Quantum Computing Trends

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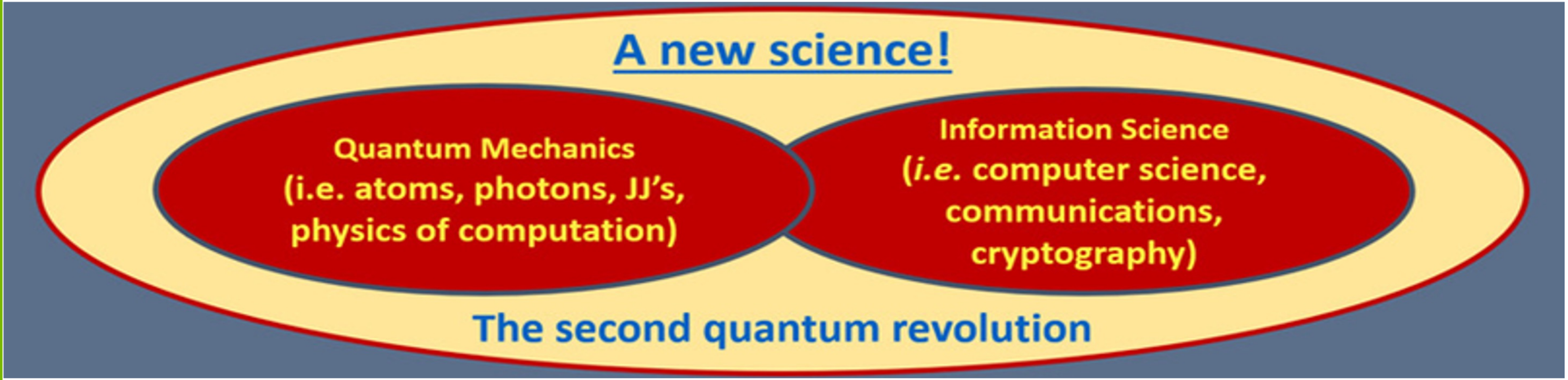
Quantum Information Science (QIS)

- Quantum mechanics explains how world works at microscopic level, which governs behavior of all physical systems, regardless of their size
- Information science revolutionized how information is collected, stored, computed, analyzed, manipulated, protected, and moved
- We see convergence of two 20th century greatest revolutions in the form of Quantum Information Science (QIS)

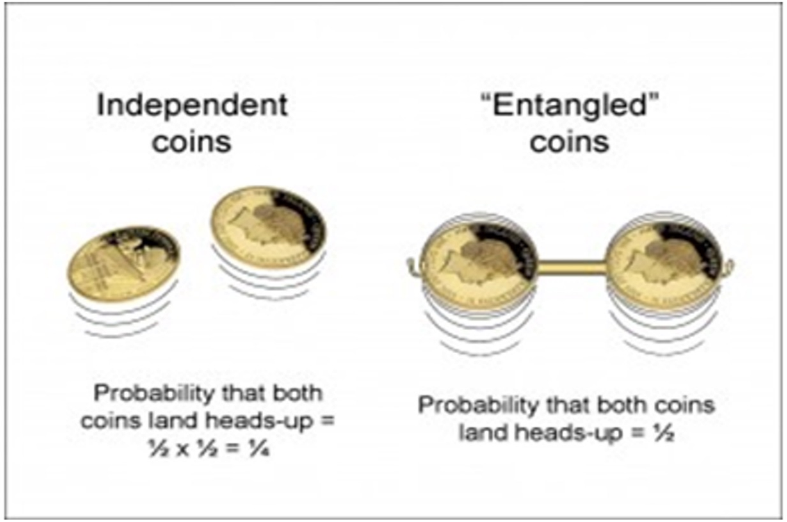


Quantum Information Science

QIS exploits unique quantum effects such as superposition, interference, and entanglement to obtain, compute, and transmit information in the ways that are superior compared to classical technology (digital, Newtonian)

The key concept is entanglement ("spooky action at a distance", EPR pair). Works only for only very small object (electrons, photons, atoms etc). It is proven to be essential to achieve "quantum advantage" or for "quantum teleportation"

Classical	
Outcome	Probability
00	1/4
01	1/4
10	1/4
11	1/4



Quantum	
Outcome	Probability
00	1/2
01	0
10	0
11	1/2

Quantum Information Science

QIS areas of application and research:

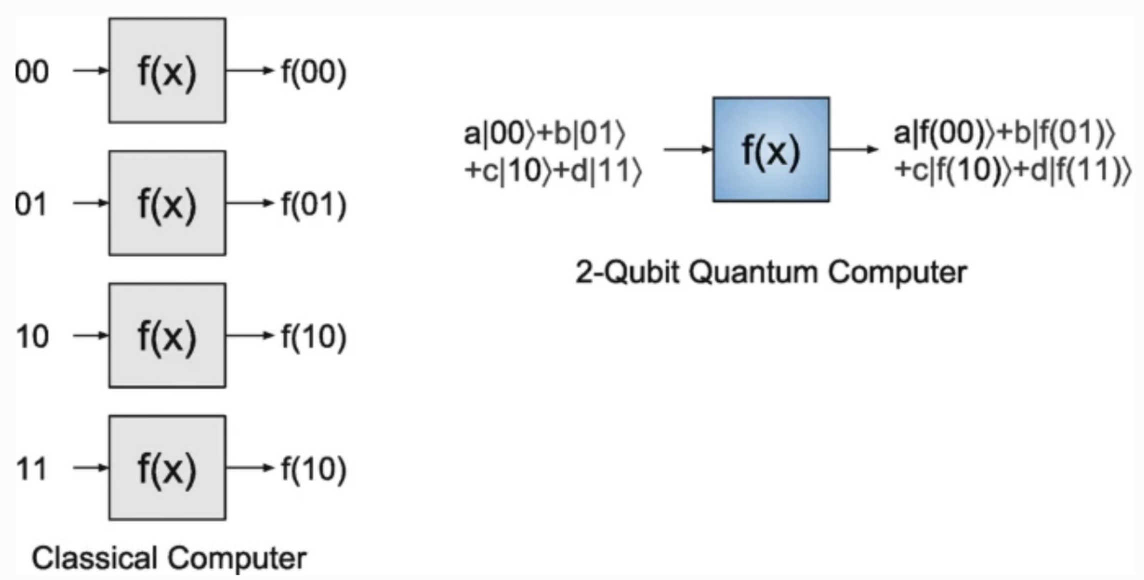
- **Quantum computing**
- Quantum communication
- Quantum sensors

Quantum Computer Definition

- Stores and computes information according to the principles of quantum mechanics
- Uses qubit or quantum bit is a basic unit of quantum information
- Information is encoded in the Hilbert space using qubits. To be precise, it is stored in the amplitudes that can be positive and negative
- Allows to solve certain problems much faster than classical computers
- Hard to build and operate, need hard to achieve complete isolation from the environment
- We are still in early stages

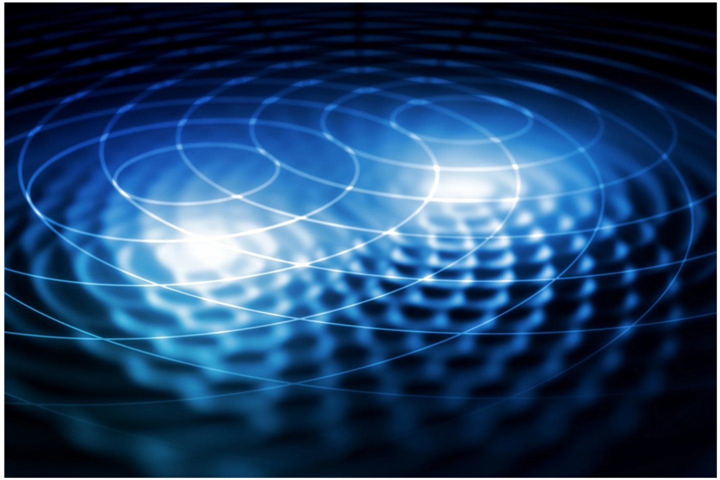
Power of quantum computers

The main advantage that quantum computers have over classical computers is parallelism. Because qubits can be in a superposition of states, a quantum computer can perform an operation on many states simultaneously. Let’s say we want to know the result of applying some function f(x) to some number x.



Quantum Speed Up

- Quantum computers operate using interference between computational paths
- Quantum interference is when subatomic particles interact with and influence themselves and other particles while in a probabilistic superposition state
- Quantum algorithms perform operations in such way that paths to a solution interfere positively and negatively for non-solutions
- Quantum mechanics allows efficient high-dimensional interference

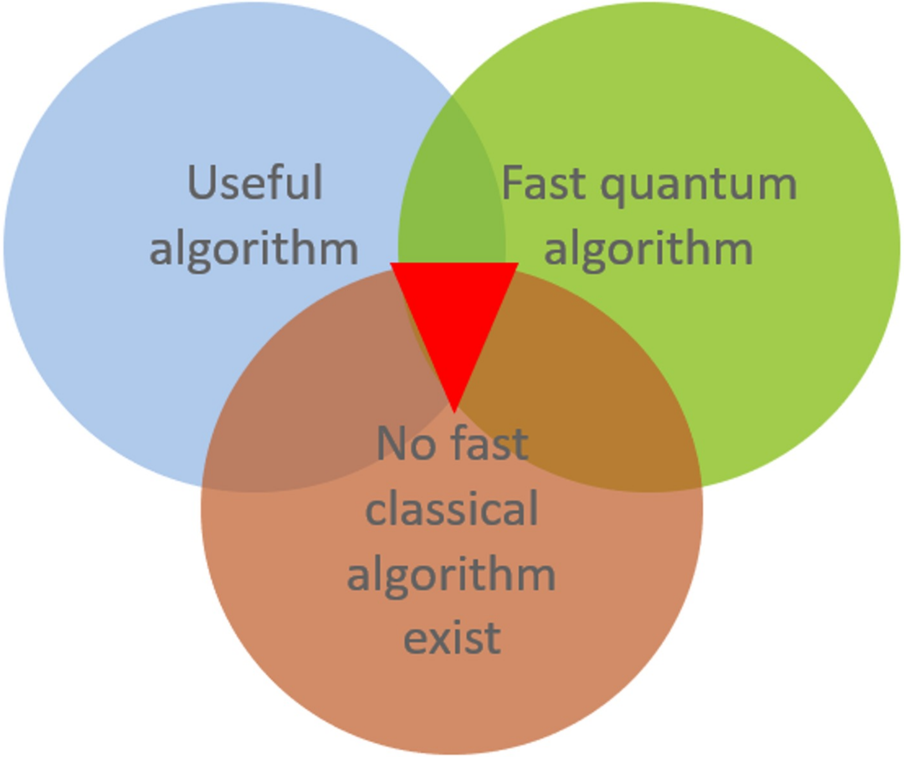


Quantum Parallelism

- Is quantum parallelism same as exponential parallelism?
- It is not the case because of linearity of quantum mechanics
- Efficient parallelism can be achieved only for certain types of problems
- Key requirements: need to have a structure and be non-symmetric

Quantum Algorithms

Fundamental algorithms expected to provide a speedup over their classical counterparts: Shor's factoring algorithm, Grover's search algorithm, HHL’s linear system solver, QAOA, QPE, and quantum simulation



Quantum Algorithms

- 50+ algorithms with known some quantum speed up
- Can any of them used in real-world applications?
- NIST quantum zoo link: https://math.nist.gov/quantum/zoo/

Quantum Algorithm Zoo

This is a comprehensive catalog of quantum algorithms. If you notice any errors or omissions, please email me at stephen.jordan@microsoft.com. Your help is appreciated and will be acknowledged.

Algebraic and Number Theoretic Algorithms

Algorithm: Factoring
Speedup: Superpolynomial
Description: Given an *n*-bit integer, find the prime factorization. The quantum algorithm of Peter Shor solves this in $\widetilde{O}(n^3)$ time [82,125]. The fastest known classical algorithm for integer factorization is the general number field sieve, which is believed to run in time $2^{\widetilde{O}(n^{1/3})}$. The best rigorously proven upper bound on the classical complexity of factoring is $O(2^{n/4+o(1)})$ via the Pollard-Strassen algorithm [252, 362]. Shor's factoring algorithm breaks RSA public-key encryption and the closely related quantum algorithms for discrete logarithms break the DSA and ECDSA digital signature schemes and the Diffie-Hellman key-exchange protocol. A quantum algorithm even faster than Shor's for the special case of factoring "semiprimes", which are widely used in cryptography, is given in [271]. If small factors exist, Shor's algorithm can be beaten by a quantum algorithm using Grover search to speed up the elliptic curve factorization method [366]. Additional optimized versions of Shor's algorithm are given in [384, 386]. There are proposed classical public-key cryptosystems not believed to be broken by quantum algorithms, *cf.* [248]. At the core of Shor's factoring algorithm is order finding, which can be reduced to the Abelian hidden subgroup problem, which is solved using the quantum Fourier transform. A number of other problems are known to reduce to integer factorization including the membership problem for matrix groups over fields of odd order [253], and certain diophantine problems relevant to the synthesis of quantum circuits [254].

Navigation

Algebraic & Number Theoretic
Oracular
Approximation and Simulation
Acknowledgments
References

Other Surveys

For overviews of quantum algorithms I recommend:

Nielsen and Chuang
Childs
Preskill
Mosca
Childs and van Dam
van Dam and Sasaki
Bacon and van Dam
Loceff
Montanaro

Customers Early Applications

Optimization

Multi-period portfolios

Internet ad placement

Satellite Placement

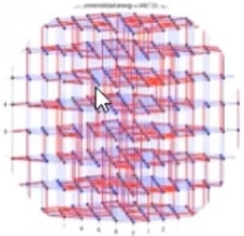
Machine Learning

Image recognition

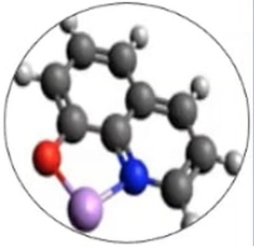
Tree cover classifier

Higgs Boson Detection

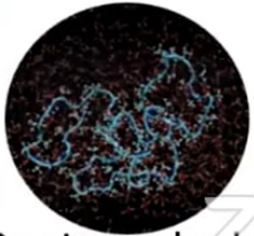
Quantum Materials



Quantum solid state



Quantum Molecules



Quantum molecular dynamics

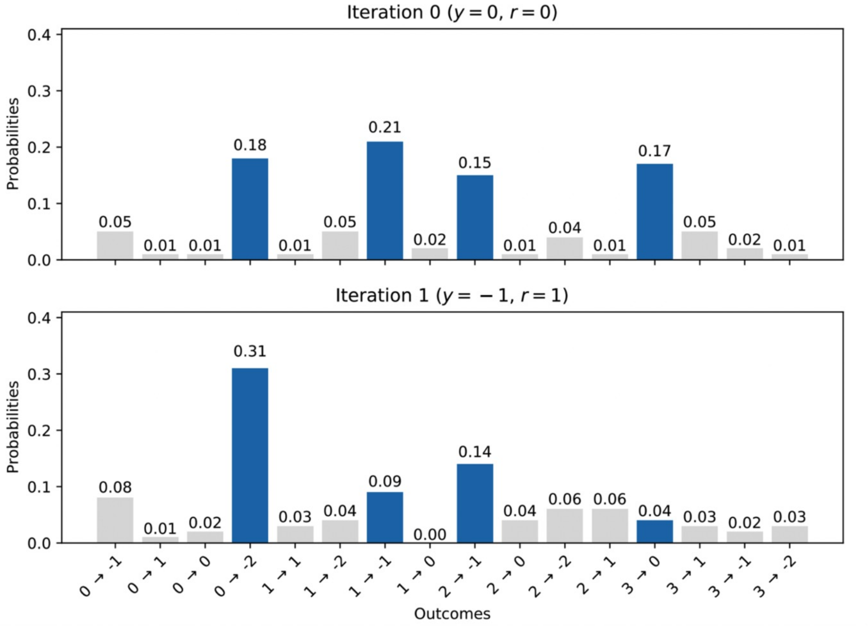
Quantum Speedup

Algorithm	Classical resources	Quantum resources	Quantum speedup	Requirements
Quantum simulation	2^N	$\sim N^6$	Exponential	100+ qubits, millions of gates
Factorization	2^N	N^3	Exponential	200+ qubits, millions of gates
Solving linear systems	N^2	Log(N)	Exponential	Millions of gates and qubits
Unstructured search	N	$\sqrt{N}$	$\sqrt{N}$	Millions of gates and qubits

N-complexity of the problem

Grover’s algorithm

Grover's algorithm, also known as the quantum search algorithm, is a quantum algorithm for unstructured search that finds with high probability the unique input to an unknown function that produces a particular output value, using just **O(√N)** evaluations of the function.



Gilliam, Austin, Stefan Woerner, and Constantin Gonciulea. "Grover adaptive search for constrained polynomial binary optimization." *Quantum* 5 (2021): 428.

Quantum Simulator Use Cases: Simulation of Supremacy Circuits

Article | Published: 23 October 2019

Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, [...] John M. Martinis

Nature **574**, 505–510(2019) | Cite this article

799k Accesses | **693** Citations | **6025** Altmetric | Metrics

(CNN Business): Google claims it has designed a machine that needs only 200 seconds to solve a problem that would take the world's fastest supercomputer 10,000 years to figure out.

Quantum Machine Learning

- Quantum machine learning is a promising area, and potentially quantum devices might be very useful for large-scale classical machine learning problems like training large scale models (LLMs)
- We designed an algorithm scaling as **$O(T^2 \times \text{polylog}(n))$**, where n is the size of the models and T is the number of iterations in the training, as long as the models are both sufficiently dissipative and sparse
- We estimated that our algorithm will perform training very large LLMs in seconds vs years using classical computing (1 second vs 87 years)

Eisert, Jens, Junyu Liu, Minzhao Liu, Jin-Peng Liu, Ziyu Ye, Yuri Alexeev, and Liang Jiang. "Towards provably efficient quantum algorithms for large-scale machine learning models." (2023). Submitted to Nature Comminications

Quantum Machine Learning

Sparsity

Large scale → Harrow-Hassidim-Lloyd (HHL) algorithm in quantum computing

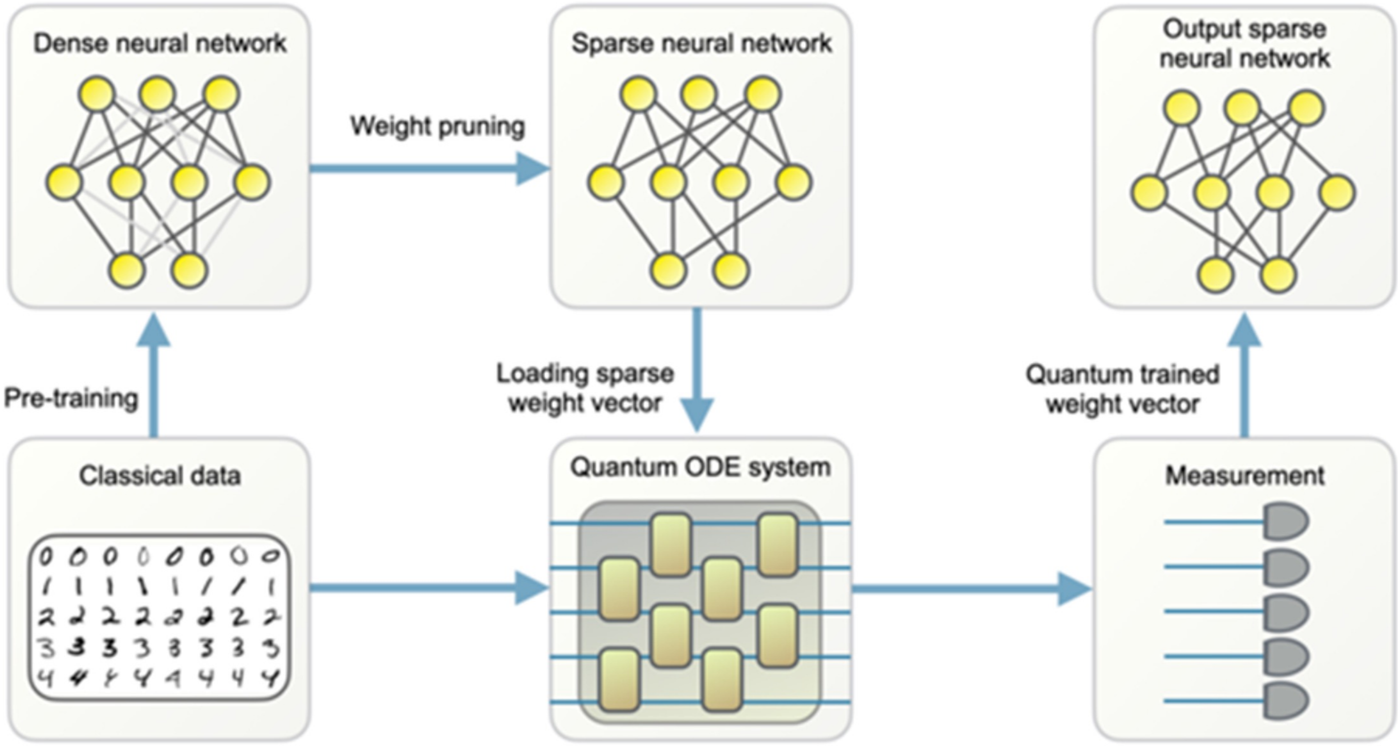
Matrix Inversion

Exponential improvement in the matrix size of A

$$A\left|x\right\rangle = \left|b\right\rangle \rightarrow \left|x\right\rangle = A^{-1}\left|b\right\rangle$$

One of principal paradigms for FTQC QML

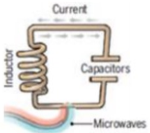
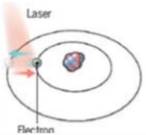
Quantum Machine Learning



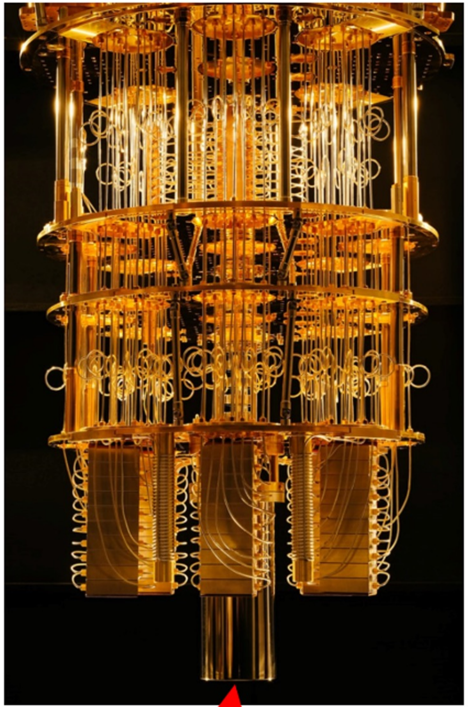
Key concepts

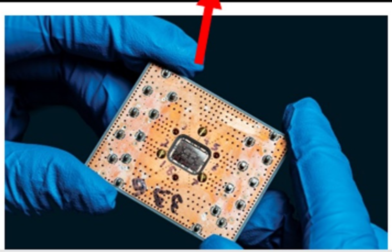
- Qubit - basic unit of quantum information, which is the quantum version of the classical binary bit. It can exist in superposition – any state between 0 and 1
- Qubit fidelity – how long qubit stays coherent/operational
- Quantum effects - superposition, interference, and entanglement
- NISQ - Noisy Intermediate-Scale Quantum technology, often refers in the context of modern very noisy quantum computers
- QASM - Quantum Assembly used for programming quantum computers
- Quantum supremacy - demonstration of that a programmable quantum device can solve a problem (any problem) that no classical computer can solve in any feasible amount of time
- Quantum advantage - same as supremacy, but for useful applications

Modern Quantum Computers

Operate at almost absolute zero temperature -460 F or -273 C, colder than deep space 	 Computers are ranked by number of qubits decoherency time	**Superconducting (IBM, Google, Rigetti)**	**Trapped ions (IonQ, U. of Innsbruck)**
Qubit Modality	Materials	Al on the Silicon substrate	Yb+, Ca+, Sr+, Be+, Ba+, Mg+
	Type	Transmon	Optical transitions
	Control	Microwaves	Microwaves + optics
	State	Junction phase	Atomic state of election
Approximate Decoherency Times (ns)		~100-200	Very long
	1qb gate	10	5,000
	2qb gate	40	50,000
Fidelity	1qb gate	99.9%	99.999%
	2qb gate	99.0%	99.5%
Speed (MHz)	1qb gate	100.00	0.20
	2qb gate	25.00	0.02

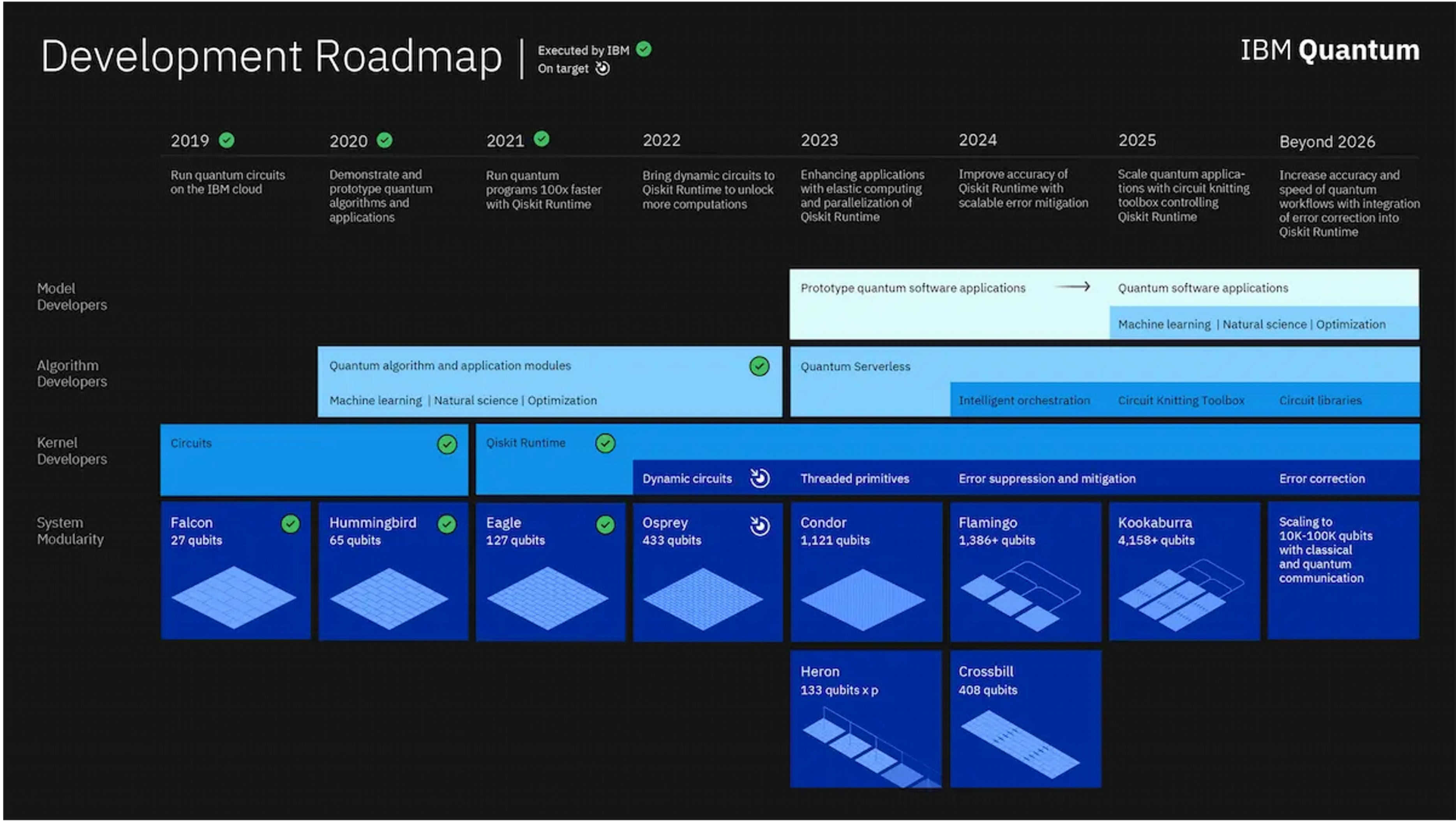
IBM quantum computers

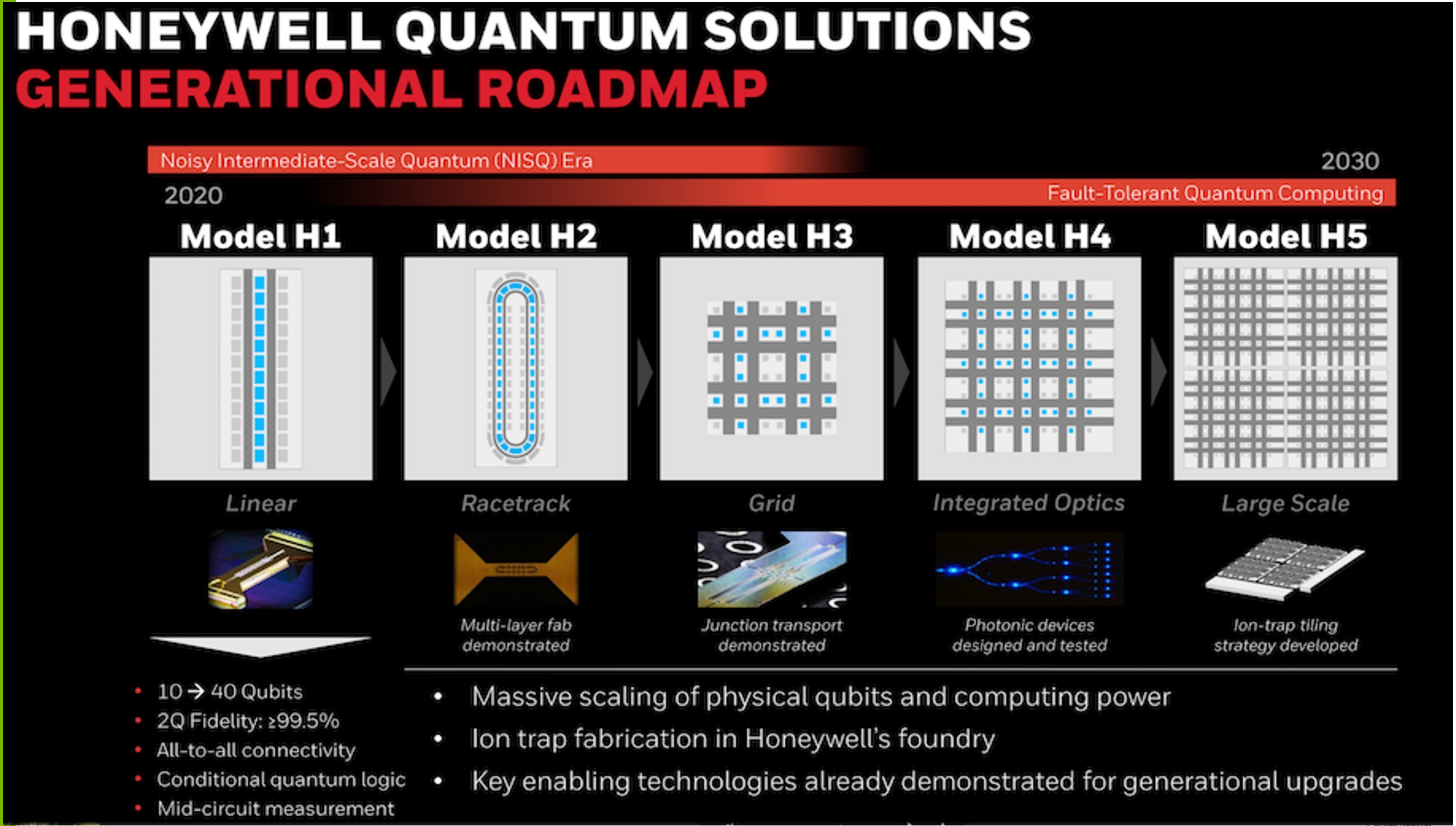




The key piece of the Quantum Computer is the Dilution Refrigerator
Working Temperature 15 mK uses mix of $^3He/^4He$

Source: IBM Research


Development Roadmap
Executed by IBM
On target
IBM Quantum
2019
Run quantum circuits on the IBM cloud
2020
Demonstrate and prototype quantum algorithms and applications
2021
Run quantum programs 100x faster with Qiskit Runtime
2022
Bring dynamic circuits to Qiskit Runtime to unlock more computations
2023
Enhancing applications with elastic computing and parallelization of Qiskit Runtime
2024
Improve accuracy of Qiskit Runtime with scalable error mitigation
2025
Scale quantum applications with circuit knitting toolbox controlling Qiskit Runtime
Beyond 2026
Increase accuracy and speed of quantum workflows with integration of error correction into Qiskit Runtime
Model Developers
Prototype quantum software applications
Quantum software applications
Machine learning | Natural science | Optimization
Algorithm Developers
Quantum algorithm and application modules
Machine learning | Natural science | Optimization
Quantum Serverless
Intelligent orchestration
Circuit Knitting Toolbox
Circuit libraries
Kernel Developers
Circuits
Qiskit Runtime
Dynamic circuits
Threaded primitives
Error suppression and mitigation
Error correction
System Modularity
Falcon
27 qubits
Hummingbird
65 qubits
Eagle
127 qubits
Osprey
433 qubits
Condor
1,121 qubits
Flamingo
1,386+ qubits
Kookaburra
4,158+ qubits
Scaling to 10K-100K qubits with classical and quantum communication
Heron
133 qubits x p
Crossbill
408 qubits


HONEYWELL QUANTUM SOLUTIONS
GENERATIONAL ROADMAP
Noisy Intermediate-Scale Quantum (NISQ) Era
2030
2020
Fault-Tolerant Quantum Computing
Model H1
Model H2
Model H3
Model H4
Model H5
Linear
Racetrack
Grid
Integrated Optics
Large Scale
Multi-layer fab demonstrated
Junction transport demonstrated
Photonic devices designed and tested
Ion-trap tiling strategy developed
10 → 40 Qubits
2Q Fidelity: ≥99.5%
All-to-all connectivity
Conditional quantum logic
Mid-circuit measurement
Massive scaling of physical qubits and computing power
Ion trap fabrication in Honeywell's foundry
Key enabling technologies already demonstrated for generational upgrades

IBM Quantum Experience Plans

Current Premium Plan systems:

27-qubit Falcon

127-qubit Eagle

433-qubit Osprey (exploratory)

Pay-As-You-Go Plan:

Access our 27-qubit Falcon R5 processors

Pay $1.60 per runtime second with a credit card or IBM Cloud credits

Open Plan

Run your first quantum circuits for free on cloud simulators and 7 qubit free quantum systems.

Use free cloud simulators (Statevector, MPS, Stabilizer)

QCUP

Oak Ridge Leadership Computing Facility (OLCF) Quantum Computing User Program (QCUP)

https://www.olcf.ornl.gov/olcf-resources/compute-systems/quantum-computing-user-program/

Quantum Project Application:

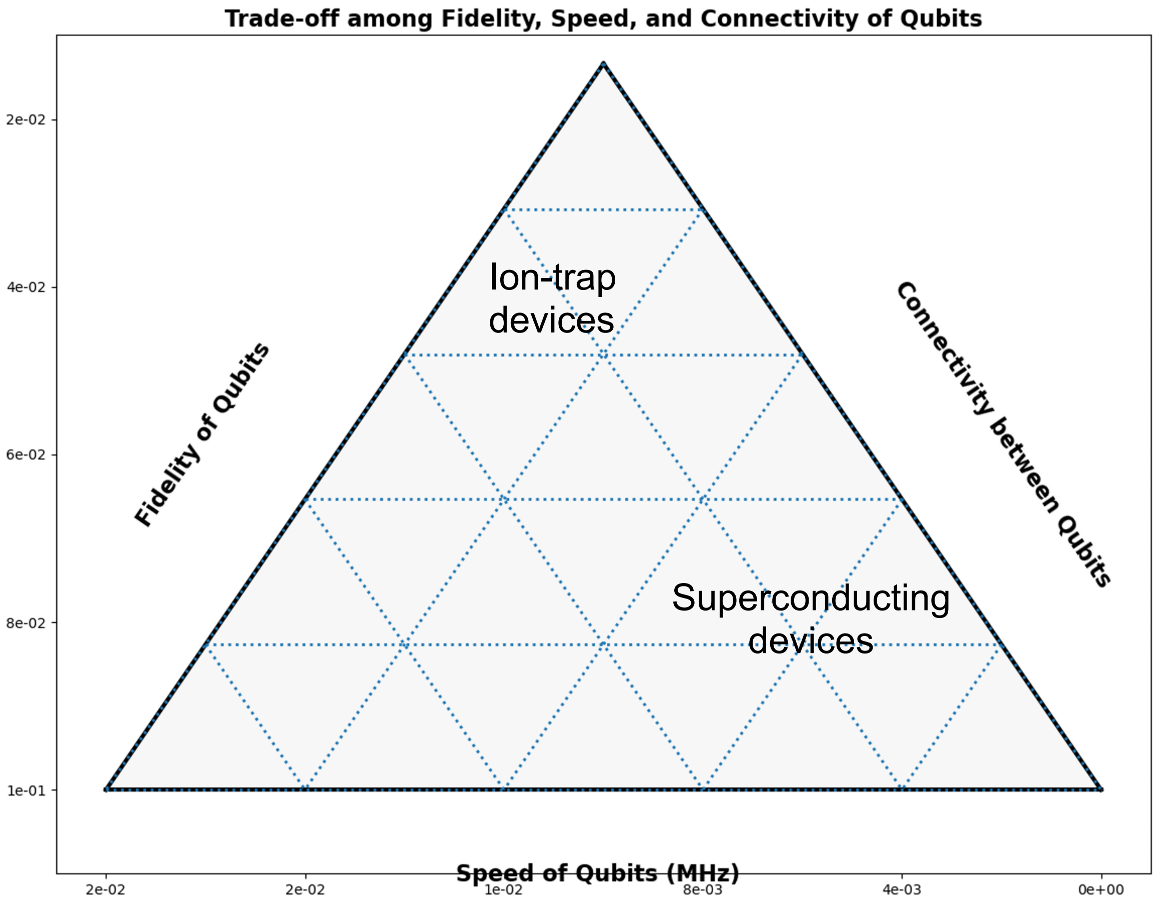
https://www.olcf.ornl.gov/for-users/documents-forms/quantum-project-proposal/

Quantum Account Application:

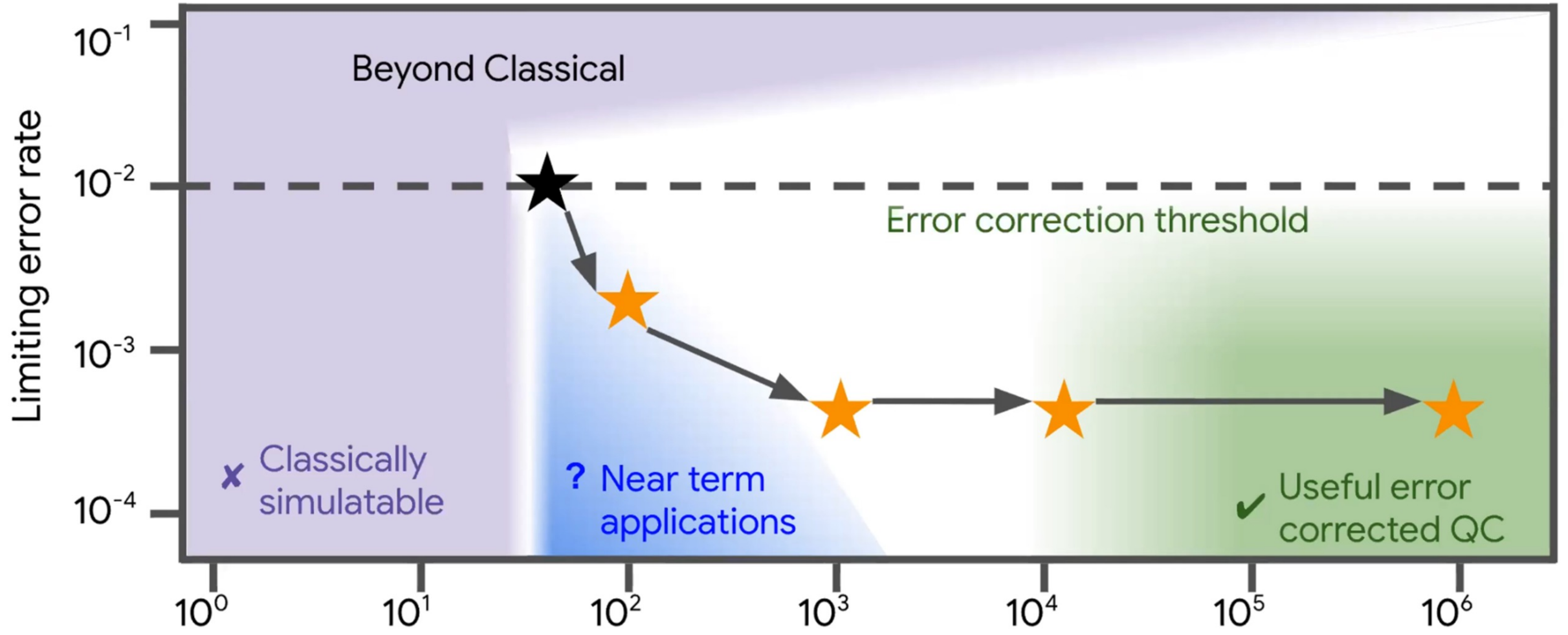
https://www.olcf.ornl.gov/for-users/documents-forms/quantum-account-application/

Available quantum systems: IBM, Rigetti, Honeywell

Quantum Computer Design

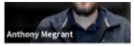


Google's path to an error corrected machine



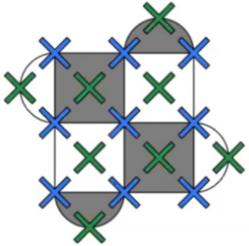
- Can quantum outperform classical on any computation task?
- Can we demonstrate a path toward achieving low *enough* error rates for practical tasks?
- Can we achieve such a low error rate?
- Can we build a large *enough* system with low error rate?

Next Milestone: Logical Qubit Prototype



2019 — 2029 Year

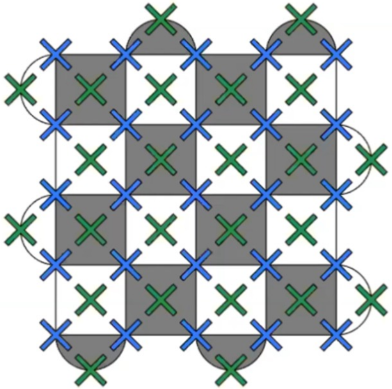
Physical qubits	54	10^2	10^3	10^4	10^5	10^6
	Beyond classical	**Logical qubit prototype**	1 Logical qubit	Tileable module (Logical gate)	Engineering scale up	Error-corrected quantum computer



distance=3

Beat threshold: Λ > 1

Bigger system = lower logical error



distance=5

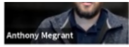
Physics behind error correction works

Integration test for QEC system performance

Quantum AI

https://www.nature.com/articles/s41586-021-03588-y

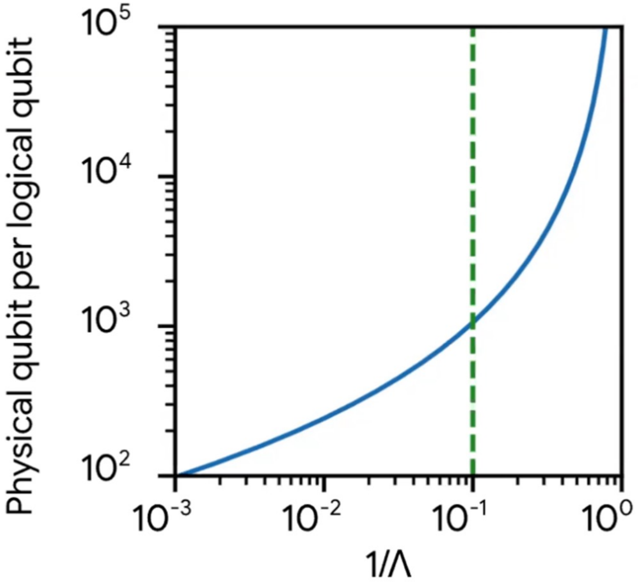
Logic qubit milestone: Achieving 10^{-10}



2019					2029	Year
54	10^2	10^3	10^4	10^5	10^6	Physical qubits
Beyond classical	Logical qubit prototype	**1 Logical qubit**	Tileable module (Logical gate)	Engineering scale up	Error-corrected quantum computer	

Physics derisking

Demonstrate error rates < 10^{-10} achievable
- Performance: $\Lambda = 10$
- System size: 1000 physical qubits



Quantum AI

Major Players in U.S.

Technological giants: IBM, Google, Microsoft, Amazon, Intel, Tesla, Alibaba, JPMorgan Chase

NSF Quantum Leap Challenge Institutes (total 5)

DOE National Quantum Centers:

ANL: Q-NEXT · Next Generation Quantum Science and Engineering

BNL: C2QA · Co-design Center for Quantum Advantage

FNAL: SQMS · Superconducting Quantum Materials and Systems Center

LBNL: QSA · Quantum Systems Accelerator

ORNL: QSC · The Quantum Science Center

Q-NEXT: Quantum Information Science Research Center at Argonne

- **Major Cross-Cutting Challenge:** Manipulating and interconnecting entangled states of matter.
- **Mission:** Deliver quantum interconnects and establish a national resource to provide pristine materials for new quantum devices.
- Nearly 100 researchers from 3 national laboratories, 10 universities, and 10 industry partners
- $115M from DOE and an additional $93M from industry partners

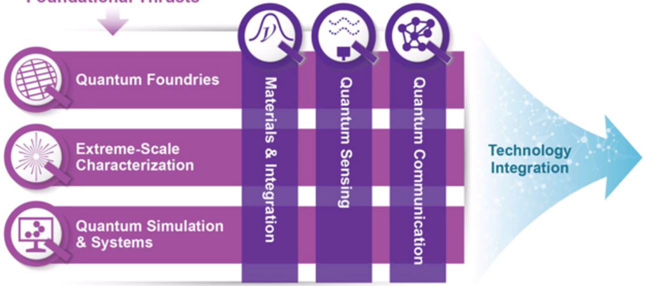
Thrusts and Argonne Leadership:

Executive Team:

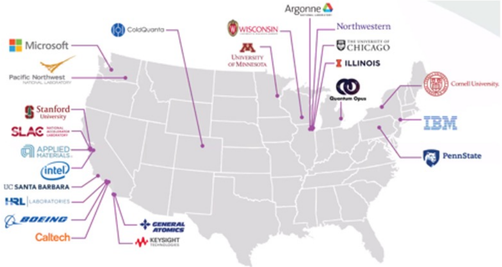
Thrust Leaders:

Executive Team: P. Kearns, D. Awschalom, S. Guha

Thrust Leaders: J. Heremans, M. Holt, M. Suchara



Partner institutions:



Q-NEXT Mission

- ✓ Deliver quantum interconnects
- ✓ Establish national foundries
- ✓ Demonstrate communication links, networks of sensors, and simulation testbeds

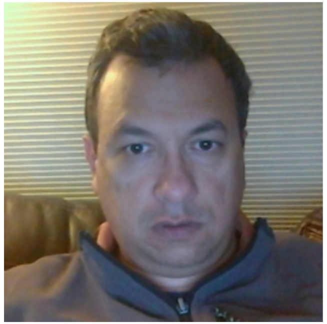
Acknowledgements

Q-NEXT: Quantum Simulation Team

Sahil Gulania, ANL

Bo Peng, PNNL

Niri Govind, PNNL



Funding:

DOE Q-NEXT: *This work was supported by the DOE Office of Science (National Quantum Information Science Research Centers)*

DOE ASCR: This research used resources of the Argonne Leadership Computing Facility, which is a DOE Office of Science User Facility supported under Contract DE-AC02-06CH11357.

DOD DARPA: *This research was partially supported by the the Defense Advanced Research Projects Agency (DARPA) project*

How HPC can help QC?

Verification of quantum advantage

Design of new compact quantum algorithms

Use classical quantum circuit simulators to find optimal circuit parameters

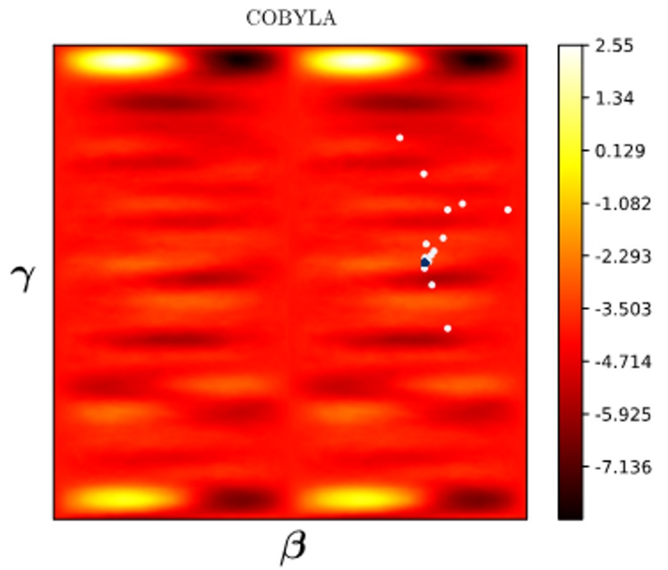
Circuit compiling and optimization:

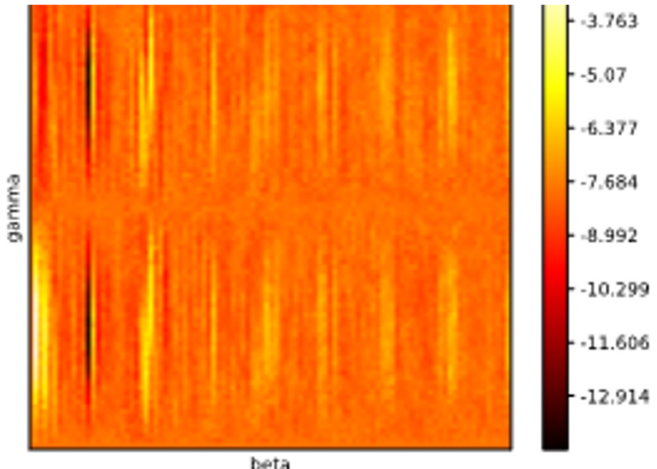
- Circuit synthesis
- Circuit transpiling
- Pulse optimization
- Circuit cutting

Error decoding and mitigation

Quantum Simulator Use Cases

- Verification of quantum advantage and supremacy claims (3 quantum advantage claims are underway to be verified)
- Verification of large quantum devices
- Co-design of quantum computers
- Energy efficiency studies of quantum computers
- Design of new quantum algorithms
- Finding parameters for variational quantum algorithms
- Debugging of quantum devices





Limitations of quantum simulators to store 2^N state vector

Qubits	Memory	Time per operation
10	16 KB	Microseconds on a smartwatch
20	16 MB	Milliseconds on a smartphone
30	16 GB	Seconds on a laptop
40	16 TB	Seconds on a PC cluster
50	16 PB	Minutes on modern supercomputers
60	16 EB	Hours on post-exascale supercomputers?
70	16 ZB	Days on supercomputers in distant future?