gathers new partners from the Netherlands, France, Finland, Germany, Hungary and Sweden, for a total of 28 partners from 10 countries.

- **QLSI** (France) is a Quantum Flagship project that started in March 2020 to fund four years of fundamental research in silicon qubits. It is driven by the Grenoble team from CEA-Leti. The project funding of €14M is spread over 19 organizations: Bull (Atos/Eviden), STMicroelectronics, SOITEC, CNRS Institut Néel, TU Delft, University of Twente and TNO in the Netherlands, IMEC in Belgium, UCL and Quantum Motion in the UK, Infineon, RWTH Aachen, University of Konstanz, Fraunhofer and IHP Frankfurt in Germany, University of Copenhagen and University of Basel. A new QLSI 2.0 was launched in July 2024 for a new round of years and €25M.

- **SPINUS** (Germany) is a €10M consortium for the development of an NV-center and SiC gate-based quantum computer (with up to 100 qubits) and quantum simulator (with up to 1,000 qubits), running over 2024-2027. It is led by Fraunhofer Institute for Applied Solid State Physics IAF, along with the Universities of Ulm and Stuttgart, FZ Jülich, Quantum Brilliance (all in Germany), Hasselt University (Belgium), Linköping University (Sweden), DTU (Denmark), Wigner Research Center for Physics (Hungary), Bruno Kessler Foundation (Italy), TU Delft (the Netherlands), and AMIRES s.r.o. (Czech Republic). The project complements similar projects funded by DLR in Germany.

- **NEASQC** (NExt ApplicationS of Quantum Computing, France) was a collaborative project launched in September 2020, to develop practical applications of NISQ (noisy quantum computers, an intermediate step before scalable quantum computers). It is an H2020 project that brings together European players including Atos, Total, EDF, the Loria laboratory from the University of Lorraine, Astrazeneca, HQS Quantum Simulations, HSBC and the University of Leiden (the Netherlands). The project ended in 2024.

Then we have four quantum simulator projects:

- **PASQuanS2** (Germany, €16.6M) aka Programmable Atomic Large-Scale Quantum Simulation is shooting for the creation of large-scale atomic quantum simulators with up to 10,000 atoms. It is coordinated by the Max Planck Institute of Quantum Optics, with 25 academic and technology partners from Austria, France, Germany, Italy, Slovenia and Spain. It is funded through the Horizon Europe Framework Programme. It is the successor of PASQuanS (€9.25M), launched in 2018, which aimed at creating is a cold atoms or trapped ions quantum simulator project based with up to 1,000 qubits. A goal that has not been achieved yet.

- **PhoQuS** (France, €3M) is a photonic based quantum simulator project led by a PSL research team. It involves the use of polaritons.

- **Qombs** (Italy, €9.3M) is another photonics-based quantum simulator project.

- **SQUARE** (Germany, €2.99M) a quantum simulator project using trapped ions led by the University of Karlsruhe which involves laboratories from Denmark, Sweden, Spain and France, including Thales.

Let's continue with projects in quantum communication and telecom security.

- **Quantum Internet Alliance** (the Netherlands, €10M) (QIA) aims at building a full-stack, entanglement-based quantum Internet rather than a classical network protected by QKD. Its roadmap covers several node and repeater technologies, including NV centers, trapped ions and atomic ensembles, with a first multi-node network demonstrator. The project is led by TU Delft University. The CNRS participates in it, notably Eleni Diamanti, Elham Kashefi and Iordanis Kerenidis. The Sorbonne University also participates. Other participants include Swiss, Germans, Danes and Austrians.

- **QRANGE** (Switzerland, €3.87M) is a project to improve quantum random number generation techniques.

- **CiViQ** (Spain, €9.9M), or Continuous Variable Quantum Communications, is another QKD-based fiber telecommunications security project. The project involves 21 stakeholders covering the academic and industrial world, including CNRS, Institut Mines-Telecoms, Nokia Bell Labs France, Inria, Orange, as well as Mellanox.

- **Uniqorn** (Austria, €9.9M) is in the same niche and is working on a random number generator and a QKD system. It associates 17 organizations from 9 countries (Austria, the Netherlands, Italy). The Israeli Mellanox is also involved there.

- **S2QUIP** (the Netherlands, €3M), Scalable Two-Dimensional Quantum Integrated Photonics, is another QKD-based secure communication project.

- **2D-SIPC** (Spain, €2.9M) is a project for the development of photoelectronic components made for QKD-secured networks.

- **QMICS** (Germany, €3M) or "Quantum Microwave Communication and Sensing" is about creating microwave links and networks between superconducting network nodes with applications in distributed quantum computing and also in quantum sensing.

And at last:

Figure 39: European Quantum flagship projects as of 2022. 🅭 Olivier Ezratty, 2019-November 2024.

- **QTEdu** (Italy) is about creating the quantum education ecosystem in the European Union. It is funded by H2020 [350].

- **QUCATS** (France) was the project handling the coordination for European Quantum Flagship projects. It covered the 2022 to 2025 period and is coordinated by Philippe Grangier (CNRS, France). It is a follow-up to the QFLAG (Germany, €3.48M) project launched in 2018. It was replaced in 2026 by QOMPASS (Quantum Competitiveness Alignment, Scaling, and Support).

Then we have the five quantum sensing projects already seen in the Sensing section of this book.

Large countries are present in many of these projects. As an example, France is involved in many of these projects. CNRS (France) alone was involved in 14 of the 20 projects when the Flagship was launched [351].

The EU quantum strategy is formalized in its **SRIA** (Strategic Research and Industry Agenda) that was published first in November 2022 [352], updated in February 2024 [353, 354] and being updated in 2026. It consolidated the SRA and SIR. The **SRA** (Quantum Flagship Strategic Research Agenda) defined goals for the Quantum Flagship, and details them for the next three years, with an outlook for six to ten years. It contains typical goals like helping NISQ and FTQC scale through better qubits, error correction mechanisms and various enabling technologies, developing software algorithms and tools, cloud offerings. The **SIR** (QuIC Strategic Industry Roadmap) described the needs of the EU quantum industry, as represented by the QuIC consortium, in education and skills buildup, standards, IP and trade and governance principles.

In December 2023, 11 EU member state countries published a political declaration aimed at organizing the cooperation at the EU level between countries on their national quantum strategies [355]. Most of the other member states joined the band later on in 2024.

As of mid-2026, the governance of all these things leverages multiple boards: the EuroHPC Governing board, the Quantum Computing Advisory Board (which I am part of since April 2026), the Quantum Technologies Advisory Board (which advises the EuroHPC JU) and the High Level board (with high-level folks like a couple Nobel laureate in physics, including Alain Aspect and Anne L'Huillier).

EuroHPC JU

The EuroHPC Joint Undertaking program is a joint initiative between the EU, European countries and industry partners to develop a supercomputing ecosystem in Europe. The project will be funded with €1.5B over 10 years, over a total of €5B which covers the buildup of exascale HPCs. The first exascale EuroHPC, JUPITER, was deployed in Germany at the Jülich Supercomputing Center in 2025, with a total cost of €500 M. It is the 4th largest supercomputer in the world and consumes 13 MW [356].

EuroHPC is funding eight quantum computers already installed or to be integrated into existing supercomputers centers in Czechia (superconducting qubits), Germany (cold atoms and superconducting qubits), Spain (superconducting qubits), France (cold atoms and photonic qubits), Italy (cold atom qubits) and Poland (trapped-ion qubits) for a total hardware investment of €145M. The first of these systems are operational with one Pasqal system at Jülich in Germany, one IQM system at LUMI in Finland, a Pasqal and a Quandela system at TGCC in France, a Qilimanjaro system in Spain and an AQT system in Poland. EuroHPC was extended in 2024 with two additional projects in the Netherlands (project SURF with semiconductor spin qubits) and in Luxembourg (MeluXina-Q, also with spin qubits).

HPCQS corresponds to the first deployments of the Ruby and Jade analog quantum simulators that were deployed in Germany and France as part of the project. They are equipped with 100+ qubits analog quantum simulators from Pasqal. These were inaugurated in November 2025.

HPCQC is an initiative created by Technical University of Munich (TUM), the Danish Technical University (DTU) and the Leibniz Supercomputing Centre (LRZ) which wants to consolidate a community of HPC and quantum computing specialists, focused on creating interfaces and benchmarks.

EuroQCI. The European quantum Internet research program is a joint program with ESA and is funded with €1B over 10 years with a terrestrial and a satellite segment.

Chips Act. Launched in 2022, it has allocated about €500M to quantum technologies manufacturing. It will certainly have several components and RFP (request for proposals).

Quantum Act

In July 2025, the EU announced its new Quantum Strategy with some early proposals. It leads to a Quantum Act, which the Commission scheduled for adoption in 2026 and which then has to go through the European Council and the European Parliament.

The strategy goal is to make the EU a global leader in quantum technologies in 2030. With, for example, the support of 100 logical qubits. It was judged to be too shy compared to many industry vendor roadmaps, but meanwhile, maybe more realistic [357].

The plan has five typical clusters: one on research and innovation, another on quantum infrastructures for production, design, and application development, one on investments in startups and scaleups, securing supply chains and the industrialization of quantum technologies, one on space and dual-use quantum technologies for security and defense and a last one on skills development. It will need to provide real clues on how to better fund the best scaleups or how to drive some (demand side) market consolidation and how to trade well with the USA. You can always dream about the size of the EU internal market but its cultural and practical fragmentation makes it an obstacle for any technology startup to scale fast vs their US competitors even though this caveat is not that strong in very specialized professional markets.

The Quantum Act was supposed to be finalized in 2026 and voted by the EU Parliament in 2027. The related funding is not yet known. See a long independent comment paper on the Quantum Act by Mauritz Kop [358].

Manufacturing pilot lines

Qu-Pilot and **Qu-Test** were two new projects launched in 2023 and running until 2026 as part of the Chips Act. Coordinated by VTT, Qu-Pilot aims to federate and expand European production facilities for quantum technologies in a trusted supply chain. It gathered 21 partners from 9 different countries and covered quantum computing, communication and sensing needs through 13 service-provider organizations.

Qu-Test complemented Qu-pilot with three test beds. One the Quantum Computing Testbed for the characterization and validation of cryogenic quantum devices, cryogenic qubits such as superconducting and semiconducting qubits, photonics qubits and ion traps circuits. A Quantum Communication Testbed will characterize devices for QKD and QRNG solutions. And the Quantum Sensing Testbed will benchmark sensing and metrology instruments.

Qu-Pilot and Qu-Test were established under Horizon Europe's Quantum Flagship initiative and were experimental or "research pilot lines". Their goal was to support early-stage R&D, provide open-access testing capabilities, and help researchers prototype technologies in lab environments. Then, the Chips JU Pilot Lines created under the newer European Chips Act are industrial pilot lines, with high-yield, stable, and reproducible manufacturing. Their target TRLs are set call by call and technology by technology in the Chips JU work programme, and should be quoted from it rather than generalized, TRL 9 normally denoting an actual system proven in an operational environment.

Because the Chips JU pilot lines were the logical next step to Qu-Pilot, there is significant institutional overlap. Major European Research and Technology Organizations (RTOs) like Fraunhofer, imec, VTT, and CEA-Leti are involved in both projects.

Each pilot line project has about €50M of funding with a total funding of about €300M, half coming from the EU and the other half from member states.

SUPREME was launched in July 2025, and coordinated by VTT, to industrialize superconducting quantum chip fabrication over six years by creating stable, high-yield manufacturing processes accessible to European academia and industry vendors. It will develop and validate angle evaporated and etched Josephson junctions, 3D integration methods, and hybrid quantum processes for large-scale QPUs, TWPA and SNSPDs. The first phase was to be launched in 2026, with the first stable quantum chip fabrication processes available to external users in 2027 via process design kits (PDKs). The consortium involves 23 partners from 8 EU member states. First, with RTOs and academia: VTT (Finland), coordinator; TNO (Netherlands), TU Delft (Netherlands), TU Munich (Germany), Fraunhofer (Germany), Max-Planck-Gesellschaft (Germany), Leibniz Institute of Photonic Technology (Germany), CEA (France), University of Naples Federico II (Italy), Fondazione Bruno Kessler (Italy), IFAE (Spain) and Silicon Austria Labs (Austria). And with industry vendors: Infineon (Germany), IQM (Finland), Arctic Instruments (Finland), Alice & Bob (France), QuantWare (Netherlands), Single Quantum (Netherlands), QphoX (Netherlands), Peak Quantum (Germany), Silent Waves (France), Amires (Czech Republic) and Qilimanjaro (Spain).

CHAMP-ION is focused on manufacturing ion traps for the EU ion trap ecosystem. It involves startups from Germany (EleQtron, Qudora, NeQxt) and Austria (AQT) as well as the Netherlands, and Infineon. It covers the full value chain from design and microstructuring to integrating electronic and photonic structures on a single chip. It is coordinated by Silicon Austria Labs (SAL), an RTO located in Villach in the south of Austria, next to the Infineon plant where ion traps are manufactured and tested. It was launched in May 2026.

SPINS develops industrial chips using pure silicon or SiGe structures. It leverages standardized CMOS production techniques to enable scalable semiconductor-based spin qubits for computing applications. It is coordinated by Imec (Belgium) and was launched in April 2026.

P4Q is about scaling the manufacturing and reliability of photonic quantum chips for applications across enhanced sensors, full-stack quantum computers, and secure quantum communication networks. Chips will use silicon nitride (SiN), thin-film lithium niobate (TFLN), and alumina (AlOx). It is coordinated by the University of Twente (Netherlands). It was launched in June 2026.

DIREQT is about scaling the fabrication of nitrogen-vacancy (NV) centers in single-crystal synthetic diamonds which are used in quantum sensing, computing (mainly in Germany with SaxonQ, XeedQ and Quantum Brilliance), and communications. It is coordinated by CNR (Italy). It was launched in May 2026.

Q-PLANET is pilot line for neutral atom components, including lasers at four key wavelengths (461 nm, 698 nm, 795 nm and 1013 nm), atom chips for quantum sensing and computing, and vapor cells for atomic clocks and field sensors. It is coordinated by Pasqal (France). It was launched in July 2026.

Other EU programs

Figure 40 makes an inventory of the various EU programs funding quantum technologies R&D.

ERC grants funds for individual researchers with four levels, from €150K to €14 M (Proof of Concept, Starting, Consolidator, Synergy). A couple dozen quantum researchers are awarded with such a grant every year.

EIC programs fund transfer from research to innovation, and mostly startups, with several levels (Pathfinder, Transition, Accelerator and an upcoming Challenge). In one year, €1B funds were allocated in deep tech startups.

COST Actions are funding the buildup of research communities with up to €5.8M each. It covers the organization of scientific events, short-term scientific missions, training schools, communication activities, and virtual networking tools.

QuantERA I (2016), II (2021) and III (2023, 2025) is an alliance of research funders from member states created to reinforce transnational collaborations in inspiring multidisciplinary quantum research. The QuantERA II Consortium assembles 38 Research Funding Organizations from 30 countries, some being extra-EU. It complements the Quantum Flagship in early stages, serving as an incubator of new ideas which then can get integrated in Quantum Flagship projects but comes from participating countries (€45M for QuantERA I and €40M for QuantERA II) and the EU (€11.5M for QuantERA I and €15M for QuantERA II). There were two calls for projects in QuantERA I, one in QuantERA II and two for Quantera III, the last one closing in September 2025.

EQUALITY was a Horizon Europe-funded project spanning from 2022 to 2024 on the development of hybrid quantum-classical workflows, benchmarking tools, and real-world use cases in fields like chemistry, finance, and logistics. It brought together 11 partners from 7 countries, including Atos, ICHEC, Fraunhofer FOKUS, Forschungszentrum Jülich, ParityQC, Multiverse Computing, University of Latvia, University of Vienna, University of Innsbruck, University of Tartu, and Teratec. The project emphasized open-source development, integration with HPC infrastructures, and performance metrics for near-term quantum devices.

Other quantum projects

These various quantum projects are also funded or cofounded by the EU through various funding sources.

ELENA is a 42-months and €5M EU-funded project launched in June 2025 to create a supply chain for lithium niobate on insulator (LNOI) substrates, used in creating photonic integrated circuits (PICs) targeting multiple applications: ion trapping, optical clocks, entangled photon generation, >400 Gbit/s modulators, DWDM and CMOS-compatible transceivers for telecoms, lightweight, low-power PICs for satellite commu-

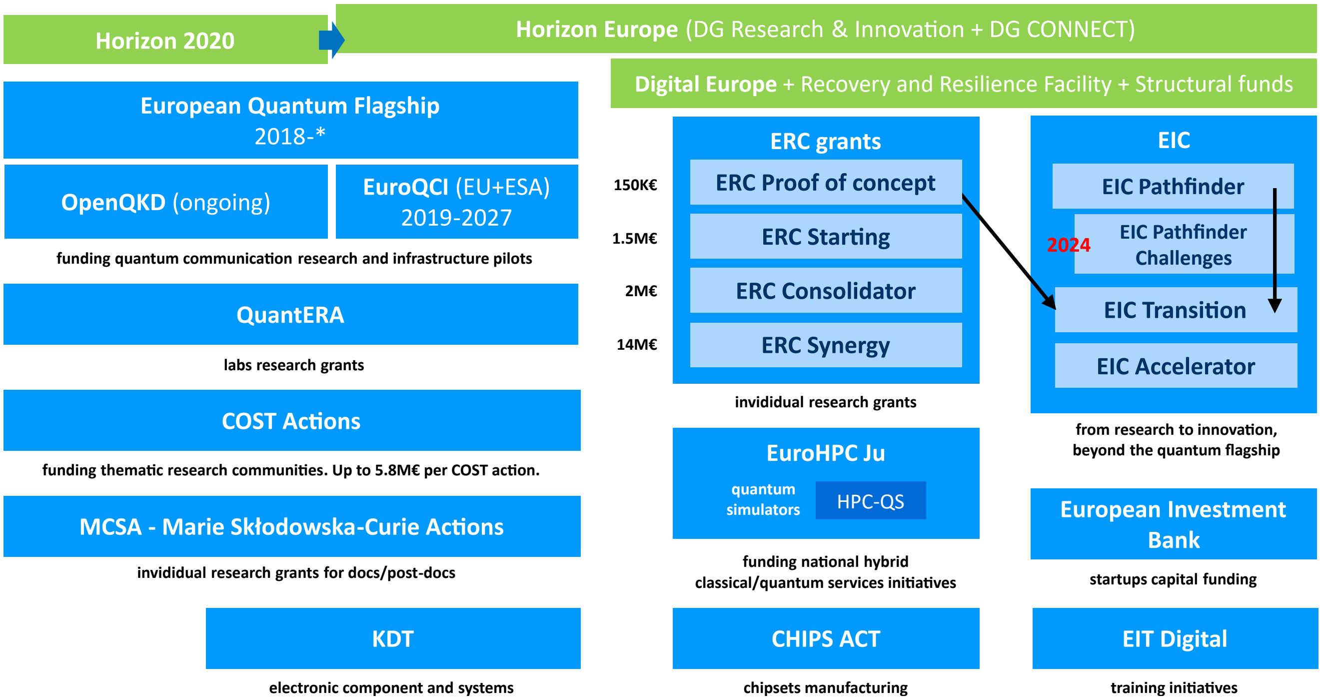


Figure 40: The web of European projects funding the quantum field both at the research and industry levels. 🅭 Olivier Ezratty, 2023.

nications, LIDAR and sensing for automotive, medical, and environmental monitoring. It includes CCRAFT, an open-access 150 mm wafers foundry for producing thin-film lithium niobate (TFLN) photonic chips, at the Swiss Center for Electronics and Microtechnology's (CSEM). The partners are CEA-Leti (France), SOITEC (France), VPI (Germany), ETH Zürich (Switzerland), Vanguard Automation (Germany), Thales (France), III-V LAB (France), ROS (Germany) and L-up (France).

MATQu (Materials for Quantum Computing) is developing a European value chain to manufacture superconducting qubits. This H2020 project running from 2021 to 2024 with a total cost of €21M with EU funding of €6.5M is led by the Fraunhofer Group for Microelectronics, IAF and IPMS with the participation of CEA-Leti, IMEC, Soitec, BE Semiconductor Industries (semiconductor assembly equipment), IQM, VTT, Keysight, Siltronic (silicon wafers production), Kiutra, Atos, Mellanox, Beneq (atomic layer deposition equipment), Orange Quantum Systems and Technic France (engineering).

SPROUT (Scalable Platform for Quantum Technology) is a project launched in November 2021 by Delft Circuits and kiutra to provide a scalable cryogeny platform funded by the EU Eurostars program. They develop a demonstrator for a <1K cryogen platform based on cryogen-free magnetic cooling (the Kiutra specialty) and a multi-channel electrical cabling.

QLUSTER is a 4-year European academic consortium launched in 2022 to advance classical and quantum soft matter science. It aims to bridge distinct communities studying cluster formation and mesophase organization across scales—from subatomic particles to macromolecules—by focusing on ultrasoft interactions that drive complex behaviors in systems like polymers, colloids, Rydberg atoms, and nucleons. It fosters interdisciplinary collaboration, trains adaptable young scientists, and promotes science communication. By integrating quantum and classical many-body physics, it positions the EU to lead innovation in sectors such as cosmetics, food science, and quantum technologies. The project is driven by CSIC in Spain with partners in Germany, France, Austria, Slovenia, Italy and Greece.

LSQuanT is an initiative funded by the EU that was launched in 2021 and is dedicated to promoting "large-scale quantum transport methodologies", which deals with the physics of quantum transport digital simulation, to invent new quantum materials and devices [359].

EQUIPE (Enable Quantum Information Processing in Europe) project aims to advance the industrialization of the creation of quantum computing and telecommunications solutions for industry [360]. It was funded by an ERC for €1.4M.

QEX, is a European Quantum Excellence Centre launched in November 2025 to drive the creation of quantum computing applications. It is funded by the EuroHPC JU, most of the partners being in Denmark, Spain, Ireland, the Netherlands and Germany.

Quantum Grand Challenge was a call launched in 2025 for industry vendors working on quantum computing. The results of the calls were not public as of September 2026.

DigiQ (Denmark, €17M) is a quantum training initiative providing master courses.

It gathers contributors from Denmark, Finland, France, Germany, Italy, the Netherlands, Portugal, Spain and Czechia. It is funded by Digital Europe.

QTIndu (Quantum Technology Courses for Industry, €5.6M) is a project launched in January 2023 which is creating industry-specific Quantum Technology (QT) training programs targeting SMEs and large companies from various vertical markets. It is led by a pan-European consortium with 11 academic and industry partners that are coordinated by QURECA (UK).

ARCTIC is a consortium working on the creation of cryo-CMOS control electronic chips, with a budget of €11M over three years. It gathers 36 international academic and industry partners like IMEC, Fraunhofer IPMS, Qblox, TU Delft, Infineon, STMicroelectronics, CEA, Alice & Bob, Quobly, SemiQon, IQM and Bluefors.

ETP4HPC is the European HPC association, a private member of the EuroHPC JU which is interested in the integration of HPCs and quantum computers.

EQSI (European Quantum Software Institute) is an initiative supported by the EU which aims to create a strong research and industry ecosystem in quantum software.

It was launched in November 2022 by the Paris Centre for Quantum Technologies (Iordanis Kerenidis), PQI – Portuguese Quantum Institute (Yasser Omar), QMATH / Copenhagen (Matthias Christandl), QuSoft / Amsterdam (Harry Buhrman), the Technical University of Munich (Robert Koenig), and the University of Latvia (Andris Ambainis). In 2025, the EQSI published a Manifesto, asking for the consideration of the EU to fund specific quantum academic efforts in software [361].

Industry associations

European research is federated under the umbrella of **QCN** (Quantum Community Network).

Its industry counterpart is the **QuIC** (Quantum Industry Consortium) announced in June 2020 and formally launched in April 2021 [362].

Founding members were companies involved in at least two European Quantum Flagship projects, including Bosch, SAP, Atos, Thales, Muquans, Airbus and many others. The consortium has an extensive work plan covering market needs assessment, analysis of the quantum technology value chain, development of standards and regulations, sharing of best practices in intellectual property protection and market evangelization, access to infrastructure, linking startups and investors, skills development issues and coordination with public authorities. In January 2024, QuIC published its Strategic Industry Roadmap 2024 [363]. QuIC also organized its first Q-EXPO event in Amsterdam in June 2024 gathering the European quantum ecosystem with a mix of an exhibition, a one-day conference, and 300 participants from around the world. The second Q-Expo was also organized in Amsterdam, in May 2025. QuIC published in March 2025 a set of recommendations for the EU in light of the preparation of the upcoming Quantum Act [364] and after the July 2025 announcement, a set of comments on the Quantum Act [365]. The consortium advocates for the creation of "Made in Europe" quantum computers, with a focus on scalable and cost-effective qubit control and readout electronics, error correction, cryogenic, quantum interconnects, and photonics infrastructure.

ICQIA (International Council of Quantum Industry Associations) is a metaconsortium created in January 2023 by Quantum Industry Canada, QED-C (USA), Quantum Strategic Industry Alliance for Revolution (Q-STAR, Japan) and QuIC to consolidate their joint work in developing the worldwide quantum ecosystem.

|QBN⟩ (Quantum Business Network) is a European Quantum Community, which connects industry vendors, users, and the academic world.

1.8.23 Ukraine

Ukraine is at war with Russia, but its diaspora is active in the quantum industry.

Haiqu is a Ukrainian-American quantum software startup founded in 2022, with co-founders Richard Givhan (CEO) and Mykola Maksymenko. The company is based in New York but has R&D teams in Ukraine.

Aegiq is a startup developing quantum photonic technologies created in 2019 by Maksym Sich, Andriy Yamshanov and Scott Dufferville. They are based in Sheffield, UK.

HIMERA is a Ukraine-based tactical communications company created in 2022, created to address communication failures experienced by Ukrainian's army. It announced a deal with Quantropi (Canada) to integrate PQC in their tactical radio systems.

1.9 Russia

Russia is not very visible in the quantum scene, maybe because they have not built the same research and industry partnership that are seen in the western world.

Public funding

Like with AI, its government realized that quantum technologies were critical for sovereignty. In December 2019, Russia announced its own plan of attack on quantum technologies, which seemed very focused on military, intelligence and cryptanalysis applications [366].

This plan got a five-year funding of $790M. In practice, it covers almost all fields of quantum technologies [367] as shown in Figure 41. In January 2022, Russia created its National Quantum Laboratory (NQL) run by Rosatom and with NRU HSE and MIPT, MISIS, the Lebedev Physical Institute of the Russian Academy of Science, the Russian Quantum Center and the Skolkovo Foundation. The center hosts a nano-fabrication center of 2,000 m^2 in Skolkovo. One might wonder how things will fare with exports restrictions to Russia after it started its war against Ukraine in February 2022. Many Western countries equipment vendors won't be in position to sell their hardware and Russia will not be able to count on China this time since it does not seem to manufacture the sophisticated equipment used in nanofabrication facilities. Still, Russia is expanding its international collaboration with eyes on India and China.

In March 2025, the 4 million inhabitants Russian Republic of Tatarstan launched a quantum technologies initiative. It is federating its university resources in a consortium to position itself in the promising sector of quantum technologies. They plan to create a quantum market by 2027, without further details.

Research

In January 2022, Rosatom announced a plan to build a trapped ions quantum computer that would be made available on the cloud by 2024. It is being developed by the Russian Quantum Center and the Lebedev Physics Institute of the Russian Academy of Sciences. They started with 4 qubits, against about 20 to 30 for the commercial trapped-ion systems from AQT, IonQ and Quantinuum. In July 2023, Russian scientists presented to their President Vladimir Putin a good intermediate result with a 16-qubit trapped ion quantum computer. Putin made a speech dedicated to the role of quantum technology. In 2024, Russian scientists said they expected to reach 50 qubits by the end of 2024. This is quite a challenge considering only one company in the world achieved this so far, with way more research and technology development work (Quantinuum with 56 qubits in June 2024). Scientists from Lomonosov Moscow State University and the RQC actually created the first prototype of a 50-qubit QPU in 2025, but with rubidium atoms (cold atoms).

Before all of that, the **Russian Quantum Center** was created in 2010, a private research center dedicated to the various application areas of quantum computing, including quantum cryptography.

It employs over 200 researchers and covers many quantum computing branches: superconducting, trapped ions, photons and NV centers qubits, quantum sensing, QKD and a single photon detector. They collaborate with some international research organizations in the USA (MIT), Canada (University of Calgary), Germany (Max Planck Institute for Quantum Optics) and UK (University of Bath) [369].

The St. Petersburg **ITMO University** has a QKD research laboratory as well as the **Kazan Quantum Center** which has deployed a QKD on a 160 km network in Kazan. The country also plans to launch a QKD quantum key communication satellite in 2023. A few other laboratories are invested in quantum technologies such as the **NTI Center for Quantum Communications** at MISiS University and the **NTI Technologies Centre** at Moscow University.

Industry

On the industry vendors and startup scene, most of the players are in the cybersecurity and quantum cryptography domain, with only three identified startups, **Photonanobeta** (a producer of diamonds with cavities), **Qrate Quantum Communications** and **QSpace Technologies**, the others being established companies, such as **Infotecs**, **Scontel** and **Smarts QuantTelecom** [367]. There is also a software player with **Q Deep**, located in... Tatarstan.

International

The Western world nearly cut all scientific ties with the Russian quantum ecosystem after the start of the war in Ukraine. As a result, Russia is forced to develop partnerships with developing countries. As such, Rosatom launched in 2025 a set of scientific partnerships with Vietnam and Egypt in quantum technologies. It also works with China on quantum communications, India, and Iran.

1.10 Africa, Near and Middle East

1.10.1 Israel

Israel was relatively quiet about quantum technologies until 2018, although it had and has a significant research ecosystem.

You heard about Israel through Gil Kalai from the Hebrew University of Jerusalem who, since 2013, has shown a deep-rooted skepticism about the future of quantum

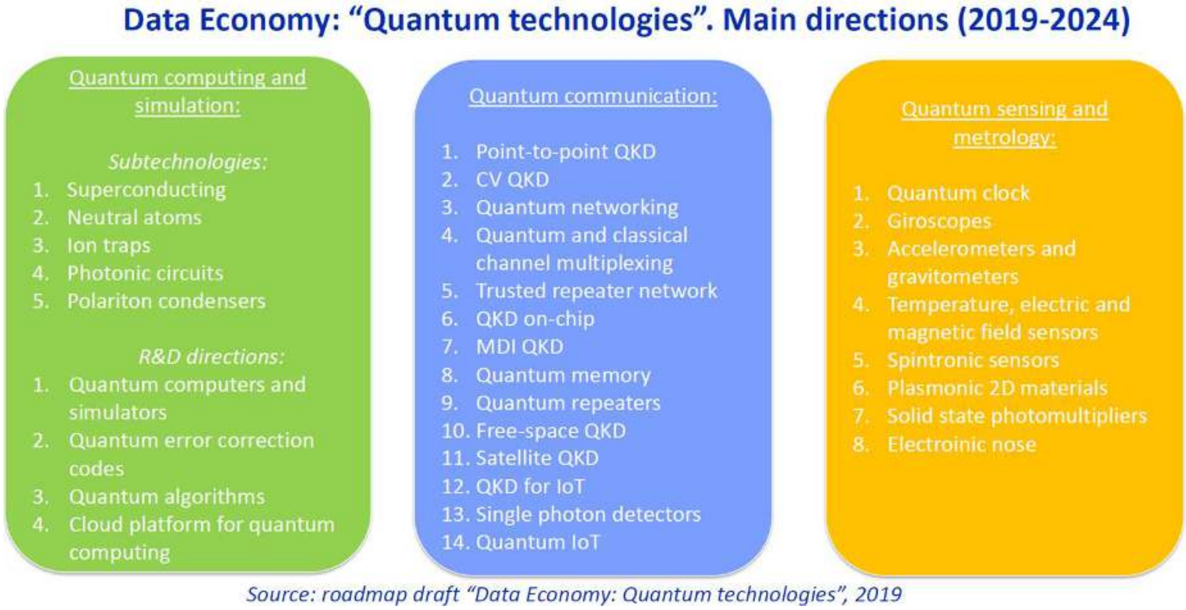


Figure 41: Russia's quantum plan priorities as of 2019. Source: [368].

computers. I was also relatively surprised in 2018 to find out that the country was not very visible in the quantum research and entrepreneurship. It was a stark contrast with other fields where this relatively small country has a significant impact worldwide: in software, artificial intelligence (where they have in excess of 400 startups), Internet, semiconductors, electronics, medtechs and biotechs to name a few. It changed a lot since then.

Government funding

Then, things started to change [370]. After a study carried out in 2017 by Uri Sivan from Technion to evaluate the country's quantum technologies efforts, a first initiative to better fund its research was launched in 2018 by the country's government and endowed with €75M. It went mainly to Technion and the University of Haifa, which wants to design its own quantum computer and had also received a donation of $50M.

In December 2019, a panel of specialists commissioned by the government proposed a plan to invest $350M over 6 years in quantum technologies [371, 372]. In just a few months, the government approved this proposal which ended up with a funding of $400M, 60% of it supposed to fund academic research. The plan is fairly standard with an investment in human capital (faculty hiring and launching training courses), research and scholarships funding, attracting foreign researchers and the like. The usual quantum technologies domains were picked with computing hardware and components, telecommunications, cryptography and sensing (with $40M), particularly with its military applications.

The Israel National Quantum Initiative (INQI) plan follows-up in naming the US plan announced in December 2018.

In March 2021, Israel announced it planned to create its own quantum computers, allocating a budget of $60M taken out of the national initiative. The goal was to create 30- to 40-qubit quantum systems. It was to take bids from both local players and international vendors, with a build or buy approach depending on the outcome.

In July 2022, the government announced the creation of a quantum computing R&D center with a budget of $30M over a three-year period. It selected their local star vendor, Quantum Machines to create the center that works on superconducting qubits, cold atoms, trapped ions and quantum optics computers [373]. The company works with Classiq and Elbit Systems. Still, the ploy became a "buy" with Israel announcing the same month the procurement of an Orca Computing (UK) photonic quantum computer. They also work with Infleqtion who already partners with Quantum Machines (like Pasqal in France) and Classiq [374]. At last, the first superconducting qubit QPU was inaugurated in June 2024 at the Israeli Quantum Computing Centre (IQCC) in Tel Aviv University, equipped with a 24-qubit QuantWare Contralto chip and integrated with the help from ParTec AG (Germany).

In January 2023, $32M were added by the Israel Innovation Authority to a new quantum computing consortium assembling defense industry companies and startups, to be focused on superconducting and trapped ion QPUs. It is probably related to the Weizmann Institute (trapped ions) and Bar-Ilan University where Michael Stern's team is working on fluxonium qubits.

In July 2025, Israel and the USA ambition to create a $200M joint quantum and AI investment fund, with potential contributions from Gulf states, covering the 2026-2030 period. It's a little concerning that they are merging AI and quantum in the same fund, will make it difficult to sort things out.

In July 2026, Israel launched an RFP for the creation of a national quantum computing R&D infrastructure providing industry and academia access to at least three quantum computers. It is a follow-up program to IQCC, with a similar funding of about $33M.

Research

There are about 125 "principal investigators" in quantum technologies research in Israel spread in the following research institutions:

Ariel University with its Wireless Communication & Radars Lab, located in the Israeli settlement of Ariel, in the West Bank. They work on millimeter wave and Terahertz sensors.

Bar Ilan University (Ramat Gan near Tel Aviv) with the Photonics and Optics group (Avi Peers, Eli Barkai and Dror Fixler) and the Institute of Nanotechnology and Advanced Materials which works on superconducting qubits (Michael Stern). These are integrated in QUEST (Quantum Entanglement in Science and Technology), a quantum research center launched in 2017.

Ben-Gurion University of the Negev (Beer Sheva) with the Sensing Technologies Lab (Asaf Gros), Quantum Magnetometry Group (Reuben Shuker) and the Atom Chip Group (Ron Folman). The startup AccuBeat (1993) which produces rubidium quantum atomic clocks, is a product of this university.

Hebrew University of Jerusalem with the Nano-Opto Group and Time Dissemination Group, and the Center for Nanoscience and Nanotechnology that works on superconducting qubits. The University also established its Quantum Information Science Center in 2013 to focus on secure quantum communication (QKD).

Technion (Haifa) with Quantum Information Processing lab (Tal Mor) which works on photonics, NMR and silicon qubits, the Russell Berrie Nanotechnology Institute created in 2005 (Gadi Eisenstein) and the Helen Diller Quantum Center which is working on photonics, quantum dots, super-conducting qubits and cold atoms (Yosi Avron). On top of this, the Technion AdQuanta Group is a sort of research accelerator to develop new concepts and proof-of-concepts (sensing, quantum optics, imaging, polaritons, etc.), led by Ido Kaminer.

Tel Aviv University with its QuanTAU, their Quantum Science and Technology Center, working among other things on superconducting qubits.

Weizmann Institute of Science in Rehovot with the Center for Quantum Science and Technology (Adi Stern), the Quantum Circuits Group (Serge Rosenblum) working on superconducting qubits [375] and the trapped ions group (Roee Ozeri) which created the first Israeli quantum computer in 2022 with 5 trapped ions qubits [376]. These qubits use strontium and their fidelity is 99.64% for a single qubit gate and 97.3% for two-qubit gates. The team is also looking at ways to use it in simulation mode [377]. In June 2025, part of the Weizmann Institute was destroyed by missiles sent by Iran with yet unknown consequences on quantum research.

In December 2024, Israel announced the creation of a domestically built QPU with 20 qubits, realized by Israel Aerospace Industries (IAI), with the Hebrew University of Jerusalem and Nadav Katz's team. It seems that it is using a chip from IQM [378].

Quantum industry

The Israeli startup scene was a little modest until 2020 but is developing strongly since then. The most visible startups in the field are **Quantum Machines** (qubit control hardware and software), **Classiq** (error control and compilers), **Accubeat** (atomic clocks), **Elta** (sensing), **Hub Security** (PQC in HSMs), **Mellanox Technologies** (quantum communications, part of Nvidia), **PhotonicsQ** (cold atoms interconnection), **Qedma Quantum Computing** (software tools), **QuantLR** (QKD), **Quantum Source Labs** (photonic computing), **Quantum Transistor** (NV center QPU), **Raicol Crystals** (photonics), **Tabor Electronics** (RF electronics). Google's R&D lab in Tel Aviv also hosts researchers in quantum computing.

The **Quantum Technologies Consortium** created in 2019 assembles research institutions and industry vendors.

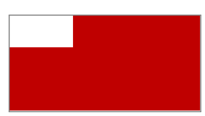
1.10.2 South Africa

South Africa launched a formal Quantum Technologies Initiative in 2023.

It consolidates the efforts from the University of the Witwatersrand (Wits University), Stellenbosch University, University of KwaZulu-Natal, Cape Peninsula University of Technology and the University of Zululand. Wits University is coordinating this group with an initial funding of $3M.

These five universities will expand the number of quantum research centers. They will focus on software and applications. The 2023 initiative followed South Africa's Quantum Initiative (Sa QuTI) launched in September 2021.

1.10.3 United Arab Emirates



The UAE also entered the field and decided to "build" its own quantum computer.

Even if "build" or "buy" have interchangeable meanings in such situation. Still, it comes after the establishment of a Quantum Centre at the Technology Innovation Institute (TII) which hosts about 20 researchers coming from the Emirates and from various countries: Italy, Spain, Brazil, Greece, UK and Germany. This lab complements other labs in robotics, cybersecurity and energy. It even has some qubits manufacturing tooling.

Jose Ignacio Latorre is the chief scientist of this quantum research laboratory. He is a professor of theoretical physics at the University of Barcelona currently on leave, cofounder of Qilimanjaro and the director of the Singapore CQT since July 2020. Their key partners are Qilimanjaro, the Università di Catania in Sicily and INFN, an Italian research network.

The QC-TII organized a webinar conference in June 2021, Atomtronics@Abudhabi with about 500 participants. In April 2023, IonQ announced an agreement with TII to provide it with access to IonQ Aria QPU. In August 2023, Abu Dhabi University created a quantum academic lab in Abu Dhabi in partnership with Vernewell Group. The lab was planning the use of SpinQ's NMR educational quantum computers. It also works on cybersecurity, optimization algorithms and quantum blockchain. Vernewell Group (Dubai) is a service and management consultant company.

Intqlabs (2022, Dubai) is a contract research company created by Ankur Srivastava, from India, formerly an independent researcher, not affiliated with any lab.

The company works in various fields: quantum computing, reversible classical computing, geo-magnetism and cybersecurity. They are talking about some form of "quantum and reverse computing" that would solve all current problems with quantum computing.

It is quite difficult to figure out whether it is some form of quantum computing or of classical reversible computing. All of this is patent pending, meaning that for at least a year and a half, you will have no idea what it's all about. Wait and see. They plan to license their technology to hardware manufacturers. They have otherwise created NGNSS (New Global Navigation Satellite System), an alternative to classical GPS solutions which as its name doesn't tell, is not requiring a satellite to function and uses magnetism detection and mapping.

1.10.4 Qatar

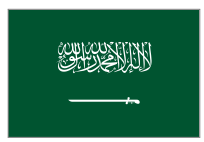
Qatar has also some ambitions in quantum technologies.

In April 2022, Hamad Bin Khalifa University (HBKU) announced the creation of the **Qatar Center for Quantum Computing** (QC2). It received a $10M research grant from Barzan Holdings, a local defense industry vendor. Its first international partners are Xanadu and Q-CTRL. In August 2024, Ooredoo, a Qatar telecommunications operator and ICT provider, announced a funding of $750K to QC2 to support its QKD testbed project.

In May 2025, HBKU formally launched the first QC2 quantum computing lab, with $10M grant from the Ministry of Defence, and with a broad set of covered research domains, on quantum algorithms, quantum error correction, cryptography, and hardware benchmarking. The lab is run by Saif Al-Kuwari, who has published some research in the field of quantum machine learning and quantum communications.

In May 2025, Al Rabban Capital from Qatar announced an "up to" $1B investment over 10 years with Quantinuum taking the form of a Joint Venture. Its aim is to accelerate quantum computing adoption in Qatar with some training, readiness and joint research efforts, along with HBKU, like in quantum chemistry and quantum machine learning. Plus, probably, some capital investment in Quantinuum [379]. HBKU also partners with Q-CTRL, Xanadu and Planqc in quantum computing and with the local telecommunication company Ooredoo in quantum communications.

1.10.5 Saudi



As of 2024, the Saudi Kingdom's quantum strategy has the form of the **Quantum Economy Project** spun out of C4IR [380].

C4IR is the Centre for the Fourth Industrial Revolution, a "do tank" for the advancement of advanced technologies.

The Quantum Economy Project is a World Economic Forum blueprint for the creation of a roadmap across academia, industry and government to help countries develop, support and commercialize their quantum technology initiatives. It doesn't seem to be formally implemented in Saudi as of July 2024.

Meanwhile, the Kingdom established various ad-hoc partnerships with foreign quantum vendors. KAUST (King Abdullah University of Science and Technology) started with Zapata AI in 2021. In May 2024, Aramco signed an agreement with Pasqal to install a 200-qubit analog quantum computer in Saudi Arabia by the end of 2025. It already had a partnership in place with D-Wave on geophysical optimization use cases, out of its Delft Research Laboratory.

A report published in December 2024 by the C4IR mentions the need to create a "quantum foundry" supporting the production of 200 mm wafers, without specifying what purpose (superconducting qubits, silicon, others?) [381]. The practical efforts mainly deal with training in the country's universities [382].

At the beginning of 2025, the country announced various initiatives aimed at manufacturing chips, via the "National Semiconductor Hub" which is to host Silicon Valley companies. For the time being, this concerns a handful of players such as UltraSense, a startup launched in 2017 and with a funding of $24M that develops touch sensors for the automotive industry, ACT-card (Advanced Card Technology), a credit card manufacturer presented as being from Saudi Arabia when it is a UK company launched in 2002 and acquired by Fujitsu in 2015. The country also plans to create a quantum computer (FTQC) by 2045 in conjunction with the creation of a "National Alliance for Quantum Computing".

1.10.6 Turkey

Türkiye has several universities doing academic research in quantum science and technologies, plus a couple startups.

Bilkent University hosts the Quantum Computing and Topology group (Cihan Okay) which runs a project funded by the US Air Force Office of Scientific Research, the Quantum Devices and Sensors Research Group (Hilmi Volkan Demir) and the Quantum Photonics Lab (İbrahim Sarpkaya).

Hacettepe University has a lab working on quantum chemistry (Uğur Bozkaya). Mersin University has teams working on atomic force microscopy and scanning tunneling microscopy. Istanbul Technical University (ITU) has a Condensed Matter Physics & Quantum Technologies in Energy group. Koç University has the Quantum Enabling System Technologies (QuEST) group covering open quantum systems, quantum thermodynamics, quantum metrology and quantum information science. Sabancı University has a Quantum Transport & Nano Electronics Laboratory. Gazi University has a Photonics Research Center.

İzmir Institute of Technology has an Applied Quantum Research Center (AQuReC, Lütfi Özyüzer). Finally, Selçuk University has an Advanced Technology Research and Application Center.

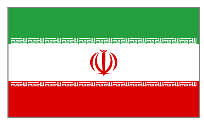
In November 2024, TOBB University of Economics and Technology (ETÜ) in Ankara announced having created the first Turkish quantum computer named QuanT with 5 superconducting qubits [383] (Figure 42). It fits in a Bluefors XLD cryostat and is probably using a chip from QuantWare or IQM.

QTurkey is a communication and collaboration network for quantum technologies activities. It organizes workshops, creates and disseminates popular science content in Turkish, and organizes a student community at the country level.

In the industry, Türkiye has one quantum startup, **Qubitrium** which develops entangled photon sources, SPAD photon detectors and a CubeSat bundle for QKD experiments. Otherwise, **Turkish Airlines** is studying potential use cases of quantum computing to optimize its operations. And the venture branch of Sabancı Holding invested in QuEra, along with Google, as part of the $230M funding round closed in February 2025.

Figure 42: TOBB 5-qubit superconducting QPU presented in 2024.

1.10.7 Iran



Israel is not the only country in the Near and Middle East that seems to be invested in quantum research.

Iran is also involved with at least two research laboratories, **Sharif University** which is working on quantum physics in partnership with Canada and the **Quantronics Lab** of the Iranian Technological University which is dedicated to quantum communication (QKD) [384].

The **University of Tehran** also hosts quantum researchers working on spin qubits [385]. The country even organizes its conference on quantum computing, the **IICQI**, since 2007. It opened its first large laboratory dedicated to quantum physics, the **National Center for Quantum Technology** in Isfahan, also named ICQTS, in 2021 [386]. There is also an Iranian Quantum Technologies Research Center (IQTEC-EN) located in Tehran.

The Iran research community is obviously not well connected to the Western world. You can see from time to time their contribution in various arXiv preprints, mostly on theoretical work [387], some work on superconducting readout in partnership with Turkish researchers [388, 389], on quantum chemistry done with a VQE algorithm on an undisclosed 4-qubit photonic processor [390], on the evaluation of parametric microwave amplifiers (JPA and TWPAs) [391], in quantum sensing [392] including quantum radars [393], and in quantum algorithms [394, 395].

In June 2023, the country's Navy officials showcased the first Iran "quantum processor" in an event. The pictured processor was a classical Digilent ZedBoard Zynq-7000 ARM/FPGA SoC Development Board bought for $600 in the USA [396]. At best, it is using some quantum inspired algorithm running on the FPGA board or the board is used to drive some qubits. The announcement was ridiculed but it is not that far from many quantum computing case studies showcased here and there in the Western world which happen to be just quantum inspired or running in classical emulation mode. In the end, the Iran government withdrew its statement and said it was misunderstood by their local media [397].

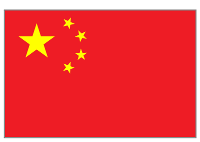
1.10.8 Pakistan

Pakistan started to appear in the quantum radar in October 2022 when announcing a partnership with Ireland [398].

Two quantum research teams can be identified in the country, **QuantuC**, with five full time researchers at the University of Lahore is working on quantum chemistry quantum algorithms and another one works on quantum physics at **LUMS University** [399]. In October 2025, Pakistan and China signed a memorandum of understanding to collaborate on quantum technologies. China Electronics Technology Group Corporation (CETC) will help the country create its National Centre for Quantum Computing.

1.11 Asia-Pacific

1.11.1 China



As in many technology sectors, **China** is loudly and clearly asserting its ambitions and power in quantum technologies [400, 401].

As in the UK, this domain was taken seriously by the government and as early as 2013 with the involvement of Chinese president Xi Jinping, during a visit to the Anhui laboratory, focusing on quantum cryptography, combined with a training session.

Government funding

In 2015, Xi Jinping integrated quantum communication into the country's scientific priorities, in the 13th plan covering 2016-2020. Maybe was it a benefit from having a government comprising many politicians with some scientific background and also the result of Snowden's revelations on NSA's spying capabilities in 2013.

Assessing the government and regional investments in quantum technology is not an exact science. Many amounts are hard to check, and some are clearly false. The usual $15B to $25B estimates spread in most analyst reports are most certainly largely exaggerated and should be used using the conditional tense [402–405].

You can see them in various McKinsey, BCG, World Economic Forum, Qureca [77] and other reports updated every year. It is tiring to see these unchecked and non-official numbers since China's government has never communicated in a consistent and consolidated manner about its investments in quantum contrarily to most developed countries. Why are these false numbers circulating broadly in the Western world without being checked? For many different reasons. Unchecked numbers from untrusted sources circulate easily when broadcasted by some Western trusted sources [406]. Everybody's quoting everybody without checking the original data source [407, 408].

People do not have the time to check these numbers or just look at their scale. There are sometimes currency errors [409] or aggregate amounts with funding not related to quantum science [410]. It happens to be a funding for scientific education which covers quantum and many other topics. There is also some internal China politics at play with some regions playing an announcement game to compete with each other, or with the country's government [411]. Many economic indicators are known to be false in China's communication. Some, like in the USA, are also happy to amplify the strategic and business threat coming from China to drive more policy makers attention and public investments [412].

Very few sources, like a February 2022 report from **Rand Corporation**, are pinpointing this and detailing China's real quantum investments which are probably either on par or below similar investments in the USA and Europe, in the broad range of $2B to $4B over 10 years [413].

Extracts on China: "*Even higher levels of announced investment are associated with the main Chinese quantum research facility, the Hefei National Laboratory for Physical Sciences at the Microscale (HFNL), which is led by Pan and a part of the University of Science and Technology of China in Hefei, Anhui Province. Chinese language news media reported $1.06 billion in laboratory funding in 2017, and the Anhui Business Daily newspaper reported plans (though not confirmed funding) for $2.95 billion per year over the 2017–2022 period.* ***These announced spending goals are in stark conflict with the government-wide spending estimates*** *given in Table 4.11. The $1.06 billion start-up funding that Chinese news media announced in 2017 for Pan's quantum laboratory alone hugely exceeded Pan's own 2019 estimate for the PRC's total government spending over the same time period.* ***Our team's China experts assess that these conflicting reports of funding levels are not unusual in China; the PRC government often announces ambitious (and often highly politicized) spending goals, and it is not uncommon for these goals to go unmet…*** *[…] In summary, official reports of the PRC's government investment in quantum R&D in recent years have varied widely, from a low of $84 million per year (Pan's estimate) to a high of at least $3 billion per year (the Anhui Business Daily's reported funding for Pan's laboratory). We are unable to assess from public information which figure is more accurate. By comparison, the U.S. gov-*

*ernment has spent $450–$710 million per year in recent years; **we cannot determine whether the PRC total is higher or lower than this amount***". The Rand Corporation report estimated that only 1,700 students earned a PhD in quantum technology in China.

In a long New Yorker 2022 piece, a senior researcher from China working with Jian-Wei Pan even did cast doubts on the $15B estimate, saying the truth was probably below $4B, in line with what I had found initially [414] and Jian-Wei Pan announced that their processor had solved a computational task millions of times faster than the best supercomputer. [...] Lu Lu immediately began debunking claims made by his competitors, and even claims made about his own effort. **One widely reported figure stated that China *has invested fifteen billion dollars in developing a quantum* computer. *"I have no idea how that was started,"* Lu said. *"The actual money is maybe twenty-five per cent of that.*** (Figure 43).

This was confirmed in a thorough long-read paper written by Rachel Cheung from The Wire China in February 2025 [415].

Some are arguing that the space QKD program may explain such a high investment. Let's compute that! The Micius satellite weighs 640 kg. According to various estimates, it costs less than $50M to launch such a satellite in low-earth orbit. When adding the cost of the satellite R&D and manufacturing, plus the related ground stations, you may find at worst that the Micius program total budget was around a couple hundred million US dollars. Not billions! It will be the same for the thousands of kilometers of terrestrial QKD networks, that are probably using existing dark fiber infrastructure and require a trusted repeater every 80 km.

So, let's try to find some realistic numbers here and identify their sources. Government's funding of quantum R&D was $160M in the **11th plan** covering 2006-2010, from $490M to $800M in the **12th plan** covering 2011-2016 and $320M to $337M in the **13th plan** starting in 2016-2020, supplemented by $640M of region funding [416–418], 12th and 13th plan investment in quantum science. We don't know if this is covering legacy or just incremental funding. Later, China's government communicated an amount of $34B corresponding to several scientific priorities including quantum. This represented probably less than $1B between 2016 and 2020 and a total of $1.76B over 10 years. Other estimates were lower, in the $1.5B range for the 2006-2020 period [419].

In 2021, China announced its new **14th five-year plan** on research, with an 11% global funding increase but with no details regarding quantum investments [420]. At most, it would bring their 2006-2027 total quantum investments to about $4B, but definitively not anywhere between $10B and $25B as shown in most Western world reports (McKinsey, BCG, WEF, others).

The Chinese quantum efforts are coordinated by the **USTC** (University of Science and Technology of China) of **CAS** (Chinese Academy of Sciences), under the leadership of Jian-Wei Pan [421]. These investments are mainly concentrated over Beijing, Shanghai and Hangzhou, Hefei in the Anhui province (500 km west of Shanghai), the Wuhan region and the Shenzhen, Hong-Kong and Guangzhou zone (Figure 45). They specialize respectively in quantum communications, trapped ion computing, topological qubit computing and quantum materials for Beijing, silicon qubit computing, NV centers and photons, quantum communications and metrology in Hefei, and communication, superconducting and cold atom qubit computing and photon detection in Shanghai.

The most ambitious project is the "$10B" national quantum research lab that partially opened in 2020, the **NLQIS (**National Laboratory for Quantum Information Sciences) of Hefei. This laboratory is focused on quantum computing and metrology for military and civilian applications. The lab currently hosts between 300 and 600 researchers depending on the estimates (Figure 44).

The initial plan announcement mentioned about 1,800 researchers, including 560 full-time researchers spread across two labs, three universities and a fab [422, 423]. The zone has its own "Quantum Avenue" of several hundred meters in Hefei, Yunfei Road, with the NLQIS lab and 20 startups including the three largest quantum startups in China (Origin Quantum, QuantumCTek, Ciqtek). These seem to be the largest employers here thanks to the burgeoning business of selling quantum computer to universities in China [424].

Adding to the confusion, China's government announced in 2025 the creation of a huge fund of $138B for deeptech startups, including quantum startups [425]. Adding the two announcements to reach $153B for quantum (138+15) would be a category error, since the larger figure covers deeptech as a whole, of which quantum is an undisclosed fraction. Any such comparison with US federal spending also needs the same period, the same currency and the same distinction between announced envelopes and disbursed funds.

Now, let's get some update with 2026 new numbers. China's 15th Five-Year Plan announced in March 2026 lists quantum technology among seven "future industries" and keeps national R&D spending growing at more than 7% per year, but with no specific budget line on quantum [426].

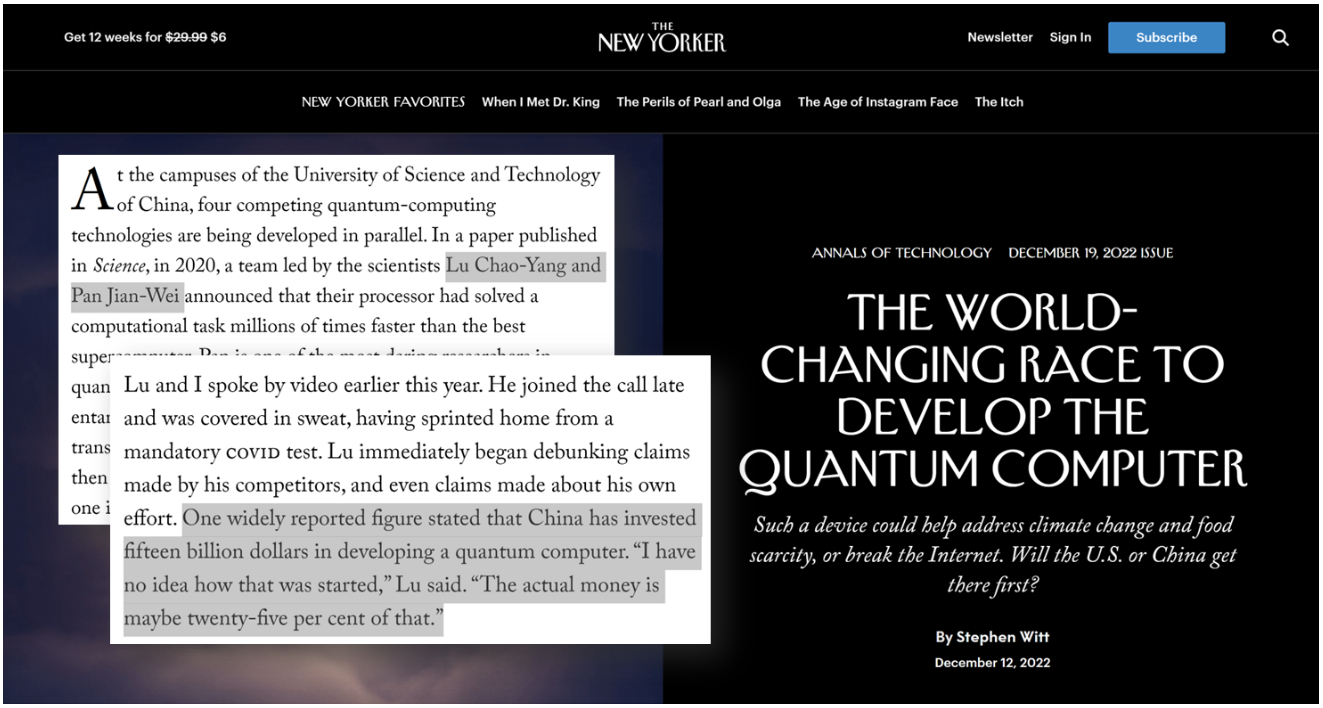


Figure 43: Even preeminent researchers from China don't believe this "$15B" investment tag even though they mention only the buildup of quantum computers. Source: [414].

Figure 44: Hefei's quantum lab as pictured in 2022 (source). Added in 2023.

The largest identifiable funding vehicle is the National Venture Capital Guidance Fund launched in December 2025, with $14B of central government seed capital, a 15 to 20 year lifespan and a target $140 billion with additions from local governments, state-owned enterprises, financial institutions and private investors, at least 70% of it directed at early-stage companies [427, 428]. There are then regional funds [426]. But the projects to be funded also cover semiconductors, quantum technology, biomedicine, brain-computer interfaces, aerospace, AI and future energy. So, it's not appropriate to trust the $17B quantum investments reported here and there [427].

Private and government investment in Chinese quantum startups was about $600M in 2024 by a raw Chinese estimate [429], to be compared to $2.0B of worldwide startup funding that year [430].

Industry vendors revenue is also two orders of magnitude below some reported numbers. QuantumCTek booked $14M over the first three quarters of 2024 [431], and the Hanyuan-1 cold-atom orders totaled $5.6M [432]. The claim that the Chinese quantum computing sector reached $1.6B in 2025 comes from a CCID Consulting forecast published in June 2025, stated in the future tense [433].

Research

On the quantum computing side, Chinese laboratories are testing all imaginable qubit technologies and regularly announce technological progresses. They seem to be rather ahead in photon qubits as we have seen about their boson sampling experiments but not really with other qubit types.

Key academic scientists are, beyond Jian-Wei Pan, Peng Cheng-Zhi in quantum communications, Lu Chao-Yang in solid-state quantum photonics, Guo Guangcan and Guo-Ping Guo who cofounded Origin Quantum, also in the CAS Hefei lab, Gui-Lu Long in quantum communications at Tsinghua University, Dapeng Yu in Shenzhen on condensed matter physics, and Kihwan Kim in trapped-ions computing also at Tsinghua University.

In 2017, the Hefei laboratory announced the realization of a test system of 10 superconducting qubits in aluminum and sapphire [434] (Figure 46). The two qubit gates error rate of 0.9% was not best-in-class. They were at 24 superconducting qubits in 2019 (Figure 47). Their

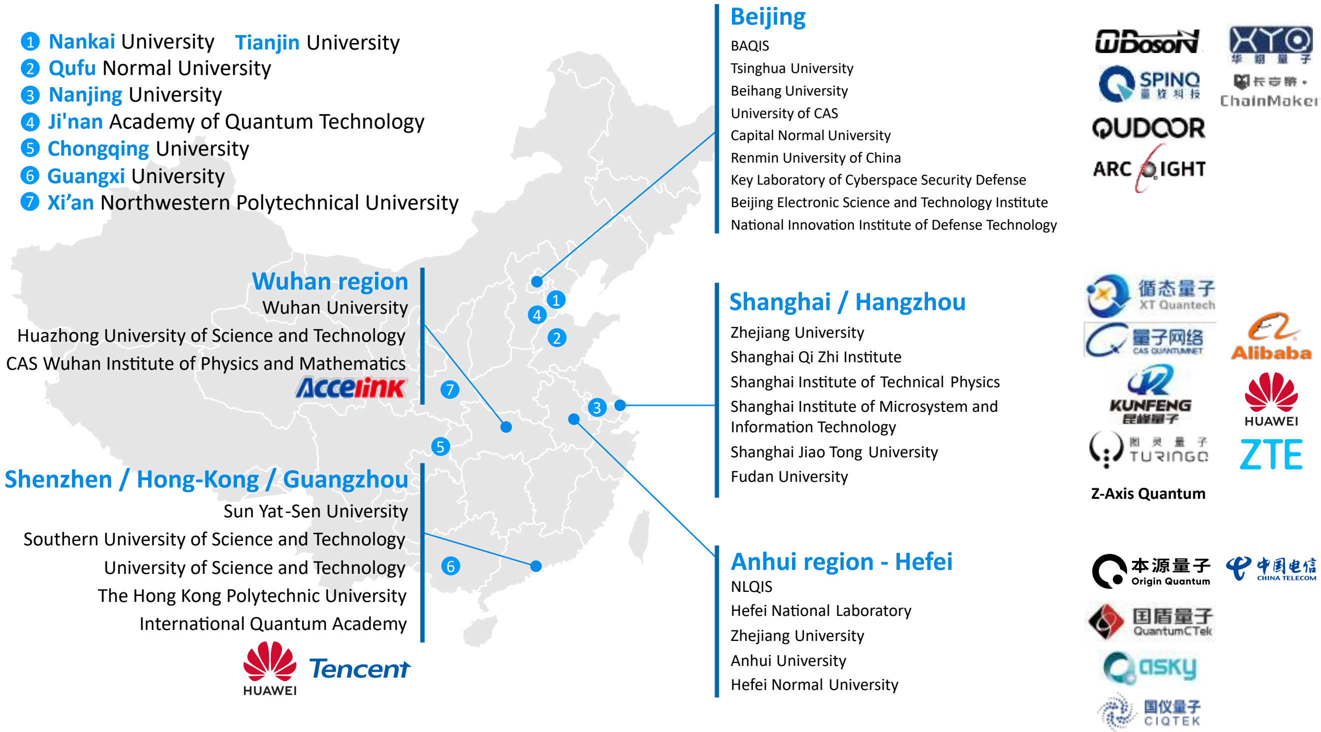


Figure 45: China's quantum ecosystem with its main universities and academic laboratories and their industry vendor ecosystem. 🅭 Olivier Ezratty, September 2024.

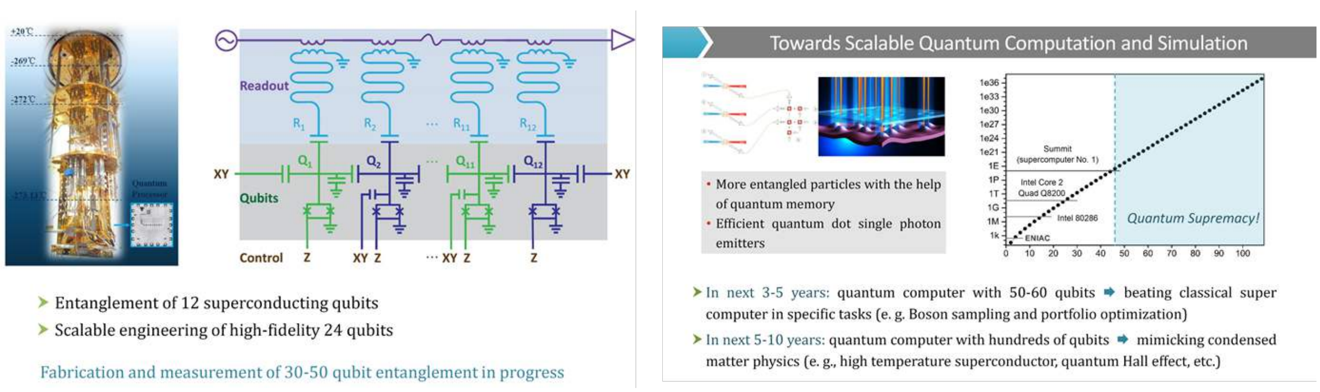


Figure 46: China superconducting state of the art in 2017. Much progress has been accomplished since then. Source: [434].

single-qubit gates fidelity was 99.9% and two-qubit CZ gates at 99.5% on two-qubit CZ gates, which is much better [435].

Their T_1, which defines the coherence time of the qubits was 40 μs, equivalent to what IBM obtains with its Q System One at 20 qubits. The Jian-Wei Pan team planned to reach 50 superconducting qubits by 2023.

It delivered early on this promise in May 2021 with 62 superconducting qubits, implementing a quantum walk algorithm, which makes comparisons difficult, for example with IBM's 65 superconducting qubits system launched online in September 2020 [436]. They followed with the announcement of a 66 superconducting qubits system quantum advantage, with an architecture and a benchmarking protocol closely following Google's Sycamore and in 2023, they had 176 qubits with a new version of Zuchongzhi-2, but which accounted for two-qubit couplers. The Wukong system from Origin Quantum has 72 qubits with reported two-qubit gate fidelities below 97%, against 99.7% median two-qubit fidelity reported by IBM on 156 qubits, bearing in mind that these numbers come from different benchmark protocols and different qubit subsets and are not strictly like-for-like. Zuchongzhi 3.0 was released in December 2024 with 105 qubits and a reported average two-qubit gate fidelity of about 99.62% [437], with enough spread across the chip that some qubits were deactivated for the random circuit sampling experiment.

Why is China lagging behind the US, and particularly IBM and Google? It is hard to guess but we can count on qubit chips manufacturing techniques which are hard to master. All in all, China is still behind the US and particularly IBM, in designing superconducting qubits QPU [438].

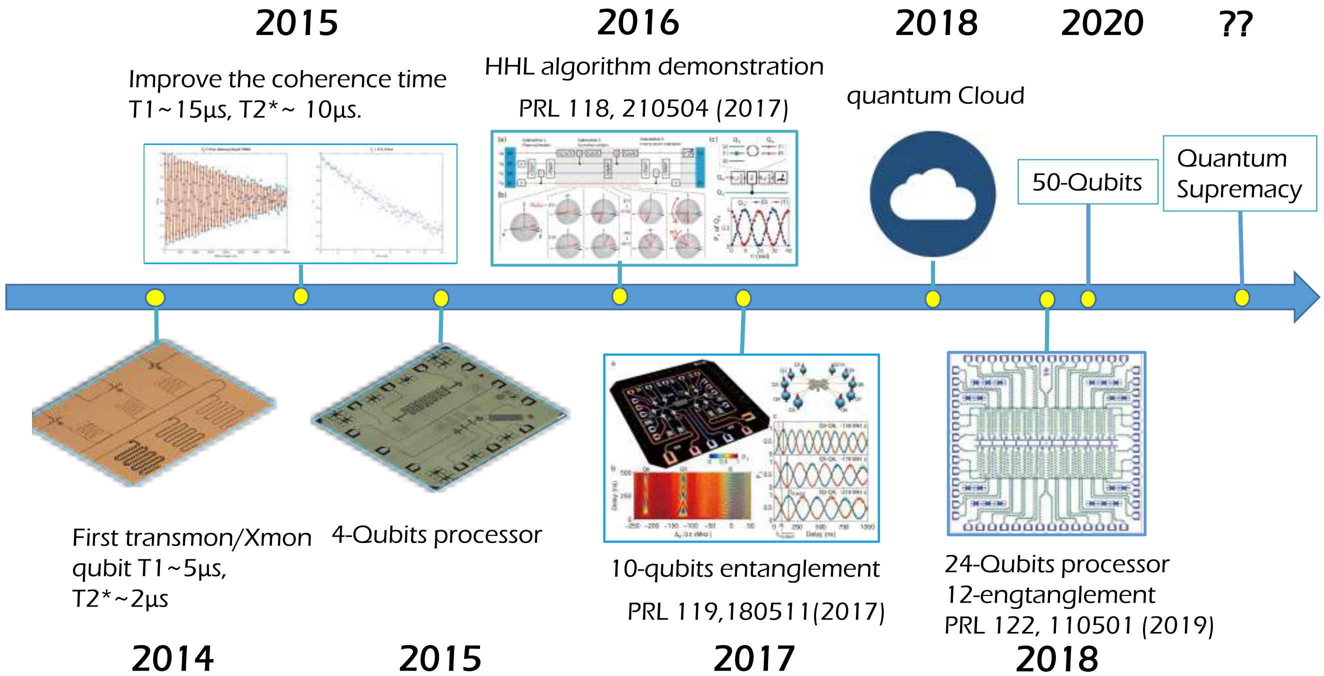


Figure 47: China's initial progress in superconducting qubit. As of mid-2025, it supports currently 105 NISQ qubits (Zuchongzhi 3.0). Source: Superconducting Quantum Computing by Xiaobo Zhu, June 2019 (53 slides).

The quantum scientific and technology level in China is good but not yet stellar. They mostly improve technologies developed in Western countries and do not generate many new ideas. On the other hand, they create experiments like boson sampling or QKD deployments at a large scale.

Now, regarding quantum sensing, the country has some interesting startups (shown in Figure 49). They also communicate on their ability to detect nuclear submarines or stealth aircraft with quantum radars and other quantum sensors, which drives serious doubts with Western scientists. Reports on China's quantum sensing are very shallow in technical information on their actual capabilities [439].

China does not seem to have a significant influence in the academic world on quantum algorithms and programming tools. We must never forget the strategic role of software and platforms in the digital economic battles! It looks like History is repeating itself in China for this respect. But they probably have the capability to catch-up here as well.

Quantum industry

Public-private partnerships have been put in place, such as with **Alibaba,** who invested in the USTC to launch in 2015 the Shanghai Alibaba Quantum Computing Laboratory. It focuses on quantum cryptography and quantum computing. Quantum cryptography could be used to secure e-commerce transactions and data centers connections. In January 2018, Alibaba even launched a cloud-based 11 qubits system developed by USTC. Alibaba was a serious contender in the superconducting qubit space with its fluxonium qubits variation. But they decided in 2023 to pull the plug from this quantum computing effort. The related research team created the startup Z-Axis Quantum that, for the moment, is still stealth.

Baidu launched in 2018 its **Institute for Quantum Computing,** which was being deployed in their Technology Park in Beijing. Led by Runyao Duan, a specialist in quantum information theory, with Artur Ekert as board member, they were mainly developing quantum software stacks in their QIAN full stack quantum software and a hardware platform. They developed a quantum emulation solution in their cloud resources named Quantum Leaf [440] and a bunch of other tools: Paddle Quantum (quantum machine learning), Quanlse (quantum pulse control for superconducting qubits), Qulearn (a quantum knowledge base), plus quantum error processing, measurement and control [441], network architecture and quantum electronic design automation. They also worked on the development of some quantum Internet stacks. In August 2022, they announced their first superconducting qubits quantum computer with 10 qubits named Qian Shi to be expanded later to 36 qubits. But late 2023, like Alibaba, they decided to cut short their quantum computing investment.

Tencent also launched a Quantum Lab in 2018, led by Shengyu Zhang and based in Shenzhen. They planned to offer quantum computing resources in the cloud. The lab publishes work in quantum simulation and machine learning algorithms. It develops QuAPE, a quantum control microarchitecture for superconducting qubits supporting multi-core QPUs parallelism that was prototyped with a FPGA circuit. They are also working on superconducting qubits [442].

ZTE and many telecom operators and manufacturers are involved in the deployment of secure fiber networks by QKD (**China Telecom, China Cable, China Comservice, China Unicom**) as well as various banks that use them.

China Telecom announced it invested $434M in the creation of a quantum technology group in May 2023. They deployed "Tianyi Quantum Secret Talk", a smartphone service seemingly supporting a QRNG-based key generation within a SIM card, a solution jointly developed with ZTE and QuantumCTek which had one million users as of October 2023.

China's quantum startups ecosystem is quite poor compared to the country GDP and its public investments in quantum science, whether you use $4B or $25B as a reference (Figure 49). The country quantum startup and small business ecosystem is the 10th largest in the world in number of entities and the 5th in capital investments, in between France and Israel, the source being my own database of quantum and small business startups used to create various charts in this book and as of July 2023. When considering only startups, China is 6th in number of entities [443]. One of the reasons may be that public research laboratories are well funded, and researchers have less incentive to create companies. One exception is **Origin Quantum Computing** which raised a record $163.4M to develop a full-stack superconducting qubits offering and sells it mostly to universities in China.

Figure 48: Origin Quantum high-density microwave system looks like equivalent you can find with Bluefors and Oxford Instruments.

Most other startups in China are in the quantum communication field, like **QuantumCTek** and **Qasky Science,** and have joined with ID Quantique and Battelle to form the **Quantum-Safe Security Working Group,** which federates the quantum cryptography industry.

A project led by Shan Lei and Wang Shaoliang from **Anhui University** is to create a dilution refrigerator operating at 8.5 mK. They will spin out a startup from their lab in Hefei [444]. It is mandated by the export controls from Wassenaar's agreements and other exports limitations which limits China's capacity to import large dilution refrigerators like the ones coming from Bluefors [445].

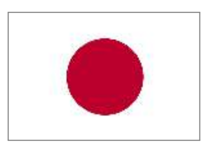
Likewise, Origin Quantum developed a high-density microwave interconnect module, touting an upcoming strategic independence (Figure 48) [446].

This kind of module is not the highest technology you need in the electronics value chain in a superconducting qubit QPU. Higher value components are active electronics: AWG, DAC, ADC, JPA/TWPA amplifiers, HEMT amplifiers, cabling, and QEC error syndrome decoding. They may be accessible to China's high-tech infrastructure.

China's dominance may also be exaggerated in the patents area. There was indeed an increase of China patents in quantum technologies from 137 in September 2020 to a total of 804 by October 2022 according to the Global Quantum Computing Technology Patent Filings Ranking List (Top 100) from IncoPat Global Patent Database [57]. It includes 234 patents from Origin Quantum. The US accounts for 40% of the patents, IBM being first with 1,323 patents, China with 15% and Japan with 11% [58]. IBM alone has more patents on quantum technologies, mostly on quantum computing, than China.

This can also be found in the work from Zeki Seskir and Kelvin W. Willoughby who created a supervised machine-learning method to create a new classification to build a cleaner quantum technologies patents dataset [447]. The hybrid human/AI tool analyzed 11,600 patents and eliminated 6,000 patents that were not describing a genuine quantum technology invention. In the end, the USA and China seem on par with regards to the number of patents in quantum technologies.

1.11.2 Japan



Japan stands out for its very active and long-term oriented fundamental research initiation of two key technological waves in quantum computing.

It started with the creation of the principle of quantum annealing by **Hidetoshi Nishimori** in 1998 [448]. Then, there was the creation of the first superconducting qubits in 1999 by **Yasunobu Nakamura**, **Jaw Shen Tsai** (both then at NEC) in liaison with **Yuri Pashkin** (Lancaster University, UK). Unfortunately, this was not turned into some industry lead.

Research

Japan's public research is conducted by several independent agencies attached to various ministries that fund public laboratories, university laboratories and research partnerships with companies [449]:

- **AIST** (National Institute of Advanced Industrial Science and Technology) is mainly funded by METI. It employs about 2300 researchers in all. Several laboratories appear to be dedicated to nanomaterial

Figure 49: Market map of China's quantum industry vendors. (cc) Olivier Ezratty, 2023-2024.

sciences. There is also a research group on precision measurement. It is the global research and development hub for business by quantum-AI technology (G-QuAT).

- **RIKEN** (Institute of Physical and Chemical Research) also funded by the Ministry of Research (MEXT), with a total of about 3,000 researchers including a total staff of 210 in quantum technologies and a yearly budget of $30M [450]. It includes a laboratory in theoretical quantum physics, headed by Franco Nori, and another in photonics, headed by Katsumi Midorikawa. They work in particular on silicon and superconducting qubits. RIKEN collaborates with Fujitsu since 2020 to build a superconducting qubit computer. In April 2025, RIKEN and Fujitsu announced the creation of a 256-qubit QPU made of 4 modules of 64 qubits. Its characterization data was not available. They also have a lab working on the integration of HPC and quantum computers led by Mitsuhisa Sato.

- **NICT** (National Institute of Information and Communication Technologies) includes the Quantum ICT Advanced Development Center, which specializes in quantum cryptography. In July 2017, the institute carried out a demonstration of quantum telecommunications using a microsatellite, reminiscent of the Chinese experiment with the Micius satellite carried out the same year.

- **NII** (National Institute of Informatics) includes a hundred or so researchers and focuses on research in theoretical quantum computing but also works on superconducting and silicon qubits.

- The Japanese French Laboratory for Informatics (JFLI) created in 2009 is based in Tokyo and hosted at both the NII and the University of Tokyo. It brings together researchers from the Universities of Tokyo, Keio, NII, CNRS, Sorbonne University (LIP6), Inria and Université Paris-Sud. It covers fundamental physics, algorithms and studies the feasibility of large-scale quantum computing as well as quantum cryptography. The laboratory is co-directed by **Kae Nemoto**, then at NII and since 2022 at OIST, one of the few women in this whole panorama.

- **NEDO** (New Energy and Industrial Technology Development Organization) which is attached to the Ministry of Economy and Industry, METI. It is particularly invested in quantum annealing with a project running from 2018 to 2022 with $4.5M per year.

- **QST** (National Institutes for Quantum and Radiological Science and Technology) was launched in April 2016 with an annual budget of $487M. This impressive amount is not exclusively allocated to quantum technologies. It mainly covers the vast field of quantum sensing and in particular medical imaging.

- **JST** (Japan Science and Technology Agency) funded by the Ministry of Research and which funds deep tech research projects and promotes science to the general public and international scientific collaboration. In 2016, JST launched a project by Yasunobu Nakamura of "Macroscopic Quantum Machines" to assemble 100 superconducting qubits.

The Japanese government had launched various quantum initiatives such as **PRESTO** (since 2016) or the **CREST** cross-cutting program (also since 2016) as well as the **ERATO** projects in 1981 (Exploratory Research for Advanced Technology).

The country's quantum initiatives are currently part of its Sixth Science, Technology and Innovation Basic Plan, running from 2021 to 2025. In a typical Japanese way, this plan is linked to a societal goal "Society 5.0" to bring cyberspace and physical space closer together to solve society's social problems and create a human-centered society (Figure 51). All this with AI, quantum sensors and cybersecurity.

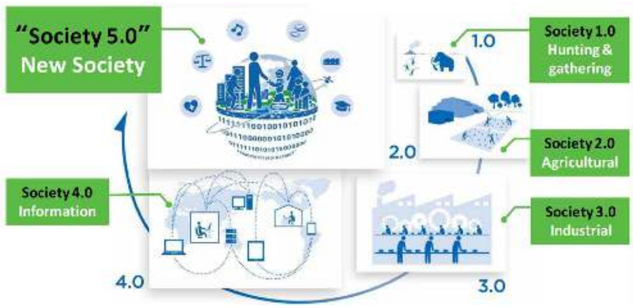


Figure 51: Japan's classical societal angle to sell some new technology wave.

Here are a few leading researchers in Japan in addition to those mentioned above:

At the University of Tokyo, **Akira Furusawa** has the ambition to create a large-scale quantum computing solution with photon-based qubits. He's teaming up with NTT (see below) and plans to create a scalable computer by 2030, which led to the creation of the OptQC startup in 2025 [451]. **Yasuhiko Arakawa** (1952) specializes in semiconductor physics and optoelectronics, at the origin of new processes for the exploitation of quantum dots in sensing.

Yasunobu Nakamura (1968) who specializes in superconducting qubits and serves at the RCAST (Research Center for Advanced Science and Technology) of the University of Tokyo and at the CEMS (Center for Emergent Matter Science) of RIKEN [452].

Mio Murao created and manages the Quantum Information Group at the University of Tokyo that bears her name (Murao Group).

This group specializes in distributed quantum computing, quantum systems simulation algorithms, quantum telecommunication protocols and quantum algorithms. She is very fluent in English, which has enabled her to serve as a connecting point between Japan and research teams in the USA (video).

At the University of Osaka, **Masahiro Kitagawa** specializes in atomic nucleus spin-based quantum sensing in nuclear magnetic resonance with notable applications in medical imaging. **Nobuyuki Imoto** leads research in quantum cryptography and telecommunications. **Keisuke Fujii** is the Deputy Director of the Center for Quantum Information and Quantum Biology where **Wataru Mizukami** is an associate professor. **Makoto Negoro** leads a group working on superconducting and trapped-ions qubits. **Kosuke Mitarai** is an assistant professor focused on quantum machine learning and is also a cofounder of QunaSys. This is part of the **QSRH** (Quantum Software Research Hub) from Osaka University.

Then:

Kohei Itoh of Keio University has been managing the Q-LEAP project since 2018, which focuses on assembling different silicon isotopes into CMOS components and on NV center based quantum magnetometry (video). He is also a partner of IBM's Q Lab in Tokyo.

Yoshihisa Yamamoto (1950), a Stanford professor emeritus and director of the NTT Physics and Computer Science Laboratory, who worked in photonics, QKD and quantum dots. He is very influential in Japan on the country's technological choices [453]. He is the pilot of the Quantum Information Project (QIP), one of the national research program projects from FIRST selected in 2009 and which covered all branches of quantum applications.

François Le Gall is a French researcher based at Nagoya University who specializes in quantum computing theory, mathematics, quantum algorithms and cryptography. He is also interested in distributed quantum computing. He has been living in Japan for more than 20 years.

Masahito Hayashi of Nagoya University was originally a mathematician who then became a specialist in theoretical quantum computing. He coordinated the ERATO project on theoretical quantum computing.

Masahide Sasaki of NICT leads much of Japan's quantum cryptography efforts. In particular, he has contributed to the SOTA project for quantum key communication using satellites [454].

Government funding

The *flagship* project **Q-LEAP** launched late 2019 by the Ministry of Research (MEXT) seems the most ambitious and aims to catch up with both China and the USA, even if an alliance with the USA also seems to be on the agenda [455, 456]. The roadmap extends over 10 years with \$200M. The program targets quantum computing, quantum sensing and next-generation lasers.

Most qubits technologies are funded: superconducting, cold atoms, trapped ions and electron spin. This "Flagship" will run until 2027 [449].

As part of its broad quantum computing plan, the Ministry of Economy, Trade and Industry is investing \$31.7M to create a cloud quantum computing offering, led by the University of Tokyo. This cloud platform will enable access to both 27-qubit and 127-qubit QPUs from IBM, the first one being installed at the University [457].

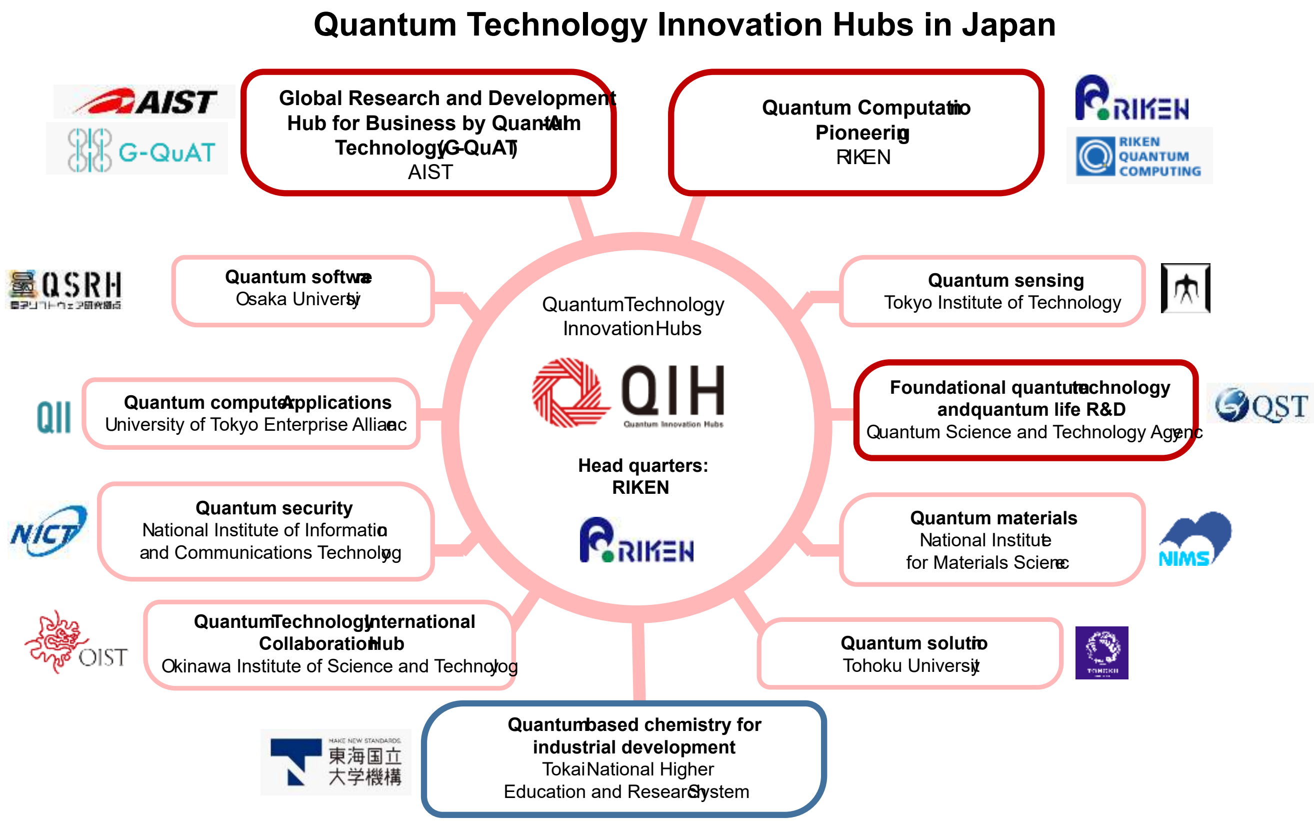


Figure 50: Map of the Japan quantum technology innovation hubs, run by academic institutions. Source: Global R&D for Business by Quantum-AI Technology in AIST by Shiro Kawabata, Q2B Santa Clara, December 2024 (12 slides).

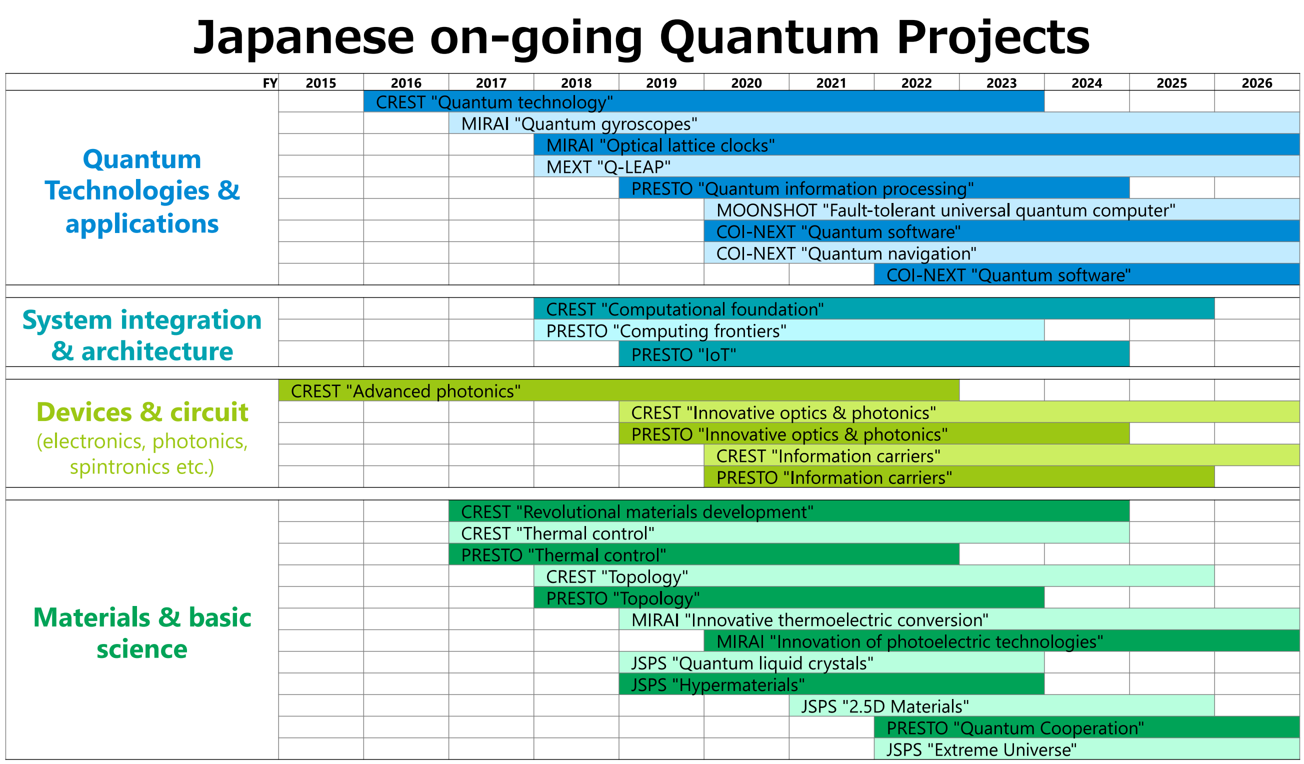


Figure 52: Japan's quantum project inventory. Source: QC Benchmarks seen from science policy & science communication perspective by Yoshiaki Shimada, Center for Research and Development Strategy, Japan Science and Technology, May 2023 (15 pages).

So, how much is Japan investing in quantum technologies? The reconciliation of their public and private investments is not easy. It seems that the country doubled its annual expenditure to $590M in 2022 as part of its new quantum strategy announced that year [458, 459]. One of this strategy's goals includes having 10 million users by 2030 which is typical from a very dubious claim made for politics. In quantum computing, we then have multiple goals with 100,000 qubits by 2033.

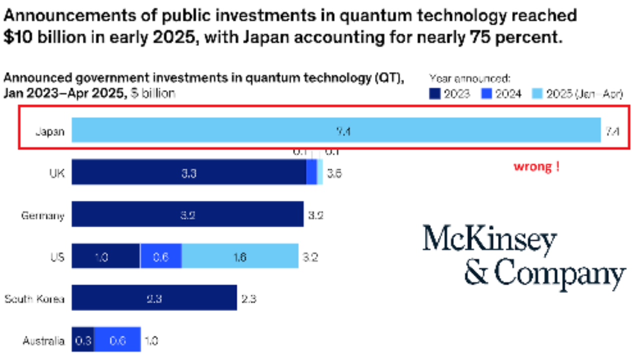


Figure 54: How Japan's 2025 semiconductor plan is misinterpreted by McKinsey in its 2025 report on quantum technologies. McKinsey folks, what skill is missing that prevents you from properly read a press release? Source: [461]

In January 2025, Japan did create even more confusion on its investments in quantum with announcing a plan of $7.4B on semiconductor manufacturing and quantum technologies. It is part of 5-year $70B investment in semiconductors and AI [462]. It is quite easy to detect that the quantum part of this plan is minimal since the main companies getting the fund will be Rapidus, TSMC, and Micron Technology, none of which being officially invested in quantum whatever. This plan is their version of the US and EU "Chips Acts", to restore the capability to produce chips with the highest density. So, if like in the latest McKinsey May 2025 report [461], you see Japan leading the word with public investments in quantum, you now know that it's not right at all (Figure 54).

The confusion went on in 2026 with new investment announcements defying gravity. Japan's government announced on June 24, 2026 a new growth strategy, finalized in July, targeting more than ¥370 trillion (about $2.3T) in public and private investment spread over 17 sectors until fiscal 2040 [463]. It represents about 4% per year of the current country GDP. For quantum technologies, it ends up becoming $71B for computing, $10B in communications and $10B in sensing. Normalizing it per year since it's spread over 14 years, it makes $5B per year just on quantum computing, without considering a potential ramp-up which may lead this number to reach $10B at peak year. The category matters here: this is a sector-wide mobilization target combining public and private capital over 14 years, not a public quantum budget, and the government does not control the private share. The quantum share, the public/private split and the annualized versus cumulative amounts have to be isolated before this figure can be compared with anything.

Quantum industry

Japanese startups are rather specialized in software and in particular for quantum annealing computing running either on D-Wave quantum annealers or on Fujitsu digital annealers. We have **A*Quantum** (2018, QA software), **D Slit Technologies** (2018, software), **Groovenauts** (2012, QA software), **Jij** (2018, QA software framework), **MDR** (2008, chemical simulation), **QunaSys** (2018, healthcare), **Sigma-I** (2019, QA software) and **Tokyo Quantum Computing** (2017, QA software) (Figure 55).

Softbank's investment fund, endowed up to $100B partly by Saudi Arabia's Public Investment Fund, was also planning to invest in quantum technologies [464]. However, several years after its announcement, the fund did not seem to have a single stake in quantum technologies. They have first to get rid of Wework!

In the private sector, Japan's major industry groups are mainly focused on quantum telecommunications and cryptography, as well as on quantum and non-quantum annealing-based computing.

Hitachi also has a research laboratory located at the University of Cambridge (UK) that works on quantum key distribution, quantum computing and the creation of SQUID components for superconducting qubits. They are also working on silicon spin qubits quantum computing. In February 2025, it announced the creation of a venture fund of $400M targeting AI, quantum, nuclear fusion, and other deep techs. Their existing 38-startup portfolio contains only one company in the quantum ecosystem: Strangeworks.

Toshiba Corporation has been involved in quantum cryptography since 2003. They are working on it with the Quantum Information Group (QIG) at the University of Cambridge, UK. They performed a first demonstration of quantum communication in 2014, sending 878 Gbits/s of secure data over a 45 km fiber between two areas in the Tokyo area over a cumulative period of 34 days, at a rate of 300 kbits/s. They were continuing the experiments in 2019 and beyond and with British Telecom in the UK [465].

NTT maintains four applied quantum research laboratories, focused on quantum telecommunications and quantum cryptography, all with about 40 researchers. This leads to raising wages inflation for the most talented people, a bit like in Silicon Valley, but probably only for some extreme cases [466].

QNNcloud

In 2017, **NTT** launched a prototype photonic system marketed as a Quantum Neural Network (QNN), in collaboration with the **National Institute of Informatics** and the **University of Tokyo**. Despite the name, it is a coherent Ising machine, an optical paramet-

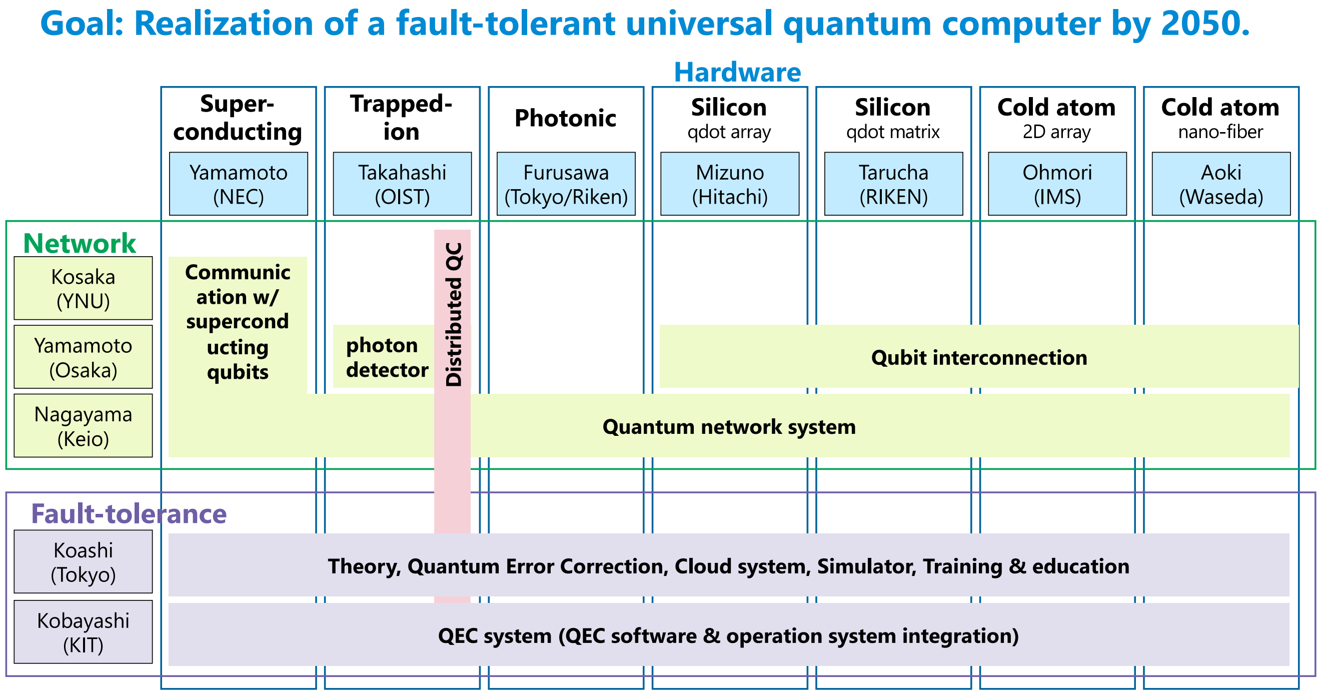


Figure 53: Japan's quantum computing project inventory per qubit type. Source: [460].

Figure 55: Japan's quantum industry vendors. © Olivier Ezratty, 2022-2024.

ric oscillator network solving Ising problems, and not a gate-model quantum neural network. It was available on the cloud at qnncloud.com (video) but the service was discontinued in March 2019 [467]. This was done with Toshiba, NEC and the NICT in Tokyo with three nodes and 45 km apart [468]. They also work in the CMOS quantum dots qubits. NTT also developed LASOLV, a photonic based coherent Ising system with 2000 nodes [469]. NTT is also involved in the development of superconducting qubit control software along with Fujitsu and RIKEN.

Several non-quantum annealing optimization computation projects on CMOS components have been launched. There is the **Fujitsu** offering, and also the NEDO project led by Masanao Yamaoka and Masato Hayashi at **Hitachi** in partnership with the AIST, RIKEN and NEDO (New Energy and Industrial Technology Development Organization, the equivalent of the energy branch of the CEA) laboratories [470–472].

And then the **NEC** project in quantum annealing led by **Yuichi Nakamura** in liaison with Waseda, Yokohama and Kyoto Universities, AIST and Titech (Tokyo Institute of Technology). They are optimizing the classical part of annealing processing with NEC vector processors. The quantum part seems to be managed on D-Wave machines. NEC is also versed in quantum keys (QKD).

Recruit Communications Ltd (1960), a large $16B company specializing in HR, communications and marketing, distinguished itself by launching a partnership with D-Wave in 2017 to develop quantum annealing-based solutions for the operational optimization of marketing, communications and advertising. They developed the PyQUBO open-source library, which simplifies the development of quantum annealing software applications [473].

In September 2021, **Q-STAR** (Quantum Strategic Industry Alliance for Revolution) was launched. It is an industry alliance to promote the usage of quantum technologies and particularly quantum computing and cryptography in various industries with the participation from Toshiba, Toyota, NEC, NTT, Hitachi, Fujitsu, Mitsubishi Chemical and Sumitomo among others.

QPARC is a community created in 2020 that gathers researchers and the industry, including the Japan quantum computing industry and some US vendors like IBM, Microsoft, Rigetti, IonQ, and Google.

IBM announced at the end of 2019 the opening of a Q Lab in Tokyo in partnership with the University of Tokyo. IBM's investment in Japan follows a model already inaugurated in France in Montpellier in 2018, in Germany in September 2019 and in Canada with the Institut Quantique in June 2020. It contains a partnership with a university, investments in training and above all, a technical and marketing investment to evangelize quantum among major customers [474, 475]. In August 2020, IBM extended this partnership by announcing the creation of a consortium for the adoption of quantum technologies in Japan [476, 477].

In May 2023, Japan formalized two partnerships, on the road to the buildup of a 100,000 qubits quantum computer. The first with **IBM** which will bring $100M to the table over 10 years, including funding for the University of Tokyo and also for the University of Chicago. It seems to be an extension of the partnership established in 2019 with the University. The second is with **Google** which will do the same, with $50M [478]. On top of that, **Intel** is partnering with RIKEN in a broad field encompassing classical and quantum computing [479].

In 2023, Japan's third superconducting QPU with 64 qubits from RIKEN was installed at Osaka University, through a partnership including Osaka University, RIKEN, AIST, the Superconducting ICT Laboratory at NICT, AWS, Fujitsu, NTT, QuEL and QunaSys. It has been available in the cloud since December 2023.

Japan is also developing its enabling technologies industry with the aim, like China, the EU and the USA, to be as self-reliant as possible. And this includes software as well [480].

At the international scale, Japan is partnering with the US (IBM, Google, in 2026 as part of the DoE Genesis program), the EU (letter of intent signed in May 2025, and with the Q-Neko program, and the Q-Neko/EuroHPC partnership) and within Europe, with QDNL in the Netherlands (MOU signed in May 2025).

1.11.3 Singapore

The state of **Singapore** is known for its economic and entrepreneurial dynamism. It is a strategic digital hub in South-East Asia.

Its quantum ecosystem is built around the **National University of Singapore** (NUS), **Nanyang Technological University** (NTU), **Singapore University of Technology and Design** and the **Agency for Science, Technology and Research** (A*STAR), mapped in Figure 57.

Research

Within NUS, quantum research was consolidated in 2007 in the **Center for Quantum Technologies** (CQT) with an annual funding of about $15M. It was created thanks to some real political leadership, coming from the then Defense Minister of Singapore.

Artur Ekert says he was persuaded to join Singapore in 2000 by Tony Tan, who was then the country's defense minister. He had met him at a conference where his visionary speech, for a politician, had impressed him. In 2005, Tony Tan took charge of the sovereign wealth fund Singapore Investment Corporation and then Singapore's National Research Foundation. He was at the origin of the strategy of targeted investment in cutting-edge research fields, which today we call deep tech. This Tony Tan then became the President of Singapore between 2011 and 2017. The CQT was launched in 2007. The story is told a book published by Tony Tan in 2017 [481]. His personal credo: to be successful, you need to attract the right people, original ideas and then funding. Too often, this happens through funding.

CQT is vested in both quantum computing (cold atoms in Berge Englert's group, photons and superconductors in Dimitris Angelakis'group, trapped ions in Dzmitry Matsukevich's group), quantum cryptography (Kwek Leong Chuan's group) and quantum metrology (notably atomic clocks in Murray Barrett's group). The CQT was led from its inception until July 2020 by Artur Ekert. Since then, it is run by José Ignacio Latorre. It brings together about twenty teams representing 22 permanent researchers, 60 research fellows and 60 PhD students, covering the four usual fields of quantum technologies.

This represents a total of 350 people as of November 2025. Of the 22 research supervisors, about a quarter are Singaporeans who have usually done a thesis abroad. Singapore is doing well to attract talented foreigners and to ensure that they settle permanently in this country of close to six million people.

Quantum communication is one Singapore specialty. Since 2016, CQT has been associated with the telecom company **Singtel** and the NUS for the deployment of QKD on optical fibers with repeaters.

At the end of 2019, a team from NTU developed a 3 mm-sided chip capable of integrating a CV-QKD, a continuous variable quantum key-based encryption system [482].

In 2015, Singapore launched its Galassia-2U nanosatellite, created by CQT and used to experiment encrypted QKD-based quantum communications. Galassia is integrated into a two-unit CubeSat format (two cubes on top of each other, see Figure 56).

It weighs only 3.4 Kg in total. It was sent to space with 5 other satellites including the telecommunications satellite TeLEOS-1 (400 kg) at the end of 2015 by an Indian launcher.

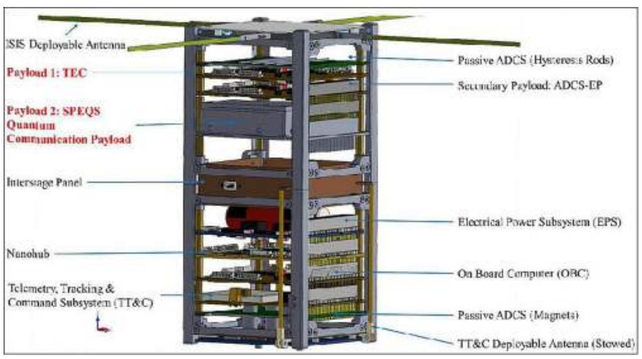


Figure 56: A two-unit CubeSat format QKD satellite. Source: Satellite missions Galassia

The lifetime of this type of satellite is six months. These experiments led to the creation of the S-Fifteen Space Systems. However, solutions have yet to be found to ensure that these satellites last longer in their low orbit and do not contribute even more to low orbit pollution.

Government funding

In May 2022, as part of its **Quantum Engineering Programme** (QEP) started in 2018, Singapore launched three national platforms with a total funding of $23.5M for 3.5 years with a pooling of the resources and skills from CQT at NUS and NTU Singapore, A*STAR's Institute of High Performance Computing (IHPC) and the National Supercomputing Centre (NSCC).

- The **National Quantum Computing Hub** develops quantum computing capabilities and use cases for the industry.
- The **National Quantum-Safe Network** conducts trials of quantum-safe communication technologies for critical infrastructure.
- The **National Quantum Fabless Foundry** supports microfabrication techniques for quantum devices and enabling technologies. Hosted at A*STAR's Institute of Materials Research and Engineering (IMRE), it manages the micro and nanofabrication of quantum devices and related enabling technologies. This complements the Quantum Science and Engineering Centre (QSec) launched in December 2021 by NTU to design and manufacture various quantum chips using classical semiconductor manufacturing technologies.

In May 2024, Singapore announced an investment of $222M into its National Quantum Strategy to advance the growing quantum industry. It was somewhat connected to the launch of the Green Data Centre (DC) Roadmap which supports the deployment of green technologies for data centers, particularly in AI. The funding will feed the CQT, a new National Quantum Sensor Programme, a new National Quantum Processor Initiative (NQPI) for the buildup of a Singapore quantum processor. In July 2024, the Monetary Authority of Singapore launched the FSTI Quantum Track as part of Financial Sector Technology & Innovation Scheme (FSTI 3.0), with a funding of $74M to support innovation in quantum and AI, the share allocated to quantum being not precise.

In March 2025, Singapore launched a $24.5M HPC-quantum initiative, HQCC 1.0 focusing on talent and expertise development, particularly on middleware and hybrid algorithms development (quantum processors rely on classical control and are commonly embedded in hybrid workflows, though not every quantum algorithm is intrinsically hybrid). It is led by Singapore's National Quantum Office and implemented at the National Quantum Computing Hub (NQCH), on top of the infrastructure of the National Supercomputing Centre (NSCC) and the A*STAR Institute of High Performance Computing and the CQT.

In February 2026, Singapore announced its "Research, Innovation and Enterprise 2030" plan which supports emerging technologies including quantum. The plan is to get $37B of funding until 2030, targeting research, innovation, and industry vendors. This plan benefits from a 32% increase compared to the previous $28B plan. The technology split is not available. So, you may end-up seeing $37B in analysts public investments inventory in a couple months.

International

Singapore is partnering with many countries in the quantum space, including new projects with Germany in communication and cybersecurity announced in February 2025. The German side of this partnership is the Dieter Schwarz Foundation and the Technical University of Munich (TUM). The Singapore side is NUS and CQT.

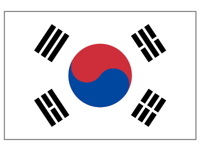
The French and Singaporean quantum ecosystems are also well connected. The CQT welcomes several researchers from France, including **Steven Touzard**, **Miklos Santha** and **Christian Miniatura**. Since January 2023, **Alexia Auffèves** is leading **MajuLab**, the joint CNRS-NTU/CQT/NUS research laboratory on quantum science since January 2023. NUS is also partnering with the **Thales TRT** research lab based at the CQT, in security and sensing [483]. **Sondra Lab** is another Franco-Singapore lab with CentraleSupelec, ONERA, NUS and DSO which is working in the fields of electromagnetism and signal processing applied to radar. At last, Quobly also established a subsidiary in Singapore and is collaborating with A*STAR on chip characterization.

Other academic/industry partnerships were announced with Quandela (May 2025), Keysight (December 2025), AWS (March 2023), IQM and VTT (August 2022), and Xanadu (December 2025). Singapore's Digital and Intelligence Service (DIS) and Defence Science and Technology Agency (DSTA) are also partnering with IBM as announced in July 2026, and for the development of quantum optimization solutions for logistics. It is quite ambitious from the technical standpoint.

Quantum industry

Several startups emerged from CQT like **Entropica Labs** (quantum algorithms), **Horizon Quantum Computing (**software), **Innovatus Q (**hybrid algorithms), **S-Fifteen Instruments (**quantum cryptography) and **SpeQtral** (satellite QKD). In 2024, Horizon Quantum made the acquisition of a Rigetti Novera 9-qubit QPU. Various research institutions including A*STAR launched a partnership with Quantinuum for the development of hybrid classical-quantum solutions and with the acquisition of a Helios system.

1.11.4 South Korea



South Korea quantum investments are all over the place in national universities, with companies like SK Telecom, and with an emerging quantum startups ecosystem.

Viewed from the bridge, the country seems mainly focused on quantum communications due to SK Telecoms's past investment in IDQ. But its national quantum strategy announced in 2023 is now multifold, and now includes quantum computing.

Research

When you look at the South Korean academic landscape, it is as diverse as in most developed countries. Pukyong National University has a Department of Scientific Computing, Computer Engineering and artificial intelligence and a Nanomaterials Lab, and works on superconducting qubits. Sung Kyun Kwan University's Center for quantum materials and superconductivity works on skyrmions. Korea University of Science and Technology in Daejeon has a Quantum defects lab and a Quantum Information and Quantum Sensing lab, and work on quantum batteries and on quantum algorithms. Seoul National University's Quantum Information and Quantum Computing Lab works on silicon qubits, boson sampling and cryoelectronics. Gyeongsang National University's department of physics works on quantum information theory. Yonsei University's Institute of Quantum Information Technology is partnering since 2022 with IBM on quantum software. Ewha Womans University works on quantum annealing software.

KAIST (Korea Advanced Institute of Science and Technology) has a quantum computing lab, a quantum optics and quantum information lab, and quantum device lab working on quantum computing and communications, and the OQT (Opto-Quantumics) lab which is partnering with many western QPU vendors like QuEra, Pasqal and Xanadu.

In January 2023, Xanadu announced this partnership with the aim to create quantum algorithms for designing next-generation lithium-ion batteries, a rather long-term goal given it indeed sits in the FTQC realm [485]. In September 2023, this partnership was extended "*to train and educate South Korea's future quantum workforce*".

Finally, KRISS (Korea Research Institute of Standards and Science) opened in January 2024 an institute specialized in developing military quantum computing and sensing technology, located in Daejeon.

Government funding

In June 2023, the South Korea government announced an ambitious quantum investment plan funded with $2.6B over 12 years including industry investments by Samsung, SK Telecom and Hyundai [486]. However, the numbers do not add up very well since the South Korean government allocated only $136M in quantum for 2025 [487].

Like most developed countries in the world, it wants a greater piece of the upcoming quantum technologies market, from 1.8% to 7.3%. It also plans to extend PhD training from 300 to 2,000 and workforce extension from 953 to 10,000, and to grow the number of startups from 9 to 100 as well as the number of technology companies making use of quantum technologies. Korea will start to invest about $300M in quantum computing with focusing on cold atoms and superconducting qubits. Their goal is to reach 1,000 physical qubits. They plan to create their own dedicated fab.

The plan is structured around 9 goals including the creation of a 5-qubit QPU (with any type of qubit except superconducting qubits), a 50-qubit QPU by 2026 and 1,000 qubits by 2032, a bit late in the game, develop core technologies for QPUs, develop a quantum simulator for new material, exploring quantum computing applications, create quantum sensors, core quantum communication and Internet technologies, develop inter-

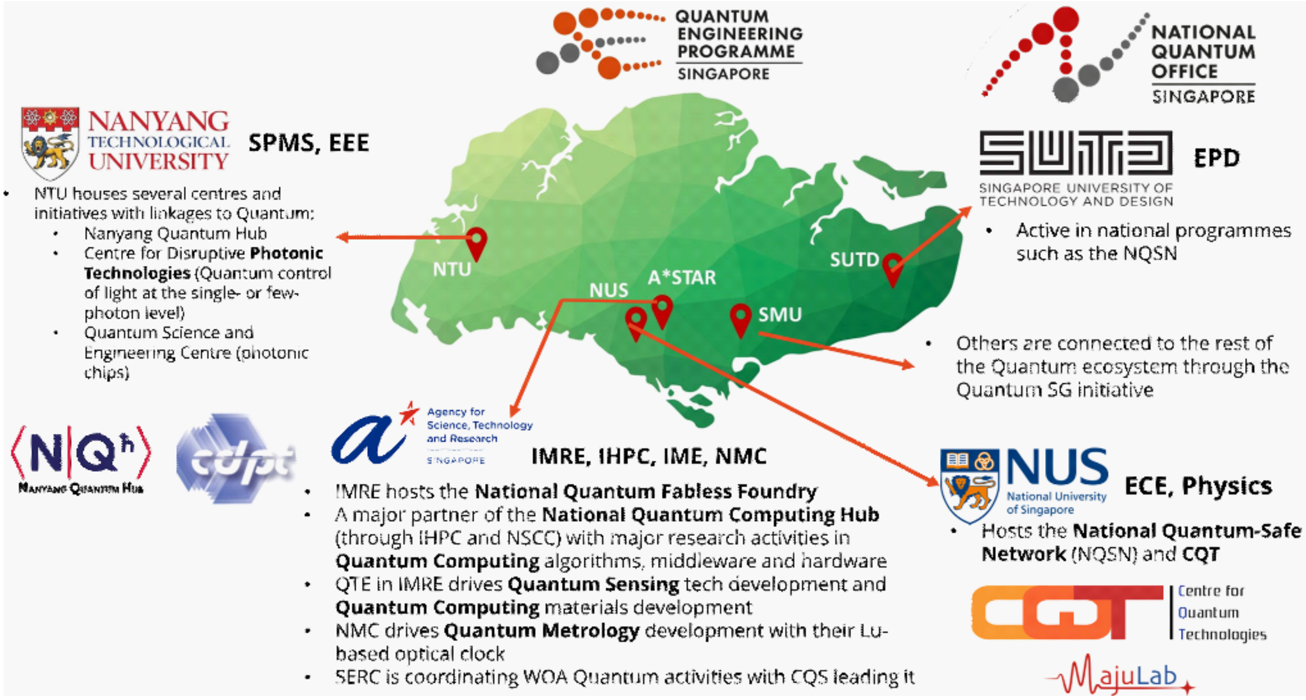


Figure 57: Singapore quantum ecosystem in 2023. Adapted from [484].

national partnerships including one with NIST, build the quantum ecosystem and the talent force.

Of course, the USA is part of the game with their generic country level partnership template signed with so many developed countries, particularly in Europe [488].

Quantum industry

SK Telecom made inroads in quantum telecommunications [489]. They are partnering with Florida Atlantic University. They also took a controlling share of the Swiss startup ID Quantique in 2016. It is also partner since 2017 with Nokia in the QKD field as well as with Deutsche Telekom with whom they have established a "Quantum Alliance" to create secure telecommunications. SK Telecom has deployed a QKD network in the backbone of its network in the city of Sejong on two links of 38 and 50 km respectively [490]. They also announced a memorandum of understanding with the government of Luxembourg in October 2023, in relation to their LuxQCI satellite QKD project led by SES Astra.

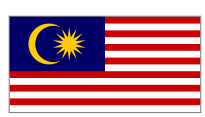
Samsung is also investing in QKD and cryptography. They integrated a quantum random number generator in a dedicated version of a Galaxy smartphone for the Korean market in April 2020, with a component from ID Quantique. A new version was launched in April 2021.

Hyundai invested in IonQ and is teaming up with them to build quantum algorithms for the simulation of batteries chemistry. These algorithms require fault-tolerant quantum computing resources that will be available only in the distant future. As a result, IonQ signed a partnership with the country to develop its regional quantum computing ecosystem [491].

The South Korea startup ecosystem is still rather small with **First Quantum** (quantum circuits optimization software), **CryptoLab** (HEaaN homomorphic encryption), **QSIMPLUS** (software emulator for quantum communication and optical network design) and **Qunova Computing** (quantum software).

In August 2024, the Ministry of Science and ICT announced the creation of the **Quantum Frontier Strategy Council**, a committee for connecting the public and industry. Its 23 members are representatives from IDQ Korea, SDT, LG Electronics and Pharos iBio, a potential user of quantum computing for drug design.

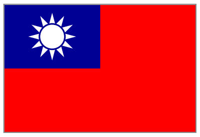
1.11.5 Malaysia



In 2024, Malaysia created its Quantum Intelligence Center with SDT (South Korea) and Anyon Technologies (Singapore).

The center was launched with MIMOS Berhad (Malaysia's national applied research and development centre). This quantum computing R&D center will work on AI, security, and biotechnology. Construction began in 2024, with an opening planned in 2026. In December 2025, a team of Malaysians laid out a proposal for the development of the country's quantum ecosystem [492].

1.11.6 Taiwan



Taiwan is a land of digital technology, most famously known for its leadership position in semiconductors manufacturing (TSMC, UMC).

It is also leading with consumer and professional electronics manufacturing (Foxconn, Quanta), and all sorts of technology products (personal computers with Asus and Acer, PC boards with Gigabyte and MSI, Internet of things, etc).

It was logical in these conditions that the country became interested in quantum technologies.

Public research is organized through various organizations: the NTU and NTHU Universities with various principal investigators in all typical quantum technologies domains, National Cheng Kung University (NCKU), Academia Sinica, and ITRI (Industrial Technology Research Institute) which is an equivalent to KAIST in South Korea and AIST in Japan. I used to see some of their research output in the consumer electronics domain when I was visiting the CES in Las Vegas from 2006 until 2020.

In December 2020, Taiwan launched a quantum plan with a funding of $282M over 5 years. It consolidated its investments in the Southern Campus of Academia Sinica, the national academy of Taiwan, in Tainan. They planned to create a Quantum Technology R&D center between 2022 and 2024. In April 2022, the government announced as part of this plan the selection of 17 research teams in universities and the hiring of 72 project directors and 24 IT companies. They are looking at ways to improve quantum hardware and software and to leverage, if possible, their semiconductor industry. The country will probably play a key role in the future in the manufacturing and integration of large scale quantum computers, a bit like what they do today in the chips and PC industry.

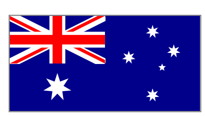
The selected projects cover silicon, cold atom and superconducting qubits and their manufacturing, cryo-CMOS (particularly at ITRI and NTU), QKD light sources, QRNG sources, multinode quantum networks, VQE algorithms and error mitigation, GKP error correction codes, financial applications, and at last, code verification and compilation (Link, to translate from Chinese). On top of that, Hon Hai (FoxConn) created a Quantum Computing Research Center in January 2021 that is focused on quantum information science (algorithms for their own use, mostly for solving manufacturing optimization problems), on trapped ion qubits, on enabling technologies (which they could manufacture) and on cybersecurity.

I visited Taiwan in September 2023 and met various researchers at NTU, NTHU and ITRI and from their national quantum initiative team, on top of Foxconn (Min-Hsiu Hsieh). I was welcomed by Ching-Ray Chang who is a professor at NTU and the president of TAQCIT, the Taiwan Association of Quantum Computing and Information Technology. Also, let's mention that IBM established a foothold in the country to help it adopt quantum technologies, with an IBM Quantum Lab at NTU, who is accessing online QPU from IBM's Poughkeepsie datacenter in the USA.

In January 2024, the team of Chii Dong Chen from Academia Sinica unveiled a 5-qubit superconducting QPU with single-qubit gates fidelities of 99.9%. The project was run in collaboration with UCSB and the University of Wisconsin-Madison, which probably helped them design the cryoCMOS and a parametric amplifier that was used in the QPU [493]. Another team at Academia Sinica is working on fluxonium qubits and seemingly tested only one qubit [494]. Meanwhile, IQM delivered in 2025 a Spark 5-qubit QPU to Taiwan's Semiconductor Research Institute's (TSRI). In 2026, Academia Sinica unveiled a 20-qubit system using frequency-tunable couplers with an excellent T_1 coherence time of 530 μs, particularly given it seems to be based on a transmon [495, 496].

In April 2026, Taiwan's government created the Quantum Industry Technology Promotion Office (QITPO). The technology focus will be in advanced connector technologies, semiconductor manufacturing and system integration, and along the lines of international collaboration, industrial support and ecosystem platform. A couple examples are with the Quobly (France) and its partnership on software with Hon Hai / FoxConn announced in May 2026 and SEEQC (USA) with ITRI (Industrial Technology Research Institute) for the creation of a dedicated manufacturing line for its SFQ superconducting control chips announced in December 2025.

1.11.7 Australia



Australia is a key APAC (Asia-Pacific) player in quantum technologies both at the academic and startup levels.

Its academic research stars are Michelle Simmons, Andrew S. Dzurak and Andrea Morello (UNSW), Andrew G. White, Gerard Milburn and Jacqui Romero (University of Queensland) and Gavin Brennen (Macquarie University) to name a few.

Research

Key universities are University of Sydney, University of Technology of Sydney, UNSW and Macquarie University (all in New South Wales), University of Queensland, and the University of Melbourne.

In December 2020, Australia launched the **Sydney Quantum Academy,** a joint effort from Macquarie University, UNSW Sydney, the University of Sydney and UTS.

It consolidates training offerings implemented by the partner Universities for undergraduates, PhDs plus some fellowship's programs.

Government funding

The Australian National Innovation and Science Agenda announced in 2015 included 24 initiatives and $820M in funding over 4 years, of which $19M were allocated to the Center for Quantum Computation and Communication Technology (**CQC2T**) over 5 years in quantum computing [497]. **CQC2T** was created in February 2019 at UNSW, headed by Michelle Simmons. The goal was to create an electron spin quantum computer. With federal funding of AUS $33.7M, it brought together a community of 200 researchers [498]. An investment fund of the Ministry of Defence, the **Australian Next Generation Technologies Fund** allocated $730M in 2016 to 9 areas including one on quantum technologies over 10 years [499]. Assuming that these funds were distributed evenly among the 9 initiatives, this gives us $8M of additional funds per year on quantum technologies for military uses, including sensing.

In May 2020, CSIRO published a quantum opportunity white paper [500, 501]. Their (fairly optimistic) ambition was to turn it into a $4B industry creating 16,000 jobs by 2040 out of a projected global total revenue of $86B, an amount which will probably land in the unkept promises realm. The projected breakdown was $2.5B and 10,000 jobs for computing, $900M and 3000 jobs for sensing and $800M and 3000 jobs for telecommunications. The goals? To define a coordinated strategy, to finance research and business creation, to train talents and to create a coherent industrial value chain. A relatively new point in such a plan was to explore the ethical, social and environmental issues that could be raised by quantum technologies. The subject has been growing in importance since 2020. They also address the question of the supply chain of key components and materials for quantum technologies.

In November 2021, the Australian government allocated an additional US $80M to its quantum efforts, particularly for supporting the commercialization, adoption and use of quantum technologies and create new jobs. It includes US $51M for the creation of a "quantum commercialization hub" with the task to build strategic partnerships with "like-minded countries" to sell Australia's quantum technologies, starting with the usual Commonwealth country partners and the USA.

As a follow-up from the famous AUKUS nuclear submarine deal with the USA (at the expense of a predating classical submarine deal with France) announced in September 2021, Australia cemented a global quantum partnership with the USA in November 2021, covering in a fuzzy way the exchange of quantum knowledge and skills. The University of Sydney is already part of an international consortium integrated in the US IARPA **LogiQ** program. In terms of international partnerships, the country is also associated with the University of Singapore for the creation of quantum telecommunication satellites and with Japan.

In June 2023, Australia formally launched its national quantum strategy. Like every country, the goal is to become a global and leading player in quantum technologies. The plan funding was $670M spread over 7 years. It contains investments in research, workforce development, standards, quantum infrastructure and materials, and a trusted and inclusive ecosystem [502].

On a regional basis, the **Queensland Quantum and Advanced Technologies Strategy** announced in 2023 is a multipronged plan of $62M [503]. It covers various typical aspects (education, research, fabs), with some original items like funding application research in quantum biology through the ARC Centre of Excellence in Quantum Biotechnology and on decarbonation.

Late April 2024, Australia rocked the quantum world with its controversial US $617M investment in **PsiQuantum** to fund its installation in Brisbane, which we already described in detail when covering the company in the photonic qubit part of this book. It seems that a significant part of this investment covered the infrastructure of the upcoming Brisbane PsiQuantum R&D center, particularly given it may need up to 100 MW of electrical power to fuel its huge cryogenic facility supporting a hundred cabinets cooled at about 4K.

Nearly simultaneously, the Australian government awarded the University of Sydney with AUS $18.4M to fund the creation of **Quantum Australia**, a national center of innovation and collaboration on quantum technologies, to drive the expansion of the country's quantum industry and ecosystem [504]. The stakeholders of this center are the same behind the creation of the Sydney Quantum Academy (SQA).

In May 2024, the University of Sydney Nano Institute got a $10M grant from US's IARPA and the US Army Research Office to work on quantum error correction methods for a duration of four years in a project led by Stephen Bartlett, the director of the Nano Institute [505]. This work will be done in collaboration with IBM researchers. Barlett's documented work is along mixing error mitigation and correction [506], color codes [507], and magic states distillation optimization [508].

In June 2024, the Australian government launched the AUS $36M Critical Technologies Challenge Program (CTCP) to "*drive private sector demand*" and "*de-risk adoption of quantum technology across the economy*" [509]. The application goals are to optimize the performance, sustainability, and security of energy networks to help the transition to Net Zero, improve medical imaging and medical sensors to support diagnosis, treatment of disease and monitoring activities inside the human body, enhance communication with autonomous systems in varying environments and optimize efficiency and reduce the impact of resource exploration, extraction, and mineral processing. The selected projects will be funded in two stages: one with $500K for feasibility studies, and one with $5M to develop demonstrators and proof of concepts.

In its 2024 report [510], the Australian government upgraded its 2020 economic forecast, planning for the creation of a AUS $6B (US $4B) economy, and the creation of 20K jobs by 2045. As if history repeated itself, these are nearly the same numbers and always "in 20 years". It also indicates that the country invested AUS $236M (US $155M) in quantum since May 2023.

Quantum Industry

On the entrepreneurial side, there are various startups in the field of quantum technologies with **Quintessence-Labs** (QKD optical keys), **QuantX Labs** (sapphire-based cryogenic clocks), **Silicon Quantum Computing** (silicon qubits), **Diraq** (silicon qubits), **Quantum Brilliance** (2019) on top of which should be added **Archer** and their carbon electron spins qubits. Rigetti is there thanks to the acquisition of QxBranch in 2019, a US company with Australian roots. Also, **Q-CTRL** is known for its quantum error suppression offering.

In September 2022, the Tech Council formed the **Australian Quantum Alliance** to consolidate its quantum tech industry.

The country is also prolific in public-private partnership projects associating Australia with other countries [511].

In 2017, the University of New South Wales (UNSW), the Commonwealth Bank of Australia and Telstra provided $52M in funding for the creation of a silicon quantum bit processor.

Also, **EQUS** (ARC Centre of Excellence for Engineered Quantum Systems) is a national quantum sensing research center. It partners with Microsoft, Moglabs and Lockheed Martin, among others.

In July 2022, Google announced new partnerships with Australian universities including UNSW and the University of Sydney.

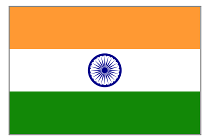
It extends what they already do with US universities, mostly for the development of quantum algorithms on Sycamore QPUs.

In December 2022, the **Australian Quantum Software Network** (AQSN) was created to consolidate the quantum software R&D ecosystem, with 110 participants from nine universities and several local startups (SQC, Quantum Brilliance and Diraq in hardware, and two in software). It also has extended partnerships with other countries ecosystems in the USA (Google Quantum AI), Japan (Okinawa Institute of Science and Technology), Finland (Aalto University).

A little later, the government signed a 7-year procurement agreement with IBM related to various digital needs, which was beautified with some quantum computing nuggets [512].

In July 2024, **Microsoft** announced the closure of its Research lab in Australia that was working noticeably on cryo-CMOS electronics and topological qubits [513]. You can't have it all!

1.11.8 India



Some preeminent Indian scientists made critical contributions to the field of quantum physics.

The first one, **Chandrasekhara Venkata Raman** (1888-1970), was awarded the Nobel Prize in Physics in 1930 for the discovery of the Raman effect, in which light scatters off a material, resulting in a change in the light's wavelength and energy.

Satyendra Nath Bose (1894-1974) is known for his work leading to the development of Bose-Einstein statistics and the theory of the Bose-Einstein condensate and to the naming as bosons for the particles that obey Bose-Einstein statistics.

Research

Academic research in India is centered around a couple preeminent public labs:

- **MeitY** (their Ministry of Electronics and Information Technology) which launched in August 2021 the Quantum Computer Simulator (QSim) toolkit that was created by IISC Bangalore, IIT Roorkee and C-DAC (Centre for Development of Advanced Computing). This software emulator of gate-based quantum code must not be confused with Qsim from Qsimulate and Google. C-DAC announced some technology partnerships with Rigetti and QuantWare in 2025.

- The **Quantum Computing Applications Lab** (QCAL) launched by the Ministry of Electronics and Information Technology (MeitY) with AWS provides access to quantum computing resources (CPU, software tools, training) to researchers and developers.

- The **Quantum Measurement and Control Laboratory** (QuMaC) works on superconducting qubits. It is working on creating a home-made QPU with 24 qubits in 3 years and 100 in 5 years (as of 2024) and in partnership with the service company Tata.

- The **Indian Institute of Technology** (IIT) Madras and the **Harish-Chandra Research Institute**

(HRI) in Allahabad conduct research in quantum computing. It also partners with IBM [514].

- The **Indian Institute of Science** (IISc) in Bangalore works on quantum information sciences.

- **IIIT-Delhi** (Indraprastha Institute of Information Technology Delhi) created its Center for Quantum Technologies (CQT) in 2022, consolidating R&D in all quantum technologies, a bit like Singapore's CQT. It is starting with 9 principal investigators [515].

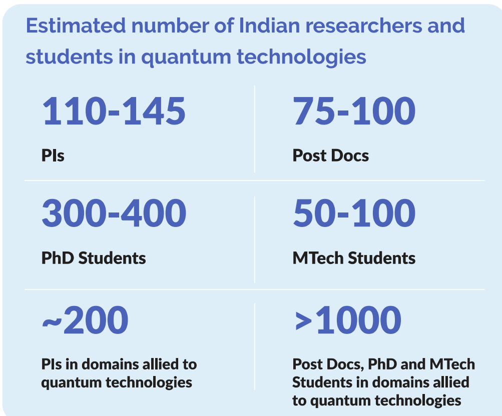


Figure 58: The size of India's quantum academic ecosystem seems quite small. Source: [516].

- The **Indian Army** launched its Quantum Research Laboratory in January 2022. Later, in May 2025, DRDO (Defence Research and Development Organisation) opened the Quantum Technology Research Centre (QTRC) in Delhi. It will experiment secure communications, timekeeping, sensing and advanced materials.

Surprisingly for a country with more inhabitants than China, its quantum academic size is quite modest. It is even smaller than the ones from France, the UK or Germany (Figure 58). However, there are 82,110 students in quantum technologies relevant fields in the country, more than in China. It seems to include broad fields like electronics, electrical and photonics engineering.

Government funding

At the beginning of 2020, India launched an investment plan in quantum technologies, the **NM-QTA** (National Mission on Quantum Technologies & Applications). This plan is well funded as a proportion of the country's GDP, with $1.12B over 5 years, at the same level as the American National Quantum Initiative Act of 2018 or the European Flagship launched the same year [517]. It had the goal, among others, to build a 50-qubit quantum computer, which is yet to be seen as of mid-2025.

The plan covered the usual suspects: quantum computing, quantum telecommunications and quantum sensing with the creation of related hubs, a bit like in the UK. Ironically, the CEOs of IBM, Google and Microsoft who are strong investors in quantum computing are all from India (Arvind Krishna, Sundar Pichai and Satya Nadella)! The Indian 'National Quantum Mission' plan had an eye on China and wanted to turn the country into a quantum leader, particularly in computing, telecommunications, and cryptography (Figure 59).

In 2023, the quantum plan received an additional funding of $732M covering the 2023-2030 period with one goal being to create 50 to 1,000 qubits QPUs and 2,000 km of quantum communication networks. The plan also deals with satellite QKD and quantum sensing [518]. The country also wants to be "quantum safe", meaning, in a position to resist the potential cybersecurity threat created by future quantum computers. It is still hard to understand what came out of the initial $1.12B investment. India is willing to expand its scientific collaboration with Russia, which is currently a pariah in the Western world [519].

In February 2022, **Avasant** (an US consulting firm with a branch in India) and **NASSCOM** (the Indian software and IT service trade association) published a report on the opportunities of quantum technologies for India [520]. It contained several nuggets like a quantum tech potential providing between $152B and $310B cumulative value to the Indian economy by 2030 with a maturity inflection point positioned in 2027. It reuses similar forecasts at the worldwide scale from McKinsey et BCG. They expect that 10K logical qubits will be available by 2030 (100 would be so nice…). But they forecast a moderate workforce impact of 25K to 30K people in 2030. Also, India plans to develop a quantum computer with about 50 qubits by 2026. They position the quantum Internet to be related to FTQC in their roadmap for 2027 and beyond, which makes some sense for QPU interconnect. The document also shows the key role of the large Indian IT services companies in the adoption of quantum computing. As an example, in September 2021, Infosys Cobalt was partnering with AWS Braket to explore the business potential of quantum computing.

In 2024, India's Department of Science and Technology (DST) launched I-HUB QTF, a Technology Innovation Hub (TIH) dedicated to quantum technology.

NITI Aayog, an Indian government think tank, published in March 2025 a report on the state of quantum technologies in India with a look at national security. It rang the alarm bell on the risk of being overcome by other countries [521]. The implementation of the Indian quantum plan seems to be experiencing administrative failures and delays. The country does not yet seem to be producing scientific advances or startups in critical numbers. The report contains a naively optimistic view of Microsoft's Majorana qubits.

Another report was then published by the government in April 2025 [522]. It highlighted a field that is not talked about much, quantum materials. He also makes an interesting analysis of scientific publications and patents per domain and on the raw material supply chain. Their data on investment in startups is inaccurate, apparently extracted from an unreliable database, Tracxn, a US database of startups. They have $1.33B of private funding in the Netherlands (I was at less than €100M in mid-2025!), the never-ending fake public funding for China ($15B) and Germany (€4.9B). Their inventory of the best-funded quantum startups in the world contains Quantum Metric, a US classical software company.

Figure 59: There is even a book touting India's quest for quantum leadership, *ala* "Startup Nation", the famous book describing the Israeli startup ecosystem [523]. The author works with IBM.

In September 2025, the Karnataka state in the South-West part of India launched the plan to create a Quantum City in its capital Bengaluru. The goal is to create a $20B quantum economy by 2035. The initial funding is of about $113M (INR 1,000 crore). They will start to fund 150 PhD fellowships and plan to support the creation of over 100 startups and 200,000 jobs. The quantum fairy tale force is strong in this program. In October 2025, the Maharashtra state, the largest in India with Mumbai as its capital, announced the creation of a quantum corridor along with IonQ and Scandia AB from Sweden, a construction company specialized in smart cities.

In December 2025, the government published a quantum roadmap [524] with some ambitious goals: place India in the top 3 quantum powers by 2035, create ten quantum startups, each with over $100M in revenue, capture over 50% of the global quantum software and services market, plans deployments in various verticals (army, energy, logistics, transportation, finance, and healthcare). Half of the lead contributors from this report work for IBM in India. It recycles the quantum materials proposal from the April 2025 paper but unfortunately, doesn't formulate any scientific and engineering challenge.

Early in 2026, the Andhra Pradesh government launched a challenge for their scientists: obtain a "Nobel Prize in Quantum Science" (which is the Nobel in physics prize) and obtain a reward of about $10M. They may be better off funding some actual research with that amount. Or is the announcement a way to save this money given the probability that such Nobel lands there by magic? The goal is to motivate and inspire young talents. If they are ready to wait 20 to 40 years to get the Nobel!

Quantum industry

Among other things, the Indian plan has also accelerated the creation of startups in India, some being king in overselling their technology advances. This is the case of **QPI** and their projects of a one million silicon qubits and hybrid processor. Many of their new startups are multi-domains, such as:

- **QRLAB** (2020, India) who is a contract research, education and consulting company focused on quantum computing. They develop quantum inspired software, QML and work on quantum Internet and cryptography.
- **Qulabs.ai** (2017, India) which builds quantum networks and has some expertise in QML in finance and for new drug discovery. That's quite broad in scope! Their QuAcademy facilitates students training.
- **Fractal Analytics** (2000, India, $685M) is an AI/data analytics company and a unicorn. It is creating an in-house quantum computing lab.

The **Chatterjee Group** (TCG) is a private equity firm with assets in petrochemicals, pharmaceuticals, biotech, financial services, real estate and various other industry sectors. Its TCG CREST (Centres for Research and Education in Science and Technology) contains the Centre for Quantum Engineering, Research and Education (CQuERE) which is planning to build a quantum computer with, as a starter, 4 superconducting qubits by 2027 with a first investment of $1.2M to be extended to $12M [525]. They started with importing a Bluefors dilution refrigerator and to work on the qubit designs with the **Tata** Institute for Fundamental Research in Mumbai. They also have a partnership with Qilimanjaro.

Indian IT services company have also started to launch various ventures in quantum technologies:

- **Infosys** has a Quantum Living Labs that helps customers develop quantum computing proofs of concepts in various verticals.
- **Tata Institute of Fundamental Research** (TIFR) created a superconducting 5-qubit QPU with a 7-qubit version in the making. In August 2024, it

ended up being a 6-qubit QPU codeveloped with DRDO Young Scientists Laboratory for Quantum Technologies (DYSL-QT), using a ring-resonator design created at TIFR in 2020 [526].

- **Wipro** partners with Tel Aviv University.
- **Tech Mahindra** partners with IQM since December 2022 to deploy various use cases of quantum computing [527].
- **HCL Technologies** works with Sydney Quantum Academy in various student programs.
- **Mphasis** partners with IIT Madras to fund startups and train the workforce. It launched a partnership with Classiq in June 2024.

IBM sold a 156-qubit Heron QPU to India. The deal involves TCS (Tata Consultancy Services). The QPU will be installed in the Quantum Valley Tech Park in Amaravati, the capital of Andhra Pradesh state, with the financial participation of the latter.

1.12 Quantum ecosystems around the world key takeaways

- The quantum startup scene saw its peak company creation in 2018. A small number of startups like D-Wave, IonQ, Rigetti, PsiQuantum and Xanadu collected about 70% of the worldwide quantum startup funding. The investors FOMO (fear of missing out) and the "winner takes all" syndromes explain this situation. But startup funding in the quantum space is faring relatively well considering the long-term business prospects, particularly with the surge of SPACs and IPOs for companies like D-Wave, IonQ, Rigetti, Infleqtion, Xanadu, and Pasqal. Quantinuum also did its IPO in 2026, without a SPAC. We describe these funding mechanisms in the book. We show the dominance of the USA in the private sector investment, which adds the best funded startups in the world to large established companies significant investments, topped by IBM's recent $10B 5-year plan announced in June 2026.
- Most developed countries now have national quantum plans, often with a strong emphasis on quantum computing. Cross-country investment comparisons require explicit accounting rules because announced totals can mix incremental and pre-existing funding, different time windows, public and private investment, and supranational programs such as European Union funding. Meaningful comparisons therefore require a common normalization period, source date and inclusion rule. These plans generally support fundamental research, industrial ecosystems and workforce development, while governments also support suppliers through procurement programs.
- China's public investment in quantum technologies is difficult to compare with that of the United States or Europe because program scope, disclosure practices and accounting conventions differ. Published estimates such as $15B to $25B can't be compared directly with US or European investments unless they use the same time window and include the same categories of spending. The book therefore treats such country totals as ranges or source-dependent estimates rather than precise figures.
- Europe and the United States are among the largest investors in quantum science and technology, but their relative ranking depends on the accounting perimeter, time window and treatment of national, supranational and private investment. Europe has substantial public investment through both the European Union and member states, while the United States has major private investment from large technology companies and venture-backed startups.
- Many countries have placed quantum technologies in the critical field of "digital sovereignty" like if they were some sort of nuclear weapon equivalent. Many countries launched specific defense related quantum investment plans and competitions like DARPA's QBI, and equivalent programs in France, Germany and elsewhere.
- Each country has its own strengths and specialties although most of them invest in all the fields of quantum technologies (computing, telecoms/cryptography and sensing).
- Some analysts are wondering whether we'll get soon into a quantum winter, like the ones that affected artificial intelligence in the 1970s and the 1990s. One way to avoid it is to limit overpromises coming both from the academic and industry vendor spaces. The intensity of the hype is very strong in this industry, but so far, it has resisted the bubble burst effect.

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This **Quantum ecosystems around the world** section contains 527 bibliographical references and notes containing at least 7,393 pages.

2 Corporate adoption

Out of the many audiences of this book interested in quantum technologies are companies that may wonder what to do about it. They are the target of a deluge of information, hype, imperatives, complexity and uncertainty. This comes in addition to other technological waves to assimilate such as generative artificial intelligence and its disruptive large language models and agentic AI tools, cybersecurity with or without quantum computing threats, cryptocurrencies and other blockchain technologies, not to mention cloud deployments and their perpetual classical business applications backlog. This part of the book provides some guidance for end users on the way to navigate the quantum world.

What should corporations do with quantum technologies as they are encouraged by influential analysts to jump now on the bandwagon or to lose market share against their competitors and become obsolete? The pressure is indeed significant, BCG and McKinsey being the most vocal analyst shops on this. The pressure is based on a push-pull approach: one is about fear with the threat of quantum computing-based cryptanalysis which endangers cybersecurity, the other corresponding to the potential applications of quantum computers, sensors and communications, the attention being mainly focused on computing. It drives a typical FOMO phenomenon ("fear of missing out").

2.1 Understand the imperative

Large customers and their IT, digital transformation, innovation and R&D departments are exposed to a continuous stream of industry analyst and vendor pitches creating a sense of urgency for the adoption of quantum computing. It comes for example from **Capgemini** [528, 529], **McKinsey** [530], **Bain** [531], **Deloitte** [532], **Accenture** [533], **EY** [534], **Arthur D. Little** [535], from **Pathstone**, a financial advisor company [536] or the CEO of **SAP** [537] and the **World Economic Forum** [538]. It can take the form of a survey commissioned by a vendor, like **Zapata Computing** [539] (which ceased operations in October 2024 and returned to operations in September 2025 as Zapata Quantum, after a debt restructuring) or **QuEra** [540]. Some misstate the role of quantum computing in cybersecurity, or oversell the practicality of existing quantum computers [541].

A new incentive to drive the attention of corporate users consists of publishing end-user organization rankings per quantum readiness level and vertical market. It drives competition between players in the same sector [542].

BCG started to promote in 2021 the "*it's not an if but a when*" mantra about the advent of practical quantum computing, whereas it should be said with much more caution, given the many scientific and technological uncertainties that are still lingering in the fields of quantum physics, hardware, and algorithms [543]. We could make a half-joke using Heisenberg's uncertainty principle and complementary variables analogies. If there's no "if", it means that its complementary variable "when" is highly uncertain and spread over an infinite time scale. To reduce the uncertainty on the "when", you'd need to accept that there is an "if", and understand its decomposition.

Reading guide

This part of the book on Corporate adoption is quite small with only 6 pages. Hopefully, other parts of the book are directly touching on the topic.

- The key part is the Applications section of the software part of the book which describes market predictions, provides some tools to analyze use cases and case studies, and inventories these for a wealth of vertical markets.
- A large portion of the book is for your education on the basics of quantum physics and quantum technologies.
- It also describes in detail the technology of over 850 vendors, some with great details like with the Tier 1 quantum computing providers (IBM, IQM, Quantinuum, QuEra, Pasqal, Quandela, AQT, etc.).
- The Quantum Engineering part also contains a section on the economics of quantum technologies which is highly relevant for end-user corporations.
- The Quantum Ecosystems in the World section explains the dynamics of the quantum ecosystems, their funding mechanisms, the role of governments, dual use, geopolitics, and the like.

Late 2022, according to BCG, 50% of corporate customers did spend $1M to create a quantum computing proof of concept, mainly in the finance and energy verticals. Well, it did not correspond to 50% of all corporate

	Overall Score	Workforce Quantum Team and Resources	Research and Development Quantum Research and Patents	Adoption Quantum POCs and Collaborations
Boehringer Ingelheim	1	1	1	1
Cleveland Clinic	2	2	3	2
Merck Group	2	2	3	2
Roche	3	3	2	5
Moderna	3	4	5	1
Amgen	4	4	5	3
Astex Pharmaceuticals	5	5	6	9
Sanofi	5	5	9	6
Novo Nordisk Foundation	5	5	6	9
Pfizer	6	6	7	11
J&J	7	8	4	7

Figure 60: The 2025 Quantum Innovation Index from The Quantum Insider and HorizonX Consulting creates a ranking between end-user organizations in vertical sectors, here in life sciences. It creates incentives to invest or invest more in quantum computing. Source: [542].

customers, but to 50% of the corporate customers who started to evaluate quantum computing.

Four years later, the McKinsey April 2026 monitor provided a better order of magnitude of what corporate involvement actually costs [530]. Out of the more than 300 organizations already working with quantum vendors, 162 were analyzed. The sample is selected for engagement, so the percentages below describe those 162 respondents and not corporate users in general, and McKinsey does not publish the response rate, respondent roles or field dates. A third of them supposedly allocated more than $10M to quantum computing in 2025, 7% spent over $50M and the largest single budget reached $200M. Most of that money went into use case exploration and internal teams rather than into hardware acquisition. European companies made up 43% of the analyzed customers, ahead of the USA at 29% and Asia at 22%, and 72% of the activity took place in privately owned companies. These are the numbers of the most engaged players. A reasonable watching brief is one to two orders of magnitude cheaper with one to three full time equivalents (FTE), some cloud QPU credits and the participation to a couple of conferences per year.

Consultants and analysts touted an imperative to build an IP strategy coupled to a discourse of a "*winner takes all the value*" for end-user customers, due to assumed scarce resources, both in talent pools and in quantum computers availability. This doesn't make a lot of sense given the maturity of the sector and what happened in other digital domains [544].

They upped the ante in 2023 in writing that "*Quantum computing is becoming business ready*" [545]. The given business use case examples? As shown in Figure 61, three applications in the financial sector, including two that were tested with at most 7 and 4 qubits. Ideal systems of that size are readily simulated classically, so these experiments do not show any computational or economic quantum advantage. The third, related to a CACIB fallen angel detection application running on a Pasqal analog quantum simulator looked promising but did not deliver a quantum advantage in any dimension, given the suited hardware won't be available for a couple of years.

None of the three papers said what BCG said it said. The IBM and IRIS Analytics credit card fraud detection experiment [546] ran a quantum support vector machine on 3 to 7 qubits, entirely on state vector and qasm simulators, the authors stating explicitly that the real hardware implementation would come in a separate manuscript. The data set was shrunk from 2.4 million real transactions to about 2,500 records to fit the quantum part. The best mixed quantum-classical ensemble reached 81.0% accuracy against 80.0% for an optimized XGBoost, a one point difference. The 5% reduction in false negatives advertised by BCG is nowhere in the paper: the only figure of that magnitude is the 5.2% to 5.5% disagreement rate between the classical and the quantum classifiers, which is the complementarity the authors were measuring, not a performance gain.

The Goldman Sachs, QC Ware and IonQ amplitude estimation experiment [547] did not outperform any classical computer. It used just 4 qubits to estimate the inner product of randomly chosen four-dimensional unit vectors, with circuits reaching 92 two-qubit gates and a depth of 62, for a mean additive error of 0.0138. The authors wrote that this was a proof of concept of the scaling advantage of amplitude estimation, that their own classical sampling baseline ran on the quantum computer, and that significant quantum computer improvements are needed before any practical advantage, which was not quantified.

The CACIB fallen angel detection [548] was the most substantial of the three cases but it still fell short. QUBOs of up to 60 qubits were solved on a Pasqal analog neutral atom QPU, the best classification being obtained at 50 qubits with a precision of 27.9% against 28.0% for the bank's 1,200 tree random forest at the same 83% recall. The quantum model matched and in fact marginally trailed the classical benchmark, at equal recall and without a preregistered success criterion or reported uncertainty on the precision figures. BCG's "96% fewer initial classifiers" claim was correct, 50 learners against 1,200, and the interpretability gain was real, but the 29% precision that does beat the benchmark was obtained with 90 learners on a quantum-inspired tensor network optimizer, and ran on a classical computer. The authors extrapolated that around 1,800 atom qubits would be needed for the QPU version to pass the classical threshold.

Three years later, is quantum computing really business ready? As we have seen in the quantum application section from this book, most identified applications are small-scale NISQ case studies without any quantum advantage [549], some NISQ applications with a quantum advantage but which are irrelevant in the industry since it's about simulating some physics phenomenon not related to industry problems like in chemistry or material design, and finally, use cases made for future FTQC systems.

We have also seen the push from McKinsey in the market predictions mentions in the quantum computing applications part of this book. Their 2026 monitor revised their estimate upwards, to $1.3T to $2.7T of economic value created worldwide by 2035, against up to $2T by 2035 in their previous editions [530]. These are value-at-stake numbers obtained by attributing a share of industry-wide cost savings and revenue increases to quantum computing, not quantum vendor revenue. The very same report sizes the quantum computing market itself at $43B to $71B by 2035 and at slightly over $1B in 2025, which is three orders of magnitude below the headline number.

It takes some time and effort to check all of that and cut through the hype. The wave of quantum technologies is unique in that it is even more unpredictable and difficult to grasp than other digital technologies waves. This large book is the largest I have ever published, which demonstrates this indirectly. It is more than twice as large as my largest book on artificial intelligence, which had 742 pages [550]. Also, the discrepancy between the real technology readiness and what industry vendors and analysts say about it is huge.

Proof check your writings!

In the paper "Quantum Computing for Business Leaders" published in 2022 in Harvard Business Review authored by Jonathan Ruane, Andrew McAfee (both at the MIT Sloan Management School) and William D. Oliver (MIT Lincoln Lab, a top scientist in the field of superconducting qubits) [551], you could read the following: "*Quantum computing will enable businesses to better optimize investment strategies, **improve encryption**, discover products, and much more*".

Improve encryption? How is such an error possible? I happen to have met William Oliver at the MIT in April 2025. He said that I was right to pinpoint that! The error was coming from an uncontrolled edit of the paper by the publisher!

This is a good warning for any specialist in the quantum science and technology space. Always check what is made of your talks and writing before it is published, particularly in interviews. Intermediates (HBR reviewers, journalists, analysts) will always try to simplify your complicated explanation. The risk that an error creeps into the result is high enough that the check is always worth doing.

And yet, the topic is worth the attention, particularly in certain key verticals such as finance, healthcare, energy utilities, and transportation.

Despite all the required care that is mandated here, there are several reasons why, still, corporations should evaluate quantum technologies:

- They need to build some understanding of the trend, the buzz and the technology. The pay-off of being

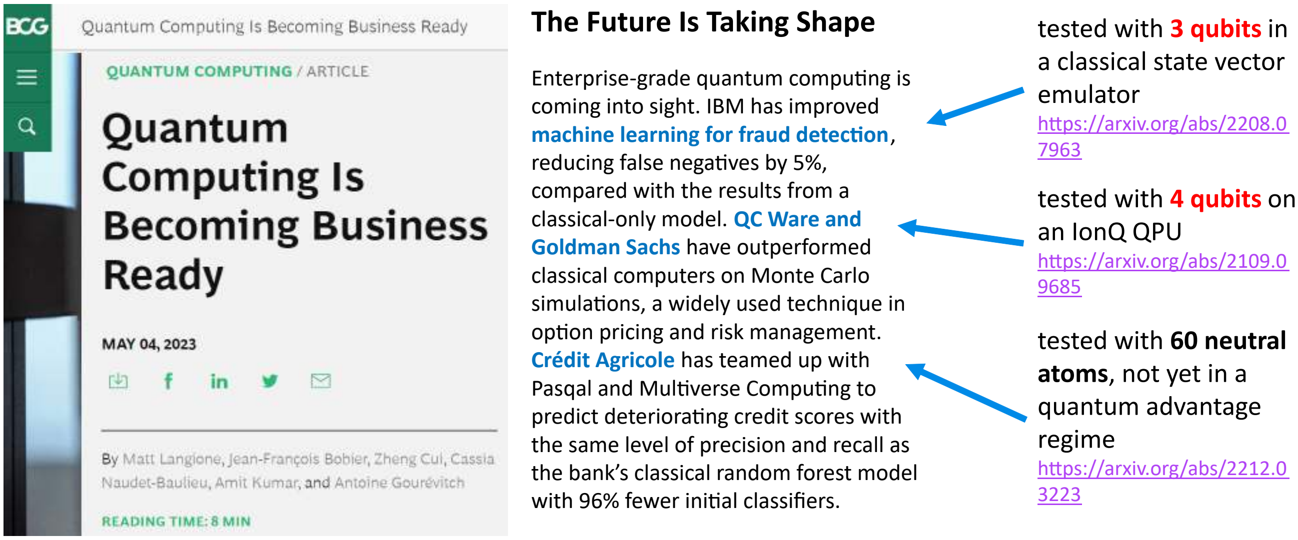

Figure 61: When the BCG was overpromising in 2023 the business readiness of quantum computing. Their more recent publications are more cautious. Source: [545].

Four questions that sort out most quantum use cases

- **What is the classical baseline?** Not the vendor's own implementation on a laptop but the best available classical solver, properly tuned, on comparable hardware. Most published quantum advantage case studies compare against a weak baseline.
- **How many qubits, what circuit depth, and on what machine?** A simulator run and a QPU run are not the same claim. Define what the pilot is meant to establish: control integration, workflow, device characterization, or application benchmarking. Then judge the demonstrated fidelity, circuit depth and the business decision it actually supports, rather than the qubit count alone.
- **What is the exponent of the speedup?** Under the surface code assumptions used by Babbush et al., the space-time volume of a logical Toffoli gate sits roughly ten orders of magnitude above that of a CMOS NAND gate, which is an illustrative estimate for one code, one physical error rate and one hardware generation, not a universal constant [552]. With overheads of that order, quadratic speedups like Grover search and amplitude estimation are unlikely to pay off on early fault-tolerant machines, but the conclusion depends on end-to-end resources estimates, data encoding, output accuracy and the classical comparable, and must be recomputed algorithm by algorithm [553].
- **How much data goes in and out?** In the standard access model, loading a large classical data set into a quantum computer costs at least as much time as reading it classically, which is a serious limitation for most big data and machine learning pitches. Ask which input model is assumed, and what state preparation costs, since the conclusion changes when the data are generated in the computation rather than loaded [553].

educated is a better ability to discuss with industry vendors.

- Building a small workforce around quantum technologies is an excellent way to attract high-level and skilled talent with a lot of potential. Corporations are competing with startups and IT vendors and need to find ways to attract PhD level algorithms developers, mathematicians and even physicists, e.g. when they are in the chemical and drug businesses.
- Investing in quantum technologies is not just about quantum computing but deals with other technologies like quantum sensing and quantum communications which are somewhat more mature than quantum computing.
- As the quantum threat on current public key cryptography is also part of the buzz, it has to be factored in. Even though the timeline for a cryptographically relevant quantum computer remains uncertain, store-now-decrypt-later exposure and long migration lead times are separate matters, and many legacy cryptographic infrastructures will need to be upgraded, pushed by standardization and, sometimes, government regulations.

- Working on quantum computing is an excellent way to revisit classical computing solutions. All the fuss on quantum computing potential benefits is creating a strong emulation with classical computing specialists, whether it works or not. As a matter of fact, classical algorithms are making a lot of progress in optimization, operations research, chemical simulations and machine learning.

To undertake this, here is a relatively simple and, all in all, fairly classic approach for corporations, which is laid out in a dozen points, some of which coming from the experience of major large companies (Figure 62).

2.2 Technology screening

You don't adopt any new technology after only reading some news clips. But your management may push you to look at the trend and understand it. This top-bottom approach is amplified by the strategy consultants and analysts who are ringing the alarm bell in the direction of "business decision makers", up to, if they can, CEO and executive boards.

The task is hardened with quantum computing because we are still in an intermediate exploratory phase where quantum computers are neither functional for industry use cases nor able to overcome the capabilities of classical computing systems.

- Of course, you start with looking at the various **use cases** and **case studies** of quantum technologies in a "top-to-bottom" approach and what added value it could potentially bring to a business either in the present or the future. This book can help you with its broad inventory of business application case studies or use cases, where I propose a methodology to classify these case studies in a structured way, sorting out the future and the present. Topics are organized by vertical market. If your market is not there, it doesn't necessarily mean that you shouldn't care. If you have a developer and/or mathematical background, you can have a look at what can be done at a lower level with quantum algorithms by looking at the algorithms part of this book.
- Understand the multiple facets of **quantum computing advantage** (speedups, results quality, energy consumption) and fact-check them. Learn why interesting case studies start to show up for fundamental physics simulation research and do not yet correspond to the needs of applied research in Corporations. Look at their potential to convert into useful industry applications.
- Then, you still need to understand the **technological dimensions** of quantum computing and related telecommunications and cryptography matters. One thing is to understand what the state of the art is, how it is changing over time, what are the scientific and technology challenges. This technology screening must be done on a continuous basis. Things are changing fast in this domain with a mix of good and bad news.
- Don't miss the potential of **quantum sensing**. It may be significant in various industries where precision is mandated. Quantum sensing helps measure with greater precision nearly any physical dimension value: time, gravity/acceleration, magnetism, electromagnetic waves and the like.
- Learn how to **decode** analysts, research labs and vendors lingua, particularly in the field of overpromises. I provide a few examples in this book, about the fact that quantum computing is not a miracle solution that can speed up all computer processing. Learn some tricks to assess the real technology readiness level (TRL) of advertised quantum innovations. Also, understand that quantum computing is not adapted for big data applications. One important aspect here is the timing of innovations given the analysis timeframe is quite large, sometimes accounted in decades. You can now use modern LLM-based chatbots to fact-check any new paper, the most simple question to ask being: "*is this paper demonstrating some quantum advantage?*", which you can complement with asking how many qubits were used, what was the circuit size, or what would be the space and time resource estimates in the case of future FTQC applications.
- Use **independent validation** as a filter. Vendor roadmaps are marketing documents. DARPA's Quantum Benchmarking Initiative is the most useful public filter to date, although they have not documented their industry vendor actual evaluations. It evaluates whether any approach can reach utility-scale operation, meaning a computational value exceeding its cost, by 2033. In November 2025, 11 of the 18 Stage A participants moved to the year-long Stage B, and the names that did not advance are as informative as those that did. Stage C decisions were expected by the end of 2026.
- Attend **ecosystem events** such as the QC Ware Q2B conference, Le Lab Quantique meet-ups, or quantum business conferences that are now organized all around the world. Also prefer those events where at least some scientists are delivering keynotes.
- Use **LLMs** like Claude Pro or ChatGPT to fact check news announcements. For example, you can ask them to check the claims, find the scientific references and the consistency between the provided references and the marketing announcement. You can also ask for comparisons with other state of the art systems, how the announcement is providing a practical improvements to end-users, whether the solution delivers a real quantum advantage and of which nature. You can also dig a little more with asking for comparisons between papers from multiple vendors.

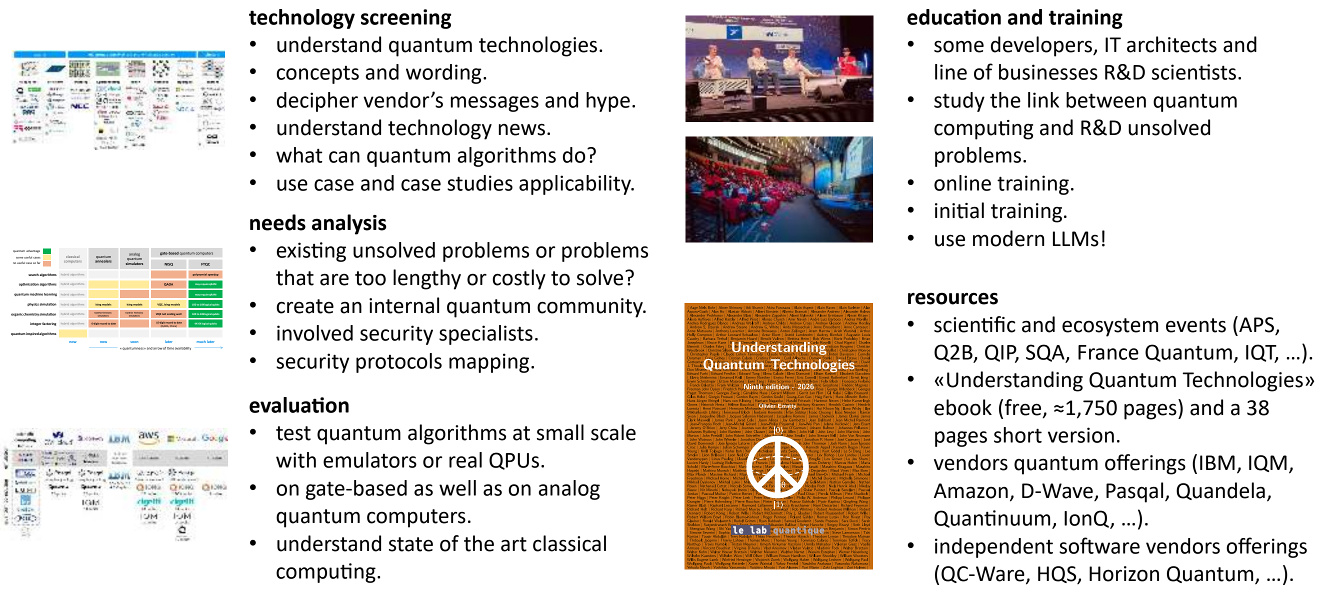

Figure 62: Simple method to adopt quantum technologies. © Olivier Ezratty, 2022-2026.

2.3 Needs analysis

Many vendors will push you to look at your needs even before describing what is really possible to do today. This is one reasonable approach, but it should not be implemented independently from a real technology assessment.

- Identify **intractable problems** in the company's applications and business needs portfolio. This is a question that developers and data scientists can sometimes answer. For example, these can be complex optimization problems involving the orchestration of many resources. You must first look at your current existing or potential usage of high-performance classical computing. What if scenarios can also be built on the power quantum computing can bring. For example, what if you could solve such or such complex business problems that was never addressed?

- Then, back to technology, look at the related (prospective) use case or (retrospective) case studies, existing algorithms that are supposed to solve these problems. Understand the **scope of existing cases**: are they small scale pilot projects or deployable applications? Most of the time, they are in the first category with no quantum advantage at all. Then, ask vendors and independent specialists on the size and characteristics of the quantum computers and/or hybrid systems associating a quantum computer and classical computers that would solve the business problem with a real-world size.

- Create an **internal community** of engineers and business specialists interested in quantum technologies, as Goldman Sachs, JPMorgan Chase, BMW, Volkswagen, Airbus, EDF, and TotalEnergies have done, for example. It can be fed with presentations from research labs and vendors and sharing the understanding engineers have about quantum technologies, identify key questions to ask, brainstorm about business needs where quantum technologies could help.

- Launch a mapping of **security protocols** threatened by quantum computers and the infamous Shor integer factoring algorithm. What data intercepted now could still have some value for an attacker in the future? If present data has some value more than 5 to 10 years from now, you may need to start worrying and looking at QKD and PQC solutions or even revisit the way you implement applications in the cloud. Many service vendors are proposing methodologies and services to run security audits [554]. The regulatory calendar is now a better planning basis than Q-day guesswork. NIST finalized three PQC standards in August 2024, ML-KEM, ML-DSA and SLH-DSA, selected HQC as a code-based backup key encapsulation mechanism in March 2025 and submitted the FALCON-based FN-DSA draft in August 2025. NIST IR 8547 proposes deprecating RSA-2048 and ECC P-256 after 2030 and disallowing them after 2035. The NSA CNSA 2.0 suite requires quantum resistant cryptography for new national security systems acquisitions from 2027. The EU coordinated implementation roadmap published in June 2025 asks member states for national plans by the end of 2026, high-risk use cases migrated by the end of 2030 and the remaining systems by the end of 2035. On the threat side, resource estimates keep moving the wrong way: factoring a 2,048-bit RSA key was estimated in 2019 at 20 million noisy qubits and 8 hours, and in 2025 at less than a million noisy qubits and less than a week, under the same physical assumptions of 0.1% gate error rate and a 1 μs surface code cycle time [555]. This is still two to three orders of magnitude above any existing machine, but it is a 20-fold move in six years, and it went unnoticed by most corporate security teams. It is similar with cold atoms and trapped-ions when you consider similar computing time estimates.

- Look at what your **peer companies** and those from your own ecosystem are doing with quantum technologies. Some may be vocal, like in the financial sector, some less. But there's now no lack of industry events where this topic is discussed (Figure 60). The McKinsey April 2026 quantum technology monitor did show that European companies were leading their USA peers in evaluating quantum computing in a couple of verticals like the automotive and energy sectors, while lagging behind in financial services and life sciences (Figure 63).

2.4 Training

Training a core team of people will be necessary to launch the two previous steps.

- Train a **few developers** in quantum programming. This can be done by letting people interested in the matter spend time on it on their own. The information and tools are available online with IBM, Microsoft, Eviden, D-Wave and many other places. Open-source cloud-based tools are already there. The youngest and most curious developers will probably be the ones who will best adapt to quantum computing programming paradigms, which are difficult to assimilate when being trained for classical programming. These must also have a stronger mathematical background than the average developer. Analog electronics engineers can also be drawn to quantum programming, given the analog nature of the underlying processes like interferences between qubits.
- Understand the links between **quantum computing and artificial intelligence**. Quantum machine learning is a new sub-discipline of quantum algorithms that deserves to be explored and understood. You may discover that classical machine learning and deep learning will fare well for a long time. Quantum computing won't solve the energy consumption uptick generated by mass-usage generative AI.
- The small hidden advertising in this book is here: I propose a **one to three days customized training** for corporate engineers, IT people, R&D and innovation specialists who are curious to discover the whereabouts of quantum computing and other quantum technologies.

2.5 Evaluation

- Talk to the many quantum computing **independent software vendors**, particularly with those who are specialized in your vertical.
- Test **some algorithms** in the cloud with gate-based quantum computers (IBM, AWS and Microsoft cloud, OVHcloud, etc) or quantum annealers (D-Wave) or with emulators (Quirk, Eviden, IBM, Microsoft, AWS, Google). The available case studies are discussed in this book in the section on algorithms and applications by market.
- Do not hesitate to test algorithms on D-Wave **quantum annealers** despite their relatively poor image among universal quantum computer purists. D-Wave advertises these systems for complex optimization problems in domains such as biology and finance. Treat this as a vendor claim: ask for the problem class, the tuned classical baseline, the solution quality, the runtime, the scaling, and any independent validation. But challenge D-Wave on where the advantage comes from. Their hybrid solver is a black box combining classical optimizers and their annealer, and the respective roles of each are not evident.
- Keep an eye on **analog quantum simulations** which may become useful for solving several classes of problems: quantum materials simulations, combinatorial and decision problems, and some machine learning problems. Pasqal (France) and QuEra (USA) are delivering interesting hardware here, with systems of 100 to 256 cold atom qubits. Both companies target a quantum advantage on analog simulation workloads, which remains a stated objective rather than a demonstrated result, and should be judged against a named problem, a tuned classical baseline and an independent benchmark.
- Learn about the various **benchmarking techniques** that are being proposed to compare quantum computing and classical solutions, particularly the ones that are positioned at the application level. Look for example at [556] which proposes a way to evaluate quantum computing solutions on optimization problems with keeping an eye on the existing capabilities of classical computing systems.
- Beware of the **classical baseline trap**. Several headline quantum advantage claims evaporated as soon as somebody wrote a decent classical algorithm. For ground state energy estimation in quantum chemistry, no exponential advantage has been established for the molecular systems and accuracy targets studied so far, given the classical baselines available [557]. And Grover's quadratic speedup can disappear end-to-end once the oracle is written out explicitly and its internal structure is exploited classically, which depends on the oracle implementation and on the query cost [558]. Ask every vendor which classical method they compared against, who tuned it, and on what hardware it was using.
- Ask for **end-to-end resource estimates**, not gate counts. What matters for a future FTQC application is the complete pipeline including state preparation,

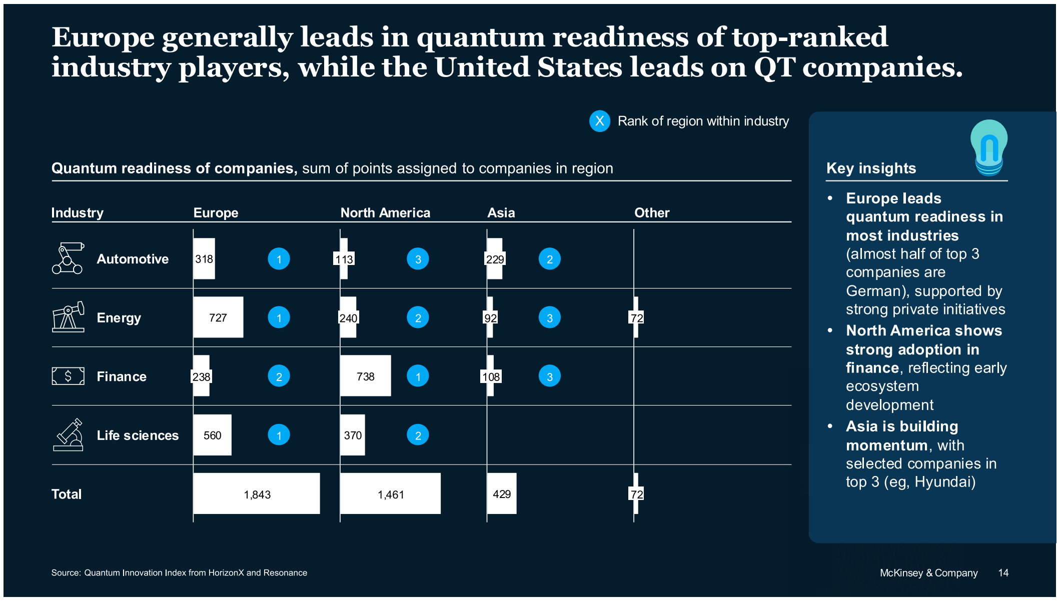

Figure 63: A McKinsey April 2026 quantum technology monitor survey did show that European companies are leading their USA peers in evaluating quantum computing in the automotive and energy verticals, while lagging in financial services and life sciences. Source: [530].

data loading, error correction overhead and readout, which is precisely where most published speedups vanish. The Dalzell et al. survey is the reference inventory of these end-to-end complexities across chemistry, optimization, finance and machine learning [559].

- Prefer **proportionate monitoring** to either extreme. Adoption takes time, so a watching brief, some skills development and a few stage-gated experiments are reasonable, and each gate should have an explicit criterion for stopping. This is not contradictory with avoiding the current hype. In the worst case, you may discover ways to improve your classical applications classically.

Congratulations, you have saved yourself an overpriced McKinsey or equivalent study!

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3 Quantum technologies and society

We leave the fields of quantum physics, hardware, mathematics and algorithms to focus here on the links between quantum technologies and society. We are still at the very beginning of this technological revolution. What will follow is a mixture of observations and interpolations. Like with any digital technology wave, the quantum wave will affect society and industries at several levels, some of which can be anticipated, others less easily.

This part deals with connecting the potential impact of quantum computing with regards to mankind ambitions, the role of science fiction in the buildup of quantum imaginary, the way in which religions and spiritual movements may embed quantum whatever in their thinking, quantum technologies ethics, education and training in quantum computing, the role of gender balance in the field and, at last, quantum vendors marketing side effects and the never ending related hype.

3.1 Human ambition

Quantum computing is easily presented to the general public, or understood, as bringing a computational power defying imagination, going beyond anything that has been done so far. Quantum computing would thus be a way to circumvent the current sluggishness of Moore's law. It would make it possible to maintain some sort of eternal technology growth exponentiality. This may give the impression that, with quantum computing, mankind will have a tool providing infinite power and total control of information, in the line of many myths built around artificial intelligence and its ultimate mythical destiny, Artificial General Intelligence (AGI). In 2018, the futuristic American physicist and author **Michio Kaku** predicted that quantum computers will be the ultimate computers capable of surpassing human intelligence [560]. Here we go again with the Singularity!

Artificial intelligence and quantum computing seem to have no boundaries. They illustrate mankind's desire for power and omniscience, to shape matter if not minds, and to have the capacity to predict the future, making it almost deterministic.

Quantum physics has generated its share of questions about the nature of the world. The indeterminism of quantum state measurement has become that of life. Quantum entanglement has given rise to pseudo-scientific explanations of telekinesis and the transmission of thought. We will see in the following section how quantum medicine mixes nano and macro worlds in a fancy way. The mechanical nature or not of consciousness is at stake. For **epiphenomenalism** (definition), our consciousness is the result of physical phenomena in our body and brain but without direct external physical effects. Behavior is the result of the brain's action on the muscles. For **mysterianism**, the understanding of consciousness is beyond the reach of Man. As consciousness depends at a low-level on quantum phenomena which govern at a minimum the relations between atoms of the molecules of our brain, some people deduce a little quickly that quantum computing would allow AI to become general as in this debate! But these are at this stage fancy elucubrations.

Ambitious projects such as the European **Human Brain Project** led by Henri Markram aim to simulate the brain's behavior in a computer and thus to understand how it functions from start to finish, even if it is not possible to do so on even a molecular scale. In another fashion, the ability of quantum computers to simulate quantum phenomena has also sustained the idea that we are objects of a great simulation. An idea that ignores the constraints of dimensionality.

An exploration of the mysteries of quantum computing and of computational complexity theory allows us to put our feet back on the ground. Computational complexity theory describes various limits to the nature of problems that can be solved with quantum computing. Computational omnipotence does not exist. We will always be obliged to use various forms of reductionism to simulate the world, i.e. we will only be able to do it correctly at "macro" scales and not at "micro" or "nano" scales for matters related to computational magnitude [561]. A bit like predicting the weather thanks to the finite element method applicable to large portions of sky and not at the level of each water molecule.

The limits of the possible will be constantly pushed back, but they will stay there. Just like those of understanding the world which are confronted with the temporal and spatial limits of the Universe. We will probably not be able to know what was happening before the big bang nor to evaluate the existence of multiverse. Being unverifiable, these interpretations of the world can only remain speculations and not become real science. In the same way, our physical means will probably never make it possible to simulate our world in-extenso.

The macroscopic world introduces a lot of chaos and randomness into biology that no computer will ever be able to fully simulate and control. In a way, reductionism is an opposite to the notion of emergence [562]. Reductionism tries to apply some bottom-up lens to explain everything with the idea that a complex system can be fully understood by analyzing its constituent parts and their interactions. One typical example is trying to explain consciousness in terms of neurons and synapses. Emergence is often described as a top-down view, asking how complex systems made of simpler systems generate structure and order. Emergent behavior arises from the interactions of a system's parts and is generally not predictable, explainable or reducible from those parts taken alone. It creates unexpected novel features that cannot be deduced from the multiple system components. One example is the flocking behavior in birds, market dynamics in economics, or the emergence of life from non-living molecules.

Now, comparing the impact of the current AI wave and the future impact of quantum computing creates quite an uneven picture. Generative AI is a really revolutionary phenomenon transforming all knowledge related processes. How we learn, teach, research, develop software, write, compare, fact-check, all this can benefit from generative AI and LLMs in extraordinary ways that we didn't even discuss a couple editions of this book back in time, before 2022. This has been enabled by the Transformers model invented in 2017 and the sheer power increase of GPUs. Can quantum computing bring a similar revolution? I doubt it can with a similar impact. One first reason is that quantum computing won't be an end-user technology. It's not adapted to real-time computing and end-user interactions. It is for back-end computations a bit like weather forecasts has running for decades. Even when looking at chemical simulations, we know that quantum computing may someday extend the reach of simulations, but to a moderate extend. We'll extend our capabilities from a couple dozen orbitals to a couple hundred maximum. This will limit chemical simulations to rather small molecules and chemical reactions. Further down the road, quantum computing will help engineer multiple products and processes. It may be a revolution similar to computer aided design (CAD), that started in the early 1980s with software like CATIA. Even if Autodesk is more affordable, it is not yet a consumer product. Generating digital twins beyond the realm of classical computing may extend the reach and nature of what can be simulated for professionals. If it changes society, it will be way more indirect than the many consumer digital revolution society went through since the 1970s.

Figure 64: Source: A tale of quantum computers by Alexandru Gheorghiu (131 slides, dead link).

Finally, this quote from Scott Aaronson sums up the quest for quantum computing (Figure 64). This would be justified by the desire to counter those who say it is impossible. The rest is the icing on the cake [563–565]. This is obviously not to be taken at face value!

3.2 Science fiction

Science fiction and particularly movies and TV series have been great sources of inspiration and of delirium about the potential of quantum technologies [566] (Figure 65).

They have created an imaginary world made of teleportation (**Star Trek)**, supraliminal speed transportation (**Star Trek**, **Star Wars)**, various entanglements and miniaturization (**Ant Man** [567]), states superposition (**Coherence)**, parallel or multiverse worlds (**Fringe**, **Spiderman**, **Counterpart**, **Dark**, **Doctor Strange in the Multiverse of Madness**) or time travel (**Interstellar**, **Umbrella Academy**).

In some cases, the quantum term is used without any scientific connection to quantum physics, as in the 2013 James Bond **Quantum of Solace**, which is the smallest amount of comfort or peace needed to sustain a relationship or endure hardship.

Or it plays the role of the "MacGuffin", popularized by **Alfred Hitchcock,** the gizmo that the protagonists will look after from the beginning to the end of a movie without us really understanding what's inside or all about. This is the case with the **Ronin** movie. We find another one in the movie **Hard Kill** with Bruce Willis released in February 2020. Bad guys are trying to get the "code" that will activate a "quantum AI", but its contours are quite blurred. All we know is that it could eventually do some "good" things just like hacking an airliner to crash it. In short, it is a banal "dual" civilian-military solution. The bullets will rain down until the bad guy is dead without us really knowing what it's all about. However, a small 11-page guide tries to explain quantum physics to screenwriters [568]! It contains some language basics that can be used to create scripts. Another 2022 paper portrays the role of quantum computing in movies [569]. The usual scriptwriters do not hesitate to twist things, like **Christopher Nolan** with his elastic vision of time arrows in Interstellar or Tenet. Although not being about science fiction, Nolan's **Oppenheimer** released in 2023 showcases famous quantum scientists like Niels Bohr, Albert Einstein, Isidor Isaac Rabi and even Richard Feynman. Antman's **Quantumania** has a good name, way too many special effects and a bad script [570].

In March 2020, the eight-episode TV mini-series **Devs** was the first to be built around the prowess of a quantum computer capable of reconstructing the past up to Christ's crucifixion and predicting the future anywhere on Earth. With a video! Of course, this doesn't make any sense with today's technologies, but also with those of tomorrow. The stylized quantum computer features an elongated chandelier that looks like those from IBM

Figure 65: Quantum in science fiction movies and TV series.

and Google quantum computers. It is not connected to anything at all from the top, but that's okay! The whole thing is enclosed in a huge cube that is suspended and magnetically isolated. See this beautiful analysis of the series.

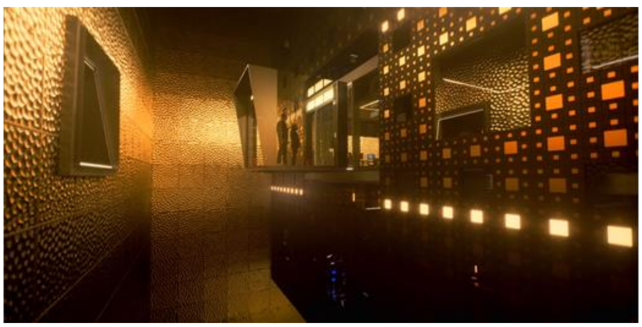

Figure 66: Dev's series quantum computer is sitting in a suspended huge cage.

It is a level of complexity problem and about getting the training data. Even assuming that the Universe is totally deterministic, it is impossible to capture the precise position of all particles in space to determine their past and future. And this comes up against one of the key principles of quantum physics, the Heisenberg uncertainty principle.

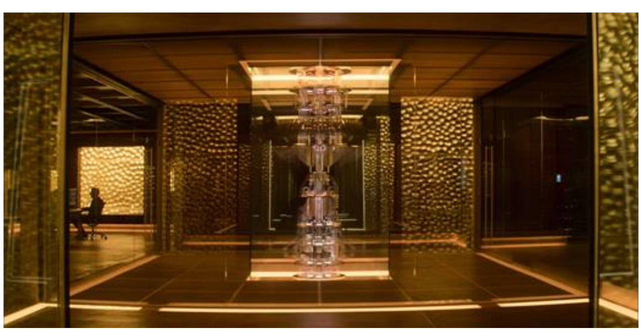

Figure 67: Dev's quantum computer is not well isolated…!

It states that the position and momentum of a particle cannot both be known with arbitrary precision. From this point on, everything falls into place to model and simulate the world with precision (Figure 67)!

In 2015, episode 11 of season 2 of **Scorpions** featured a quantum computer made of lasers and a large plexiglass cube capable of injecting ransomware into the US Federal Bank with just 4 qubits! Quite a feat! The heroes hack the computer dressed as cosmonauts and by redirecting the beam of one of the lasers towards the luminous cube (Figure 1024). We are far off from any realistic quantum computer here!

Figure 68: Scorpion's quantum computer could endanger banks with…4 qubits!

Quantum science being trendy, it is showcased in more TV series. In 2023, the **Bird Box** movie and Netflix series is playing with the nerves of the audience with unseen monsters which are quantum beings due to these being in an undefined state. **Hijack** episode 3 deals with quantum, a Schrödinger's cat and the nerves of the audience, with blank (or not blank) cartridges in a gun. **Black Mirror** season 6's first episode "Joan is awful" showcases a mysterious quantum computer that runs a virtual world. In the **1899** series that takes place in a Titanic like ocean liner, one episode showcases a quantum computer driving a giant simulation. **Heart of Stone** (Netflix) also showcases some omniscient quantum computer. The **Quantum Leap** series from NBC is about a time machine. And in 2024, Apple TV's **Dark Matter** started with a course on Schrödinger's cat, which is a thought experiment criticizing the naive extension of superposition to macroscopic objects, not a claim about actual cats and then some alternate world [571]. Quantum whatever can also be showcased in games, like in the **Quantum: Recharged** game launched by Atari in August 2023 [572]. Quantum computers are making appearances in **The Wandering Earth 2** 2023 movie and in **Origins**, the 2017 novel from Dan Brown.

Science-fiction is fine when it stays in the science-fiction realm. The problem starts when pseudo-researchers present science-fiction as if it was actual science instead of classifying it in a rough "hard science-fiction" category that is looking for some form of scientific credibility although being most of the time heavily far-fetched.

So, when some singularist tells you science and quantum physics could help resuscitate the dead using some fancy Dyson sphere and the like, just forget it or just have some fun [573, 574]. The same can be said about this work by two researchers from Germany and Georgia (the country) who published an amazing pre-print explaining that some quite advanced extra-terrestrial could have built a very powerful quantum computer out of a black hole and propose to detect it through SETI. It seems like an updated version of Dyson's sphere, a hypothetical spherical structure envisioned by Freeman Dyson in 1960 that would capture all energy from a star of galaxy and would be detectable in the infrared spectrum. The paper is weak on quantum engineering on how an ETI (extra-terrestrial intelligence) would control qubits within a black hole from a practical standpoint [575, 576]. This idea was also theoretically studied by Michele Reilly and Seth Lloyd in 2025 to assess the upper bounds of computation up to using a black hole [577].

Science fiction can even come from quantum startups, like this paper from a team at Terra Quantum dealing with quantum simulation worlds [578]. Other sci-fi scientists create weird concepts of a quantum computer being the size of a planet [579]. Meanwhile, some scientific papers describe protocols that reverse the dynamics of a quantum state, sometimes called quantum echoes, which the media take too literally as travel into the past [580].

These science-fiction dreams are far removed from the science of today and probably tomorrow. Their benefit is to create vocational aspirations. Dreaming drives innovation. Even when a young person discovers that science does not allow them to realize the scenarios of these fictions, they can discover the infinite field of applications of quantum physics and still be creative. If real-world quantum technologies are less impressive than Star Trek magic, it still can do wonders and bring new generations of researchers and innovators.

The use of quantum physics in Hollywood movies can also be used to convey other messages. As is often the case, they can agitate the potential of an external threat against which the USA should respond with strength. It would not be surprising to see fictions emerge in which the quantum threat comes from China. These movies often illustrate the myth of the hero who can get through adversity, also illustrating an alternative to the centralized powers of governments [581].

In novels, fiction can also have pedagogical virtues. This is to some extent the case of **The Key of Solomon,** a novel by Portuguese author José Rodrigues Dos Santos published in 2015. In an affair mixing espionage and quantum computing, the hero spends his time teaching quantum physics to the other protagonists of the story. This gets the message across in a didactic way and without overly taxing science.

The quantum sci-fi wave may still be short-lived with the advent of LLM based chatbots. They are reviving the fears around so-called artificial general intelligence (AGI) and its potential ability to create an artificial super-intelligence (ASI) that would take over the world and humankind [582].

3.3 Responsible quantum innovation

We deal here with the broad topic of responsible innovation and ethics pertaining to quantum technologies. We will draw some lessons from the current quantum hype and from what happened with artificial intelligence. We will also look at the various initiatives around the world to embed ethical concerns into design processes and regulations.

3.3.1 Quantum hype side effects

The "quantum hype" has been perceived as being problematic for a while, mostly by many scientists who fell that the field was oversold, particularly by industry vendors of all sizes [583–587]. It is hard to date the peak of the quantum hype ("Quipe" for some authors [588]) but at least, with following the money invested in startups, 2021-2022 were defining years with the large funding rounds of startups like PsiQuantum and the initial public offerings (IPOs) through SPACs (special purpose acquisition companies) of IonQ, Arqit, Rigetti and D-Wave. Governments have been fueling this hype with their large national, and sometimes nationalistic, quantum initiatives and their aspirations for some technological sovereignty.

While technology hypes have always existed and contributed to drive emulation, innovations, and a field attractiveness, it works well when scientists and vendors deliver progress and innovation on a continuous basis after a so-called peak of expectations [589, 590]. It fails with exaggerated overpromises and under deliveries that last too long. In that case, it could cut short research and innovation funding, creating some sort of quantum winter, although government investments are reducing the risk [591, 592].

In the "Mitigating the quantum hype" paper published in January 2022 [593], I drove some lessons from past technology hypes and investigated the current quantum hype and its specifics. I laid out the structural changes happening like the vendors hype profound and disruptive impact on the organization of fundamental research. I then made some proposals to mitigate the potential negative effects of the current quantum hype including recommendations on scientific communication to strengthen the trust in quantum science [594], vendor behavior improvements, benchmarking methodologies, public education and putting in place a responsible research and innovation approach. Four years later, the hype did not stop. It is still fueled again and again, showing an even larger discrepancy between the promoted and real capacities of quantum computers, particularly when some vendors and analysts claim that, here we are, quantum compting is ready for business applications. The incremental tens of billions of dollars poured by governments and investors into quantum computing are confused with its scientific and technology maturity. Unfortunately, it is not correlated. And the messages usually come from visible people who have a very poor knowledge of the real whereabouts of quantum computers. They tend to confuse the long term future and the present.

They are themselves exposed to the overselling from different players, both from industry vendors and some researchers. You've had this infamous 2023 **Time Magazine** piece and misleading cover touting "*This machine can solve problems that used to take years*", in your dreams only. The numerous paper mistakes were hopefully debunked by a UK Twitter account [595]. It contained a nice nugget: "*In November (2022), IBM unveiled its new 433-qubit Osprey chip - the world's most powerful quantum processor, the speed of which, if represented in traditional bits, would far exceed the total number of atoms in the known universe*". But since when are we measuring speed in bits?. Also, IBM Osprey has qubits that are so noisy that they are useless and IBM unplugged its QPU late 2023. Even John Preskill stated on Twitter as well: "*Quantum science and technology is exciting when discussed accurately and responsibly. It's disappointing that @TIME would publish such a misleading article*".

It was followed by the promotional tour of **Michio Kaku's** Quantum Supremacy book that is full of hyperboles and exaggerations on the potential impact of quantum computers. Up to saying that these computers will replace digital computers. Scott Aaronson published a harsh review of the book [596] but he didn't have the visibility of Michio Kaku who was invited in a TV show of 46 mn by Neil deGrasse Tyson [597]. That's the very best example of Brandolini's law at play according to which "*The amount of energy needed to refute bullshit is an order of magnitude bigger than that needed to produce it*".

It looks like we could turn this into an exponential law for the case of quantum computing [598]. Debunking is done in specialized media like Dulwich Quantum [599, 600] which rightfully "*hopes to encourage quantum computing experts to be more outspoken. If quantum hype and bullshit are left unchecked, they will eventually damage the reputation of the whole field, thus hurting everyone, including those who are trying to make legitimate progress*" while the nonsense is broadcasted more widely.

You can then wonder why Michio Kaku was invited to talk by Google in July 2023 [601]! But they are also hype contributors like with their paper on a traversable wormhole simulation [602, 603]. Whatever the limits of a simplistic mathematical simulation. See some Twitter explanations here and there by Nirmalya Kajuri and Sabine Hossenfelder, and by Peter Woit in This Week's Hype, November 2022. It was run on 9 noisy qubits on a machine with a power of 25 kW while it could be emulated with better precision on your own smartphone!

When you know the field a little, you can easily spot the mistakes. But how about regular corporate people? Let me showcase some typical mistakes fueling the hype:

Quantum and cryptography confusion like in a paper from Inquirer.net in 2023 which started with "*The NIST announced four quantum computing algorithms*" which is totally wrong [604]. The NIST proposed four post-quantum cryptography protocol standards which are classical, not quantum, and designed to resist attacks of (far in the) future quantum computers.

Quantum computing speed overselling is quite commonplace, by pundits who do not know that faster than infinite times may mean very long computing times. There are no known cases of quantum computing algorithm which could run instantaneously in a quantum advantage regime [605]. No quantum computers will solve complicated problems in milliseconds [606, 607]. It is not really made for real-time computing nor for embedded systems.

Case studies that are not implementable due to their resource requirements. Many papers like to present "actual uses" for near-term quantum computers with case studies targeting long-term FTQC systems that won't be available for at least a decade [608].

Corporate adoption. Another one makes economic predictions based on the assumption that the problem is the speed of adoption by (supposedly sluggish) corporate organizations when it is about delivering the technology itself. Analyst companies also tend to exaggerate the speed of progress in the industry [609].

Classical and quantum computing confusion. When some algorithms are promoted to be quantum ones when they are classical ones, like quantum inspired based classical solutions [610].

Quantum computing and big data, when the idea is conveyed that quantum computers will be suited to big data applications, and why not, for training and running large language models *ala* ChatGPT to save time and energy [611]. It will probably not do anything of the kind, as we show in this book on the part dedicated to quantum machine learning [612]. There are no known exponential speedups for these problems.

Crappy reports trying to explain quantum whatever to decision making people in too few pages. It ends up becoming so simplistic that the conveyed message may be entirely wrong [613–615].

Scientific communication is also fueling the hype. It can come from academic institutions communication or from scientific media who create fancy titles exaggerating the impact of new low TRL research work, turning some new quantum object research into a solution to scalable quantum computing [616, 617]. Interestingly, this hype and the debunking imperative have two consequences on scientific education. First, the hype can attract students in the field which is good news. Then, it drives professors and teachers to adapt their course to correct major misconceptions coming from the hype without discouraging the students [618].

Now, hopefully, there are some reasonable people with a voice. In 2024, **Chris Ferrie** published a small book on arXiv that debunks some of the myths on quantum computing [619]. **DARPA** published a series of benchmarks on actual needs showing the associated sheer resource requirements [620]. A team of scientists from labs and vendors made a reasonable assessment of the state of the art and roadmap also in 2024 (Figure 1026). Some short reports can also be of a good quality [621].

Another way to mitigate the quantum hype is to use humor, like with the anonymous developer who published a paper on "quantum disadvantage" simulating IBM's quantum utility on a Commodore 64 (which can't work for this purpose) [622] or some 2024 April's fool paper on "Is Winter coming" [623].

3.3.2 Learnings from AI

Artificial intelligence ethical concerns became a real political issue in 2018. This was very apparent in France in the **Villani Mission Report on Artificial Intelligence published in** March 2018 as well as in a **Report of the House of Lords** published the same month and on the same subject in the UK [625].

It highlighted the need to ensure, at least morally, but, if possible, practically, that AI-based solutions respect society and avoid generating or perpetuating training data-originated discriminations. Hence two salient topics such as the explicability of algorithms and the limits of the manipulation of our emotions, particularly via more or less humanoid robots and voice agents.

The difficulty of explaining how deep learning algorithms work has been exaggerated. If it is true that multilayer neural networks are somewhat abstract. But it is equally abstract for almost any software, with or without AI, that can affect our daily lives. But we've forgotten that a little. When a software from the Visa group rejects your credit card payment abroad, we almost never get an explanation of the why and how it was rejected and how to avoid it. Bayesian fraud and machine learning based detection techniques are not explained to consumers.

3.3.3 Ethical quantum

Quantum computation is likely to amplify this quest for explicability. It is even less obvious to be satisfied with quantum algorithms, which follow a logic that few developers can grasp. Quantum algorithms are likely to be even more complicated and less understandable than those of today's AI. This is amplified since we cannot observe their inner working and intermediate quantum states. Only the "classical" result is measured at the end of the operations. Moreover, starting with about 100 quality qubits, it becomes difficult to emulate a quantum algorithm on a classical computer.

Their possible biases will not necessarily come from the data that feeds them because, for a certain period, quantum computers will probably not exploit large volumes of data. We can therefore speak literally of the term algorithm bias, whereas when we talk about AI, we are dealing more with training data bias rather than algorithms bias.

But this will be judged on a case-by-case basis. Depending on whether the applications of quantum computing optimize automobile traffic, manage energy distribution, optimize financial portfolios of the wealthy, create new molecules in chemistry or biology or help the NSA break the codes of private communications, the stakes will not be the same [626].

Ethical questions related to quantum technologies will undoubtedly emerge. They will be associated with a whole range of applications of quantum computing: the simulation of the dynamics of organic molecules. It will probably be limited at the beginning to the simulation of relatively simple molecules. The simulation of complex proteins folding is a hypothesis that has not yet been validated. In a distant hypothetical future, we may be able to simulate larger biological ensembles.

When this is simulated and then altered, for example to create new therapies, the rejection of GMOs or vaccines will seem like distant memory. New fears will show up and scientists will have to get involved to prevent them from spreading. These irrational fears will emerge because of exaggerations about the capabilities of quantum computers.

Each time, we will have to take a step back. In 2022 emerged a proposal to quantumly link the brain with a quantum computer [627]. Not only was it totally farfetched but it is probably not a good idea to create trust with quantum computing to elaborate such crazy scenarios. We have enough of it with Neuralink, the Elon Musk startup that works on neural implants that would supposedly be connected to some AI to augment the brain capacities, when it is more relevant for treating some neurodiseases like Parkinson's. Fears about quantum driven robots are also probably misplaced [628, 629].

A good approach for the quantum scientific community would be to pre-empt these fears by analyzing them as early as possible and defusing them if possible, so as not to be in a situation that would block scientific progress and innovation useful to society because of these irrational fears [630, 631]. Also, good examples can be given with researchers who admit having published scientific erroneous papers [632].

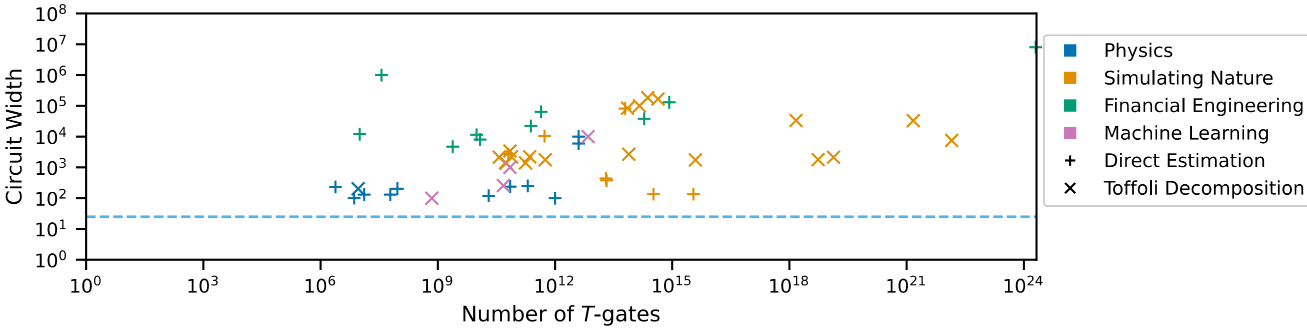

Figure 69: Some resource estimates for key applications. Physics applications like the dynamics of spin chains require the fewest resources, both in terms of number of qubits and gates. The horizontal line is at a circuit width of 25, a rough and crude limit for circuit widths below which classical simulation is tractable. Simulation remains feasible up to widths of approximately 50, though the required computing resources scale towards those of supercomputers. Source: [624].

Another potential worry is rising with scientists that deals with military usages of quantum technologies [633]. Some quantum scientists even published in 2026 a manifesto against the use of quantum research for military use [634]. All new technologies are "dual" whatever the domain. How will quantum technologies be used in defense and offense? We know about some use military cases like optimizing swarms of drones. What can be done about it? The usual approach consists of developing ethical frameworks, raising awareness with policy makers, and pushing for transparency. Some technologies may be designed with safeguards, like preventing in the future the usage of large scale quantum computers by untrusted parties.

Various initiatives started to pop-up in 2021 around quantum ethics in Australia, the UK, the Netherlands, Canada and the USA. It follows a similar pattern than with artificial intelligence but earlier given the maturity of the sector.

So far, contrary to what's happening in the AI field, it has not yet been hijacked by large industry vendors or even regulators although some consulting companies may publish reports on the topic [635]. Most initiatives were born out of the research community.

Still, there are already some similarities and overlaps between the AI and quantum ethics frameworks that are showing up. On the AI side, many AI charters have been published since 2018. One of these comes from the **GPAI** (Global Partnership on AI) launched by 15 countries in June 2020 with Canada, Germany, France, Australia, South Korea, USA, Italy, India, Japan, Mexico, New-Zealand, UK, Singapore, Slovenia and the European Union. Its goal is to foster the development of responsible and inclusive IAs based on human rights, favoring diversity, while driving innovation and economic growth. GPAI did organize experts working groups on responsible AI, data governance, the future of work and finally, on innovation. OECD launched its **AI Policy Observatory** (OECD.AI) in February 2020, an online platform consolidating information to help states craft their public AI policies. OECD defined its own AI principles (OECD AI Principles) that were adopted by 42 countries in May 2019. Also in 2020, the **AI Rome Call for AI ethics** gathered the Vatican, Microsoft [636], IBM and others to whitewash about the same goals as GPAI. And these are just a couple of initiatives among many others, frequently driven by industry vendors who are lobbying for self-regulation instead of tight government-based regulations.

In the quantum space, **Australia** was the first country that launched a quantum ethics initiative. Early on, in 2019, **CSIRO**, the Australian scientific research agency, mentioned the need to explore and address any unknown ethical, social, or environmental risks that may arise with the next generation of quantum technologies [637, 638]. It was followed in 2021 by a white paper published by Elija Perrier from the Centre for Quantum Software and Information at the Sydney University of Technology [639]. It was spun out of the **Association for the Advancement of Artificial Intelligence** (www.aaai.org). The paper starts with defining the quantum physics postulates, then cover ethical quantum computation and asks many ethical related questions that could be asked for any kind of classical computing. They mention the complicated question of quantum algorithms auditing. Quantum algorithms raise real verification and explainability questions, although for a different reason than deep learning: the fact that intermediate states cannot be read out without disturbing them limits observability, not analysis, since the circuit, the encoding and the objective function all remain inspectable. Bias can still enter through the data, the objective, the encoding, the constraints and the deployment context, so the usual data and model governance controls remain necessary. So, on top of the various XAI (explainable AI) initiatives like the one launched by DARPA in the USA, will we see the emerging field of XQC for Explainable Quantum Computing?

It also mentions the need for some Quantum Fair Machine Learning (QFML). It may not be such a problem since QML may not be used to process huge volumes of personal data due to quantum computing limitations in data loading techniques, which may last for a long time. They even go as far as asking whether quantum interferences implemented in quantum algorithms are ethical in nature. They also cover privacy and cryptography matters. Is Shor going to kill our private life? How could some differential privacy be implemented with quantum computing [640, 641]?

Other topics involve distributional ethics and fair distribution which are classical economic questions arising with any new technology. Finally, they wonder about the impact of quantum simulations and whether it could be implemented to simulate people's personal behavior. The paper seems highly influenced by the works on ethical AI and sometimes mixes science-fiction with real state of the art understanding of what can and will be done with quantum computing [642]. But it asks good questions. Another Australian paper focused in 2021 on the need to involve all stakeholders, beyond the classical market awareness creation [643].

In the **UK**, ethical quantum computing became a topic promoted by the media The Quantum Insider starting in December 2020. They released a short video documentary trying to explain what quantum computing is and the related ethical issues involved with researchers like John Martinis and entrepreneurs like Ilana Wisby [644, 645]. They are highlighting the need for democratizing quantum technology skills, mentioning the risks on privacy and security and the need to address quantum AI bias. They also pinpoint the "Hype-Fear-Disappointment Cycle" and recommend setting realistic expectations to avoid triggering fears and biases. Researchers from Oxford University are also studying responsible innovation in quantum technologies [646]. It spun the ResQCCom project (Responsible Quantum Computing Communications) out of the university's Responsible Technology Institute (RTI). In Summer 2024, the NQCC launched in 2025 its "*principles for responsible and ethical quantum computing*". There are 6 such principles: innovations must be societal beneficial, trusted, accountable, transparent and explainable, equitable, fair and inclusive, and safe, reliable and secure. I'm not that sure about the "explainable" on nearly any quantum algorithm, at least in layman's terms.

In the **USA**, some spare initiatives are launched by academics like Chris Hoofnagle from Berkeley, or a while ago, by Scott Aaronson [647–649].

In **the Netherlands**, the government €615M initiative launched in April 2021 includes a €20M plan on quantum ethics and societal impact research run out of the Living Lab Quantum and Society spun out of Quantum Delta NL, the foundation established to run the Netherlands quantum program. The program is led by Pieter E. Vermaas. They also create ethical, legal and societal standards for quantum technologies and their applications. There was even a quantum hype PhD proposal, as of October 2023 at the University of Leiden [650]. They also look at how to build a responsible quantum Internet [651, 652]. One researcher at QuSoft, Eline de Jong advocates that understanding quantum technology usages and not their underlying mechanism is enough for the ethical debates [653]. I am not so sure about it because use cases without understanding if and when the hardware will support it will generate bad understanding on the timing of innovations.

In **Switzerland**, the GESDA (Geneva Science and Diplomacy Anticipator) launched the **Open Quantum Institute** that is working on supporting the development of quantum use cases designed towards accelerating the achievement of the UN Sustainable Development Goals (SDGs). It was inaugurated at CERN Geneva in October 2024. GESDA and OQI are funded by the UBS bank. As documented in [654], the use cases cover the fight against hunger (plant Genomics, last-mile food delivery optimization), health and well-being (antibacterial discovery, predicting gastrointestinal cancer), clean water and sanitation (water leak detection, eliminating chemicals from water sources, molecular docking to clean up pollution), affordable and clean energy (optimizing the layout of wind turbines, smart grid management) and climate action (catalytic carbon capture). These are indeed use cases since they correspond to quantum algorithm which require futuristic QPUs to deliver actual value.

In **Canada**, The Perimeter Institute launched the **Quantum Ethics Project** that is providing full-length courses on ethics and social impacts of quantum technology [655]. **Q4Climate** is an initiative for using quantum technologies in climate research, an initiative coming from the Institut Quantique, the University of Waterloo and Zapata Computing. It explains how some quantum chemistry algorithms could potentially solve some environmental problems [656]. The Council of Canadian Academies (CCA) also published a report on the responsible adoption of quantum technologies in 2023 [193].

The **World Economic Forum** launched its Quantum Computing Governance initiative in February 2021 [657]. It wants to standardize an ethical framework enabling the responsible design and adoption of quantum computing. They ask the everlasting question: will the public trust technologies which they cannot understand and whose results they cannot verify as if they could do it with existing digital technologies. They advocate the use of preemptive involvement in technology design to make sure ethical issues are addressed as early as possible. With that, they are assembling a "*global multi-stakeholder community of experts from across public sector, private sector, academia and civil society to formulate principles and create a broader ethical framework for responsible and purpose-driven design and adoption of quantum computing technologies to drive positive outcomes for society*". They frame the conversation, drive quantum ethical issues awareness, study quantum related risks, design quantum computing ethics principles and framework, and test it with some case studies.

Other responsible quantum frameworks are proposed, with similar focus on cybersecurity and privacy issues, workforce diversity and societal dialogue [658, 659].

Other ethical issues to be addressed cover the potential harmful manipulation of the human genome fears, the (positive) quantum use cases to find environmental solutions and the energetic footprint of quantum computing.

Interestingly, none of these initiatives mention the field of quantum sensing, which could also have some underlying ethical issues to be addressed, particularly when used in the military. Quantum radars, quantum imaging, precision gravity measurement and its impact on underground resources exploitations are a couple examples.

3.3.4 Philosophy Beyond Quantum Foundations

The current philosophical approach to quantum physics baffled me a bit when I discovered it around 2019. Most of the writings in this discipline are full of mathematics and physics. They must break records in this respect compared to any other subject covered by the field of philosophy. Above all, they do not deal much with human sciences per se.

What are the human consequences of these different interpretations of quantum physics? Are there philosophical questions other than these related to the interpretation of realism at low-level? There is much to be done in this area.

The notions of uncertainty and indeterminism inevitably lead to the notion of free will and destiny (as seen by Pascual Jordan). The quantum philosophical focus on the microscopic and nanoscopic scale of physics could also be a form of reductionism preventing a wide-angle view of its societal impact. Also, is the extension of the scientific field infinite? What are the limits of human knowledge that seeks to explain and interpret everything about the way the Universe works? What do we miss and why? What links can be made with our humility? What are the structural limits to our insatiable curiosity? This is only reformulating the very notion of Kantian metaphysics, the "*science of the limits of human reason*".

The philosophical question thus concerns the notion of the feasible and the unfeasible and its evolution over time, a perspective provided by the history and philosophy of science. What are the limits of human ingenuity? What is superhuman? Will we be able to create ultra-reliable and *scalable* quantum computers? Complexity classes should also serve as tools for this kind of thinking.

How to extend the interpretation of quantum physics to the metaphor of quantum computation: highly rich and complex inside but simple after measurement is done? Could it be used to simulate the living and create it in silico? This will then raise questions about man's power over nature and the associated responsibilities. We will also see the resurgence of debates on scientism, the "*science-led society*", as well as on technology solutionism, a concept described by **Evgeny Morozov**, which could provide answers to all problems, especially environmental and health problems, which cannot be treated properly with the required urgency.

These questions arise more and more at a time when precaution prevails over everything, when there are fears of technological blunders in almost every field (nuclear, GMOs, fertilizers, vaccines, artificial intelligence and 5G), when the very notion of scientific progress is no longer accepted and when cognitive relativism no longer allows us to distinguish between the serious and the farfetched, leading to a collective mistrust in science.

In the section on quantum foundations earlier in this book, we precisely studied a question that belongs to the field of philosophy, the question of the ethics of quantum computing.

Are these questions specific to quantum physics and quantum computing? Aren't they recurrent as soon as a major new technology shows up? Perhaps, but these questions deserve to be asked, like those raised by the commoditization of artificial intelligence since 2012, and with large language models *ala* ChatGPT. The interpretations of quantum physics are in any case there to remind us that in all matters, we must multiply the angles of view of problems to better analyze them. This is obviously full of lessons from a metaphorical point of view.

I wonder about all these questions by observing that, if they are not dealt with, they tend to become the field of esotericism and charlatanism as we will see in a following section dedicated to quantum pseudosciences. It is a bit as if the philosophy of quantum physics had remained at the stage of fundamental research without moving on to the stage of applied research. In a way, it is in line with the level of market maturity of the technologies of the second quantum revolution. Let's bet that, as quantum technologies mature, the more this applied philosophy will develop and allow us to write a new chapter in this exciting history of science.

3.4 Religions and mysticism

In recent millennia, humans have developed the habit of devoting a cult to one or more higher divine powers of an imprecise nature but explaining everything and everything else.

Mankind probably began to attribute this power to natural phenomena that he could not explain like the Sun or the stars. Mankind then went from multiple systems of gods to a single all-powerful God. In a way, the monotheistic religions realized before time the theory of unification so much sought after by physicists. This story is told with hindsight by **Yuval Harari** in Sapiens and with cynicism by **Richard Dawkins** in "The God Delusion".

For some scientists or believers in an afterlife, quantum physics renews the desire to explain the inner works of the Universe by some divine power. It gives the impression of providing an ultimate scientific explanation for everything, of God, and of his ability to control and supervise everything.

The quantum function most often emphasized in these explanations is entanglement and sometimes measurement [660] without providing any reference! It may be true for some interpretations like the von Neumann - Wigner consciousness driven measurement process collapse and the Bohm interpretation, but not all of them. It makes it possible to envision a Supreme Being who, thanks to this physical phenomenon, can control all the particles of the Universe and at a distance. It would also explain strange synchronicity phenomena. The wave-particle duality also makes it possible to imagine or explain many magical scenarios such as remote healing, telekinesis or telepathy [661].

Some of the protagonists of these theories are themselves quantum physics scientists. One of the best-known is **David Bohm** (1917-1992), already mentioned in the quantum foundations section, who came closer to Indian spiritualism in the 1960s, simultaneously with the Beatles! He was convinced that the laws of the Universe were governed by some spirit [662]. He is one of the initiators of the theories of **quantum cognition**, a field of cognitive theories based on the mathematical formalism of quantum mechanics and relying on analogies.

3.5 General public education

Quantum computing may amplify a situation observed with artificial intelligence: a huge gap between those who understand it and those who use it, coupled with a shortage of skills. Quantum science and technology is right now definitely a world of specialists, and it is even harder to grasp than most other digital-related disciplines. Today, this world is balanced between specialists in quantum physics and quantum algorithms and software [663].

By extrapolating a little and drawing inspiration from the history of computer science, we can anticipate that software will gradually take over when quantum computing becomes commonplace, especially if it leads to applications in all sectors of industry. But this will be slow, considering the long and winding road to industry-grade FTQC.

In today's digital economy, there are many more software specialists than there are with semiconductors. The economies of scale are much greater with the latter between producers and users. Quantum computing will probably not escape this, even if initially the market for quantum computers will not be a volume market.

In the short term, there is a great need to popularize the field and avoid its technical jargon. You must proceed step by step, broadening the audience in a progressive way from the techie to the non techie [664]. In parallel, training decision-makers in the industry and with various institutions, including policy makers, must also be done.

It is becoming even more important as the quantum technologies hype is peaking with the flurry of vendors and research labs announcements that are regularly showing up [665].

There is a thin line between selling a dream and not overselling it, and not confusing the future and the present. There are also many misconceptions to counter both on quantum physics (the cat…), quantum computing (it won't solve every problem, is not instantaneous, won't break the Internet in two years) and quantum communication (not faster than the speed of light or existing telecommunications).

Many initiatives around the world are launched to train the public on quantum physics and technologies.

The **National Q-12 Education Partnership** launched as part of the US National Quantum Initiative targets middle-school and high-school students. Industry participants include IBM, Google, Microsoft, AWS, Rigetti, Intel, Lockheed Martin, Boeing, Zapata Computing, APS Physics, Optica, IEEE USA and QubitbyQubit (a training organization). They organized the event QuanTime in spring 2022 with hundreds of quantum activity classrooms for K-12.

Many initiatives to gamify the learning process have been launched like:

- **Quantum Odyssey** from Quarks Interactive (2020, Romania, €230K) that was launched in 2020. It replaces Dirac's bra-ket notation and linear algebra used by scientists by a visual puzzle-building approach. It is proposed to discover and learn gate-based quantum algorithms.
- **Quantum Chess** from Quantum Realm Games (2019, USA). The game embeds quantum phenomenon in the game play with pawns able to make multiple moves simultaneously in sort of superposition.
- **The Quantum Prisoner** is a free online adventure game launched by CEA in France in 2020, in English, inspired by quantum logic and targeting kids over 12 (meaning, adults are welcomed…). It has 10-12 hours of gameplay with a journey across the globe to find out what happened to a physician who mysteriously disappeared in the 1960s. Playing as Zoe, a young woman, gamers must solve over 30 technology, science, and engineering-based puzzles.
- **Quantum Games with Photons** from the MIT which is an open-source puzzle game with 34 levels and a sandbox.
- **The Virtual Quantum Optics Laboratory**, an optical lab running in a browser which enables you

to build quantum optics experiments with all sorts of optical devices (lasers, PBS, depolarizer, etc, in Figure 1027 *on the right*).

- **Quantum cinema**, an open-source initiative from China that uses generative AI to create 3D immersive views [666].
- **Qualia** was cofounded in 2026 by Universum Labs (which creates an open-access scientific knowledge graph, cofounded by Bob Coecke) and NEUROssance (an Oxford-based startup and educational initiative focused on improving human cognitive capabilities to keep up with the Quantum and AI, cofounded by Cierra Lunde Choucair formerly from The Quantum Insider). It stands for Quantum & AI Learning and Innovation Alliance. It is an international consortium focused on building research-grounded cognitive infrastructure for quantum and AI education. Apparently, using knowledge graphs and other visuals.
- **Qolour** sells Qubi, an educational tool for learning quantum computing. Sort of. It is a luminous Bloch sphere. Two were sold for $390 as of September 2026. Of course, it has a companion mobile application. With two sphere, you can visualize entanglement.

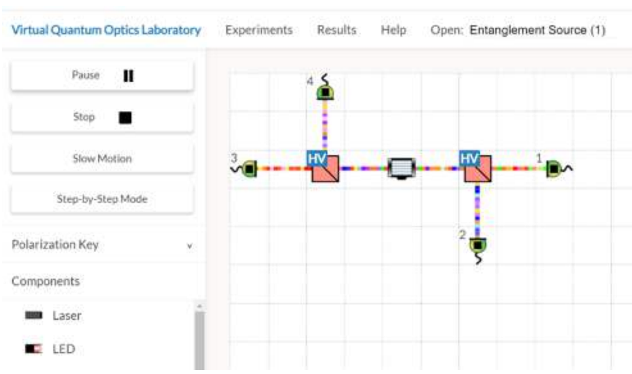

Figure 70: The Virtual Quantum Optics Laboratory.

- **CoSpaces** is a similar simulation tool created in Italy and aimed at teaching quantum computing [667].
- Other quantum games have been launched for educational purposes, like **Alice Challenge**, **Hello Quantum** and **Hello Qiskit** by IBM and the University of Basel, **Particle in a Box**, **Psi and Delta**, **QPlayLearn** (covered later), **Quantum Cats**, **Quantum Flytrap**, the **Virtual Lab** by Quantum Flytrap, **ScienceAtHome** [668].

Educational can also use other media like theater plays, as tested in “A quantum of hope”, a play script created in the USA (MIT, Harvard) and Germany (University of Leibnitz Hannover) [669]. The story is about the fate of Earth hanging in the balance when an alien civilization announces its impending demolition to make way for a research station. Humanity is given five years to prove its worth—through the lens of quantum science and technology. In the play, five academia and industry experts are locked in a room, asked to select a single project proposal to represent Earth’s quantum capabilities. Then arise the collision between scientific ambition, ethical dilemmas, and clashing personalities, following the spirit of Douglas Adams with the tense deliberations of “12 Angry Men”. It deals with the breadth and uncertainty of research in quantum science, its underlying motivations and trying meanwhile to explain concepts like NISQ and FTQC, quantum foundations, quantum simulators, and quantum sensors.

3.6 Professional education

All these countries launching well-funded quantum plans create a significant challenge with professional education along the whole cycle from bachelor to doctorate. Before becoming an industry competition, quantum technologies are creating a talent one. There may be more money to spend than talent to hire for a while [670].

3.6.1 Training cycles

One cycle started at least around 2020 with the development of quantum startups. Some of these being relatively well funded, they hired a lot of researchers and engineers, but mostly young scientists with a fresh PhD. It progressively dried the pipe of PhD to post-docs. In most countries, post-doc tenures are temporary positions while being hired by a startup may be more attractive to young scientists. They are better paid, have a fixed position (well, while the startup is still alive) and work in a more technologically diverse environment. This complements the other path with scientists turning into startup entrepreneurs. Figure 1028 shows the great diversity of training paths for initial and continuous training.

Quantum professional training was initially preeminent in quantum physics. Most universities in the world have special programs from bachelors/licenses and master’s to PhDs. Some groups are organizing summer schools for PhD level students like the famous **Ecole de Physique des Houches** doctoral and summer school in the French alps with various sessions on quantum physics.

There are a couple of new disciplines where more and more people will need to build knowledge and skills on. Quantum systems engineering is about creating real machines that work from start to finish. This requires decompartmentalizing disciplines and bringing together physicists and engineers.

The technologies involved are varied and include photonics and lasers, analog and digital electronics, thermodynamics, fluid mechanics, various components manufacturing techniques, and the design of complete systems. Quantum engineering involves many complementary disciplines.

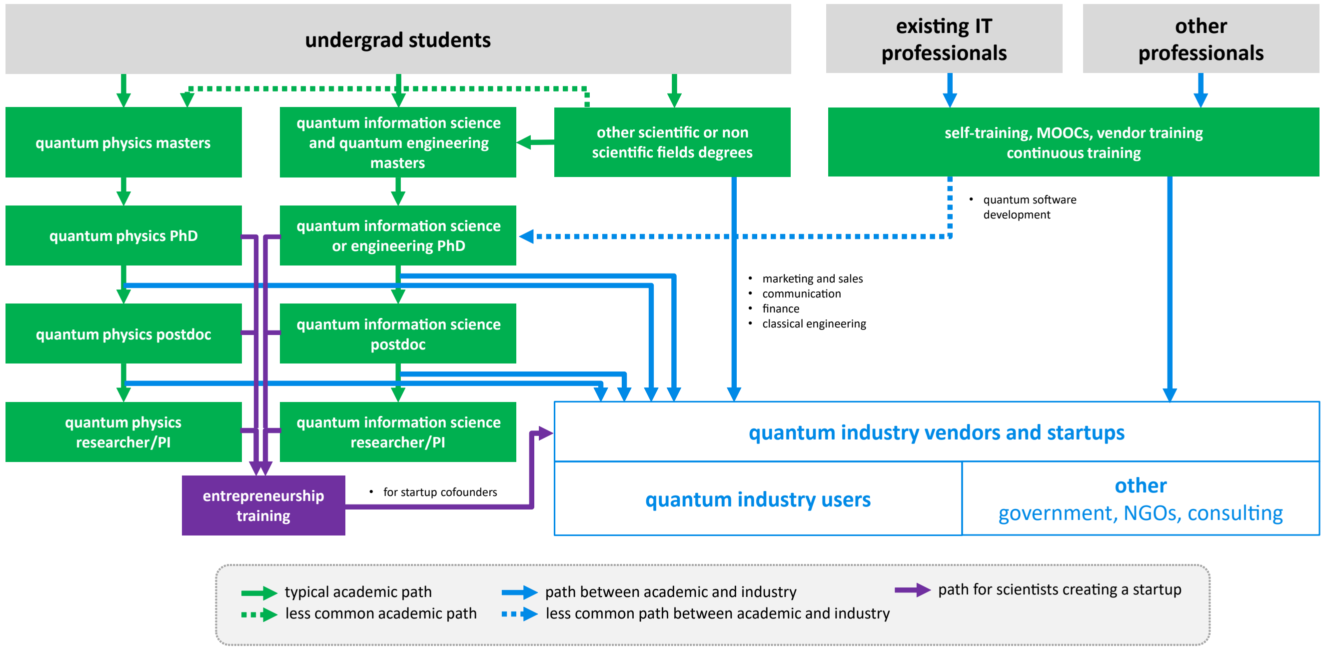

Figure 71: The many training paths in the academic world and between the academic and industry worlds. ⓒ Olivier Ezratty, July 2024.

In the mathematical and software fields, other important disciplines come into play for creating end-to-end quantum solutions: algorithms design, software tools design and applications software development and software and infrastructure cloud support. Added to this is the field of post-quantum cryptography which is specific to the cybersecurity domain.

The creation of business applications also requires skills at the crossroads between the above and vertical markets, which are often themselves scientific as in life sciences (organic chemistry, protein folding, photosynthesis, ...), materials sciences (battery chemistry, superconducting materials) or other branches such as portfolio management and risk assessment in finance or optimization problems in logistics, transportation and marketing.

3.6.2 Quantum professions

Quantum technologies will be found with many different professions [671]:

- **Fundamental physicists** (solid-state physics, condensed matter physics, light-matter interaction, quantum optics) who combine theoretical and experimental approaches to understand low-level phenomena.
- **Quantum technologies researchers** who turn fundamental discoveries into first proofs of concept in the laboratory. These research teams combine physics, technology and engineering researchers.
- **Design engineers** who create technical subsets of quantum computers to complete finished products. They essentially do the "D" of "R&D" by relying on the R of physicists.
- **Research engineers**, who participate in the development of new materials and new technologies in semiconductor fabs, or process engineers who design the manufacturing processes for these integrated circuit systems supporting qubits.
- **Technicians** for certain components manufacturing and/or for the deployment of technologies such as quantum cryptography in the telecom space. But only once this technology is deployed on an industrial scale, probably by generalists or specialized telecommunications operators.
- **Software tools developers** who must be associated with previous researchers and engineers. Indeed, for the time being, the design of these tools still has to take into account the physical characteristics of quantum calculators/accelerators.
- **Application developers**, whose numbers will increase as the computing power of quantum computers grows. Most of the time, they will need to have three key sets of technical skills: one is being able to program quantum computers, the second will be the ability to turn business problems into quantum programs (including the related mathematical/physics related know-how) and at last, they will have to know about classical programming, since quantum processors rely on classical control and most current workflows are hybrid, even though not every quantum algorithm is intrinsically hybrid.
- **Project managers** who manage projects and teams that combine these different professions.
- **Business strategists**. Brian Lenahan went as far as defining the job of "quantum business strategist" in

2021, which looks like an equivalent of the chief digital officer for quantum technologies related projects, creating the link between IT and business managers. This role is about crafting a quantum plan with mission, vision, goals, strategies, KPIs and tactics. In other words, it is an old-fashioned consultant [672, 673]!

- **Support activities** like in HR, marketing, business development (managing industry partners) and sales (to end-customers), communication, public relations, legal, finance, startup creation and acceleration.

As in many disciplines, researchers and engineers are increasingly required to be versatile. Teams must be structured around a strong interdisciplinarity and transversality. They need "technological polyglot" teams that link all these professions and skills. Physicists will have to be increasingly interested in engineering and engineers in physics [674–676].

Finally, when you turn to the business side with actual products that can be marketed and sold, you need the whole mix of skills usually found in technology marketing and sales: product marketing, operational marketing, business development and partnerships, creating ecosystems and, above all, pure and simple B2B sales for a starter. This is completed by the generic skills associated with deep-tech startups creation (organization, business planning, recruitment, funding, etc.) and with intellectual property attorneys who must grasp the specificities of the quantum vocabulary.

Quantum sensing products are beginning to be marketed, and in a market that is currently niche.

Quantum cryptography systems are in the experimental field phase and could be deployed on a larger scale in the coming decade.

Quantum communications with the objective of leading to quantum communications networks will develop in a second phase, combining fiber and satellite networks with quantum ground relays. This is a complementary field to the development of quantum computers.

Finally, quantum computing will progressively evolve and see their field of application widen as the qubits number and quality in quantum computers grow. It will be a process of continuous innovation. As in the case of classical computing, the weight of software is bound to become dominant in skills requirements. This explains why many publications insist on the need for quantum application developers. This is what the major players such as IBM, Google and Microsoft, not to mention D-Wave, Rigetti and IonQ, are "evangelizing" about [677–680].

Nevertheless, in parallel with the software market development, an intermediate phase will require a lot of skills in engineering and in the different branches of quantum technologies (Figure 1029).

3.6.3 Academic training

Training in public higher education should introduce quantum science and technology as early as possible in the bachelor's and master's degree programs. There are now more master's degrees in quantum engineering, bringing the world of research and engineering closer together [682–684].

In some cases, training can be shared between universities, particularly when teachers are scarce. That's what is implemented in the Université Paris-Saclay with the ARTEQ interdisciplinary year positioned before masters M1 and M2, to feed M2 masters in quantum physics and quantum information science.

The training offer depends on several parameters: funding for teacher-researchers or teaching positions, the creation of vocations, the ability to attract teachers and students from wherever they come.

It will also be necessary to attract as many women as men in these courses, otherwise there is a risk that a whole sector will develop, as in AI, which is far too masculine. Not to mention the increase in the diversity of students' social backgrounds, which remains a key channel of social mobility through public education, despite its current decline.

Upstream of all these courses, the creation of vocations among young people is indispensable. Science fairs can also contribute to this. It is a long-term task, as is the creation of vocations in science in general and in the scientific and technical professions of the digital world in particular.

3.6.4 Continuous training

Continuing education may include both scientific and technological courses (quantum physics, quantum communications, quantum algorithms and software) and strategic courses (understanding of the issues, knowledge of the players, economics of the sector, good practices). This is probably the least well addressed market need, so far. It can or could be delivered by private organizations, by higher education organizations as well as via online courses offered by Coursera and others.

Self-training allows enthusiasts to discover these sciences and technologies by themselves, but it is not self-sufficient as it is sometimes the case in artificial intelligence. It must be complemented by quality pedagogical support, if only to do and correct exercises.

As far as the software part is concerned, this will perhaps change the day when development tools will be possible with higher levels of abstraction than today.

Learning quantum software development is not like learning a new programming language ala Python or PHP. While you can learn classical programming without having any idea of how a microprocessor works, it is a bit different with quantum computing. One reason is the

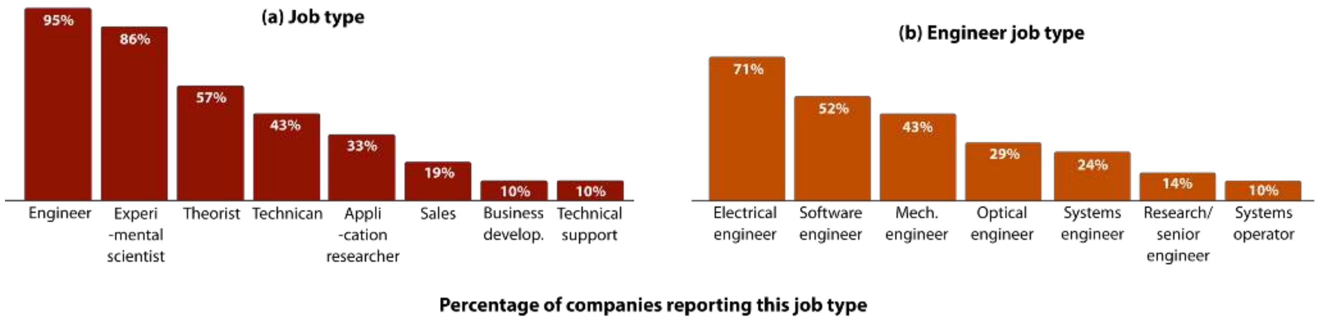

Figure 72: An American inventory of engineering jobs and skills in quantum technologies. Source: [681].

tighter links between what can be achieved with quantum computers and their physical characteristics. You must understand for example how qubits are physically implemented, their noise and its impact on quantum software. Creating a “mental image” of what is a quantum algorithm is not straightforward, particularly given the breadth of paradigm around (gate-based, annealing, analog, MBQC, …) [685]. Innovative training methodologies still must be invented here.

Scientific events organized by quantum hubs, research laboratories and companies serve to facilitate transdisciplinarity among researchers and engineers. They can be interdisciplinary symposia, thematic conferences or workshops.

There are some pure players around in the quantum computing educational market, many of them offering open-sourced eLearning contents:

Q-munity (2019) is a training organization and community connecting young individuals in quantum computing.

With its 1,000 members, it organizes summer camps (well, outside pandemics), conferences and workshops. It was created by Anisha Musti, a quantum computer scientist who worked on Shor’s algorithm, quantum teleportation and quantum machine learning. In May 2024, Q-munity was acquired by The Quantum Insider [686].

QubitbyQubit (USA) is a quantum programming online learning initiative from The Coding School, created by a Brown University undergraduate in 2014.

It was created by Kiera Peltz and is sponsored by IBM and Google.

Qplaylearn (2020, Finland) develops an online visual quantum programming training tool targeting a broad audience including high school students.

They collaborate with various universities in Finland as well as with IBM.

Quantum Country (USA) is a tutorial website on quantum programming created by Andy Matuschak and Michael Nielsen. It contains “mnemonic medium” that makes it easy to remember what you read. These are long reads including some good story telling and some exercising. It starts with the basics of quantum programming, then covers key algorithms like Grover search.

QuTech Academy is offering free online courseware on quantum technologies for engineers [687].

Qureca (2019, UK) sells online “Quantum for Everyone” courses for business people (at £400). These courses are delivered by Araceli Venegas-Gomez, the founder of Qureca, Bruno Fedrici, a French consultant and lecturer on quantum technologies and QuantFi, a French Startup specialized in Finance applications. The company also offers hiring services and other professional services for startups and businesses (community management, events organization, business development and strategy).

CERN has a series of introductory conferences on quantum computing from **CERN** (7 x two hours tracks), broadcasted in November and December 2020, also targeting engineers [688].

EFEQT (Empowering the Future Experts in Quantum Science and Technology for Europe) provides a learning experience between academic research and free interdisciplinary exploration for 25 students and young researchers. It takes the form of a scientific hackathon, the first one was organized in October 2021 and ended with a graduation in September 2022. The best participants will receive a fast-track access to do a PhD or post-doc at EFEQT partner universities in Germany and Strasbourg in France. The program is supported by the Quantum Flagship’s Quantum Technology Education Coordination and Support Action (QTEdu CSA).

3.6.5 Jobs impact

Finally, what about the future of quantum-related employment, a question that Sophia Chen asked herself in Wired in June 2018 [689]? It is difficult to assess because we are thinking over several decades and about use cases that are still uncertain. There will be, as with

AI, those who know and those who don't, those who code and those who use stuff, those who create wealth and those whose jobs are threatened.

For the moment, quantum computing does not generate any specific jobs threats, because it will enable us to do things that mankind can't do today. There is no logic of replacement, at most optimization as for applications based on graph optimization like those of the traveling salesperson problem.

3.7 Gender balance

Gender unbalanced in all STEM jobs and particularly in computer science is a known fact and it has been so for a long time. You can look at all the statistics and they are not good. It started to go awry in computer science in the early 1980s when computing became mainstream.

Many initiatives have been launched worldwide to rebalance gender in all these domains. They have mostly failed, or maybe did they just made things better than if nothing was done. Are quantum technologies different for gender balance?

3.7.1 Problems

This domain is already highly male-dominated, in the lineage of computer science and artificial intelligence. The specialty is still too masculine as it stands. Quantum physics founder in History books are mostly men, particularly in the seven first quantum wave theoreticians narrow club with **Planck-Einstein-De Broglie-Schrödinger-Heisenberg-Dirac-Born**.

You have to really dig into the History of science to recognize the role of **Emmy Noether** and **Chien-Shiung Wu**, the few female scientists of this era. Also, only five women have been awarded the Nobel Prize in Physics: **Marie Curie** (1903), **Maria Goeppert Mayer** (1963, for her work on nuclear structure), **Donna Strickland** (2018, for chirped pulse amplification), **Andrea Ghez** (2020, for the supermassive compact object at the center of our galaxy) and **Anne L'Huillier** (2023, for attosecond pulses). But besides Marie Curie, they don't yet have the recognition status of **Ada Lovelace**, **Grace Hopper** and **Margaret Hamilton** in computer science.

The statistics are depressing with only 20% women in STEM (in the USA) and it doesn't seem to be better in quantum science [690–693]. Women's representations in culture, media and toys still play a leading role in crafting this unbalanced world. And this is just about gender balance. In the USA quantum scientific community, many groups are fighting against discrimination beyond gender balance issues.

Only a few countries are faring better, like in Asia. Is the condition of women in universities and research labs different than in business organizations? It probably depends on their values, leadership and culture. The scientific world seems as competitive and tough as the private sector even if its rules are different, based on h-indexes, conference talks and the like. Still, in most places, research is a longer term activity which may create better conditions for women.

On top of that, the language used in quantum science is very masculine [694]. Wiesner and coauthors argue that "supremacy" carries the connotations of the phrase "white supremacy" in the US political context, and that "ancilla", from the Latin for female servant, carries a gendered one, the technical term having been introduced in 1995. These are contested etymological and sociological readings rather than settled facts, and they are reported here as such. These are symbolic items, but they deserve to be corrected. One solution is to talk about quantum advantage even if the meaning is slightly different from quantum supremacy (doing impossible things in classical computing vs doing things better and useful). Some are advocating the usage of "useful advantage" in reference to use cases that provides some value with data inputs and outputs, but it doesn't embed the distinction between supremacy and advantage. Another solution already mentioned consists of using the term **primacy** [695].

A mix of other authors ask for creating a language void of competition connotations that should be comprehensible, specific and practical, open, accessible, responsible, culturally embedded and meaningful [696].

3.7.2 Hope

There is still hope. It seems easier to identify dozens of women who are real inspiring role models and play a key role in quantum science and technologies and anywhere in the world (Figure 1030). Many of these were at the origin of key scientific advancements in quantum technologies.

You may know the famous threshold theorem co-demonstrated by **Dorit Aharonov**! There are a few startups created by women like **Silicon Quantum Computing** (SQC, Australia), created by **Michelle Simmons, Oxford Quantum Circuits** that is led by **Ilana Wisby**, Quobly (France) which was cofounded and is run by **Maud Vinet**, **Quandela,** co-founded by **Pascale Senellart, VeriQloud** co-founded by **Elham Kashefi** and Qureca, created by **Araceli Venegas-Gomez**. In the Corporate world, **Krysta Svore, Patty Lee** and **Anne Matsuura** play leading roles at respectively Microsoft, Quantinuum and Intel. In Europe, **Laure Le Bars** leads SAP's quantum research efforts on top of being the first President of the QuIC industry consortium. **Brigitte Léridon** is the CEO of Pioniq in France.

The Quantum Insider launched in 2021 a series of interviews of key women working in the quantum industry. It included for example **Mercedes Gimeno-Segovia**, Sys-

Figure 73: Some women role models around the world, from research to the industry. Ⓒ montage by Olivier Ezratty, 2021-2023. Photo credits: Olivier Ezratty for Maud Vinet, Elham Kashefi, Pascale Senellart, Elvira Shishenina and Eleni Diamanti and various other photographers for the other scientists. Updated in September 2026.

tems Architecture VP for PsiQuantum, **Olivia Lanes** North-America lead for Qiskit at IBM, **Helena Liebelt** from Deggendorf Institute of Technology, Intel and SheQuantum, **Christine Johnson**, CEO of Ingenii, **Lior Gazit**, quantum software engineering team lead at Classiq, **Ying Lia Li**, CEO from Zero Point Motion (UK), **Katerine Londergan**, CMO at Zapata AI, **Anindita Banerjee**, Security VP at QNU Labs, and **Rojalin Mishra**, senior hardware verification engineer at Riverlane. Also, **Masako Yamada** is the director of applications at Quantinuum.

Also, quantum tech is still a green field, and it is not too late to attract young women in this emerging and promising discipline. There are already women playing leading technical and business roles in quantum startups on top of the cofounders mentioned above [697].

3.7.3 Initiatives

Some initiatives have been launched around the world to promote and help women in quantum technologies. They are matching what has been done for a while in the computer science and information technology fields.

Gender-oriented actions are a mix of associations, events and media visibility initiatives. Too many of these are seasonal, and centered around International Women's Day, on March 8, every year.

Let's mention a few of these:

- The **Women 4 Quantum Manifesto** published in May 2024 by several preeminent quantum scientists throughout the world calls for a change in the current model of scientific leadership, funding, authority and working environment that does not represent or respect well women [698, 699]. It advocates for some form of power redistribution, if not decentralization, and to increase the representation of women in decision-making bodies at all levels in research. It also wants to fight unconscious gender-bias, microaggressions, and various forms of harassment, which are common in all workplaces, and not just in research. The next step is to determine actionable items.
- **Women in Quantum** by **OneQuantum** is a think tank gathering quantum leaders worldwide in dedicated chapters, with the goal to influence government action, vendor relationships and the quantum ecosystem. It offers a resources, services and events platform for quantum startups to collaborate. Women in Quantum is one of the "chapters" of this organization, run by Denise Ruffner (also, Chief Business Officer of Atom Computing), organizing quarterly Women in Quantum events, the last one being held online in June 2021.
- **Women in Quantum Development** is a professional network of quantum tech enthusiasts in the Netherlands, with events and mentoring programs. It belongs to a new trend, with national quantum plans containing specific initiatives around the ethics and social impact of quantum technologies. Netherlands

is a good best practice for that respect. There's also a gender equality workgroup in the **EU Quantum Flagship**.

- Some research labs and organizations showcasing their women quantum scientists and engineers like at the **Lawrence Berkeley National Lab** from the DoE in the USA [700], at the **Harvard** Center for Integrated Quantum Materials [701], at **Yale University** [702], with **IBM** [703] and **Microsoft**.
- **SheQuantum** (2020, India) is an eLearning provider offering quantum computing education content targeting women.

3.7.4 Solutions

Like in any domain, particularly in social science, there's not yet a common agreement on what should be done to create a better gender balance in STEMs and in quantum science.

Should we encourage some affirmative actions or not? Some are worth the effort like the European Union ERC Grant program which extends since 2010 the age limit by 18 months per child plus other anti-bias measures. Paternity leaves are also taken into account [704].

In the way women scientists and entrepreneurs are promoted, I believe we should be more engaged but with subtlety. For example, it is more efficient to value scientists and entrepreneurs for their achievement and who happen to be women instead of doing this explicitly because they are women. Implicit communication is sometimes more efficient than an explicit one. Finding women talents should be a sort of backstage work. It requires some discipline. When organizing training and events, and with any media speaking opportunity, make sure gender balance is respected. It involves having some knowledge of the field ecosystem and of its female leaders. Don't say "there are only a few of them", but "where are they?" and look for them. Also, let them talk about their science.

We should also promote a broad range of role models in different fields and jobs to inspire young talents. It is also about building inclusive and welcoming work environments in universities, research labs and commercial vendors. Education remains a key vehicle to drive interest in science, and then, quantum science [705].

Of course, on a broader scale, media and fiction play a key role. The geek in TV series and movies is too frequently an introverted male. We need more Felicity Smoak, the geek from the TV Series Arrow! At last, do that all year long and not just on March 8$^{\text{th}}$.

3.8 Quantum technologies marketing

The last point to be mentioned here is the role of marketing and propaganda. Quantum technologies are the perfect spot to broadcast extraordinary and impressive claims that few specialists can fact-check. It is a world of superlatives and exaggerations. It started in 2019 with Google's supremacy claim.

We are drowned in innovation propaganda that blurs things. Scientists in the field no longer recognize some of their creations. Popular news related to quantum computing continues to start explaining qubits with their superposed states 0 and 1 and... stop there! Consulting and analyst firms also strive for simplifications.

Marketing and communication are all about making fancy claims and simplifying facts with wild exaggerations. One can wonder, how is the bs created in marketing when there's so much science behind most projects? It starts with the "businessification" of quantum technologies. The rules of the game for a staring looking for some VC funding is to talk about customer use cases and market size, creating an echo chamber to the crazy numbers published by industry analyst firms. You will therefore have plenty of quantum computing hardware and software companies web site presenting the same story about the beauties of quantum computing in pharma, financial services, transportation and the industry, if not to fix climate change, but nearly nothing on their actual technologies and products.

An easy way to detect bias comes from quantum hardware startups who hide simple technical information and figures of merit like the number of qubits of their QPU. It usually means that they are too shy to say that they have fewer than 5 or 10 operating qubits and therefore are not competitive against companies like IBM (who had 156 qubits as of September 2025), Rigetti (84 qubits as of the same date) and Quantinuum (56 qubits). How about qubit fidelities? It is often hidden data as well.

Another doubtful practice from quantum hardware vendors connects the dots between customer orientation and immature hardware platforms is to say: we create application-specific quantum hardware. This can be a rational co-design choice, and fixed-function devices, analog simulators, accelerators and programmable gate-model processors must each be judged against their target task and benchmark. But it carries an economic risk. Successful hardware companies create economies of scale, like IBM in the 1960s with its family of IBM 360 mainframes. Hardware must be generic for a large range of applications. Like Nvidia GPGPUs (general purpose GPUs) that are used for both machine learning and scientific applications thanks to a broad software support. On top of that, if one hardware platform has so many limitations that it is bound to be used for only one category of application, you as a customer will be potentially locked in. Then, you can listen to the technical rationale behind custom-hardware platforms. But specialists will tell you it doesn't make much sense in general.

At last, some quantum hardware vendors will sell you fancy customer-oriented application benefits, without presenting any real quantum advantage whether in results precision, execution time, solution price or energy spent for the environmentally conscious as compared to best-in-class classical solutions. It turns something that should be better than legacy systems to "*it barely works*" at small scale and without any technical or economic advantage.

3.9 Quantum technologies and society key takeaways

- Quantum technologies can become one expression of humanity's technological ambitions, pushing the limits of what can be measured, simulated and computed, as artificial intelligence has done in other domains. Quantum computing nevertheless has fundamental and practical limits. No finite model can reproduce every detail of the universe without assumptions and finite resource bounds, and quantum computing does not make arbitrary future prediction possible. Claims about determinism, free will or the ultimate social impact of quantum technologies require more careful philosophical and scientific qualification. The quantum revolution may therefore be oversold when such claims go beyond demonstrated capabilities.
- Science fiction has built an imaginary around quantum technologies, including teleportation, superluminal travel, extreme entanglement and miniaturization, parallel worlds and time travel. These ideas do not all have the same scientific status. Some conflict with established physical constraints, while others are speculative interpretations, limited laboratory phenomena or capabilities that are simply not technologically realizable today. Science fiction can nevertheless inspire scientific vocations and motivate new generations to solve real problems.
- The quantum scientific community is investigating the ethics of quantum technologies. As with artificial intelligence, it will be questioned on algorithm explainability and auditability, on what it will do to simulate if not tweak matter and life and on how to handle public education. Some related initiatives have already been launched by scientists in Australia, The Netherlands, Canada and the UK.
- The education challenge around quantum sciences and technologies is enormous, both for the general public and for specialists. There's a need for better pedagogy, accessible educational content and for sound fact-checked information, and for the creation of suited teams for both creating and using quantum technologies.
- Gender balance remains an issue in quantum technologies, with women underrepresented in many parts of the field, particularly among technology vendors. There are nevertheless many women scientists and entrepreneurs who can serve as role models for girls and young women. Numerous initiatives around the world have been launched to improve participation and representation.
- Finally, quantum-technology vendors marketing must be watched carefully. It is and will be full of exaggerations and approximations. The worst is found with vendors from outside the quantum technology sphere.

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4 Quantum pseudosciences

One of the most fascinating topics in the mainstream impact of quantum physics is the way some people integrate it into alternative dubious scientific approaches. The vast framework of “quantum medicine” is a coherent stream of thought and practice from this point of view. It has given rise to the proliferation of gurus of all kinds and to voluntary or involuntary scams based on miracle machines for detecting electromagnetic waves or vague energies and restoring your body balance. Perceived benefit from these products may reflect expectation, the natural course of a condition, or concurrent medical care. Product-specific efficacy has not been established for any of them, and an ineffective product can delay appropriate treatment.

Other fields took over quantum physics and long before quantum computing became a visible subject: management and marketing, not to mention politics. The concept of quantum politics is still in its infancy, and let’s say, immature [706–710].

Quantum physics is essentially used there as a source of inspiration by analogy. But the “gurutisation” of these sectors is also quite common, linking together currents of thought that revolve a lot around magical thinking.

This chapter of this book on quantum fake science was created in its first edition, back in 2018, and updated since then. In 2023, **Chris Ferrie** published an entire book on this matter that drew some attention [711, 712]. It gives some useful quantum physics insights and background to separate real quantum science from fake science. This part is pinpointing with more details various examples of fake sciences and their associated commercial products.

4.1 Quantum biology

The starting point of quantum medicine is, however, scientifically highly relevant and interesting. Many low-level biological phenomena can be well explained at a low-level by quantum physics. Of course, since everything is quantum on the atomic scale! All the field of chemistry depends on quantum physics.

To mention just a few examples, this is obviously the case of **photosynthesis** in chlorophyll and plants, where an absorbed photon promotes an electron in a chlorophyll molecule and drives a chain of photochemical electron transfers, leading after the Calvin cycle to the production of glucose that is used to store energy. All the **nitrogen fixation** pathway in cyanobacteria in soil and legume roots extensions relate to quantum physics and quantum chemistry as we’ve seen when covering the famous FeMoCo simulation case study. The same applies to **retina cones and rods** which capture light. **UV-B rays** participate in the synthesis of Vitamin D3 precursors in the skin again through a photochemical reaction but at a different wavelength [713]. Quantum physics also explains the **capture of terrestrial magnetism** in the brains of many birds via a special protein called cryptochrome [714]. The leading hypothesis is the radical-pair mechanism, in which the spin state of a photoinduced electron pair is sensitive to the geomagnetic field. Evidence for it has accumulated but the mechanistic chain from spin dynamics to behavior is not complete [715–717]. Likewise, proton tunneling between the paired bases of the two DNA strands has been proposed as a contributor to spontaneous mutation, which remains a hypothesis rather than an established mechanism [718]. Understanding quantum biology can lead to biomimetism innovations such as the development of artificial nose sensors [719].

All biochemistry is quantum, involving different mechanisms with at least quantization, light-matter interactions and even sometimes superposition and entanglement. So, quantum biology is a serious scientific domain, and it deserves its proper attention while it stays in the scientific realm [720–725]. Some would obviously say, “*in the official scientific realm*”.

So far so good.

Then, some renowned scientists want to explain the origin of consciousness with quantum physics, when conscience is itself not a clearly defined concept. Several major schools of thought are related to each other like the **Orch-OR theory** (Figure 74), the **holographic** dimension of DNA and **biophotons**. And then there are all the works around **structure of water** and **water memory**.

None of these works obtained the agreement of most scientists, but it still deserves a little review. If only to understand how they are quickly being misused by the quantum medicine charlatans around the world, and particularly naturopaths.

4.1.1 Orch-OR Theory

According to **Roger Penrose** (British, 1931) and **Stuart Hameroff** (American, 1947), consciousness is housed and managed by microtubules, the complex fibrous structures that, together with actin filaments and intermediate filaments, constitute the structure of neuron cells, called the cytoskeleton, and in the case of neurons, the dendrites, synapses and axons.

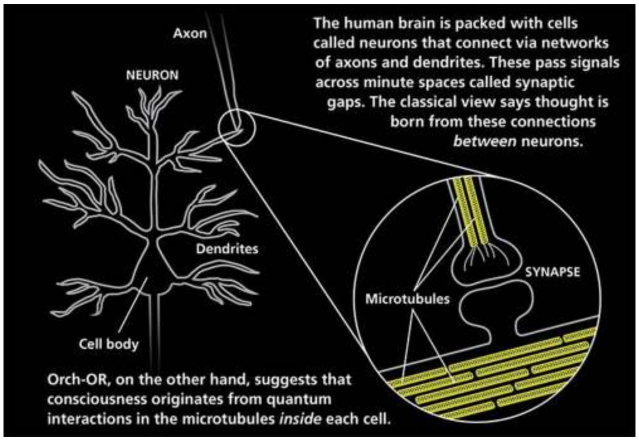


Figure 74: Orch-OR top-level view. Source: [726].

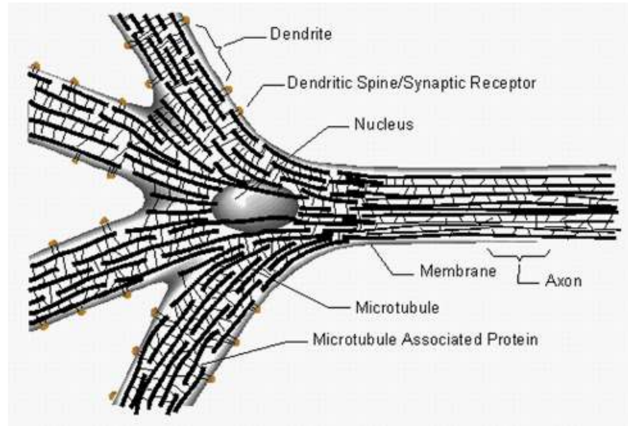


Figure 75: Orch-OR low level view with neurons and their microtubules.

In 1996, they proposed the Orch-OR (Orchestrated Objective Reduction) model according to which these microtubules were coherent quantum systems explaining consciousness. For them, consciousness is managed in the neurons within these microtubules and not by their interconnections via dendrites/synapses pairs.

In 2011, Roger Penrose and Stuart Hameroff even suggested that these microtubules, shown in Figure 75 would be quantum nano computers capable of managing qubits and associated calculations. According to other theories, quantum entanglement also operates at the level of the phosphorus atoms associated with calcium in the brain. This would be responsible for the creation of quantum bonds between neurons [727]. If this were true, the power of this computer in number of qubits would be immeasurable because a single neuron comprises about 100 million tubules, the brain 86 billion neurons and more than 600 trillion connections between neurons! These theories obviously do not specify how the entanglement between these qubits would work on this scale.

Ironically, the indirect impact of this gargantuan sizing would be to push back even further in time a possible singularity, the moment when a computer would reach the computing capacity of a human brain in raw computing power [728–732]. We are dealing here with another current of thought, promoted by **Ray Kurzweil**.

The Orch-OR theory was revived in 2014 with the discovery of quantum vibrations in microtubules by **Anirban Bandyopadhyay** from the National Institute for Materials Science in Japan [733]. But that doesn't explain anything. Roger Penrose and Stuart Hameroff also asserted that this behavior is influenced by some type of gravity-related wavefunction collapse. A physics experiment did invalidate most of this theory [734]. A 2023 experiment revived the quantum consciousness craze [735–737]. All sorts of theory abound in that field [738].

Roger Penrose was awarded the Nobel prize in physics in 2020 for his seminal work on black holes. Hawking's PhD supervisor was Dennis Sciama; Penrose was an influential collaborator, and the two proved the singularity theorems together. Hawking radiation, which combines general relativity and quantum field theory, is Hawking's own later result and is distinct from that joint work. But all this work is unrelated to the Orch-OR theory.

Hartmut Neven from Google AI wants to go even further than Neuralink with its brain-computer interface to "entangling" a person's brain with qubits in a quantum processor, being inspired by Penrose and Hameroff's work [739]. This is also the project of **Gonzalo Florez Giraldo** with his Manifesto for Ontological Quantum Computing (Year 3000) published in 2025, and who created the company Quantum Computing Engineering to deliver his vision of the fusion of consciousness and computation [740].

Consciousness is probably a combination of "nanoscopic" and "macroscopic" phenomena. Trying to explain a complex "macroscopic" phenomenon by a "nanoscopic" process is meaningless because it completely gets rid of the entire biological hierarchy between the two and the thousands of other nanoscopic mechanisms at stake in the nervous system: neurons themselves, neurotransmitters, synapses and dendrites, neurons nucleus, brain regulatory glial cells, and on a larger scale, senses and brain macro-organization [741].

For example, we could use some forceful reductionism to explain a good part of living things via the weak hydrogen bonds (which are of quantum nature, of course) that pair the complementary nitrogenous bases of the two DNA strands, or with the covalent phosphodiester bonds of the sugar-phosphate backbone, which are strong and hold each strand of DNA and RNA together, as shown in Figure 76. Likewise, how about LLM-based chatbots? These are just based on matrix multiplications (let alone some nonlinear activation functions)!

However, this is obviously not enough to explain consciousness or how your heart, eyes and kidneys work. One could just as easily build a throwaway theory associ-

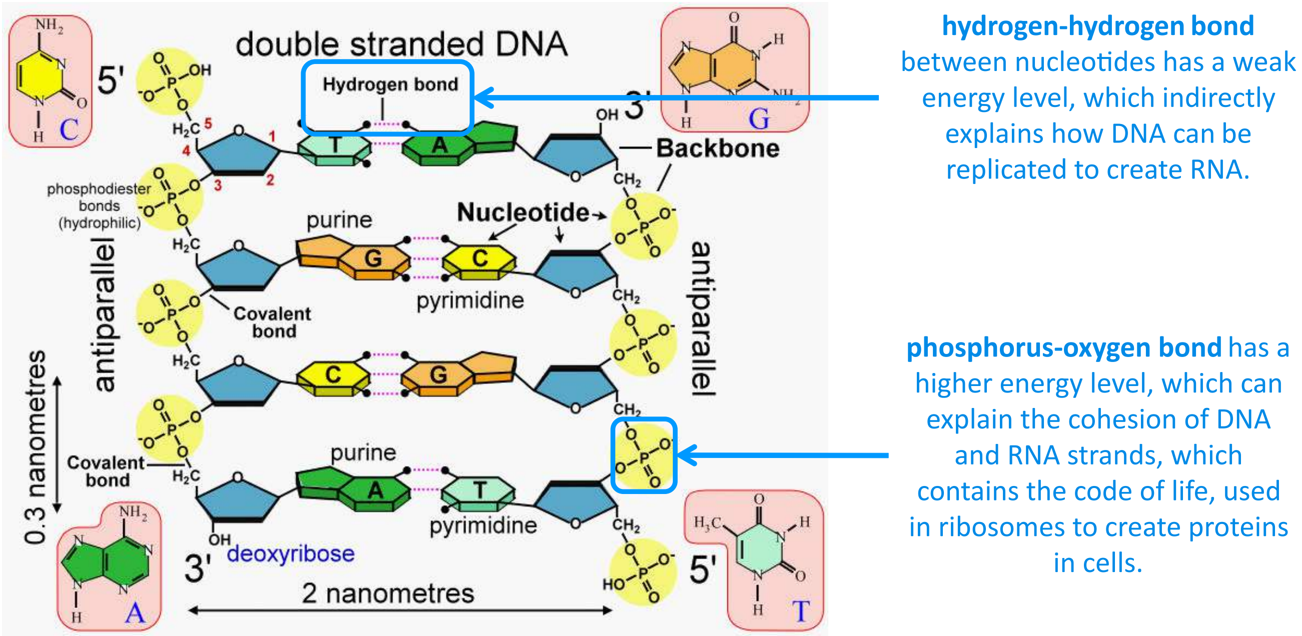


Figure 76: You can build a whole explanatory theory on life with just two kinds of chemical bond: the hydrogen bonds pairing complementary bases, and the covalent phosphodiester bonds of the backbone. Source.

ating consciousness with electrons if not with quarks and gluons. Indeed, without electrons, there's no chemistry and no consciousness! The Schrödinger's wave equation explains the chemical bonds between atoms. It can also be the mother of consciousness!

Fortunately, nobody has yet ventured into this kind of explanation. In short, explaining consciousness by the possibly quantum nature of a particular structure in neurons is the most simplistic reductionism possible, ignoring all the other knowledge available... or yet unavailable [742, 743]. This comes from the fact that some are playing with words and confusion between biological processes [744, 745] and philosophical concepts. Conscience relates to both.

DNA would also have a quantum function. A curious paper of Russian, German and English origin describes quantum and non-localized phenomena in DNA, verified in a famous experiment based on laser light diffraction, as shown in Figure 77 [746]. Through quantum entanglement, the chromosomes of several cells would interact with each other via these radiations. The leader of this work is a certain **Peter Gariaev**, creator of the concept of BioHolograms within his **Wave Genetics Institute** in Moscow [747].

One philosophical quest behind these theories is to explain freewill, or wonder whether there is even freewill.

Other attempts to explain consciousness with quantum physics have been created. **Matthew Fisher** from UCSB wanted to investigate the brain's potential for quantum computation, based on phosphorus ions spin entanglement [727]. He launched his **Quantum Brain Project** (QuBrain) with a €1M funding in 2018 from the Heising-Simons foundation. Since then, the Project was discontinued. Maria Strømme published a paper on bridging consciousness and quantum physics in 2025 but it was retracted in 2026 due to "*concerns about its scientific validity*" [748].

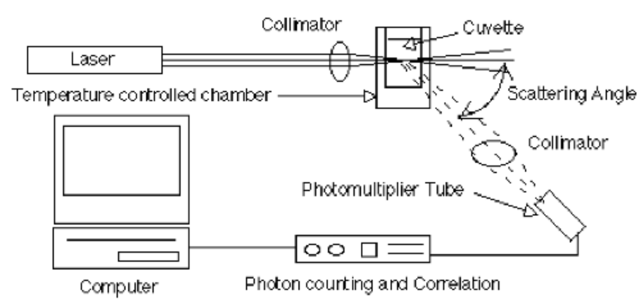


Figure 77: Testing DNA's quantum function. Sort of. Source: [746].

Quantum consciousness could emerge from the electromagnetic field surrounding neurons like a sort of force field. This is the Conscious Electromagnetic Information (CEMI) Field Theory, proposed by **Johnjoe McFadden** from the University of Surrey in the UK [749]. It has weak scientific grounds given this field would have some fuzzy global control, not necessarily at the individual neuron level [750]. Some journalists invent some quantum influence where it doesn't exist [751–754]. **Rodolfo Gambini** from Uruguay developed his "panprotopsychism" solution based on quantum states and events to explain the emergence of complex phenomenal qualities and conscious subject, ... at the scale of the universe [755].

The Quantum Conscious Agency Theory (QCAT) developed by **Suzanne Gildert** in her startup Nirvanic Consciousness Technologies (Canada) relies on the hypothesis that "*technological systems might become conscious if they process quantum information in very specific ways, using entanglement of qubits and wave function collapses*". It could help create "*safer, human-aligned artificial intelligence systems*" and robots. It could help create "*AI with qualities like intuition and empathy*". Btw, could it work with some humans? Suzanne Gildert co-founded Kindred AI with Geordie Rose [756], from D-Wave and Sanctuary AI, and previously developed quantum machine learning algorithms at D-Wave.

For other computational oriented theories, consciousness emerges from the molecular interactions between neurons. It looks quite reasonable compared to the other theories [757].

4.1.2 Biophotons

Another alternative school of thought is related to **biophotons**. These are ultraweak photon emissions, in the visible and near infrared, produced by living organisms as a byproduct of oxidative metabolism. The phenomenon itself is established. Claims that this light is coherent or nonclassical are not supported by robust current evidence. Early work is attributed to **Alexander Gurwitsch** (Russia) in 1922, and the biophoton framing was developed by **Fritz Albert Popp** (Germany). It complements at a low-level the hologram DNA thesis.

It describes the emission of photons from molecules such as DNA, but also the emission of photons related to the energy metabolism of cells such as the transformation of ADP molecules into ATP in the mitochondria of cells.

The biophotons are ultraviolet and visible light emissions, at levels that are much lower than the mid-infrared emission occurring at around 12 microns wavelength. Up to a few hundred photons per square centimeter of organ analyzed could be detected, often at the skin level. These biophotons are also made of coherent light - photons with the same frequency. They would constitute a form of inter-cellular communication [758, 759]. They have been observed in brain cells in Italy in 2025 [760].

I wonder how this communication works: at what range, due to the obvious attenuation of photons scattering, and with what precision targeting (direction, orientation).

According to Fritz Albert Popp, raw foods emit more biophotons than cooked foods, and organic raw plants emit five times more biophotons than traditionally grown plants. Conclusion: eat raw and organic! This is also a reason to have prehistoric men regret having discovered fire!

In any case, the detection of biophotons on the 10 fingers of the hand would make it possible to detect cardiac pathologies [761]. The **ClearView** scanner used exploits a curious process: it sends a high-voltage pulse that ionizes the air around the finger, creating a corona discharge between the sensor and the finger. What is recorded is that discharge, not amplified endogenous photon emission (Figure 79, *left*) that ionizes the air, generating the emission of UV and visible light. This is the **Kirlian effect**, discovered by the Russian Semyon Kirlian in 1939.

The ionization that is captured by the camera (Figure 79, *right*). The software analyzes the generated shape and compares it to a pathology database. I have a hard time figuring out the exact link between bioluminescence and this process! And what about the receptors of these biophotons?

Well, it comes from the neuron microtubules, of course, closing the loop [762] (Figure 78)!

David Muehsam mentions many biological effects of biophotons, which would be involved in the regulation of neurotransmitters secretion (for rats) but without the distinction between correlation and causality being visibly made in the associated publications [763].

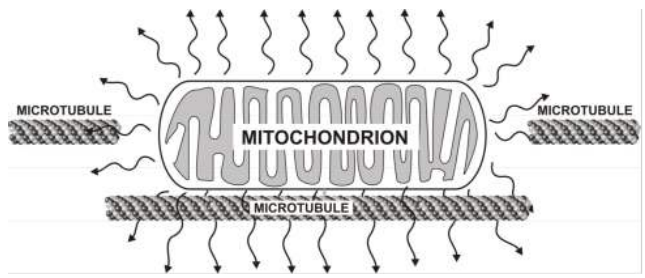


Figure 78: Biophotons emitted by mitochondria near microtubules. Source: [762].

If all that was just science and research! But hell no. It helps snake oil vendors to sell miracle healings through the control of the body by consciousness. Practitioners of quantum medicine are very often psychosomaticians exploiting mysticism and autosuggestion to generate, in the best of cases, a good placebo effect that can work with certain mild pathologies. Even so, they justify their methods on the contested work of researchers such as Roger Penrose and Stuart Hameroff, already mentioned, but also Karl Pribram and Henry Stapp, who want to explain human consciousness by quantum phenomena intervening at a low-level in the brain that would also explain a so-called immortality.

Wikipedia's Quantum Mind[W] fact sheet reports on the evolution of this branch and the associated criticisms. It underlines the fact that there is no way to apply possible quantum phenomena such as entanglement at the scale of macroscopic brain molecular or cellular structures.

Entanglement is even less justifiable to connect the brain at long distance to the "*holographic global consciousness of the Universe*" promoted by **Karl Pribram** and **Paola Zizzi** [764].

Similarly, it does not necessarily make sense to link mind and matter as waves and particles and their famous duality. This otherwise leads to absurdities that explain psychic phenomena of synchronicity by the conscious-

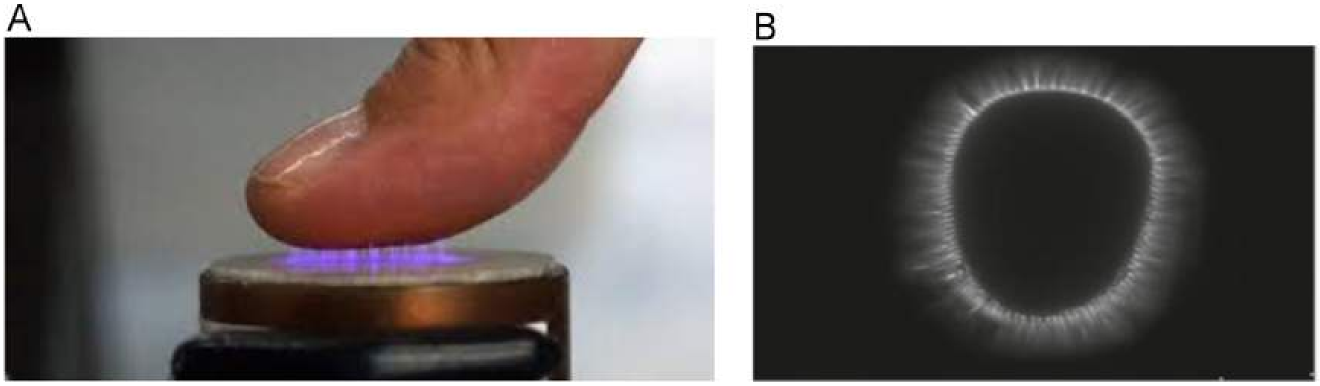


Figure 79: Biophotons. Source: [761].

ness wave function collapse, an explanation that is as absurd as is the Schrödinger's cat thought experiment. Even if Penrose and Hameroff's theories were verified, the shortcut would be a little hasty, connecting way too fast a nanoscopic phenomenon to a macroscopic phenomenon!

The other commonly proposed method involves the use of various electromagnetic waves, including the famous and smokey **scalar waves**. The idea is to exploit them to restore the balance of unbalanced organs, exploiting the wave-particle duality and the ability to restore the basic energy level of... we don't know. Particularly given the proposed waves are not really targeted.

It is notable, however, that few scientific specialists in quantum medicine mention the capabilities of future quantum computers to simulate the operations of organic molecules and create new therapies. Maybe because known applications of quantum computing in health care are part of traditional allopathic medicine, that they usually avoid or at least complement.

However, I found a vague trace of this with **Matti Pitkänen** (Finland) who, in the framework of his work on TGD (Topological Geometrodynamics), proposes a unified theory of physics, and puts forward the idea of creating DNA-based quantum computers [765]. He believes that DNA communicates "with the Universe". It is also based on **Luc Montagnier**'s (France, 1932-2022) experiments on DNA. Matti Pitkänen provides the basis for highly speculative theories on the supposed consciousness of the Universe [766]. His theories of the unification of physics are so complex that they are impossible to understand, and eventually to validate by experience or to refute.

In the field of light-based therapy, one puzzling solution being sold comes from **Bioptron AG** (1988, Switzerland), part of **Zepter Group** (1986, Switzerland), since 1996. Its "Bioptron Quantum Hyperlight" uses "hyperpolarized light" generated with fullerene (C_{60}), a molecule also used by Archer for trap its electron spin qubits. Among other benefits, it treats injuries pain, avoiding pain killer drugs. So far, so good. The system generates some vertically linearly polarized light which passes through a filter containing these fullerene molecules which happen to rotate at a 1.8×10^{10} frequency per second. It creates "*perfectly ordered hyperpolarized light*" that is supposed to have some quantum properties similar to those of the biomolecules inside our bodies. Practically, this light is made of both vertically and horizontally polarized photons that "*without exaggeration, [...] reestablish the balance and harmony of energetic processes in biostructures and to harmonize cells, bringing them to back to their initial state of natural equilibrium*". Contrarily to many of the pseudo-quantum scams we'll cover later in this section, this offer is fairly well documented, even scientifically [767, 768]. You're flooded by tons of scientific information, historical references, links to Nobel prize inventions and scientific publications. But many indices generate serious doubts [769]. Among others, it mentions these dubious Emoto's research on water structure and the way it can be changed with music and good mood. It shows that most scientific surveys were of small scale and non audited and with no control group trials. It was done only on wounds healing. But the vendor web site touts many medical indications that their device is supposed to treat, without any scientific evidence, beyond wounds healing: osteoarthritis, arthroses, lowered motivation and the inability to feel happy. All are good indications, in the best case, of some placebo effect. On top of that, the Zepter also sells blue and red LED light therapy devices, for €500. The Bioptron is priced at about €1,000

In December 2023, **Guerlain** launched a "quantum rejuvenating cream" in France and worldwide. It drove a significant pushback from the scientific community. There was nothing quantum in the cream, which was based on orchids. The quantum part was in a process the company used to evaluate the efficiency of the cream which was based on detecting the change in ultra weak photons (ala biophotons) emissions by the skin, the lesser the better, since aged skins are supposed to emit more biophotons [770]. These biophotons are weak light covering the spectrum from UVA to near infrared that are generated by cells metabolism. Large emissions are supposedly linked to an excess of oxidation in the skin, due to aging. Guerlain's "science" was linked to some work done in Czechia [771, 772].

4.1.3 Water memory

The last area on the thin line between science and charlatanism is that of water. It features a model of thought close to Roger Penrose's **Orch-OR** theory, which explains everything about life based on a few isolated physical phenomena at the microscopic level. The phenomenon of the **memory of water**, its explanation by **electromagnetism**, and parallel theories on the **water structure** are all mixed.

One of the starting points around the role of water is **Jacques Benveniste**'s work on water memory. This immunology and allergies specialist was a director of an Inserm research laboratory in Clamart, France. He conducted experiments that led to the conclusion that "*water could preserve a memory, a print, of substances that have passed through it*". With Israeli, Italian and Canadian researchers, he published a landmark article in Nature in 1988, which was soon contested [773]. He also published a book on 2005 telling his story, with a preface by Brian Josephson, who became an adept of many fringe sciences [774]. In the Nature paper, Benveniste described a series of experiments that showed the effectiveness of anti-IgE (anti-immunoglobin E) causing the loss of histamine-containing granules by a type of white blood cell, basophilic cells, even when this anti-IgE is repeatedly diluted to the point where no anti-IgE molecule can be found in solution. For this to work, solutions must be shaken vigorously after each dilution, using the "dynamization" principle!

In the article, Benveniste hypothesized that the phenomenon could be explained by the creation of structured networks in water or by persistent electric or magnetic fields. They would constitute some sort of "water memory" which would "record" the allergen characteristics and reproduce its effects on basophilic cells. This was supposed to explain high dilutions used in homeopathy (Figure 80)!

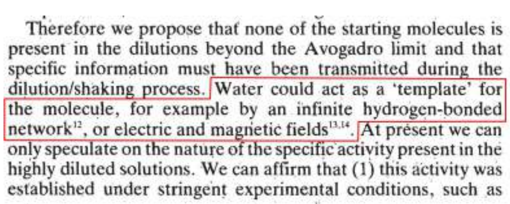

Therefore we propose that none of the starting molecules is present in the dilutions beyond the Avogadro limit and that specific information must have been transmitted during the dilution/shaking process. Water could act as a 'template' for the molecule, for example by an infinite hydrogen-bonded network[12], or electric and magnetic fields[13,14]. At present we can only speculate on the nature of the specific activity present in the highly diluted solutions. We can affirm that (1) this activity was established under stringent experimental conditions, such as

Figure 80: Water memory key description in Benveniste's Nature paper. Source: Human basophil degranulation triggered by very dilute antiserum against IgE, Jacques Benveniste et al., June 1988 (3 pages).

The promoters of this empirical medicine devised by **Samuel Hahnemann** around 1810 and explained in the book "The Organon" thought they had finally found their scientific support.

Testing and evaluation protocols were flawed in many ways. Solutions were not analyzed by spectrographic analysis to deduce their molecular composition (Raman spectrometry was used in other experiments, starting in 2007, on various homeopathic strains). Only electrophoresis was used to detect the presence of ions. At high dilutions, electrophoresis showed that there was no anti-IgG molecule left in the active ingredient. The presence of histamine resulting from the release of granules from the basophiles had not been assessed.

It was realized in other experiments that there was none! Moreover, the phenomenon presented a cyclic character of a period of 8 dilutions (in Figure 81), according to the successive dilutions, but being out of phase by four dilutions from one experiment to another. No explanation is given for this cyclic phenomenon [775]. Ironically, the process used does not prevent allergic reactions as is expected in homeopathy, which wants to treat evil with evil, but in low doses. Here the anti-IgE causes the production of histamine and does not prevent it. The electromagnetic theory that would explain the phenomenon is his other Achilles'heel.

It is weakly substantiated. These waves are neither characterized nor measured and their source has not been explained. The story of Jacques Benveniste is the story of a curious experimenter who lacks, however, the bases in adjacent disciplines around electromagnetism. However, he did investigate long-range electromagnetic fields, inspired by the work of Italian physicists specialized in quantum electrodynamics, **Giuliano Preparata** (1942-2000) and **Emilio Del Giudice** (1940-2014). In 1990, he set up an experiment with the CNRS Central Laboratory of Magnetism in Meudon, France, which showed that the activity of the diluted solution is modified by prolonged exposure to a magnetic field. The experiment used animal hearts with an electrical apparatus invented by **Oskar Langendorff** (1853-1908).

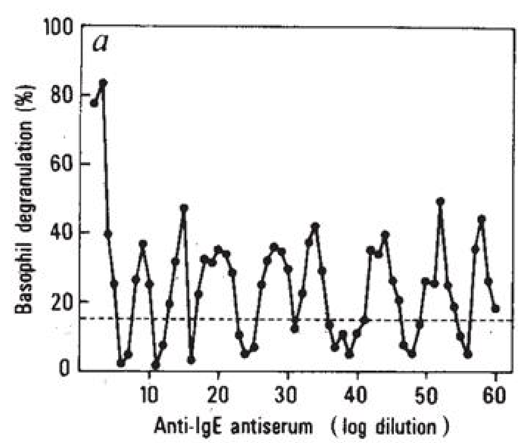


Figure 81: The 1988 Jacques Benveniste water memory experiment plot. Source: [773].

In another experiment carried out over several years, he also uses an amplifier using a sound card from a microcomputer to transmit the properties of a solution to another neutral liquid. This leads to the concept of "digital biology" [776].

After the death of Jacques Benveniste in 2004, his work was taken over by **Luc Montagnier** (1932-2022, French), who created the first AIDS treatment and got the Nobel Prize in medicine in 2008. He described low frequency waves (7 Hz) that would be emitted by DNA strands. He set up an experiment in which the waves of DNA molecules are transmitted through a coil fed at 7 Hz to pure water in another test tube. A PCR is then used to regenerate the DNA in this test tube (DNA multiplication process, "polymerase chain reaction"). And gel electrophoresis is used to decode the replicated DNA! In the experiment, this DNA corresponds exactly to the original DNA.

His code would have been transmitted by electromagnetic wave [777, 778]. But the documentation does not specify which DNA was used as a primer for PCR! Indeed, a PCR does not start from zero and a bunch of nucleotides but uses DNA strands to replicate them. This PCR problem is noticed in [779].

The work of Luc Montagnier is related to **Emilio Del Giudice**, again, on the structure of liquid water [780]. It will not surprise you to learn that this kind of discovery is rather controversial among specialists [781].

Luc Montagnier's paper was not published in a peer-reviewed journal, but he continued to publish, with international teams, on interesting research explaining with quantum field theory how DNA polymerase works [782]. The relationship between water and quantum physics is being emulated by others and drove the creation of many scams selling structured water [783].

Konstantin Korotkov (Russia) did some experiments supposed to show that projecting negative emotions on water reduced its energy level and vice versa [784, 785]. Korotkov created IUMAB (International Union of Medical and Applied Bioelectrography), an organization that promotes the use of bioelectrography devices [786]. He is promoting DGV Bio Well cameras, aura detection systems around patients that would materialize the chakras, via the analysis of the "gas discharge" (Figure 83). It spurred the creation of various scam businesses like Quantum Lab in France.

We then have **Mazaru Emoto**'s MRA (Magnetic Resonance Analyzer) (1943-2014). He conducted experiments analyzing the impact of emotions on the structure of water. Experiments that were never reproduced independently [787]. You probably guessed it! [788] makes a good inventory of structure water commercial offerings in the USA. Masaru Emoto also certified an effect of exposing "zam zam" water that is produced at Mecca to Quran. The water is supposed to have similar miraculous effects, a bit like Lourdes' water in France.

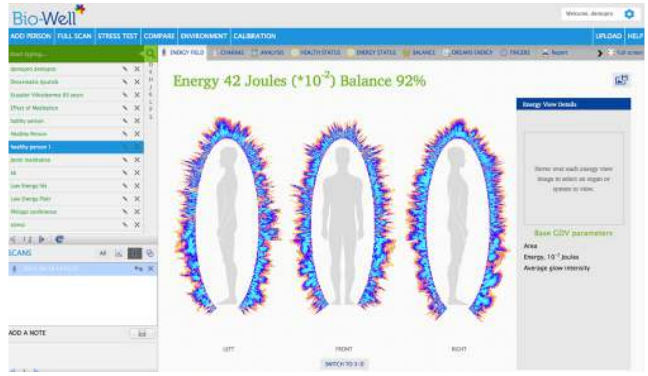


Figure 84: The Bio-Well measures human energy using bio-electrography, a technique inspired by Konstantin Korotkov. These are clearly scams.

OK, emotions can generate infrared waves and gases that can be exhaled, producing in turn a minute reaction on exposed water [789]. This makes it possible to sell a concentrated structured water that can be used to prepare distilled water, **Indigo Water** (in Figure 85). Here is the description: "*A geometrically perfect water with the 'Message' your body is waiting to receive. Dr. Emoto's Indigo Water contains eight ounces of highly charged hexagonally structured concentrate. By mixing one ounce of concentrate with one gallon of distilled water, you are creating eight gallons of structured water from this 8 ounce Indigo water. This is about a one month supply of structured water*". For $35. By the way, it doesn't mention if it's drinking water or shower water!

The delirium continues with the structured water of **Rustum Roy** (American). Structured water is said to be an antibiotic: "*One molecule of structured water in 100 million molecules of drinking water can destroy all germs present in a wound. The American army has used this water in Iraq and Afghanistan. Obama uses structured water to wash his hands*". Verification made, the only example that can be found is the healing of a foot wound and it's water associated with money [790, 791]. And how can we restructure water, so to speak? Simple: by heating it, with vortexes, magnetic fields, music, the force of thought, "frequencies" or minerals!

The concept of wormholes comes from the astronomer **Nicolaï Kosyrev** (1905-1983) who discovered lunar volcanism and the biologist **Rupert Sheldrake** (1942), who became an expert in telepathy. This led to **Vodaflor**'s Voda vortexors which generate vortexes in water to structure it with models ranging from €936 to €3,300 depending on the desired water structuring rate.

Then, the discourse around the benefits of water in homeopathy was renewed with the integration of quantum electrodynamics as an explanatory feature. Why not, since almost nobody can understand anything about it, except the few physicists in this domain [792]. Not to mention the lack of experimental protocols to verify anything. Again, we are confronting a fake science because it cannot be refuted!

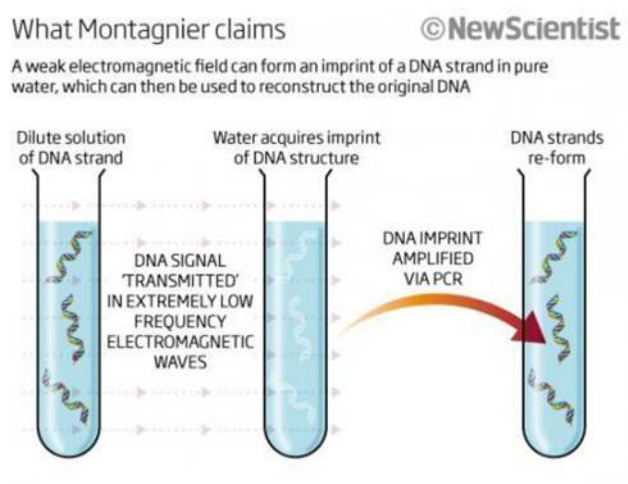


Figure 82: Montagnier claimed DNA could be created in water containing just…water molecules. How did carbon, phosphorus and nitrogen atoms appear? Source: NewScientist.

Figure 83: DGV Bio Well camera.

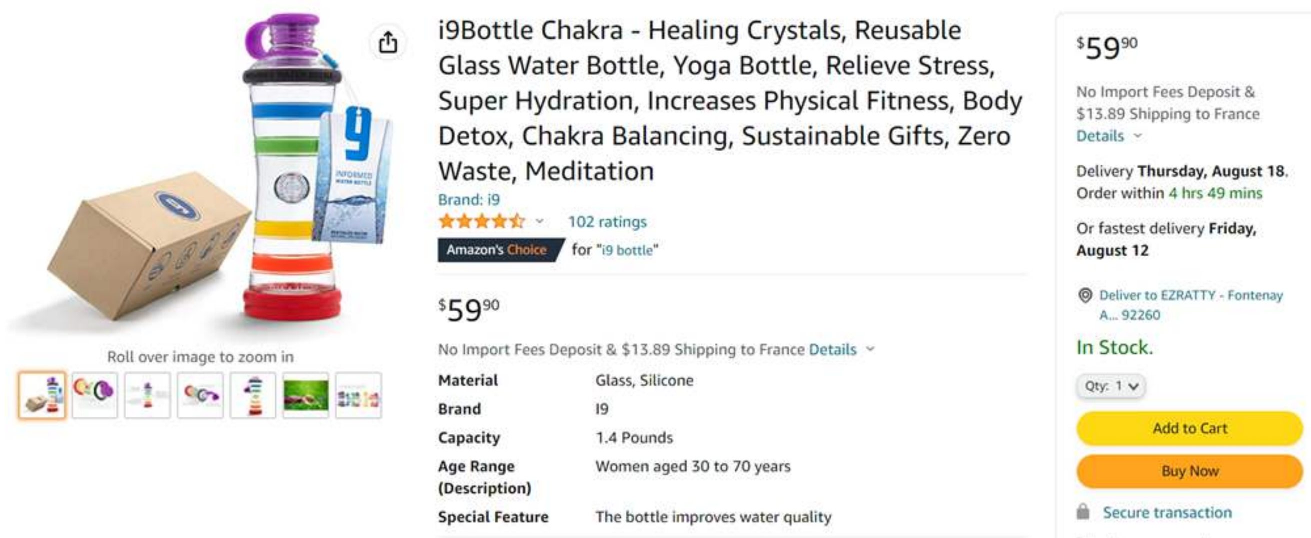


Figure 86: You can buy plastic bottles that will structure your drinking water. It is even not a thermos!

The structured water business has evolved a little. Instead of selling structured water, some companies are now selling bottles that create this structured water with regular water. It is just a bottle, or sometimes it contains a regular battery-powered blender. It sells for about $60 on Amazon (Figure 86).

Figure 85: A structured water scam. Source.

To conclude this part before moving on to the most beautiful scams of pseudo-quantum medicine, let us recall that there is a fine line between low-level science and its high-level interpretation, especially when it is then exploited by unscrupulous entrepreneurs.

And we are not done finding more of the same such as some weird quantum behavior of water in carbon nanotubes [793], superconductivity in the brain [794] or other elucubrations on quantum cognition [795]. This will undoubtedly fuel new waves of quantum mysticism[W]!

4.2 Quantum medicine

As Wikipedia's quantum healing page[W] on quantum medicine points out, this discipline misuses the jargon of quantum physics to make people believe in magical cures for certain pathologies that traditional medicine, well or badly practiced, cannot treat properly. The phenomenon is already over a decade old.

4.2.1 Method for detecting false sciences

The methods used to promote false quantum science in health (and in general for that matter) are easily detectable to an educated person, or just with some common sense:

- It starts with some **scientific statement** associating very quickly humanities and biology and making approximate shortcuts on quantum physics.
- The solutions are being promoted with some **esoteric jargon** using unprecise terms like wave, matter, vibration, vortex and energy. Like in this website in [796] which consolidates all these fancy alternative quantum medicines, mostly all based on placebo effect. You have consciousness awareness techniques, acupuncture, homeopathy, electromagnetic resonance, color, light, sound and music therapy.
- When they exist, **tests are performed with small samples** that are not statistically representative. The arguments are often based on non-verifiable anecdotes. The miraculous healings observed in Lourdes, France, are even better documented and, moreover, as probable as those occurring in the hospital environment [797], i.e., between 1/350,000 and 1/100,000 cases.
- Many specialists sell various, rather expensive, **healing materials or devices**, not considered as medical devices, and whose effectiveness is clearly related to the placebo effect.
- These solutions' marketing target **vulnerable people** (sick, elderly, etc.). It can be seen in the media used for advertising it.
- The **vague side of the pathologies covered**. Some are related to pain management or to what can be treated by placebo effect, such as psychonomy which is yet another false science associating mind and body. Others target all the major pathologies of the moment: chronic diseases, cancers and in some cases even neurodegenerative diseases.
- **Extended resumes** with impressive diplomas and scientific guarantees to be taken with a grain of salt for many quantum medicine specialists. There are even "diploma mills" in the USA, where you can buy a doctorate in medicine or another junk discipline at a reasonable price. A bit like in the late Trump University.
- Rare **scientific publications** and when they exist, rarely published in peer-reviewed journals, knowing that this validation is already not enough to be a guarantee of seriousness. These therefore become "private" publications. Or it can't be falsified, like with this paper on quantum immortality that is based on a mathematical approach the many-worlds interpretation [798].
- Some **conspiracy theories** about the pharmaceutical companies lobbying and other healthcare professionals who will do anything to prevent alternative solutions from emerging.

Nonetheless, there are positive comments from readers of these books that show that the market for gogos is a thriving one. It takes place in a context of loss of confidence in politics, media and science and the development of many conspiracy theories, fueled by the fluidity of the Internet and social networks.

4.2.2 Quantum medicine marketing

Let's review some of the reference books that promote this curious quantum medicine.

Quantum Healing by Deepak Chopra (1988) seems to be foundational. It comes from a former endocrinologist. He became an Ayurvedic practitioner, coming from traditional Indian medicine. According to him, quantum thinking explains some cases of psychosomatic healings that resemble self-healing. The author is a star in the field, especially in India and the USA, with a total book sale of over 10 million copies and a personal fortune estimated at over $80M [799]. The content of his works is of course quite weak scientifically speaking, especially when he deals with quantum physics, mostly in metaphorical terms. Of course, all of this is plain nonsense and has been widely debunked [800]. The author admitted that his work was "parabolic".

It was debunked by Richard Dawkins during a debate with Deepak Chopra in 2013 [801]. It highlights the difficulty of reconciling Chopra's emotional and symbolic approach with Dawkins'rationalist and scientific approach. At one point, the debate focused on the supposed Universe intelligence that exists according to Chopra and at all levels, from elementary particles to the entire Universe. While this makes no sense to

Dawkins beyond biological beings with brains, or computers imitating them. It is a homothetic debate with the link between consciousness and the pathologies that consciousness would or would not necessarily control. The other interesting part of this debate deals with the notion of "quantum leap" on the appearance of language or certain biological evolutions that make no sense for Richard Dawkins. He even blames Chopra's "deliberate obscurantism". For him, consciousness is explained or will be explained by neuroscience and certainly not by Deepak Chopra's meta-consciousness fallacies (Figure 87).

Amit Goswami's **The Quantum Doctor** (2004) is along the lines of Deepak Chopra's theories. The author is an Indo-American physics teacher who practiced in Oregon between 1968 and 1997, but in nuclear physics. He defines himself as a quantum activist who even has his own Quantum University which seems to be to healthcare what Trump University was to business schools.

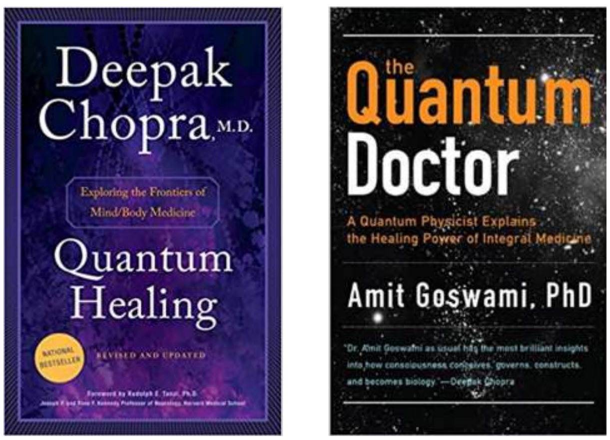


Figure 87: Deepak Chopra and Amit Goswami are promoting a quantum medicine with no scientific content. At best, it can generate some placebo effect.

According to him, quantum activism through consciousness can save civilization. He also demonstrates scientifically (!) the existence of God by building upon Deepak Chopra's consciousness of the Universe thesis. In his work, he explains the therapeutic effectiveness of "integral medicine" which combines allopathic medicine and more or less soft, alternative and traditional medicines, particularly Indian and Chinese. But god's existence can also be proven with some laser beams [802]!

The scientific content of the book fits on a tiny postage stamp. It looks even like a giant quantum joke. The idea is the following: your organs are born in good health. A time passes, like a qubit would become after a Hadamard gate, it becomes superposed in good and bad health. Then, with the strength of your consciousness, you could provoke a quantum wave function collapse of your organs into the health version. That simple! It's a scam version of this poor Schrödinger's cat.

The work also seeks to explain the effects and precepts of oriental medicines (chakras, reincarnation, ayurvedic medicine, acupuncture). Here are a few selected excepts with the "*morphogenetic fields of the vital body*", "*when the mind creates the disease, sometimes healing is impossible to achieve on the mind level. One must then make a quantum leap to the supramental to heal*" or "*quantum collapse is also fundamentally non-local. Therefore, the nonlocality of healing, as in healing through prayer, finds a clear explanation within the framework of quantum thinking*". With quantum entanglement, one can relate everything to everything and explain everything.

Amit Goswami mentions distant healings through prayer by referring to an experiment by physicist **Randolph Byrd** in 1988. The statistical representation was very weak with 6 healings out of 26 patients of not well specified cardiac pathologies. It may not surprise you to find out that it was demonstrated that prayers did not have any large-scale effects [803].

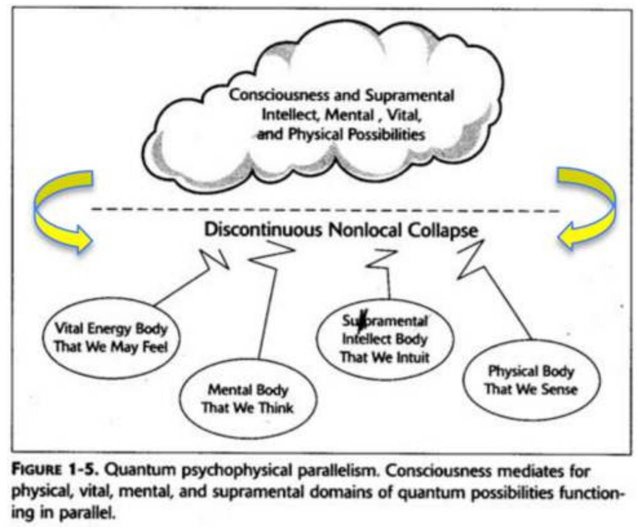


Figure 88: The nonsense describing quantum consciousness in Chopra's books. Source: [804].

He also quotes the telepathy experiment of **Jacobo Grinberg-Zylberbaum** (Mexico) [805, 806]. It involved measuring EEG waves on a participant to assess the impact on him of a flash of light arriving on one of the participants, both of whom were in Faraday cages. The experiment was repeated later between 2000 and 2004 using MRI [807]. A small technical detail: there cannot be any radio waves transmission between the participants who are in Faraday cages, no photon either, nor particles with a common history in the brain of the participants.

Others have a slightly more scientific view of the quantum nature of consciousness, such as **Ervin Laszlo**, even if the latter relies a bit too much on quantum entanglement in his explanations [808, 809].

Then we have the many pseudo-scientists who promote fancy theories related to the so-called quantum medicine.

James Oschman (USA) promotes a concept of life energy, based on electric currents and water related quantum phenomenon. He invented the concept of perineural brain cells, which are obviously only the glial cells that surround neurons, but with a different name and which generate energy that goes to the hands [810].

Kiran Schmidt is a German who does "information medicine". He also promotes strange machines that are supposed to cure everything, especially under the brand **lnergetix CoRe**.

Nassim Haramein deals with the energy of creation and also water memory. He is selling fancy products through his Resonance Science Foundation. The starting point? Some work on his unified field theory, an old Holy Grail of fundamental physics [811]. This scientist thinks he has discovered an infinite source of energy. Of course, none of the work of this "scientist" was validated by his peers. Nassim Haramein published work on neutrons and protons. Some of his papers were published in the journal Neuro Quantology which is not considered as being serious and whose review committee does not include any scientist in quantum physics or neuroscience. This publication process is known and exists in other fields such as medicine.

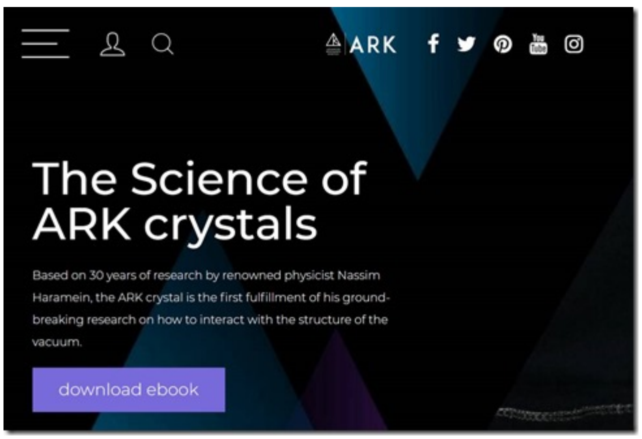
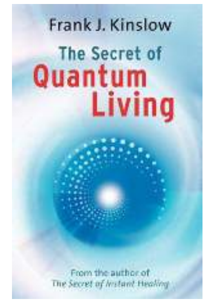


Figure 89: There's no science in ARK crystals, it is a scam.

This guru markets ARK crystals, which are magical crystals that heal or improve the performance of athletes (Figure 89). The company even published a study on how to improve athlete performances. It used a double-blind method with a placebo effect for half of the test subjects. Given the study involved only 10 athletes, 5 men and 5 women, with progress of about 10%, thus within the margin of error of the sample. The study was done by the Energy Medicine Research Institute laboratory, versed in studies of fancy products such as LifeWave placebos marketed in a Tupperware-style pyramidal model.

These crystals would also help accelerate plant growth! Prices range from €277 to €1,850. This is part of a trend in the sale of magic crystals, with a plethoric offer [812–815].



Frank J. Kinslow's **The Secret of Quantum Healing** (2011) introduces the notion of "Quantum Training", a "*scientific, fast and effective* method that *reduces pain and promotes healing"*. In a few words, it is about having your consciousness send vibratory waves to your organs to heal them. By the play of interferences, they will cancel the evil.

Another Schrödinger's cat trick with the application of the quantum mechanics of the pico (elementary particles) to the macro (the organs). It is mainly aimed at physical and emotional pain. It is a variant of meditation. It should be avoided for the treatment of hypothyroidism or about anything else by the way!

This kind of work has the particularity of always being very vague on the notion of pathology treated, especially if a pseudo-medical apparatus is involved, as is the case here. Even if the "Quantum Training" is supposed to work remotely.

Quantum Intronic Medicine from Christian Daniel Assoun deals with quantum biology. It is a form of epigenetic treatise describing DNA memory by quantum mechanics. According to him, "*WATER is the first quantum liquid: its current state is liquid* whereas *its state should be gaseous"*..

This book describes the presence of a third DNA catenary in the form of physical plasma (hydrogen) [816, 817]. He states that his "*work is currently focused on the INTRONIC parts which represent 95% of our DNA and which are unfairly classified as silent or even useless".* Intronic is used in the sense of DNA "introns", the part of DNA genes that is transcribed into RNA when the genes are expressed.

These are eliminated during splicing which generates mature RNA that will then be used in the ribosomes to make proteins. In fact, introns represent only 25% of human DNA. The rest, about 73%, corresponds to sequences that are effectively non-coding in the DNA of our chromosomes, but whose role in the regulation of genes is progressively revealed with research. Exons, the coding part of genes, represent 1.5% of human DNA (source[W]).

Christian Daniel Assoun believes that DNA could be strengthened with "the *help of new tetravalent elements such as Germanium or Silicon (reverse optoquantic properties)"*. Why germanium and silicon? Because they are in the same column of Mendeleev's table as carbon with four free electrons. This is a good idea for creating extraterrestrial life. So why didn't life on Earth use silicon, which is far more abundant than carbon in the Earth's crust? One of the reasons is that silicon oxide (SiO_2) is inert and solid while carbon oxides (CO, CO_2) are gaseous and therefore more easily recombinable with other atoms and molecules. Carbon chemistry also forms stable chains and rings with a versatility that silicon does not match under terrestrial conditions.

Christian Daniel Assoun is also the founder of the **Glycan Group**, in 1996, a company selling organic silicon for various uses and notably as a food supplement. Their subsidiary Glycan Pharma was struck off the commercial register in 2012. The company is in competition with Silicium Espana, a company linked to Loic Le Ribault, who died in 2007, who was also passionate about organic silicon. The two companies had a legal dispute in 2011 over the use of the G5 trademark.

Finally, you also can count on the many books on Transurfing by **Vadim Zeland** who introduces himself as a physicist. This quantum model of personal development is based on the idea that "*When the parameters of mental energy change, the organism moves to another lifeline. [...] the organism moves towards another life line*". So be it!

4.2.3 Scalar wave generators

The best of the quantum medicine scams are the **scalar wave generators**. Their promoters describe them as the combination of a horizontally polarized wave and a vertically polarized wave of the same frequency, a quarter cycle out of phase. Two orthogonal components in phase quadrature produce circularly polarized light, which is an ordinary transverse electromagnetic wave. Maxwell's equations admit no scalar electromagnetic wave, and the associated claims about propagation from the Sun alongside neutrinos without energy loss have no experimental support.

Scalar waves were initially promoted by a certain **Thomas Bearden** in the USA as well as by the Russian **Sergei Koltsov** with his Functional State Correctors (CEF [818]). Bearden explains this in a 1991 interview. He had also invented a **MEG** (Motionless Electromagnetic Generator) capable of extracting free energy from the vacuum and thus, of generating more energy than it consumed. A product that has of course never been commercialized.

Scalar waves were also promoted by a German scientist, **Konstantin Meyl**, with a paper that had to later be retracted [819, 820]. The general public propaganda on scalar waves is a big fantasy and always linked to alternative medicine literature. These waves would come from the Sun with neutrinos and have no energy loss over distance. The brain is supposed to produce and sense scalar waves with its own interferometer. It would explain telepathy and other paranormal effects. Well well.

Scalar waves would also make it possible to treat diabetes (I or II? Who cares...), kidney stones, Parkinson's disease, heart attacks, osteoarthritis, cancer and also aging. As for type I diabetes, which is linked to the autoimmune destruction of beta cells of the islets of Langherans in the pancreas, it is not clear how waves of any kind would bring dead cells back to life. The proposed solution?

Scalar wave generators such as the **INDEL** at €8,820 (Figure 90). Given its price, it targets professionals in a kind of Ponzi model. This generator produces a scalar wave field with a voltage of 2V. It also includes a music modulation accessory for therapy practices and wellness centers. It is also available at **QuWave**.

You can also (not safely) rely on the **ETHX-SCIO Biofeedback** from William Nelson, which combines global therapies and advanced quantum physics (in Figure 91). The device scans the body on 10,400 different frequencies to detect many pathologies. It then rebalances the body's energy with quantum biofeedback. The toy also runs 200 biofeedback therapies with the world's largest health software that integrates Western and Eastern philosophies [821]. The EPFX-SCIO includes a wave diffuser box, connected to the patient with sensors attached to his ankles, wrists and skull. One could almost do both an EEG and an ECG with it! All this for getting some placebo!

In the scam devices category, you also find the **Healy** and its bioresonance features using some electrodes and supposed to cure many illnesses [822]. At best, it can be a temporary pain killer. Another device, the **TimeWaver**, is based on "quantum field theory" from a certain Burkhard Heim (1925 -2001, German) on the 12-dimensional composition of the universe where "*the light quantum effect communicates mainly with the Global Information field (GIF) i.e. at a nonenergetic, non-phenomenal and therefore more causative level*". It looks like a biofeedback device similar to the one above. Burkhard Heim did try to unify all quantum theories, but he was neither a Dirac or a Feynman [823]! The TimeWaver site mentions **Kozyrev's mirrors** using cylindrical aluminum sheets that were used for extrasensory perception experiments in Russia. But it doesn't seem to be involved in the TimeWaver device. It hopefully has a disclaimer: "*Science and conventional medicine does not acknowledge the existence of information fields their medical and other important TimeWaver systems and their applications due to lack of scientific evidence. The said application is based on, treatment options, experiences and anecdotal reports from the practice*".

Other various Russian 'quantum' scientists, dead or alive, are frequently used in support of these scam devices like Nikolai Kozyrev, Vlail Kaznacheev or Alexander Trofimov. When you look at their biographies online, you quickly find that they were not at all mainstream quantum scientists. This is all full of esoterism, not science.

Figure 90: Scalar waves apparels cost a lot and do nothing.

Figure 91: SCIO Biofeedback is not better.

You can also discover the **PRK-1U** scam. This device is based "*on the fundamental level of information and the principle that a thought has some physical activity*" (Link). It is probably some basic electronic system delivering some low-voltage DC current. Of course, it is quantum!

4.2.4 Quantum medallions

Quantum medallions for smartphones have become commonplace for several years and target another phobia, electromagnetic waves and 5G. This is the case of **Quantum Science**'s Quantum Shield medallions (on Amazon and Alibaba). One also finds some in the form of USB keys **5G BioShield** which contain a "*quantum holographic catalyst*" (Figure 92).

It is obviously a huge quantum scam. It is accompanied by a scientific justification that is not worth a lot of money [824]. The American FTC has flagged these products as vulgar scams [825]. It was even later discovered that some of these medallions were radioactive due to their component metals. Worn on over a long period of time, they could actually be dangerous [826].

Figure 94: A so-called quantum ozone generator sold for indoor air purification. It is not quantum, and ozone generators should not be operated in occupied spaces.

In the field of wacky quantum devices, let's finish with the **Quantum 5 Ozone Generator** using Neos Technology from the **Longevity Resources** (sources). It uses a quartz electrode (Figure 94). It is advertised for indoor air purification. The US Environmental Protection Agency states that at concentrations that do not exceed public health standards, ozone is generally ineffective at removing many indoor air pollutants, and that at higher concentrations it can irritate and damage the airways. These devices should not be operated in occupied spaces. In short, quantum medicine may one day emerge in the wake of scientific discoveries, but the ones proposed today is for the time being full blown charlatanism.

They have the advantage of generating at least a placebo effect for users and filling the wallets of their promoters. Except that this can be dangerous if the placebo effect is used instead of a traditional treatment that is essential to stay alive.

I will not, however, trash all the techniques and approaches mentioned here. Some may make sense, even though there is still a lack of both a scientific corpus and more solid evidence to support them. But most are fake sciences and are quite easily detectable.

4.2.5 Quantum skin care

I discovered the scam category of **quantum cosmetics products**, coming mainly from China that was mentioned in a 2022 Rand Corporation on China and the USA investments in quantum technologies. In it, Jian-Wei Pan is said to have criticized companies claiming to sell "quantum skin care" products in China [413].

Let's make a roundup of these scams. We have for example a Quantum Health Super Lysine+ ColdStick sold on Amazon, Energecia Quantum Beauty sells quantacosmetics fairy dust, BioEqua sells energized nanospray skin care, probably with stirred magic water, Age Well Fundamentals sells Phyto5 quantum energy facial skin care that balances the energy vitals and is made in Switzerland (but not at ETH Zurich), Quantum Botanika,

Figure 92: A quantum medallion which supposedly protects you from nasty 5G waves but without preventing you from using your smartphone. Go figure!

Figure 93: The 5G quantum key is another gadget of this kind, sold into a large consumer market.

Halcyon Skin Care, Ratzilla Cosme, Quantum Aestetics, Quantum Life and Igesto. In the same vein, Boiron is selling X-ray homeopathy products for curing skin rash. You read it well!

4.3 Free energy scams

Quantum fake science also helped renew the fake free energy creation scams that have been flourishing since at least the 1970s. The modern cold fusion controversy began with the 1989 Fleischmann and Pons announcement at the University of Utah, and subsequent replication attempts did not establish their claimed fusion result [827], like with the e-Cat, for energy catalyzer, developed by Andrea Rossi [828].

One new trend is the willingness to capture energy from vacuum quantum fluctuations.

A French SME **What-Innove** from the East of France, specialized in renewable energies, claimed in 2020 that it was creating an engine that captures energy from vacuum. How does it work? An unlikely mix combining a quantum field generator, the creation of photons from vacuum energy exploiting the Casimir effect, the combination of magnetodynamics and space-time, ambient temperature and pressure superconductors (which would win them a Nobel Prize in physics if it worked), and negative entropy. They just needed €2.7M of funding to move ahead and industrialize their functional prototype!

There's also a company named **Empere** created by Eddie Oquendo Virella in the USA. They are specialized in quantum superconductivity electromagnets. They are developing the IP-QHBG process to generate energy. Simply told, "*it eliminates input energy sources, including oil, natural gas, hydrogen, nuclear, diesel, solar, and wind energy, for electricity generation*". It offers "*state-of-the-art quantum power plants that can operate indefinitely without requiring input power consumption, and work independently at 100% efficiency with a 1:1 MVAR output power ratio, ensuring a stable and clean energy supply year-round*". It targets various markets: data-centers, electric vehicles, electric aerial vehicles, water treatment and distilled water production. MVAr is a unit of reactive power, not an efficiency or an energy output ratio, so the advertised "1:1 MVAR output power ratio" is dimensionally meaningless, and a self-powered plant running at 100% efficiency conflicts with energy conservation unless an external source is identified. The claim rests on a patent granted by the USPTO in 2018, based on an antenna receiving radiofrequency energy around 945 MHz. A granted patent assesses statutory requirements and is not scientific validation: what would be needed here is an independently reproduced net-energy measurement with complete input and output accounting and stated uncertainty.

Brilliant Light Power is another startup created by a certain Randall Mills that developed "*a new commercially competitive, non-polluting, plasma-based primary source of massive power from the conversion of hydrogen atoms of water molecules to dark matter, the previously unidentified matter that makes up most of the mass of the universe. The SunCell that was invented to harness the new power source catalytically converts hydrogen directly into dark matter form called Hydrino releasing brilliant high-energy light which is down-converted in energy to facilitate the production of electricity using commercially-available concentrator photovoltaic cells*". You even have some more fancy details that would kill Niels Bohr a second time: "*The electricity producing SunCell uses a catalyst to cause hydrogen atoms of water molecules to transition to the lower-energy Hydrino states by allowing their electrons to fall to smaller radii around the nucleus. This results in a release of energy that is intermediate between chemical and nuclear energies and a nonpolluting product*". The "Hydrino" is the company's own term and is not an accepted lower-energy state of hydrogen. Dark matter accounts for roughly 85% of the matter in the universe and about 27% of its total mass-energy under the standard cosmological model, and it has no established connection to hydrogen chemistry. The claims have been made since 1991 and no independent replication has been located. But, McKinsey folks, you may have missed a PetaTrillion dollar potential market!

Quantum Kinetics Corporation is a startup that developed an elements transmutation engine. Their "Particle Oscillations as an Energy Generator" has a wealth of amazing applications: atomic transmutation (up to uranium), radioactive waste water treatment (using their Quantum Kinetic Fusor [829]), carbon sequestering ambient air (no more need for a quantum computer to simulate it!), hydrolysis to extract hydrogen and oxygen from water, and electron harvesting from dielectric mediums. So why not turn iron in gold and get rich quick?

4.4 Other borderline artefact

There are many startups or ventures surfing on the quantum technology wave with various intentions. Some are just quantum startups with fluffy claims and others have only quantum in their name but nothing else.

One classical exaggeration comes with making cross-predictions between one digital trend and quantum computing. This one predicting that we'll have **quantum digital twins** is based on the usual wrong premise that quantum computing is made for compiling huge swaths of data [830].

Quantum scientists also contribute to the creation of exaggerations with inventing new weird and exotic concepts using common language metaphors like **quantum obesity** (not clearly defined in [831]), **quantum scars** (quantum systems with unstable periodic orbits [832]), **quantum sabotage** (sort of randomness generated in a Boolean function [833]), **quantum censorship** (a mechanism regulating quantum communications [834]), **quantum potato chips** (to represent quantum states [835]), **quantum printing** (transferring quantum states in quantum matter [836]) and **quantum telepathy** (correlated behaviors due to entanglement [837]). Some go as far as proposing theoretical constructs to send messages from the future to the past, using closed time-like curve, a path through spacetime that loops back on itself which are solutions to Einstein's field equations in general relativity [838]. These are seemingly scientific work but the wording use contribute to create some confusion.

In quantum error correction, you deal with **magic** and **magic state distillation** or **magic state surgery** which are not magic at all, but rather difficult to understand. These protocols consume noisy resource states to supply the high-fidelity non-Clifford operations needed for universal fault-tolerant computation. Any speedup comes from the algorithm and the problem assumptions, not from the distillation itself.

Some researchers can be very creative up to using dubious analogies in their paper title like **turning water into wine** [839] or even with **time crystals** (which are not time machines, sorry). In 2025 and onward, I also discovered **scramblons** [840], **neglectons** [841, 842], **instantons** [843], **twirlators** (related to quantum machine learning) [844], **frozonium** (a type of superconducting qubit) [845], **distimation** (a protocol to analyze entangled states) [846], **matroids** (in quantum error correction) [847], **mereology** (about causal order) [848], Bell **polygamy** and **hyper-polygamy** [849], **quantum barcodes** [850], **quantum homeopathy** [851], **quantum pseudotelepathy** [852], a **quantum mirror** [853], **quantum dragons** (quantum devices exhibiting perfect transmission) [854], **quantum suicide** in many worlds (an April fool's) [854], **quantum caustics** (on extreme effects of quantum interference phenomena) [855], **quantum smells** (related to Bell inequalities measurement) [856], **quantum aesthetics** (how quantum concepts become aesthetic phenomena through artistic mediation) [857], **quantum cinema** (a pedagogical approach to quantum computing) [666], **quantum instruments**, which have nothing to do with music [858, 859], **quantum simulacra** (some quantum physics phenomenon) [860], **fracton topological holography** [861], **quantum cheese** [862], **quantum fragmentation** [863], **quantum Hamlets** [864], and the **quantum ratio** [865].

Dark Star Quantum Lab (2020, USA) introduces itself as a contract defense and space research company covering applied quantum physics and quantum information science (QIS).

They develop tons of quantum stuff: quantum software and quantum emulation solutions, unspecified hardware, a 'Sentinel' mobile phone including a QRNG.

They also claim to have developed a Qloud high-frequency trading, a Qoin (quantum-secured cryptocurrency), a BloQchain (quantum-secured blockchain working with Qoin), a use-case of Nash embedding to create error-free qubits and, also, some Star Trek Tricorder fancy stuff. This laundry list of things is not credible. And they don't seem to have any real defense customers. Looks like it's not really serious [866].

Also quite weird is this **Quantum_AI Group Of Companies** with its 15 branches dealing with aerospace, artificial intelligence, naval, finance, energy, automotive, electronics and... quantum computing. They develop, take it or leave it: Nano-Flux, a range of flux-qubits superconducting computers, Q-optic, the most powerful optical qubits quantum computer, BEC, the fastest Bose-Einstein condensate based trapped ions computer (seems they mixed some things here) and also SSL, a solid-state quantum computer and Infinity-Q a high-performance heavy load quantum computer. Interestingly, these 4 ranges of systems have respectively 40, 200, a 1.6 and 128 billion qubits and they look the same in their 3D rendered pictures. They are supposed to be based in Stanford, Boston, India, Abu Dhabi, Dublin and Tel Aviv. They still have a CEO, a certain Ranobijoy Bhattacharya. If it is not an April's fool, what is it? Some new form of mythomania?

QiQuantum (USA) or Quaternary Interpretation Quantum, is a company from Pravik Mailik who plans to create an Integrated Quantum Computational Intelligence (IQCI) Nano-Cyborg built on quaternary principles of organization of light, matter, and life. Good luck with that. His web site contains a flurry of videos and "scientific" papers describing the company's vision and technology [867–870].

Qleap is a project from a certain Bosco Bellinghausen from Munich who wants to create spin qubits with semiconducting quantum dots suspended in structured water. The qubit states are encoded in the electronic energy levels of the quantum dots (ground and excited states), which form a two-level quantum system. It hypothesizes that water's coherent domains which can be observed in ma-rine photosynthetic organisms can stabilize these quantum states at room temperature, eliminating cryogenic requirements. The control mechanism is a multi-modal approach combining acous-tic waves (for positioning and coupling), optical pulses (for state manipulation), and magnetic fields (for bias control). This is inspired by how biological systems use multiple environmental factors to maintain quantum coherence. The project is looking for partners to test its hypotheses. Its TRL must be near -9 3/4.

Quantum physics abuse can be found in various other product categories. In China, for example, a so-called **quantum satellite camera** was used to produce high-resolution panoramas. The view presented was that of Shanghai with 195 billion pixels. Practically, the pictures were captured from the top of a skyscraper - there is no shortage of them in Shanghai - and not by any satellite. It used conventional high-resolution cameras that have nothing more quantum than conventional semiconductor photodetection in CMOS image sensors, where absorbed photons generate charge carriers. The information is totally bogus and was only used to generate buzz. Unfortunately, many media outlets around the world took the bait without casting any doubt [871, 872].

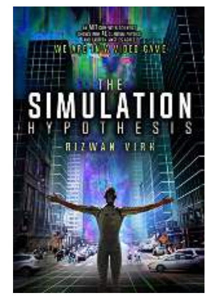
Figure 95: The non-quantum cooler from Chillout System.

You are also entitled to a beautiful **quantum cooler** from **Chillout Systems** that has only quantum in its name. It uses a compact classic compressor [873] (Figure 95). And **HiroMatch**, an online dating service in Japan using quantum instead of AI to improve people's matching.

Other cases extrapolate to the macro scale quantum phenomena observed at a nano scale. This is the case of **time inversion** with quantum computing, a view of the mind that is linked to the reversible nature of quantum gates but does not imply macroscopic backward time travel [874].

Equally wild theories aspire to **predict the future** with quantum computing. Superposition lets a register carry amplitudes over many basis states at once, but measurement returns a single outcome and no algorithm evaluates every candidate solution for free. Useful algorithms work by arranging interference so that the wanted outcomes are amplified, which applies to narrowly structured problems and not to the complexity of macroscopic life, even if it were deterministic [875]. The next step is to consider that we are living in a **simulation**.

This is the theory presented in Rizwan Virh's The Simulation Hypothesis. The author presents himself as an MIT Computer Scientist, whereas he is more of an entrepreneur in video games, more accustomed to books on entrepreneurship than on science. This kind of simulation scenario is roughly equivalent to believing in a kind of omnipotent God who controls everything or who created the simulation tool.



The question can moreover be recursively implemented: if this creator has developed a simulation tool, who created his universe and isn't this one also a simulation?

Another case that should inspire the utmost caution is that of this curious company **Precog Technologies**, which claims to offer solutions for teleportation, time travel and anti-gravity systems. Miracles one stop shopping! The company was created to monetize the intellectual property of a certain Anisse Zerouta that is covered in a dubious scientific paper [876]. Created in September 2018, Precogtec would have a CTO, François Bissege, who has a PhD in sociology (source) and another employee, Julien Darivel, who worked in the automotive industry. It's strange!

Figure 96: Do you spot the scam? If not, you need some training.

We also saw the first quantum financial scam appear in 2018 with this fake article in the Guardian reporting a quantum computer project for Elon Musk's finance (it's now no more online). The trained eye quickly detects that it is a montage, like this series of **Quan-**

tumAI quantum computers that are nothing more than D-Waves annealers whose logo has just been photoshopped. Second, the article is supposed to come from the Guardian, but not the url (Figure 96, Figure 97)!

It quotes several scientists from research laboratories around the world, all with Russian names. The article points to **QuantumAI**'s online service which would be able to go around robbing the rich and redistributing the money to the poor. And the site indicates that the startup has Jeff Bezos and Bill Gates as advisors and IBM, Microsoft and OpenAI as partners (Figure 97).

There is another, called **Quantum Code**. Obviously, run away! The site displays the common indicators of a high-risk investment lead generation scheme. No official enforcement finding has been located as of September 2026, and readers should not provide personal or financial information to it. The site asks users to create an account with providing their personal details. These are then resold to unscrupulous companies of shady financial products that exploit leads of prospects easy to fool. Other financial scams promising skyrocketing return on investment on mysterious quantum investments in the stock market are now current.

Figure 97: The QuantumAI scam, created long ago, when merging quantum computing and AI was not yet fashionable. These were visionaries!

We can also quote **Qubole** which launched its Quantum SQL server, which has nothing quantum [877]. The **Samsung** Quantum 8K processor launched in 2018 was not particularly quantum either, except via its classical CMOS transistors.

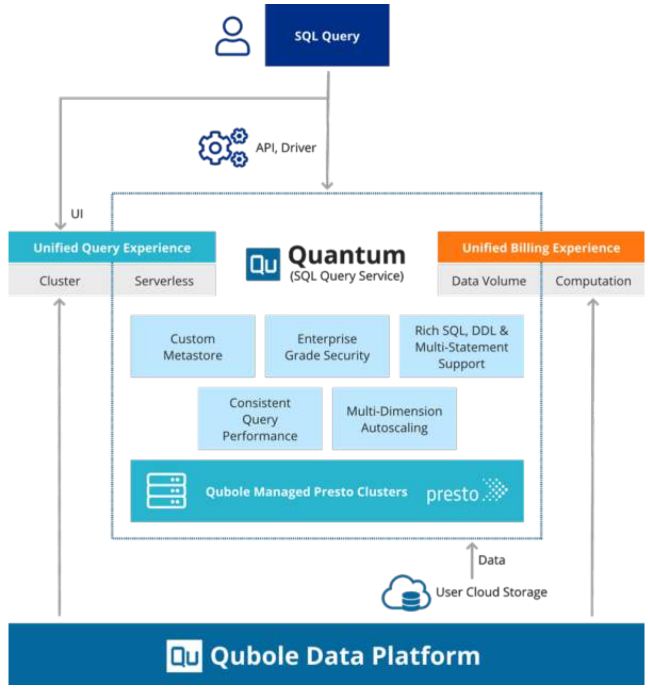


Figure 98: QuantumAI and its financial scam.

In consumer products goods, we have this washing powder **Quantum Max** of the brand **Finish** from the Reckitt Benckiser group (Figure 99). Then **Quantum American** PQ rolls and Quantum red wine from **Beringer,** a brand from Napa Valley, California. You can even buy a **Qbit troller** for your babies [878], a **quantum razor** from Phoenix Artisan Accoutrements [879] (Figure 101) and even a **quantum blender** using some induction electric motor.

Otherwise, **Quantum Corp** (USA) does nothing quantum and just manages tape storage. The same goes for **Quantum Entanglement Entertainment** (Canada) which, as its name indicates, is in the content market. **Quantum Surgical** (France) makes surgery robots for liver cancer, which have nothing quantum. **QuantumScape** is a solid-state lithium battery manufacturer in the USA. **QuantumSi** created a silicon-based DNA advanced sequencing machine that doesn't seem to use any second-generation quantum technology, **Quantic** Executive MBA has only quantum in name. **Quantum Metric** provides cloud based digital content design software tools. There is even a Chinese company created in 2016 named **Quantum Technologies** (officially "Guandong Technology") that sells some augmented reality product with nothing quantum at all. **Quantum Switch** is not a quantum switch from the physical standpoint. It states that it creates "*A New Era In Quantum Defined Data Centres*" but does just service classical colocation data centers (Figure 103). **QuantumCat** is a South-Korea startup which creates gold nanoparticle catalysts. In May 2026, Callaway launched its Quantum gold drivers with some design and materials improvements, unrelated to any quantum technology.

FirstQuantum (Canada) is a minerals company, **Quantum Zero** (Japan) helps organizations clean up

Figure 99: Finish Quantum Max quantumly washes your dishes.

Figure 100: Anything can be quantum, your washing machine powder, your toilet paper and your wine or beer.

Figure 101: The quantum razor from Phoenix Artisan Accoutrements. Source: [879].

Figure 102: Soft paper can also be quantum. I'm not referring to a weak paper published on arXiv.

their classified data assets and **Quantum Dao** (Luxembourg) is an investment fund. At last, **QuantumLeaf** is a cannabis software company servicing the cannabis industry in the USA.

Quantum of the Seas is a famous cruise ship covering all oceans. Even **McKinsey** got into this game, labelling its data-science consulting and service offering QuantumBlack! And don't be confused between **Quantum Health,** which provides healthcare services to company's employees and **Quantum Health** which sells among other things an insect repellant. Hopefully, despite the company name, they don't claim the repellant uses a specific quantum effect. It is just branding washing, not more. We're safe!

And a couple new ones discovered in 2025, **inQubit** an IT services but not quantum, **QuantumCS**, is another IT services company, and **Quantifeed** which develops a digital wealth platform for financial institutions.

4.5 Quantum management

Quantum management is a new and fashionable practice that seeks to draw inspiration from the general principles of quantum mechanics. Its practitioners are frequently followers of more or less occult sciences who have converted to target corporate markets that are more financially attractive than consumer markets. The vulnerability of educated executives and managers to the most outlandish proposals is always amazing.

However, we can indeed identify many analogies between quantum physics and management in the broadest sense of the term. For this purpose, I have pushed the envelope and reused advanced quantum physics fundamentals and applied it to your usual business life. Any resemblance with a real-life situation would be totally fortuitous or entirely intentional, as you will guess [880]. As a warning, I must state that all of this is not serious at all. It is a way to make fun of many things, on the various

Figure 103: All those companies chose to use quantum in their name, but they have nothing quantum, whether from the first or second quantum revolution. Consolidation: Olivier Ezratty, 2021-September 2026.

gurus using quantum physics in scams and, also, about life in various human organizations (startups, corporations, political parties, associations, research labs, ...) (Figure 104) [881].

Quantization means that certain observables of a given system are restricted to a discrete set of allowed values rather than a continuum, like the bound energy levels of a hydrogen atom. Discrete does not mean precisely known, and not every observable has a discrete spectrum. After all, an employee is just a cell in a spreadsheet. He's there one day and gone the next. Workforce management is indeed quantum. A company's workforce at a given time is a discrete integer number.

But if we average it over a period of time, taking into account departures during the period, part-time employees, fixed-term contracts, apprenticeships, subcontractors and people whose real activity we are not sure of, it is no longer an integer but a number of FTEs (full time employees) or FTEs (full time equivalents) that is at least a sum of fractions. Fortunately, it is never a complex number and one escapes Hilbert's spaces to represent them.

Quantization also manifests itself with sand bagging, when a sales manager is distributing his own sales goals to his team by adding a quantum margin of safety. The last link in the chain, the unfortunate poor salesperson, will be assigned a goal that is greater than that of all the layers of management above. Only certain layers of sales management have this flexibility.

The end result is that salespersons become Rydberg state atoms: they are excited with a very high level of energy and they sometimes burn out. This system is designed so that the base salesperson does not reach his or her objective and is penalized on the bonus side, unlike managers above him or her. Particularly if you want to fire him or her. Judgment about individuals is also subject to quantization. A person is often rated as excellent, acceptable, or beyond saving. Personal judgments are rarely nuanced in grey. Yet, in a purist application of quantum physics, this kind of judgment should be a more vague and subtle wave function, until you measure it during a stressful experience.

The top of quantization? Those nasty Internet popups where the given choice is "OK" or "Later". For the quantum measurement guru, it is a real-life example of an exaggerated POVM (see Glossary).

Superposition is very common in business. For example, thanks to smartphones and other laptops, employees are kept both at work and in their personal lives all day long. It can also manifest itself in regulatory compliance, which is variable geometry in many companies. And then, of course, in the application of the company values defined in Powerpoint slides and rehashed by managers or the HR department. States superposition also manifests itself in the evaluation of leads that are closed or not in a sales pipeline. They are usually assigned a closing rate which is an amplitude and phase $|\psi\rangle$ until it is known whether the deal is lost or won, which is like the wave-packet collapse happening with quantum measurement, on a basis state $|0\rangle$ or $|1\rangle$. This collapse also occurs if an external event creates a lead quantum state decoherence. For example, a competitor who wins the deal under the nose of the salesman. This quantum analogy, however, will not help you improve your sales pipe closing rate.

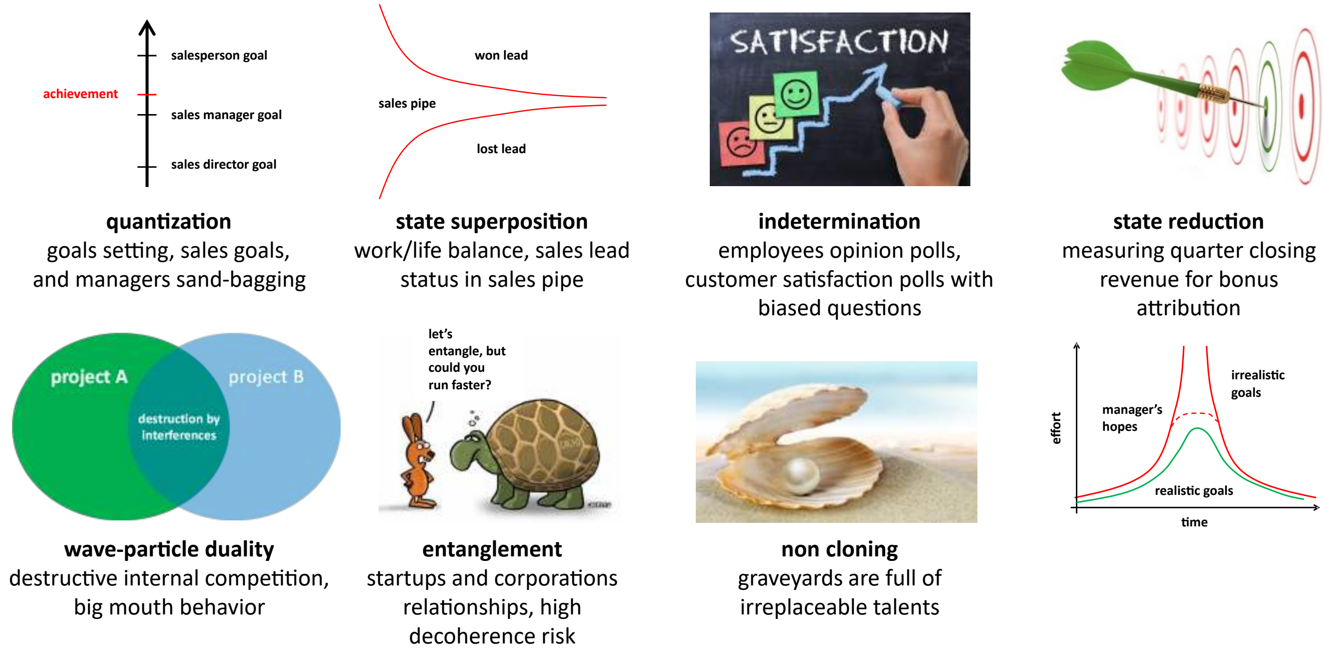


Figure 104: My useless framework for quantum management. 🅭 Olivier Ezratty, 2022.

Measurement back-action works with the measurement of employee satisfaction, where the measuring tool always influences the quantity to be measured. This is true as well in the questions asked in opinion polls, which are often oriented [882]. More generally, the measurement of any parameter in a company by a consulting firm like McKinsey, particularly during an audit, will probably lead to changes in the measured quantities (e.g., downsizing, management change, reorganization and the like). You just hope that your enterprise won't become a planar wave afterwards.

One variation of the Heisenberg uncertainty principle is that the position and momentum of a particle cannot both be known with arbitrary precision. The analogy in business would be the observation of a growing startup: by the time one understands where it is at a given moment, it has already changed its situation (headquarters, staff, CEO, turnover, M&A, company name, product, done a pivot). This is why it takes an infinite amount of energy to create an up-to-date startup base in one country or worldwide, even with only quantum technologies startups. So, thank you Crunchbase for the effort!

Measurement is in line with the history of quantization when measuring revenue at the end of a fiscal quarter. In this case, one is obliged to provide numbers and not to rely on some closing rates fuzzy logic. If only to determine the bonuses of sales representatives. Otherwise, Bill Gates said loud and clear in 1997 that "*bad news should travel fast in efficient companies*". But not too fast my dear, otherwise you will get fired. That's what is called a non self-demolition measurement.

Wave-particle duality manifests itself with real people in companies who work on competing projects and happily annihilate each other. It is the phenomenon of interference linked to the waveform aspect of every project! You also have the loudmouthed managers facing their teams (thus, in the state of solid particles) who turn compliant in front of their own management (thus, in the state of very low-energy waves).

This behavioral duality is also often observed with irascible managers who become docile sheep once at home, or who fail to properly educate their children. Can a trendy startup Chief Happiness Officer be quantum? In any case, this person must fight on a daily basis against a universal phenomenon: a good number of passions quickly fade with time, such as the amplitude of a Rabi oscillation, which is commonly observed in quantum physics and is related to superconducting qubit decoherence (Figure 105).

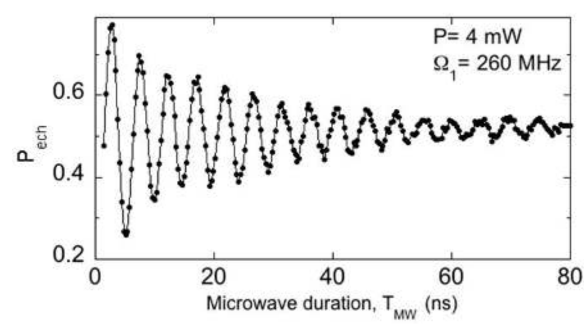


Figure 105: The Rabi oscillation of your motivation over time.

The Doppler effect also makes it possible to indirectly put an end to a messed-up project with light, for example, via a well-managed leak in the media. Remember Theranos?

Entanglement applies to startups that are integrated into the open innovation programs of large companies.

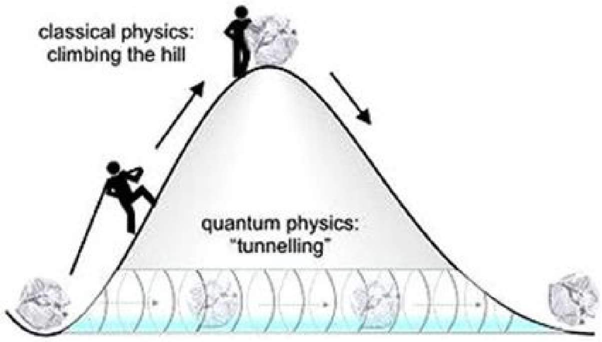


Figure 106: The quantum tunnel effect.

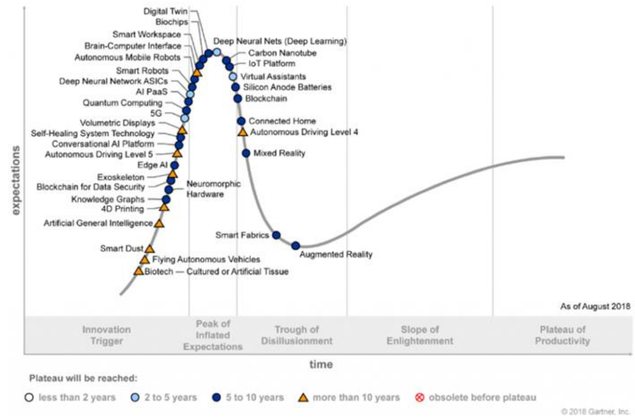


Figure 107: The quantum hype effects. Sometimes, hype is so strong that it creates a pass-through from hype to success without a valley of death.

Everything goes well until the appearance of decoherence between the startup and the corporation! I create a product, and you want a customized solution, I need speed and you're too slow, etc!

Entanglement also occurs with the teleportation of rumors faster than light. It is also known that the coherence time of qubits is linked to their good physical, magnetic and vacuum insulation, often at very low temperature, in order to avoid any external disturbance. This is the opposite of the open spaces in companies where employees are crammed together! It has long been claimed that open spaces improve teamwork, whereas their main purpose is to compress real estate costs!

No-Cloning Theorem says that it is impossible to identically clone the state of a qubit or quantum, has an application in business life with all those people who are believed to be irreplaceable until the day they leave or die. The theorem applies in particular when the departing manager is not replaced and whose role is then distributed among several existing managers, a bit like a quantum error correction with ancilla qubits and projective measurements. The theorem also works with successful entrepreneurs who find it difficult to replicate a success from one area to another.

Tunnel effect makes it possible to implement change management. It presents a wonderful future situation and making people forget the difficulties of getting there. The principle could also be adopted by the Gartner Group with its famous innovation adoption cycle curves ("hype cycle"), as some technologies do not necessarily pass through the valley of death, as was the case for smartphones (Figure 107). It had benefited from the reality distortion field of a certain Steve Jobs, a great adept of quantum management principles. By the way, the trajectory Apple-Next-Apple was a great application of the tunnel effect, Next being a relative failure while both Apple were successes.

Superconductivity is linked to meeting rooms. Employees and managers are conditioned to behave as even-spin particles, which can be piled up in meeting rooms. Organizational superconductivity also avoids resistance to change. You freeze employees and their resistance to change disappears. Which is a bit paradoxical because once frozen, you are as solid as a rock, and defrosting is not obvious. If we take the principles of Deepak Chopra's quantum pseudo-medicine, a company is in a superposed state between a healthy leader and a declining star. The strength of leadership should theoretically allow the wave packet function of the company's quantum state to collapse in the healthy leader state. In real life, this collapse is tricky to achieve, and companies simply collapse. The processes that lead the company to find itself in a declining situation are most often irreversible and linked to a slow decoherence with the environment, competitors and customers who have not waited to adapt. Corporate life is not a reversible quantum gate nor any sort of linear algebra. It is mostly nonlinear. Try, for example, to turn Nokia into the leader of Android smartphones!

Universal Gates Quantum Computing has a beautiful analogy in the life of companies with the management of calls for tenders such as those for communication agencies. The responses of candidate agencies are superposed states of a quantum register.

They undergo a simultaneous evaluation process, as in an oracle-based quantum algorithm. In the end, only one offer emerges: the winner. But during this process, there may be some quantum entanglement affecting the winner's final proposal. Translation: the elements of certain answers will magically appear in the winner's answer. Again, perhaps via the enterprise quantum tunnel effect.

Finally, let us mention this other universal principle, the very famous **quantum teleportation** of human stupidity to large sections of the company or in the population. It uses superdense falsehoods encoding. And contrary to actual teleportation, it travels faster than light. It is so fast that it is the only plausible explanation.

All these analogies are amusing but not very useful for improving management. Even if its scientific dimension is more than questionable, parody is finally an interesting form of pedagogy!

4.6 Quantum fake sciences key takeaways

- Quantum physics has been for a while integrated in highly dubious offerings, particularly in the healthcare and energy production domains.
- There is a proliferation of products and services making unsupported health claims based on electromagnetic waves, vaguely defined “energies” or alleged restoration of a body’s “balance”. Expectation and placebo responses do not establish that such a product has the claimed therapeutic efficacy. These claims should be evaluated against controlled clinical evidence, plausible mechanisms and applicable regulatory findings. Otherwise, these are just scams.
- Some proposals attempt to explain consciousness using quantum physics, but broad claims of this kind currently have limited theoretical and experimental support. This form of reductionism has very limited theoretical and experimental grounds. Likewise, products marketed around scalar-wave detectors or generators, healing crystals, structured water or “quantum” medallions are also pure scams.
- This part of the book proposes a simple methodology for identifying unsupported or misleading healthcare claims using scientific evidence, reproducibility, plausible mechanisms and regulatory information.
- We uncover some other scams in the free energy generation category. These systems are supposed to extract some energy from vacuum when their only actual effect is to pump money out of your wallet.
- Quantum physics is sometimes used in management and marketing. This book offers you a nice in-depth parody of these methodologies.
- At last, we showcase a few companies using quantum in their branding which have nothing quantum at all to offer. It spans a large number of product and service sectors.

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[868] Envisioning A Light-Based Quantum-Computational Nano-Cyborg, by Pravir Malik, IEEE, June 2022 🔒.

[869] A Second Quantum Computational Agenda, by Pravir Malik, January 2024.

[870] Leveraging Imagination to Surface Quantum Technologies, by Forbes Councils, January 2024.

[871] 60 seconds over sinoland: quantum satellite camera used to do movable, panoramic photos of Shanghai, by Jeff J. Brown, December 2018.

[872] Truth Behind Viral 24.9 Billion Pixel Image Taken By Chinese "Quantum Satellite", by Anmol Sachdeva, December 2018.

[873] Chillout Systems Quantum Cooler V3, by Chillout Systems.

[874] Arrow of time and its reversal on the IBM quantum computer, by G. B. Lesovik et al., arXiv, 2018 (14 pages).

[875] Interfering trajectories in experimental quantum-enhanced stochastic simulation, by Farzad Ghafari, 2019 (7 pages).

[876] The Seed Theory: Unifying and replacing quantum physics and general relativity with "state physics", by Anisse Zerouta et al., 2017 (28 pages).

[877] Qubole launches Quantum, its serverless database engine, by Frederic Lardinois, June 2019.

[878] Qbit + All Terrain Velvet Black Stroller, August 2023.

[879] The Quantum Razor: The Eclipse Red Ring Reincarnated, by Leisureguy, Sharpologist, January 2025.

[880] Toward a Quantum Theory of Humor, by Liane Gabora et al., January 2017 (10 pages).

[881] A Quantum Probability Driven Framework for Joint Multi-Modal Sarcasm, Sentiment and Emotion Analysis, by Yaochen Liu et al., arXiv, June 2023 (16 pages).

[882] Yes, Prime Minister, question order does matter - and it's certainly not classical! But is it quantum?, by Dorje C, arXiv, September 2024 (12 pages).

This **Quantum pseudosciences** section contains 179 bibliographical references and notes containing at least 5,332 pages.

5 Conclusion

After reading parts or the totality of this book, you may find out that its premise was maybe misleading. “Understanding quantum technologies” is indeed more a quest and a journey. You may never reach the destination. That’s the fate of science which makes continuous progress and where we continuously improve our understanding of nature or of the artificial tools and virtual structures we are building and experimenting. Even though it is not obvious to decide where to start in the book, its structure makes it possible to start whenever you want. Some favor learning about quantum physics before jumping onto use cases in quantum computing, communications or sensing, or the other way around. Others want to learn about the basics of what is a qubit before knowing the various components of a quantum computer. The book adopts an engineering view with decomposing systems in various parts and explaining how they interact with each other. I was influenced by the Canadian TV documentaries “How it’s made” that I used to watch with my kids a couple of decades ago. That’s why I explain how an algorithm is decomposed as well as how a helium dilution refrigerator works, down to trying to understand how you control qubits whether they are solidstate, atom or photon based.

There’s always something you didn’t understand well and need to review again and again. It is true for me as a writer. It takes me a long time to understand how things work. One archetypal example are the quantum error correction and fault-tolerance schemes, with the difference between a logical qubits and how logical operations are implemented fault-tolerantly. Depending on the topic and my own understanding, this book contains a variable mix of data, raw information, knowledge and sometimes, wisdom.

As an end-user organization, you are probably still wondering about the use cases that will make sense for your activity and when they will become implementable with some real business benefit. And you must manage conflicting information between those who say that quantum computing is there now and others who view it as being a couple decades away.

Updating this book is definitively a crazy task, trying to cover such a broad spectrum of topics, with physics, mathematics, technology, computer science, human science and the rest. It is extreme in complexity and diversity. I try to be a “quantum engineer”, keeping a holistic view of the domain. That is what makes this field so interesting. It is full of uncertainties. Too many business-biased people think that the uncertainty is about “the market” when it is above all about the underlying science and technology. The advent of useful quantum computers is tied to our ability to control large numbers of entangled quantum objects, and it is quite hard to determine the limits there.

I also discovered how understanding classical technologies is so important here. It plays a role in the various enabling technologies needed to build quantum products, particularly quantum computers. But also, in knowing the playing field of classical computing, both hardware and software that runs along quantum computers or is compared to it.

To write this book over the course of the last eight years, I downloaded and compiled thousands of documents, viewed hundreds of hours of conferences and courses on YouTube, and met several hundred researchers and entrepreneurs. The only reassuring thing is that this book pagination grew linearly over time, and not exponentially. For this edition, my use of LLM-based tool has also expanded, inline with what’s happening in many research domains. The wealth of information they can analyze and synthesized is mind-boggling, whatever the scientific or technology domain.

Like in a PhD thesis, I have here to thank many people and friends who helped me craft this book over my journey in quantum science and technologies. First of all, **Fanny Bouton**, with whom I started this quantum adventure in 2018 and who now runs quantum operations at OVHcloud. This shows how you can turn from being an observer into becoming a driving force in the quantum ecosystem.

Now, let’s do some names dropping! In chronological order, the first scientists and other people we met back in 2018 were **Alain Aspect** (IOGS), **Daniel Esteve** (CEA Quantronics), **Christian Gamrat** (CEA LIST), **Maud Vinet** (CEA Leti in Grenoble, now at Quobly), **Tristan Meunier** (CNRS Grenoble, also now at Quobly), **Alexei Tchelnokov** (CEA Grenoble), **Laurent Fulbert** (CEA-Leti Grenoble), **Cyril Allouche** and **Philippe Duluc** (Atos), **Bernard Ourghanlian** and **David Rousset** (Microsoft), **Pat Gumann** (IBM), **Etienne Klein** (CEA), **Christophe Jurczak** and **Zoé Amblard** (Quantonation), **Nicolas Gaude** (Prevision.io) and **Françoise Gruson** (Société Générale).

Then, in 2019, with **Philippe Grangier** (IOGS), **Elham Kashefi** (LIP6 and VeriQloud), **Marc Kaplan** (VeriQloud), **Pascale Senellart** (C2N and Quandela), **Franck Balestro** (UGA, Institut Néel), **Alexia Auffèves** (CNRS), **Matthieu Desjardins** (C12), **Jacqueline Bloch** (C2N), **Iordanis Kerenidis** (CNRS),

Heike Riel (IBM Zurich) and **Vern Brownell** (then D-Wave CEO).

In 2020, **Artur Ekert** (CQT Singapore), **Patrice Bertet** (CEA SPEC), **Xavier Waintal** (CEA IRIG), **Yvain Thonnart** (CEA LIST), **Rob Whitney** (LPMMC Grenoble), **Damian Markham** (CNRS LIP6 and then, at JFLI in Tokyo), **Bruno Desruelle** (Muquans now Exail), **Georges-Olivier Raymond** and **Antoine Browaeys** (Pasqal), **Théau Peronnin** and **Raphaël Lescanne** (Alice&Bob), **Jeremy O'Brien** (PsiQuantum), **Magdalena Hauser** and **Wolfgang Lechner** (ParityQC), **Roger McKinley** and **Peter Knight** (UK) and the IBM Zurich research teams. I also had discussions with the teams from **Qblox**, **Qilimanjaro**, **Quantum Machines**, **Seeqc**, **Quantum Motion**, **Strangeworks**, **IQM**, **EeroQ**, and **Quantum Brilliance**.

There were these countless discussions with **Jean-Christophe Gougeon** from Bpifrance, **Neil Abroug**, who was between 2021 and 2024 the coordinator of the quantum strategy in France, as well as **Charles Beigbeder** and **Christophe Jurczak** from Quantonation and Le Lab Quantique, who wrote the foreword of this book. I should also mention the numerous exchanges related to quantum investments with **Cédric O** and his team, in the French government from 2019 to 2022.

In 2022 and onward, I had a chance to discuss about the quantum ecosystem with **Rainer Blatt** (AQT and Munich ecosystem), **Jonathan Home** (ETZ Zurich), **Cornelius Hempel** (PSI), **Tommaso Calarco** (Jülich), **Jay Gambetta** and **Jerry Chow** (IBM) as well as with **Simone Severini** (then at AWS, now at Google) and **John Preskill** (Caltech). I also met with countless other quantum physicists and entrepreneurs, including in 2024 **David Wineland** (Oregon University), **Bill Phillips** (NIST) and **Serge Haroche** (Collège de France and LKB). And of course with all the guests from the Decode Quantum podcasts since 2019.

Switching to English, the fourth edition in 2021, fifth edition from 2022, sixth edition in 2023, seventh edition in 2024 and eight edition in 2025 benefited from the feedback of many reviewers, usually in the parts related to their domain of expertise [883–887].

This 9^{th} edition benefited from the feedback from Jean-Philippe Nominé, Michel Kurek, Daniel Vert, Vincent Pinte-Deregnaucourt, and various LLM systems.

And I hope, many more of you, next time :)!

Best,

Olivier Ezratty, September 2026

5.1 Bibliography and notes

These are the bibliographical references and notes for the **Conclusion** section.

[883] The 2021 edition were Alexia Auffèves (CNRS, measurement, energetics, quantum foundations, photon qubits), Antoine Browaeys (IOGS and Pasqal, cold atoms), Christophe Chareton (CEA LIST, linear algebra, quantum algorithms and development tools), Cyril Allouche (Atos, supercomputing, emulators, European projects), Daniel Esteve (CEA DRF, superconducting qubits), Eleni Diamanti (CNRS LIP6, quantum communications and cryptography), Elvira Shishenina (BMW, proof-read all the document), Frédéric Nguyen Van Dau (Thales, quantum sensing), Georges Uzbelger (IBM, quantum algorithms and software tools), Jonas Landman (CNRS IRIF, quantum algorithms), Léa Bresque (CNRS Institut Néel, quantum physics 101, quantum postulates and measurement), Marc Kaplan (Veriqloud, quantum communications and cryptography), Michel Kurek (proof-reading), Peter Eid (Arm, classical and unconventional computing, communications and cryptography), Philippe Grangier (Institut d'Optique, quantum foundations), Pol Forn-Díaz (Qilimanjaro, superconducting qubits), Théau Peronnin and Jérémie Guillaud (Alice&Bob, cat-qubits) and Valérian Giesz (Quandela, photon qubits and photonics).

[884] The 2022 edition reviewers were Jean-Philippe Fauvarque (Plassys-Bestek, manufacturing), Antoine Gras (Alice & Bob, manufacturing), Frédéric Wyczisk (quantum matter, formerly at Thales), Michel Kurek (proof-reading master), Antoine Browaeys (Pasqal/IOGQ, neutral atoms computing), Bruno Desruelle (ixBlue, quantum sensing), Christophe Jurczak (foreword), Marco Fellous-Asiani (energetics, control electronics, superconducting qubits), Clément Barraud (MPQ, quantum matter), Georges-Olivier Raymond and Nicolas Proust (Pasqal, cold atoms qubits), Léa Bresque (Institut Néel, energetics), Luc Gaffet (Air Liquide, cryogeny), Olivier Hess (Atos, software), Jérémie Guillaud, Blaise Vignon (Alice&Bob, superconducting qubits), Thomas Ayral (Atos, various parts), Loïc Chauvet (CACIB, software tools), Daniel Vert (CEA, quantum annealing), Xavier Vasques and Jean-Michel Torres (IBM, on IBM quantum software stacks), Stéphane Louise and Christophe Chareton (CEA LIST, algorithms), Marc Kaplan (VeriQloud, quantum telecommunication and cryptography), Maud Vinet (history, silicon qubits) and André M. Konig (Global Quantum Intelligence, various places).

[885] The 2023 edition reviewers where Michel Kurek (Multiverse), Vincent Pinte-Deregnaucourt (research consultant), Jeremy Stevens and Cécile M. Perrault (Alice&Bob), Neil Abroug (SGPI), Philippe Grangier (IOGS), Ekaterina Alekseeva (Eurodecision), Jonas Landman (LIP6, QC Ware), Nicolas Delfosse and Vivien Londe (Microsoft), Marie-Elisabeth Campo (Air & Space Force, France Minister of the Armed Forces), Yves Colombe (Infineon), Cornelius Hempel (PSI/ETH Zurich), Davide Boschetto (ENSTA), Alex Challans (The Quantum Insider) and Jean-Philippe Nominé (CEA).

[886] The 2024 edition reviewers where Michel Kurek (Multiverse), Philippe Grangier (spins, quantum foundations), Robert Whitney, Marco Fellous-Asiani and Jeremy Stevens (quantum energetics), Raphael Lescanne (cat-qubits), Alain Chancé (fermionic analog simulation), Matthieu Desjardins (carbon nanotube qubits), Frédéric Nguyen Van Dau (sensing), Nayla Farouki (quantum foundations), Vincent Pinte-Deregnaucourt (algorithms, complexity classes), Jean-Philippe Nominé (many parts) and Chiara Decaroli (trapped ions).

[887] The 2025 edition reviewers were Lucas Leclerc (Lieb-Robinson), Stefan Bogdanovic (case studies evaluation), Raphael Lescanne (cat-qubits), Olivier Hess (Eviden), Tom Darras, Mathys Rennela and Kenzo Bounegta (Welinq), Pierre Desjardins, Lydia Baril and Evan Tanner (C12), Jean-Philippe Nominé (multiple parts), Elisabeth Eude (economics), Jonatan Wicht (satellite optics), Alexandre May (microwave photon counters), Maxime Remaud (quantum arithmetics), Igor Vujic (all parts), and Fanny Bouton (cloud). I also thank Vincent Pinte-Deregnaucourt for his suggestion and hard push to move this book to LaTeX Michel Kurek for his continuous support in proof checking the document and who develop some custom tooling to clean up the huge bibliography of this book, and to Christophe Jurczak (Quantonation) for his updated foreword. This book is also supported by **le Lab Quantique** (for its visibility).

This **Conclusion** section contains 5 bibliographical references and notes.

6 Resources

The part contains a set of resources with events, from scientific to business conferences, news sites, podcasts and then some reference books on quantum science and technologies that I consulted or discovered to prepare and update this book, sometimes, a while ago. I also added a one-page timeline of key events in quantum computing since 2018 (Table 3)

6.1 Events

There are numerous conferences on the different scientific branches of quantum technologies and a growing number of quantum "business" conferences associating some scientific content, industry-vendor talks (and sponsoring) and customer-use-case testimonials.

I found online various inventories of quantum related scientific events on quantum.info (which also inventories some quantum physics predatory journals), Conference service, Conference Index and Quantum Computing Report.

Many of these events are fee-based for both participants and speakers. It costs up to $1,000 to participate as an attendee, plus extra fees for speakers and poster sessions. It is a business!

6.1.1 Quantum Scientific events

Let's quickly cover the main quantum related events where the audience is mainly made of scientists and the content is likewise highly scientific [888]. It is about how to organize scientific quantum events.

APS Global Physics Summit, previously named APS March Meeting, is the largest physicists conference in the world with over 14K attendees, hundreds of sessions, thousands of presented papers, and a significant part of them are in the quantum physics disciplines, including enabling technologies like cryogeny. Other talks cover different parts of physics like high-energy particles physics or astronomy. They have over 100 exhibitors. Their industry tracks showcase scientific advancements from the main quantum computing players like IBM, Google, IonQ and others. The 2027 edition will be held in Atlanta in April. This four-day event is organized by the American Physical Society, which also publish the reference journals PRX Quantum, PRX, PRL (Physical Review Letters) and PRA (Physical Review A), that are frequently mentioned in this book's bibliographical references.

Photonics West in January/February is the largest photonics related conference and vendors exhibition, including quantum photonics, their related enabling technologies (lasers, photon counters, …) and covering medtechs, organized at the Moscone Center in San Francisco. It also hosts industry related events.

Laser World of Photonics and the **World of Photonics Congress** is another photonic major congress, happening in Germany. The 2027 edition takes place in June in Munich with over 30K visitors and 6,000 congress participants. There are also editions of the conference in India and China.

QIP (Quantum Information Processing) is an important quantum information conference with prestigious scientific speakers. The 2027 edition is organized in February in Singapore.

QUANTUMatter gathers various communities in quantum information and quantum matter involved in all branches of quantum technologies (computing, sensing, telecommunications). The 2027 edition is planned in October in San Sebastian (Spain).

QPL (Quantum Physics and Logic) is about the mathematical foundations of quantum computation, quantum physics and related areas with a focus on the use of mathematics, formal languages, semantic methods and other mathematical and computer scientific techniques to the study of physical systems and processes. The last edition was in Amsterdam in August 2026.

ASC (Applied Superconductivity Conference) is a superconducting related event. The 2026 edition is planned in Pittsburgh, in September. It covers quantum systems, computation, sensing and networking, control and readout electronics, fabrication, packaging, and scalable infrastructure, and hybrid or novel quantum systems.

SQA (Superconducting Qubits and Algorithms Conference) covers science, technology, and algorithms related to superconducting quantum computing organized by IQM. The summer 2026 edition took place late August in Gothenburg, Sweden.

Spin Qubit is a conference on spin qubits. The 7^{th} edition was organized in Delft in July 2026. It covers NV and SiC centers qubits, quantum dots spin qubits and the like.

ICDCM (International Conference on Diamond and Carbon Materials) is the conference where NV center and SiC cavities are talked about.

QTML (Quantum Techniques in Machine Learning) focuses not surprisingly on quantum machine learning, gathering researchers and industry players.

QRE is a yearly workshop on Quantum Resource Estimation also dealing with benchmarking and performance analytics. The 5^{th} edition took place in September 2024 in Montreal, as part of the IEEE Quantum Week.

QEC'26 was the 8th International Conference on Quantum Error Correction held in Santa Barbara, USA in June 2026. The 2027 edition is planned in Paris, France, in June 2027.

Adaptive Quantum Circuits is a new conference organized by Quantum Machines to cover hybrid quantum-classical methods. Its first edition took place in September 2024 in Brewster, Massachusetts.

Quantum Thermodynamics Conference took place in Vienna in July 2023, at the University of Maryland in August 2024, in Singapore in July 2025 and in Brazil in February 2026.

Quantum Energy Initiative workshops cover the energetics of quantum technologies, mostly computing and communications. The fourth edition is planned in Lisbon in September 2027, after past editions in Singapore, Grenoble and Barcelona.

ICQE (International Conference on Quantum Energy) was organized in Sydney, Australia, in December 2023 and Padova in June 2025. It covers the topic of energy in quantum systems, like energy harvesting, conversion, storage, and transport processes.

Quantum Computing Scalability Conference was organized by NQCC in 2025 in the UK, and the next edition is in March/April 2027 at the University of Oxford.

Quantum Information and Probability is a conference on quantum foundations. It is organized every June in Växjö, Sweden.

Fault-Tolerant Quantum Technologies with the last edition in Bristol, UK, in August 2026.

Munich Quantum Software Forum (MQSF) brings together the "who's who" in quantum computing software. The fourth edition is planned in October 2026.

IEEE organizes many quantum related scientific conferences including QSW (International Conference on Quantum Software), in Helsinki in July 2025, the IEEE Quantum Week (September 2025 in Albuquerque) and IEDM (International Electron Devices Meeting) in September in San Francisco which covers silicon spin qubits and qubit control electronics among other topics.

Lindau Nobel Laureate Meetings are organized every year in the south of Germany, at the Lindau Island in lake Constance since 1951. It gathers between 30 and 40 Nobel laureates in physics and chemistry plus over 600 young scientists from around the world who are selected by their research institutions, and a couple hundred additional people, mostly from foundations, governments, academic institutions and industry sponsors. This is a once-in-a-lifetime experience for young scientists to network at a global level across many disciplines. They can obtain a "second" ticket by becoming a laureate of a Nobel prize in physics or chemistry, or optionally, obtaining a Fields medal.

I had a chance to participate in a panel discussion with two Nobel laureates in the 2024 edition [889] (Figure 108).

GDR TEQ gathers international quantum scientists covering all fields, with tutorial sessions, docs/post-docs sessions and poster sessions. It has been organized by the research group on quantum technologies from CNRS in France every fall since 2011, formerly as GDR IQFA.

6.1.2 Quantum Business conferences

And now, onto the quantum business events which usually provide a mix of scientific and business related content.

Q2B is a conference organized by QC-Ware since 2017. Initially happening in California each December, it also happens every year in Paris (France) and in Tokyo. It is a good opportunity to learn about scientific progress from major industry players in quantum computing.

Inside Quantum Technology is a series of quantum business conferences organized in several like The Hague (February 2022), San Diego (May 2022), New York (October 2022), San Jose, California (April 2023), The Hague (April 2024 and Gothenburg in Sweden (IQT Nordics, May 2025).

Quantum+AI is a new conference organized by the team producing the Inside Quantum Technologies conferences. Its first editions took place in New York City October 2024, 2025 and 2026.

Quantum.Tech World is another conference focusing on industry use cases of quantum technologies. The next edition is in Boston in May 2027.Quantum Innovation Summit

Commercialising Quantum was organized in May 2022, May 2023 and June 2024 in London by the Economist, London with a mix of in-person and virtual events.

QTech (Quantum Technology International Conference) is organized in Berlin, Germany in September 2024. It presents the latest developments in all quantum technologies.

QBN (Quantum Industry Summit) was organized in Munich in October 2023. Sessions cover politics, business and Ecosystem, quantum technologies and supply chains, industry applications and user access, and business and investment opportunities.

EQTC (European Quantum Technologies Conference) is the showcase and community gathering of the European Quantum Flagship. The 2026 edition takes place in Dublin, Ireland, November/December.

World in Quantum Munich is organized as part of Laser Worlds and Photonics. The June 2023 edition attracted about 9K visitors and 75 exhibitors. The last edition took place in June 2025 and the next one is planned in 2027.

Figure 108: The panel I participated in at the Lindau Nobel Laureate meetings on July 2nd, 2024. (c) Lindau Nobel Laureate meetings.

Quantum World Congress had its first edition in December 2022 in Washington DC with 700 attendees and delegations from 18 countries with 120 speakers (videos). It mainly covers innovation policy. The 2023 and 2024 editions happened in Virginia in September.

QHack is a mix of a fan expo, hackathon and scientific conference for quantum software developers. The last edition was organized online in February 2024.

World Quantum Day is a virtual global event, consolidating events happening one day in April all over the world, targeting broad audiences.

France Quantum is a conference that was launched by Startup Inside and OVHcloud in June 2022 at the Eiffel Tower to promote the French quantum ecosystem. The 2023, 2024, 2025 and 2026 editions were organized at Station F in Paris in June and May. The 2026 edition gathered a record 1,200 participants. The 2027 edition is planned on June 15th.

Quantum Cannes Festival is an event organized in Cannes, France, in the Palais des Festivals, on November 17th and 18th, 2026 but a long line-up of scientific and business speakers.

Quantum Eastern Europe is a 2-day online event gathering quantum stakeholders from Eastern Europe. The 2022 edition happened in May.

Investment Summit for Quantum Startups was organized in October 2021 at Maryland University as a gathering of investors and startups.

Quantum Innovation Summit happens in Dubai in February. Its third edition was planned in September 2026.

6.2 Websites and content sources

The Quantum Insider (USA, formerly The Quantum Daily) is a media and market intelligence company dedicated to the quantum technology industry.

They provide data on companies, investors, academic groups, and government programs related to quantum technologies through their subscription data platform and their advisory services. The company also provides daily news updates, interviews, and content related to quantum technology. They are a portfolio company of Resonance. The company is run by Alex Challans out of the USA.

Postquantum is a blog on quantum technologies by Marin Ivezic, from AppliedQuantum. He provides excellent and continuous insights to debunk the continuous stream of news in quantum technologies.

AzoQuantum (UK/Australia) an information site on quantum science news with a supplier's directory, focused on manufacturing equipment and some interviews, mostly written by young researchers.

Quantum Zeitgeist (USA) is another quantum news media that also maintains an online database of startups in the field and a quantum jobs board. Their about talks about "we" but they provide no name of who's behind the site. The site belongs to a company named Hadamard LLC based in Wyoming, and created in July 2021.

Global Quantum Intelligence is an analyst shop created by André M. Konig, David Shaw and Doug Finke that consolidated in 2022 the activities from The Quantum Report (Doug Finke), Fact Based Insight (David Shaw) and André M. Konig's consulting activities. They provide data and insights on an annual subscription basis.

The Quantum Leap is a blog of news on the quantum ecosystem published by Russ Fein, a venture investor passionate of quantum computing and based in the USA.

Quantiki is an information site on quantum computing. It looks like they became mainly a jobs board.

Quantum Journal - the open journal for quantum science, a site of scientific news on quantum physics, mostly showcasing preprints published on arXiv.

The Qubit Report (USA) is a news media focused on quantum vendors launched in 2017.

Qosf, a site that inventories guides and training for developers of quantum applications.

Impact quantum, a web site launched in 2020 on quantum technologies. It also published interview podcasts run by Frank La Vigne and Candice Gilhooly.

Quantum Economy Podcast by Anders Indset which started in 2025 and had 4 episodes in store as of September 2025.

The Quantum Dragon is the news web site from Brian Siegelwax, tainted with a lot of humor and sarcasm.

Quantum Times is a media dedicated to quantum geopolitics created by Ylan Tran (Quantonation) and Victor Kerros (Alice & Bob).

Future of computing publishes text interviews done by Emily Eisenblaetter.

6.3 Podcasts

The Superposition Guy's Podcast series is run by Yuval Boger, with short-format interviews. It was formerly known as the Qubit Guy's podcast.

Quantum Tech Pod are podcasts by Christopher Bishop on quantum technology news, published on Inside Quantum Technology's web site. These are mostly half-an-hour interviews of quantum startup founders. It started mid-2021.

Between Two Kets from Marco Cerezo who works at Xanadu, and which started in 2023.

The New Quantum Era started in August 2022 and is run by Sebastian Hassinger and Kevin Rowney.

Qubit Confidential is a series of podcasts launched in 2024 by Christopher Bishop.

Entangled Things Podcast is a podcast run by Patrick Hynds and Ciprian Jichici focused on quantum computing.

Maria Violaris, now at OQC, runs a series of podcasts focused on the theme of quantum foundations.

Blond&Quantum is a podcast series launched by Eva Galant from Quantonation in October 2025 to explain quantum science and technologies in plain language with interviews of entrepreneurs and scientists.

Beyond the Qubit is a podcast animated by Frank Dekker, who is an investor passionate by quantum technologies.

There also podcast or webcast series launched by industry vendors like Quantum Builders by Qblox and Quantum Mattershttps://www.dwavequantum.com/learn/quantum-matters-podcast/ by D-Wave.

The Quantum podcasts that I have been recording regularly (in French) since September 2019 with Fanny Bouton (OVHcloud). They are available on all audio platforms (Spotify, iTunes, Deezer, ...) as well as on YouTube in video version. It covers quantum news including what's happening in the ecosystem, with startups and in research. We decipher many scientific and industry announcements. Our first episode was on Google's supremacy! A of September 2026, we had recorded 83 recorded episodes.

They are complemented by the Decode Quantum interviews that we have been publishing since March 2020 with a great variety of personalities (lead researchers, startup founders, investors, user companies, public servants, etc.) in partnership with Frenchweb. Some episodes and with English speaking guests (Jay Gambetta from IBM, Jan Goetz from IQM, David Wineland from NIST, William Phillips, …). We made a pause since March 2026.

A few other quantum podcasts existed but seem to have vanished: Quantum Computing Now by Ethan Hansen (2019-2023), The Quantum Analysts Roundtable (2022-2023) and run by Doug Finke, David Shaw, Shahin Khan, James Sanders and André M. König, insideQuantum (2022-2023) and QViews from Anastasia Marchenkova (2022).

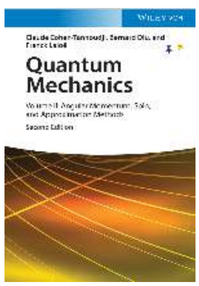
6.4 Books and ebooks

If you wander in Amazon or your other preferred real-life of virtual scientific bookstore or University library, you'll find an abundant literature on quantum physics and quantum information. Many people willing to learn in these domains have a hard time finding the "right" book that is adapted to their existing knowledge and particularly, to their fluency in mathematics. Here's a not-too long list of books for this purpose.

It is mostly adapted to students since, if you work in the industry, you probably won't have much time to read many of these thick books. Many of these ebooks are open-source and/or free to download. You can also use Publicly available quantum computing books (WIP) which is a list of open access books on quantum computing, a bit lazily done with urls without titles.

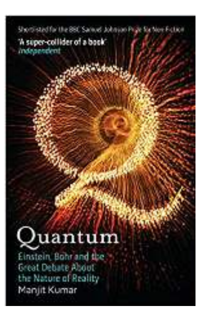
6.4.1 Quantum physics

Quantum Mechanics, Volume 1: Basic Concepts, Tools, and Applications, Second Edition, 2017, by Claude Cohen-Tannoudji, Bernard Diu and Franck Laloë (879 pages) is an undergraduate reference series of books to learn quantum physics. It is considered to be the reference or the bible by many students and teachers of quantum physics.

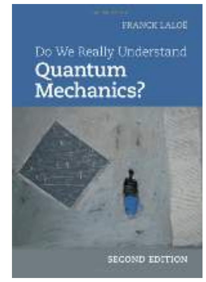


Quantum Mechanics, Volume 2: Angular Momentum, Spin, and Approximation Methods, Second Edition, 2017, by Claude Cohen-Tannoudji, Bernard Diu and Franck Laloë (688 pages). It is focused on spins in general. I told you so. Spins are everywhere in quantum physics and technologies.

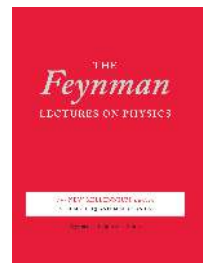
Quantum Mechanics, Volume 3: Fermions, Bosons, Photons, Correlations, and Entanglement, Second Edition, 2017, by Claude Cohen-Tannoudji, Bernard Diu and Franck Laloë (747 pages). Among other things, it covers the study of interactions between atoms and photons.



Quantum: Einstein, Bohr, and the Great Debate about the Nature of Reality by Manjit Kumar, 2009 (480 pages) is an excellent history book about the creation of quantum mechanics. It centers a lot on the works from Max Planck, Niels Bohr, Albert Einstein, Max Born, Werner Heisenberg and Erwin Schrodinger. It's a good account of the history of ideas and how quantum physics saw the day of light. It also showcases a lot of lesser known scientists who played key roles around the most famous ones and the balance between theoreticians and experimentalists.

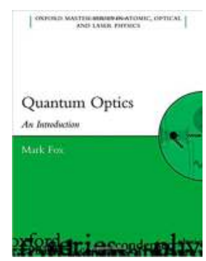


Do we understand quantum mechanics? Second Edition by Franck Laloë, 2019 (550 pages) is an interesting piece that documents the debates on quantum foundations and how to interpret quantum physics. Do we really understand quantum mechanics? by Franck Laloë, 2004 (118 pages) is a shorter and older version of this book, in public access.



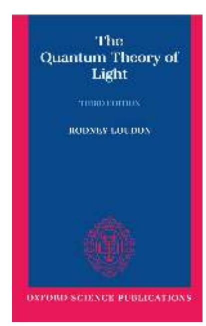
The Feynman Lectures on Physics - Volume III on Quantum Mechanics by Richard Feynman, Robert Leighton and Matthew Sands, (688 pages). It contains lecture notes of Feynman legendary courses from the early 60s. These are treasures of pedagogy with a content that is still up to date to grasp the fundamental of quantum physics.

One advantage is it doesn't make any abuse of mathematics.



Quantum Optics An Introduction by Mark Fox, 2015 (397 pages) is an excellent coverage of the broad field of quantum optics, starting with Maxwell's equation and classical optics and up to the second quantization, and hovering onto photon statistics, antibunching, squeezed light, photon number states, and atoms in cavities.

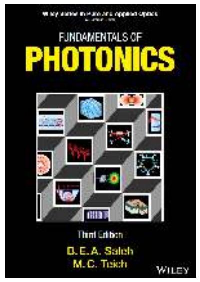
It then deals with applications in computing and cryptography.



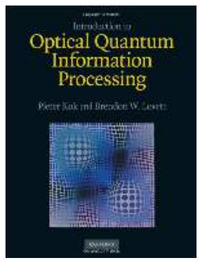
The Quantum Theory of Light by Rodney Loudon, 1973-2001 (450 pages) is a classic book on quantum light, that is useful to later better understand the physics of the various photon qubits used in quantum computing, telecommunications and cryptography.

It classically starts with Planck's radiation law, then covers lasers, light-matter interactions, Mach-Zehnder interferometry, light quantization, single mode, multi-mode and continuous-mode optics and nonlinear optics.

Fundamentals of Photonics by Bahaa Saleh and Malvin Teich, 2019 (1,401 pages, not far from this book's pagination) is a comprehensive quantum optics books that also covers instrumentation (metal, metamaterials, guided-wave optics, fiber optics, resonator optics, lasers, acousto-optics and electro-optics, nonlinear optics).

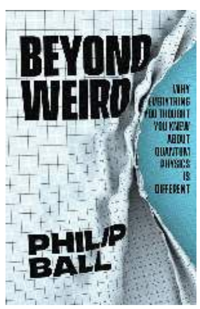


Introduction to Optical Quantum Information Processing by Pieter Kok and Brendon W. Lovett, 2010 (506 pages) is another classic quantum photonics books covering quantum information systems, including quantum communications with continuous-variable optics and all quantum systems that are controlled with photons.



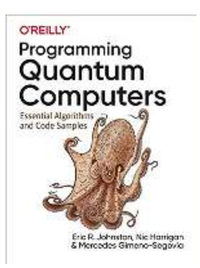
I Don't Understand Quantum Physics by Douglas Ross, 2018 (104 pages) helps conceptualize and visualize many quantum phenomena. It describes the founding experiments of quantum physics (blackbody radiation, photoelectric effect, Compton scattering, etc), wave-particle duality, matter wave, indeterminacy, Schrödinger's equation, superposition and the EPR paradox.

Beyond Weird - Why Everything You Thought You Knew about Quantum Physics Is Different by Philip Ball, 2018 (370 pages) is sort of quantum foundations for dummies journey. It explains the basics of quantum physics, trying to interpret it: superposition, coherence, measurement, entanglement. It doesn't deal, though, with quantum technologies.

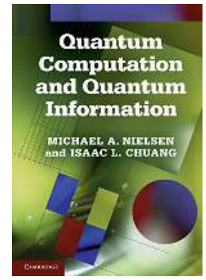


6.4.2 Quantum information

Programming Quantum Computers - Essential Algorithms and Code Samples by Eric R. Johnston, Mercedes Gimeno-Segovia and Nic Harrigan (2019, 336 pages) is an excellent and detailed description of key quantum algorithms like the QFT, phase estimation and the like.



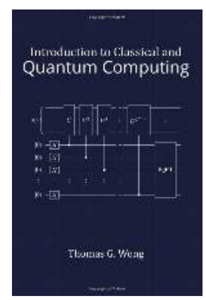
Quantum Computation and Quantum Information by Michael Nielsen and Isaac Chuang, 2010 (10th edition, 704 pages, public access) is a reference on the basics of quantum computing. It answers many key questions, in particular on the mathematical models of linear algebra used in quantum computing.



It also covers the basics of quantum physics, quantum postulates, problems complexity classes, quantum measurement, quantum algorithms, how qubits are realized (harmonic oscillators, trapped ions, photons, NMR), the impact of quantum noise and decoherence, how quantum error corrections work, what is fault-tolerant quantum computing, how about Shannon and von Neumann information entropy and the like. It also covers quantum key distribution and cryptography. It is outdated from the quantum technology standpoint given the scientific and technology progress from the last 15 years. Isaac Chuang still teachers at the MIT and you'll find his name in many bibliographical references in Understanding Quantum Technologies.

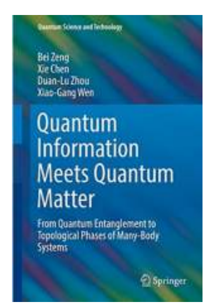
Quantum Information Science by Riccardo Manenti and Mario Motta, November 2023 (768 pages) is a good scientific primer to the broad field of quantum information science.

Introduction to Classical and Quantum Computing by Thomas Wong (2022, 400 pages), a book that is free to download in PDF and available in paperback on Amazon. It makes a good comparison between classical and quantum computing. Like most quantum books for developers, it covers only classical gate-based algorithms with nothing on quantum annealing and quantum simulation.

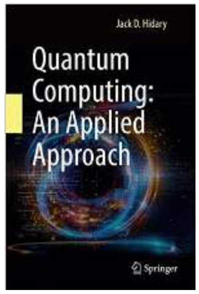


And it says nothing about the hardware and what it can do. It also makes some confusions between phase flip errors and decoherence related errors, which create mixed state when a simple phase error preserves a pure state.

Quantum Information Meets Quantum Matter by Bei Zeng, Xie Chen, Duan-Lu Zhou and Xiao-Gang Wen. It is available in a February 2018 version on arXiv as a free download (373 pages). It deals with error correction, local Hamiltonians, topological order, and long-range entanglement.



Quantum Computing: An Applied Approach (2021, second edition, 445 pages) by Jack Hidary, a fairly comprehensive book covering quantum algorithms and their mathematical foundations. It briefly describes the different architectures of quantum computers.

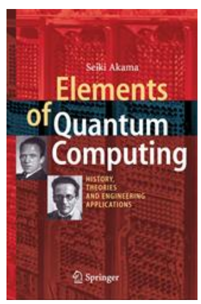


Introduction to quantum computing algorithms by Arthur Pittenberger, 2001 (152 pages) which describes classical quantum algorithms with a good part dedicated to error correction codes.

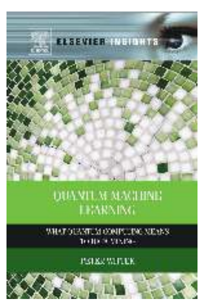
An Introduction to Quantum Computing by Phillip Kaye, Raymond Laflamme and Michele Mosca, 2007 (284 pages) which starts with some mathematical foundations of quantum physics and quantum computing. By reference authors such as Raymond Laflamme (Canada) who is one of the fathers of error correction codes.

Quantum computing by Joseph Gruska (1999, 390 pages) is an ebook containing another fairly comprehensive base covering all aspects of quantum computing and communication.

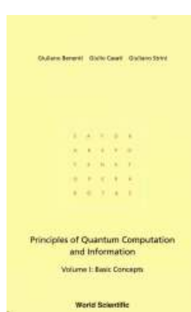
Elements of Quantum Computing by Seiki Akama (133 pages), which is at the same time concise, precise and quite complete on the nuts and bolts of quantum physics and quantum computing, with a good historical overview.



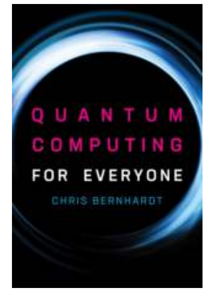
Quantum Machine Learning - What quantum computing means to data mining, by Peter Wittek, 2014 (176 pages) is a good introduction to machine learning and quantum machine learning although many progresses were made since this book's publication.



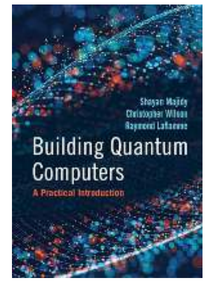
Principles of Quantum Computation and Information, A Comprehensive Textbook by Giuliano Benenti, Giulio Casati, Davide Rossini and Giuliano Strini, December 2018 (598 pages).



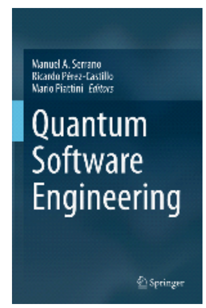
Quantum Computing for Everyone by Chris Bernhardt, 2019 (216 pages) which describes the basics of quantum computing starting with the inevitable qubit, quantum gates, accelerations brought by quantum algorithms and the main components of a quantum computer.



Building Quantum Computers by Shayan Majidy, Christopher Wilson and Raymond Laflamme (2024, 272 pages) describe with some explanations how QPU work with some qubit modalities: nuclear magnetic resonance, photons, trapped ions, and superconducting qubits, although with not many engineering details. It also contains 80 exercises.



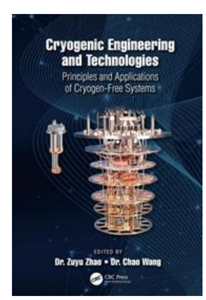
Quantum Software Engineering is a book edited by Manuel A. Serrano, Ricardo Pérez-Castillo and Mario Piattini from University of Castilla-La Mancha in Spain, 2022 (321 pages). It provides an overview of this emerging discipline, describing key concepts, the related vocabulary and formal methods. It also presents Q-UML, a quantum modeling language.



Quantum computing for dummies by William Hurley, April 2023, has yet to deliver its nuggets!

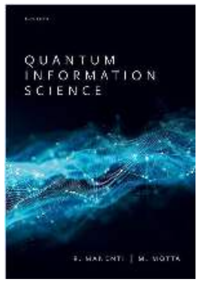
Unconventional Computation by Bruce MacLennan, University of Tennessee, October 2019 (304 pages) which discusses the energy issues of computation (reversible, non-reversible) and various alternative methods of computation including quantum computing and molecular computing.

Cryogenic Engineering and Technologies by Zuyu Zhao and Chao Wang, October 2019 (386 pages) is a reference book on cryogenic issues with a very extensive and well-documented history.

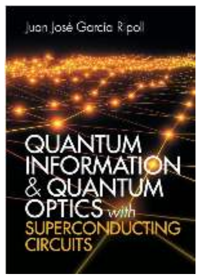


There is an excellent chapter on dry dilution cryostats used in quantum computers. This helped me to prepare the part of this book on cryogenics in addition to an interview with the team of the French startup CryoConcept and with researchers from CNRS Institut Néel in Grenoble.

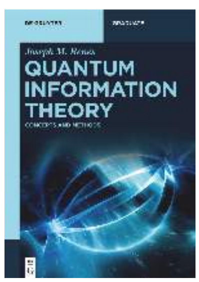
Quantum Information Science by Riccardo Manenti and Mario Motta, August 2023 (768 pages) covers quantum computing with going through mathematics, quantum physics, quantum algorithms including quantum chemistry and quantum hardware, focused on superconducting qubits.



Quantum Information & Quantum Optics with superconducting qubits by Juan José García Ripoll, August 2022 (300 pages) covers superconducting quantum circuits and qubits, up to their applications in quantum computing and quantum simulation. Why optics? Because you control superconducting qubits with microwaves, which are photons!



Quantum Information Theory by Joseph M. Renes, August 2022 (250 pages) is a graduate textbook introducing the mathematical theory for quantum communication, computation, and cryptography with focusing on the concept of quantum channels, understanding fidelities and entropies in the quantum world, and the interrelationship of various quantum information processing protocols.



The Quantum Internet by Peter P. Rohde, December 2021 (300 pages) examines in detail how the quantum internet will take share, focusing on the technology and on its economical and political implications.

Introduction to Quantum Cryptography by Thomas Vidick (Caltech) and Stephanie Wehner (TU Delft), September 2023, provides background theory and mathematical techniques on the design of quantum cryptographic protocols, including QKD, quantum money, and delegated quantum computation.

The New Quantum Era: An Outsider Introduction by Sebastian Hassinger, May 2026 (220 pages) is a primer to explore quantum computing concepts for non-technical audience, with an historical perspective. It says it distinguishes real progress from hype in quantum technologies.

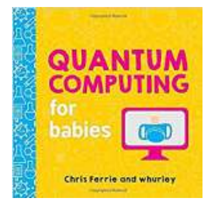
Quantum Computing Strategy by Elena Yndurain, March 2025 (236 pages) wants to demystify quantum concepts through accessible explanations, practical case studies from multiple industries, including a business perspective on practical applicability.

Quantum Computing: Foundations and Practice Get access Arrow by Steven Herbert, December 2025, is focused on explaining quantum algorithms and their potential uses, after a primer on quantum physics, seemingly skipping like most books all quantum computing engineering.

The Business of Quantum Technologies - From Theory to Innovation Strategy by Chander Velu, Keith Norman, Yuzhen Zhu, Fathiro Hutama Reksa Putra and Christopher Noble, 2025 (152 pages), open access. It is also focused on the applications of quantum computing, communications and sensing.

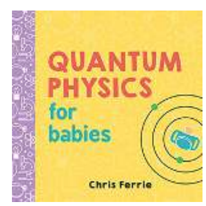
6.5 Comics

Quantum Computing for babies by Chris Ferrie and William Hurley, April 2018, is aimed more at children or teenagers. The book popularizes the major concepts of physics and quantum computing in a very colorful way.

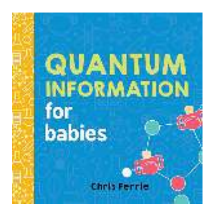


It comes from a professor of quantum computing at Sydney University of Technology, who became an entrepreneur, creating the startup Quokka, and the founder of the American startup Strangeworks.

Two other books in the same vein from Chris Ferrie were also released: Quantum Physics for babies



And Quantum Information for babies, all for less than $10. I “read” the last one (24 pages) and I'm not sure even an adult would really understand how quantum computing after looking at it. This is the danger of oversimplification and information dilution.



6.6 Training

Videos from the Stanford Quantum Computing course.

Quantum Computing Fundamentals course offered by MIT.

Online training course on quantum programming offered by Brillant in partnership with Microsoft.

QSIT course (FS 2016) at ETH Zurich with its slides and lecture notes.

Quantum Computing as a High School Module, a curriculum with exercises on the basics of quantum physics for students at the BAC level.

6.7 Reports

Inside Quantum Technology, an analyst company dedicated to quantum technologies, which sells industry reports.

You can also find analysts reports on quantum technologies with McKinsey, BCG, Yole Development and other analyst companies. We mentioned a lot of them in this book although I cautioned you to be very careful about their assessments on the maturity of quantum computing.

6.8 Miscellaneous

Designing and Presenting a Science Poster, Jonathan Carter, Berkeley (20 slides) which is intended to help researchers design a good research project presentation poster.

6.9 Bibliography and notes

These are the bibliographical references and notes for the **Resources** section.

[888] Q-Turn: Changing Paradigms In Quantum Science, by Ana Belén Sainz, arXiv, July 2022 (14 pages).

[889] Back from Lindau, by Olivier Ezratty, Opinions Libres, July 2024.

This **Resources** section contains 2 bibliographical references and notes containing at least 14 pages.

Year	Hardware	Software	Ecosystem
2018	• IBM 20-qubit QPU. • IonQ 11-qubit QPU. • Preskill's NISQ concept. • IQM, Atom Computing, QuEra, Quantum Machines, Qblox creation.	• IBM open-source QASM. • Ewin Tang's QML tensorisation. • Quantum Error Mitigation. • Google Cirq. • DAQC.	• EU Quantum Flagship. • US NQIA launch. • Israel NQI. • Peak year in startup creation. • QED-C creation.
2019	• Google 53-qubit supremacy. • IBM Q System One. • Oxford Ionics, Nord Quantique creation. • Pasqal creation.	• Gidney Shor-2048 estimate. • ADAPT-VQE. • Amazon Braket. • Multiverse creation.	• UK quantum strategy renewal. • Russia Quantum Technologies Roadmap.
2020	• D-Wave Advantage. • Quantinuum 20-qubits QPU. • IBM, Google first roadmaps. • Alice&Bob, C12, Eleqtron creation. • Jiuzhang 1.0 GBS.	• Quantum kernel methods. • Algorithmiq, Classiq, ParityQC, Qedma creation.	• Germany's €2B quantum plan. • USA NQIA extension. • First India quantum plan.
2021	• IBM Eagle 127-qubit QPU. • Quantinuum creation. • PsiQuantum FBQC proposal. • First logical qubits. • Jiuzhang 2.0 GBS.	• Floquet Code. • XZZX surface code. • Kipu Quantum creation. • Nvidia cuQuantum.	• France NQS launch. • IonQ and Rigetti IPO. • QuiC consortium creation. • First English edition of this book.
2022	• Xanadu quantum advantage. • Diraq, Quobly, Planqc, Welinq creation.	• NIST PQC draft standards. • Nvidia CUDA-Quantum.	• Aspect-Clauser-Zeilinger Nobel laureates. • D-Wave IPO. • QEI launch.
2023	• QuEra logical qubits. • IBM Heron and Condor. • IBM quantum utility Nature paper. • Jiuzhang 3.0 GBS. • ETH superco QPU interconnect.	• VQE and QAOA refinements.	• India National Quantum Mission. • South Korea quantum plan.
2024	• Google Willow. • Origin Quantum Wukong. • Quantinuum H2 56-qubits QPU. • 6,100 controlled atoms at Caltech. • Qolab creation.	• FTQC advances. • FTQC vendor roadmaps. • Google DQI algorithm. • Zapata bankrupt. • LLMs getting used in quantum computing. • NIST PQC standards.	• UK NQCC inaugurated. • First QPUs delivered to EuroHPC. • PsiQuantum deal with Australia.
2025	• Microsoft Majorana-1. • IBM Nighthawk. • IBM 122-qubits GHZ state. • D-Wave Advantage 2. • Oxford Ionics acquisition by IonQ. • Equal1 and Quantum Motion full-stack QPUs. • Jiuzhang 4.0 GBS.	• D-Wave quantum advantage on Ising model. • Google Magic state cultivation. • IBM bivariate bicycle qLDPC code. • EU AI/quantum white paper. • Zapata back from the dead. • Google Echoes-OTOC experiments.	• EU Quantum Strategy. • DARPA QBI selection. • US NQIA renewal in the making. • PsiQuantum raises $1B. • Record funding year (>$2B WW). • Clarke-Devoret-Martinis Nobel laureates.

Table 2: Some key events in quantum computing since 2018. Ⓒ Olivier Ezratty, November 2025.

Year	Hardware	Software	Ecosystem
2026	• More logical qubits experiments, like with Quantinuum Helios. • Oratomic creation and funding. • Microsoft Majorana-2. • Modular cryostats at Bluefors, Maybell Quantum and IBM.	• New QEC/FTQC architectures and resource estimations for breaking RSA-2048 and ECC-256 keys. Iceberg Quantum Pinnacle, Oratomic, Q-CTRL, Google, IonQ, and Quandela. • IBM “quantum advantage” claims with U. Chicago, Qedma and Algorithmiq. • Q-CTRL quantum advantage paper. • Accelerated PQC migration timelines.	• USA POTUS Quantum Executive Orders, Dept Commerce led $2B manufacturing investment and DoE’s Quantum Genesis program and competition. • IBM’s $10B 5-year quantum investment announcement. • France National Quantum Strategy renewal. • Infleqtion, Xanadu, Horizon Quantum, IQM, Quantinuum and Pasqal IPOs. • Another record funding year.

Table 3: Some key events in quantum computing in 2026. 🅭 Olivier Ezratty, September 2026.

7 Making of

This 9th edition of Understanding Quantum Technologies is the second I edit in LaTeX. In the last edition's similar "making of" section, I focused on the complex migration process from Word to LaTeX for the 8th edition. This time, we switch gear on another tooling that grew in importance in this book's editing which is the use of LLM-based generative AI. I described in the "research for dummies" part how these tools are revolutionizing the research and academic landscape in general and in quantum science and technologies in particular, and showing the new various AI-related disclaimers that are now commonplace in academic papers. This part is an equivalent where I document where and how I used these AI tools to improve my productivity and the quality of the book, with caring about the related side effects.

You can imagine how updating this book every year can be a tedious task. I collect references to new academic papers throughout the year and in May/June I start to update the book. It is a bottomless pit as every other day brings its own load of news and papers. So, for every updating or content cleaning task, I now have the habit to ask myself: how can AI help me be more efficient and improve the quality of the book?

For any problem, any question, and tedious and repetitive task, there's often a smart way to delegate some work to LLMs. It's sometimes just about imagination. I'll cover here some of these things I successfully tested during the book update. How I now ask LLMs to create Python code to create complex charts based on my own data or third party data, how I built parametric models that I can then run myself, how I converted old Powerpoint tables into clean and documented LaTeX tables, how I profiled stealth companies, updated the book glossary, fact-checked the book content, and ended up using these tools against each other as contradictory reviewers.

7.1 Charts

I wanted to speedup the process of updating charts which I was creating using Excel data and charts. My old process was very manual: updating pivot tables, manually arranging data, cutting and pasting charts to Powerpoint to add some captions and artefacts.

A first example is Figure 109 which shows the best funded startups per country and the share of the funding they got in their respective country. I've been updating the chart every year for many years now. To do that, I provided Claude Pro with an example of my Excel data source, pointing to where it is on my laptop. Then, I extracted the company logo LaTeX macros from the TeX files containing them, generating a new LaTeX file containing correspondences between the logo file names and the company names. I added the legacy PDF chart and asked Claude to regenerate it in Python with specifying the location of the logos.

It didn't work right away and required at least about one hour of tuning work. But now, the Python script directly fetches the data from my Excel company database and updates the whole two-part chart in a single PDF file. It also dynamically recomputes the numbers in the caption.

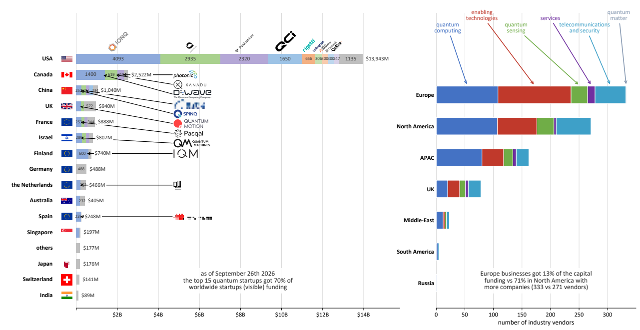


Figure 109: A first example of chart generated in Python by Claude Pro which directly fetches the data in my Excel company database and use logos from the book media folder.

Now, let's look at a more sophisticated chart creation. Since the 2024 edition, I was using Figure 110 with its pie-chart done with Excel consolidating data from the World Bank. Since the data is now old (2022) and predates the LLM usage surge that started late 2022, I wanted to create a new chart showing the evolution.

I asked Claude Pro to look at the data I was using, to find new data sources and to consolidate energy and power figures for 2022 and 2026 actuals, and 2030 forecasts. The result is in Figure 111. It didn't come in one round. I had to fact check Claude Pro's computing method and data sources, make sure the orders of magnitude were correct. It had the idea to use a dual Y scale for energy and power. I asked it to place energy consumption data above the X axis and energy manufacturing costs below it. I then asked Claude Pro to compute the ratio of ICT-related energy consumption vs worldwide electricity consumption. The result is a better estimation of this ratio than in most publications, which sometimes forecast that ICT or LLM will consume between 30% and 50% of the whole electricity worldwide.

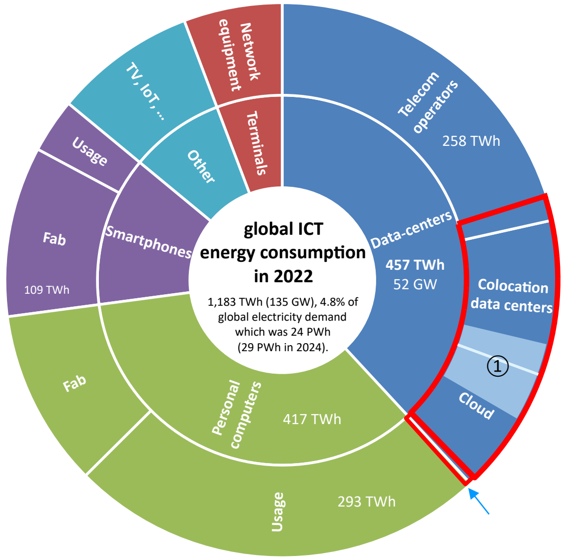


Figure 110: The original chart I created in Excel in 2024 showing the distribution of power and energy consumption between end-user devices and servers worldwide in 2022, based on data coming from the World Bank and other sources.

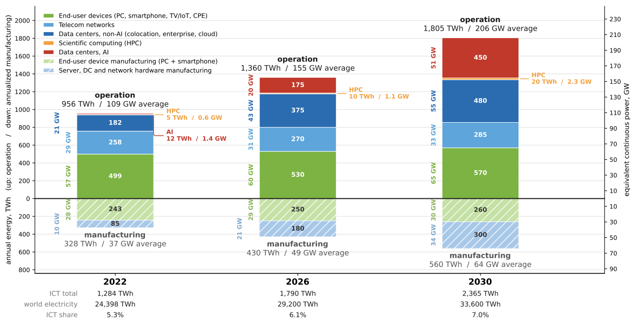


Figure 111: The new energy and power consumption chart generated with the help of Claude. I insert it in a single-column version for the sake of showing the result. The one page version of this chart is in the book, in quantum computing engineering / energetics.

This other example in Figure 112 shows the amazing Claude Pro capability to create 3D charts based on your own ideas. For the gate-based computing part of the book, I wanted to show that there are multiple theoretical paths, or quantum trajectories, to create a gate turning one state into another.

There's a shortest path, a longest path, and an intermediate path. It worked like a charm and I got rather quickly this SVG/PDF vector chart. But I also got the related caption explaining that in practice, the gate decomposition to create such unitary being more complicated, using X and Z rotations for example, or T and H gates sequences for FTQC systems.

I also assembled charts on traded quantum vendors revenue and losses. LLMs are now fetching the data automatically in SEC reports and the result is pretty smooth.

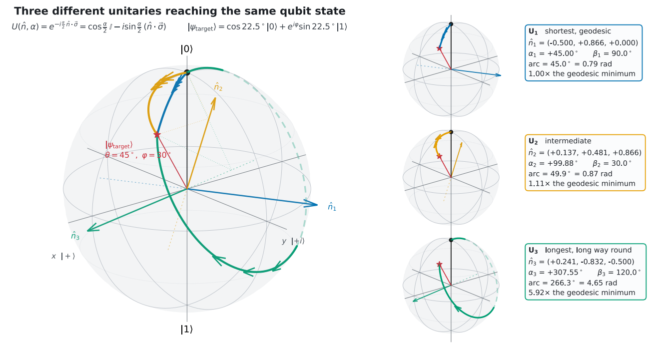


Figure 112: An example pedagogical chart created by Claude Pro with a Bloch sphere and several transitions from one state to the other.

Another usage of LLMs I adopted was to ask them to turn into Python-generated vector files some charts that are in JPEG/PNG versions in the book. I did it a couple times.

7.2 Converting tables

Previous editions of this book contained a lot of tables exported from Powerpoint. In scientific publication, this is not the right way to proceed since all assertions and facts must be documented with a reference. Also, updating the chart with exporting it from Powerpoint in SVG first and then converting it to PDF was a tedious task.

So, I provided the PDF from original tables like this four-color table on qubit type characteristics in Figure 113 and first asked Claude Pro to create a LaTeX template for it, and then fill it. It worked in about two hours of work, the most difficult task being to keep the gradient in the orange cell.

I then provided Claude Pro with the related section LaTeX file and its bibliography file and asked it to add references found in my own book to substantiate the items in the bullet lists. Or, alternatively, to fact-check, update, and correct it, and to propose additional references.

Figure 113: A qubit type summary chart, the old way.

Claude Pro did that very well, and with no hallucinations (Figure 114). Most of the references were already in my own text, and the ones it added were all relevant. The caveat was that the tables are a bit larger but in that case, it was OK.

I did that for many other tables related to benchmarking methods, quantum advantage and supremacy papers, qubit types figures of merit, qubit type challenges, qubit type energetics, and raw materials used in quantum technologies. Some of the resulting tables are now much larger, and harder to visualize, due to Claude Pro's capacity to be very precise. It needed some editing on my side.

One side effect of these conversions was the fact-checking that came along with them. On the trapped ions tables, I asked Claude Pro not to silently fix what it thought was wrong, but to leave a % comment in the LaTeX source above each cell it disagreed with, and to let me arbitrate. It flagged that I had the wrong ion species for the IonQ Forte NISQ system, which uses $^{171}Yb^+$ and not $^{133}Ba^+$, that the Forte operates below 10 K and not at room temperature, that the AQT gate wavelength is 729 nm and not 397 nm which is the detection line, that Quantum Art uses $^{88}Sr^+$, and that two columns looked swapped between Oxford Ionics and Universal Quantum. I then checked each error myself against the vendors' documentation before touching the source. This convention of flagging instead of correcting is now in all my prompts for table and text work. In such a large book, a silent correction is more dangerous than a visible error, because the visible one gets reviewed and the silent one gets published.

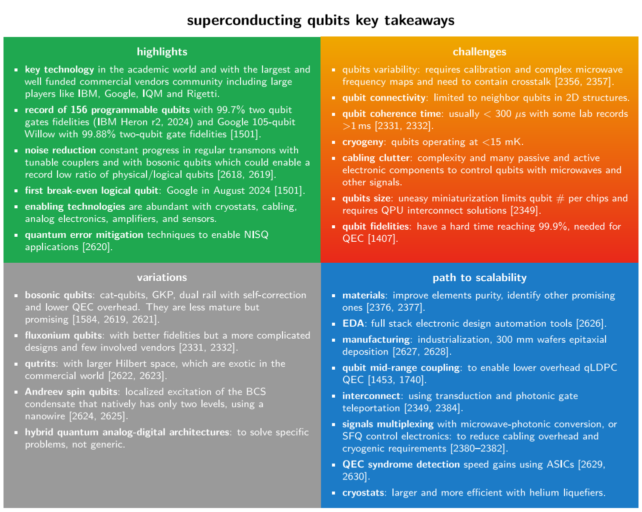


Figure 114: The new version of the chart in LaTeX generated by Claude Pro with the citation references for most bullets.

7.3 Creating tables

LLMs also helped create some tables from scratch. It is the case for the quantum computers cloud access pricing table in the economics subsection from the engineering section. The result looks good and correct, with the right reference links.

7.4 Building models

In my work on the book and on papers related to quantum computing energetics, I asked Claude Pro to build resource estimate models. I wanted to compare the qubit, time, and energy budgets of a logical memory correction including its decoder, the generation of logical Clifford gates with lattice surgery or transversal two-qubit gates, and magic state generation and teleportation. I asked Claude Pro to read the 2025 RSA-2048 resource estimation papers from Craig Gidney [890], from Iceberg Quantum with their Pinnacle architecture [891], and from the Oratomic neutral atom architecture [892], and then to build an Excel model that I could play with on my own. Claude Pro analyzed the three papers and additional papers on magic state cultivation and yoked surface codes. It produced a seven sheets Excel workbook covering five qubit modalities and their cryogenic parameters, a QEC code library with seventeen entries each sourced to a specific paper section, an algorithm library covering RSA-1024/2048/3072 and ECC-256, a calculator tab sheet controllable by drop-downs buttons, and a sensitivity grid varying cycle time and parallelization.

With its default settings, the model built by Claude Pro reproduced the published numbers of the papers. It landed exactly on Gidney's 897,864 physical qubits, 12.07 hours per shot and 4.96 days in total. Asking for this kind of self-check against published values is highly valuable. The remaining work on my side was to check the parameters that the papers do not provide at all, and there are many of those, particularly on the energy side where the vendors' own numbers are scarce. I however didn't integrate this generated content in the book. It played the role of some background check.

7.5 Profiling companies

This book is not only about science and technology in general, but also about describing the industry vendor ecosystem in many different fields. Every other year, I add about a hundred new companies that I discover in various places: presentations, LinkedIn posts, arXiv paper authors list, etc. But most new companies have really bad websites and getting information about them is never easy. I used to look at their scientific cofounders on LinkedIn and then see what they published on arXiv. It took a lot of time. I created a small related prompt in my Claude Pro user profile and when I ask it to generate a company profile, it generates a very detailed description of the company, its cofounders scientific and/or business track-record. Claude Pro is collecting everything that results from multi-criteria Google searches, and it analyzes all page results and compile it. It can find multiple connections between the startup founders, their scientific lab, identify their product strategy, even for companies with just an empty landing page website. It was usually very verbose so I had to cherry pick what was relevant in the result and still, check everything.

This process was particularly useful for companies based in China, which can have several names. It can say for example that this cofounder was the PhD or post-doc of this principal investigator in such lab and so on. For one company (Peak Quantum), I also provided all the arXiv papers I had from their original lab's work and asked Claude Pro to guess what they were actually doing (transmons? fluxonium?). It provided some very interesting clues. The negative results are just as valuable in this exercise. When I ask for a company's peer-reviewed publication record and the honest answer is that there is none, that single fact tells me more about the company's maturity than the three pages of marketing prose on its website. I now ask explicitly for what could *not* be found, which is a question these tools answer well only if you force them to.

7.6 Comparing papers

Every other working day, I filter manually the quantum physics arXiv dump to find interesting papers for my work and for the book. I keep an average 20% of each day's production. Like many academics, I look at the abstract, figures and conclusion/discussion parts. Unfortunately, the real useful information is often hidden in weird places in the paper: in charts, in some convoluted vocabulary, or it is just absent. So, taking the example of some quantum algorithm, I ask simple questions like was some quantum advantage demonstrated? What resources were used? Where was the code executed? This is very basic stuff and Claude Pro, Gemini Pro and ChatGPT fare very well in general.

I now add one sentence to the prompt asking the tool to push back and to show the limitations of the paper, and above all, to push back on my own reading of it. This is where it gets interesting. On a 2026 paper proposing an accuracy metric for quantum annealing and benchmarking it against large scale classical Monte-Carlo simulations of Rydberg systems [893], I proposed my own summary, which was that noise degrades the annealing results as you scale the qubit count, and that this is what makes the dynamics classically simulable. Claude Pro answered that my reading was right on one point and wrong on two others. The paper contains no noise model, no decoherence simulation and no experimental data whatsoever. The band in the figure that I had read as an experimental result was the authors' own estimate, based on published noise levels and, in their own words, private discussions. What the paper does demonstrate is the accuracy scaling of their own variational ansatz, which reaches a relative accuracy below 10^{-2} at 10^8 atoms and below 10^{-4} at 10^5 atoms, and this is a statement about classical simulation quality, not about hardware. Without this question, I would have written a wrong paragraph with the right references, which is not a good combination. Correcting your own views on a paper is of high value to check your own understanding of complex matters.

7.7 Fact-checking the book

In more advanced tasks, I asked Claude Pro and ChatGPT to fact-check entire sections and subsections of the book. The main text contains about 80 such sections and subsections with lengths ranging from ten to about a hundred pages. I provide the section LaTeX file and the related bibliography file which is generated automatically in my LaTeX compilation workflow, not the whole 11.7K bibliography.

My prompt asks the LLM for a grammatical check, a data and mathematical check, scientific soundness, a consistency check, and a citation relevance check.

Based on my prompt, Claude Pro (or another LLM) then generates an annotated and corrected version of my LaTeX file with comments around the modified text. Most of the time, it is perfectly on point and very useful feedback. Many times, it finds errors which are difficult to spot by a regular human reviewer. It even spot them in the charts embedded in the text when I provide the compiled PDF version of the part to fact-check.

For example, I had an invalid chemical formula, $BrCH_4CHO$ coming from [894], instead of $BrCH_2CHO$! Claude Pro challenged a sentence still listing recommendation systems among the exponential quantum speedups, which is considered obsolete since Ewin Tang's dequantization in 2018 [895], although this is still debated. There was a citation inversion where I presented Lin and Tong's paper as sitting at the $O(1/\epsilon^2)$ sampling noise limit when it actually achieves Heisenberg-limited scaling, which turned the reference into an argument for the opposite of what it proves [896]. There was also a two days discrepancy between the 175 days I quoted and the 177 days of the paper.

Another amazing experience was with the integration of two charts on atomic transitions from a Mark Saffman paper Figure **??**. I extracted the SVG vector version from the paper and provided it to Claude. I wanted to colorize the transitions based on the figure caption, to identify transitions per categories. It did it perfectly after some iterations. But Claude pro spotted a small error in one rare transition wavelength. After pushing it, it explained the origin of the error (an unit error), provided the right wavelength and a source which computed it.

One impressive dialog was not on the book but on the FTQC energetics paper I am co-authoring. I asked for a check of the cryogenics section. Claude Pro back-computed the entire Carnot efficiency table from my own power figures, noticed that four slightly different values for the pulse tube stage were floating around in the text and the table (0.891%, "about 1%", 1.33% and

1.4%), and identified that the 1.4% shown in the table was in fact the ideal COP and not a Carnot efficiency. It then found the real problem, which is that my Carnot efficiency for the PT410 pulse tube only accounted for the second stage cooling power at 4.2 K and ignored the 40 W available at 45 K on the first stage. Correcting that turns a stated 0.89% device efficiency into a true 3.8%, and the error propagated into the comparison table where it inflated the apparent advantage of liquid helium over pulse tubes, to the point where the ranking of two scenarios flipped once fixed. I sent back a corrected paragraph. It replied that the numbers still did not match the table by a factor of ten because I had dropped a zero, which was true. I sent a third version, which it validated in a single line. This is precisely what a good reviewer does and what a tired co-author does not do at 11 pm.

7.8 Enriching the bibliography

In September 2026, I had the idea to add lock icons for paid peer-reviewed papers, and an unlock icon with a related hyperlink to add an arXiv or other preprint link. I asked this to ChatGPT 5.6 which, after some back-and-forth discussions, created a 4,000 lines script that scanned my 11K+ bib file in one and half hour, and found ways to add relevant tags in the bibliography.

I still had to complete the task manually in the end for paid papers where the tool didn't find a preprint when there was actually one available. The result is quite nice and practical for readers who don't work with an organization with licenses for accessing these peer journals paid content Figure 115. But I have not yet finished looking for alternate versions for some paid papers.

[4053] Controversial quantum-computing paper gets hefty correction — but concerns linger, by Dan Garisto, Nature, August 2025.

[4054] Chiral Majorana fermion modes in a quantum anomalous Hall insulator–superconductor structure, by Qing Lin He et al., Science, 2017 (7 pages) (preprint on arXiv).

[4055] Editorial Expression of concern, by Science, December 2021.

[4056] Major Quantum Computing Strategy Suffers Serious Setbacks, by Philip Ball, September 2021.

[4057] Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices, by Vincent Mourik et al., April 2012 (preprint on arXiv).

Figure 115: The rendering of the bibliography with lock and unlock icons showing paywalled peer review papers with or without an alternate free source, usually as the paper preprint version. Added in September 2026.

7.9 Complement the glossary

In this process, I also now provide the book glossary LaTeX file and ask Claude Pro to add terms in the scanned section/subsection that would deserve to show-up in the glossary, with a definition that is either generated using my own text, or from scratch. It does it very well although I edit many proposed definitions. As a result, the glossary grew again significantly in size. It shows the breadth of the terminology employed in this field. Scanning it is a good way to check your knowledge. I know only a few readers do this, but... I do!

7.10 Comparing LLMs

From May to September 2026, I have been mainly using Claude Pro, with the $23 monthly subscription. Then, I added a similar subscription to Gemini Pro and ChatGPT. And I also use Copilot which is part of my Office365 license. I use these tools based on their capabilities, and also, with managing my credits carefully. On the paid subscriptions, you have a token quota for 5-hour and 5-day windows. I figured out a way to optimize my tokens consumption to avoid overpaying them, although I did add some credits for Claude Pro. One example is that I'm asking simple Python and LaTeX coding advice from Gemini, ChatGPT or CoPilot instead of Claude Pro that I reserve for the most demanding scientific tasks.

Using several tools creates a new task that did not exist before, which is arbitrating between them. While sorting review comments on quantum energetics, Gemini Pro stated that my sentence about IBM's Nighthawk was wrong, that Nighthawk was an older roadmap benchmark and that Heron and Flamingo were the real scale-in ceiling before the shift to modularity. I passed the comment to Claude Pro, which had reviewed the very same section, and rather bluntly asked it why it had made this mistake. It pushed back and told me that this evaluation was not from it, that it had read the same sentence and deliberately left it alone because my draft was correct, and that whoever wrote the comment had the roadmap chronology inverted. Nighthawk, announced in November 2025 with 120 qubits, is the newer processor, and it has fewer qubits than Heron r2 precisely because moving from a heavy-hex lattice to a square lattice with degree-4 connectivity trades qubit count for the denser coupling needed on the way to Loon and its degree-6 connectivity supporting bivariate bicycle codes. It also suggested I add half a sentence explaining this apparent qubit count regression, since any reader could fall into the same misreading. I then had to admit that the faulty comment came from Gemini Pro and not from Claude Pro.

The explanation it gave for this episode is worth keeping in mind. Its explanation, which I report as its own and have not measured, is that a model is most confidently wrong on facts recent enough to be badly represented in its training data but familiar enough to feel settled, and that high internal confidence is exactly what prevents it from triggering a web search. Models also err on old, niche, ambiguous and reasoning-heavy material, so this is not a general law. The practical consequence is the useful part: when two tools disagree, treat the disagreement as a prompt to consult a primary source, not as an invitation to a third prompt to either model.

7.11 Side effects

I started using LLMs to update UQT in 2023 and my usage grew again in 2024 and 2025. But this time was different. LLMs became indispensable tools to update this large book. They are my sparring partner. They behave as if I had a couple hundred top-level academics behind my shoulder explaining new concepts to me, and the like. They consolidate information like I dreamed before LLM's advent and even later. Between 2022 and 2025, their ability to consolidate data was not good. Now that they can fetch data online and consolidate it, they are really powerful.

The second phenomenon that is mind-boggling is the apparent reasoning capabilities these systems are exhibiting. On the tasks described in this section, and on that sample only, these systems display useful reasoning capabilities in the scientific realm despite their flaws. This is an observation about my own workflow, not a measured comparison with domain specialists. They can decompose a problem into subproblems, show their reasoning, accept criticism (which not all humans do), correct course, and so on. And the progress is staggering.

There are a couple caveats of course.

One is the famous slop effect with the heavy and convoluted language generated by these tools [897]. You can limit this effect with good prompting and with asking them to reuse your own style. But they have a tendency, in the scientific domain, to overuse highly technical terms without defining them, and sometimes, it generates some nonsense. You need to make sure you understand the production before accepting it. Many users ask LLMs to polish their text. The result is clean but too clean and it shows up quickly. You now can guess that such text was AI generated. I sometimes use a reverse approach with tuning text coming from AI, making it simpler, use my own words, add my own explanation.

The second are hallucinations particularly with references. ChatGPT and Gemini were generating a lot of these. But since I've been using heavily Claude Pro starting earlier in 2026, I have not detected such hallucinations in the bibliographical references it generated, which is not the same as their absence, and I still verify every suggested reference. There can be some glitch mixing references between the arXiv and peer reviewed version of a paper. This is real progress. I still verify all suggested references and their content.

The third caveat took me longer to identify, and it is the most insidious one. Nothing in the output tells you what was actually verified. At some point I asked Claude Pro how many of the claims in a section it had really checked against primary sources rather than against its own memory. The answer was four web searches for well over a hundred claims, the rest having been checked against training knowledge, with the 2026-dated references explicitly flagged as unverifiable. This is worrying since a model which verifies all claims vs one that checks only of few of them produces text with similar structure. As a result, I now ask to systematically check claims one by one. This can be further automatized with AI agents programming.

And these tools do make mistakes on my own turf. In one session on neutral atoms, Claude Pro casually grouped Alice & Bob with the cold atom platforms, when it is a superconducting cat qubit company. I caught it quickly. One reason my error rate with these tools seems reasonable is that I know enough to catch them. But in some domains like in complex quantum algorithms, I'm not that sure I can check potential errors.

Another bothering phenomenon related to so-called "'guardrails" is the overly political correctness of some recommendations. One example arose when I asked ChatGPT to correct the key takeaways on the quantum fake science part. My original text was: "*We uncover some other scams in the free energy generation category. These systems are supposed to extract some energy from vacuum when their only actual effect is to pump money out of your wallet*". It proposed to replace it with "*We also examine unsupported "free energy" claims. Devices presented as extracting usable energy from the vacuum must be assessed against conservation laws, reproducible measurements and independent testing. Claims of fraud or deliberate deception should be reserved for cases supported by authoritative findings or documented evidence*". It reversed the charge of the proof for scams which have no proofs and are not sustained by peer reviewed scientific papers. I kept my version! A scam remains a scam.

Brain saturation is the other side effect of using LLMs. They deliver far more information than you have time to absorb. So imagine my position when updating this book! It was like having all the experts in the world on my screen hammering me with their authoritative and extensive knowledge. It is just yet another humility lesson about accepting not to understand everything, and to learn stuff step by step. By the way, after I wrote this text, I asked Claude Pro to fact-check it and to find other interesting anecdotes. With the conversation history feature enabled on my account, it retrieved earlier exchanges and completed the text with some of them. It is embedded in this text and it is up to you to find it. Even though I edited what Claude generated, you can still spot it.

7.12 Bibliography and notes

These are the bibliographical references and notes for the **Making of** section.

[890] How to factor 2048 bit RSA integers with less than a million noisy qubits, by Craig Gidney, arXiv, May 2025 (40 pages).

[891] The Pinnacle Architecture: Reducing the cost of breaking RSA-2048 to 100 000 physical qubits using quantum LDPC codes, by Paul Webster, Lawrence Z. Cohen, et al., arXiv, February 2026 (22 pages).

[892] Shor's algorithm is possible with as few as 10,000 reconfigurable atomic qubits, by Madelyn Cain, Qian Xu, Robbie King, Lewis R. B. Picard, Harry Levine, Manuel Endres, John Preskill, Hsin-Yuan Huang, and Dolev Bluvstein, arXiv, March 2026 (15 pages).

[893] A fidelity metric for quantum annealing benchmarked by extreme scaling quantum Monte-Carlo simulations, by Gabriel Gouraud, Miha Srdinsek, and Xavier Waintal, arXiv, July 2026 (19 pages).

[894] End-to-End Simulation of Chemical Dynamics on a Quantum Computer, by Elliot C. Eklund, Arkin Tikku, Patrick Sinnott, William J. Huggins, Guang Hao Low, Dominic W. Berry, and Ivan Kassal, arXiv, March 2026 (69 pages).

[895] A quantum-inspired classical algorithm for recommendation systems, by Ewin Tang, arXiv, May 2019 (32 pages).

[896] Heisenberg-limited ground state energy estimation for early fault-tolerant quantum computers, by Lin Lin and Yu Tong, arXiv, February 2022 (31 pages).

[897] AI Has Finally Learned to Write Perfectly. That's the Worst Thing That Could Have Happened. by Nick Rogers, Silent-Room Journal, August 2026.

This **Making of** section contains 8 bibliographical references and notes containing at least 228 pages.

8 Glossary

What is the purpose of a glossary? It allows you to find your way around in a new terminology and to step back to understand new concepts. For the author, it was also a good checkpoint of his own understanding and ability to popularize scientific and technological concepts. Some of these descriptions are simplified versions derived from Wikipedia definitions. Welcome to the lingua franca of quantum sciences and technologies!

137: the approximate inverse of the fine-structure constant $\alpha \approx 1/137.036$, the dimensionless quantity characterizing the strength of the electromagnetic interaction. Being dimensionless, it has the same value in any system of units. In the Bohr model of hydrogen, α is also the ratio between the speed of the electron in the ground state and the speed of light, which is an interpretation valid for that model rather than a definition. 137 is a bit like 42 in quantum physics. Wolfgang Pauli died after an operation for pancreatic cancer, while his hospital room was number 137.

1WQC: one way quantum computing, another name for MBQC (Measurement Based Quantum Computing). The computation starts from a large entangled resource state, usually a cluster or graph state, which is progressively consumed by adaptive single-qubit measurements with classical feedforward, the choice of each measurement basis depending on earlier outcomes. The resource state is used up, hence the name, but the logical map that is implemented can be an arbitrary unitary, so the model is not logically irreversible.

3D NAND: flash memory technology stacking memory cells vertically instead of shrinking them horizontally. Layer counts went from 24 in 2013 to 321 in mass production at SK hynix and 332 sampled by Kioxia and SanDisk in 2026, with Samsung ramping a 400-layer class generation and demonstrating a 900-layer research device. It is a case of vertical scaling replacing lithographic scaling, an approach that logic chips are only starting to follow with CFETs and 3D stacking.

2DEG (Two-Dimensional Electron Gas): electron system confined strongly in one spatial direction while remaining mobile in the other two. In semiconductor spin qubits it is commonly formed in a quantum well or at a heterointerface and then locally depleted or accumulated by gates to define quantum dots.

Abelian: qualifies a group whose operation is commutative, meaning A*B = B*A, after the Norwegian mathematician Niels Henrik Abel (1802-1829). In quantum technologies, the distinction matters for anyons: Abelian anyons only pick up a phase when they are exchanged, while non-Abelian anyons apply a non-commuting operation on a degenerate ground state, which is what makes topological qubits conceivable.

ABRC: Asynchronous Ballistic Reversible Computing, a reversible classical computing paradigm promoted by Michael P. Frank's team at the DoE Sandia Labs, where information-bearing signals propagate ballistically between devices without a global clock, and which they plan to implement with Josephson junction circuits. It is one of the explored avenues to build qubit control electronics that would not dissipate energy at the Landauer limit. It is a classical scheme, not a quantum computing paradigm.

Active space: subset of molecular orbitals and electrons that is treated exactly in a quantum chemistry computation, the other orbitals being frozen or handled at a mean-field level. It is noted CAS(Ne, No) for a complete active space with Ne electrons in No orbitals, as in the CAS(54e, 54o) usually retained for FeMoCo. The active space selection is a purely classical choice which drives the qubit count and the chemical relevance of the result, which makes it a frequent hidden variable in quantum advantage claims.

Active Volume: architectural and compilation framework introduced by PsiQuantum which reduces the hardware resources and runtime of large fault-tolerant circuits by exploiting non-local connectivity, counting the cost of an algorithm in logical blocks rather than in space-time volume.

ADAPT-VQE (Adaptive Derivative-Assembled Pseudo-Trotter VQE): VQE variant created by Harper Grimsley, Sophia Economou, Edwin Barnes and Nicholas Mayhall in 2019 which builds the ansatz operator by operator instead of using a fixed circuit. At each iteration, it measures the energy gradient of all operators of a predefined pool (fermionic or qubit excitations) and appends the one with the largest gradient. It generates shallower and more accurate circuits than hardware-efficient ansätze and mitigates barren plateaus, at the cost of many additional measurements in the classical outer loop and of hundreds to thousands of iterations for correlated molecules. Its variants include qubit-ADAPT, CEO-ADAPT, continuous-variable ADAPT-VQE and ADAPT-GQE.

Adaptive quantum circuits: circuit combining local unitary gates, mid-circuit measurements, and feedforward operations. It is used for efficient state preparation, particularly on NISQ QPUs.

ADC: analog-digital converter. Converts an analog signal into a digitized signal. In quantum technologies, one example of an ADC use case is the conversion of the reflected microwave pulse signals used in superconducting and electron spin qubits readout.

AC Stark shift: energy-level shift produced by an oscillating electric field, usually an off-resonant optical field. In neutral-atom systems it is used to create optical dipole traps and tweezers and to provide local state-dependent detunings. It is also called the light shift and differs from the DC Stark effect produced by a static electric field.

Adiabatic: quantum computation method used with D-Wave quantum annealing computers and also more classical gate-based quantum computers. A complex Hamiltonian describing a complex system is first determined whose fundamental state describes a solution to the problem under study. A system with a simpler Hamiltonian is then prepared and initialized in its fundamental state. This Hamiltonian is then evolved adiabatically into the complex one, meaning slowly enough relative to the relevant spectral gaps and matrix elements, and not meaning thermally isolated. If the evolution is slow enough compared to the inverse square of the minimum gap, the adiabatic theorem states that the system stays in its ground state and its final state describes a solution to the problem. The condition can fail when the gap closes too fast, which is the main practical limitation of the approach.

Adiabatic theorem: quantum mechanics concept created by Max Born and Vladimir Fock in 1928. It states that a quantum system prepared in an eigenstate of its Hamiltonian remains in the corresponding instantaneous eigenstate if the Hamiltonian changes slowly enough with respect to the energy gap separating it from the neighboring levels. Under rapidly varying conditions, the state has no time to follow and the population spreads over several levels. This can be used to find Hamiltonian energy minimums with quantum algorithms running on various architectures: gate-based, annealing and quantum simulation.

ADR: Adiabatic Demagnetization Refrigeration, a magnetic cooling technique which exploits the magnetocaloric effect of the electronic spins of a paramagnetic salt. The salt is magnetized while thermally connected to a 1K to 4K bath, then isolated, and the field is slowly removed, which lowers its temperature. A single-shot ADR reaches 50 mK and a continuous version (cADR) sustains 10 to 50 mK, which positions it against a dilution refrigerator but not below it. Going deeper requires nuclear demagnetization (NDR). It is used by Kiutra.

Advantage: see quantum advantage.

aka: shortened version of "also known as".

AKLT state: quantum state used in condensed matter physics which can be implemented using a classical Matrix Product State (MPS). It provides insights into the properties of certain spin chains and their ground states. It illustrates concepts such as symmetry-protected topological order and entanglement in many-body quantum systems.

Algorithm: a method of problem solving that is made up of a finite sequence of operations or instructions. The word comes from the name of the 9th century Persian mathematician, Al-Khwârizmî.

Algorithmic qubit: vendor-defined benchmark metric proposed by IonQ, written #AQ, corresponding to the largest circuit width at which a suite of algorithmic benchmark circuits still passes a defined success threshold. The suite, its version and the threshold have changed over time and must be quoted with their date. Earlier IonQ material described an approximate correspondence with $\log_2$ of IBM's quantum volume in the absence of error correction, which is not a general identity.

Amdahl's law: rule stated by Gene Amdahl in 1967 bounding the speedup of a parallel computing system by the fraction of the workload that remains sequential. With 10% of sequential code, the maximum speedup is 10x whatever the number of cores. It explains why multicore scaling saturates, and it also applies to hybrid classical-quantum algorithms where classical data preparation and post-processing can dominate the total runtime.

AFC (Atomic Frequency Comb): optical quantum memory protocol where the inhomogeneously broadened absorption line of a rare-earth doped crystal is spectrally tailored into a periodic comb of teeth spaced by Δ. An absorbed photon is re-emitted as a collective echo after a fixed time $1/\Delta$ set by the comb spacing. Transferring the excitation to a spin state gives on-demand recall and much longer storage, up to one hour demonstrated. It is a workhorse of solid-state quantum repeater memories.

Amplitude: this term has various meanings depending on the context. It can be the classical amplitude of a wave, i.e. half of its maximal variation, as opposed to its phase. For a quantum object, it can be the complex amplitudes of its basis states or eigenvectors. For a pure qubit state, up to a global phase, $|\psi\rangle = \cos(\theta/2)|0\rangle + e^{i\varphi}\sin(\theta/2)|1\rangle$, where θ is the polar angle and φ the relative phase in the Bloch sphere. The coefficients $\alpha = \cos(\theta/2)$ and $\beta = e^{i\varphi}\sin(\theta/2)$ are the probability amplitudes, and the probabilities of measuring 0 and 1 are their squared magnitudes.

Amplitude amplification (QAA): generalization of Grover's search created by Gilles Brassard, Peter Høyer, Michele Mosca and Alain Tapp in 2000. It iterates an operator combining an oracle phase flip of the marked states and a reflection around the mean amplitude, rotating the state vector toward the marked subspace. Finding one of M marked items among N requires about $\frac{\pi}{4}\sqrt{N/M}$ iterations, hence a quadratic speedup. It is a building block of Grover, QAE, Grover adaptive search and many optimization variants. Non-Boolean oracle versions also exist.

Anharmonic oscillator: contrarily to harmonic quantum oscillator that have the same energy difference between ach each consecutive energy levels, an anharmonic quantum oscillator has different energy differences between consecutive energy levels. This is the case of superconducting qubits, in order to create two manageable energy levels that are controlled with microwaves with the highest energy transition level of the oscillator.

Angular momentum: vector quantity characterizing rotational motion, not to be confused with angular speed. The orbital angular momentum of a particle is $\mathbf{L} = \mathbf{r} \times \mathbf{p}$, while spin is an intrinsic angular momentum with no classical rotation counterpart. In quantum physics both are quantized, in units of the reduced Planck constant $\hbar$, and the total angular momentum is their sum.

Anomalous heating: heating of trapped-ion motional modes driven by electric-field noise at the ion position, often associated with electrode surfaces. Experiments frequently find a strong dependence on ion-electrode distance, often parameterized as $d^{-\alpha}$ with α of order 2 to 4, but the exponent is device- and frequency-dependent rather than universally 4. Mitigations include surface cleaning and treatment, optimized materials and geometry, larger ion-electrode distance and, in many systems, cryogenic operation.

Ansatz: in quantum computing, is another name for the parametrized quantum circuits or parametric quantum circuits that contain CNOT gates and single qubit rotation gates with the parameters of the problem to encode in a variational quantum optimizer defined by a classical optimizer. Typically used in most variational algorithms (QAOA, VQE, QML).

Antibunching: property of a light field where two photons are less likely to be detected together than in a coherent laser beam. It is quantified by the second-order correlation function at zero delay, $g^{(2)}(0)$, which equals 1 for a coherent state, 2 for a thermal source and drops below 1 for antibunched light. An ideal single photon source reaches $g^{(2)}(0) = 0$ since it never emits two photons at once. It is measured with a Hanbury Brown and Twiss intensity autocorrelator, which shows a dip instead of a peak at zero delay. Antibunching usually comes with sub-Poissonian photon statistics but the two are distinct properties, the first concerning the timing of pairs of detections and the second the counting statistics over a time window. First observed in 1977 by H. Jeff Kimble, Mario Dagenais and Leonard Mandel.

Anyon: type of elementary quasiparticle found in two-dimensional systems. It is a generalization of the concept of bosons and fermions. Anyons have intermediate statistical behaviors between the two types of elementary particles. They are collective excitations of an effectively two-dimensional many-body system, and not virtual particles. Candidate platforms include fractional quantum Hall states, spin liquids and engineered superconductor-semiconductor structures, so they are not limited to electron holes in superconducting metal. Non-Abelian anyons are the resource of topological quantum computing, and Majorana zero modes in superconducting systems, studied at Microsoft, are one proposed realization, which is distinct from a fundamental Majorana fermion.

arXiv: initially Cornell University's site, and a spare non-profit company since 2026, that allows researchers to publish scientific papers prior to publication in peer-reviewed journals such as Nature, Science or Physical Review. It can take up to 9 months between publication of an article on arXiv and publication in a peer-reviewed journal. In the latter case, the article will have eventually evolved. The interest of arXiv in literature search is that publications are open and free of charge whereas most of the peer-reviewed journals are not free. The disadvantage is that the articles are not necessarily validated and that one has to make his own evaluation. It should be noted that in a researcher's publication, there are often several authors, up to several dozen. The first author is generally the PhD student who has carried out a large part of the work, particularly its experimental part. Others are contributors who helped him/her. The last author is the thesis director or principal investigator (PI), the group leader or the laboratory director who has closely or remotely supervised the project. He/she probably contributed significantly to the article writing and cleanup.

Antisymmetry: is related to the behavior of particles with half-integer spin like electrons. They obey the Pauli exclusion principle which states that two identical fermions cannot occupy the same quantum state simultaneously leading to the way electron shells are filled in atoms. Antisymmetry also shows up mathematically with the wave function of a multiple fermions system to change sign when the location of two fermions are exchanged.

AOD: acousto-optic deflector, an acousto-optic modulator geometry optimized for angular beam steering. AOM is the broader device class, so AOD and AOM are not exact synonyms. An RF-driven acoustic wave creates a traveling refractive-index grating that diffracts and frequency-shifts light. In neutral-atom tweezer systems, AODs provide rapid beam steering, rearrangement and transport, often complementing an SLM that generates a larger static or slowly reconfigurable trap pattern.

Approximate Amplitude Encoding: or AAE, prepares a quantum state whose amplitudes approximate a given classical data vector using a shallow parameterized quantum circuit (PQC). It trains a parameterized circuit to minimize the difference between the state it produces and the target amplitude-encoded state.

Artificial atoms are artificial quantum systems which behave as quantum objects with observable quantized energy levels, quantum coherence and superposition. Examples are superconducting qubits, color centers in diamond, photon emitting quantum dots or silicon quantum dots.

ASIC, Application-Specific Integrated Circuit, is a custom-designed chip built to perform a specif-ic task or set of tasks with high efficiency. Unlike general-purpose processors, ASICs are optimized for one application such as cryptocurrency mining, video encoding, or networking offering faster performance and lower power consumption. The alternative chip technology is a FPGA, field pro-grammable gate array, which logic is dynamically programmable. Both FPGA and ASIC can be used to handle for example quantum error correction. Technical requirements, energetics and eco-nomics drive the choice between FPGAs and ASICs. FPGAs have a small fixed-cost but a higher variable cost and energetic cost. ASIC have a high fixed cost, long manufacturing times and low variable costs and energetic costs.

Assumptions: the word I fear the most in scientific papers, particularly in the FTQC realm. These are made for example when estimating quantum computing resource estimates with quantum error correction and fault-tolerance. Like having qubits with all operations done with a fidelity of 99.9%, some qubit connectivity, some error correction round time, etc. These assumptions usually do not correspond to the actual capabilities of the hardware, today, and even tomorrow. It is the same with quantum speedups and advantages for some algorithms, particularly with quantum machine learning, when the assumption leaves aside the cost of data encoding in the circuit. Assumptions are the devil in the details in quantum technologies.

Atoms: the smallest constituent element of matter that manifests chemical properties. It consists of a nucleus, with one or more positively charged protons and zero or more neutrally charged neutrons, around which negatively charged electrons occupy quantum orbitals. In a neutral atom, the number of electrons is equal to the number of protons. Otherwise, the atom is negatively or positively charged and forms an ion. The number of protons determines the nature of the atom in Mendeleev's Elements Periodic Table. An atom with one proton is hydrogen, with two protons it is helium, etc. Uranium has 92 protons. The nucleus represents the bulk of the atom mass. The isotopes of an element correspond to variations in the number of neutrons. Light elements have roughly as many neutrons as protons, but the neutron-to-proton ratio grows with atomic number and reaches about 1.5 for the heaviest stable nuclei. In the shell model developed by Niels Bohr between 1909 and 1913, electrons are distributed in shells numbered from 1 to 7 for the known elements, each holding at most $2n^2$ electrons (thus 2, 8, 18, 32, 50, 72 and 98). Actual filling follows the orbital energy ordering, so the upper shells of heavy atoms are never filled to those maxima. The chemical properties of the element depend on the number of electrons of the last layer which is called the valence layer. If this number is $2n^2$, the atom will be inert and will not combine chemically with other atoms. Carbon has three layers of electrons, the last one having 4 which allows it to combine with other atoms such as hydrogen (1 layer, 1 electron) or oxygen (6 electrons in the last layer).

Auger effect: the emission of an electron rather than of an X-ray photon when an atom relaxes after an inner-shell vacancy has been created. Described by Lise Meitner in 1922 and by Pierre Auger in 1923, the latter giving it its name.

Autonomous quantum error correction (AQEC): quantum error correction codes and architectures that does not require error syndrome measurement. It replaces real-time feedback by analog feedback circuits using engineered dissipation with the reservoir engineering technique. It couples the system with a dissipative reservoir to transfer the entropy created by errors to an ancillary system, the reservoir. This entropy is then evacuated via the strong dissipation of the ancilla. This technique is used in cat-qubits and GKP qubits.

AWG: arbitrary waveform generators, create electromagnetic pulse forms that are then combined with a tone pulse of high frequency like 5 GHz in the microwave regime. These are usually Gaussian form pulses. AWG are used to create single qubit gates and readout pulses for superconducting qubits.

Axion: hypothetical light pseudo-scalar particle first introduced to solve the strong CP problem of quantum chromodynamics and now one of the leading dark matter candidates. Its mass would sit in the μeV to meV range, between 10^{-12} and 10^{-9} of the electron mass. Haloscope experiments like ADMX try to convert axions into microwave photons in a strong magnetic field, which makes them a direct customer of quantum sensing techniques such as squeezing and single microwave photon counting.

BB84: prepare-and-measure QKD protocol introduced by Charles Bennett and Gilles Brassard in 1984. Alice randomly encodes bits in one of two mutually unbiased bases and Bob measures in randomly chosen bases. Basis sifting, parameter estimation, information reconciliation and privacy amplification are then used to derive the final secret key.

Back action: in quantum measurement, this is the physical impact of the measurement device on measured quantum objects. Quantum measurement usually modifies the state of the measured quantum object unless it is already in a basis state (mathematically, one of the eigenvectors of the measurement observable operator...). After measuring a quantum object state, performing the same measurement on the already measured system will not provide any additional information. In order to increase our knowledge on the final state of some quantum computation, the only solution is to start again the computation from the beginning and measure again the final state. The subtlety being that this new final state has not yet been measured and thus corresponds exactly to the one we are trying to infer. Then, we compute an average of the obtained results across several experiments. Some measurement techniques like gentle measurement or weak measurement are designed to minimize this back action and are sometimes used in quantum error correction codes.

Backside power delivery: chip design technique moving the power distribution network from the front side to the back side of the wafer, freeing the front-side metal layers for signal routing. Intel calls it PowerVia and TSMC Super Power Rail. It is one of the levers used to keep improving density and performance once transistor ground rules stop shrinking, starting around 2031-2034.

Balmer series: set of four spectral emission or absorption lines with the hydrogen atom, generated by electron transitions between the second and higher energy levels of the atom.

Band gap: forbidden energy level in semiconductors and transistors. It refers to the energy difference between the top of the valence band and the bottom of the conduction band and corresponds to the energy required to excite an electron from the valence band to the conduction band. The notion is related to the electrical conductivity of solid materials. Wider band gap materials are generally more insulating and also are transparent while narrower band gap materials are generally more conductive and are opaque. Semiconductors have an intermediate band gap. Band gap size is determined by the arrangement of atoms in the material crystal lattice. The closer they are, the smaller the band gap is.

Balanced beam splitter: beam splitter where the light is equally divided in two streams.

Barren plateaus: regions of the cost-function landscape of a variational quantum algorithm where gradients become exponentially small with system size, so resolving a useful descent direction can require exponentially many circuit samples. For random or sufficiently expressive ansatzes and global observables, results of the form $\mathrm{Var}[\partial_k C] = O(2^{-n})$ occur under specific theorem assumptions. Barren plateaus are not universal to every deep circuit. Their occurrence depends on ansatz expressivity, initialization, cost-function locality, symmetries, depth and noise. Local cost functions with structured circuits of depth $O(\log n)$ can retain polynomially large gradients in some settings. A large dynamical Lie algebra can indicate a high barren-plateau risk, but it is not by itself a universal finite-depth no-go theorem. Mitigations include local cost functions, problem-inspired ansätze, warm starts, symmetry restrictions and adaptive circuit construction. An important caveat is that some structures that guarantee trainability also make the circuit or loss classically simulable, creating a trainability-versus-simulability tension.

Baryon: class of elementary particles of the first level of the nuclei of atoms. It contains protons and neutrons.

Base temperature: the lowest temperature a cryostat reaches with no heat load applied, as opposed to its cooling power which is quoted at a higher operating temperature. Commercial dry dilution refrigerators announce base temperatures between 4 mK and 10 mK while quantum processors actually run at 10 to 25 mK, because the wiring, filters, attenuators and the qubits themselves inject enough heat to push the mixing chamber above its no-load point.

BCS theory: microscopic theory of superconductivity built in 1957 by John Bardeen, Leon Neil Cooper and John Robert Schrieffer. Electrons of opposite spins pair up through a phonon-mediated attraction into Cooper pairs, which are composite bosons that can all occupy the same quantum state and flow through the crystal lattice without friction. It explains conventional s-wave superconductors but not the cuprates. The three authors were awarded the 1972 Nobel prize in physics, a second one for Bardeen after the transistor.

Beam splitter: optical device that splits a beam of light in two. It's usually made with two glued triangular glass prisms. Polarizing beam splitters are a particular class of beam splitters that use birefringent materials to split light into two beams of orthogonal polarization states.

Bell inequalities: Bell's 1964 are the relations that measurements on quantum entangled states must respect under the hypothesis of a local deterministic hidden variable theory. Experiments show that Bell inequalities are violated by entangled states, which forces one to give up at least one of the assumptions behind the derivation. The usual list is local causality, meaning that no influence propagates faster than light between the two measurement events; measurement independence, sometimes called free choice, meaning that the setting choices are not correlated with the hidden variables, whose denial is superdeterminism; and the existence of predetermined values carried by the particles, usually called realism. Which assumption to abandon is interpretation dependent, and the violation does not by itself allow faster-than-light signaling.

Bell states: or EPR states are maximally entangled states of two qubits. There are four of them: $|\Phi^+\rangle = (|00\rangle + |11\rangle)/\sqrt{2}$, $|\Phi^-\rangle = (|00\rangle - |11\rangle)/\sqrt{2}$, $|\Psi^+\rangle = (|01\rangle + |10\rangle)/\sqrt{2}$ and $|\Psi^-\rangle = (|01\rangle - |10\rangle)/\sqrt{2}$. $|\Phi^+\rangle$ generalizes to GHZ states with n qubits, and $|\Psi^+\rangle$ generalizes to W states.

Bell test statistic: it is a test of correlation of quantum state detection with two entangled quantum objects which can have values A and A', and B and B'. The CHSH statistic is $S = \langle AB\rangle + \langle AB'\rangle + \langle A'B\rangle - \langle A'B'\rangle$, where each term is the expectation value of the product of the two ±1 outcomes for that pair of settings, and not a probability. Any local hidden-variable model obeys $|S| \leqslant 2$. Quantum mechanics allows up to the Tsirelson bound $2\sqrt{2} \approx 2.828$, which is reached only for maximally entangled states and optimal settings, so a real experiment generally returns a value between 2 and $2\sqrt{2}$. The measured observables are usually photon polarizations. This test is also a way to evaluate the entanglement of two qubits in quantum computers.

Bernstein-Vazirani (algorithm): oracle-based algorithm created by Ethan Bernstein and Umesh Vazirani in 1993 which retrieves an n bits secret string hidden in an oracle function with a single oracle query, where a classical algorithm needs n queries. It was designed to prove an oracle separation between the BQP and BPP complexity classes and has no real use case of its own. Its 2-forrelation variant realizes the maximal separation between classical and quantum query complexity and is used as a quantum advantage benchmark.

Basis encoding: direct encoding of an N-bit classical string into an N-qubit computational-basis state by applying X gates to the qubits corresponding to classical 1 bits. It stores one classical bit per qubit and does not provide exponential data compression.

Betti number: topological invariant counting the number of k-dimensional holes of a topological space, the zeroth one counting its connected components. It is the main quantity estimated by topological data analysis (TDA) algorithms and it measures the connectivity of the simplicial complex built from a high-dimensional data set.

Bichromatic field: laser or microwave drive containing two frequency components, usually detuned symmetrically around a qubit transition so as to address simultaneously the red and blue motional sidebands. It is the standard way to implement Mølmer-Sørensen two-qubit gates with trapped ions.

Bright/dark fluorescence readout: state-dependent trapped-ion measurement in which one qubit basis state is coupled to a cycling optical transition and scatters many photons, the bright state, while the other is off-resonant or shelved and scatters few photons, the dark state. The assignment of $|0\rangle$ and $|1\rangle$ to bright and dark is an encoding convention.

Bias-preserving gate: logical or physical gate designed to preserve a strongly asymmetric noise channel instead of converting the dominant error into a different Pauli error. It is important for cat qubits and other biased-noise encodings because QEC overhead reductions rely on retaining the error bias during computation. A gate with excellent average fidelity can still be unsuitable if it destroys this bias.

Biphoton: a pair of photons that are produced together in a single quantum process and are described by a joint two-photon quantum state. They can be entangled in one or more degrees of freedom like polarization, time-energy, frequency and position-momentum, and must be treated as a single two-particle quantum object. Biphotons are created with SPDC (Spontaneous parametric down-conversion) in nonlinear crystals with one pump photon converting into a correlated photon pair (signal and idler) or with SFWM (Spontaneous four-wave mixing) in optical fibers with two pump photons generating a correlated pair. Both methods are standard sources used in quantum optics labs and integrated photonics experiments.

Black body: a body that is in thermal equilibrium with the radiation it emits. It can be the inside of a furnace or a star. It is by studying the radiation of the black body and its frequency distribution as a function of the body temperature that Max Planck uncovered the existence of energy quanta in 1900. Written blackbody or black body depending on the source.

Blind Quantum Computing: delegated quantum-computing protocol in which a client uses a remote quantum server while hiding, depending on the protocol, the input, the algorithm, the output, or several of these from the server. Blindness is a cryptographic property and does not by itself imply verifiability. Protocols differ in the quantum capabilities required on the client side.

Angle encoding: data encoding method in which classical real values parameterize single-qubit rotations such as R_x, R_y or R_z. Encoding N independent values uses O(N) single-qubit gates and can have O(1) depth when the rotations run in parallel. The prepared register is a product state unless later entangling gates are applied.

Amplitude encoding: data encoding scheme mapping a classical vector of up to 2^{N} components onto the amplitudes of the computational-basis states of N qubits, after normalization so that the squared moduli sum to 1. Generic exact preparation of an arbitrary N-qubit state requires $\Theta(2^N)$ elementary-gate resources in the standard circuit model. Structured, sparse or approximate states can be cheaper. Efficient qRAM is one possible input-access assumption, but it is not the only state-preparation model.

Bloch states: quantum wavefunctions describing particles like electrons that are moving in a peri-odic potential, such as the repeating atomic structure of a crystal. They are central to understanding the electronic properties of solids. They manifest in semiconductors to explain how electrons move through materials and why some conduct electricity while others don't, in photonic and phononic crystals with being applied to light and sound waves in periodic media and in quantum transport, to model current flow, tunneling, and other transport phenomena.

Bloch sphere: geometric representation of a qubit state with a vector in a sphere of radius 1. The qubit ground state is an upwardly directed vector $|\mathbf{0}\rangle$ and the excited state is a downwardly directed vector $|\mathbf{1}\rangle$. An intermediate state vector is defined by its amplitude and phase, in line with the wave-particle duality of the qubits. It models the state of a qubit using polar coordinates with two angles, one indicating the amplitude of the quantum and the other its relative phase.

Brightness: figure of merit of a single-photon source, the number of photons it emits per unit time, usually quoted per pulse or per second at the fiber output. It is distinct from the source efficiency, which is the probability of getting at least one photon per pump pulse.

Bucket brigade: qRAM addressing architecture proposed by Vittorio Giovannetti, Seth Lloyd and Lorenzo Maccone in 2008, based on a binary tree of three-level quantum routers holding a wait, left or right flag. Address qubits propagate down the tree and set the routers they cross, so only O(log N) routers are active per query instead of the O(N) switches thrown in a fanout architecture. Its main virtue is noise resilience: errors on unqueried branches stay localized, giving a query infidelity growing polylogarithmically with the memory size, a scaling proven for arbitrary error channels by Connor Hann et al. in 2021. Its main cost is that the tree still needs O(N) physical routers.

Block-encoding: technique embedding a generally non-unitary matrix A, rescaled by a normalization factor α, as a block of a larger unitary U acting on system and ancilla qubits. Projecting the ancillas onto the designated state recovers A/α. It is an entry point for qubitization and QSVT-based algorithms. Block-encoding is efficient only when A has a suitable access structure, such as sparsity, an efficient oracle, LCU, QROM or arithmetic construction. A generic dense classical matrix is not made cheap merely by representing it as a block-encoding.

Bond dimension: dimension χ of the indices connecting the tensors of a tensor network like an MPS. It bounds the entanglement entropy that the network can represent, at most $\log_2 \chi$ across any cut, and it drives the classical computing cost which typically scales in $O(n\chi^3)$. A state well approximated with a small bond dimension is classically simulable, which is why bond dimension is the yardstick used to challenge quantum advantage claims on quantum simulation and optimization tasks.

Born rule: postulate of quantum mechanics created by Max Born in 1926 giving the probability that a measurement of a quantum system will yield a given result. It states that the probability density of finding a particle at a given point, when measured, is proportional to the square of the magnitude of the particle's wavefunction at that point.

Born-Oppenheimer approximation: mathematical approximation used in molecular dynamics that treats separately the wave functions of atomic nuclei and electrons in molecules. The nucleus being much heavier than the electrons, its coordinates are approximated as being fixed, while the coordinates of the electrons are dynamic. This approximation was proposed in 1927 by Max Born and his 23-year-old graduate student J. Robert Oppenheimer.

Bose-Einstein Condensate, or BEC: phase of a dilute bosonic gas in which a macroscopic fraction of particles occupies a single quantum state below a critical temperature. The first dilute-gas BEC was observed in ^{87}Rb by Eric Cornell, Carl Wieman and collaborators at JILA in 1995; Wolfgang Ketterle and collaborators independently realized sodium BEC later in 1995. Cornell, Wieman and Ketterle shared the 2001 Nobel Prize in Physics. Superfluid ^{4}He is related to Bose condensation but is a strongly interacting liquid and should not be treated as a simple dilute-gas BEC. Ultracold BEC physics supplies trapping, cooling and many-body techniques relevant to neutral-atom quantum technologies.

Bose-Hubbard model: lattice model of interacting bosons with tunnelling between sites and on-site interactions. Ultracold bosonic atoms in optical lattices are a canonical experimental realization, including the superfluid-to-Mott-insulator transition.

Boson sampling: typical experiment with photons qubits that mixes photons in an interferometer. It's hard to emulate on a classical computer and is used to show a specific quantum advantage. The caveat is that these devices are not universal and only weakly programmable, so their scope is limited to sampling tasks and to a few proposed applications such as molecular vibronic spectra and graph similarity, and their performance cannot be compared with that of gate-based machines on general workloads.

Boson: particles with gregarious behavior, which can accumulate in arbitrarily large numbers and in the same state. Bosons comprise photons and composite objects with whole integer spin such as hydrogen-1, lithium-7 and rubidium-87 atoms, whether an atom is a boson depending on the total spin of the isotope considered, so that carbon-12 is a boson while carbon-13 is a fermion. For a neutral atom, this is determined by the evenness of the number of neutrons. These particles escape Pauli's exclusion principle. They have a symmetrical wave function.

Bosonic codes: hardware system that implement quantum error corrections with bosonic modes, using a quantum harmonic oscillator with continuous energy levels. It includes cat-qubits, GKP codes (Gottesman-Kitaev-Preskill) and binomial codes.

BQP (problem class): complexity class of problems that can be handled by quantum algorithms in a bounded-error polynomial time. It is the class of decision problems solvable by a uniform family of quantum circuits of polynomial size, with an error probability of at most 1/3 on every input, the threshold being arbitrary since it can be made exponentially small by repetition. P is contained in BQP, but the relationship between BQP and NP, and in particular whether BQP contains any NP-complete problem, is an open question.

Bra-ket (notation): a notation model describing quantum state, possibly a qubit or set of qubits, in the form $|\psi\rangle$ and $\langle\psi|$. It was created by Paul Dirac in 1939. A ket $|\psi\rangle$ is a column vector describing the quantum state. Its bra $\langle\psi|$ is the corresponding conjugate-transpose row vector, an element of the dual space. It facilitates the writing of operations with quantum states, like inner products $\langle\phi|\psi\rangle$, outer products $|\phi\rangle\langle\psi|$ and projections $\langle\psi|\mathbf{A}|\psi\rangle$.

Brane: extended object of p spatial dimensions appearing in string and M-theory, generalizing the point particle which is a 0-brane and the string which is a 1-brane. Open strings end on D-branes. They are not point particles.

Bravais lattice: one of the 14 possible three-dimensional periodic arrangements of points in a crystal, grouped in 7 crystal systems named triclinic, monoclinic, orthorhombic, tetragonal, trigonal, hexagonal and cubic, with primitive, base centered, body centered and face centered variants. Combined with the point symmetries, they generate the 230 crystallographic space groups, and 1,651 magnetic space groups once spin ordering is taken into account.

Break-even: said of a quantum computing hardware and associated quantum error correction code enabling the creation of logical qubits having an error rate below the error rate of its physical qubits, usually assessed as two-qubit gate errors.

Brillouin scattering: the inelastic scattering of light on the acoustic vibrations of a medium, predicted by Léon Brillouin in 1922, which shifts the scattered photon frequency by a few GHz. Not to be confused with the Brillouin zones, which delimit allowed electron energy bands in a periodic crystal lattice.

BSM: Bell state measurement.

cADR: continuous Adiabatic Demagnetization Refrigeration, an ADR variant which chains several magnetized and demagnetized cooling units so that the cold stage never warms up between cycles. See ADR.

Cap table: list of equity investors in a company.

Capex: capital expenditure, the fixed acquisition cost of a system such as the purchase price of a QPU and of its enabling technologies. It is opposed to opex. Both add up in a TCO.

Carleman linearization: technique converting a system of nonlinear differential equations into an infinite system of linear ordinary differential equations built on the monomials of the original variables, then truncated at some order to become tractable. It is the most common way to feed nonlinear problems like fluid dynamics into quantum linear solvers. Its main limitation is that convergence requires a small nonlinearity to dissipation ratio, usually R < 1, and that the truncation error grows with the simulated time, which restricts it to weakly nonlinear and strongly dissipative regimes.

Carnot efficiency: for a refrigerator, the best coefficient of performance allowed by thermodynamics when extracting heat at a cold temperature T_c and rejecting it at a hot temperature T_h, equal to $T_c/(T_h - T_c)$. Removing one watt at 15 mK therefore costs at least about 20 kW of input power in the ideal case. Real dilution refrigerators sit one to two orders of magnitude above this bound, which is why the wall-plug power needed to evacuate a given heat load grows very fast as the target temperature drops.

Casimir effect: attractive force appearing between two parallel electrically conductive and uncharged plates, predicted by Hendrik Casimir in 1948 and first measured by Steve Lamoreaux in 1997. It comes from the vacuum electromagnetic modes being constrained between the plates while they are not outside, creating a larger radiation pressure outside than inside. The force scales as $1/\mathrm{L}^4$ for plates separated by L, which makes it measurable only below a few micrometers. It is used in NEMS and MEMS actuation and is regularly and wrongly invoked by free energy scams, since the fluctuation-dissipation theorem forbids extracting net work from it.

Cavity: enclosed space used in quantum technologies that reflect light or other electromagnetic waves like microwaves. It creates standing wave patterns. They are characterized by their quality factor (Q factors), the higher it is meaning it can trap light for a longer time. Cavities are often placed in controlled environments, such as cryogenic or vacuum chambers, to minimize thermal and electromagnetic noise coming from the outside world. The two most used cavities in quantum technologies are superconducting cavities which are made of superconducting materials with very low resistance and trap light in the microwave spectrum and optical cavities that use mirrors or other reflective surfaces trapping light in the visible or infrared spectrum. Cavities are used in quantum computing, quantum communications and quantum sensing. In superconducting qubits, the cavity component is the resonator. Superconducting 2D cavities are made of parallel waveguides using aluminum or niobium nitride thin film materials deposited on silicon or sapphire. Superconducting 3D cavities are made of niobium or copper and shaped into cylindrical or spherical structures. It confines microwave photons more efficiently than 2D cavities with longer coherence times but is more bulky and less scalable. Optical cavities are frequently used to trap optical fields that interact with cold atoms, often, in combination with a magneto-optical trap.

Cavity quantum electrodynamics (CQED): field of quantum physics coupling trapped atoms in physical cavities and microwaves. It is about the interactions between photons and electrons and atoms.

CFD (Computational Fluid Dynamics): numerical simulation of fluid flows, generally solving the Euler or Navier-Stokes equations after a spatial and temporal discretization. Quantum proposals rely on quantum linear solvers, LCHS, Carleman linearization, the quantum lattice Boltzmann method, Schrödingerization or variational algorithms. The three recurring bottlenecks are the nonlinearity of the equations, the loading of the initial flow field and the readout of a full solution field, which is a large classical data set that a quantum state cannot deliver in one shot.

CFET: Complementary FET, transistor architecture stacking the nFET on top of the pFET instead of placing them side by side, roughly halving the standard cell footprint. It is the generation planned after nanosheets in the IMEC and IEEE IRDS roadmaps, around 2031.

Chandelier: nickname of the quantum computing system located inside the cryostat of a superconducting or electron spins quantum computer. It contains several stages made of copper disks covered with gold. These disks are crossed by numerous coaxial cables that are used to drive the qubits and read their state with microwaves. It is completed by filters, attenuators and amplifiers for the microwaves that circulate in these wires, various sensors, and heat exchangers that cool the copper disks, which in turn cool the elements that are placed on them.

Chern number: topological invariant which is an integer counting the winding of the wave function over the Brillouin zone. It cannot change under a continuous deformation of the Hamiltonian, which is what protects the edge states of topological insulators and quantizes the Hall conductance. It changes only across a topological phase transition, where the band gap closes.

Chi: Greek letter denoting the optical susceptibility of a medium. $\chi^{(n)}$ is the nth-order susceptibility, the coefficient of the nth-order term in the expansion of the induced polarization as a function of the applied field. A medium with a nonzero $\chi^{(2)}$ has a second-order nonlinearity. It is used for example for the frequency doubling of laser light. With $i = 3$, it is a third order nonlinearity, which is used for example in four-wave mixing. The induced polarization density P, which is the dipole moment per unit volume and not a phase, expands as $P = \epsilon_0(\chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \ldots)$ as a function of the applied electric field E.

Chip: integrated circuit built on semiconductor material, usually silicon, but also III/V materials like gallium or indium.

Chipset: refers to specialized integrated circuit containing various features that complement the features from a CPU.

Chiplet: packaging containing several chips or integrated circuits usually built with different technologies.

CHSH inequality: the Clauser-Horne-Shimony-Holt reformulation of Bell's inequality, published in 1969, which turned Bell's theorem into a form testable with real detectors and imperfect polarizers. It is the inequality actually measured in Alain Aspect's 1982 experiments and in all subsequent Bell tests.

CIM: Coherent Ising Machine, an optical system that maps a combinatorial optimization problem onto an Ising Hamiltonian and lets a network of degenerate optical parametric oscillators settle into its lowest-energy spin configuration. It uses squeezing, delay lines, time-division multiplexing and measurement feedback. It is an analog optical solver rather than a quantum computer in the gate-based sense.

Circuit quantum electrodynamics (cQED): architecture used in solid state qubits systems using superconducting qubits and microwave photons. Science behind the interactions between microwaves and electromagnetic circuits.

Circuit synthesis: decomposes a known unitary matrix U into its corresponding quantum circuit made of the gates from a given primary gate set of a quantum computer.

Classical shadows: measurement protocol created by Hsin-Yuan Huang, Richard Kueng and John Preskill in 2020 which builds a compact classical description of a quantum state from randomized measurements in random bases. It predicts

M observables with a number of samples scaling in O(log M) instead of one estimation per observable. It is used to reduce the shot count of VQE, quantum machine learning and quantum simulation, and in oracle sketching techniques.

Clifford group: group of quantum gates (unitaries) that map the Pauli group onto itself under conjugation. Circuits built only from Clifford gates, with stabilizer inputs and Pauli measurements, are efficiently classically simulable under the Gottesman-Knill theorem. A standard generating set is the Hadamard gate H, the phase gate S and the CNOT, arbitrary axis rotations being not in the group. These gates make quarter turns or half turns in the Bloch sphere. They are not sufficient to create a universal gate set. You need non-Clifford gates like the T gate.

Circulators: used in the qubit readouts chain at the lowest level of a cryostat to isolate the qubit from the signal that is amplified by a parametric amplifier (TWPA or JPA).

Circuit: describes a set of quantum gates applied in an orderly fashion to a register of qubits. In other word, it is a quantum program for a gate-based quantum computing system. A graphical representation of a quantum circuit shows qubits in stacked horizontal lines, quantum gates as boxes labelled X, Y, Z, H and others applied to single qubits and two or three quantum gates with vertical lines connecting qubits. The X axis represents time and gates are executed from left to right.

Clock qubit: qubit encoded in a transition whose frequency is first-order insensitive to a perturbation, most commonly magnetic field, at a chosen operating point. For a magnetic clock transition $d\nu/dB = 0$ locally, which strongly suppresses dephasing from small field fluctuations but leaves second-order Zeeman and other shifts. Hyperfine and optical trapped-ion qubits can both provide clock transitions.

Cluster state: the starting point for an MBQC (Measurement Based Quantum Computing) calculation with a grid of embedded qubits that are usually initialized in an entangled state. Used mostly with photon qubits.

CLOPS: circuit layer operations per second, which defines the speed of QPUs, labelled in Hz.

CMOS: complementary metal oxide semiconductor, a common semiconductor fabrication technique used to produce processors and memory, and which is reused to create qubits that manipulate electron spins as well a cryo-CMOS electronics to generate solid states qubit control signals operating at cryogenic temperatures.

CNOT: controlled-NOT two-qubit entangling gate which inverts the target qubit state when the control qubit is in the $|1\rangle$ state, also written C-NOT or CX. Associated with arbitrary single qubit rotations, it forms a universal gate set. Its count in a circuit is one of the most common cost metrics for NISQ algorithms since two-qubit gate errors dominate the total circuit error budget.

Coarse graining: procedure that replaces a fine-grained description of a system by a reduced one, obtained by grouping or averaging microscopic degrees of freedom that are not resolved by the observer or the measuring apparatus. The discarded information usually shows up as entropy in the reduced description, which is how irreversible thermodynamic behavior emerges from reversible microscopic dynamics. In quantum physics, coarse-graining covers different related practices: tracing out unobserved degrees of freedom to obtain a reduced density matrix, binning measurement outcomes so that neighboring eigenvalues become indistinguishable, and rescaling a lattice model by blocking sites together as in the renormalization group.

Coaxmon: three-dimensional packaging architecture developed at Oxford and used by OQC in which the superconducting qubit and resonator are addressed by coaxial wiring perpendicular to the chip plane. It should be distinguished from the dimon, which is the multimode superconducting circuit used by OQC for a dual-rail encoding.

Code distance: notion used in quantum error correction codes and with the stabilizer codes formalism defined as the minimum weight of an undetectable error, that is, of a Pauli operator that acts as a nontrivial logical operation while commuting with all the stabilizers. A code of distance d detects up to $d-1$ errors and corrects up to $\lfloor (d-1)/2 \rfloor$ of them. Surface code distances are usually odd numbers (3, 5, 7, …), so a distance 7 code corrects at most 3 errors.

Coherence: quantum coherence is the ability of a quantum system to demonstrate interference. The coherence between different parts of a wave function allows for the famous double-slit interference and the formation of short quantum wave packets propagating in space. Two sources are coherent when a stable phase relation exists between them, which is quantified by the correlation functions of the field rather than by strict identity of frequency and waveform. There are temporal coherence (same waveforms with some time delay), spatial coherence (in 2D or 3D such as with plane waves) or spectral coherence (waves of different wavelengths but with a fixed relative phase form a wave packet). In quantum physics, coherence comes with linear superposition of various states of a quantum system containing one or several quantum objects (represented by a wave due to the wave-particle duality). Formally, coherence lives in the off-diagonal terms of the density matrix in a chosen basis. It degrades through interactions with the environment, on a characteristic coherence time, and a measurement also suppresses it, though what survives depends on the measurement basis and on whether the outcome is recorded.

Coherence fraction: task-specific measure of how strongly a quantum state overlaps with a maximally coherent reference state. For a density operator ρ and a chosen maximally coherent state $|\eta\rangle$, one common form is $f_c(\rho) = \langle\eta|\rho|\eta\rangle$. It appears in analyses of generalized Grover search with nonuniform initial states, where it can bound attainable search success. It is not a synonym for standard coherence measures such as the l_1 norm of coherence or relative entropy of coherence.

Coherence length: the distance over which a wave keeps a predictable phase relationship with itself, equal to c times the coherence time $\tau_c \approx 1/\Delta\nu$, $\Delta\nu$ being the spectral width of the source. For a single photon it is the longitudinal extent of its wave packet, and it has nothing to do with the wavelength: an atomic transition with a 1 ns excited state lifetime emits a packet about 30 cm long, or 500,000 wavelengths at 600 nm, while a 10 fs laser pulse is only 3 μm long. It sets the maximum path difference over which interference fringes survive in an interferometer, and it is the quantity that must be matched between two photons for a Hong-Ou-Mandel dip to reach zero.

Cold atoms: atoms cooled at very low temperatures, generally with techniques using lasers and the Doppler effect. They are used in certain types of quantum computers called cold atom quantum computers. The atoms used are neutral atoms (not ionized) and quite often rubidium, an alkali metal.

Cold plate: one-stage copper plate thermalized at a given cryostat temperature, on which experimental devices, filters, attenuators, amplifiers and the quantum processor are bolted. They are made of 99.99% pure oxygen-free copper (OFHC) and covered with a few microns of gold to protect against oxidation and improve the thermal and mechanical contact. They must be optically tight so that no infrared photon leaks from one stage to the next. Their diameter has converged around 30 to 50 cm, slightly decreasing from the top to the bottom of the chandelier because of the concentric radiation shields.

Cold trap: liquid nitrogen tank at 77K, containing about 20 liters, used in a dry dilution refrigerator to filter the helium gas and remove its impurities on zeolite powder before it enters the cryostat. It is the last cryogen left in a so-called cryogen-free system and must be refilled every few weeks. Some designs replace it with a 50K stage filter to remove cryogenic liquid handling altogether.

Compatible properties: physical properties of a quantum system that can be measured in any order or simultaneously.

Commutativity: mathematically, two variables A and B commute when A×B=B×A. They do with integers but not with non-square matrices. Even square matrices operations don't necessarily commute. These are then "noncommutative" matrix operations.

Commutator or commutation operator: Characterize the level of non-commutativity between two variables, usually matrices. For two square matrices A and B, their commutator is [A,B]=AB-BA.

Complementarity: principle of quantum physics introduced by Niels Bohr in 1927 according to which quantum objects have certain pairs of complementary properties which cannot all be observed or measured simultaneously. These are incompatible properties. Another version of this principle is that it's not possible to simultaneously observe a quantum object as a particle and as a wave, like in the Young slit experiments.

Complementary variables: pairs or complementary variables or properties according to the Bohr complementary principle. The common example are the position and momentum of a particle which are continuous. A more "quantum" example is the spin of an electron. You cannot evaluate the spin in a direction (X) and another one (Y or Z) which are both discrete quantities yielding +1/2 or -1/2.

Complex number: set of complex numbers created as an extension of the set of real numbers, containing in particular an imaginary number noted i such that $\mathbf{i^2 = -1}$. Any complex number can be written in the form a + ib where a and b are real numbers. These numbers are used in particular to describe the state of a qubit and to represent the phase of a quantum object with its complex component.

Complexity (theory): branch of theoretical computer science and mathematics that plays an important role in quantum computing to evaluate its performance compared to traditional Turing/Neumann machine computing. It defines classes of problems by levels of complexity, in terms of computing time or even the memory space required, with, in particular, problems that are solved in polynomial time in relation to their complexity (class P) and whose results are verifiable in polynomial time (class NP). The methods used to solve these problems are most often based on the brute force of navigating through an increasingly large space of combinations to be evaluated according to the size of the problem to be solved.

Compton effect: effect which demonstrates that photons can have some momentum and behave as particles, that was demonstrated by Arthur Holly Compton in 1922 with scattering of X rays and gamma rays photons by atomic electrons.

Computational basis: naming of the basic states of a qubits register. For a single qubit, this corresponds to the $|\mathbf{0}\rangle$ and $|\mathbf{1}\rangle$ states. For a register of N qubits, the computational basis is made of the 2^{N} combinations of series of N 0s and 1s, named in Dirac's notation$|\mathbf{000}\ldots\mathbf{000}\rangle$ to $|\mathbf{111}\ldots\mathbf{111}\rangle$. All these states are mathematically orthogonal with each other. A N qubits register in a pure state mode is a linear superposition of all these states using complex amplitudes.

Concatenated codes: describes the recursive application of error correction codes where in an error correction code, a physical qubit is replaced by a logical qubit, and so on.

Condensed matter physics: branch of physics that studies the macroscopic properties of matter (solids, liquids, glasses, polymers) and in systems where the number of constituents is large and the interactions between them are strong. Condensed matter physicists seek to understand the behavior of these phases using the laws of physics (quantum mechanics, electromagnetism and statistical physics). In practice, it mainly covers low temperature superconducting, ferromagnetic, antiferromagnetic and ferrimagnetic phases of spins in crystalline lattices of atoms, spin glasses, spin liquid, and Bose-Einstein condensates. Physicists working on superconducting qubits are part of this discipline.

Conjugate variables: pairs of dynamic variables describing the state of a quantum object, like position and momentum, that are related to the other with the Heisenberg indeterminacy principle which prevents a precise measurement of both variables.

Concurrence: entanglement measure for a two-qubit state, noted C and ranging from 0 for a separable state to 1 for a maximally entangled one. For a pure state $\alpha|00\rangle + \beta|11\rangle$ it is simply $C = 2|\alpha\beta|$. It is easier to compute than the von Neumann entropy of the reduced density matrix, which is the other usual measure, and unlike it, the concurrence extends to mixed states through the Wootters formula.

Consistent histories: interpretation of quantum physics proposed by Robert Griffiths in 1984, *aka* quantum history, which describes physical processes as families of alternative histories obeying a consistency condition, without any wave function collapse. It aims at getting rid of the measurement problem by treating measurement as an ordinary physical process.

Constructor theory: meta-theoretic framework proposed by David Deutsch in 2013 and developed with Chiara Marletto, which expresses physical laws as statements about which transformations, called tasks, are possible or impossible, and introduces constructors, entities able to perform a task repeatedly without degradation. It does not compete with the usual interpretations, it treats quantum theory as a subsidiary theory within a broader framework built on superinformation.

Contextuality: fundamental concept in quantum physics where the outcome of a measurement on a quantum system depends not only on the system intrinsic properties but also on the context of other measurements being performed concurrently. As a result, measurements of quantum observables do not reveal pre-existing values. In classical physics, the value of a property of an object is intrinsic and independent of how or when it is measured. See Kochen–Specker theorem. The study of contextuality is a major topic of discussion in quantum foundations. Quantum contextuality is also said to be one of the origins of quantum computational speedups and quantum advantage in quantum computing.

Continuous variables quantum computing (CV): a type of quantum computing that encodes information in bosonic modes, or qumodes, whose quadrature observables have continuous spectra, rather than in two-level qubits. Used in two types of quantum computers: analog quantum simulators (particularly based on cold atoms) and CV photon-based systems.

Cooper pair: pair of correlated electrons carrying the dissipationless current of superconducting materials at low temperature. In the conventional BCS case, the two electrons have opposite momenta and opposite spins, giving a total spin of zero, and the binding energy is small, of the order of the superconducting gap, with a coherence length that can reach hundreds of nanometers, so the pair is correlated rather than tightly bound. They become bosons and can accumulate and form macro quantum objects.

COP (Combinatorial Optimization Problem): class of problems searching for an optimal object in a finite but exponentially large set of candidates, like MAXCUT, TSP, maximum independent set, graph coloring, knapsack and scheduling problems. Classically solved with exact methods (branch-and-bound, branch-and-cut, integer programming) and with approximate metaheuristics (tabu search, simulated annealing). Quantum approaches include QAOA, quantum annealing, Grover adaptive search, DQI and quantum walk based algorithms.

Copenhagen interpretation: interpretation of quantum physics elaborated by Niels Bohr in Copenhagen and by Werner Heisenberg, although it was never clearly formalized. Applied to individual quantum objects, it is mostly based on Bohr's correspondence and complementarity principles, Heisenberg's indeterminacy principle, Born's probability interpretation of the Schrodinger wave function and on the wave function collapse and its fundamental indeterminism. It avoids describing any reality beyond what can be measured like an exact position of an electron. The completeness of this theory was challenged by Albert Einstein. Physicists are still debating about this interpretation, as part of the quantum foundation field.

Coplanar waveguide (CPW): type of transmission line used to guide electromagnetic waves, commonly at microwave frequencies, which consists of a central conducting strip, usually a superconducting material like niobium, flanked by two ground planes, all lying on the same plane, typically on the surface of a dielectric wafer substrate like silicon oxide or sapphire.

CPLEX (IBM ILOG CPLEX Optimization Studio): classical mathematical programming solver handling linear programming (LP), mixed-integer programming (MIP) and quadratic problems with simplex, barrier, branch-and-bound and branch-and-cut methods. With Gurobi and specialized solvers like Concorde for TSP, it is one of the classical baselines that quantum optimization algorithms must beat to demonstrate any practical advantage.

Cryo-CMOS: Cryogenic Complementary Metal-Oxide-Semiconductor, CMOS technology engineered to operate at extremely low temperatures, usually below 4 K. Their usual function is to handle part of the qubit control and read out operations. They are designed to minimize heat dissipa-tion and minimize power consumption to accommodate for a sufficient number of qubits. They are however dissipative and don't scale that much beyond a couple hundred physical qubits with current dilution cryostats.

Correspondence principle: principle formulated by Niels Bohr in 1920 which states that the behavior of systems described by quantum physics matches classical physics in the limit of large quantum numbers (large orbits and large energies or electron quantum numbers).

Coulomb blockade: decrease of electrical conductance at small bias voltages of small electronic devices containing at least a low-capacitance tunnel junction. As a result, the conductance of the devices may not be constant at low bias voltages, but disappears for biases under a certain threshold, i.e. there is no current flows.

Coulomb force: electrostatic force between electrically charged particles like electrons and protons. Its strength is inversely proportional to the square of their distance and proportional to the product of their respective charge.

Counterfactuals: conditional statements about what would have happened if circumstances had been different. These make sense when grounded in known laws and patterns of nature.

Counterfactual models: concepts extending from the counterfactual phenomena observed in quantum mechanics. It deals with the ability to obtain information or produce an effect in the absence of a direct physical interaction. It includes quantum entanglement where quantum systems can be interconnected so that the state of one seems to instantaneously affect the state of the other, regardless of the distance between these systems and with no persistent physical connection. Another such model is the quantum Zeno effect (also defined in this glossary).

CPTP map: completely positive and trace preserving map or operator also referenced as a quantum channel or superoperator. It is a linear operator that turns a density matrix describing a mixed state system into another density matrix. Its size is then the square of the density matrix size, so 2^{4N} for a system of N qubits. It can describe any operation on a mixed state system: some quantum gates, any sort of measurement, quantum filters, as well as feedback networks in quantum control theory.

Crosstalk: in the qubit field, is a phenomenon where an action on a given qubit or set of qubits has a side effect on other qubits. Of course, various techniques are employed to minimize it like, in the case of superconducting qubits, using tunable couplers between qubits. Then, there are several crosstalk types like IX, IY, IZ, ZX, ZY, ZZ which depend on the type of interactions between qubits.

Cryocooler: closed-cycle mechanical refrigerator producing low temperatures without any cryogenic liquid. The main families are Gifford-McMahon coolers, Stirling coolers and pulse tubes. In quantum computing, a two-stage 4K pulse tube cryocooler provides the 50K and 4K stages on top of which the dilution unit takes over. Its cooling power collapses with temperature, from about 50W at 50K to 1W to 2W at 4K for a 10 to 12 kW compressor.

Cryogenics: cooling technology. Very low temperature cryogeny is used with superconducting and electron spin qubits computers. The temperatures required to stabilize qubits and reduce their error rate are very close to absolute zero: around 15 mK. The most commonly used systems are dilution refrigerators that use helium-3 and helium-4. Cryogenics is also used for photon generators and photon detection systems, but at a higher temperature situated between 2K and 10K.

Cryopumping: vacuum pumping produced when residual gas molecules condense or adsorb on cold surfaces. In cryogenic neutral-atom systems, cryopumping reduces background-gas collisions and can greatly extend atom-trap lifetimes.

Cryostat: the whole enclosure that maintains a payload at low temperature, containing the vacuum can, the concentric radiation shields, the cold plates and the cooling stages. For superconducting and electron spin qubits, it houses the chandelier and the quantum processor at its bottom. It is fed by an external compressor and, for a dilution system, by a gas handling system (GHS).

CSCO: complete set of commuting observables, the most complete measurement of a quantum system comprised of compatible properties that can be measured in any order.

CSM: Contexts, Systems and Modalities, the quantum foundations interpretation proposed in 2015 by Alexia Auffèves and Philippe Grangier to reconcile the Copenhagen interpretation with realistic models. It attributes measured properties, called modalities, jointly to a system and to a context, meaning a completely specified measurement device with its settings, which builds a contextual objectivity. Its second phase, CSM2, combines the Koopman representation of classical systems with type III von Neumann algebras to locate the Heisenberg cut.

Butterfly velocity: speed at which an initially local operator grows in support under time evolution, measured with out-of-time-ordered correlators (OTOCs). It is the operational speed of information spreading, as opposed to the Lieb-Robinson velocity which is a rigorous upper bound on it. The two can differ by an order of magnitude or more, which is why an LR velocity quoted for a hardware platform should be read as "no faster than" rather than as the actual propagation speed.

Cuprate: family of copper oxide ceramics whose superconductivity was discovered in 1986 by Georg Bednorz and Alex Müller at IBM Zurich, with a d-wave pairing symmetry. YBCO and the ReBCO family have a T_C above the 77K of liquid nitrogen, which makes them usable in HTS cables and magnets. Their pairing mechanism is still not explained by BCS.

CV-QKD: Continuous-Variable Quantum Key Distribution. QKD family encoding information in optical-field quadratures, usually with coherent or squeezed states and homodyne or heterodyne detection. It can use Gaussian or discrete modulation and is attractive for integration with coherent telecom photonics.

CVaR (Conditional Value at Risk): cost function used in variational optimization, introduced in this context by Panagiotis Barkoutsos, Giacomo Nannicini, Stefan Woerner et al. in 2020. Instead of minimizing the full expectation value of the Hamiltonian, it minimizes the mean of the best tail of the measured energy distribution, usually the best few percent of the shots. It fits combinatorial optimization better since only the best sampled bitstring matters, and it improves the convergence of QAOA and VQE on these problems.

CVD: chemical vapor deposition, an additive manufacturing technique for semiconductors, where the target surface is exposed to one or more volatile precursors, which chemically react and/or decompose on the target surface to leave a thin film deposit on the target, e.g. using silane SiH_4 to deposit Si on the wafer, generating 2 H_2 molecules.

DAC: digital-analog converter. Classical electronic device converting a digital signal into an analog signal. Is used in the microwave generation systems implemented to control superconducting and electron spin qubits.

DAQC (Digital-Analog Quantum Computing): hybrid computing model combining digital single qubit gates with analog multi-qubit evolutions of a natural hardware Hamiltonian, instead of decomposing entangling operations into long sequences of two-qubit gates. It makes a more efficient use of the hardware resources and is less sensitive to noise, but it is harder to debug and its speedups depend strongly on the algorithm class.

Data re-uploading: variational-circuit technique that inserts input-dependent encoding gates repeatedly between trainable circuit layers. Repetition can generate higher-order trigonometric or Fourier features of the classical input and thereby support nonlinear classical decision functions after measurement, although the underlying quantum state evolution remains linear.

Dark count: photons detected by photon detectors that come from the environment and thermal or tunneling effect. This explains why most single photon detectors must be cooled at a temperature usually below 10K.

Dark energy: unknown component accounting for about 68.5% of the energy content of the Universe in the Planck 2018 ΛCDM fit and driving its accelerated expansion. Its energy density is tiny, at about $5{\times}10^{-10}$ J/m^3. Associating it with the quantum vacuum energy of quantum field theory leads to the cosmological constant problem, a mismatch of many orders of magnitude between the predicted and observed values.

Dark matter: non-luminous gravitating component accounting for about 26.5% of the energy content of the Universe in the Planck 2018 ΛCDM fit. Its existence is inferred from galaxy and cluster dynamics, gravitational lensing, the cosmic microwave background and large-scale structure, but its microscopic identity remains unknown. Candidates include axions, WIMPs, sterile-neutrino models and primordial black holes. Several searches use quantum sensing techniques.

Dark photon: hypothetical gauge boson associated with an additional $U(1)$ field that can couple weakly to the ordinary photon through kinetic mixing. Depending on its mass and production mechanism, it can be a dark-matter candidate or a mediator between dark and visible sectors. Resonant cavities, atomic sensors and precision electromagnetic measurements are among the search techniques.

Dark silicon: phenomenon by which a growing share of a chip's transistors cannot be powered simultaneously because the resulting power density would exceed what cooling can evacuate. It is a direct consequence of the end of Dennard scaling and it is handled with core and function shutdowns, per-core voltage and clock adjustments and heterogeneous architectures like Arm big.LITTLE and DynamIQ.

Dark state: *aka* "coherent population trapping state" or "dark resonance" is a specific quantum superposition of states in a quantum system that does not couple to a particular external field or interaction. The dark state remains unaffected by certain interactions that would normally cause transitions between other states.

Dark state protocols: methods used to create, manipulate, or utilize "dark states" that are special quantum superpositions insensitive to certain interactions. These are used in quantum optics, atomic physics, and quantum information processing to enhance precision and reduce sensitivity to noise. Examples include techniques like electromagnetically induced transparency (EIT, which can be used in quantum memories) and coherent population trapping (CPT, used in quantum clocks and magnetometers).

DCE (Dynamic Casimir Effect): creation of real photon pairs out of the quantum vacuum by a mirror moving at relativistic velocity, predicted by Gerald Moore in 1970. It was first observed in 2011 at Chalmers with a SQUID modulating the boundary condition of a superconducting transmission line at about 11 GHz, which is equivalent to a mirror moving at a few percent of the speed of light. The energy comes from the mirror movement, not from the vacuum, so there is no energy conservation violation.

DCQO (Digitized Counterdiabatic Quantum Optimization): gate-based optimization algorithm which digitizes an adiabatic evolution and adds counterdiabatic terms to the Hamiltonian to suppress transitions to excited states when the evolution is accelerated, in the spirit of shortcuts to adiabaticity. It uses a series of discrete unitary gates like a QAOA ansatz but with a shallower circuit, which makes it more resilient to NISQ noise. It is notably promoted by Kipu Quantum.

DDS: direct digital synthesizer, an electronic component which directly synthetizes a wave pulse, as opposed to an AWG which generates a waveform pulse that is then mixed with a tone pulse. DDS are used in trapped ions and other qubits control electronics.

DQC: Distributed Quantum Computing, architecture in which distinct QPUs cooperate on a computation. In the networked sense used in this book, quantum links distribute states or entanglement and enable nonlocal quantum operations. This is distinct from classical task farming where independent QPUs solve subproblems and exchange only classical data.

De Broglie wavelength: wavelength of a particle calculated as h/p with its momentum p and h being Planck's constant.

Decoherence: marks the end of the coherence of a quantum object or a qubit. It is notably caused by the interactions between quantum objects and their environment. Coherence time and decoherence time are often used interchangeably for the same characteristic duration, but they should be distinguished from the underlying processes and their separate metrics: T_1 is the energy relaxation time, T_2 the dephasing time including relaxation, and T_2^* the inhomogeneously broadened value, with $T_2 \leqslant 2T_1$.

Degenerate: a quantum system energy level is degenerate if it corresponds to two or more different measurable states with different quantum numbers. Mathematically, a quantum state is degenerate when several linearly independent eigenvectors may have the same eigenvalue. A normalized linear combination of these eigenvectors is also an eigenvector with the same eigenvalue. The number of linearly independent eigenvectors having the same eigenvalue corresponds to the degree of degeneracy of the quantum system. The number of different eigenstates corresponding to a particular energy level is the degree of degeneracy of the level. This happens for example when the energy level alone is not sufficient to characterize the state of a quantum system. That's where we need other quantum numbers to characterize the state. This is the case with the hydrogen atom electron. Its energy level depends only on its principal quantum number n (the electron layer), and not the three other electron quantum numbers (orbital angular momentum, magnetic moment and spin, although this degeneracy can be broken using relativistic quantum mechanics and hyperfine structure splitting of electron energy levels). But you also have degenerate quantum error correction codes, which are supposed to correct more errors than they actually detect, particularly with noisy quantum channels (meaning practically qubits gates). Another example is an atom's nucleus energy level that is only dependent on its orbital angular momentum in the absence of magnetic field. Different energy levels arise with a magnetic field due to the nucleus magnetic quantum number.

Delayed-choice experiment: a thought experiment proposed by John Wheeler in 1978 where the choice of measuring the wave or particle behavior of a quantum is made after the quantum has entered the interferometer. It was implemented with single photons in 2006-2007 by Jean-François Roch, Philippe Grangier et al., confirming that the observed behavior depends on the measurement setting and not on any prior decision by the photon.

Dennard scaling: empirical rule stated by Robert Dennard in 1974 by which the power density of transistors stays constant as they shrink, since voltage and current scale down with their dimensions. It broke down around 2005 because of leakage currents, which is one reason why Koomey's law slowed down after 2000 and why classical processors moved to multiple cores instead of higher clock frequencies.

Density matrix: positive semidefinite Hermitian matrix of unit trace describing the state of a physical system. It is more general than the state vector, not more precise: a pure state is the special case $\rho = |\psi\rangle\langle\psi|$ with $\mathrm{Tr}(\rho^2) = 1$, while mixed states require the full matrix. They are used to describe what happens to subsystems of entangled systems, when decoherence happens and also, during measurement.

Dequantization: construction of a classical algorithm that reproduces the relevant performance of a quantum algorithm under comparable input-access assumptions, typically with at most polynomial overhead. A landmark result was Ewin Tang's 2018-2019 quantum-inspired recommendation algorithm, which used length-squared sample-and-query access to remove a previously claimed exponential quantum speedup. Dequantization is especially important in quantum machine learning and quantum linear algebra, where the apparent speedup can depend on assuming efficient quantum state preparation while charging the classical algorithm for ordinary sequential data access. The term is unrelated to numerical quantization of neural-network weights.

Determinism: philosophical view that events are completely determined by previously existing causes. Applied to classical mechanics, this relates to the ability to predict an object's position and momentum based on its initial conditions. Contrarily, in quantum physics, it is not possible to determine simultaneously the position and momentum of any particle with precision at any instant. This indeterminism is also observed with quantum measurement of a quantum object in a superposed state. These concepts are also applicable to computing. Classical computing is usually deterministic. Same entry data, same output data. In quantum computing, one circuit execution doesn't yield the same result when implemented in the exact same way. The result is usually probabilistic, at least, when the result is not a single computational basis of the state vector.

Deutsch-Jozsa (algorithm): quantum algorithm created in 1992 by David Deutsch and Richard Jozsa. Under the promise that a Boolean function is either constant, returning the same bit for every input, or balanced, returning 0 and 1 equally often, the algorithm distinguishes the two cases with one exact quantum oracle query. A deterministic classical algorithm needs up to $2^{n-1}+1$ oracle queries in the worst case, whereas a bounded-error randomized classical algorithm needs only a constant number of queries for a fixed error probability. The often-quoted exponential separation therefore concerns deterministic query complexity, not a generic practical speedup.

DFT (Density Functional Theory): mathematical model used to describe the structure of molecules at rest as a function of inter-atomic interactions. Used in high-performance computing as well as in quantum computing for chemical simulation.

Dimon: multimode superconducting circuit with two coupled transmon-like modes. OQC uses a dimon inside its coaxmon packaging architecture to create a dual-rail encoded qubit. Photon-loss events can then leave the computational subspace and be detected as erasures, but residual Pauli errors still require an outer QEC code.

DI-QKD: Device-Independent Quantum Key Distribution. QKD trust model in which security is inferred from observed Bell-nonlocal correlations rather than from a detailed model of the internal quantum devices. It requires a loophole-free Bell test plus secure laboratories, private randomness, authenticated classical communication and prevention of information leakage.

Dicke state: specific type of highly entangled quantum state, relevant in quantum optics and quantum information. It was defined by Robert H. Dicke in the context of spontaneous radiation from an ensemble of two-state atoms. For a system of N qubits with k excitations or k qubits with the $|1\rangle$ state and $N-k$ are in the $|0\rangle$ state), the Dicke state, denoted as $|D_k^N\rangle$, is an equal superposition of all $\binom{N}{k}$ distinct permutations of these states. In Dicke states, all particles are entangled with the other. Its entanglement is robust against particle loss. Dicke states are used in quantum metrology to enhance measurements precision beyond the standard quantum limit, in quantum networking, quantum compression, and quantum optimization algorithms and in quantum optics for understanding collective phenomena in light-matter interactions, such as superradiance.

A common example is the 3-qubit Dicke state with one excitation ($N=3, k=1$), also known as the W-state:

$$|D_1^3\rangle = \frac{1}{\sqrt{3}}(|100\rangle + |010\rangle + |001\rangle)$$

For a system of $N=4$ qubits, Dicke states are defined by number of excitations (k).

$k=0$**:** All qubits are in the $|0\rangle$ state.

$$|D_0^4\rangle = |0000\rangle$$

$k=1$**:** One qubit is in the $|1\rangle$ state, and three are in the $|0\rangle$ state. There are $\binom{4}{1}=4$ such permutations.

$$|D_1^4\rangle = \frac{1}{\sqrt{4}}(|1000\rangle+|0100\rangle+|0010\rangle+|0001\rangle)$$

$k=2$**:** Two qubits are in the $|1\rangle$ state, and two are in the $|0\rangle$ state. There are $\binom{4}{2}=6$ such permutations.

$$|D_2^4\rangle = \frac{1}{\sqrt{6}}(|1100\rangle + |1010\rangle + |1001\rangle + |0110\rangle + |0101\rangle + |0011\rangle)$$

$k=3$**:** Three qubits are in the $|1\rangle$ state, and one is in the $|0\rangle$ state. There are $\binom{4}{3}=4$ such permutations.

$$|D_3^4\rangle = \frac{1}{\sqrt{4}}(|1110\rangle+|1101\rangle+|1011\rangle+|0111\rangle)$$

$k=4$**:** All qubits are in the $|1\rangle$ state.

$$|D_4^4\rangle = |1111\rangle$$

Diffraction: phenomenon created when a wave encounters an obstacle or opening, like a small hole or slit. It is generated by the bending of photon waves around the corners of the obstacle. It creates interferences between the passing waves as they are detected in a plane further down the waves path. The phenomenon can be described classically with the Huygens–Fresnel principle that considers points in the hole or slit as a collection of individual spherical wavelets. The interference pattern shows up with laser light and can also be explained by the photon wave functions and their probability distribution. All-in-all, you can consider that a Young single-slit experiment also create quantum interferences!

Dilution refrigerator: name given to the very low temperature cryostats used to cool quantum computers below 1K. They cool superconducting or electron spin chips to respectively 15 mK and 100 mK. Dilution is related to the use a mixture of two helium isotopes (3 and 4), which are diluted in a mixing chamber, the two isotopes having slightly different physical properties. A helium 4 cryostat only goes down to about 2.8K, a helium 3 cryostat goes down to 300mK while a cryostat using both goes down to 10mK. The most common variant is the "dry" as opposed to "wet" dilution refrigerator. This version uses less helium and leaves more space in the chandelier to house electronic and quantum devices.

Dirac's notation: see bra-ket.

Dirac constant: Planck constant divided by 2π, also called reduced Planck constant and denoted $\hbar$ (h-bar). Some physicists called sometimes, abusively, this constant "Planck constant".

Discrete log problem: mathematical problem consisting of finding, in a finite cyclic group with generator g, the integer x such that $g^x = h$ for a given element h. It is believed hard classically in the multiplicative group of a finite field and on elliptic curves, which is what ECC security relies on. It is used in finding the solution of cryptographic problems with quantum algorithms. Shor's dlog algorithm is a quantum algorithm solving discrete log problems.

Dissipation engineering: deliberately coupling a quantum system to a controlled bath so that its dissipation becomes a computing resource instead of a nuisance. It enables quantum measurement, quantum state preparation and quantum state stabilization. It is used with bosonic qubits like cat-qubits where an engineered two-photon dissipation exponentially suppresses bit-flips, and it can also help efficiently prepare entangled Bell states.

Distillation: technique used in quantum error correction codes based on magic states. It combines several magic state qubits to feed others with a lower error rate. Distillation has the effect of purifying the state of qubits, meaning turning mixed states into pure states.

DLA (Dynamical Lie Algebra): Lie algebra generated by the Hamiltonian generators of a parameterized quantum circuit. Its dimension and decomposition characterize the dynamical subspace reachable by the ansatz and are useful diagnostics of expressivity and trainability. Exponentially large DLAs are associated with barren-plateau behavior for several random or sufficiently expressive circuit ensembles, while polynomially sized invariant subspaces can support trainability and may also facilitate classical simulation. Neither implication is universal without specifying the ansatz, observable, initialization and symmetry sector. DLA analysis has become an important tool for studying QAOA and other VQAs.

DMRG (Density Matrix Renormalization Group): classical variational algorithm created by Steven White in 1992 which finds the ground state of a many-body Hamiltonian by sweeping over an MPS and truncating the least significant Schmidt values at each step. It is the reference classical baseline for one-dimensional and quasi-one-dimensional strongly correlated systems and quantum chemistry, and the algorithm that regularly dequantizes quantum simulation advantage claims. DMRG is an optimization algorithm running on top of an MPS ansatz, contrarily to MPS, PEPS, TTN and MERA which are state families.

Domain specific architecture: DSA, processor design specialized for one class of workloads instead of general-purpose computing, trading flexibility for speed and energy efficiency. GPU cores, tensor cores, video codecs and transformer-only ASICs like Etched's Sohu are examples. Quantum computing control electronics follow the same logic with FPGA and ASIC based waveform generation and readout.

Doppler cooling: first laser cooling stage, using a laser slightly red-detuned from an atomic transition so that atoms or ions moving toward the beam preferentially absorb photons and are slowed down. It was created by David Wineland at NIST starting in 1979 with magnesium ions. It brings ions to the millikelvin range and is usually followed by resolved sideband cooling or EIT cooling to reach the motional ground state.

Doppler effect: shift in the electromagnetic spectrum due to the speed at which the source moves away from or closer to the observer. If the source moves away from the observer, the light wavelength is shifted towards the red (redshift), otherwise towards the blue. This effect is used in particular in the technique of atoms laser cooling. It illuminates atoms that are in thermal motion with a wavelength that is just below the absorption level of the atoms. Those atoms moving towards the laser beam will absorb the photon, which will reduce their kinetic energy and movement. Those atoms moving in the other direction will not absorb it because the apparent frequency of the photon will be too low to change the energy state of the atoms. As atoms get cooled, the cooling laser wavelength has to be adjusted. This technique allows atoms to be cooled to below mK (milli-Kelvin).

DV-QKD: Discrete-Variable Quantum Key Distribution. QKD family encoding information in discrete photonic degrees of freedom such as polarization, phase or time bins. BB84, BBM92 and many decoy-state protocols are DV-QKD protocols.

D-Wave: Canadian company designing quantum annealing computers. They do not have the same power as universal gate quantum computers with equal numbers of qubits. The current generation of D-Wave "Advantage" using Pegasus chips includes 5,000 qubits.

DQI (Decoded Quantum Interferometry): algorithm introduced by Stephen Jordan et al. at Google in 2024 which turns discrete optimization problems like max-LINSAT and max-k-XORSAT into classical decoding problems handled with a QFT and a classical decoder, akin to qLDPC syndrome decoding. It interferes constructively the symbol strings with a high objective value. It targets a superpolynomial advantage on structured instances like the Optimal Polynomial Intersection (OPI) problem, but its resource estimates are large, between 907 and 41,132 logical qubits and up to 12 TeraQops, and classical solvers like Gurobi and Markov chain Monte Carlo sampling remain competitive on practical instance sizes. HDQI (Hamiltonian Decoded Quantum Interferometry), introduced in 2025 by Google, MIT and EPFL, generalizes it to arbitrary signed Pauli Hamiltonians, enabling the preparation of Gibbs states, ground states and spectral filters.

DRAG: Derivative Removal by Adiabatic Gate, a leakage avoiding technique with superconducting qubits using control pulse adjustments to avoid the unwanted transition to $|2\rangle$.

DRAM: Dynamic Random Access Memory, volatile memory storing each bit in a capacitor that must be refreshed periodically. It is denser, cheaper and slower than SRAM and sits outside the processor die, in DIMM modules or in HBM stacks. It was invented by Robert Dennard at IBM in 1966.

Dressed state: resulting quantum state of an atomic or molecular system when interacting with an electromagnetic field. For example, when exposed to a continuous magnetic field or an electronic field, an atom can showcase additional energy level splitting, known as respectively Zeeman splitting and Stark splitting. One other case is when the external electromagnetic field is applied with a frequency close to the energy difference between the atom's original energy levels. The atom then undergoes Rabi oscillations between the dressed states.

Dual-rail encoding: photonic qubit encoding where the logical state is the presence of a single photon in one of two spatial modes or time bins, $|0\rangle$ meaning the photon is in the first rail and $|1\rangle$ the second. It is the encoding of the KLM scheme and of the PsiQuantum architecture. A Pauli X gate is simply a swap of the two rails. It is also used with superconducting qubits like with Quantum Circuits Inc, part of D-Wave since 2026.

Dual-species: or mixed-species, trapped ions or cold atoms architecture. In the case of trapped ions, using two different ion species or isotopes in the same trap, one dedicated to storing quantum information and the other to sympathetic cooling and sometimes to readout. Quantinuum uses $^{137}\mathrm{Ba}^+$ for data and $^{171}\mathrm{Yb}^+$ for cooling in Helios. It avoids the decoherence which would come from illuminating the data ions with cooling light. With cold atoms, is used for measurement ancilla qubits.

E91: entanglement-based QKD protocol introduced by Artur Ekert in 1991. Entangled pairs are distributed to Alice and Bob and Bell-inequality statistics are used to constrain eavesdropper correlations. E91 should not be confused with device-independent QKD, which imposes a stronger trust model and loophole-free Bell-test requirements.

EBL: electron beam lithography, a lithography technique that is focusing a beam of electrons on an electron-sensitive resist film to remove matter in specified areas, without requiring a mask like with photolithography. It is used to create 1nm precision nanostructures like with photon-generating quantum dots and also superconducting qubit chips. It's a rather slow process compared with photolithography that is adapted to low volume and custom productions.

EDSR (Electric-Dipole Spin Resonance): coherent spin-control technique in which an oscillating electric field drives spin rotations through spin-orbit interaction or through motion in a spatially varying magnetic field, such as the field from a micromagnet. EDSR is a control and spectroscopy mechanism, not a readout mechanism by itself.

Eigenstate: for a quantum object, these are the elementary wave functions in which it is possible to decompose it. They are represented by eigenvectors.

Eigenvalue: see eigenvector.

Eigenvector: an eigenvector x of a square matrix A is a vector that verifies the equation $\mathrm{Ax} = \lambda\mathrm{x}$, λ being an eigenvalue. When the matrix is Hermitian, λ is a real number. In other words, the direction of the vector x does not change once multiplied with matrix A.

Einselection: environment-induced superselection, the process by which the interaction with the environment destroys the coherences of a quantum system in all bases but a preferred one, whose surviving states are the pointer states. Introduced by Wojciech Zurek, it is the mechanism underlying decoherence and quantum Darwinism.

Electromagnetic spectrum: all electromagnetic radiation from the largest radio waves to X-rays and gamma rays. Visible light is only a very small part in the middle of this spectrum. An EM wave is decomposable in a number of photons, the smallest elementary unit of an EM wave.

EIT (Electromagnetically Induced Transparency): quantum interference effect where a strong control field renders an otherwise opaque atomic medium transparent over a narrow spectral window, with a steep dispersion that slows light down drastically. Ramping the control field down stores the photon as a collective spin excitation and ramping it back up retrieves it. It is the dominant protocol for cold atom ensemble quantum memories, reaching efficiencies above 85% and fidelities above 99% for polarization qubits.

Electron: elementary particle found in atoms, where it occupies quantum orbitals around the nucleus rather than following a classical trajectory, but also in freeform traveling between atoms and creating something we know as being electric current. In Bohr's 1913 model, the electron occupies discrete orbits, which quantum mechanics later replaced by orbitals, probability distributions labeled by quantum numbers. A transition between two levels corresponds to the absorption or emission of a photon. Electrons are elementary particles in the standard model because it is not composed of sub-particles, unlike neutrons and protons which are composed of quarks. According to quantum physics, electrons, as many other particles, behave as a particle and as a wave. Electrons are often used in qubits, in the form of electrons circulating in semiconductors loops or who are trapped in quantum dots or electromagnetic cavities and whose spin is controlled.

Electron gas: describes the behavior of free valence electrons in metals and semiconductors when they move around free of the atom nucleus. Their behavior is governed by the Pauli exclusion principle (1925), Dirac-Fermi statistics (1926) and Arnold Sommerfeld's quantum theory of metal (1927). Electron gas enables the modelling of electric conductivity, electron heat capacity and electric thermal conductivity as well as the Hall and quantum Hall effects. There are 1D, 2D and 3D electron gases. 1D electron gas are observed in semiconductor nanowires and carbon nanotubes. 2D electron gas show up in semiconductor quantum wells and in graphene sheets.

Elliptic Curves Cryptography (ECC): a type of public key cryptography that is potentially broken by Shor's quantum algorithm. One of its advantages is that it requires small keys, about three times smaller in number of bits than RSA public keys.

Energetics of quantum technology: cross-disciplinary research field and sector studying the energetics of quantum computing but also quantum telecommunications, cryptography and sensing. It's about making sure quantum technologies are not power hungry and also dealing with the energetic constraints related to quantum computing scalability. It's about balancing the act between cooling requirements, cabling, control electronics to ensure quantum computers can scale in number of physical and logical qubits.

Engineering: discipline that applies scientific principles and other craftsmanship to design, build, and optimize systems and technologies. While deeply rooted in science, engineering differs in intent, methodology, and constraints vs fundamental research and science. It is not a branch of science, but a separate domain focused on functionality, efficiency, and real-world impact. Engineers use modeling, simulation, and experimentation to create efficient, safe, and sustainable solutions across industries. It solves practical problems using mathematics, physics, and other sciences.

Entanglement: quantum phenomenon where two quantum objects are related with each other in a way that a measurement done on these two objects generates a correlated (but random) value. Mathematically speaking, two quantum objects are entangled when their quantum state (psi, vector state) cannot be expressed as the tensor product of individual quantum states. This process is used to link qubits together through two or three qubit quantum gates in quantum computers. It is also used in quantum cryptography and telecommunication systems based on entangled photons in QKDs.

Entropy: measures the degree of disorder and randomness of a physical system. Key concept related to the second law of thermodynamics that states that the entropy of an isolated system cannot decrease spontaneously. In quantum mechanics, the (von Neumann) entropy of a system is $-\operatorname{tr}(\rho \log \rho)$ where ρ is the density matrix describing the system state.

EPLG (Error Per Layered Gate): IBM processor-level benchmarking metric derived from layered randomized benchmarking. It estimates the effective error accumulated by a layer of simultaneously executable two-qubit gates and therefore includes more processor-wide effects than quoting the best isolated gate fidelity.

EPDA: Electronic-Photonic Design Automation, the family of CAD tools used to design photonic integrated circuits together with their driving electronics. It is the photonic counterpart of EDA and is still far less mature, which is a practical bottleneck as photonic circuits scale.

Epistemology: branch of philosophy dealing with how valid knowledge is obtained, mostly through observations. It is opposed to, or complementary to, ontology. In quantum foundations, a psi-epistemic interpretation views the quantum state as knowledge about future measurement outcomes rather than as a physical thing.

EPR paradox: the 1935 argument by Albert Einstein, Boris Podolsky and Nathan Rosen that quantum mechanics is either incomplete or non-local, based on two particles having interacted in the past. The paper never uses the word entanglement, which Schrödinger coined the same year, and hidden variables appear as a consequence of the argument rather than as an initial hypothesis.

EQA: exponential quantum advantage.

Erasure error: quantum error for which the location of the affected qubit or mode is known, or is heralded by a measurement. Photon loss from a dual-rail encoding is a typical example because the state leaves the computational subspace and the loss can be detected. Erasures are easier for QEC codes to correct than unknown Pauli errors because the decoder already knows where the error occurred. Leakage can behave as an erasure only when it is reliably detected and converted into a located error.

ERC Grants : European Research Council grants. Funding of European research projects with several levels, the top of which is the Synergy Grant which funds "moonshots" in European research associating at least two principal investigators (PIs) from public or private research laboratories. €14M is the maximum funding for such a project with €10M of core funding and €4M which can notably finance heavy investments or access to large infrastructures. Other levels include the Starting grants with up to €1.5M for 5 years and the Consolidator grants with €2M also for 5 years.

Ergodicity: capacity of a moving system to explore all parts of the space in which it can move in, in a uniform and random manner. The phenomenon occurs with many physical systems like electrons. Quantum ergodicity states that in the high-energy limit, quantum objects tend to uniformly distribute in the classical phase space.

Ergotropy: maximum amount of work that can be obtained from a quantum system.

Error Correction Codes: describes both logical methods and physical architectures to correct physical errors happening in both classical and quantum computing and telecommunication technologies.

Errors: a major concern in the operation of quantum computers. Operations on qubits: one and two qubit gates and qubit readouts generate errors that must be minimized. Error rates are in 2023 between 0.1% and 2% for two-qubit quantum gates. When several quantum gates are chained together, the rates of correct results (1 - error rate) multiplies quickly to the point of distorting everything. This is avoided either by reducing the physical level error rate like with cat-qubits, using shallow algorithms (low number of gates) or with error correction code systems. Errors also happen at qubit initialization (aka preparation) and readout.

ESR (Electron Spin Resonance): coherent spin-control and spectroscopy technique in which an oscillating magnetic field is applied near the electron Zeeman resonance frequency. In semiconductor spin qubits the resonance is typically in the GHz to tens-of-GHz range depending on magnetic field and effective g factor. ESR itself is not a qubit-readout method.

Eta letter: η, used to describe error rates or efficiency, Carnot engine efficiency, and also Landau symmetry breaking.

EUV: Extreme UltraViolet lithography, using 13.5 nm light to print chip features at nodes below 7 nm. The light comes from a plasma created by a high-power CO_2 laser vaporizing about 50,000 molten tin droplets per second. The whole optical path is reflective and under vacuum since EUV is absorbed by nearly everything, including air and glass. ASML is the only supplier of production systems, with China reported to have built a first prototype light source in Shenzhen in 2025.

Exchange-only qubit: encoded spin qubit using three exchange-coupled electron spins, usually in the total-spin $S = 1/2$ subsystem. Single-qubit operations are generated by electrically pulsing the exchange couplings between neighboring spins, avoiding local oscillating magnetic fields.

Exciton: quasiparticle made of an electron and a hole bound by Coulomb attraction, generated in a semiconductor by an absorbed photon. The notion was created by Yakov Frenkel in 1931. Coupled to a cavity photon, an exciton gives an exciton-polariton.

Exclusion principle: see Pauli exclusion principle.

Expectation value: average or mean value of an observable. With an observable operator A on a quantum state ψ, the expectation value is $\langle a \rangle = \langle \psi | A | \psi \rangle$. In other words, it is the inner product of ψ with the vector obtained by applying the operator A to ψ. For a mixed state described by a density matrix ρ, it becomes $\mathrm{Tr}(\rho A)$. In layman's term for a qubit, it is either the average value that would be obtained when doing an experiment, a large number of times and measure the value of the qubit yielding 0 or 1, and making an average, or the result of its mathematical evaluation if you have a clear idea of the qubit quantum state description. For example, after a Hadamard gate is applied to a $|0\rangle$ qubit, the expectation value of its measurement in in the typical z basis will be 0.5. Some algorithms, like in chemical simulations, output real number values that are obtained through expectation value assessment using a large number of circuit runs.

Euclidean networks: class of encryption algorithms used in post-quantum cryptography (PQC).

Extended Church-Turing thesis: the strengthened claim that any physically realizable computing model can be simulated by a probabilistic Turing machine with at most a polynomial overhead. It is not demonstrable, and quantum computing is the main candidate for falsifying it.

Fabry-Pérot cavities: equipment used in lasers that combines two parallel mirrors, one of which is semi-reflective. This contributes to the creation of the laser effect in the cavity. The length of the cavity is generally a multiple of the laser light wavelength, at least if we want to emit coherent light with photons having all the same phase. The name of the cavity comes from the French scientists Charles Fabry (1867-1945) and Alfred Pérot (1963-1925).

FBQC: fusion-based quantum computation, a variant of MBQC crafted by PsiQuantum that is based on micro-clusters states with groups of 4 qubits connected together and using Resource State Generators (RSGs). It's replacing measurement of entangled states in MBQC with double measurement of non-connected adjacent qubits to create entanglements between them.

FD-SOI: Fully Depleted Silicon On Insulator, planar transistor technology from CEA-Leti and STMicroelectronics adding a thin buried oxide layer under the channel, which limits leakage currents and enables body biasing. It is used in RF front-end chips and low-power designs, and is also a substrate of interest for silicon spin qubits and cryo-CMOS control electronics.

Feedforward (also spelled feed-forward): qualifies quantum computing and communications operations involving some quantum measurement and quantum teleportation protocols, where the measurement outcome can be random and will be used in subsequent operations. It is used in error correction protocols, to implement conditional quantum gates and with quantum teleportation, where the state of a qubit is transferred from one location to another, without physically transporting the qubit itself.

Fermi's golden rule: the formula giving the transition rate between an initial and a final quantum state under a weak perturbation, proportional to the squared matrix element and to the density of final states. It was actually derived by Paul Dirac in 1927 and named after Enrico Fermi, who called it his "golden rule number 2" in his 1950 lecture notes.

Fermi sea: electrons filling the lowest atom orbits or degenerate low-energy states within a solid and at very low temperature near 0 K. It corresponds to low-energy states that do not participate in materials thermal activity.

Fermi-Hubbard model: theoretical model in condensed matter physics that describes the behavior of interacting fermions on a lattice structure. It is named after Enrico Fermi and John Hubbard, who contributed to the development of the model. It helps understand the behavior of electrons in solids, where they interact with each other and move within a crystal lattice. It is used to study systems like strongly correlated materials, high-temperature superconductors, and ultra-cold atomic gases trapped in optical lattices. Fermi-Hubbard models are typically solved at a small scale with VQE algorithms running on NISQ quantum computers and also on analog quantum computers.

Fermions: particles with individualistic behavior. Two particles of this type cannot be in the same state at the same place. This includes electrons, quarks, half-integer spin composite objects. For example, deuterium, lithium-6, potassium-40 atoms (source: Jean Dalibard). In contrast, integer spin bosons such as photons and some atoms can accumulate in the same state. In a word, bosons are communists and fermions are ultra-liberals.

Fine structure: splitting of an energy level or spectral line into several distinct components that take into account electron spins and relativistic corrections to Schrodinger's wave equation.

FinFET: transistor architecture where the channel is a vertical fin surrounded by the gate on three sides, providing better electrostatic control than planar transistors. It was introduced by Intel at the 22 nm node in 2011 and used down to the 5 nm generation, before being superseded by nanosheets.

First quantization: many-particle representation in which registers encode particle coordinates, momenta or single-particle basis-state labels and the many-particle wavefunction is represented directly, with the required symmetry or antisymmetry imposed for identical bosons or fermions. In quantum algorithms it contrasts with second quantization, where qubits encode occupations of modes.

First quantum revolution: set of technologies created from the 1940s onwards which exploit quantum physics at the level of large ensembles of quantum objects without controlling them individually, like transistors, lasers, LEDs, photovoltaic cells, MRI, quantum dots displays and atomic clocks. It is opposed to the second quantum revolution which controls individual quantum objects and uses superposition and entanglement as computing or sensing resources.

Floquet code or Planar Honeycomb Code is a family of quantum error corrections codes created by Matthew B. Hastings and Jeongwan Haah from Microsoft in 2021. It simplifies toric codes with fewer qubits and stabilizers and is adapted to qubits architectures implementing pairwise qubit measurements like with the elusive Majorana fermions.

Fine-structure constant: the dimensionless constant $\alpha \approx 1/137$ measuring the strength of the electromagnetic interaction, introduced by Arnold Sommerfeld in 1916. It equals the ratio between the velocity of the electron on the first Bohr orbit of hydrogen and the speed of light. Measured to 2.0×10^{-10} at Berkeley in 2018 and to 8.1×10^{-11} at LKB in Paris in 2020.

FOFI: First-Order Field-Insensitive transition, a qubit transition operated at a bias field where the first derivative of its frequency with respect to magnetic field vanishes, $d\nu/dB = 0$. It is therefore a clock-like operating point with residual second-order magnetic sensitivity.

Fluxonium: superconducting qubit made from a Josephson junction shunted by a large capacitance and a superinductance, often implemented with a Josephson-junction array. Its computational states are eigenstates of the nonlinear phase/flux degree of freedom and are not simply two persistent-current directions. Fluxonium combines large anharmonicity with long coherence, with laboratory T_1 and T_2 values reaching the millisecond range and two-qubit fidelities above 99.9% in small devices. Its challenges include the superinductor, flux biasing, low transition frequencies in some designs and scaling control/readout to many qubits.

Flying qubits: qubits that can move, as opposed to stationary qubits that do not move. They are usually photons but there's a small branch of flying qubits studying electrons.

Fock space: algebraic structure used to describe the quantum state of a set of identical particles whose number is variable or unknown. It is a Hilbert space made up of the sum of the tensor products of Hilbert spaces for the particles that make up the set.

Fock state: defines a group of quantum objects, like photons, who have the same quantum numbers and are indistinguishable. They are defined by their number, a photon number in the case of photons, and their common quantum numbers describing the quantum objects state.

Flux biasing: technique used to control with some direct current the resonant frequency of a frequency-tunable superconducting.

Foliation: technique that turns a two-dimensional stabilizer code into a three-dimensional cluster state whose sequential measurement reproduces the code's error correction in time. Foliated codes are how surface-code style protection is implemented in MBQC and FBQC architectures.

Fourier Transform: mathematical decomposition of a time domain signal into elementary single frequency signals with their frequency, amplitude and phase. It is a complex-valued function of frequency. Each coefficient has a real and an imaginary part, from which the magnitude, its modulus, and the phase offset, its argument, of the corresponding sinusoid are derived. The inverse Fourier transforms that frequency decomposition function back into its original compound signal.

FPGA: Field Programmable Gate Arrays. Integrated circuit where some or all functions can be dynamically defined and program on-demand. It can have analog and digital features. Modern FPGAs also embed full-fledge processing units (Arm cores, GPUs, neural processing units, networking units). FPGAs are used in qubit control electronics for reading out the signals coming from the resonators attached to superconducting and electron spin qubits. It measures the phase and amplitude of the reflected microwaves after they are converted from analog to digital with an ADC (analog-digital converter) that can be embedded in the FPGA.

Fredkin gate: quantum gate operating on three qubits that swaps the second and third qubits if the control qubit is 1, and leaves them unchanged otherwise. Also called CSWAP gate (conditional SWAP).

Free Electron Laser (FEL): a source of coherent light where relativistic electrons from an accelerator pass through an alternating magnetic field (an undulator), emitting radiation tunable from infrared to hard X-rays. Unlike conventional lasers, there is no atomic or molecular gain medium and no fixed transition frequency.

FTQC: Fault-Tolerant Quantum Computer. Error-resistant quantum computer that is based on logical qubits made of many physical qubits and implementing quantum error correction. Fault-tolerance is based on the error correction making sure errors don't propagate to other qubits. Also, errors must be corrected faster than they are created in the system.

GAA: Gate-All-Around, transistor architecture where the gate surrounds the channel on all four sides. Nanosheets and nanowires are its main implementations, deployed at the 2 nm class nodes by TSMC, Samsung and Intel.

GAN (Generative Adversarial Network): machine learning architecture where a generator network and a discriminator network are trained against each other, the first one creating synthetic content and the second one telling it apart from real data. Its quantum versions belong to the quantum generative learning models (QGLM) family, which also covers quantum circuit Born machines (QCBM) and quantum variational autoencoders (QVAE). They are used to generate synthetic training data sets for classical models, but most demonstrations so far involve circuits which are classically simulable at negligible cost.

GAS (Grover Adaptive Search): optimization scheme formalized by Austin Gilliam, Constantin Gonciulea and Stefan Woerner in 2019 which turns Grover's search into an optimization by repeatedly searching for a solution better than the current incumbent threshold, the threshold being updated at each round. It is the baseline for Grover-based combinatorial optimization and it handles QUBO, PUBO and noisy objective functions, but it inherits Grover's quadratic query scaling only, and it requires a FTQC QPU given its circuit depth.

Gatemon: hybrid superconductor-semiconductor qubit in which the Josephson weak link is a semiconductor nanowire or two-dimensional electron gas whose Josephson energy is tuned electrostatically with a gate voltage. It retains a transmon-like electromagnetic mode while replacing magnetic-flux tuning by voltage control. This can simplify wiring but current devices still have lower coherence and two-qubit fidelities than leading all-superconducting transmons.

Gate-based quantum computing: the broader category of quantum computing systems based on qubits and quantum circuits implementing quantum gates on 1, 2 and 3 qubits at a time.

Gate teleportation: implementation of a quantum gate by consuming pre-shared entanglement together with local operations, measurements and classical feed-forward. In distributed quantum computing it enables nonlocal gates, such as a remote CNOT or CZ, between qubits held in different QPUs without physically moving the data qubits themselves.

Gaussian Boson Sampling (GBS): variation of a boson sampling experiment that uses continuous variables based on Gaussian states photons as input. It is a physical model that is even more difficult to digitally simulate than a boson sampling since the underlying mathematical object is a Hafnian instead of a permanent, that is even more complicated to compute classically.

Gaussian state: bosonic states whose Wigner function is a Gaussian, so it is everywhere nonnegative. This does not make them classical: squeezed states and two-mode squeezed entangled states are Gaussian and nonclassical. Non-Gaussian states, which include Fock, cat and GKP states, can exhibit Wigner negativity, and that negativity is the resource needed to go beyond efficient classical simulation of Gaussian circuits.

GBS: Gaussian Boson Sampling, the variant of boson sampling where the inputs are single-mode squeezed states rather than single photons. Its output probabilities are given by matrix hafnians. Introduced in 2017 by Craig Hamilton, Christine Silberhorn, Igor Jex and colleagues, it underpins the Jiuzhang and Xanadu Borealis quantum advantage experiments.

GGSA: generalized Grover search algorithm which replaces the initial standard Hadamard layer with an arbitrary unitary transformation U to prepare non-uniform initial states.

GHS: Gas Handling System, the rack-mounted subsystem of a dilution refrigerator which stores, circulates and controls the helium 3 and helium 4 mixture, with its pumps, valves, sensors and control software. It consumes about 1 to 2 kW, which is small compared to the 10 to 12 kW of the 4K compressor, and it is what makes automated cooldowns possible.

GHZ: means something other than giga Hertz in quantum computing! It is a multi-qubit Greenberger-Horne-Zeilinger superposed state that rules out local hidden-variable models, under the usual locality and measurement independence assumptions, for at least three particles and with a finite number of measurement settings, without needing a statistical inequality. The concept dates back to 1989 and has been experimentally validated in 1999. The typical experimental GHZ states use three qubits. A large GHZ state with many qubits is a typical large entangled state that could be use in photonic qubit computing based on the MBQC paradigm. It is also used in quantum metrology to reach the Heisenberg limit in precision.

Gibbs state: describes the equilibrium state of a quantum system at a given temperature. It represents a probability distribution over the system's possible states, weighted by their energy. It is central to statistical mechanics and quantum physics. In quantum physics, the Gibbs state is described by the density matrix $\rho_G = \frac{e^{-H/k_B T}}{Z}$, where H is the Hamiltonian (energy operator), k_B is Boltzmann's constant, T is the temperature, and $Z = \mathrm{Tr}(e^{-H/k_B T})$ is the partition function, ensuring normalization. A Gibbs state is invariant under the system's time evolution when governed by a time-independent Hamiltonian, meaning the statistical properties of the system remain unchanged over time. At absolute zero (0 K), the system is almost certainly in its lowest energy state *aka* the ground state. As the temperature increases, the system explores higher-energy configurations with probabilities determined by the Boltzmann factor $e^{-E/k_B T}$. Gibbs states are widely used in Markov Chain Monte Carlo methods in computational physics and machine learning, and in quantum information theory to describe mixed states and thermal noise.

Gifford-McMahon: also spelled GM, a cryocooler cycle using a valved compressor and a moving displacer with a regenerator in the cold head. It reaches 4K and is widely used in MRI systems, cryopumps and semiconductor manufacturing. Its moving cold-end displacer generates more vibrations than a pulse tube, which is why pulse tubes are preferred for qubit cryostats.

Ginzburg-Landau theory: theory of superconductivity published jointly in 1950 by Vitaly Ginzburg and Lev Landau, seven years before BCS which describes the superconducting state with a complex order parameter instead of dealing with the microscopic pairing. It predicts the Meissner effect, the formation of vortices and the distinction between type I and type II superconductors. Gor'kov showed in 1959 that it is a limiting form of BCS near the critical temperature T_C.

GKP qubits: bosonic code proposed by Gottesman, Kitaev and Preskill that encodes a qubit in the infinite-dimensional Hilbert space of a harmonic oscillator, using a grid of translations in phase space, so that small displacement errors become detectable and correctable. In the optical case, Gaussian operations and homodyne detection suffice for the Clifford gates once the non-Gaussian GKP resource state has been prepared, which is the hard part. GKP qubits are being created with photons (Xanadu) as well as well as with superconducting circuits (Nord Quantique).

Gleason's theorem: according to Andrew M. Gleason's theorem proven in 1957, in a Hilbert space of dimension at least three, any assignment of probabilities to projectors that is additive on orthogonal families is necessarily given by $\mathrm{Tr}(\rho P)$ for some density operator ρ, which is the Born rule. This determines the way to calculate probabilities and the set of possible quantum states.

GPGPU: General Purpose Graphical Processing Unit, used for simulation, scientific computing and machine learning, like the Nvidia V100, A100 and H100. These are coprocessors which are mostly not anymore used for graphics software or gaming but more for machine and deep learning and scientific computing, thus the "general purpose" nickname addition.

GQE (Generative Quantum Eigensolver): approach proposed by Kouhei Nakaji, Alán Aspuru-Guzik et al. in 2024 which uses a generative model, usually a transformer, to produce ground state preparation circuits instead of variationally optimizing the parameters of a fixed ansatz. The ADAPT-GQE variant from Quantinuum and Nvidia is trained on ADAPT-VQE reference circuits and refined with reinforcement learning, generating circuits an order of magnitude faster at a comparable accuracy.

Graviton: hypothetical massless spin 2 boson that would mediate gravity in a quantum theory of gravitation, joining the photon, the gluons and the W and Z bosons. It has never been detected and the cross sections involved make a direct detection extremely unlikely.

Green's function: mathematical tool used to solve inhomogeneous differential equations, particularly in physics and engineering. It represents the response of a system to a point source or impulse, and allows one to reconstruct the full solution by integrating over sources. It is like a "echo map". If you shout at a point in space, the Green's function tells you how the sound propagates and reflects throughout the environment. To find the total sound field from multiple shouts, you add up all the echoes.

Grotrian diagram: diagram used to show the various electronic energy transitions for a given atom, introduced in 1928 by the German physicist Walter Grotrian. The frequencies of transitions to higher energy levels provide an indication of their source like lasers (in the hundreds of nm wavelengths) or microwaves (in the 4-20 GHz frequency regimes).

Ground state: lowest energy state of an atom or a composite quantum system, other states being their excited states. The hydrogen atom ground state happens when its electron occupies the lowest energy level (with main quantum number n = 1). More generally, is also said of a qubit that is in its ground basis state $|\mathbf{0}\rangle$.

Grover (algorithm): quantum algorithm for finding an element in a non-indexed array or a unique element for which an oracle function returns 1. Theoretically provides a polynomial acceleration which is deemed not that interesting compared to quantum algorithms providing an exponential acceleration.

GSA: Grover search algorithm, another name for Grover's algorithm.

Gurobi: classical optimization algorithm and software tool. It is today one of the faster classical solvers.

H-bar: see Dirac constant.

Haar random matrix: represents a uniformly distributed random rotation or a completely random quantum evolution in the Hilbert space. The distribution is designed to evenly cover the whole Hilbert space starting from a reference state. It is used as a benchmark for typical or random behavior in quantum physics like quantum chaos and thermalization, quantum chaos, and randomized benchmarking. A Haar-random pure state is obtained by applying a Haar-random unitary to a fixed reference state.

Hadamard (gate): quantum gate creating an evenly superposed state between $|\mathbf{0}\rangle$ and $|\mathbf{1}\rangle$ in a qubit when starting with $|\mathbf{0}\rangle$ or $|\mathbf{1}\rangle$. In the Bloch sphere representation it is a half turn about the axis bisecting X and Z, equivalently $R_y(\pi/2)$ followed by $R_z(\pi)$ up to a global phase, and not a simple quarter turn about y. It maps $|0\rangle$ to $(|0\rangle + |1\rangle)/\sqrt{2}$ and $|1\rangle$ to $(|0\rangle - |1\rangle)/\sqrt{2}$, and it is its own inverse.

Hafnian: matrix function that counts the perfect matchings of a general graph, where the permanent counts those of a bipartite graph. It gives the output probabilities of Gaussian boson sampling. The two are related by $\mathrm{per}(A)$ = haf of the block matrix built from A and A^T.

Hall effect: production of a voltage difference across an electrical conductor that is transverse to an electric current in the conductor and to an applied magnetic field perpendicular to the current. The effect was discovered by Edwin Hall in 1879.

Hamiltonian: operator representing the total energy of a system, kinetic plus potential. It generates the time evolution of the state through the time-dependent Schrödinger equation $i\hbar\,\partial_t|\psi\rangle = H|\psi\rangle$, and its eigenvalues are the allowed energies. Hamiltonians are everywhere in quantum physics. Among other places, it is used in analog quantum computers like D-Wave quantum annealers or Pasqal simulators. "Preparing a Hamiltonian" in this kind of computer is equivalent to setting up a matrix of qubits linked together by potentials, and which will seek a minimum energy resulting in a balanced Hamiltonian corresponding to the solution of the problem to be solved. The solution is about finding the right combination of qubits states (up/down for quantum annealing) that minimizes the energy of the whole system.

Hamiltonian simulation: computing the time evolution operator e^{-iHt} of a quantum system described by a Hamiltonian H, which is the historical motivation of quantum computing formulated by Richard Feynman in 1982. It is implemented with product formulas (Trotter-Suzuki decomposition), with linear combinations of unitaries, with qubitization and QSP or QSVT which reach an optimal query scaling, and with variational and analog methods. It is a subroutine of QPE, chemistry algorithms, quantum machine learning and differential equations solvers.

Hamming distance: metric used to compare two binary data strings of equal lengths. It is the number of bit positions in which the two bits are different. For two strings a and b, it is denoted as d(a,b).

Harmonic oscillator: in classical mechanics, system that, when displaced from its equilibrium position, experiences a restoring force proportional to its displacement x with a frequency that does not depend on the amplitude. Quantum physics formalizes the whereabouts of many harmonic oscillators including photons in cavities, superconducting qubits, phonons, diatomic molecules, etc.

Hartree-Fock: mean-field variational approximation method computing the electronic structure of atoms and molecules from the time-independent Schrödinger equation, where the many-electron wave function is restricted to a single antisymmetrized product of one-electron orbitals, a Slater determinant, solved self-consistently. The missing electron correlation is what post-Hartree-Fock methods and quantum algorithms aim to recover.

HBM: High Bandwidth Memory, DRAM dies stacked vertically and connected to a processor through a silicon interposer with a very wide interface. HBM3e delivers about 1.2 TB/s per stack over a 1,024-bit interface, HBM4 doubles it to 2,048 bits and 2 TB/s, and HBM6 targets 8 TB/s around 2032. Memory bandwidth being the main bottleneck of LLM inference, this is where much of the AI hardware race is playing out.

Heisenberg (principle of indeterminacy): fundamental principle of quantum mechanics which postulates that there is a lower limit to the precision with which one can measure two independent parameters relating to the same object such as its speed and position or the energy emitted and the duration of emission.

Heisenberg cut: conceptual boundary in quantum physics that separates a quantum system being observed from the classical measuring apparatus. It's a key idea in the Copenhagen interpretation of quantum physics, introduced by Werner Heisenberg in the early 20th century. Below the cut, we observe quantum behavior like coherence, superposition and entanglement, while above the cut, we have classical outcomes with wavefunction collapse and definite results. Discussions abound about where to place the Heisenberg cut. For example, with the Schrödinger cat thought experiment, the cut can be naively placed at the observer level who opens the box. A more precise approach would place the cut at the Geiger counter that detects the alpha ray (still a quantum level object) emitted by the decaying radium atom and turns it into a macroscopic classical signal. However, the distinction between classical and quantum can be drawn at the quantum object levels. For example, in multipartite states, classicality/nonclassicality boundary corresponds to the distinction between separable and entangled quantum objets or subsystems [898]. Others describe the classical world as emerging from the quantum world at its entropy limit [899].

Heisenberg limit: in quantum metrology, conventional ideal scaling in which the standard deviation of an estimated parameter decreases as $1/N$ with the relevant coherently used resource N, compared with the independent-probe or shot-noise scaling $1/\sqrt{N}$. Entangled states such as NOON or GHZ states, squeezing and coherent multipass protocols can attain this scaling in suitable noiseless models. The exact bound depends on how physical resources such as probe number, generator strength and interrogation time are counted, and loss or decoherence can remove the asymptotic advantage.

Helium 3: a rare isotope of helium that is used in cryogenic quantum computer systems to generate temperatures below 1K as part of dilution refrigeration systems. It is usually produced from tritium in specialized nuclear power plants, including the US Department of Energy's Savannah River nuclear power plant.

Helium 4: a common helium isotope that is also used in cryogenic systems operating at 3K to 10K temperatures.

HEMT: microwave pulse amplifiers using high-electron-mobility transistors, used at the 4K cryostat stage. They provide a large gain amplification of about 40 dB with high dynamic range and a bandwidth greater than 6 GHz for the inbound microwave readout signal coming from the parametric amplifiers (JPA, TWPA) sitting in the first cryostat stage. HEMTs are built using various semiconductors like indium phosphide (InP), gallium arsenide (GaAs), and gallium nitride (GaN) grown on substrates like silicon carbide (SiC), sapphire (α-Al_2O_3), or silicon.

Hermitian matrix: a square complex matrix equal to its own conjugate transpose, with real values on its diagonal, named after Charles Hermite. Its eigenvalues are real, which is why quantum observables and measurement operators are represented by Hermitian matrices.

Heterostructures: refers to Photonic Integrated Circuit (PIC) III-V heterostructures which are semiconductor circuits combining III/V materials such as gallium, indium and arsenic) on silicon or sapphire wafers. Typical III/V chips used for single photon emitters and detectors are bonded on silicon wafers containing waveguides and other elements transforming light (phase shifters, polarizers, beam splitters). It enables assembling components with different electronic and optical properties. Heterostructures are used in photonic circuits thanks to their ability to efficiently manipulate light and exhibit strong optoelectronic properties.

Heuristic algorithm: procedure that determines near-optimal solutions to an optimization problem. It trades optimality, completeness, accuracy, or precision for speed. Heuristics are used for problems that do not have an exact solution or for which the formulation is unknown and when the computation of a problem is computationally intensive.

Heralded single-photons: pairs of single photons can be generated in highly correlated states from using a single high-energy photon to create two lower-energy ones. One photon from the resulting pair is detected to "herald" (or "signal") the other so its state is pretty well known prior to its own detection or whereabouts. The two photons need not be of the same wavelength, but the total energy and resulting polarization are defined by the generation process. Two common types of heralded single-photon sources are SPDC (spontaneous parametric down-conversion with line width in the THz range) and SFWM (spontaneous four-wave mixing with line width in the MHz range or even narrower). It's used with QKD and also in photonic computing (Xanadu, PsiQuantum).

Helicity: projection of a particle spin on its direction of motion. For a single photon, whose spin quantum number is $s = 1$, the helicity takes only two values, $+\hbar$ and $-\hbar$, corresponding to right and left circular polarization. Unlike a linear polarization, which depends on the polarizer angle chosen by the observer, the helicity of a photon is observer independent.

Heterodyne measurement: method used for extracting information from an oscillating signal along two orthogonal components in phase space like the in-phase and quadrature signals coming out of an I/Q mixer. In this type of measurement, two conjugate operators are measured simultaneously, which create added noise.

HHL: quantum linear-system algorithm created by Aram Harrow, Avinatan Hassidim and Seth Lloyd in 2009 which prepares a normalized quantum state proportional to the solution $x = A^{-1}b$ of a linear system. The original construction combines preparation of $|b\rangle$, Hamiltonian simulation, QPE, a controlled rotation implementing eigenvalue inversion and inverse QPE. For a $D \times D$ sparse matrix, its oracle-model complexity is polylogarithmic in D but polynomial in the sparsity s, condition number κ and inverse precision. The potential exponential-in-log D advantage therefore requires efficient input access, favorable sparsity and conditioning, and an output that can be extracted as a compact observable. Reading all D components of x removes that output advantage.

High-NA: latest generation of ASML EUV lithography scanners, with a numerical aperture of 0.55 instead of 0.33, reaching an 8 nm single-exposure resolution and required for nodes under 3 nm. An EXE:5200B system costs about $380M. The following generation, Hyper-NA, is of doubtful economic viability even according to ASML. High-NA optics are also at play for controlling cold atoms.

Hilbert (space): real or complex vector space with a Euclidean or Hermitian scalar product. It is a generalization of the concept of three-dimensional Euclidean space. A Hilbert space is a complete inner-product space. In quantum physics, a system with d linearly independent basis states is described by a vector in a d-dimensional Hilbert space, the dimension being set by the number of basis states and not by the number of observables. These are geometrical spaces with lengths and angles, projections on dimensions and orthogonality between abstract vectors. Bosonic modes and other continuous-variable systems require infinite-dimensional Hilbert spaces.

Holevo bound: theorem by Alexander Holevo bounding the classical information accessible from an ensemble of quantum states. For an unconstrained ensemble of n qubits with no additional shared resource, the accessible classical information is at most n bits. Protocols such as superdense coding do not violate the bound because pre-shared entanglement is an additional communication resource. It is one reason why quantum states are not a generic exponentially dense classical data-storage medium.

Hong-Ou-Mandel effect (HOM): two-photon interference effect published in 1987 by Chung Ki Hong, Zhe-Yu Ou and Leonard Mandel. Two photons arriving simultaneously on the two input ports of a balanced beam splitter, and not on a Mach-Zehnder interferometer, always leave through the same output port when they are perfectly indistinguishable, because the two amplitudes leading to one detection on each side cancel. Scanning the relative delay between the photons produces a dip in the coincidence rate, the "HOM dip", whose depth measures the photon indistinguishability. It is, with the $g^{(2)}(0)$ autocorrelation, one of the two standard benchmarks of a single photon source.

Hidden variables: interpretation proposals of quantum physics based on the use of (yet) unobservable hypothetical entities what would explain phenomena like entanglement, nonlocality and describe the physical reality. Bell's theorem implies that local hidden variables of certain types cannot exist while being compatible with quantum physics postulates. This relates to the assumption, promoted by Albert Einstein in the famous 1935 EPR paper, that quantum physics is an incomplete theory that does not describe entirely the physical reality.

HOBO: higher-order binary optimization. See HUBO.

Homodyne measurement: method used for extracting the amplitude and phase quadrature of an oscillating signal by mixing it with a local oscillator at the same carrier frequency. It is widely used for dispersive readout of superconducting resonators and for RF-reflectometry or resonator-based readout of semiconductor quantum dots.

Hopfion: three-dimensional topological soliton, a closed loop version of the skyrmion where the field lines are linked. Observed in chiral magnets and in structured light.

HPC: high-performance computing, using high-end classical computers. A subset of these are supercomputers, which are ranked in the TOP500 list, updated twice a year.

HPQC: High Performance Quantum Computing, an emerging and mostly promotional label for the tight integration of high-performance classical computing with one or several QPUs. It is not a standardized architecture class. Multi-QPU systems and the partitioned or multi-tenant sharing of a processor between several users are separate implementation and service questions, and a processor is not a matrix of qubits.

HSP (Hidden Subgroup Problem): generic problem consisting of finding an unknown subgroup hidden within an oracle function which is constant on the cosets of that subgroup. Simon's and Shor's algorithms are both instances of the abelian version, which quantum computers solve efficiently with a QFT over the relevant group. The non-abelian version, which would cover graph isomorphism and the shortest vector problem used in post-quantum cryptography, has resisted for over two decades and has no efficient quantum solution.

HTS: High-Temperature Superconductors, also named HTC for high critical temperature. Materials whose critical temperature is high relative to the 1K to 9K of conventional superconducting metals. Strictly speaking, only the cuprates operate above the 77K of liquid nitrogen, MgB_2 at 39K and the iron-based superconductors between 26K and 55K being high temperature only by comparison with NbTi.

Hubbard model: physics simulation model of mixed conducting and isolated systems based on a simple Hamiltonian. It is a typical physics problem that is used in testing the capabilities of quantum computers. See also Fermi-Hubbard model.

HUBO: high-order unconstrained binary optimization, a generalization of QUBO where the objective function contains products of more than two binary variables. It is also named HOBO (higher-order binary optimization) and PUBO (polynomial unconstrained binary optimization). These problems can be reduced to QUBO with auxiliary variables and penalty terms, at the cost of extra qubits, or handled natively by gate-based QPUs, by some classical solvers and by annealers with multi-body couplers.

Hybrid bonding: technique directly bonding the copper pads and dielectric of two chips face to face at pitches below 10 microns, instead of using solder microbumps. It enables dense 3D stacking of logic on logic or memory on logic, and is also used in quantum computing to assemble superconducting qubit chips with their interposers and control chips.

Hyperentanglement: entanglement created simultaneously between several different degrees of freedom of the same pair of quantum objects, for example the polarization and the orbital angular momentum, or the polarization and the emission time bin, of a pair of photons. It multiplies the dimension of the entangled space without needing more particles, which is used for dense coding, for complete Bell state analysis that is otherwise impossible with linear optics alone, and for building photonic cluster states. Not to be confused with entanglement between two degrees of freedom of a single particle, sometimes called intra-particle entanglement, which involves no non-locality.

Hybrid quantum algorithm: an algorithm that combines classical processing running on classical computers and some processing performed on quantum computers, where needed. Variational algorithms are a category of hybrid quantum algorithm.

Hyperfine structure: small splitting of atomic energy levels or spectral lines with electrons with the same quantum numbers into several distinct components that are explained by the interactions between the nucleus and electron clouds.

Hyperfine qubit: trapped ion qubit encoded in two hyperfine sublevels of the electronic ground state, separated by a few GHz, which exist only in ions having a nonzero nuclear spin like $^{171}Yb^+$, $^{133}Ba^+$ or $^{43}Ca^+$. They are driven by microwaves or by two-photon Raman transitions and reach coherence times in the seconds to hours range when operated as clock qubits. Quantinuum, IonQ, Oxford Ionics and Universal Quantum use them.

Iceberg code: quantum error detection code used by Quantinuum which encodes k logical qubits into $k+2$ physical qubits with two stabilizers, detecting but not correcting errors. It is cheap in qubit overhead and is used in partially fault-tolerant schemes with postselection, discarding the runs where an error is flagged, at the cost of a discard rate growing with the circuit size.

IDR: Inverted Dilution Refrigerator, a wet dilution design where the mixing chamber sits above the sample space instead of below it, which allows fast and easy sample loading and fast cooldowns. It is used in physics laboratories rather than in commercial quantum computers.

In-memory computing: family of architectures performing computation inside or immediately next to the memory array to avoid moving data back and forth, since data movement dominates the energy budget of large AI clusters. Also called compute-in-memory or compute-near-memory.

Indeterminacy principle: the impossibility of simultaneously assigning arbitrarily precise values to two conjugate observables such as position and momentum, formulated by Werner Heisenberg in 1927 and written in its inequality form by Earle Hesse Kennard the same year, with $\Delta x \, \Delta p \geqslant \hbar/2$. The standard English name, used throughout this book, is uncertainty principle, even though indeterminacy is the more faithful rendering of Heisenberg's Unbestimmtheit and avoids suggesting a limitation of the measurement apparatus rather than a property of quantum states. Note that energy-time relations are of a different nature, since time is not an operator conjugate to energy in the same sense.

Indistinguishability: relates to bosons quantum objects that have the same quantum state in a given location and are impossible to separate with any measurement tool.

Indistinguishable photons: see Indistinguishability, photons being a common type of boson.

Integrated Quantum Photonics (IQP): technologies exploiting photons as quantum information carriers and implemented on chips using wafer-scale fabrication, mostly in silicon-based CMOS or with III/V materials like gallium arsenide (GaAs) and indium phosphide (InP). IQP is used in quantum telecommunications and computing. It uses optical waveguides to guide and route single-photons, provides miniaturized split and phase control circuitry, entangled state generation, overall manipulation and sometimes even photons generation and photons detection.

Interference: fundamental phenomenon of quantum physics used with the wave aspect of quantum objects, when probability amplitudes combine, constructively or destructively, increasing or decreasing the probability of particular measurement outcomes. Amplitudes cancel, not energy or particles.

Interposer: passive or active substrate, usually silicon, carrying dense wiring between several chips placed side by side in a single package. This is called 2.5D packaging, as opposed to 3D packaging where the chips are stacked on top of each other. Interposers are also used in superconducting quantum processors to route control and readout signals under the qubit chip.

Intersubjectivity: refers to the idea that multiple observers can agree on the outcomes of measurements even when those measurements are made on quantum systems that are inherently probabilistic and observer-dependent. This concept is used in some quantum physics interpretations like QBism (Quantum Bayesianism) where quantum states reflect personal beliefs of agents and inter-subjectivity challenges the idea that different agents might have incompatible views. In the Wigner's friend thought experiment, it raises questions about whether two observers can agree on what "actually happened" in a quantum measurement. With quantum contextuality, intersubjectivity is not just about agreeing on what is observed, but agreeing on how and under what conditions observations are made.

Invertible computation: involves computations that run both forwards and backwards so that the forward/backward semantics form a bijection. In classical computing, it can correspond to some symmetric logical circuits that can process data forward and backwards with both ends used as inputs and outputs. It's used for example in MemComputing classical processors. The principle was created by Supriyo Datta from Purdue University in Indiana, USA.

Irreversible: said in computing of a calculation that makes it impossible to compute the initial values using the calculation result. This is the case with all two-classical bits gates (NOR, OR, AND). Contrarily, quantum computing gates are mathematically reversible since relying on unitary transforms that, multiplied with their transconjugate, generate an identity operator. In plain language, if you apply a unitary (set of quantum gates) to a set of qubits, you can reverse this computing with the transconjugate of this unitary. Practically, it means playing in reverse order the gates initially applied. This technique is used in the uncompute trick that we describe elsewhere. Qubit measurement is also an irreversible process unless they happen to be in their $|0\rangle$ or $|1\rangle$ state and not entangled with other qubits.

Ion: non-neutral atom, which has a positive or negative electric charge. It is negative if its number of electrons exceeds the number of protons (anions) and positive in the opposite case (cations).

Ion shuttling: physical transport of trapped ions between zones of a segmented trap by dynamically changing electrode potentials. It is central to QCCD architectures, allowing ions that are not initially co-located to interact in a common gate zone. Individual transport primitives can range from tens of microseconds to milliseconds depending on distance, junctions and required motional excitation, while complete algorithmic cycles can be much longer. Shuttling can add motional excitation and therefore may require recooling.

Ion traps: circuit devices used to control trapped ions in trapped ions quantum computers.

I/Q mixer: in phase and quadrature mixer, which adds two pulse signals of same frequency but with different amplitude and phase. The In-phase signal is a sinusoid, and the quadrature signal is a cosine. They have a delay of $\pi/2$ or 90°. When added up in the mixer, the sum of both signals creates an arbitrary phase and amplitude signal of the same frequency.

Ising (model): a statistical physics problem that can be simulated and solved using quantum algorithms, especially on quantum annealers like those from D-Wave and quantum simulators ala Pasqal. It models the interactions between two-states particles (spin, ferromagnetism). Some optimization problems can be mapped on an Ising model.

Isotopes: variations of atoms where the number of protons and electrons is the same, sharing the same atomic number, but when the number of neutrons is different. For example, helium can exist in the form He^3 and He^4 with one and two neutrons. Many materials involved in quantum technologies are used with particular isotopes, like Si^{28} in silicon wafer used with electron spin qubits, the reason being the number of neutrons has an influence on atom nucleus spins, that can interfere with their electron spins.

IT: information technologies.

Jaynes-Cummings Hamiltonian: Hamiltonian used to describe the total energy of a system linking a resonator usually implemented as a coplanar waveguide (CPW) resonator with a superconducting circuit.

Jevons paradox: also called the rebound effect, formalized by the British economist William Stanley Jevons in 1865 in *The Coal Question*. Efficiency gains reduce the cost of a resource and, without regulation of markets and uses, lead to an increase in its global consumption instead of a decrease. It explains why the spectacular energy efficiency gains of classical computing and of LLM training did not prevent an explosion of the global ICT energetic footprint.

JJ: "jay-jay", nickname for Josephson junctions.

Josephson (effect): coherent tunneling of Cooper pairs between two superconductors separated by a weak link, which is the Josephson junction (JJ). The weak link can be a thin insulating barrier, a normal metal, a semiconductor or a geometrical constriction, and no loop is required. The supercurrent and the voltage across the junction are governed by the gauge-invariant phase difference, which makes the junction a nonlinear inductance and gives the anharmonic energy level spacing that superconducting qubits rely on. This technique is used in superconducting qubits from quantum systems such as those of IBM and Google. A loop containing one or two such junctions forms a SQUID, used in quantum sensing (superconducting quantum interference devices) that are used as very sensitive magnetometers.

JPA (Josephson Parametric Amplifiers): simple amplifiers, using one or two Josephson junctions that are used for the first stage amplification of readout microwaves in superconducting or silicon spin qubits. Their narrow bandwidth prevents their implementation with frequency-domain qubits readout multiplexing.

Kapitza resistance: the thermal boundary resistance between a solid and liquid helium, caused by the mismatch of their acoustic impedances. The heat flow it allows scales as $A(T_1^4 - T_2^4)$, so it collapses as T^4 when the stage gets colder. It is the reason why the discrete heat exchangers sitting above the mixing chamber are filled with sintered silver powder, whose specific surface reaches a fraction of a m^2 per gram.

Kerr effect: change of the refractive index of a material that is quadratic in the applied electric field, in the DC or electro-optic case, or proportional to the optical intensity in the optical Kerr effect, both originating from the third-order susceptibility $\chi^{(3)}$. It is distinct from the Pockels effect, whose index change is linear in the field and which originates from $\chi^{(2)}$, so it only exists in noncentrosymmetric materials.

Ket: vertical vector describing in Dirac's notation the state of a quantum object, with the symbols | and ⟩ forming a psi vector noted $|\psi\rangle$. It contains complex number amplitudes defining the relative weights in the computational basis. For a qubit, it's a 2 complex numbers vector. For a register of N qubits, it's a 2^N size vector of complex numbers defining the amplitudes of each combination of N 0s and 1s, which are orthogonal states in the 2^N state vector Hilbert space.

Klein-Gordon equation: the relativistic wave equation for spin-0 particles, obtained in 1926 by Oskar Klein, Walter Gordon, Vladimir Fock and others. It applies to pions and to the Higgs boson, whereas spin-1 gauge bosons such as photons and gluons follow the Proca and Yang-Mills equations and spin-1/2 fermions follow the Dirac equation.

Kochen-Specker theorem: no-go theorem stating that, in a Hilbert space of dimension at least three, no noncontextual assignment of predetermined values to all observables can reproduce the predictions of quantum mechanics while respecting the functional relations between commuting observables. In other words, the value attributed to an observable cannot be independent of the set of compatible observables measured alongside it. This is the formal basis of quantum contextuality, and the dimension condition means it does not apply to a single qubit.

Koomey's law: empirical trend documented by Jonathan Koomey in 2010 by which the number of computations per joule of dissipated energy doubled about every 1.57 years, roughly every 18 months, from the 1950s onwards. Koomey and Naffziger later showed that the doubling time slowed to about 2.6 years after 2000 with the end of Dennard scaling, and an analysis of Green500 data over 2008-2023 lands at about 2.29 years. It is the classical computing moving target against which any quantum energetic advantage must be assessed.

Koopman–von Neumann (KvN) theory provides a framework that presents classical physics in a manner similar to quantum mechanics, using an operator-based formalism. This approach represents classical states using complex wavefunctions $\psi(q,p)$ in a Hilbert space, where position and momentum are treated as multiplication operators $\widehat{q}$ and $\widehat{p}$. The time evolution of these classical states is governed by the Liouville operator $\widehat{L}$, similar to the Hamiltonian in quantum mechanics, leading to a KvN version of the Liouville equation $i\frac{\partial\Psi}{\partial t}=\widehat{L}\Psi$. It allows classical observables to be represented by operators, and their expectation values to be calculated similarly to quantum mechanics. It thus provides a bridge between classical and quantum descriptions, facilitating the study of systems with both classical and quantum components by leveraging non-commutativity and operator techniques without relying on quantum effects like superposition or entanglement. This approach offers insights into the emergence of classical behavior from quantum systems and enables advanced computational methods for hybrid systems.

Lamb shift: small energy gap of 1,057 MHz observed in 1947 by Willis Lamb between the $2s_{1/2}$ and $2p_{1/2}$ levels of the hydrogen atom, which Dirac's theory predicts to be exactly degenerate. It is explained by the interaction of the electron with the fluctuating quantum vacuum, mostly through the electron self-energy, vacuum polarization contributing only about −27 MHz. Its interpretation by Hans Bethe the same year launched modern QED renormalization.

Lamb-Dicke regime: regime in which the spatial extent of a trapped particle's motion is small compared with the inverse optical wave vector projected along the motional mode. It is commonly expressed as $\eta\sqrt{2\bar{n}+1} \ll 1$, where η is the Lamb-Dicke parameter and $\bar{n}$ the mean phonon occupation. It enables resolved carrier and motional-sideband control with weak recoil-induced coupling between distant motional states.

Landauer limit: minimum energy of $k_B T \ln(2)$ that must be dissipated per logically irreversible bit operation, such as erasing a bit or merging two computation paths, stated by Rolf Landauer in 1961. It amounts to about 3×10^{-21} J or 18 meV at room temperature. Current classical computing operates many orders of magnitude above it. Beware of energetic estimates of quantum computers that use this bound as a proxy for the real cost of a qubit gate, since it ignores qubit control, cryogenics and error correction, which dominate by far.

Larmor frequency: frequency of the Larmor precession (magnetic moment rotation). It is frequently mentioned in papers related to electron spins qubits.

Larmor precession: rotation of the magnetic moment of an object like an electron when it is exposed to an external magnetic field. This rotation happens along the axis of the magnetic field.

Laser: coherent light source invented in 1960 and used in many fields such as CD and DVD players, fiber optic communications, surgery, ophthalmology and dentistry, LiDARs. They are also often found in quantum computing to control cold atoms or manage photon-based qubits as well as in quantum cryptography and telecommunications (QKD & co). Laser means Light Amplification by Stimulated Emission of Radiation. It produces highly directional, narrowband light with high spatial and temporal coherence, emitted in a narrow beam. A real laser field has a finite linewidth, residual phase noise, a spatial mode structure and sometimes several polarizations, and the individual photons of a coherent state do not each carry one fixed optical phase. Light amplification uses a process of stimulated emission in an amplifying active medium made of solid, fiber, liquid, gas or semiconductor which is placed in the center of a resonant optical cavity with a reflecting mirror on one side and a semi-reflecting mirror on the other side, which allows the light beam to exit. The wavelength and power of light radiation depends on many parameters. The energy comes from an excitation or pumping system: primary laser, laser diode, flash lamp or electric discharge.

Lattice surgery: technique implementing logical two-qubit gates between surface code or other topological code patches by merging and splitting them along their boundaries with stabilizer measurements, instead of using transversal gates or anyons braiding. It is the mainstream approach to logical gates in planar architectures and can also connect patches belonging to two different codes.

LCHS (Linear Combination of Hamiltonian Simulations): technique created by Dong An, Jin-Peng Liu and Lin Lin in 2023 which solves non-Hermitian linear differential equations by writing their evolution operator as an integral, discretized as a weighted sum, of unitary Hamiltonian simulations. It avoids calling a quantum linear solver and reaches a near optimal scaling in the evolution time, with much better constant factor overheads than earlier ODE solvers.

LCU (Linear Combination of Unitaries): technique created by Andrew Childs and Nathan Wiebe in 2012 which implements an operator written as a weighted sum of unitaries $\sum_k \alpha_k U_k$ using ancilla qubits and a PREPARE, SELECT and unPREPARE sequence followed by a postselection on the ancillas. It is the standard way to build a block-encoding of a Hamiltonian decomposed into Pauli strings and it is used in Hamiltonian simulation, quantum linear solvers, QSVT and state preparation.

Leakage errors: error type corresponding to a qubit drifting and stabilizing in another energy state than the basis states $|0\rangle$ or $|1\rangle$. This can occur for example in the $|2\rangle$ level of a superconducting qubit. It is one category of erasure error that is relatively easy to detect and correct.

Learning: in quantum physics, learning refers to the process of extracting patterns, making predictions, and optimizing quantum systems using various techniques often inspired by classical machine learning. They are applied to quantum data coming from measurements. It helps modeling and analyze quantum systems. This includes classifying quantum phases, representing quantum states with neural networks, and optimizing quantum control protocols. It helps gain insights into quantum behavior and design better experiments. Kernel methods are used to map data into higher-dimensional spaces where patterns become more distinguishable. In quantum machine learning, quantum kernels compute similarity measures between data points embedded in quantum-enhanced feature spaces. This involves encoding classical data into quantum states and using quantum operations to evaluate their overlap or fidelity.

Leggett-Garg inequality: mathematical inequality fulfilled by macroscopic physical theories and systems. It says that a macroscopic object which has two or more distinct states, is at any given time in of those states. And it is possible in principle to determine which of these states the system is in without any effect on the state itself, or on the subsequent system evolution. This inequality is violated by quantum systems when superposition and entanglement are put in play like in interference processes.

Leggett inequalities: inequalities proposed by Anthony Leggett in 2003 that constrain a broad class of *non-local* hidden variable models, going beyond Bell's inequalities which only address local ones. Their experimental violation by Anton Zeilinger's group in 2007 restricts naive non-local realism without invalidating the de Broglie-Bohm pilot wave.

Kraus operators: set of operators $\{K_i\}$ describing a quantum channel acting on a density matrix as $\mathcal{E}(\rho) = \sum_i K_i \rho K_i^\dagger$, with the completeness condition $\sum_i K_i^\dagger K_i = I$. Named after Karl Kraus. The decomposition is not unique and the individual operators are not required to be local, even when the channel itself is quasi-local. It is the operational way to describe noise, measurement and dissipation on a qubit register, as opposed to a unitary acting on a pure state vector. See CPTP map.

Lie groups: mathematical objects in groups theory that are frequently encountered in quantum physics and quantum computing. They combine the notions of a group and a smooth manifold. Lie groups are used to describe symmetries and transformations in various mathematical and physical contexts. It is also used in quantum error correction codes.

Lindblad equation: equation describing the time evolution of the density matrix ρ of a quantum system that preserves the laws of quantum mechanics, meaning it preserves the trace and positiveness of the matrix. But the transformation is usually not a unitary due to decoherence. Also named a Lindbladian, a quantum Liouvillian, and in the long form, a Gorini–Kossakowski–Sudarshan–Lindblad equation (GKSL equation, for Vittorio Gorini, Andrzej Kossakowski, George Sudarshan and Göran Lindblad, created in 1976). It is the most general Markovian master equation describing the time evolution of an open quantum system interacting with its environment.

Linear algebra: branch of mathematics that is used in quantum physics and quantum computing. It is based on the manipulation of vectors and matrices. In the case of quantum physics and computing, we use Hilbert spaces. The state of a sets of qubits is represented by vectors in a Hilbert space of size 2^N when N is the number of qubits. Computing with qubits consists of applying linear transformations to these states.

Linear optics: field of quantum mechanics that manipulates photons based on their classical properties: polarization, phase or frequency.

Lieb-Robinson bound: upper bound on the speed at which information and correlations propagate in a non-relativistic quantum many-body system with local interactions, demonstrated in 1972 by Elliott Lieb and Derek Robinson. It states that the commutator of two observables separated by a distance d is exponentially small outside an effective light cone expanding at a finite Lieb-Robinson velocity v_{LR}. It is the quantum analogue of relativistic causality for lattice systems, without invoking the speed of light. It is related to area laws for entanglement entropy, the exponential clustering theorem, the stability of quantum phases and the locality assumptions behind quantum error correction threshold theorems. Its practical relevance to gate-based quantum computing is bounded by the fact that in a digital circuit the effective light cone is set by gate connectivity and circuit depth rather than by free Hamiltonian evolution.

Light cone: region of spacetime causally connected to a given event. In quantum many-body systems, an effective light cone emerges from the Lieb-Robinson bound, with correlations decaying exponentially outside it. Three distinct light cones matter for a quantum computer: the Lieb-Robinson cone of the free Hamiltonian evolution, the circuit cone set by the depth and connectivity of the gate sequence, and the control light cone set by classical cabling, controller and feedforward latency. The last two usually dominate.

LNOI: Lithium Niobate On Insulator, a photonic substrate where a thin film of lithium niobate sits on an oxide layer. It combines a strong electro-optic effect with low-loss waveguiding, which makes it attractive for fast phase shifters and modulators. Also called TFLN.

Local Friendliness: set of metaphysical assumptions strictly weaker than those of Bell's theorem, the conjunction of absoluteness of observed events, locality and no-superdeterminism, introduced in 2020 by Kok-Wei Bong, Eric Cavalcanti, Howard Wiseman et al. Quantum theory predicts a violation of the associated LF inequalities in extended Wigner's friend scenarios, so at least one of these assumptions has to be false.

Loophole-free Bell test: a Bell inequality test closing simultaneously the detection loophole (enough detected pairs to avoid a biased sample), the locality loophole (space-like separated and genuinely random setting choices) and the freedom-of-choice loophole. First achieved in 2015 in Delft, Vienna and at NIST, and reproduced with superconducting circuits in 2023.

Lorentz factor: the relativistic factor $\gamma = 1/\sqrt{1 - v^2/c^2}$. An electron is conventionally called relativistic when $\gamma \geqslant 2$, corresponding to about 86% of the speed of light. Inner-shell electrons of heavy atoms reach velocities above c/2, which explains the color of gold and the fact that mercury is liquid at room temperature.

LPPT: Loss Per Photon Threshold, the PsiQuantum figure of merit giving the maximum optical loss per photon that a fusion-based architecture can tolerate and still be fault-tolerant. Improved codes raised it from about 1% to 18.8%, at the cost of heavier resource state preparation.

LQG (Loop Quantum Gravity): quantum gravity theory created in the 1980s by Abhay Ashtekar, Carlo Rovelli and Lee Smolin which quantizes space itself into discrete areas and volumes connected by spin networks, the Universe becoming a gigantic spin foam. Contrarily to string theory, it does not attempt to unify all interactions. It is so far without experimental validation.

M-theory: conjectured 11-dimensional theory proposed by Edward Witten in 1995 that would unify the five known superstring theories, which are related to each other by dualities. Its full formulation does not exist yet.

Many-worlds interpretation: the interpretation of quantum mechanics in which the wave function never collapses and every measurement outcome is realized in a branch of a universal wave function. It derives from Hugh Everett's 1957 relative-state formulation and owes its name and its popularity to Bryce DeWitt in the 1970s.

max-LINSAT max-k-XORSAT: constraint satisfaction optimization problems targeted by the DQI algorithm. max-LINSAT maximizes the number of satisfied linear constraints over a finite field, each constraint accepting a subset of allowed values, and max-k-XORSAT is its parity version where each constraint is a XOR of k variables. They are NP-hard in the general case and map onto scheduling, production planning, network flow, paint shop and portfolio allocation with soft constraints.

LLM: large language model. These natural language processing models fueling ChatGPT (GPT), Claude (Opus, Fable), and others. These are classical tools which are not suited for a quantum computing implementation due to the size of the models, which may store trillions of parameters.

Locality (principle): in classical physics, principle according to which distant objects cannot have a direct influence on each other. An object can only be influenced by its immediate environment. This principle, derived from Albert Einstein's special relativity, is put under strain by the violation of Bell inequalities observed experimentally since at least 1982 with photons, in Alain Aspect's famous experiment (with Philippe Grangier and Jean Dalibard). Closing the locality loophole means arranging the timing and the geometry of the setup so that the setting choice and the outcome on one side are spacelike separated from those on the other. The violation does not allow any faster-than-light signaling, since the marginal statistics on each side are independent of the distant setting, which is the no-signaling property. But there are various interpretations of quantum physics which explain entanglement without resorting to nonlocality.

LOCC (Local Operations and Classical Communication): class of protocols where separated parties act only on their own subsystem and exchange classical messages. LOCC cannot create entanglement, but combined with pre-shared entanglement it enables teleportation and teleported gates. It is the natural operating model for distributed quantum computing, where global unitaries across modules are replaced by local unitaries plus a classical channel.

Logical Qubit: an assembly of physical qubits implementing hardware and software quantum error correction. Seen from the software developer's point of view, it creates a virtual logical qubit with a very low error rate. The fidelity of logical qubits depends on the number of physical qubits they contain, the quality of the error correction codes and the qubits fidelity stability with the increase in the number of physical qubits.

Loophole: in quantum physics experiments, refers to a potential flaw or limitation in the experi-mental setup that could allow classical explanations to account for results that appear to support quantum mechanics. They are mentioned in relation to Bell test violation experiments to test non-classicality of entanglement. There are various loopholes like the locality loophole where particles might influence each other faster than light or the detection loophole where inefficient detectors might skew results. These can undermine the validity of tests meant to confirm phenomena like quantum entanglement or violations of Bell's inequalities

LRU: leakage reduction units used in error correction. It is usually a circuit sitting next to a surface code QEC. Aka LRC for leakage reduction circuits (LRCs).

LSTM (Long Short-Term Memory): breed of recurrent neural network using gated memory cells to retain long-term dependencies in sequences, used for time series prediction and natural language processing. Quantum LSTMs are implemented as NISQ variational circuits and are exposed to barren plateaus, with demonstrations limited to small models.

MAGIC: Magnetic Gradient Induced Coupling, technique introduced by the University of Siegen in 2012 which creates a static magnetic field gradient along an ion string. It makes individual ions addressable in frequency space and induces a spin-spin coupling between them, enabling entangling gates driven by microwaves only, with no laser. It is used by eleQtron. The challenge is to create strong and stable magnetic gradients at the very ions location.

Magic: refers to the quantum states or operations that are outside the Clifford group and the stabilizer formalism used in quantum error correction and which are necessary to achieve universal quantum computation and obtain a potential exponential speedup. Entanglement and superposition are not enough to obtain some quantum advantage. The Gottesman-Knill theorem proves that quantum circuits restricted entirely to stabilizer operations (Clifford gates, Pauli measurements, and preparation of computational basis states) can be efficiently simulated on classical computers, despite generating massive amounts of entanglement. To break this classical simulation barrier and enable full universality, non-stabilizer resources collectively termed as magic must be injected into the circuit. In simpler terms, it is all about enabling arbitrary and continuous rotations in the Hilbert space. These rotations can't be implemented with Clifford group gates which cover a discrete number of states in the Hilbert space. In NISQ mode, arbitrary rotation gates enable this. In FTQC, you rely on the creation of T or Toffoli states which can be teleported on logical qubits.

Magic states distillation: protocol that consumes several noisy copies of a magic resource state and outputs a smaller number of copies of higher fidelity, using only Clifford operations and Pauli measurements. These states are what allows non-Clifford gates such as the T gate to be applied fault tolerantly, which is what makes the computation universal. Any algorithmic speedup comes from the algorithm, not from the distillation itself. It is one of the ways to create fault-tolerant quantum computers, but it has a high overhead cost with physical qubits. It was proposed in 2004 by Emanuel Knill, Sergey Bravyi and Alexei Kitaev. It is implemented in a so-called magic state factory. The resulting states are teleported transversally to a target logical qubit.

Magic state cultivation: alternative to magic state distillation proposed by Craig Gidney, Noah Shutty and Cody Jones in 2024, which grows a high-fidelity T state directly inside a small code patch and then expands the patch, instead of consuming many noisy states in a distillation factory. It reduces the spacetime overhead of non-Clifford gates by roughly an order of magnitude compared with 15-to-1 distillation.

Magneto-Optical Trap (MOT): device that captures, cools and confines neutral atoms using three orthogonal pairs of red-detuned, circularly polarized laser beams and a weak quadrupole magnetic field. Doppler shifts provide velocity-dependent damping while position-dependent Zeeman shifts make the radiation-pressure force restoring. A MOT is distinct from a Zeeman slower, which uses a spatially varying magnetic field to keep a decelerating atomic beam resonant with one counter-propagating laser.

Magnon: quasiparticle which is the quantum of a spin wave in a magnetic material, usually a crystalline lattice. Conceptualized by Felix Bloch in 1930 and detected in 1957 by Bertram Brockhouse with neutron scattering. Magnons behave as bosons, can be coupled to microwaves and to superconducting qubits and are used in hybrid quantum sensors.

Majorana fermion: three distinct notions share this name. Ettore Majorana proposed in 1937 a fermion that would be its own antiparticle, a hypothesis still open for neutrinos. In condensed matter, a Majorana zero mode is a quasiparticle excitation localized at the end of a topological superconducting wire or at a vortex, obeying non-Abelian exchange statistics, and it is not a virtual particle. It is this second object that topological quantum computing, pursued at Microsoft, aims to use. Reported experimental signatures, mostly zero-bias conductance peaks, remain contested, and a signature is not by itself proof of a topological qubit.

Manifold: in mathematics, a topological space that locally resembles a Euclidean space, which is the setting for the Bloch sphere and for the state spaces of quantum mechanics. In spectroscopy and in the qubit literature, the word is also used loosely for a level manifold, meaning a set of states grouped by energy or by a shared quantum number. For example, the computational manifold of a spin qubit is made of spin up and down in a given direction. In a superconducting qubit, these are the first energy level of an anharmonic oscillator in a cavity using a Josephson junction. For a photon, it can be its vertical and horizontal polarization. For a qutrit, it can be three level of energy of a given quantum object like an ion.

Markovian process: quantum process where the system's evolution at any given time depends only on its current state and not on its history. It has no memory of the past.

Matchgate circuits: class of nearest-neighbor two-qubit circuits equivalent to non-interacting fermions, which are classically simulable in polynomial time as shown by Leslie Valiant in 2001 and by Barbara Terhal and David DiVincenzo in 2002. They define a classical simulability class distinct from stabilizer circuits and from low-entanglement tensor networks. The number of added non-matchgate gates, named the doping parameter, plays the same role as the T-count for Clifford circuits, quantifying the distance to classical simulability.

Matrix: mathematical object made of rows and columns of values.

Matter wave: principle of quantum physics enacted by Louis De Broglie in 1924 according to which massive objects can also behave as waves. The De Broglie wavelength of a massive particle is the Planck constant divided by its momentum.

MAXCUT: graph partitioning problem where the goal is to divide the vertices of a graph into two distinct subsets such that the number (or weight) of edges between the two subsets is maximized.

Maxwell's demon: thought experiment proposed by James Clerk Maxwell in 1867 where an entity observing individual molecules and operating a frictionless trapdoor would seemingly decrease the entropy of a gas and violate the second law of thermodynamics. The paradox is resolved by accounting for the energetic cost of the information acquired and erased by the demon, at the Landauer limit. Its quantum versions are an active research topic in quantum thermodynamics, including autonomous implementations with qubits and cavities.

MBE: molecular beam epitaxy, a variety of PVD process (thin-film deposition), used to create a single orderly crystal structure in semi-conductor manufacturing. Is notably used to produce semiconductor quantum dots in III/V materials.

MBQC: Measurement Based Quantum Computing, a quantum computing method invented in 2001 by Robert Raussendorf and Hans Briegel that uses a high number of groups of pre-entangled qubits, called cluster states, embedded in two-dimensional grids in which qubit state readouts modify the grid structure and help create quantum gates. The last measured qubit gives the result of the algorithm. This technique is particularly useful with flying qubits like photons because it can be implemented in a highly parallel way and support the finite depth of quantum gates that these qubits enable.

MCMC (Markov Chain Monte Carlo): family of classical sampling algorithms exploring a probability distribution with a Markov chain, used in optimization, statistical physics and machine learning. It is both a classical baseline that quantum optimization algorithms must beat, notably against DQI, and the target of quantum-enhanced variants where a quantum proposal step accelerates the thermalization of the chain.

MCMR: mid-circuit measurement and reset, combining a qubit readout in the middle of a circuit with the reinitialization of that qubit for reuse. It is required for quantum error correction, measurement-based state preparation and qubit recycling. With trapped ions, it usually involves shuttling the measured ions to a dedicated zone so that the readout fluorescence does not hit the neighboring data qubits.

MDI-QKD: Measurement-Device-Independent Quantum Key Distribution. QKD architecture in which Alice and Bob send states to a central measurement station that can be fully untrusted. It removes detector-side-channel assumptions at the relay while retaining assumptions about state preparation at the users.

MegaQuop: term coined by John Preskill designating a quantum computer able to run about one million reliable quantum operations, hence a logical error rate around 10^{-6}. It describes an early fault-tolerance regime sitting between NISQ and large-scale FTQC. GigaQuop and TeraQuop machines are the following steps.

Meissner effect: expulsion of the magnetic field from the inside of a superconductor when it is cooled below its critical temperature, discovered in 1933 by Walther Meissner and Robert Ochsenfeld. It is not a mere consequence of zero resistance, since a perfect conductor would trap the flux instead of expelling it. It is complete in type I superconductors and only partial in type II ones above their lower critical field.

MERA (Multiscale Entanglement Renormalization Ansatz): hierarchical tensor network created by Guifré Vidal in 2007 which alternates disentanglers and isometries across successive coarse-graining layers. Its scale-invariant structure fits critical systems whose entanglement grows logarithmically with the subsystem size, contrarily to MPS which are limited to area law states.

Mesoscopic: subdiscipline of condensed matter physics that deals with materials of an intermediate size. The size ranges from a couple atoms to a μm.

Metaheuristic algorithm: type of algorithm used to find approximate solutions to optimization problems. They are relevant when the exact solution is too computationally expensive to find. It works by iteratively improving a solution until it is good enough to be considered the final answer. There are many different types of metaheuristics, each with their own strengths and weaknesses. Some of the more popular metaheuristics include simulated annealing, genetic algorithms, and particle swarm optimization. They are used for solving optimization problems. They can sometimes find sub-optimal solutions. There are classical and quantum versions of metaheuristics.

Metal layers: in semiconductor chips, correspond to the layers containing wires connecting the various transistors and other electronic elements. These layers are surrounded by some insulator (silicon oxide or other). In typical CMOS processors, you have over 12 metal layers of decreasing density as you move father from the logic layer, In superconducting qubits, you have no metal layers on top of the Josephson junctions since it must be as isolated as possible.

Metasurface: engineered surface patterned with subwavelength structures that modifies properties such as optical phase, amplitude, polarization and propagation in a thin element. A conventional passive metasurface does not dynamically change the optical frequency. In neutral-atom systems, holographic metasurfaces can generate very large static tweezer arrays, while dynamic rearrangement requires an additional active optical element or a tunable metasurface.

Microring resonator: tiny optical waveguides looped back onto themselves in circle or spiral which enable interference phenomena, the creation of delay lines, and various other optical devices used for example in entangled photon generation.

Mid-circuit measurement: measuring one or more physical or logical qubits during the execution of a quantum circuit. Outside of quantum error detection and error syndrome extraction, it serves as an algorithmic control tool, a hardware resource optimizer, and an execution primitive. It is used in dynamic feed-forward and conditional logic where the classical bit produced by the readout help determine subsequent unitary operations. It can serve for qubit reuse and to teleport quantum states across registers, perform entanglement swapping, or generate target states such as GHZ or W states. Algorithmically wise, mid-circuit measurement is also a way to introduce non-linearity in the process, which can help in solving non-linear partial differential equations.

MIS (Maximum Independent Set): graph problem searching the largest set of vertices with no edge between any two of them. It is NP-hard and it maps natively onto neutral atom analog QPUs thanks to the Rydberg blockade, which naturally forbids two neighboring excited atoms, for the unit disk graph variant (UD-MIS). More general graphs require embedding schemes with extra qubits.

Microwave-to-optical transduction: coherent conversion of a microwave photon, the quantum carrying medium of superconducting qubits, into a telecom or optical photon that can travel in a fiber, and back. It is the enabling brick for networking superconducting QPUs over distance. Implementations use electro-optic (Pockels) coupling, piezo-optomechanical resonators, or rare-earth ion doped crystals. Efficiencies reached the percent level by 2025, with added noise close to one photon, which is still far from what entanglement distribution at scale requires.

Mixing chamber: the coldest component of a dilution refrigerator, where the helium 3 rich concentrated phase floats on the helium 3 poor dilute phase and where helium 3 atoms cross the phase boundary, an endothermic process which produces the cooling. Its cooling power follows $\dot{Q}_m = 84\,\dot{n}_3 T^2$ with $\dot{n}_3$ the helium 3 molar flow rate in mol/s and T in Kelvin, which is why the available budget is only 12 to 34 μW at 20 mK against 250 to 2,000 μW at 100 mK. The plate attached to it is the mixing chamber cold plate, where the quantum processor sits.

Moore's law: empirical observation published by Gordon Moore in 1965, based on five data points, predicting a doubling of the number of components per integrated circuit every year, which he revised to every two years in 1975. The frequently quoted 18 months variant comes from David House at Intel and refers to performance, not to component count. Transistor counts per chip still follow the trend, while single-thread performance, clock frequency and power per chip stalled around 2005 with the end of Dennard scaling. There is no equivalent law for qubits, since qubit fidelities and other figures of merit do not improve exponentially.

More than Moore: extension of Moore's law focused on functional diversification rather than on density, integrating sensors, RF, power management and other non-digital functions in a single chip or package, along with heterogeneous integration and new materials.

MRAM: Magnetoresistive Random Access Memory, non-volatile memory storing bits in the relative magnetization of two ferromagnetic layers separated by a tunnel barrier, switched by spin-transfer or spin-orbit torque. It is used in embedded caches and stacked on top of processing cores in 3D chiplet architectures.

MZI: Mach-Zehnder Interferometer, an optical circuit splitting a beam into two arms with a controllable relative phase before recombining them. In photonic quantum processors, a mesh of MZIs with tunable phase shifters implements an arbitrary programmable unitary on the spatial modes. Transmittance per MZI, currently around 90% to 95%, is a limiting figure of merit.

Mølmer-Sørensen gate: or MS gate, two-qubit entangling gate for trapped ions created by Klaus Mølmer and Anders Sørensen in 1999, applying bichromatic laser or microwave fields to the ions, coupling their internal spin states to their collective motional or vibrational modes and creating entanglement between them without needing to cool them to the motional ground state. It is the workhorse two-qubit gate of most trapped ions vendors and can entangle more than two ions at once.

Motional mode: quantized normal mode of the collective motion of a trapped-ion crystal. A chain of N ions has $3N$ normal modes in three dimensions. Their quanta are phonons and selected modes are used as a quantum bus for entangling gates.

Micromotion: driven motion of an ion at the radio-frequency trapping frequency in a Paul trap, superimposed on the slower secular motion. Ideal micromotion is intrinsic to RF confinement, while excess micromotion from stray fields displacing the ion from the RF null degrades spectroscopy and gate fidelity and must be compensated.

MNR: Metric-Noise-Resource, the first methodology proposed to assess the energetic performance of quantum technologies, created in 2021 by Marco Fellous-Asiani, Alexia Auffèves, Robert Whitney et al. It connects an algorithmic metric to reach, the noise affecting the qubits, and the macroscopic resources spent to fight that noise, and it looks for the parameter regimes that minimize energy consumption under the constraint of reaching a target computational performance. It focuses on the physics parts of computing and does not yet cover algorithms, compilation and software engineering.

Mode-locked laser: pulse laser generating streams of very short pulses of light formed of wave-packets in the picosecond to femtosecond range. These pulses are generated thanks to the emitted photons being synchronized in phase. A synonym of mode-locked is phase-locked!

Mott insulator: material that are expected to conduct electricity but are insulators, particularly at low temperatures, and under certain conditions which can be controlled, leading to so-called Mott transitions.

Mott transition: change in a condensed matter material's behavior from insulating to metallic generated by multiple factors like and ambient electric field changing the band structure of the material like with some metal oxides.

MPO (Matrix Product Operator): operator version of an MPS, representing an operator acting on a chain of sites as a product of rank-4 tensors. It is used to encode Hamiltonians, noise channels and time evolution operators in tensor network simulations, and to bound the classical simulability of shallow circuits in the Heisenberg picture.

MPS (Matrix Product State): one-dimensional tensor network where the state of n qubits or sites is written as a chain of rank-3 tensors. It represents states with bounded entanglement with a number of parameters growing linearly in n and quadratically in the bond dimension χ, instead of exponentially. It is exact for ground states of gapped one-dimensional Hamiltonians which obey an area law, and it is the workhorse of quantum circuit emulation, of DMRG and of many quantum inspired algorithms. Its quantum version, qMPS, embeds an MPS structure in a variational quantum circuit.

MVP: Minimum Viable Product. Concept used mostly in startups consisting of creating the simplest form of a product before starting to sell it. Opposite to full-fledged product with tons of R&D and an ever-lasting perfectionist approach.

MINLP: Mixed Integer Non Linear programming, a class of complex problems that can potentially be solved with quantum algorithms. It is about finding the minimum(s) of nonlinear functions and under constraints that aim to respect nonlinear functions. The variables in the equation are a combination of integers and floating-point numbers. The applications are numerous in all cases where one seeks to optimize a constrained function (energy distribution, optimum take-off of an aircraft, optimization of financial portfolio, minimizing risk in insurance or credit, etc.).

Mixed state: quantum objects state that is a classical statistical combination of several pure states. They can be prepared by physically associating several sources of pure states, like merging two laser beams in one beam. A subsystem of an entangled quantum objects system is also a mixed state. A mixed state is mathematically represented by a density matrix operator, providing all the information that can be obtained about the related quantum system.

MNIST: Modified National Institute of Standards and Technology database, a large database of handwritten digits that is used for training various machine learning systems including quantum machine learning algorithms. It contains 60,000 training 28×28 pixel images and 10,000 testing images. Created in 2017, Fashion MNIST consists of 70,000 28×28 grayscale images of fashion products from 10 categories. Recognizing these images is more challenging than with MNIST images. Classical error rates obtained with classical convolutional neural networks is about 25%.

Modality: in the CSM interpretation, a measured property attributed jointly to a system and to its context, and not to the system alone. Within the usual quantum formalism, a modality is a pure state and a context implements a complete set of commuting observables (CSCO), with N mutually exclusive modalities per context, N being the dimension of the system and being independent from the context.

Momentum: physical property of an object or particle that for a massive particle is equivalent to its mass multiplied by its velocity. Usually denoted p. A photon, although massless, carries a momentum $p = h/\lambda = \hbar k = E/c$, inversely proportional to its wavelength.

Multimode: said of an optical fiber with a larger core (about 50 to 62 μm) where several light beams can be transported, usually with different wavelengths. Light propagation uses bouncing inside the fiber walls. These fibers are used for short distances communications of less than a kilometer and with bit rates reaching 200 GBit/s. The contrary of multimode fibers are monomode fibers. Also said of multimode photons, with an entirely different meaning. Modes here are the orthogonal solutions of the field, labeled by frequency, polarization, transverse profile or arrival time. A single-mode photon populates one such mode, while a multimode single photon is spread over several. That spread is a coherent superposition, and therefore a pure state, whenever the relative phases are well defined. It becomes a statistical mixture only under incoherent preparation or when correlated degrees of freedom are traced out, and that distinction is what governs the interference visibility between two sources.

Muonic atoms: atoms like hydrogen where the electron is replaced by a muon, which has the same electric charge and spin ½ but a mass 207 times larger and a smaller magnetic moment. Its lifetime is very small, about 2.2 μs when free and shorter when bound. Three processes must be distinguished: the atomic cascade of the muon toward the lowest orbitals, which emits characteristic X rays; the weak decay of the muon into an electron and two neutrinos; and nuclear capture, in which the muon is absorbed by a proton of the nucleus, a channel whose rate grows steeply with atomic number. Muons are generated in high-energy particle accelerators. They can help study the structure of atom nucleus. A muonic atom like muonic hydrogen is an atom where the electrons are replaced by muons. Muonic helium has one of its electrons replaced by a muon, whose orbit is about 200 times smaller, so its wave function overlaps the nucleus substantially, which is what makes these atoms a probe of the nuclear charge radius, without the muon being inside the nucleus.

Mutually unbiased bases: it is a concept mostly used in quantum key distribution. Bases is a set of orthogonal vectors in a Hilbert space. Mutually unbiased bases are two bases where the measurement of one of the vectors of one basis will yield a random result on the other base.

Nanosheet: transistor architecture where the channel is made of several stacked horizontal sheets of silicon, typically three of about 4 to 5 nm thickness, entirely surrounded by the gate. It succeeded FinFET at the 2 nm class nodes and its sheet thickness is one of the very few features that actually matches the nanometer figures used in node marketing names.

NDR: Nuclear Demagnetization Refrigeration, a demagnetization technique using nuclear spins in copper or $PrNi_5$ instead of the electronic spins used in ADR. Precooled by a dilution refrigerator, it reaches temperatures below 1 mK, down to 0.16 mK in dry setups, with a cooling budget in the tens of nW. It is used for condensed matter physics experiments, not for solid-state qubits which do not need to go below 10 mK. Its continuous version is noted cNDR.

NEMS (Nano Electro-Mechanical Systems): mechanical resonators and actuators at the nanometer scale, the smaller cousins of MEMS (Micro Electro-Mechanical Systems). They are used in quantum metrology, in optomechanics and in Casimir force measurements, and can be cooled to their motional ground state.

NFQC: Near-Field Quantum Control, approach used by Qudora which embeds the microwave and oscillating magnetic field sources directly inside the ion trap chip, close to the ions, including for qubit readout. It removes the need for individually addressed laser beams for gate operations.

NISQ: Noisy Intermediate-Scale Quantum, a name for current and near future gate-based quantum computers, which are intermediate in terms of number of qubits (a few tens to hundreds) and subject to quantum noise that limits their capabilities. This acronym was created by John Preskill.

No-go theorem: theorem that demonstrates that a physical phenomenon is not possible. In quantum physics, famous no-go theorems are Bell's theorem and the Kochen–Specker theorem which constrain hidden variable theories trying to explain nonlocality and entanglement with an underlying deterministic model featuring hidden states and variables. You also have the no-cloning and no-deleting theorems which prevent the cloning and deletion of a quantum object state.

Non-Clifford gates: said of quantum gates outside the Clifford group, the group of unitaries normalizing the Pauli group, a standard generating set of which is H, S and CNOT. Being non-Clifford does not mean being an arbitrary rotation: what matters is that Clifford circuits alone are classically simulable and not universal, so a non-Clifford resource has to be added. The single qubit T gate (one eighth turn in Bloch's sphere) is the minimum additional gate, that, combined with the others, enable by approximation the creation of any arbitrary gate and unitary transformation.

No-cloning theorem: theorem stating that no physical operation can perfectly copy an arbitrary unknown quantum state while leaving the original unchanged, that is, no universal transformation can map $|\psi\rangle|0\rangle$ to $|\psi\rangle|\psi\rangle$ for every $|\psi\rangle$. It does not say that every attempted copy must destroy the original. Orthogonal states or states drawn from a known distinguishable set can be copied after suitable measurement or control.

No-signaling: principle stating that the choice of a local operation or measurement on one part of a multipartite quantum system cannot change the unconditional measurement statistics observed at a spacelike-separated part. Entanglement can therefore produce nonlocal correlations but cannot by itself transmit controllable classical information faster than light.

Nonlinear optics: field of optics where the optical properties of materials depend on the light amplitude and lead to the creation of new frequencies. Nonlinearity qualifies the response of a medium to an excitation that is generally quite energetic from intense fields, mainly from lasers, especially femtosecond pulsed lasers. In this case, the response of a material to the sum of two electromagnetic fields is not equal to the sum of the response to each individual field. Nonlinear optics can be used to create two-photon quantum gates with continuous variables photons. See also Chi.

Nonlocality: property of quantum correlations that cannot be reproduced by local hidden-variable models, as demonstrated by Bell-inequality violations. Entangled systems can exhibit correlations over arbitrary separation that are stronger than any local classical model allows, but the local outcomes remain intrinsically random and obey the no-signaling principle. Quantum nonlocality therefore does not enable controllable faster-than-light communication.

Non-Markovian process: refer to the dynamics of a quantum system where the system's future evolution depends on its past states. It means there is some memory effect in the system-environment interaction.

NMR: Nuclear magnetic resonance, a type of qubit that was investigated in the 1990s and early 2000s and was then nearly abandoned. The reason is it didn't scale well at all and these were very noisy qubits and difficult to entangle. It was based on exploiting quantized states of atoms nuclei spins. However, the Chinese startup SpinQ is offering a desktop NMR-based quantum computer with 2 to 5 qubits. It is useful only for educational tasks.

Non-classical light: forms of light and electromagnetic fields treated as quantum systems. It contains single photon wave packets, pairs of entangled photons and squeezed states of light.

Non-demolition measurement: see QND.

Non-selective measurement: measurement that is physically done but not yet read. Its outcome is not available either because it wasn't yet used or because it is inaccessible when measurement is done by the environment.

NOON state: many-body entangled state superposing N quantum objects, usually bosons, in two modes. Namely, it superposes all the objects in one mode and all the objects in the other mode. This kind of superposition is used in quantum metrology to obtain a precision reaching the Heisenberg limit, which is better than a standard quantum limit based measurement.

Noether's theorem: result established by Emmy Noether in 1918 according to which every continuous symmetry of a physical system action corresponds to a conserved quantity. Invariance under time translation gives energy conservation, under space translation gives momentum, and under rotation gives angular momentum. Its quantum counterpart is that an observable commuting with the Hamiltonian is a constant of the motion. It is exploited in quantum simulation when a computation is restricted to a fixed particle number or fixed total spin sector, which shrinks the Hilbert space that has to be explored, and in variational algorithms where symmetry-preserving ansatze avoid wandering into unphysical states.

Normalization: in quantum physics, normalization is used in many situations like with scaling wave functions so that the sum of probabilities equal one. This 1 is considered as a normalization constant or constraint. Born's rule is a normalization constraint.

NP (problem class): class of decision problems whose candidate solution can be verified in polynomial time relative to the size of the instance, equivalently solved in polynomial time by a nondeterministic Turing machine. It is not defined by an exponential solution time, and it contains all of P, so many NP problems are easy. Whether NP contains problems requiring superpolynomial time is the open P versus NP question, and whether a quantum computer can solve NP-complete problems efficiently is also open, BQP being believed not to contain NP-complete problems.

NP-complete (problem class): decision problem for which it is possible to verify a solution in polynomial time and for which all problems of the NP class are reduced to it via a polynomial reduction. This means that the problem is at least as difficult as all other problems of the NP class. The decision versions of the traveling salesperson and knapsack problems, asking whether a solution of cost at most k exists, are NP-complete, while their optimization versions are NP-hard. The concept dates from 1971 and comes from Stephen Cook.

NP-hard (problem class): problem to which any problem of the NP class can be reduced by a polynomial reduction. It need not be a decision problem, and it need not be in NP. If it is also in NP, it is NP-complete. If P $\neq$ NP, then no NP-hard problem can be solved in polynomial time. The French "NP-difficile" translates as NP-hard, not NP-difficult.

NQS (Neural Quantum States): variational wave function ansätze parameterized by a classical neural network, introduced by Giuseppe Carleo and Matthias Troyer in 2017 with restricted Boltzmann machines, and later extended to autoregressive models and transformers. They are optimized with variational Monte Carlo sampling and they are, with tensor networks, the main classical competitor of VQE for ground state search. Their expressivity is bounded, with entanglement entropy scaling like O(k log n) for feed-forward architectures with k nonlinearities on n spins.

NV center (nitrogen–vacancy center) is a point defect formed by a substitutional nitrogen atom next to a missing carbon atom in a diamond. This defect traps an extra electron, giving it well-defined spin states that can be initialized, manipulated, and read out optically at room temperature. It has very good quantum coherence and sensitivity to magnetic and electric fields, making it a solid-state platform for quantum sensing, quantum communication, and, potentially, quantum computing.

Observable: equivalent in quantum mechanics of a physical quantity in classical mechanics, such as position, momentum, spin or energy. In quantum physics, an observable is a mathematical operator used for the measurement of one property using its quantum state description.

ODE (Ordinary Differential Equation): differential equation involving a function of a single variable and its derivatives. Quantum solvers reduce them to linear systems handled with a QLSA, or use LCHS, Schrödingerization or variational schemes. Nonlinear ODEs first require a linearization, generally with the Carleman method. Exponentially small amplitudes in the solution frequently make quantum ODE solvers exhibit exponential runtimes in practice.

ODMR: Optically Detected Magnetic Resonance, a double-resonance technique in which the spin state of a defect such as an NV center is optically initialized and read through spin-dependent fluorescence while a microwave field drives spin transitions. A magnetic field shifts the resonance frequencies through the Zeeman effect. ODMR is widely used for NV-center magnetometry, thermometry and related sensing. Sensitivity is commonly quoted in $\mathrm{T}/\sqrt{\mathrm{Hz}}$ and varies by many orders of magnitude with sensor volume, spatial resolution, bandwidth and collection efficiency.

OFHC: Oxygen-Free High thermal Conductivity, the grade of 99.99% pure copper with a very low oxygen content used for cryostat cold plates and thermal links. Removing the oxygen raises the residual resistivity ratio and hence the low temperature thermal conductivity, which is what allows a plate to thermalize the components bolted onto it.

On-premise: said of hardware that sits in a user site or datacenter. It is the opposite of sitting in a datacenter from a cloud vendor. Often simplified as 'on prem'.

Ontology: branch of philosophy dealing with what exists, with the types and structures of objects, properties, events, processes and relationships. Classical physics comes with an intuitive ontology of positions and motions, while quantum physics was built as a predictive formalism without one, which is what the various quantum interpretations are trying to fix.

OPA: Optical Parametric Amplifier, a nonlinear device that amplifies one quadrature of an optical field while attenuating the other. It generates squeezed states and can serve as a homodyne detector for continuous variable qubits.

Opex: operational expenditure, the recurring running cost of a system. For a QPU it includes electricity, cooling, helium, maintenance and operators. Energy can represent over 30% of the TCO of an FTQC system. It is opposed to capex.

Operator norm: for an operator O, the quantity $\|O\| = \sup_{\|\psi\|=1} \|O\psi\|$, meaning the largest length by which O can stretch a unit vector. It measures the maximum strength of an operator's action, independently of any particular state. It is the quantity appearing on both sides of the Lieb-Robinson bound, which is why that bound is relative to the magnitude of the observables involved and not an absolute count of bits.

OPO: Optical Parametric Oscillator, an OPA placed inside a cavity so that it oscillates above a pump threshold. It is the workhorse squeezed-light source of continuous variable photonics and the spin element of coherent Ising machines.

OTOC (Out-of-Time-Ordered Correlator): correlation function of the form $\langle W^\dagger(t)V^\dagger W(t)V\rangle$ which measures how much a local perturbation V affects a distant observable W after a time t. It is the standard experimental probe of information scrambling and of the light cone, since it is directly related to the squared norm of the commutator bounded by the Lieb-Robinson inequality. Measured on trapped ions in 2019, on a superconducting lattice in 2022, and used at scale by Google in its 2025 Quantum Echoes experiment.

Optical molasses: laser-cooling configuration in which three orthogonal pairs of counterpropagating red-detuned beams create, through the Doppler effect, a velocity-dependent radiation-pressure force that damps the atomic motion. Nothing holds the atoms together and there is generally no spatial confinement, hence the need to add a magnetic gradient to obtain a magneto-optical trap. The viscous analogy refers to the damping force, not to cohesion.

Optical pumping: technique used to modify the states of atoms by increasing their energy level using polarized photons. Alfred Kastler, invented it in 1950 and was awarded the Nobel prize in Physics in 1966. The technique is used in lasers and quantum sensing. Optical pumping passes through three to four energy levels of atoms (E0, E1, E2, E3). Pumping moves an atom from its fundamental level E0 to E3. A (mechanical) relaxation brings the atom back from the E3 state to E2. In lasers, this generates a population inversion between the E1 and E2 states, so that there are more atoms in the E2 state than in the E1 state. The spontaneous and stimulated emission of photons of E2-E1 energy can then take place. The atom in the E1 state then returns to the E0 state by relaxation. **Optical qubit**: trapped ion qubit encoded in a ground state and a long-lived metastable excited state connected by a quadrupole or octupole transition in the visible or near infrared, like the $S_{1/2}$-$D_{5/2}$ transition at 729 nm for $^{40}Ca^{+}$ used by AQT. Its coherence time is bounded by the metastable state lifetime, of about a second, and its control requires a very narrow linewidth laser.

Optical tweezer: tightly focused far-detuned laser beam that traps a neutral atom through the optical dipole force. Arrays of tweezers can be generated and rearranged with SLMs, AODs, microlens arrays or metasurfaces and are a central hardware element of neutral-atom quantum processors.

Oracle: black-box function embedded in a quantum circuit as a reversible unitary. An oracle acts coherently on a superposition of computational-basis inputs, so the resulting amplitudes can interfere, but this does not provide simultaneous classical access to all function values. Depending on the algorithm, the oracle can write a function value into an ancilla register or mark selected states through a phase. It is used in the Deutsch-Jozsa, Bernstein-Vazirani, Simon and Grover algorithms. Its cost in gates, depth and ancilla qubits is often abstracted away in query-complexity comparisons, although it can dominate the practical cost of an implementation. An oracle separation therefore does not automatically imply an end-to-end real-world speedup.

Orbital angular momentum (OAM): is a quantum number for electrons, nucleons and photons. With electrons, it describes in a quantized manner the shape and size of the subshell where the electron sits. It has a different meaning with photons. Discovered in 1992 by Les Allen et al. from Leiden University, photon OAM is more difficult to visualize than spin angular momentum. Photon OAM is a property of the spatial mode, not a rotation of the particle. A paraxial beam carrying an azimuthal phase $e^{i\ell\varphi}$, such as a Laguerre-Gaussian mode, has a helical wavefront and carries $L_z = \ell\hbar$ per photon, where the integer ℓ is the topological charge and is unbounded in principle. Record values reported in the literature reach several thousand, and any figure quoted should come with its source and its date. Being quantized, it can lead to superposition and entanglement. It can also be used to encode information on fibers.

Oscillator: see harmonic oscillator and anharmonic oscillator.

Overhauser field: effective magnetic field created at an electron spin by the surrounding nuclear spins in a solid. In quantum dots it is the dominant source of spin dephasing and must be neutralized or averaged out to extend the spin coherence time.

P (problem class): problem that can be solved in polynomial time with respect to its size, on a deterministic Turing machine.

Paramp: parametric amplifier using a parametric nonlinearity and a pump wave. Paramps exist for photos in the visible spectrum (these are OPA for optical parametric amplifiers) as well as for microwaves. In this last case, they are used to amplify readout microwaves from superconducting or silicon spin qubits. The most recent breed of paramps are the TWPAs.

Paul trap: ion trap developed by Wolfgang Paul and collaborators in the 1950s, with early three-dimensional realizations around 1954-1955. It confines charged particles with radio-frequency quadrupole electric fields, often combined with static endcap or segmented-electrode potentials, without requiring a magnetic field for radial confinement. Paul received the 1989 Nobel Prize in Physics for the development of the ion-trap technique.

Pauli (exclusion principle): states that two identical fermions cannot occupy the same one-particle quantum state, which follows from the antisymmetry of the total wave function under exchange of two identical fermions. The quantum state is specified by the full set of quantum numbers, including spin, and not by position and energy alone. This is what makes the degeneracy pressure of white dwarfs and neutron stars, and what forces electrons to fill successive atomic shells. Fermions have half-integer spin, measured in units of the reduced Planck constant $\hbar$.

Pauli spin blockade: spin-to-charge conversion mechanism in a double quantum dot. The Pauli exclusion principle blocks a selected interdot charge transition for a triplet-like two-electron spin configuration while allowing the corresponding singlet-like transition. A charge sensor can then distinguish the spin configurations electrically.

Pauli string: tensor product of single qubit Pauli operators (I, X, Y, Z) acting on a n qubits register. Any Hamiltonian can be decomposed into a weighted sum of Pauli strings, which is the input format of VQE, of LCU based block-encodings and of Trotterized Hamiltonian simulations. The number of Pauli strings, which scales in $O(N^4)$ with the number of orbitals N in quantum chemistry, drives the number of measurements and is a key cost driver of variational algorithms. Grouping commuting Pauli strings reduces the shot count.

PBR theorem: from Matthew Pusey, Jonathan Barrett and Terry Rudolph in 2012 [900], a psi-ontology theorem showing that, under a preparation independence assumption, the quantum state cannot be a mere statistical description of some underlying real state, which rules out a broad class of psi-epistemic models.

PCA (Principal Component Analysis): dimensionality reduction technique extracting the eigenvectors with the largest eigenvalues of the covariance matrix of a data set. Its quantum version qPCA was proposed by Seth Lloyd, Masoud Mohseni and Patrick Rebentrost in 2014 with an exponential speedup claim which assumes a qRAM and low-rank data, and which was dequantized by Ewin Tang and followers.

PDE (Partial Differential Equation): equation involving an unknown multivariable function and its partial derivatives, like the heat, wave, Poisson, Navier-Stokes and Schrödinger equations. Quantum solvers discretize the PDE with finite differences or finite elements and turn it into a linear system solved with a QLSA, or use LCHS, Schrödingerization, quantum lattice Boltzmann, quantum physics informed neural networks or variational solvers. Initial state preparation and the readout of the full solution field are the recurring end-to-end bottlenecks.

PDK: Process Design Kit, the package a foundry provides to circuit designers, containing device models, validated building blocks, design rules, a verification deck and process parameters. A mature photonic PDK is a prerequisite for outsourcing quantum photonic chip production.

Penning trap: charged-particle trap combining a static electric quadrupole potential with a strong static magnetic field. Its name refers to Frans Penning's earlier magnetron work and the trap was developed for precision charged-particle experiments by Hans Dehmelt and others. Dehmelt built a high-vacuum magnetron/Penning trap in 1959, while the first isolated single electron was trapped in 1973. Penning traps avoid RF trapping micromotion and are being revisited for two-dimensional microtrap arrays.

PEPS (Projected Entangled Pair States): two-dimensional generalization of MPS created by Frank Verstraete and Ignacio Cirac in 2004, where tensors sit on a lattice with one index per neighbor. It represents 2D area law states, which makes it well suited to simulating 2D quantum circuits and lattice models, but its exact contraction is exponential and requires approximate schemes. TPS (Tensor Product States) denominates a closely related family.

Permanent: matrix function defined for an $n \times n$ matrix A as $\mathrm{per}(A) = \sum_{\sigma \in S_n} \prod_i A_{i,\sigma(i)}$, that is, the determinant without the alternating signs. It can be complex. Its exact evaluation is #P-hard, it counts perfect matchings in bipartite graphs, and it gives the transition amplitudes of boson sampling experiments, which is where its relevance to quantum computing comes from.

Phase Estimation Algorithm: algorithm introduced by Alexei Kitaev for estimating an eigenphase θ of a unitary U from $U|\psi\rangle = e^{2\pi i\theta}|\psi\rangle$, provided the input state has overlap with the relevant eigenstate. Textbook QPE uses controlled powers U^{2^k} followed by an inverse QFT on a phase register. Resolving phase to additive error δ requires total coherent controlled-unitary evolution or query cost of order $1/\delta$, with an additional logarithmic factor when the failure probability must be strongly suppressed. QPE is used in Shor order finding, Hamiltonian eigenvalue estimation and many fault-tolerant algorithms.

Phase: an important physical property of quantum objects given they all can behave as waves. It explains interferences between all sorts of quantum objects, like electrons on top of photons. Phase is a continuous quantum property.

Phase classification: systematic categorization of different quantum phases of matter, the distinct states that quantum systems can occupy, especially at 0K. These phases are defined not just by symmetry as in classical physics, but also by topological and entanglement properties that are uniquely quantum. Examples of phases are quantum spin liquids, topological phases and Landau-ordered phases like ferromagnetism and superfluidity.

Phase kickback: mechanism where the phase created by a controlled unitary applied on a target register in one of its eigenstates is transferred back to the control qubits, which carry the useful information at the end of the computation. It is the complement of oracle-based marking and it is at the heart of the Deutsch-Jozsa, Bernstein-Vazirani, Grover and quantum phase estimation algorithms.

Phase space: mathematical framework used to describe the complete state of a physical system by combining its position and momentum coordinates. In classical mechanics, each point in phase space represents a unique state of the system. In quantum physics, it treats position x and momentum p as non-commuting variables, meaning they cannot be simultaneously known with arbitrary precision due to the Heisenberg uncertainty principle. Instead of a probability distribution, quantum systems are described by quasiprobability distributions like the Wigner function, which can take negative values reflecting quantum interference and non-classical behavior. In quantum physics, phase space can be generalized to describe any pair of complementary, or conjugate, variables like energy and time, photon number and optical phase or spin components in different orthogonal direc-tions.

Phasor diagram: two-dimensional diagram describing electromagnetic field quadratures positioning the statistic characteristics of a photon source, with X1 and X2 orthogonal axis corresponding to two oscillating electric fields that are out of phase by 90°.

Phonon: collective excitation in a periodic, elastic arrangement of atoms or molecules in condensed matter, specifically in solids and some liquids. In quantum information technologies, it is mostly used with trapped ions to provide a n-to-n connectivity between qubits. A phonon is a quantized normal mode of the vibration of the lattice itself, carried by the motion of the nuclei, which provide both the framework and the mass. Electrons are not what constitutes a phonon, but they couple strongly to them, and this electron-phonon coupling is what governs electrical resistivity, conventional superconductivity and much of the decoherence of solid-state qubits.

Photoelectric effect: emission of electrons from a material like a metal when electromagnetic radiation above a certain minimum frequency strikes it, independently of its intensity. Formalized by Albert Einstein in 1905.

Photoionization: process removing an electron from a neutral atom with photons to create the ion which is then trapped, using 423 nm with calcium at AQT. It is more isotope-selective and less polluting for the trap electrodes than electron impact ionization.

Photolithography: patterning process in semiconductor manufacturing used to define in which zones matter must be removed or added in subsequent steps. It uses ultraviolet rays illuminating a photomask that exposes a photoresist film or coating. For very high densities, the exposure is done with extreme ultra-violet waves. The related manufacturing tools are now produced by a single company in the world, ASML (the Netherlands).

PIC: Photonic Integrated Circuit, a chip integrating waveguides, beam splitters, phase shifters and sometimes photon sources and detectors, replacing an optical table with a few square millimeters of silicon, silicon nitride, lithium niobate or III-V material. The key figure of merit is propagation and coupling loss.

PIM (Processing In Memory): classical architecture placing compute units inside or next to the memory array to avoid moving data to the processor, as with UPMEM's DRAM Processing Units, proprietary 32-bit RISC cores paired one per 64 MB DRAM bank. A quantum processor is natively an in-memory processing machine, since gates are applied directly on the qubit register holding the data.

Photon: quantum of energy associated with electromagnetic waves ranging from radio waves (long waves, low frequencies) to gamma rays (very short waves, very high frequencies) through visible light. Its mass is zero. It is a spin-1 boson, and being massless it has only the two helicity states ± 1 along its direction of propagation, which correspond to the two circular polarizations, with no zero-helicity state. Photons are absorbed and emitted by atoms during transitions between energy levels.

Photon measurement: measurement of a photon where the degree of freedom is the excitation quanta. A photon-number measurement counts quanta but says nothing about the field phase. Other degrees of freedom have their own detection schemes: spectrometers and time-resolved detection for frequency and arrival time, polarization analyzers, and homodyne or heterodyne detection for the field quadratures and hence the phase.

Pilot wave: the deterministic interpretation of quantum mechanics proposed by Louis de Broglie in 1927 and revived by David Bohm in 1952, in which particles have definite trajectories guided by a wave. It is explicitly non-local, which is why it survives the violation of Bell's inequalities.

PKI: Public Key Infrastructure, set of roles, policies, hardware, software and procedures used to create, manage, distribute, use, store and revoke digital certificates and manage public-key encryption.

Planck constant: fundamental constant of quantum physics ($h=6.626\times10^{-34}$ Js). Created in 1900 with Max Planck's explanation of black body radiation spectrum and then used in most other quantum physics equations, including Schrodinger's wave equation.

Planck length: length scale of 1.6×10^{-35} m built from $\hbar$, c and G, below which the classical description of spacetime is expected to break down. It is the typical size assumed for strings in string theory.

Planck units: the system of natural units built in 1899 from $\hbar$, G, c and k_B: Planck length (1.6×10^{-35} m), Planck time (5.4×10^{-44} s, the time light takes to cover a Planck length), Planck mass (about 22 µg) and Planck temperature (1.4×10^{32} K). They mark the scale at which a quantum theory of gravity would become necessary.

Plasmon: quantum of the collective oscillation of a free electron gas in a conductor. A surface plasmon is the version localized at the interface between a metal and a dielectric, and it becomes a surface plasmon polariton when it is coupled to an incident photon, a mechanism used in SPR biosensors.

PMT: photomultiplier tube, vacuum tube detector converting a single photon into a measurable electron avalanche. It is used with trapped ions to collect the state-dependent fluorescence during qubit readout, alongside CCD and CMOS imagers when a spatially resolved readout of many ions is needed.

PNRD: Photon Number Resolving Detector, a detector that reports how many photons arrived rather than merely whether at least one did. It is built either from transition edge sensors or from spatially or temporally multiplexed arrays of SNSPDs. It is required for GKP state preparation, for heralding, and for Gaussian boson sampling beyond the threshold-detector regime.

Pockels effect: effect used in optical modulators where a medium refraction index changes in a linear manner as a function of the electric field applied to it.

Poincaré sphere: the geometric representation of the polarization states of light on a unit sphere, introduced by Henri Poincaré. It is the optical ancestor and exact analogue of the Bloch sphere used for qubits.

Pointer states: the states of a quantum system which are selected by its interaction with the environment, survive decoherence and are redundantly imprinted onto many fragments of that environment. They are the states that observers end up perceiving as classical. See einselection and quantum Darwinism.

Polarized Beam Splitter (PBS): class of beam splitters that use birefringent materials to split light into two beams of orthogonal polarization states.

Polaritons: quantum quasiparticles with strong interactions between light and matter in semiconductors. It results from the coupling between photons and an electrical polarization wave which occurs in particular in plasmons (oscillations of free electrons in metals), phonons (oscillations of atoms, especially in crystalline structures) and excitons (pairs of electron holes generated by photons in semiconductors).

Postselection: technique used in quantum computing and physics operations consisting of verifying that a result of some operation yields a valid result, and discarding it if not, before continuing operations. It can be used when preparing a specific quantum state like an entangled Bell pair of photons, before injecting it in a computation or for connecting two qubits. The state preparation can be done independently in the background. Another option is to run some post-selection during computation, like in quantum error correction, when some parity checks is violated and lead to discarding the outcome of the circuit. It can work on small circuits only. Postselection can also be about conditioning the outcome of a quantum measurement on the value of some other qubit or on a preset arbitrary probability distribution.

POVM: Positive Operator-Valued Measure, quantum measurement generalizing projection-valued measures (PVMs), described by a set of positive semidefinite operators E_k summing to the identity, the probability of outcome k being $\mathrm{Tr}(\rho E_k)$. These elements need not be projectors, need not be orthogonal and need not be as many as the dimension, so a POVM does not define a basis. Any POVM can be realized as a PVM on a larger space, by Naimark dilation. POVMs that are not PVMs are called non-projective measurements. They have many use cases like enhancing quantum states tomography, help detect entanglement and allow unambiguous state discrimination of non-orthogonal states, with applications in quantum cryptography and randomness generation.

PQC: Post Quantum Cryptography, cryptography resistant to quantum computers-based codebreaking algorithms. It relies on public-key schemes whose security rests on mathematical problems for which no efficient classical or quantum algorithm is known, such as structured lattices, error-correcting codes, hash functions and multivariate systems. This is a computational hardness assumption, not a proof, and PQC is not unbreakable.

PQE (Projective Quantum Eigensolver): alternative to VQE created by Nicholas Stair and Francesco Evangelista in 2021 which formulates the ground state search of a unitary coupled cluster ansatz as a root finding problem on residuals, meaning projections of the Schrödinger equation, instead of an energy gradient minimization. It targets the same weakness as ADAPT-VQE, the number of iterations and measurements of the classical outer loop.

PQS: Programmable Quantum Simulator, or analog quantum computers.

Prefactors: multiplicative constants appearing in the implementation of various quantum algorithms, equations, or expressions. These constants do not change the overall structure of the quantum state or algorithm, but they do affect the magnitude or scale of specific terms. Prefactors are important in determining the efficiency, success probability, or resource requirements of quantum computations. They can for example limit the quantum advantage of some quantum algorithm to only very large scale applications, where the benefit compared with classical solution only appear after non reasonable times accounted in decades, centuries or more. This can happen with implementations of Grover's search algorithm.

Prepare-and-measure: QKD architecture in which Alice prepares quantum states selected from a random alphabet and Bob measures the received states. Alice does not prepare and transmit a pre-existing final key. After sifting, parameter estimation, information reconciliation and privacy amplification, Alice and Bob derive a shared secret key. BB84 is the main example of a P&M QKD.

Private Key: in symmetric cryptography, the single secret key shared by the parties and used both to encrypt and to decrypt. It is either distributed beforehand through a secure channel or established by a key agreement protocol such as Diffie-Hellman, which lets the two parties derive a shared secret without transmitting it, and which is neither an encryption algorithm nor a hash function. In public-key cryptography, the private key is instead the secret half of a key pair, never transmitted.

Process Design Kit (PDK): set of files and software tools used to specify, develop, simulate and then manufacture integrated circuits using a specific manufacturing technology.

Property: physical characteristic of a physical object. In quantum physics, observables are the mathematical operator used to compute properties values using the quantum object state vector. For a photon, it can be for example its phase, polarization and wavelength. In quantum physics, it's not possible to evaluate the values of all properties of quantum systems to describe it, due to Bohr's complementarity principle.

Psi-ontic and psi-epistemic: the two broad families of quantum interpretations, depending on whether the wave function describes a physical reality existing independently of any observer (psi-ontic, like MWI, de Broglie-Bohm and objective collapse theories) or the information and rational beliefs of an agent about its future measurement outcomes (psi-epistemic, like Copenhagen and QBism). Psi stands here for the mathematical description of the quantum system state.

Public key: the freely distributable half of a mathematically related key pair, the other half being the private key kept secret. Anyone can encrypt with the public key or verify a signature with it, while only the holder of the private key can decrypt or sign. Public-key schemes also cover key establishment. Security rests on a computational hardness assumption, such as integer factoring for RSA or the discrete logarithm for ECC, and recovering the private key from the public one must be computationally infeasible. Post-quantum schemes are public-key schemes too.

PUBO: polynomial unconstrained binary optimization. See HUBO.

PUE: Power Usage Effectiveness, a ratio dividing the total power consumed by a data center by the power consumed by its IT equipment (compute, storage, networking). The difference is mostly the cost of cooling that equipment. It is about 1.05 to 1.1 in the best cases. PUE has not been defined yet for NISQ or FTQC systems given their specific cryogenic cooling requirements, and it is not even clear what would count as IT there, since it should include all the classical computing and the electronics and photonics involved in driving the quantum processor.

Pulse tube: cryocooler with no moving part at its cold end, using the oscillating compression and expansion of a helium gas driven by a remote compressor. Pulse tubes provide the 50 K and 4 K stages of a dilution refrigerator, on top of which the still, the heat exchangers and the mixing chamber reach the millikelvin range. Adding pulse tubes is one of the engineering paths to increase the available cooling power of a large cryostat, at the cost of more compressor power and of the water cooling that goes with it.

Purcell effect: relaxation or loss of energy of a superconducting qubit through its readout resonator. More generally, it's the enhancement of a quantum system's spontaneous emission rate by its environment, discovered in the 1940s by Edward Mills Purcell with the spontaneous emission rates of atoms when incorporated into a resonant cavity.

Purcell filter: high and low-band filter that reduces the Purcell effect between a superconducting qubit and its readout resonator.

Pure state: quantum state of an isolated quantum system of one or several objects constructed as a linear superposition of the states from its computational basis.

Purification: process applied to a mixed state which integrates it in a larger system to create or reconstruct a pure state. It can be applied to a set of entangled qubits as well. It is used in some error-correcting codes both in quantum telecommunications and quantum computing.

PVD: physical vapor deposition, is a material deposition technique in semiconductor manufacturing where the material to deposit is first turned into vapor and then condenses on the target surface. There are various PVD methods like sputtering that is using ion projection to pull material from a source and deposit it on the target,

PVM: projection-valued measure, the standard projective measurement, described by a set of mutually orthogonal projectors summing to the identity, one per outcome. It applies to any quantum system and any observable, not only to qubits, and a measurement of a qubit along an axis of the Bloch sphere is the two-dimensional special case.

Q factor: quality factor, dimensionless value defined as the ratio between the energy stored in a resonator and the energy dissipated per oscillation cycle times 2π. With the frequency of the oscillator, it provides an indication on the oscillator lifetime. For a single mode decaying exponentially at angular frequency ω, the stored energy lifetime is $T_1 = Q/\omega$. In a real superconducting qubit, the measured T_1 is set by whichever loss channel dominates, among dielectric loss, quasiparticles, two-level systems and the Purcell effect through the readout resonator, so it is not determined by a cavity quality factor alone. One also distinguishes the internal Q of a resonator, its coupling Q and the resulting loaded Q. The higher the better, this factor can exceed 10^7. The dissipation comes from cavity losses and depends on the materials and structure of the electromagnetic cavity. Another definition for Q factor for an oscillator is the ratio between the main resonance frequency and its bandwidth.

Q-Score: open benchmark created by Atos, then Eviden, measuring the largest combinatorial optimization problem instance a QPU can solve with a result better than a given classical baseline, typically a MaxCut on a random graph. Contrarily to low-level metrics like qubit fidelities or quantum volume, it is an application-level benchmark, which makes it a better basis for energy efficiency comparisons between QPUs and classical solvers.

QAA (Quantum Adiabatic Algorithm): exact optimization algorithm which encodes the problem in a Hamiltonian whose ground state is the solution, prepares the ground state of a simple initial Hamiltonian and evolves slowly enough to stay in the ground state, per the adiabatic theorem. Its runtime scales with the inverse square of the minimum spectral gap along the path, which is generally unknown and can be exponentially small. It is the theoretical foundation of quantum annealing and of DCQO. Caveat, some authors also use the QAA acronym for quantum amplitude amplification.

QAE (Quantum Amplitude Estimation): algorithm introduced by Gilles Brassard, Peter Høyer, Michele Mosca and Alain Tapp which estimates a success probability or expectation value encoded as a quantum amplitude. The original QPE-based algorithm achieves additive error ϵ with $O(1/\epsilon)$ coherent uses of the state-preparation or Grover operator, compared with $O(1/\epsilon^2)$ independent samples for ordinary Monte Carlo at comparable confidence, giving a quadratic query advantage. QFT-free iterative and maximum-likelihood variants reduce ancilla or coherent-depth requirements, but they do not remove state-preparation and noise costs and are not generically "NISQ ready".

QAI (Quantum Artificial Intelligence): broad field covering quantum machine learning (QML), quantum reasoning, quantum automated planning and scheduling (QPS), quantum natural language processing (QNLP), quantum computer vision (QCV) and quantum agents and multi-agent systems (QMAS). Most QNLP and QCV implementations actually rely on machine learning techniques, which makes QML the core of the field.

QACM (Quantum Access Classical Memory): in the taxonomy of Samuel Jaques and Arthur Rattew, a memory holding classical data and queried with a superposed quantum address. It is what the bucket brigade and QROM both implement, and what nearly all algorithmic speedup claims actually need. Contrast with QAQM.

QAQM (Quantum Access Quantum Memory): memory holding genuine quantum data and queried with a quantum address, also named explicit qRAM. Much harder than QACM, since the stored states are subject to decoherence and cannot be copied or refreshed, the no-cloning theorem forbidding it.

QAOA: Quantum Approximate Optimization Algorithm created by Edward Farhi in 2014 which is a combinatorial optimization algorithm finding approximate solutions with graph and slice management problems (Max-Cut), various tasks and jobs scheduling problems like the Binary Paint Shop Problem (BPSP), TSP (traveling salesperson problem) as well as for solving 3SAT Boolean satisfiability problems.

Quantum Alternating Operator Ansatz: generalization of Farhi's QAOA introduced by Hadfield et al. in 2019, which keeps the acronym while replacing the two fixed Hamiltonian evolutions by a more general alternation between a phase-separating operator and a family of mixing operators, chosen so as to preserve the feasible subspace of a constrained problem. The original algorithm is the special case where the mixer is the transverse field.

QBER. Quantum Bit Error Rate. Fraction of erroneous bits found in the sifted key of a QKD link, estimated after basis reconciliation on a randomly disclosed subset of the key and before error correction and privacy amplification. Deployed fiber systems usually have a QBER between 0.5% and 3%, and the Micius satellite downlink averaged 1.1% over one orbit and 1% to 3% over 23 sessions spanning 645 km to 1200 km [901].

QBism: Quantum Bayesianism, an interpretation started in 2002 by Carlton Caves, Christopher Fuchs and Rüdiger Schack, in which a quantum state is not an objective description of a system but the personal degree of belief of an agent about the outcomes of its own future measurements, updated with Bayes' theorem. Each agent has its own quantum state and measurement outcomes are created during the measurement act. Its main open difficulty is explaining the intersubjective agreement between agents who compare their data.

QCCD: Quantum Charge-Coupled Device, trapped-ion architecture proposed by David Kielpinski, Christopher Monroe and David Wineland in 2002 in which a segmented trap contains storage, interaction, cooling and measurement zones connected by ion shuttling. It provides direct many-to-many connectivity inside an interaction zone and effective non-local connectivity across the processor by moving ions. The cost is transport, recooling, scheduling and calibration overhead, not an intrinsically fixed gate-cycle time.

QCKA: see Quantum Conference Key Agreement.

QCaaS: quantum computing as a service, a fancy acronym for quantum computing running in the cloud.

QCNN (Quantum Convolutional Neural Network): quantum neural-network architecture inspired by classical convolutional networks. The original QCNN construction alternates local unitary "convolution" layers with pooling or coarse-graining operations and was designed primarily for quantum many-body data. A QCNN is not synonymous with a "quanvolutional" neural network, where small quantum circuits act as local feature-extraction filters on classical data such as image patches [902]. Hierarchical locality can improve trainability in some architectures, but logarithmic depth does not by itself guarantee the absence of barren plateaus or imply that every QCNN is efficiently classically simulable.

QCV (Quantum Computer Vision): image and video analysis tasks handled with quantum algorithms, mostly implemented as variational quantum machine learning circuits. Demonstrations cover SAR image classification, medical image recognition and object detection with a handful of qubits, usually on downscaled images and without addressing the data loading question.

QFC: Quantum Frequency Conversion, coherent conversion of a photonic quantum state from one optical frequency or wavelength to another while preserving the quantum information encoded in the relevant degree of freedom. A common quantum-network use is conversion between visible or near-visible atomic transitions and low-loss telecom wavelengths.

QET (Quantum Energy Teleportation): protocol proposed by Masahiro Hotta in 2008 where a measurement performed on an entangled ground state at one location, combined with the classical communication of its result, allows extracting a small amount of energy at another location. The energy is not created, it is injected by the measurement itself, so there is no free lunch. It was demonstrated on superconducting and trapped ion QPUs.

QFHE: Quantum Fully Homomorphic Encryption. A method of quantum information encryption allowing to perform processing on encrypted data.

QFT: Quantum Fourier Transform. Unitary transform mapping the amplitudes of an N-dimensional quantum state to their discrete Fourier-transform amplitudes. For $N = 2^{\mathrm{n}}$, the textbook circuit uses $\mathrm{O}(\mathrm{n}^2)$ gates, with lower gate counts possible for approximate variants. The transformed amplitudes are not directly readable as a complete classical Fourier spectrum. A measurement returns samples from the Fourier-domain probability distribution, which is why the QFT is most useful as an internal primitive in algorithms such as quantum phase estimation rather than as a generic replacement for a classical FFT.

QGLM (Quantum Generative Learning Models): family of quantum generative models covering quantum GANs, quantum circuit Born machines (QCBM) and quantum variational autoencoders. They are used to generate synthetic training data sets and to sample complex distributions. See GAN.

QIP: Quantum Information Processing, a name sometimes used to information tools based on second-generation quantum technologies. It contains quantum computing, quantum simulation, quantum cryptography and quantum telecommunications.

QHO: quantum harmonic oscillator.

QIR (Quantum Intermediate Representation): an intermediate representation for quantum programs launched in September 2020, serving as a layer between gate-based quantum programming languages and target quantum computers. It can also be used to run code on an emulator. It is supported by the QIR Alliance launched in November 2021 and is part of the Linux Foundation. The Alliance founding members are Honeywell, Microsoft, the DoE Oak Ridge National Laboratory, Quantum Circuits Inc. and Rigetti Computing.

QITE (Quantum Imaginary Time Evolution): ground-state preparation technique based on normalized imaginary-time evolution $|\psi(\tau)\rangle \propto e^{-H\tau}|\psi(0)\rangle$, which suppresses excited-state components when the initial state has nonzero ground-state overlap. Since $e^{-H\tau}$ is non-unitary, the original QITE algorithm approximates each short imaginary-time step by a local unitary obtained from measured expectation values and a classical linear solve. Variational imaginary-time methods provide another implementation route. Convergence and resource scaling depend on locality, correlations, overlap, measurement cost and noise.

QKD: Quantum Key Distribution, a family of protocols that lets authenticated parties establish shared symmetric secret keys using a quantum channel and an authenticated classical channel. QKD can be prepare-and-measure, entanglement-based, discrete-variable or continuous-variable. It does not make keys "tamper-proof" or literally detect every interception; the observed channel statistics determine whether a composably secure key can be extracted or the protocol must abort.

QLBM (Quantum Lattice Boltzmann Method): quantum version of the lattice Boltzmann method which models a fluid as populations of particles moving and colliding on a discrete lattice, an alternative to solving the Navier-Stokes equations directly. It is not a variational algorithm and requires FTQC QPUs. Its weaknesses are an expensive data encoding and a large number of quantum adders. Extensions cover walls, inlets, outlets, external forcing and phase change heat transfer.

qLDPC: quantum Low Density Parity Check codes, family of quantum error correction codes with sparse stabilizers which encode many logical qubits with a much better rate than surface codes, at the cost of requiring long-range connectivity between physical qubits. This requirement matches well the all-to-all connectivity of trapped ions and neutral atoms.

QLM: Quantum Learning Machine, initial name of the Atos quantum emulator appliances using classical hardware (Intel and/or Nvidia). Now Qaptiva.

QLSA (Quantum Linear System Algorithm): generic name of the algorithm family solving the quantum linear systems problem (QLSP), starting with HHL in 2009 and continued with variants based on QSVT, on the discrete adiabatic theorem and on LCU, whose scaling in the condition number κ went from quadratic down to linear and near optimal. All of them share the same end-to-end caveats on state preparation and on solution readout.

QLSP (Quantum Linear Systems Problem): formal problem of preparing a quantum state proportional to the solution x of a linear system Ax = b, given a block-encoding of A and a state preparation unitary for b. It is the problem solved by QLSA algorithms and, in the NISQ regime, by variational quantum linear solvers (VQLS).

QMA: Quantum Merlin Arthur, a class of problems that is verifiable in polynomial time on a quantum computer with a probability greater than 2/3. It is the quantum analogue of the "traditional" NP complexity class. QML: Quantum Machine Learning. Branch of quantum algorithms used in machine learning.

QML: Quantum Machine Learning. Class of quantum algorithms implementing machine learning or deep learning techniques.

QND: quantum non-demolition measurement, a sequence of measurements where results are completely predictable using the result of the first measurement. Practically, it stays the same. Let's say we measure the state of a qubit that yields a $|0\rangle$ or a $|1\rangle$. The measurement is a QND one if a new measurement will yield the same $|0\rangle$ or a $|1\rangle$ coming out of the first measurement and so on. In mathematical parlance, it means the measurement observable commutes with itself at different times. How about a destructive measurement of a qubit? It can happen for example with a photon detector which absorbs it. The photon is then entirely destroyed (and converted to some current in the detector) and cannot be measured a second time. Usually, a QND signal is quantum and extremely weak and is obtained with a quantum probe.

QNLP (Quantum Natural Language Processing): application of quantum algorithms to text processing tasks like classification, sentiment analysis, translation and question answering, with compositional models such as DisCoCat mapping grammatical structure onto quantum circuits. Implementations are small scale variational circuits and there is no demonstrated advantage over classical language models.

QPE: quantum phase estimation, or quantum phase estimate. See Phase Estimation Algorithm.

QPINN (Quantum Physics Informed Neural Network): variational quantum or hybrid quantum-classical neural network trained with a loss containing residuals of a differential equation together with initial or boundary-condition penalties. As in classical PINNs, this usually imposes the physical equations as soft constraints and does not guarantee that they are satisfied exactly. Hard enforcement requires a specially constrained ansatz, output transformation or other construction. QPINNs can reduce parameter counts in some examples, but no generic quantum advantage over classical PINNs has been demonstrated.

QPU: quantum processing unit. This is the "processor" within a quantum computer, like a superconducting chip or an ion-trap on a carrier PCB or in a socket attached to a cold head and/or inserted into a vacuum chamber. In the case of photonic quantum computers, it should contain at least photon sources and detectors and other photonic circuits. For cold atoms, it's the vacuum chamber hosting a MOT and the atoms, surrounded by lasers and light-forming devices (SLMs, AODs).

qRAM: quantum random access memory, an addressable memory model that coherently maps an address superposition to corresponding data. The bucket-brigade architecture was proposed by Vittorio Giovannetti, Seth Lloyd and Lorenzo Maccone in 2008. No large-scale fault-tolerant qRAM has been demonstrated, and fault-tolerant implementation would require substantial protected memory and routing resources. Efficient qRAM is a strong assumption in some quantum machine-learning and linear-algebra speedup proposals, but other algorithms use explicit arithmetic, QROM, sparse-access or block-encoding models instead.

QRC: quantum reservoir computing. See Quantum reservoir computing. Since only the classical readout layer is trained, QRC has no quantum gradient and no barren plateau, which makes it the cheapest QML family to run on current hardware and explains its 2025-2026 publication surge.

QRNG: Quantum Random Number Generator, the optical random number generators used in quantum cryptography, like those of the Swiss IDQ.

QROM (Quantum Read-Only Memory): reversible circuit which converts an address register in superposition into a superposition of the corresponding classical data words, using a sequence of multi-controlled operations instead of a physical memory. Contrarily to qRAM, it is implementable with regular quantum gates, with a tunable trade-off between T-count and ancilla qubits count in its SELECT-SWAP variants. It is a workhorse of FTQC chemistry algorithms and of state preparation with precomputed lookup tables.

QSA: Quantum Spring Array, 2D QCCD ion trap architecture demonstrated in 2024 by AQT and its research partners, developed and manufactured with Infineon on a fused silica substrate. It uses registers made of 6-ion strings which are dynamically coupled.

QSCI (Quantum-Selected Configuration Interaction): hybrid quantum chemistry method which samples the most relevant Slater determinants of a many-electron wave function on a QPU and then diagonalizes the Hamiltonian classically in that restricted subspace. It is noise resilient since only the sampled configurations matter, and it computes ground and excited states, but its scaling to large systems is questioned since the number of relevant determinants grows quickly.

QSP (Quantum Signal Processing): framework developed by Guang Hao Low and Isaac Chuang which realizes a degree-d polynomial transformation of the eigenphases or spectral variable of a signal unitary by interleaving O(d) uses of that signal operation with carefully chosen single-qubit phase rotations. Computing the phase sequence is a nontrivial classical preprocessing problem. QSVT generalizes QSP to polynomial transformations of the singular values of a block-encoded matrix. QSP and QSVT underlie optimal Hamiltonian simulation, amplitude amplification and modern quantum linear-algebra primitives, but they do not imply a generic exponential speedup by themselves.

QSDC: Quantum Secure Direct Communication, protocol family in which the message itself is encoded into quantum states rather than using the quantum channel only to establish a secret key as in QKD. Security is protocol- and implementation-dependent, and practical schemes can still require authenticated classical communication for control, testing or parameter estimation.

QSS: Quantum Secret Sharing. Multiparty primitive that distributes a classical or quantum secret so that only authorized subsets of participants can reconstruct it. QSS is related to QKD but is not restricted to sharing cryptographic keys.

QST (Quantum State Transfer): protocol moving an arbitrary quantum state from a sender subsystem to a receiver without copying it, since the no-cloning theorem forbids copying an unknown state. Ideal QST preserves coherence, phase relations and entanglement with external systems. It can be implemented with SWAP networks, quantum teleportation or engineered Hamiltonian interactions mediated by spin chains, photons, phonons or cavity modes. Practical quality is measured by transfer fidelity, while Perfect State Transfer denotes unit fidelity in an ideal model.

QSVD (Quantum Singular Value Decomposition): variational NISQ algorithm generalizing the classical singular value decomposition, which decomposes a quantum state or an operator into a set of singular values and their corresponding orthonormal bases. It is used in proposals like quantum page rank. Its main practical weakness is that the orthogonality of the produced vectors is not guaranteed at convergence.

QROAM: SelectSwap variant of QROM introduced by Guang Hao Low, Vadym Kliuchnikov and Luke Schaeffer, which duplicates the output register λ times to trade ancilla qubits against T gates. Its T-count is O(N/λ + λd) for N words of d bits, minimized at O($\sqrt{Nd}$), a near quadratic saving over plain unary iteration. Most FTQC chemistry resource estimates rely on it.

QSVT (Quantum Singular Value Transformation): quantum algorithm that performs a polynomial transformation of the singular values of a linear operator embedded in a unitary matrix. Was created by András Gilyén, Yuan Su, Guang Hao Low and Nathan Wiebe in 2018.

Quantics representation: encoding of a function sampled on a 2^n points grid where the successive binary digits of the coordinate become the successive indices of a tensor train, so that the scale hierarchy of the function maps onto the position along the chain. It lets MPS and tensor cross interpolation compress smooth or multiscale functions with a small bond dimension and it is increasingly used in tensor network PDE solvers.

Quantization: in quantum physics, happens with quantum objects having some physical properties that are discontinuous and not continuous, like electron energy levels and electron spins.

Quantronium: the superconducting charge qubit demonstrated in 2002 by the CEA Quantronics group, operated at an optimal working point where its transition frequency is first-order insensitive to charge and flux noise. It was an important intermediate step between the 1998-1999 Cooper pair boxes and the transmon.

Quasi-locality: property of an operator or a quantum channel which is not strictly supported on a bounded region but can be approximated by one, with an error decaying exponentially with the distance outside it. It is what Lieb-Robinson bounds actually establish for time-evolved observables, and the reason a strictly local description remains usable at finite time. The associated mathematical toolbox includes quasi-local algebras and quasi-adiabatic continuation.

Quantum accelerator: quantum computer used as a complement to a supercomputer or HPC, usually to run hybrid algorithms like VQE (Variational Quantum Eigensolvers) combining a classical part that prepares the data structure that feeds a quantum accelerator.

Quadrature: one of the two orthogonal components X_1 and X_2 of an electromagnetic field mode, corresponding to the real and imaginary parts of its complex amplitude, or to the cosine and sine components of the oscillating electric field. They are the continuous variables of quantum optics and play the role that position and momentum play for a massive particle, obeying the same kind of indeterminacy relation. A coherent state has equal uncertainty on both quadratures, a squeezed state has less on one and more on the other, and a homodyne detector measures whichever quadrature the phase of its local oscillator selects.

Quantum advantage: occurs when a quantum computer executes some processing faster than its optimum equivalent adapted to a supercomputer, with a useful algorithm. This advantage can be declined on another aspect than the duration of the calculation. For example, a quantum energy advantage relates to energy consumption instead of computing time.

Quantum algorithm: often used as a synonym of a quantum circuit. In a purist fashion, it is the whole code solving a problem with a quantum computer. It therefore contains the classical code and algorithm that generates the quantum circuit and the circuit itself, but also, all classical pre and post-processing tasks, and even some classical tasks run during the circuit execution if any.

Quantum annealing: technique used to find the global minimum of a given objective function over a given set of candidate solutions, based on using quantum fluctuations. It is used to solve combinatorial optimization problems with a discrete search space. This computational process is in D-Wave quantum computers. It doesn't use any thermodynamics effect but rather a magnetically induced annealing process, relaxing a transversal magnetic field controlling the qubits state.

Quantum batteries: quantum systems used to store and deliver energy, where collective and entangled effects could in principle speed up charging compared to independent cells. Their application to quantum computing is studied for improving the energy efficiency of the superconducting qubit drive. They have been experimented at small scale, and scaling them faces frequency crowding, battery decoherence, the recharge problem, control precision and crosstalk.

Quantum channel: transformation of a quantum state resulting from any kind of interaction with a quantum environment. It is modelized with a density matrix superoperator. It is useful to modelized subsystems, decoherence, quantum error correction and qubits noise.

Quantum Chaos: branch of physics studying how chaotic classical dynamical systems can be described with quantum theory. It deals with the relationship between quantum mechanics and classical chaos and with the boundaries between classical and quantum physics in modelling chaos.

Quantum chromodynamics: describes the strong interaction, one of the four fundamental forces, that governs the interactions between quarks and gluons and the cohesion of atomic nuclei. Why "chromo"? Because we describe the states of elementary particles with color codes: blue, green and red for particles, then anti-blue, anti-green and anti-red for anti-particles. This theory is based on the quantum field theory. This part of quantum physics is not used in the creation of qubits. It is used for the physics of elementary particles and is verified in large particle accelerators such as the CERN LHC in Geneva.

Quantum circuit: see circuit.

Quantum cognition: descriptive model of the functioning of human knowledge (language, decision-making, memory, conceptualization, judgment, perception) based on the mathematical formalism of quantum mechanics, proceeding mainly by analogy, without going through physical explanations or quantification of the neurosciences, which themselves fall within the "quantum mind" field resulting from the work of Roger Penrose.

Quantum computer: or QC, self-sufficient system able to execute a quantum circuit and process its results. It contains one or several interconnected quantum processors, all the electronics and photonics controlling it, all required cryogenics, and classical computing resources necessary to control it, particularly for quantum error correction, handling circuit execution and post-processing. I mistakenly use the QPU acronym for quantum computers in this book and need to correct it selectively.

Quantum Conference Key Agreement (QCKA): multiparty extension of key agreement in which several users establish a common secret key. Protocols can use multipartite GHZ-type entanglement, post-selected correlations, phase-matching architectures or continuous variables; GHZ states are one implementation family, not a requirement.

Quantum Darwinism: Wojciech Zurek's proposal that classical objectivity emerges because certain pointer states of a system are redundantly imprinted onto many independent fragments of the environment, so that many observers can access the same information without disturbing it.

Quantum data center: site-scale computing architecture hosting multiple QPUs connected by quantum links and coordinated by low-latency classical control, with the goal of operating modular processors as a larger quantum-computing resource. Unlike a generic quantum network, its primary purpose is computation within one facility or closely coupled site.

Quantum dots: we can mention at least three different types of quantum dots: the tiny semiconductor particles of a few nm used in LCD screens that convert the blue backlighting LED light into green or red light based on their grain size. Then we have the quantum dots used to generate single photons. Finally, we have quantum dots used to trap electron spins in spins qubits.

Quantum Electro-Dynamic (QED): branch of quantum physics, or QED, which is "*a physical theory that aims to reconcile electromagnetism with quantum mechanics using a relativistic Lagrangian formalism. According to this theory, electric charges interact by photon exchange*" (Wikipedia). This is the basis of the quantum field theory which applies to all elementary particles.

Pauli propagation: classical simulation technique that evolves observables expressed as sums of Pauli strings through a quantum circuit, usually in the Heisenberg picture. Exact propagation may generate exponentially many Pauli terms, so practical methods often truncate terms according to weight or magnitude. It is particularly useful for estimating expectation values and can complement tensor-network simulation.

Quantum emulator: software and/or hardware using a conventional computer to execute a model of software intended for a quantum computer. Full state-vector emulation requires $\mathcal{O}(2^N)$ memory, but specialized methods such as stabilizer, tensor-network and Pauli-propagation techniques can exceed fifty qubits for restricted circuit families or observables. In this book, quantum emulation refers to executing quantum-computing code classically, while quantum simulation refers to computing the physics or dynamics of a quantum system. The terminology in the literature is not fully standardized.

Quantum energetics: study of the flows of energy, entropy and information between quantum systems without necessarily involving temperature or heat baths. Where quantum thermodynamics implies a thermal context, quantum energetics explores engines and processes powered purely by quantum resources, such as the energetic cost of a quantum measurement and its backaction, the role of entanglement, or the cost of overcoming quantum noise. It aims at determining the ultimate energy cost of qubit operations, with consequences on the energetic understanding of quantum error correction.

Quantum engineering: is about developing quantum technologies in computing, telecommunications, cryptography and/or sensing with a pluridisciplinary approach merging quantum physics and other related sciences and technologies like thermodynamics, cryogeny, electronics, semiconductors, cabling, mathematics, information theory, programming and the like.

Quantum Field Theory (QFT, not to be confused with the Quantum Fourier Transform): framework combining quantum mechanics, special relativity and classical field theory, where particles are excitations of underlying fields which can be created and annihilated. It covers QED, quantum chromodynamics and the standard model, as well as condensed matter collective phenomena. It is the origin of the notions of quantum vacuum fluctuation and renormalization. It has not been reconciled with general relativity.

Quantum Fisher Information (QFI): quantity measuring how sensitively a parameterized quantum state changes with an unknown parameter. It determines the quantum Cramér-Rao bound for parameter estimation, $\mathrm{Var}(\hat{\theta}) \geq 1/(\nu F_Q)$ for ν independent repetitions under the usual conditions. For specified generators it can also witness useful multipartite entanglement, but it is not itself a universal entanglement measure.

Quantum Cramér–Rao bound (QCRB): lower bound on the variance of an unbiased parameter estimator obtained from the Quantum Fisher Information. For one parameter and ν independent repetitions, $\mathrm{Var}(\hat{\theta}) \geq 1/(\nu F_Q)$. In multi-parameter problems, bounds derived from the QFI matrix are not always jointly attainable because optimal measurements can be incompatible.

Quantum foundations: branch of science philosophy that aims to build some understanding and description of the real world in quantum physics and, as such, associate it to some ontology.

Quantum gates: operations modifying the state of one or several qubits. Multi-qubit gates (Toffoli, Fredkin, ...) exploit the principle of quantum entanglement. The operations of quantum gates are generated by physical actions on the qubits which depend on their nature. For superconducting qubits, this involves sending microwaves between 5 and 10 GHz via electrical conductors. For trapped ions, these are laser-controlled operations. For electron spins qubits, these are a mix of electrical voltages and microwave pulses. For qubits based on mass particles (electrons, ions, cold atoms), quantum gates act on the qubits but these do not move in space. For flying qubits based on photons or electrons, these circulate and cross quantum gates which modify their state (phase, frequency, or other).

Quantum Hall effect (QHE): or integer quantum Hall effect is a quantized version of the Hall effect which is observed in two-dimensional electron systems at low temperatures and under a strong magnetic field, in which the Hall resistance Rxy has quantized values. It is related to the field of quantum matter. The effect was discovered by Klaus von Klitzing in 1980, who was awarded the Nobel prize in physics in 1985.

Quantum hydrodynamics: studies the hydrodynamic effects of quantum systems such as superfluid elements (helium at very low temperature) or polaritons and associated light fluids.

Quantum illumination: target-detection protocol that prepares correlated signal and idler modes, sends the signal through a lossy noisy region and performs a joint measurement of the returned mode with the retained idler. Its theoretical advantage can survive even when loss and noise destroy the original entanglement, because the receiver exploits residual signal-idler correlations. It does not identify individual returned photons as the original partners of particular idlers.

Quantum Internet: marketing term describing a quantum network enabling quantum telecommunications based on entanglement, particularly to connect quantum systems like quantum computers and quantum sensors. By extension, it also includes quantum key distribution infrastructures that are used to secure information exchange with encryption keys that are shared quantumly between senders and receivers.

Quantum jump: describes the continuous change happening during the measurement of a quantum object. It is not instantaneous.

Quantum kernel: function computing a kernel matrix, given a set of datapoints x and y, it looks like the dot product $\langle f(x),\ f(y)\rangle$, f being a function mapping data from a low dimensional space (n) to a higher dimensional space (m). Quantum kernel matrices are used in quantum machine learning algorithms for various tasks like SVM, PCA, classification and regressions.

Quantum capability learning: technique used to predict which quantum programs a particular quantum computer can reliably execute.

Quantum logic: framework proposed by Garrett Birkhoff and John von Neumann in 1936 in which propositions about a quantum system correspond to projection operators on a Hilbert space, forming a lattice which, unlike classical Boolean logic, is not distributive. A proposition negation corresponds to the orthogonal complement in the Hilbert space. Quantum set theory is an extension of it.

Quantum matter: materials or assemblies of few atoms whose observable properties like magnetism, electronic state or optical response can only be described by advanced quantum physics and by the collective behavior of their electrons. There is no consensus definition, one of the simplest being materials where electrons do interesting things. It covers superconductors, superfluids, topological and strongly correlated materials, quantum spin liquids, supersolids, and time crystals.

Quantum medicine: in general, fake science and charlatanism based on totally fanciful interpretations of quantum mechanics.

Quantum Non Demolition measurement (QND): type of measurement in which the uncertainty of the measured observable does not increase from its measured value during the subsequent normal evolution of the system. QND measurements are the least disturbing type of measurement in quantum mechanics. In other words, for a qubit, it would mean that after a $|\mathbf{0}\rangle$ or $|\mathbf{1}\rangle$ is measured, subsequent measurements will always yield the same $|\mathbf{0}\rangle$ or $|\mathbf{1}\rangle$ that was obtained in the first place.

Quantum numbers: variables describing quantum objects physical quantities or variables that are discrete. Electrons have four quantum numbers: principal quantum number (energy level or electron shell), angular momentum also named azimuthal or orbital quantum number describing electron subshell, magnetic quantum number describing the electron energy level within its subshell and spin projection quantum number, being either +1/2 or -1/2, in a given spatial direction.

Quantum postulates: basis of quantum physics formalism. These are postulates and not laws because it describes a mathematical formalism that cannot be proved per se. There are many different presentations of quantum postulates in reference sources (Nielsen & Chuang, Preskill, Cohen-Tannoudji, Wikipedia, ...). Depending on the sources, you'll find 3, 4, 5, 6 or even 7 of them.

Quantum Physical Unclonable Functions (qPUF): quantum based physical identifiers that can be used to create unique and unclonable security keys.

Quantum repeater: intermediate quantum-network node that extends entanglement distribution by connecting shorter elementary links, usually through heralding and entanglement swapping. Many architectures use quantum memories, purification or quantum error correction, while all-photonic repeaters can avoid long-lived matter memories. Unlike a trusted QKD relay, an ideal quantum repeater does not need access to the final secret key.

Quantum reservoir computing: specific category of recurrent neural networks used to process time series. It uses a set of neuron weights and links between neurons randomly fixed in the reservoirs, all with nonlinear activation functions. The hundreds of neurons in a reservoir are fed by input data stored in the reservoirs. The activation functions nonlinearity makes this memory evanescent. The training parameters of these networks are located in the weights of the neurons that connect the reservoirs to the output data. It can be implemented with boson samplers [903].

Quantum reservoir engineering: set of techniques for managing qubits through their interaction with a "quantum thermal bath" (quantum bath) to reduce energy consumption, reduce the duration of the measurement of the state of the qubit and allow a non-destructive and reversible measurement of this state ("Quantum non-demolition" or QND). Reservoir engineering is used in cat-qubits.

Quantum resource estimator: software tool that converts an algorithmic workload plus hardware and QEC assumptions into resource estimates such as logical and physical qubit counts, non-Clifford resources, space-time volume, failure probability and execution time.

Quantum simulator: system that is able to compute the physics of a many body quantum system. It can be done on a classical computer or a quantum computer. In that case, it refers to analog quantum computers that are capable of simulating quantum objects and solving related problems, particularly in materials physics. By abuse of language, the name is used for classical computers capable of emulating quantum code. In this case, it is preferable to use the term quantum emulator.

Quantum speed limit: concept that sets a limit on how quickly a quantum system can evolve from one state to another, including during measurement. It provides a boundary on the minimum time required for a quantum system to transition between states while still obeying the laws of quantum mechanics. There's a general trade-off between the energy uncertainty and the time it takes for the transition to occur. The quantum speed limit can be expressed in terms of the system's Hamiltonian (or energy operator) and the state's initial and final states. It involves Planck's constant and the difference in energies between the initial and final states.

Quantum spin liquid: state of a magnetic material where the electron spins stay entangled and disordered down to zero temperature instead of ordering as in a ferromagnet or an antiferromagnet. Envisioned by Philip W. Anderson in 1973 with the resonating valence bond model. It could host anyons. No material is an undisputed quantum spin liquid to date, the best candidates being α-$RuCl_3$ and the herbertsmithite kagome lattices.

Quantum state: mathematical object used to compute at a given time the probabilities of a quantum object or set of object property values that would be obtained when measuring it and to predict their evolution over time. It is usually represented by a vector in a Hilbert space (linear, metric and complete). This is however only the case for a pure state. A mixed state is represented by a density matrix. The notion of quantum state is usually the first quantum postulate.

Quantum state tomography: technique used to characterize the quality of qubits and qubits gates or any quantum channel. It is used to experimentally reconstruct a density matrix of a set of qubits. It also requires a lot of classical computing to process the experimental data obtained with repeated state preparation and measurements.

Quantum Steering: quantum measurement phenomenon when one subsystem can influence the wave function of another subsystem by performing specific measurements. It sits between entanglement and Bell nonlocality in the hierarchy of quantum correlations. Pure entangled states (like Bell states) always exhibit steering since they are maximally correlated. Steering also shows up with mixed states, which combine pure states and may contain noise or decoherence. Not all mixed entangled states exhibit steering. Some mixed states allow steering which can help build one-sided device-independent quantum cryptography, where only one party's device is trusted.

Quantum supremacy: describes a situation where a quantum computer can perform some computation that is inaccessible to the best current supercomputers with the best classical algorithm and in a humanly reasonable time. The computing time differential between quantum computing and classical computing must be several orders of magnitude. It can deal with a useful calculation or not. Thus, the quantum supremacy claimed by Google in October 2019 dealt with a random algorithm that had no practical interest. The term was coined by John Preskill in 2011. Nowadays, the trend is to use the quantum advantage denomination.

Quantum switch: creates a series of qubit transformations that can be implemented simultaneously in different orders, creating an indefinite causal order computing flow.

Quantum teleportation: protocol transferring an unknown qubit state from Alice to Bob without physically transmitting the original carrier. Standard teleportation consumes one previously shared Bell pair. Alice performs a Bell-state measurement and sends two classical bits to Bob, who applies a conditional correction. The protocol therefore cannot communicate faster than light. Alice's measurement removes the original unknown state as part of the protocol, consistently with the no-cloning theorem, but the no-cloning theorem is not itself the dynamical reason for this destruction. Teleportation is a central primitive of quantum networks and distributed quantum computing.

Quantum thermodynamics: study of energy and entropy flows at the microscopic scale, relying on concepts adapted from classical physics such as temperature, thermal baths, and heat engines extracting work from thermal gradients. It covers quantum heat engines and refrigerators, the thermodynamic cost of measurement, the role of entanglement in thermodynamical systems, and the quantum versions of Maxwell's demon. It is distinguished in this book from quantum energetics, which does not require a thermal context.

Quantum transduction: coherent conversion of quantum information between different physical modes or frequency bands, for example between microwave photons and optical photons, while preserving the relevant quantum state and adding sufficiently little noise. Conversion efficiency, added noise and bandwidth are key figures of merit. Quantum transduction is more demanding than ordinary classical frequency conversion because coherence and nonclassical statistics must be preserved.

Quantum trajectories: describe the continuous time evolution of quantum systems and their quantum state, for example when executing a quantum gate.

Quantum utility: notion promoted by IBM since 2023 designating the regime where a NISQ QPU with over a hundred good quality physical qubits, combined with efficient quantum error mitigation, produces results that are useful for a scientific or industrial problem, without necessarily beating the best classical method. It is a weaker claim than a quantum advantage, and most quantum utility demonstrations have since been matched or beaten by tensor network based classical emulations.

Quantum variational circuits: type of quantum algorithm used to implement machine learning.

Quantum volume: or QV, benchmark metric created by IBM in 2018 measuring the largest square random circuit of n qubits and n layers that a QPU can run with a heavy output probability above 2/3. It is expressed as 2^n and captures qubit count, gate fidelity, connectivity and compiler quality in a single number. Its limitations are that it saturates quickly and becomes intractable to verify classically beyond about 50 qubits. IonQ's algorithmic qubits metric is its $\log_2$.

Quantum walk: quantum analog of classical random walks introduced by Yakir Aharonov, Luiz Davidovich and Nicim Zagury in 1993, in discrete time versions using a coin register and in continuous time versions driven by the adjacency matrix Hamiltonian of a graph. The walker spreads ballistically, in O(t) instead of $O(\sqrt{t})$ classically, which yields quadratic to exponential speedups depending on the graph structure. It underpins element distinctness, spatial search, QWOA optimization and some Hamiltonian simulation and linear solver constructions.

Quantum Zeno Effect: situation where the frequent observation of a quantum system inhibits its evolution and freezes it. It is used in some communication protocols where information can be passed between two locations without any physical particles traveling between them. It uses specific settings of quantum channels and particles, such that the presence or absence of an object like a message encoded in a quantum state is inferred through quantum measurements without the object directly traversing the space be-tween sender and receiver.

Quasiparticles: physical concept which treats elementary excitations in solids like spin waves, as particles. As the particles do not consist in actual matter, they are called quasi particles. Majorana fermions and polaritons are examples of quasiparticles.

Qubit or physical qubit: the elementary unit of information in quantum computing in quantum computers and quantum telecommunication. It stores a quantum state associating two distinct states of a particle or of a quantum system (electron spin, energy level of a superconducting loop, energy level of a trapped atom or ion, polarization or other property of a photon). Its mathematical representation is a vector comprising two complex numbers in a Bloch sphere.

Qubitization: technique introduced by Guang Hao Low and Isaac Chuang which constructs, from a suitable block-encoding or state-preparation/select oracle pair, a walk operator whose eigenphases encode the Hamiltonian spectrum. Combined with quantum signal processing, it yields Hamiltonian-simulation query complexity essentially linear in the normalized evolution time and logarithmic in the inverse target error, rather than linear in $1/\epsilon$. It is a central primitive in many modern fault-tolerant quantum-chemistry resource estimates.

QUBO: Quadratic Unconstrained Binary Optimization problem to optimize a quadratic function of n binary values. It is a generic NP hard combinatorial optimization problem and its related algorithm which can help solve many applications in finance, logistics and other domains. Many classical combinatorial problems like maximum cut, graph coloring and the partition problem, can be turned into a QUBO problem. QUBO problems can be solved on all three quantum computer paradigms (gate-based, annealing, simulation).

Qudits: quantum system whose Hilbert space has dimension d instead of two, a qubit being the case $d = 2$. A qudit is therefore not a form of qubit, it is the general case of which the qubit is the smallest instance. It is rarely used, at least in quantum computers outside research laboratories.

Quench refers to a sudden change in the parameters of a quantum system, altering its Hamiltonian and driving the system out of equilibrium. It can help understanding non-equilibrium quantum physics and thermalization processes. Aka quantum quench, quantum quench dynamics.

Qumode: the continuous variable analogue of a qubit, a single mode of the electromagnetic field whose quantum information is carried by the quadrature amplitudes rather than by a two-level discrete state. Xanadu, ORCA, OptQC and Qluster encode in qumodes.

Qunat: nonstandard term occasionally used for continuous-variable encodings. The accepted term is qumode, the bosonic mode of the electromagnetic field. Use qumode.

Ququart: four-level quantum object, a qudit of dimension four. Photonic ququarts have been implemented with path encoding on silicon chips and with orbital angular momentum encoding.

Qutrit: a qudit of dimension three, meaning a quantum system with three basis states instead of the two of a qubit. No commercial quantum computer implement this model.

QWOA (Quantum Walk Optimization Algorithm): non-variational alternative to QAOA which alternates a phase separation unitary encoding the objective function and a continuous time quantum walk mixer restricted to the feasible solution space, which handles constraints natively instead of adding penalty terms. It is benchmarked on weighted MAXCUT and claims a more predictable parameter setting than QAOA.

Rabi (oscillation): oscillations between states of a two-level system excited at a frequency close to its resonance. This phenomenon is observed between two spin states in nuclear magnetic resonance as well as when an electric field acts on the transitions from one electronic state of a system to another for an atom or molecule. The curve describing the oscillation resembles a sinusoidal curve that attenuates over time. Isidor Isaac Rabi is an American physicist of Hungarian origin (1898-1988) who was awarded the Nobel prize in Physics in 1944. Rabi's oscillations can be found almost everywhere, especially in the operation of superconducting qubits with microwave pulses.

Racetrack: closed-loop QCCD ion trap topology used in Quantinuum's H2 system where the ions circulate in an oval track equipped with junctions. It removes the need to reverse the ion ordering and provides an all-to-all connectivity across the register.

Raman cooling: variant of the Doppler effect using the Raman effect used to cool atoms below the limit of Doppler-based cooling, under 1μK. It uses two counter-propagating laser beams. This effect is used in cold atom based interferometry in absolute gravimeters. Also known as Raman sideband cooling.

Raman effect or Raman scattering: shift in wavelength of an inelastically scattered radiation where an incident monochromatic photon energy and momentum are both changed. Discovered by Chandrasekhara Venkata Raman (1888-1970, India), Nobel prize in Physics in 1930. This is a small effect that accompanies the predominant Rayleigh scattering of light (unchanged wavelength). The incident polarized light is scattered at its original frequency (Rayleigh elastic scattering) and with higher and lower frequencies (Raman stokes and anti-stokes anti-elastic scattering).

Raman spectroscopy: determines vibrational and rotational level spacings from the energy (wavenumber) shifts of inelastic scattered light (*aka* Raman scattering). It is used to analyze multi-atoms molecules through their vibrational modes, particularly in organic chemistry.

Raman transition: couples two atomic levels by the absorption of a photon in one Raman beam (pump beam) and by stimulated emission of another one in the other beam (Stokes beam). It is used in cold atom interferometry to split a cold atom cloud into two superposed matter waves of different energy levels and vertical velocity.

Ramsey experiment: technique used to measure the T_2^* of a superconducting qubit, with applying one Hadamard gate, waiting a time t, then applying another Hadamard gate, and measuring the output. The sinusoid curve amplitude slowly decreases around a probability 0.5. T_2^* is obtained when the probability reaches 1/e.

Rayleigh scattering: predominantly elastic scattering of electromagnetic radiation by particles that are much smaller than the radiation wavelength. Elastic scattering happens with incident photons whose direction is changed but not their energy (color or wavelength). It explains why the sky is blue, linked to blue light being more scattered than green and red light, and also polarized.

RBM (Restricted Boltzmann Machine): two-layer generative stochastic neural network with visible and hidden units and no intra-layer connections, whose training relies on sampling a Boltzmann distribution. It has been tested on D-Wave annealers, which natively sample such distributions, and it is the historical ansatz of neural quantum states.

Realism: in science, a philosophical view according to which there exists a reality independently of an observer. The Copenhagen interpretation of quantum physics is said to be non-realist since it believes reality is only what can be observed and measured. In the CSM ontology (described in the quantum foundation section in the Prologue volume), reality is described independently of the observer but in a given measurement context.

Rebound effect: see Jevons paradox.

Reduced Planck constant: see Dirac constant.

Reflectometry: technology used with superconducting and electron spin qubits readout. It sends a microwave to the qubit and analyzing the reflected microwave, which can have different phase and amplitude depending on the measured qubit state.

Register: set of bits or qubits. In the case of qubits, it provides an exponentially growing computational base space with the number of qubits.

Relational quantum mechanics: or RQM, the interpretation crafted by Carlo Rovelli in 1994 in which a quantum state is not intrinsic to an object but defined by the relation between two systems, one of them possibly being an observer. It creates relative facts which become approximately stable facts when one of the systems is large enough. It is inspired by the reference frame reasoning of special relativity.

Relaxation: corresponds to the T_1 or lifetime of a qubit, which defines when the qubit loses its amplitude.

ReLU (Rectified Linear Unit): nonlinear activation function of the form f(x) = max(0, x) used in classical neural networks. Nonlinear activations are hard to implement in quantum circuits since quantum gates apply linear transformations only, but ReLU is easier to approximate than sigmoids, using mid-circuit measurements, ancilla qubits or classical layers in hybrid architectures.

Renormalization: set of techniques created in the late 1940s by Shin'ichirō Tomonaga, Julian Schwinger, Richard Feynman and Freeman Dyson to remove the infinite quantities showing up in quantum field theory computations, by absorbing them into the measured values of masses and charges. It made QED predictive and remains a cornerstone of modern particle physics. It is unrelated to the density matrix renormalization group (DMRG) used in tensor networks, apart from the shared idea of scale-dependent effective descriptions.

Renyi entropy: generalized version of entropy that can be used as a measure of entanglement. Shannon entropy is a special case of Renyi entropy.

Repumping: laser bringing back atoms or ions which have fallen into a dark state outside of the cooling or detection cycle, using 866 nm with calcium ions at AQT. Without it, the cooling and readout cycles would stop after a few photon scattering events.

Reticle limit: maximum area a lithography scanner can expose in a single shot, about 26×33 mm or 858 mm^2. It caps the size of monolithic chips, which is circumvented with chiplets, or by stitching several reticle fields together as Cerebras does with its wafer-scale engines.

Retrodiction: the process of making probabilistic statements about past events from current information, the time-reversed counterpart of prediction. Quantum retrodiction relies on Bayesian inference and quantum state smoothing and can even reveal the past entanglement between a system and its environment.

Reversible computing: computing paradigm using only logically reversible gates, which produce as many output bits as input bits and therefore never erase information, so that the calculation can be rewound and the energy spent in the forward direction be partly recovered. It was theorized by Charles Bennett in 1973 and Tommaso Toffoli in 1980 and would escape the Landauer limit. It was not the path chosen by the classical computing industry, because of the steadiness of Moore's law for decades and because of the significant transistor and memory overhead it requires. Gate-based quantum computing is logically reversible by construction since all its gates are unitary, qubit readout being the exception.

RIE: reactive ion etching, a process used to remove some material on a semiconductor target using accelerated molecular or atomic ions in vacuum.

RSA: a public key encryption system based on the difficulty of factoring a public key formed by multiplying two very large prime numbers. This factorization is theoretically possible with Peter Shor's quantum algorithm. However, it requires a very large fault-tolerant machine to break the most common RSA keys at 1,024 or 2,048 bits, and no single qubit count follows from a gate-fidelity threshold, since the resource estimate depends on the architecture, the physical error model, the cycle time, the code, the decoder and the target runtime. As an illustration, Gidney and Ekerå estimated in 2019 about 20 million noisy physical qubits and 8 hours for a 2,048-bit modulus, assuming a 0.1% gate error rate and a 1 μs surface code cycle, an estimate Gidney revised in 2025 to under one million qubits and less than a week under the same physical assumptions.

RUS: Repeat Until Success, a strategy where a probabilistic entangling operation is retried until a heralding signal announces it worked, the qubits being reset or preserved in between. It is how Quandela's SPOQC architecture implements its CZ gates between quantum-dot spins.

RSG: Resource State Generator, the subsystem of a fusion-based quantum computer that produces the small entangled photonic cluster states, four qubits in the PsiQuantum design, which fusion measurements then stitch into a fault-tolerant lattice.

Rydberg state: highly excited atomic electronic state with a principal quantum number $n \gg 1$. Its characteristic electronic radius scales approximately as $n^2 a_0$ and its radiative lifetime approximately as n^3 before blackbody-induced transitions are included. Neighboring Rydberg atoms can have very strong dipole-dipole or van der Waals interactions, which are exploited for blockade, entangling gates and programmable many-body Hamiltonians. Neutral-atom processors commonly use n values of several tens to about one hundred, but no particular value defines a Rydberg state.

Rydberg blockade: suppression of simultaneous Rydberg excitation of nearby atoms when the interaction-induced energy shift of the doubly excited state is large compared with the excitation linewidth and Rabi frequency. It is the main interaction mechanism used for many neutral-atom entangling gates and for Rydberg analog Hamiltonians. The blockade radius depends on the Rydberg states, Rabi frequency, detuning and geometry rather than on a universal principal-quantum-number threshold.

Sapphire: aluminum oxide crystals (Al_2O_3) that is sometimes used as a substrate instead of silicon for the manufacturing of superconducting qubits chips. In that case, wafers are made of synthetic sapphire.

SAT: class of logic problem or Boolean satisfiability problem, of 0-order logic. It is a decision problem, which, given a propositional logic formula, determines whether there is an assignment of propositional variables that makes the formula true. As when looking for Boolean variables x, y and z that satisfy the equation $(x \vee y \vee z) \wedge (\overline{x} \vee \overline{y}) \wedge (\overline{x} \vee y \vee z)$, $\wedge$ meaning "and", and $\vee$ "or" or "and". $\overline{\mathbf{x}}$ being the negation of x. The problem becomes very complex if the number N of variables becomes very high because to test their combinatorics with brute force, we will have to test 2^{N} combinations. This problem has been highlighted by Cook's theorem according to which the SAT problem is NP-complete. The SAT problem also has many applications, notably in constraint satisfaction, classical planning, model verification, diagnostics, up to the configurator of a PC or its operating system: we go back to propositional formulas and use a SAT solver.

Scrambling: spreading of initially local quantum information over the many-body degrees of freedom of a system, until it becomes inaccessible to any local measurement while remaining globally recoverable in principle. It is probed with OTOCs and bounded in speed by Lieb-Robinson bounds. Fast scrambling is a resource for random circuit sampling and a nuisance for error correction, since it turns a local error into a delocalized one.

Scale-out: generic information technology term describing the capacity to expand computing power with several processors connected to the other. This is done in classical server clusters and datacenters, using both hardware (multiple processors on same board, high-speed connectivity between boards and servers, high-speed data storage, ...). Such techniques are envisioned with quantum computing, consisting of connecting different processing units, usually using photons and entanglement resources.

Scattering: deflection of moving particles by some physical medium or radiation.

Schrödinger (equation, wave function): describes the evolution in time and space of the wave state of a quantum object with a mass like an electron, i.e. the probabilities of finding the object at a given place and time in time.

Schrödingerization: mathematical embedding that maps selected nonunitary or dissipative linear evolution equations into a higher-dimensional unitary Schrödinger-type evolution, generally by introducing an auxiliary variable or dimension. The resulting unitary dynamics can then be treated with quantum Hamiltonian-simulation or signal-processing techniques. The method does not automatically linearize nonlinear equations such as the full Navier-Stokes equations, and it does not remove state-preparation or readout costs.

Schrödinger wave function collapse: in the case of a qubit, the measurement update that assigns it one of its basis states ($|\mathbf{0}\rangle$ or $|\mathbf{1}\rangle$) in the measured basis, once the outcome is recorded. This must be distinguished from environment-induced decoherence, which suppresses the off-diagonal terms of the reduced density matrix without selecting any outcome and without requiring any collapse postulate, and which need not leave the system in a single definite pure state. Whether an actual physical collapse occurs is interpretation dependent, unitary formulations such as many-worlds and decoherent histories doing without it.

SDP, **LP**, **MIP** and **ILP**: classical mathematical programming formulations. LP is linear programming, optimizing a linear objective under linear constraints over continuous variables. MIP is mixed-integer programming and ILP is integer linear programming, where some or all variables are integers, which makes them NP-hard. SDP is semidefinite programming, optimizing a linear objective over positive semidefinite matrices. Quantum SDP solvers offer speedups in the problem dimension but with a bad scaling in precision, and mature classical solvers like CPLEX and Gurobi remain the baselines to beat.

Second quantization: many-body representation in which the basic degrees of freedom are occupation numbers of single-particle modes and observables are expressed with creation and annihilation operators obeying bosonic or fermionic commutation relations. In quantum computing, a fermionic problem in second quantization typically maps spin-orbital occupations to qubits through encodings such as Jordan-Wigner or Bravyi-Kitaev. It contrasts with first quantization, where registers encode particle coordinates or basis-state labels and antisymmetry is imposed on the many-particle wavefunction.

Second quantum revolution: covers advances in quantum physics since the 1980s, when we began to control the properties of individual quanta, at the level of photons (polarization, ...), electrons (spin) and atoms and use superposition and entanglement. It covers the uses of these properties in cryptography and telecommunications, quantum computing and quantum sensing. The term was created simultaneously in 2003 by Alain Aspect, Jonathan Dowling and Gerard Milburn.

SED (Stochastic Electrodynamics): fringe classical theory which replaces quantization by a real random background electromagnetic field with a zero-point spectrum. It is used by zero-point energy extraction startups like Jovion to justify their claims. It reproduces some harmonic oscillator results but fails on most quantum phenomena, and is not accepted as a substitute for quantum electrodynamics.

Semiclassical QFT: measurement-based implementation of a QFT that is immediately followed by computational-basis measurement. Controlled phase gates between output qubits are replaced by sequential measurements and classically feed-forward single-qubit phase corrections. In iterative phase-estimation or Shor constructions, a single control qubit can additionally be recycled across successive phase bits.

Semi-classical light: describes interactions between quantized matter (atoms, electrons) and classical light fields. Laser light belongs to this category.

SFQ: Single Flux Quantum, a digital logic technology used in superconducting electronics. It leverages the quantization of magnetic flux to represent binary data using extremely fast and energy-efficient pulses. SFQ circuits operate at cryogenic temperatures and are promising for high-speed, low-power computing applications, including qubit control systems as well, potentially, as classical computing components. In the qubit control realm, there are only two companies developing SFQ components: SEEQC (USA) and QuamCore (Israel).

Shelving: transferring the population of one qubit state into a long-lived metastable state so that it stays dark during the fluorescence readout, which is how trapped ions state discrimination reaches fidelities above 99.9%. AQT uses a 854 nm laser for this with calcium ions. Also named electron shelving, it was proposed by Hans Dehmelt.

Shor (algorithm): integer quantum factorization algorithm invented by Peter Shor in 1994. It would theoretically make it possible to break RSA public keys by decomposing them into prime numbers.

Shortcuts to Adiabaticity: or STA, are advanced control techniques in quantum physics and quantum computing enabling systems to evolve rapidly while mimicking the outcome of slow, adiabatic processes. Usually, adiabatic evolution requires gradual changes to a system's Hamiltonian to keep it in its ground state, but this slowness hits the wall of decoherence and noise in gate-based and analog quantum computing. STA bypasses this by introducing additional control fields or engineered protocols that suppress unwanted transitions and guide the system efficiently to its target state. STA is used with methods like counter-diabatic driving.

Sideband: motional sideband, transition located at the qubit frequency plus or minus the frequency of a trap motional mode, corresponding to the qubit flipping while adding, for the blue sideband, or removing, for the red sideband, one phonon of collective motion. Driving the red sideband implements resolved sideband cooling and driving both simultaneously with a bichromatic field creates Mølmer-Sørensen gates.

Silicon 28: silicon isotope allowing the creation of silicon wafers suitable for the creation of silicon qubits. Silicon 28 has a zero spin that does not affect the spin of the trapped electrons used to manage the qubits. It can then be deposited in a thin layer using silane gas (SiH_4) and CVD (chemical vapor deposition) on conventional silicon.

SIMD: Single Instruction Multiple Data, processing model applying the same operation to many data elements in parallel. It is the backbone of GPUs, GPGPUs and most AI accelerators, and is well suited to the matrix multiplications used in machine learning and in classical quantum computing emulators.

Simon (algorithm): oracle-based algorithm created by Daniel Simon in 1994 which finds the hidden period s of a two-to-one function verifying f(x) = f(x ⊕ s), with an exponential speedup over classical algorithms in the query model. It is an instance of the abelian hidden subgroup problem and it directly inspired Peter Shor's integer factoring algorithm.

Single mode: said of an optical fiber using a small core (around 9 μm) and transporting a single light beam that doesn't bounce off the inside walls of the fiber. It has low loss and is adapted to long distance transport, usually in the 1,310 nm or 1,550 nm wavelengths. These cables still use multiple wavelengths, with WDM (wave-division multiplexing). Also said of a single mode photon, see Multimode.

SKR. Secret Key Rate, also secure key rate, the rate in bits per second of keys generated by a key generation system like a QKD, after sifting, error correction and privacy amplification. This is the main QKD figure of merit with distance and QBER.

Singlet-triplet qubit: encoded qubit using two electron spins, typically in a double quantum dot. A common logical basis uses the singlet $|S\rangle$ and unpolarized triplet $|T_0\rangle$, controlled by exchange and by a magnetic-field or Zeeman-energy gradient.

Sign problem: difficulty in Monte Carlo simulation when different configurations contribute positive and negative, or complex, statistical weights whose cancellations make the signal-to-noise ratio exponentially small. It is particularly important in many fermionic models, although some Hamiltonians, bases and parameter regimes are sign-free. A generic polynomial-time solution of the fermionic sign problem is NP-hard.

Sisyphus cooling: polarization-gradient sub-Doppler cooling mechanism described in 1989 by Jean Dalibard and Claude Cohen-Tannoudji. In the usual picture, an atom repeatedly climbs a light-shift potential hill before optical pumping transfers it to a lower-energy sublevel, removing kinetic energy. It can cool atoms well below the Doppler limit and, under suitable conditions, toward the photon-recoil energy scale.

Skyrmion: vortex-like topological quasiparticle excitation of spins in a magnetic material, forming a nanometer-scale magnetic whirl with particle-like properties. Named after Tony Hilton Royle Skyrme who formulated the underlying field theory in 1961, predicted in magnetic materials in 1989 by Bogdanov and observed in 2009 in MnSi crystals. Their topological protection and their nanometer size make them candidates for high-density memories, spintronics, neuromorphic processing and even qubits.

SLM: Spatial Light Modulator, a pixelated device that modulates the phase and/or intensity of an optical field. Phase SLMs used for neutral-atom tweezer arrays are commonly based on liquid-crystal-on-silicon technology and create programmable holograms that generate many optical traps. The trap pattern is diffraction-limited, while calibrated atom positions can be estimated and controlled much more precisely than the optical spot size.

SNAQ (Shuttling-capable Narrow Array of spin Qubits): proposed silicon spin-qubit architecture that uses coherent electron shuttling in narrow arrays to reduce wiring and geometrical overhead while preserving interactions needed for quantum error correction.

SNSPD: Superconducting Nanowire Single-Photon Detector, a photon detector made of a meandering superconducting nanowire biased just below its critical current, where a single absorbed photon triggers a measurable resistive transition. It has a high detection efficiency, low dark counts and low jitter. Such detectors are used in photonic quantum computing, QKD and quantum sensing. They operate between 1K and 4K, which needs a pulse tube or a 1K stage but no dilution.

SoC: System on Chip, single die integrating a CPU, a GPU, memory controllers, signal processors, radio functions and various accelerators. Smartphone chips are the archetype.

SOI: Silicon On Insulator, a wafer where a thin silicon device layer sits on a buried silicon oxide layer. The index contrast between the two is what confines light in silicon photonic waveguides. Not to be expanded as "silicon oxide insulator". The technique is also used with silicon spin qubits wafers. These wafers are manufactured by the smartcut technology invented at CEA-Leti and industrialized by SOITEC.

SPAC: special purpose acquisition company. A funding mechanism used by IonQ and HQS (Honeywell Quantum Systems) consisting of getting acquired by an investment fund creating a dedicated fund for the company and raising money on both limited partners (individual corporate ventures and the like) and on the stock market like the NASDAQ.

SPAD: Single Photon Avalanche Diode, a reverse-biased photodiode operated above breakdown so that a single absorbed photon triggers an avalanche. It detects photon arrivals but not photon number, works at or near room temperature, and has lower efficiency and higher dark counts than an SNSPD at telecom wavelengths.

SPAM: State Preparation And Measurement, the combined error or fidelity associated with preparing a known state and discriminating the measured state. SPAM is not a gate-fidelity metric unless a specific benchmarking protocol deliberately folds gate operations into the sequence. It is usually reported as an error probability or fidelity for the preparation-plus-readout process.

Spectral lines: lines obtained graphically after decomposing an electromagnetic radiation into frequency components, usually with some spectrography apparatus. You have absorption and emission spectral lines depending on the source of light (indirect, direct). Each line corresponds to the emission or absorption of photons in atoms at particular energy levels, then wavelength and frequency.

Spectral decomposition: mathematically, spectral decomposition applies to operators and not to vectors. A Hermitian operator A with a discrete nondegenerate spectrum decomposes as $A = \sum_i a_i|a_i\rangle\langle a_i|$, and a state vector is then expanded in that eigenbasis as $|\psi\rangle = \sum_i c_i|a_i\rangle$. It can be related to the wave-duality aspect of all quantum objects. A quantum object pure state is indeed decomposable in a coherent superposition of elementary waves, the eigenstates.

Spin: intrinsic quantum angular momentum carried by elementary and composite particles. For a spin-1/2 particle such as an electron, measurement along a chosen axis gives two projections, conventionally $+\hbar/2$ and $-\hbar/2$. The particle does not have a classical vector that is literally rotating in space. Composite-particle spin results from quantum coupling of constituent spin and orbital angular momenta. Integer-spin particles are bosons and half-integer-spin particles are fermions.

SpinBus: proposed semiconductor spin-qubit architecture in which coherent electron shuttling transports spin states between spatially separated processing sites, reducing the need for dense nearest-neighbor static coupling.

Spin-to-charge conversion: readout step that maps a spin state or spin parity onto an electrically distinguishable charge occupation or tunneling event. The resulting charge signal is then detected by a SET, quantum-point contact or gate-based RF sensor.

Spin-boson model: describes the interaction between a two-level quantum system (referred to as a spin) and a bosonic environment (a collection of quantum harmonic oscillators or QHOs). It is used in fields including condensed matter physics, quantum optics, and quantum information science, to study decoherence and dissipation.

Spin glass: magnetic material where the electron spins freeze in a disordered configuration below a non-zero temperature, because of competing and frustrated interactions. Its energy landscape with a great many local minima is the origin of several optimization and annealing benchmarks.

Spinor: vector representing the spin of a 1/2 spin particle using the notation $\chi = \begin{pmatrix}\chi_1 \\ \chi_2\end{pmatrix}$, with $\chi_1$and χ_2 being the complex components of the spin up and down along a given Z direction. Given its normalization constraints (norm 1, and no global phase), it belongs to a Hilbert space of dimension 2.

Spintronics: a set of technologies based on the manipulation of electron spin. It is found in memristors as well as in hard disks using giant magnetoresistance (GMR). The latter was discovered by Albert Fert (France) and Peter Grünberg (Germany) independently and the same year, in 1988. This got them the Nobel prize in Physics in 2007.

Spontaneous emission: when an atom emits a photon resulting from the transition of an electron from an excited to a lower energy state.

Spontaneous Four-Wave Mixing (SFWM): photons pairs source category based on pumping nonlinear optical waveguides or cavities.

Spontaneous Parametric Down-Conversion (SPDC): system converting high-energy photons into pairs of photons of lower energy, based on pumping nonlinear optical waveguides (crystals) or cavities. It can be used to create pairs of entangled photons as well as single photons sources.

SPOQC: Spin-Optical Quantum Computing, the fault-tolerant architecture introduced by Quandela in 2023 which uses quantum-dot spins as computing qubits and photons as ancillas, connecting the spins through probabilistic repeat-until-success CZ gates and photon routing. Its gating requirement is a long enough quantum dot spin coherence time.

Squeezed states of light: correspond, in a quadrature or phasor diagram representation, to wave functions which have an uncertainty in one of the quadrature amplitudes (phase or photon number) smaller than for the groundstate corresponding to the vacuum state. It can be generated by different means like a parametric down conversion. In other words, it's a way to increase the measurement precision of one of the photons characteristics at the expense of another characteristic.

Squeezing: technique that reduces uncertainty (or quantum noise) in one property of a quantum system like position or phase while increasing it in a complementary property, such as momentum or amplitude, in accordance with Heisenberg's uncertainty principle. This redistribution allows for more precise measurements of the targeted variable, and is crucial in applications like quantum sensing, atomic clocks, and gravitational wave detection. Spin squeezing is a variant of squeezing that improves the precision of measurement of some quantum object spin in one direction (Z) at the expense of the two complementary directions (X, Y).

SQUID: Superconducting Quantum Interference Device, an extremely sensitive magnetic-flux sensor based on a superconducting loop interrupted by one or more Josephson junctions. SQUIDs are used in magnetometry, MEG, cryogenic detector readout and superconducting electronics. They are also used to read out some superconducting qubits, but a SQUID is not itself synonymous with a superconducting qubit.

SRAM: Static Random Access Memory, fast volatile memory using six transistors per bit and requiring no refresh. It sits on the processor die and supports the caches. Its area has nearly stopped shrinking with recent nodes, which is one reason why cache sizes and chip costs are growing.

Stabilizer gates: quantum gates that are used in error correction systems: CNOT, H (Hadamard) and P (phase).

Standard model: theory describing the known elementary particles, the twelve fermions of matter with quarks and leptons, the gauge bosons mediating the electromagnetic, weak and strong interactions, and the Higgs boson whose existence was confirmed at CERN in 2012. The expression dates back to 1975. It excludes gravity, dark matter, dark energy and neutrino masses, which is why it is deemed incomplete.

Standard quantum limit: characteristic precision scaling for independent, uncorrelated probes in many sensing problems. The estimator standard deviation typically scales as $1/\sqrt{N}$ and its variance as $1/N$, where N is the relevant number of independent resources or trials. It is often associated with the shot-noise limit. Entanglement or squeezing can beat this scaling in suitable measurements, subject to loss and noise. See Heisenberg limit.

Stark shift or Stark effect: shifting and splitting of spectral lines of atoms and molecules due to the presence of an external electric field. This is the electric-field analogue of the Zeeman effect which is linked to the effect of the magnetic field,

State reduction: update rule applied to the description of a system after a measurement, which replaces the pre-measurement state by the one consistent with the recorded outcome. The result is definite in the basis of the measured observable and not in any other, and whether this update describes a physical process or only a change of information is interpretation dependent. For a projective measurement of a qubit in the computational basis, the outcome is one of the two basis states: excited or non-excited, horizontal or vertical polarization for a photon, spin orientation for an electron, excited state for an ion or a cold atom, etc.

Retargetability: compiler property describing how readily the same source program or intermediate representation can be compiled for different quantum hardware backends, gate sets, connectivity graphs and control constraints.

Strong simulation: classical simulation task that computes specified output amplitudes, probabilities, marginals or expectation values of a quantum circuit rather than merely drawing samples. A full state vector can support strong simulation, but strong simulation does not imply that the simulator must store the full state vector.

State vector: Hilbert space vector representing a pure state of a quantum object.

Stationary qubits: stationary (or static) qubits, which do not move in a circuit. This is the case of superconducting qubits, trapped ions and cold atoms qubits as well as electron spin qubits. They are opposed to flying qubits that move, like photons.

Stern-Gerlach experiment: deviation of projected atoms placed under an intense magnetic field, which is explained by electron intrinsic angular momentum or spin.

Still: also called the boiler, the stage of a dilution refrigerator sitting around 700 mK to 1K where helium 3 is selectively evaporated out of the dilute phase, its vapor pressure being much higher than that of helium 4. The pumping applied on the still is what drives the helium 3 circulation through the whole dilution loop.

Stimulated emission: when an incident photon is not absorbed by an excited atom but stimulates the atom to emit a second photon with the same wavelength. This principle is used in lasers to amplify light in their cavity.

String theory: theory where elementary particles are one-dimensional vibrating strings of the order of the Planck length rather than point particles, with vibration modes defining the particle nature. It naturally contains a massless spin 2 state identified with the graviton, which makes it a candidate quantum theory of gravity. Its supersymmetric extension, superstring theory, adds fermions and requires 10 dimensions, with five variants that M-theory attempts to unify in 11 dimensions. It has no experimental confirmation to date.

Sturm–Liouville problem: mathematical problem consisting of solving some second-order differential equations where the unknown is a density function and finding eigenvalues and eigenvectors and satisfying bound limits. Solving Schrodinger's wave equation is a particular case of such a problem.

Superabsorption: collective effect where N emitters placed in a cavity absorb light faster than N independent emitters would, the counterpart of superradiance. It is the mechanism invoked for the fast charging of quantum batteries, with an effective coupling scaling as $\sqrt{N}$ and a charging time scaling as $1/\sqrt{N}$.

Superatom: ensemble of atoms confined within one Rydberg-blockade volume and collectively driven so that, to a good approximation, at most one Rydberg excitation is shared by the ensemble. The symmetric collective ground state and single-excitation state can behave as an effective two-level system with collectively enhanced optical coupling.

Superconductivity: the ability of some materials to conduct electricity without resistance. It generally occurs at low temperatures. It is linked to the behavior of electrons in some crystalline structures who happen to gather in pairs, Cooper pairs, who become bosons, and have a collective behavior enabling them to move around within the structure. Superconducting and electron spins qubits use this effect. The first with superconducting loops traversing a Josephson barrier and all of them with cabling and some surrounding electronics.

Superdense coding: entanglement-assisted communication protocol in which Alice can transmit two classical bits by sending one qubit to Bob when Alice and Bob already share one entangled qubit pair. It was proposed by Charles Bennett and Stephen Wiesner in 1992 and experimentally demonstrated in 1996 by Klaus Mattle, Harald Weinfurter, Paul Kwiat and Anton Zeilinger. It does not violate the Holevo bound because the pre-shared entangled pair is an additional resource that must be included in the communication accounting.

Superdeterminism: the position according to which the apparent randomness of quantum measurements comes from underlying deterministic processes whose hidden variables also correlate the measured systems with the choice of the measurement settings, possibly at the Planck scale. It escapes Bell's theorem by denying its statistical independence assumption. Proposed by Carl H. Brans in 1988, named by John Bell in 1985 and promoted by Sabine Hossenfelder and Tim Palmer.

Superfluidity: state of a fluid flowing with zero viscosity and infinite thermal conductivity. Helium 4 becomes superfluid below 2.17K at ambient pressure, as a manifestation of Bose-Einstein condensation. Helium 3, being a fermion, must form Cooper pairs first and becomes superfluid only at 2.49 mK on its melting curve and 0.93 mK at saturated vapor pressure, which is well below the 10 to 20 mK of a dilution refrigerator. This difference between the two isotopes is what makes dilution refrigeration possible. The superfluid film of helium 4 creeping up the still walls is a parasitic effect that designers block with a film burner or a knife-edge orifice.

Supersonic propagation of correlations: regime in which correlations spread faster than any finite light-cone velocity, observed in systems with cavity-mediated or otherwise global couplings. It is not a violation of the Lieb-Robinson theorem, whose hypotheses require interactions that decay with distance, but a case where those hypotheses simply do not apply. It is accessible in analog platforms with long-range or all-to-all couplings, much less so in gate-based architectures.

Superoperator: linear operator that transforms a linear operator like a density matrix. It must be a CPTP map, completely positive and trace preserving map (see CPTP definition).

Superposition: property of quantum objects and qubits to be able to be in several states at the same time. This can be explained by the wave-like nature of quantum objects. A superposition is a linear combination of quantum eigenstates (the $|0\rangle$ and $|1\rangle$ in the case of qubits).

Superradiance: phenomenon first described by Robert H. Dicke in 1954 where under certain conditions, a group of atoms behaves like a single giant dipole, leading to enhanced radiation. Excited atoms or quantum emitters radiate light collectively in a way that dramatically enhances the intensity and speed of emission compared to independent spontaneous emission. In quantum optics, superradiance occurs when a group of N emitters, such as excited atoms, interact with a common light field. If the wavelength of the light is much greater than the separation of the emitters, then the emitters interact with the light in a collective and coherent fashion, causing the group to emit light as a high-intensity pulse (with rate proportional to N2).

Superselection. A superselection rule forbids certain quantum states from being coherently superposed, even though such superpositions are mathematically possible. It divides the space of quantum states into distinct sectors called superselection sectors between which no observable can detect interference or transitions. For example, states with different electric charges cannot be superposed because charge conservation prevents any physical process from connecting them. This means that if two states belong to different sectors, any observable will yield zero when trying to measure their overlap, effectively making them behave like separate classical alternatives. One example is the parity superselection rule with fermionic systems, which forbids superpositions between states of even and odd fermion number.

Supersolid: state of matter which is simultaneously crystalline, with a spontaneous spatial density modulation, and superfluid, with a global phase coherence. Predicted in 1969 by David J. Thouless and, independently, by Alexander Andreev and Ilya Lifshitz. A 2004 claim on solid helium 4 was retracted by its own authors in 2012 and the first uncontested supersolids were obtained in 2019 with ultracold dipolar gases of erbium and dysprosium.

Surface codes: type of quantum error correction code that is tolerant to high qubits error rates and require a larger number of physical qubits per logical qubits and have a design constraint for physical qubits that must be connected to their immediate neighbors in a 2D structure. This is the QEC architecture chosen by Google.

Surface trap: ion trap where all electrodes sit in a plane on a chip surface, the ions floating a few tens of micrometers above it. It is manufactured with standard semiconductor processes at foundries like Infineon, Global Foundries, Skywater or NXP, which makes it scalable and allows integrating waveguides, photodetectors and microwave circuitry on chip. Its counterpart is a higher anomalous heating rate than with 3D traps.

SVD: singular value decomposition, a mathematical process to factorize any mxn complex values matrix into three matrices: a unitary mxm matrix, a rectangular diagonal mxn matrix (which has no zero values only in its diagonal) and a unitary nxn matrix. SVD is used in QSVT algorithms.

SVM (Support Vector Machine): supervised classification method separating data classes with an optimal margin hyperplane in a feature space, using a kernel function to handle nonlinear separations. Its quantum version QSVM replaces the classical kernel by a quantum kernel estimated on a QPU. Its advantage depends entirely on the existence of a classically hard to estimate but useful kernel, which has not been demonstrated on real data sets so far.

SWAP: quantum gate that inverts the state of two qubits. It is very useful since most qubit geometries don't allow an any-to-any qubit connection. The SWAP gate enables this kind of connection that is mandatory for many quantum algorithms.

s-wave, p-wave and d-wave: classification of superconductors by the orbital angular momentum of the Cooper pair wave function, respectively 0, 1 and 2, with letters borrowed from the sharp, principal and diffuse notation of atomic spectroscopy. s-wave pairing is isotropic and is the conventional BCS case, which is why it is the one used in Josephson junctions and superconducting qubits. d-wave, typical of the cuprates, is anisotropic with a gap changing sign under a 90 degree rotation and vanishing along nodal directions.

SWSPD: Superconducting Wide-Strip Photon Detector, a variant of the SNSPD using a wider superconducting strip instead of a meandering nanowire. It offers higher efficiency and a larger active area, and operates in the 1,550 nm telecom band.

SYK (Sachdev-Ye-Kitaev): model of N Majorana fermions with random all-to-all interactions and strongly chaotic dynamics, derived from the 1993 Sachdev-Ye spin liquid, revisited by Alexei Kitaev in 2015 and formalized by Juan Maldacena and Douglas Stanford in 2016. Its low-energy behavior is holographically dual to two-dimensional Jackiw-Teitelboim gravity, which makes it a favorite testbed for quantum simulations of quantum gravity on NISQ QPUs. Its sparse variants reduce the number of terms to simulate.

Symmetry: refers to situations where physical properties remain unchanged when a specific transformation is applied to a system like spatial rotations, translations, reflections, time inversions, and more. Symmetry is deeply linked to the conservation laws in physics, where the invariance of certain quantities like energy, momentum, and angular momentum under specific transformations leads to the conservation of those quantities. For example, the Schrödinger equation exhibits rotational symmetry. See also antisymmetry. The Noether's theorem establishes a deep connection between symmetries and conserved quantities in physical systems.

Sympathetic cooling: cooling the data ions through their Coulomb coupling with other ions of a different species or isotope which are laser cooled, without illuminating the data ions themselves. It removes the motional heating accumulated during shuttling and gates without destroying the stored quantum information.

Szilard engine: the 1929 single-particle idealization of Maxwell's demon by Léo Szilard, where one bit of information about the particle position is converted into k_BT ln2 of extractable work. It is the direct ancestor of the Landauer limit and of information thermodynamics.

T gate: single qubit gate implementing a "quarter turn" phase rotation around the Z axis in the Bloch sphere. It is a very important gate enabling (on top of the three-qubit Toffoli gate) the creation of a universal gate set.

T-count: number of T gates required in a quantum algorithm. It is an important metric since T gates are the most expensive to correct with FTQC.

T-depth: number of circuit layers implementing one or several T gates in a quantum algorithm.

Tachyon: hypothetical particle traveling faster than light, with an imaginary rest mass. No tachyon has ever been observed. In quantum field theory, a tachyonic mode is now usually interpreted as the signature of an unstable vacuum rather than as a real superluminal particle.

Tau scaling law: principle introduced by Huawei in May 2026 at IEEE ISCAS proposing to replace geometric scaling with the reduction of the signal propagation time τ as the guiding metric of semiconductor progress. It is implemented with LogicFolding 3D stacking and presented as a way to reach a transistor density equivalent to a 1.4 nm node by 2031 without any EUV lithography, a claim which relies on a favorable density formula and must be taken with caution.

TCI (Tensor Cross Interpolation): classical learning algorithm which builds an MPS representation of a function or of a large tensor from a limited number of its evaluations, chosen adaptively with a cross approximation scheme, without ever forming the full tensor. It is the companion of the quantics representation for PDE solving and function compression.

TCO: Total Cost of Ownership, the sum of the fixed costs (capex, mostly hardware acquisition) and of the variable costs (opex, including the energetic costs) of a computing solution over its lifetime. Divided into the economical benefit it generates, it gives the return on investment (ROI) of the solution. For FTQC systems, energy can represent over 30% of the TCO, which is what makes energetics an economic and not only an environmental question.

TDA (Topological Data Analysis): extraction of shape-related and connectivity summaries from high-dimensional data, using persistent homology on a simplicial complex built from the data points and characterized by its Betti numbers. It identifies clusters and holes in data. The LGZ quantum algorithm proposed by Seth Lloyd, Silvano Garnerone and Paolo Zanardi in 2016 claimed an exponential speedup on Betti number estimation, later reduced to a polynomial advantage by dequantization results, and its practical regime requires FTQC resources.

TDP: Thermal Design Power, the amount of heat that a chip cooling system must be able to evacuate, in watts. It is a design target and not the maximum instantaneous power draw. It reaches 2,300 W for a Nvidia Rubin GPU package and about 15 kW for a Cerebras wafer-scale engine, to be compared with the few kW of a dilution refrigerator hosting superconducting qubits.

Technology node: commercial label given to a semiconductor manufacturing generation, like 5 nm, 3 nm or 2 nm. Since about 2017, these names no longer correspond to any physical transistor dimension and have become pure marketing denominations. A 3 nm node has a 24 nm metal pitch and a 48 nm gate pitch, and its smallest features are the 4 nm nanosheet thickness and a sub-nanometer gate oxide, which is a vertical and not a horizontal feature.

Tensor network: factorization of a high-dimensional tensor, like the 2^n amplitudes state vector of n qubits, into a network of small interconnected tensors whose graph structure mirrors the entanglement structure of the state. The main families are MPS, MPO, PEPS, TPS, TTN and MERA, with DMRG and tensor cross interpolation as the optimization and learning algorithms running on top of them. Tensor networks are used to emulate quantum circuits on classical hardware, to compress quantum circuits and data encodings, and they are the main source of dequantization results.

TF-QKD: Twin-Field Quantum Key Distribution. Interference-based QKD family in which Alice and Bob send phase-related optical fields to an untrusted central measurement station. Its secret-key-rate scaling can beat the direct-transmission repeaterless PLOB scaling without using a quantum repeater, although practical implementation requires demanding phase stabilization and very low detector noise.

TFLN: Thin-Film Lithium Niobate, a photonic platform combining a strong Pockels electro-optic effect with low propagation loss, allowing fast, low-heat phase shifters and modulators. It is pursued by Q.ANT, Quantum Computing Inc, TuringQ and Xanadu with Hyperlight, as an alternative to thermo-optic phase shifters.

TES: Transition Edge Sensor, a superconducting microcalorimeter biased at its superconducting transition, where the temperature rise caused by absorbed photons is proportional to the deposited energy. It is intrinsically photon-number resolving with very high efficiency, but it is slow and must be cooled to about 100 mK, which requires a dilution refrigerator. Used by Xanadu in their PNRDs. It currently used by Xanadu in its heardling-based photon generation.

THC (Tensor Hypercontraction): factorization technique coming from classical electronic structure theory which decomposes the two-electron integrals tensor into a product of low-rank factors, reducing the Hamiltonian representation cost from $O(N^4)$ to $O(N^2)$ with N the number of orbitals. It cut the T-gate counts of FTQC quantum chemistry algorithms by orders of magnitude, as in the FeMoCo resource estimates.

Theory of everything: hypothetical single framework consolidating quantum physics, the standard model and general relativity. Candidates include string and superstring theories, loop quantum gravity, causal sets and twistor theory. None is complete and none has experimental support so far.

TSP (Traveling Salesperson Problem): NP-hard combinatorial optimization problem searching the shortest tour visiting each of n cities exactly once. It is the canonical benchmark of quantum optimization, addressed with QUBO and HUBO encodings, QAOA, VQE, quantum annealing, Grover adaptive search and quantum walks, so far with no quantum advantage. The classical Concorde solver handles instances with tens of thousands of cities, which sets a high bar.

T_1: qubit amplitude coherence time, which indicates the end of coherence of the qubits linked to a loss of amplitude ("energy relaxation"). Aka qubit lifetime.

T_2: phase related coherence or time when some phase shift occurs, i.e. a rotation around the z axis in the Bloch sphere of the qubit state.

Tabu search: metaheuristic local search method used for mathematical optimization. It currently fares better than quantum algorithms using QAOA (for gate-based systems) or QUBO (for annealers/simulators).

TDSE: acronym for time dependent Schrodinger equation.

Tensor: in multilinear algebra and differential geometry, a tensor designates a very general object whose value is expressed in a vector space. In quantum physics and computing, tensors are used to describe the state of a compound quantum object with several quanta or qubits. A qubit is represented by a vector of 2 complex numbers. A register of N qubits is represented by a vector with 2^N complex numbers resulting from the tensor product of N vectors of 2 complex numbers. In a way, the tensor product represents the combinatorial space of the values that a combination of qubits can take. Before entanglement comes into play to mix things up and create non separable vector states, i.e., which cannot be expressed as tensor products of individual quantum states.

TeraQuop: tera quantum operations, a threshold for fault-tolerant quantum computers before a single logical error appears. Now, it depends on how you define an error.

Thermodynamics first law: the internal energy of an isolated system is a constant, applying the principle of the conservation of energy. Inside the system, the form of energy can however be transformed.

Thermodynamics second law: the entropy of a closed system cannot decrease. In other words, heat does not flow spontaneously from cold to hot objects. Was formalized by Rudolph Clausius in 1854.

Time crystal: also, DTC for discrete time crystal is a topological state of condensed matter at very low temperature where atoms in their ground state are periodically arranged in both space and time with in a permanently oscillating structure with a given period (for discrete time crystals).

Time domain: deals with the evolution of some value and signal over time. It's frequently opposed to frequency domain where a signal is analyzed by decomposing it into frequencies (mathematically, with a Fourier transform).

Time reversal: clearly a misnomer. It describes situations when from a given point in time, for some physical property like energy, a system presents a symmetry when you evaluate it with look forward or backward at time. It's a mathematical symmetry. You don't change the arrow of time backwards. Time reversal is not a time machine!

Toffoli (gate): also called CCNOT is quantum gate operating on three qubits which modifies the value of the third qubit if the value of the first two is 1.

Topological: topological quantum computing is based on the notion of anyons which are "quasiparticles" integrated in two-dimensional systems. The anyons are asymmetric and two-dimensional physical structures whose symmetry can be modified. This allows the application of topology principles with sets of successive permutations applied to pairs of anyons that are in proximity in circuits. The associated algorithms are based on the concepts of topological organizations of braids or nodes ("braids"). There is an algorithmic equivalence between computation with universal gated qubits and topological qubits.

Topological insulator: material whose bulk is insulating and whose surface or edges carry conducting states with counterpropagating spins and no net charge current. These states are protected by a topological invariant and are robust against disorder. Predicted for graphene in 2005 by Charles Kane and Eugene Mele, then measured in 2007 in mercury telluride quantum wells at Würzburg. High-throughput screenings have since catalogued thousands of them.

Time-bin entanglement: encoding where a photon qubit state is carried by its arrival time, in an "early" or "late" bin created by sending the photon through an unbalanced interferometer whose long arm adds a fixed delay. Two photons prepared this way have correlated time-bin states. Introduced in the late 1990s as a refinement of the energy-time entanglement proposed by James Franson in 1989, it is far more robust than polarization entanglement in optical fibers, where birefringence scrambles polarization over long distances, which makes it the encoding of choice for long haul quantum communications.

Tsirelson bound: maximum value $2\sqrt{2} \approx 2.83$ that the CHSH correlation S can reach within quantum mechanics, demonstrated by Boris Tsirelson in 1980. It sits above the local realism ceiling of 2, which is what a Bell test has to exceed to be passed, and below the algebraic maximum of 4 that a hypothetical stronger-than-quantum theory could reach, such as the Popescu-Rohrlich (PR) box [904]. The gap between 2.83 and 4 is one of the open questions of quantum foundations, since no known physical principle forbids the higher values.

Transmon: transmission-line shunted plasma oscillation qubit, the dominant superconducting-qubit design. It is a Cooper-pair box operated at large E_J/E_C, with a large shunt capacitance that strongly suppresses charge dispersion. The Josephson nonlinearity makes the oscillator energy levels unequally spaced so that the two lowest states can encode a qubit and be selectively driven with microwave pulses. The word "plasma refers here to the Josephson plasma mode of the circuit, not to a free-electron plasmon in a normal metal.

Transpiler: source-to-source compilers used in classical computing and quantum computing to use the universal gate set available in the quantum processor. It is usually associated with an optimizer that optimizes the source code to reduce the number of gates to execute and as a result, reduce errors (particularly with NISQs) and the algorithm execution time.

Transpilation: code conversion and optimization achieved by transpilers.

Transversal gates: relate to quantum error correction and fault tolerance. These are gates implemented with QEC where there is a 1-1 correspondence and link between all qubits from a given corrected qubit with a similar corrected qubit, when they are assembled through concatenation. This mechanism limits the propagation of errors between logical and physical qubits.

Trapped ions: these are ions used in certain types of quantum computers. They are usually trapped magnetically or electrically, and their state is controlled with lasers. Their readout uses a laser excitation and an imager readout of the resulting ions fluorescence. Trapped ions are controlled by ion traps circuits, using electromagnetic waves in the microwave regime and coming from laser beams.

Trotterization: technique used in quantum computing that breaks down the evolution of quantum systems into smaller time steps. This time discretization is used to simulate the time evolution of quantum systems with complex interactions, making it easier to implement it with quantum algorithms.

Trusted node: intermediate QKD-network relay that receives or reconstructs key material and forwards fresh keys to the next link. End-to-end security therefore requires physical and operational trust in every such intermediate node.

TSV: Through Silicon Via, vertical copper interconnect crossing a silicon die to connect its two faces. It enables 3D stacking of chips, in HBM memory stacks, in chiplets and increasingly in superconducting qubit chips where signals are routed from the back side to avoid crowding the qubit plane.

TTN (Tree Tensor Network): tensor network with a hierarchical tree topology which encodes multiscale and hierarchical data with a logarithmic distance between any two sites, contrarily to the linear chain of an MPS. It is used for strongly correlated systems, quantum chemistry and the computation of thousands of vibrational eigenstates.

TTSB: Time Translation Symmetry Breaking, the property that defines a time crystal, whose structure oscillates with a period which is not the period of the drive that sustains it.

Tunnel effect: property of a quantum object to cross a potential (or energy) barrier even if its energy is less than the minimum energy required to cross this barrier. This effect is used in D-Wave's quantum annealers to quickly determine the minimum energy of a complex system ("Hamiltonian" implemented as an Ising model).

Twistronics: engineering of the electronic properties of stacked two-dimensional materials by controlling the rotation angle between the layers. At the magic angle of about 1.1 degrees, bilayer graphene develops flat bands, correlated insulating states and superconductivity.

Two-Level Systems (TLS): other descriptor of quantum systems used to implement qubits. A qutrit is a three-level system.

TWPA (Travelling Waves Parametric Amplifiers) microwave readout amplifiers implemented in a long array of SQUIDs. Their broad bandwidth that can reach 2 GHz with a 15 dB amplification enables up to 20 qubits readout multiplexing. But it depends on the gate speed since the faster the gate, the smaller the microwave pulse bandwidth will be large.

Type I and type II superconductors: type I superconductors have a single critical magnetic field B_C, expel the magnetic flux entirely below it and lose superconductivity abruptly above it. They are usually pure metals like lead. Type II superconductors have a lower critical field B_{C1} and an upper critical field B_{C2}, and between the two they let the flux penetrate as quantized vortices while staying superconducting. This is what makes NbTi and the cuprates usable in MRI magnets, particle accelerators and maglev trains.

UCC (Unitary Coupled Cluster): quantum chemistry ansatz built from the exponential of an anti-Hermitian excitation operator, usually truncated at single and double excitations (UCCSD). It is chemically motivated and more accurate than hardware-efficient ansätze but generates deep circuits, which is why ADAPT-VQE and PQE were created to build or optimize it more efficiently.

UHV: Ultra High Vacuum, the ultra-high vacuum required to operate certain types of qubits. It is mainly used for cold atoms and trapped ions. Superconducting qubits are integrated in a vacuum cryostat that does not require ultra-high vacuum.

UBDM (Ultralight Bosonic Dark Matter): class of dark-matter models in which very light bosons have very large occupation numbers and can often be treated locally as coherent oscillating classical fields. Candidate fields include axions, axion-like particles, scalar fields and dark photons over model-dependent mass ranges.

Ultraviolet catastrophe: expression of Paul Ehrenfest, linked to the Rayleigh-Jeans law proposed in 1900 to explain the black body radiation spectrum, which was diverging to infinite values as the temperature was growing, when reaching ultraviolet wavelengths. Planck's law based on quanta solved the problem and got rid of the ultraviolet catastrophe.

Unary iteration: technique of Ryan Babbush et al. building the one-hot indicator qubits of an address register one at a time to apply an indexed operation. It implements a SELECT or a QROM lookup over N entries with 4N-4 T gates and only O(log N) ancilla qubits, its T-count being independent of the data word width. It is the reference construction against which any claim about the cost of a QROM query should be checked.

Unary gates: single qubit gates. Not to be confused with unitary operations that are the result of the combination of all qubit gates on a given set of qubits. A unitary transformation of the computational state vector is a matrix operator that is equal to its transconjugate. It is a mathematically reversible operation.

Uncompute trick: reversible-computing technique that applies the inverse of a computation to erase intermediate "garbage" and disentangle work ancillas while preserving the desired result in an appropriate output register. Bennett's compute-copy-uncompute construction can copy a classical computational-basis result before reversing the work computation. An arbitrary unknown quantum state cannot in general be copied this way because of the no-cloning theorem. The extra gate cost depends on which subcomputation must be reversed and is not universally an exact factor of two for the whole algorithm.

Unconventional Computing: computing methods that do not fall under the classical computing principles of Turing and Von Neuman machines. Covers non-traditional tools and methods that include, but are not limited to, quantum computers. It also includes molecular computers and neuromorphic processors.

Unitary operation: linear operation on a vector that preserves its length. In the case of qubits whose vector always has a length of 1, the unitary quantum gates apply on it a transformation that preserves this length and is also reversible. In the representation of qubits in the Bloch sphere, the operation rotates the vector representing the state of the qubit in this sphere.

Universal quantum computer: most generic form of a quantum computer exploiting a universal quantum gate set, and which can both simulate quantum physics and implement any operations of a classical computer.

Universal quantum gates: sets of quantum gates from which all other quantum gates can be reproduced to create any unitary transformation on any number of qubits (by approximation and under a given error rate). It requires a non-Clifford group gate, like a T gate or a Toffoli gate.

Unruh effect: relativistic thermodynamic effect with a black body radiation showing up in vacuum at relativistic speed. Il has some connection with quantum noise.

Vacuum fluctuation: perpetual fluctuation of quantum fields in their ground state, a direct consequence of quantum field theory and of the indeterminacy principle. It explains spontaneous emission, the Lamb shift, the electron anomalous magnetic moment and the Casimir effect. It is a noise source in high-precision measurements and in photonics. It cannot be used as an energy source since it is by definition the lowest energy state of the fields.

Vacuum polarization: screening of an electric charge by the virtual electron-positron pairs it creates in its vicinity, which makes the effective charge and the fine structure constant depend on the energy scale of the probe. It contributes about −27 MHz to the 1,057 MHz Lamb shift and would make the vacuum birefringent under an extremely intense electromagnetic field.

Value migration: economic concept popularized by Adrian Slywotzky in 1995 describing how value shifts from one business design to another within an industry. Quantum computing is likely to complement classical computing rather than to replace it, which limits the value migration it could trigger in the computing sector.

Variational algorithm: see VQA.

von Klitzing constant: $\mathrm{R}_K = \mathrm{h}/\mathrm{e}^2 = 25812.80745\ \Omega$ exactly, the resistance quantum revealed by the integer quantum Hall effect discovered by Klaus von Klitzing in 1980. Hall resistance plateaus appear at R_K divided by an integer, which made it possible to define the resistance standard without reference to any material artifact.

VQA (Variational Quantum Algorithm) generic quantum hybrid algorithm using a classical optimizer that is used to train a parametrized quantum circuit. It could lead to obtain some quantum advantage with NISQ quantum computers. VQA has a broad set of applications: finding ground and excite states (VQE), quantum simulations (VQE), machine learning (QML) and optimizations (QAOA).

VQC (Variational Quantum Circuit): parameterized quantum circuit whose rotation angles are tuned by a classical optimizer, the generic building block of all variational algorithms like VQE, QAOA and QML. Also named PQC for parameterized quantum circuit. See Ansatz and VQA.

VQE (Variational Quantum Eigensolver): hybrid quantum algorithm used in chemical simulation created in 2013. Its main contributor is Alán Aspuru-Guzik, a researcher at the Zapata Computing startup. It is also used in machine learning tasks. VQE was the first proposed VQA.

VQLS (Variational Quantum Linear Solver): NISQ algorithm proposed by Carlos Bravo-Prieto, Ryan LaRose, Marco Cerezo, Lukasz Cincio, Patrick Coles et al. in 2019 which solves a linear system Ax = b by variationally minimizing a cost function measuring the misalignment between $\mathrm{A}|x\rangle$ and $|b\rangle$. It is used in machine learning and to solve PDEs, including in CFD. Estimates indicate it would require over 96 qubits with 99.99% two-qubit gate fidelities to bring any computing advantage, which is not in the radar yet.

Wafer-scale engine: processor occupying an entire 300 mm wafer instead of a single die, like the Cerebras WSE-3 and its 4 trillion transistors, 900,000 cores and 44 GB of on-chip SRAM over 215×215 mm. It circumvents the reticle limit by being exposed in several stitched runs and tolerates manufacturing defects by disabling the faulty cores.

Warm start: initialization of a variational algorithm with a classically computed approximate solution, either as the initial state or as the initial ansatz parameters, instead of a random or uniform initialization. It shortens the convergence, mitigates barren plateaus by starting in a region with non-vanishing gradients and lets the quantum part act as a refinement step. Its caveat is that the quantum contribution then becomes hard to isolate from the classical preprocessing in the final result.

Weak simulation: classical simulation task that generates samples from a quantum circuit's output distribution, exactly or approximately. It does not require storing all amplitudes or all output probabilities and is distinct from strong simulation, which evaluates probabilities, marginals or expectation values.

Wave packets: burst of electromagnetic wave that travels as a unit. It is formed by the addition of an infinite number of sinusoidal waves of different frequencies, phases and amplitudes creating constructive and destructive interferences on a small region in space, and destructively elsewhere. Wave packets are used in many quantum technologies such as with microwaves sent to superconducting and electron spin qubits or by femto- and picoseconds lasers. In these cases, their decompositions in frequencies lead to so-called frequency combs. A single photon is itself a wave packet, spread over many frequency modes with a fixed relative phase, and it has no intrinsic size. Its longitudinal extent is $L \approx c/\Delta\nu$, set entirely by the spectral width of the emission process. It ranges from a few micrometers for a femtosecond pulse to tens of centimeters for a narrow atomic transition. This must not be confused with a Fock state, which groups several photons in one and the same mode.

Wave-particle duality: the property of elementary particles such as electrons, neutrons, atoms and photons to behave as both particles with momentum and waves that can generate interference. It is verified with the famous Young's slits experiment which shows these interferences with both photons and electrons.

Wavicle: wave particle function according to Franck Wilczek.

Weyl fermion: massless fermion predicted by Hermann Weyl in 1929 and found in 2015 as a quasiparticle excitation in Weyl semimetals like TaAs. Their high mobility makes them interesting for low-consumption spintronics, magnetic memories and ultrafast photodetectors.

Wien's displacement law: describes the relationship between peak wavelength and temperature in black body energy spectrum. Discovered by Wilhelm Wien in 1893.

Wigner crystal: crystal made of electrons alone, predicted by Eugene Wigner in 1934, where the Coulomb repulsion dominates the kinetic energy at low density and low temperature and freezes the electrons into a lattice. Observed in one dimension in 2018 with carbon nanotubes at 10 mK and in two dimensions in 2020 in a monolayer semiconductor at 80 mK.

Wigner function: quasiprobability distribution representing a quantum state in phase space, which reproduces the correct marginals for each quadrature but can take negative values. Negative regions witness nonclassicality, while their absence does not imply classicality or separability: squeezed states and two-mode squeezed entangled states have everywhere nonnegative Wigner functions. So it is not a scalar measure of the level of quantumness. It is usually visualized in a 3D chart with peaks and lows. Also called Wigner quasiprobability distribution or Wigner-Ville distribution. It was created by Eugene Wigner in 1932.

Wigner's friend: thought experiment proposed by Eugene Wigner in 1961 which extends Schrödinger's cat. A friend inside a sealed laboratory measures a quantum system and obtains a definite outcome, while an outside superobserver describes the friend, the laboratory and the system as a single entangled superposition.

WIMP (Weakly Interacting Massive Particle): historical class of dark-matter candidates, typically with masses from roughly the GeV scale to the TeV scale and interaction strengths around or below the electroweak scale. The term does not require that the particle interact literally only through the Standard Model weak force and gravity. Direct-detection, collider and indirect searches have excluded large regions of canonical WIMP parameter space, motivating broader searches including axions and lighter dark-sector candidates.

X: quantum gate at a qubit that inverts its amplitude, goes from $|\mathbf{0}\rangle$ to $|\mathbf{1}\rangle$ or from $|\mathbf{1}\rangle$ to $|\mathbf{0}\rangle$ for the basis states.

XY gates: two qubit entangling gate.

Y: single-qubit quantum gate that performs a 180° rotation around the Y axis in the Bloch sphere.

Z: quantum gate to a qubit that applies a sign change to the β component of the qubit vector, i.e. a phase inversion and a 180° rotation with respect to the Z axis. More generally, Z gates are also a denomination for phase change gates.

Zeeman effect: splitting of spectral lines when atoms are placed in a static magnetic field. It comes from the coupling between the magnetic field and the magnetic moment of the atom, and from the nuclear magnetic moment for the nuclear Zeeman effect. Two regimes are distinguished. The normal Zeeman effect, observed on singlet transitions where the total spin is zero, gives a splitting into three components set by the orbital angular momentum alone. The anomalous Zeeman effect, which is the general case, involves the spin through the Landé g factor and gives a richer pattern with a splitting that differs between levels.

Zeeman slower: atomic-beam decelerator in which counter-propagating resonant laser light slows atoms by photon recoil while a spatially varying magnetic field continuously changes the atomic Zeeman shift to compensate the changing Doppler shift. It increases the fraction of atoms slow enough to be captured by a MOT. It is not a sub-Doppler cooling mechanism.

Zeeman qubit: trapped ion qubit encoded in two Zeeman sublevels of the electronic ground state split by an external magnetic field, with an energy separation of a few MHz. They are simple to implement, available on any ion species, but very sensitive to magnetic field noise, requiring good magnetic shielding and field stabilization.

Zero-point energy: it is the non-zero minimum energy of a quantum system in its ground state. It is a consequence of the Heisenberg uncertainty principle, which prevents the system from having precisely zero kinetic energy. It applies to massless quantum systems as well as to quantum fields. In this case, the vacuum state of a field is not empty but has fluctuations due to zero-point energy. These fluctuations can be observable like with the Casimir effect.

Zoo: inventory of the multiple variants of techniques in a given domain. In the realm of quantum physics and technologies, this book refers to a quantum algorithms zoo, a quantum communications protocol zoo, a quantum error correction zoo and a quantum benchmarking zoo.

ZX calculus: graphical language and formalism used to visualize in quantum programming the notions of entanglement, complementarity, causality and their interactions. It can be used for Measurement Based Quantum Computing (MBQC), the creation of error correction codes and compiler optimization techniques.

This glossary contains a total of 911 terms.

8.1 Bibliography and notes

These are the bibliographical references and notes for the **Glossary** section.

[898] Reassessing the boundary between classical and nonclassical for individual quantum processes, by Yujie Zhang, David Schmid, Yìlè Yīng, and Robert W. Spekkens, arXiv, March 2025 (36 pages).

[899] Classical mechanics as the high-entropy limit of quantum mechanics, by Gabriele Carcassi, Manuele Landini, and Christine A. Aidala, arXiv, December 2024 (14 pages).

[900] On the reality of the quantum state, by Matthew F. Pusey, Jonathan Barrett, and Terry Rudolph, Nature Physics, November 2012 (3 pages) 🔓 (preprint on arXiv).

[901] Satellite-to-ground quantum key distribution, by Sheng-Kai Liao, Jian-Wei Pan, et al., arXiv, July 2017 (18 pages).

[902] Quanvolutional Neural Networks: Powering Image Recognition with Quantum Circuits, by Maxwell Henderson, Samriddhi Shakya, Shashindra Pradhan, and Tristan Cook, Quantum Machine Intelligence, June 2020 (9 pages) 🔓 (preprint on arXiv).

[903] Quantum optical reservoir computing powered by boson sampling, by Akitada Sakurai, Aoi Hayashi, William John Munro, and Kae Nemoto, Optica Quantum, May 2025 (8 pages).

[904] A Proof of Specker's Principle, by Guido Bacciagaluppi, arXiv, November 2023 (26 pages).

This **Glossary** section contains 7 bibliographical references and notes containing at least 114 pages.

9 Revisions history

This book improved over time with successive revisions. The first editions from September 2018, 2019, and 2020 were published in French and this ninth one is the sixth published in English. It is freely downloadable on this link. The present and past editions of the book are available on this link. I also publish the book on arXiv, about a month after it's available on the above link.

Different PDF formats are available: **A4 in full resolution in a single volume** (about 585MB), **A4 in reduced resolution in five parts** and the same in **Letter format** for USA and Canada readers who would like to print it on their own.

After a couple of weeks of post-publication proofreading and corrections, I then publish the book on arXiv.

I update the book on a regular basis as I find editorial issues, mistakes, misspellings, and the like. You can submit me any comment, correction, suggestion, or even request for digging into some untapped topic (`olivier@oezratty.net`).

This log describes the various successive editions and minor revisions (in .x numbering although it could be more relevant to use a .0x versioning).

Version 1.0, September 2018, (332 pages).

First version of this document published in French and consolidating 18 posts published between May and September 2018 on www.oezratty.net.

Version 2.0, September 2019, (504 pages).

Second edition, also in French. New content on superconductors, superfluidity, quantum sensing, quantum supremacy, quantum computing emulation, cryogeny, hybrid algorithms, algorithms certification, quantum teleportation, blind computing. Addition of a glossary and bibliography.

Version 3.0, September 2020, (684 pages).

Third edition, also in French. New content on Maxwell, Schrödinger and Dirac's equations, relativistic quantum chemistry, how research works, lasers and masers, polaritons, extreme quantum, linear algebra, quantum gates classes, quantum error correction codes, cryo-electronics, MBQC, quantum cloud, qubits technologies, unconventional classical computing, quantum hype cycle, quantum foundations and on the influence of science fiction.

Version 4.0, September 2021, (838 pages).

Fourth edition, the first one in English. Main new features vs the 3.0. on top of updates nearly everywhere: new section on quantum physics postulates, more on wave-particle duality and on photon qubits physics, improvements and extensions on linear algebra, on quantum measurement and quantum memory. New part on vacuum in enabling technologies, much improved section on algorithms, including data preparation and debugging, expanded part on QRNG, went from 265 to over 450 vendors covered in the various sections of the book, more on ethical issues and gender balance, additional covered countries: Belgium, Portugal, Italy and Abu Dhabi and nice ecosystems maps for the USA and the UK, added an index with company names, people and some scientific terms and many terms in the glossary (from 179 to >280).

Added a new graph explaining Dirac $\langle A|B|C\rangle$ notations in the measurement section, added a roadmap for managing the energetic footprint of quantum computing, added American Binary (Ambit) in the quantum cryptography vendors section that starts page 1036, small update related to D-Wave gate-based quantum computing announcement in the quantum annealing section, added Energetics of quantum technology, Quantum postulates, QML, QLM and scale-out in the glossary. Corrected wrong naming for Atos QLM (instead of Atos QML or Atos aQML), update on Origin Quantum and their cloud quantum emulation offering, added StarX Electronics in the inventory of enabling technology vendors and Chipiron in quantum sensing imaging, added Two-Level Systems in glossary, added a chart from Joseph Bardin describing the various microwave and other signals used to drive superconducting, electron spin and trapped ions qubits, added Algorithmic qubit, anharmonic oscillator, cQED, CQED, fluxonium, Q-factor, Dirac and Reduced Planck constants, homodyne detection and Universal quantum computer in the glossary, updates on IBM and its 127 qubits processor announced in November 2021, the related qubits fidelities chart with the best-in-class IBM 27, 65 and 127 QPUs, some updates on IQM and OQC (on Amazon Braket), updates on Kipu Quantum and on Quantinuum (new name for HQS/CQC merger), added a mention on Alexia Auffèves quantum energy initiative, updates on Quandela, Qu&Co (acquired by Pasqal) and Rahko (acquired by Odyssey Therapeutics), added Mikhail Lukin in the quantum computing physicists section, added Black Quant and Runa Capital in the quantum investors section.

Version 5.0, September 2022, (1,132 pages).

Why: new intro, rearranged and updated the part on Moore's law. Removed the long abstract from the previous version.

History and scientists: updated scientists with more stuff on Marc Benioff, David Deutsch, David Hilbert, Daniel R. Simon, Erwin Schrodinger and new bios for Andrew G. White, Gaston Floquet, Bruce Kane, Daniel Kleppner, Daniel Loss, Frank Wilczek, Gerhard Rempe, Herbert Walther, James Clarke, Jeff Kimble, Jian-Wei Pan, Leo Kouwenhoven, Menno Veldhorst, Steven Girvin, Rob Schoelkopf, Roy J. Glauber, Jay Gambetta, Alexandre Blais, Robert Raussendorf, Maciej Lewenstein, Ronald Walsworth and Philip W. Anderson. More details on how research works, papers published and evaluated.

Quantum physics 101: added a table listing the various quantum physics postulates versions, added nuclear quantum numbers in quantization, added a part on quantum matter, including on quantum batteries, time crystals and skyrmions.

Gate-based quantum computing: various updates on quantum gates, added illustrations on quantum computing dimensionality, better differentiation between quantum emulation and quantum inspired software.

Quantum computing engineering: simplified qubit type descriptions, update content on exotic qubits, better explained how error rates are measured, many updates on quantum error corrections, definitions of FTQC, universal QC and LSQC. Described in detail the whereabouts of the Quantum Energy Initiative. Added a definition of quantum switch.

Quantum computing hardware: added vendor investment comparisons per type of qubit, types of use cases per qubit type, inventory of scalability challenges per type of qubit, rearranged and standardized the presentation of each qubit type with history, science, qubit operations, research and vendors. More schematics. More science on quantum annealing. Genealogy of superconducting qubits. Updated content on IBM, Google, Rigetti, IQM, OQC and added Atlantic Quantum, Baidu and Toshiba in superconducting computers vendors. Comparisons of different types of quantum dots spin qubits. Added Diraq in quantum dots spin qubits vendors, XeedQ in NV centers qubits vendors, It's Q, Quantum Source

Labs and TuringQ in photonic qubits vendors and Crystal Quantum Computing and Planqc in neutral atoms qubit vendors, and Hon Hai / Foxconn in the trapped ions vendors list. Added coherent Ising machine in quantum photonics systems. Archer Materials, Atom Computing, Bleximo, BosonQ Psi, Nord Quantique and QBoson.

Quantum enabling technologies: rearranged the section on control electronics. Added ICE, Maybell Quantum and FormFactor, and updated myCryoFirm in cryostats vendors, Active Technologies, Keysight, QuantrolOx and Scalinq in control electronics vendors, Qubic Technologies, Raditek, QuinStar Technology, RF-Lambda, Wenteq Microwave Corp, Holzworth Instrumentation, apitech, Analog Quantum Circuits, CryoHEMT and Silent Waves in cryoelectronics vendors, CryoCoax, XMA and Rosenberger Group in cable and filtering vendors and Alcyon photonics, Teem photonics and Scintil Photonics in photonic enabling technologies vendors, AnaPico, Diatope, HiQeTe Diamond, Orsay Physics, QuantTera and Quantum Diamant in other enabling technologies vendors. Added a new part on fabs, processes and manufacturing tools. Added here many manufacturing tools vendors like BESI, PlasmaTherm, Picosun Group, NanoAcademic Technologies and QuantCAD. Updates on raw materials.

Quantum algorithms: added a part on tensor networks. Significant updates on quantum machine learning.

Quantum software development tools: updates on emulation software, restructured and updated the part on benchmarking.

Quantum business applications: updated all vertical case studies lists. Added Arclight Quantum, Allosteric Bioscience, Artificial Brain, ColibrITD, Dirac, Foqus, GenMat, Good Chemistry Company, Ingenii, Qbraid, QEDma, Qoherent, Quanscient, Quantagonia, Sanctuary, SavantX, Tinubu Software and Turing in the software and tools vendors inventory. Created a section on IT service vendors working on quantum technologies. Added DN-Quantum Computing, Kvantify, Plantagenet Systems, Protiviti, Psi-Ontic, Quantum Computing Engineering, Quanvia, quGeeks, Quant-X Security & Coding, Qubitech and Unitary Zero Space. Updated information on AegiQ, Azurlight Systems, Cogniframe, exaQ.ai, Horizon Quantum Computing, HQS Quantum Simulations, Multiverse Computing, and Nomidio, Phasecraft, OTI Lumionics, Q.ant, Quantum Computing Inc, QunaSys, Q-Ctrl, Strangeworks and Terra Quantum.

Quantum enabling technologies: I singled out this part and moved it to the second volume. Content has been sporadically updated.

Quantum telecommunications and cryptography: added a part on quantum photon sources and detectors in the QKD section, improved description of trusted nodes and repeaters, rearranged and enriched the quantum interconnect and telecommunication part. Update on PQC with NIST 2022 selection results. Added Abelian, ComScire in QRNG vendors, Bohr Quantum Technology, Photoniq and Entanglement Networks in quantum telecommunications, NodeQ, Patero, QANplatform, Quantum Collective, SandboxAQ, Synergy Quantum and ThinkQuantum in quantum telecommunications and cryptography vendors. Updated information on Post-Quantum, IDQ, Qnu Labs, QphoX and, Qunnect.

Quantum sensing: added new parts on quantum sensing taxonomy and on quantum pressure sensing. More details on quantum thermometers. Added OK Quantum and Zero Point Motion in quantum gravimeters and accelerometers, Improved the technical description of a quantum gravimeter. QuSpin, Siloton, QLM Technology and Mag4Health in imaging sensors and qdm.io and Elta Systems in quantum magnetometers. Updated information on Chipiron.

Quantum technologies around the world: updates in investments data, new part disappeared startups, SPACs, government spending and quantum national initiatives rationales. Added Finland, Norway, Hungary, Ireland, and Qatar in countries overview and Intqlabs startup in UAE. Updated nearly all other countries quantum activities. Added a map of Canada's quantum ecosystem.

Quantum technologies and society: added EFEQT in scientific education and on quantum technologies marketing.

Bibliography: reshuffled the quantum events section, added an events timeline.

Glossary: added Ansatz, Bell state, Chi (nonlinearity order), Circuit, Coulomb blockade, crosstalk, CVD, Fermi sea, Floquet code, EBL, electron gas, FTDQC, Flux biasing, Gaussian Boson Sampling (GBS), Hall effect, Heterodyne and Homodyne measurements, I/Q mixer, Jaynes-Cummings Hamiltonian, JPA, Leggett-Garg inequality, MBE, Magneto-Optical Trap, mesoscopic, metal layers, microring resonator, Mott insulator and Mott transition, Mutually unbiased bases, no-go theorem, normalization, on-premises, ODMR, paramp, photolithography, Purcell effect, Purcell filter, purification, PVD, Quantum Hall effect, QHO, QND, QSVT, QUBO, quantum steering, quantum switch, Ramsey experiment, relaxation, Renyi entropy, RIE, Sapphire, surface code, SVD, time crystals, time reversal, TWPA, Stark shift, Unruh effect and Zeeman cooling.

Added over 900 figure captions with sources and sorting out how figures are referenced in the text (mostly).

Version 5.1, October to December 2022, (1,132 pages).

Several corrections in the precursors and founders sections with errors in Einstein's photoelectric and Dirac's relativistic equations and other hidden details, added Nobel prize mentions for John Clauser, Alain Aspect and Anton Zeilinger. Updates on Alain Aspect's experiment and its explanation, integrated some corrections suggested by André Konig, various improvements in the part on quantum error correction. Modifications in the FTQC/LSQ nomenclature with suggestions from Alastair Abbott and Tristan Meunier and thoughts about the progressive growth of logical qubits fidelities, presentation improvements in quantum physics simulation algorithms, various edits in satellite QKD, China funding, Google Sycamore, NV centers frequency analyzers in sensing, updates in insurance use cases, added the class NISQ in quantum complexity classes, added quantum amplitude estimation in the algorithm toolbox, precisions on transpilers and transpilation in the gates section and with the glossary, added T gate, T-count and T-depth in the glossary, added IonQ, Rigetti and D-Wave quarterly revenue in the investor section, added a new partnership between Switzerland and the USA, updated the record "non-Shor" integer factoring algorithms in the quantum cryptoanalysis threat section, updated chart on algorithms per computing paradigm and UK industry ecosystem, updates on Keequant, Orca Computing, Quantopticon, Quantum Brilliance, QuiX, Q.ANT, Qunnect and XeedQ using content from the Optica Conference in November 2022. Updates on M Squared and Exail (formerly ixBlue) in the quantum sensing part. Added LuxQuanta in QKD vendors. Added Siquance in the silicon qubits startups.

Version 6.0, September 2023, (1,364 pages).

274 new or updated figures, over 1330 new references.

Why: rewrote much of this part, mainly the "Why quantum computing" section with a rearrangement of the section on Moore's law and transistor density story. Added a one page table with common misconceptions and their explanation and location in the book.

History and scientists: added Immanuel Bloch in quantum physicists. Sorted the hall of fame into subcategories. Rewrote and completed the Research for dummies part, adding my own experience on publishing a paper in a peer-reviewed journal, and using ChatGPT.

Quantum physics 101: added some explanation of the quantum nature of continuous quantum variable systems, added measurement techniques of nuclear spin, added the first quantum battery vendor, Planckian in the quantum matter section, reorganized the part on superconductivity and added news about LK99.

Gate-based quantum computing: various minor corrections on linear algebra mathematics. Added a space vs time advantage comparison. Updated some illustrations.

Quantum computing engineering: updates and new illustrations in the quantum error correction and quantum error mitigation part, various updates in the energetics with a new chart on quantum computing power decomposition, and economics part.

Quantum computing hardware: added an insert on the key review papers for the main qubit categories, updates on qubit figures of merit, many updates for major superconducting vendors (IBM, Google, …), added ARQUE and SemiQon and QSi in silicon qubit vendors, added neQxt, Quantum Art and Qudora Technologies in trapped ions qubit vendors, NanoQT, GDQLABS and QUANTier in neutral atoms qubit vendors, Quantum Transistor and SaxonQ in vacancies qubits, Quanfluence and Rotonium in photonic qubits. Added a part on how Majorana qubits operate.

Quantum enabling technologies: added Zero Point Cryogenics and Ulvac Cryogenics in cryostats vendors. Added Ohtama, QuEL and T0.Technology in electronics vendors, ParTec in other enabling technologies vendors, and Onnes Technologies in fabs/characterization vendors. Added ConScience in foundries.

Quantum algorithms: new segmentation of algorithms and better semantics about problems, algorithms and models, arithmetic part of Shor's algorithm, PDEs (partial differential equations), added VQLS and QSVD in NISQ algorithms, added a long part on NISQ algorithms, new part on algorithms hybridization. Better explanations on complexity classes.

Quantum software development tools: new parts on abstraction levels, code factoring, securing quantum computing, and resource estimators. Clarifications on the difference between emulations and simulations. Added Wolfram quantum framework in emulators.

Quantum business applications: added a framework to assess quantum computing case studies, added a part on climate change, rewrote many parts particularly on healthcare, chemistry/energy, including a detailed overview of the famous FeMoCo case study, and finance applications. Added Beyond Limit, BlueQubit, First Quantum, Haiqu, Kunfeng Quantum Technology, InstaDeep, MolKet, Qbrain, QCentroid, QPerfect, Qruise, QSIMPLUS, Quantagonia, QAR-lab and Qausal.ai in the software and tools vendors list. Added Applied Quantum Computing, AngelQ, QuantumBCS, Qdeeptech and Reply Sigma in the IT service vendors list.

Unconventional computing: rewrote many parts, restructured the optical computing part. Added Quantum Silicon Inc in the classical computing space.

Quantum telecommunications and cryptography: changed some schematics and added some new ones, added a small part on quantum computing cryptography, added descriptions for Temporal entanglement, Quantum Secure Direct Communication, Quantum Pseudotelepathy, Quantum Conference Key Agreement, added a part on PQC and blockchain, added Alea Quantum Technologies in QRNG vendors. Added vendors in QKD/PQC: CAS QuantumNet, Craft Prospect, Quantum Bridge, levelQuantum, Wisekey, Seal SQ, Xiphera, Cryptolab, HEaaN CryptoLab, Cyfer-All, Icarus Quantum, LQUOM, QTI, Qtlabs and Q-Bird. Added MemQ and PhotonicsQ in interconnect vendors. Added BTQ Technologies and ChainMakers in vendors.

Quantum sensing: extension and news schemas about sensing taxonomy and measurement precision, added Delta G, Euqlid, GLOphotonics and Guoyao Quantum Radar Technology in vendors.

Quantum technologies around the world: added a part on patents, added Brazil, Pakistan and South Africa. Updates on most other countries and related charts. Country map for Germany. Market map for China.

Quantum technologies and society: minor updates, particularly on the quantum hype phenomenon.

Quantum fake sciences: minor updates.

Resources: a couple additions in events and books.

Glossary: added antisymmetry, Born-Oppenheimer approximation, cap table, chip, chipset, chiplet, contextuality, dark state, dark state protocols, dressed state, Fermi-Hubbard model, Gate teleportation, Gurobi, HPC, Lamb-Dicke regime, Lie groups, LLM, non-selective measurement, postselection, prepare-and-measure, QAOA, Quantum Conference Key Agreement (QCKA), Quantum Fisher Information, Quantum jump, Quantum Kernel, Quantum Speed Limit, Quantum trajectory, Tabu Search, TDSE, TeraQuop, Trotterization.

Version 6.1 to 6.8, September 2023 to April 2024 (1,366 pages).

Some updates in quantum physics history and timelines. Added some scientist's names in the hall of fame sections at the beginning. Some historical updates on Eistein, Hadamard, Heisenberg and Schrodinger. Added a reference explaining why Albert Einstein didn't get the Nobel prize in physics for his work on relativity. Added a mention on the 2023 Nobel prizes in physics, and attolasers in the lasers section in enabling technologies. Corrected Lov Grover's biography. Modified schematics of quantum numbers and properties for atom/ions, electrons, nucleons and photons. Added the SX gate in the quantum gates description. Updated the qubit fidelities chart in the error correction section. Update on the energy consumption table per qubit type. Small improvements in the quantum memory part.

Added IQM's 20 qubits fidelities in the scatter plot chart in the QEC section. Mention of IQM's Q-Score of 8. IonQ's Tempo's 64-qubit announcement and more on IonQ's touted case studies. Added Quoherent in the topological qubit vendors. Latest news on C12, Quantum Motion, QuEra, InfinityQ, IQM, Atom Computing, Oxford Ionics, Infineon, Photonic and Quandela. Added the new IBM Layer Gate Fidelity benchmark (in the quantum volume section). Update on Photonic and their architecture. News on Orca Quantum Computing, Quandela and Multiverse. News on Alibaba, Baidu, Infleqtion, IBM, OQC, IBM, Riverlane, Harvard/QuEra, Rigetti, Origin Quantum, Quantinuum and Qphox. Updated the Grotrian diagram of NV center qubits and related explanations. Added Atom Quantum Labs in cold atom computing vendors. Added Cryotech Instruments and Qlibri in enabling technology vendors. Added minor edits in the complexity classes section, mentioning that these refer to worst case scenarios that may not be applicable in real-life applications. Updated complexity classes chart and Simon's algorithm chart. Corrections about Shor's algorithm description and quantum algorithms inputs/outputs. Tweaked the case study evaluation framework.

Added a mention of the Quantum Position Verification protocol in quantum telecommunications. Some updates in quantum sensing and quantum radars. Changed Wainvam into Kwan-Tek in magnetometer sensor vendors and added QuantumDiamonds in quantum sensing vendors. Safran, Cryolock becoming QuantX lab. Added a mention of Quantum Italia and Redstone VC in investment funds. Updates on the economics of quantum computers.

Added QDC.ai, Quantum AI and Inspiration-Q in quantum computing software vendors, Qurv, Vector Atomic and ZebraKet in quantum sensor vendors and g2-zero in photonics enabling technologies vendors. Update information on Algorithmiq in quantum software vendors. Added FermionIQ in software vendors. Updated enabling technology vendor map. Update on Aliro Quantum. Updated software vendor map. Update on Riverlane.

Defined the notion of quantum ecosystem and their evaluation metrics. Corrected global investment chart (Australia being there twice). Added a map of the Netherlands research ecosystem. Updates on Australia. Small updates on the Denmark and Finnish quantum ecosystems. Small edits in the quantum hype section. Added Erasure error, Leakage error, band gap, break-even, cavity, counterfactual models and feedforward in glossary.

Version 7.0, September 2024 (1,554 pages).

Removed the table of illustrations to save space. Reorganized the book in five volumes.

History and scientists: added David Mermin in quantum physicists. Some minor updates.

Quantum physics 101: added a definition of science vs engineering vs technology, added a chart on atom electronic levels, added a part explaining why spins are everywhere in quantum technologies, added a definition of phase space in quantum measurement, added definitions of Mermin inequality, polytope, parameter and outcome independence in the part on entanglement, added Pioniq in quantum matter startups.

Gate based quantum computing: added a definition of shadow tomography in the measurement part of the qubit section. Moved qubit type segmentation in the computing hardware section.

Quantum engineering: restructured the part describing qubit error types, added more stuff on erasure errors and erasure conversion, Markovian and non-Markovian noise, stochastic Pauli noise, dynamical codes and code switching in QEC. Added a detailed segmentation of the energetic cost of existing digital technologies, a more structured critical assessment of energetic cost estimates of quantum computing, a list of good news that may change the picture favorably with regards to a quantum energetic advantage in the quantum energetic section.

Computing hardware: completed summary chart with highlights, challenges, variations and paths to scalability for each qubit class. Added NEC and Qolab in superconducting qubit QPU vendors, Quantum Brain in topological qubit vendors, Aegiq in photonic qubit QPU vendors. Added HYQ Co in trapped ions vendors. Added a part on native fermionic computing in the cold-atom section. Updated the quantum computing hardware part for nearly every vendor. Updated and improved the exotic qubits section, now at the end of quantum computing hardware.

Enabling technologies: added China's advancements and offerings in dilution refrigerators. Updated the consolidated Added Advanced Quantum, Paragraf and Elemental Instruments in other enabling technologies vendors. Added Aresis, Artilux, Covesion, Astrolight, ephos, Photonscore, Exosens, Liquid Instruments, Micro Align, Oxxius, Photec Quantum Composers, Quintescent, Redback Systems in photonics enabling technologies vendors. Added Tabor Electronics, NF Corporation, Seiken Co, Kawashima Manufacturing, Japan Communication Equipment and SDT, in electronics enabling technology vendors. Added Q-Block Computing and UQDevices in photonics equipment vendors. Added ATLANT-3D and Beamfox in fab tools vendors. Added Conductor Quantum in EDA vendors. Added Crystal Systems in materials vendors, where I moved all NV centers vendors.

Unconventional computing: added Akhetonics, Extropic, Normal Computing, Vaire Computing and Mythic in unconventional computing vendors. Added two categories with analog computing and neuromorphic computing.

Communications: added SeQure Quantum and Toshiba in QRNG vendors, added Quantum Random Access Codes in quantum communication protocols, mentioning Quantum Financial System (QFS) in the QKD and blockchain part, reorganized and updated the quantum distributed computing part. Added Ammolite Analytics, CEW Systems, Infosec Global, IronCap, Pauli Group, Astrolight, Cavero Quantum, QuDef, QuNETT, QuantumPrime, QUBO Technology, TheGreenBow and XunTai Quantum Technology in quantum communication vendors.

Sensing: added Aeris Technologies / Project Canary, Advanced Navigation, Advanced Quantum, Phantom Photonics, Phasor Innovation, Mesa Quantum, Quantum Technologies, QT Sense, QuantX Labs, SQUTEC and Xairos in quantum sensing vendors.

Algorithms: improved the data loading part, added block-encoding in data preparation techniques, and semi-classical QFT in algorithms. Improved explanation of Shor integer factoring algorithm and of the QPE algorithm. Added a table summarizing the differences between Shor integer factoring, Shor discrete log and quantum phase estimate algorithms. Updated the NISQ part considering recent progress in qubit fidelities with IBM and Quantinuum QPUs. Better explanation of the DAQC computing paradigm. Added a chart positioning classical and quantum methods to solve combinatorial optimization problems. Added some complexity classes: FP, PostBQP. FPTAS, PTAS, APX and NPO in the complexity classes section. Updated some charts and created new ones.

Software tools: restructured the emulators section, updated data on Nvidia plus a new chart, added various emulators, Quantum Rings and Quokka. Added a machine learning section.

Case studies: updated all parts on case studies per vertical market. More stuff on quantum art. Added Bloq Quantum, FalconDale, Fixstars Amplify, IFF Technologies, Moth Quantum, Orientum, Qognitive.ai, QMill, QRS, Quanmatic, QPurpose, Quantum Intelligence Corp, Quantum Signals, Snowdrop and Type one systems in software vendors. Added coreDevX, Expleo Group, LTIMindtree, Quantimize, QuantyMize and Qinetiq in service providers.

Global ecosystem: added some thoughts about quantum startup creations and their modus operandi, added a part on export controls. Added Chile, Luxembourg, Saudi Arabia, Slovenia and Türkiye in countries. Many updates in other Countries like USA, UK, Germany, The Netherlands, Finland, Denmark, Sweden, Italy (NQSTI creation), China (added a geographical map of their quantum ecosystem), Japan, South Korea, Australia and India.

Society: restructured a bit the part on quantum education. Updates everywhere else.

Glossary: added Adaptive quantum circuits, AKLT state, Circuit synthesis, DRAG, EQA, Heuristic algorithm, LRU, Markovian processes, Metaheuristic algorithm, Non-Markovian process, Prefactors, Quantum capability learning, Quench, Spin-boson model, spinor, Wavicle and Zero point energy.

Version 7.1, November 2024 (1,554 pages).

Version published on arXiv and Amazon.

Update on Ettore Majorana. Updated the caption on the QPU qubit fidelities scatter plot. Updates on Google QEC, Amazon cat-qubits, IQM, Quobly, ARQUE, Planqc, HYQ Co, XeedQ and Universal Quantum, Quandela, QCi and Xanadu. Added Zuriq in trapped-ion QPU vendors. Added a short mention of Peak Quantum in the superconducting qubit QPU vendors. Added Sweden Quantum in cabling, connectors and filter vendors. Added Spectrum Instrumentations, TreQ and Withwave in other enabling vendors. Added Basel Precision Instruments and Architect Instruments and control electronics vendors and Meca Magnetic in other enabling technology vendors. Added eQsparse NextGen Technologies in services companies and reorganized this part per country. Updated content on Toptica in photonic enabling vendors, added Munich Quantum Instruments. Added the alternative "007" fun table of content at the end of volume 2 (after "Unconventional Computing"). Updates on the (bad) scalability or Grover search algorithm. Added a chart on the difference between classical and quantum code compiling. Added Anzaetek and Qdaria in quantum computing software vendors. Added Ceruleant Systems and Vergence in PQC vendors. Added Quantum Scopes AB, RobQuant and Serino in imaging quantum sensors. Cleaned the section on disappeared startups, including Zapata AI. Added QuantAzur, CESQ, CHREA and IM2NP in the French research ecosystem. Updates and addition in cybersecurity threats assessment. Minor other updates and corrections, thanks to the help from Jean-Philippe Nominé. Some recent arXiv or peer-reviewed papers bibliography additions. Added heterostructures in the glossary.

Version 7.2, March 2025 (1,554 pages).

Other recent arXiv or peer-reviewed papers bibliography additions. Small updates on paper retractions and abuses of ChatGPT in scientific papers writing. Corrections and update related to Google Willow 2024 logical qubits, which are memory logical qubits that don't yet implement logical qubit gates. Updated qubit fidelities chart by adding Atom Computing numbers. Update on Qolab in superconducting qubit vendors and Atom Computing in cold atom vendors. Added Open Quantum Design in trapped ions QPU builders. New logo for Quandela. Added Fixstars Amplify in photonics QPU (cloud) vendors. Small updates and edits in the cabling part of the qubits control electronics section. Updated quantum algorithms speedup chart. Small update on QPE, regarding exponentiated unitary preparation techniques. Update on optimization algorithms. Corrected various spelling and text errors in the quantum algorithm part. Updated quantum interconnect chart. Added Lightsynq Technologies in QPU interconnect vendors. Added Quantum Corridor in quantum communications vendors. Corrected reference in Figure 951 (schematic of a monolithic diamond nanopillar probe…) and Figure 960 (Qnami NV center based imaging). Added QbitFlow in services vendors. Updated chart of worldwide public/private investments. Added SPINUS in European Flagship projects.

Version 8.0, September 29^{th}, 2025 (1,512 pages).

First version edited in LaTeX.

History. Added JJ Thomson, Klaus von Klitzing and Ronald Hanson in the hall of fame. Updated content related to Planck constants. Explained why 2025 was the 100th anniversary of quantum mechanics. Small updates on Schrödinger's cat, yes. Added more stuff on LaTeX (surprise) and on paper mills in "research for dummies".

Quantum 101. Added an inventory of quantum numbers used in elementary particles. Added a frame explaining the difference between an electromagnetic wave, and a wave like in the Schrödinger wave equation. Added more stuff on entanglement, loophole free experiments, GHZ, W states and Dicke states, energy-time and time-bin entanglement, quantum steering, Bell tests on high-energy physics particles. Added a small subsection on the role of symmetries in quantum physics. Revisited the part on quantum batteries. Added a frame explaining the difference between a wave and a field. Added Constructor Theory, Local Friendliness no-go theorem, the BHSI, RQD, Algorithmic Idealism and Topos Quantum Theory interpretations, and retrodiction in quantum foundations. More on realism.

Gate based. Added matchgates and fermionic SWAP gate in gate types. More details on exotic quantum computing paradigms.

Quantum engineering. Differentiating errors, noise and decoherence. Explaining how a magic state is consumed to implement a T gate on a target qubit. Added explanations on error syndrome decoding on entanglement purification. Added a description of 2D, 3D and 4D error correction codes. Added explanations on Single-Shot Error Correction. Added some background on the parallel between classical memory hierarchy and quantum memory. Reorganized the part on quantum energetics. Added a frame listing best practices in quantum computing energetic estimations. Added data on supercomputers energy consumption. Added a new subsection on the Lieb-Robinson bounds. Restructured and improved the part on quantum uncertainty (optimism vs pessimism). Added some estimations of deployed QPUs worldwide per vendor country origin.

Quantum hardware. Lots of updates on D-Wave. Updates and cleanup of China's superconducting qubit efforts. Added a description of the Niemeyer–Dolan bridge used in manufacturing Josephson junctions. Significant updates on IBM and Google. Added Anyon Technologies, QuamCore and Qarakal Quantum in superconducting qubit vendors. Significant update in IonQ's and Quantinuum. Added Logiqal in the cold atom vendors. Two tables summarizing the key technology differences between trapped-ions QPU vendors.

Quantum enabling technologies. Added Linde in cryogenics vendors. Removed Air Liquide / CryoConcept from dilution vendors. Added Rhonexum in cryo-electronics vendors. Added SynkTek in room temperature control electronics vendors. Added Bifrost Electronics and Isentroniq in cabling/connectivity vendors. Added Mirega, Nüvü Cameras, Pinc Technologies, OptQC and QC82 in photonics vendors. Added Iceberg Quantum in other enabling technologies vendors. Added CDimension in fabs related vendors. Added a chapter on PDK in manufacturing. Added Arctic Instruments, ASP Isotopes, ConScience, Dimira Technologies, Infineon, Intelune, Mind Foundry, Prenishq, Pristine Diamonds, Qprobe, Quan2D Technologies, Quanastra, Quantcore, QETSweden, Quantamap, Socionext, Yquantum and WiMi Hologram Cloud in enabling technology vendors.

Unconventional computing. Added Linque and Q.ANT in photonic unconventional computing vendors. Added Snowcap Compute in superconducting computing vendors.

Quantum algorithms. Added a frame explaining how you create or use algorithms. Added quantum state transfer in basic quantum algorithms. Added a description of Hamiltonian encoding. Added the nuance between deterministic and non-deterministic versions of Grover algorithm. Added the QITE and Decoded Quantum Interferometry algorithms. Added Concorde in classical optimizers. Added Digitized Counter-Diabatic Quantum Optimization in NISQ algorithms. Added LIN and PQP in the complexity classes. Updates and corrections about the QFT and its speedup. Defined the orthogonality catastrophe with QPE. More stuff on quantum machine learning and AI challenges. Added definitions for Kryolov and Komolgorov complexities.

Software tools. Added QLOPS in benchmark types. Added Phase2, Q-Gear, QEA and Qimax in quantum emulators. Added China's cloud offering from China Telecom and China Mobile in the quantum cloud section.

Applications. Added semantic definitions of case studies, use cases, proof of concepts and benchmark studies. Added a cheat sheet to avoid being cheated by case studies and use cases. Added content on the paint shop problem in automotive manufacturing. Added a part on civil engineering case studies. Added protein dynamics computation in life sciences. Added Commutator Studios, FirstQFM, Global Data Quantum, Harmoniqs, MagiQware, Miqro-Era, Qodex Quantum, Q Deep, Quantum Elements, Quminex and SuperQ Quantum in software vendors. Added AQMATICS, Blanqet, Emergence Quantum, Gradiom Sarl, Qnow, Quantific, Quantum Net, Quantum Ket, Qounselor, Qwatch, Sonovero R&D, and Tata Consulting Services in services vendors. Added Sylgaldry Technology in cloud vendors.

Quantum communications and cryptography. Added Arobs Polska, Cisco, EnQase, Fortaegis Technologies, Keyfactor, IonQ, Quantum2Pi, Portyq, Quantum Optics Jena, Qryptonic, Quranium, Silq Connect, Wultra, and ZeroThird in communications and cryptography vendors.

Quantum sensing. Added a frame explaining how we measure the electric and magnetic fields of photons. Added a subsection on dark matter quantum sensors. Addded Adamant Quanta, CAS Cold Atoms, Damavan Imaging, Deteqt, Diasense, sDiffraqtion, Flari Tech, Florence Quantum Labs, Hangzhou Weijia Quantum Technology, Hensoldt, QSensato, QuPrayog, Xmagtech, Zhongkeqidi Optoelectronic Technology in quantum sensing vendors.

World. Updates many charts on startup numbers and funding. Added one chart on the best funded startups across the top 6 countries (USA, Canada, UK, France, Finland, Israel). Many updates on most countries. Added Slovakia and Malaysia in countries overview.

Corporate adoption. Added some stuff and a book reading frame.

Quantum fake sciences. Added a couple of new fake quantum science scams, like in the production of free energy.

Resources. Added a table summarizing the key quantum computing advances per year since 2018.

Glossary. Added AOD, Approximate Amplitude Encoding, Artificial atoms, ASIC, AWG, Bloch state, cryo-CMOS, Dicke state, Gibbs state, Heisenberg cut, HEMT, Intersubjectivity, learning, Loophole, MNIST, PDK, phase classification, phase space, SFQ, Shortcuts to Adiabaticity, SLM, Squeezing, Superradiance, Superselection and Zoo.

Version 8.1, September 30th to October 31st, 2025 (1,522 pages). The arXiv version.

Corrected various spelling mistakes. Added some thinking on FTQC QPU pricing and potential unit sales. Corrected some braket notations in Dirac notation presentation. Updated chart on qubit types figures of merit. Added a mention of the Google OTOC Nature paper in the superconducting subsection and in the Lieb-Robinson limit subsection, in relation to its light-code propagation effect. Updated references and content on microwave photon counters. Added Pinc Technologies in photonics vendors. Added QFX in other enabling technology vendors. Added LH3M in materials vendors. Added DB-QITE in quantum algorithms. Added amplitude amplification and QQSP in algorithms (it was a missing part from the 2024 edition in the first releases from the 2025 edition). Added neural quantum states in quantum inspired techniques. Added NVQlink in Nvidia's offering (in the emulation subsection). Added box on HSBC-IBM case study. Improved captions for several figures. Added Serge Aa in quantum artists. Added FirstQFM and Yiyaniq in software vendors. Added Quantum Momentum in service vendors. Added two charts in the dark matter sensing section. Added 55 North in the investors in quantum startups. Added many additional scientific papers in various domains. Added a 7-page section with the making of this book with LaTeX. Added the terms engineering and Green's function in the glossary.

Version 8.2, November 20th, 2025 (1,522 pages). Amazon KDP version.

Added more scientific references. Update on Quantinuum (Helios QPU release) with new illustrations and data. Thoughts on quantum in space. News on Planckian and PhaseCraft. Added Qool in quantum software service vendors. Updated the quantum supremacy and advantages table with D-Wave, Google Echos, BlueQubit random peaked circuits proposal and PhaseCraft quantum advantage experiments. Added a historical view box insert on Store Now Decrypt Later applied to old historical letters. News on DARPA QBI phase 2 and updated chart. Added Biphoton, QPU, and quantum computer in glossary.

Version 8.3, April 23rd, 2026 (1,524 pages).

Various spellcheck and other corrections. Cleaned-up some dead links. Corrected the portrait of Henri Poincaré (it was Lorentz!). Correction of the text and visual explanation of the Hadamard gate (thanks to Felix Berthier from EPITA) and the related figure. Correction is the chart on the 3-qubit flip quantum error correction code and various other corrections on quantum error correction. Updated the Sankey chart on quantum computer sales in the economic section. Updates on the subsection on the Lieb-Robinson limit. Added references on the FTQC industry vendors roadmaps chart. Updates on D-Wave and its acquisition of QCI. Update on Zuchonzhi 3.2 in superconducting qubits. Update on QuantWare. Updates on Quobly. Updates on Universal Quantum in the trapped-ions qubit subsection and on Aegiq in the photon qubit subsection. Updated the two tables on trapped ions consolidated figures of merit and specifications. Added Yaqumo and Matriq in cold atom quantum computer vendors. Update on Quandela. Update on Eviden who's been renamed into Bull. Updates on quantum music in the quantum computing applications section. Updated map of quantum companies in France. Updates on Quemix. Additional scientific references.

Version 8.4, May 13th, 2026 (1,524 pages).

Fixed the figure numbering between single column and wide page figures. Corrected the black-body chart formulas. Recreated the S-curve chart in Python with correct angles. Updated information on AQSolotl in control electronics enabling technologies. Added NV center in the glossary. In the bibliographies, added a keylock indicating paid papers, and their preprint link when available and found (semiautomatically).

Version 9.0, September 28th, 2026 (1,822 pages).

AI help. This edition benefited from a wealth of support from generative AI, spread over Claude Pro Opus 4.6 to 5.0, Gemini Pro, and ChatGPT up to 5.6. It helped me check all the parts and find errors (grammar, references, dates, facts, mathematics, consistency). It also added references and explanations on complicated topics (physics, algorithms, etc.). It helped convert multiple tables into LaTeX and adding the related cite references. I used it to create many charts in Python or to convert pixelated pictures into vector charts. All this is detailed in the "making of" section in 7. It normalized the amounts in Euros with the € sign being placed before the amounts.

Why. Updated content on classical semiconductor technologies, X-ray lithography, memory access with future HBM versions, Huawei Tau architecture, Nvidia, Cerebras, Vsora and Euclyd updates.

History. Added Christiane P. Koch, Valentina Parigi, and Tommaso Calarco in quantum physicists. Updated all parts, including on the impact of LLMs on quantum research.

Quantum 101. Added a comparison table summarizing the differences between classical and quantum physics. Improved explanation between intrinsic and extrinsic properties and between discrete and continuous variables. Move in this part the basics of quantum photonics and photon quantum number (previously in the photon qubit subsection in quantum computing hardware). Added explanation on the way to set and measure a photon OAM. Adding a definition for the Non Linear Schrödinger Equation. Added a photon frequency-time domain depiction explaining Heisenberg's indeterminacy principle. More explanations on entanglement, including a chart on the hierarchy of entangled mixed states. Added a description of quantum speed limits in the measurement part, including a chart differentiating QSL and actual qubit measurement times per qubit types. Added Casimir Inc and Jovion in the quantum vacuum fluctuation subsection.

Added some content on real or complex numbers in quantum foundations.

Gate based. Added a description of the quantum teleportation protocol. Added a chart explaining how multiple unitaries can land on the same target state on the Bloch sphere.

Quantum engineering. Improved some explanations on exotic quantum computing paradigms like holonomic quantum computation. Added meromorphic quantum computing, idle time optimizations, autonomous quantum machines, high-order quantum computing and fuzzy quantum computing. Restructured and significant rewriting of the whole QEC/FTQC subsection, better differentiating what belongs to QEC and FTQC, described what happens to an idle qubit, define a gadget, a circuit noise model, pseudo-threshold vs break-even and practical threshold, a diamond norm, embedding content from an author's March 2026 paper on the topic, adding and removing charts, added a frame better explaining the difference between surface codes and qLDPC codes, added Reed-Muller codes, explaining the role of pipe diagrams, adding a comparison table of QEC/FTQC publications by hardware vendor, added a frame on the role of QND, added some stuff on noise models and detector error models, added the definition of hook errors, and the difference between QEC/FTQC fidelities assumptions and real-life hardware, new table comparing error suppression, mitigation, detection, and correction, new frame on whether real full-stack FTQC architectures were demonstrated, new part on resource estimates, space-time trade-offs and FTQC application requirements. Added a frame explaining why NISQ applications are not really made to run in FTQC systems. Added a frame on misleading logical qubit labeling. In quantum memories, added explanations on QROM. In the energetic part that is restructured, updated the chart on ICT energy consumption with 2026 data and 2030 forecasts, added a definition of quantum energy teleportation. Frame on counter intuitive facts. Updated chart on energy consumption decomposition. Added some thermodynamics in the Lieb-Robinson part. Lots of additions and corrections after a Claude Pro review of this part. It reduces the impact of the LR bound on gate-based quantum computing systems. In economics, updated the Sankey chart with quantum processor sold and deployed. Added a table with pricing of quantum processors available in the cloud.

Quantum hardware. What is the most promising qubit type? frame in the segmentation subsection, with updated tables including references. The 4-color key takeways charts for each qubit types are now in LaTeX and contain clickable references. The key figures of merit per qubit table has been converted the same way. Updated D-Wave and Qilimanjaro in annealing. Corrections on various figures related to superconducting qubits. Added some details on leakage errors with superconducting qubits. New part on hybrid semiconductor-superconductor qubits. Added D-Wave, Logical Qubit Technology, Qbit Force Quantum, Qolumbus, Quint Computing, SDT and Srsti Quantum Technologies in superconducting qubit quantum computer vendors. Updated content on IBM, Google, Rigetti, IQM, OQC, Alice & Bob. Updated content on Diraq, Intel, SQC, Quobly, Equal1, and ARQUE. And QuEra, Pasqal, IonQ, Quantinuum, and all other major vendors. Updated information on Quantum Transistor. Added Qubitcore and Unitary Quantum Co in trapped ion vendors. Updates on IonQ, Quantinuum, and AQT. Added a definition of clock qubits, a table listing the characteristics of ions with their transitions and gates and a table detailing the implementation of microwave driven gates. Corrected the two tables summarizing the key technical aspects of 10 vendors. Updated the table comparing the different cold atom architecture implementations. Added a chart with energy transitions for cold atoms. Added an explanation of glass cells. Added Oratomic, CAS Cold Atom, Google, Taiyi Quantum, and Q-Factor in the cold atom computing vendors. Updated information on QuEra, Atom Computing, Logiqal and Planqc. Better description of the relative value of SOI, SiN, TTFLN and BTO for PICs. Added Photonic quantum memristors as a quantum photonic paradigm. Added a table comparing losses in various PIC components. Updated information on PsiQuantum, Xanadu, QuiX, Quandela, Qboson, QCi, Quantum Source in photonic qubits. Added HeliQ Standard CompuTech Co, Q.Ant and Qluster in photonic qubit vendors.

Enabling technologies. Restructured the cryogenics subsection with a better organization. Added a part dedicated to 4K cooling. Added a table consolidating 4K cooling offering and updated and completed the dilution vendor comparison table. Added Boreas Cryogenics, Casqi, CryoPride, Hexin Instruments, Physike, and ZL Cryogenic in cryogenic vendors. Improved explanations on the basics of control electronics, improved and added charts. Added QuantumCore and Qanova Tech in TWPA vendors. Update on QuantrolOX. Restructured and improved the cabling section. Additions on Delft Circuits. Added QREX in cable related vendors. Added Frostbyte, and IceCirc in cryo-CMOS vendors. Moved Semiqon from silicon qubits to cryo-CMOS vendors. Added Quantum Logic in cabling/mux/demux vendors. Added S-Transistors in superconducting control electronics. Added With Wave in TWPA vendors. Update on Quantcore. Added Quantum Queue, Qsculptor in other electronic vendors. Added AQLS, Quantum Pulse Ventures and Silicon Light Machines in photonics vendors. Separated single photon sources and detectors from the crowd of photonics vendors. Added an inventory of the key figures of merit of single photon sources and their origin. Added Arkeon Technologies and Chiral Nano in fab tools vendors. Moved Emergence Quantum from services companies to cryo-electronics vendors. Added an explanation of how Quandela's quantum dots are manufactured and wired. Rewrote and completed the helium part. New tables summarizing materials role, source, issues and environmental footprint.

Unconventional computing. Various updates on supercomputers based on TPC500 from June 2026. Added Quantum Dice in probabilistic computing vendors. Added Arago, Neurophos, Q/C Technologies. Added unconventional memory technologies. Added momentum computing.

Algorithms. Converted in LaTeX and added references to the table inventorying key quantum algorithms input and output. Added a definition of circuit sampling. Explain difference between unstructured vs promise oracle. Added GGSA, a variant of Grover. Table on QPE logical resources estimates for FeMoCo ground state evaluation. Many corrections, clarifications and additions on QPE, including on readout distribution explanation. Explanation of QLSA. Corrections and complements on Grover algorithm. Corrections on the Bernstein-Vazirani and Simon algorithms. Table showing the conditions to avoid QML dequantization. Frame explaining the meaning of learning in the context of quantum computing. Frame on oracle sketching. More details on how training and inferences work with quantum machine learning in NISQ and FTQC fashions. Updateon NISQ charts. Frame on will there be some quantum LLMs? Frame on DQI capabilities. Added a frame on the spectral gap and shortcuts to adiabaticity. Added a frame explaining the difference between arbitrary rotations and magic for obtaining an exponential speedup.

Software tools. Added a comparison in operations for standard algorithms with different coding frameworks. Added more details on circuit synthesis techniques. Added a frame on can I run my classical code faster with a quantum computers? Added AutoQuREO in resource estimators. Added the role of machine learning in emulators. Added Q.TEA, SOFT and TensorCircuit-NG in emulators. More on FTQC compilers. Frame on how to get free quantum computer access and on HPC and quantum computers colocation. Added Qrisp in academic tools. Many updates on vendor software tools. Updated charts on tools summary per large vendor. Added a chart on quantum cloud offerings in Japan and China. Added QAI.AI in cloud vendors. Updated the quantum advantages/supremacies and added a column on classical simulation / dequantization.

Applications. New framework to segment use cases and case studies. Using badges to flag the level of case studies (FTQC, NISQ, analog, with or without some quantum advantage, or for future systems). In quantum chemistry, added a frame to define basis sets and active spaces and a definition of QSCI and SQD, more on ground state preparation, plus some new papers and NISQ and FTQC use cases. Reorganized the defense application part.

Updated all parts with new references. Added AGI Quantum, Conductor Quantum, Dark Qore, EdenCode, Intelligent Quantum Inception, Prediqt Technologies and Prediqt Quantum, /q99, Q-Alchemy, QEC Labs, Qclairvoyance, Qmatter, Qodex Quantum, SQK and WYW (OpenVQA Hub), QuantonomiQS, Qubitra Technologies, QubitSolve, Qutwo, Racine AI, RAQS Quantum, SoftwareQ, Softquantus and TraverseQuantum in software vendors. Changed Coherent Computing into Cascade Quantum. Added Gladiolus Veritatis Consulting, Qubitsok, Quantsoc and Qonsultancy in services companies. Updates on Algorithmiq, Bloq, Entropica Labs, Kipu Quantum, ParityQC, Phasecraft, PolarisQB, Q-CTRL, Qedma, QMill, Qubit Pharmaceuticals, Riverlane and Terra Quantum.

Quantum communications and cryptography. Many updates on quantum computing crypto threats. Completed the PQC timeline, updated the final names of the NISQ PQC standards. Added a definition of Quantum Secret Sharing in QKD. Added some stuff on distributed quantum computing (DQC) deployment scenarios. Added a frame on "What is the difference between direct and heralded transduction?". Added Cavilinq and Cisco in quantum interconnect vendors. Added 3D QRNG in QRNG. Added Arq Quantum Technologies, Celare Quantum Communications, EigenQ, Lastwall, Project Eleven, pQCee, QLocked, Quantum Blockchains, QIZ Security, STmicroelectronics, Thales, Transilvania Quantum, ZeroRISC and ZeroTier in quantum communications vendors. Updates on Qtonic Quantum, formerly Qryptonic and on Quantum eMotion. Changed Q*Bird into Falqon Systems.

Quantum Sensing. Added Leidos and Shanghai Quantum Sensing Intelligence in PNT sensing. Added Dirac Labs in magnetometry sensing. Added Magnolia Quantum Sensing in quantum imaging. Description of the LZ dark matter detector and experiment uncovered in September 2026.

Quantum ecosystems around the world. Added Ground State Ventures, Deep33, Firgun Ventures and Propagator Ventures in the quantum investment funds inventory. Many updates on the USA, some on the UK, Germany, France, the Netherlands and the EU (pilot lines). Added Romania and Ukraine.

Quantum and society. Made a parallel between the existing AI revolution and the potential quantum computing revolution.

Making of. It now covers the usage of generative AI / LLMs to improve this book across multiple practices.

Glossary. Added definitions for 1WQC, 2DEG, 3D NAND, Abelian, ABRC, AC Stark shift, Active Volume, active space, ADAPT-VQE, ADR, AFC, Amdahl's law, amplitude amplification, Amplitude encoding, Angle encoding, Anomalous heating, Antibunching, assumption, Auger effect, Axion, Backside power delivery, barren plateaus, Base temperature, Basis encoding, BB84, BCS theory, Bernstein-Vazirani, Betti number, Bias-preserving gate, Bichromatic field, block-encoding, bond dimension, Bose-Hubbard model, Brane, Bravais lattice, Bright/dark fluorescence readout, Brightness, Brillouin scattering, Bucket brigade, Butterfly velocity, cADR, capex, Carleman linearization, Carnot efficiency, Casimir effect, CFD, CFET, Chern number, CHSH inequality, CIM, classical shadows, Clock qubit, CNOT, coarse graining, Coaxmon, Coherence fraction, Coherence length, Cold plate, Cold trap, Concurrence, Consistent histories, Constructor theory, COP, corrects the existing Erasure error, CPLEX, Cryocooler, cryopumping, Cryostat, CSM, Cuprate, CV-QKD, CVaR, DAQC, Dark energy, Dark matter, Dark photon, Dark silicon, Data re-uploading, DCE, DCQO, DDS, Delayed-choice experiment, Dennard scaling, DI-QKD, Dimon, DLA, DMRG, Domain specific architecture, Doppler cooling, DQC, DQI (with HDQI), DRAM, Dual-rail encoding, Dual-species, DV-QKD, E91, EDSR, Einselection, EIT, Epistemology, EPLG, EPR paradox, ESR, EUV, Exchange-only qubit, Exciton, Extended Church-Turing thesis, FD-SOI, Fermi's golden rule, Fine-structure constant, FinFET, First quantization, First quantum revolution, Fluxonium, FOFI, Foliation, Free Electron Laser (FEL), GAA, GAN, GAS, Gatemon, GBS, GGSA, GHS, Gifford-McMahon, Ginzburg-Landau theory, GQE, Graviton, GSA, Haar random matrix, Hafnian, Hamiltonian simulation, HBM, HDQI, Helicity, Hermitian matrix, HHL, High-NA, HOBO, Holevo bound, Hong-Ou-Mandel effect, Hopfion, HSP, HTS, HUBO, Hybrid bonding, Hyperentanglement, Hyperfine qubit, Iceberg code, IDR, In-memory computing, Indeterminacy principle, Interposer, Ion shuttling, Jevons paradox, Kapitza resistance, Klein-Gordon equation, Koomey's law, Kraus operators, Lamb shift, Landauer limit, Lattice surgery, LCHS, LCU, Leggett inequalities, Lieb-Robinson bound, Light cone, LNOI, Local Friendliness, LOCC, Loophole-free Bell test, Lorentz factor, LPPT, LQG, LSTM, M-theory, Magic, MAGIC, Magic state cultivation, Magnon, Many-worlds interpretation, matchgate circuits, max-k-XORSAT, max-LINSAT, MCMC, MCMR, MDI-QKD, MegaQuop, Meissner effect, MERA, Metasurface, Micromotion, Microwave-to-optical transduction, Mid-circuit measurement, MIS, Mixing chamber, MNR, Modality, Moore's law, More than Moore, Motional mode, Mølmer-Sørensen gate, MPO, MPS, MRAM, MZI, Nanosheet, NDR, NEMS, NFQC, No-signaling, Noether's theorem, NQS, ODE, OFHC, Ontology, OPA, opex, OPO, Optical qubit, optical tweezer, Operator norm, oracle, OTOC, Overhauser field, p-wave and d-wave, Paul trap, Pauli propagation, Pauli spin blockade, Pauli string, PBR theorem, PCA, PDE, PDK, Penning trap, PEPS, phase kickback, Photoionization, PIC, Pilot wave, PIM, Planck length, Planck units, Plasmon, PMT, PNRD, Poincaré sphere, Pointer states, PQE, Psi-ontic and psi-epistemic, PUBO, PUE, pulse tube, Q-Score, QAA, QACM, QAE, QAI, QAQM, QBER, QBism, QCCD, QCNN, QCV, QET, QFC, QGLM, QGT, QITE, qLDPC, QLBM, QLSA, QLSP, QNLP, QPE, QPINN, qRAM, QRC, QROAM, QROM, QSA, QSCI, QSDC, QSP, QSS, QSVD, QSVM / SVM, quantics representation, Quantum algorithm, Quantum batteries, Quantum Cramér-Rao bound, Quantum Darwinism, Quantum data center, quantum energetics, Quantum Field Theory, Quantum illumination, Quantum logic, Quantum matter, Quantum repeater, Quantum resource estimator, Quantum spin liquid, quantum thermodynamics, Quantum transduction, quantum utility, Quantum volume, quantum walk, Quantronium, Ququart, qubitization, Qumode, QWOA, Racetrack, RBM, rebound effect, Relational quantum mechanics, ReLU, Renormalization, Repumping, Retargetability, Reticle limit, Retrodiction, reversible computing, RSG, RUS, Rydberg blockade, s-wave, Schrödingerization, Scrambling, SDP/LP/MIP/ILP, SED, Semiclassical QFT, Shelving, Sideband, Sign problem, SIMD, Simon, Singlet-triplet qubit, Sisyphus cooling, SKR, Skyrmion, SNAQ, SNSPD, SoC, SOI, SPAD, Spin glass, Spin-to-charge conversion, SpinBus, SPOQC, SRAM, Standard model, Still, String theory, Strong simulation, Superabsorption, Superatom, Superdeterminism, Superfluidity, Supersolid, Supersonic propagation of correlations, Surface trap, SWSPD, SYK, Sympathetic cooling, Szilard engine, Tachyon, Tau scaling law, TCI, TCO, TDA, TDP, Technology node, tensor network, TES, TF-QKD, TFLN, THC, Theory of everything, Time-bin entanglement, Topological insulator, Transmon, Trusted node, Tsirelson bound, TSP, TSV, TTN, TTSB, Twistronics, Type I and type II superconductors, UBDM, UCC, Unary iteration, uncompute trick, Vacuum fluctuation, Vacuum polarization, Value migration, von Klitzing constant, VQC, VQLS, Wafer-scale engine, Weak simulation, Weyl fermion, Wigner crystal, Wigner's friend, WIMP, and Zeeman qubit,

This book contains 904 bibliographic entries and 119 illustrations. .

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⟨ 137 | 1WQC | 3D NAND | 2DEG | Abelian | ABRC | Active space | Active Volume | ADAPT-VQE | Adaptive quantum circuits | ADC | AC Stark shift | Adiabatic | Adiabatic theorem | ADR | Advantage | aka | AKLT state | Algorithm | Algorithmic qubit | Amdahl's law | AFC | Amplitude | Amplitude amplification | Anharmonic oscillator | Angular momentum | Anomalous heating | Ansatz | Antibunching | Anyon | arXiv | Antisymmetry | AOD | Approximate Amplitude Encoding | Artificial atoms | ASIC | Assumptions | Atoms | Auger effect | Autonomous quantum error correction | AWG | Axion | BB84 | Back action | Backside power delivery | Balmer series | Band gap | Balanced beam splitter | Barren plateaus | Baryon | Base temperature | BCS theory | Beam splitter | Bell inequalities | Bell states | Bell test statistic | Bernstein-Vazirani | Basis encoding | Betti number | Bichromatic field | Bright/dark fluorescence readout | Bias-preserving gate | Biphoton | Black body | Blind Quantum Computing | Angle encoding | Amplitude encoding | Bloch states | Bloch sphere | Brightness | Bucket brigade | Block-encoding | Bond dimension | Born rule | Born-Oppenheimer approximation | Bose-Einstein Condensate | Bose-Hubbard model | Boson sampling | Boson | Bosonic codes | BQP | Bra-ket | Brane | Bravais lattice | Break-even | Brillouin scattering | BSM | cADR | Cap table | Capex | Carleman linearization | Carnot efficiency | Casimir effect | Cavity | Cavity quantum electrodynamics | CFD | CFET | Chandelier | Chern number | Chi | Chip | Chipset | Chiplet | CHSH inequality | CIM | Circuit quantum electrodynamics | Circuit synthesis | Classical shadows | Clifford group | Circulators | Circuit | Clock qubit | Cluster state | CLOPS | CMOS | CNOT | Coarse graining | Coaxmon | Code distance | Coherence | Coherence fraction | Coherence length | Cold atoms | Cold plate | Cold trap | Compatible properties | Commutativity | Commutator or commutation operator | Complementarity | Complementary variables | Complex number | Complexity | Compton effect | Computational basis | Concatenated codes | Condensed matter physics | Conjugate variables | Concurrence | Consistent histories | Constructor theory | Contextuality | Continuous variables quantum computing | Cooper pair | COP | Copenhagen interpretation | Coplanar waveguide (CPW) | CPLEX | Cryo-CMOS | Correspondence principle | Coulomb blockade | Coulomb force | Counterfactuals | Counterfactual models | CPTP map | Crosstalk | Cryocooler | Cryogenics | Cryopumping | Cryostat | CSCO | CSM | Butterfly velocity | Cuprate | CV-QKD | CVaR | CVD | DAC | DAQC | Data re-uploading | Dark count | Dark energy | Dark matter | Dark silicon | Dark state | Dark state protocols | DCE | DCQO | DDS | DQC | De Broglie wavelength | Decoherence | Degenerate | Delayed-choice experiment | Dennard scaling | Density matrix | Dequantization | Determinism | Deutsch-Jozsa | DFT | Dimon | DI-QKD | Dicke state | $k=0$: | $k=1$: | $k=2$: | $k=3$: | $k=4$: | Diffraction | Dilution refrigerator | Dirac's notation | Dirac constant | Discrete log problem | Dissipation engineering | Distillation | DLA | DMRG | Domain specific architecture | Doppler cooling | Doppler effect | DV-QKD | D-Wave | DQI | DRAG | DRAM | Dressed state | Dual-rail encoding | Dual-species | E91 | EBL | EDSR | Eigenstate | Eigenvalue | Eigenvector | Einselection | Electromagnetic spectrum | EIT | Electron | Electron gas | Elliptic Curves Cryptography | Energetics of quantum technology | Engineering | Entanglement | Entropy | EPLG | EPDA | Epistemology | EPR paradox | EQA | Erasure error | ERC Grants | Ergodicity | Ergotropy | Error Correction Codes | Errors | ESR | Eta letter | EUV | Exchange-only qubit | Exciton | Exclusion principle | Expectation value | Euclidean networks | Extended Church-Turing thesis | Fabry-Pérot cavities | FBQC | FD-SOI | Feedforward | Fermi's golden rule | Fermi sea | Fermi-Hubbard model | Fermions | Fine structure | FinFET | First quantization | First quantum revolution | Floquet code | Fine-structure constant | FOFI | Fluxonium | Flying qubits | Fock space | Fock state | Flux biasing | Foliation | Fourier Transform | FPGA | Fredkin gate | Free Electron Laser (FEL) | FTQC | GAA | GAN | GAS | Gatemon | Gate-based quantum computing | Gate teleportation | Gaussian Boson Sampling (GBS) | Gaussian state | GBS | GGSA | GHS | GHZ | Gibbs state | Gifford-McMahon | Ginzburg-Landau theory | GKP qubits | Gleason's theorem | GPGPU | GQE | Graviton | Green's function | Grotrian diagram | Ground state | Grover | GSA | Gurobi | H-bar | Hadamard | Hafnian | Hall effect | Hamiltonian | Hamiltonian simulation | Hamming distance | Harmonic oscillator | Hartree-Fock | HBM | Heisenberg | Heisenberg cut | Heisenberg ... Helium 4 | HEMT | Hermitian matrix | Heterostructures | Heuristic algorithm | Heralded single-photons | Helicity | Heterodyne ... | Hilbert | Holevo bound | Hong-Ou-Mandel effect | Hidden variables | HOBO | Homodyne measurement | Hopfion | H... PQC | ... | HTS | ...rd model | HUBO | Hybrid bonding | Hyperentanglement | Hybrid quantum algorithm | Hyperfine structure | Hyperfi... | Iceberg ... | IDR | In...y computing | Indeterminacy principle | Indistinguishability | Indistinguishable photons | Integrated Quantum Phot... | Interference | ...terposer | Int...ectivity | Invertible computation | Irreversible | Ion | Ion shuttling | Ion traps | IonQ | I/Q mixer | Ising | Isotop... | Jaynes-Cum...gs Hamiltonian | ...ons paradox | JJ | Josephson | JPA | Kapitza resistance | Kerr effect | Ket | Klein-Gordon equation | Koche...ecker theorem | ...mey's law | Koo...n–von Neumann | Lamb shift | Lamb-Dicke regime | Landauer limit | Larmor frequency | Larmor precessio... | ...aser | Lattice surg... | LCHS | LC... | Le...e errors | Learning | Leggett-Garg inequality | Leggett inequalities | Kraus operators | Lie groups | Lindblad ...ation | Linear alge... | Linear optics | Lie... ...binson bound | Light cone | LNOI | Local Friendliness | Loophole-free Bell test | Lorentz factor | LPPT | ... | M-theory | Many...ds interpretation | ...-LINSAT max-k-XORSAT | LLM | Locality | LOCC | Logical Qubit | Loophole | LRU | LSTM | MAGIC | ...c states distillatio... ...gic state cultivatio... Magneto-Optical Trap | Magnon | Majorana fermion | Manifold | Markovian process | Matchgate circuits | ...rix | Matter wa... ...UT | Maxwell's ...on | MBE | MBQC | MCMC | MCMR | MDI-QKD | MegaQuop | Meissner effect | MERA | Mesoscopic | ...aheuristic al... ...ayers | Meta...ace | Microring resonator | Mid-circuit measurement | MIS | Microwave-to-optical transduction | Mixing c...ber | Moo... ...Moore | ...AM | MZI | Mølmer-Sørensen gate | Motional mode | Micromotion | MNR | Mode-locked laser | Mott insu... | Mott... ...PO | MV... ...INLP | Mixed state | MNIST | Modality | Momentum | Multimode | Muonic atoms | Mutually unbiased bas... | Na... ...t | ND... | NEMS ... ...SQ | No-go theorem | Non-Clifford gates | No-cloning theorem | No-signaling | Nonlinear optics | Nonlocality | ...kovian pr... ...MR | ...sical light | Non-demolition measurement | Non-selective measurement | NOON state | Noether's theorem | Norma... | NP | NP...plete | NP... ...t | NQS | NV center | Observable | ODE | ODMR | OFHC | On-premise | Ontology | OPA | Opex | Operator norm | ... ...OTOC | ...ical mol... | Optical pumping | Optical qubit | Optical tweezer | Oracle | Orbital angular momentum | Oscillator | Overhauser field | P... ...Pauli spin blockade | Pauli string | PBR theorem | PCA | PDE | PDK | Penning trap | PEPS | Permanent | Phase Estimation Algo... ...se classification | Phase kickback | Phase space | Phasor diagram | Phonon | Photoelectric effect | Photoionization | Photolithography | PIC | PIM | Photon | Photon measurement | Pilot wave | PKI | Planck constant | Planck length | Planck units | Plasmon | PMT | PNRD | Pockels effect | Poincaré sphere | Pointer states | Polarized Beam Splitter | Polaritons | Postselection | POVM | PQC | PQE | PQS | Prefactors | Prepare-and-measure | Private Key | Process Design Kit | Property | Psi-ontic and psi-epistemic | Public key | PUBO | PUE | Pulse tube | Purcell effect | Purcell filter | Pure state | Purification | PVD | PVM | Q factor | Q-Score | QAA | QAE | QAI | QACM | QAQM | QAOA | QAOA | QBER | QBism | QCCD | QCKA | QCaaS | QCNN | QCV | QFC | QET | QFHE | QFT | QGLM | QIP | QHO | QIR | QITE | QKD | QLBM | qLDPC | QLM | QLSA | QLSP | QMA | QML | QND | QNLP | QPE | QPINN | QPU | qRAM | QRC | QRNG | QROM | QSA | QSCI | QSP | QSDC | QSS | QST | QSVD | QROAM | QSVT | Quantics representation | Quantization | Quantronium | Quasi-locality | Quantum accelerator | Quadrature | Quantum advantage | Quantum algorithm | Quantum annealing | Quantum batteries | Quantum channel | Quantum Chaos | Quantum chromodynamics | Quantum circuit | Quantum cognition | Quantum computer | Quantum Conference Key Agreement | Quantum Darwinism | Quantum data center | Quantum dots | Quantum Electro-Dynamic | Pauli propagation | Quantum emulator | Quantum energetics | Quantum engineering | Quantum Field Theory | Quantum Fisher Information | Quantum foundations | Quantum gates | Quantum Hall effect | Quantum hydrodynamics | Quantum Internet | Quantum jump | Quantum kernel | Quantum capability learning | Quantum logic | Quantum matter | Quantum medicine | Quantum Non Demolition measurement | Quantum numbers | Quantum postulates | Quantum Physical Unclonable Functions | Quantum repeater | Quantum reservoir computing | Quantum reservoir engineering | Quantum resource estimator | Quantum simulator | Quantum speed limit | Quantum spin liquid | Quantum state | Quantum state tomography | Quantum Steering | Quantum supremacy | Quantum switch | Quantum teleportation | Quantum thermodynamics | Quantum transduction | Quantum trajectories | Quantum utili... | Quantum walk | Quantum Zeno Effect | Quasiparticles | Qubit | Qubitization | QUBO | Qudits | Que... ...art | ...uri... | ...VD... | Rabi | Ra... ...aman cooling | Raman effect or Raman scattering | Raman spectroscopy | Ram... ...nt | Rayleigh scattering | RBM | Realism | Rebound effect | Reduced Planck constant | Reflectometry | Register | Relational quantum mechanics | Relaxation | ReLU | Renormalization | Renyi entropy | Repumping | Reticle limit | Retrodiction | Reversible computing | RIE | RSA | RUS | RSG | Rydberg state | Rydberg blockade | Sapphire | SAT | Scrambling | Scale-out | Scattering | Schrödinger | Schrödingerization | Schrödinger wave function collapse | SDP | LP | MIP | ILP | Second quantization | Second quantum revolution | SED | Semiclassical QFT | Semi-classical light | SFQ | Shelving | Shor | Shortcuts to Adiabaticity | Sideband | Silicon 28 | SIMD | Simon | Single mode | SKR | Singlet-triplet qubit | Sign problem | Sisyphus cooling | Skyrmion | SLM | SNAQ | SNSPD | SoC | SOI | SPAC | SPAD | SPAM | Spectral lines | Spectral decomposition | Spin | SpinBus | Spin-to-charge conversion | Spin-boson model | Spin glass | Spinor | Spintronics | Spontaneous emission | Spontaneous Four-Wave Mixing | Spontaneous Parametric Down-Conversion | SPOQC | Squeezed states of light | Squeezing | SQUID | SRAM | Stabilizer gates | Standard model | Standard quantum limit | Stark shift or Stark effect | State reduction | Retargetability | Strong simulation | State vector | Stationary qubits: stationary | Stern-Gerlach experiment | Still | Stimulated emission | String theory | Sturm–Liouville problem | Superabsorption | Superatom | Superconductivity | Superdense coding | Superdeterminism | Superfluidity | Supersonic propagation of correlations | Superoperator | Superposition | Superradiance | Superselection | Supersolid | Surface codes | Surface trap | SVD | SVM | SWAP | s-wave, p-wave and d-wave | SWSPD | SYK | Symmetry | Sympathetic cooling | Szilard engine | T gate | T-count | T-depth | Tachyon | Tau scaling law | TCI | TCO | TDA | TDP | Technology node | Tensor network | TF-QKD | TFLN | TES | THC | Theory of everything | TSP | T_1 | T_2 | Tabu search | TDSE | Tensor | TeraQuop | Thermodynamics first law | Thermodynamics second law | Time crystal | Time domain | Time reversal | Toffoli | Topological | Topological insulator | Time-bin entanglement | Tsirelson bound | Transmon | Transpiler | Transpilation | Transversal gates | Trapped ions | Trotterization | Trusted node | TSV | TTN | TTSB | Tunnel effect | Twistronics | Two-Level Systems | TWPA | Type I and type II superconductors | UCC | UHV | Ultraviolet catastrophe | Unary iteration | Unary gates | Uncompute trick | Unconventional Computing | Unitary operation | Universal quantum computer | Universal quantum gates | Unruh effect | Vacuum fluctuation | Vacuum polarization | Value migration | Variational

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