Introduction to Quantum Computing

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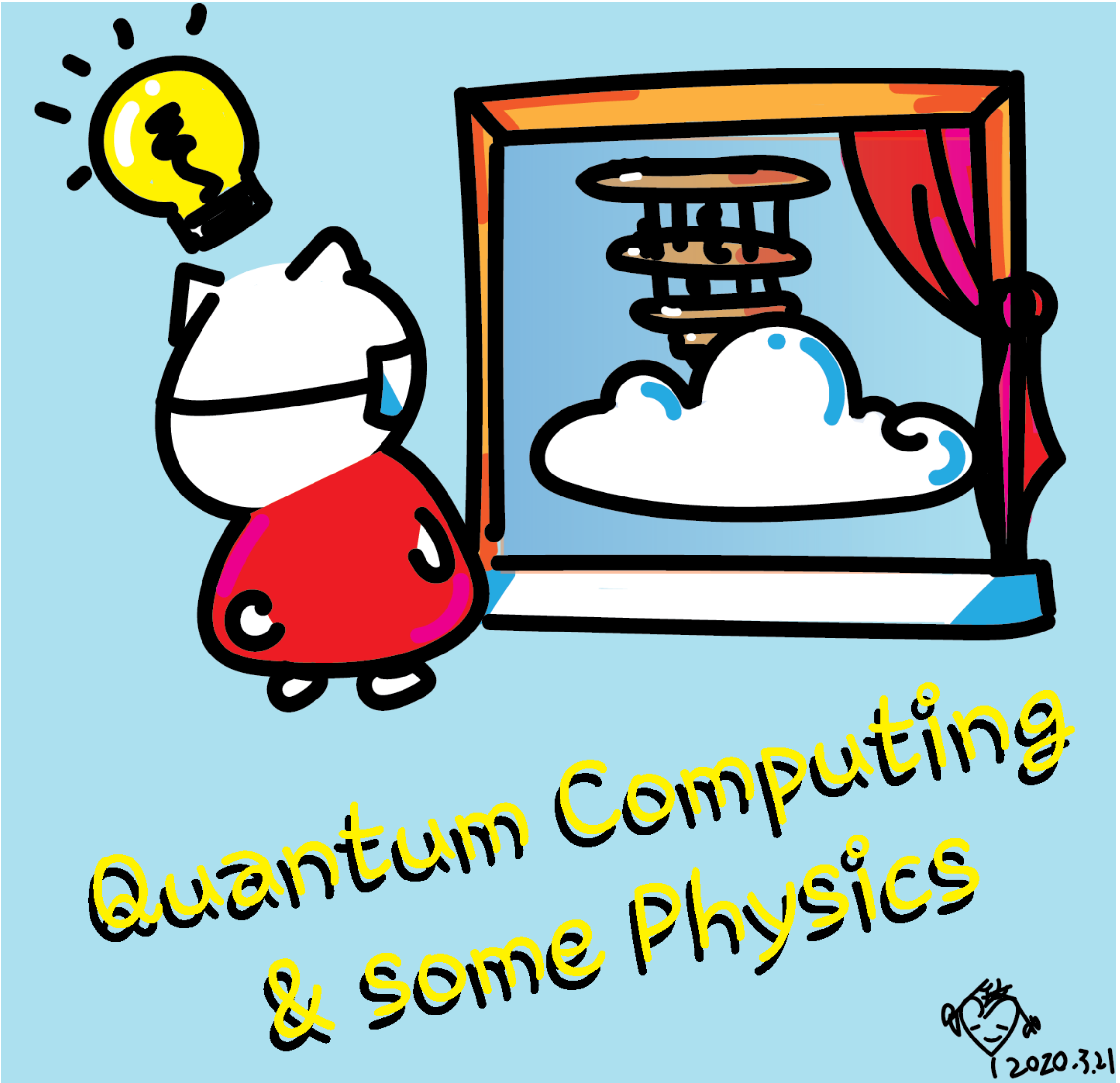
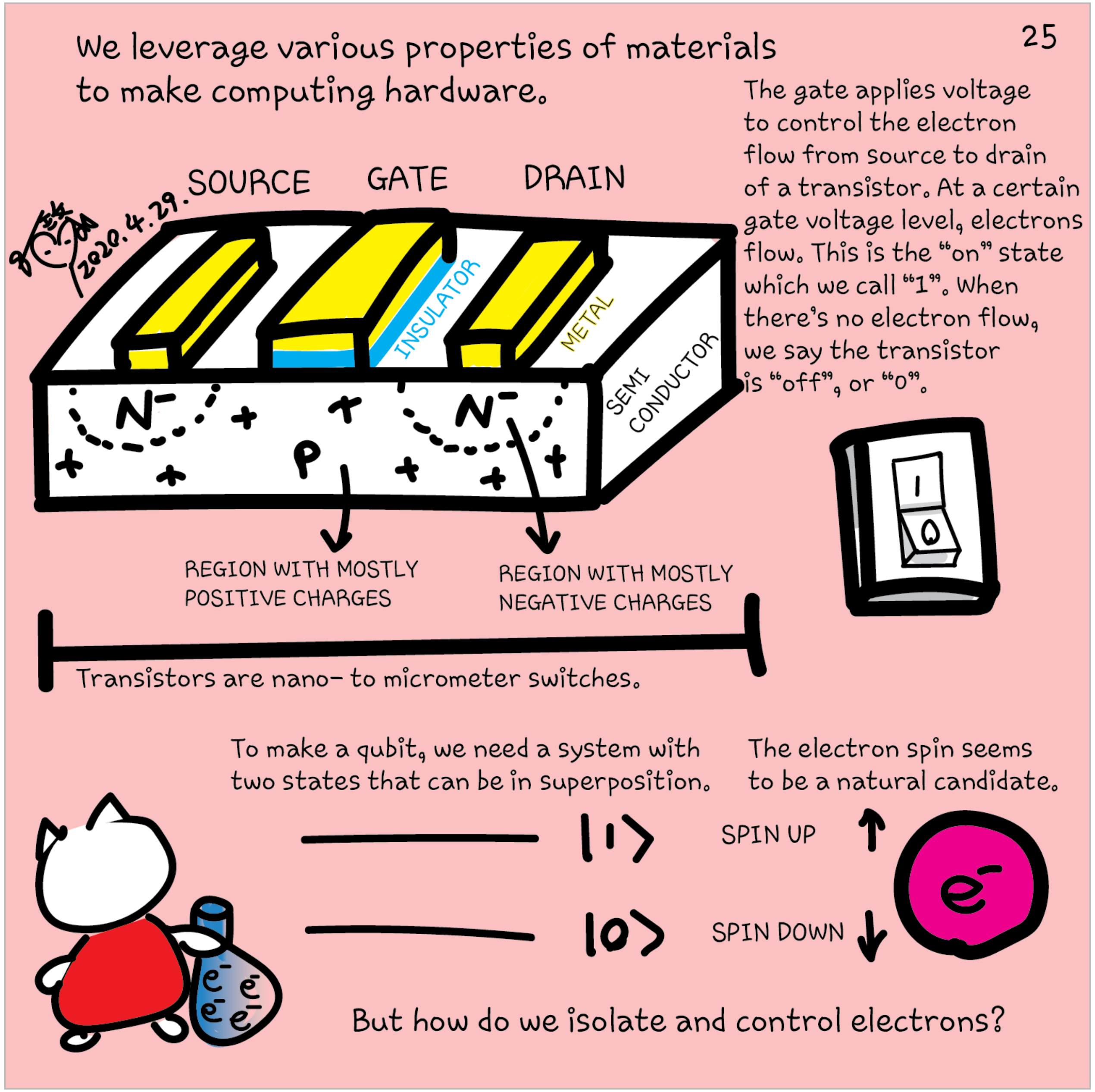
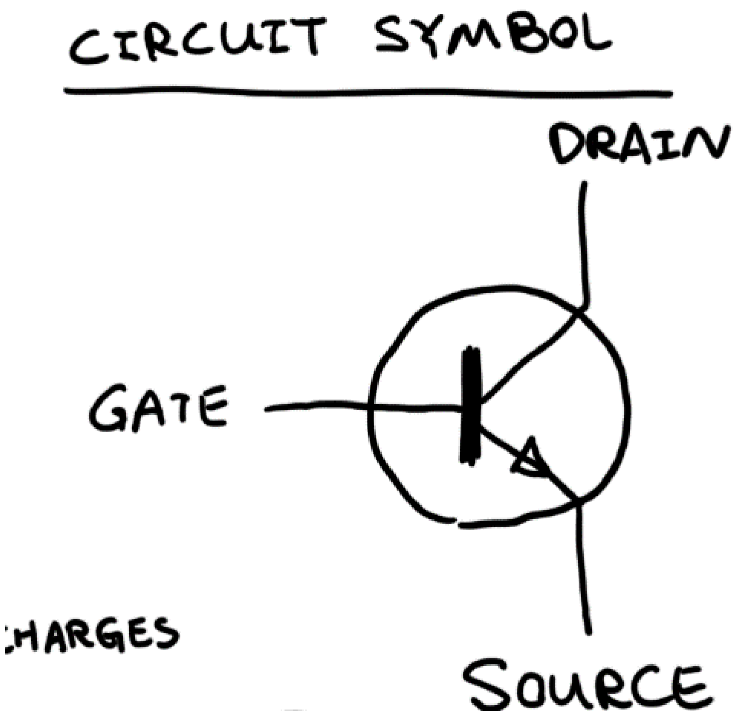
May 3, 2020
Hackaday, session 6

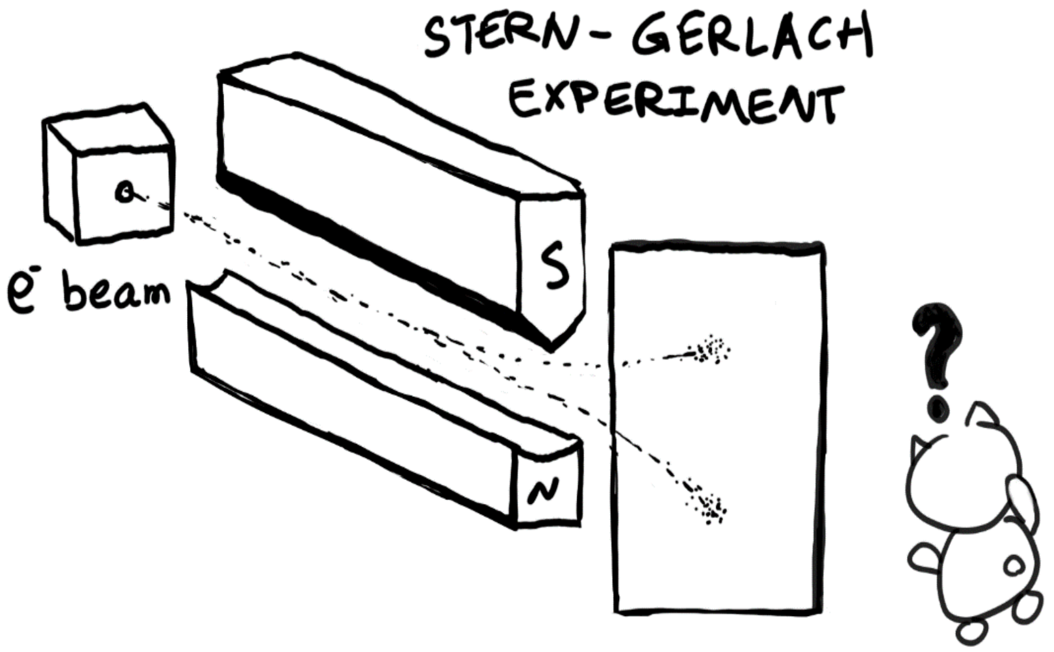
Class structure

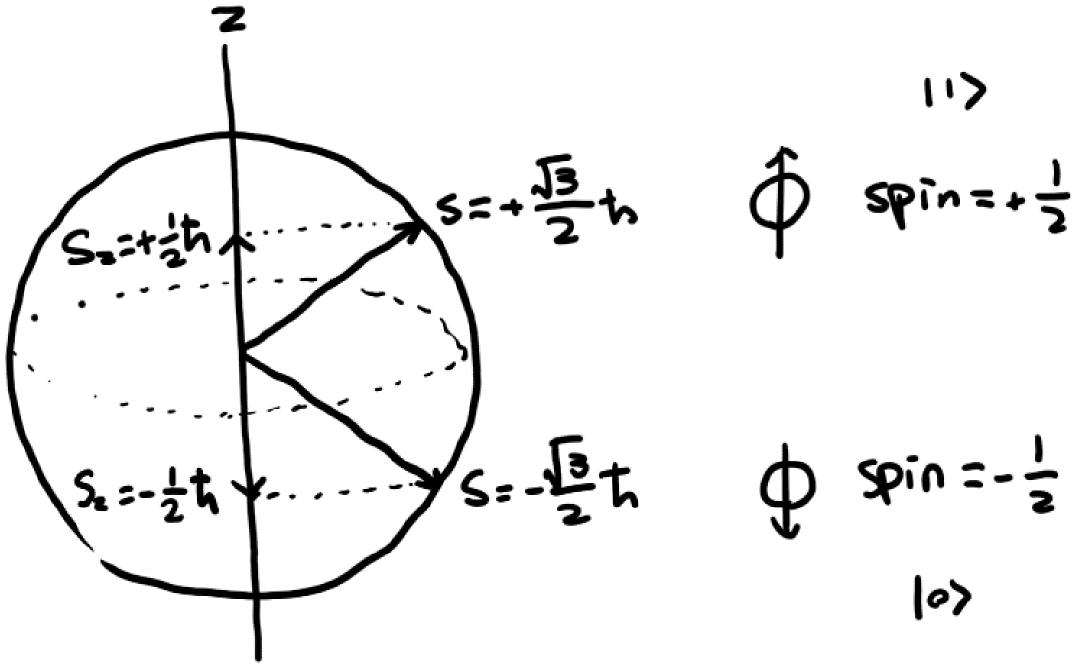
- Comics on Hackaday – Introduction to Quantum Computing every Wed & Sun
- 30 mins every Sun, one concept (theory, hardware, programming), Q&A
- Contribute to Q# documentation http://docs.microsoft.com/quantum
- Coding through Quantum Katas https://github.com/Microsoft/QuantumKatas/
- Discuss in Hackaday project comments throughout the week
- Take notes

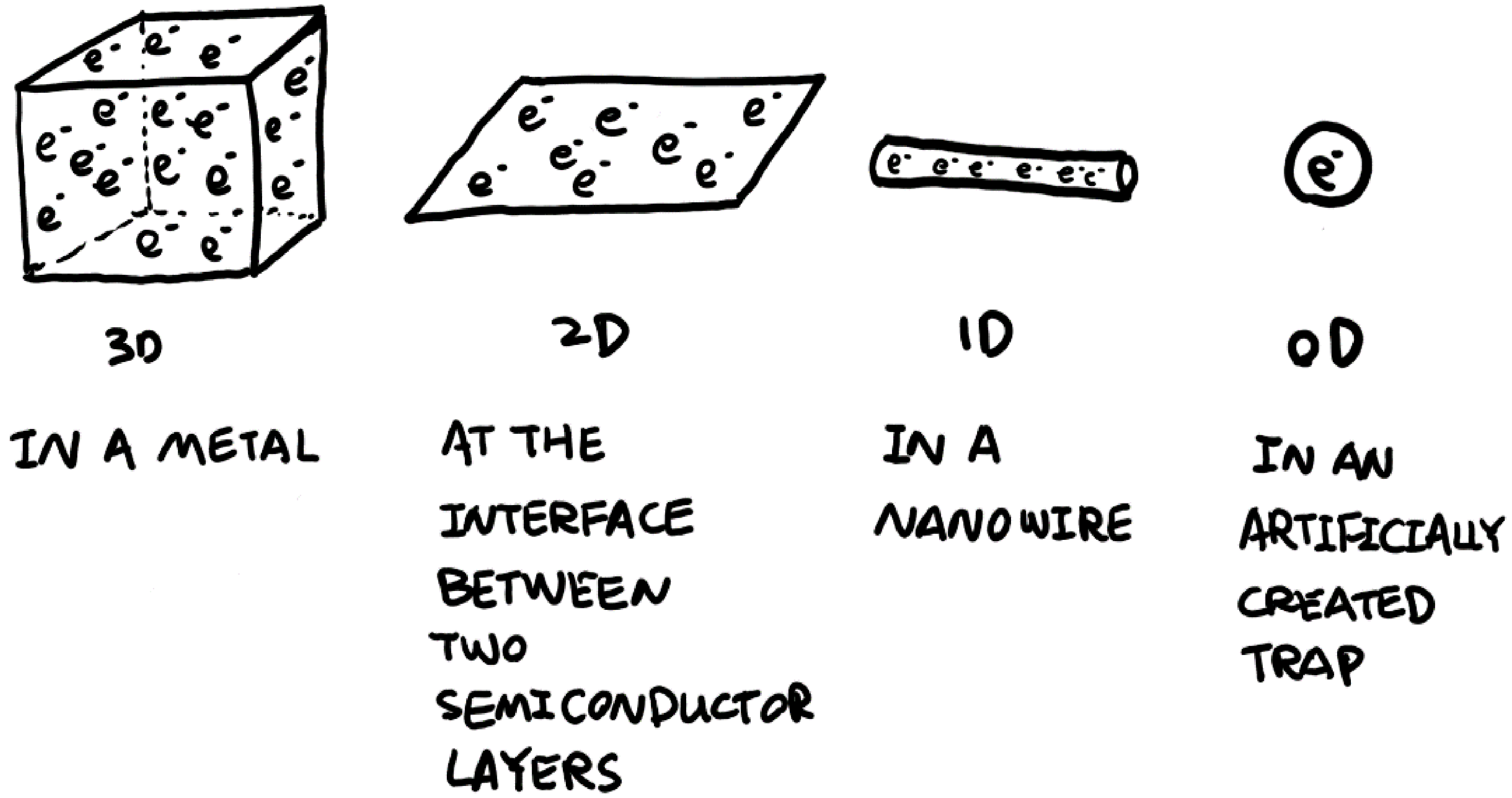


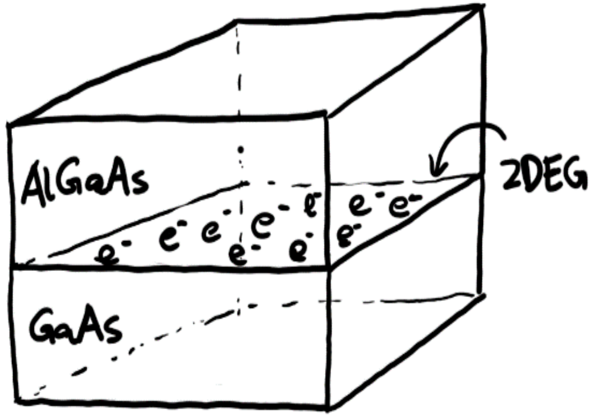

25
We leverage various properties of materials to make computing hardware.
2020.4.29.
SOURCE
GATE
DRAIN
INSULATOR
METAL
SEMI CONDUCTOR
N⁻
P
N⁻
The gate applies voltage to control the electron flow from source to drain of a transistor. At a certain gate voltage level, electrons flow. This is the "on" state which we call "1". When there's no electron flow, we say the transistor is "off", or "0".
1
0
REGION WITH MOSTLY POSITIVE CHARGES
REGION WITH MOSTLY NEGATIVE CHARGES
Transistors are nano- to micrometer switches.
To make a qubit, we need a system with two states that can be in superposition.
The electron spin seems to be a natural candidate.
|1⟩
SPIN UP
|0⟩
SPIN DOWN
e⁻
But how do we isolate and control electrons?

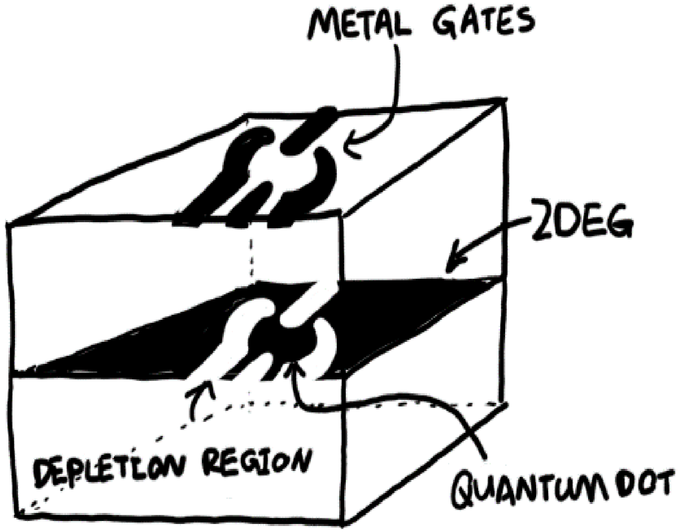

CIRCUIT SYMBOL
DRAIN
GATE
SOURCE
HARGES

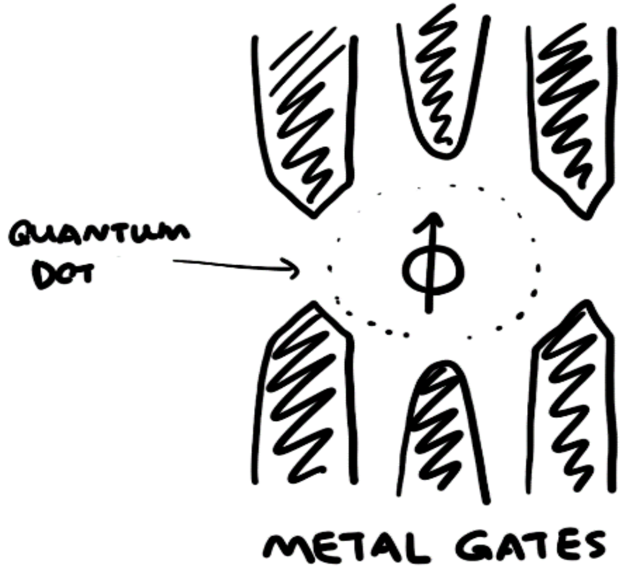

STERN- GERLACH
EXPERIMENT
e⁻ beam
S
N
?

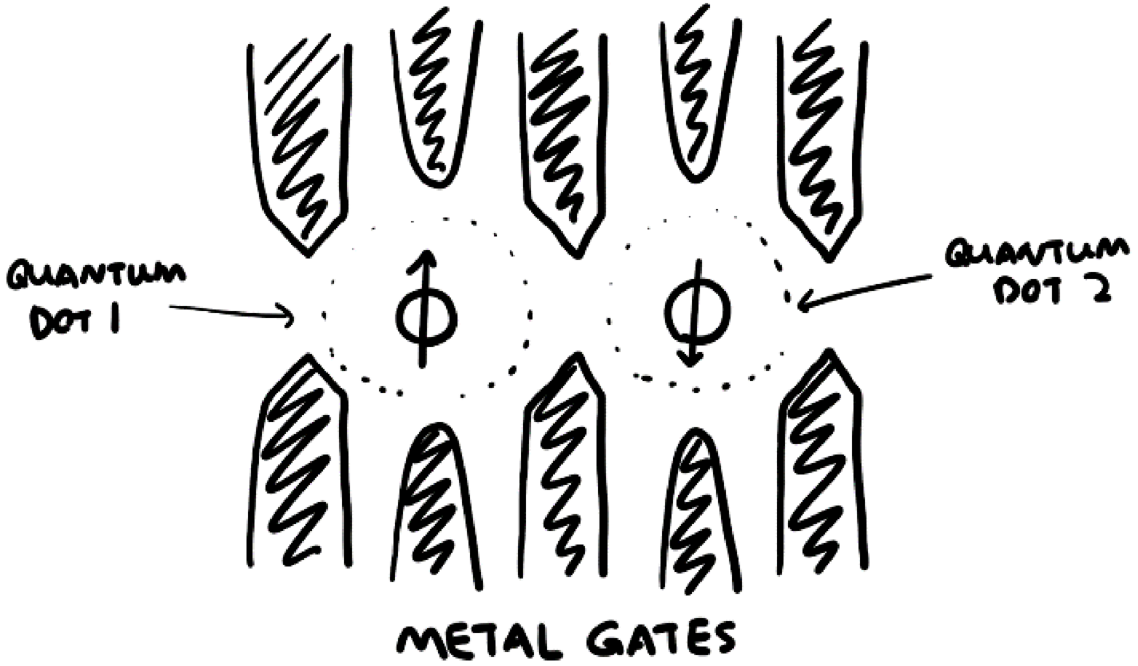

z
S_z=+½ħ
S=+√3/2 ħ
S_z=-½ħ
S=-√3/2 ħ
|1>
spin=+½
spin=-½
|0>

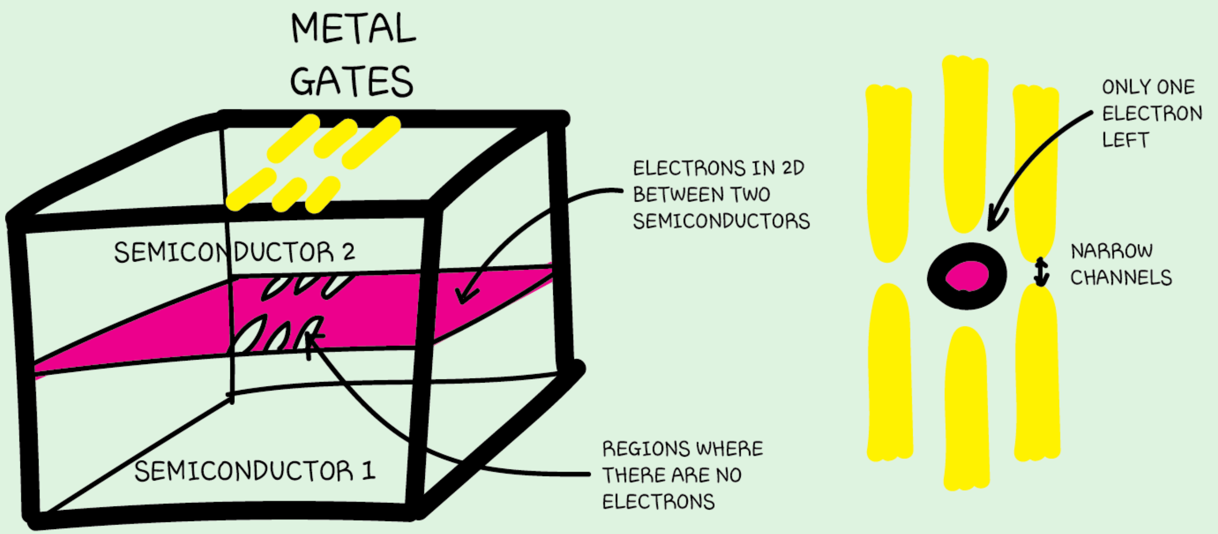

3D
IN A METAL
2D
AT THE INTERFACE BETWEEN TWO SEMICONDUCTOR LAYERS
1D
IN A NANOWIRE
0D
IN AN ARTIFICIALLY CREATED TRAP


AlGaAs
GaAs
2DEG

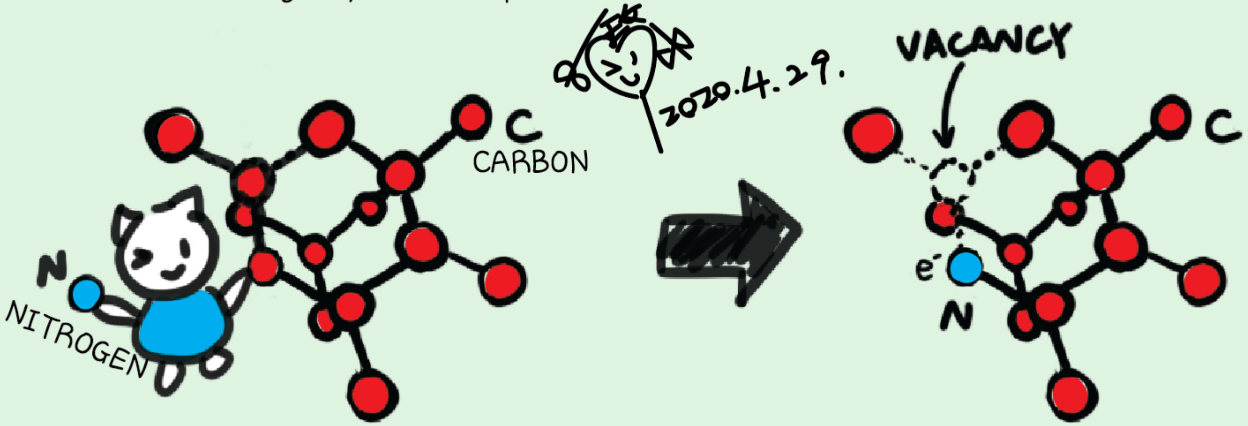

METAL GATES
2DEG
DEPLETION REGION
QUANTUM DOT


QUANTUM DOT
METAL GATES

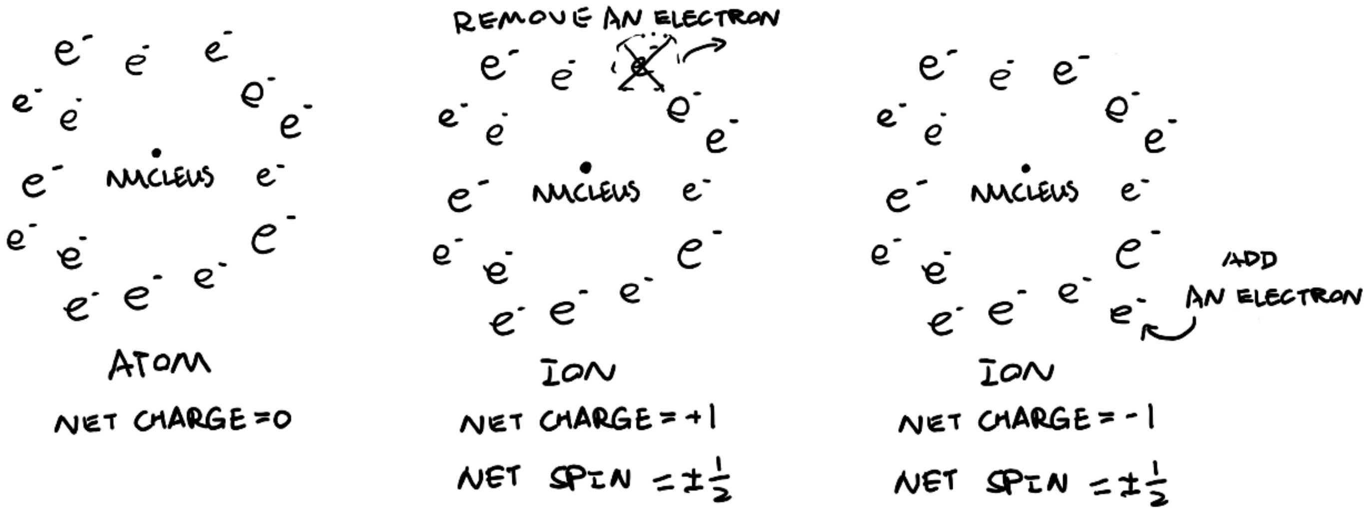

QUANTUM DOT 1
QUANTUM DOT 2
METAL GATES

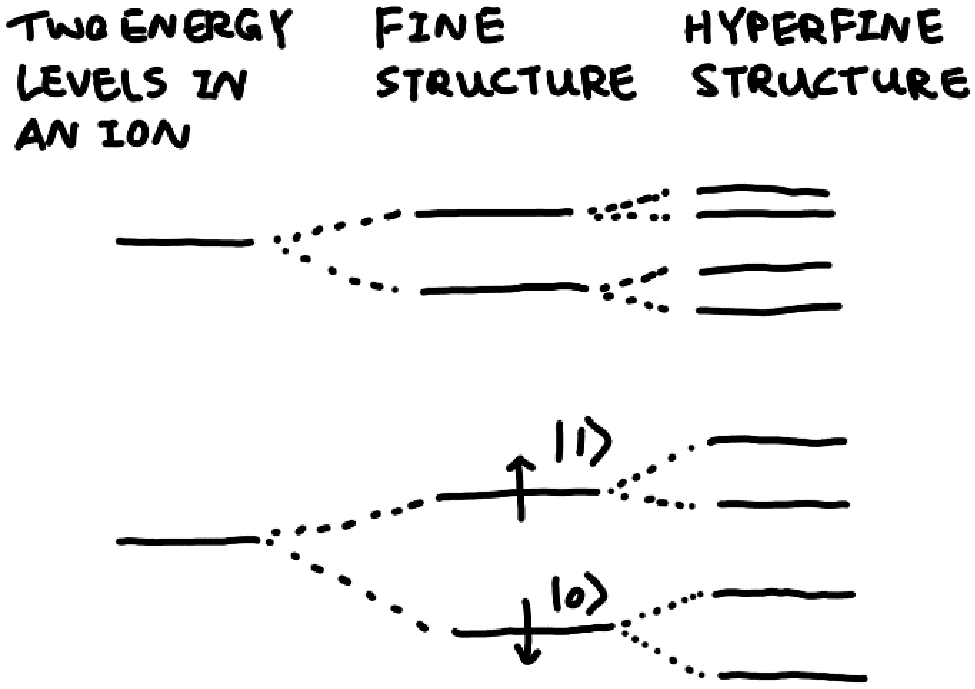


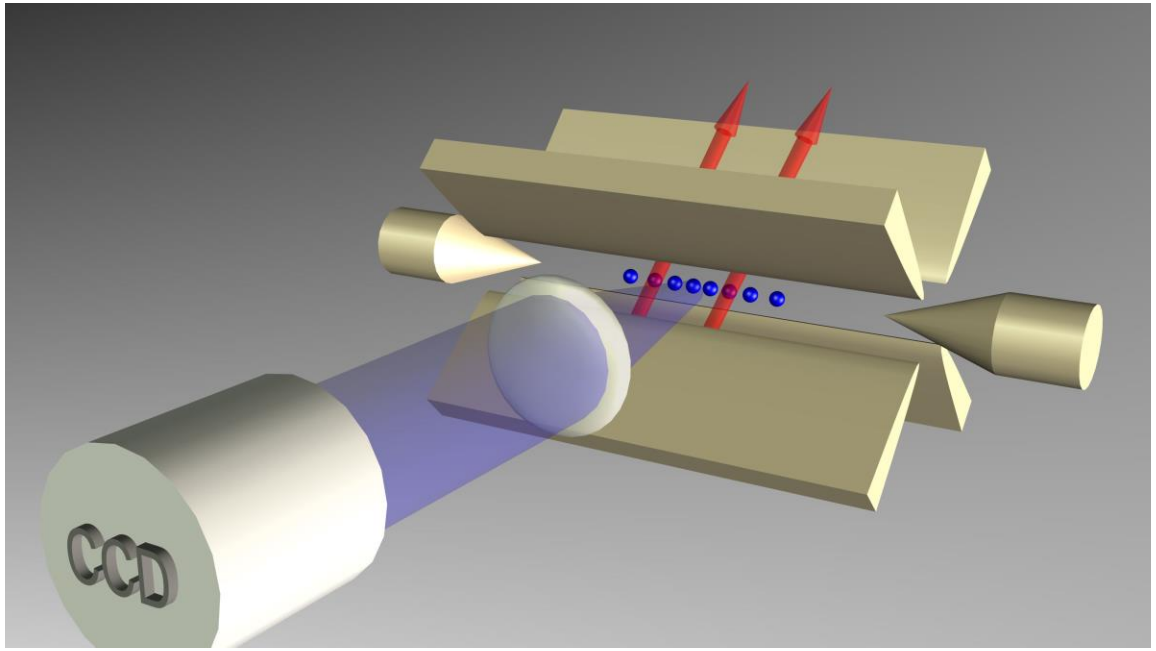
We can create a semiconductor stack. At the interface between the two semiconductors, electrons can be confined in 2D. By applying a gate voltage, the electrons underneath are removed, until there is only one electron left in a small region, called a "quantum dot".



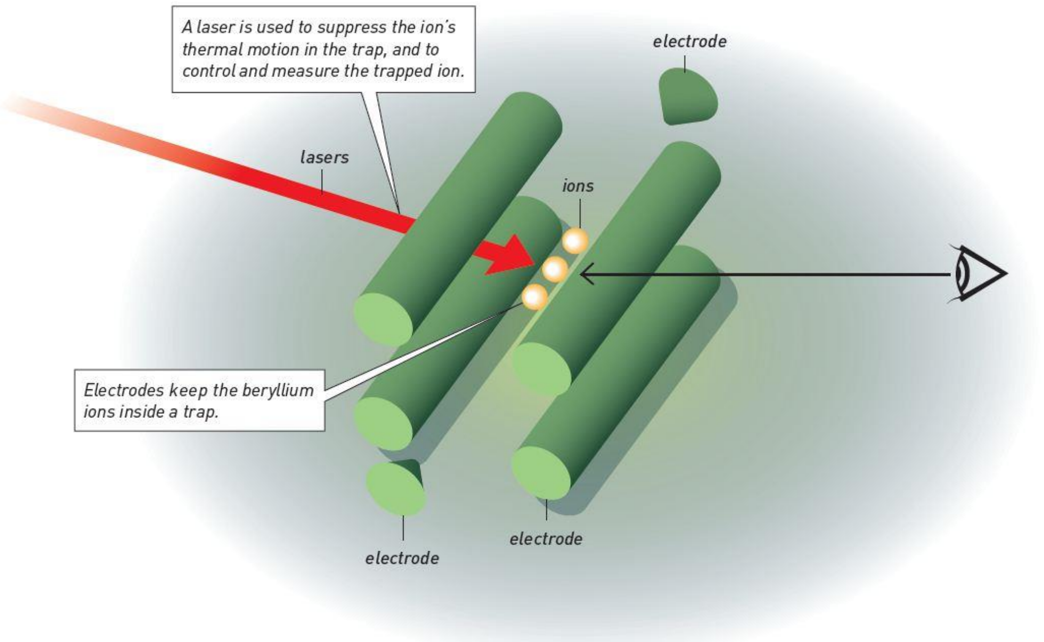
We can also use a crystal lattice, e.g. diamond. We can remove two carbon atoms (each has 6 electrons), replacing them with a single nitrogen atom (which has 7 electrons). The extra electron is bound to the nitrogen-vacancy region.


REMOVE AN ELECTRON
NUCLEUS
NUCLEUS
NUCLEUS
ADD AN ELECTRON
ATOM
NET CHARGE = 0
ION
NET CHARGE = +1
NET SPIN = ± 1/2
ION
NET CHARGE = -1
NET SPIN = ± 1/2

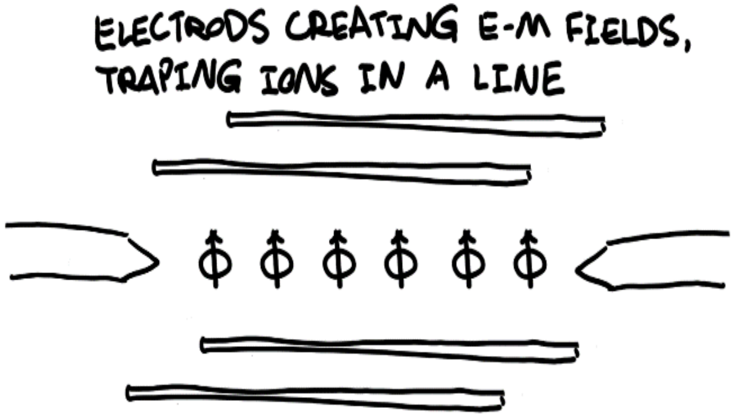

TWO ENERGY LEVELS IN AN ION
FINE STRUCTURE
HYPERFINE STRUCTURE
|1⟩
|0⟩

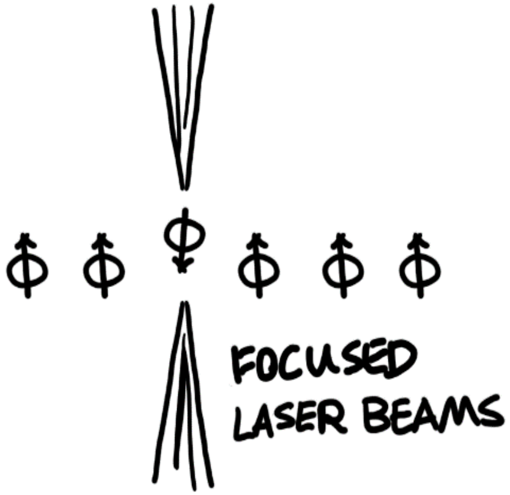


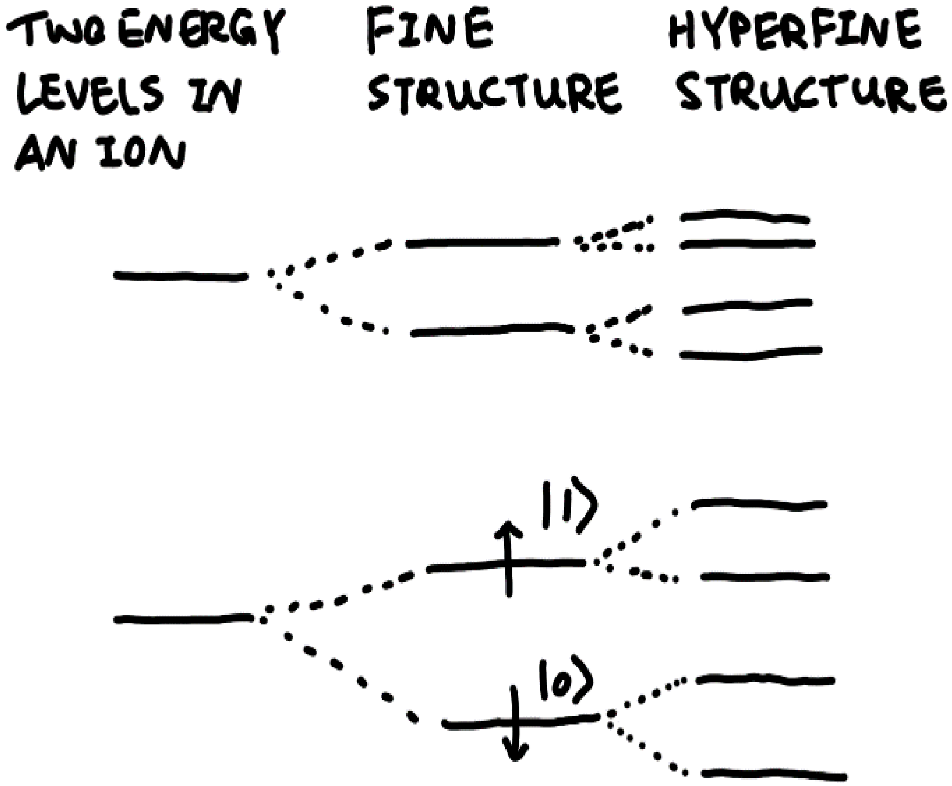
https://quantumoptics.at/en/mobile/en/news/72-scalable-multiparticle-entanglement-of-trapped-ions.html



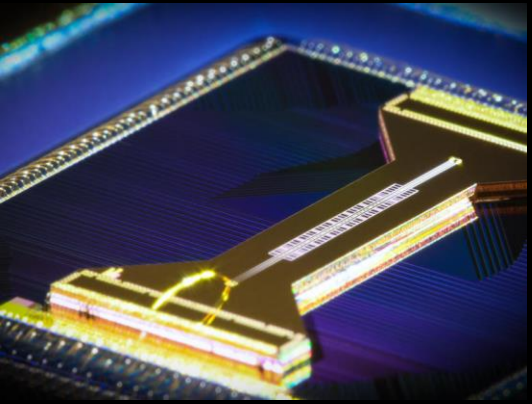
https://sciencenode.org/spotlight/nobel-prize-goes-quantum-computing-pioneers.php


ELECTRODS CREATING E-M FIELDS,
TRAPING IONS IN A LINE

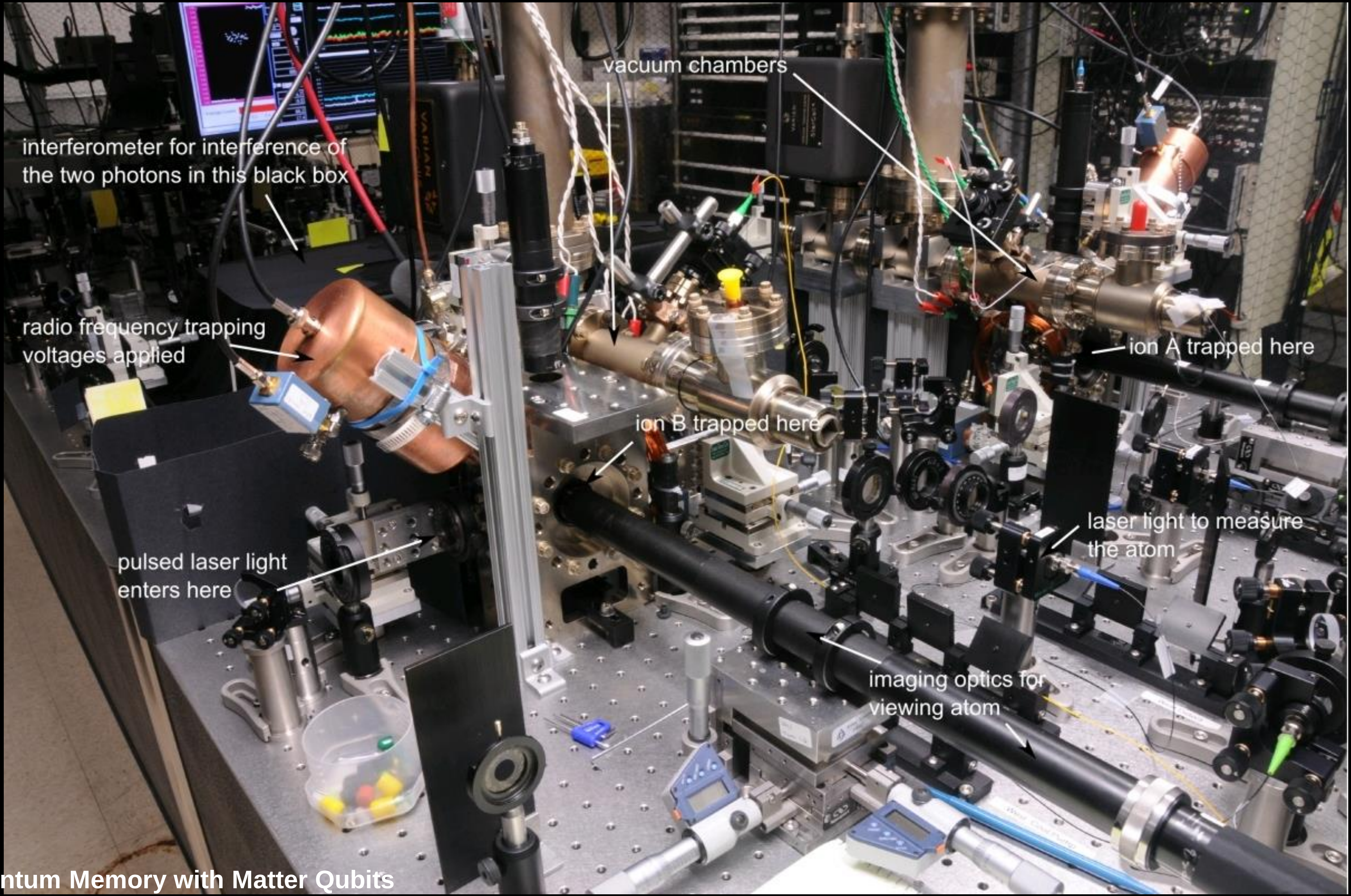

FOCUSED
LASER BEAMS


TWO ENERGY LEVELS IN AN ION
FINE STRUCTURE
HYPERFINE STRUCTURE
|1⟩
|0⟩

Trapped Ion

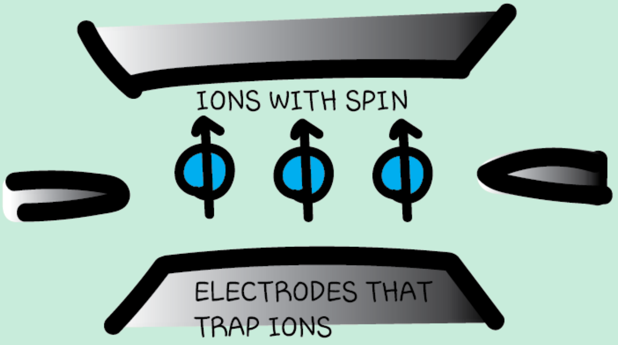


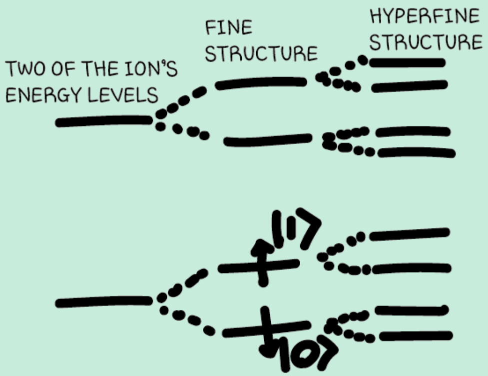
Honeywell on-chip ion trap



Physicists Demonstrate Quantum Memory with Matter Qubits
July 3, 2009 By Lisa Zyga, Phys.org

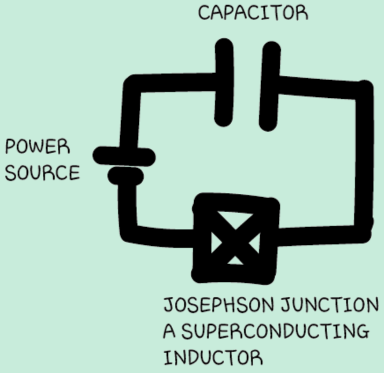
Although an electron can be conceptually the easiest qubit, it doesn't mean it is straightforward to control many electrons. There are other systems to explore.

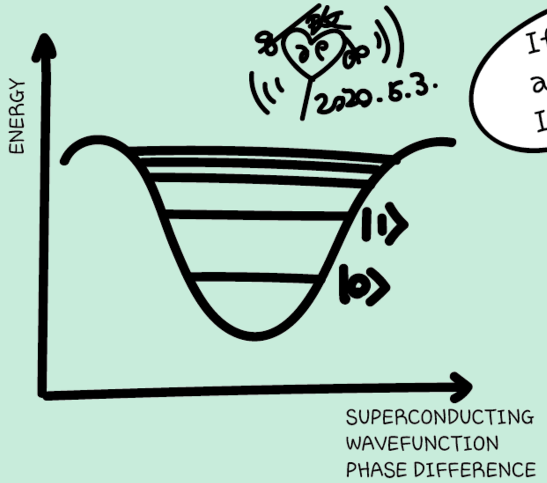




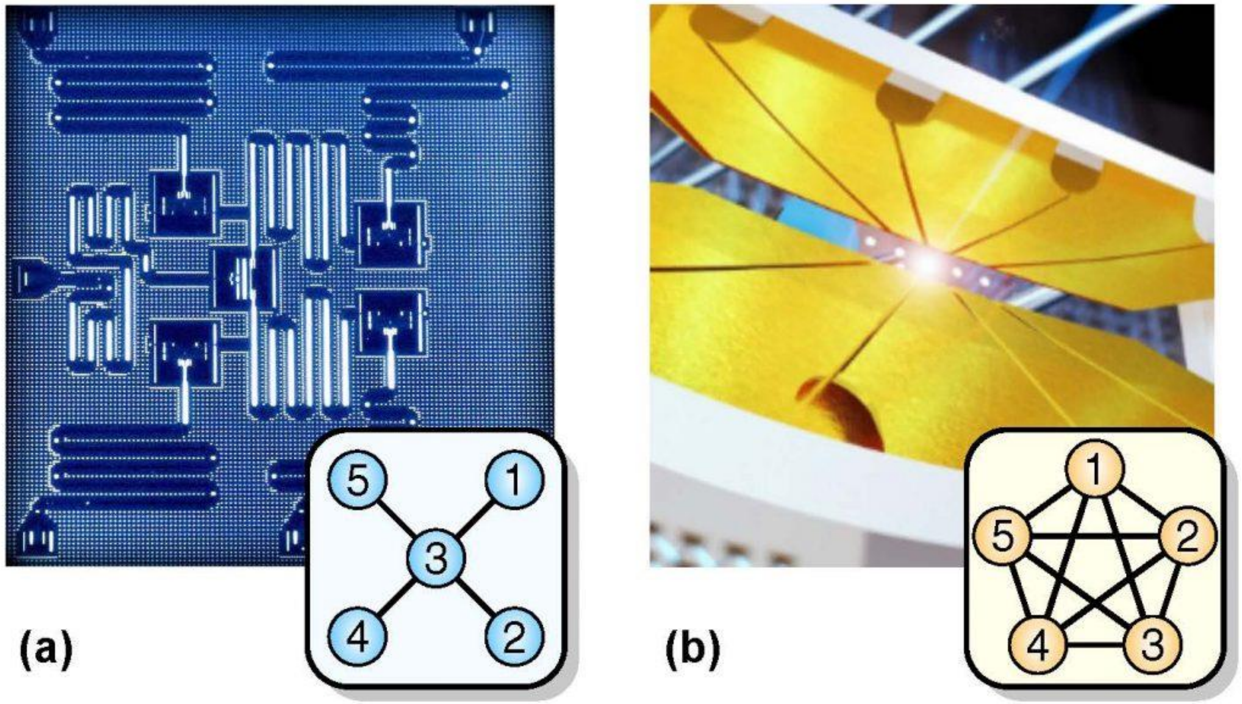
We can use two of an ion's electronic energy levels as the two qubit states. They can be the fine structure due to the ion's electron spins or the hyperfine structure due to electrons' interactions with the ion's nucleus.

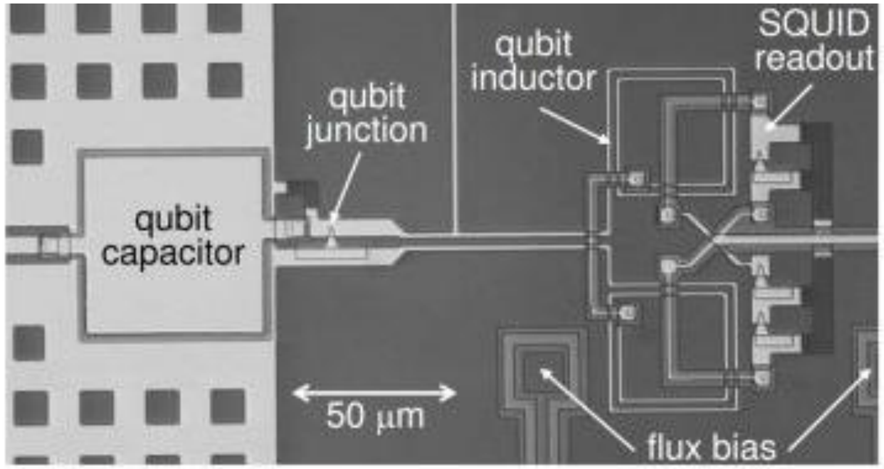
We can also make an "artificial atom" and use its energy levels as qubit states, e.g. a superconducting circuit. Its oscillation creates a set of discrete energies.





Superconducting quantum circuits

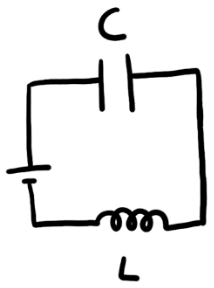


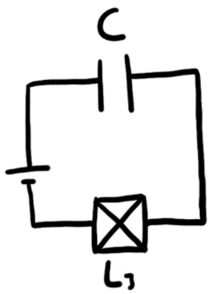


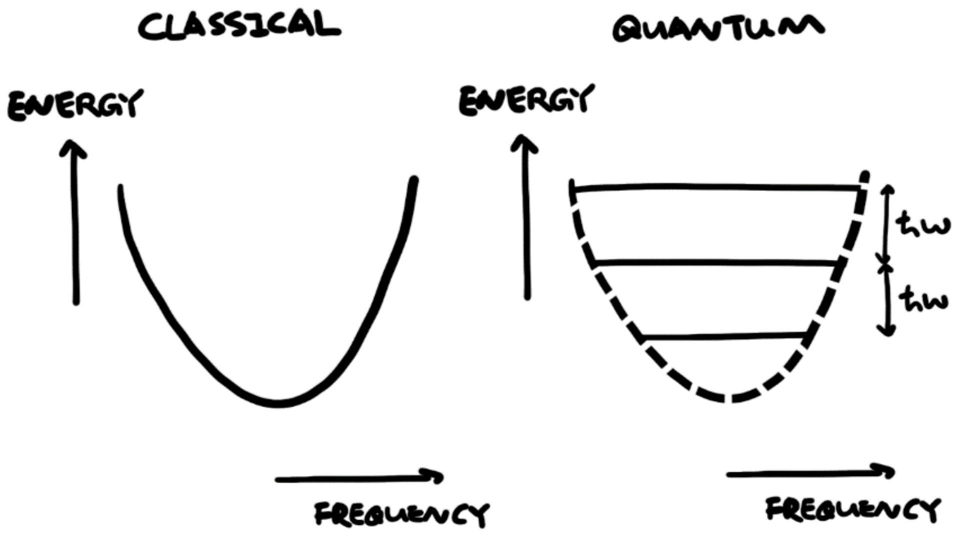
John Martinis -> Google

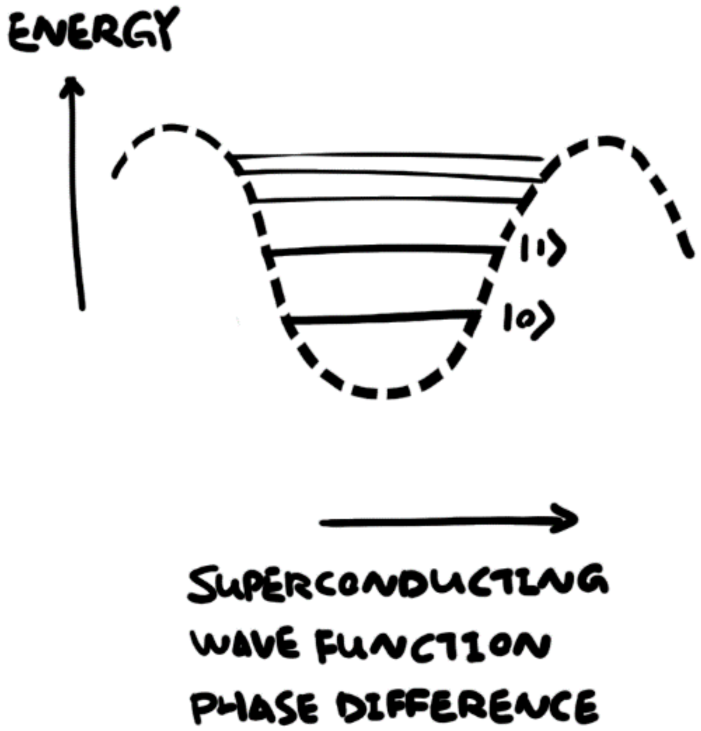
http://iontrap.umd.edu/

Superconductors vs. Trapped Ions





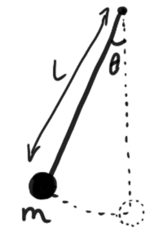




Classical to quantum mechanical:

1. effective length of the circuit is smaller than the electron scattering length in the circuit;
2. temperature is low enough: $kT < \hbar\omega$, where k is the Boltzmann constant, T is the temperature and $\omega = \sqrt{LC}$ is the natural frequency of the circuit.

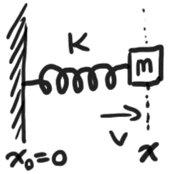
KINETIC ENERGY + POTENTIAL ENERGY



$$H = \frac{p_\theta^2}{2mL^2} + mgL(1-\cos\theta)$$

p_θ ← ANGULAR MOMENTUM

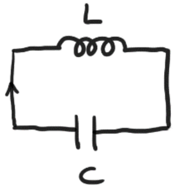
g ← GRAVITATIONAL ACCELERATION



$$H = \frac{1}{2}mv^2 + \frac{1}{2}kx^2$$

v ← SPEED

x ← DISTANCE TRAVELLED



CLASSICAL

$$H = \frac{\phi^2}{2L} + \frac{q^2}{2C}$$

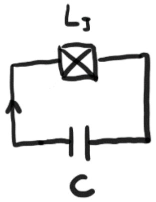
ϕ ← MAGNETIC FLUX

q ← CHARGE

QUANTUM

$$i\hbar\frac{d\psi}{dt} = \frac{\phi^2}{2L}\psi - \frac{\hbar^2}{2C}\nabla^2\psi$$

ψ ← WAVEFUNCTION



$$H = E_c(N - N_g)^2 - E_J\cos\theta$$

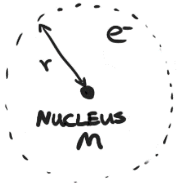
E_c ← CHARGING ENERGY

N ← # OF COOPER PAIRS

N_g ← CHARGE ON C

E_J ← JOSEPHSON ENERGY

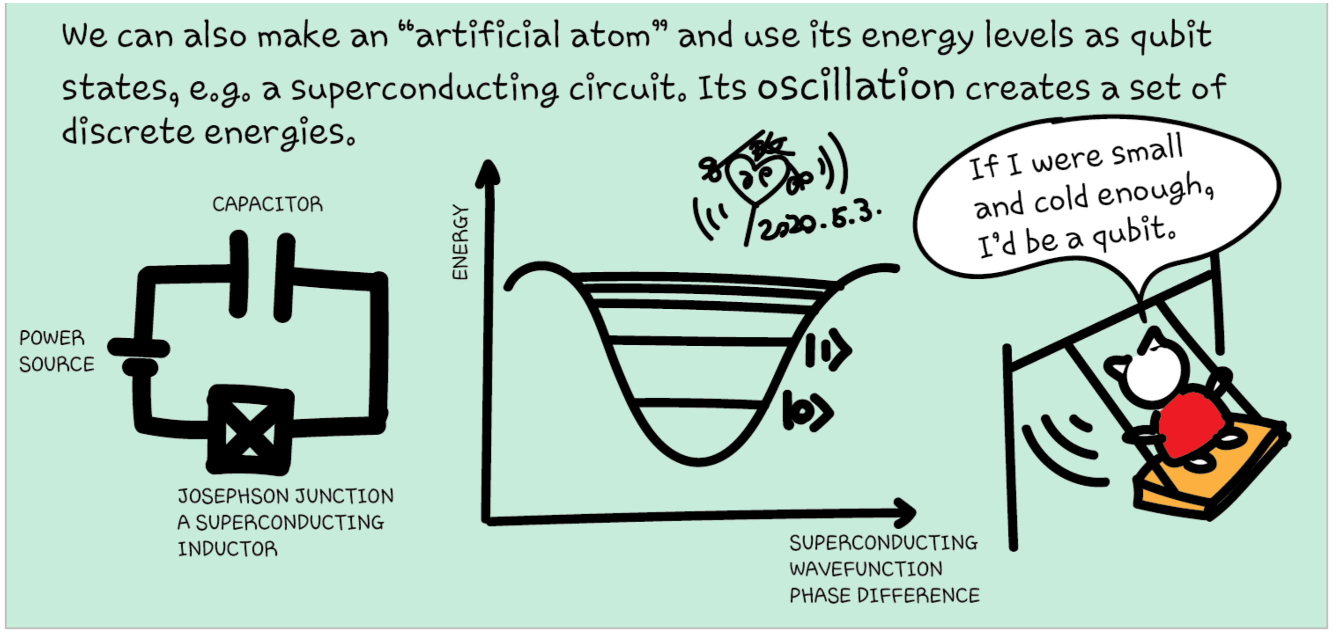
θ ← SUPERCONDUCTING WAVEFUCTION PHASE DIFFERENCE



$$E\psi = -\frac{\hbar^2}{2\mu}\nabla^2\psi + \frac{e^2}{4\pi\varepsilon_0 r}\psi$$

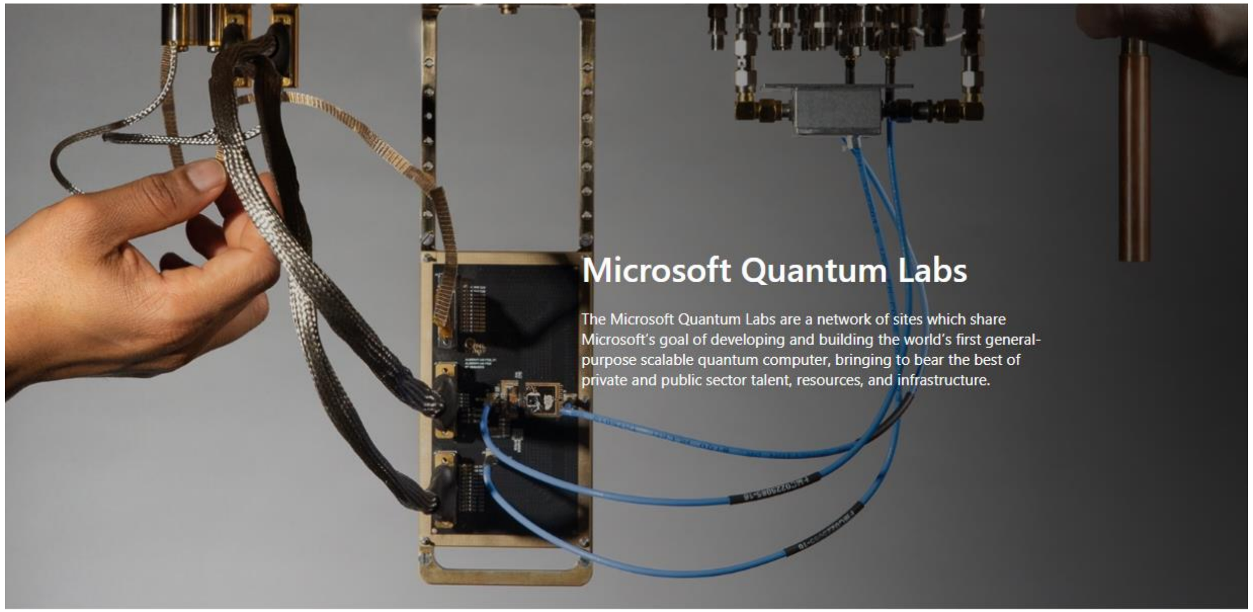
μ ← REDUCED MASS $\frac{m_e M}{m_e + M}$

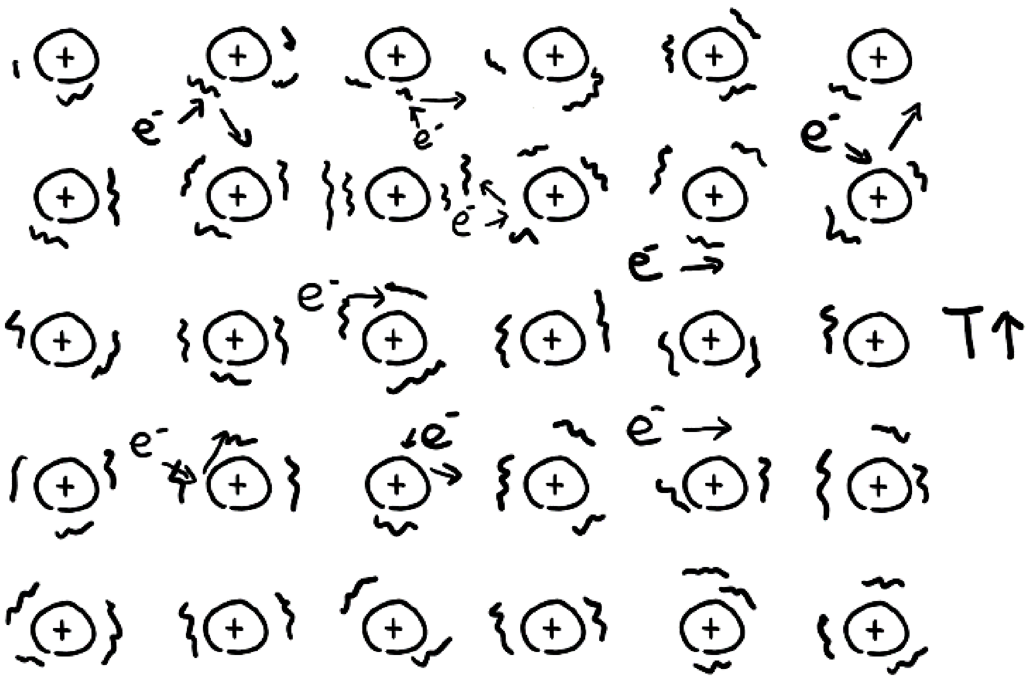
ε_0 ← VACUUM PERMITTIVITY

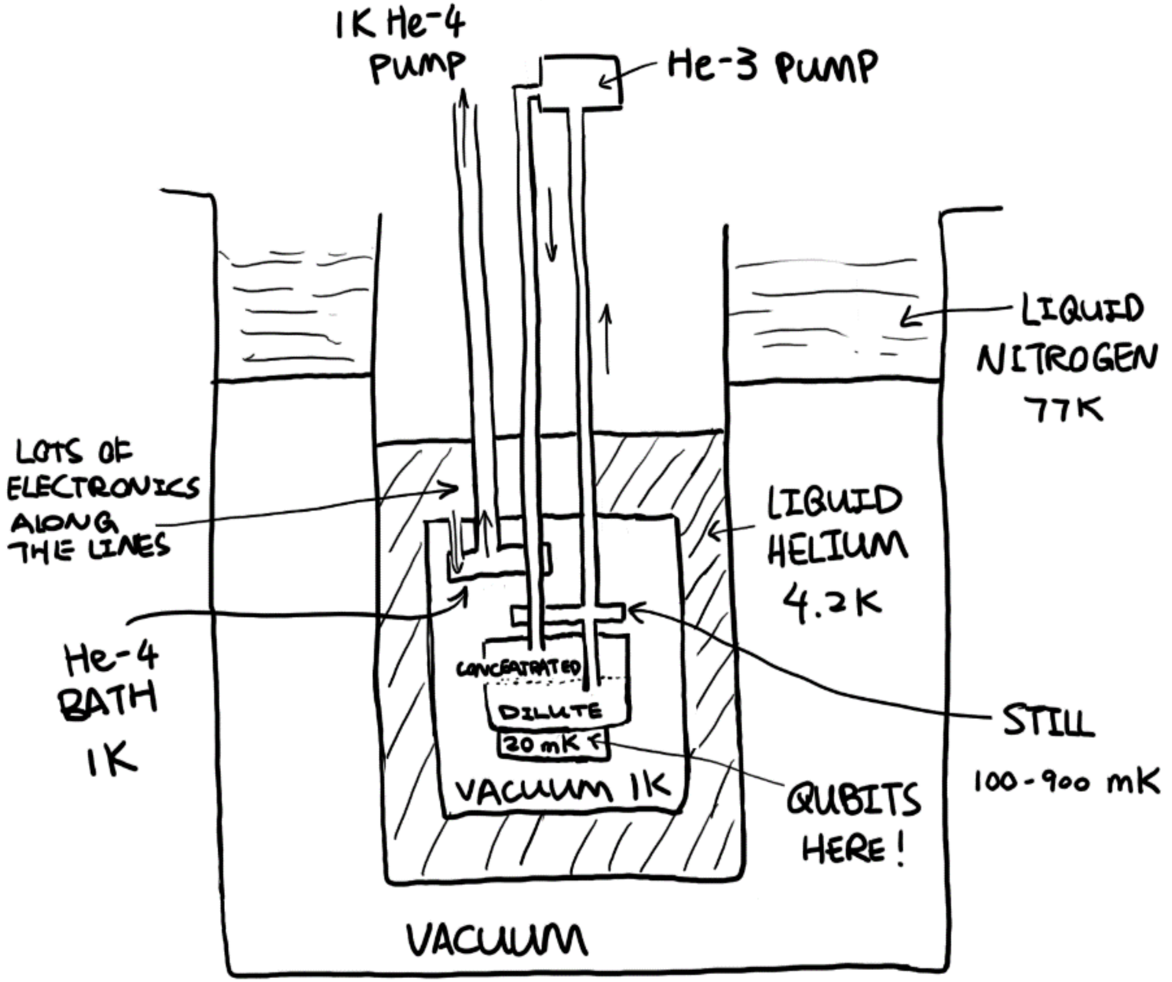


The specific criteria are: effective length of the circuit is smaller than the electron scattering length in the circuit; and the temperature is low enough. How cold is low enough? $kT < \hbar\omega$, where k is the Boltzmann constant, T is the temperature and $\omega = \sqrt{LC}$ is the natural frequency of the circuit. Typically, with small circuits we make today, the temperature could be below liquid Helium temperature at 4K.

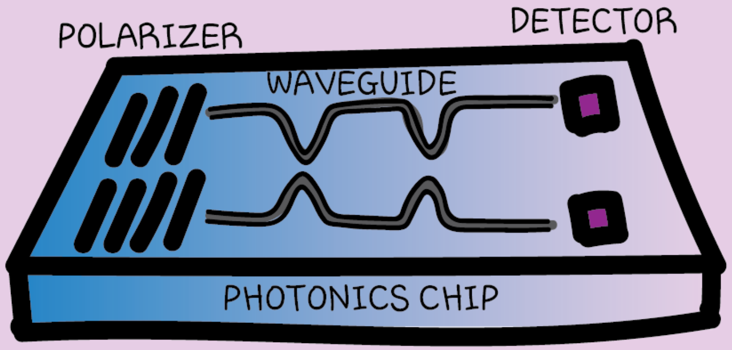
Dilution refrigerators

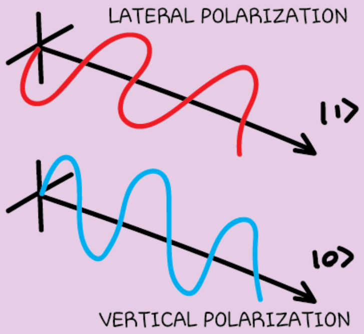



e⁻
T↑

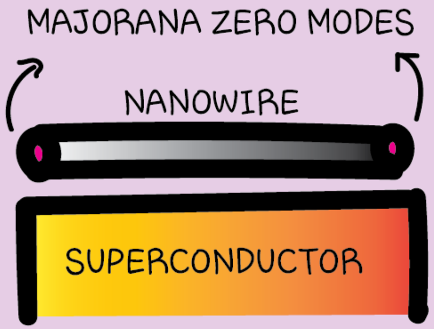

1K He-4 PUMP
He-3 PUMP
LIQUID NITROGEN 77K
LOTS OF ELECTRONICS ALONG THE LINES
LIQUID HELIUM 4.2K
He-4 BATH 1K
STILL 100-900 mK
CONCENTRATED
DILUTE
20 mK
VACUUM 1K
QUBITS HERE!
VACUUM

If we can use natural and artificial particles, such as electrons, ions or oscillating circuits, we can also try other types of particles and quasiparticles, and parameters other than energy levels.



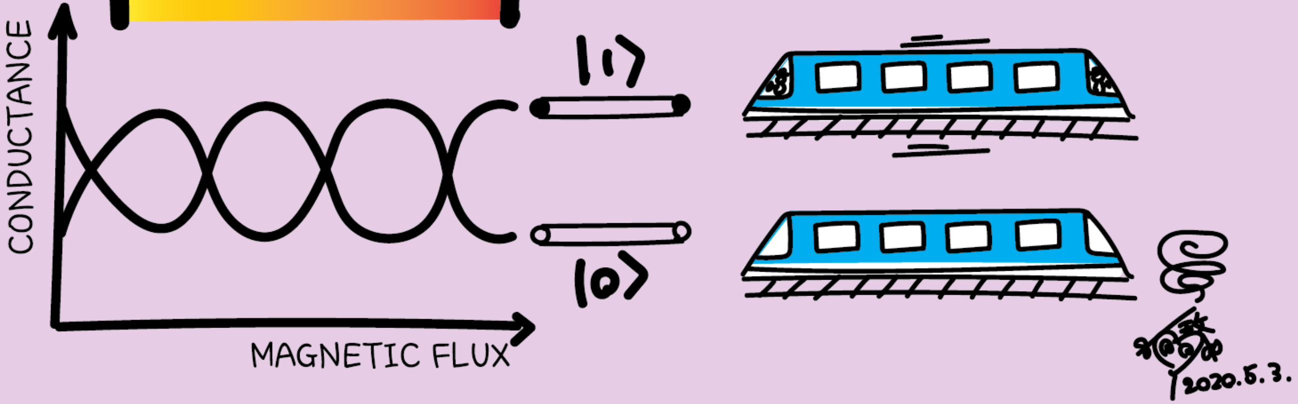


We can use photons' polarizations to encode qubit states.



Or the quasiparticles constructed in a topological material (in this case the ends of a nanowire on a superconductor).

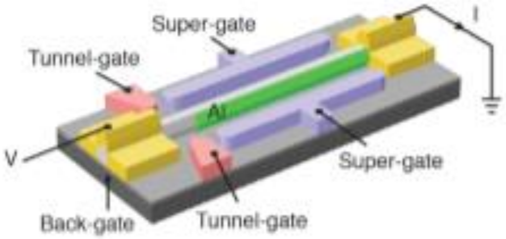
The **zero modes** are locations that can be empty or occupied by an electron, thus giving two qubit states.



Topological quantum computer

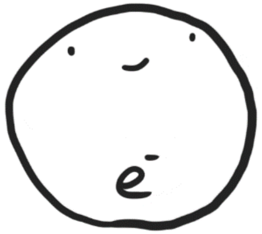
Majorana Fermions – particle equals anti-particle
Fractional quantum Hall conductance
Low temperature in magnetic field

https://arxiv.org/pdf/cond-mat/0412343.pdf



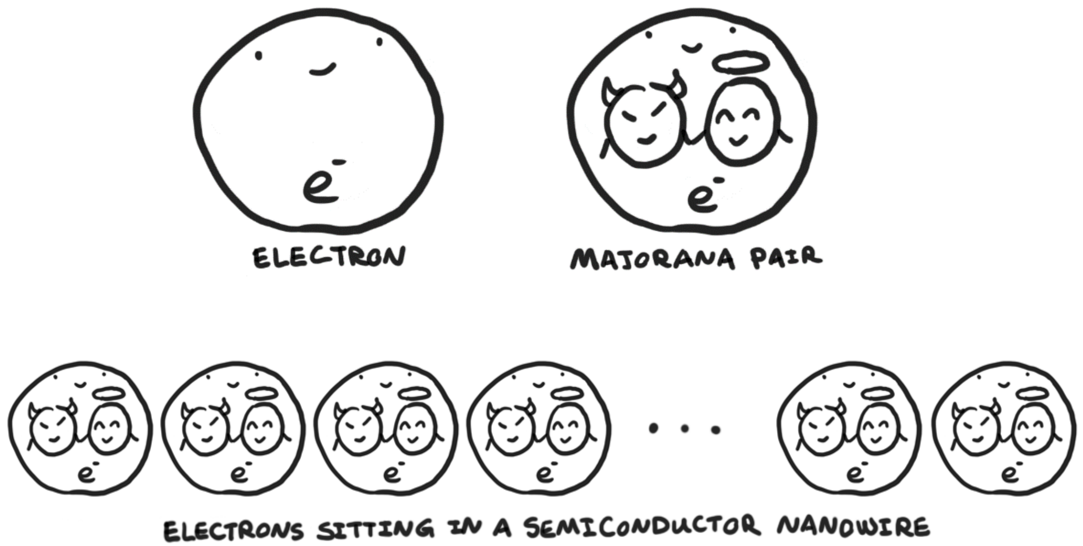
Quantized Majorana Conductance

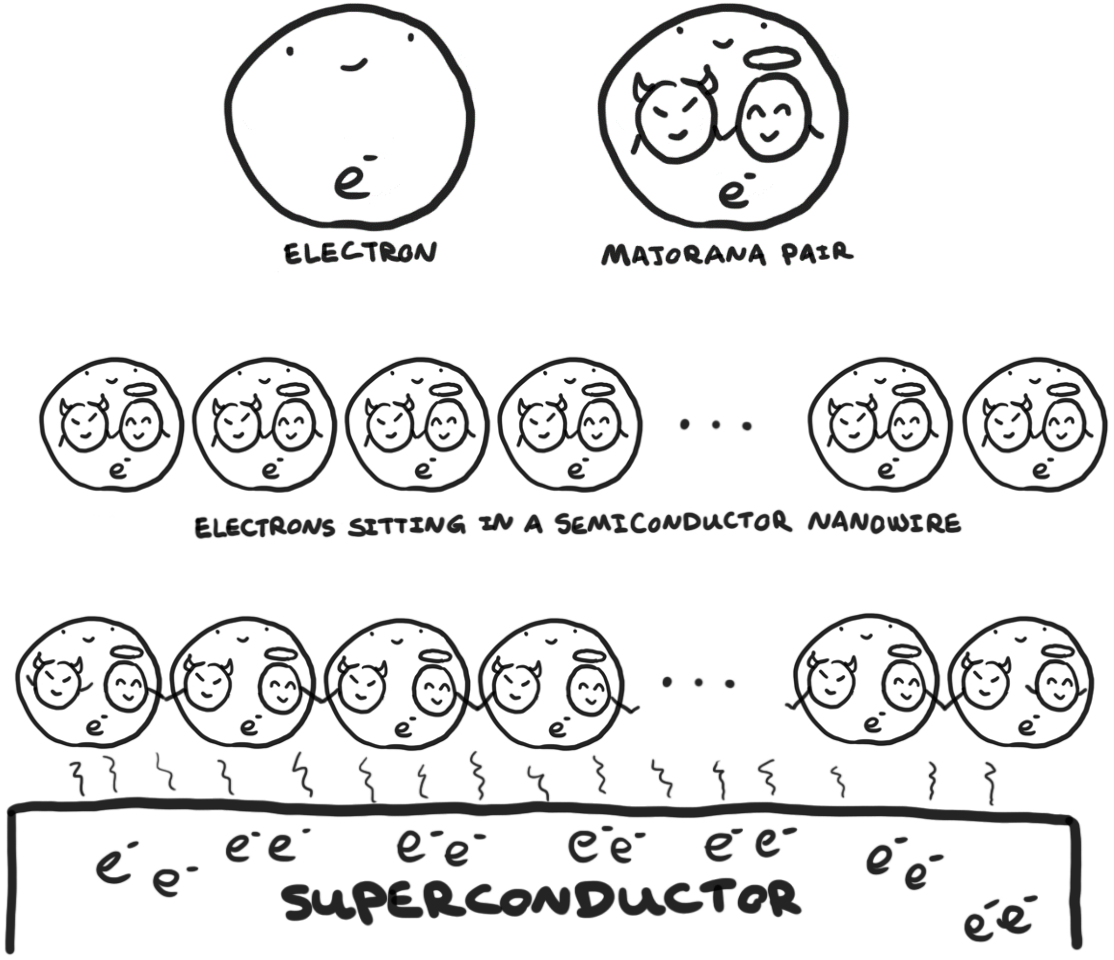
https://www.nature.com/articles/nature26142

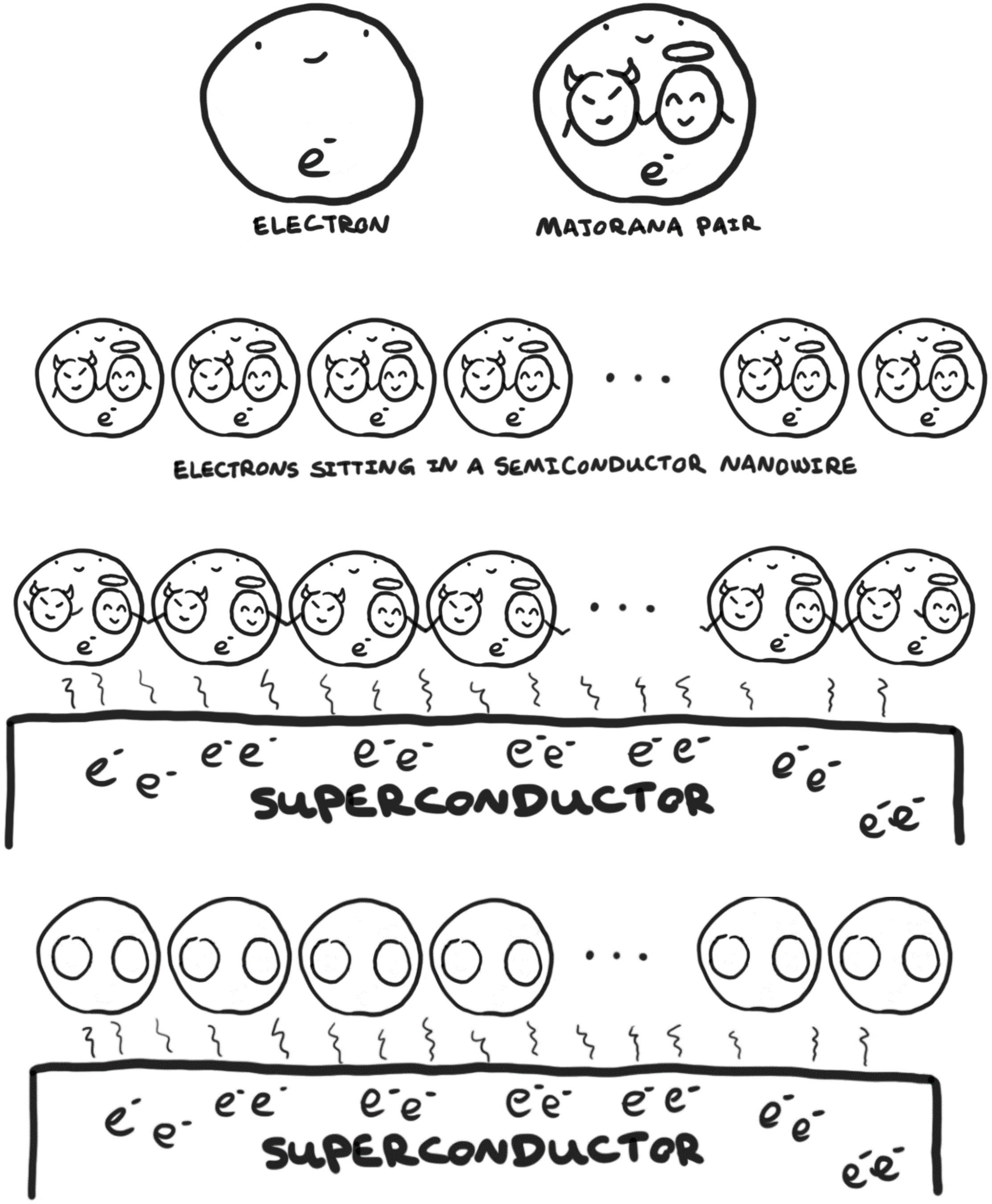


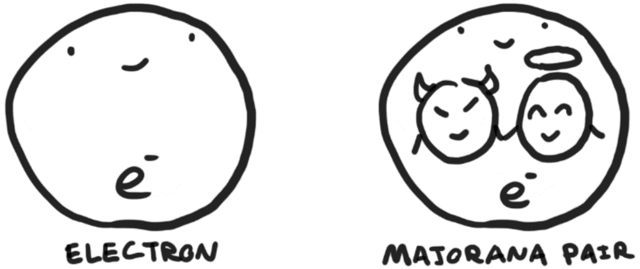
ELECTRON

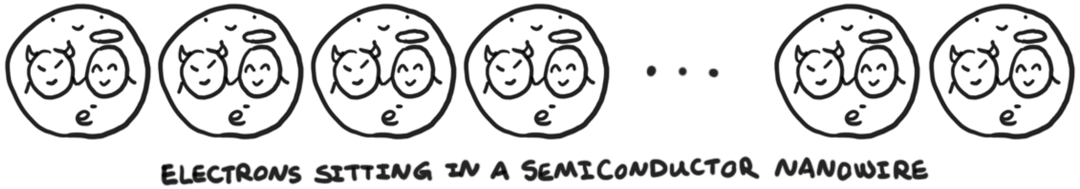
MAJORANA PAIR

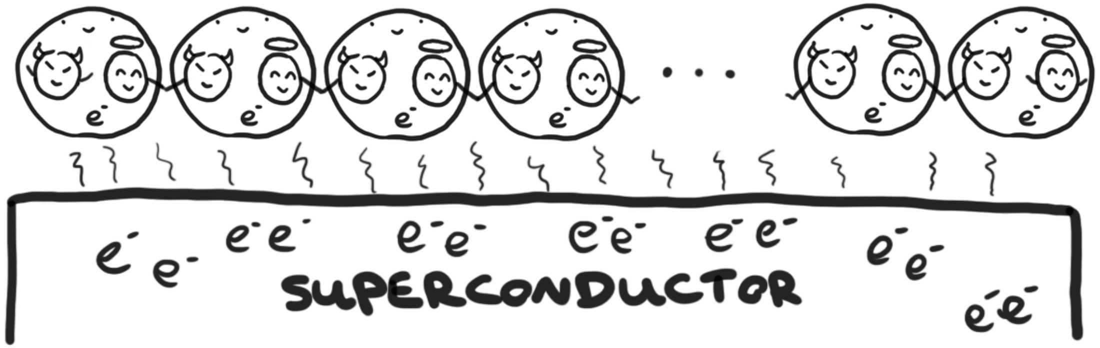

e-
ELECTRON
e-
MAJORANA PAIR
ELECTRONS SITTING IN A SEMICONDUCTOR NANOWIRE

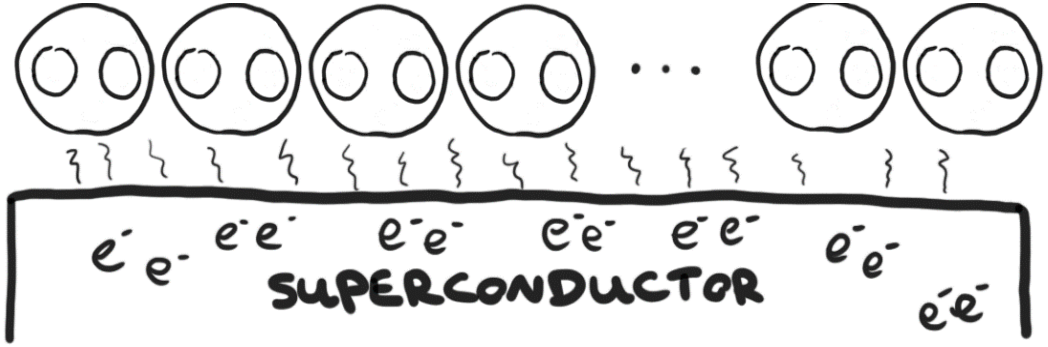

ELECTRON
MAJORANA PAIR
ELECTRONS SITTING IN A SEMICONDUCTOR NANOWIRE
SUPERCONDUCTOR

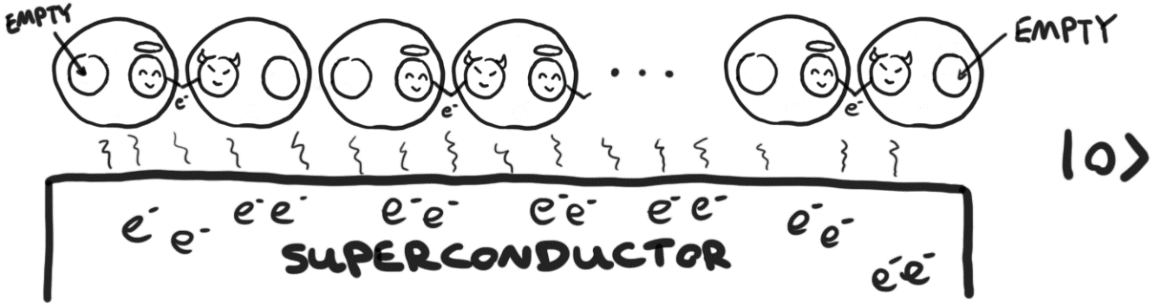

ELECTRON
MAJORANA PAIR
ELECTRONS SITTING IN A SEMICONDUCTOR NANOWIRE
SUPERCONDUCTOR
SUPERCONDUCTOR

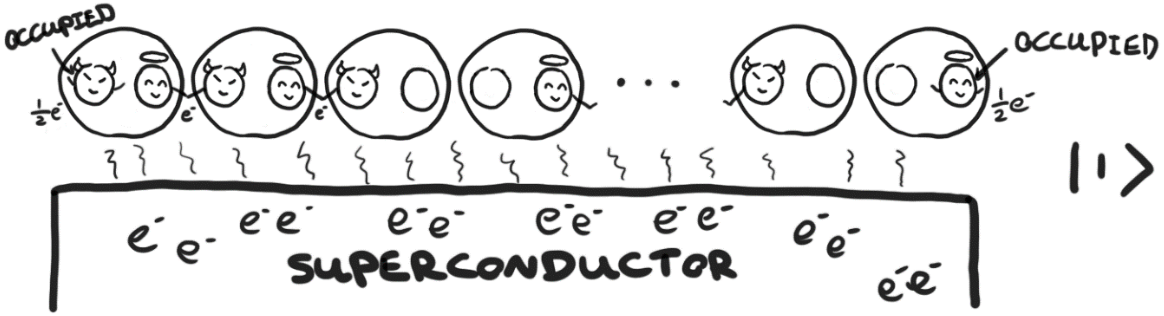

e⁻
e⁻
ELECTRON
MAJORANA PAIR

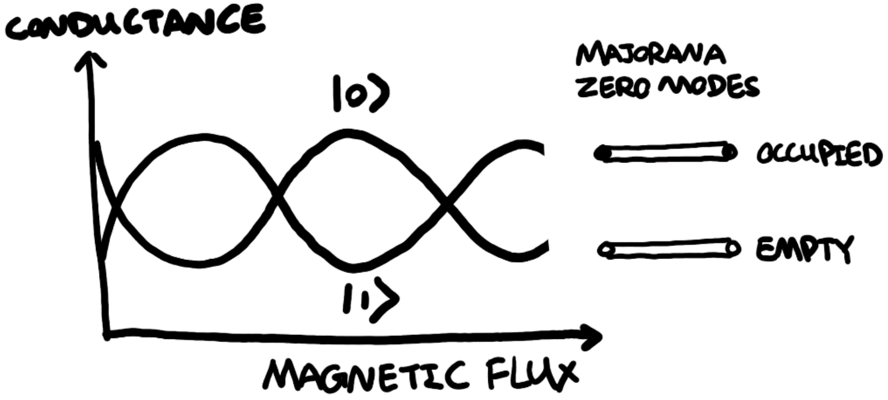

ELECTRONS SITTING IN A SEMICONDUCTOR NANOWIRE


SUPERCONDUCTOR


SUPERCONDUCTOR


EMPTY
EMPTY
|0⟩
SUPERCONDUCTOR


OCCUPIED
OCCUPIED
½e⁻
½e⁻
|1⟩
SUPERCONDUCTOR


CONDUCTANCE
|0⟩
|1⟩
MAGNETIC FLUX
MAJORANA ZERO MODES
OCCUPIED
EMPTY

Reading: Topological Quantum Computer

- https://scipost.org/SciPostPhys.3.3.021/pdf
- https://arxiv.org/abs/cond-mat/0010440
- https://arxiv.org/abs/cond-mat/9906453

Quantum Computer Hardware

A bit of the action

In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.

	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, Dec 2016, Vol 354, Issue 6316
DOI: 10.1126/science.354.6316.1090

Quantum Computer Hardware

Photonics quantum computing

A bit of the action

In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.

	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 superposition 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 semiconductor 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.
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Q# exercise: option 1

No installation, web-based Jupyter Notebooks

- The Quantum Katas project (tutorials and exercises for learning quantum computing) https://github.com/Microsoft/QuantumKatas

- Tutorials

- BasicGates
- Superposition
- Measurements
- Teleportation

- SuperdenseCoding
- DeutschJozsaAlgorithm
- GroversAlgorithm
- SimonsAlgorithm

Certificate

- Complete any one quantum katas
- Take a screenshot or photo
- Post on Twitter or LinkedIn
- **Twitter:** @KittyArtPhysics @MSFTQuantum @QSharpCommunity #QSharp #QuantumComputing #comics #physics
- **LinkedIn:** @Kitty Y. M Yeung #MSFTQuantum #QSharp #QuantumComputing #comics #physics