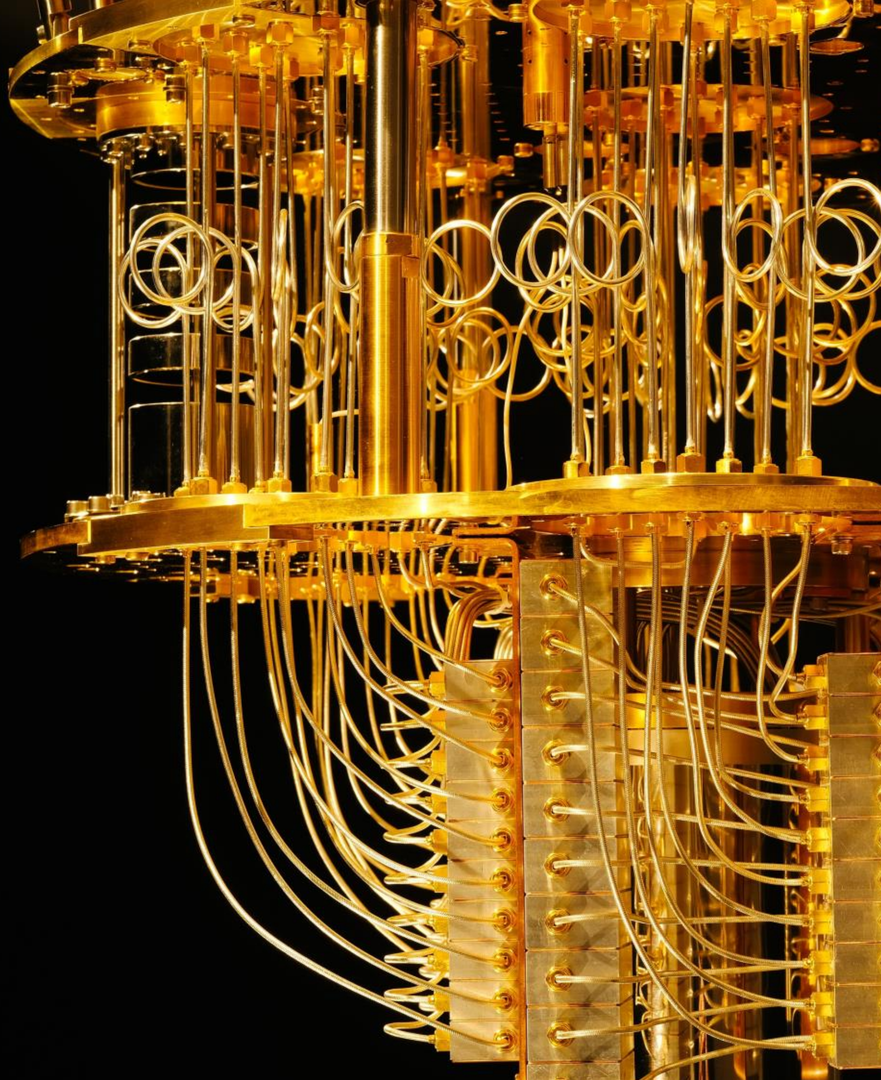
Quantum Computing
Not just a dream, …
also in practice!

May 8th, 2019

GUIDE SHARE EUROPE

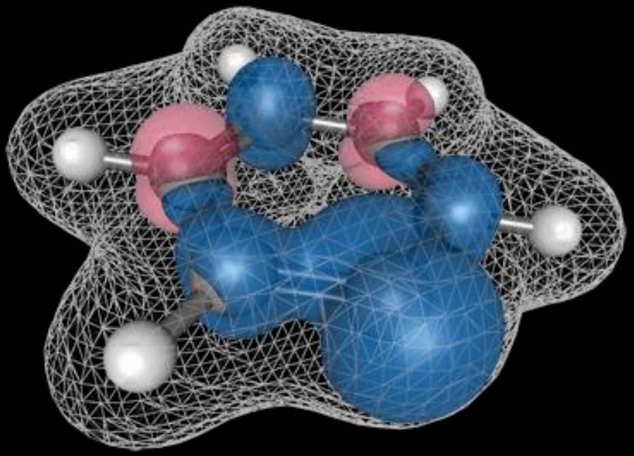
Regional Conference Belgium-Luxembourg



IBM

Hans Van Mingroot & Eric Michiels

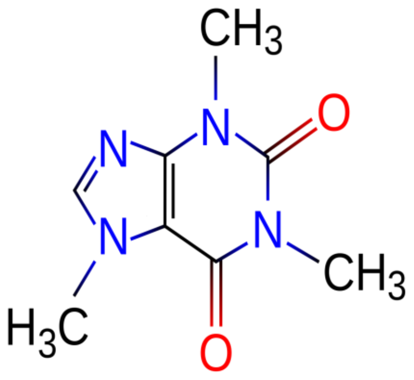
Our intuition about what we can compute is wrong...



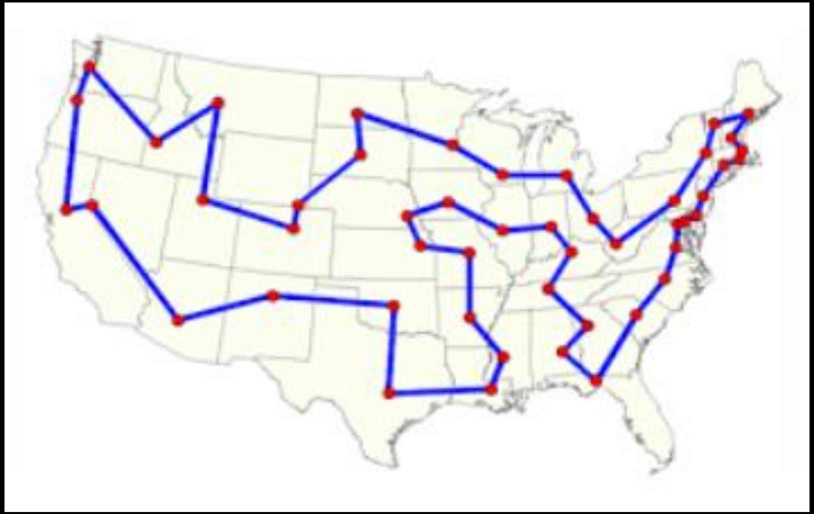
The best supercomputer in the world can only simulate a ...

40-50 electron system

It is impossible to model Caffeine on today’s most powerful super computers, but we could represent it using 160 Quantum Bits, or Qubits



The “Traveling Salesman” problem has a runtime that grows exponentially with its input size



- 5 locations: 5 * 4 * 3 * 2 * 1 = 120 = 5 !
- 10 locations: 10 ! = 3 628 800
- 20 locations: 20 ! = 2 432 902 008 176 640 000

What if we have …

- 100’s of trucks and planes
- 1000’s of parcels
- 10000’s of products
- Changing “weights” between vertices on the edges
- Changes in locations

Can a Classical Computer simulate a Physical System?

" Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly, it's a wonderful problem, because it doesn't look so easy."

Richard P. Feynman

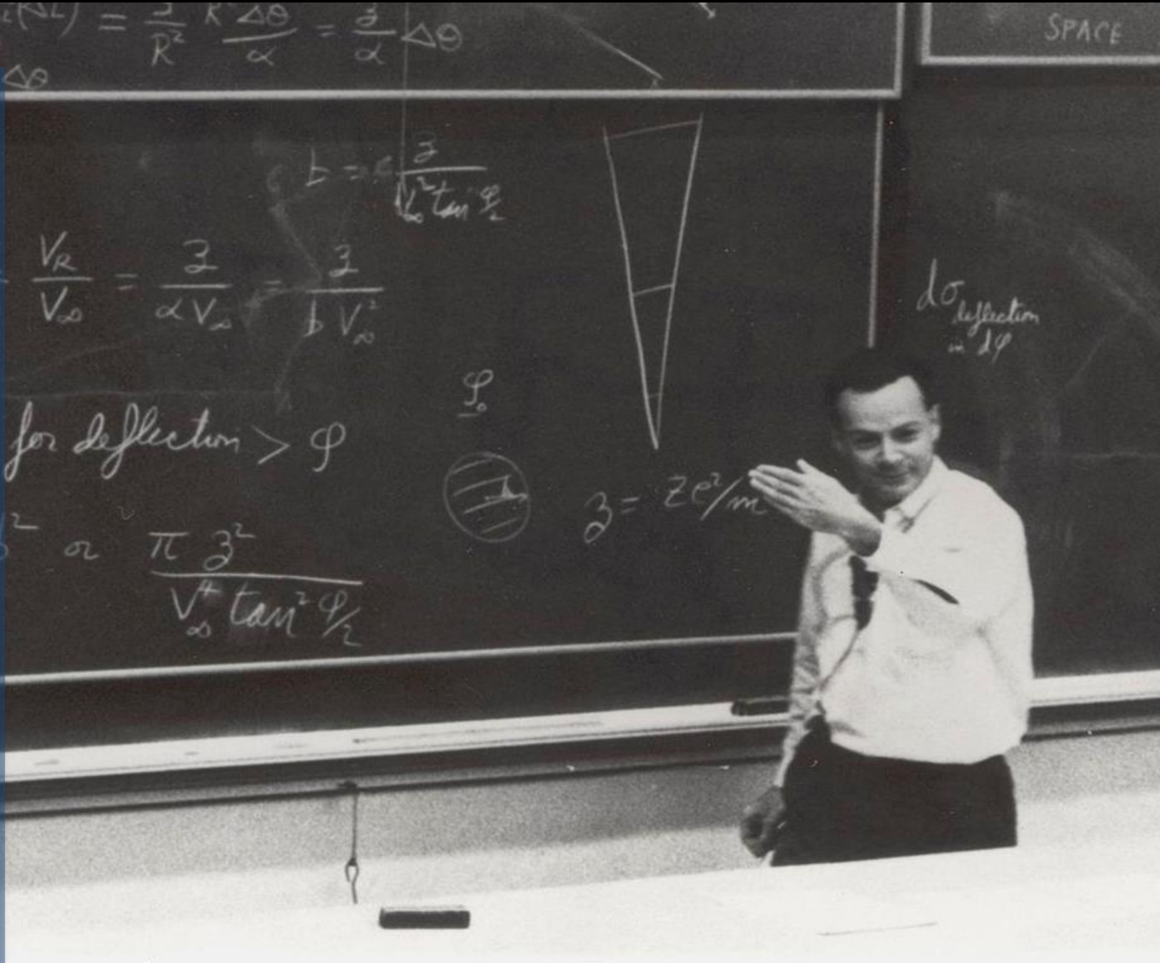


Photo: Bomazi

Bit vs. Qubit – Superposition

The **Bit:** two possible states: 0 and 1.

The **Qubit:** is 0 or 1 when you measure, or observe it.

But: while not observed: the state of a qubit can also be a *superposition*, or combination, of both 0 and 1

We can state this as

$$a\ |0> + b\ |1>$$

A single Qubit can exist in a superposition of 0 and 1, and N Qubits allow for a superposition of all possible 2^N combinations

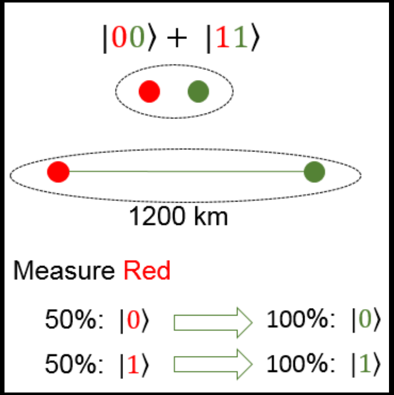
Bit vs. Qubit – Entanglement

Multiple **Bits:** can be manipulated and measured independently.

Multiple **Qubits:** can be *entangled* – the Qubits cannot be treated as separate states but together form a system as a whole.

Example:

$$a\ |00> + b\ |11>$$



"Spooky action at a distance"
or "EPR Paradox"

Quantum Computers allow you to encode a problem,
explore an exponential possibility space of solutions,
and by taking advantage of constructive and destructive interference,
read the optimal solution out of the system

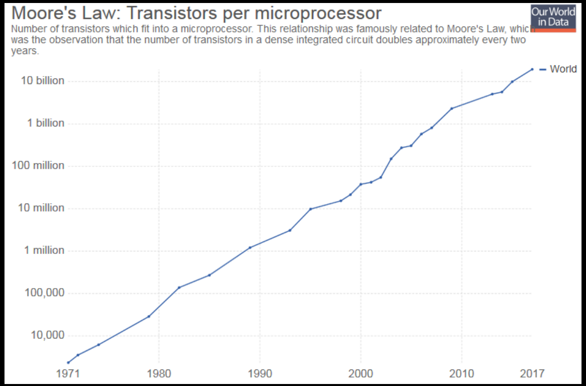
Example: Simple addition of (Qu)bits

If we have two (Qu)bits with each value 0 or 1, what are the possible outcomes of their addition?

What is the good and the bad news for Qubits?

Classical Computers

The potential power of a Classical Computer **doubles** every time you double the number of transistors



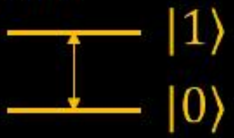
Quantum Computers

The potential power of a Quantum Computer **doubles** every time you add one additional Qubit

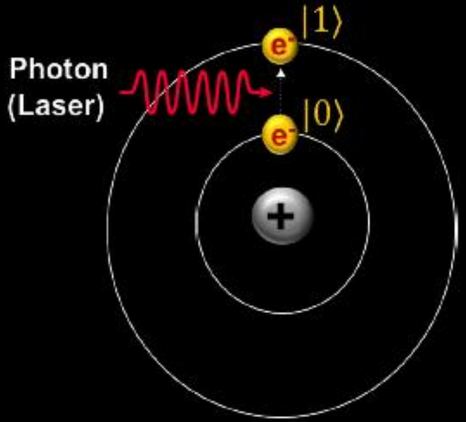
Physical Qubits Realizations

Quantum Bits:

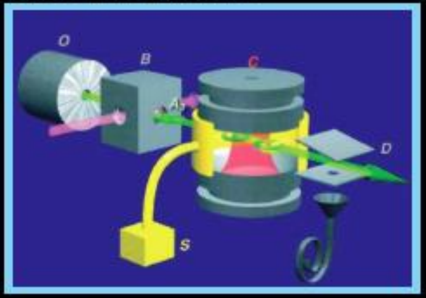
Two-Level Systems



Example:
Atom orbitals with different energetic levels

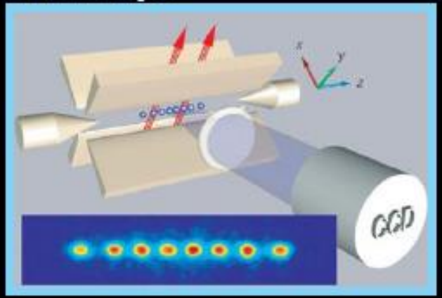


Neutral Atoms



© Haroche

Ion Traps



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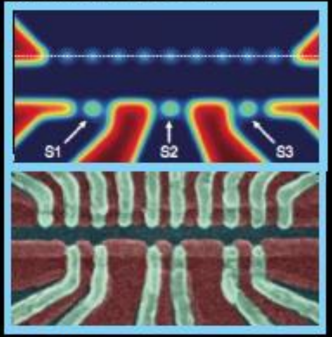
Quantum Dots



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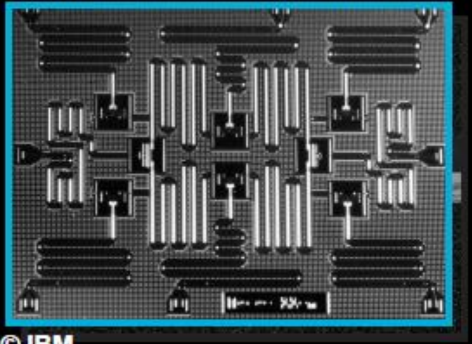
Superconducting Circuits



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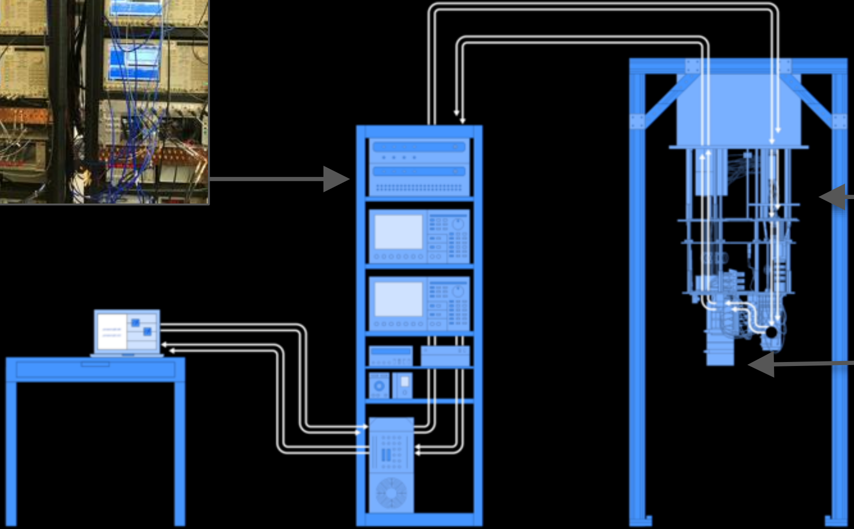
Inside an IBM Q
Quantum Computing System

Microwave electronics



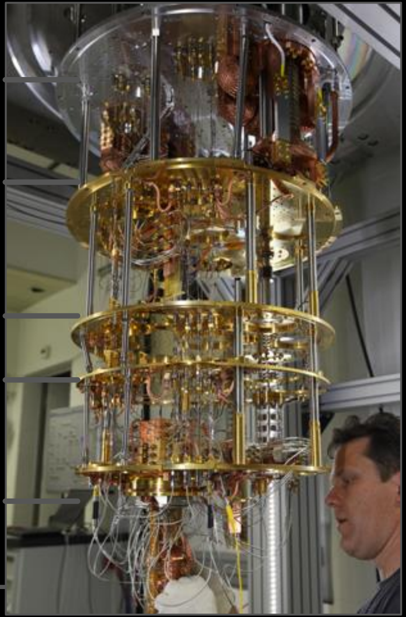
40K

3K

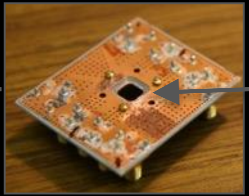
0.9K

0.1K

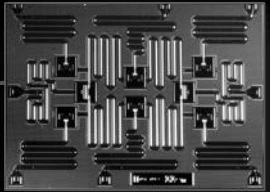
0.015K



Refrigerator to cool qubits to 10 - 15 mK with a mixture of ^3He and ^4He



PCB with the qubit chip at 15 mK protected from the environment by multiple shields

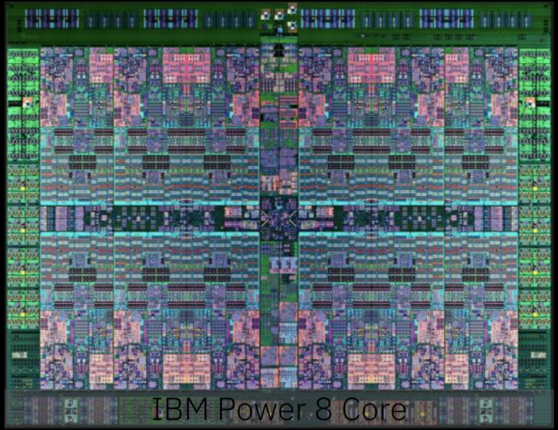


Chip with superconducting qubits and resonators

The power of Quantum Computing → N Qubits, 2^N states

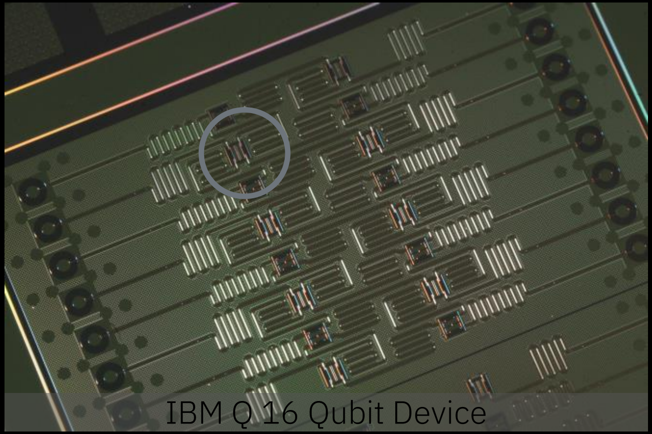
Classical Computers

There is a one-to-one relationship between the number of transistors a microprocessor has and its processing power. The potential power of a classical computer doubles every time you double the number of transistors.



Quantum Computers

In a Quantum system, the rough equivalent of a transistor is something called a Quantum Bit, or a Qubit. But there's a big difference. The potential power of a quantum computer doubles every time you add one additional Qubit.



The power of Quantum Computing is more than the number of Qubits

Quantum Volume depends upon ...

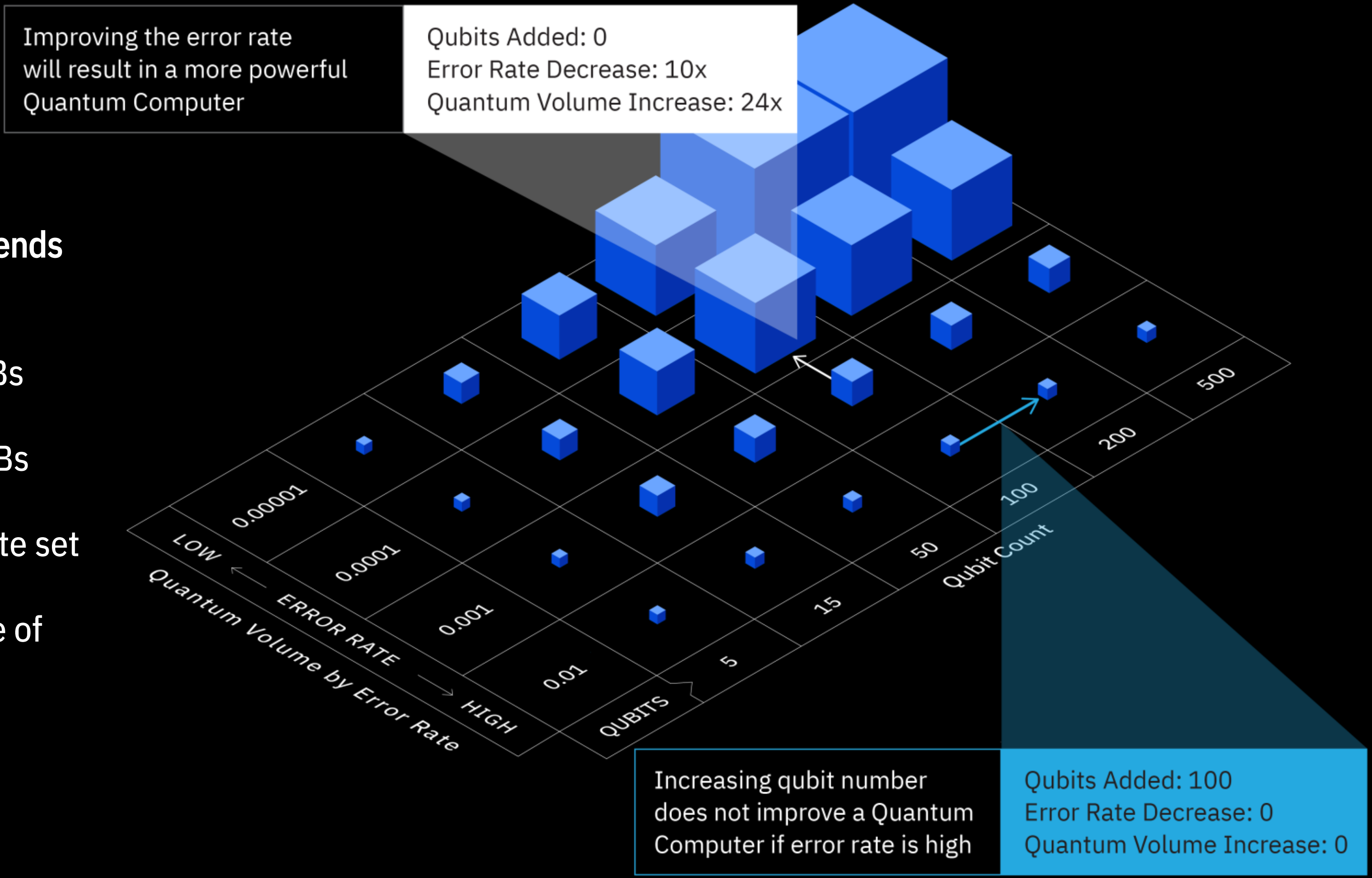
Number of physical QBs

Connectivity among QBs

Available hardware gate set

Error and decoherence of gates

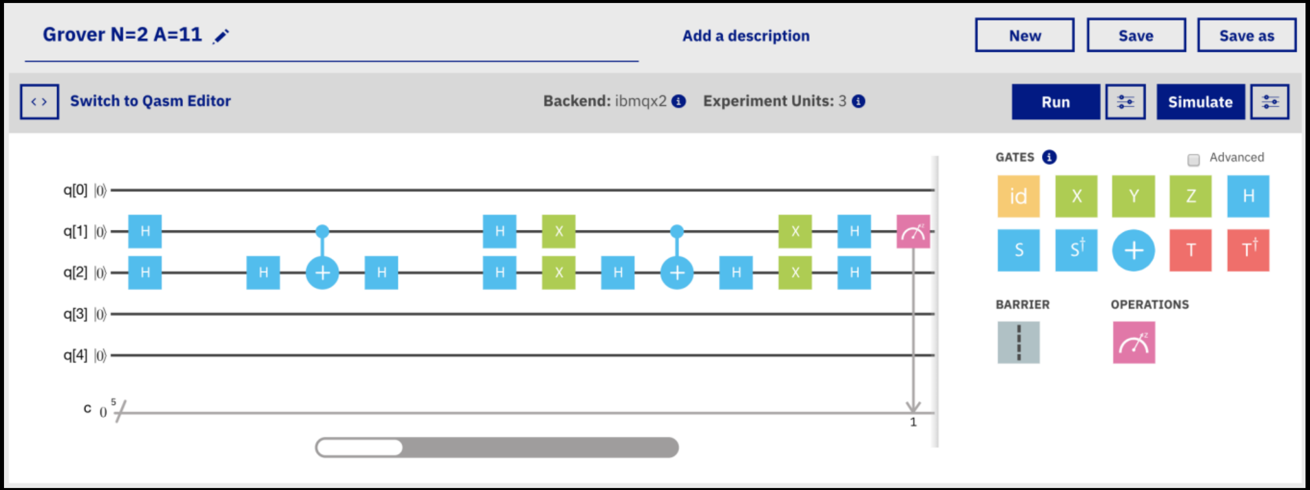
Number of parallel operations



Quantum Computing versus Classical Computing

	Quantum Computing	Classical Computing
Basic Description	Solve a specific set of complex problems that are exponential in nature with a large number of possible answers	Address problems that are less complex and involve searching relatively lesser alternatives to arrive at a solution
Information Representation	Qubits represent data	Uses binary Bits represent data
Computational Capabilities	An appropriate algorithm can allow for exponential speedup of problems that are hard in Classical. Inputs to a Quantum Computer are limited by ability to map to the available Qubits (Quantum Volume)	Data are processed sequentially, making the overall process lengthy and time consuming. Many classical algorithms have runtimes that scale exponentially with input size – these are intractable and therefore require approximations
Commercial Feasibility	Existing systems are small and devoted to research and development of commercial applicability. While commercial clients should engage now, production workloads are years away	Economical and less complex to build and operate
Interpreting Results	Takes advantage of Quantum Mechanics using Quantum Bits along with Quantum Gates to perform Linear Algebra operations. Multiple possible answers are evaluated of which the answer emanating highest confidence is measured	Takes advantage of electrical conductivity property in classical physics using semiconductor based transistors along with logical gates performing Boolean operations, Only specific results are available, limited by algorithmic design

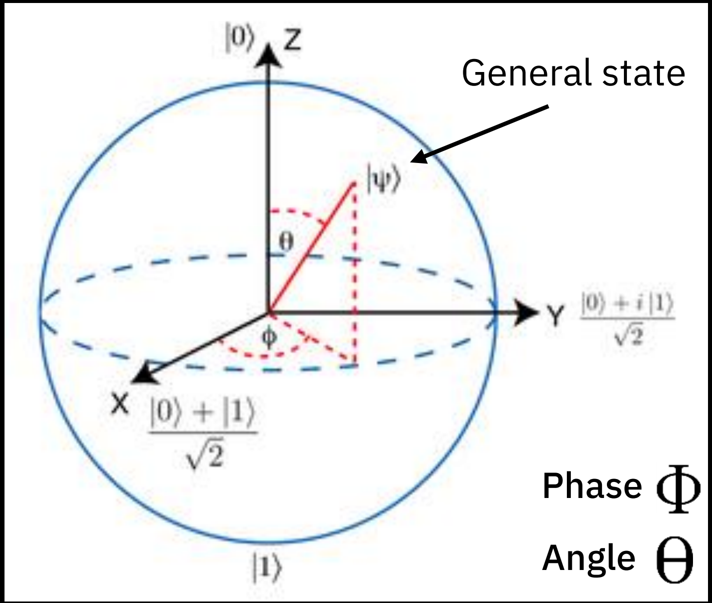
IBM Q Composer



Bloch Sphere

- The states $|0\rangle$ and $|1\rangle$ are on the north- and south pole of the Bloch Sphere
- Potential states cover the whole Bloch Sphere
- A programming step in Quantum Computing is an operation (or “Gate”) on the Qubit and on the Bloch Sphere it is a rotation
- Every step is reversible, because the Qubit can be rotated back to its starting value

state |0>



state |1>

Phase decribes rotations around Z-axis

Angle describes rotations around X-axis

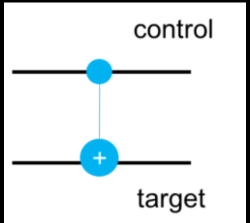
A	B	AND	OR	NOT A
0	0	0	0	1
0	1	0	1	1
1	0	0	1	0
1	1	1	1	0

Multi-Qubit Gate - CNOT Gate

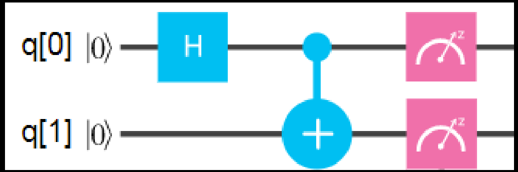
- The least significant Qubit (LSB) is listed at the far right
- The most significant Qubit (MSB) is listed at the far left
- This is consistent with classical binary representation of numbers
- Example: 50% of tile it is both 0 and 50% of the time it is both 1:

$$\frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$$

- Controlled-NOT or CNOT Gate:



Starting state		Ending State
|00>	→	|00>
|10>	→	|10>
|01>	→	|11>
|11>	→	|01>



LSB

MSB

Vector Representation – States

General state – 1 Qubit

$$|\psi> = \alpha \cdot |0> + \beta \cdot |1> = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

With $|\alpha|^2 + |\beta|^2 = 1$ (normalization)

$$P(|0>) = |\alpha|^2 \text{and } P(|1>) = |\beta|^2$$

General state – 2 Qubits

$$|\psi> = \alpha \cdot |00> + \beta \cdot |01> + \gamma \cdot |10> + \delta \cdot |11> = \begin{pmatrix} \alpha \\ \beta \\ \gamma \\ \delta \end{pmatrix}$$

With $|\alpha|^2 + |\beta|^2 + |\gamma|^2 + |\delta|^2 = 1$

Matrix Representation – Gates

General quantum gate

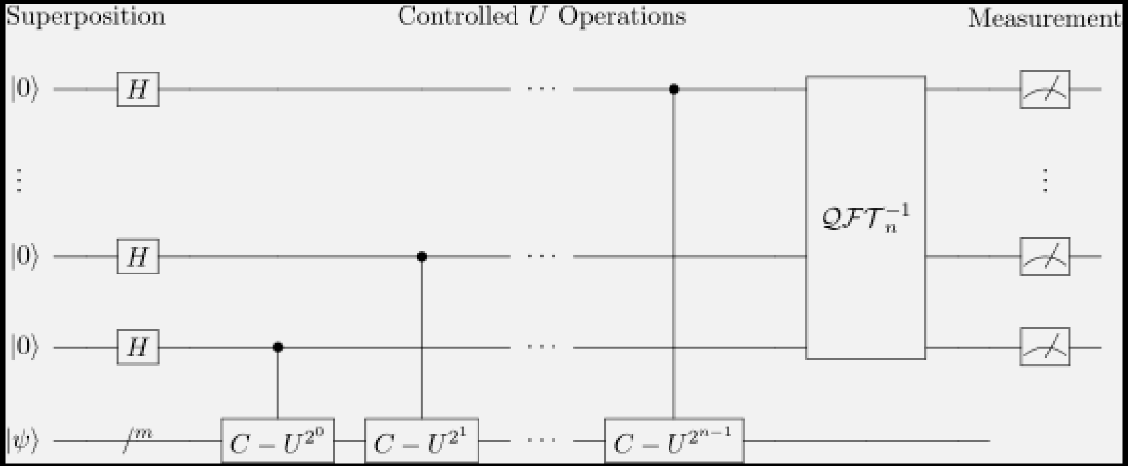
$$|\psi> \;—\; \boxed{A} \;—\; |\psi'>$$

$$|\psi'> \; = A|\psi>$$

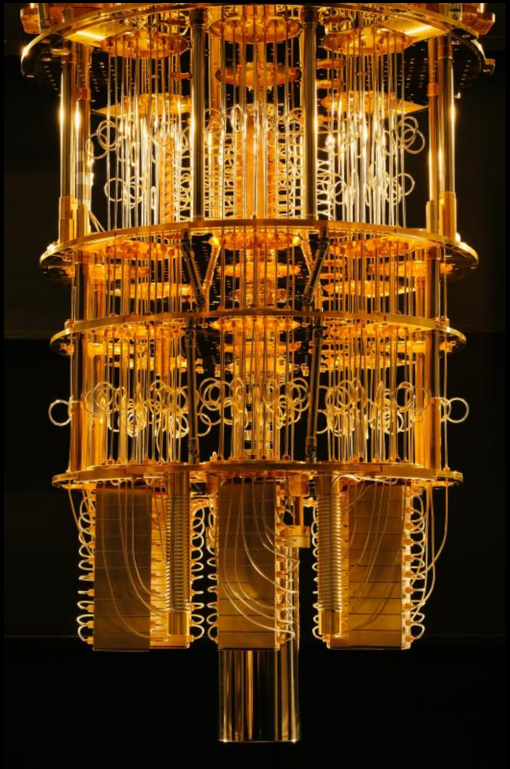
where A is a Unitary operator, which can be represented as a matrix

Quantum Algorithms – General principle

- Start with all Qubits in |0> state
- Put all Qubits in an equal Superposition state (H)
- Based on the problem you want to solve, apply tricks to
  - ✓ Earmark the solution with a phase shifts and detect the solution based on the phase shift
    - o Qubit combination with highest probability
  - ✓ Amplify the probability of measuring the solution
- Measure the result



How many Qubits are required to see Quantum Advantage?



Estimate of the number of "good" qubits required before Quantum Computing shows advantage over conventional

Problem	Type of Quantum Computer	# Qubits for advantage (est)	Years to advantage (est)
Quantum Chemistry	NISQ/Approximate QC	$10^2 \sim 10^3$	< 5 ?
Optimization (specific)	NISQ/Approximate QC	$10^2 \sim 10^3$	< 5 ?
Heuristic machine learning	NISQ/Approximate QC	$10^2 \sim 10^3$	< 5 ?
Shor's algorithm	Universal fault-tolerant QC	$> 10^8$	> 10~15 **if possible**
Big Linear Algebra Programs (FEM)	Universal fault-tolerant QC	$> 10^8$	> 10~15 **if possible**

Quantum Computing shows the potential to disrupt various industries in the time ahead

IBM experts have simulated BeH_2, the largest molecule ever on a Quantum Computer

1. Materials: Quantum Computing can untangle complexity of molecular and chemical interactions enabling **discovery of new materials** or making the **process of manufacturing an existing material more efficient**

2. Financial Services: **Financial Modelling** and **Portfolio Optimization** appear to be the key applications. Other potential uses include helping firms build more attractive asset portfolios, **isolate key global risk factors** in order to make better investments. Research is underway to identify potential applications in **asset pricing,** capital project budgeting, **fraud indication** and **data security**.

3. Oil & Gas: Improving **optimization algorithms** for oil and gas **reservoirs** and helping enterprise become more efficient and accurate, driving growth and efficiency in the resources industry thus **making investors more confident** of the returns and encouraging greater investments

Quantum Computing shows the potential to disrupt various industries in the time ahead (Continued)

4. Transportation: Enabling optimization of autonomous vehicular traffic and help solve complex issues around traffic congestion, routing and safe travel. Another use case is in understanding chemical reactions in car batteries that could lead to the storage of more electricity and a longer battery life

5. Life Sciences: Pharmaceutical companies will use Quantum Computing to identify and develop new medicines for wide range of diseases and conditions.

6. Telecommunications: Enabling optimization of network routing and infrastructure

7. Manufacturing: Supply chain optimization needs work around procurement, production and distribution aspects.

Artificial Intelligence

- Classification
- Machine Learning
- Linear Algebra

- Quantum Communication
- Quantum Simulation
- Quantum Computation
- Quantum Sensing & Metrology

QUANTUM-RESISTANT ENCRYPTION

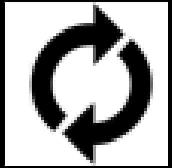
The Emerging Quantum Computing Value Chain

Research Groups ⇄ Component Manufacturers → Technology Providers → Application Developers → Independent Software Vendors (ISV) & Technology Consultants → End Users

But, there are also key Challenges ...

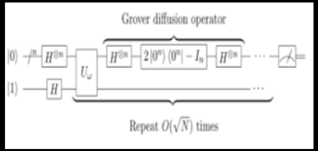
Expense
of building and operating Quantum Computers

Science
required to Scale hardware



Production
grade systems a few years away

Shortage
of skilled personnel



Limited
Quantum Algorithms and high level programming tools

Identifying
early use cases that show Quantum advantage

IBM Quantum Offerings Today

IBM Q System Access

- *Client can develop applications with API access to Qubits*
- *On-Premise Simulator with Power 9 GPUs*

IBM Q Joint Development Collaboration

- *Defined SoW*
- *Access to most advanced hardware*

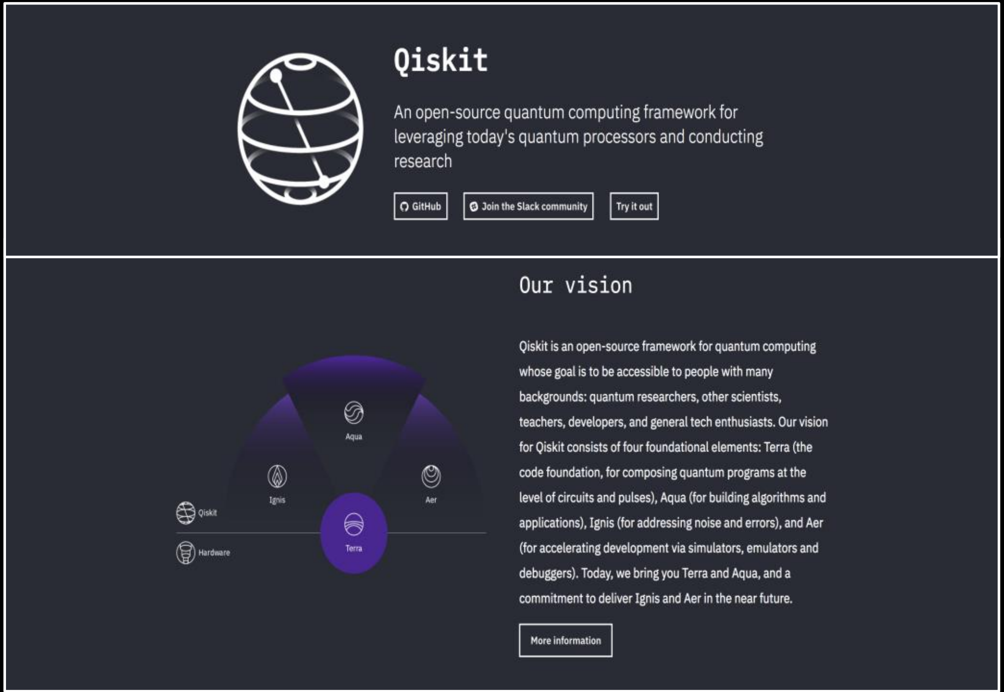
IBM Secuirty Quantum Safe Readiness Assessment

- *Educate on what kinfs of encryption are at risk*
- *Evaluate options*

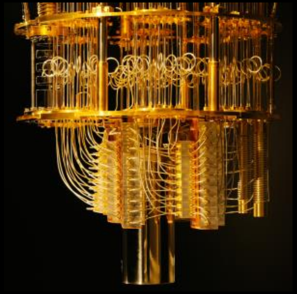
IBM Q Strategy Consulting

- *Assess apolicability of Quantum Computing in the company*
- *Develop a roadmap for Quantum Computing*

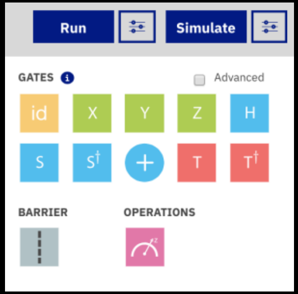
Start Here:
https://www.research.ibm.com/ibm-q/



Your next steps to getting "Quantum Ready"



Discover more about IBM's quantum computing initiative



Explore the **IBM Q Experience** and start using real machines today

Learn about and start using the **Qiskit** software development kit

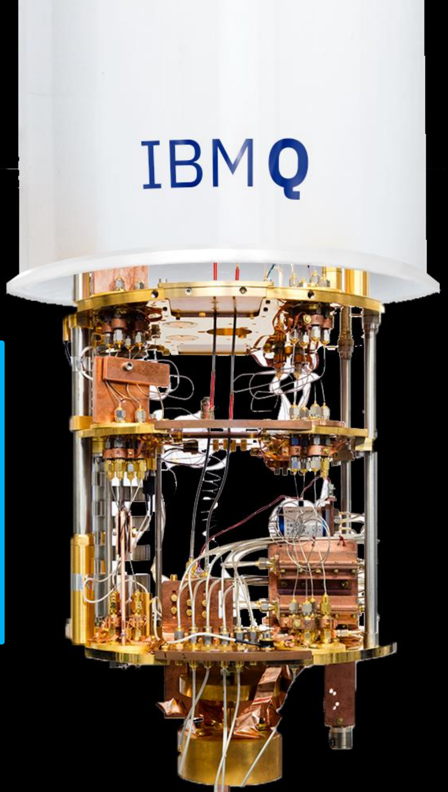
Collaborate, research, and start applying Quantum Computing through the **IBM Q Network**

Quantum Algorithm Zoo https://math.nist.gov/quantum/zoo/

Computer Science > Emerging Technologies

Quantum Algorithm Implementations for Beginners https://arxiv.org/abs/1804.03719

ThanQ for your presence and attention!



Hello Quantum