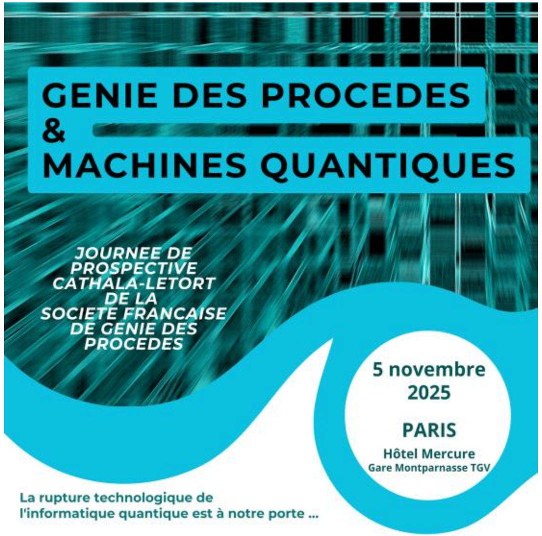


SFGP

informatique quantique

état de l'art, perspective et défis

Olivier Ezratty

⟨ ... | quantum engineer | QEI cofounder | ... ⟩

olivier@oezratty.net www.oezratty.net @olivez

SFGP, Paris, 5 novembre 2025

#QEI
the quantum energy initiative

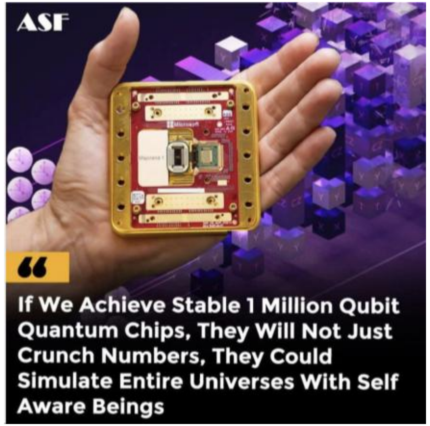
L'USINEDIGITALE

Avec son algorithme Quantum Echoes, Google se rapproche d'applications réelles pour l'informatique quantique

Julien Bergounhoux

22 octobre 2025 | 17h00

Google annonce avoir mis au point le premier algorithme au monde à démontrer de façon vérifiable un avantage quantique. Baptisé Quantum Echoes, il permettrait de mesurer des distances très précisément à l'échelle moléculaire.



New Scientist

Quantum computers have finally achieved unconditional supremacy

For the first time, researchers have mathematically proven that a quantum computer can solve a particular task faster than an ordinary computer, in a way that can never be beaten

By Karmela Padavic-Callaghan

19 September 2025

What Is Quantum Computing? Explained in 3 Minutes!

3MinExplained Subscribe 0 Share ···

THE WALL STREET JOURNAL. **** Wednesd

TECHNOLOGY

Nvidia Connects Quantum With AI

By Isabelle Bousquette

Nvidia isn't developing its own quantum computers, but Chief Executive Jensen Huang is betting the company will play a critical role in the technology's future.

Huang unveiled NVQLink, an interconnect that links quantum processors to the AI supercomputers they need to run effectively during his Tuesday keynote at Nvidia's Washington, D.C., Global Technology Conference.

"NVQLink is the Rosetta Stone connecting quantum and classical supercomputers," he said.

Quantum processors represent a fundamentally new kind of computing that harnesses the principles of quantum physics to solve problems today's classical computers can't.

KENT NISHIMURA/BLOOMBERG NEWS

Jensen Huang calls the link the 'Rosetta Stone' connecting quantum and supercomputers.

tecture and functions across different quantum modalities, including trapped ion, superconducting and photonic. The openness is critical, meaning national labs will be able to develop supercomputers primed to take advantage of quantum capabilities as they become available, Costa said.

In the future, "every supercomputer will draw on quantum processors to expand the problems that it can compute, and every quantum processor will rely on a supercomputer to run correctly," Costa said.

When can we expect to see meaningful commercial value from quantum? Costa said any answer he could give on that would probably end up being wrong.

"You can do things like linearly extrapolate based on the technology progress over the

Quantum computing's market potential could be up to $250B

Quantum computing applications

$250B

BAIN & COMPANY

What will the terminal valuation be of a quantum hardware company that succeeds to build a commercially useful quantum computer at scale ?

You can see how people vote. Learn more

Greater than $5T	30%
$1T	25%
$500B	20%
$100B	15%
Less than $50M	10%

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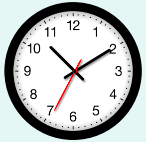
https://www.verywellmind.com/what-is-zen-meditation-4586721

potential quantum computing benefits

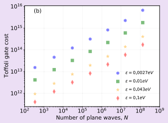


- **computing faster than classical systems.**

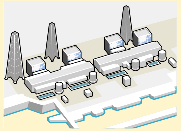
or

- **solving problems inaccessible to classical computers.**

- **reducing required training data**, particularly for machine learning tasks.



- **improving results quality**: chemical accuracy, better heuristics, etc.



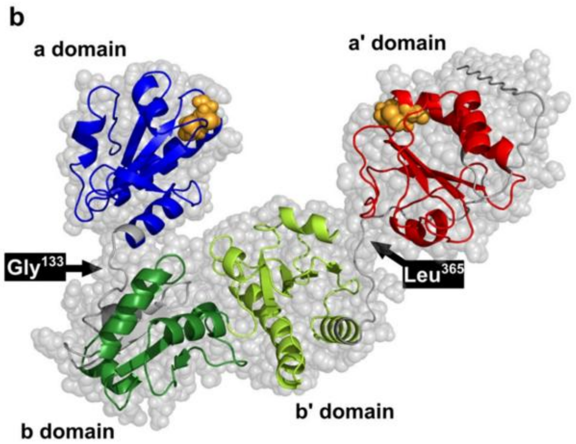
- **energetic advantage** (NISQ).

or

- **energetic acceptability** (FTQC).

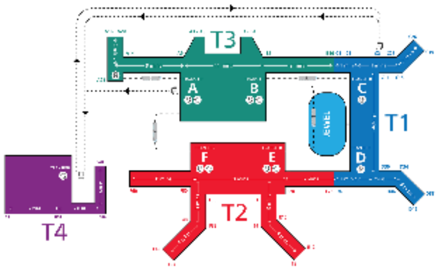
- **usefulness**: which depends on the stakeholder (fundamental research, governments, industry).

typical difficult problems

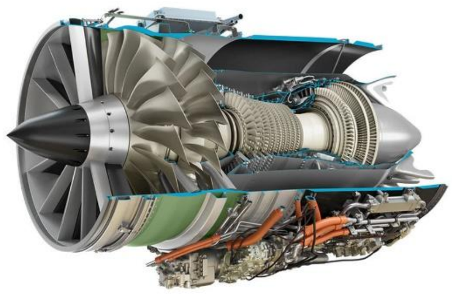


$$i\hbar\frac{\partial\Psi(x,t)}{\partial t}=-\frac{\hbar^2}{2m}\frac{\partial^2\Psi(x,t)}{\partial x^2}+V(x)\Psi(x,t)$$

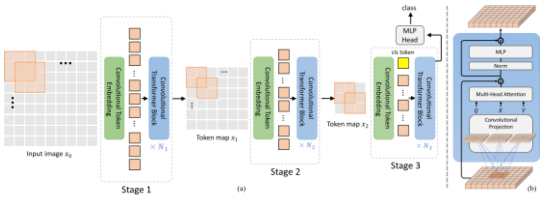
solving Schrodinger's wave equation to simulate quantum systems



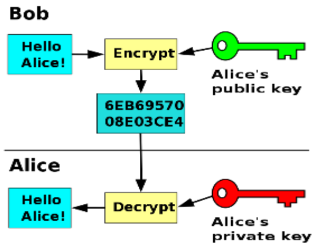
combinatorial optimizations



solving partial differential equations



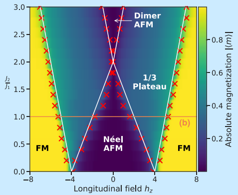
machine learning and deep learning



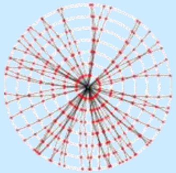
breaking asymmetric cryptography keys

from science to industry applications

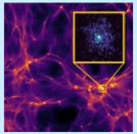
fundamental research



condensed matter physics

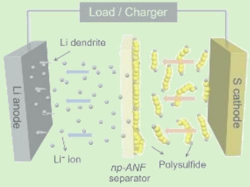


high-energy particle physics

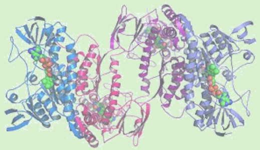


astrophysics

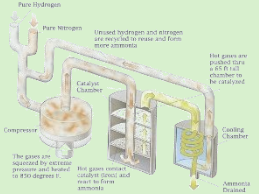
applied research



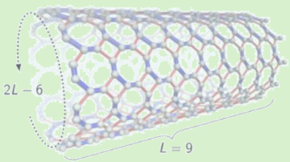
batteries



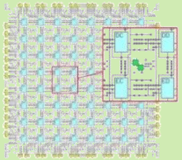
drugs



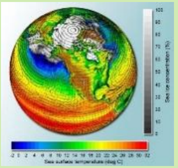
fertilizer production



material design

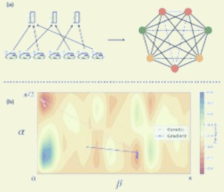


semiconductors

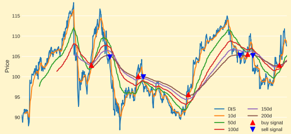


climate modeling

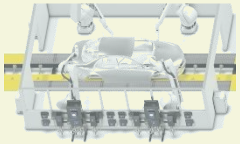
business operations



energy utilities

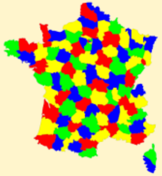


financial services



manufacturing

transportation



telecoms

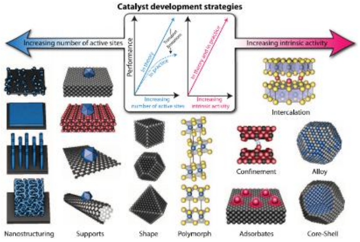
logistics and retail

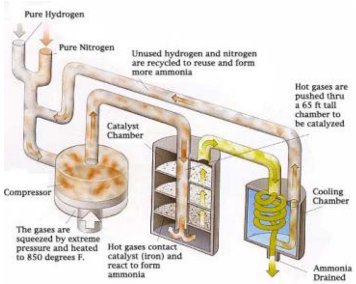
process engineering applications

chemical process engineering

modelize chemical reactions, and
complete molecular pathways

- ground state simulations.
- excited states simulations.
- virtual spectrography.
- chemical pathways simulations.
- molecular docking simulations.
- new catalyser simulations.
- corrosion simulations.
- new materials simulations.
- battery chemical simulations.
- …





process systems engineering

modelization, optimization and
control of complex processes

- combinatorial optimizations under constraints.
- solving decision problems.
- machine learning based optimizations.
- LLM-based process designs.
- process flow optimizations.
- job shop problem solving.
- cable routing optimization problem solving.
- …

what is a qubit?

mathematically

basic unit of quantum information

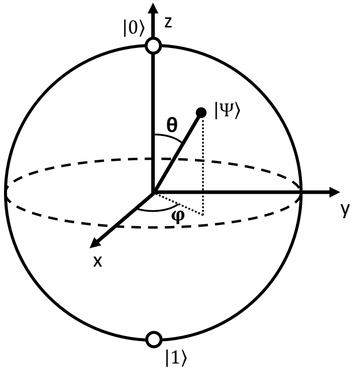
vector in a 2-dimension complex numbers Hilbert space

complex numbers amplitudes

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$$|\alpha|^2 + |\beta|^2 = 1$$

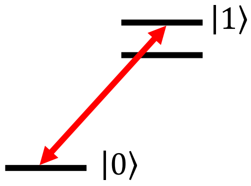
probabilities and Born normalization constraint



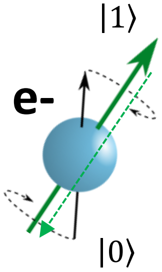
Bloch sphere representation with amplitude and phase

physically

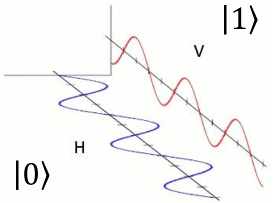
two-level state controllable quantum object



separable atom energy level

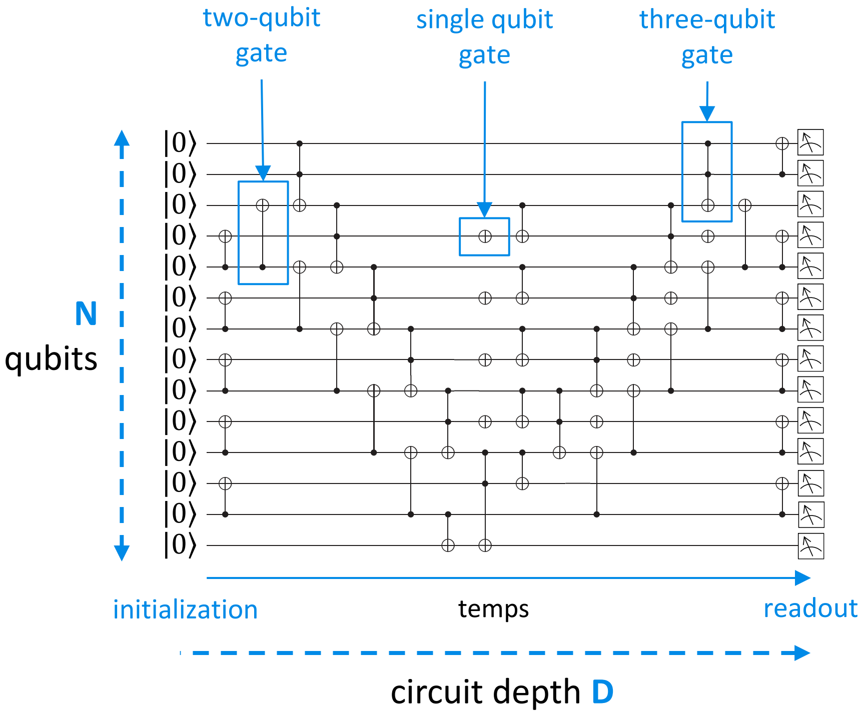


electron or nucleus spin projection



photon mode (polarization, number, frequency)

what is a quantum algorithm?



quantum algorithm: decomposes a solution to solve some mathematical problem into a quantum circuit.

quantum circuit: series of operations (gates) acting on a quantum memory, on individual qubits (superposition) or with connecting them together (entanglement).

matrix computing: operating on a memory space of dimension 2^{N+1} real numbers.

mechanism: exploit various techniques like interferences to yield a value of interest in a series of classical bits.

classical computing: used to prepare the circuit, encore data, and extract useful result from multiple circuit runs.

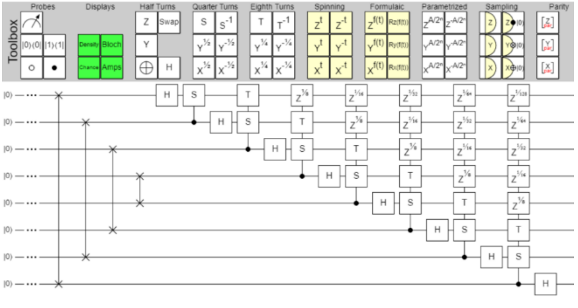
key differences vs classical computing

$$\langle \Psi_1 | \Psi_2 \rangle = [\overline{\alpha_1}, \overline{\beta_1}] \text{ x} \begin{bmatrix} \alpha_2 \\ \beta_2 \end{bmatrix} = \overline{\alpha_1}\alpha_2 + \overline{\beta_1}\beta_2$$

$$|\Psi_2\rangle\langle\Psi_1| = \begin{bmatrix} \alpha_2 \\ \beta_2 \end{bmatrix} \text{x} [\overline{\alpha_1}, \overline{\beta_1}] = \begin{bmatrix} \alpha_2\overline{\alpha_1} & \alpha_2\overline{\beta_1} \\ \beta_2\overline{\alpha_1} & \beta_2\overline{\beta_1} \end{bmatrix}$$

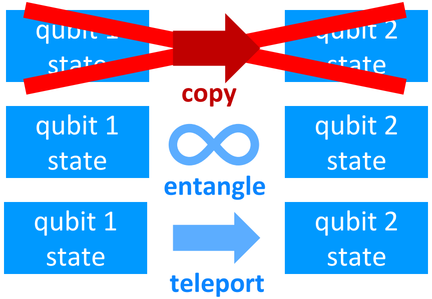
$$|\psi_1\rangle = \frac{1}{\sqrt{N}} \bigotimes_{j=1}^{n} \left(|0\rangle + e^{-2\pi i \left(\sum_{k=n-j}^{n} x_k 2^{-k} \right)} |1\rangle \right)$$

need to (re-)learn **linear algebra**

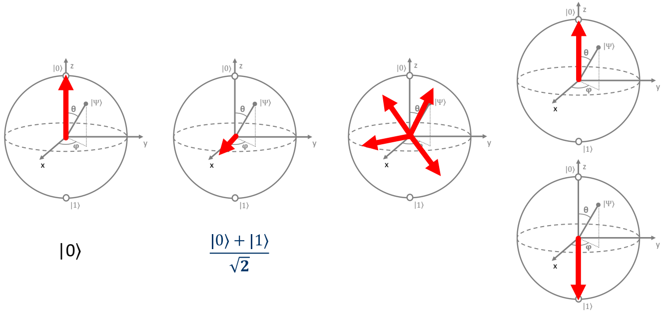


```python
# Initialize counting qubits
# in state |+>
for q in range(n_count):
    qc.h(q)

# And auxiliary register in state |1>
qc.x(3+n_count)

# Do controlled-U operations
for q in range(n_count):
    qc.append(c_amod15(a, 2**q),
             [q] + [i+n_count for i in range(4)])

# Do inverse-QFT
qc.append(qft_dagger(n_count), range(n_count))

# Measure circuit
qc.measure(range(n_count), range(n_count))
qc.draw(fold=-1)  # -1 means 'do not fold'
```

visual or Python scripted « **circuits** » programming



uncopiable data,
but transferable



probabilistic results, and repeated computing to generate a deterministic outcome

from Hamiltonians to values of interest

problem Hamiltonians

$$H = \sum_{\langle i,j \rangle} (J_x S_i^x S_j^x + J_y S_i^y S_j^y + J_z S_i^z S_j^z) + \sum_i h_i S_i^z$$

$$H = \sum_{p,q} h_{pq} a_p^\dagger a_q + \frac{1}{2} \sum_{p,q,r,s} g_{pqrs} a_p^\dagger a_q^\dagger a_r a_s$$

$$H = -t \sum_{\langle i,j \rangle, \sigma} \left(\hat{c}_{i,\sigma}^\dagger \hat{c}_{j,\sigma} + \text{h.c.} \right) + U \sum_i \hat{n}_{i,\uparrow} \hat{n}_{i,\downarrow}$$

$$H = \frac{1}{2} \sum_{i \neq j} J_{ij}^x (\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y) + J_{ij}^z \sigma_i^z \sigma_j^z$$

$$H = \sum_i h_i \sigma_i^z + \sum_{i<j} J_{ij} \sigma_i^z \sigma_j^z$$

gate based QPU

- problem decomposition.
- unitary approximation.
- circuit synthesis.

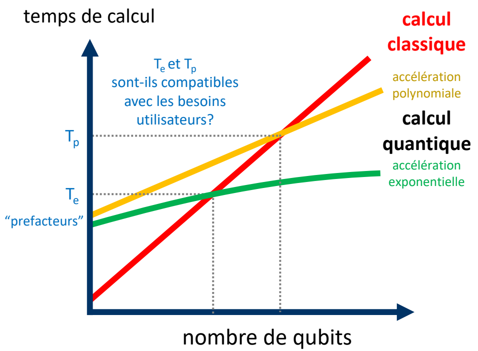
analog QPU

- problem embedding in a graph.
- QPU will search for an energy minimum.

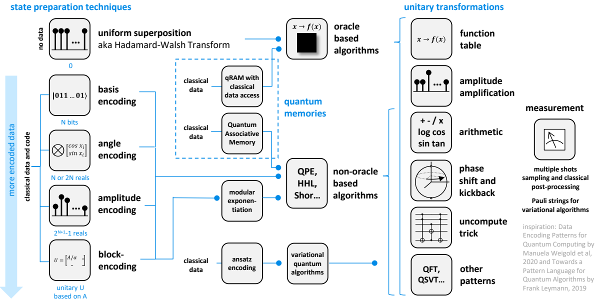
“small data”

- **ground state energy.**
- **excited states energies.**
- **other Hamiltonian eigenvalues.**
- **spectrography data.**
- **index value.**
- **…**

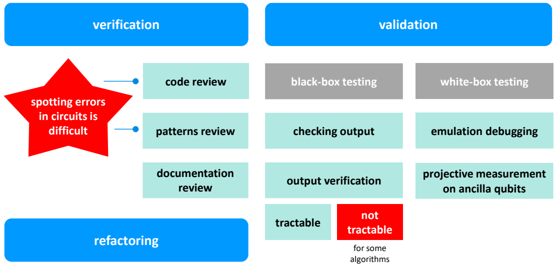
software challenges



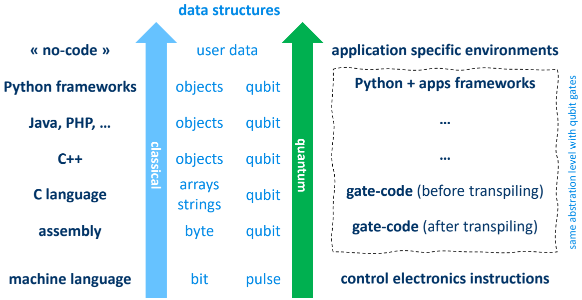
algorithms and speedups



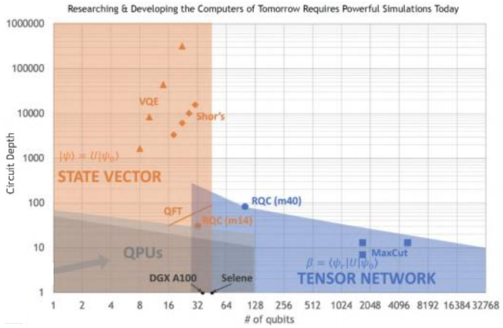
data loading



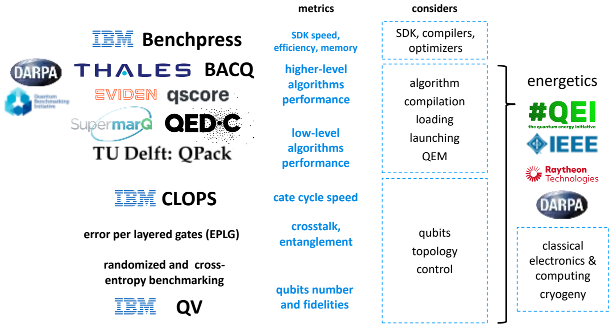
software engineering



abstraction level



tensor networks competition

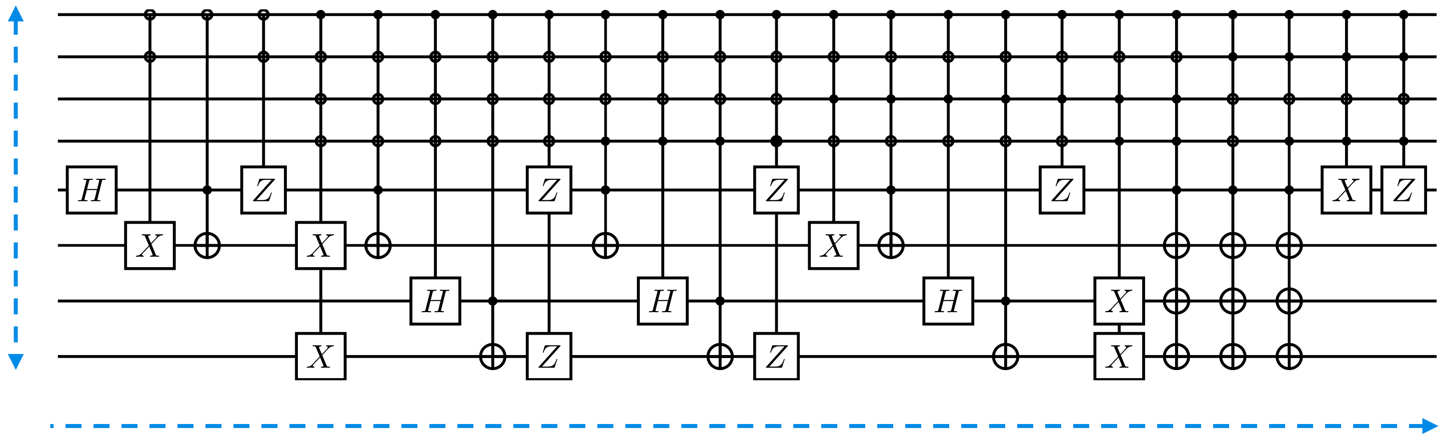


benchmarking

quantum speedup origin

space advantage

comes from N qubits handling the equivalent of 2^{N+1} floating point numbers



space/time trade-offs

one can be improved at the expense of the other, like in classical computing

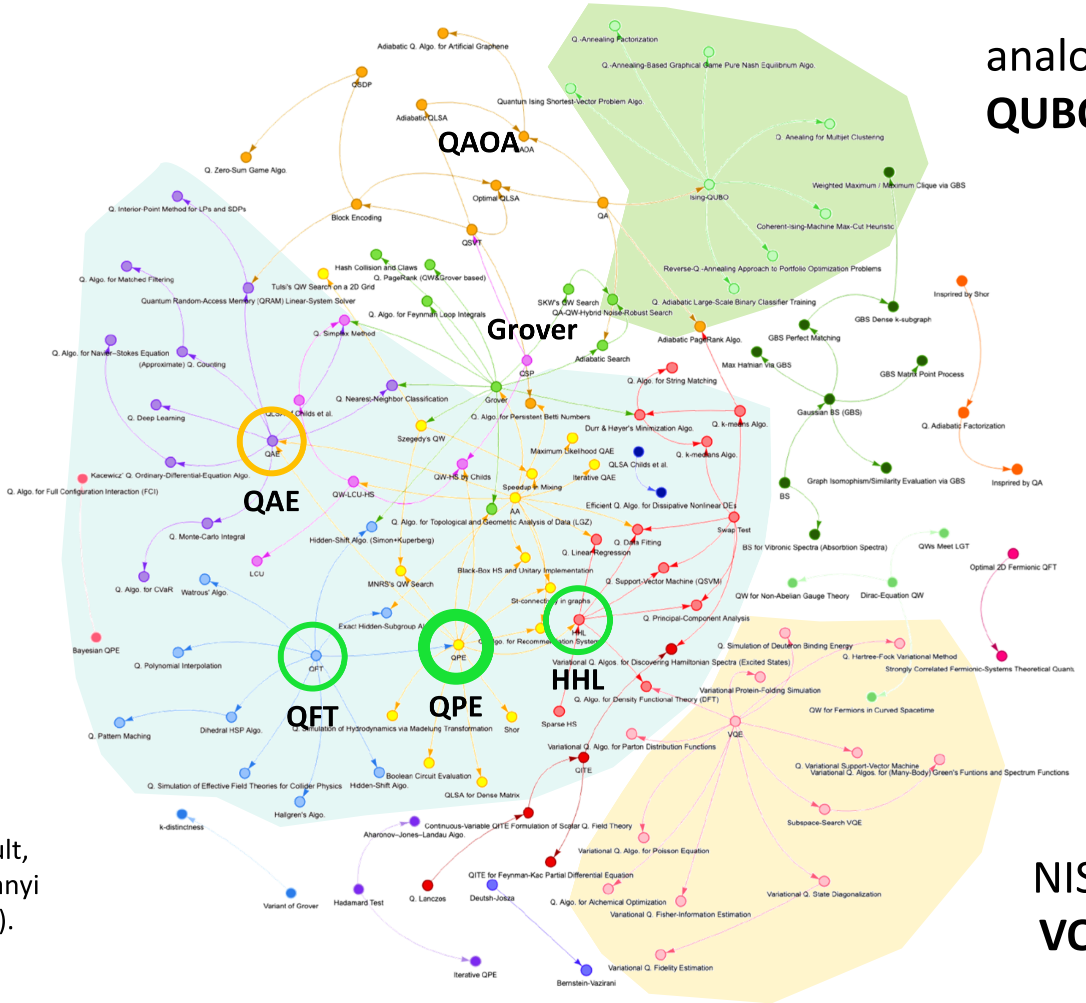
time advantage

when the number of gates cycles scales slower than with equivalent classical algorithms

1. quantum computing is a form of **in-memory processing**.
2. exploiting engineered **interference** of amplitudes.
3. using arbitrary **analog evolutions** in the Hilbert space.

1. → code compilation is a variable cost vs input data.

main known quantum algorithms



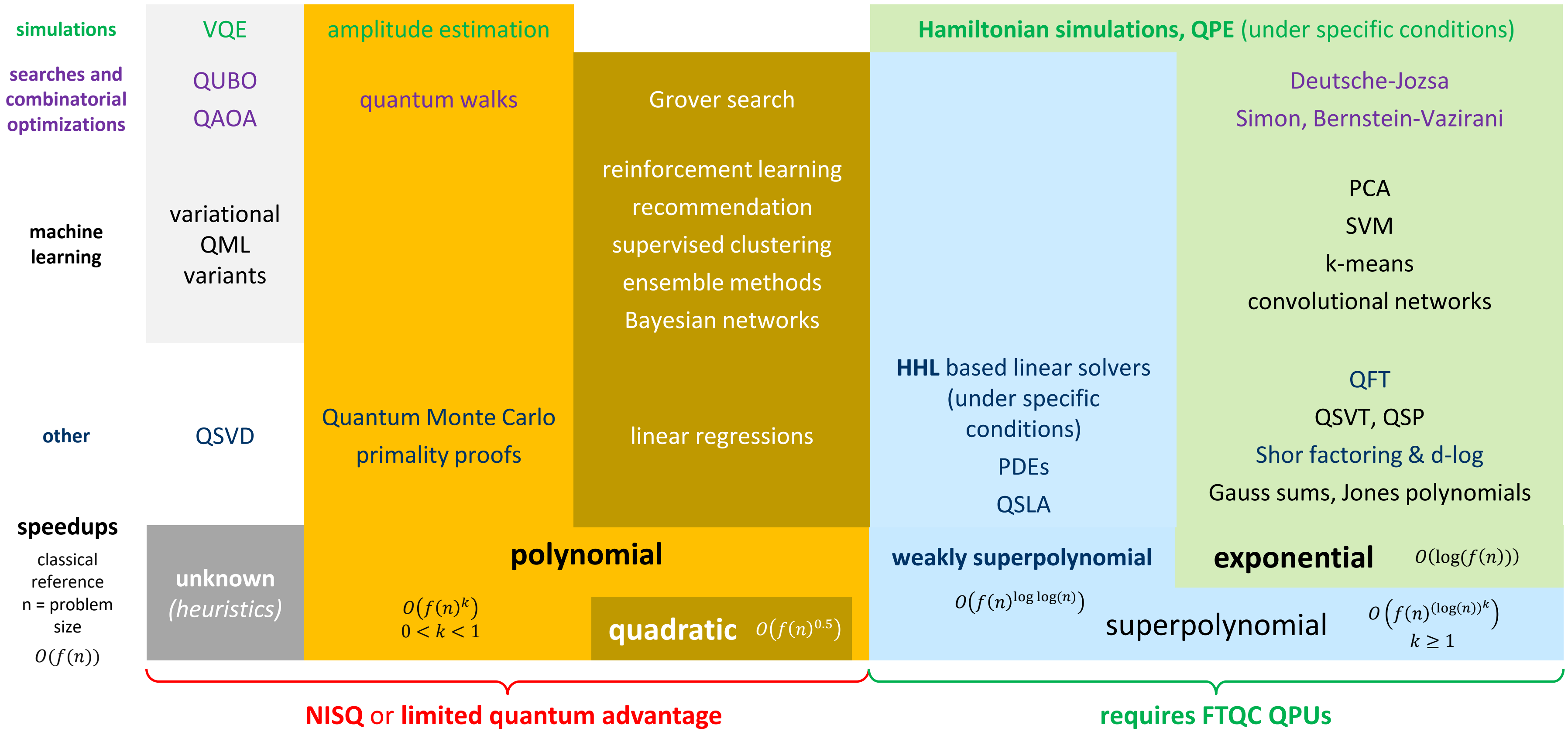
analog
QUBO

FTQC
QPE & QFT based

NISQ
VQE

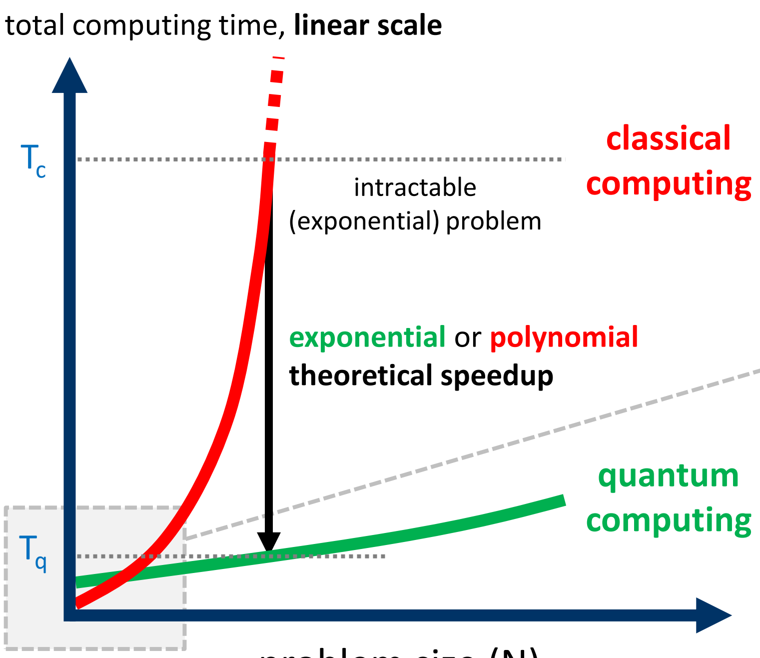
A typology of quantum algorithms by Pablo Arnault, Pablo Arrighi, Steven Herbert, Evi Kasnetsi, and Tianyi Li, Inria, Quantinuum, arXiv, July 2024 (60 pages).

potential quantum speedups

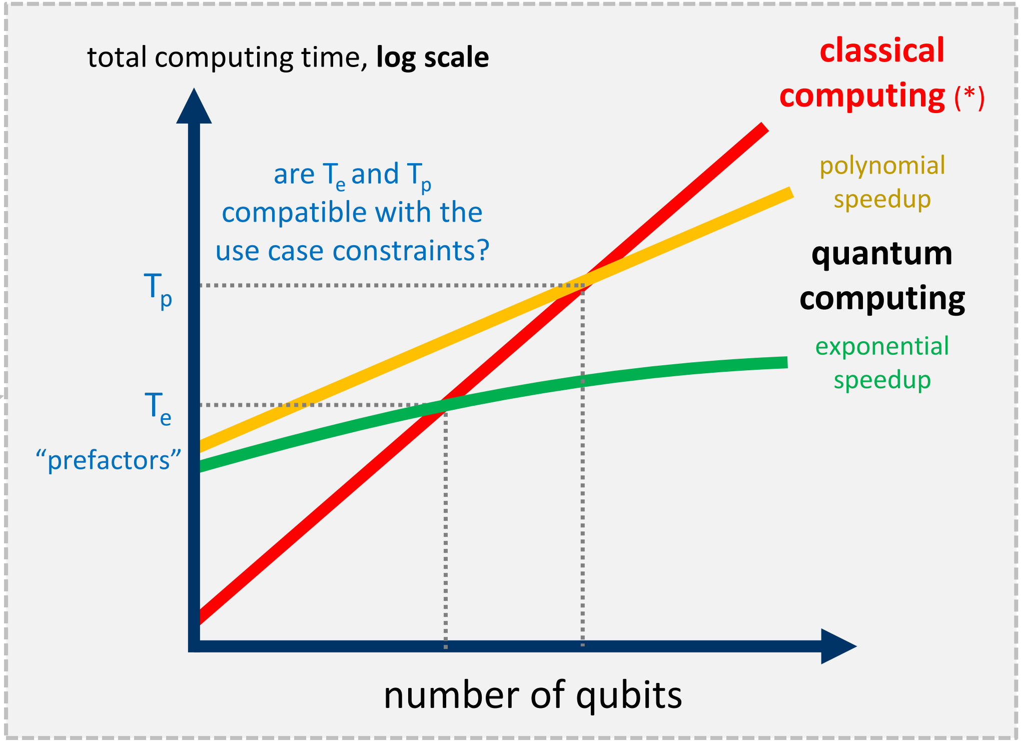


Understanding Quantum Technologies by Olivier Ezratty, as of April 2025.

theoretical vs practical speedups



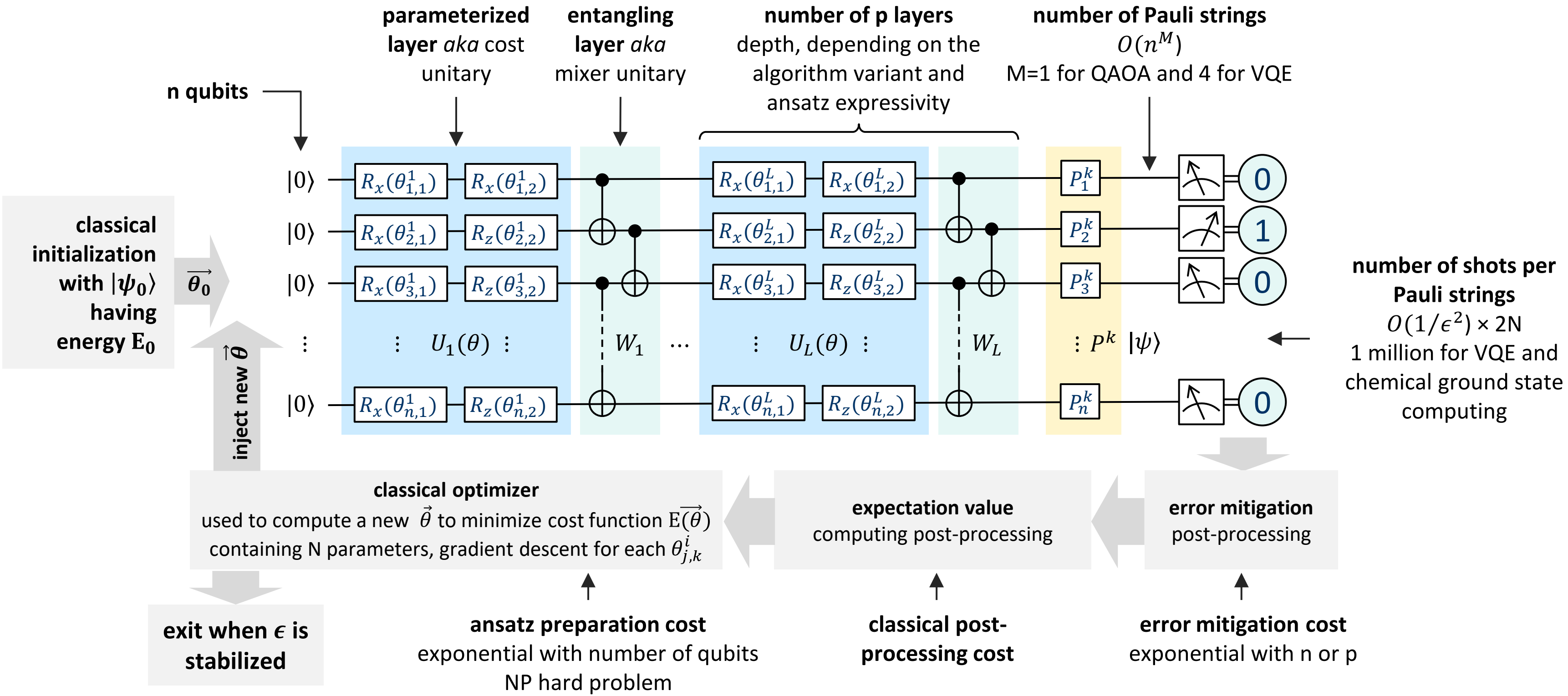
the typical and naive way to illustrate
quantum computing theoretical speedups.



inspired by [Opening the Black Box inside Grover's Algorithm]
by E. Miles Stoudenmire and Xavier Waintal, PRX, November 2024.

(*) for a fair comparison, the classical computer can be as expensive and/or energy hungry as the QPU.

NISQ variational quantum algorithms



variational algorithms barren plateaus

Small gradients → high precision required to find loss minimizing direction → resource intensive

($\sim 1/\sigma^2$ shots are required estimate a loss to precision σ)

Barren plateau (BP) phenomena:

$$\mathrm{Var}[\partial_k C] \sim \frac{1}{2^n}$$

$$+$$

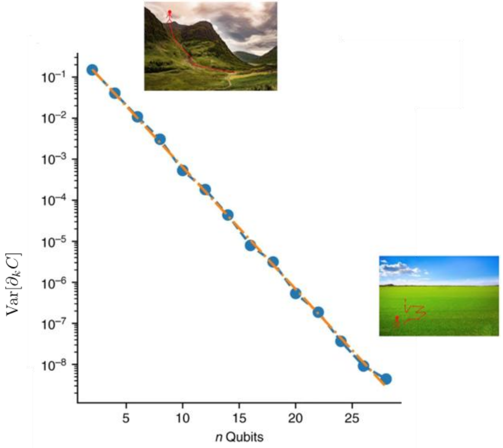
$$P(|\partial_k C| \geq \delta) \leq \frac{\mathrm{Var}[\partial_k C]}{\delta^2}$$

↓

Probability of non-zero gradients vanishes exponentially with problem size.

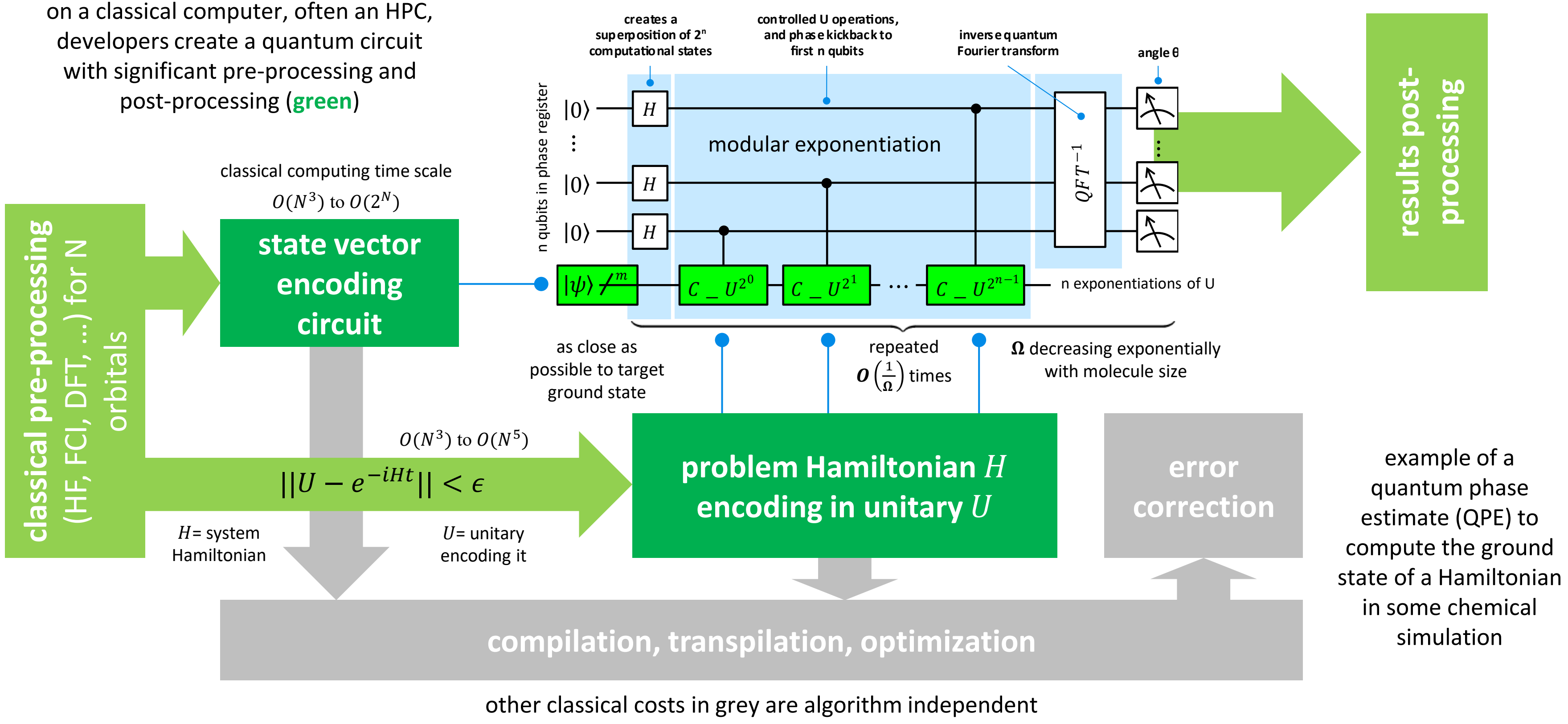
↓

Shot required for training grows exponentially with problem size.



source: Zoë Holmes, EPFL, presentation to the FTQC group from the French Academy of Technology, October 14th, 2025.

all quantum algorithms are hybrid



AI & quantum computing

As international competition escalates, a new white paper published today calls on the EU to invest in combining quantum computing and artificial intelligence to generate economic benefits and strengthen Europe's position as a prominent global player in emerging deep technologies.

Published today by a group of interdisciplinary scientists and global industry experts, the new paper shows that for Europe to remain competitive and at the cutting edge of deep-tech innovation, it must actively fund the convergence of AI and quantum computing.

Called "*Artificial Intelligence and Quantum Computing White Paper*", the new paper highlights the need for a carefully orchestrated funding strategy that spans fundamental research, talent cultivation, and technology transfer incentives to ensure a robust pathway from visionary lab-scale projects to

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https://arxiv.org/abs/2505.23860

Quantum computing and artificial intelligence: status and perspective

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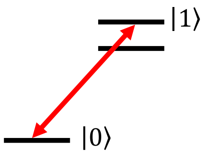
(Dated: April 22, 2025)

Contents

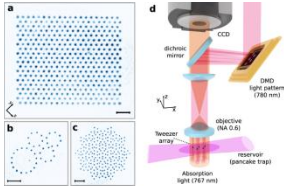
main qubit types

atoms and ions

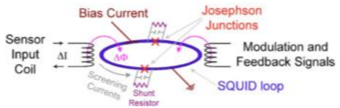


quantum states: atom energy level

physical aspect:

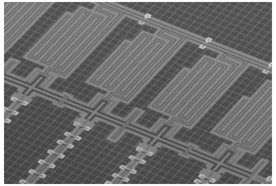


superconducting

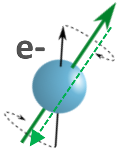


quantum states: anharmonic oscillator current phase and energy

physical aspect:

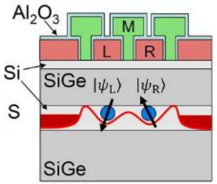


electron spins

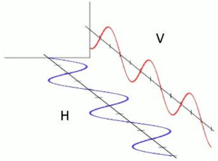


quantum states: electron spin orientation

physical aspect:

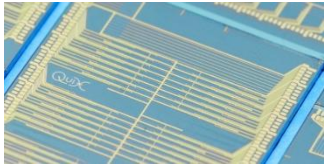


photons



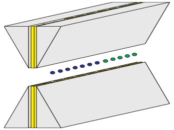
quantum states: photon polarization, or other property

physical aspect:

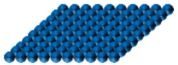


how qubits are controlled?

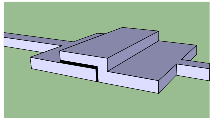
	atoms	electrons *controlled spin and microwave cavities*			photons
	trapped ions, cold atoms	superconducting, silicon	vacancies	topological	photons
initialization	optical or electromagnetic tweezers	microwave pulses	optical	DC current	single photon sources and polarizers
quantum gates	laser pulses microwaves RF signals	microwave pulses and/or DC current	optical and/or microwaves	microwave reflectometry and quadrature analysis	interferometers, polarizing beam splitters, ...
readout	laser and CCD detected fluorescence	microwave reflectometry and quadrature analysis	laser and CCD detected fluorescence		single photon detectors



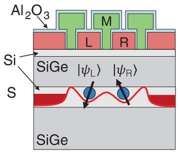
trapped ions



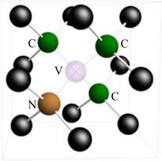
cold atoms



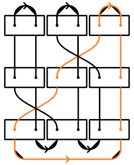
superconducting



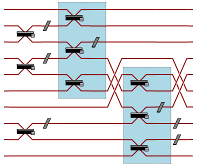
silicon



vacancies



topological

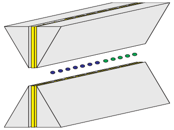


photons

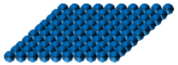
optical photons   microwave photons   other signals

>80 QPUs industry vendors!

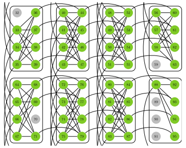
atoms	electrons *controlled spin and microwave cavities*	photons



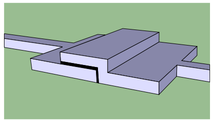
trapped ions



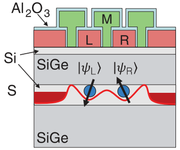
cold atoms



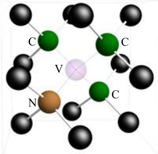
annealing



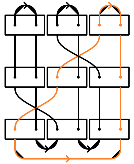
superconducting



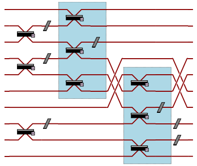
silicon



vacancies



topological



photons

trapped ions

1. Quantinuum, AQT, NEQXT, ZuriQ, Quantum Art, Foxconn, XYQ 华翊量子
2. IONQ, eleQtron, Oxford Ionics, QUDORA Technologies
3. Crystal Quantum Computing

cold atoms

4. QuEra, Pasqal, Infleqtion, QUANTier, planqc, logiqal
5. atom computing
6. Atom Quantum Labs

annealing

D-Wave The Quantum Computing Company™, QILIMANJARO Quantum Tech, NEC

superconducting

7. IBM, rigetti, IQM, Google, 本源量子 Origin Quantum, ANYON, OQC, Fujitsu, QOLAB, QuamCore, Peak Quantum
8. Alice & Bob, Nord Quantique, amazon, qci, Z-Axis Quantum

silicon

9. diraq, quobly, QπAI, Quantum Motion
10. Groove Quantum, equal1.labs, ARQUE, intel
11. Silicon Quantum Computing, EeroQ, C12, ARCHER

vacancies

12. Quantum Brilliance, TURING, XEED, SaxonQ, Quantum Transistors, Fujitsu
13. photonic

topological

Microsoft, QUOHERENT, Quantum Gravity Research, NOKIA

photons

14. PsiQuantum, QUANDELA, QUIX Quantum, ORCA Computing, Duality Quantum Photonics, aegiq
15. XANADU, QUANFLUENCE
16. QCi, QBoson

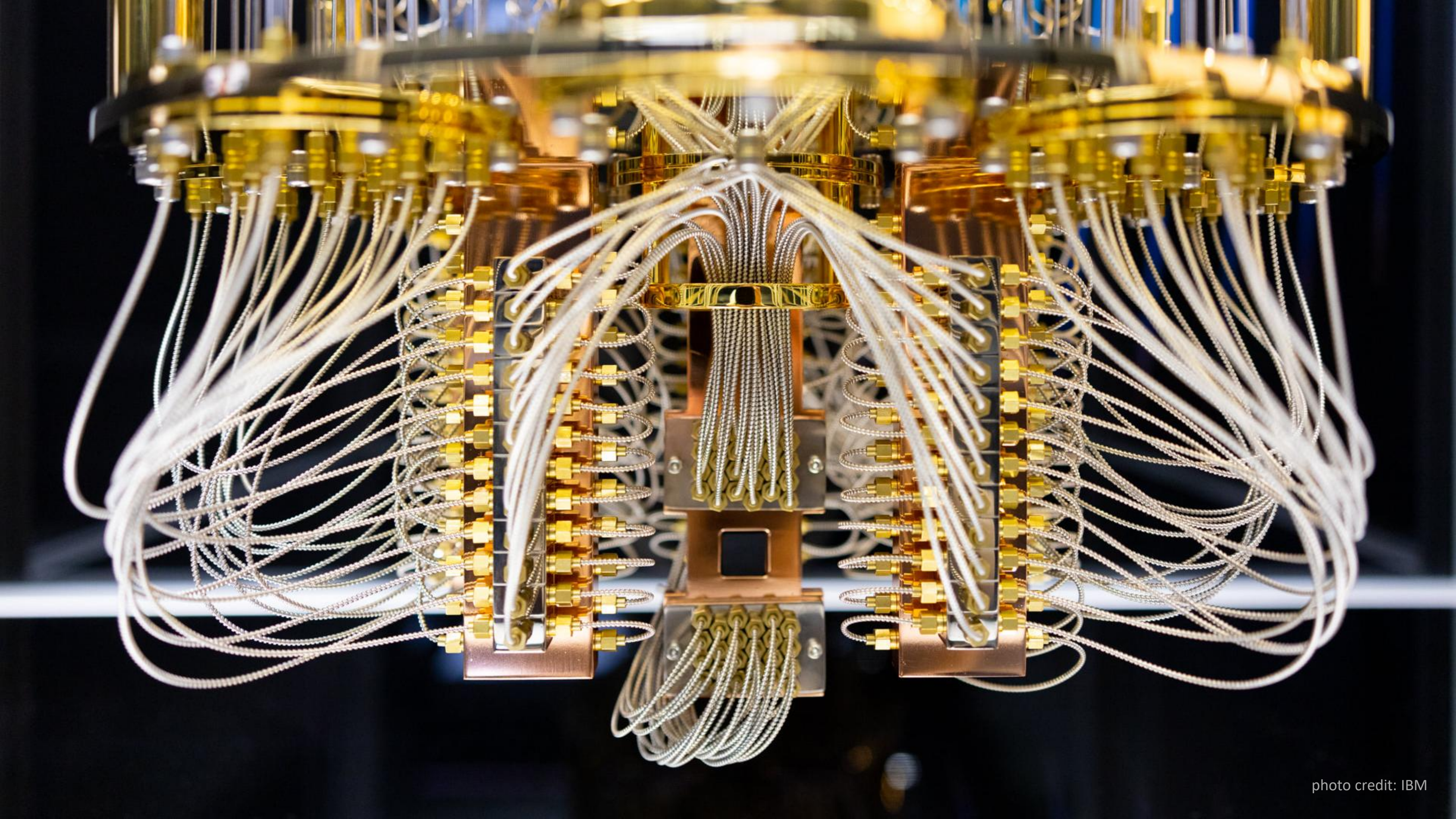


photo credit: IBM

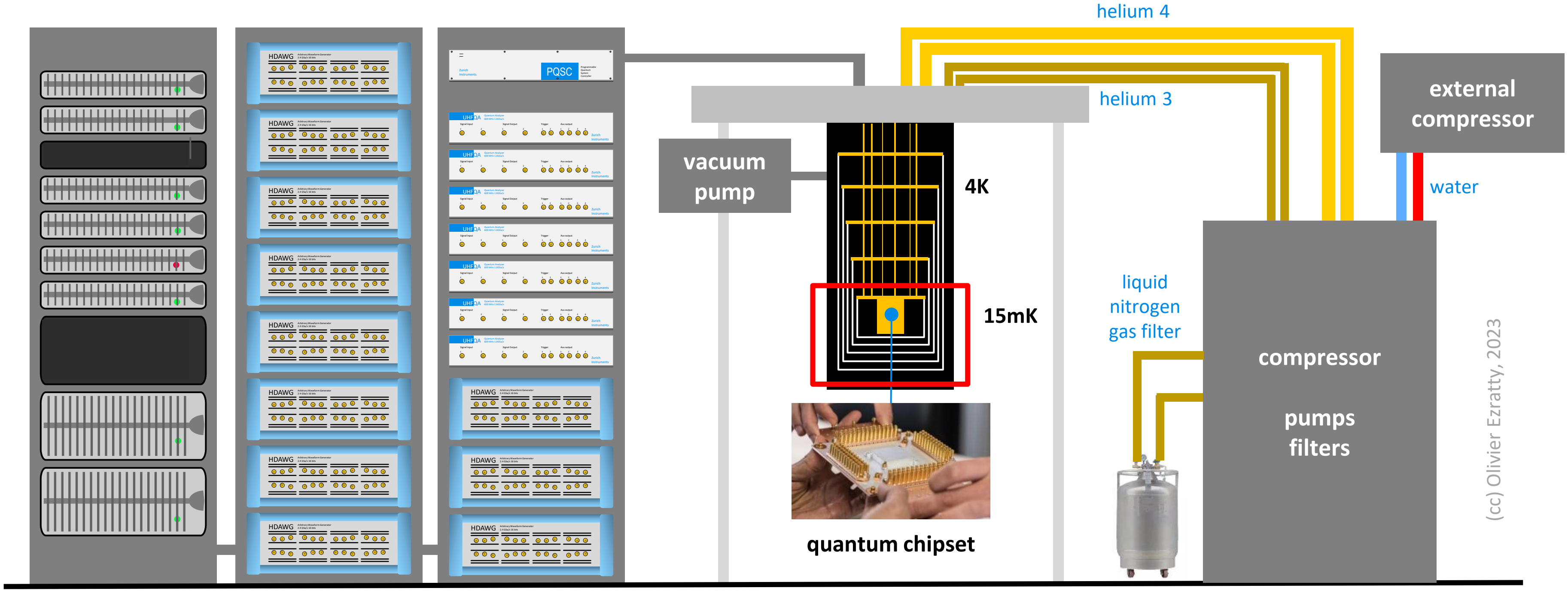
inside a typical quantum computer

computing
servers, network, software, data

qubits control electronics
microwave generators, readout systems and various electronics

« chandelier » in cryostat
where quantum stuff happens!

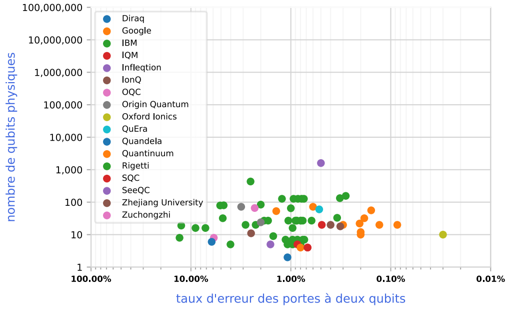
cryogenic installation
helium 3 & 4
gas pumps and compressor



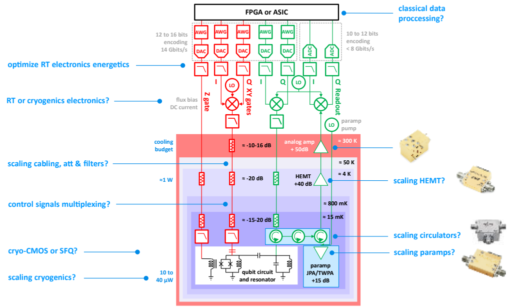
for superconducting or electron spin qubits

hardware challenges

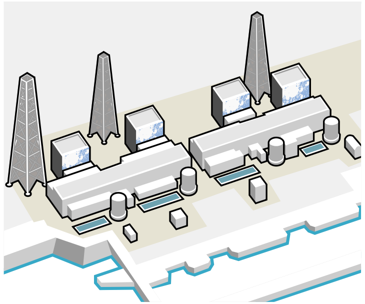
#QEI
the quantum energy initiative



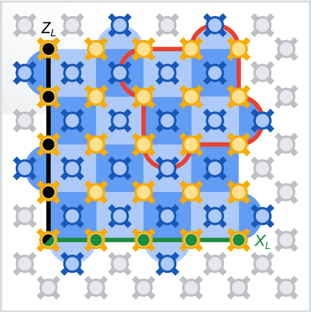
qubit quality



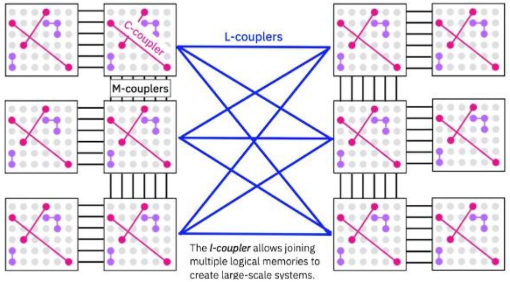
electronics, cabling, cryogeny



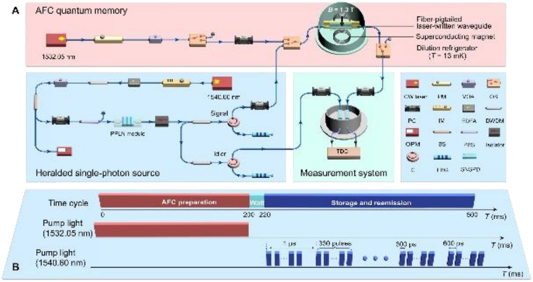
cost and power/energy



error correction

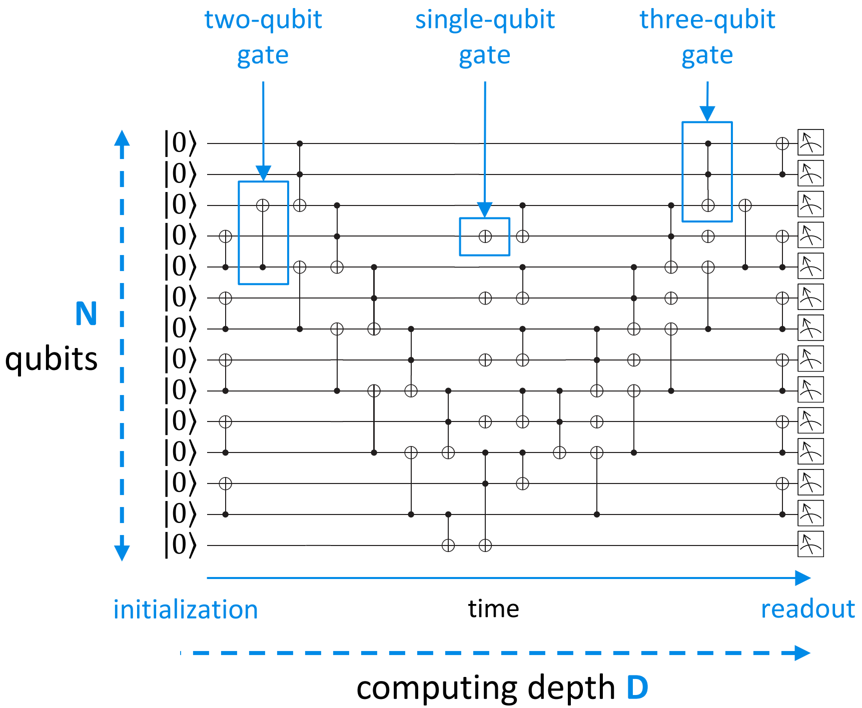


interconnection



quantum memory

algorithm fidelities requirements



each operation in blue adds errors that accumulates during computing and damage results quality, but idle operations also add errors.

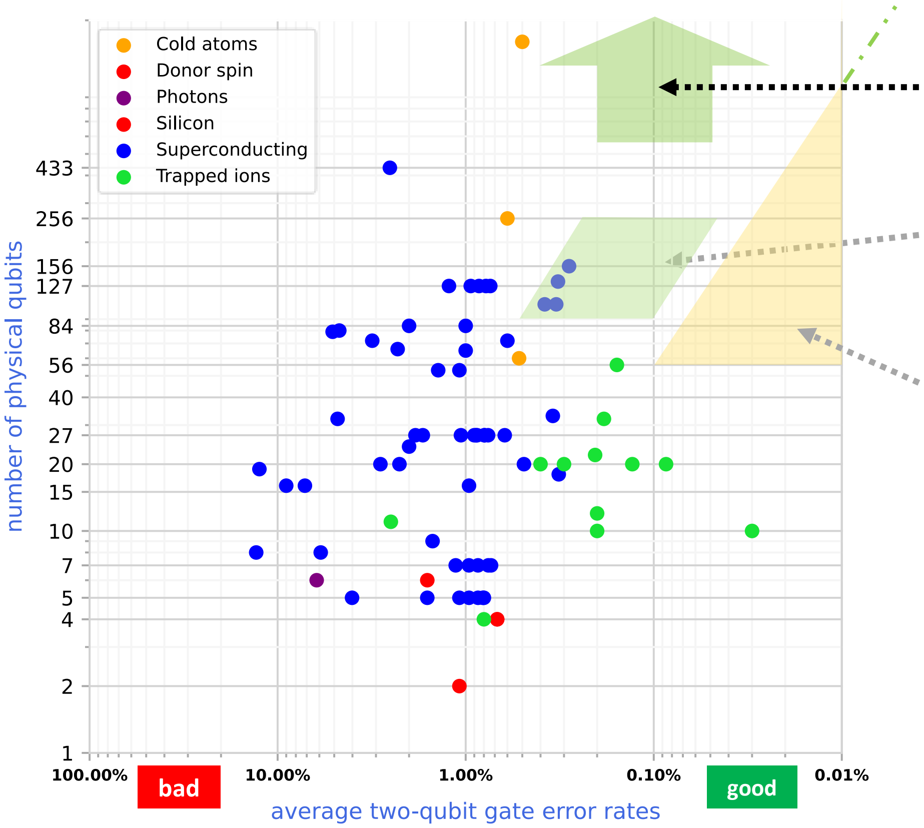
desired error rate $< \frac{1}{N \times D}$

e.g.

10 qubits × 100 gate cycles = 1000 => 99.9% fidelity

100 qubits × 100 gate cycles = 10K => 99.99% fidelity

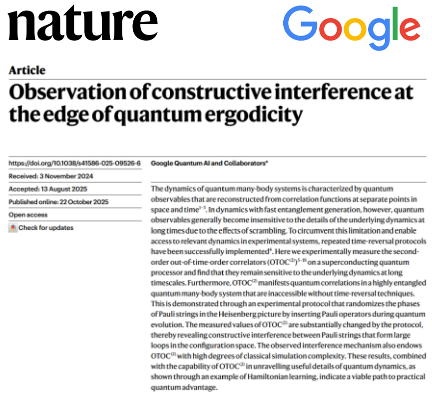
the qubit fidelities challenge



route to FTQC, requiring a large number of quality qubits

quantum error mitigation NISQ utility window

viable NISQ zone in a quantum advantage regime *without QEM* (hard to obtain)


nature

Google

Article

Observation of constructive interference at the edge of quantum ergodicity

https://doi.org/10.1038/s41586-025-09526-6
Received: 3 November 2024
Accepted: 13 August 2025
Published online: 22 October 2025
Open access
Check for updates

Google Quantum AI and Collaborators*

The dynamics of quantum many-body systems is characterized by quantum observables that are reconstructed from correlation functions at separate points in space and time[1-3]. In dynamics with fast entanglement generation, however, quantum observables generally become insensitive to the details of the underlying dynamics at long times due to the effects of scrambling. To circumvent this limitation and enable access to relevant dynamics in experimental systems, repeated time-reversal protocols have been successfully implemented[4]. Here we experimentally measure the second-order out-of-time-order correlators ($OTOC^{(2)}$)[5-10] on a superconducting quantum processor and find that they remain sensitive to the underlying dynamics at long timescales. Furthermore, $OTOC^{(2)}$ manifests quantum correlations in a highly entangled quantum many-body system that are inaccessible without time-reversal techniques. This is demonstrated through an experimental protocol that randomizes the phases of Pauli strings in the Heisenberg picture by inserting Pauli operators during quantum evolution. The measured values of $OTOC^{(2)}$ are substantially changed by the protocol, thereby revealing constructive interference between Pauli strings that form large loops in the configuration space. The observed interference mechanism also endows $OTOC^{(2)}$ with high degrees of classical simulation complexity. These results, combined with the capability of $OTOC^{(2)}$ in unravelling useful details of quantum dynamics, as shown through an example of Hamiltonian learning, indicate a viable path to practical quantum advantage.

what can be done here?

- understanding and optimizing qubit operations and readout.
- many qubit-type specific optimizations.
- improving manufacturing processes for quantum chips.
- faster chips design-to-test cycles.
- autonomous error corrections (e.g. cat-qubits).

logical qubits and FTQC

physical qubit

error rates ≈0.1%

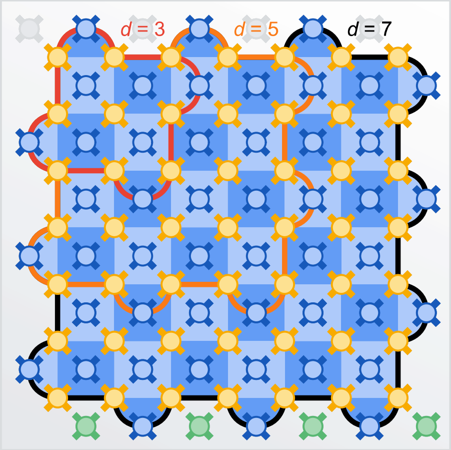
+

error correction code

threshold, physical qubits overhead, connectivity requirements, syndrome decoding and scale

logical qubits

error rate $\approx 10^{-4}$ to $\approx 10^{-18}$



tens to thousands physical qubits per logical qubits

fault tolerance (FTQC)

- implement logical gate correction.
- avoid error propagation and amplification.
- implement a universal gate set.
- fault-tolerant results readout.
- correct correlated errors.

QEC/FTQC key components

real-time error syndrome detection

code switching

logical memory qubit

single-qubit logical gate

two-qubit logical gate (*)

magic-state preparation (T) and teleportation

leakage error correction

correlated errors correction

qubit connectivity

calibration

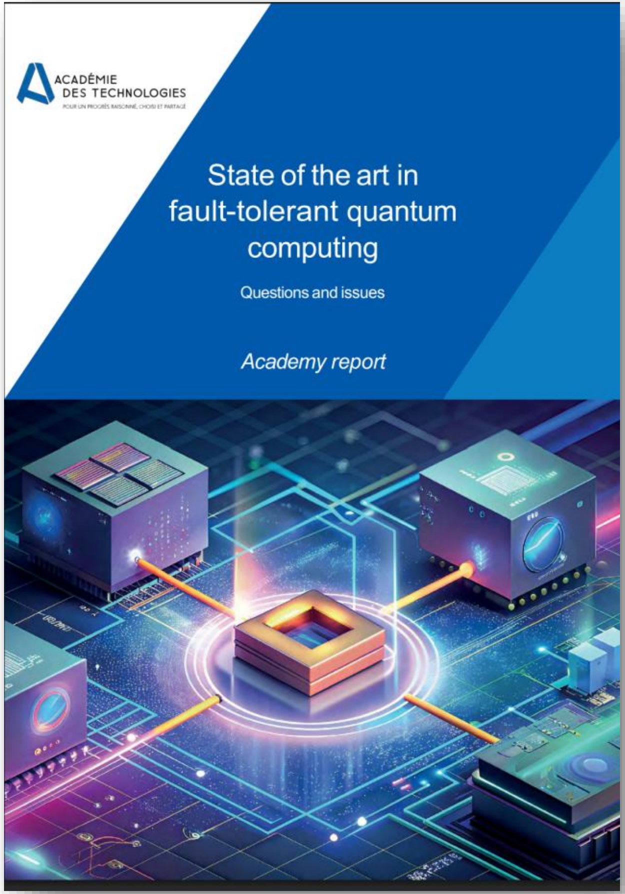
qubit fast measurement

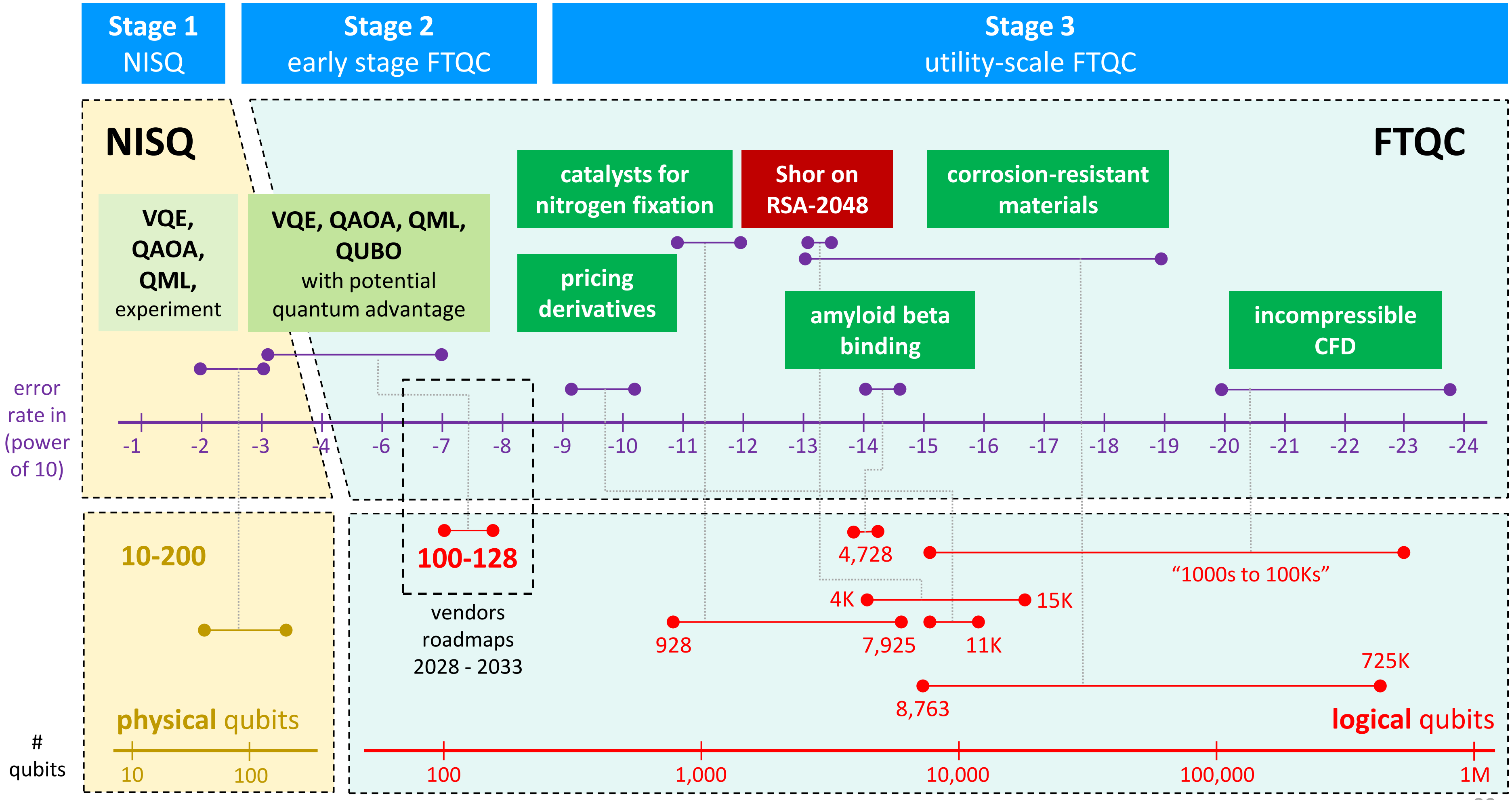
qubit physical gate fidelities >99.9% at scale

scaling QPU with interconnect and gate teleportation + circuits partitionning

(*): not using post-selection which doesn't scale to deep circuits.

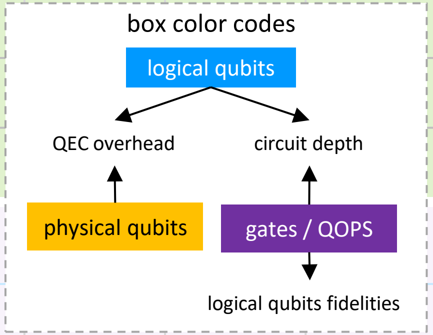
blue QEC basic component.
green FTQC component.
grey QEC hardware enablers.


ACADÉMIE
DES TECHNOLOGIES
State of the art in
fault-tolerant quantum
computing
Questions and issues
Academy report



Stage 1
NISQ
Stage 2
early stage FTQC
Stage 3
utility-scale FTQC
NISQ
FTQC
VQE, QAOA, QML, experiment
VQE, QAOA, QML, QUBO with potential quantum advantage
catalysts for nitrogen fixation
Shor on RSA-2048
corrosion-resistant materials
pricing derivatives
amyloid beta binding
incompressible CFD
error rate in (power of 10)
-1 -2 -3 -4 -6 -7 -8 -9 -10 -11 -12 -13 -14 -15 -16 -17 -18 -19 -20 -21 -22 -23 -24
10-200
100-128
vendors roadmaps 2028 - 2033
4,728
"1000s to 100Ks"
4K
15K
928
7,925
11K
725K
8,763
physical qubits
logical qubits
qubits
10
100
100
1,000
10,000
100,000
1M

		2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
superconductors & spins	IBM	156x7 PQ (2025–2028); 5K	7.5K	10K	15K	200 / 100M				2000 / 1B		
	IQM	150	300	4-36 / 1K	60-180 / 5K		240-720 / 40K	600-1800 / 100K		2400-7200 (2033–2035); 1M		
	OQC	16 1K			200 1M			5,000 1G			50K 1T	
	ALICE & BOB		4 / 48		5 / 250		100 / 2K 1M					
	Nord Quantique				100			1000				
	quobly	2-10	64	256	15 / 1K 100K	25-45 / 4K 1M	50-100 / 20K ≈1G	180-360 / 120K ≈1T	1,400 / 1M ≈100T			
cold atoms	Pasqal	140	2	20 / 200+		100	200 / 10K					
	QuEra	30 / 3K	100 / >10K									
	Infleqtion	2 / 1.6K	>10 / 8K		>100 / 40K							
tapped ions	QUANTINUUM	~ 50 / 96		~100 / 192		~100s / 1000s						
	IONQ	64	12 / 256	800 / 10K 10M	1,600 / 20,000	8,000 / 200K 1T	80,000 / 2M 1T					
	Quantum Art	50		100 / 1,000		500 / 12,000		1,000s / 40,000		10,000s / >1M		
photons	PsiQuantum						~100s / 1M					
	QUANDELA			10 50K		50s 1M						



quantum computing cloud offerings

	hybrid computing centers	OVHcloud	IBM	aws	Microsoft	Google
emulation	40 qubits EVIDEN	EVIDEN, IBM, QPerfect Pasqal, IQM, quobly QUANDELA, ALICE & BOB, C12	Qiskit on your own hardware	34-50 qubits	30 qubits	40 qubits
quantum computing	TGCC (Très Grand Centre de calcul du CEA) JÜLICH Forschungszentrum / JÜLICH SUPERCOMPUTING CENTRE LUMI lrz CINECA PCSS	Pasqal 100 qubits (analog) QUANDELA ...	IBM 127, 133 & 156 qubits	QuEra 256 qubits (analog) IONQ 36 qubits rigetti 84 qubits IQM 20 qubits	Pasqal 100 qubits (analog) IONQ 25-32 qubits rigetti 84 qubits IQM 20 qubits QUANTINUUM 56 qubits	IONQ 11 qubits ALICE & BOB 1 cat-qubit

why

- ICT energy consumption is growing in an uncontrolled way.
- energetics are usually an afterthought, like with LLMs.
- it's time to work on this as quantum technologies are being designed.

Perspective PRX QUANTUM **3**, 020101 (2022)

Quantum Technologies Need a Quantum Energy Initiative

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(Received 18 November 2021; revised 11 April 2022; published 1 June 2022)

Quantum technologies are currently the object of high expectations from governments and private companies, as they hold the promise to shape safer and faster ways to extract, exchange, and treat information. However, despite its major potential impact for industry and society, the question of their energetic footprint has remained in a blind spot of current deployment strategies. In this Perspective, I argue that quantum technologies must urgently plan for the creation and structuration of a transverse quantum energy initiative, connecting quantum thermodynamics, quantum information science, quantum physics, and engineering. Such an initiative is the only path towards energy-efficient, sustainable quantum technologies, and to possibly bring out an energetic quantum advantage.

#QEI
the quantum energy initiative

what

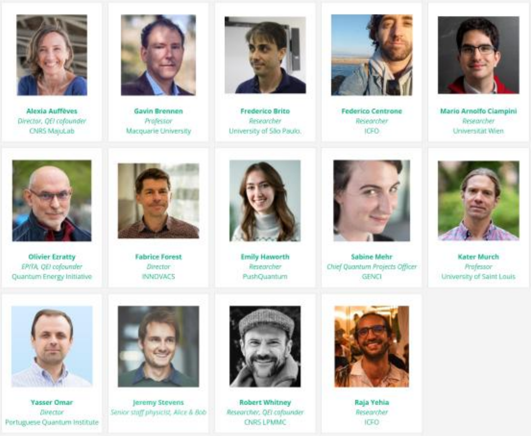
- build new science and engineering.
- create full-stack methodologies to evaluate, optimize, and benchmark QT energy consumption.

where

- academic and industry QEI workshops: Singapore (2023), Grenoble (2025), Barcelona (2026).
- APS 2025, ICQE 2025, France Singapore Symposium (Paris, 2025), Q2B Paris and Santa Clara (2025).
- online seminars, website.

who

- 4 cofounders.
- 14 scientific board members.



- 500+ community in >90 countries.
- >30 industry and academic partners.

IBM, Quandela, quobly, Pasqal, IQM, Alice & Bob, diraq, Microsoft, C12, Quantum Brilliance, Qilimanjaro Quantum Tech, Vigthor, Radiall, ATEM, riverlane, aQuantum Software Engineering, parityqc, KIPU Quantum, Eviden an atos business, BTQ, OVHcloud, Qnami

how

first methodology (2023)

PRX QUANTUM 4, 040319 (2023)

Optimizing Resource Efficiencies for Scalable Full-Stack Quantum Computers

Marco Fellous-Asiani,[1,2,*] Jing Hao Chai,[2,3,4] Yvain Thonnart,[5] Hui Khoon Ng,[6,3,7,†] Robert S. Whitney,[8,‡] and Alexia Auffèves[2,3,7,§]

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[7] *MajuLab, CNRS-UCA-SU-NUS-NTU International Joint Research Laboratory, Singapore*
[8] *Université Grenoble Alpes, CNRS, Laboratoire de Physique et Modélisation des Milieux Condensés (LPMMC), Grenoble 38000, France*

(Received 29 November 2022; accepted 31 July 2023; published 30 October 2023)

OECQ flagship project with EDF, Quandela, Alice&Bob, and CNRS (2023-*)

Accueil > Actualité

Lancement du projet "Optimisation Énergétique des Circuits Quantiques", avec le CNRS, EDF, Quandela et Alice & Bob

25 septembre 2024 INNOVATION

putting quantum technologies energetic in the EU Quantum Strategy agenda (ongoing).

QuIC European Quantum Industry Consortium

#QEI the quantum energy initiative

IEEE P3329 Quantum Energy Initiative (QEI) Working Group (2023-*)

IEEE

BACQ benchmarking project (2023-*)

BACQ - Application-oriented Benchmarks for Quantum Computing

Delivering an application-oriented benchmark suite for objective multi-criteria evaluation of quantum computing performance, a key to industrial uses

FTQC energetics paper (in preparation).

The energetic challenges of fault-tolerant quantum computing

Marco Fellous-Asiani,[1] Pierre-Emmanuel Emeriau,[2] Jeremy Stevens,[3] Marco Pezzutto,[4,5,6] Yasser Omar,[4,5,6] and Olivier Ezratty[7,8,*]

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[6] *Physics of Information and Quantum Technologies Group, Centro de Física e Engenharia de Materiais Avançados (CeFEMA), Portugal*
[7] *EPITA Research Lab*
[8] *Quantum Energy Initiative*

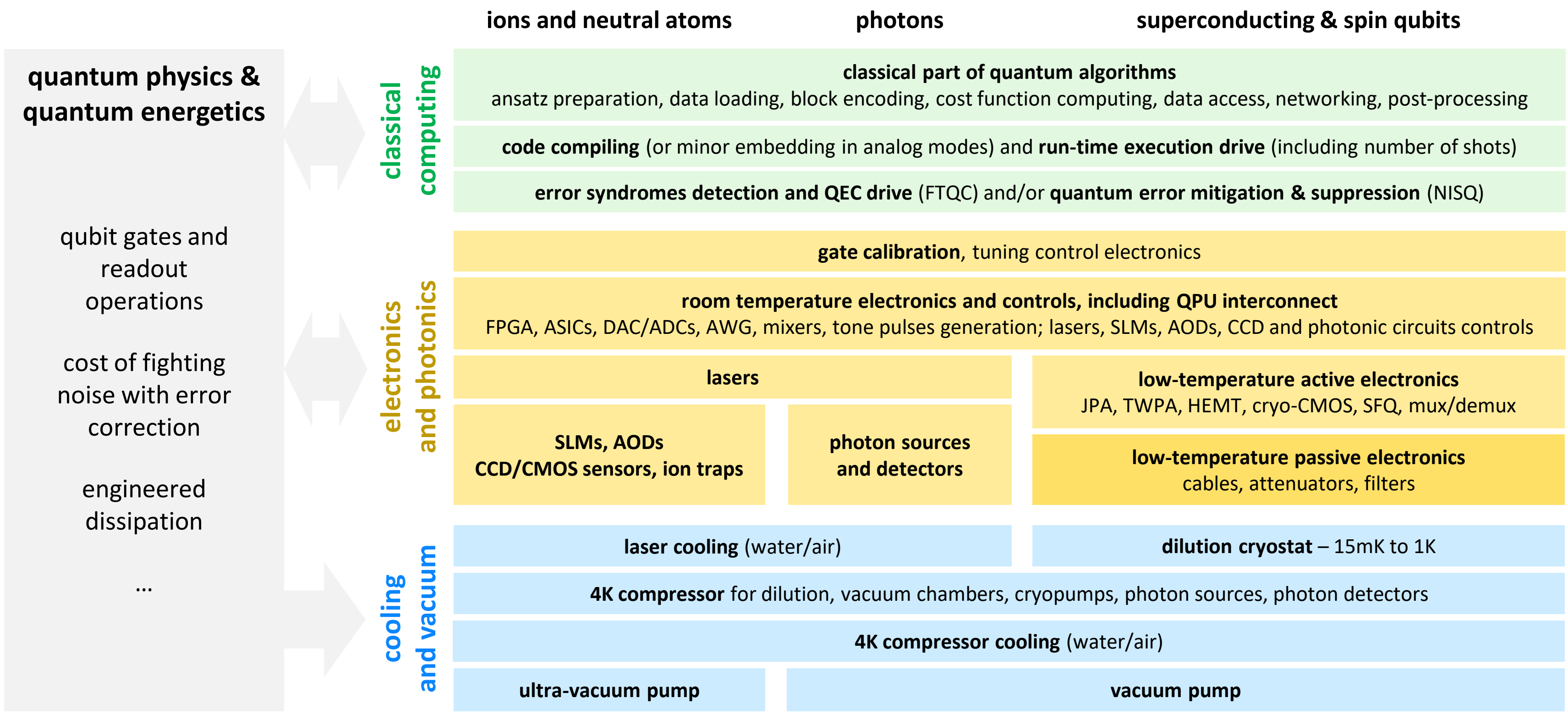
European Commission

QUANTUM EUROPE STRATEGY

July 2025

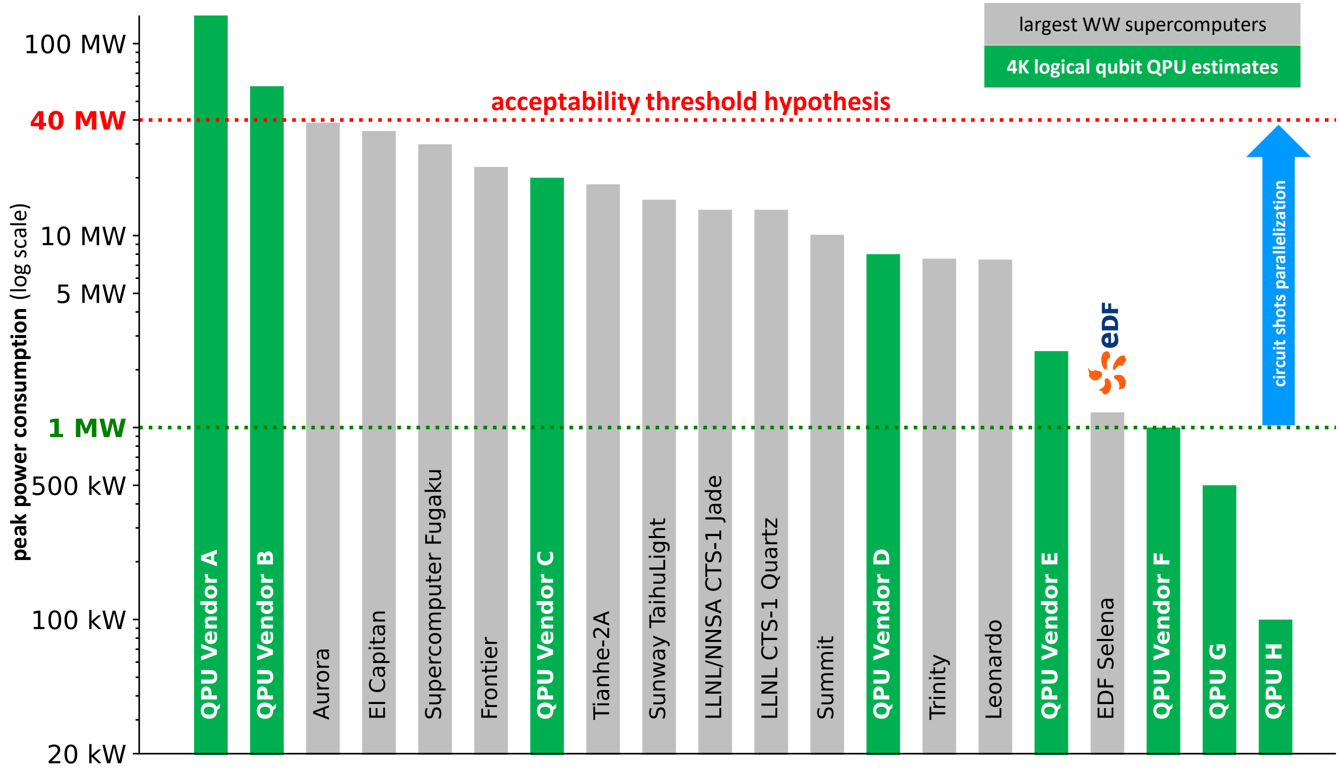
QEI roadmap (in preparation).

full-stack energetic costs decomposition



estimate power baselines, and then look for reductionist + holistic energetic optimizations

QPU vs HPC power scale guesstimates



estimate base power for various QPUs and actual for existing largest HPCs WW. HPC source: https://www.top500.org/lists/top500/2024/06/. QPU sources: official and unofficial vendor data.

https://www.youtube.com/watch?v=rUcPLZeZxG0&t=3048s

QPU energetics knowns and unknowns

knowns

- need to better understand the energetics of qubits operations.
- an energetic advantage could appear before a computational one.
- 1-to-1,000 QPU power consumption ratios guesstimates.
- agreeing on how to measure QPU energetics and power is key.
- benchmarking QPU energetics is a new discipline to create.
- reductionist and holistic energetic optimizations will be needed.
- some optimizations will be at the system level, and other will be applications dependent.

known unknowns

- correlation or anticorrelation between power estimates and technology viability: will only the fittest survive?
- total cost and scale of classical computing driving QPUs.
- QPU interconnect energetics.
- useful algorithms, particularly for business operations.
- error correction advances.
- will quantum noise be contained at scale?

economics:

- QPU total carbon footprint.
- QPU business value across verticals.
- market size and externalities.
- global QPU energy consumption sizing.
- will energetics become a key vendor differentiation factor?
- on-premise vs cloud usage?

unknown unknowns

- quantum noise at large scale.
- Lieb-Robinson limit effects in large physical scale distributed QPUs.
- can quantum algorithms progress change the energetic landscape?
- …

industry vendors ecosystem

computing

Pasqal
ALICE & BOB
C12
quobly
QUANDELA
CRYSTAL QUANTUM COMPUTING
EVIDEN an atos business

software

Qubit PHARMACEUTICALS
EVIDEN an atos business
mol|ket
ColibrITD
QPerfect
VeriQloud
QbitSoft Quantum as a Service
QUANTUM SIGNALS

cybersecurity

CRYPTONEXT SECURITY
CRYPTO EXPERTS
ravel
SECURE-IC THE SECURITY SCIENCE COMPANY
CYFERALL
QURISK ADVISORY

sensing

THALES
exail
chipiron
kwan-tek
MAG 4He alth

cryogeny

Air Liquide
CryoConcept
INNOVATIVE SOLUTIONS ABSOLUT SYSTEM

electronics

SILENT WAVES
Viqthor
Welinq
Radiall
MECA MAGNETIC magnetic shielding
ATEM
SILENTSYS ultralow noise systems

photonics

cailabs SHAPING THE LIGHT
Lytid
exail
SPARK LASERS
LUMIBIRD
AUREA TECHNOLOGY
teem PHOTONICS
SCINTIL PHOTONICS
GLOphotonics
QUANDELA

manufacturing

PLASSYS
RIBER
SERMA TECHNOLOGIES

materials

orano
PIONIQ
DIAMFAB
HIQUTE DIAMOND


Hope to see you again next year!
QuantAlps

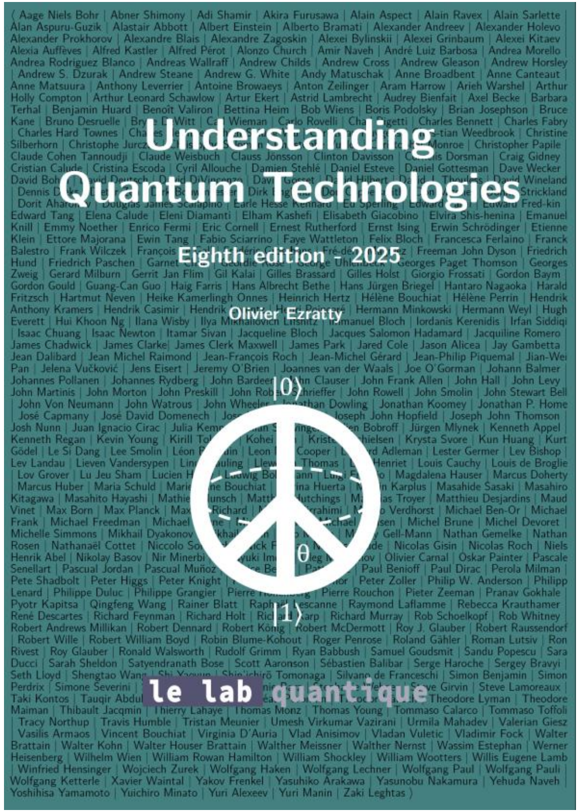

#QEI
Pasqal


PASQAL


quobly


EPITA


ALICE & BOB



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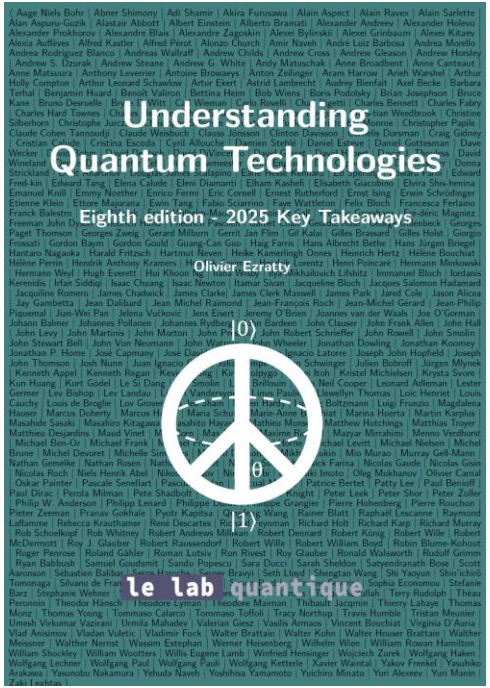

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Quantum Physics

[Submitted on 24 Nov 2021 (v1), last revised 30 Oct 2025 (this version, v6)]

Understanding Quantum Technologies 2025

Olivier Ezratty

Understanding Quantum Technologies 2025 is the 8th update of a free open science ebook that provides a 360 degrees overview of quantum technologies from science and technology to geopolitical and societal issues. It covers quantum physics history, quantum physics 101, gate-based quantum computing, quantum computing engineering (including quantum error corrections, quantum computing energetics and a new subsection of the effects of the Lieb-Robinson limit), quantum computing hardware (all qubit types, including quantum annealing and quantum simulation paradigms, history, science, research, implementation and vendors scientific and engineering approaches and roadmaps), quantum enabling technologies (cryogenics, control electronics, photonics, components fabs and manufacturing process, raw materials), unconventional computing (potential alternatives to quantum and classical computing), quantum computing algorithms, software development tools, resource estimate and benchmark tools, use case and case studies analysis methodologies, application use cases per market, quantum communications and cryptography (including QKD, PQC and QPU interconnect technologies), quantum sensing, quantum technologies around the world, quantum technologies societal impact and even quantum fake sciences. The main audience are computer science engineers, developers and IT specialists as well as quantum scientists and students who want to acquire a global view of how quantum technologies work, and particularly quantum computing. This version is an update to the 2024, 2023, 2022, and 2021 editions published respectively in October 2024, 2023, 2022 and 2021. An update log is provided at the end of the book.

Comments: 1,522 pages, over 1,200 illustrations, 9,371 bibliographical references, >880 quantum technologies vendors mentioned, Letter format, version 8.1 - October 30th, 2025. A4 version, split parts, and key takeways versions are available on the author's web site

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discussion

get the slides!