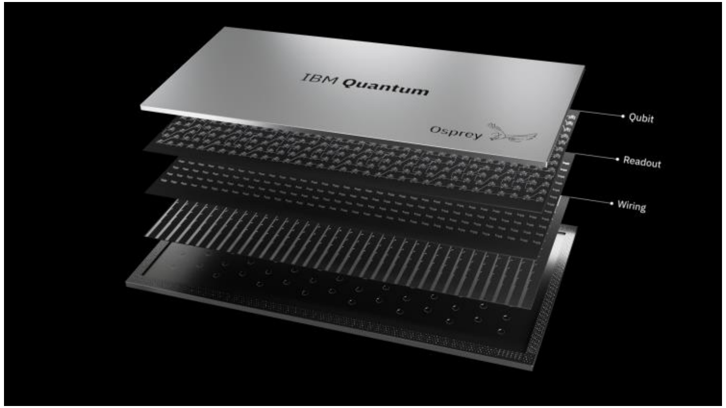
Northwestern

2023 Sievert Lectures

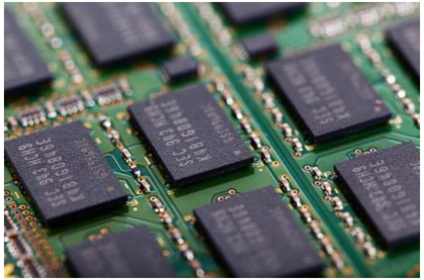
Lecture IV:
Why Quantum Computing?

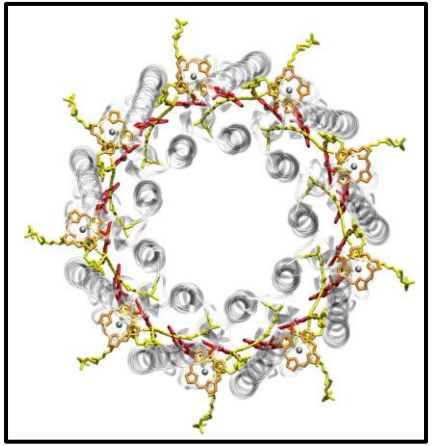


Picture from IBM quantum

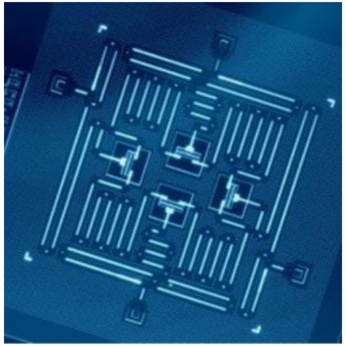
Ziwen Huang

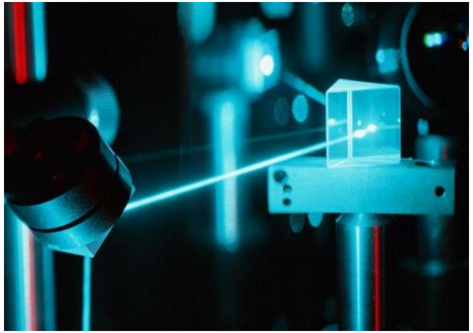
Review of the previous lectures

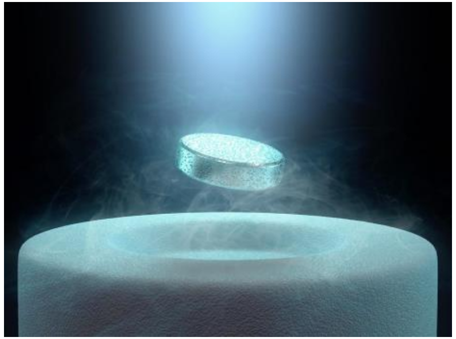




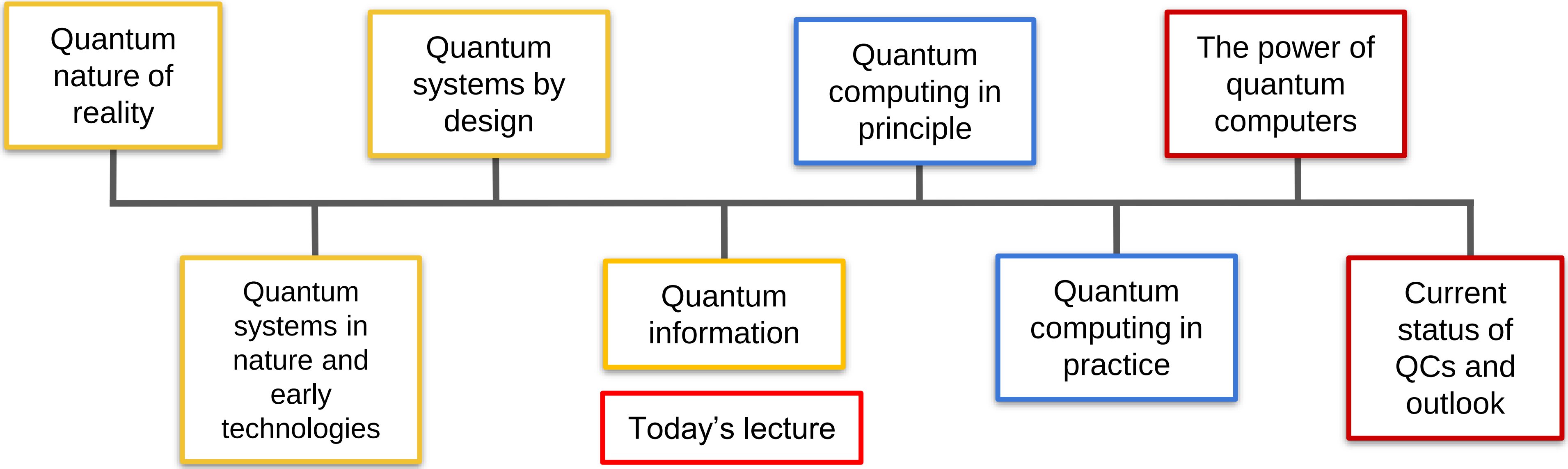
- Quantum behavior can be found in a wide range of systems in Nature.
- Many of the technologies that have been developed since the 1900s operate based on quantum effects.
- A number of devices are invented to explore quantum information science.







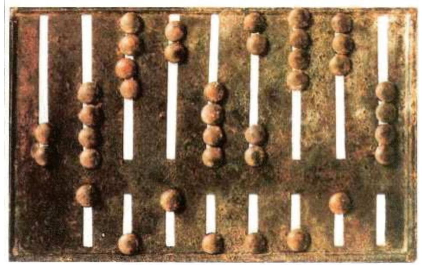
Roadmap



Quantum computing

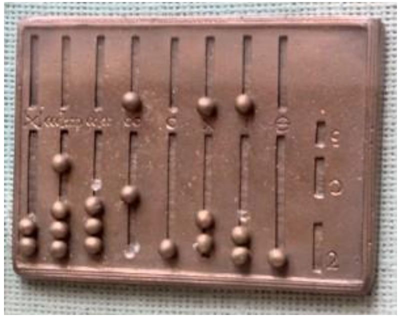
Early Computing

Ancient Sumer: Abacus
2700–2300 BC



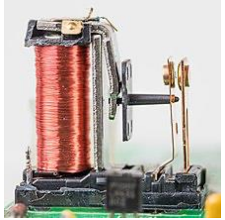
Chinese Abacus

Roman Abacus



Digital Electronic Computer

Dated from 1880

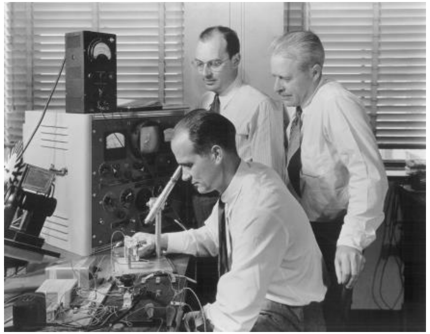


Electric switches (relays)

~1880

Vacuum tubes

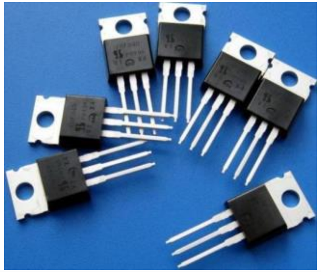
1907



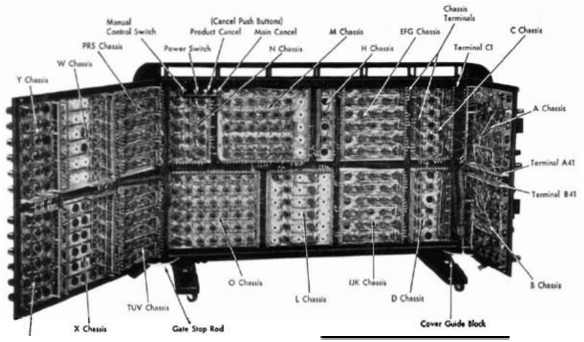
Bardeen, Brattain and Shockley

1937~1946

1946



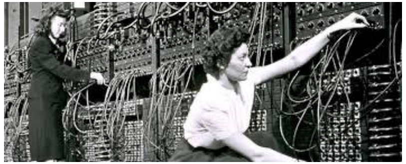
Transistor (1947)
Bipolar-junction transistor
Field-effect transistor
Silicon gate MOS integrated



IBM 603. From IBM website. 300 vacuum tubes

IBM: first electronic digital computer

ENIAC: first general-purpose computer

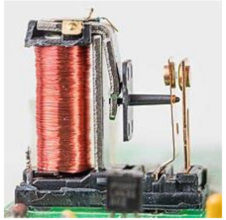


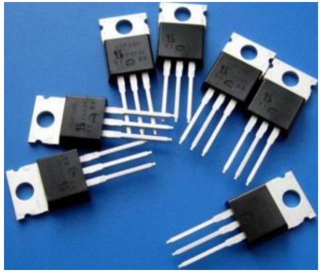
18,000 vacuum tubes,
7,200 crystal diodes,
1,500 relays,
70,000 resistors,
10,000 capacitors, and
approximately 5,000,00
hand-soldered joints.

PCs

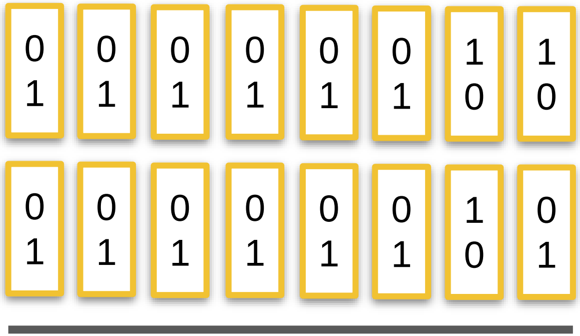
Electric Digital Computing

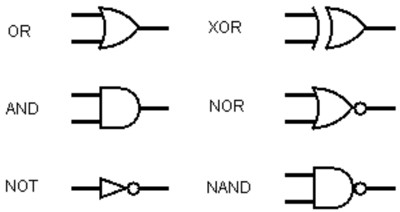
0 Low voltage (0V)
1 High voltage (5V)





Electric Digital Computing





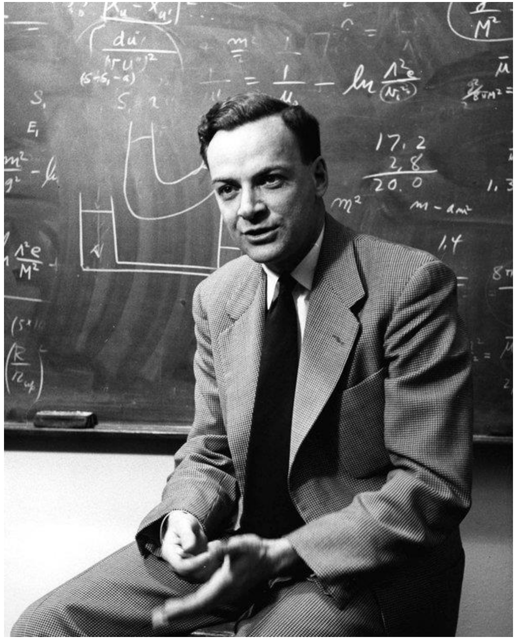
32 GB = $32*2^{30}*8$ = 274877906944 bits

10^9 calculations per second

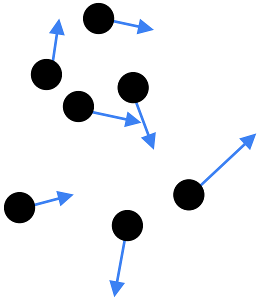
Why quantum computers?

Quantum Computing

There are still problems classical computers ***can't*** solve..
Can't: Unbearable amount of time and resource required



"But the full description of quantum mechanics for a large system with R particles is given by a function which we call the amplitude to find the particles at x_1, x_2, . . . x_R, and therefore because it has **too many variables**, it cannot be simulated with a **normal** computer"



"**Nature isn't classical**, dammit, and if you want to make a simulation of Nature, you'd better make it quantum mechanical." – Richard Feynman *The Feynman Lectures on Computation* (1981)

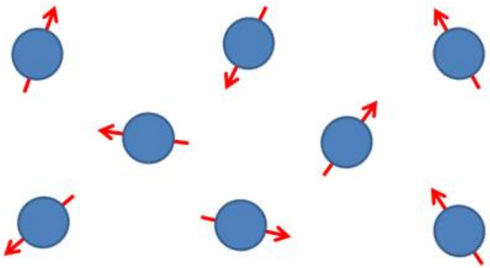
Reference: John Preskill, *Quantum Computing 40 Years Later*, arXiv:2106.10522 (2021)

Quantum Computing

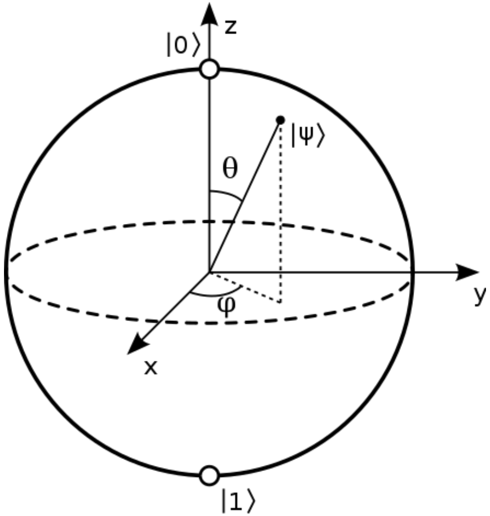
Two concepts: **Superposition**, **Entanglement**

0
1

To store a binary signal, we need one bit.



Pictures from Wikipedia and BYU bioengineering



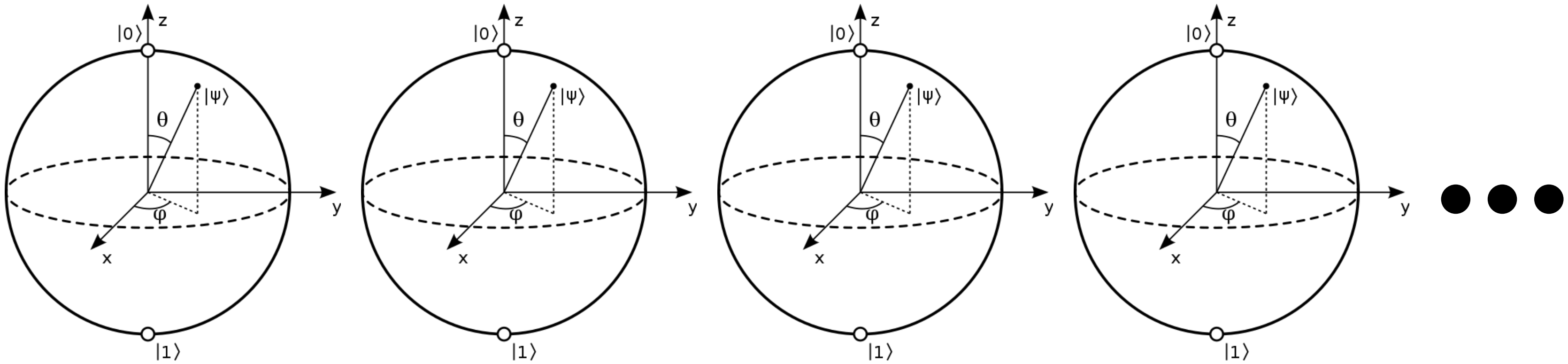
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Superposition

To store a spin state, we need a few float/double number, ~100 bits

Quantum Computing

Two concepts: **Superposition**, **Entanglement**



N spins? N*100 bits?

$(\alpha|0\rangle + \beta|1\rangle) \otimes (\alpha'|0\rangle + \beta'|1\rangle)$
S1 S2

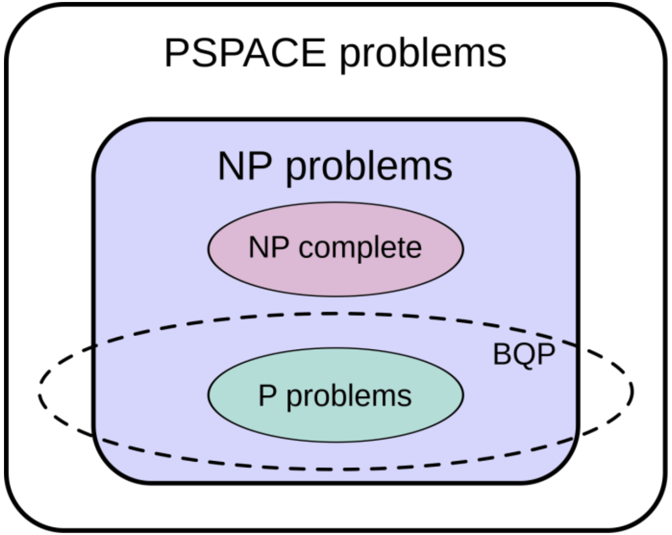
$\alpha|0\rangle \otimes |0\rangle + \beta|1\rangle \otimes |1\rangle$
S1 S2 S1 S2

Entanglement

~2^N * 100 bits

Nature isn't classical

Quantum Algorithms

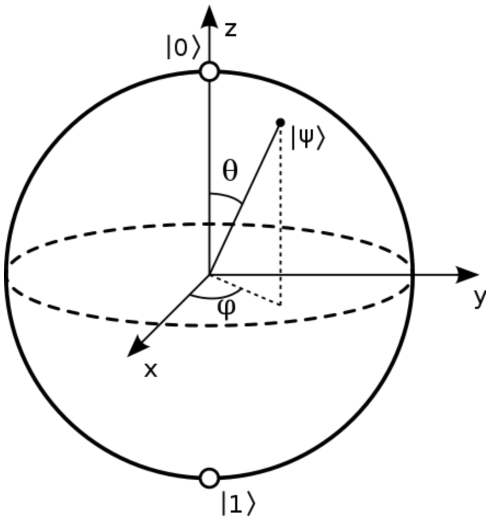


Other useful algorithms:

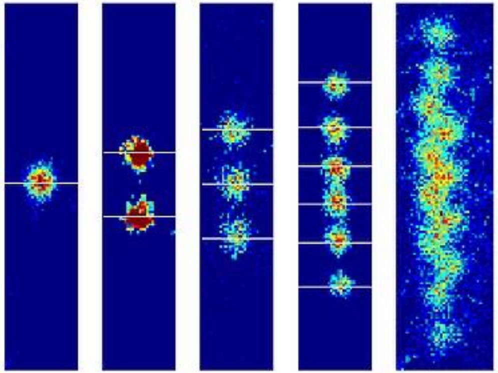
Shor’s algorithm – Prime factoring problem
Grover’s algorithm – Speed up NP-complete problems

Quantum Computing

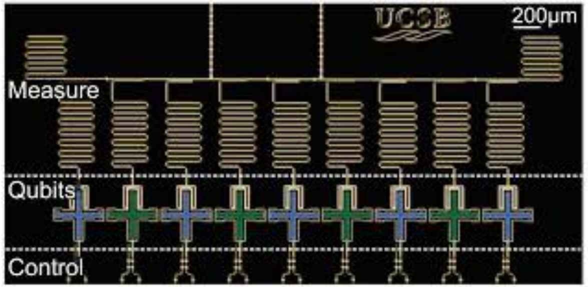
Quantum computers



Qubit



Trapped-ion qubits
(example from NIST)



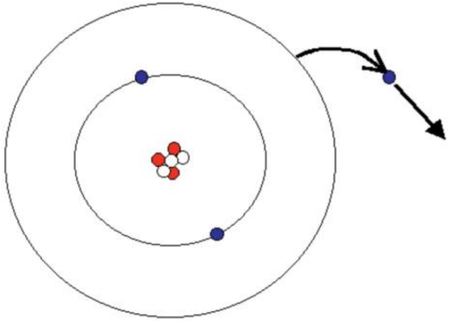
Superconducting qubits (example from UCSB)

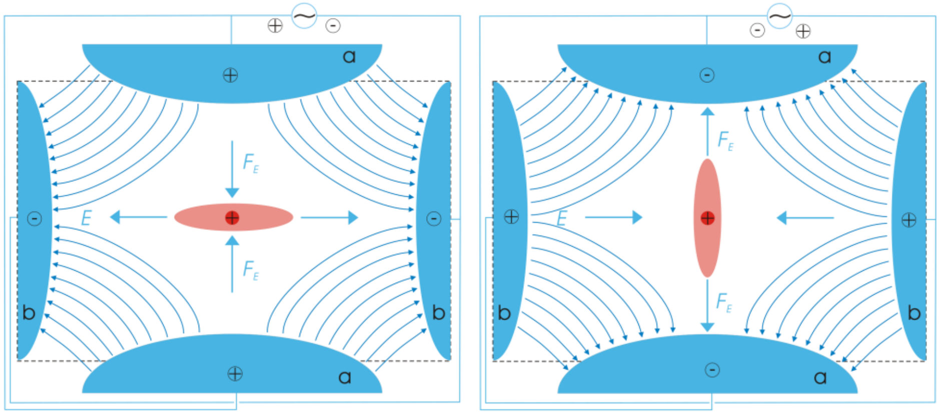
- Photonic quantum computing
- Neutral atoms
- Semiconductor qubits
- Sc-semiconductor hybrid
- Topological qubit

.....

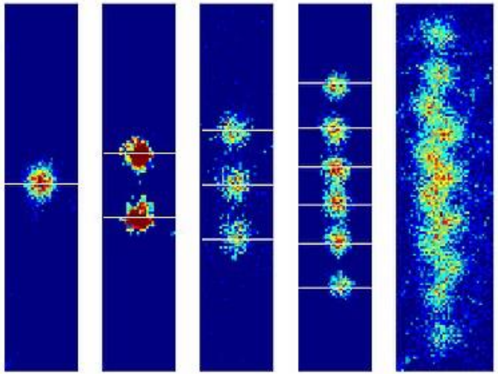
Quantum Computing

Trapped ions based on Paul traps, invented by Wolfgang Paul, Nobel Prize 1989

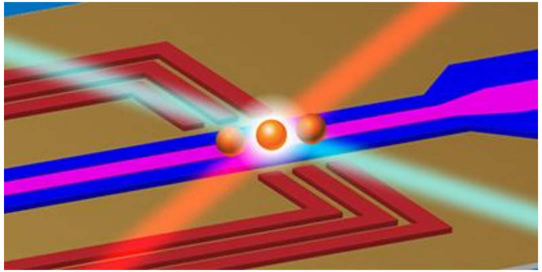




1 2



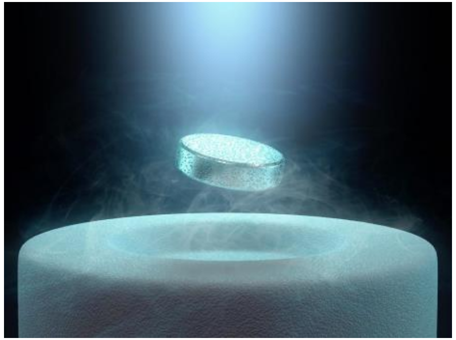
Trapped-ion qubits (NIST)

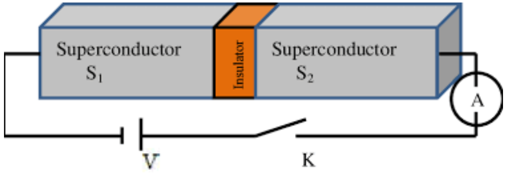


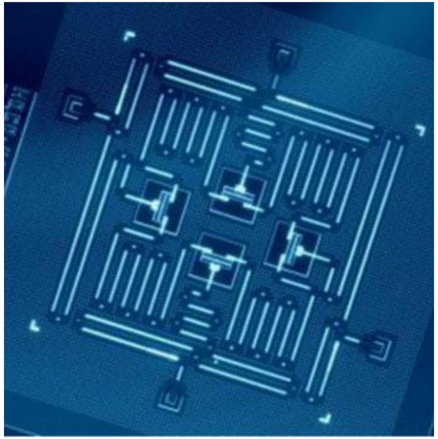
Ref: “Trapped ions make impeccable qubits” by J. Kim

Quantum Computing

Superconducting quantum computing
Superconductors and Josephson junctions

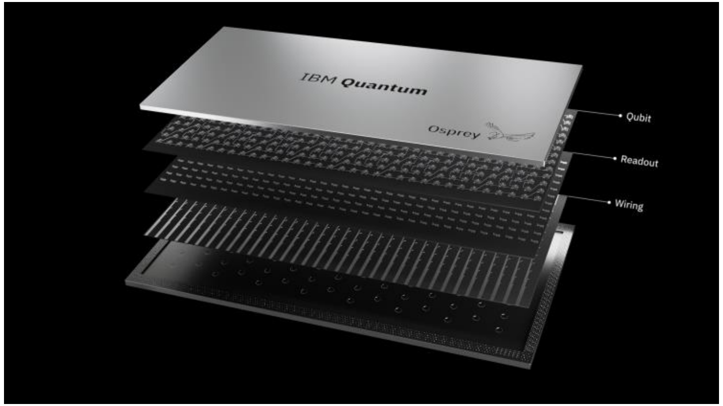




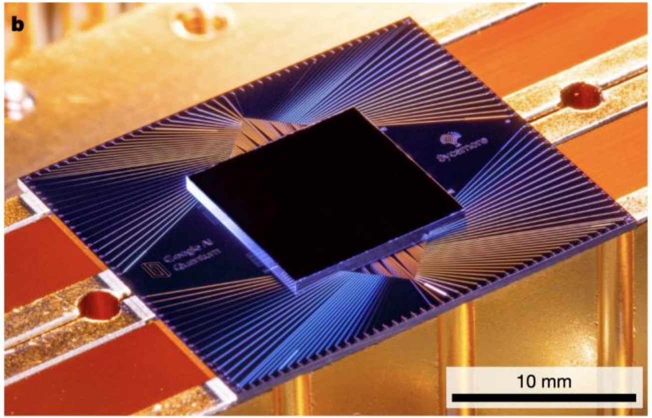


From IBM

Quantum Computing



IBM 433-qubit Osprey processor



Google Sycamore processor,
claims “quantum supremacy”

Challenges

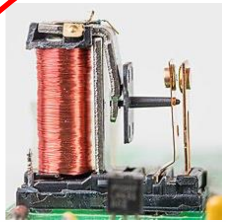
Current quantum computers are faulty

	SC	Ion
Coherence Times	10^{-1} ~ 1 ms	10^{-1} ~ 10^{3} s
Single-qubit Gate Infidelity	10^{-4} ~ 10^{-2}	10^{-6} ~ 10^{-3}
Single-qubit Gate Duration	1 ~ 10 ns	1 ~ 10 μs
Two-qubit Gate Infidelity	10^{-3} ~ 10^{-2}	10^{-3} ~ 10^{-2}
Two-qubit Gate Duration	10 ~ 10^{3} ns	1 ~ 10^{3} μs

- Error level is too high
- Error correction is challenging

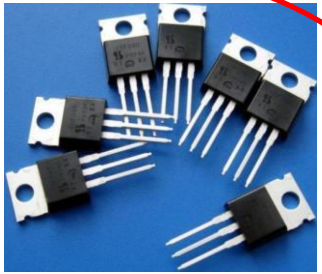
Numbers shown above are roughly summarized from Kjaergaard *et al.*, Annu. Rev. Condens. Matter Phys. 11, 369 (2020) and Bruzewicz *et al.*, Appl. Phys. Rev. 6, 021314 (2019) **Based on published results only

Digital Electronic Computer



Electric switches (relays)

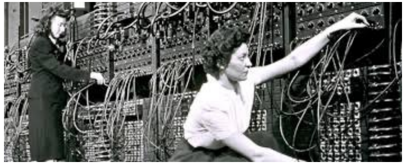
Vacuum tubes



Transistor
Bipolar-junction transistor
Field-effect transistor
Silicon gate MOS

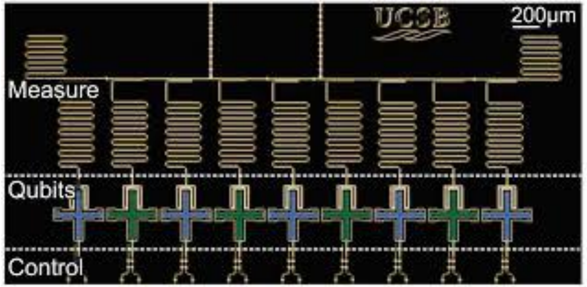
IBM: first electrical digital computer

ENIAC: first general-purpose computer

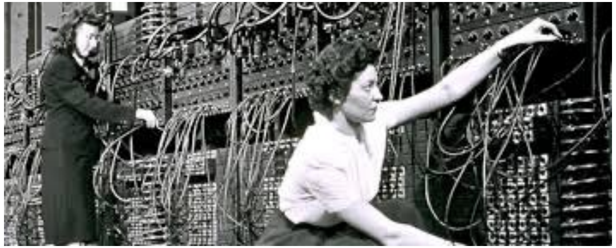


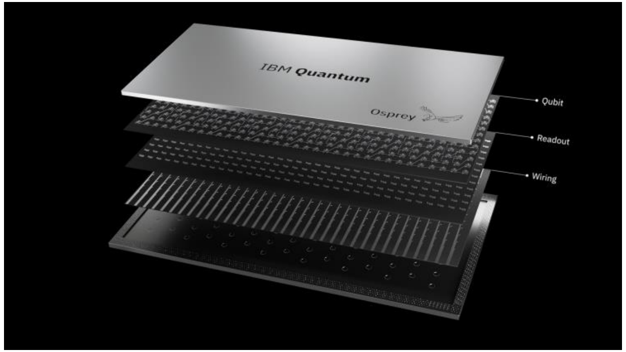
PCs

Conclusions

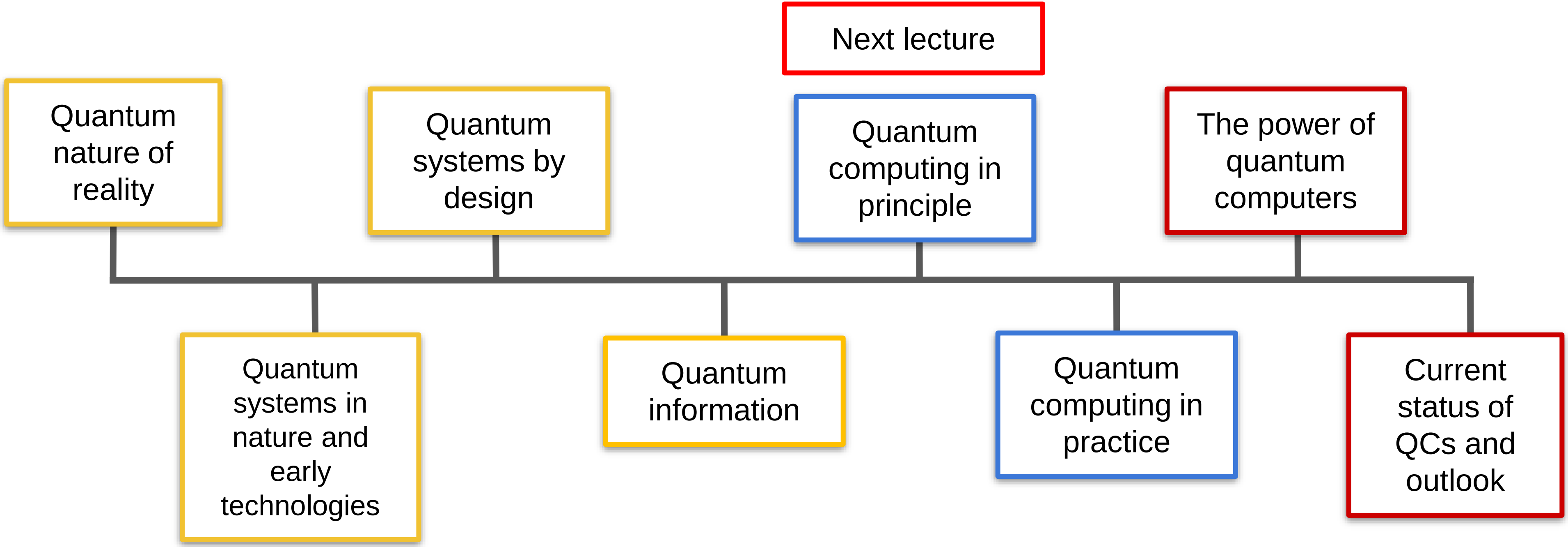


- Classical computers are very powerful, but can’t solve certain problems efficiently
- Quantum computers are made to solve quantum-related problems and beyond
- We still have a long way to go





Roadmap


Next lecture
Quantum nature of reality
Quantum systems by design
Quantum computing in principle
The power of quantum computers
Quantum systems in nature and early technologies
Quantum information
Quantum computing in practice
Current status of QCs and outlook