Perspectives on quantum computing with near-term devices

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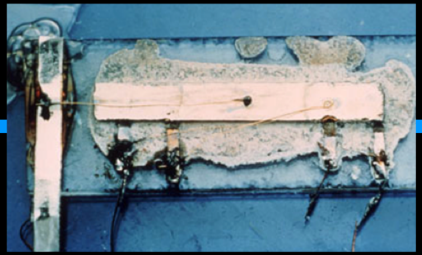
Switzerland

EMIT@CIUK Workshop, Dec 13, 2017, Manchester, UK.

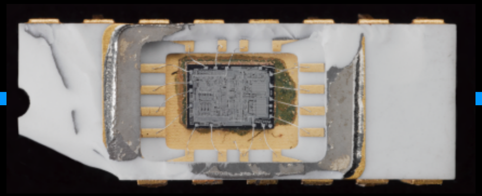
Why Quantum Computing? Why now?

1958



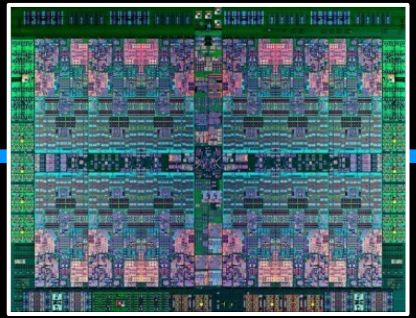
First integrated circuit
Size ~1cm^2
2 Transistors

1971

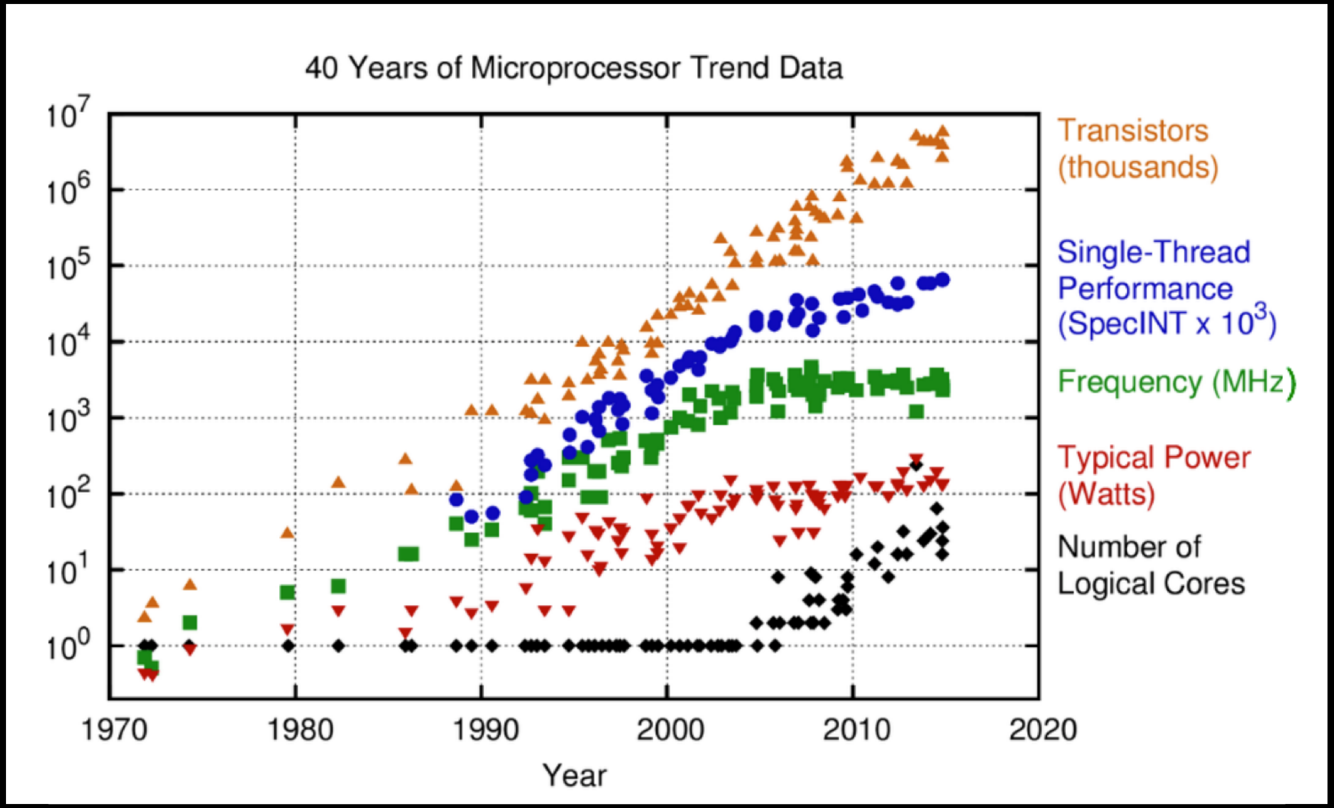


Moore's Law is Born
Intel 4004
2,300 transistors

2014

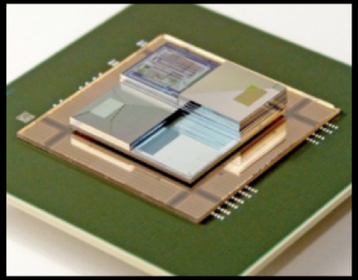


IBM P8 Processor ~ 650 mm^2
22 nm feature size, 16 cores
> 4.2 Billion Transistors



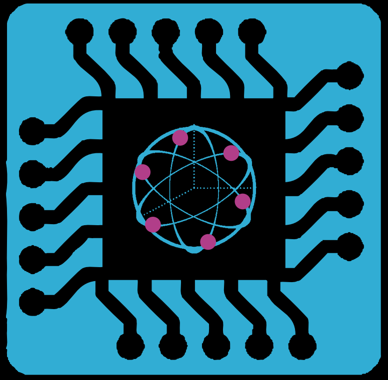
Alternative (co-existing) architectures:

next generation systems (3D/hybrid)



neuromorphic (cognitive)

quantum computing



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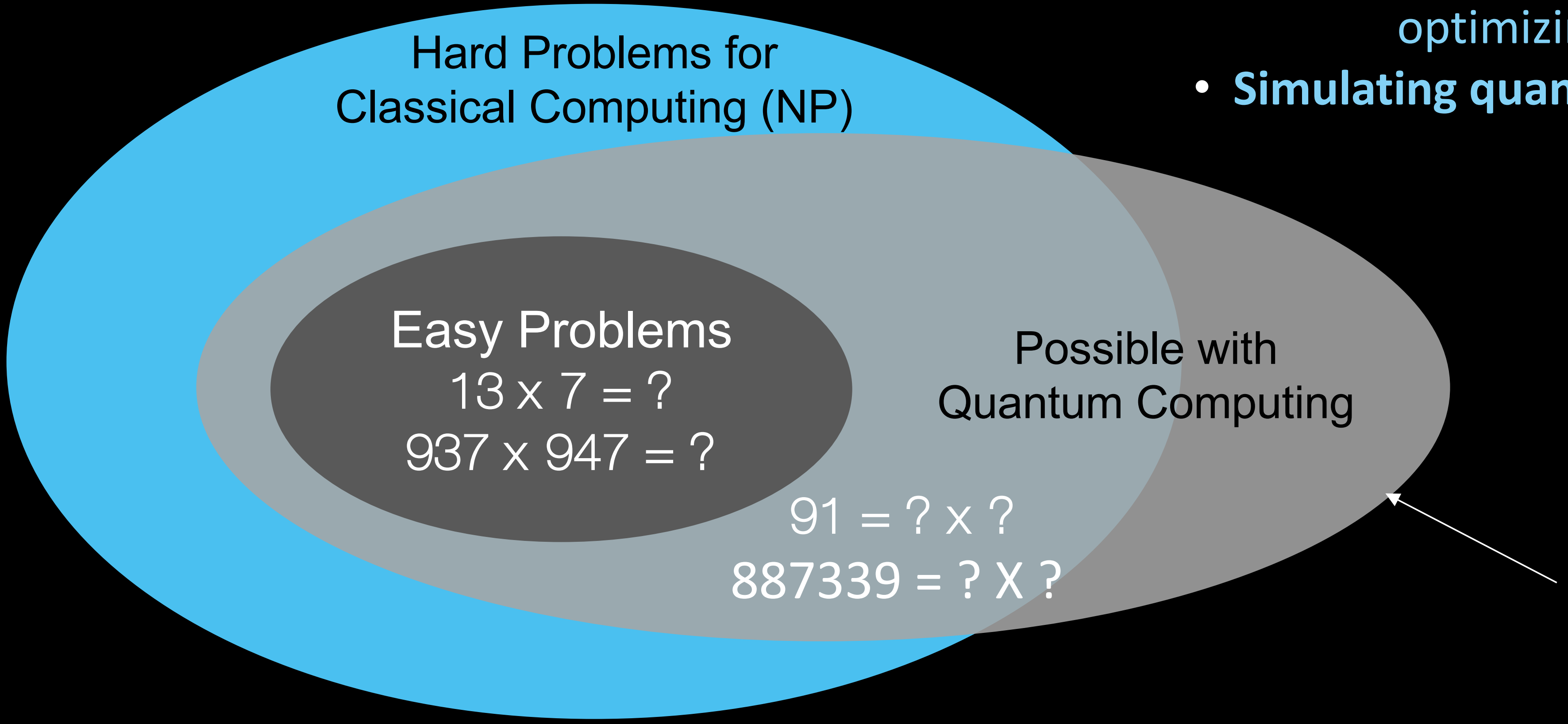
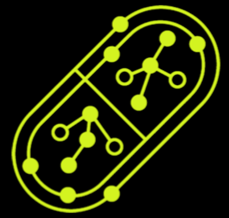
Quantum Computing as a path to solve intractable problems

Many problems in business and science are too complex for classical computing systems

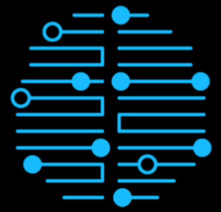
"hard" / intractable problems:
(exponentially increasing resources with problem size)

- **Algebraic algorithms** (e.g. factoring, systems of equations) for machine learning, cryptography,…
- **Combinatorial optimization** (traveling salesman, optimizing business processes)
- **Simulating quantum mechanics** (chemistry, material science,…)

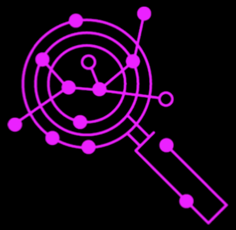




Material, Chemistry



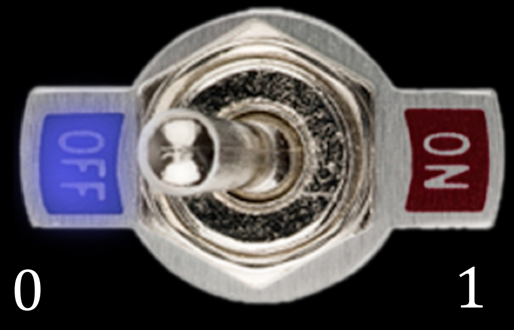
Machine Learning



Optimization

What are the basic units of information ?

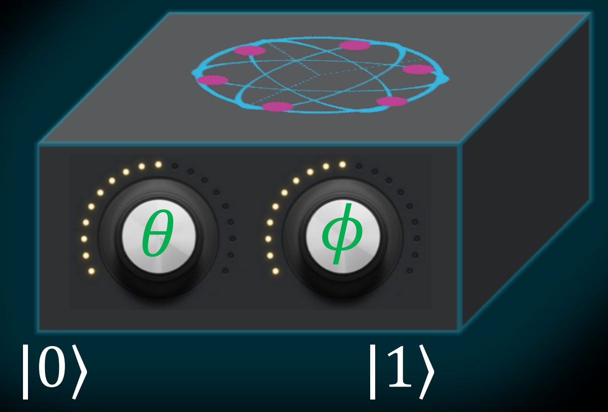
Bit:



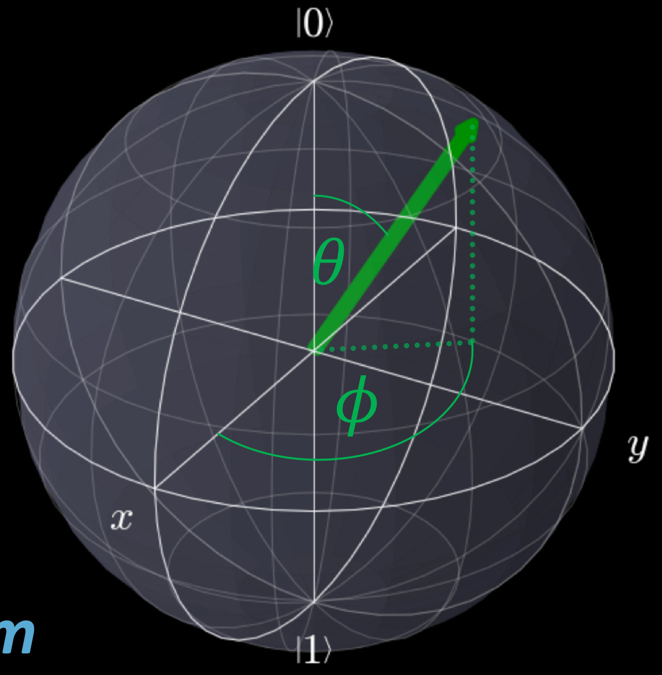
Bit state: 0 or 1

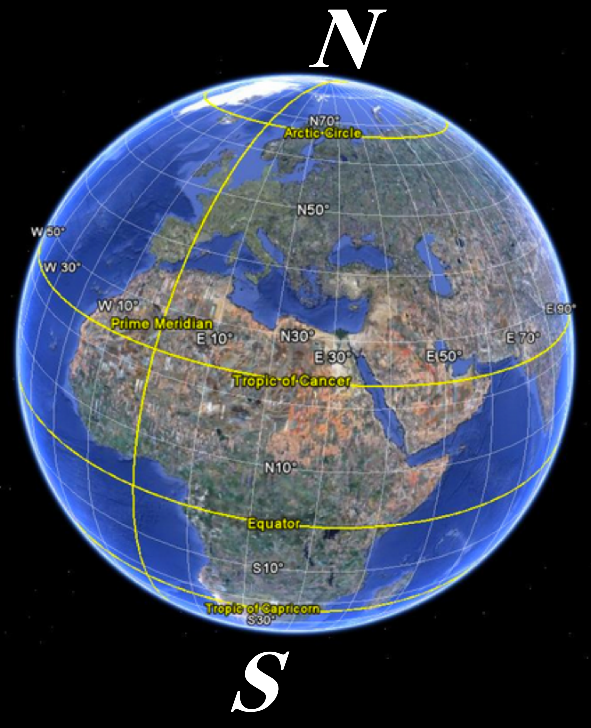
classical

Qubit:



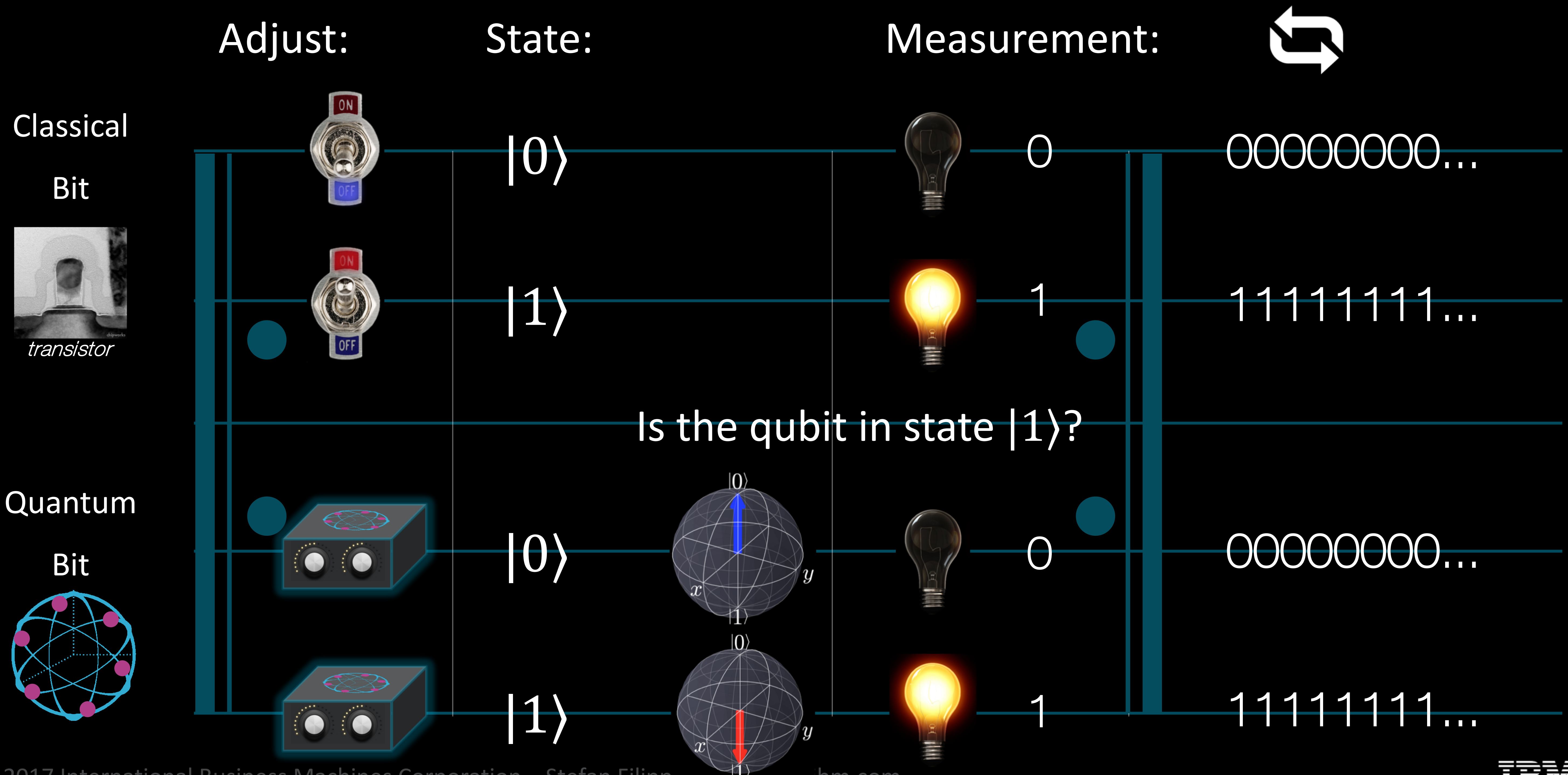
Qubit state: 0 and 1, at the same time (= superposition)
represented by point on (Bloch-)Sphere



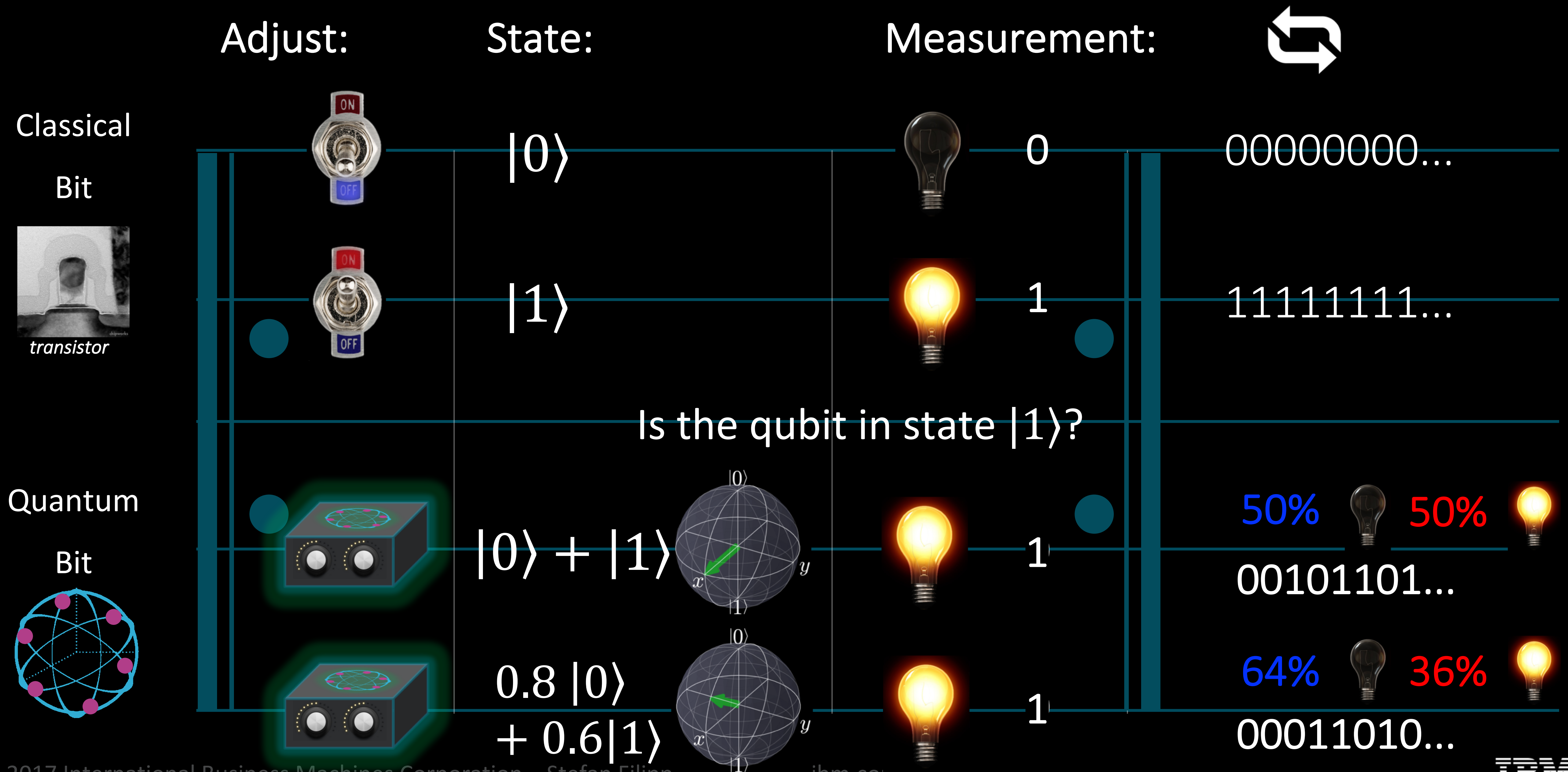


quantum

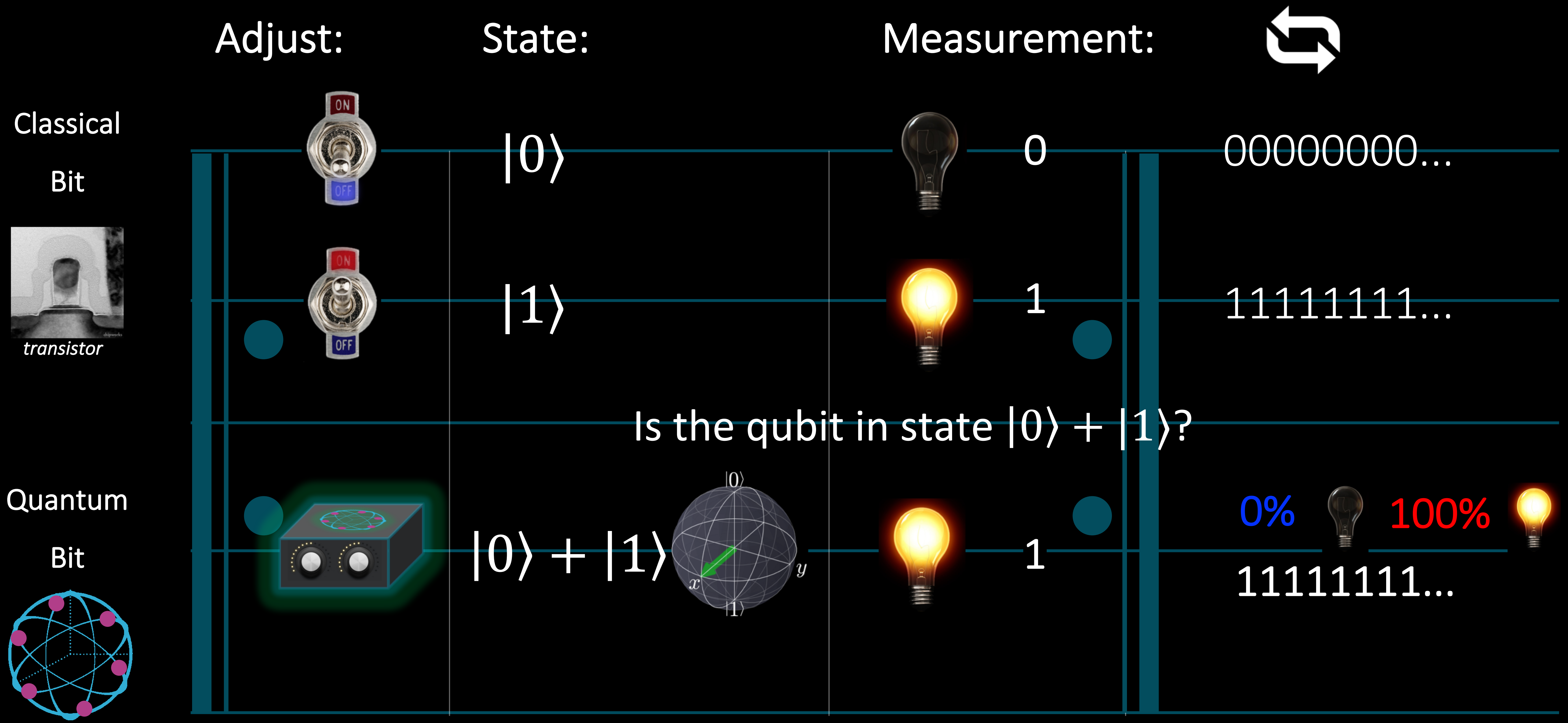
Bits and Qubits



Bits and Qubits



Bits and Qubits

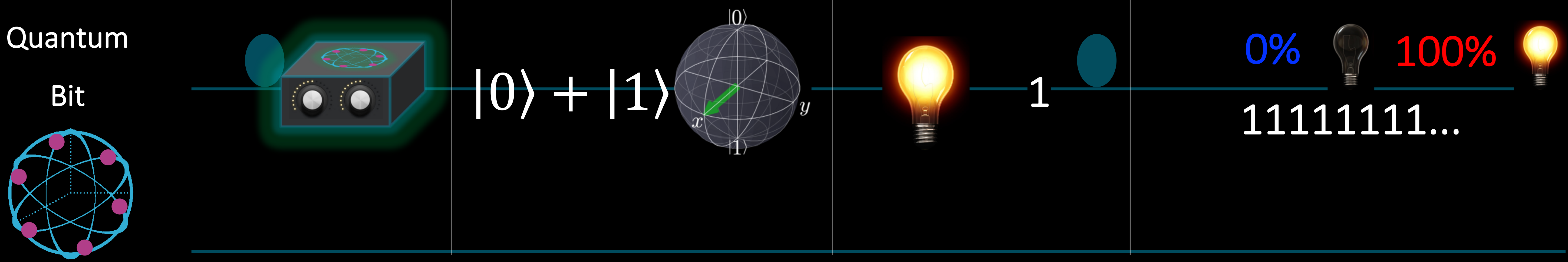


Bits and Qubits

Adjust: State: Measurement:

- ***A measurements yields always either 0 or 1.***
- ***The qubit superposition state reflects the probability to measure 0 or 1.***
- ***The measurement can destroy superpositions. Noise can be regarded as a measurement.***

Is the qubit in state $|0\rangle + |1\rangle$?



Multiple Bits: Quantum-Parallelismus

Adjust: | State: | Measurement:

Classical

Bit

$|0\rangle$

$|1\rangle$

$|01\rangle$

$|01\rangle$

100%

Multi-qubit states can 'store' many classical bits at the same time:

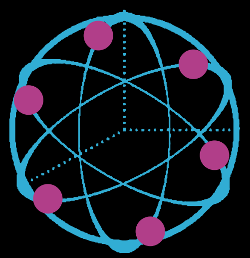
1 qubit - 2 states at the same time,

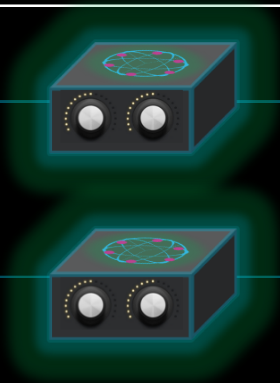
2 qubits - 4 states at the same time, …

This 'entanglement' is a key resource for quantum computing.

Quantum

Bit





$|0\rangle + |1\rangle$

$|0\rangle + |1\rangle$

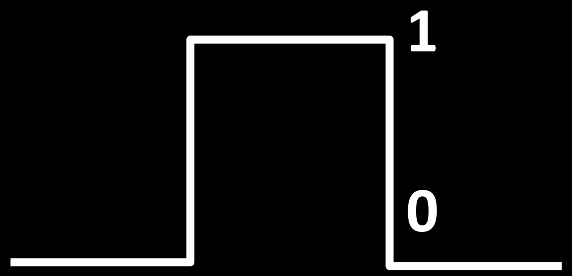
$|00\rangle+|01\rangle+|10\rangle+|11\rangle$

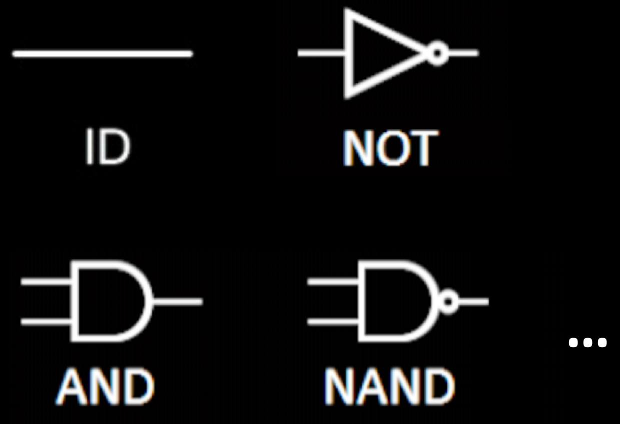
$|00\rangle$ $|01\rangle$ $|10\rangle$ $|11\rangle$

25% 25% 25% 25%

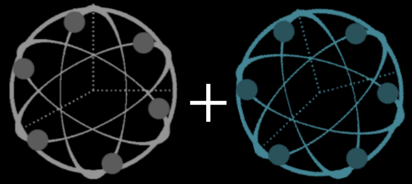
Quantum computation

Computer science:
two logical states
+ gates

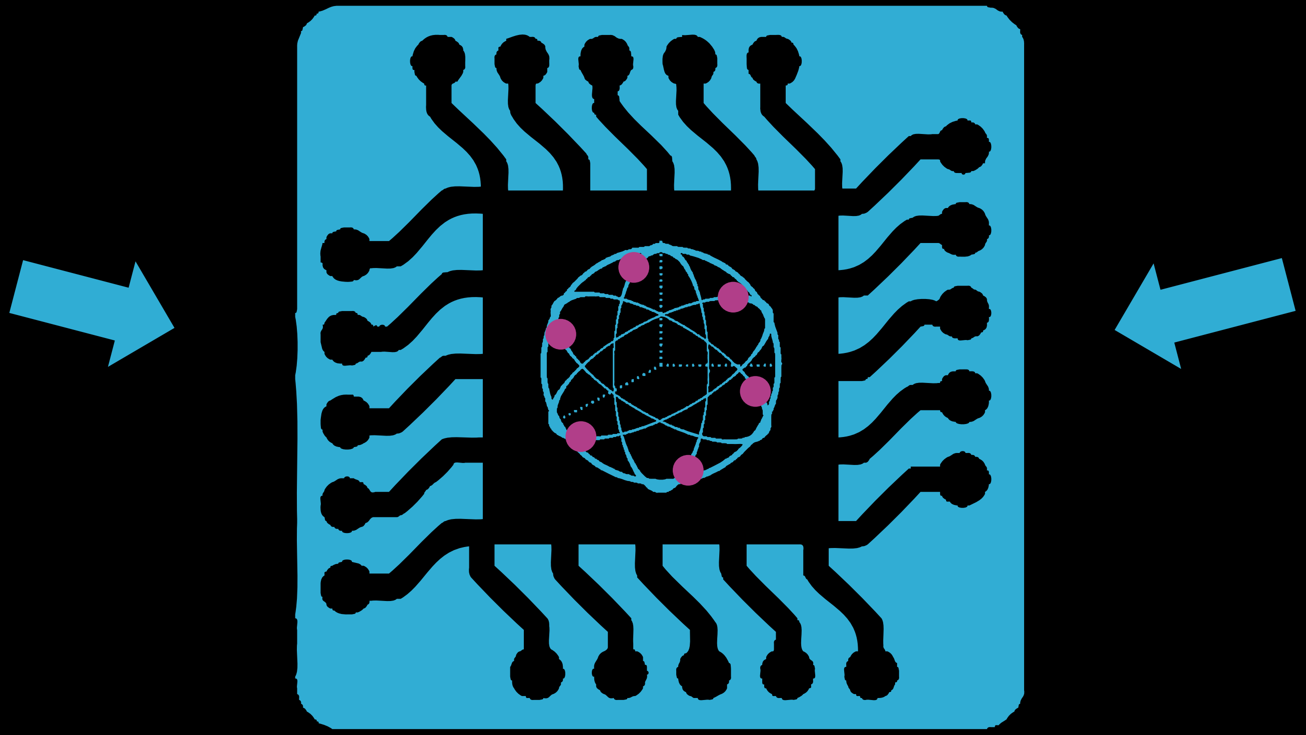




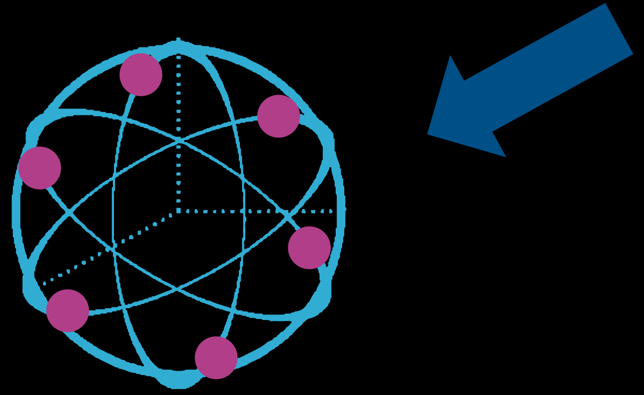
$\alpha|0\rangle + \beta|1\rangle$

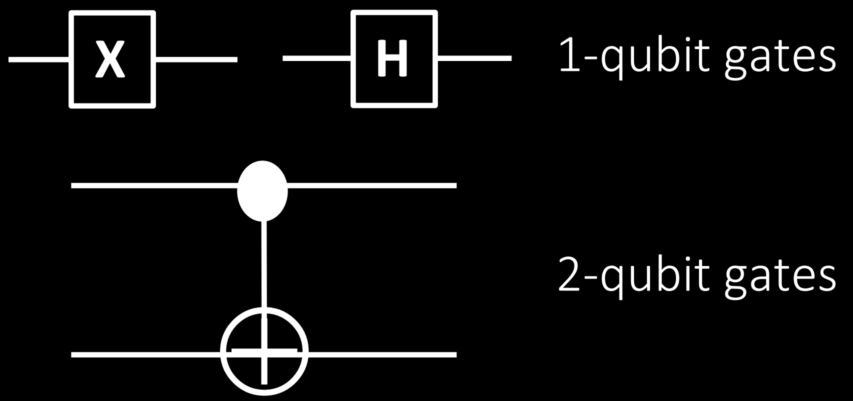


superposition

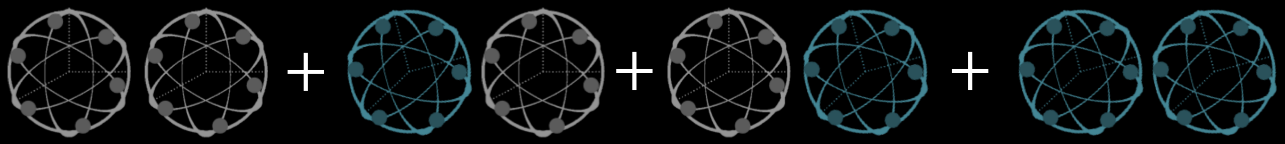


quantum physics:
discrete quantum states (qubits)
+ unitary evolution





entanglement



$\alpha|00\rangle + \beta|10\rangle + \gamma|01\rangle + \delta|11\rangle$

The Quantum Advantage – Simulation of physical systems

How much memory is needed to store a quantum state?

How much time does it take to calculate dynamics of a quantum system?

# qubits	quantum state	coefficients	# bytes	timescale
1	$a\|0\rangle + b\|1\rangle$	$2^1 = 2$	16 Bytes	
2	$a\|00\rangle + b\|01\rangle + c\|10\rangle + d\|11\rangle$	$2^2 = 4$	32 Bytes	Nanoseconds
8		$2^8 = 256$	2kB	Microseconds on watch
16	…	$2^{16} = 65'536$	256 kB	Milliseconds on smartphone
32	…	~4 billion	256 GB	Seconds on laptop
64	…	~ information in internet	74 EB (74 million GB)	Years on supercomputer
256	…	~ # of atoms in universe	…	never

classical

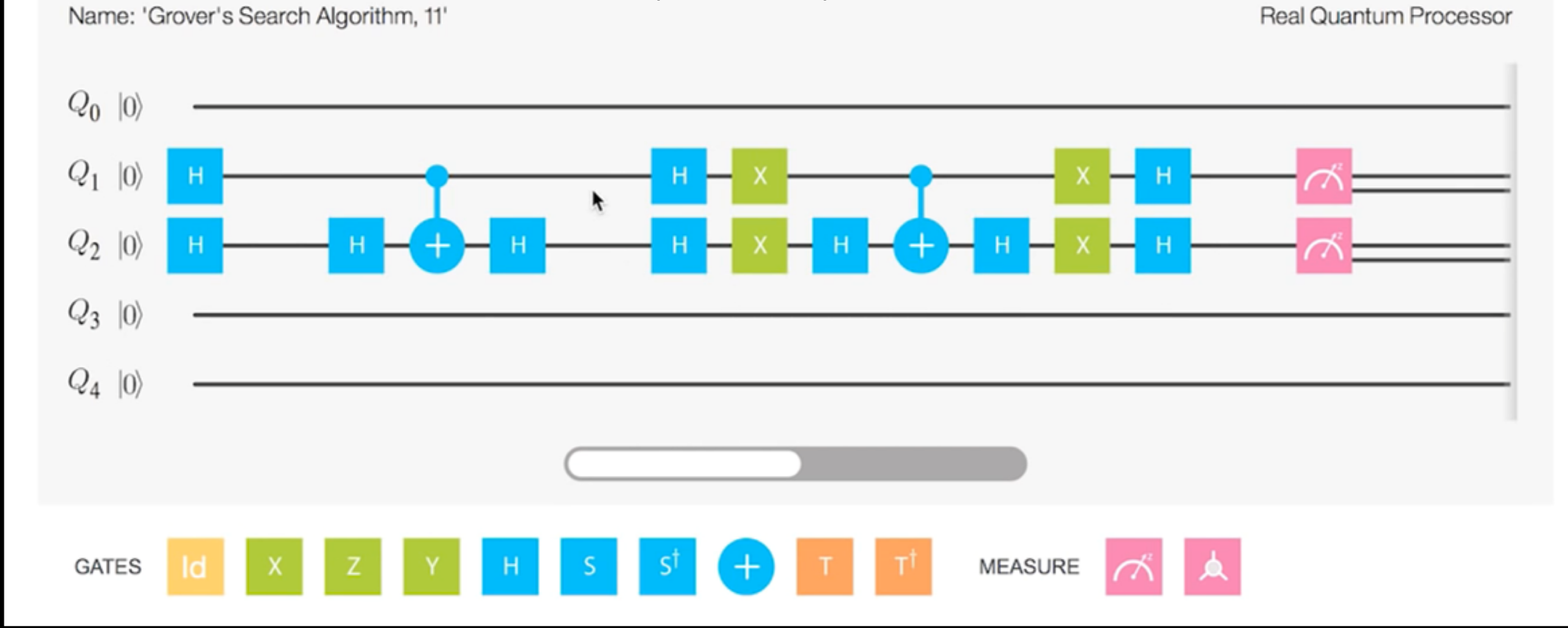
quantum

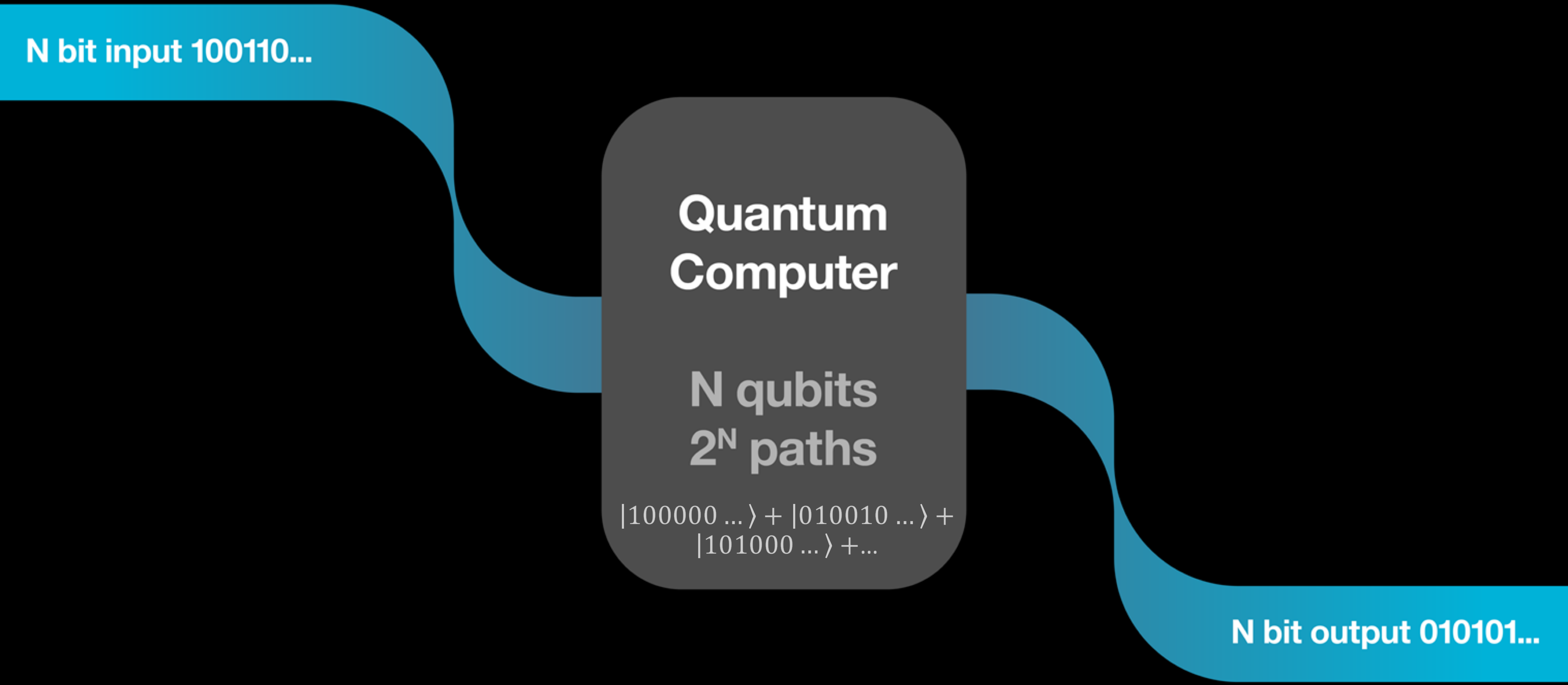
IBM

Gate based quantum computing

evolve initial states via discrete gates towards final state, the solution

IBM 'quantum experience'





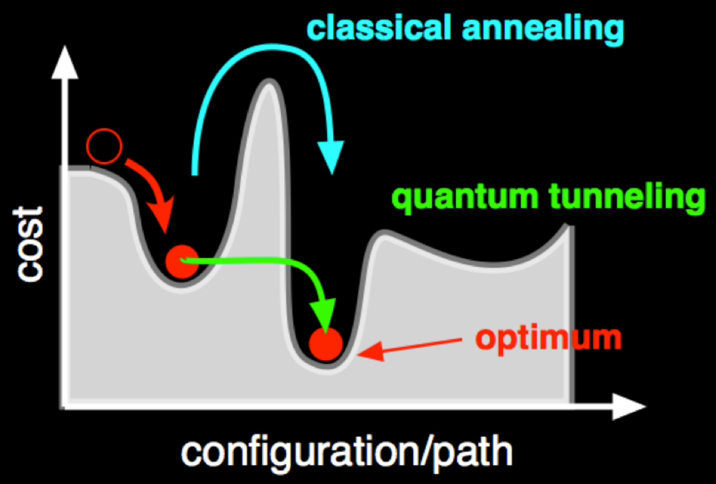
N bit input 100110...
Quantum Computer
N qubits
2^N paths
$|100000\ldots\rangle + |010010\ldots\rangle +$
$|101000\ldots\rangle + \ldots$
N bit output 010101...

Types of Quantum Computing

Quantum Annealing

Optimization Problems

- Machine learning
- Fault analysis
- Resource optimization
- etc…

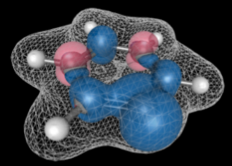


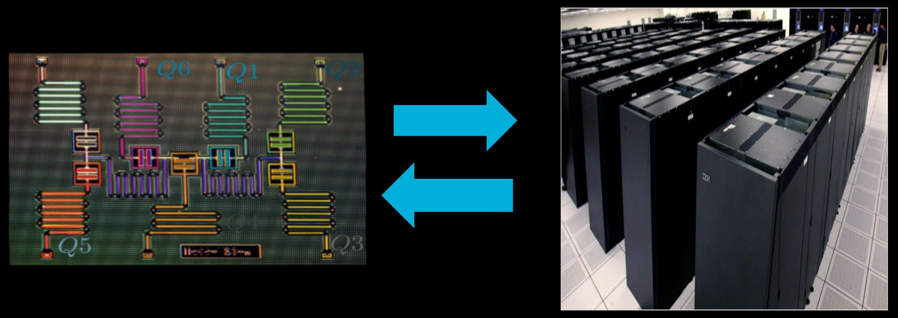
Many ‘noisy’ qubits can be built;
large problem class in optimization;
amount of quantum speedup unclear

Approximate Q-Comp.

Simulation of Quantum Systems, Optimization

- Material discovery
- Quantum chemistry
- Optimization
  (logistics, time scheduling,…)
- Machine Learning



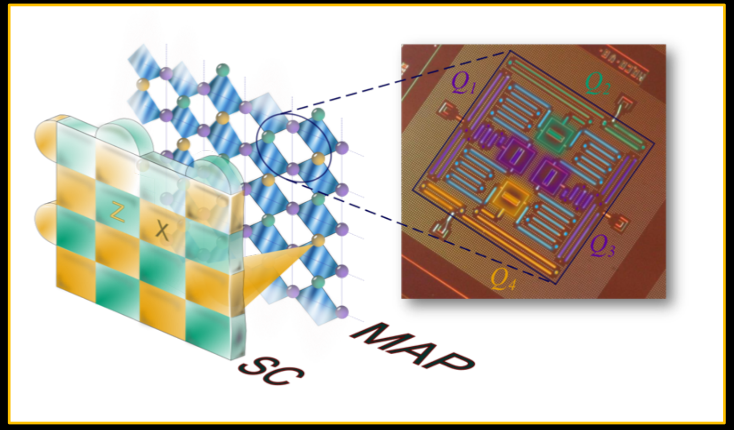


Hybrid quantum-classical approach;
already 50-100 “good” physical qubits
could provide quantum speedup.

Fault-tolerant Universal Q-Comp.

Execution of Arbitrary Quantum Algorithms

- Algebraic algorithms
  (machine learning, cryptography,…)
- Combinatorial optimization
- Digital simulation of quantum systems



Surface Code: Error correction in a Quantum Computer

Proven quantum speedup;
error correction requires significant qubit overhead.

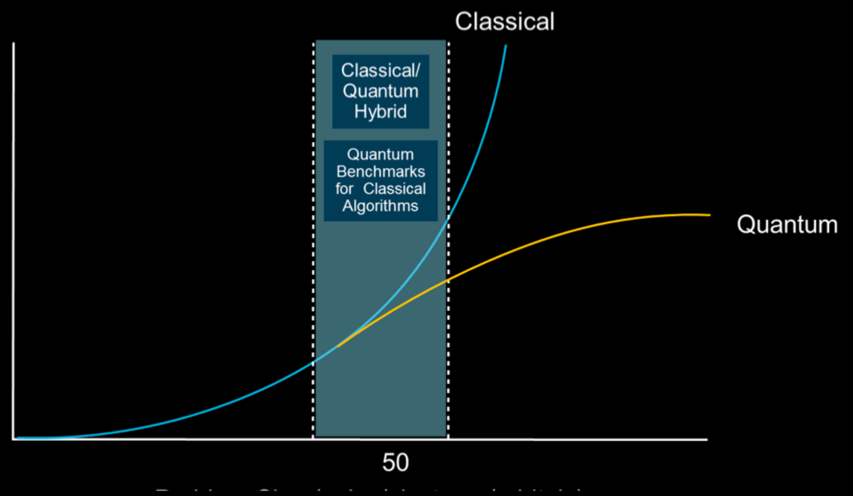
Steps towards Universal Quantum Computing

time / complexity

Demonstration of Quantum Advantage & Learning

Demonstrate an advantage to using quantum computing for real problems of interest. Create software layer, quantum algorithms and education tools.

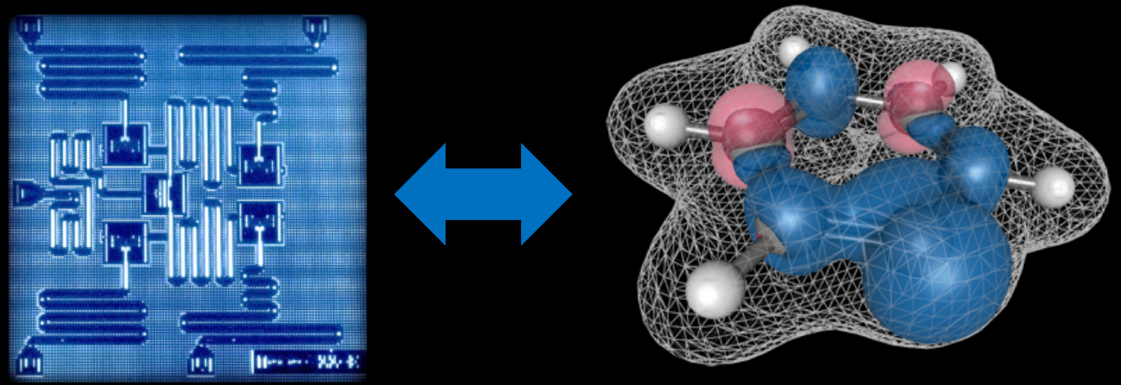
50-100 qubits



Commercialization of Approximate Quantum Computer

Have commercial impact with useful applications on a quantum computer which does not need full fault tolerance, potentially assisting conventional computers (hybrid quantum computer)

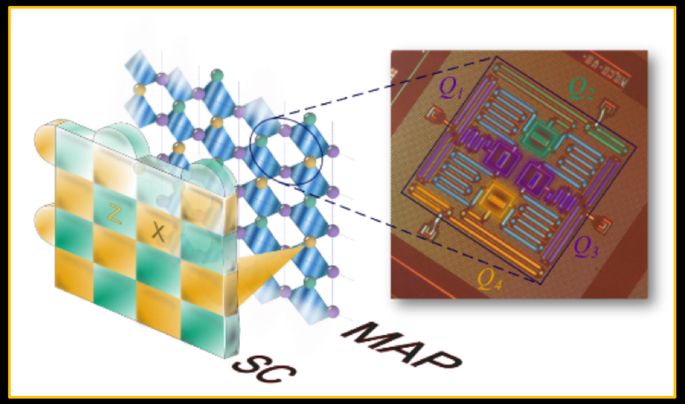
100-1000+ qubits



Universal Fault-Tolerant Quantum Computer

Run useful quantum algorithms with exponential speed up over their classical counterparts. Requires error correction.

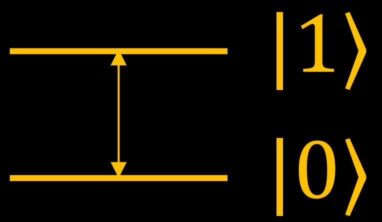
1M-10M qubits



Physical qubit realizations

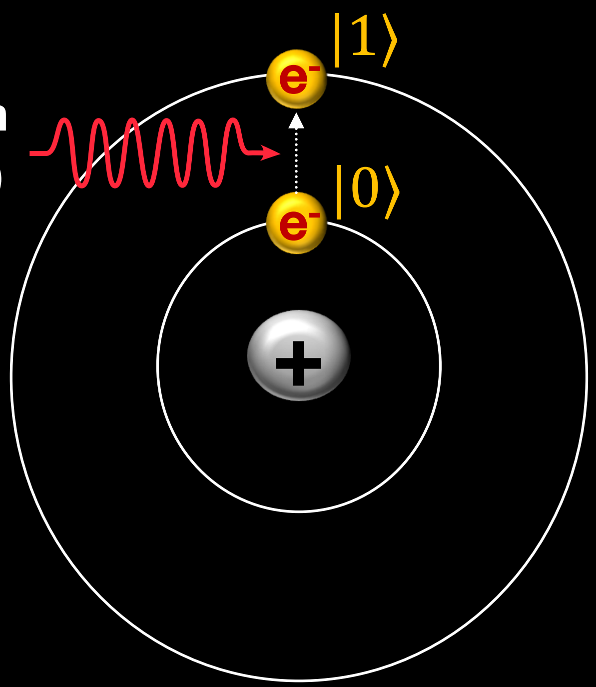
Quantum Bits:

Two-Level Systems

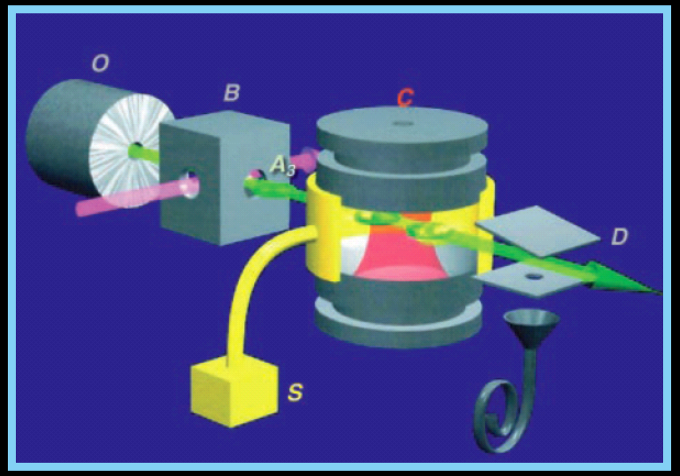


Example:
Atom orbitals with different energetic levels

Photon (Laser)

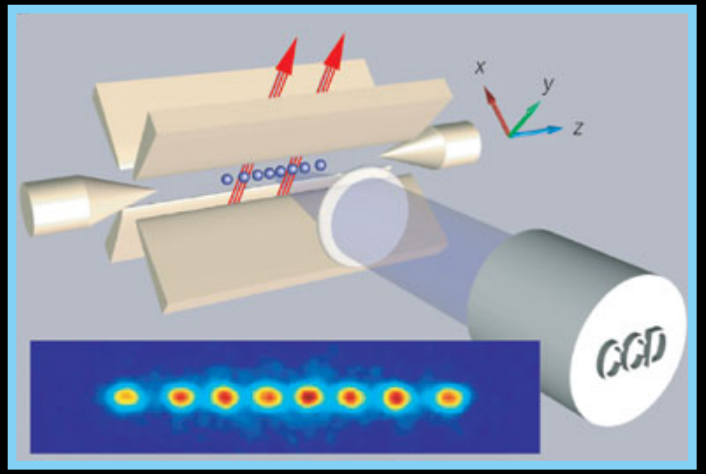


Neutral Atoms



© Haroche

Ion Traps



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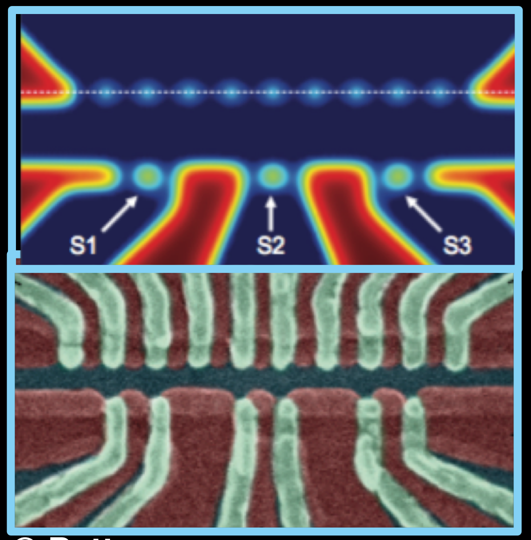
Quantum Dots



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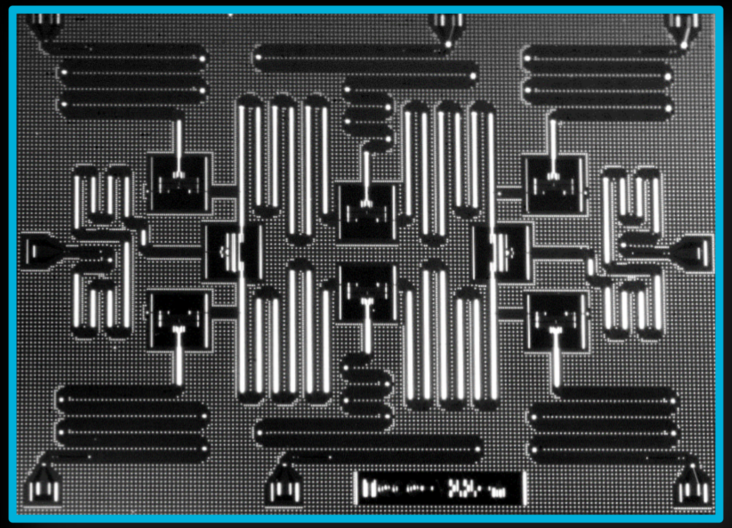
Superconducting Circuits



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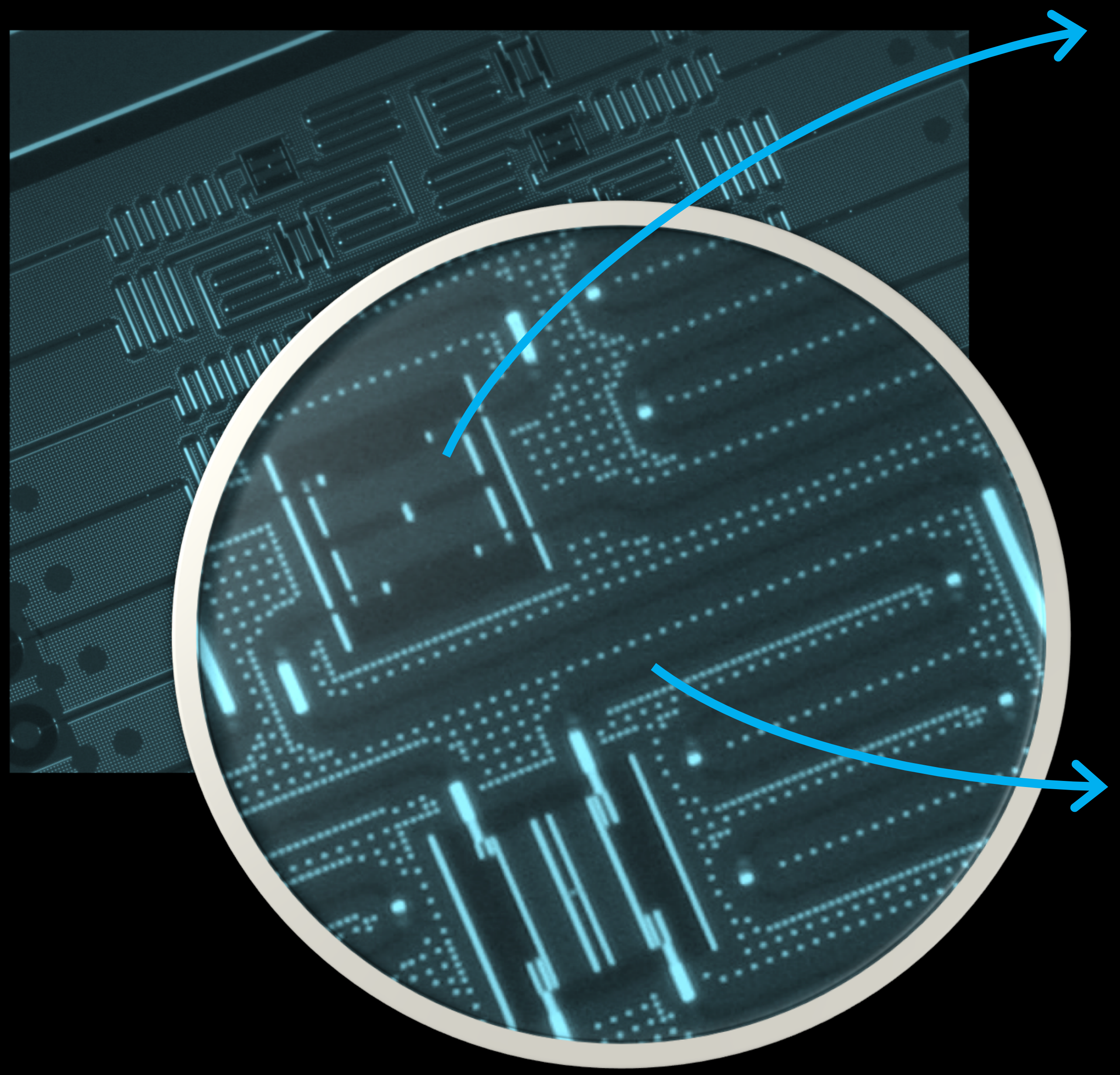
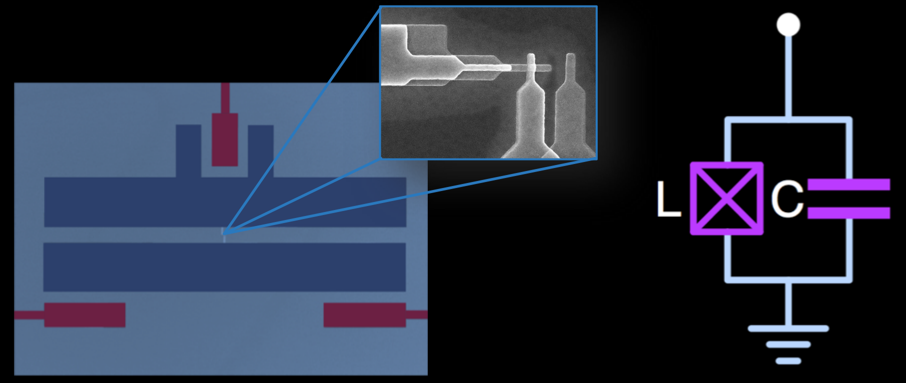
IBM: Superconducting Qubit Processor



Superconducting qubit

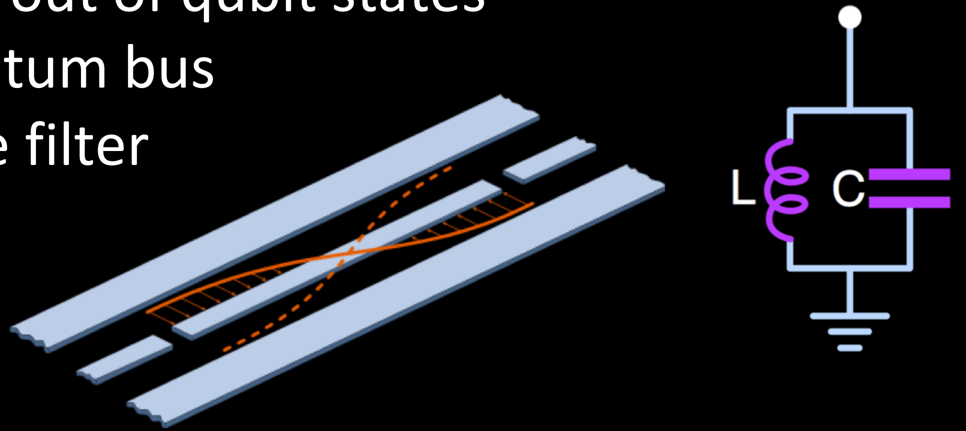
- quantum information carrier



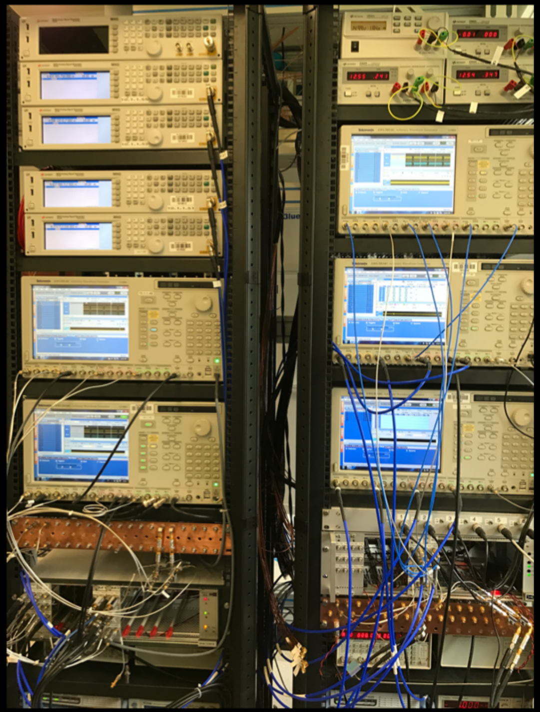
$E_{01} \approx 5\ GHz \approx\ 240\ mK$

Microwave resonator:

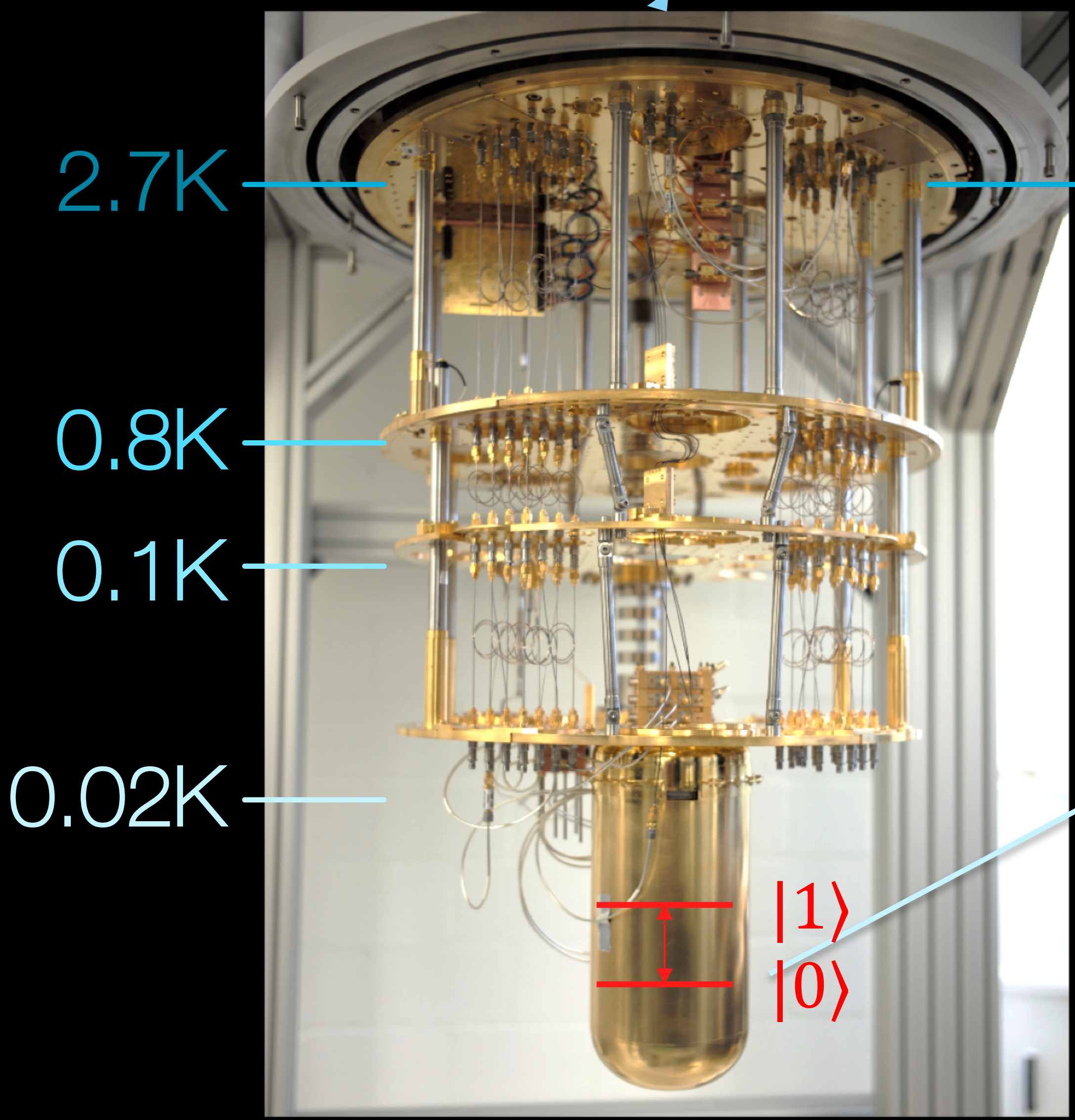
- read-out of qubit states
- quantum bus
- noise filter



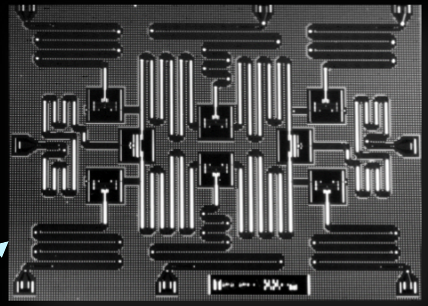
Measurement setup



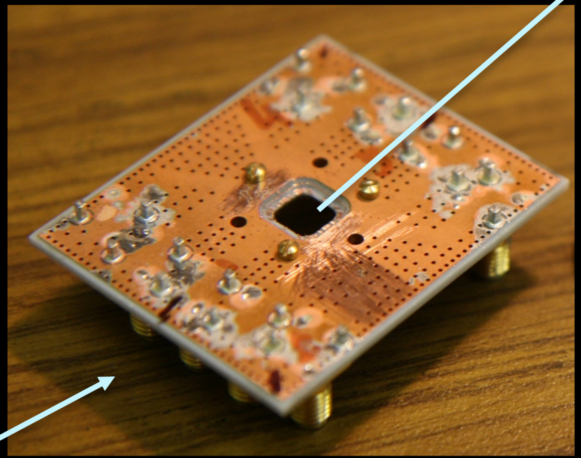
Microwave electronics



Dilution cryostat



Chip with superconducting qubits and resonators



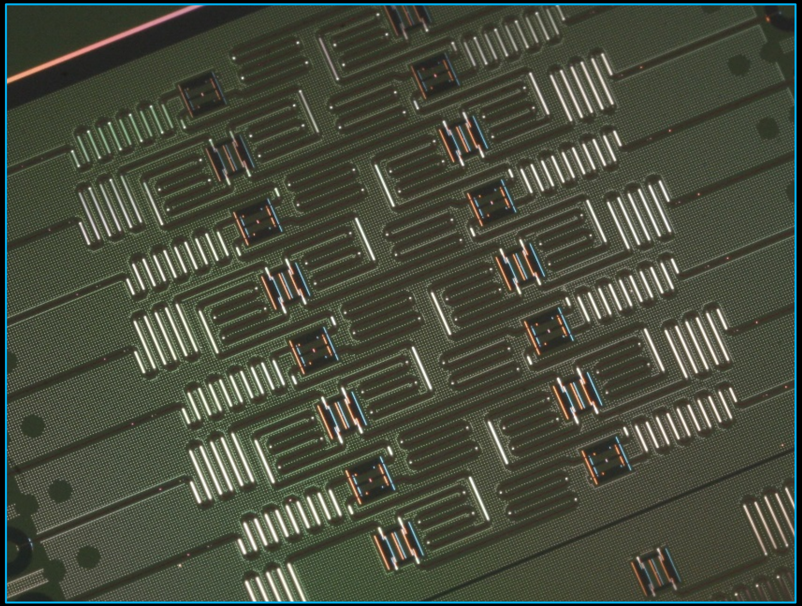
PCB with the qubit chip at 20mK
Protected from the environment by multiple shields

IBM

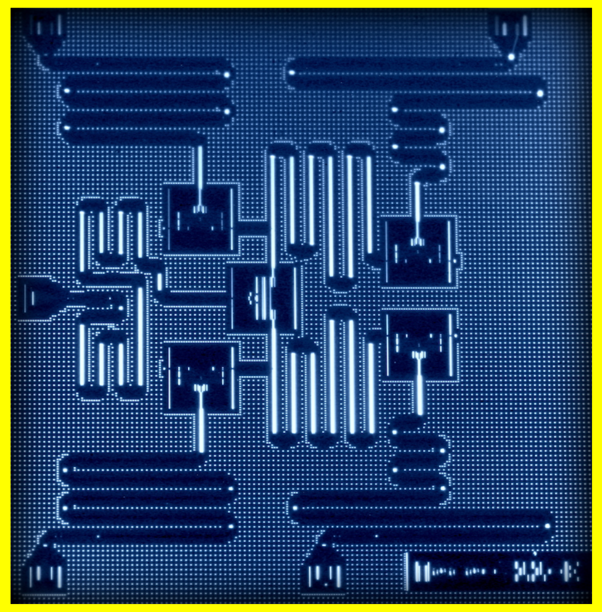
IBM qubit processor architectures

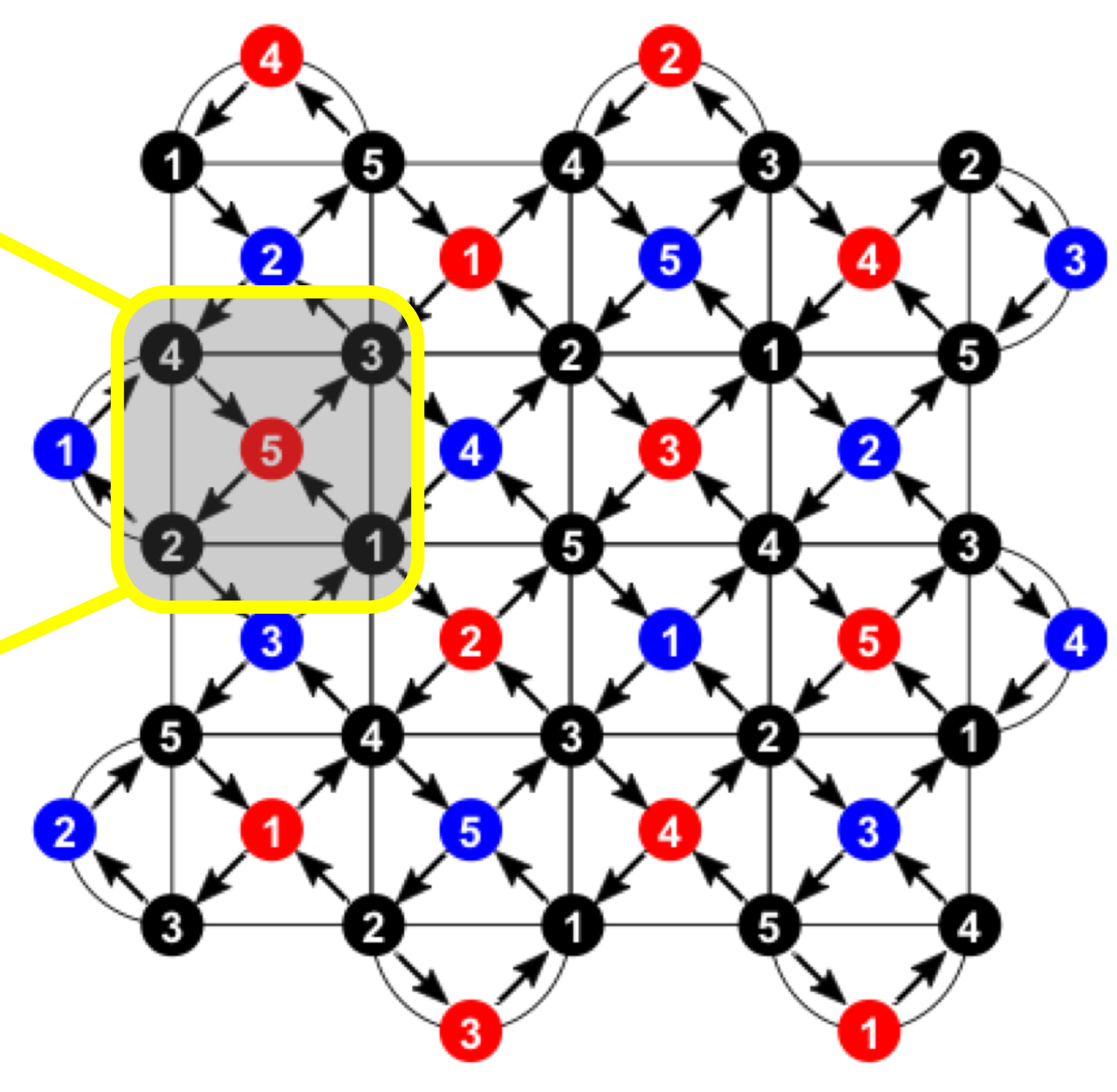
IBM Q experience (publicly accessible)

16 Qubits (2017)



5 Qubits (2016)

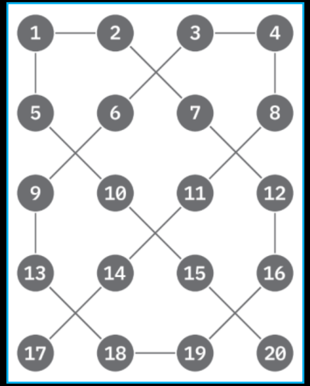




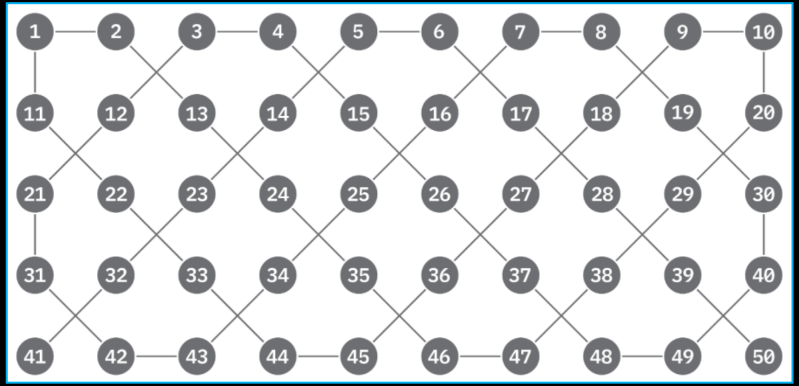
Latticed arrangement for scaling

IBM Q commercial

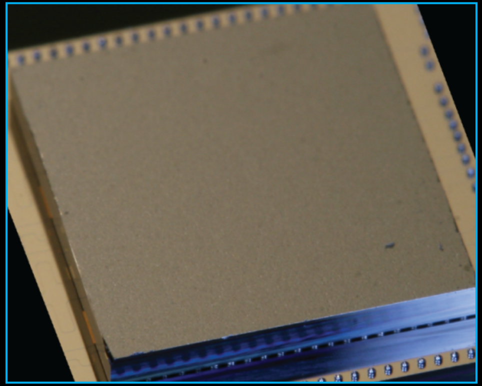
20 Qubits



50 Qubit architecture (2017)



Package



Quantum lab

Quantum chemistry

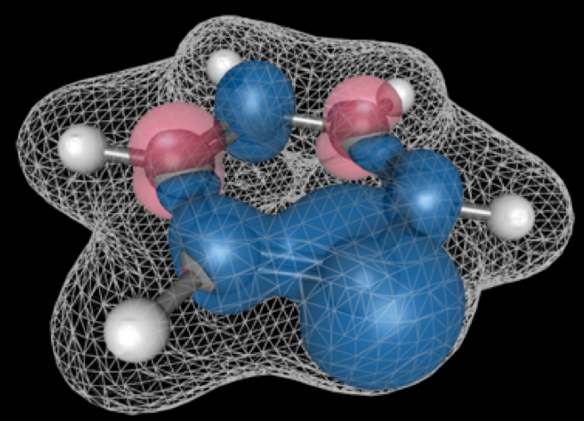
Solving interacting fermionic problems is at the core of most challenges in computational physics and high-performance computing:

$$H_e = -\sum_{i=1}^{N} \frac{1}{2}\nabla_i^2 - \sum_{i=1}^{N}\sum_{A=1}^{M}\frac{Z_A}{r_{iA}} + \sum_{i=1,j,i>1}\frac{1}{r_{ij}}$$

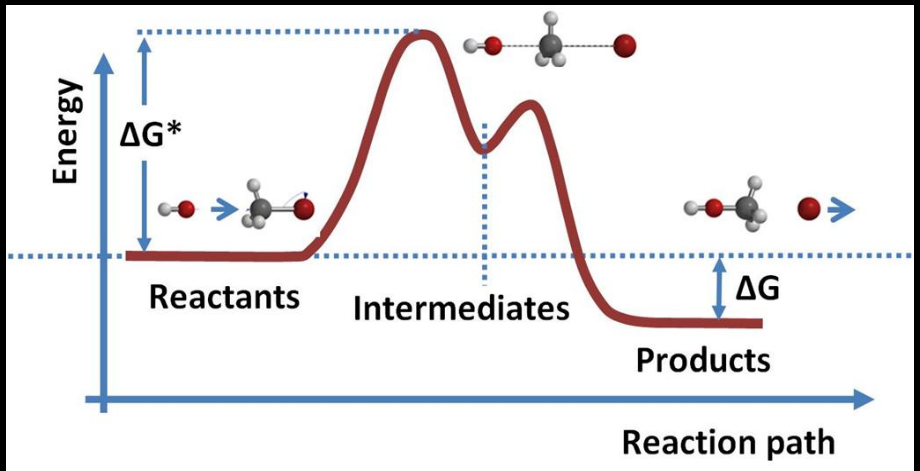
What can quantum computers do?

Map fermions (electrons) to qubits and compute

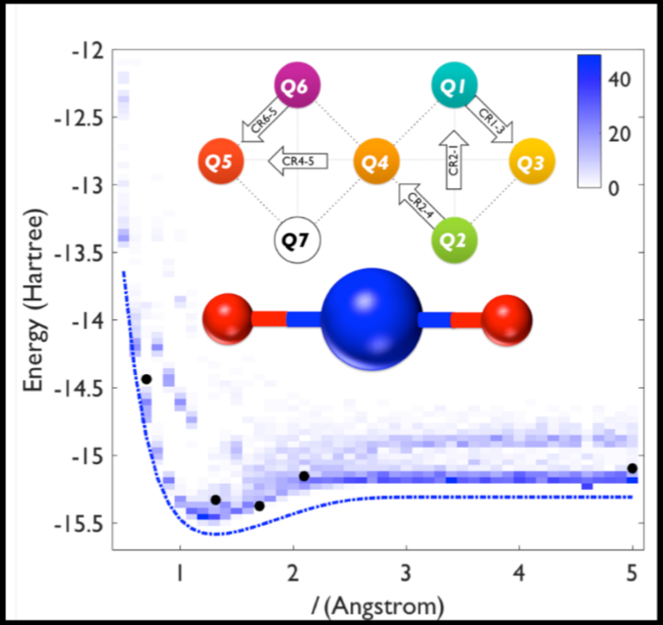
molecular structure



reaction rates



First Demonstrations:



144 pauli terms, 36 sets

A. Kandala, et al. Nature 549 (2017)

Sign problem: Monte-Carlo simulations of fermions are NP-hard [Troyer &Wiese, PRL 170201 (2015)]

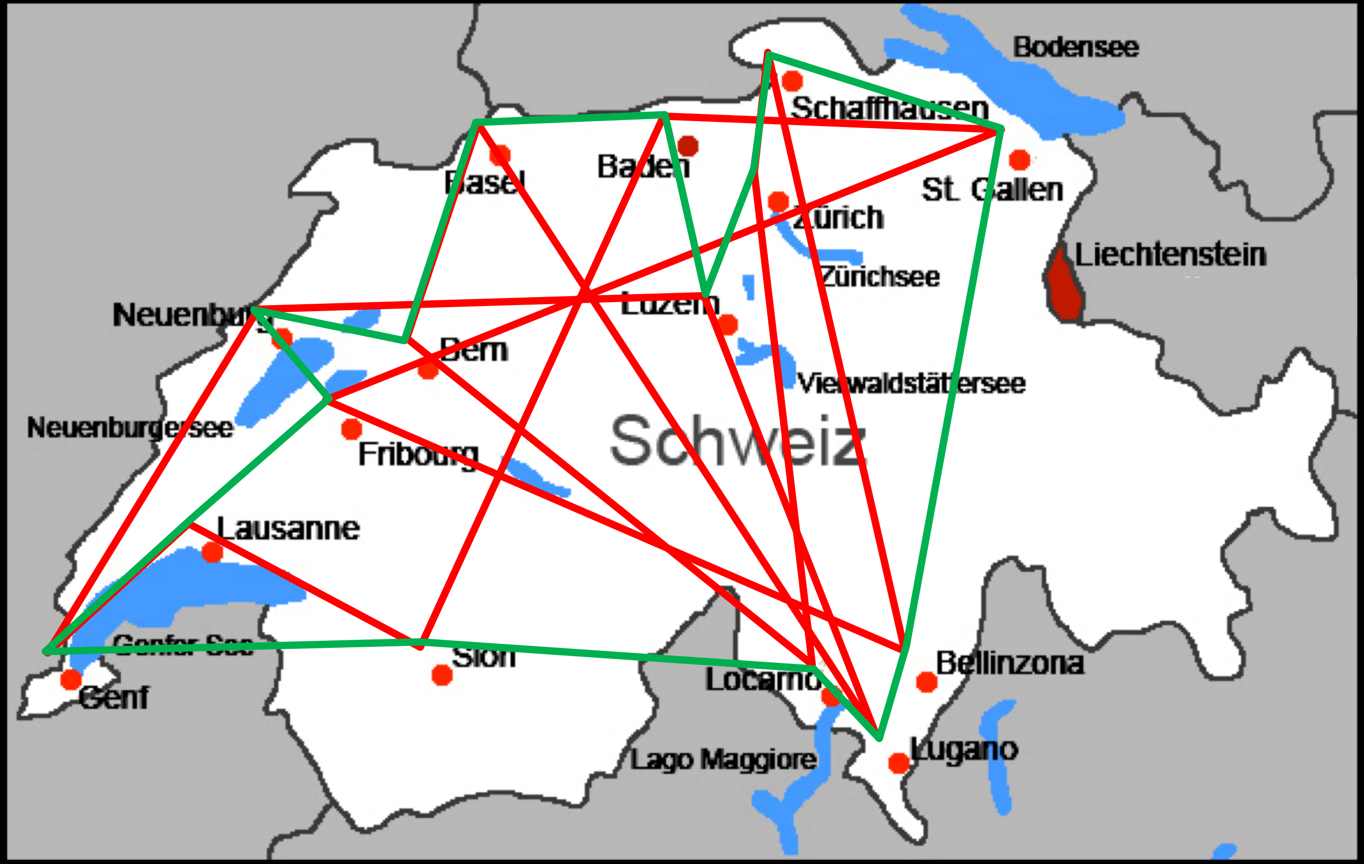
Optimization

Traveling Salesman Problem:

- Visit all cities just once
- Choose the shortest path
- Come back to starting point

17 x … x 5 x 4 x 3 x 2 x 1 = 17! = 355’687’428’096’000 possible paths

A quantum computer can explore all routes simultaneously while a classical computer has to try them sequentially.



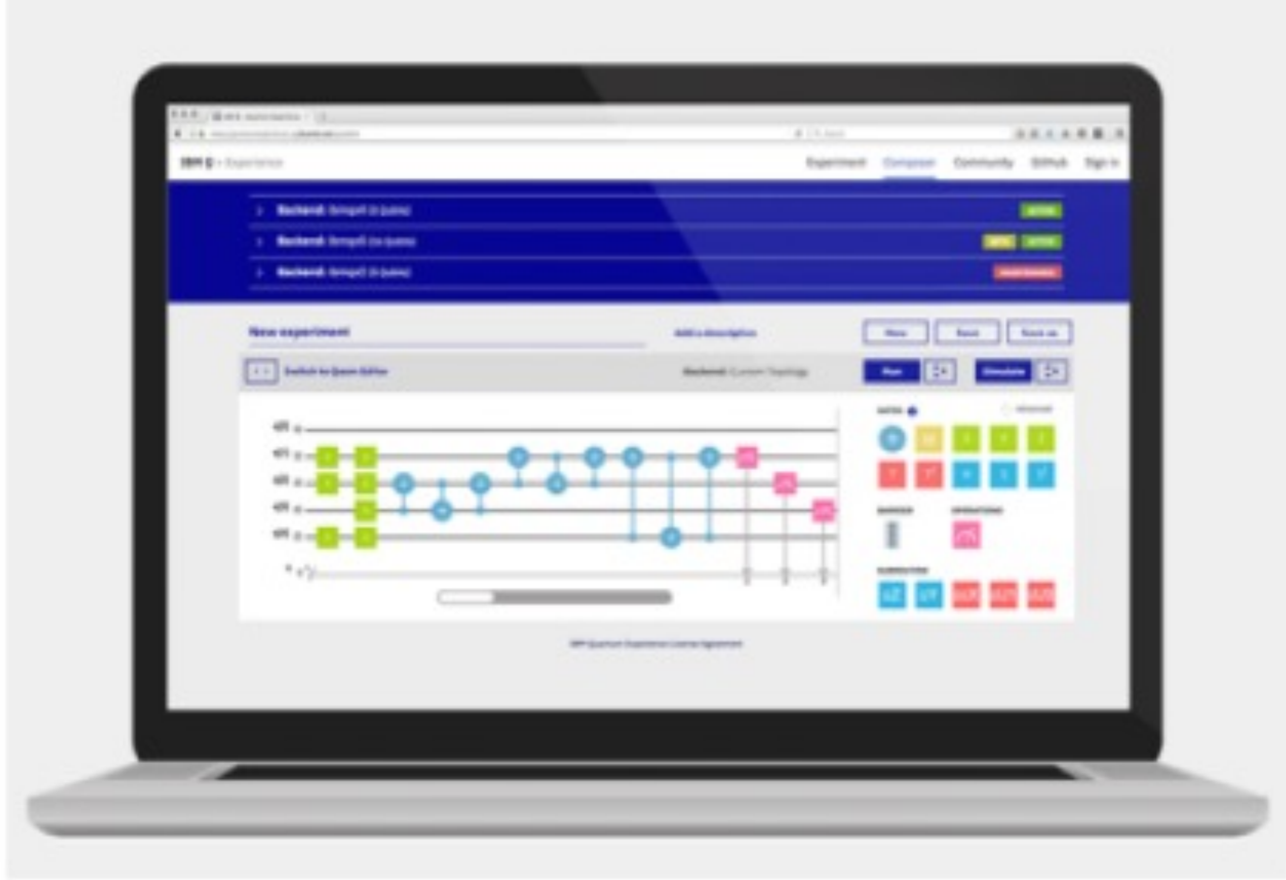
● 18 selected cities in Switzerland

IBM Quantum Experience

Public quantum computer (up to 16 qubits) and developer ecosystem

IBM QX Features

- Tutorial
- Simulation
- Graphical programming
- QASM language
- API & SDK
- Active user community



Since launch

- > 60,000 users
- > 1,700,000 experiments
- > 35 scientific publications
- > 10 professors using for quantum education
- > 300 major media articles

Experience quantum computing here:

research.ibm.com/ibm-qx

IBM Q Systems

IBM Q Systems are the world’s most advanced and first commercially available universal quantum computing systems for business and science applications.

Grand Challenge: Quantum Computing

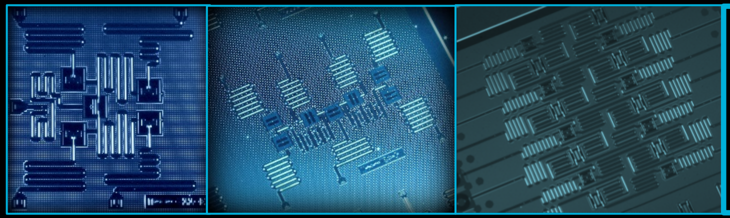
Goal:

Build computers based on quantum physics to solve problems that are otherwise intractable

Roadmap:

Small-scale (Demonstration of Quantum advantage)

- Research level demonstrations
- Verify chemistry and error correction principles
- Infrastructure & community building
- Demonstrate 'Quantum advantage'

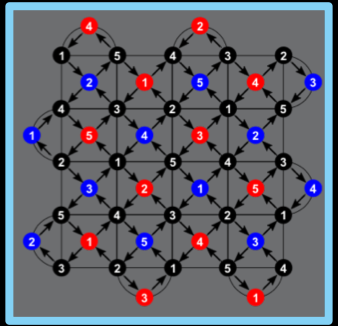


IBM Q
20XX

5-8 qubits   16 qubits   50+100 qubits

Medium-scale (Commercializing approximate QC)

- Develop "Hardware-efficient" apps
  - Chemical configurations
  - Optimization
  - Hybrid quantum-classical computers
- No full error correction available



100-1000+ qubits

Large-scale (Fault-tolerant Universal QC)

Known and proven speed-up:

- Factoring
- quantum molecular simulations
- Speed-up machine learning

Enable secure cloud computing

10^6 - 10^7 qubits