Opinions Libres

le blog d'Olivier Ezratty

# Understanding Quantum Technologies 2024

Here is **Understanding Quantum technologies 2024**, the 7th edition of this book and the fourth in English. It is always a free to download book, without any questions asked (no email, no profiling). It reaches 1,554 pages, split in five volumes for e-readers and a paperback edition is available since November 10th on many **Amazon** sites.

**Note**: this version is superseded by the 2025 version that **you can find here**.

The book and these volumes are structured as follow:

Volume 1 "**Prologue**" (372 pages) starts with describing the motivation and organization of this book, then a quantum physics history highlighting the key contributors of this field, quantum physics 101 (quantization, superposition, entanglement and the likes). It then lays-out the basics to understand quantum computing with describing how gate-based quantum computing operates (qubits, gates, measurement), and then covers quantum computing engineering which includes quantum computer physical paradigms and architecture, error handling, quantum memory, quantum energetics, economics and how to deal with uncertainty.

Volume 2 "**Computing hardware**" (458 pages) contains a description of all qubit modalities with their science, engineering and vendors offerings and roadmap, then quantum enabling technologies, and at last unconventional computing.

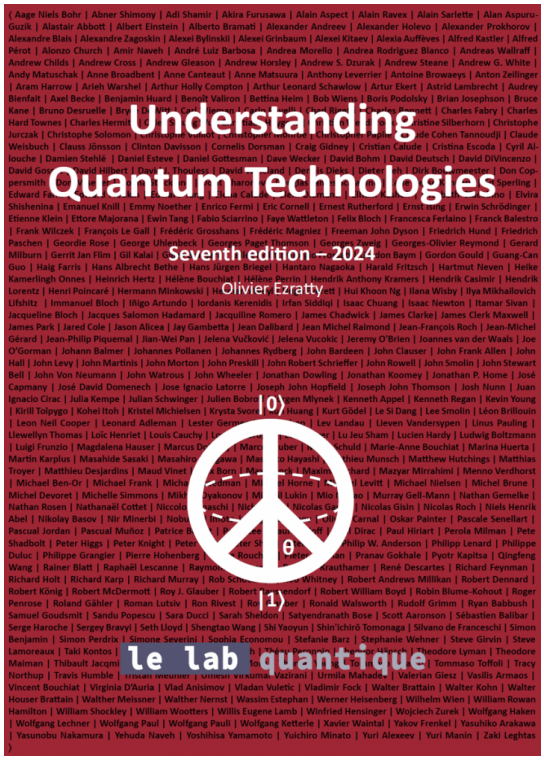
Volume 3 "**Computing software**" (344 pages) covers quantum algorithms, software tools and case studies.

Volume 4 "**Communications and sensing**" (180 pages) contains the parts related to quantum communications, quantum cryptography, quantum post-quantum cryptography and quantum sensing.

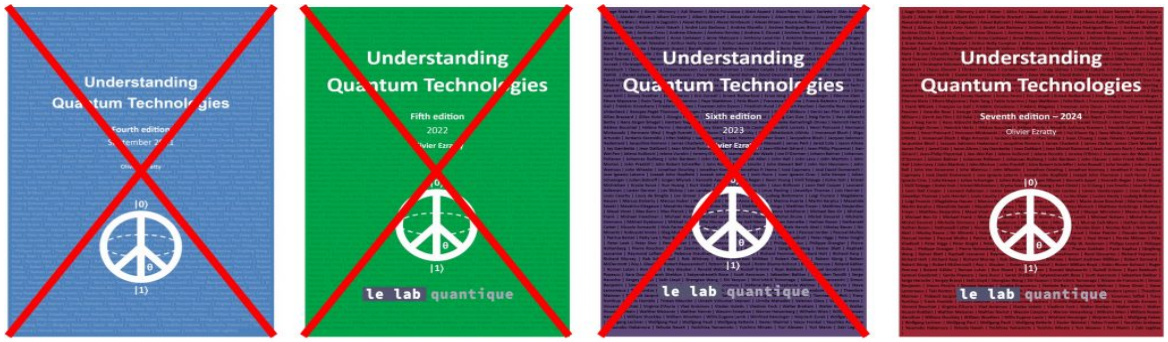
Volume 5 "**Ecosystem**" (264 pages) deals with quantum technologies around the world from the entrepreneurial to the country scene, corporate adoption, quantum technologies and society, and quantum fake sciences, plus a glossary, and index for all volumes using a continuous pagination numbering.

**ebook formats and downloads**

This book is directly downloadable as a PDF file with no required personal data, with an optional lighter version for a readers like Amazon Kindle. A paperback printed version will also be available in November 2024, on **Amazon sites**.




I use a color code to remember which edition we are talking about. The previous editions were in purple (2023), green (2022) and are all outdated.




Here are the various PDF versions available for download. You'll be better off downloading the relevant files just before your start reading it, the reason being that I continuously update the document until January next year.

This book current version is **7.2**, updated on **March 9th, 2025** (the updates log is at the end of the single volume file or at the end of volume 5). Version 7.1 – November 6th is also available on **arXiv**.

Downloads are available with either a singe PDF file containing the full book with images in full resolution (1,552 pages, 115 Mb) or split in five volumes smaller than 32 MB with images in low resolution, all in A4 or LETTER format.

The page numbers of A4 and Letter format files are consistent from volume to volume, but not from single volumes 2-to-5 and the single file versions. For example, page N in Letter Volume 3 matches page N in the A4 Volume 3. But the page numbers are not the same between the full book PDF version and the five volume versions.

**ISO A4 PAPER SIZE**

**A4 format full book**

**Vol 1: prologue**

**Vol 2: computing hardware**

**Vol 3: computing software**

**Vol 4: communications and sensing**

**Vol 5: ecosystem**

**USA/CANADA LETTER PAPER SIZE**

**Letter format full book**

**Vol 1: prologue**

**Vol 2: computing hardware**

**Vol 3: computing software**

**Vol 4: communications and sensing**

**Vol 5: ecosystem**

I also updated the short version of the book which is only 26 pages long (images in best resolution, 3 Mb). It is an illustrated compilation of the “key takeaways” from the end of each book’s parts.

**Book short version**

**Book statistics**

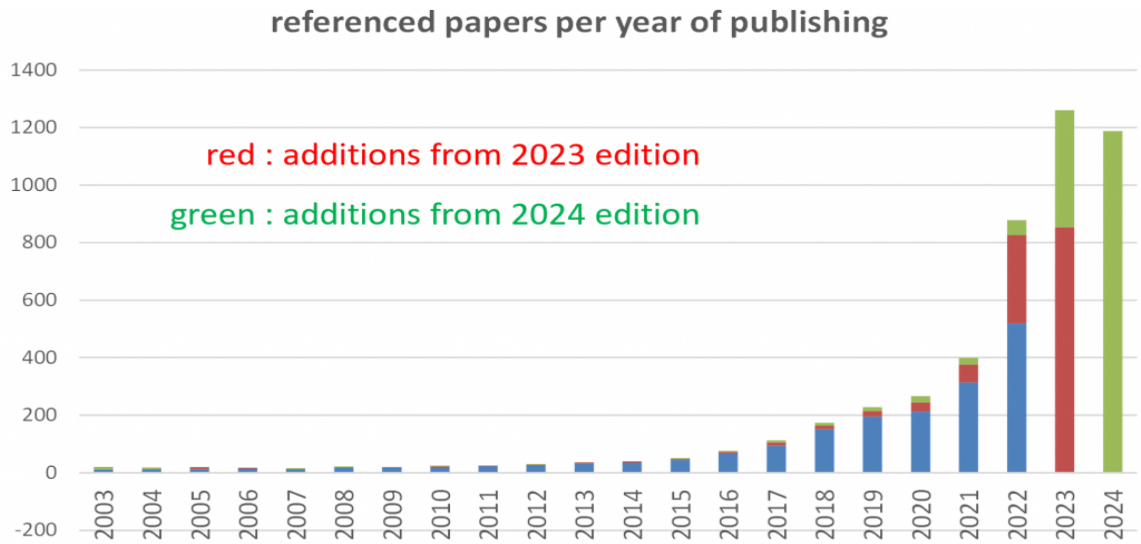
While quantum computing promise is to provide some exponential speedups to solve various computational problems, you’ll be happy to see that the growth in pagination of this book is only linear. It also demonstrates that its author is a human and not a machine, although I use a lot of various tools and tricks to improve my writing and editing productivity.

Other statistics on the book content:

- 1,059 **annotated figures** and custom schematics including 275 updated or new ones.
- 5,059 referenced **scientific papers**, totaling 146,450 pages.
- A **465 terms glossary**.
- Each part ends with a summary of about **7 key takeaways**.
- It took me **5 months** to produce this update, from May to September 2024.

And a split of referenced paper per publication year and with the additions from this 2024 edition, in green which gives you an indication on the “freshness” of its bibliography and how research is lively in the field. The X axis is the years of publication of the papers added in the bibliography. The Y is the number of papers from the bibliography. It shows that the bulk of the papers added in the 2024 edition were published in 2024, 2023

with a very small share published earlier.




**New features**

Like all previous editions, this 7th edition is an update. All pages have been corrected and updated. Here are its key evolutions and new features:

**History and scientists**: added David Mermin in quantum physicists. Some minor updates everywhere.

**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 qubits types 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 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, updates on skepticism and optimism related to quantum computing.

**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. Added Advanced Quantum, Paragraf and Elemental Instruments in other enabling technologies vendors. Added Aresis, Artilux, Covesion, Astrolight, Photonscore, ephos, 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**: updates on China and quantum satellite 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. Many new scientific papers added.

**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, 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.

**Uniqueness**

If you discover this book for the first time, here is how it is different from most books on quantum technologies and quantum computing since its inception.

- Science
  - The book recasts the history of quantum physics and gives credits to its many contributors, famous and less known, with a balance between theoreticians and experimentalists.
  - It explains the very basics of quantum physics and correct some myths (the dead and alive cat, faster than light communication, etc.). And then some of the fundamental mathematical formalism supporting quantum physics, particularly around linear algebra. It even covers quantum foundations and interpretations.
  - It is picky on terminology, like when I explain the subtle differences between simulation and emulation, correlation and communication, or ions traps and trapped ions.
  - It even explains for newcomers how research works, how scientific papers are being crafted, published and can be analyzed.
- Technology
  - It details extensively all quantum technologies from the 2nd quantum revolution: computing, communication/cryptography, sensing, and in the case of quantum computing, quantum physics 101, hardware, enabling technologies, algorithms, software tools and use cases. It even describes the relatively rarely mentioned domain of quantum matter and its potential applications.
  - It tests several pedagogical approaches to explain quantum computing, using different analogies like with using analog electronics.
  - It exposes the challenges, particularly around scalable quantum computing, and the amazing variety of solutions that are envisioned by both academic groups and industry vendors to solve complex problems. It pays tribute to all the scientists and engineers who are working on these challenges.
  - It also shows the technology context of quantum computing with Moore's law whereabouts and the state of the art in unconventional classical computing (38 pages), with identifying potential synergies with quantum computing.
- Ecosystems
  - It values Europe's role beyond the traditional USA/China presentation. About 100 pages describe the quantum ecosystems and initiatives of 41 countries over all continents.
  - And the product ranges and technologies from >750 companies from around the world, including enabling technology vendors.
- Bridges
  - The book creates a bridge between all dimensions, particularly between software and hardware.
  - It also plays a role in science intermediation, creating bridges between the classical and quantum computing worlds.

- Each part has a one pager summary for readers who are in a hurry (“Key takeaways”).

You will also see learn why quantum science and technologies are both *complicated* and *complex*. Complicated because it involves a wealth of assembled parts and components that are difficult to understand but have a somewhat predictable behavior (like cryogenics, control electronics and even quantum algorithms). Complex since quantum systems are non-deterministic and quantum probabilities, if not some form of chaos, play a role everywhere. The effects of noise are not predictable at large scale on qubits. The interactions between the many involved components of quantum systems may lead to unpredictable outcomes. It will also be the case when trying to simulate large quantum chemistry systems with quantum computers.

**Audience**

This ebook target audience is broad but rather technical. Some parts are accessible to non-scientific readers, particularly the geopolitics and societal parts at its end. Other parts require some scientific background at the licence or master level. Reading the many referenced scientific papers requires at least a master level, if not a PhD. Don’t imagine I understand all these papers. The range of my understanding is broad and between 5% and 60% in most cases.

The first target audience are computer science, information technology specialists and software developers who want to understand the whereabouts of quantum computing hardware, software and use cases. It is also made for students and professionals who are attracted by quantum technologies and would like to develop some skills in this emerging domain.

It is also interesting for most quantum scientists, engineers and entrepreneurs since most of them are specialized in a narrow field while this book provides an up-to-date 360° view on all quantum technologies. Covering all of this is nearly a full-time-job and a regular quantum physics or technology specialist don’t have the time to follow the related continuous scientific news cycle.

**Business model**

I have published tens of free books like this since 2006. I favor distribution over revenue, and am an advocate of open science. I benefited from it when looking for scientific data. Otherwise, I sell my time in a rather traditional way with speaking, teaching, training and various consulting and investor due-diligence missions. Another way to describe my business model is I give away the long version and sell the short one. Since with businesses, time is money and students have time but no money, all things go round. And this is particularly true with quantum technologies.

**Reviewers**

This book and its previous editions benefited from the help of several scientists and entrepreneurs who proofread the document, mostly on specific parts. As the book size grows, it is a huge challenge to get some time from scientists to review such a book. They are short on time!

Specific help for crafting this 7$^{th}$ edition came from **Philippe Grangier** (spins, quantum foundations), **Robert Whitney** and **Marco Fellous-Asiani** (quantum energetics), **Raphael Lescanne** (cat-qubits), **Alain Chancé** (fermionic analog simulation), **Matthieu Desjardins** (carbon nanotube qubits), **Jeremy Stevens** (quantum energetics), **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). And a special thank to **Michel Kurek** (Multiverse) who carefully reviewed several times the

whole book as with many previous editions and **Christophe Jurczak** (Quantonation) for his foreword. This book is also supported by **le Lab Quantique** (not financially, but for its visibility).

You can also send me feedback, corrections and suggestions, and even provide me with anecdotes or stories on how you are this book or its previous edition. I update the book content whenever required until the end of the year.

Best,

Olivier Ezratty

September-November 2024

Cet article a été publié le 26 septembre 2024 et édité en PDF le 14 décembre 2025.