#QEI
the quantum energy initiative

quantum computing roadmaps

and their energetics aspects

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QEI Workshop, Grenoble, January 7th, 2025

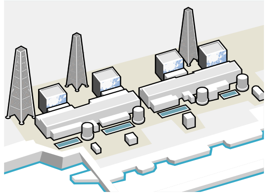
LRE
LABORATOIRE DE RECHERCHE DE L'EPITA

what is this talk about?

1. refining the definition of an **energetic quantum advantage**.
2. integrating **economic concerns** and notions.
3. estimating **resources for industry relevant applications**.
4. identifying key **emerging scalability challenges**.
5. proposing new **QEI-related research avenues**.

asking questions

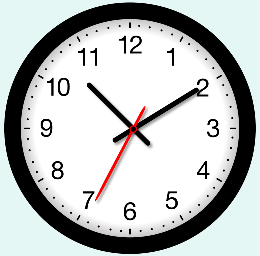
refining energy advantage taxonomy

	energy advantage	energy acceptability
comparison with classical computing	**computing accessible classically**	**computing not classically possible**
	mix of potential quantum **computing** and **energetic advantages** vs best-in-class HPCs (*).	need <u>**reasonable**</u> and <u>**affordable**</u> carbon footprint, resources and environmental impact *vs* added value and existing HPCs (*).

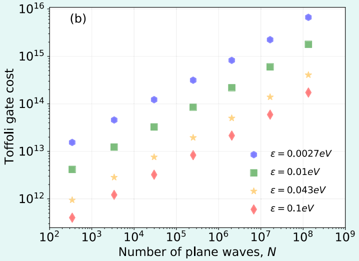
(*) including all classical costs.

quantum economics 101 for physicists

practical benefits ($|P\rangle$)



speed



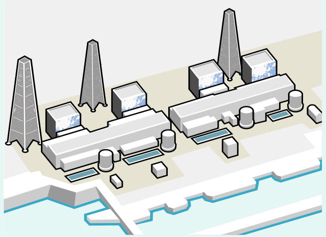
quality, required data

economics ($|E\rangle$)

€ $ £

TCO

costs



energetic

business benefit $|B\rangle$

increased revenue
reduced costs
improved service quality
competitiveness

versatility

platform effect

improves

improves

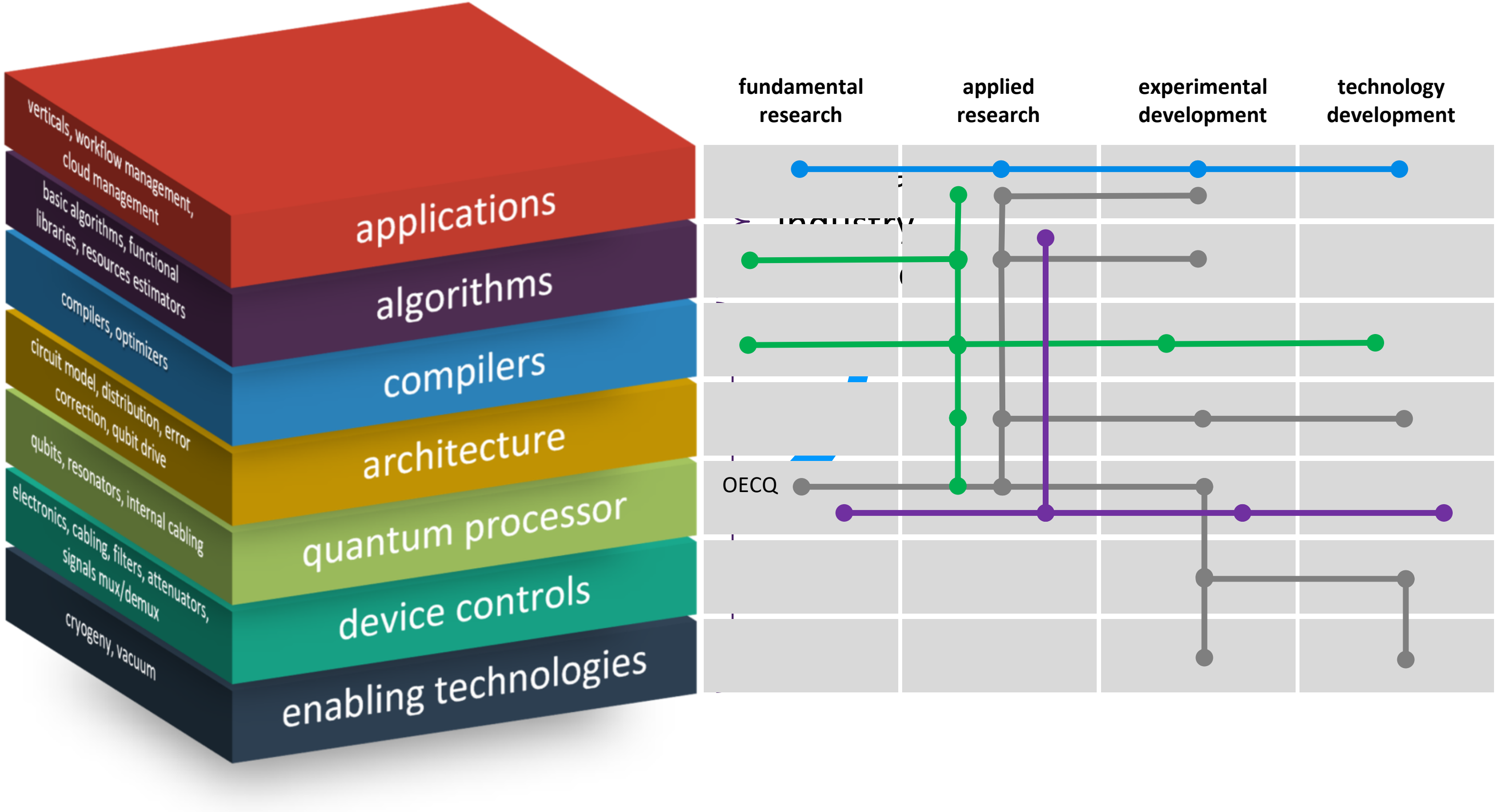
economies of scale

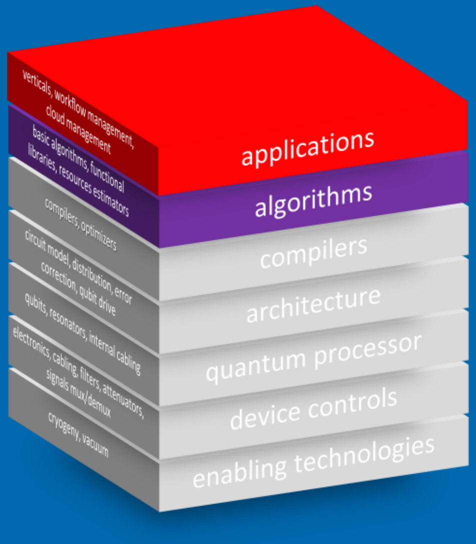
reduces

$$\textbf{ROI} = \langle P|B\rangle / tr(|E\rangle\langle E|)$$

TCO: total cost of ownership - **ROI**: return on investment

top-to-bottom approach

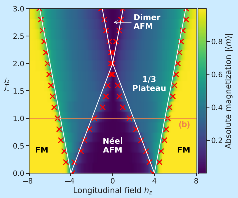




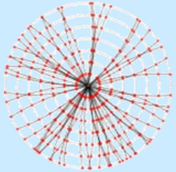
applications and algorithms

from science to industry applications

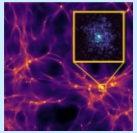
fundamental research



condensed matter physics

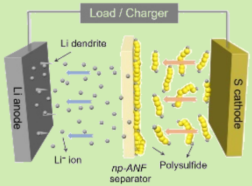


high-energy particle physics



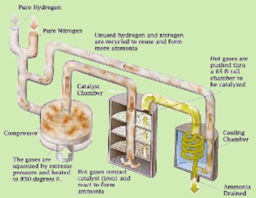
astrophysics

applied research

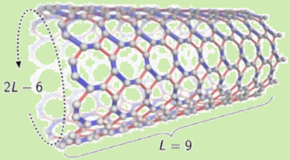


batteries

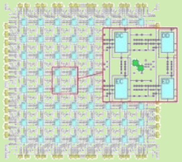
drugs



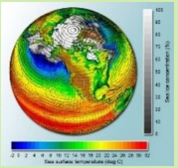
fertilizer production



material design



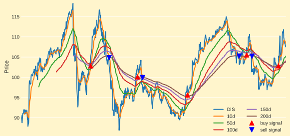
semiconductors



climate modeling

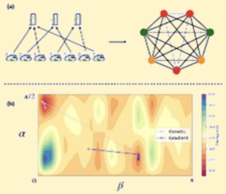
business operations

transportation

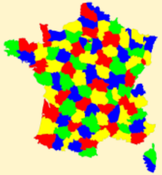


financial services

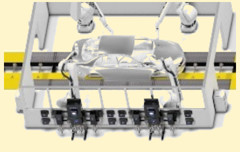
logistics and retail



energy utilities

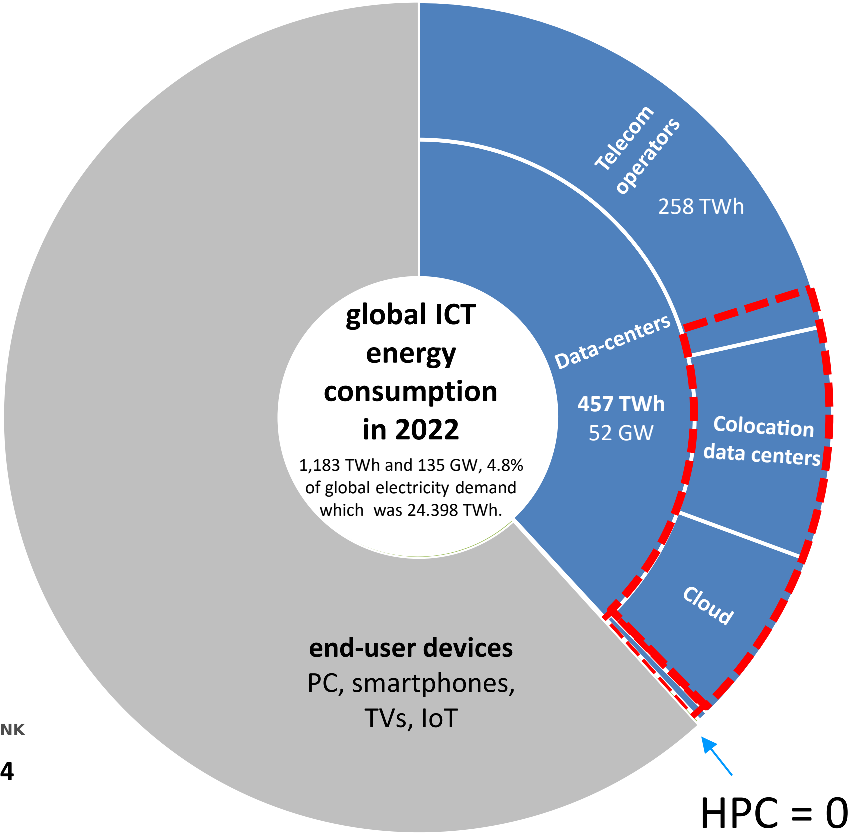


telecoms



manufacturing

sizing QPU’s energetic impact…



HPC = 0.4%

2

or that?
with business operations applications

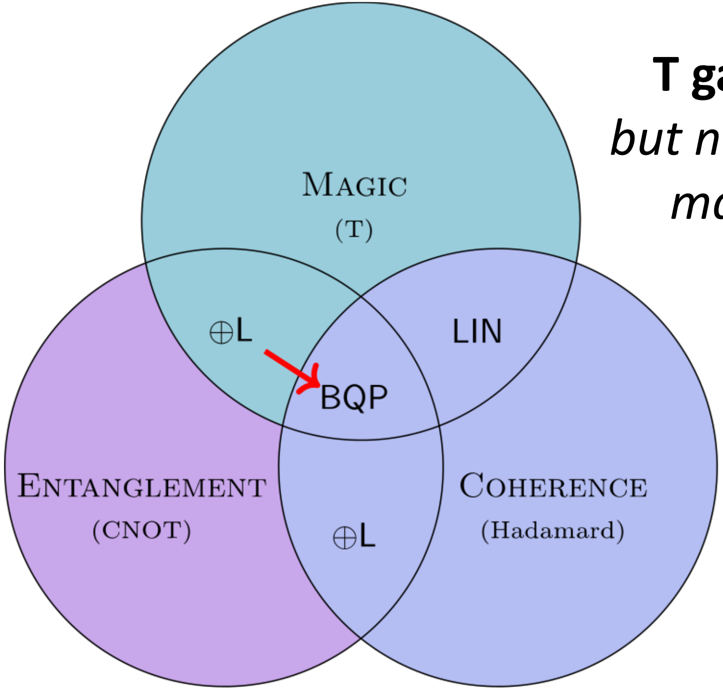
1

will quantum computing reduce or increase this?
with scientific applications

THE WORLD BANK

March 2024 report

what is a valuable quantum algorithm?



T gates
but not too many

maximally entangled states

not too deep

chart source: On the role of coherence for quantum computational advantage by Hugo Thomas, **Pierre-Emmanuel Emeriau**, Elham Kashefi, Harold Ollivier, and Ulysse Chabaud, Quandela, LIP6, Inria, University of Edinburgh, arXiv, October 2024 (20 pages).

and…

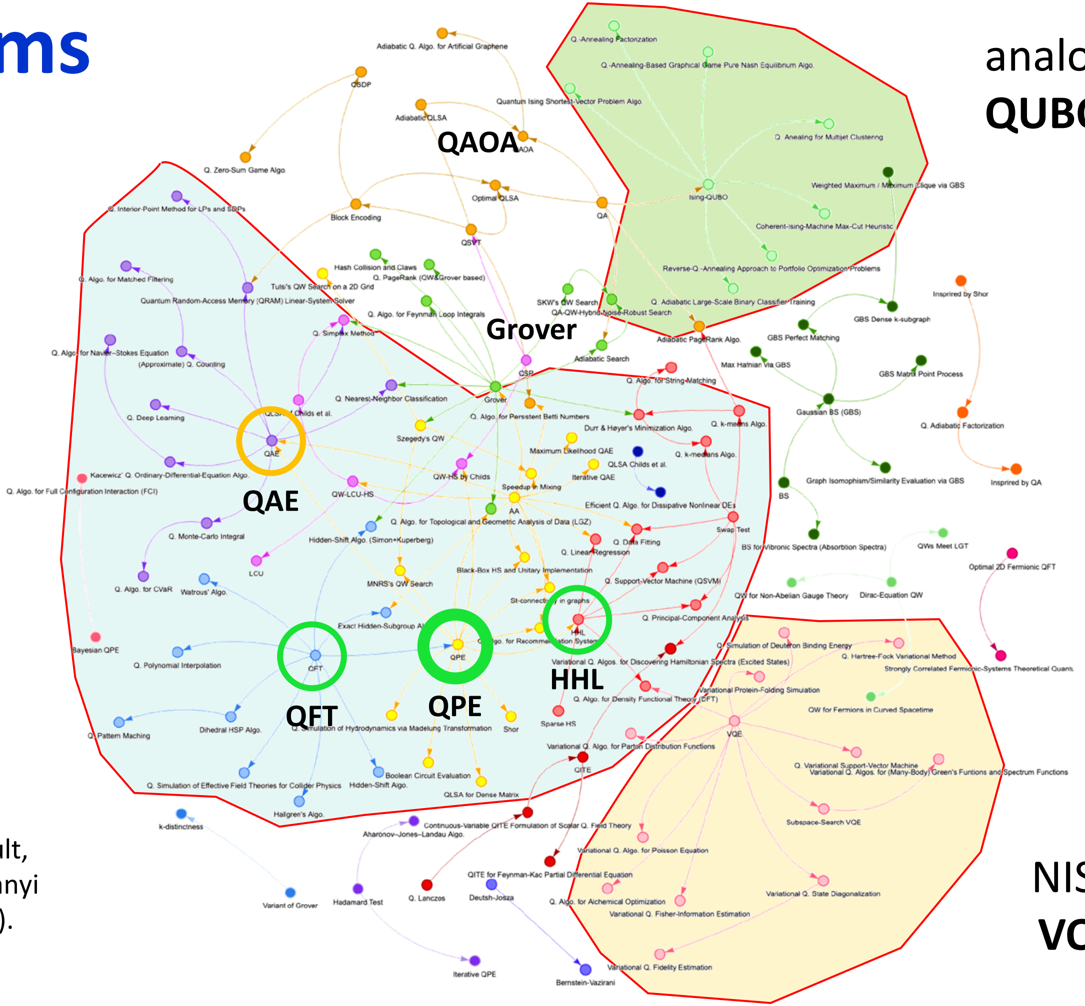
- **usefulness**: bringing some value and genericity.
- **speedup**: practical vs best-in-class classical algorithms on reasonable time scales.
- **quality**: better accuracy or heuristics.
- **data**: not too much data in, not too many samplings out, avoid use of classical oracle.

quantum algorithms interdependency clusters

analog
QUBO

FTQC
QPE & QFT based

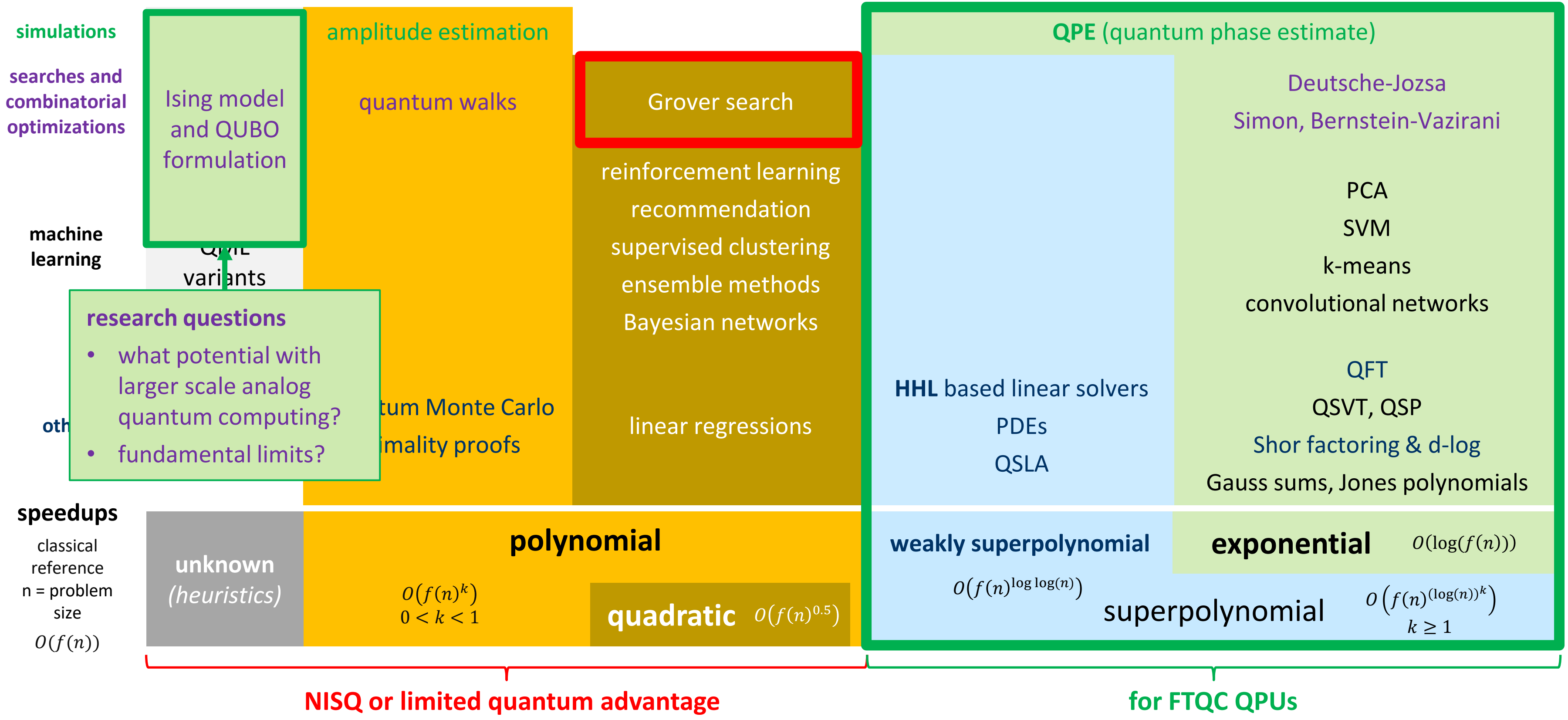
NISQ
VQE



QUANTINUUM

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



simulations

searches and combinatorial optimizations

machine learning

oth

speedups

classical reference
n = problem size
$O(f(n))$

Ising model and QUBO formulation

QML variants

research questions

- what potential with larger scale analog quantum computing?
- fundamental limits?

amplitude estimation

quantum walks

tum Monte Carlo

imality proofs

Grover search

reinforcement learning
recommendation
supervised clustering
ensemble methods
Bayesian networks

linear regressions

QPE (quantum phase estimate)

HHL based linear solvers
PDEs
QSLA

Deutsche-Jozsa
Simon, Bernstein-Vazirani

PCA
SVM
k-means
convolutional networks

QFT
QSVT, QSP
Shor factoring & d-log
Gauss sums, Jones polynomials

unknown
(heuristics)

polynomial
$O(f(n)^k)$
$0 < k < 1$

quadratic $O(f(n)^{0.5})$

weakly superpolynomial
$O(f(n)^{\log\log(n)})$

exponential $O(\log(f(n)))$

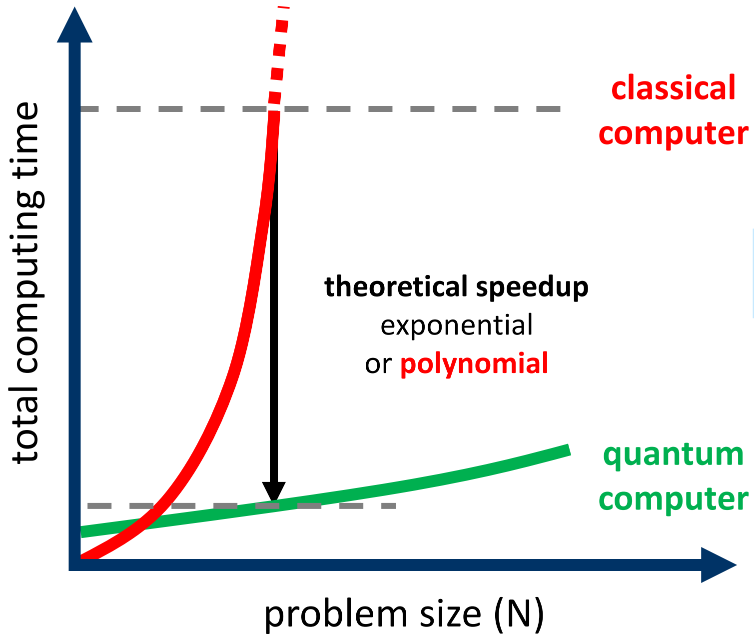
superpolynomial $O\left(f(n)^{(\log(n))^k}\right)$
$k \geq 1$

NISQ or limited quantum advantage

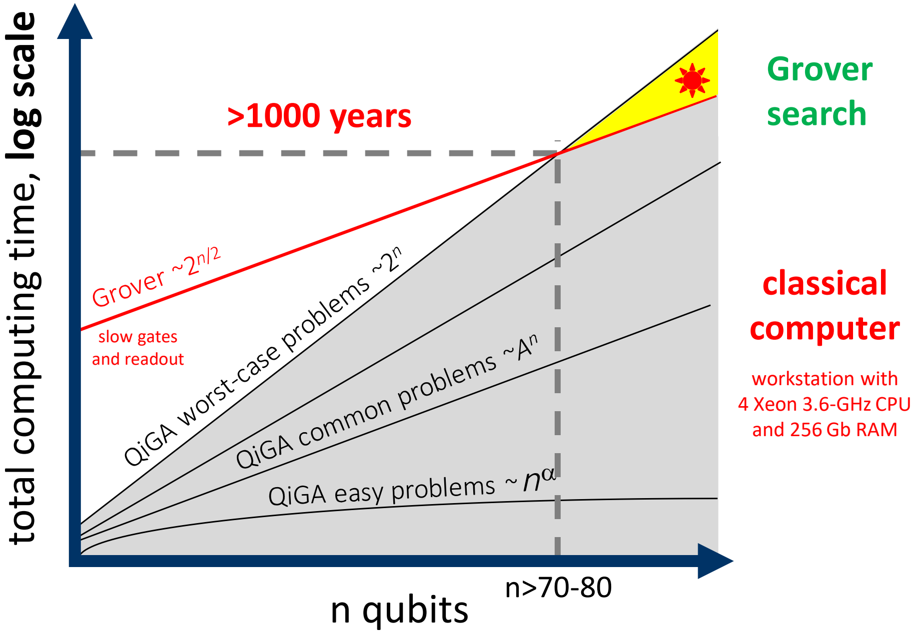
for FTQC QPUs

Understanding Quantum Technologies by Olivier Ezratty, as of November 2024.

Grover theoretical vs practical speedup



the typical way to illustrate quantum computing theoretical speedups.



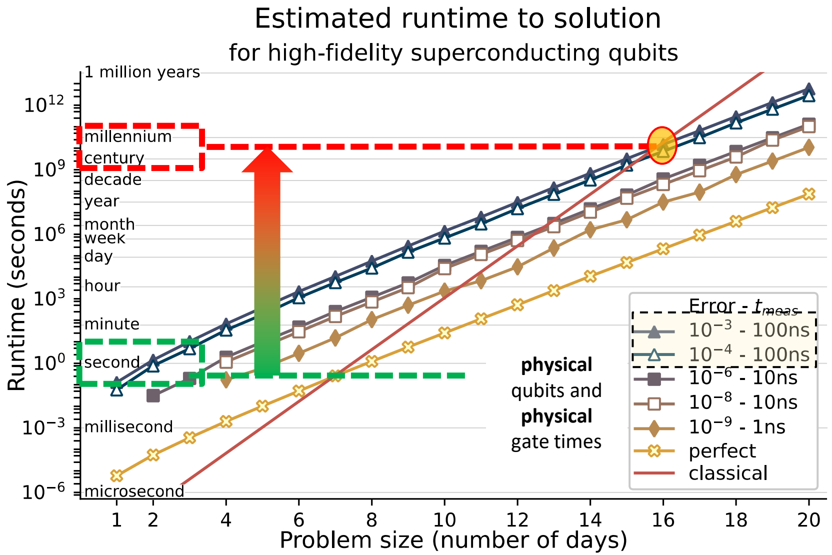
Opening the Black Box inside Grover's Algorithm, E. Miles Stoudenmire and Xavier Waintal, PRX, November 2024.

Disentangling Hype from Practicality: On Realistically Achieving Quantum Advantage, Matthias Troyer et al, ACM, May 2023.

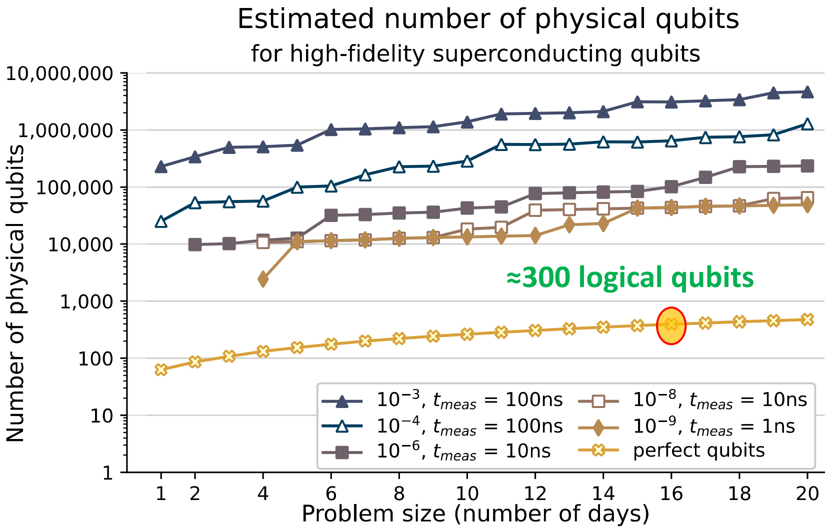
research question

- could better qubit fidelities, faster gates or else make Grover bring some quantum advantage in reasonable time scales?

Grover-based industrial shift scheduling



(a) Estimated runtime for arriving at the best solution.



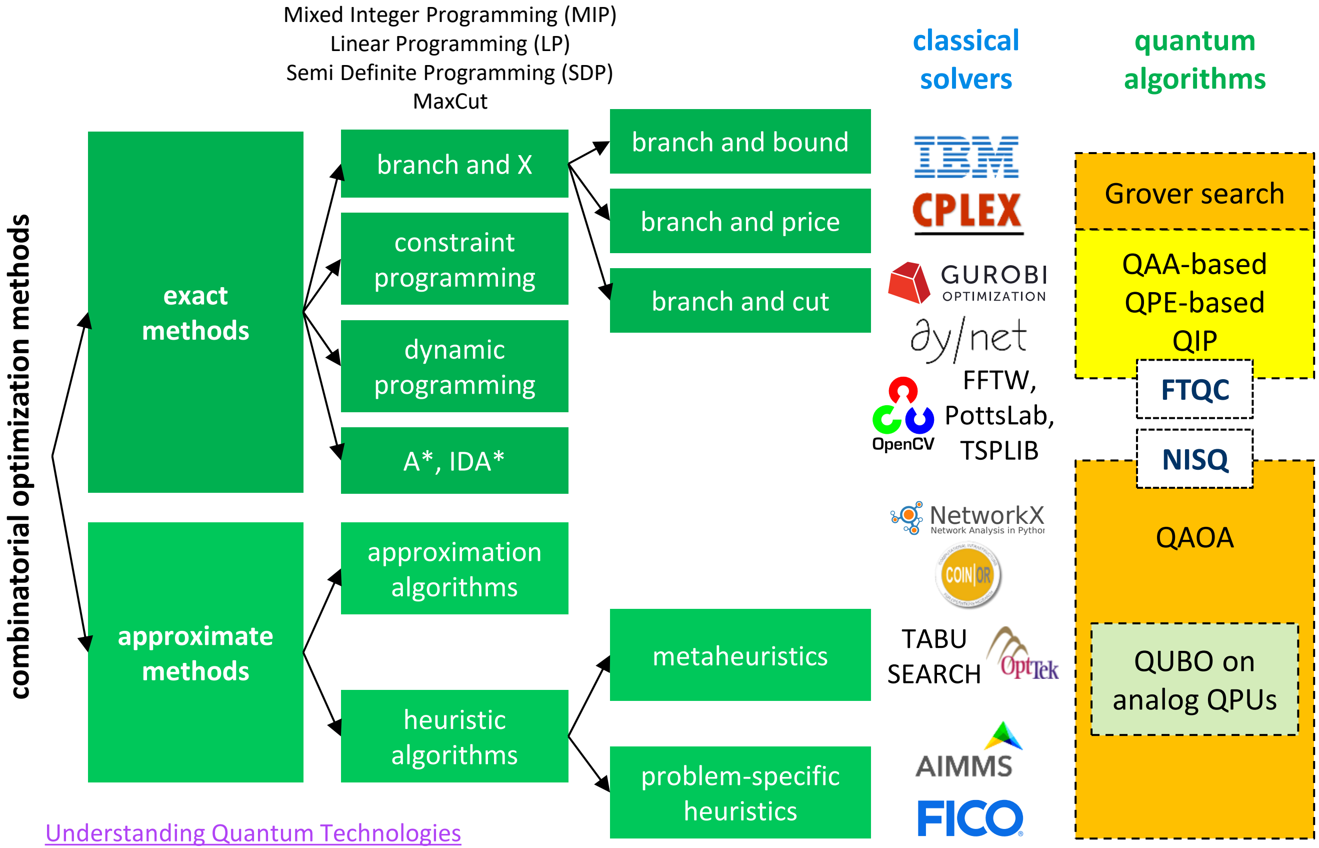
(b) Estimated number of qubits for arriving at the best solution.

with **99.9% fidelities** and **100 ns readout time**, a quantum solution would be faster than the best classical ones after **several centuries of computing**. You'd need 99.9999% physical qubit fidelities and 10 ns readout times to reduce this threshold to months.

physical qubit numbers are in the millions, which doesn't account for the cost and fidelities of interconnect solutions. However, the number of required logical qubits seems reasonable, sitting in the **300+ range** to obtain a quantum advantage regime.

Assessing the Requirements for Industry Relevant Quantum Computation by Anna M. Krol et al, TU Delft, Bosch, Entropica Labs, arXiv, August 2024.

classical and quantum solver categories



Mixed Integer Programming (MIP)
Linear Programming (LP)
Semi Definite Programming (SDP)
MaxCut

combinatorial optimization methods

exact methods

- branch and X
  - branch and bound
  - branch and price
  - branch and cut
- constraint programming
- dynamic programming
- A*, IDA*

approximate methods

- approximation algorithms
- heuristic algorithms
  - metaheuristics
  - problem-specific heuristics

classical solvers

IBM CPLEX
GUROBI OPTIMIZATION
dy/net
OpenCV
FFTW, PottsLab, TSPLIB
NetworkX Network Analysis in Python
COIN|OR
TABU SEARCH
OptTek
AIMMS
FICO

quantum algorithms

Grover search
QAA-based
QPE-based
QIP
FTQC
NISQ
QAOA
QUBO on analog QPUs

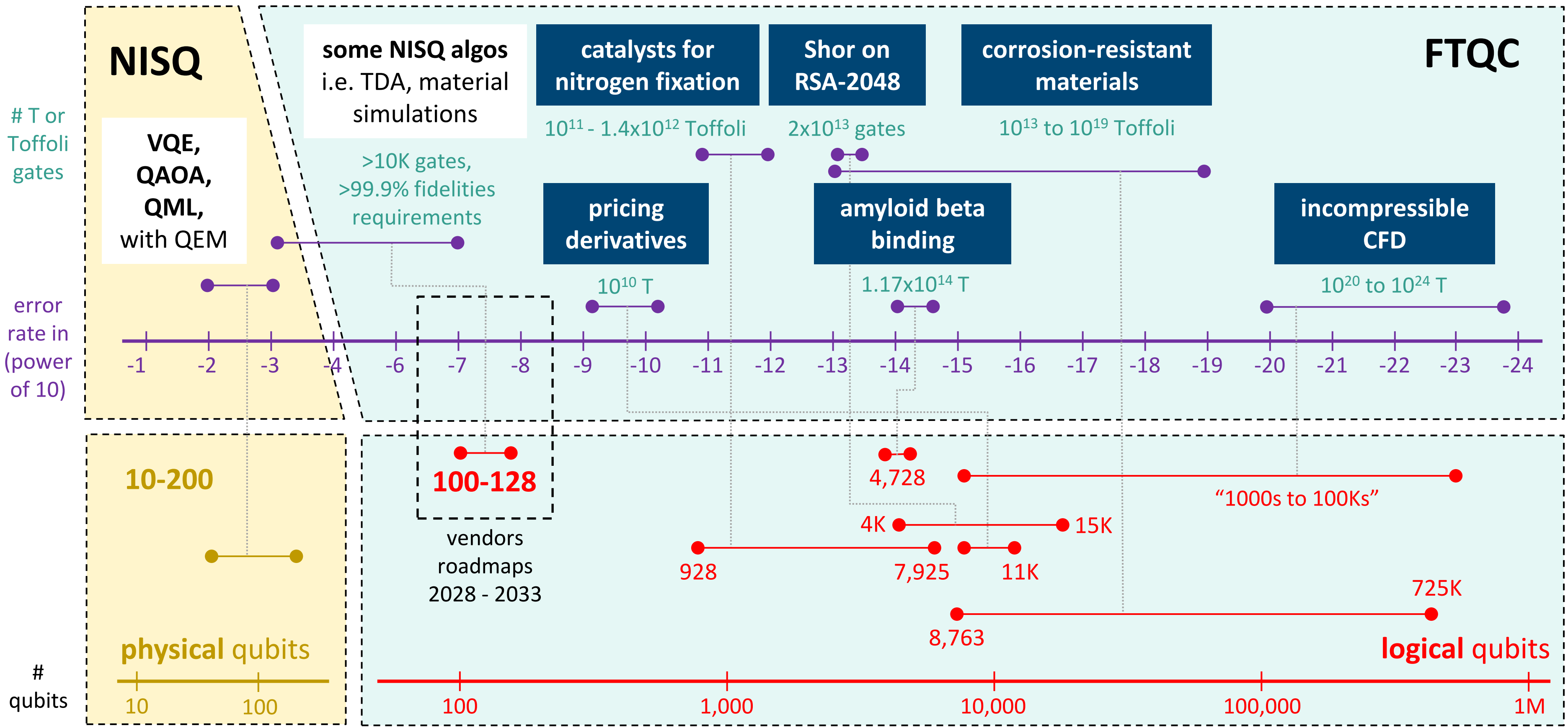
QAA = Quantum Adiabatic Algorithm

research questions:

- how could **oracle-based** algorithms bring some practical speedup?
- which decision problem solving algorithms bring an **exponential speedup**? What are their structure?
- how about **large-scale analog** solutions (QUBO, Ising models)?

Understanding Quantum Technologies
by Olivier Ezratty, as of November 2024.

most of these solutions are based on variations of QPE



NISQ

FTQC

T or Toffoli gates

error rate in (power of 10)

qubits

VQE, QAOA, QML, with QEM

some NISQ algos i.e. TDA, material simulations

>10K gates, >99.9% fidelities requirements

catalysts for nitrogen fixation

10^{11} - 1.4x10^{12} Toffoli

Shor on RSA-2048

2x10^{13} gates

corrosion-resistant materials

10^{13} to 10^{19} Toffoli

pricing derivatives

10^{10} T

amyloid beta binding

1.17x10^{14} T

incompressible CFD

10^{20} to 10^{24} T

10-200

100-128

vendors roadmaps 2028 - 2033

4,728

"1000s to 100Ks"

4K

15K

928

7,925

11K

725K

8,763

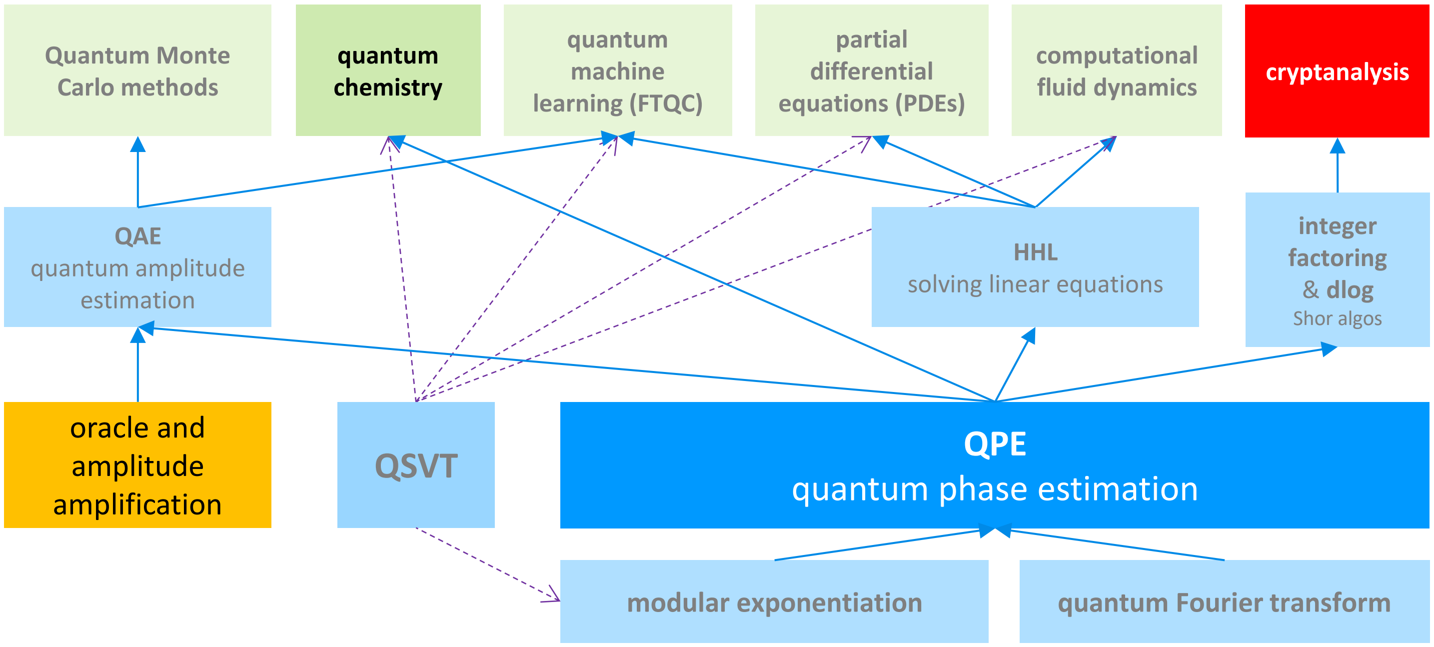
physical qubits

logical qubits

physical qubits and logical qubits are on a similar log scale. What determines the characteristics of logical qubits like the physical per logical qubit count is their target error rate itself dependent on the number of algorithms gates.

Understanding Quantum Technologies
by Olivier Ezratty, as of November 2024.

key FTQC quantum algorithms food chain



Why Haven't More Quantum Algorithms Been Found? by Peter Shor, 2003 (4 pages).

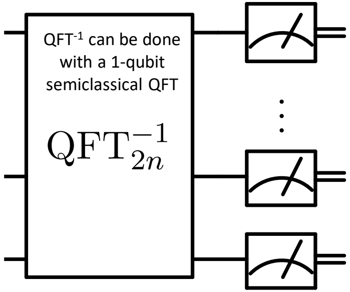
Quantum algorithms: A survey of applications and end-to-end complexities by Alexander M. Dalzell, Fernando G. S. L. Brandão et al, AWS, RWTH Aachen University, Imperial College London, Caltech, October 2023 (337 pages).

research questions:

- are QPE and QSVT the **cornerstone algorithms** for obtaining exponential speedups? if so, **why is that**?
- what is the **relative energetic cost** of their key components: classical preparation, modular exponentiation, QFT?

complexity scale: **QFT and QFT^{-1}**

- QFT is a **low-cost part** of a Shor or QPE circuit.
- QFT can also be implemented as a **semi-classical QFT with a single qubit**, particularly if it is the last part of a quantum algorithm.



factoring a 2048-bit RSA key

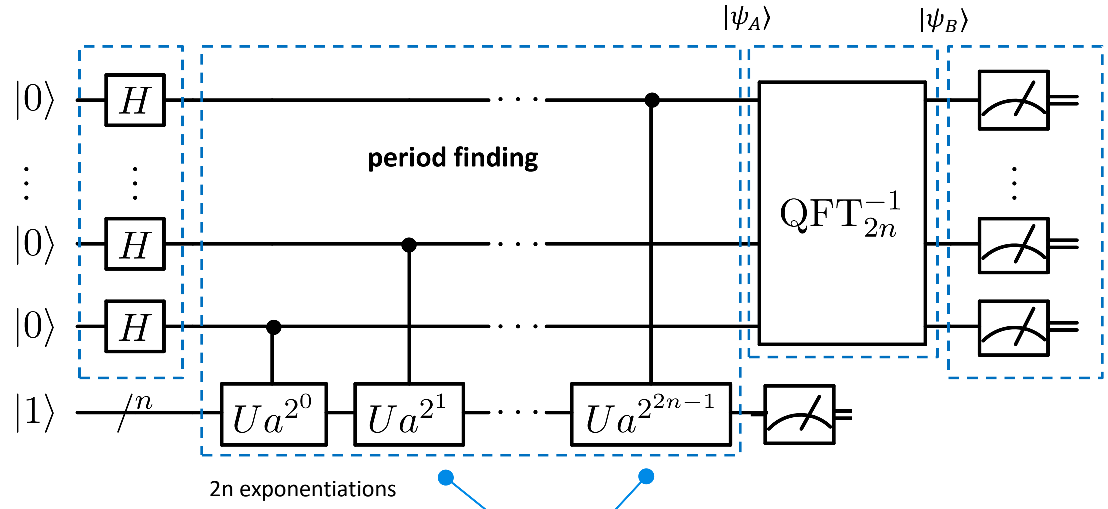
Shor part	gate scaling	gates	T gates
QFT^{-1}	$\approx O(n^{2}/2)$	$\approx 8 \times 10^6$	$\approx 10^8$
period finding	$\approx O(n^{3})$	$\approx 8.6 \times 10^9$	$\approx 10^{10}$

QFT $<$ 1% of Shor's cost

and even less with a semi-classical QFT^{-1} as in Gidney-Ekerå's 2019 paper.

How to factor 2048 bit RSA integers in 8 hours using 20 million noisy qubits by Craig Gidney and Martin Ekerå, 2019 (25 pages).

complexity scale: **QFT < Shor**



QFT^{-1} can be implemented with a 1-qubit semiclassical QFT

continuous fraction arithmetic post-processing the results to obtain the divider

no data encoding at the beginning of the circuit.

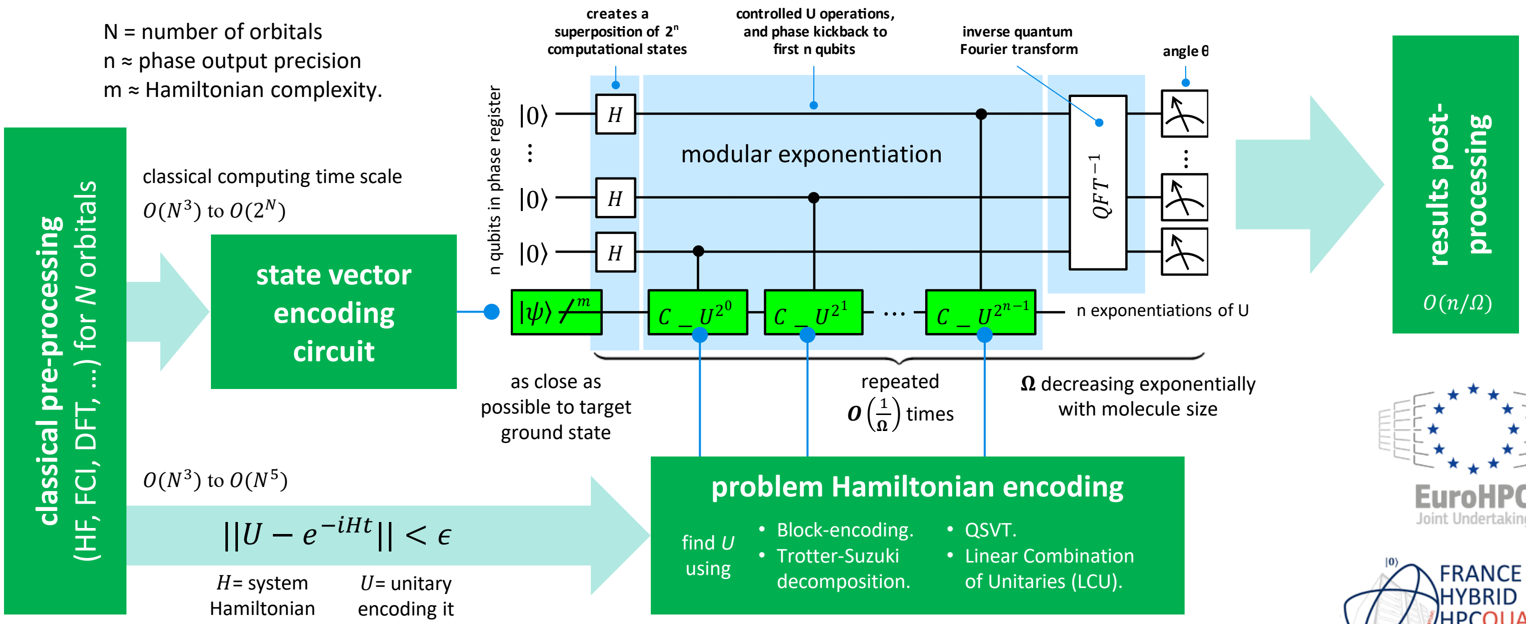
$$f(x) = a^x \mathrm{mod}\, N \longrightarrow U_f|x, 0^q\rangle = |x, f(x)\rangle$$

period finding based on complex reversible arithmetic.

lightweight classical post-processing.

complexity scale: **QFT < Shor < QPE**

N = number of orbitals
n ≈ phase output precision
m ≈ Hamiltonian complexity.



classical pre-processing
(HF, FCI, DFT, …) for N orbitals

classical computing time scale
$O(N^3)$ to $O(2^N)$

state vector encoding circuit

as close as possible to target ground state

repeated $O\left(\frac{1}{\Omega}\right)$ times

Ω decreasing exponentially with molecule size

results post-processing

$O(n/\Omega)$

$O(N^3)$ to $O(N^5)$

$$||U - e^{-iHt}|| < \epsilon$$

H= system Hamiltonian

U= unitary encoding it

problem Hamiltonian encoding

find U using
- Block-encoding.
- Trotter-Suzuki decomposition.
- QSVT.
- Linear Combination of Unitaries (LCU).

EuroHPC Joint Undertaking

FRANCE HYBRID HPCQUANTUM INITIATIVE

research questions:
- as the many-body system size and logical qubits # grow,
  classical preparation cost can scale exponentially, but how much?
- use large QPEs for full-stack energy estimates, benchmarking, comparisons and optimization?

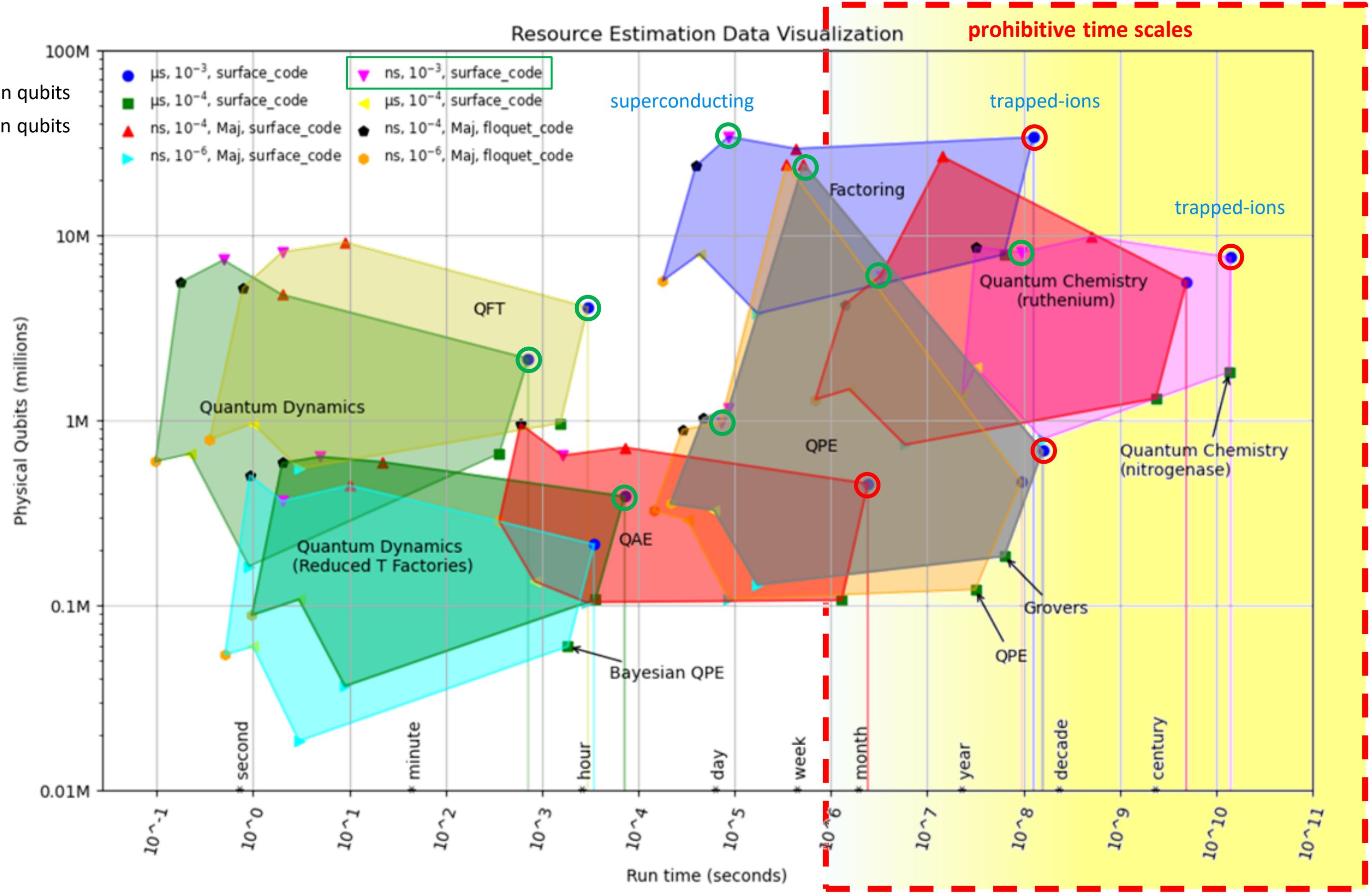
inspired by Quantum chemistry, classical heuristics, and quantum advantage by Garnet Kin-Lic Chan, arXiv, July 2024 & On the feasibility of performing quantum chemistry calculations on quantum computers by Thibaud Louvet, Thomas Ayral, and Xavier Waintal, arXiv, June 2023-October 2024.

µs gate times: trapped ion qubits

ns gate times: superconducting and silicon qubits

several scenarios are used with different physical qubit error rates and gate times. The realistic ones are with 99.9% fidelities and µs readout cycle times.

one ultimate challenge will be actual computing times!



The GQI Quantum Resource Estimator Playbook - Quantum Computing Report
by Doug Finke, Quantum Computing Report, August 2024.

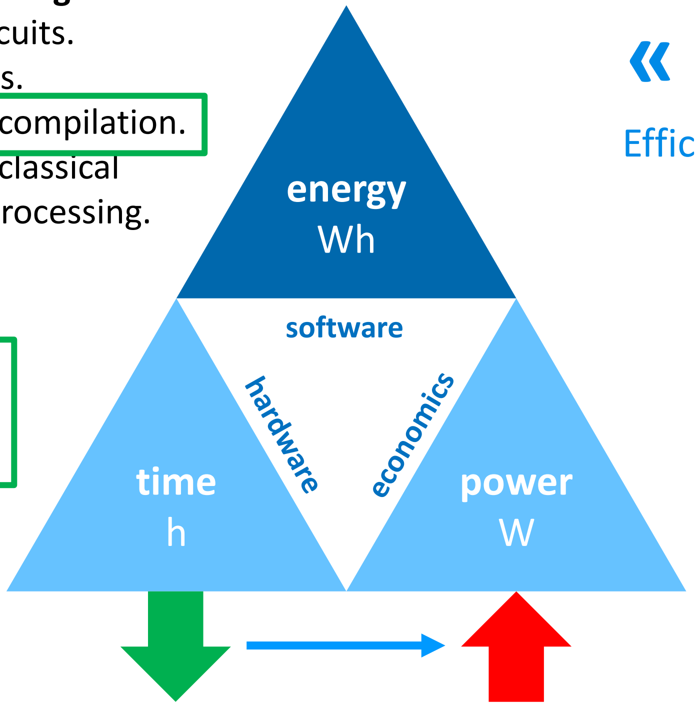
computing time optimization framework

❶

more Efficient algorithms
- smaller circuits.
- fewer shots.
- optimized compilation.
- optimized classical pre/post-processing.

« EFP »

Efficient-Faster-Parallel

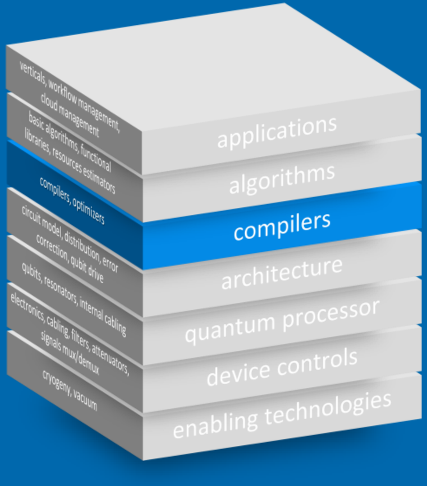


❷

Faster computing
- faster gates and readout, constrained by various limitations.
- faster classical-quantum cycles, including QEC, classical-quantum drive efficiencies.

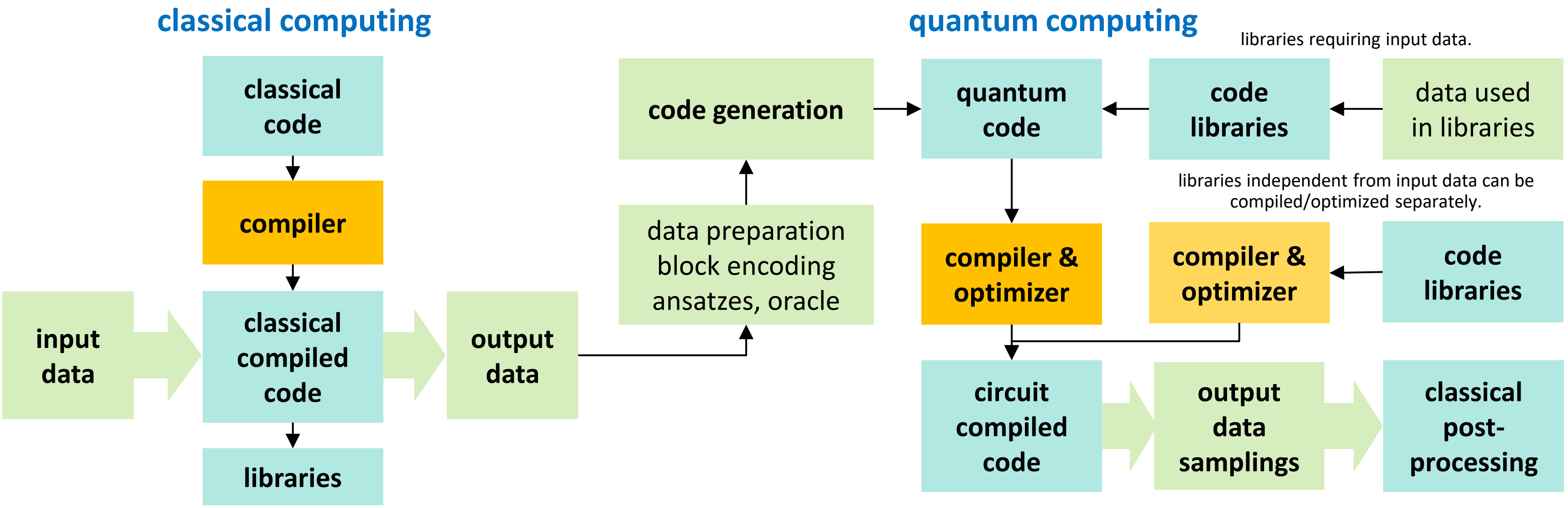
❸

Parallelizing circuit shots on multiple similar QPUs
- affordable FTQC QPUs (cost and total carbon footprint).
- manage pressure on electricity grid.



quantum compilers

compilation is usually a variable cost



classical computing

classical code

compiler

input data

classical compiled code

output data

libraries

quantum computing

code generation

data preparation block encoding ansatzes, oracle

quantum code

code libraries

data used in libraries

libraries requiring input data.

libraries independent from input data can be compiled/optimized separately.

compiler & optimizer

compiler & optimizer

code libraries

circuit compiled code

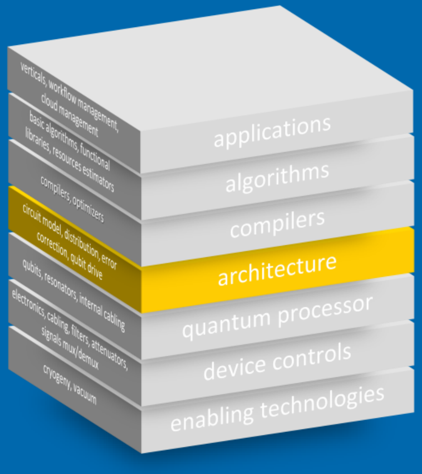
output data samplings

classical post-processing

architecture	**Von Neuman / Princeton**	**in-memory processing.**
classical compilation cost	**fixed cost vs data.**	**variable cost vs data**
libraries & data	**used by the compiled code.**	**embedded *in* circuits/models.**
classical data-ingestion	**fast.**	**slow.**
compilation	done once.	**NP hard** circuit optimization.

research & engineering questions:

- compilation cost estimations with large-scale algorithms?
- practical optimization?
- impact on business operations applications with fast duty cycles?



applications
verticals, workflow management, cloud management

algorithms
basic algorithms, functional libraries, resources estimators

compilers
compilers, optimizers

architecture
circuit model, distribution, error correction, qubit drive

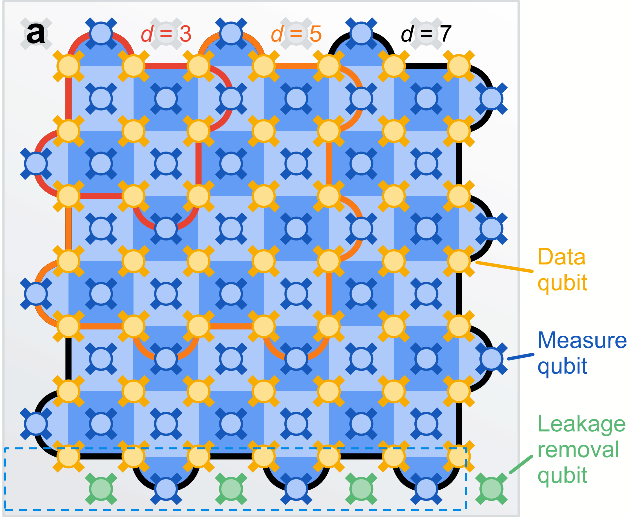
quantum processor
qubits, resonators, internal cabling

device controls
electronics, cabling, filters, attenuators, signals mux/demux

enabling technologies
cryogeny, vacuum

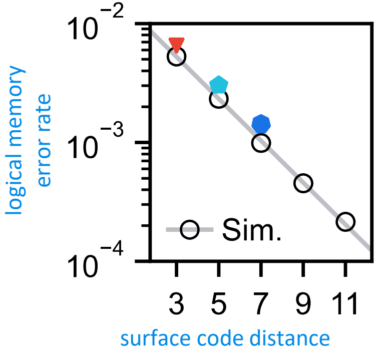
QPU architecture

Google first breakeven logical qubits



105 qubit chip with a distance-7 single logical qubit

[Quantum error correction below the surface code threshold](#) by Rajeev Acharya, Frank Arute, Michel Devoret, Edward Farhi, Craig Gidney, William D. Oliver, Pedram Roushan et al, Google, arXiv, August 2024.



10^{-6} logical error rates would require 1,457 physical qubits per logical qubits and a distance-27 surface code with existing qubit fidelities.

+

plan for 10K qubits chips

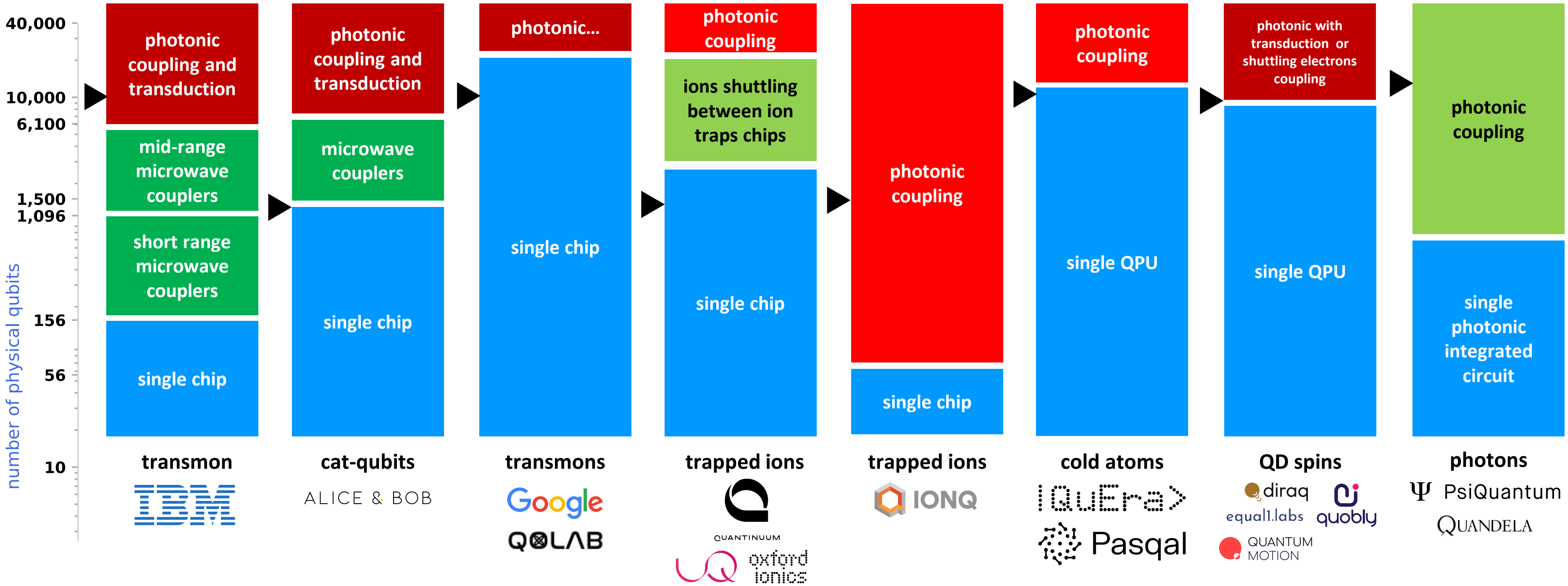
QPU interconnect

research & engineering questions:

- scaling with keeping good qubit fidelities?
- impact of chips manufacturing quality re qubit variability?
- fundamental and practical limits for scaling monolithic QPUs?
- connection with other stacks (quantum control, quantum thermodynamics, …)?
- lower overhead impact of non-local connectivity and autonomous error correction (cats, GKP).
- energetic cost and scale of machine-learning based syndrome detection techniques?

[Learning high-accuracy error decoding for quantum processors](#) by Johannes Bausch, Craig Gidney, **Demis Hassabis**, Hartmut Neven, Pushmeet Kohli et al, Google, Nature, November 2024 (28 pages).

multiple QPUs interconnect options



transmon
IBM
- photonic coupling and transduction
- mid-range microwave couplers
- short range microwave couplers
- single chip

cat-qubits
ALICE & BOB
- photonic coupling and transduction
- microwave couplers
- single chip

transmons
Google
QOLAB
- photonic...
- single chip

trapped ions
QUANTINUUM
UQ
oxford ionics
- photonic coupling
- ions shuttling between ion traps chips
- single chip

trapped ions
IONQ
- photonic coupling
- single chip

cold atoms
|QuEra>
Pasqal
- photonic coupling
- single QPU

QD spins
diraq
quobly
equal1.labs
QUANTUM MOTION
- photonic with transduction or shuttling electrons coupling
- single QPU

photons
Ψ PsiQuantum
QUANDELA
- photonic coupling
- single photonic integrated circuit

🟦 single monolithic chip or QPU
🟩 interconnect using same qubit modality
🟩 short range or mid-range microwave couplers
🟥 direct photonic coupling
🟥 photonic coupling requiring a qubit transduction

▶ approximate physical qubits # required to reach 100 logical qubits at 10^{-8} error rate, the lower being the better.

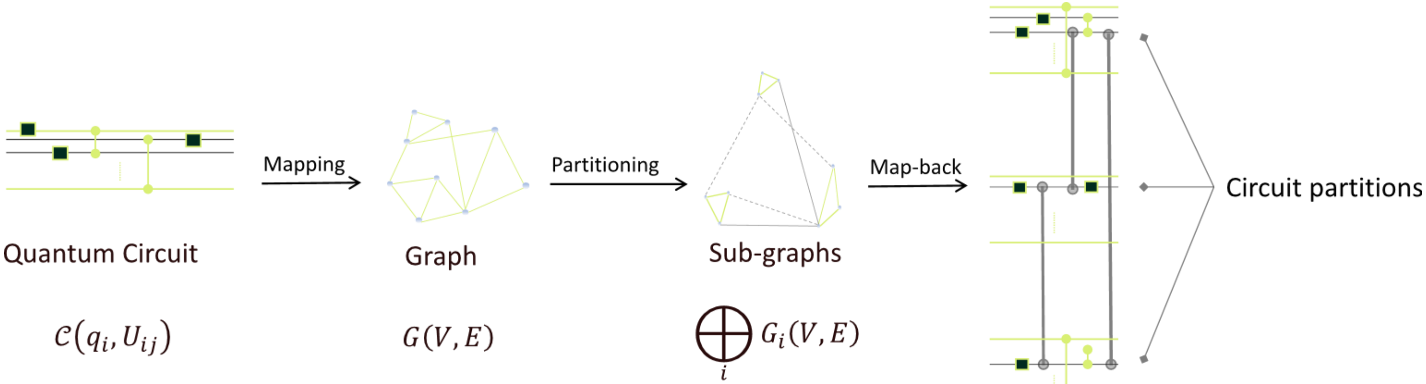
growing complexity with rough estimates thresholds requiring these techniques

Understanding Quantum Technologies by Olivier Ezratty, as of November 2024.

Distributed Quantum Computing

research questions

- what are the key figures of merit of entanglement sharing in interconnect (efficiencies, entanglement heralding, fidelities)?
- how can QEC be distributed on multiple interconnect QPUs with minimum losses?
- what is the additional compilation and optimization cost for DQC architectures?
- how far can circuit knitting be efficient in multiple QPU computing and what is its classical cost scaling?

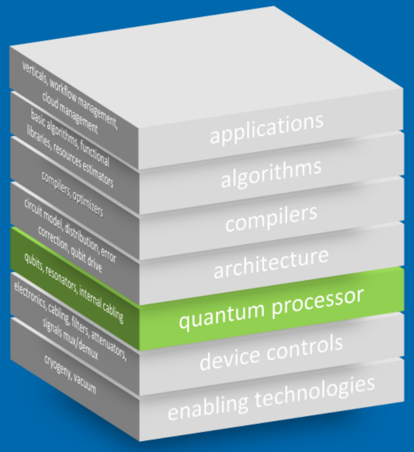


Scalability enhancement of quantum computing under limited connectivity through distributed quantum computing by Shao-Hua Hu, et al, Tamkang University, Taiwan, arXiv, May 2024 (18 pages).

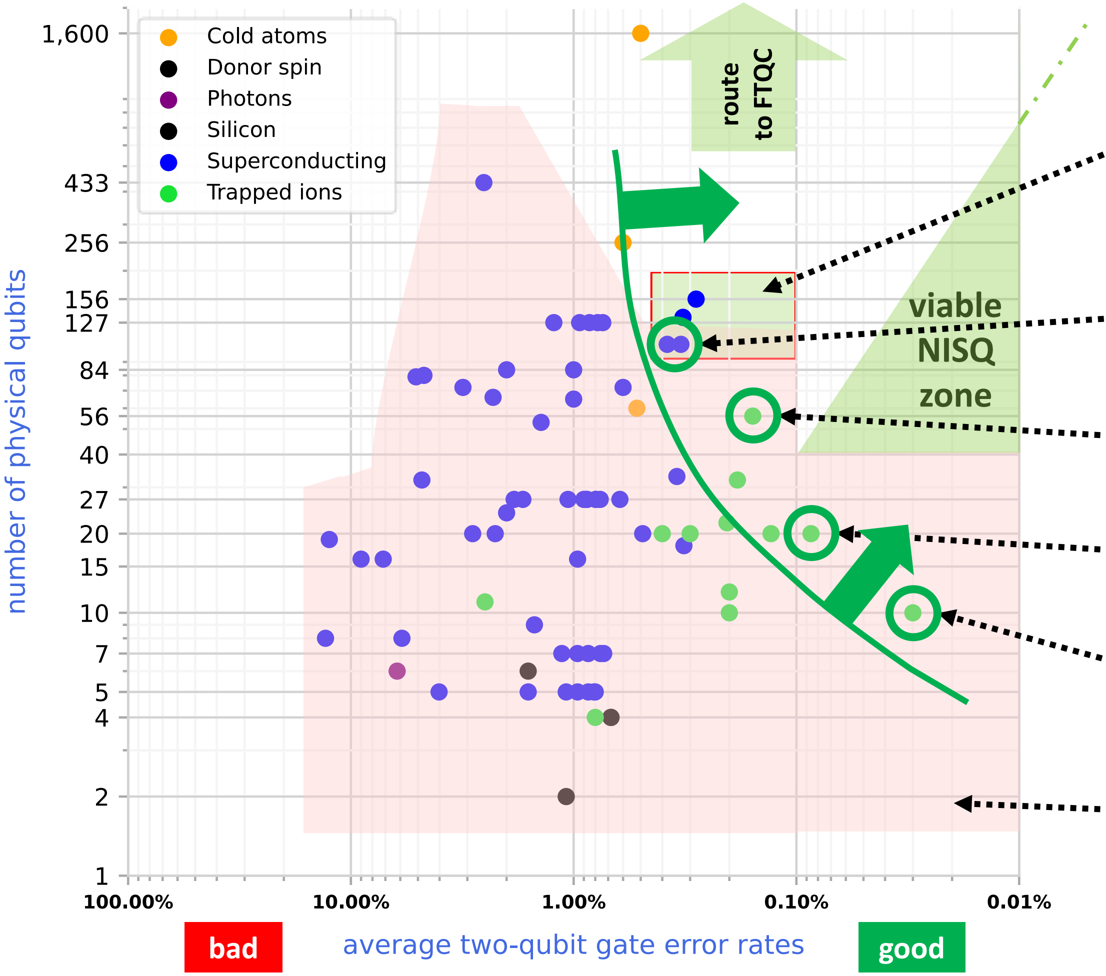
Distributed Quantum Computation via Entanglement Forging and Teleportation by Tian-Ren Jin, Kai Xu et al, Hefei National Laboratory, CAS, arXiv, September 2024 (8 pages).

Distributed Quantum Computation with Minimum Circuit Execution Time over Quantum Networks by Ranjani G Sundaram et al, Stony Brook University, arXiv, May 2024 (11 pages).

Towards Distributed Quantum Error Correction for Distributed Quantum Computing by Shahram Babaie et al, University at Buffalo, arXiv, September 2024 (12 pages).



quantum processors



quantum error mitigation NISQ utility window

algorithmiq

IBM

99.67% « Willow »
August 2024
+ China Zuchongzhi 3.0

Google

99.87%
June 2024

99.9%
April 2024

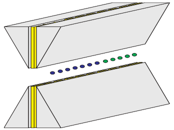
QUANTINUUM

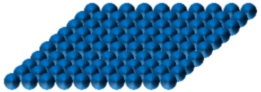
99.97%
July 2024

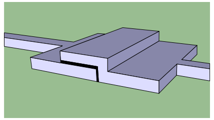
oxford ionics

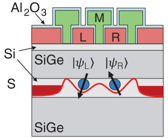
easy to emulate classically below 99.9% fidelities (tensor networks) or below 40 qubits (state vector).

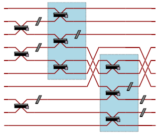
(cc) Olivier Ezratty, January 2025.







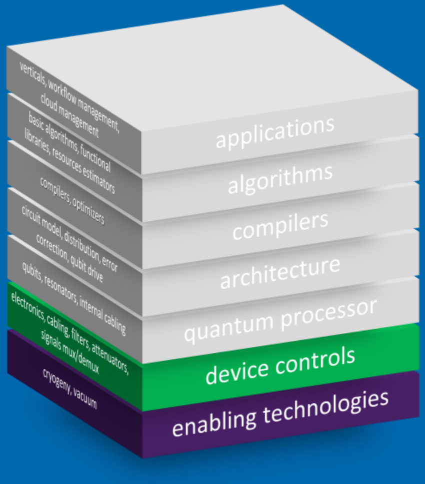




	trapped ions	cold atoms	superconducting	silicon spin	photons
existing duration - 1 qubit gate - 2 qubit gate - readout	- 1 → 10 μs - 10 → 100 μs - 10 → 100 μs	- 10 → 100 μs - 10 → 100 μs - 10 → 50 μs	- 10 → 30 ns - x0 → 500 ns - 100 → 500 ns	- 10 → 30 ns - x0 → to 100 ns - 10 → 100 ns	- photon sources clock rate, can reach ≈1 GHz - 800 ps 2QBG.
optimistic duration - 1 qubit gate - 2 qubit gate - readout	- < 1 μs - a few μs - 10 μs	- 100 ns - a few μs - 5 μs	- 10 ns - 30 ns - 50 ns	- 10 ns - 10 ns - 10 → 50 ns	- ns - 10s ns - 10s ps (SNSPD)
gate time limitations explanations	- motional modes and frequencies. - laser stability. - ions heating. - crosstalk.	- QSL and Rabi frequency.	- QSL and Rabi frequency.	- QSL: maximum achievable Rabi ies for lear spin vding	- photon travel time through optical guides. - weakness of photon-photon interactions.
qubit readout time limitations expanations	- fluorescence photo count. - shot noise & SNR.		- qubit relaxation time.	in .	- coïncidence detection overhead. - backaction (for MBQC).

fundamental questions:

- gate times and readout lower bounds?
- role of quantum speed limits?
- energetic vs speed trade-offs?
- impact on control cost?
- is all-to-all connectivity offsetting slow gates?



device control and enabling technologies

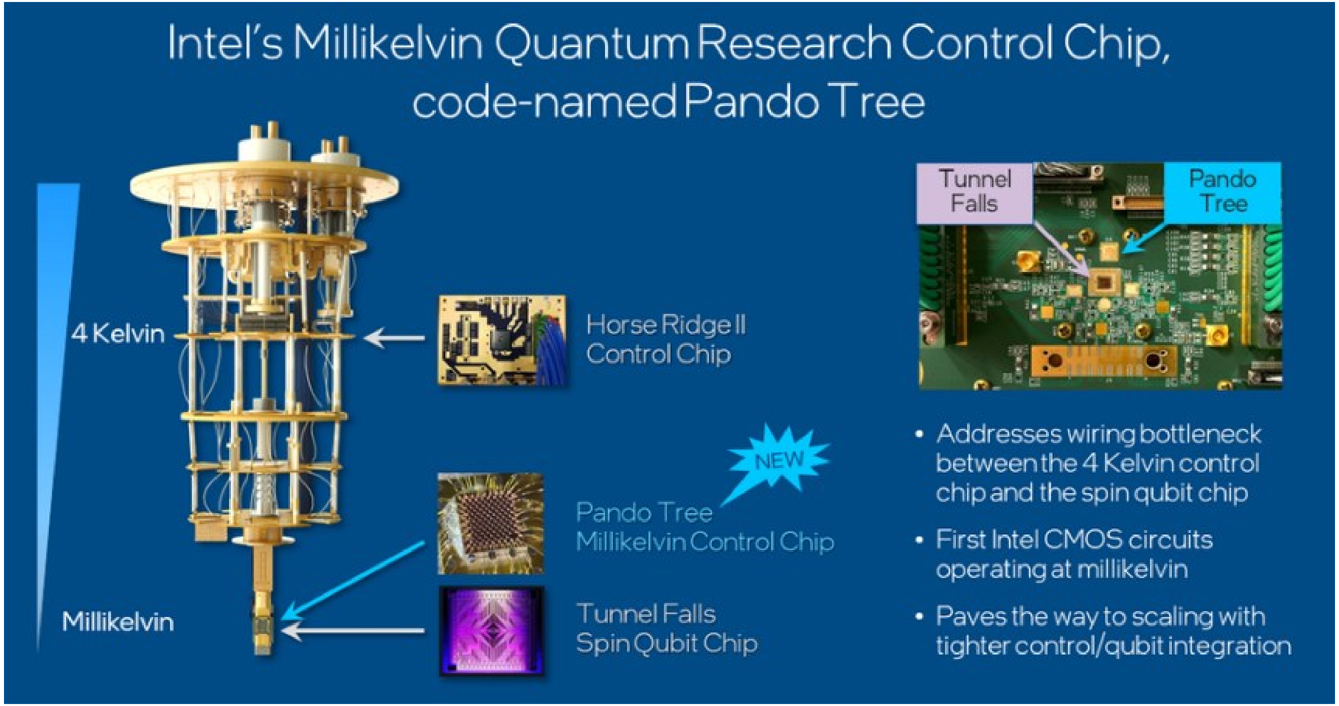
cryo-control chain from 4K to mK stage

Pando Tree
June 2024

Intel's Millikelvin Quantum Research Control Chip Provides Denser Integration with Qubits, Intel, June 2024.

engineering questions:

- trade-offs between simplifying cabling and passive electronics and cryo-CMOS dissipation cooling cost.

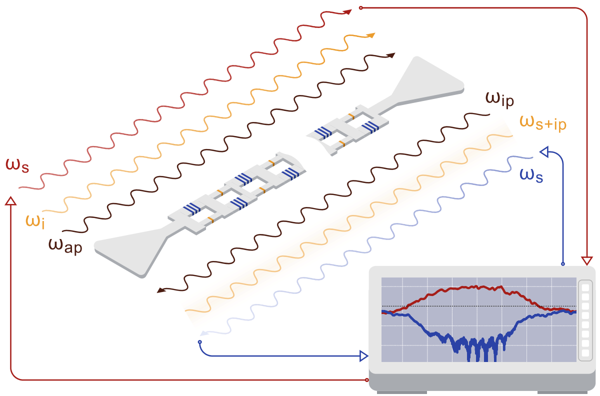


Intel's Millikelvin Quantum Research Control Chip,
code-named Pando Tree

- Addresses wiring bottleneck between the 4 Kelvin control chip and the spin qubit chip
- First Intel CMOS circuits operating at millikelvin
- Paves the way to scaling with tighter control/qubit integration

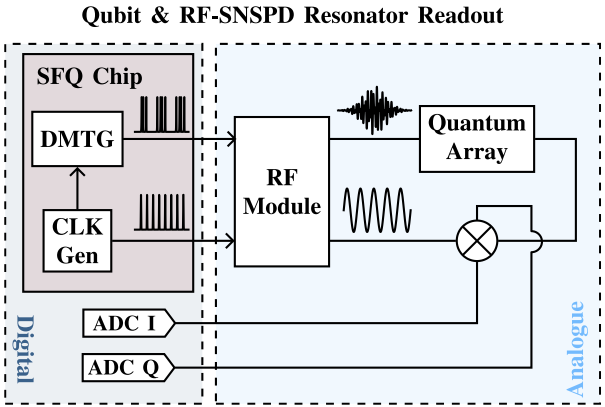
Optimizing resource efficiencies for scalable full-stack quantum computers by Marco Fellous-Asiani, Jing Hao Chai, Yvain Thonnart, Hui Khoon Ng, Robert S. Whitney and Alexia Auffèves, PRX Quantum, Octoaber 2023 (40 pages).

qubit control recent advances



A Traveling Wave Parametric Amplifier Isolator by Arpit Ranadive, Luca Planat, Nicolas Roch et al, Silent Waves, CNRS Institut Néel, KIT, University of Strasbourg, arXiv, June 2024.

TWPAs and solid-state isolator (Silent Waves)

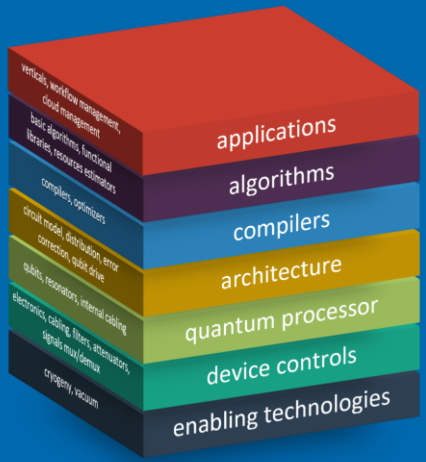


RSFQ All-Digital Programmable Multi-Tone Generator For Quantum Applications by João Barbosa, Oleg Mukhanov, Martin Weides et al, SEEQC, QuantWare, University of Glasgow, arXiv, November 2024.

SFQ progress for qubit drive and readout (SEEQC)

research and engineering questions:

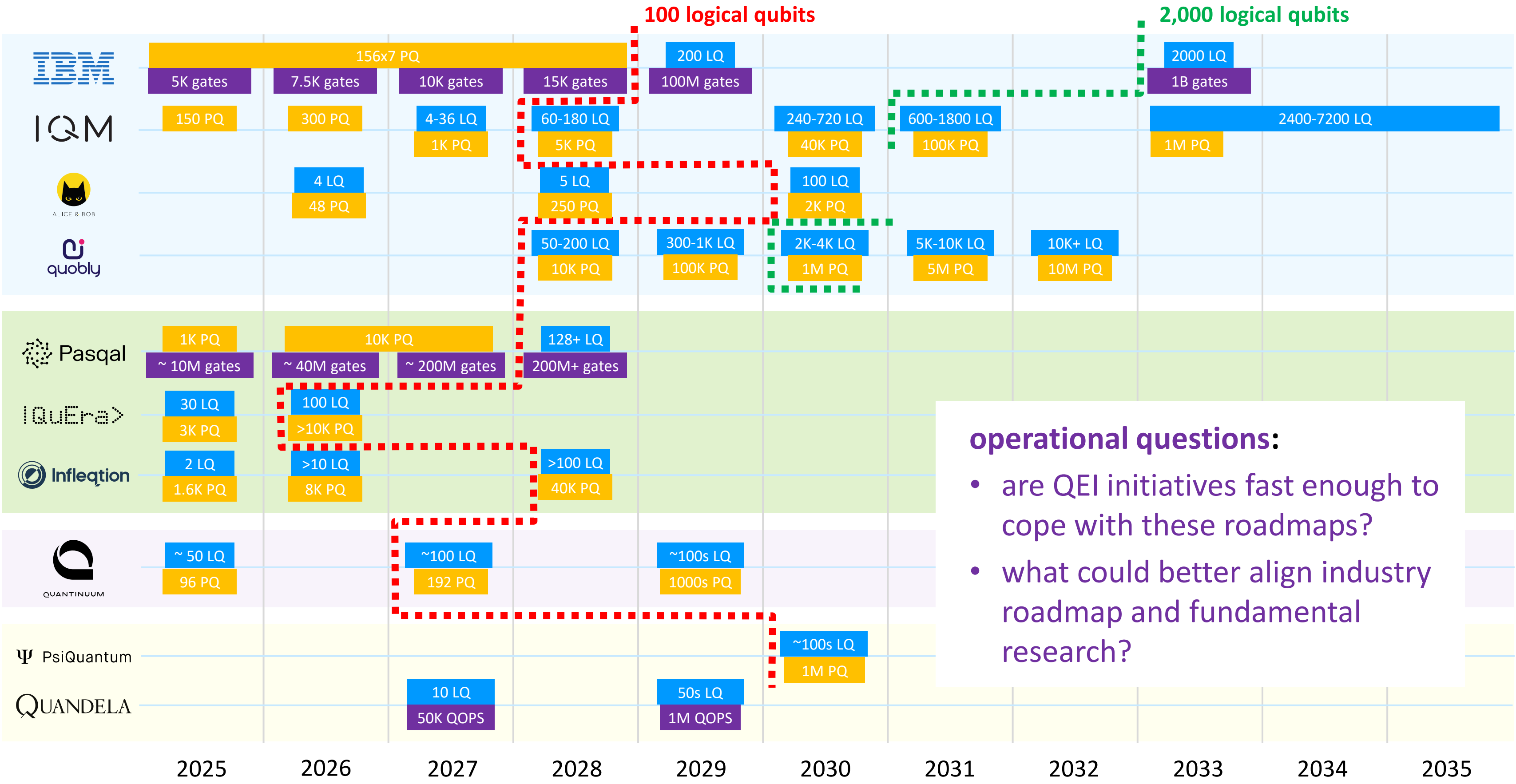
- how and where cryo-CMOS makes sense from an energetic standpoint?
- what prevents SFQ from working? What could make it operational?
- how to implement solid-state qubit readout in a simpler manner?
- progress with cabling and signals time and frequency domains multiplexing?


applications
verticals, workflow management, cloud management
algorithms
basic algorithms, functional libraries, resources estimators
compilers
compilers, optimizers
architecture
circuit model, distribution, error correction, qubit drive
quantum processor
qubits, resonators, internal cabling
device controls
electronics, cabling, filters, attenuators, signals mux/demux
enabling technologies
cryogeny, vacuum

wrap-up

QPUs roadmaps consolidation

logical qubits
physical qubits
gates / QOPS



100 logical qubits

2,000 logical qubits

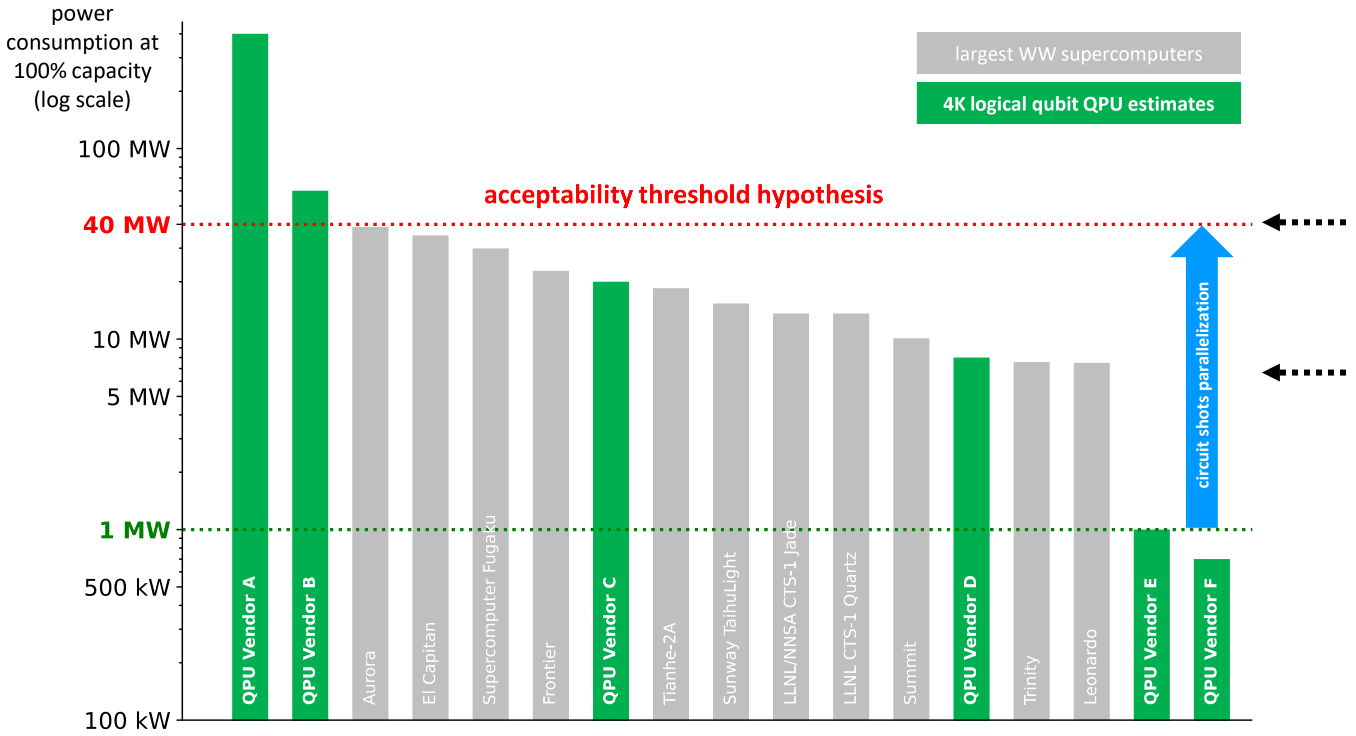
	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
IBM	156x7 PQ 5K gates	7.5K gates	10K gates	15K gates	200 LQ 100M gates				2000 LQ 1B gates		
IQM	150 PQ	300 PQ	4-36 LQ 1K PQ	60-180 LQ 5K PQ		240-720 LQ 40K PQ	600-1800 LQ 100K PQ		2400-7200 LQ 1M PQ		
ALICE & BOB		4 LQ 48 PQ		5 LQ 250 PQ		100 LQ 2K PQ					
quobly				50-200 LQ 10K PQ	300-1K LQ 100K PQ	2K-4K LQ 1M PQ	5K-10K LQ 5M PQ	10K+ LQ 10M PQ			
Pasqal	1K PQ ~ 10M gates	10K PQ ~ 40M gates	~ 200M gates	128+ LQ 200M+ gates							
QuEra	30 LQ 3K PQ	100 LQ >10K PQ									
Infleqtion	2 LQ 1.6K PQ	>10 LQ 8K PQ		>100 LQ 40K PQ							
QUANTINUUM	~ 50 LQ 96 PQ		~100 LQ 192 PQ		~100s LQ 1000s PQ						
PsiQuantum						~100s LQ 1M PQ					
QUANDELA			10 LQ 50K QOPS		50s LQ 1M QOPS						

operational questions:

- are QEI initiatives fast enough to cope with these roadmaps?
- what could better align industry roadmap and fundamental research?

(cc) Olivier Ezratty, December 2024.

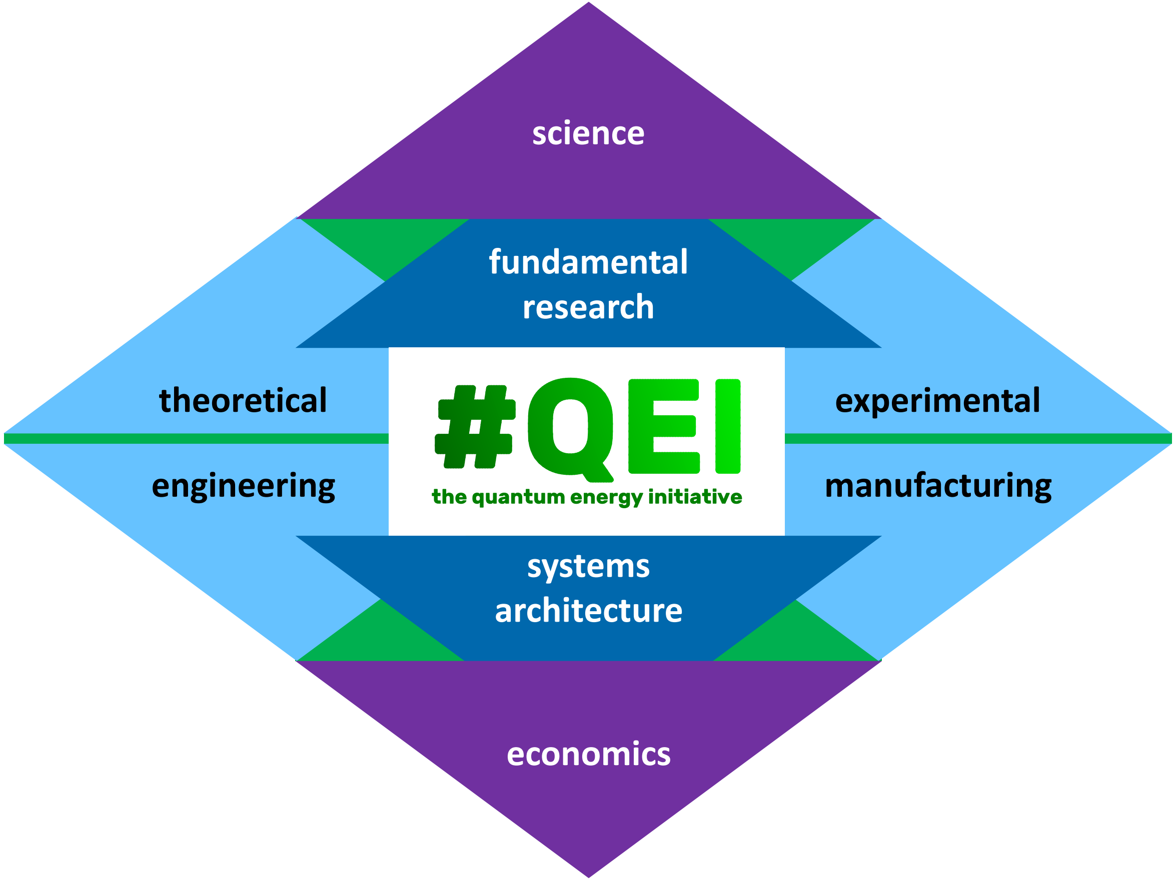
QPU vs HPC power scale guesstimates



estimate prospective base power for various QPUs and actual for existing largest HPCs WW.
HPC source: https://www.top500.org/lists/top500/2024/06/.

technology, economic and societal questions:

- what level of power consumption is acceptable vs QPUs added value?
- how many QPUs or quantum cores may be required for circuit shots parallelization?



science

fundamental research

theoretical

#QEI

the quantum energy initiative

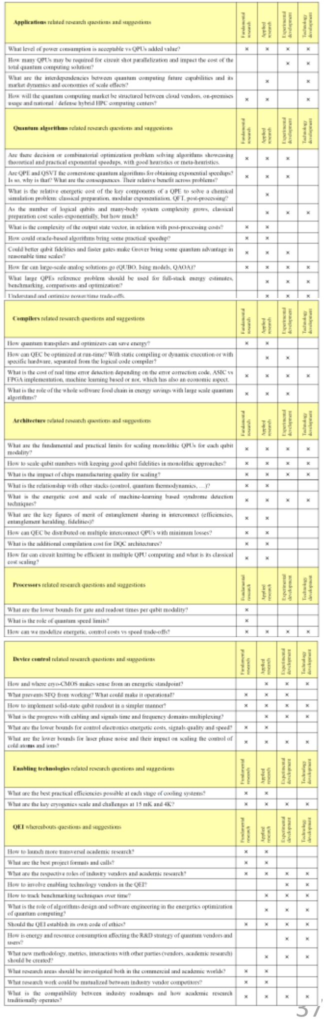
experimental

engineering

manufacturing

systems architecture

economics



Applications related research questions and suggestions	Fundamental research	Applied research	Experimental development	Technology development
What level of power consumption is acceptable vs QPUs added value?	×	×	×	×
How many QPUs may be required for circuit shot parallelization and impact the cost of the total quantum computing solution?			×	×
What are the interdependencies between quantum computing future capabilities and its market dynamics and economies of scale effects?		×		×
How will the quantum computing market be structured between cloud vendors, on-premises usage and national / defense hybrid HPC computing centers?	×	×		×

Quantum algorithms related research questions and suggestions	Fundamental research	Applied research	Experimental development	Technology development
Are there decision or combinatorial optimization problem solving algorithms showcasing theoretical and practical exponential speedups, with good heuristics or meta-heuristics.	×	×	×	
Are QPE and QSVT the cornerstone quantum algorithms for obtaining exponential speedups? Is so, why is that? What are the consequences. Their relative benefit across problems?	×	×	×	
What is the relative energetic cost of the key components of a QPE to solve a chemical simulation problem: classical preparation, modular exponentiation, QFT, post-processing?		×		
As the number of logical qubits and many-body system complexity grows, classical preparation cost scales exponentially, but how much?		×	×	×
What is the complexity of the output state vector, in relation with post-processing costs?	×	×		
How could oracle-based algorithms bring some practical speedup?	×	×		
Could better qubit fidelities and faster gates make Grover bring some quantum advantage in reasonable time scales?	×	×	×	
How far can large-scale analog solutions go (QUBO, Ising models, QAOA)?	×	×	×	×
What large QPEs reference problem should be used for full-stack energy estimates, benchmarking, comparisons and optimization?		×	×	×
Understand and optimize power/time trade-offs.		×	×	×

Compilers related research questions and suggestions	Fundamental research	Applied research	Experimental development	Technology development
How quantum transpilers and optimizers can save energy?	×	×		
How can QEC be optimized at run-time? With static compiling or dynamic execution or with specific hardware, separated from the logical code compiler?		×	×	
What is the cost of real time error detection depending on the error correction code, ASIC vs FPGA implementation, machine learning based or not, which has also an economic aspect.	×	×	×	×
What is the role of the whole software food chain in energy savings with large scale quantum algorithms?	×	×	×	

Architecture related research questions and suggestions	Fundamental research	Applied research	Experimental development	Technology development
What are the fundamental and practical limits for scaling monolithic QPUs for each qubit modality?	×	×	×	×
How to scale qubit numbers with keeping good qubit fidelities in monolithic approaches?	×	×	×	×
What is the impact of chips manufacturing quality for scaling?	×	×	×	×
What is the relationship with other stacks (control, quantum thermodynamics, …)?	×	×		
What is the energetic cost and scale of machine-learning based syndrome detection techniques?	×	×	×	×
What are the key figures of merit of entanglement sharing in interconnect (efficiencies, entanglement heralding, fidelities)?	×	×		
How can QEC be distributed on multiple interconnect QPUs with minimum losses?	×	×		
What is the additional compilation cost for DQC architectures?	×	×		
How far can circuit knitting be efficient in multiple QPU computing and what is its classical cost scaling?	×	×		

Processors related research questions and suggestions	Fundamental research	Applied research	Experimental development	Technology development
What are the lower bounds for gate and readout times per qubit modality?	×			
What is the role of quantum speed limits?	×			
How can we modelize energetic, control costs vs speed trade-offs?	×	×	×	×

Device control related research questions and suggestions	Fundamental research	Applied research	Experimental development	Technology development
How and where cryo-CMOS makes sense from an energetic standpoint?		×	×	×
What prevents SFQ from working? What could make it operational?	×	×	×	
How to implement solid-state qubit readout in a simpler manner?	×	×	×	×
What is the progress with cabling and signals time and frequency domains multiplexing?		×	×	×
What are the lower bounds for control electronics energetic costs, signals quality and speed?	×	×		
What are the lower bounds for laser phase noise and their impact on scaling the control of cold atoms and ions?	×	×	×	×

Enabling technologies related research questions and suggestions	Fundamental research	Applied research	Experimental development	Technology development
What are the best practical efficiencies possible at each stage of cooling systems?	×	×		
What are the key cryogenics scale and challenges at 15 mK and 4K?	×	×	×	×

QEI whereabouts questions and suggestions	Fundamental research	Applied research	Experimental development	Technology development
How to launch more transversal academic research?	×	×		
What are the best project formats and calls?	×	×		
What are the respective roles of industry vendors and academic research?	×	×	×	×
How to involve enabling technology vendors in the QEI?			×	×
How to track benchmarking techniques over time?		×	×	×
What is the role of algorithms design and software engineering in the energetics optimization of quantum computing?		×	×	×
Should the QEI establish its own code of ethics?	×	×	×	×
How is energy and resource consumption affecting the R&D strategy of quantum vendors and users?			×	×
What new methodology, metrics, interactions with other parties (vendors, academic research) should be created?		×	×	×
What research areas should be investigated both in the commercial and academic worlds?	×	×		
What research work could be mutualized between industry vendor competitors?	×	×		
What is the compatibility between industry roadmaps and how academic research traditionally operates?	×	×	×	×

eDF QUANDELA Pasqal quobly IBM QILIMANJARO QUANTUM · TECH

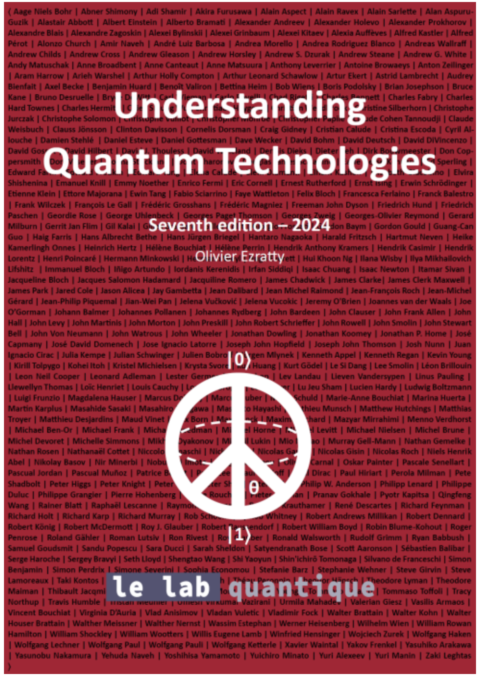
industry panel

Thursday 9th January

16:00-17:30

discussion

get the slides



Understanding Quantum Technologies

Seventh edition – 2024

Olivier Ezratty

le lab quantique

(free) 1,554 pages ebook, 7th edition including 24 pages on energetics