ACADÉMIE DES TECHNOLOGIES
POUR UN PROGRÈS RAISONNÉ, CHOISI ET PARTAGÉ

Qubits or not qubits ?
State of the art of Fault Tolerant Quantum Computing in 2025

An Academy of Technology report presented by Gérard Roucairol and Olivier Ezratty

https://www.academie-technologies.fr/publications/

Academy of technology report scope (*)

Quantum Computing Paradigms

Classical computers		Analog quantum computers		Digital quantum computers	
				gate-based	
quantum inspired	quantum emulators	quantum annealers	analog quantum simulators	NISQ Noisy Intermediate Scale Quantum	FTQC Fault-Tolerant Quantum Computers

FTQC → Universal, Reliable and Scalable Quantum Computer

(*) Applications of Quantum technology to sensors and secure communications are not considered

An Industry inspired Working Group

Steering committee

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- Jean-Philippe Nominé
- Sophie Proust
- Claude Weisbuch

With the support of the French quantum ecosystem

cea cnrs Inria Universities

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eDF TotalEnergies THALES EVIDEN an atos business

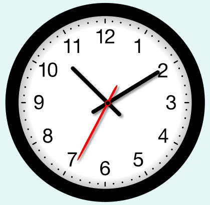
GENCI Teratec

Report main chapters

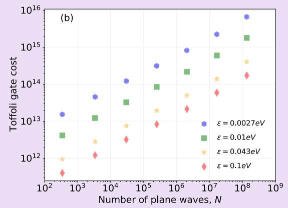
1. **Quantum advantage and its needs**
2. **Error-correcting codes**
3. **Qubit technologies**
4. **Scalability**
5. **Complementary elements**: economic analysis, competing technologies, benchmarking, HPC links, human capital, funding strategies.

Quantum Computing: benefits and challenges

Expected benefits



Potential exponential speedup



Improved results quality

However

Technology challenges

Few algorithms with an exponential speedup

Qubits sensitive to errors

Compute intensive but *not* data intensive

Implementation overhead

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Error correction: the key recent progress

Google Willow, bosonic qubits (Alice&Bob, Nord Quantique, AWS …)

physical qubit

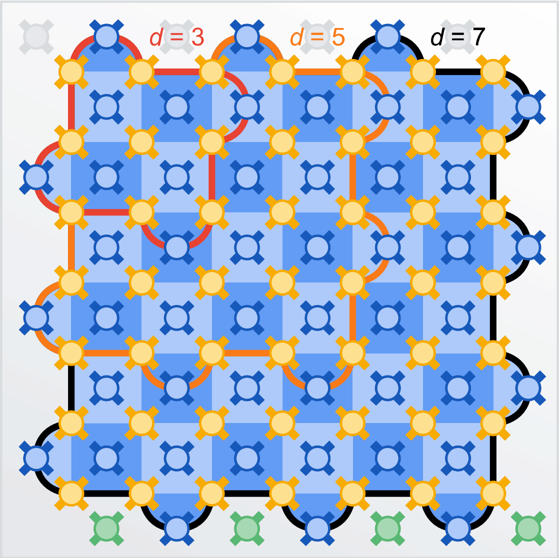
error rates ≈0.1%

+

error correction codes

logical qubits

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



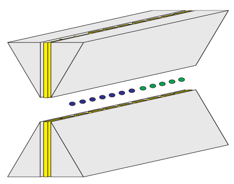
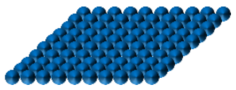
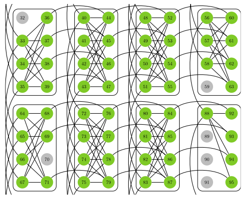
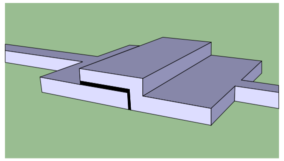
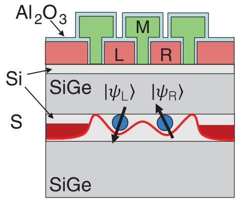
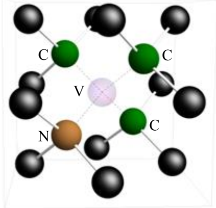
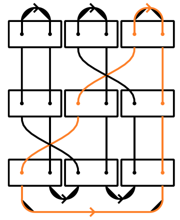
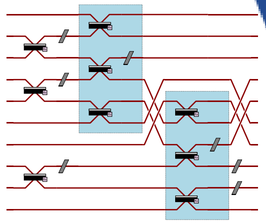
tens to thousands physical qubits per logical qubits

fault tolerance (FTQC)

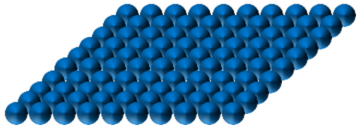
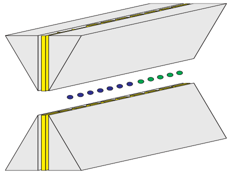
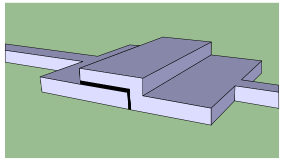
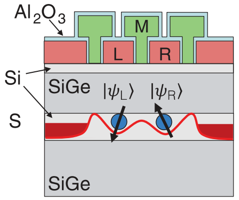
- correct errors faster than they are generated.
- avoid errors propagation.
- support a universal gate set.

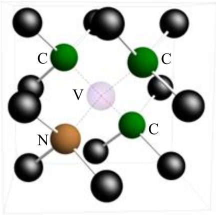
Useful applications will require hundreds to thousands of logical qubits

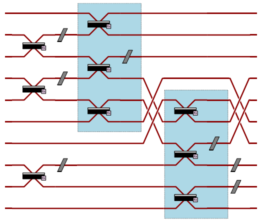
Many Qubit Technologies and many Actors

atoms		electrons *controlled spin and microwave cavities*					photons
							
trapped ions	cold atoms	annealing	superconducting	silicon	vacancies	topological	photons
Quantinuum, IONQ, AQT, oxford ionics, eleQtron, Foxconn, Quantum Art, Crystal Quantum Computing, NEQXT, Qudora Technologies, ZuriQ, HYQ Co	Pasqal, QuEra, Infleqtion, atom computing, planqc, QUANTier, NanoQT Nanofiber Quantum Technologies, Atom Quantum Labs	D-Wave The Quantum Computing Company, Qilimanjaro Quantum Tech, NEC	IBM, rigetti, amazon, Google, qci, Nord Quantique, OQC, IQM, Alice & Bob, Origin Quantum, Anyon, Atlantic Quantum, Fujitsu, QoLab, Peak Quantum, QuamCore, Z-Axis Quantum	intel, quobly, Quantum Motion, Silicon Quantum Computing, diraq, EeroQ, equal1.labs, C12, ARQUE, QπAI, Archer, Groove Quantum	Quantum Brilliance, SaxonQ, Turing, photonic, Quantum Transistors, SQutec, XeeD, Fujitsu, NTT	Microsoft, Quoherent, Quantum Gravity Research, Nokia	PsiQuantum, Quandela, Orca Computing, Xanadu, Duality Quantum Photonics, QuiX Quantum, BardeenQ Labs, Boson, QCi, photonicsQ, Quanfluence, TundraSys Global, aegiq

Nobody's perfect





	atoms		electrons *controlled spin and microwave cavities*			photons
	cold atoms	trapped ions	superconducting	silicon	NV centers	photons
operations fidelities						
gate times	with no shuttling					
qubit connectivity	with shuttling					
cooling needed	4K	4K	15 mK	≈500 mK	TBD	1.8 to 4K
qubit size						
scalability		with tiled chips				

Identified significant challenges

Hardware

- **Scaling** qubits numbers, quality, connectivity and error correction
- **Interconnecting** quantum processors
- **Enabling** technologies

Software

- **Algorithms**, software engineering and HPC – FTQC hybridization
- **Benchmarking** methodology

Ecosystem

- **Competing classical technologies** progress (AI, silicon, …)
- **Skills and funding**