Introduction to Quantum computing and superconducting qubits

NTHU Yen-Hsiang Lin(林晏詳)

@Special topics of nano physics and emergent quantum matters

2020/12/24

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THE ROYAL SOCIETY

Quantum technology: the second quantum revolution

By Jonathan P. Dowling[1] and Gerard J. Milburn[2]

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We are currently in the midst of a *second quantum revolution*. The first quantum revolution gave us new rules that govern physical reality. The second quantum revolution will take these rules and use them to develop new technologies. In this review we discuss the principles upon which quantum technology is based and the tools required to develop it. We discuss a number of examples of research programs that could deliver quantum technologies in coming decades including: quantum information technology, quantum electromechanical systems, coherent quantum electronics, quantum optics and coherent matter technology.

Keywords: quantum technology; quantum information; nanotechnology, quantum optics, mesoscopics; atom optics

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What are the new technologies that can be developed from quantum mechanics?

Different facets of quantum Technologies

"European Quantum Technologies Flagship Programme"

- Quantum computation
- Quantum simulation
- Quantum communication
- Quantum sensing and metrology

(https://ec.europa.eu/digital-single-market/en/quantum-technologies)

Different facets of quantum Technologies

"European Quantum Technologies Flagship Programme"

- Quantum computation
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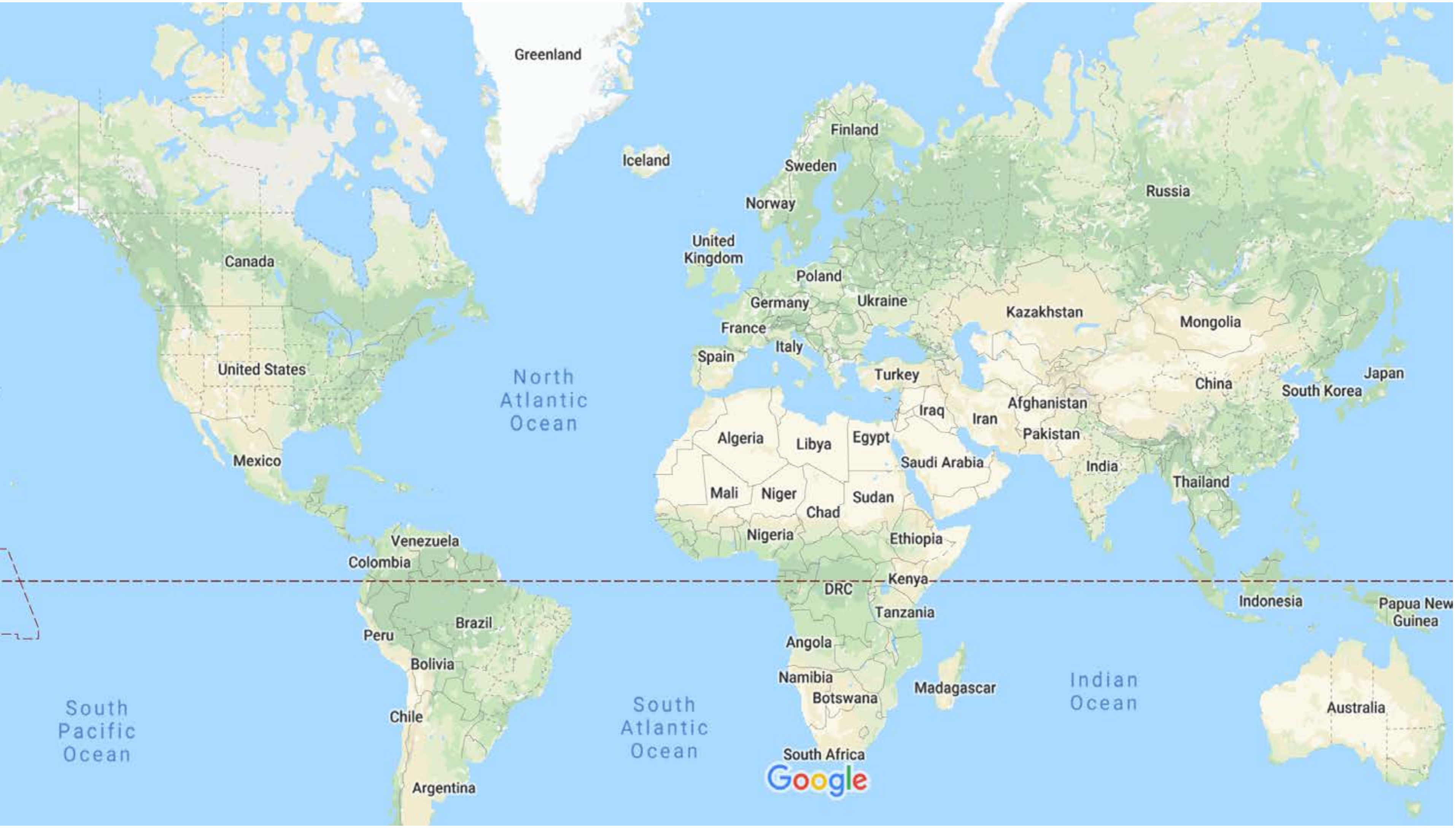
QUANTUM FLAGSHIP

(https://ec.europa.eu/digital-single-market/en/quantum-technologies)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India
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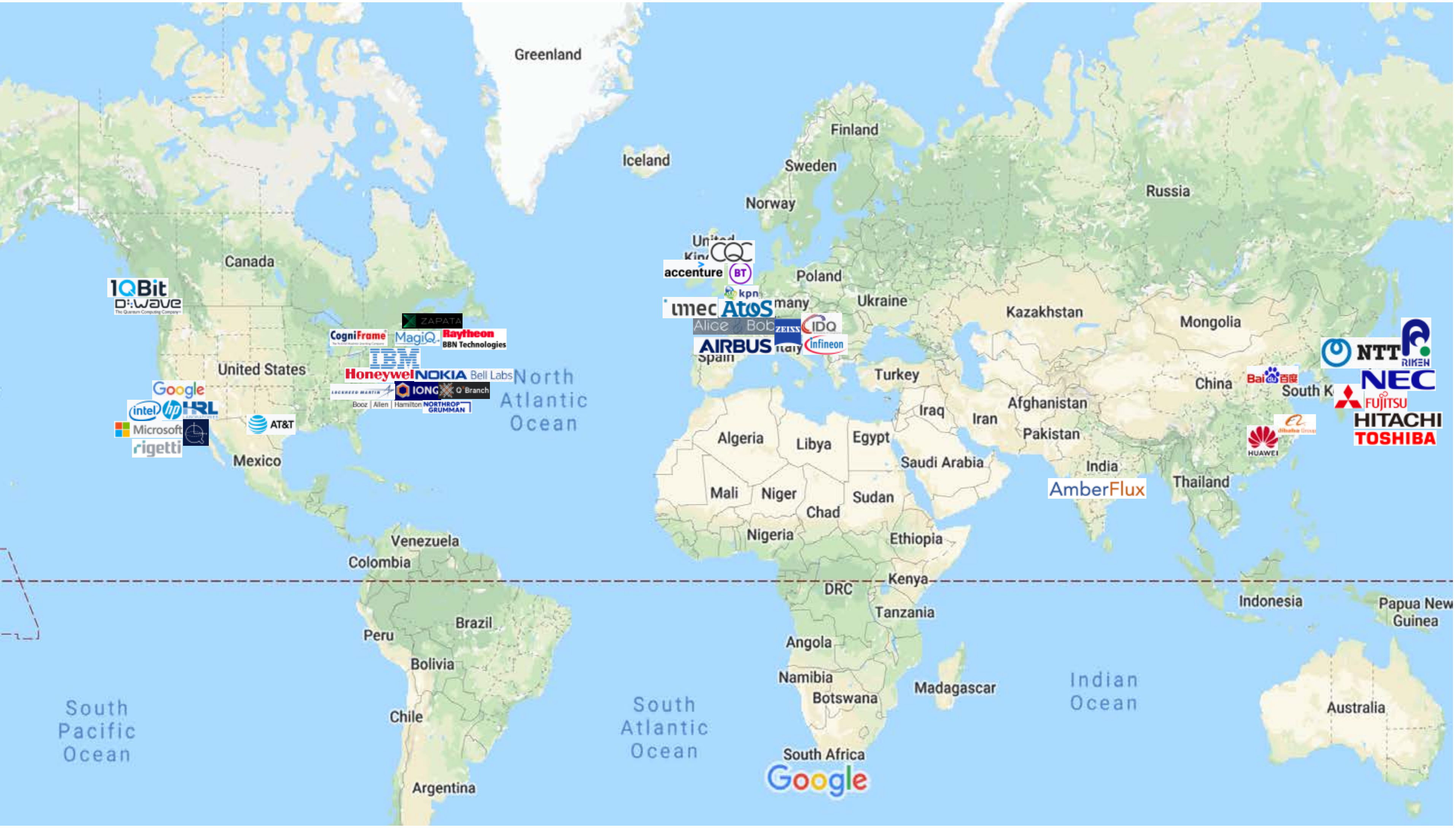
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Chile
Argentina
South Pacific Ocean
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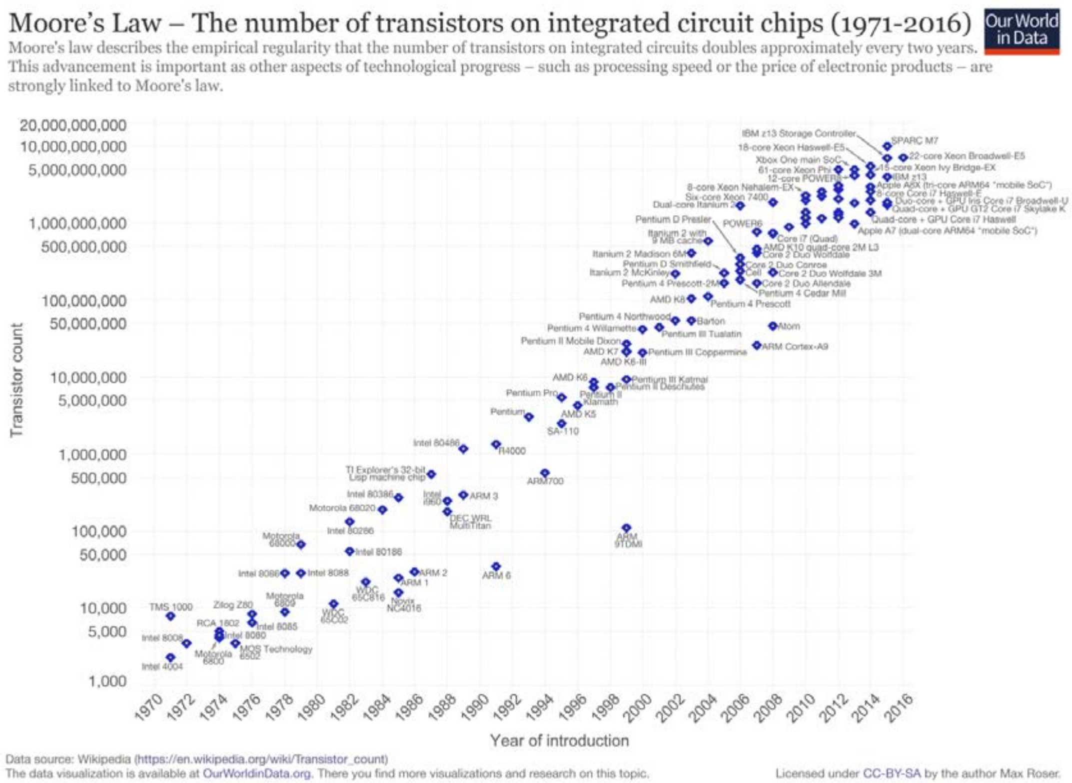
Google

What’s wrong with classical computer?

Moore's Law: the number of transistors in a dense integrated circuit doubles about every two years.

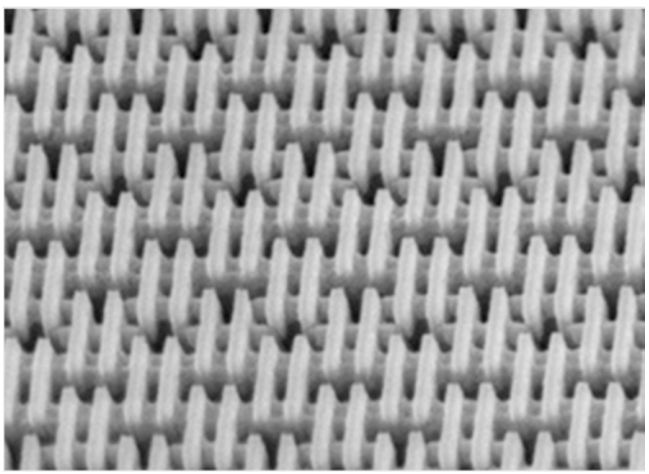


Gordon Moore in 2004

https://en.wikipedia.org/wiki/Moore%27s_law

Limitation of of Moore’s Law

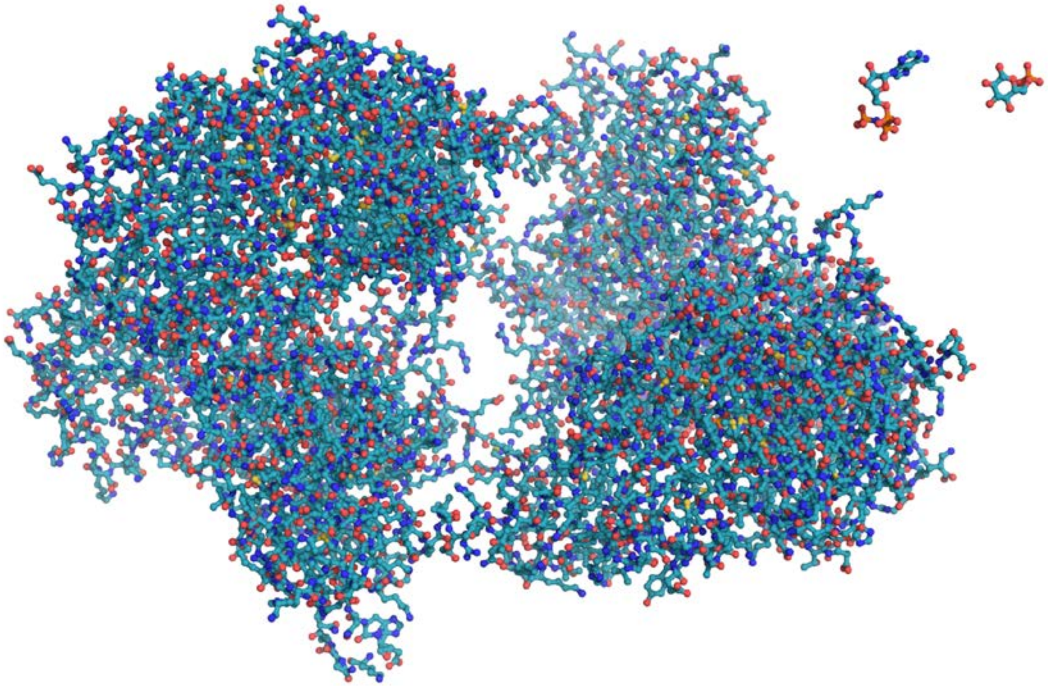
- Difficulty of fabrication
- Heat dissipation problem of nano-structures
- Quantum effects of nano-devices.



7nm MOSFETs by TSMC

https://www.tsmc.com/english/dedicatedFoundry/technology/logic.htm#l_7nm_technology

Difficulty of simulating quantum system



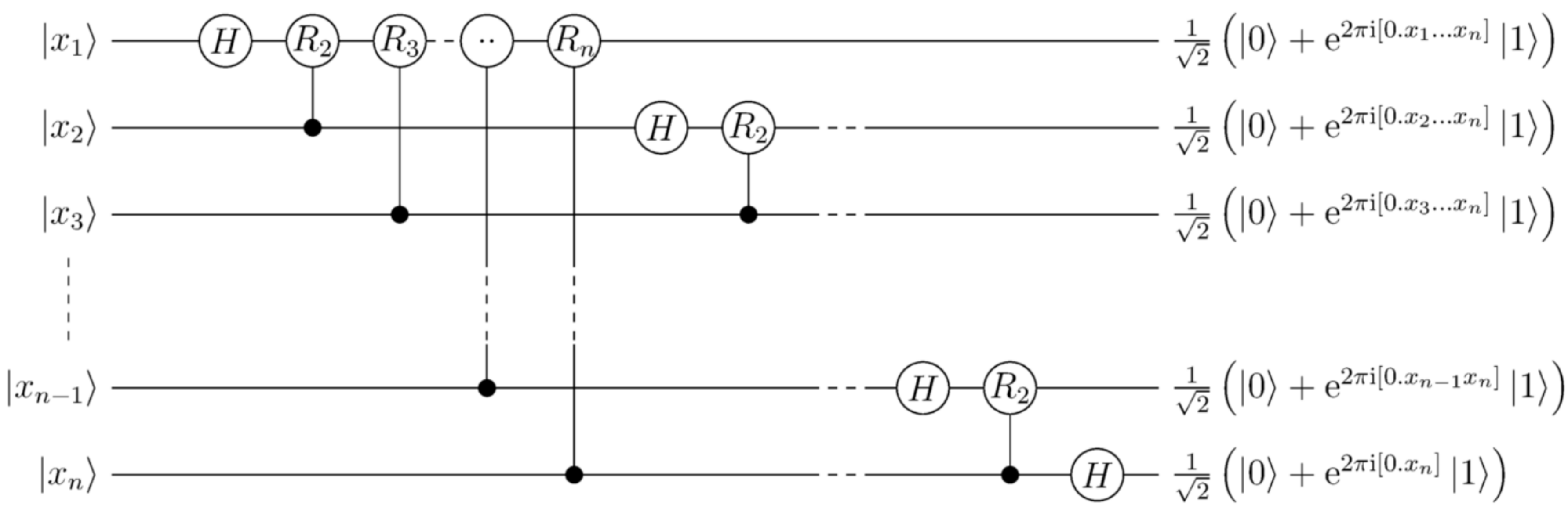
Molecule model of The enzyme hexokinase

https://en.wikipedia.org/wiki/Protein

More efficient Method to Solve Problem

- We develop new methods to solve problem more efficiently.

Quantum Fourier transform quantum circuit



What are quantum computers?

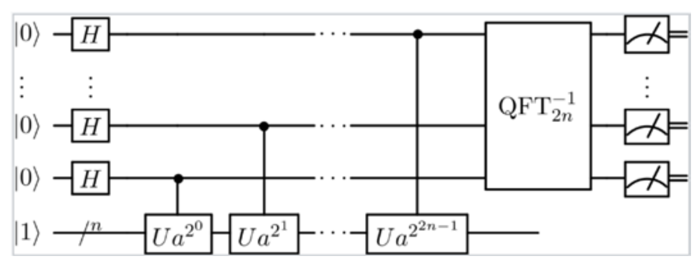
Question

Quantum computers:

Devices can store and process information according to the principles of quantum mechanics

Gate-based Quantum Computer

- Universal quantum computer.
- The processing of a task is based on a series of unitary transformation of quantum states.
- Commonly use circuit model to describe process.
- Comparable to quantum algorithm development

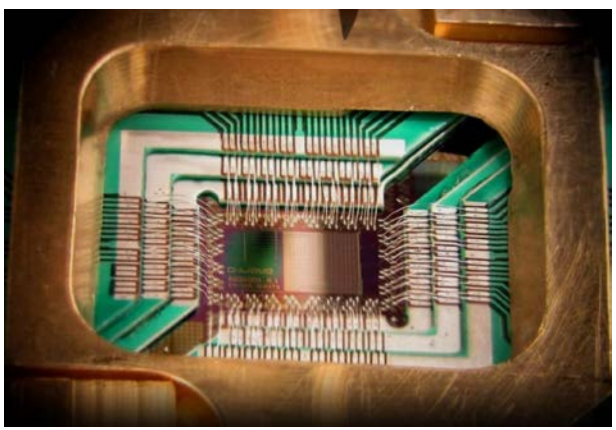


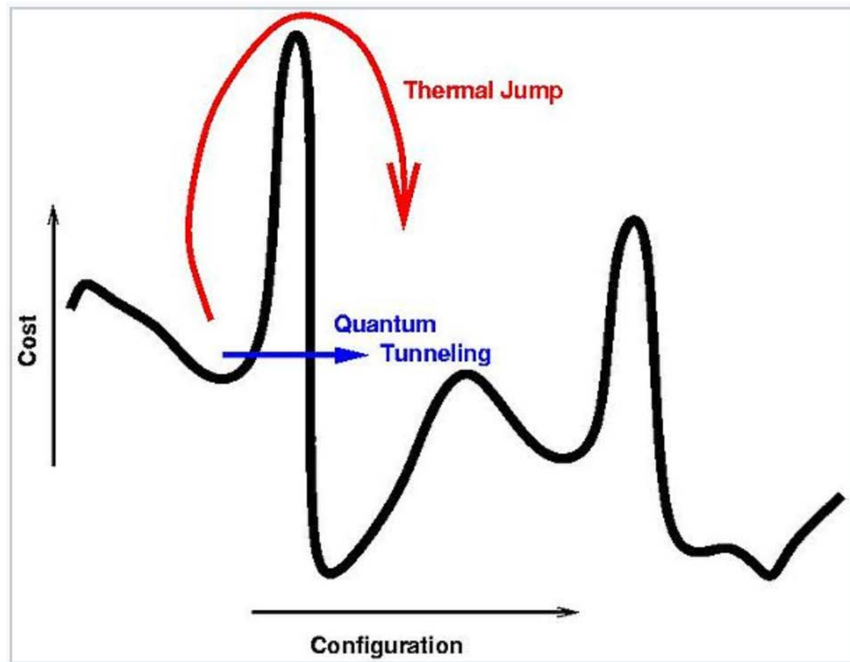
https://en.wikipedia.org/wiki/Shor%27s_algorithm

Quantum Annealer

- Cannot execute quantum circuit.
- Quantum optimization.

D-Wave
The Quantum Computing Company™

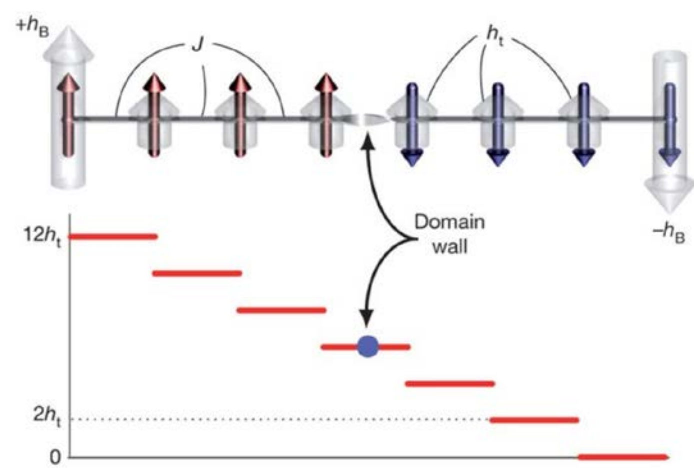




Quantum Simulator

- Construct controllable quantum sub-system to simulate real quantum system
- First Proposal: Feynman, Richard (1982). "Simulating Physics with Computers"

D:Wave
The Quantum Computing Company™



M. W. Johnson et al., *Nature* **473**, 194(2011)

Other Type of Quantum Processor

- 九章量子電腦: Special for Gaussian boson sampling

Type of Quantum Computer

- Gate-based Quantum Computer
- Quantum Annealer(Quantum optimization)
- Quantum Simulator
- Special Task Quantum processor

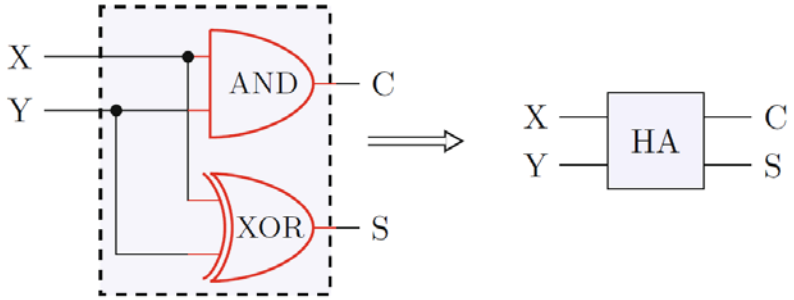
What's the difference between classical computer and quantum computer?

Circuit Model of Computation

Three main elements of circuit model:

1. A set of values.
2. A set of gate labels.
3. A labelled directed acyclic graph.

Example: The half adder(classical computation)



X	Y	$S(X \oplus Y)$	C
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

Concept of Classical vs Quantum Computing

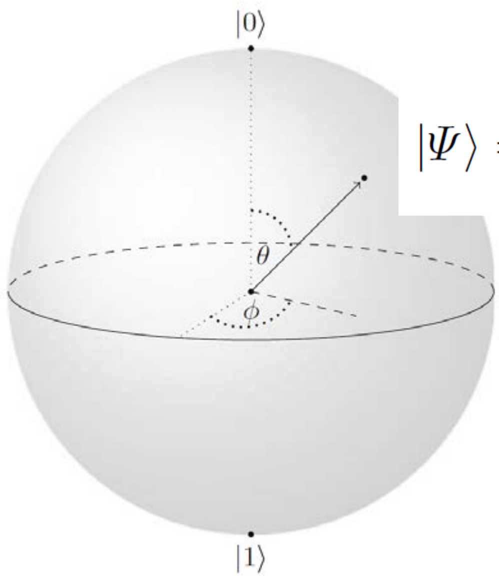
	Classical Computing	Quantum Computing
Memory Unit	Bit -> Byte	$\|0\rangle\|1\rangle$ -> $\|\Psi\rangle$
Write in	Initialize bytes	Initialize $\|\Psi\rangle$
Computation	Logic gate	Apply Operators $\mathbf{X} \equiv \|\Phi\rangle\langle\Psi\|$
Read out	Read bytes	Measure $\|\Psi\rangle$ (Born's rule)

Single Quantum Bit(Qubit)

Qubit: Information stored in $|\Psi\rangle = c_1|0\rangle + c_2|1\rangle$

$$|c_1|^2 + |c_2|^2 = 1$$

Frequently use Bloch sphere representing $|\Psi\rangle$

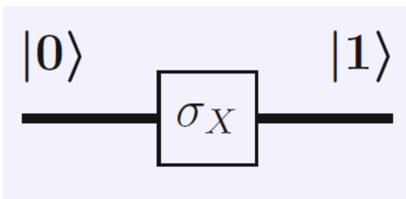


$$|\Psi\rangle = e^{i\beta}\begin{pmatrix} cos\frac{\theta}{2} \\ e^{i\phi}sin\frac{\theta}{2} \end{pmatrix} = e^{i\beta}(cos\frac{\theta}{2}\,|0\rangle + e^{i\phi}sin\frac{\theta}{2}\,|1\rangle)$$

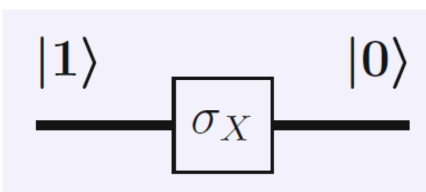
Commonly Used Single Qubit Gate

Gate	Circuit symbol	Matrix
Pauli-X (X)	**X**, $\oplus$	$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$
Pauli-Y (Y)	**Y**	$\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$
Pauli-Z (Z)	**Z**	$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$
Hadamard(H)	**H**	$\frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$
Phase (S)	**S**	$\begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}$
π/8 (T)	**T**	$\begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix}$

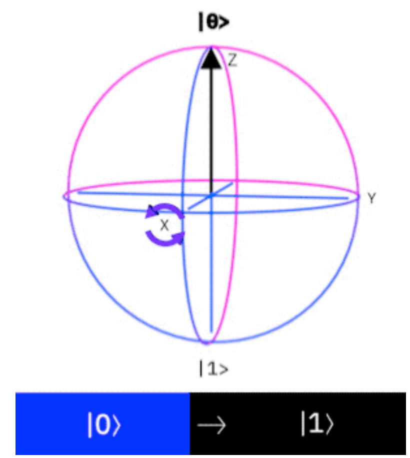
Pauli X(X) gate



$$\boldsymbol{\sigma}_X |0\rangle \Rightarrow \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \Rightarrow |1\rangle$$



$$\boldsymbol{\sigma}_X |1\rangle = |0\rangle$$

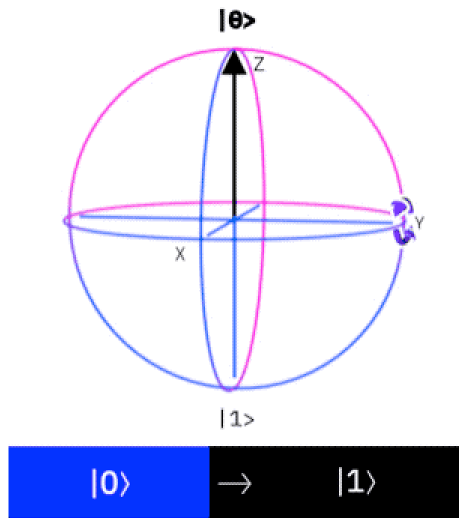


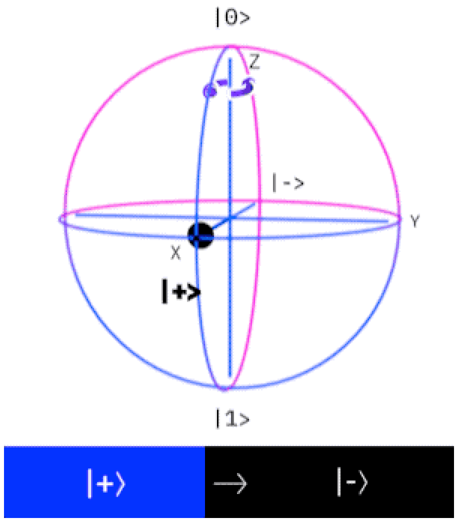
https://quantum-computing.ibm.com/docs/circ-comp/q-gates

Pauli Y(Y) and Pauli Z(Z) gate

$$\sigma_Y \equiv \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

$$\sigma_Z \equiv \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$





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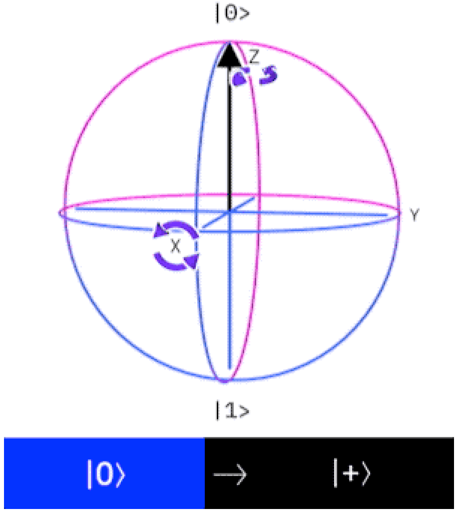
Hardama Gate

$$\mathbf{H} \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$



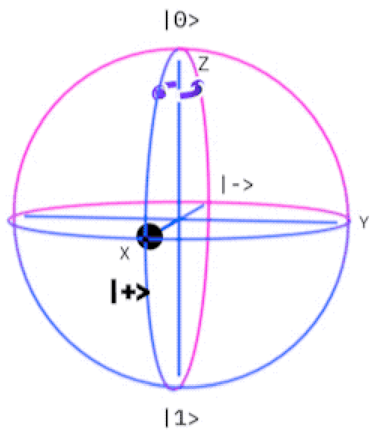
Generate superposition states of $|0\rangle$ $|1\rangle$

https://quantum-computing.ibm.com/docs/circ-comp/q-gates

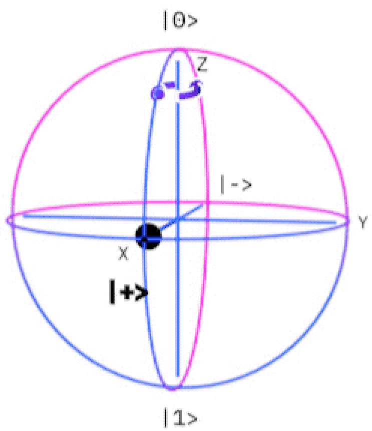
S and T Gate

Phase (S) $\begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}$

π/8 (T) $\begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix}$



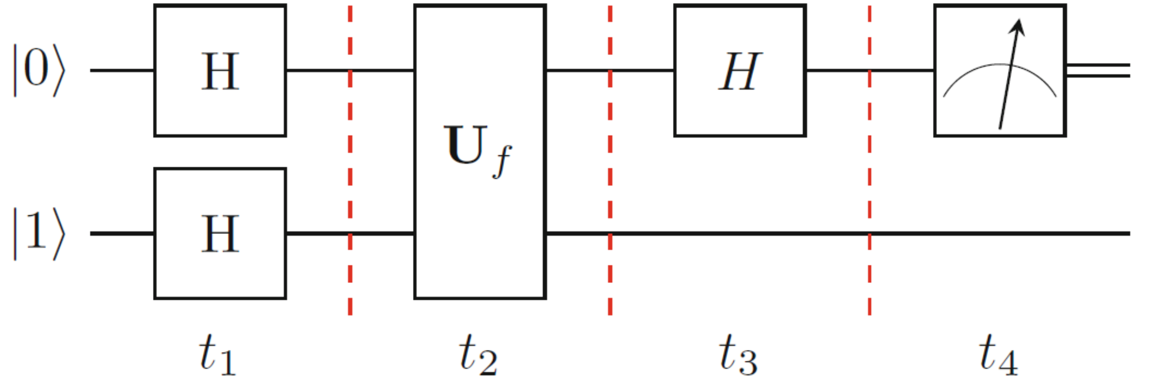
|+⟩ ⟶ (|0⟩+i|1⟩)/√2



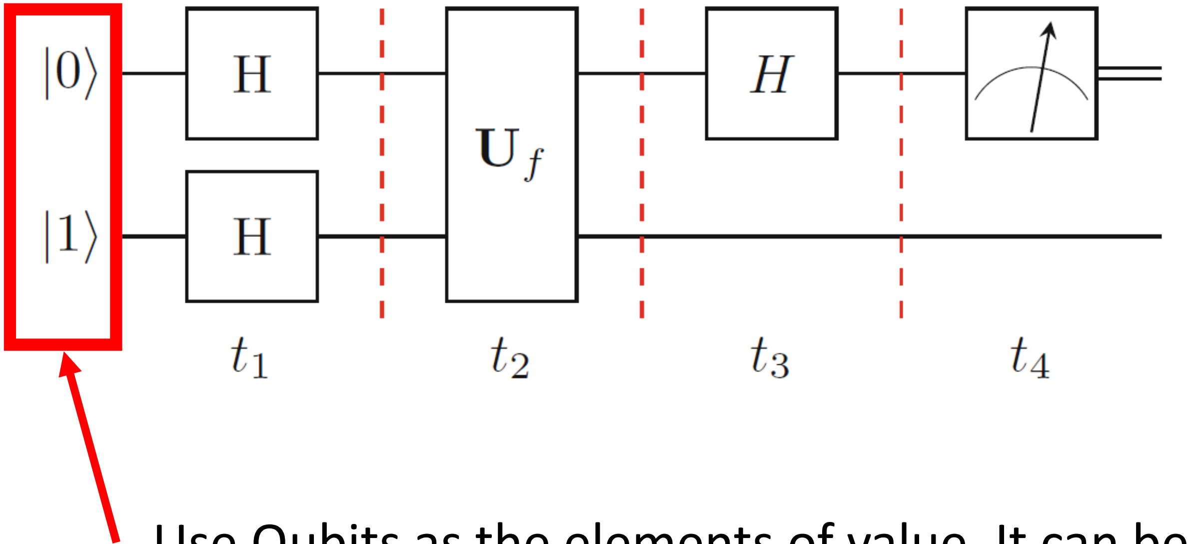
|+⟩ ⟶ (|0⟩+iπ/4|1⟩)/√2

https://quantum-computing.ibm.com/docs/circ-comp/q-gates

Quantum Circuit Model

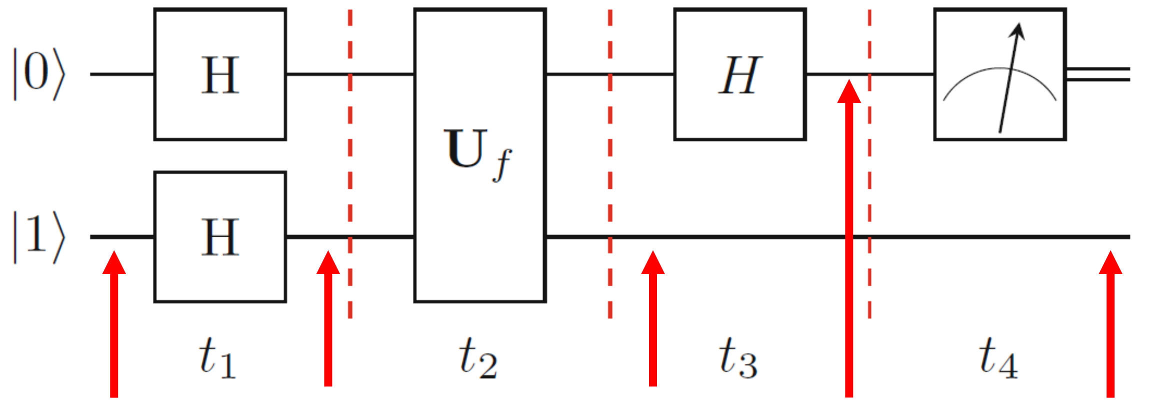


Quantum Circuit Model



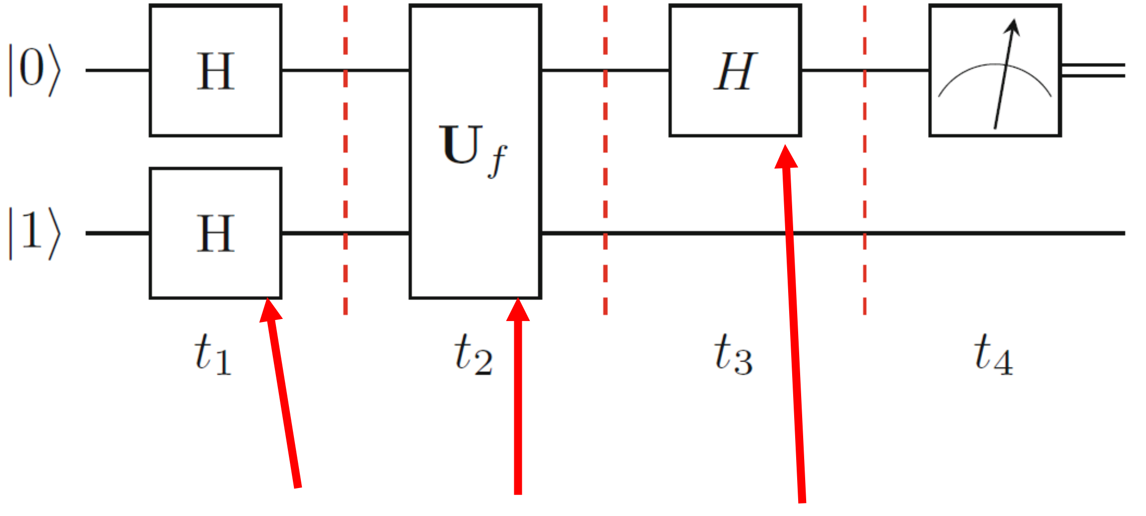
Use Qubits as the elements of value. It can be $|0\rangle$, $|1\rangle$, or $|\Psi\rangle$

Quantum Circuit Model



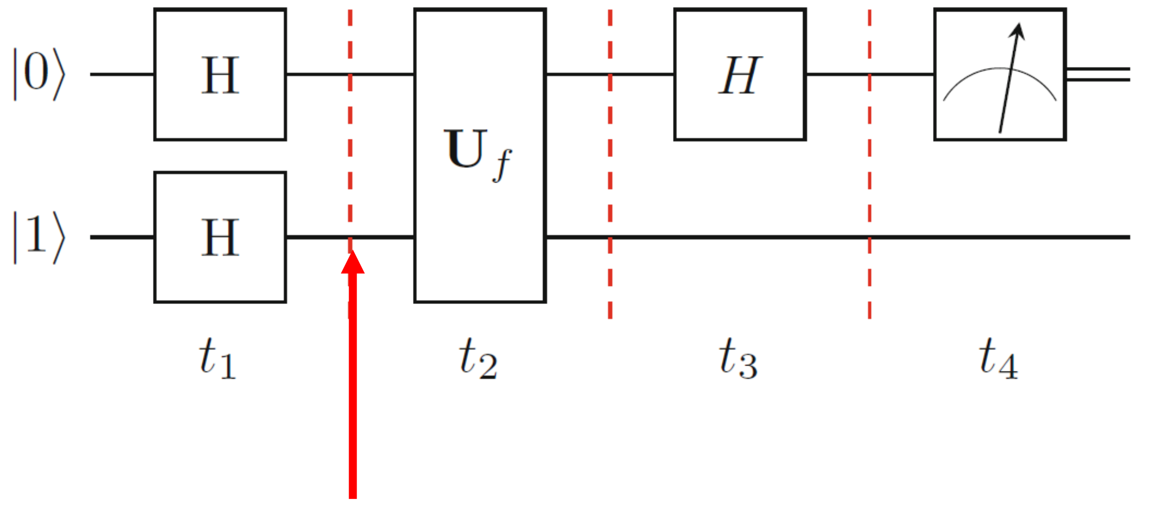
Each single wire represents a qubit ket. The convention time is assumed to run from left to right in the diagram. The state is not altered until the wire enters a quantum gate or a measurement device.

Quantum Circuit Model



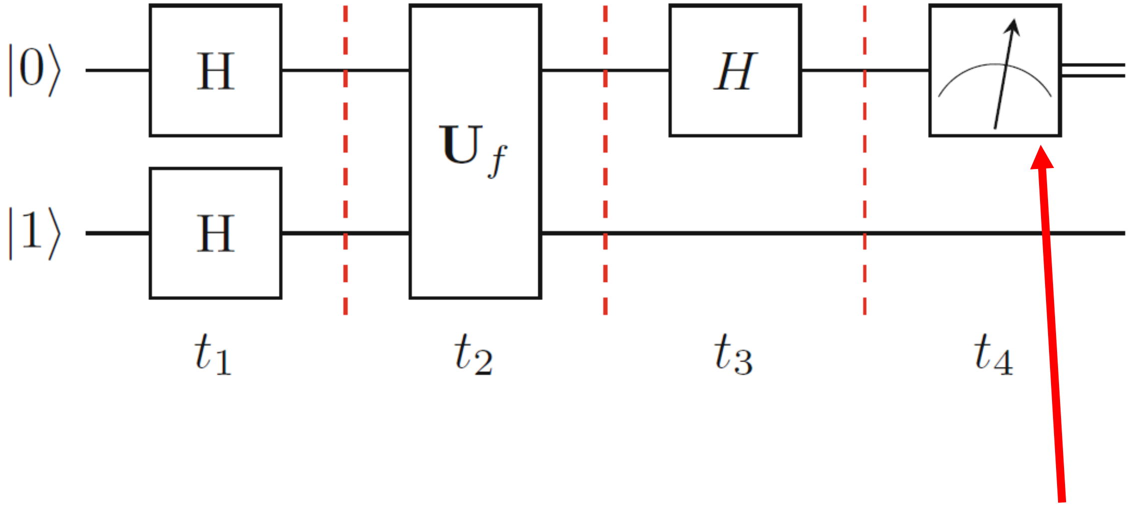
The quantum gates that represent operations to the qubit kets.

Quantum Circuit Model



The output qubit kets of previous gate become the input of the next gate.

Quantum Circuit Model



A measurement to readout the ket

Can we construct a quantum algorithm that works better than classical algorithm?

Can we construct a quantum algorithm that works better than classical algorithm?

Deutsch’s algorithm(1985): The first quantum algorithm outperformed classical algorithm.

Binary function f(x)

Consider a binary function f(x): only four possibilities

Input	A	B	C	D
0	0	0	1	1
1	0	1	0	1

Binary function f(x)

The output is independent of input: constant function(Case A and D)

The output depends on input: balanced function(Case B and C)

Input	A	B	C	D
0	0	0	1	1
1	0	1	0	1

Deutsch’s Problem

Give a binary function f(x), is f(x) a constant function of balanced function?

Deutsch's Problem

Give a binary function f(x), is f(x) a constant function of balanced function?

Constant: $f(0) = f(1)$

Balanced: $f(0) = \widetilde{f}(1)$

Classical Algorithm

Plug in 0 and 1. Find out $f(0)=?$ and $f(1)=?$ Then, one can determine $f(x)$ is a constant or a balanced function.

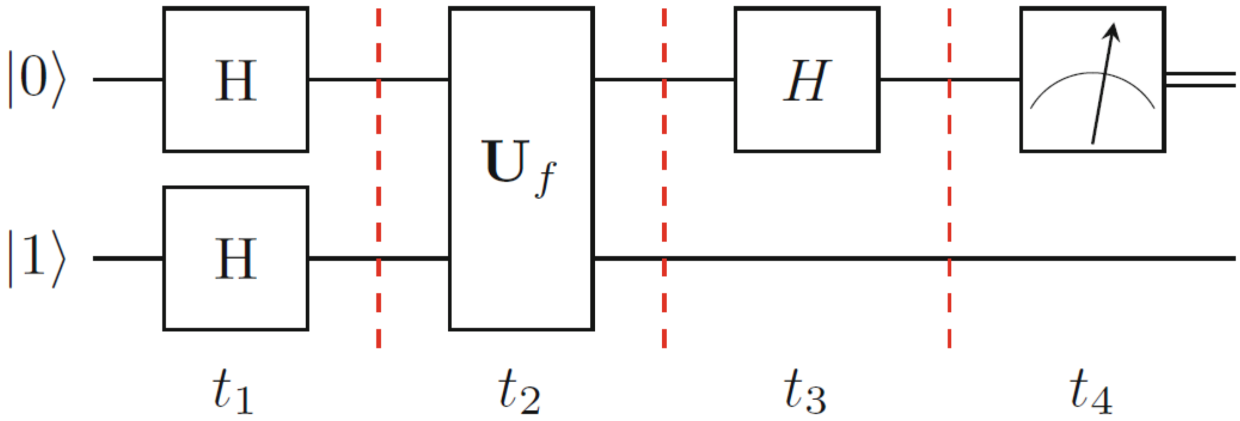
At least two evaluations to find out $f(0)$ and $f(1)$

Quantum Algorithm

Allow you to only evaluate f(x) once!

How?

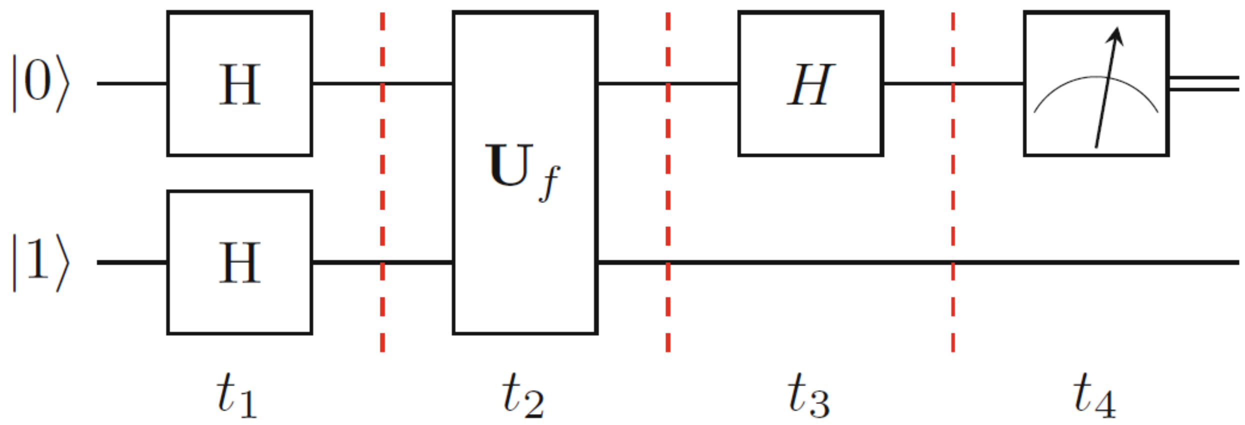
Deutsch's Algorithm



Let's look results after each gate

First initialized two qubits to be $|0\rangle$ and $|1\rangle$

Deutsch's Algorithm

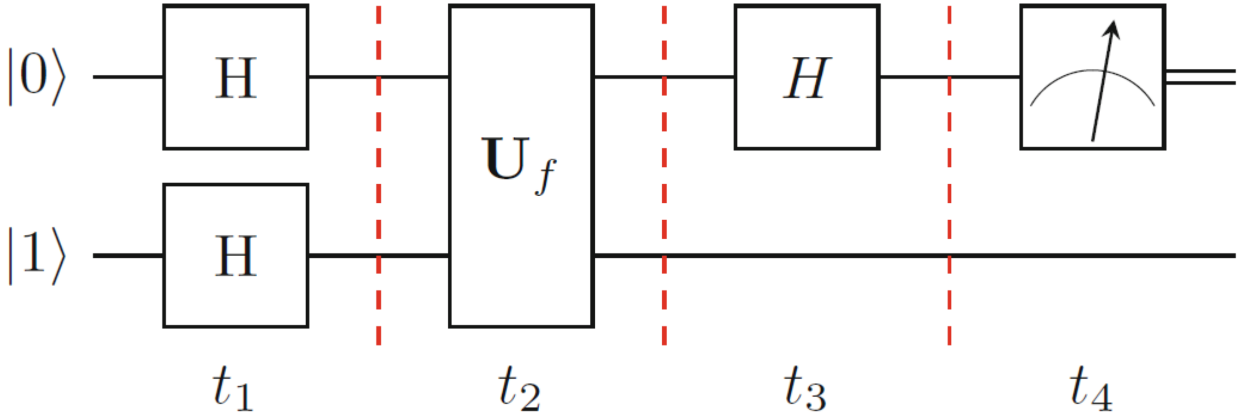


Operation of two Hadamard gates

$$\mathbf{H}\,|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

$$\mathbf{H}\,|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$$

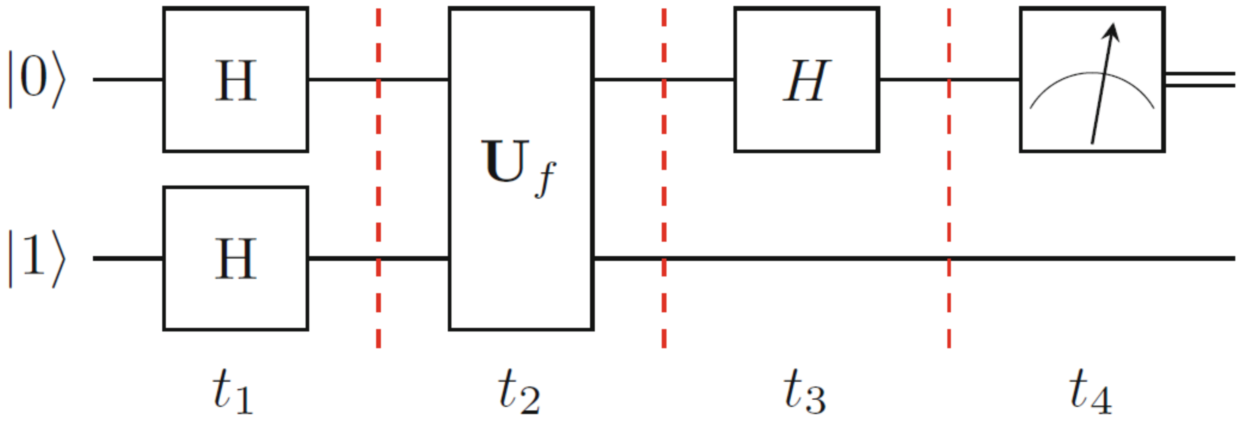
Deutsch's Algorithm



After t1

$$|\psi(t_1)\rangle = \frac{1}{2}\Big((|0\rangle + |1\rangle) \otimes (|0\rangle - |1\rangle)\Big) = \frac{1}{2}\Big(|00\rangle + |10\rangle - |01\rangle - |11\rangle \Big)$$

Deutsch's Algorithm



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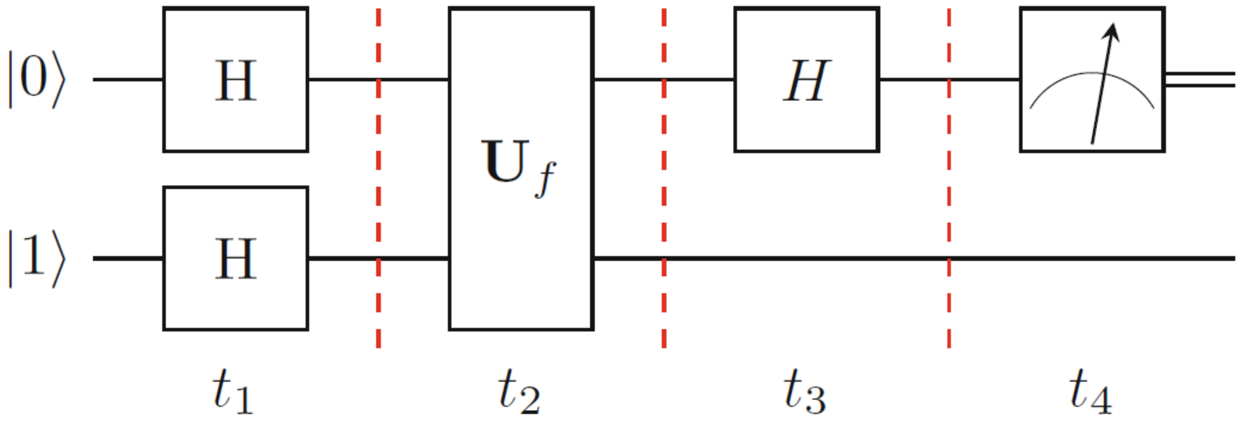
A superposition states contained all possible combinations!

Deutsch's Algorithm



After t1

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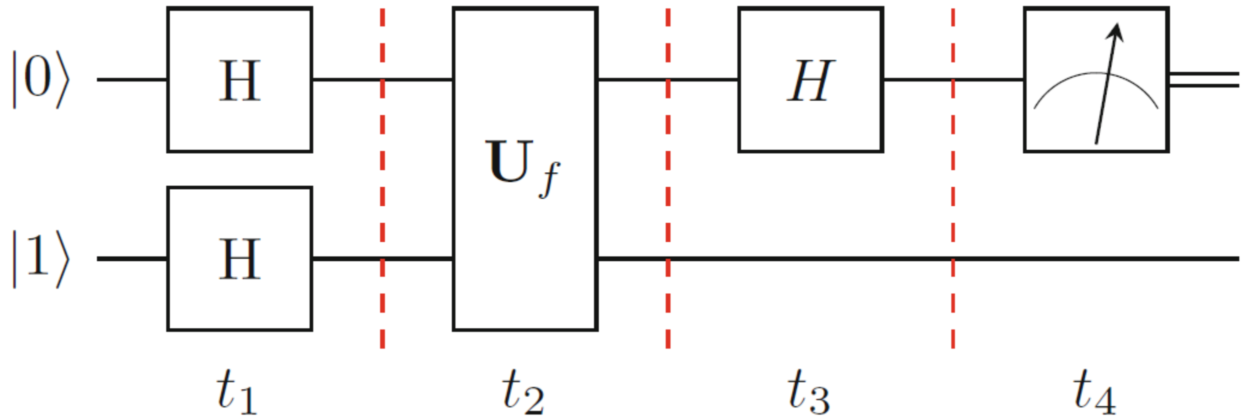
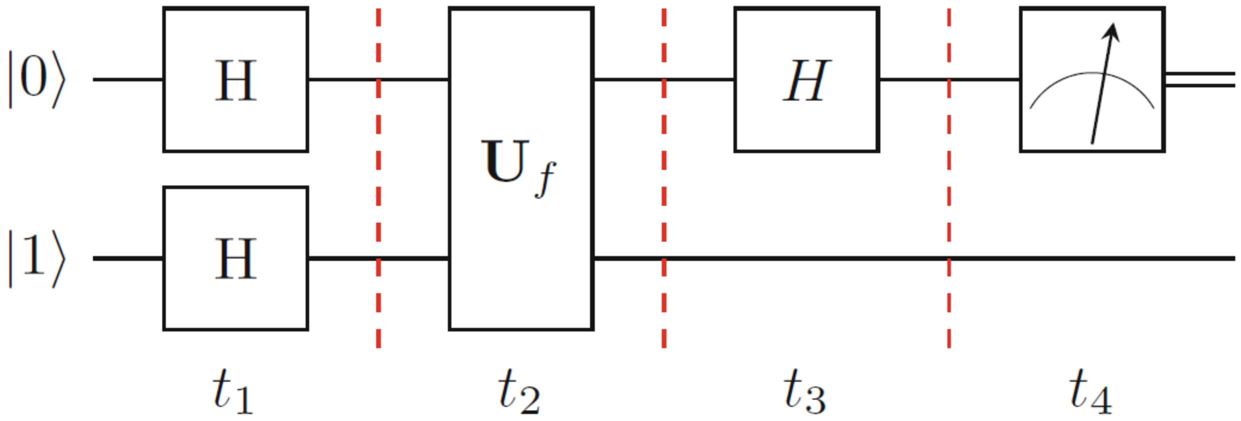
Quantum Parallelism

Deutsch's Algorithm



After t2: $|\psi(t_2)\rangle = \frac{1}{2}\Big(|0\rangle \otimes |f(0)\rangle + |1\rangle \otimes |f(1)\rangle - |0\rangle \otimes |f(0) \oplus 1\rangle - |1\rangle \otimes |f(1) \oplus 1\rangle \Big)$

Deutsch's Algorithm



After t3:

Constant: $f(0) = f(1)$

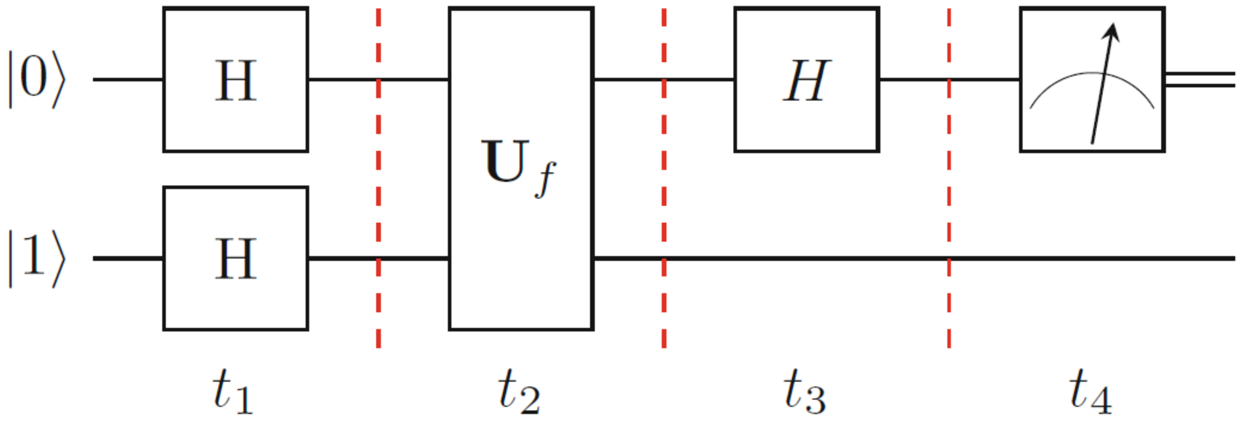
$$|\psi(t_3)\rangle = \frac{1}{\sqrt{2}}(|0\rangle) \otimes (|f(0)\rangle - |\widetilde{f}(0)\rangle)$$

Balanced $f(0) = \widetilde{f}(1)$

$$|\psi(t_3)\rangle = \frac{1}{\sqrt{2}}(|1\rangle) \otimes (|f(0)\rangle - |\widetilde{f}(0)\rangle)$$

Quantum Interference

Deutsch's Algorithm



After t4: Constant: get 0

Balanced: get 1

Only evaluate f(x) once in U_f!

Key Elements of Advantage in Quantum Information

- Superposition + Quantum interference
- Entangle States

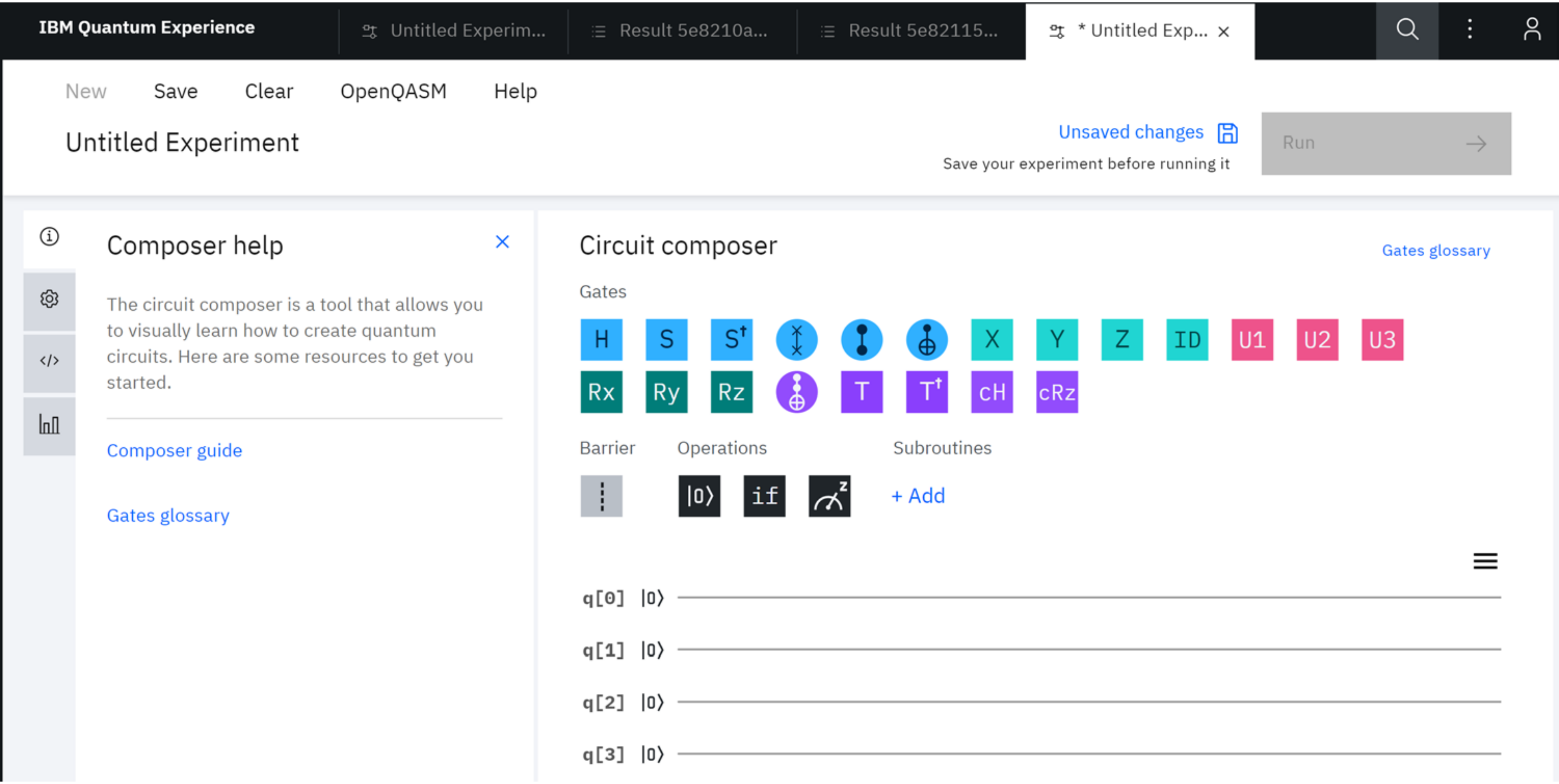
Can we use a “real” quantum computer now?

Can we use a “real” quantum computer now?

YES!!!

IBM Quantum Experience

- https://quantum-computing.ibm.com/
- You can construct your own quantum circuit online.
- Send your quantum circuit to a simulator or a real IBM quantum computer to run!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Result 5e82115...
* Untitled Exp...
New
Save
Clear
OpenQASM
Help
Untitled Experiment
Unsaved changes
Save your experiment before running it
Run
Composer help
The circuit composer is a tool that allows you to visually learn how to create quantum circuits. Here are some resources to get you started.
Composer guide
Gates glossary
Circuit composer
Gates glossary
Gates
H
S
X
Y
Z
ID
U1
U2
U3
Rx
Ry
Rz
T
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Barrier
Operations
Subroutines
if
+ Add
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q[1]
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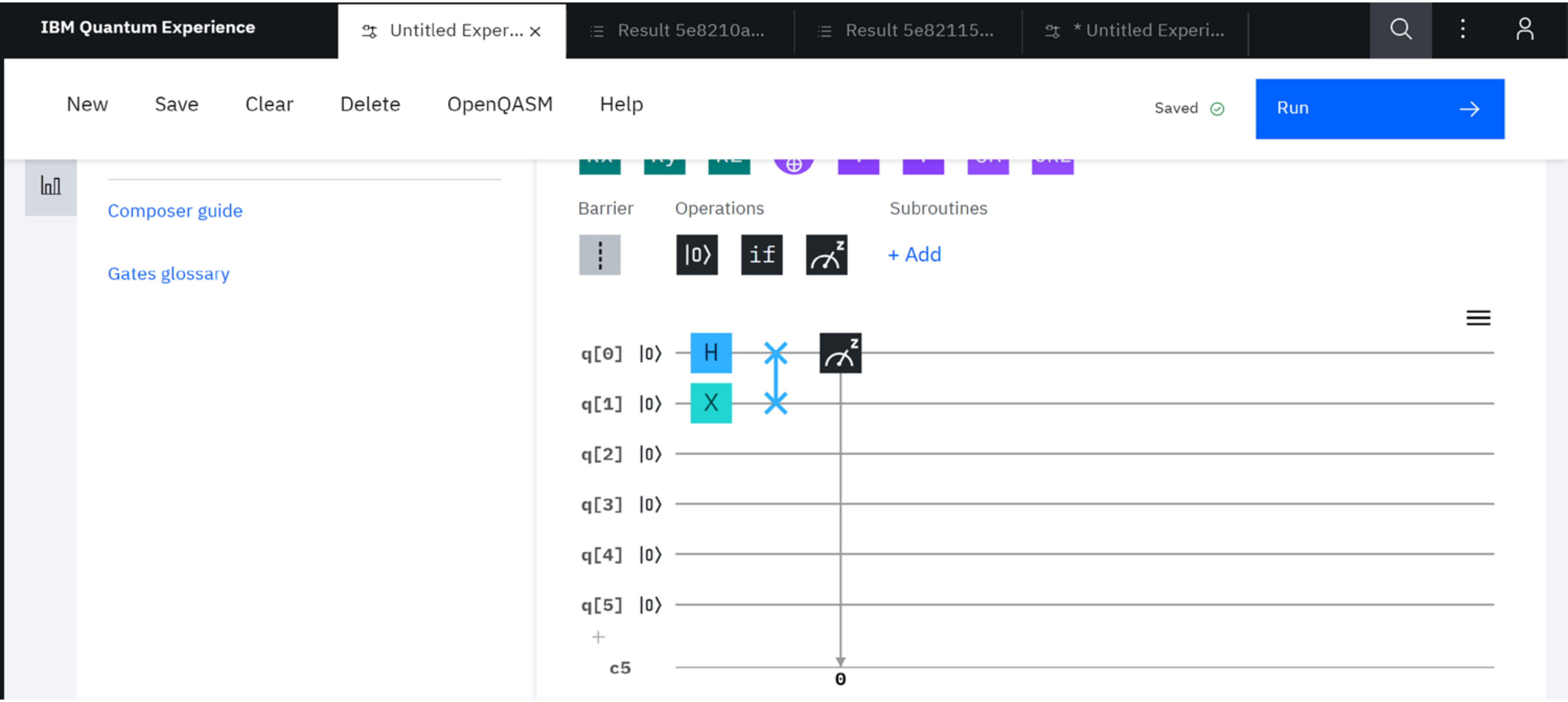
q[3]


IBM Quantum Experience
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Save
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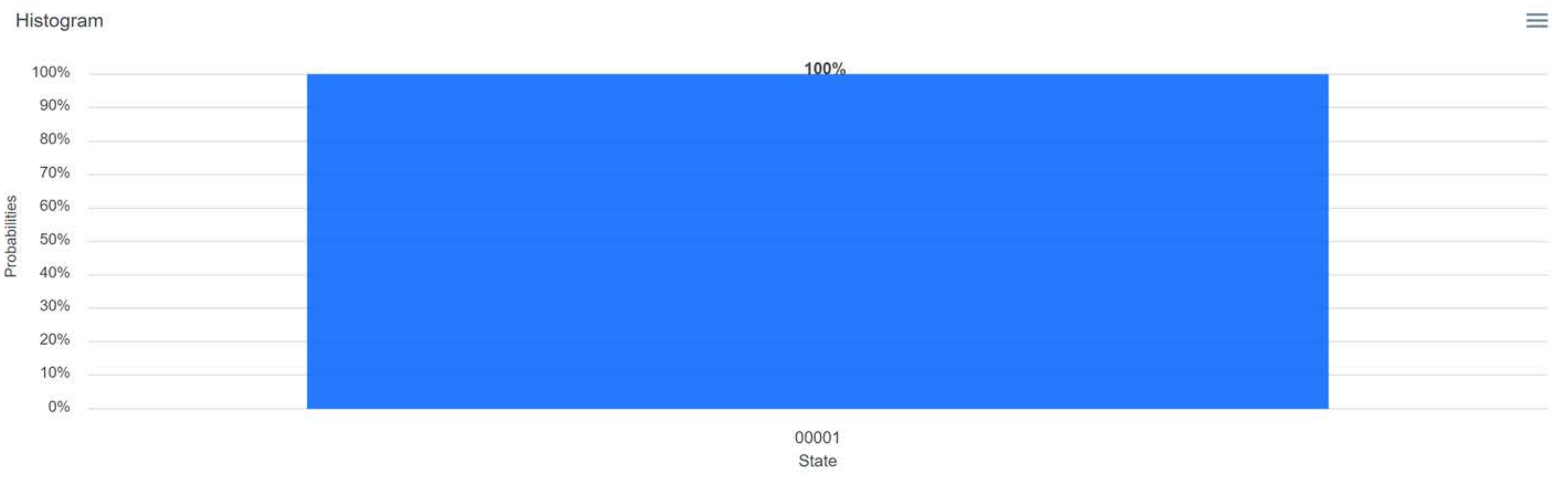
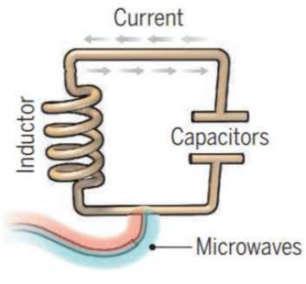
Delete
OpenQASM
Help
Saved
Run
Composer guide
Gates glossary
Barrier
Operations
Subroutines
|0⟩
if
+ Add
q[0] |0⟩
q[1] |0⟩
q[2] |0⟩
q[3] |0⟩
q[4] |0⟩
q[5] |0⟩
H
X
c5
0

Result of simulation(1024 times of measurements)

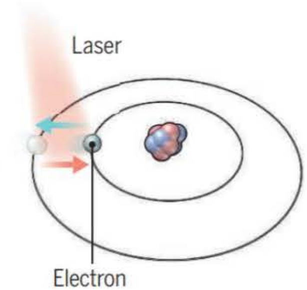


What are the possible quantum systems can be made to be quantum computer?



Superconducting loops

A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.

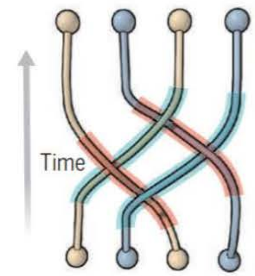


Trapped ions

Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.

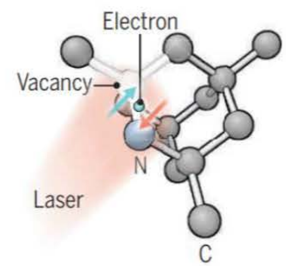
Silicon quantum dots

These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.



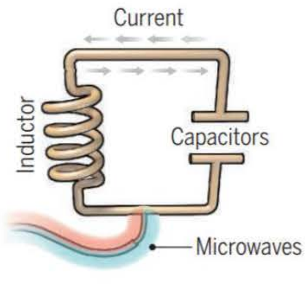
Topological qubits

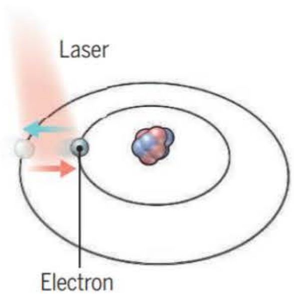
Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.

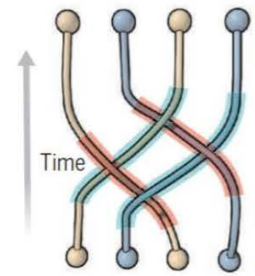


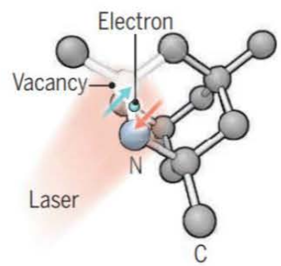
Diamond vacancies

A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.









	Superconducting loops	Trapped ions	Silicon quantum dots	Topological qubits	Diamond vacancies
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures.Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%
Number entangled	9	14	2	N/A	6
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies
Pros	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
Cons	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.

Note: Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

Science 02 Dec 2016: Vol. 354, Issue 6316, pp. 1090-1093 DOI: 10.1126/science.354.6316.1090

Quantum Hardware R&D!

Superconducting

- Alibaba Group
- Alice & Bob
- D-Wave – The Quantum Computing Company™
- Google
- IBM
- imec
- intel
- Microsoft
- qci
- QRDLAB
- Raytheon BBN Technologies
- rigetti
- RIKEN

Trapped Ions

- infineon
- IONQ
- Honeywell

Quantum Dots

- FUJITSU
- NEC
- TOSHIBA

NMR

- hp

CMOS

- HITACHI

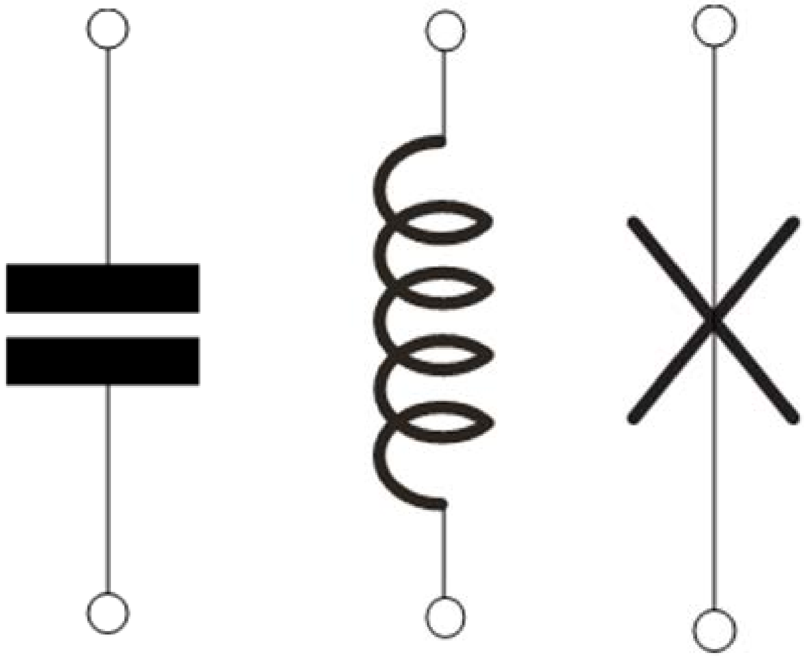
Photonic

- NTT
- PsiQ

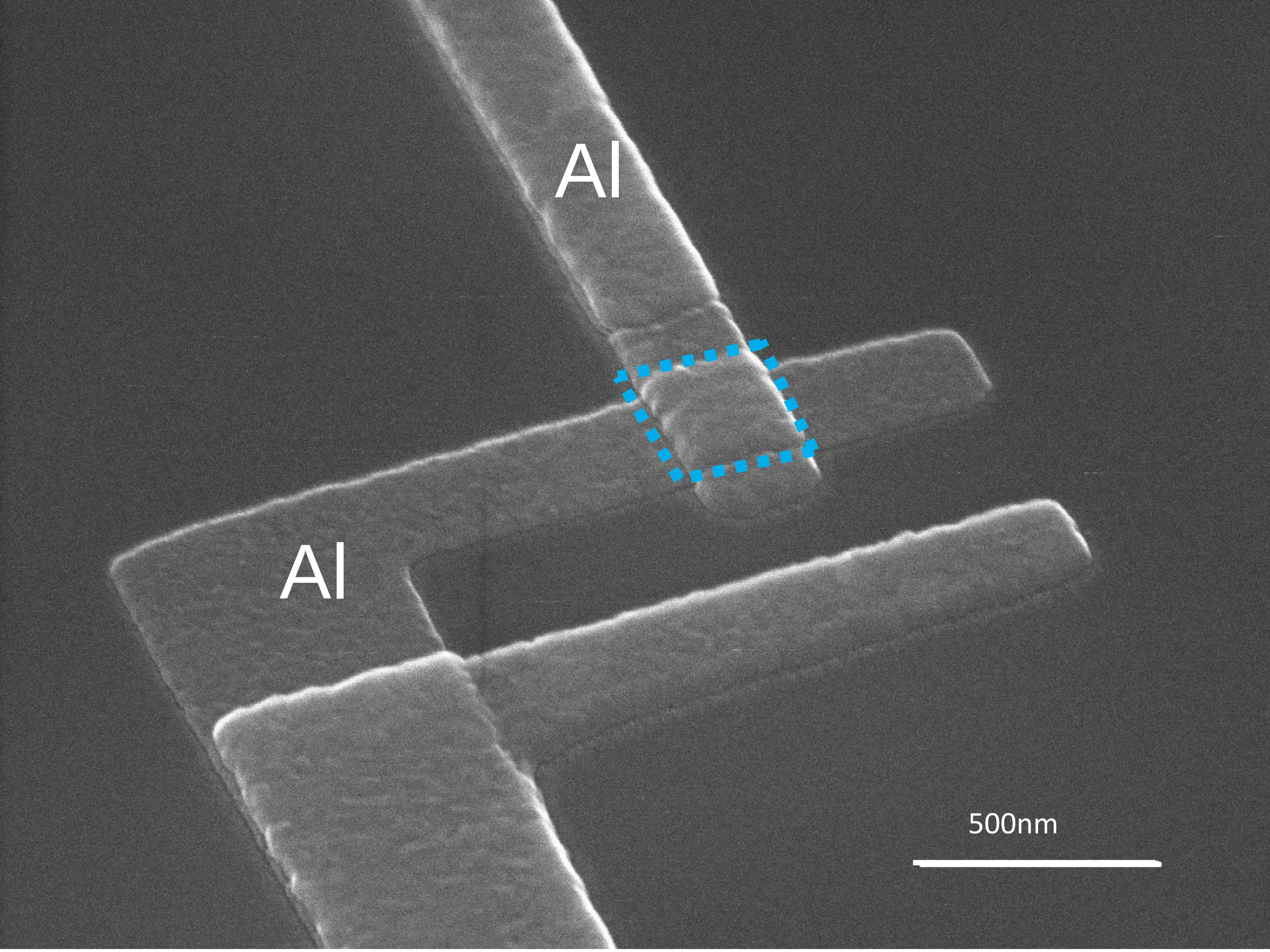
https://en.wikipedia.org/wiki/List_of_companies_involved_in_quantum_computing_or_communication

How to build a superconducting qubit?

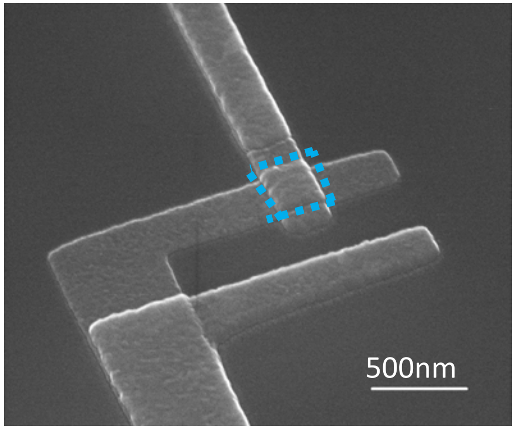
Building blocks of superconducting artificial atoms

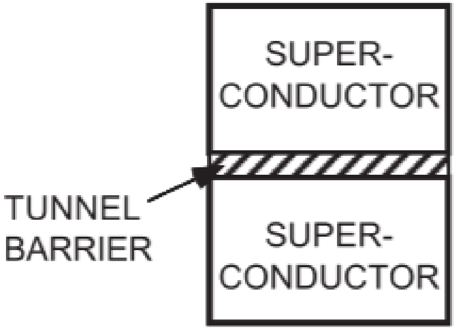


quantum LEGO set

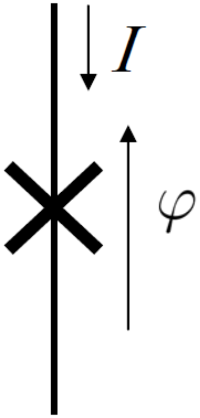

Al
Al
500nm

Josephson Al/AlOx/Al tunnel junction: a nonlinear dissipationless inductor





ω_p ~20GHz



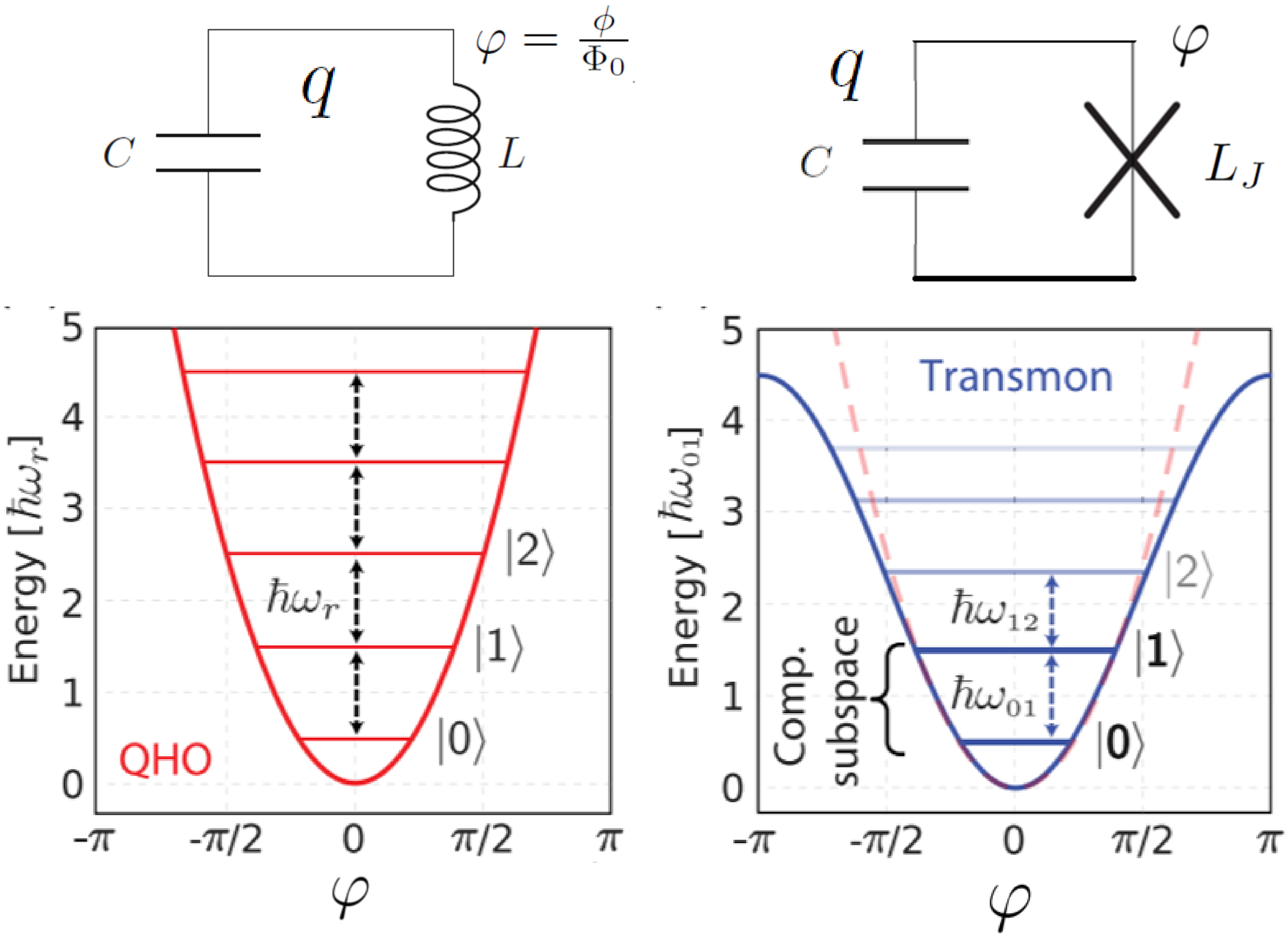
$$V = \frac{\hbar}{2e}\frac{\partial}{\partial t}\varphi$$

$$I = I_c sin\varphi$$

$$L_J(\varphi) = \frac{\phi_0}{I_c cos\varphi} = \frac{L_J(0)}{cos\varphi}$$

$$E(\varphi) = \frac{I_c\Phi_0}{2\pi}(1 - cos\varphi) \equiv E_J(1 - cos\varphi)$$

Josephson Al/AlOx/Al tunnel junction: a nonlinear dissipationless inductor

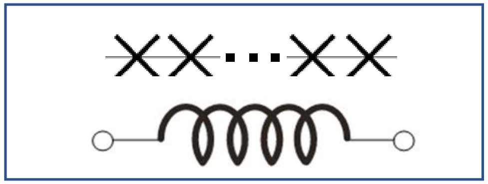


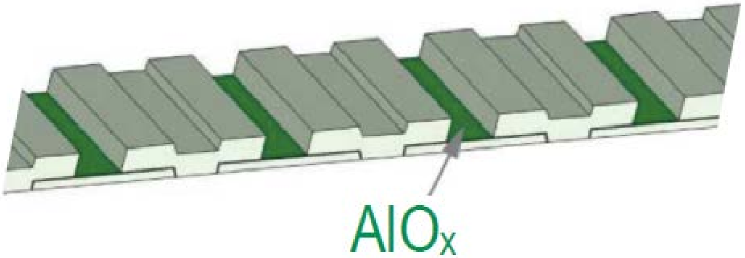
P. Krantz et al, Appl. Phys. Rev. 6, 021318 (2019);

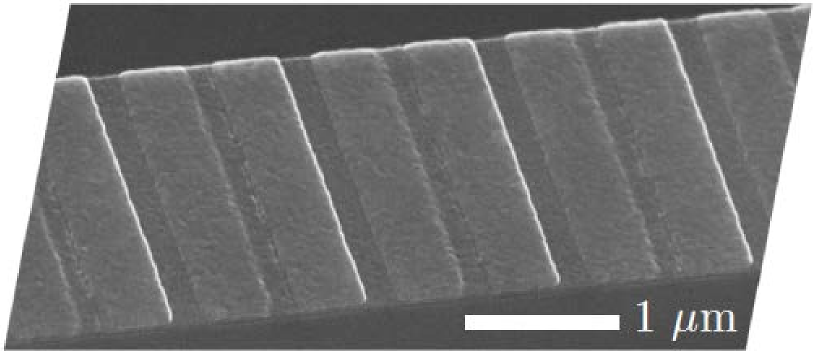
Josephson Junction Chain: Superinductor

$$L_J/\sqrt{A} > 10^4 \mu_0$$

enormous (kinetic) inductance!

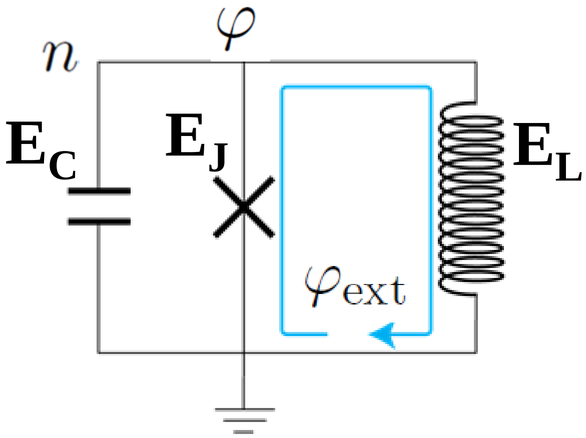






Lin et al. Phys. Rev. Lett. 120, 150503 (2018)

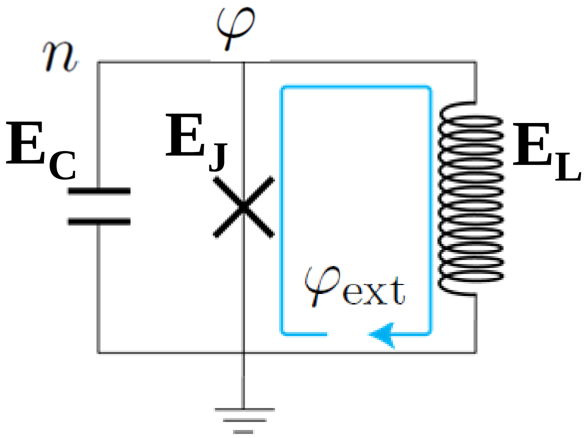
Particle in a box physics: Design box!



$$\hat{H} = 4E_c(\hat{n} - n_g)^2 - E_J cos\hat{\varphi} + \frac{1}{2}E_L(\hat{\varphi} - \varphi_{ext})^2$$

$$[\hat{\varphi}, \hat{n}] = i$$

Particle in a box physics: Design box!



$$\widehat{H} = 4E_c(\widehat{n} - n_g)^2 - E_J cos\widehat{\varphi} + \frac{1}{2}E_L(\widehat{\varphi} - \varphi_{ext})^2$$

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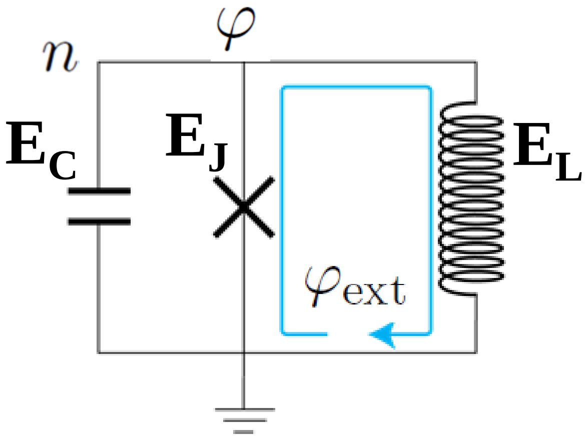
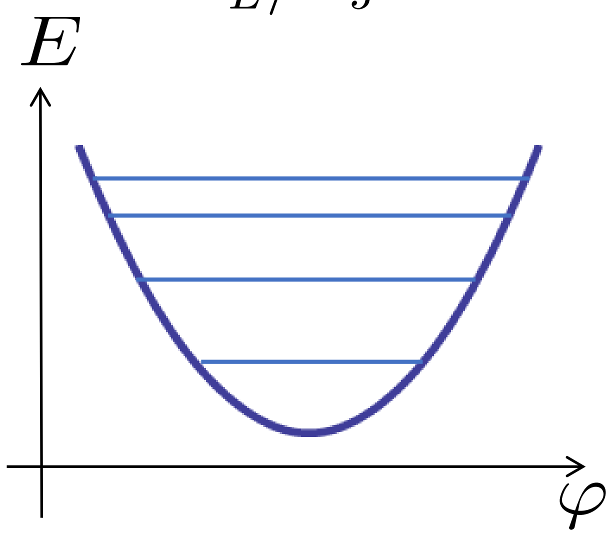
Particle in a box physics: Design box!



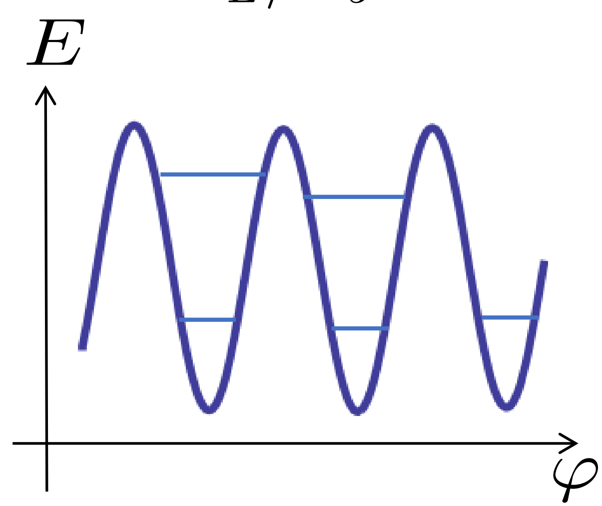
$$\widehat{H} = 4E_c(\widehat{n} - n_g)^2 - E_J cos\widehat{\varphi} + \frac{1}{2}E_L(\widehat{\varphi} - \varphi_{ext})^2$$

$$[\widehat{\varphi}, \widehat{n}] = i$$

$E_L/E_J = 10$

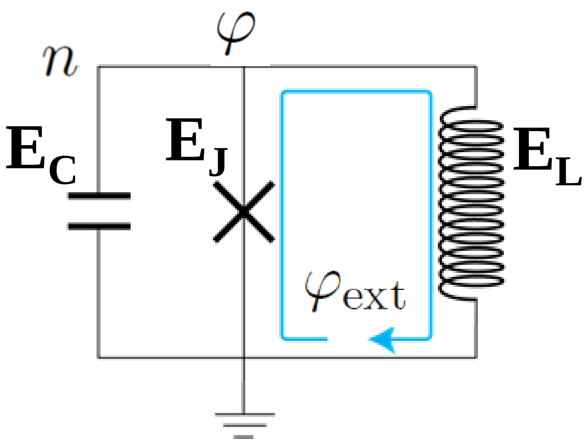


$E_L/E_J = 10^{-3}$



Artificial atoms: engineerable energy states and transitions

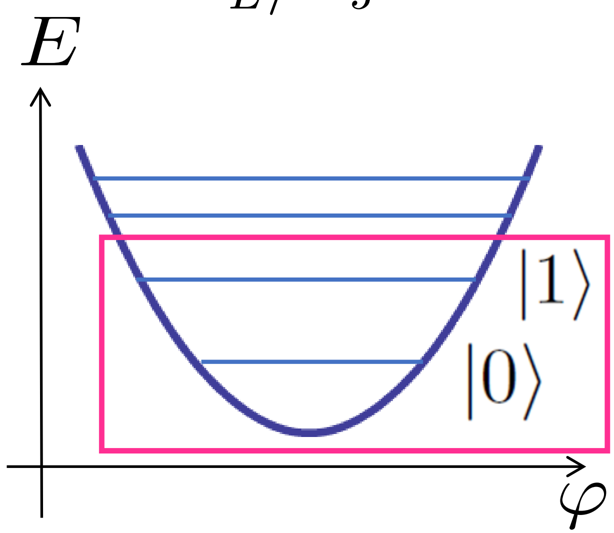
Confine Dynamics: Qubit



$$\widehat{H} = 4E_c(\widehat{n} - n_g)^2 - E_J cos\widehat{\varphi} + \frac{1}{2}E_L(\widehat{\varphi} - \varphi_{ext})^2$$

$$[\widehat{\varphi}, \widehat{n}] = i$$

$$E_L/E_J = 10$$



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

Qubit: information storage within $|\psi\rangle$

Time scale of loss information: T1 and T2

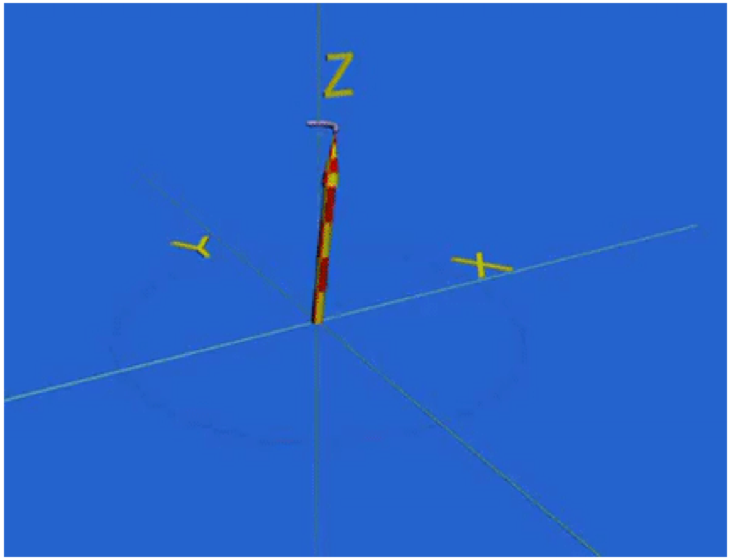
$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

Decoherence time Relaxation time Dephasing time

Time scale of loss information: T1 and T2

$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

Decoherence time　Relaxation time　Dephasing time



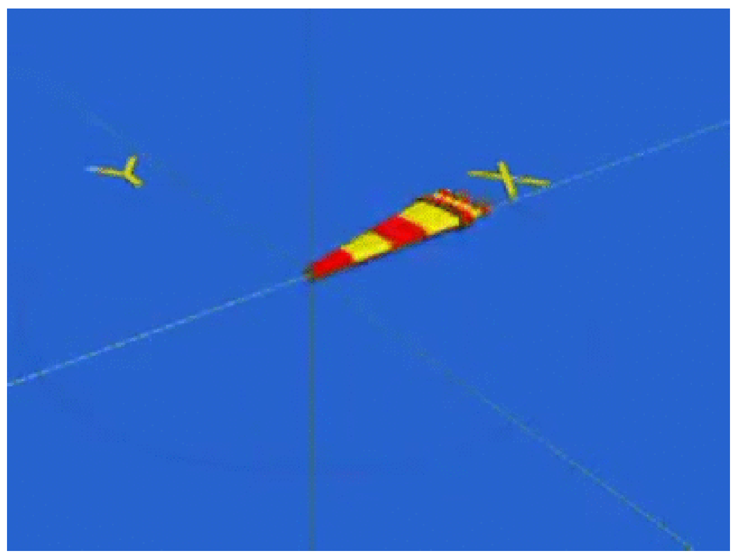
Relaxation

https://www.youtube.com/watch?v=lKp67IqQjH4&list=PL40F1EE0DF59D777A&index=1

Time scale of loss information: T1 and T2

$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

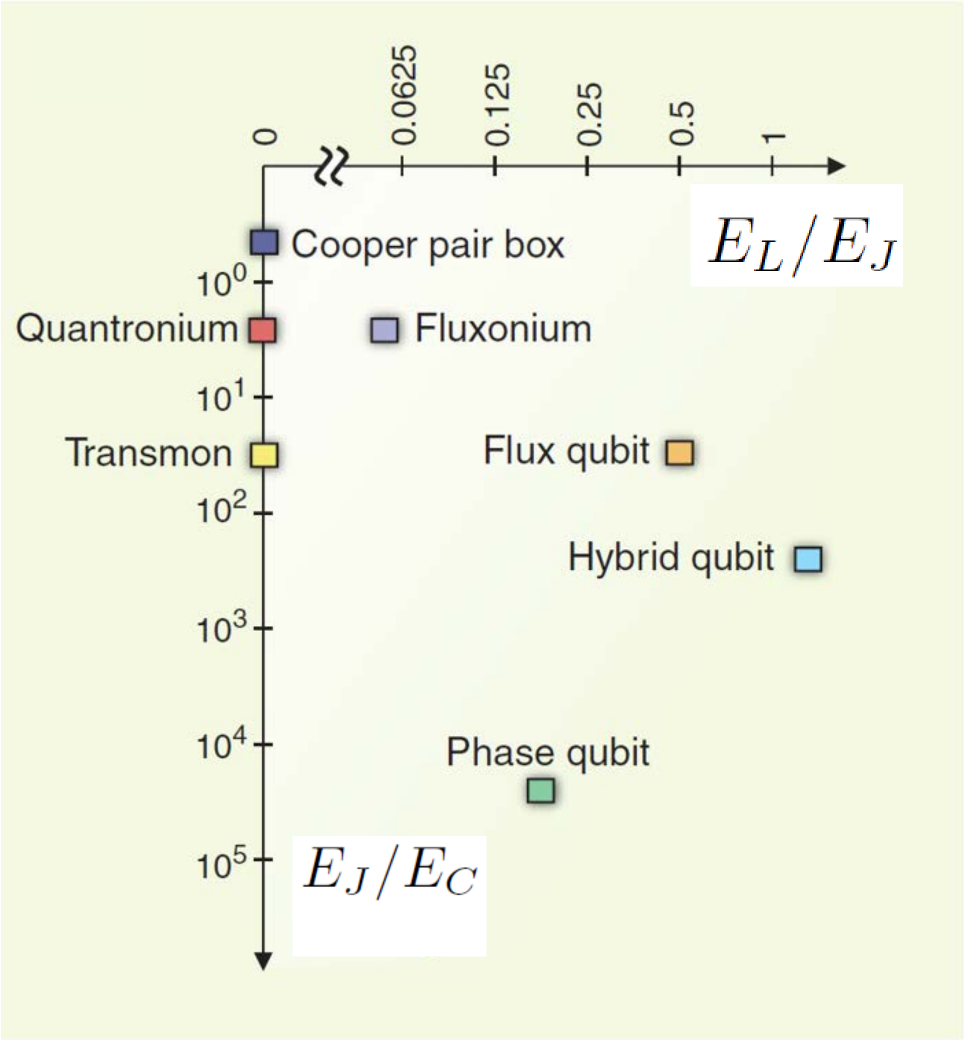
Decoherence time   Relaxation time   Dephasing time



Dephasing

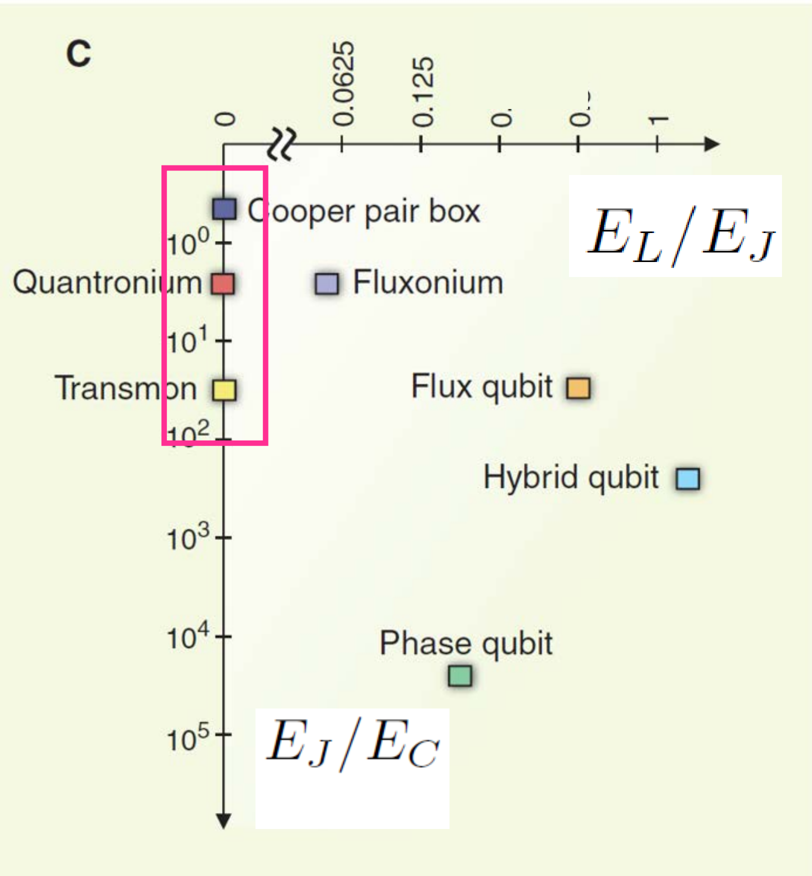
https://www.youtube.com/watch?v=is8TscwFOvM&index=2&list=PL40F1EE0DF59D777A

“Periodic table” of superconducting qubits



Devoret & Schoelkopf , Science **339**, 1169 (2013)

Control Sensitivity to Charge Noise: Ej/Ec



Devoret & Schoelkopf , Science **339**, 1169 (2013)

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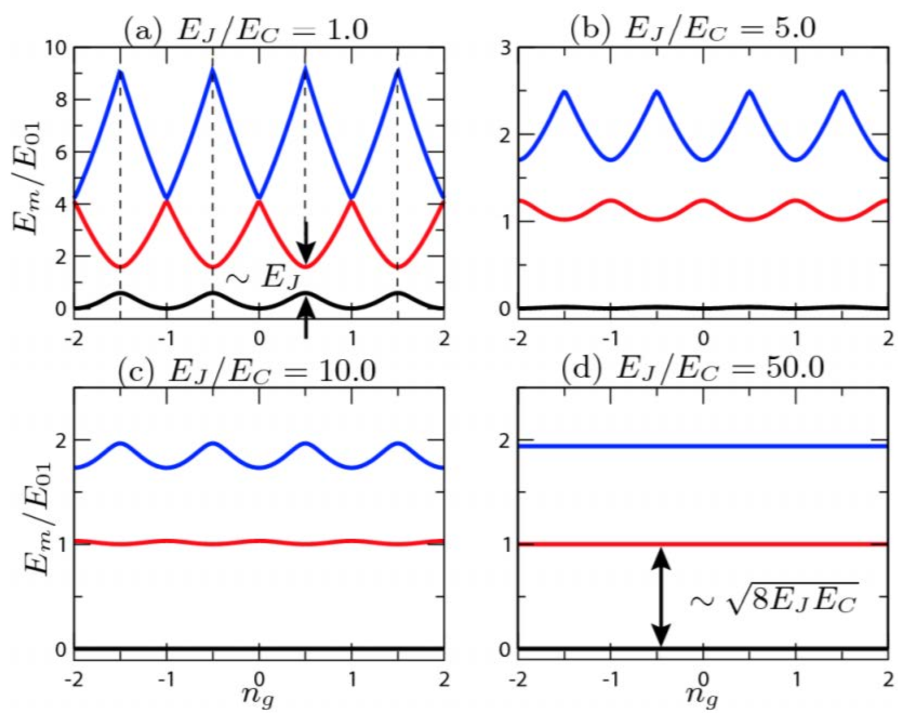
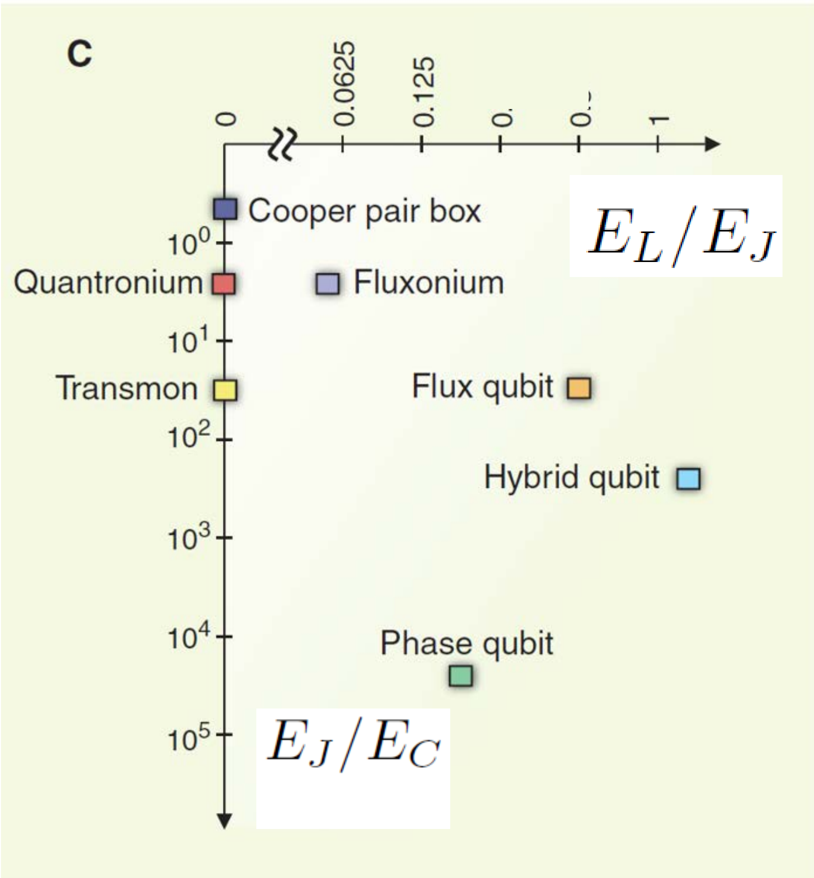
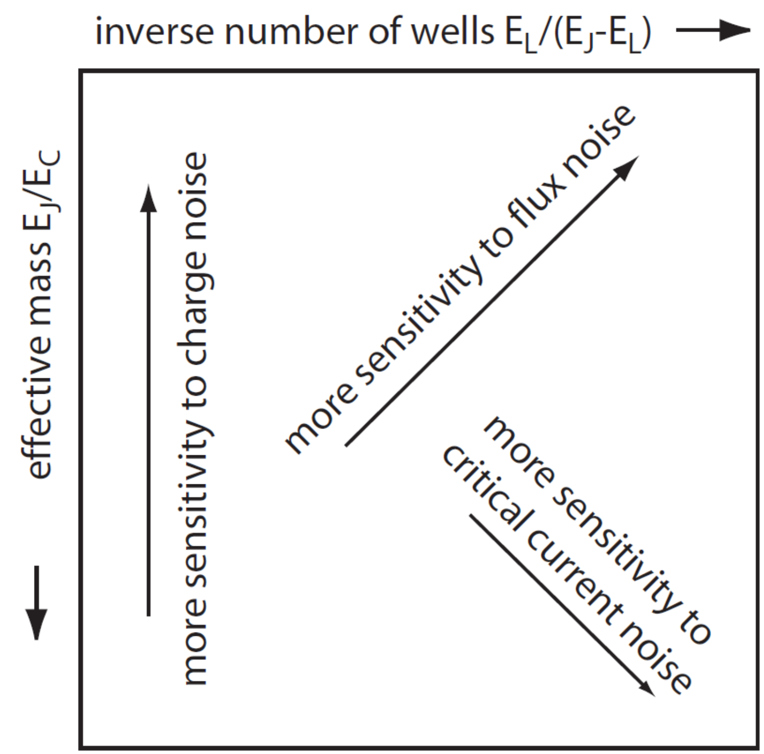


Koch et al., Phys. Rev. A 76, 042319

Control Sensitivity to Various Noise Source

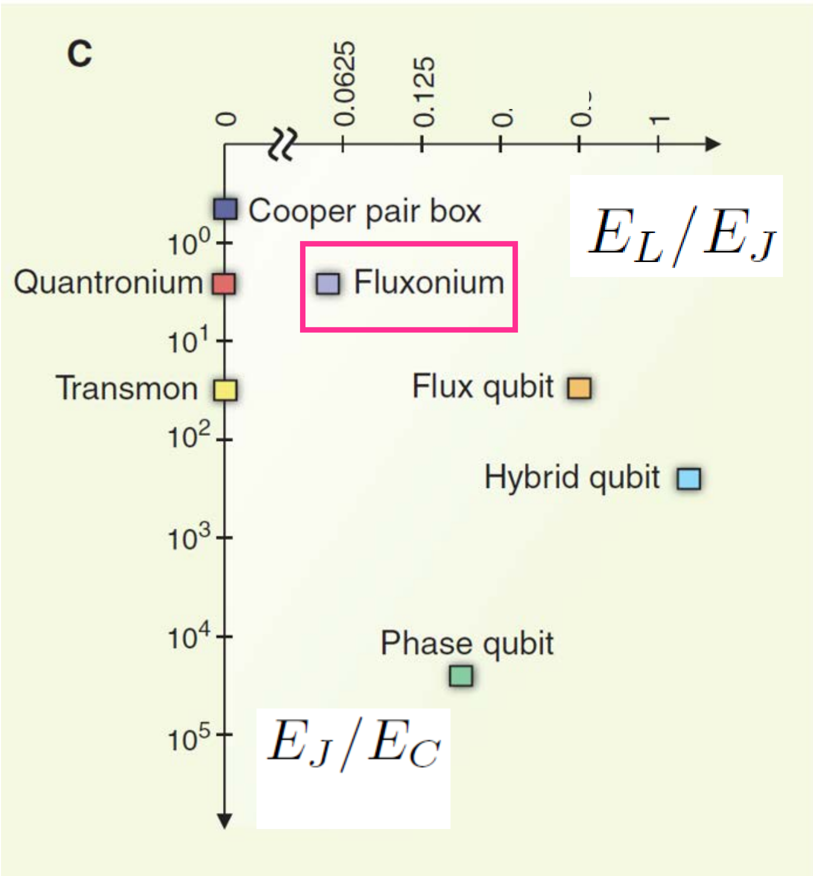


Devoret & Schoelkopf , Science **339**, 1169 (2013)

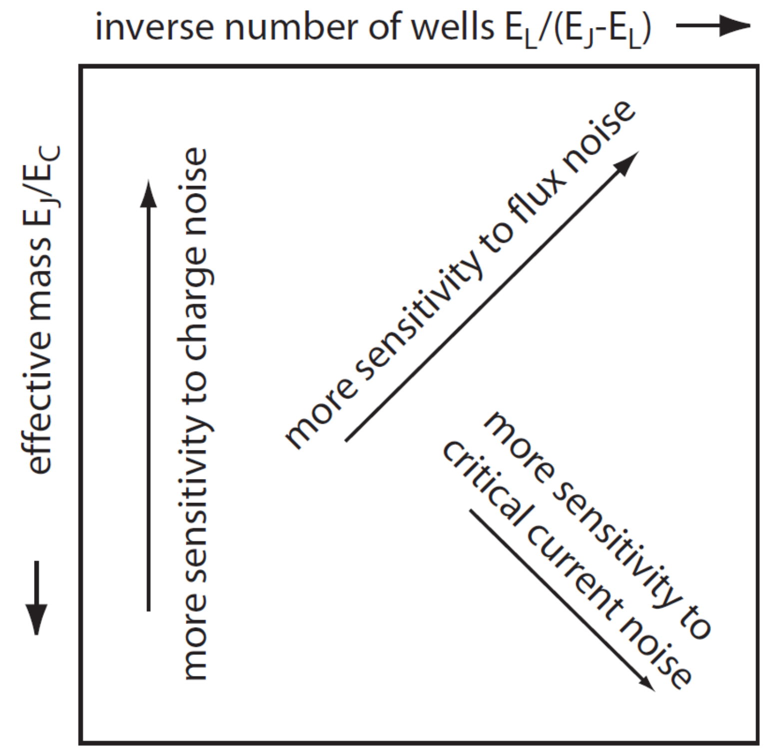


Vool & Devoret Int. J. Circ. Theor. Appl. 45, 897 (2017)

Control Sensitivity to Various Noise Source



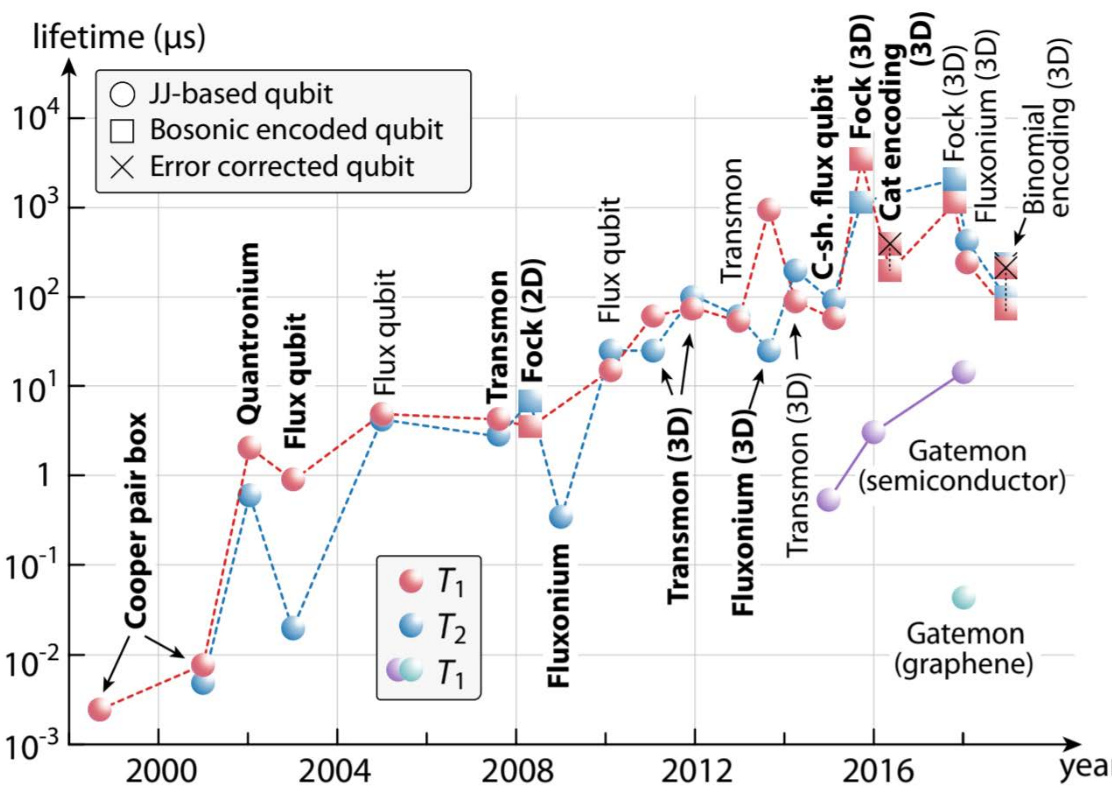
Devoret & Schoelkopf , Science **339**, 1169 (2013)



Vool & Devoret Int. J. Circ. Theor. Appl. 45, 897 (2017)

Key element: fluxonium

- Highest T1, and T2 of single superconducting qubit
- Anharmonicity can be larger than few GHz
- Very rich multi-level system



MIT group, Annual Review of Condensed Matter Physics **11**, (2019)

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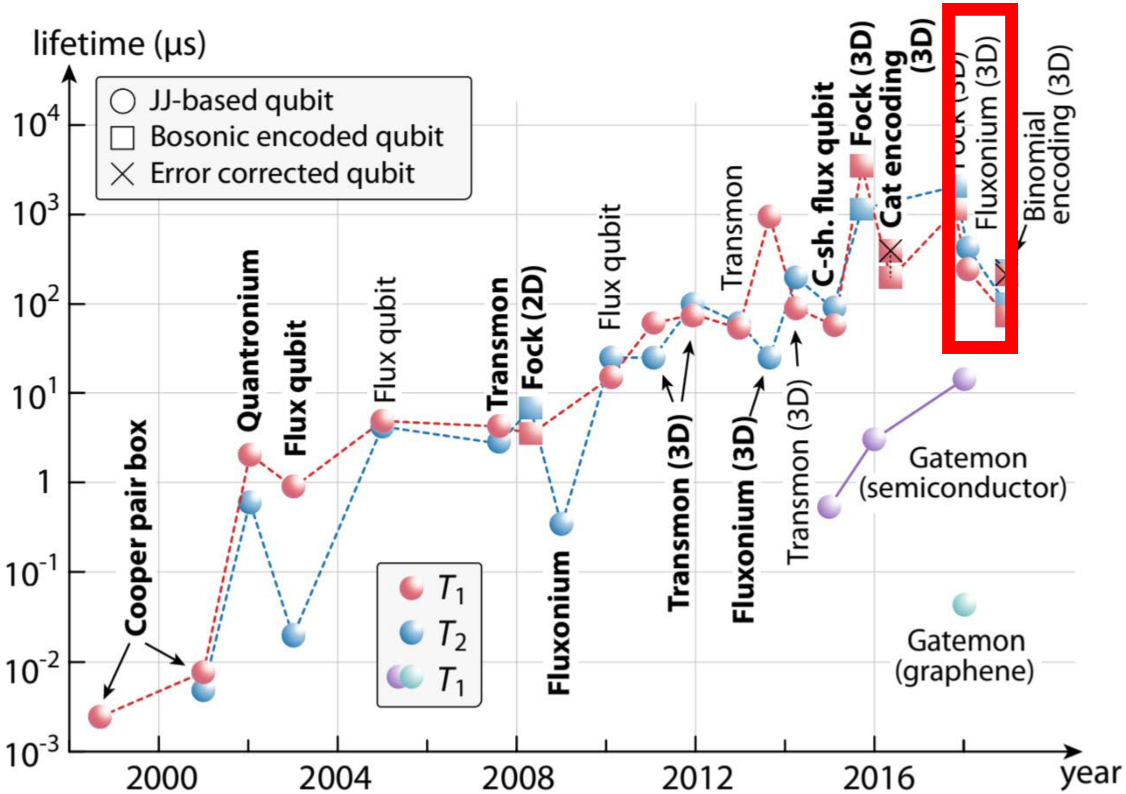
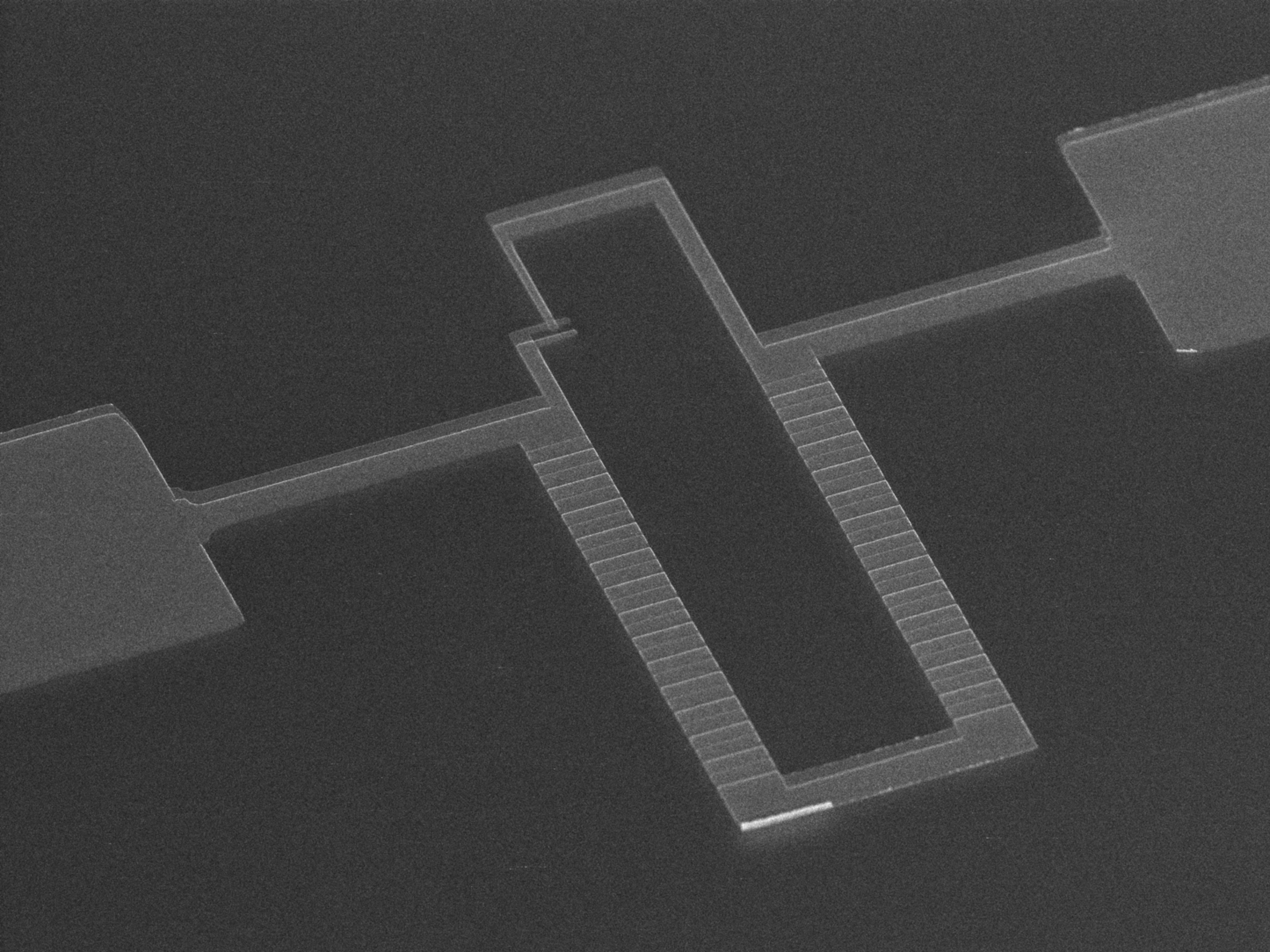
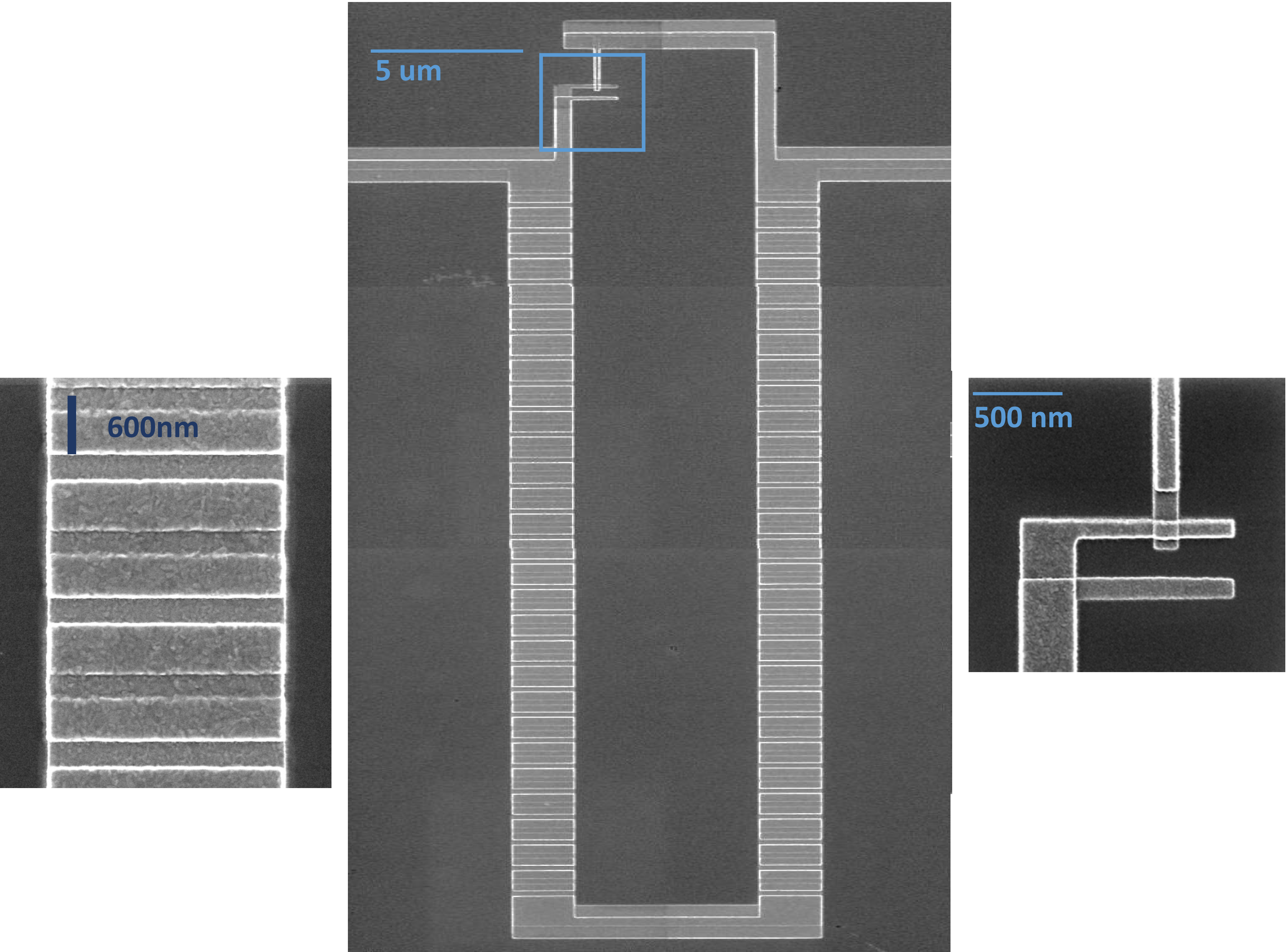
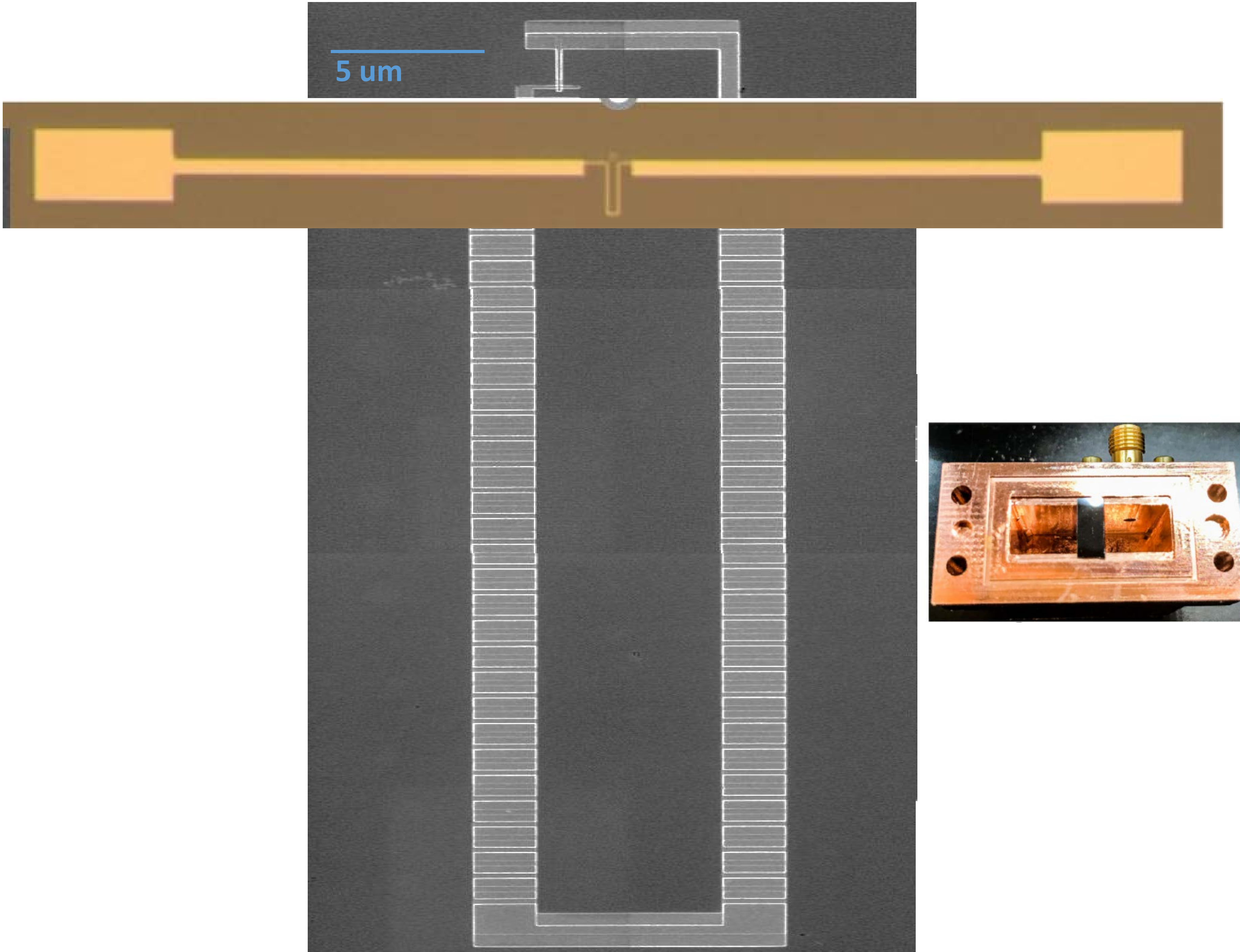
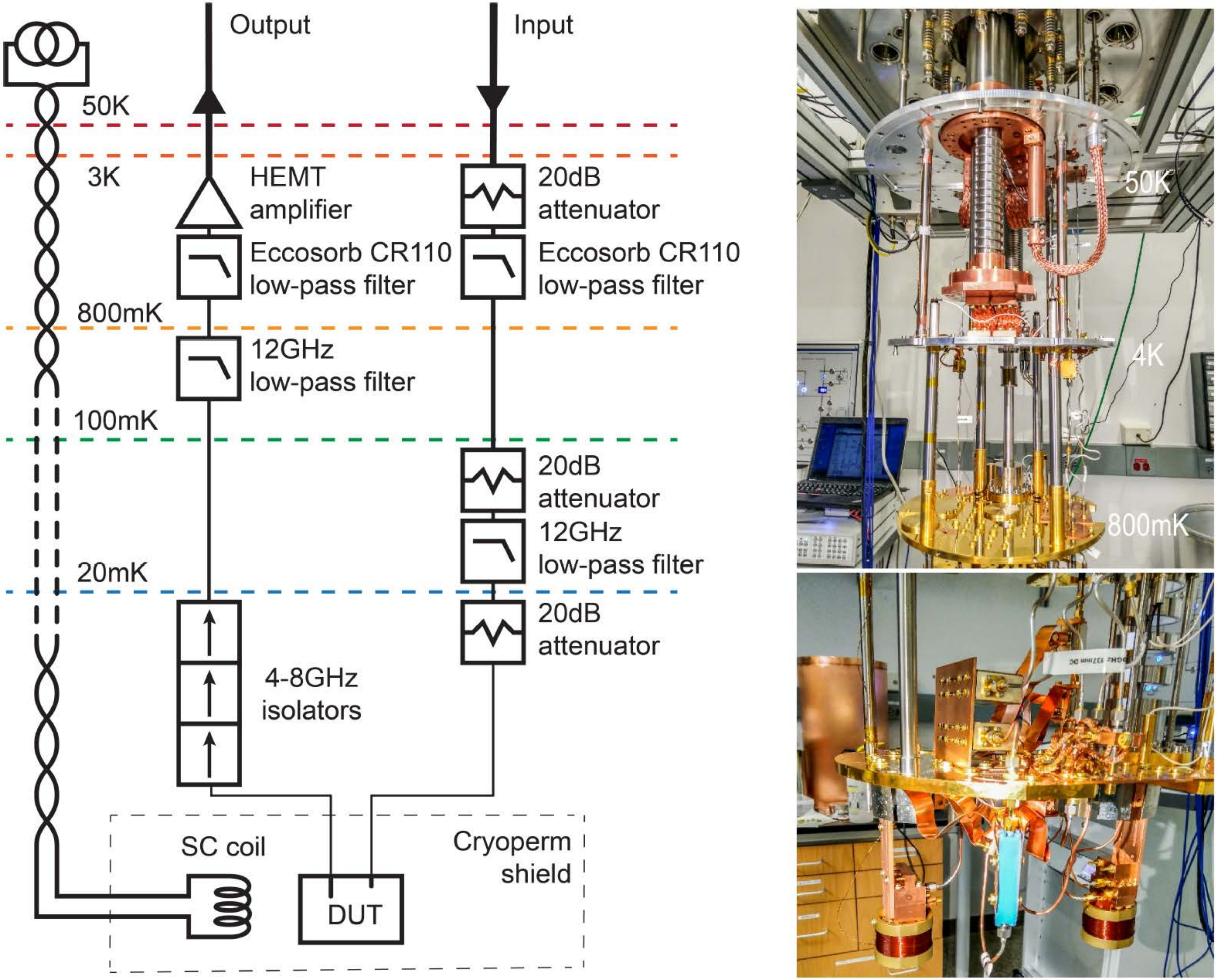


MIT group, Annual Review of Condensed Matter Physics **11**, (2019)

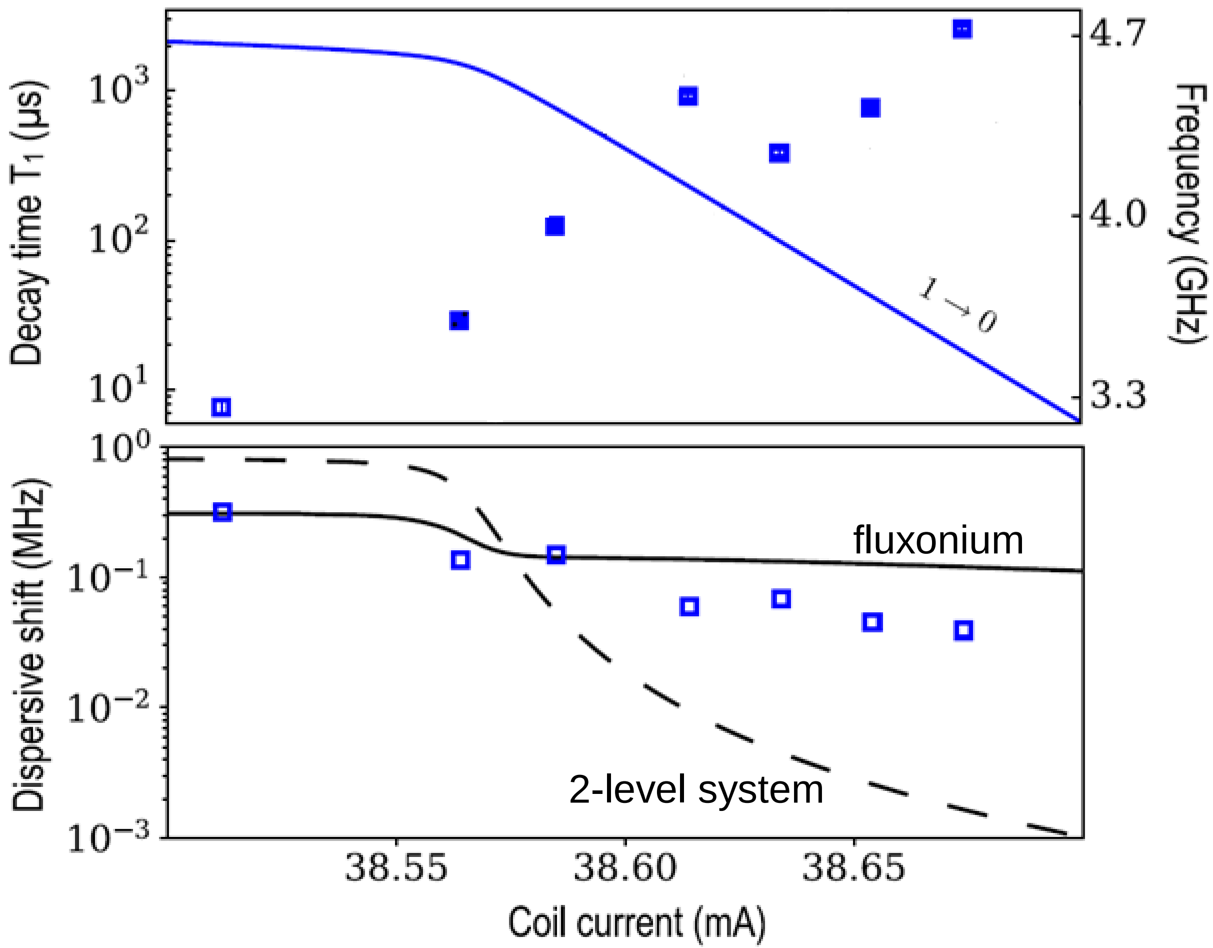



600nm
5 um
500 nm


5 um


Output
Input
50K
3K
HEMT
amplifier
20dB
attenuator
Eccosorb CR110
low-pass filter
Eccosorb CR110
low-pass filter
800mK
12GHz
low-pass filter
100mK
20dB
attenuator
12GHz
low-pass filter
20mK
20dB
attenuator
4-8GHz
isolators
SC coil
Cryoperm
shield
DUT
50K
4K
800mK

Demonstration world record T1



$T_2 \approx 4\ \mu s$ due to flux noise

But large L reduces sensitivity to flux noise

Lin, Nquyen et al.Phys. Rev. Lett. **120**, 150503 (2018)

Reproducible world record T2 of superconducting qubit

Qubit	E_J	E_C	E_L	N	T_1	T_2	$\omega_{01}/2\pi$
	GHz	GHz	GHz	-	μs	μs	GHz
A	3	0.84	1	100	110	160	0.78
B	4.86	0.84	1.14	136	250	150	0.32
C	2.2*	0.55	0.72	102	260	350	0.48
D	2.2	0.83	0.52	196	70	90	0.56
E	1.6	0.86	0.5	100	108	140	0.83
F	3.4	0.8	0.41	348	270	165	0.17
G	1.65	1.14	0.19	400	110	140	0.55
H	4.43	1	0.79	100	230	235	0.32

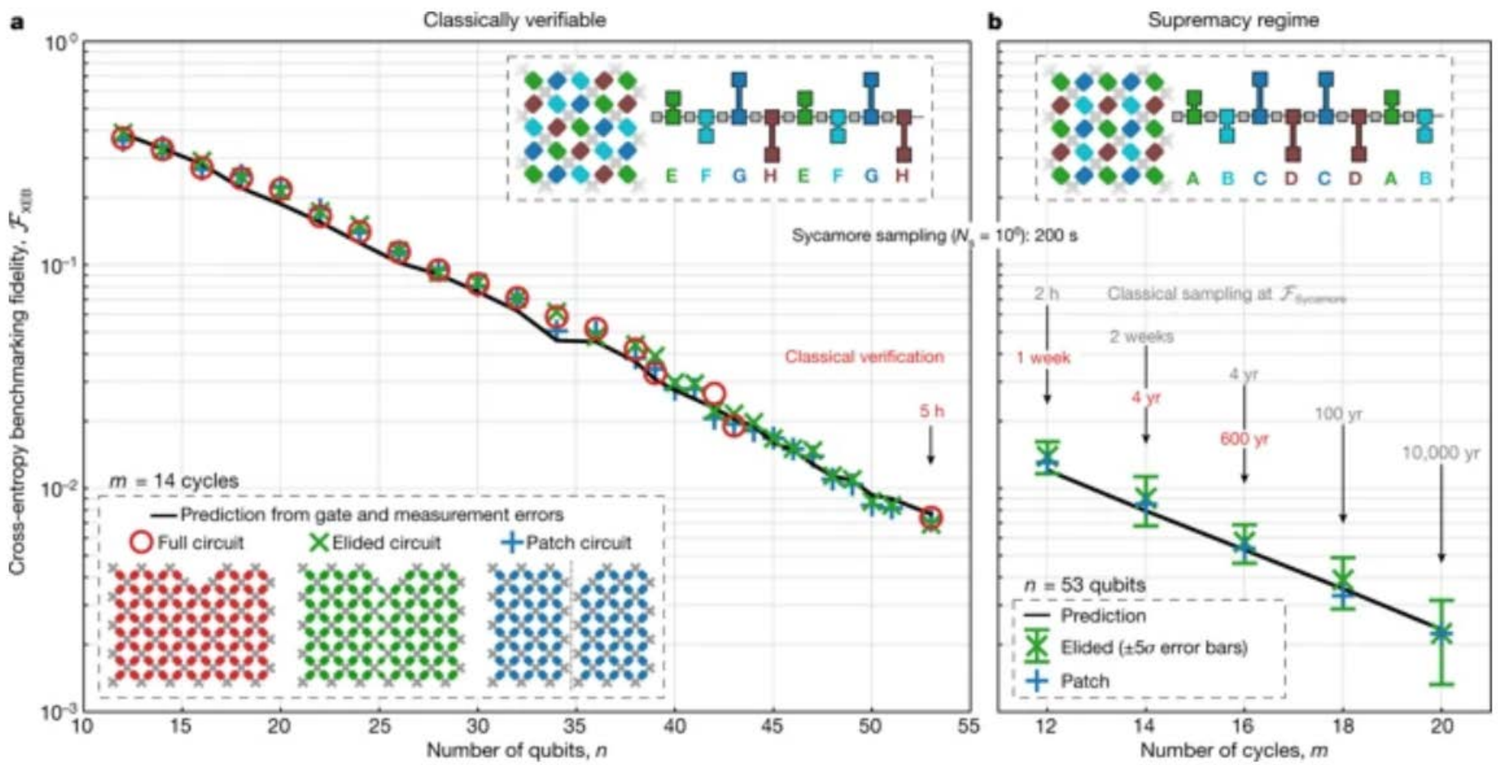
Nquyen, **Lin** et al., PRX 9, 041041(2019)

IBM Q 20 Tokyo: average T1= 78.34µs,T2=50.62µs

https://www.research.ibm.com/ibm-q/technology/devices/

State of the art of superconducting circuits in quantum information science

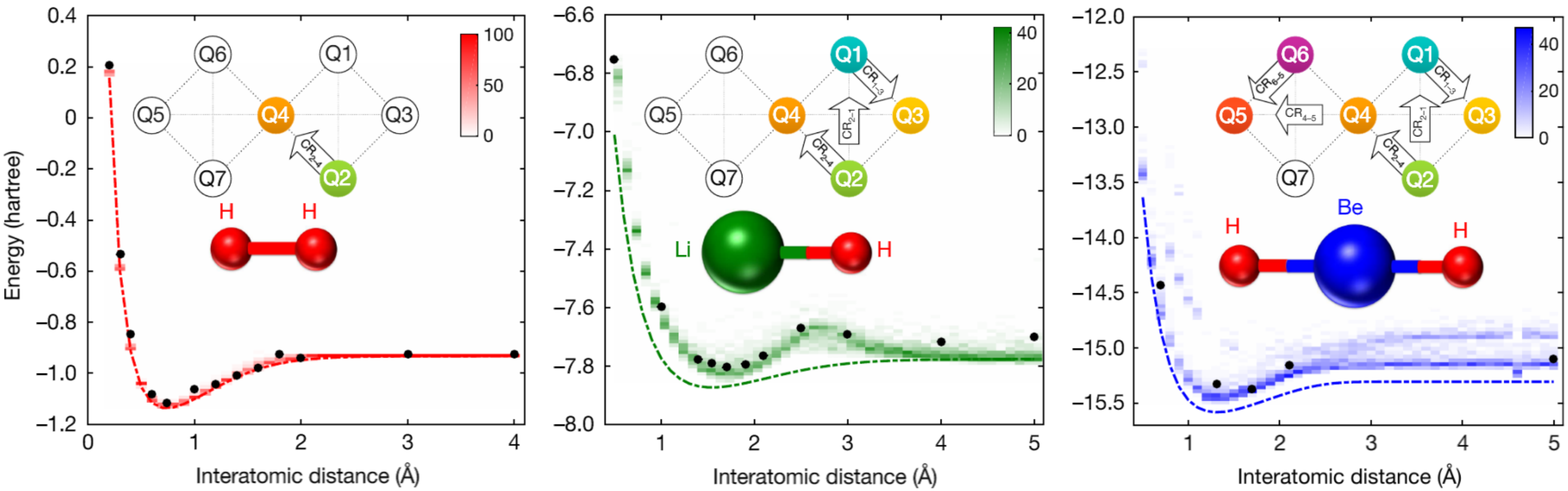
Quantum Computation



Frank Arute et al. Nature **574**, 505(2019)

State of the art of superconducting circuits in quantum information science

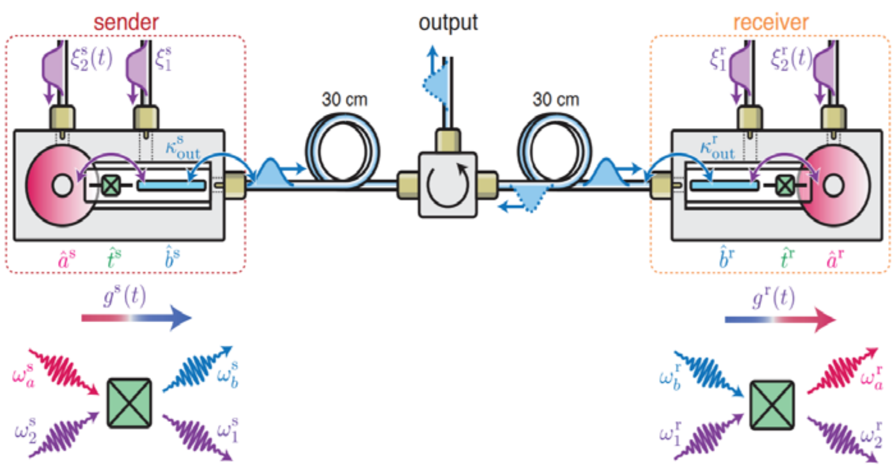
Quantum Simulation

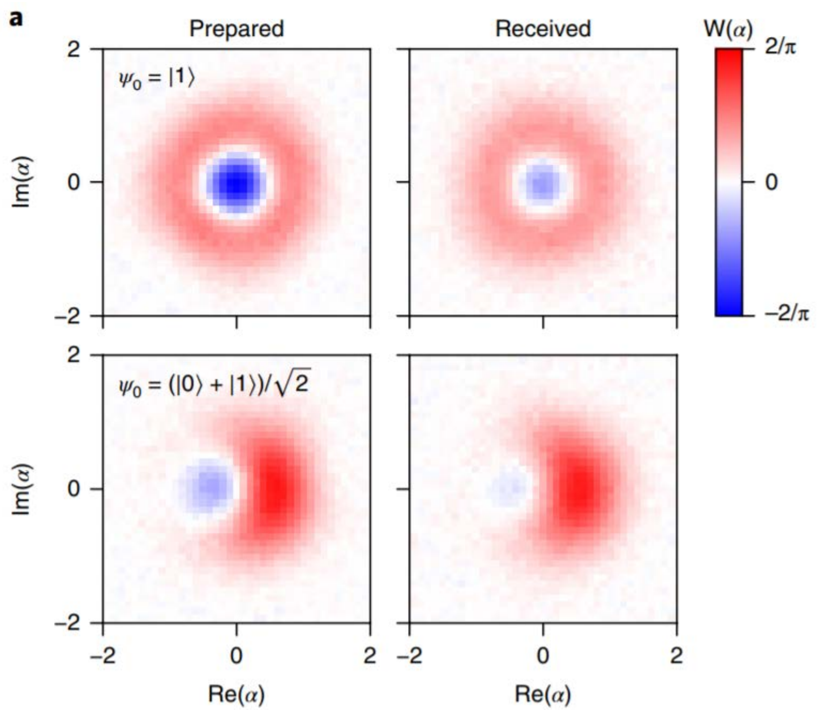


Kandala *et al, Nature.* **549**, 242 (2017)

State of the art of superconducting circuits in quantum information science

Quantum Communication

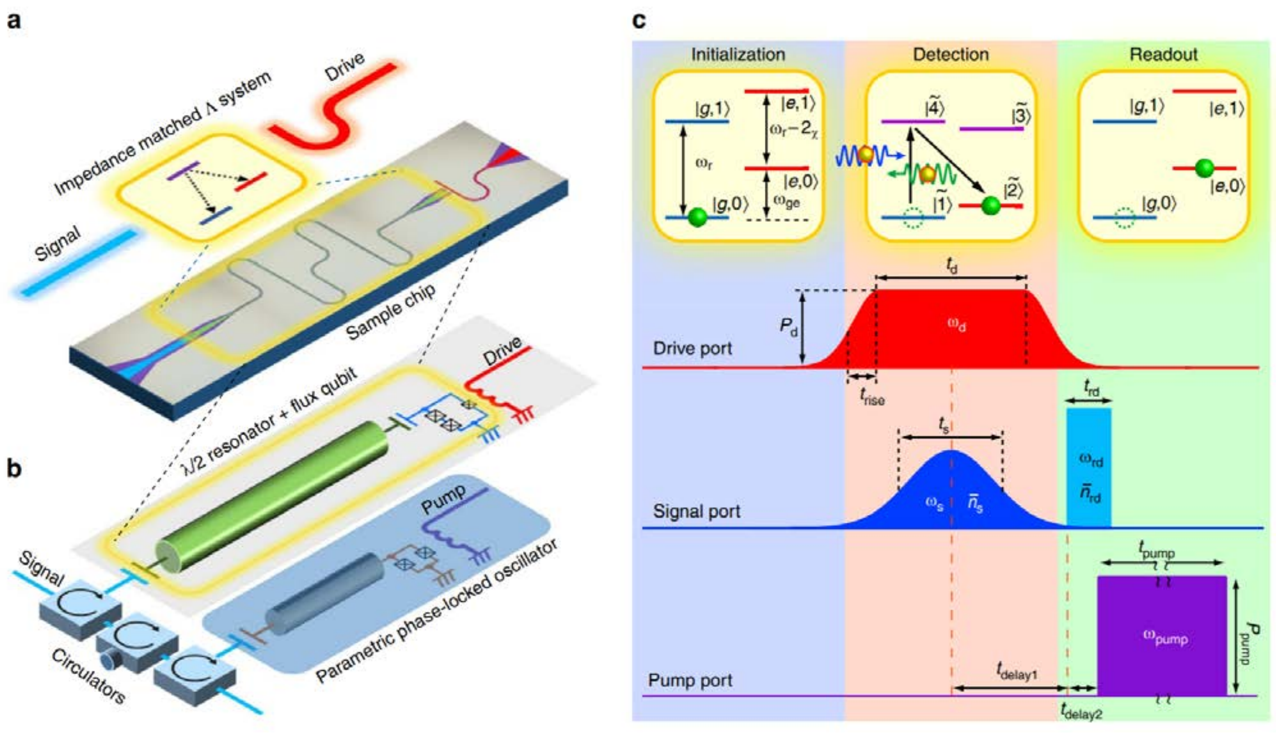




Axline et al, Nat. Phys. **14**, 705 (2018)

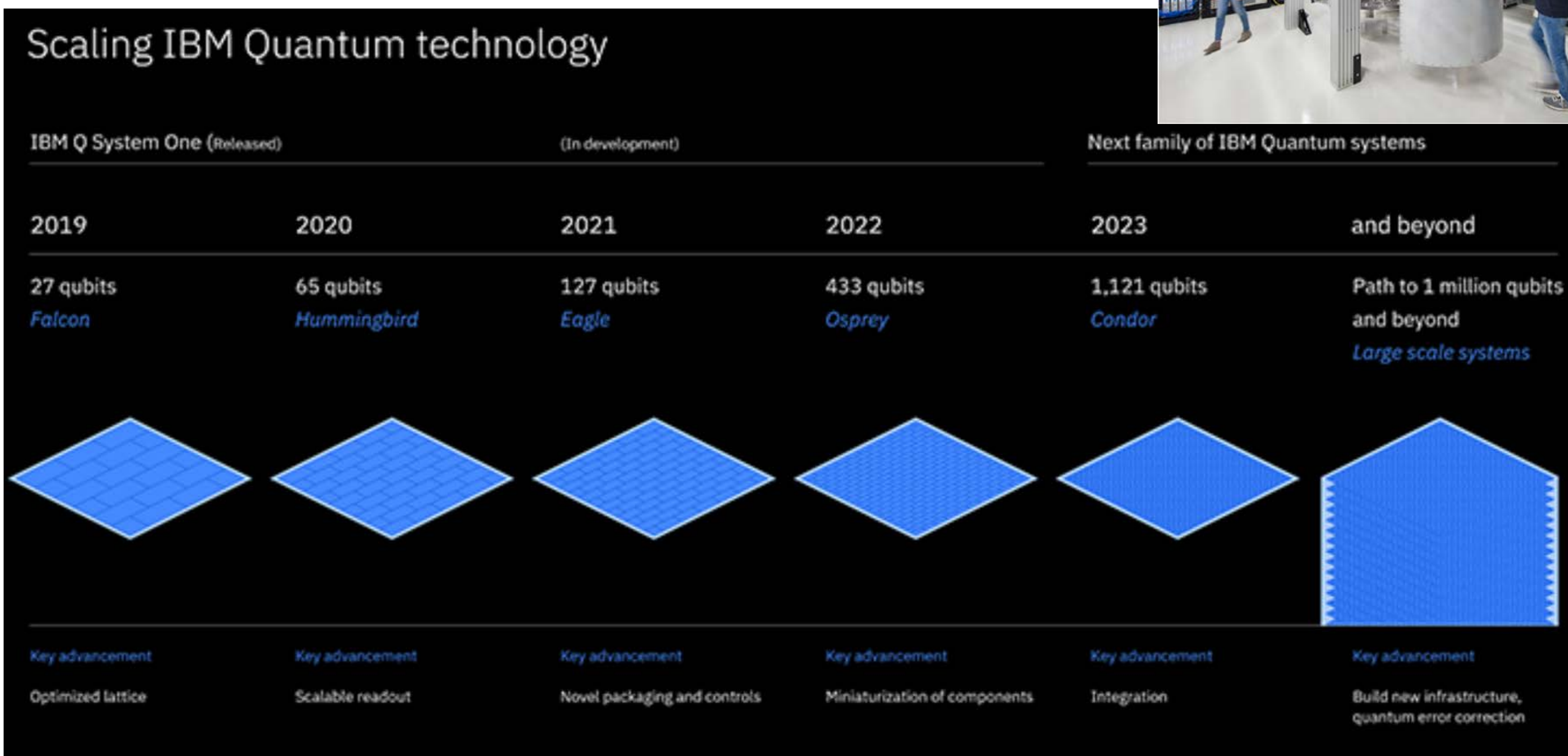
State of the art of superconducting circuits in quantum information science

Quantum sensing and metrology

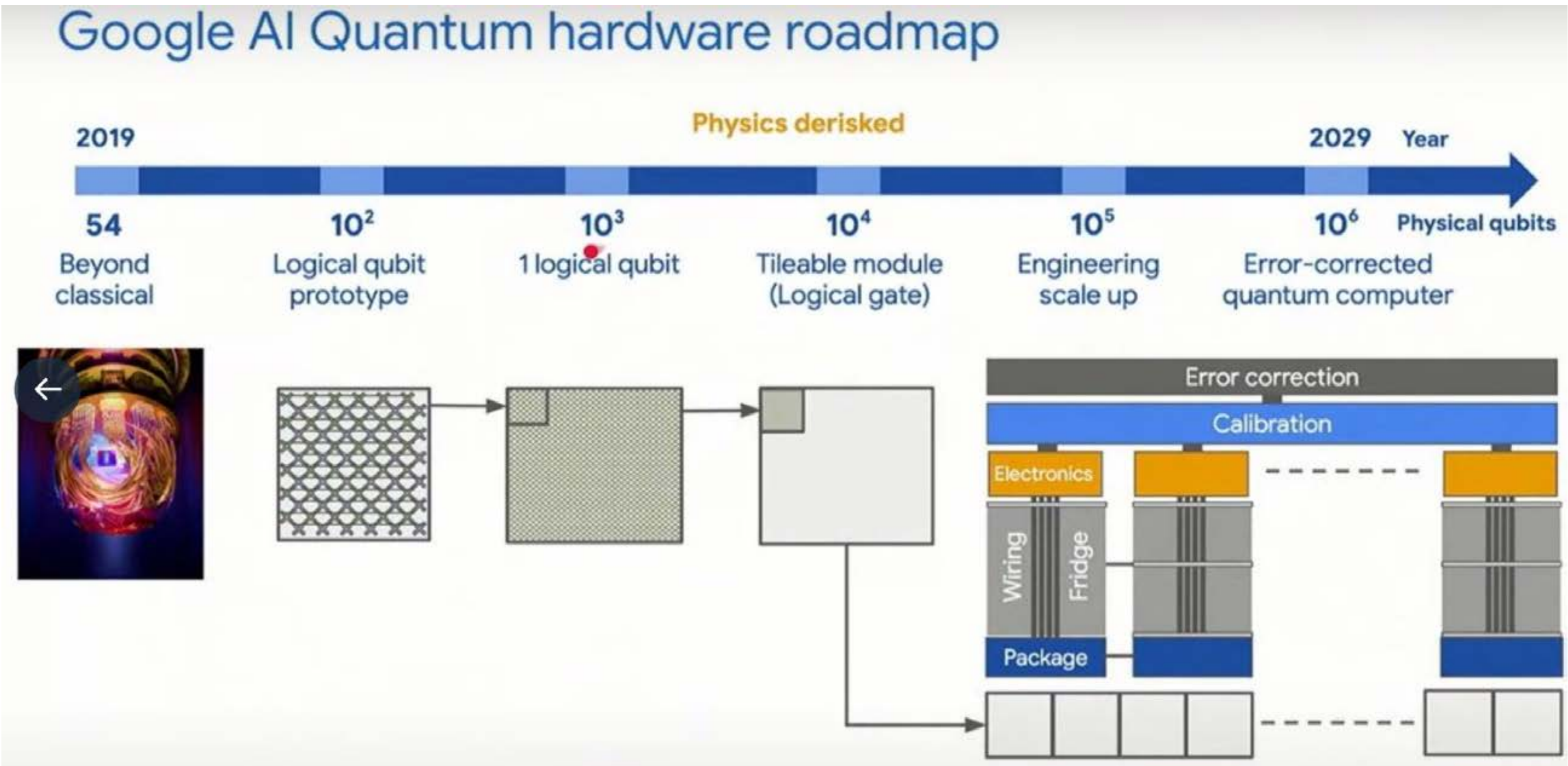


Inomata et al, Nat. Comm. **7**, 12303 (2016)

IBM roadmap for quantum computing



Google's roadmap for quantum computing



Future important development

- Improvement and Scaling up
- Quantum Algorithm
- Quantum error correction and Fault tolerant quantum computers.
- Application for Noisy Intermediate-Scale Quantum (NISQ) machine.