Path to Quantum Advantage

Dr. Voica Radescu

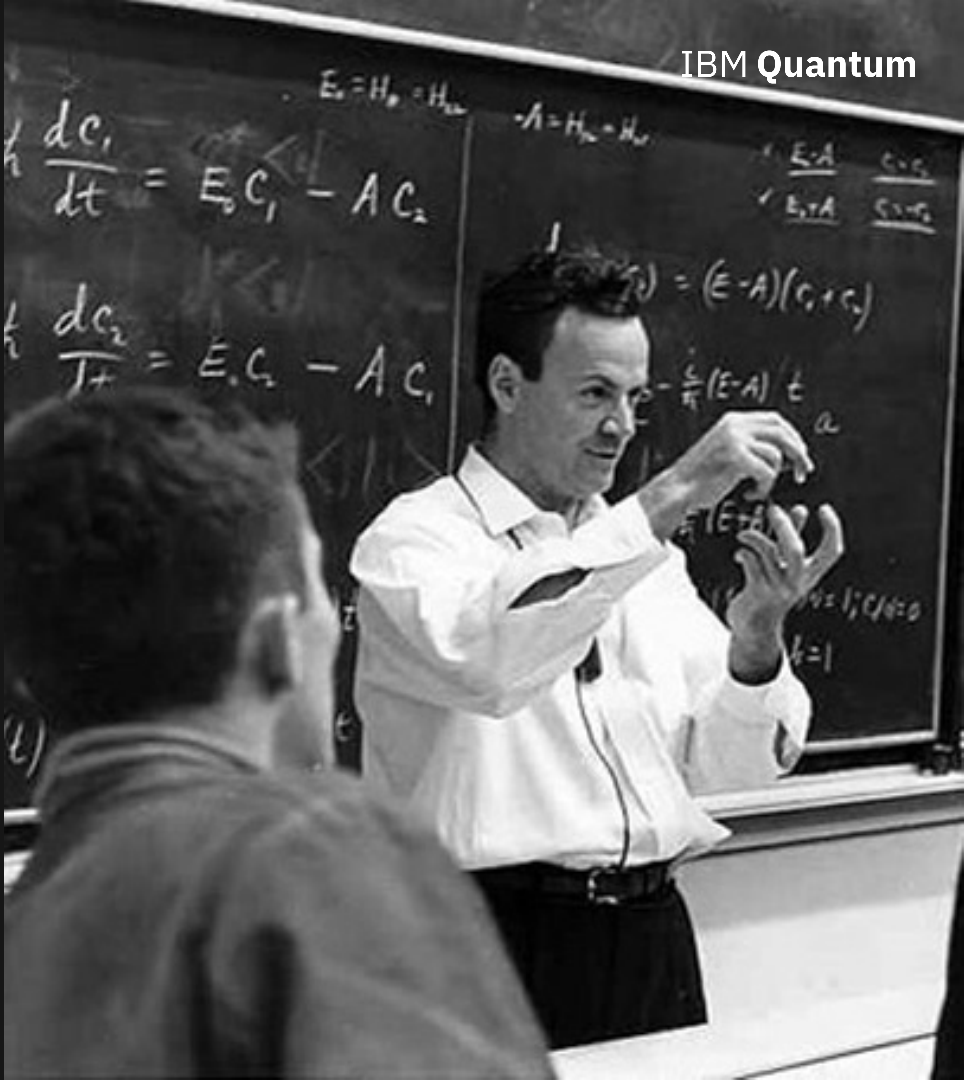
IBM Quantum Alliance Lead, Europe

IBM **Quantum**

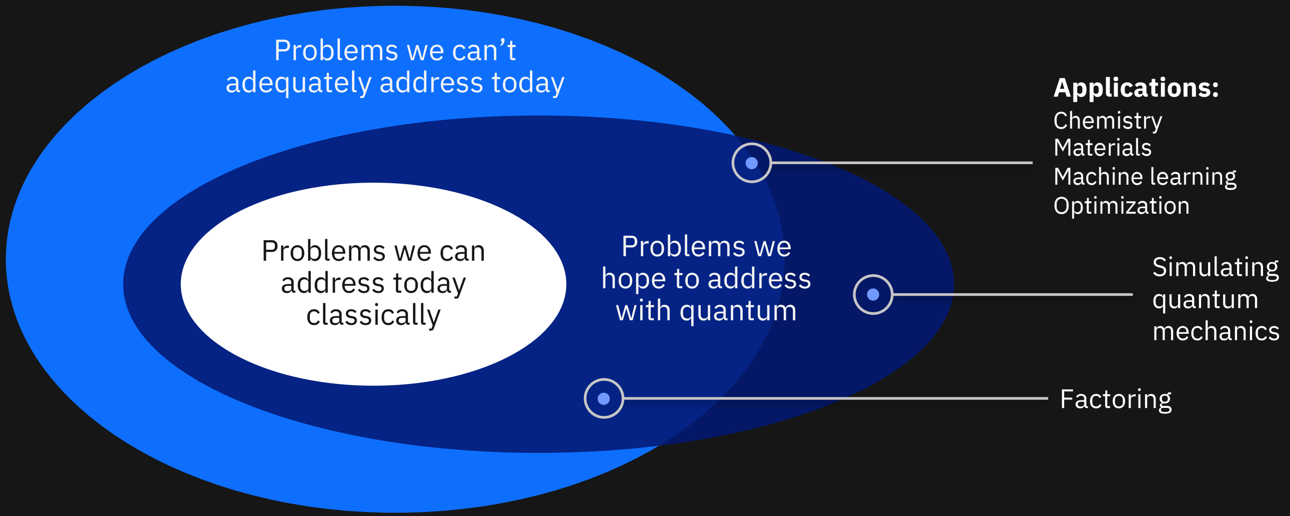
"I'm not happy with all the analyses that go with just the classical theory, because nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical …"

Richard P. Feynman
Department of Physics,
California Institute of Technology

International Journal of Theoretical Physics,
Vol 21, Nos. 6/7, 1982



Why quantum?

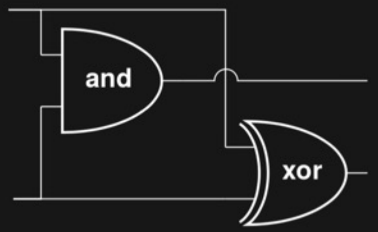


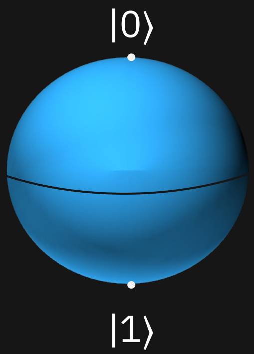
Despite how sophisticated digital "classical " computing has become, there are many scientific and business problems for which we've barely scratched the surface.

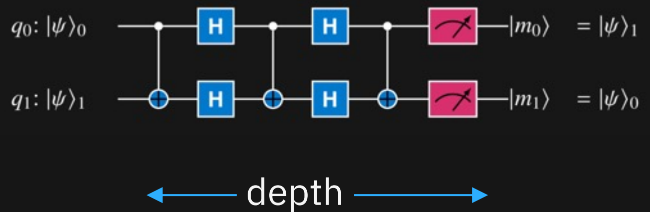
Classical vs Quantum Approach

The **bit** is the basic unit of information and has two possible states: 0 or 1.

The **qubit** is the basic quantum unit of information and also is 0 or 1 when you measure it.







A classical logic circuit is a set of gate operations on bits and is the unit of computation

A quantum circuit is a set of quantum gate operations on qubits and is the unit of computation

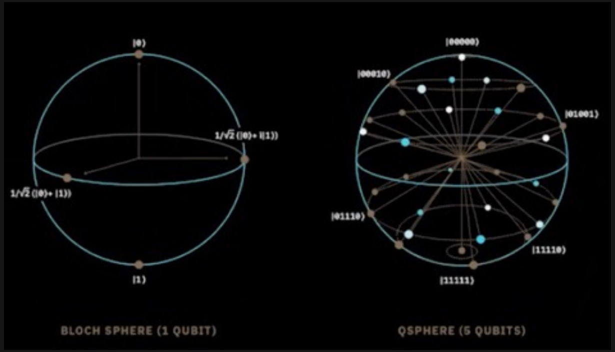
Why is Quantum Different:

Superposition allows creation of exponential number of basis states

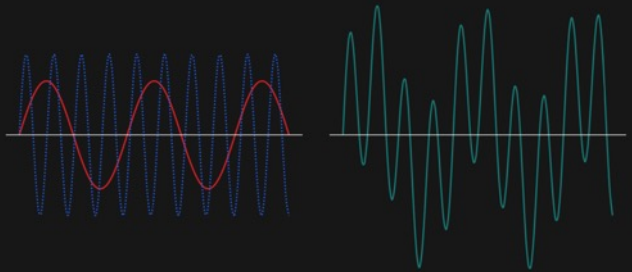
Entanglement allows for parallel exploration of these states (i.e., computational power)

n qubits – 2^n basis states

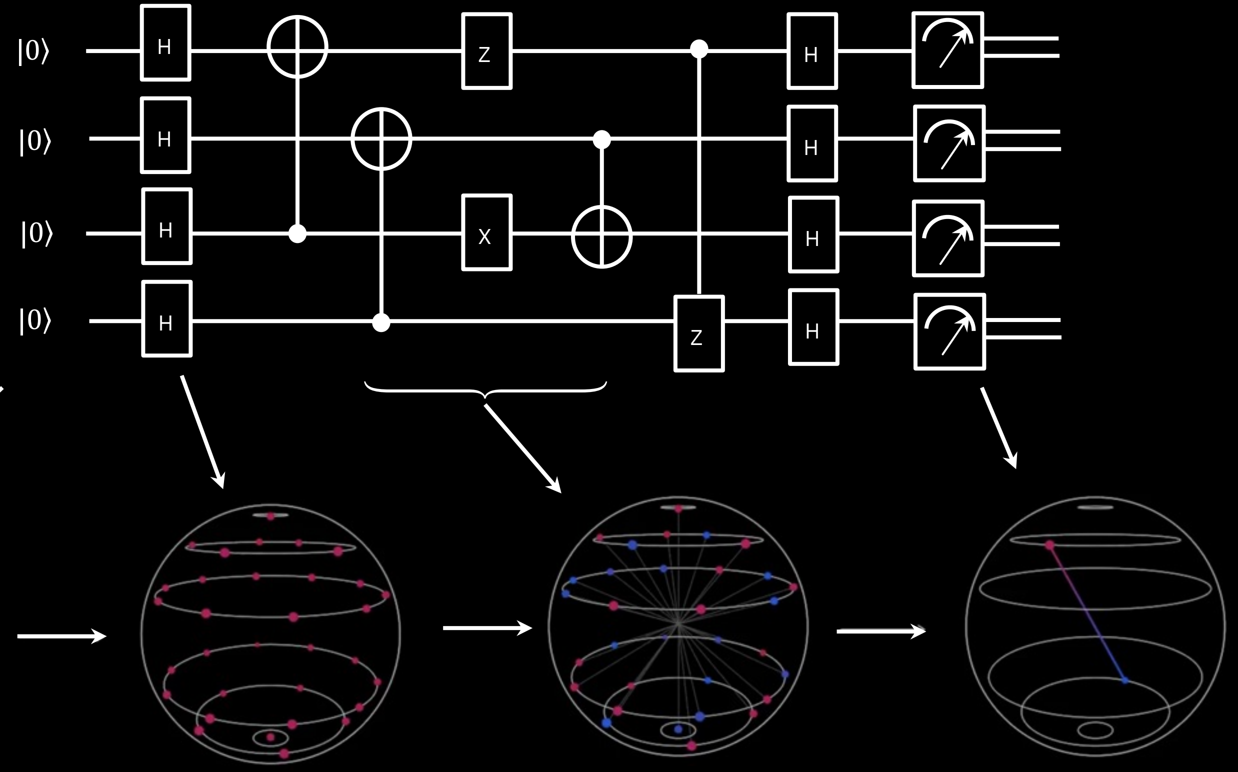
Interference allows us to increase the probability of getting the right answer and decrease the chance of getting the wrong one.



1 qubit: superposition of 2 states
n qubits: superposition of 2^n states



Quantum algorithms (simplified)



Initialize the quantum computer

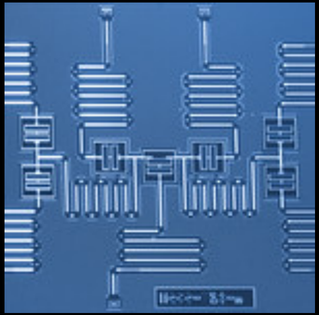
Create an equal superposition of 2^N states

Encode the problem in 2^N states by using entanglement

Interfere all states back to a few outcomes containing the solution

IBM provides a full stack solution for Quantum Computing

- Quantum Computer Hardware
- Systems
- System software layer
- Applications layer
- Services



Qiskit

The world's leading open-source quantum computing framework, built to be modular and extendable
Written in Python 3

https://qiskit.org

IBM Quantum Journey so far.

IBM Quantum has turned Quantum Computing into reality

20+

Operational systems

410k+

Users

180+

IBM Quantum Network members

3.5B

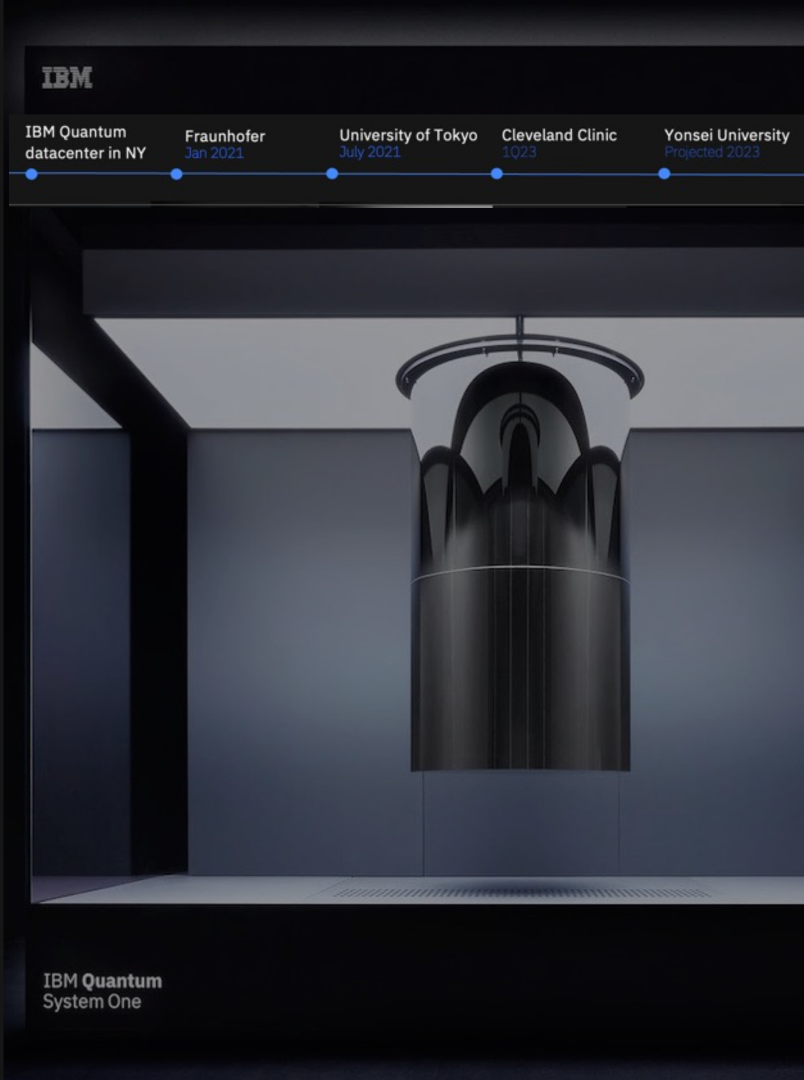
Daily executions

280+

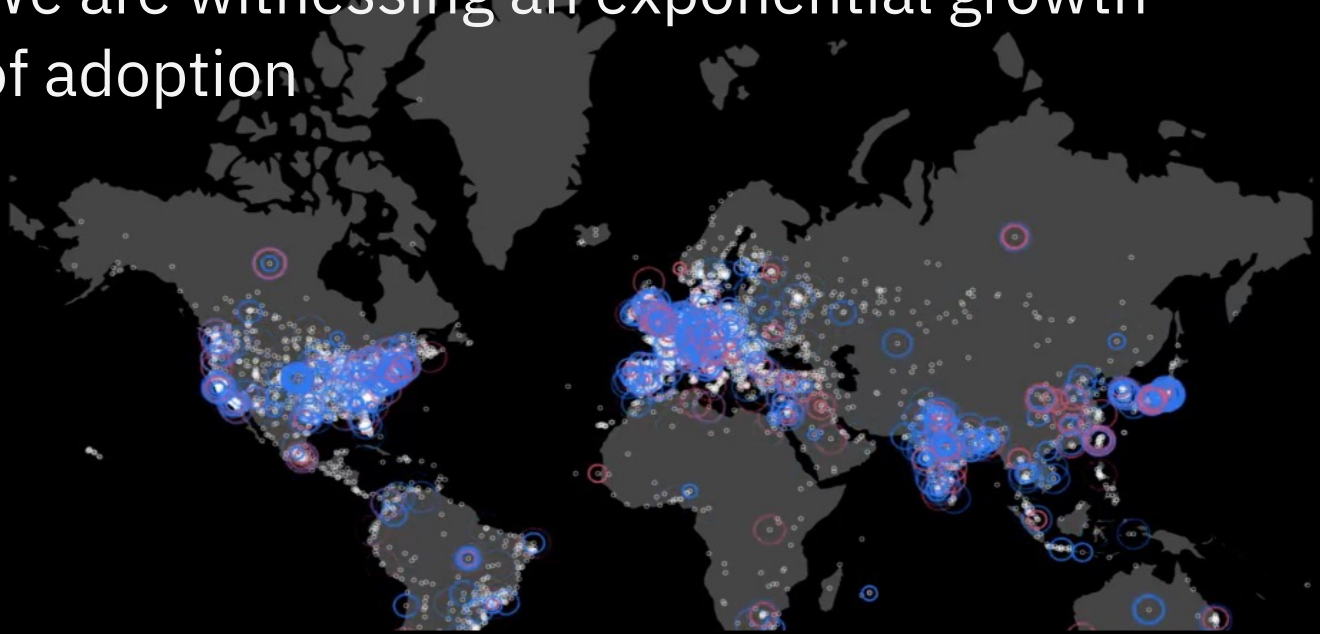
Universities

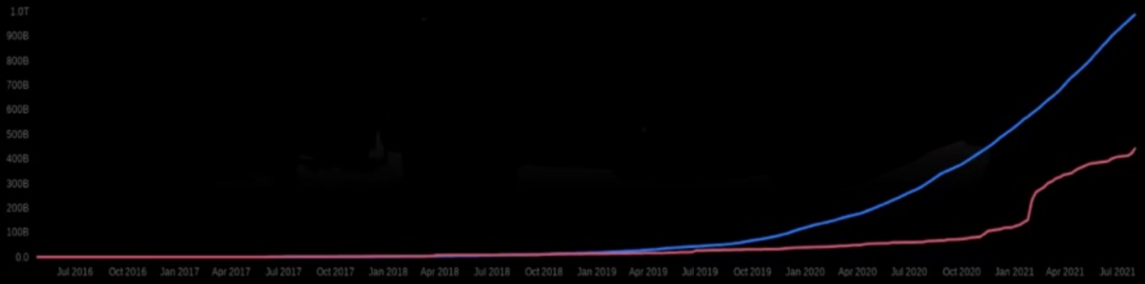
1400+

Papers written



We are witnessing an exponential growth of adoption





Mar 2022

1.6 Trillion

Quantum system

450 B

Quantum Simulator

… In order to apply quantum to real-world problems, we need to enter the realm of quantum advantage, where quantum computers are either cheaper, faster, or more accurate than classical computers at the same relevant task.

Crafting the path to Quantum Advantage.

Today Quantum is confusing.

NISQ

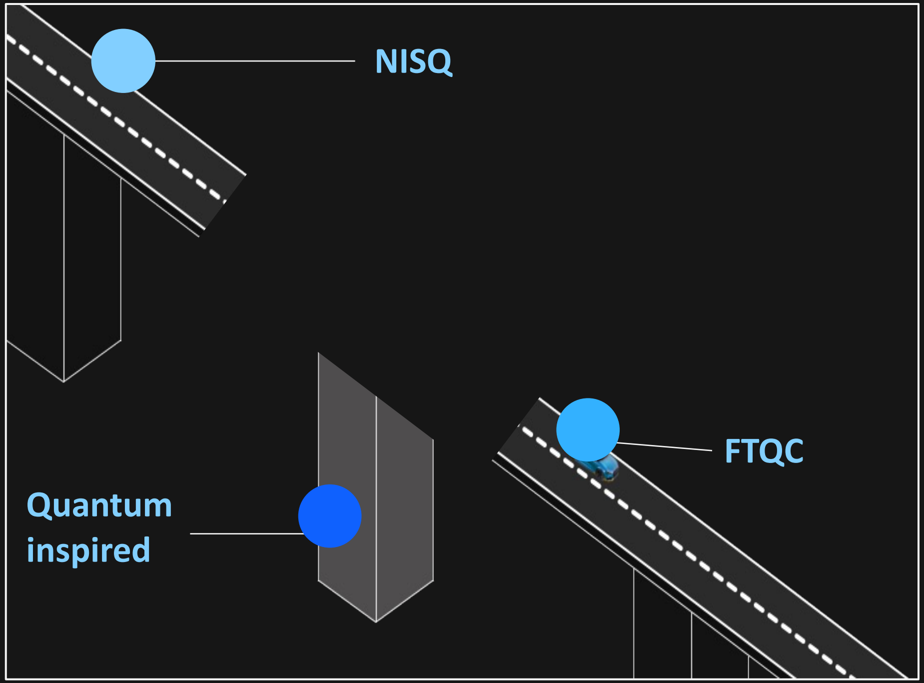
"Near term push for investigating what you can get way with"

FTQC

"Nothing is possible till there is fault tolerance"

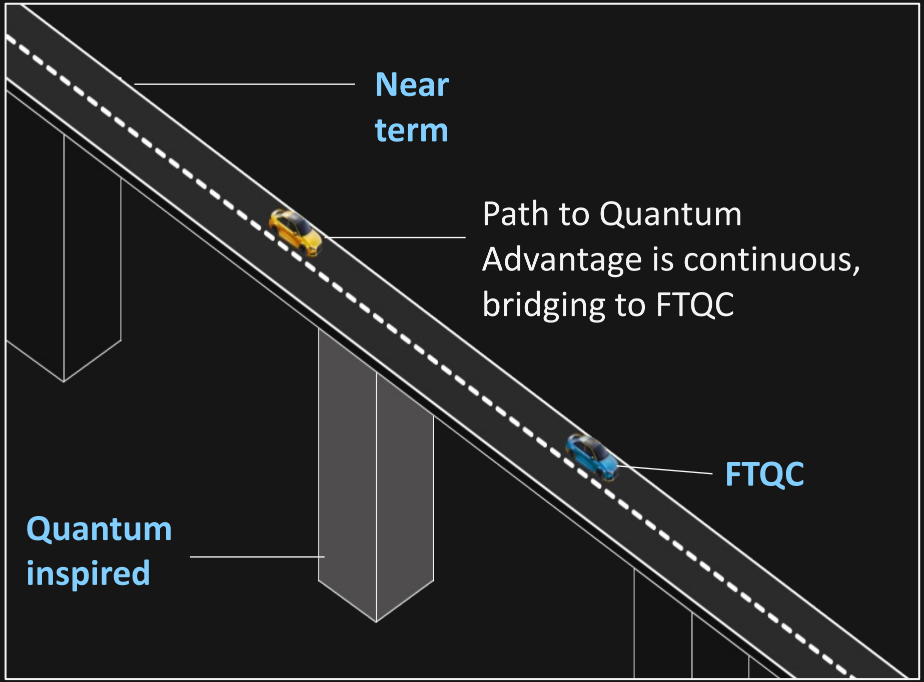
Quantum inspired

"Let's build classical algorithms so they teach us about quantum computing"



Building the bridge to Quantum Advantage

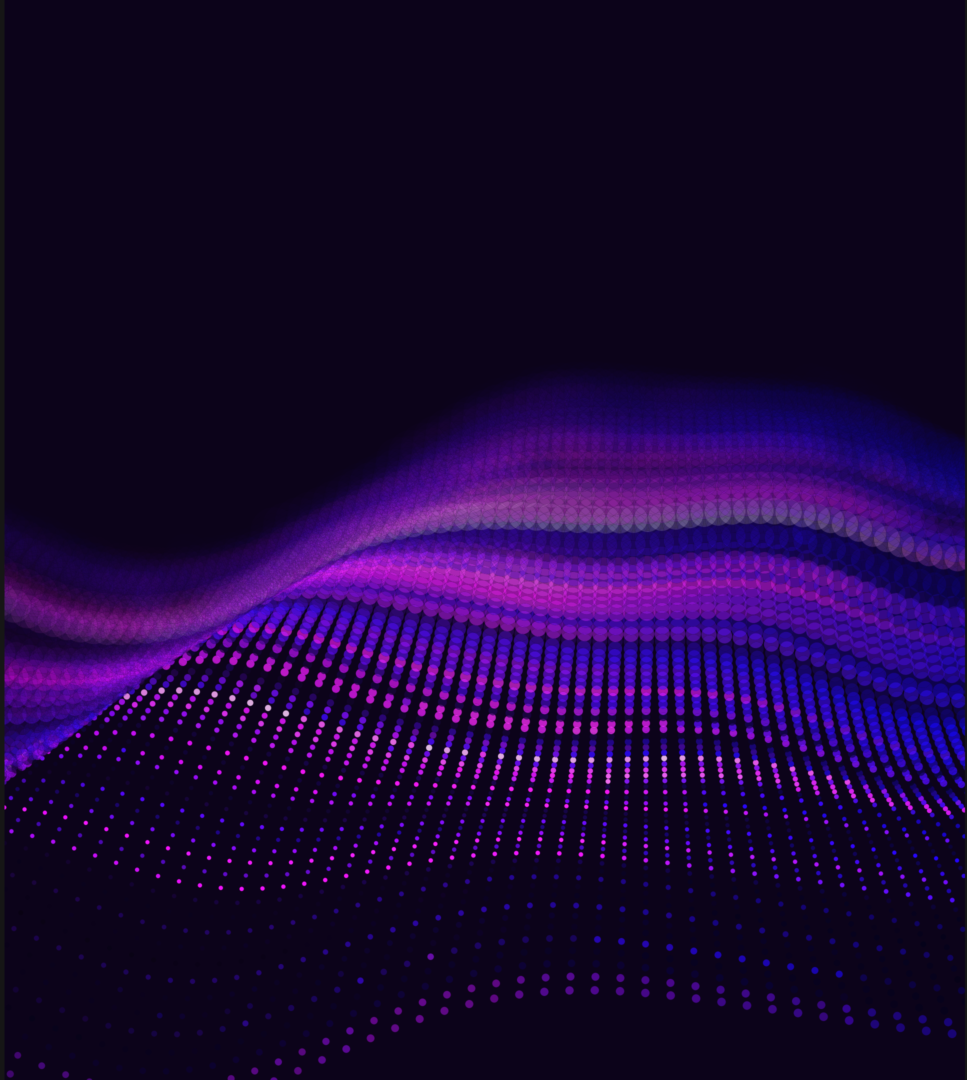
In the end, it is all about computing and reaching a solution to a useful or interesting problem within a runtime that is practical.



The path to quantum advantage

How can we Map interesting problems to quantum circuits?

How can we run quantum circuits faster on quantum hardware?



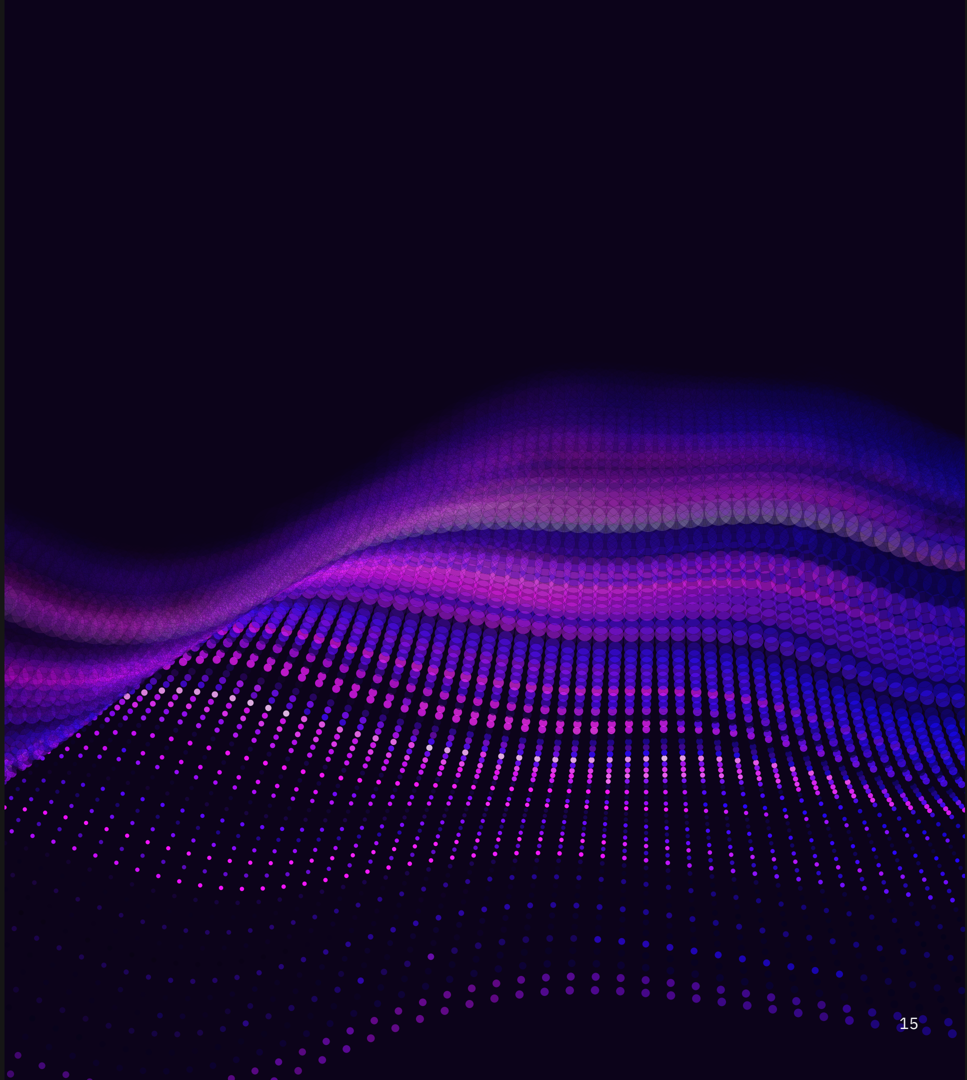
The path to quantum advantage

Map interesting problems to quantum circuits

We need applications that can only be solved with quantum circuits that are known to be difficult to simulate. This must be done in partnership with our clients and users.

IBM Quantum Network

Run quantum circuits faster on quantum hardware



The IBM Quantum Network

Largest Quantum partnership network accelerating to quantum advantage

180+

members

870+

research papers published by the IBM Quantum network

20+

Hubs

Regional centers of quantum computing education, R&D, and implementation

10+

Industry Joint Development Partners

Organizations deeply collaborating with IBM to jointly develop the first commercial applications.

30+

Industry and Research Members

Organizations building their skills, expertise, and advancing research and development.

40+

Startups

Agile innovators contributing solutions to Qiskit, and across the quantum stack

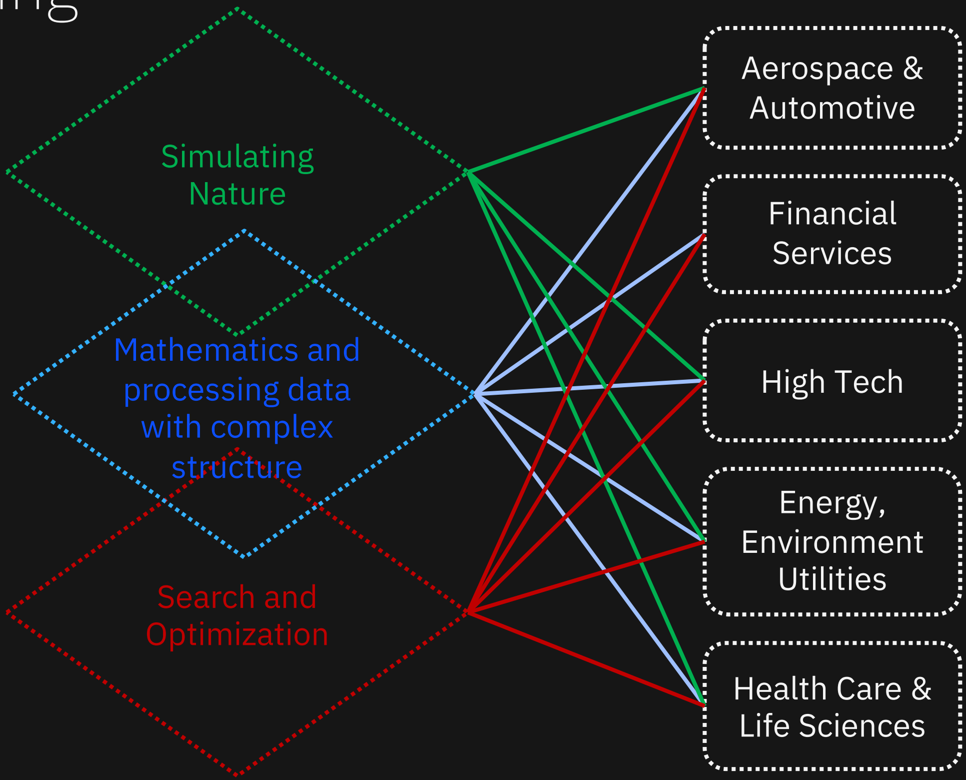
30+

Academics

Academic researchers performing advanced scientific work in quantum computing

Connecting society with problems in Quantum Computing

IBM Quantum



Aerospace & Automotive:
- Customer Experience
- Materials Design
- Structural Design Optimization
- …

Financial Services:
- Fraud Detection
- Derivatives/options pricing
- Portfolio optimization
- Risk analysis
- …

High Tech:
- Seismic Imaging
- Catalysts
- Supply chain planning
- Manufacturing scheduling optimization
- …

Energy, Environment Utilities:
- Portfolio optimization
- Grid optimization
- Risk Analysis and Options Pricing
- Battery Design
- …

Health Care & Life Sciences:
- Disease risk prediction
- Drug discovery and design
- Protein folding predictions
- …

Addressing real world problems for **society** by coupling the fundamentals of *quantum information sciences*, *software design*, and *deep subject matter expertise* to demonstrate **quantum advantage** for the applications of quantum computing.

Enterprises worldwide are developing Applications of Quantum

AMGEN

Quantum kernels for real-world predictions based on electronic health records

Relaxing combinatorial functions into quantum problems

ExxonMobil

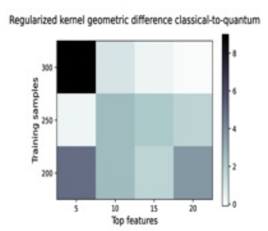
Improving accuracy and efficiency for potential-energy surface calculations

woodside

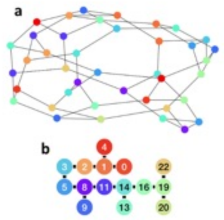
Quantum machine learning to use in the data science workflow

Keio MIZUHO MUFG

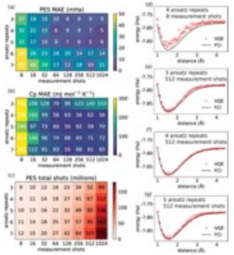
Quantum machine learning to use in the data science workflow



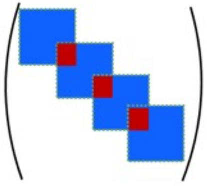
arXiv: 2112.06211(2021)



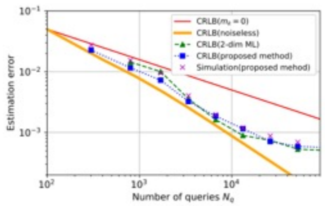
arXiv:2111.03167 (2021)



S. Stober et. al, PRA 105, 012425 (2022)



arXiv:2112.08449 (2021)

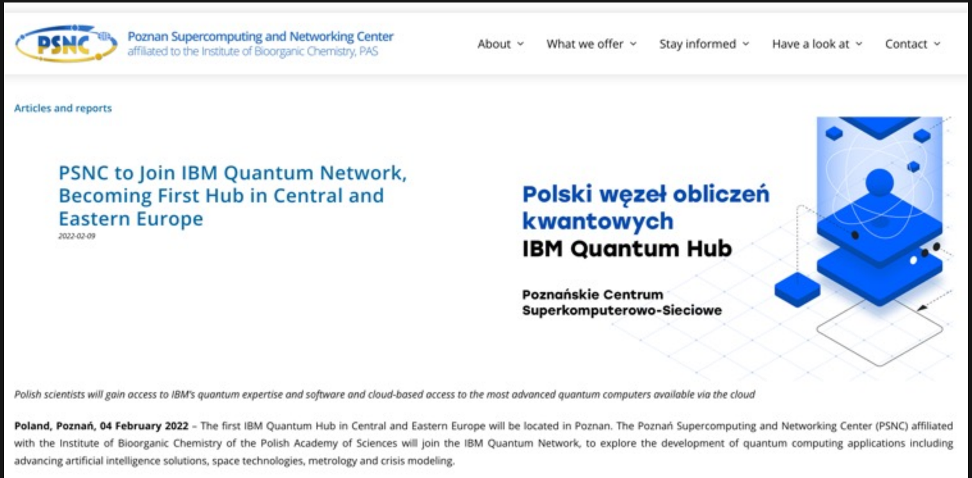


arXiv:2110.04258 PhysRevA.105.012411 (2022)

PSNC is leading the growth of Quantum Ecosystem in Poland

Poznań Supercomputing and Networking Center (PSNC) is well established within European Research space hub for providing IT infrastructures, playing an important R&D development center.

PSNC is the first IBM Quantum Hub in Central and Eastern Europe.


PSNC Poznan Supercomputing and Networking Center
affiliated to the Institute of Bioorganic Chemistry, PAS

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Articles and reports

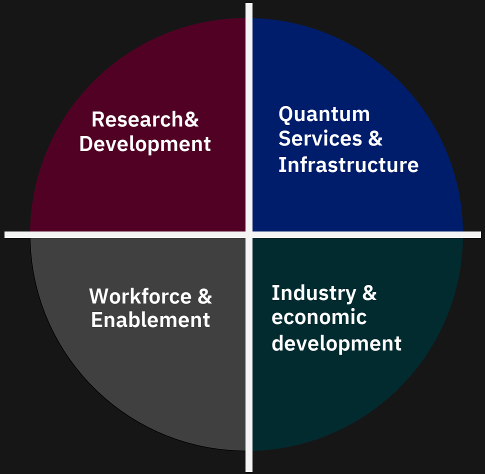
PSNC to Join IBM Quantum Network, Becoming First Hub in Central and Eastern Europe

2022-02-09

Polski węzeł obliczeń kwantowych
IBM Quantum Hub
Poznańskie Centrum Superkomputerowo-Sieciowe

Polish scientists will gain access to IBM's quantum expertise and software and cloud-based access to the most advanced quantum computers available via the cloud

Poland, Poznań, 04 February 2022 – The first IBM Quantum Hub in Central and Eastern Europe will be located in Poznan. The Poznań Supercomputing and Networking Center (PSNC) affiliated with the Institute of Bioorganic Chemistry of the Polish Academy of Sciences will join the IBM Quantum Network, to explore the development of quantum computing applications including advancing artificial intelligence solutions, space technologies, metrology and crisis modeling.



The PSNC mission focuses on digital transformation in science. Quantum Computing is one of the vessels to contribute to this. PSNC's core quantum strategy is two-fold:

- Build and Grow Quantum Computing Ecosystem by developing expertise, growing community, supporting education, and developing quantum computing applications
- Develop an advanced infrastructure to foster the research activities by expanding tools and software capabilities with runtimes

More information about Quantum IBM Hub at: https://quantum.psnc.pl/

The no-nonsense path to quantum advantage

Map interesting problems to quantum circuits

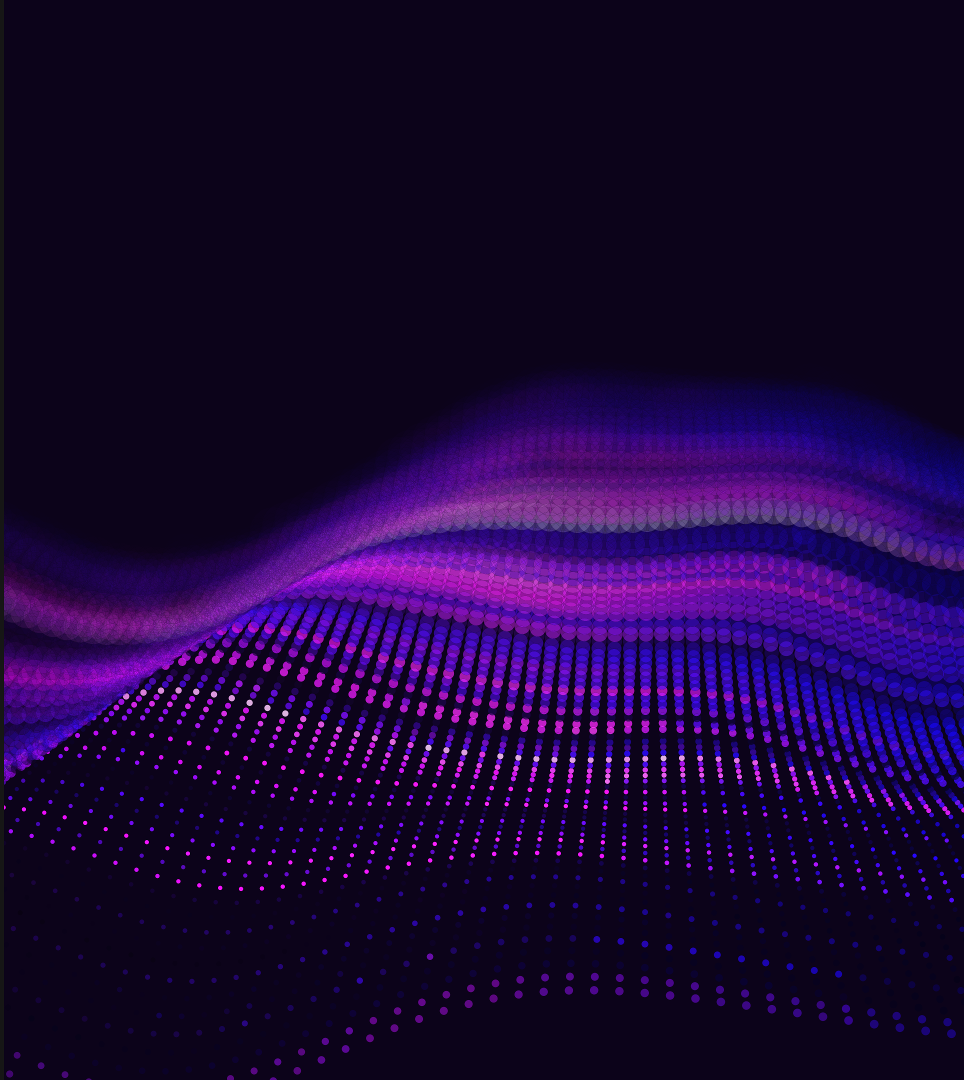
We need applications that can only be solved with quantum circuits that are known to be difficult to simulate. This must be done in partnership with our clients and users.

IBM Quantum Network

Run quantum circuits faster on quantum hardware

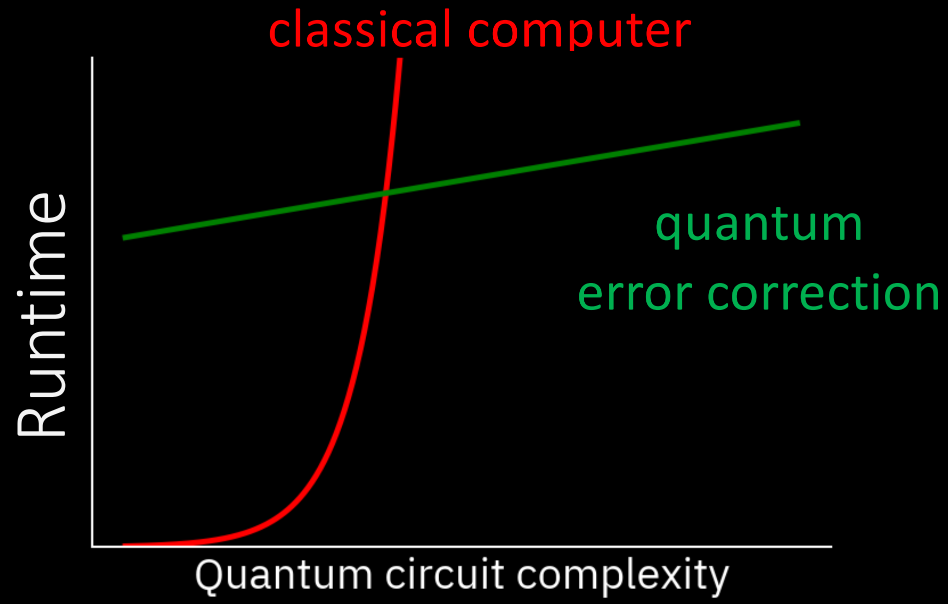
Chart a path to develop quantum technology (hardware + software) that runs noise-free estimators of quantum circuits faster than can be done using classical hardware alone

IBM Quantum Development Roadmap



The cost of estimating the output of a quantum circuit

IBM **Quantum**



Circuit complexity depends on depth and size of the quantum circuit

https://research.ibm.com/blog/gammabar-for-quantum-advantage

The cost of estimating the output of a quantum circuit

IBM **Quantum**

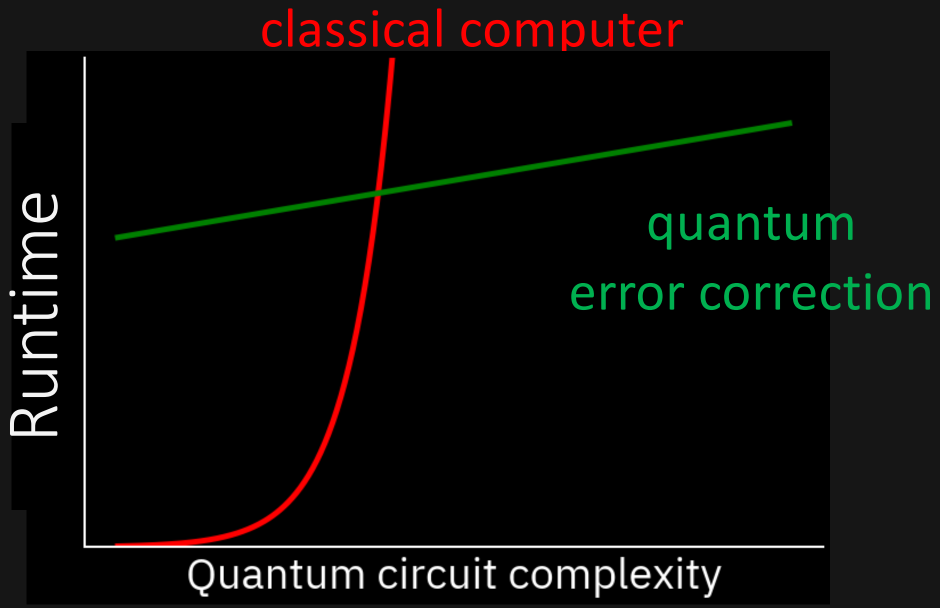
Solutions to useful problems (Noise-free estimators) can be obtained from noisy quantum computers TODAY, at a runtime cost that is exponential in circuit complexity

$$\text{Runtime} = (1/\delta) \times d \times (\gamma)^{n*d} \text{ seconds}$$

δ is a measure of how many circuit layer operations that can be done per second (increase by pushing speed)

γ is a measure of the collective quantum noise (increasing quality brings it closer to 1)

n is the number of operational qubits (increase by pushing scale)



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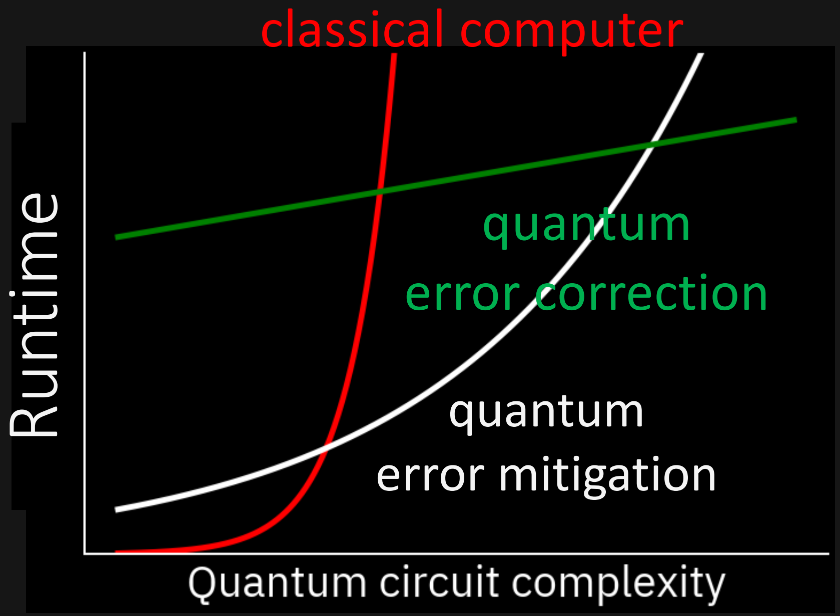

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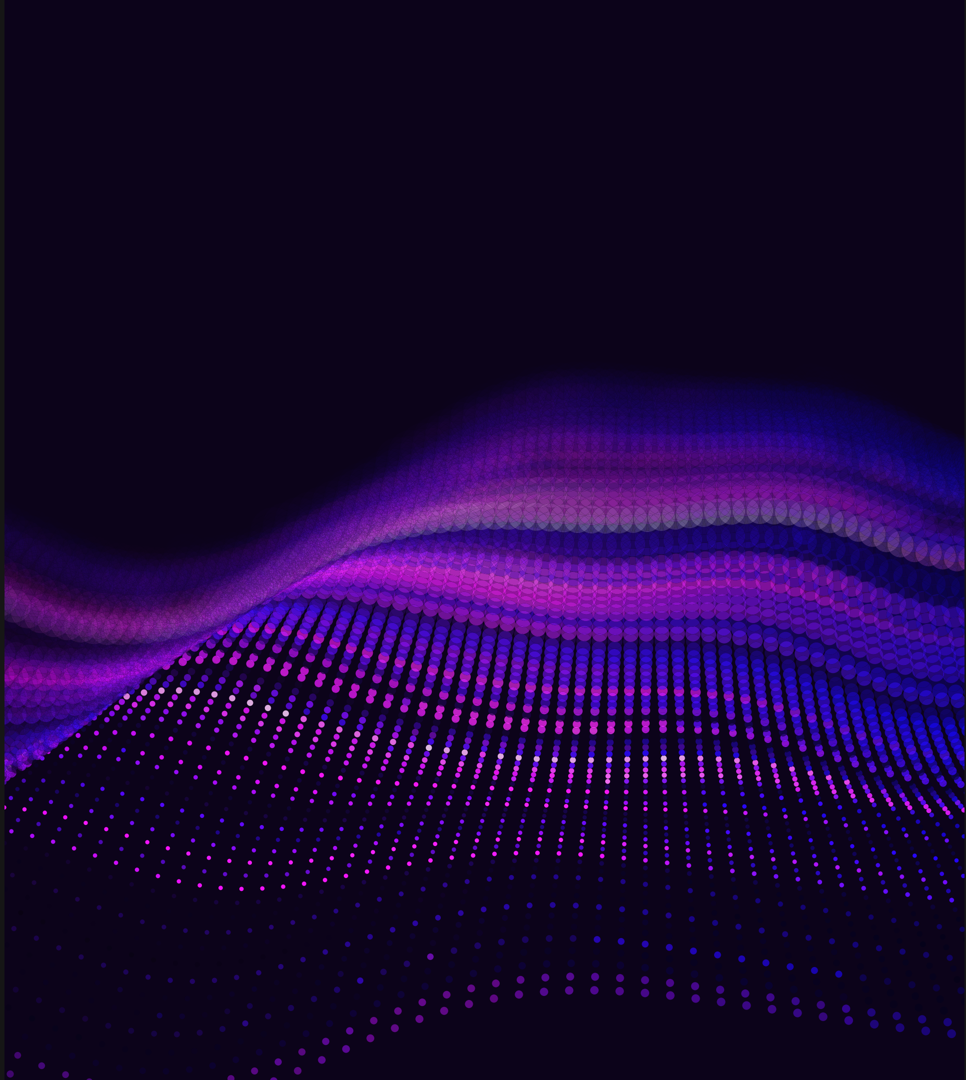
The path to quantum advantage

The path to quantum advantage will be one driven by improvements in the quality and speed of quantum systems as their scale grows to tackle increasingly complex circuits.



The three key metrics for measuring quantum computing performance

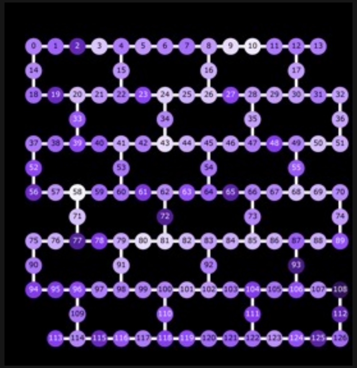
Scale

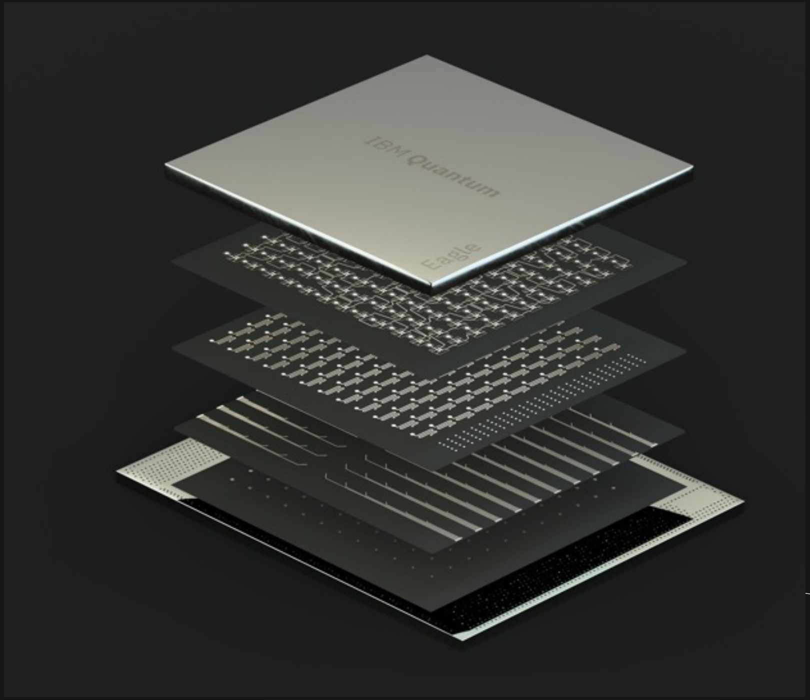
Measured by **number of qubits** which indicates the amount of information we can encode in the quantum system.

High coherence, high reliability, lower cost

2020	2021	2022
65 qubits	127 qubits	433 qubits

IBM **Quantum** Eagle Processor
with 127 qubits





https://newsroom.ibm.com/2021-11-16-IBM-Unveils-Breakthrough-127-Qubit-Quantum-Processor

The three key metrics for measuring quantum computing performance

Quality

Measured by **Quantum Volume** which indicates quality of circuits and how faithfully circuits are implemented in hardware.

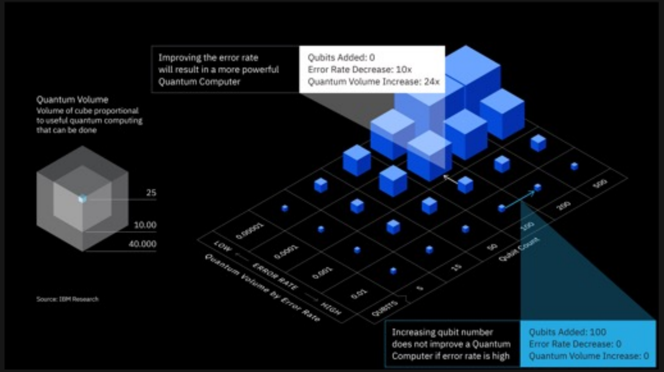
Need low operation errors, meaning large Quantum Volume

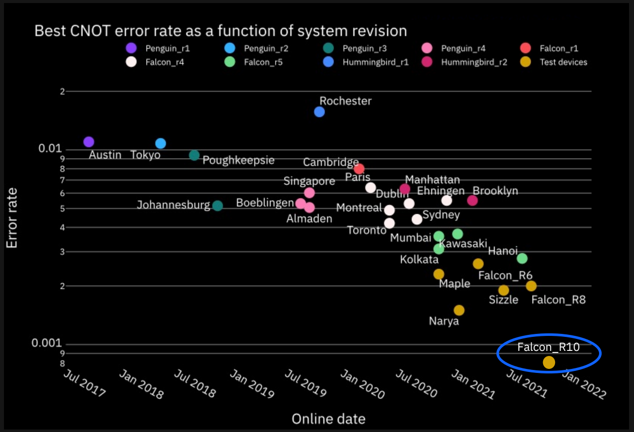
2020	Today	2022
32 QV	512 QV	1024 QV

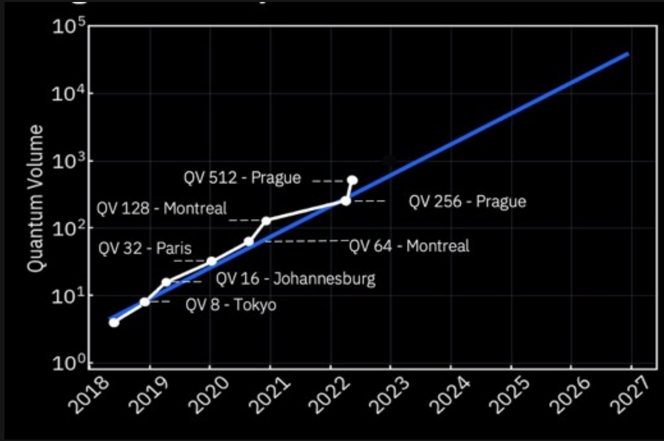
We have committed to doubling quantum volume every year. So far, we are a little ahead of pace.

Today, improvements largely come from improving physical error rates.

- Continued major progress in coherence and gate fidelity
  99.9% fidelity on Falcon R10
  Exploratory system







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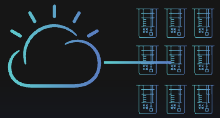


Speed

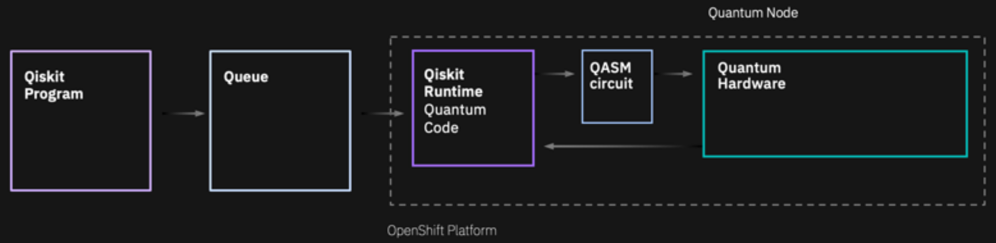
Measured by **CLOPS (Circuit Layer Operations Per Second)** which indicates how many circuits can run on hardware in a given time.

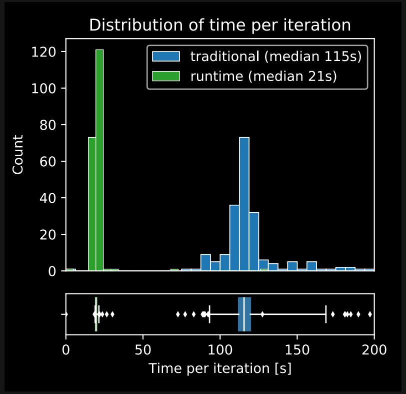
Seamless synchronization of quantum and classical circuits increases execution rate

2020	Today	2022
200 (Inferred)	1.4K CLOPS	10K CLOPS

Real workloads are not purely quantum, but rather require interaction between quantum and classical compute resources.

A high-performance system also requires low-latency interaction to generic classical compute.





Qiskit Runtime 4.0X
Algorithm 1.8X
System Software 1.5X
Control Systems 4.2X
Device Fidelities 2.8X

Total 120x improvement

Today all our devices now support Qiskit Runtime

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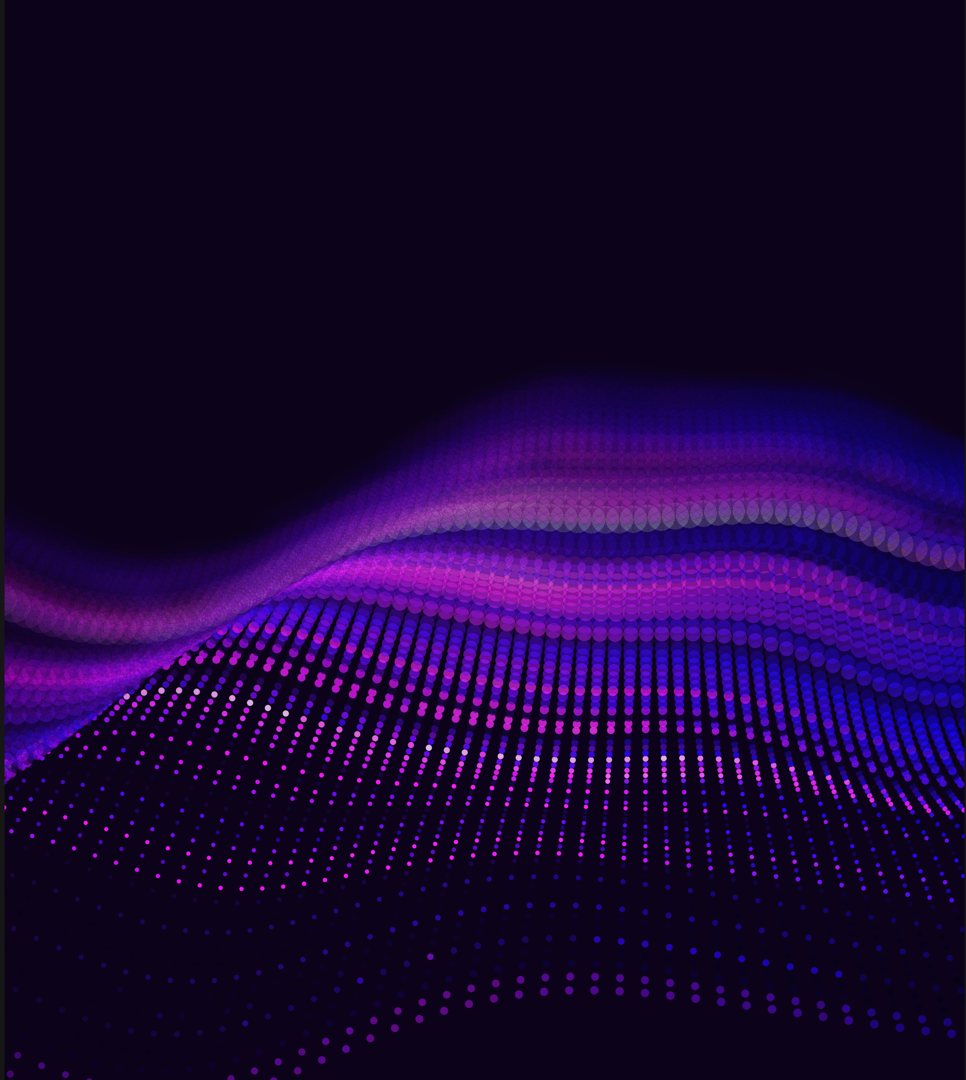
The path to quantum advantage

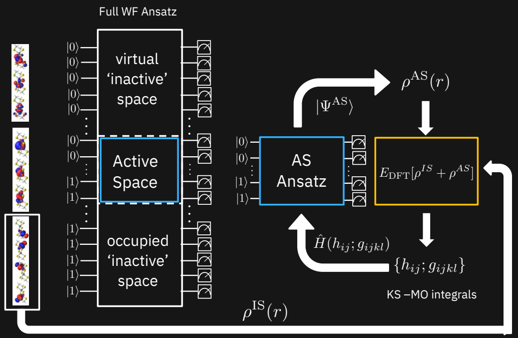
Quantum computers can offer value before we have FTQC and the path from today to then can be continuous.



Quantum + Classical = Circuit Knitting

Embedding

Use QPU for highly entangled part of the problem and CPUs for low entanglement part with classical approximate algorithms (DFT, HF).



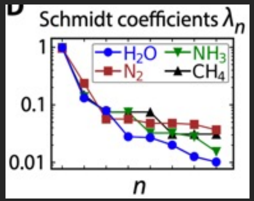
M. Rossmanek *et al.*, *J. Chem. Phys.* **154**, 114105 (2021)

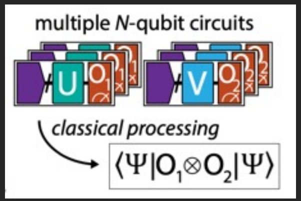
Entanglement forging

Use a Schmidt decomposition to break the problem into smaller quantum circuits.

$$|\psi\rangle = \sum_n \lambda_n U|b_{1,n}\rangle \otimes V|b_{2,n}\rangle$$

For each coefficient run the smaller quantum circuits and reconstruct the larger problem by classical processing

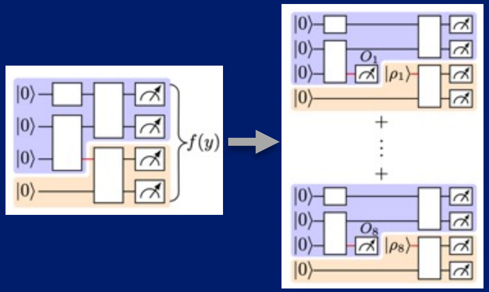




A. Eddins *et al.*, *PRX Quantum* **3**, 010309 (2022)

Circuit Cutting

Cut the system at less entangled connections into subsystems. Compute the global energy by classically coupling each of result from QPU.



S. Bravyi, G. Smith, J. Smolin, *PRX* **6**, 021043 (2016)
T. Peng, A. W. Harrow, M. Ozols, X. Wu, *PRL* **125**, 150504 (2020)

The no-nonsense path to quantum advantage

IBM **Quantum**

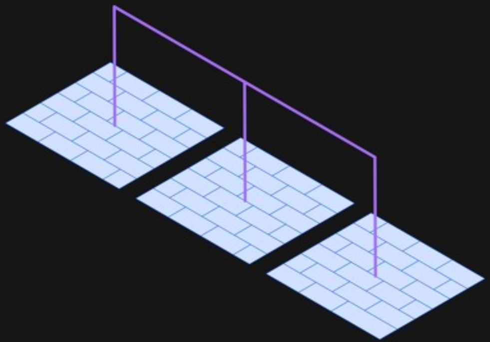
Elastic classical computing and classical communication between quantum processors will allow quantum advantage to happen faster.

IBM **Quantum**

2023

Classical parallelization of quantum processors

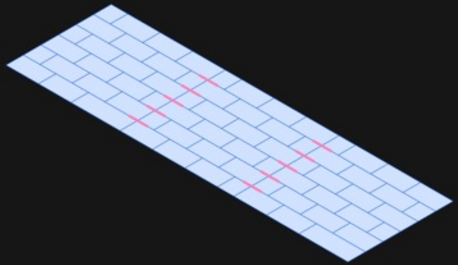
Heron
133 qubits



2024

Multi-chip quantum processors with chip-to-chip couplers

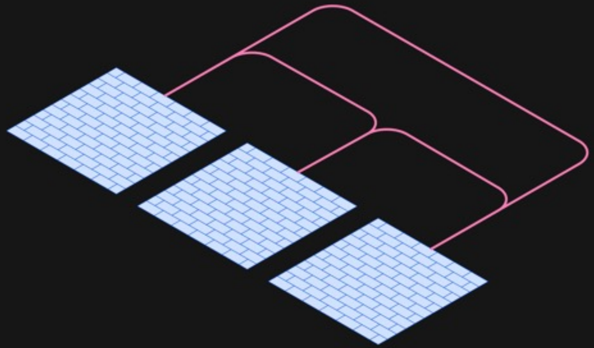
Crossbill
408 qubits



2024

Quantum parallelization of quantum processors

Flamingo
1,386 qubits



Development Roadmap | Executed by IBM ✓ On target

IBM **Quantum**

2019 ✓	2020 ✓	2021 ✓	2022	2023	2024	2025	2026+
Run quantum circuits on the IBM cloud	Demonstrate and prototype quantum algorithms and applications	Run quantum programs 100x faster with Qiskit Runtime	Bring dynamic circuits to Qiskit Runtime to unlock more computations	Enhancing applications with elastic computing and parallelization of Qiskit Runtime	Improve accuracy of Qiskit Runtime with scalable error mitigation	Scale quantum applications with circuit knitting toolbox controlling Qiskit Runtime	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 (on target) | Threaded primitives | Error suppression and mitigation | Error correction

System Modularity

Falcon ✓	27 qubits
Hummingbird ✓	65 qubits
Eagle ✓	127 qubits
Osprey (on target)	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

What does the future hold?

IBM **Quantum**

I would like to thank...

The PSNC team and Organizers

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Quantum Threats

What threats would a future 'quantum attacker' impose?

Threat 1: Loss of data confidentiality

Decryption of communicated or stored data and disclosure of confidential data.

Threat 2: Fraudulent Authentication

Gaining unauthorized access, manipulating systems or stealing company secrets.

Threat 3: Loss of data integrity & legal history

Modifying digitally signed data and forging signatures and contracts.

IBM and Quantum Safe

IBM **Quantum**

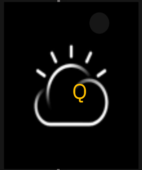
2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024

Submission to NIST
Lattice based cryptography
Code Based Cryptography
Isogeny Based Cryptography

IBM Internal Development

IBM Systems
Quantum Safe Tape announcement **IBM Z – Dilithium**

IBM Open Source Announcement - oqs



IBM Cloud
Availability of quantum safe algorithms and communication

NIST
Algorithm Announcement

IBM z16
First Quantum Safe platform

NIST
Quantum Safe Standards Ready

Early Adoption/Learning Phase

Preparation and Agility Phase

Standardization Phase

1. World leading research group on quantum safe algorithms
2. Production Quantum Safe libraries
3. Clear roadmap to quantum safe platforms
4. Commitment to opensource
5. Commitment to Quantum Safe industry standards
6. Clear understanding of cryptographic agility
7. Rapidly developing understanding in quantum safe migration
8. Research and development of approaches, tools, processes

Quantum Safe Technologies

	Confidentiality	Identification	Integrity	Non-Repudiation
Quantum Safe Cryptography (QSC) Cryptography based on mathematical problems difficult to solve for classical and quantum computers	✓	✓	✓	✓
Quantum key distribution (QKD) Allows the exchange of a cryptographic key between two remote parties exploiting quantum physical phenomena	✓	✗	✗	✗

Migrating to Quantum Safe

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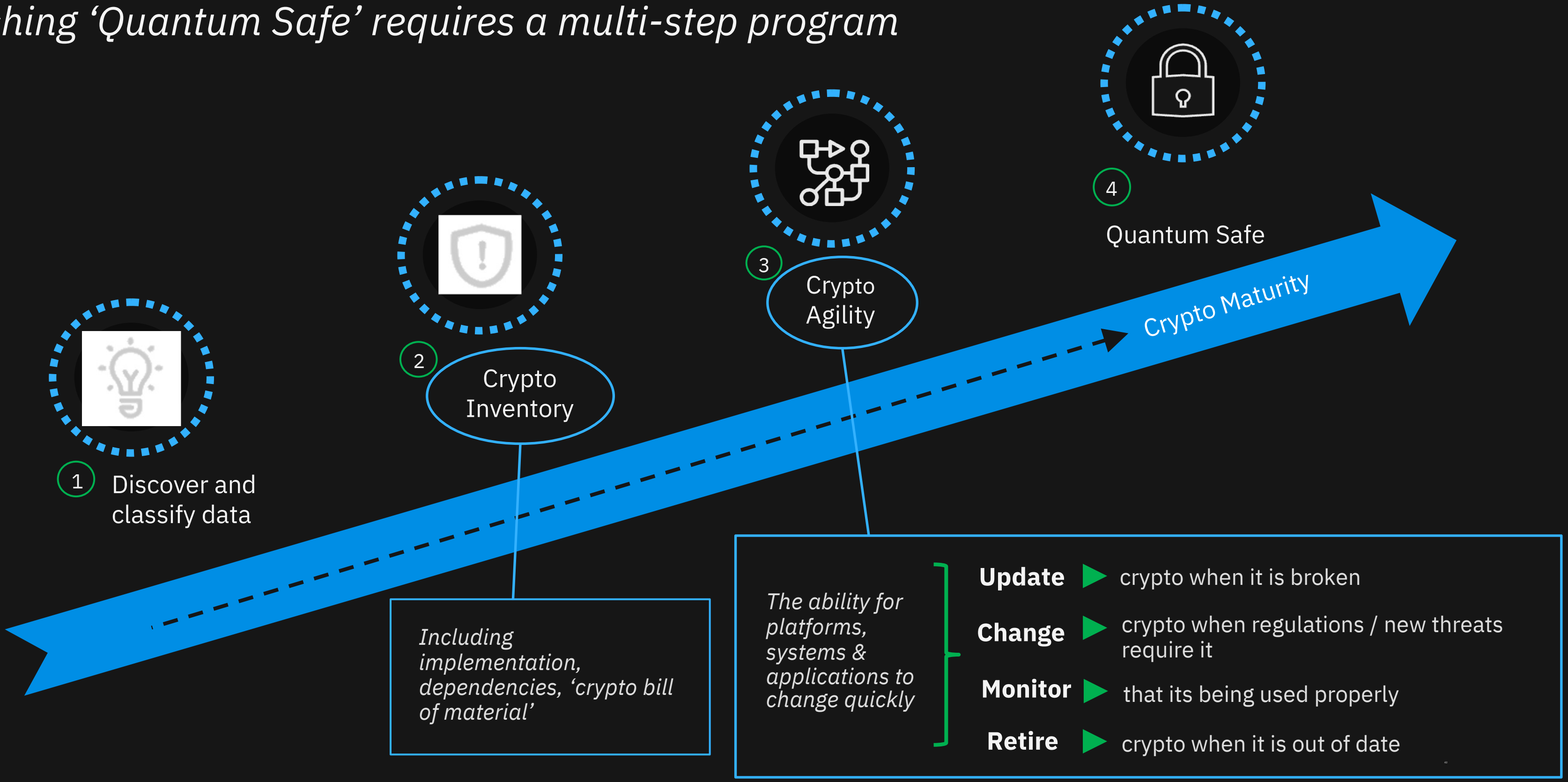
Reaching 'Quantum Safe' requires a multi-step program



Circuit knitting with classical communication

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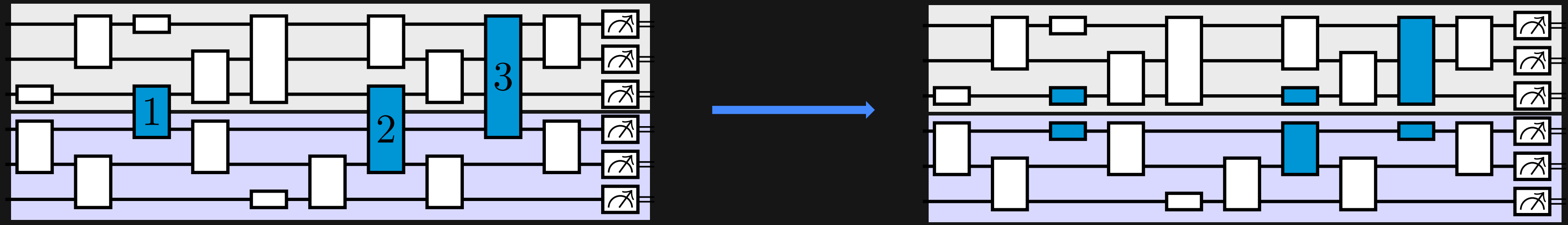
How to split a large computation into smaller subcircuits



Overhead for simulating gate 1 with local operations (LO)

Simulation overhead $\gamma_1\gamma_2\gamma_3$

Can we reduce γ if we allow for classical communication between the nonlocal parts?

$\gamma_{\mathrm{LO}}(\mathrm{CNOT}) = 3$

$\gamma_{\mathrm{LOCC}}(\mathrm{CNOT}) = 2$

$\gamma_{\mathrm{LO}}(\mathrm{SWAP}) = 7$

$\gamma_{\mathrm{LOCC}}(\mathrm{SWAP}) = 4$

C. Piveteau, *et al.* arXiv:2205.00016 (2022)