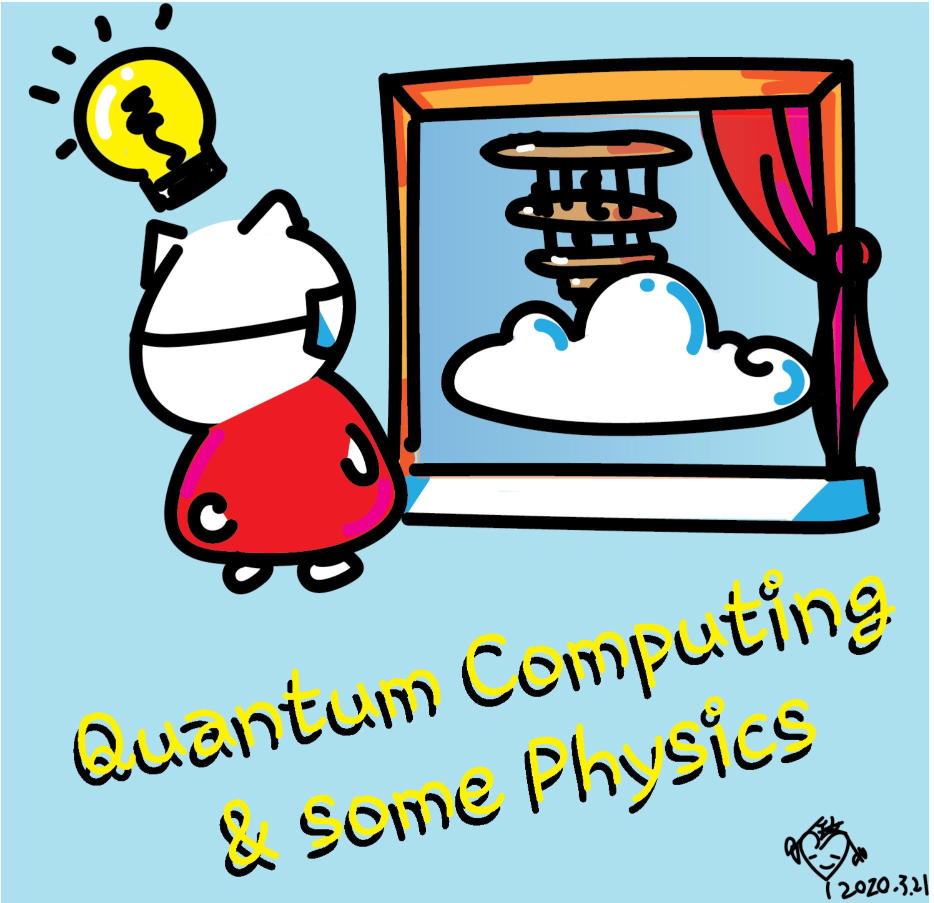
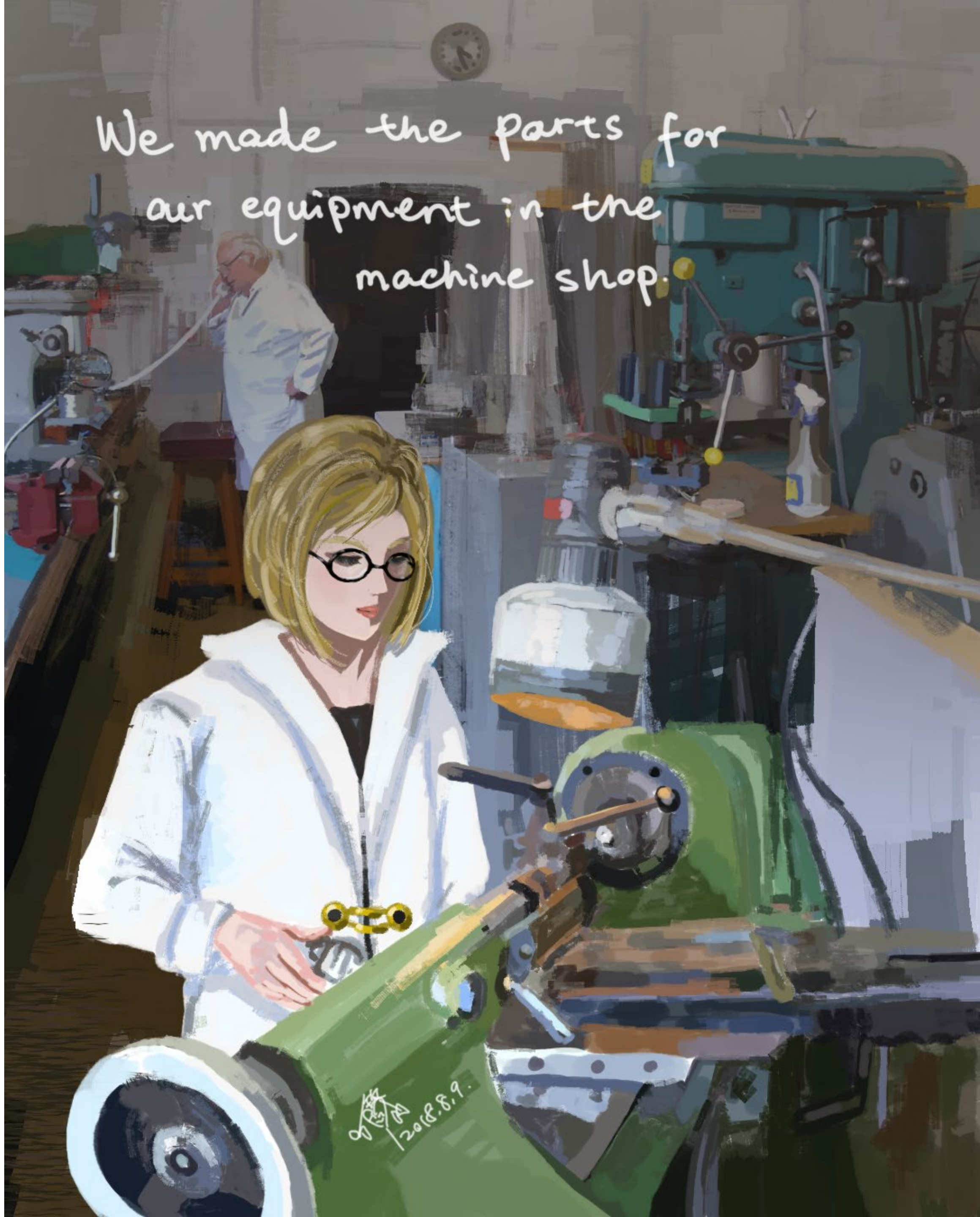
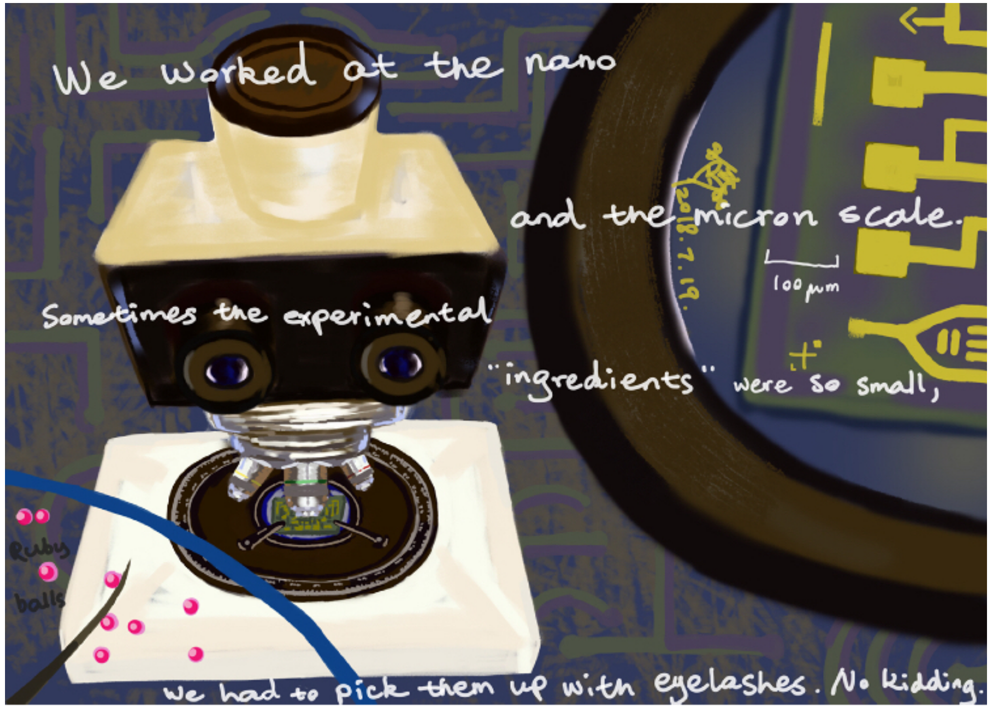
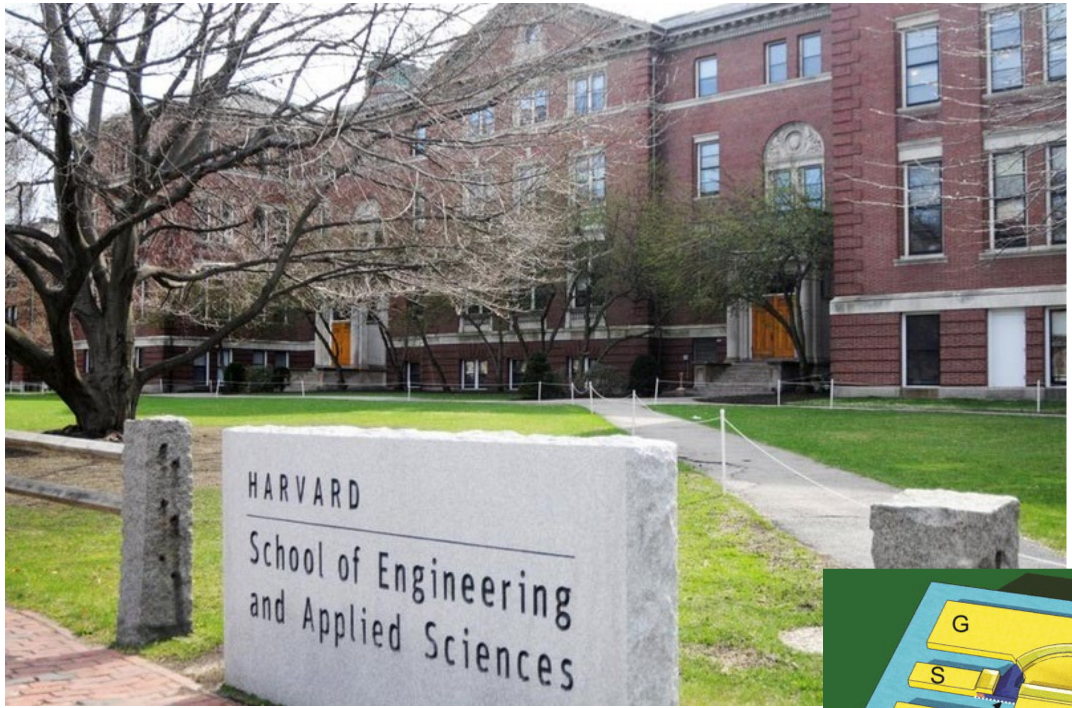


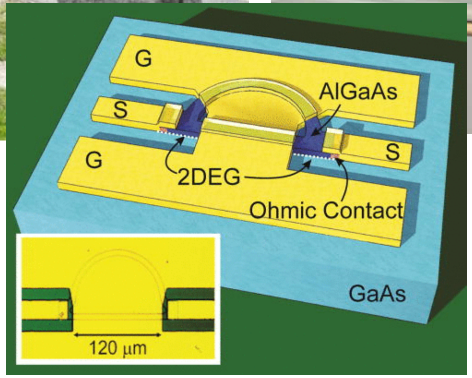
www.artbyphysicistkittyyeung.com
@KittyArtPhysics
@artbyphysicistkittyyeung

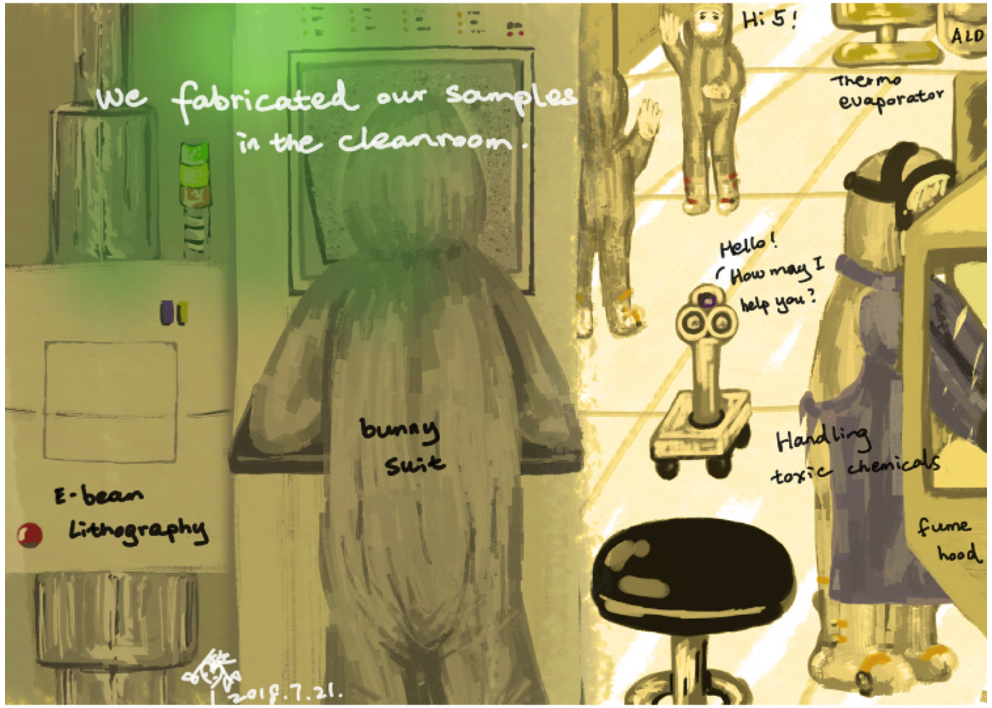

In my early career doing condensed matter experiments,
in order to study the quantum properties
of materials, we had to cool things down
to sub-Kelvin temperatures,
using
dilution refrigerators
and
liquid Helium.
2018.5.13.

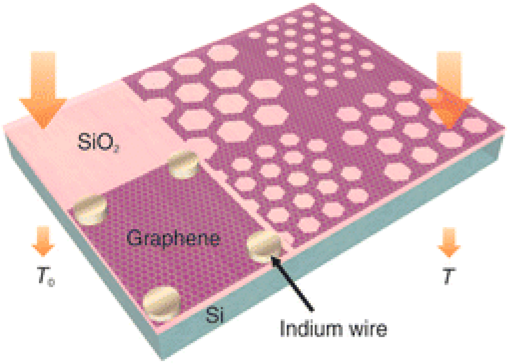

We made the parts for
our equipment in the
machine shop.
2018.8.9.

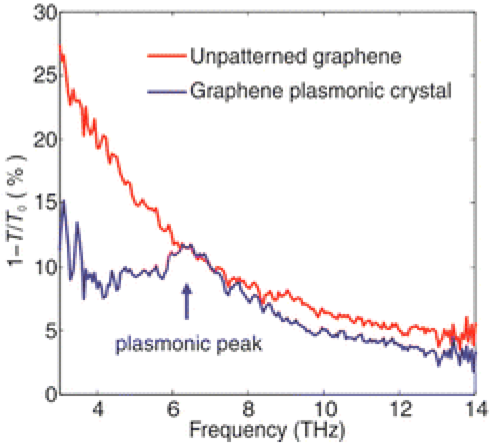

We worked at the nano
and the micron scale.
100 μm
2018.7.19
Sometimes the experimental
"ingredients" were so small,
Ruby balls
We had to pick them up with eyelashes. No kidding.

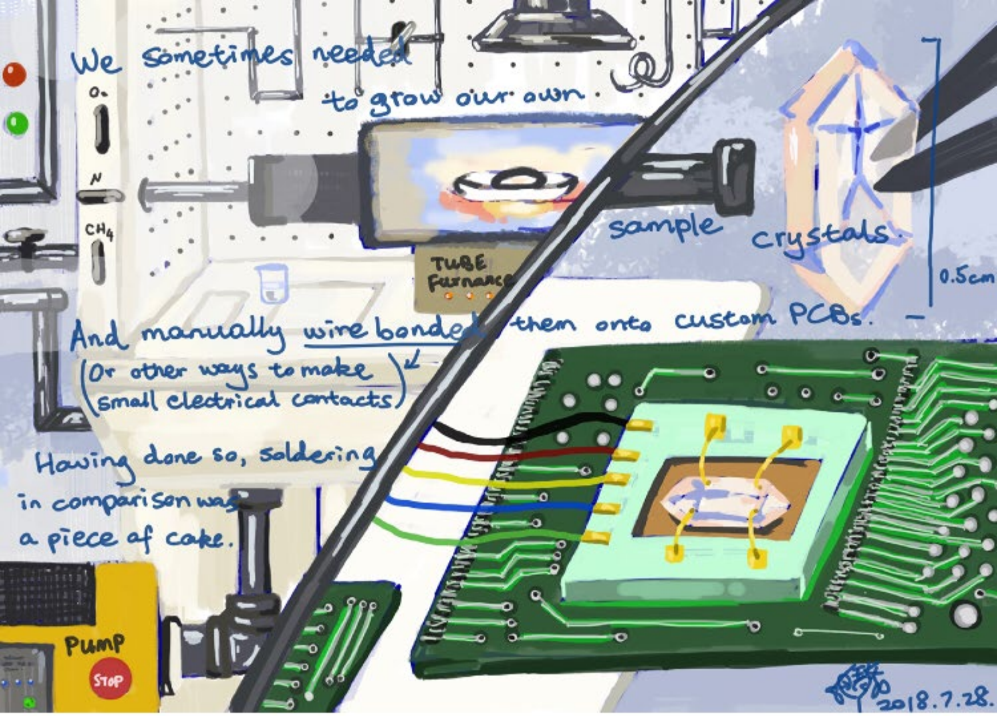

HARVARD
School of Engineering
and Applied Sciences


G
S
AlGaAs
G
S
2DEG
Ohmic Contact
GaAs
120 μm


We fabricated our samples
in the cleanroom.
Hi 5!
ALD
Thermo evaporator
Hello!
How may I help you?
bunny suit
Handling toxic chemicals
fume hood
E-beam Lithography
2018.7.21.


SiO_2
Graphene
T_0
T
Si
Indium wire

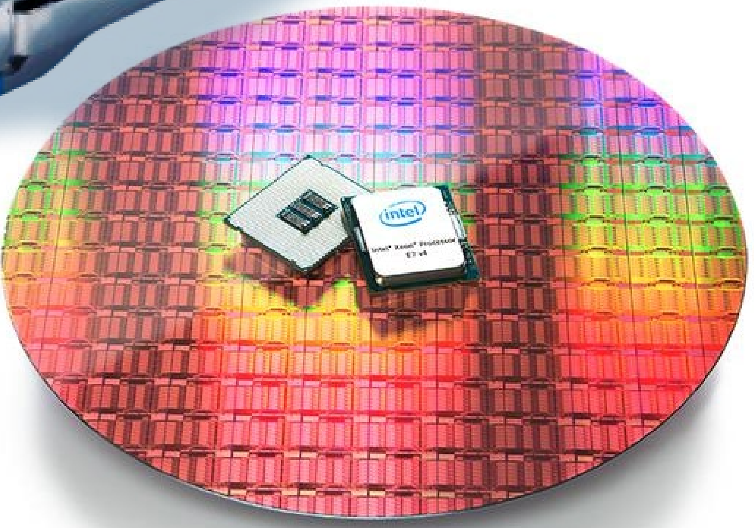

Unpatterned graphene
Graphene plasmonic crystal
$1-T/T_0$ (%)
plasmonic peak
Frequency (THz)
0
5
10
15
20
25
30
4
6
8
10
12
14


We sometimes needed to grow our own sample crystals.
0.5cm
O2
N
CH4
TUBE Furnace
And manually wire bonded them onto custom PCBs.
(Or other ways to make small electrical contacts)
Having done so, soldering in comparison was a piece of cake.
PUMP
STOP
2018.7.28.


Crystals were sliced into wafers, which were fabricated into chips based on layout designs.
Chips were mounted onto modules that were put into servers.
They formed complex systems.
Back then, quantum computers were still a "dream".
2018.8.8


intel
JOULE
570X
ENERGY TO INVENT
DESIGN FASTER.
PROTOTYPE EASIER.
INVENT MORE.


intel


intel


JOULE

KtY

Art by Physicist

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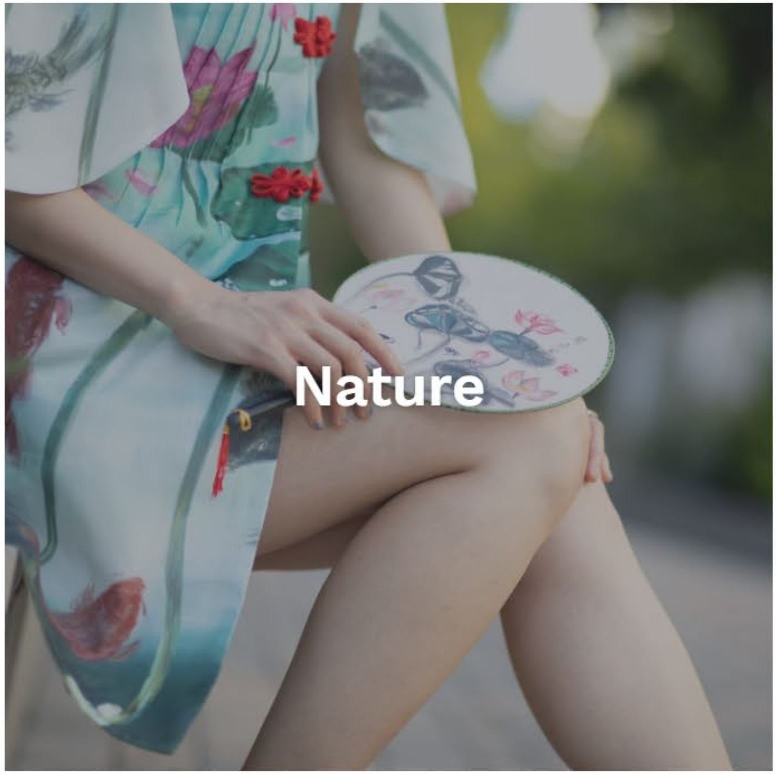
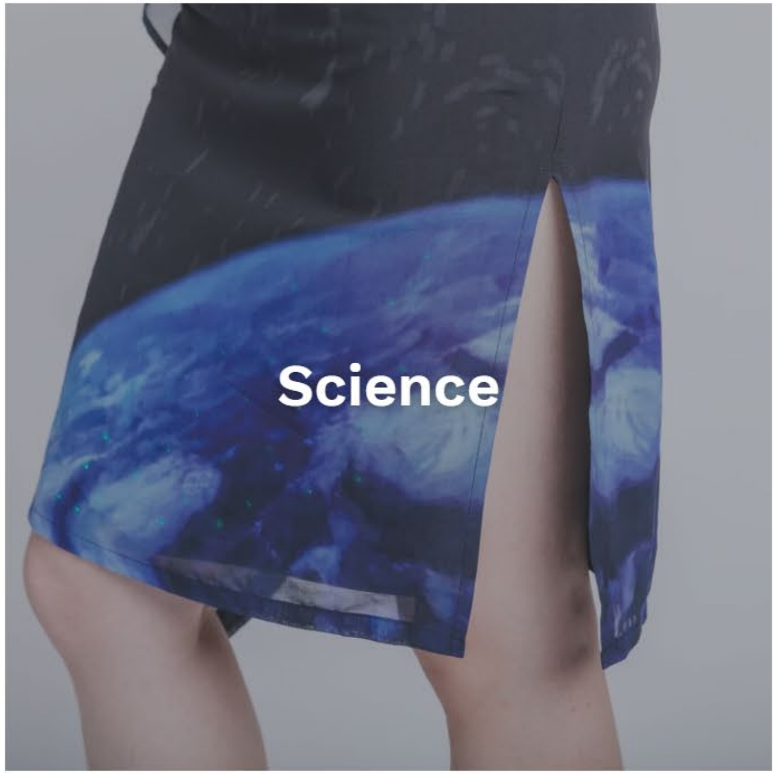
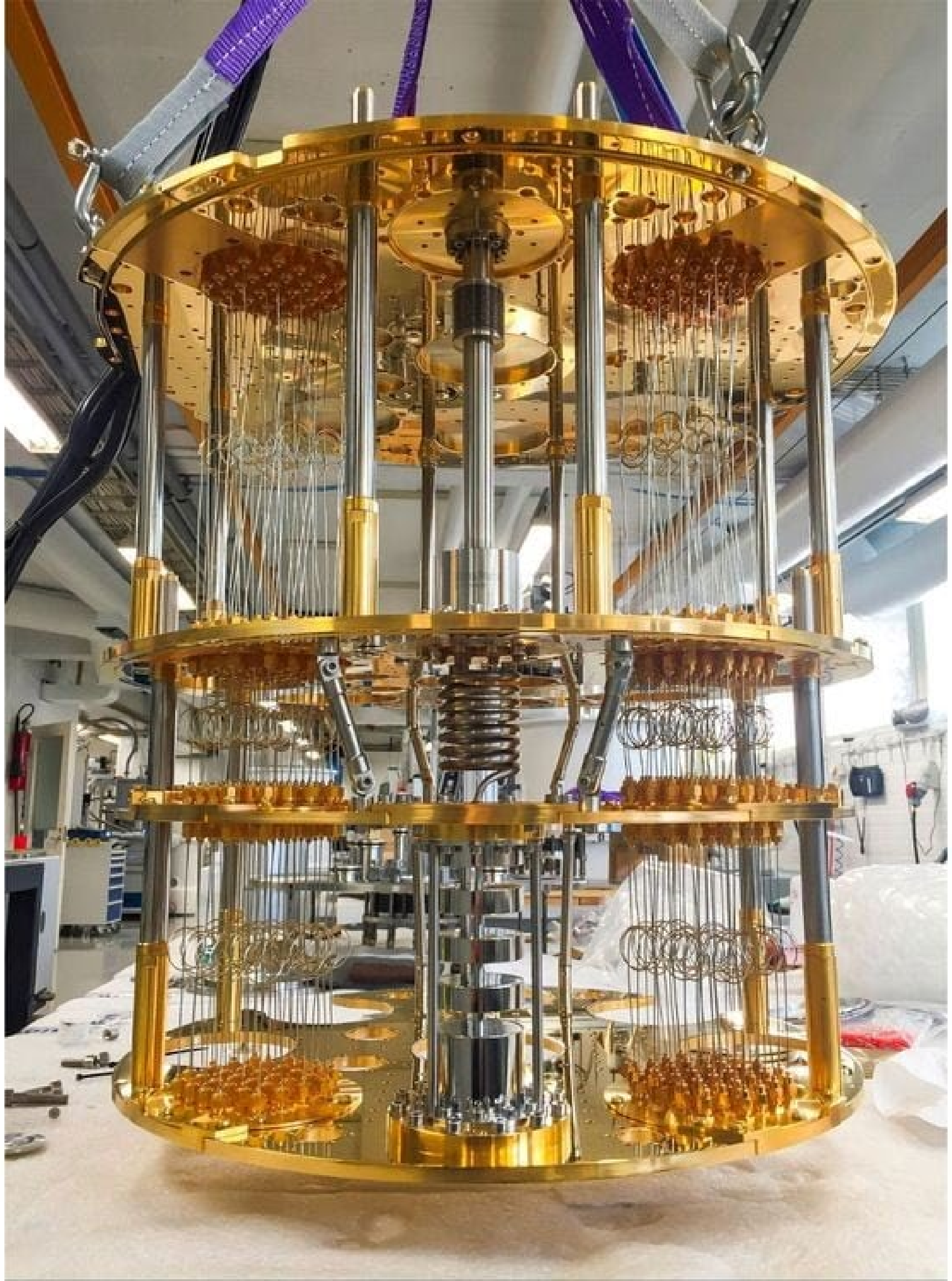
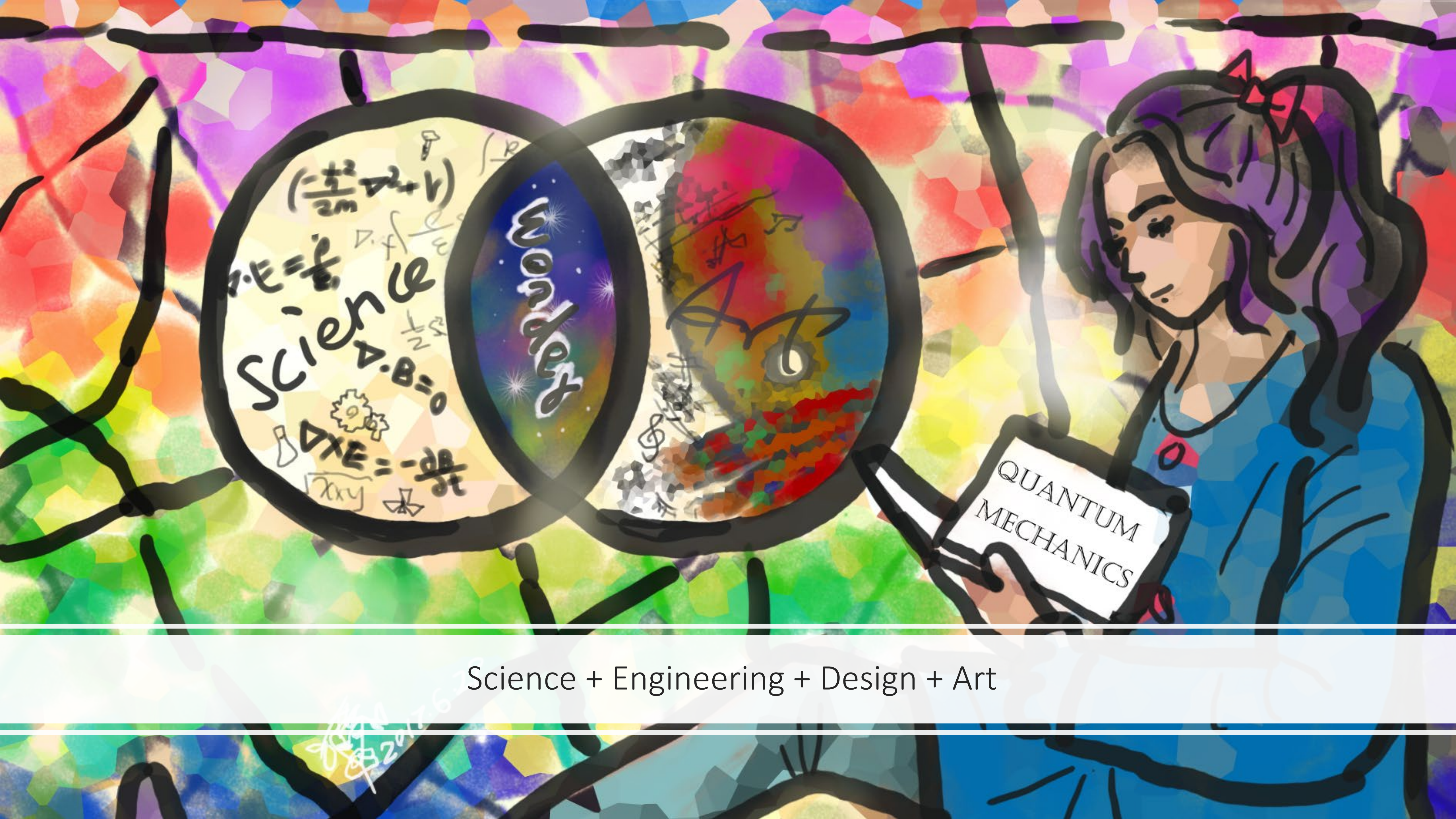


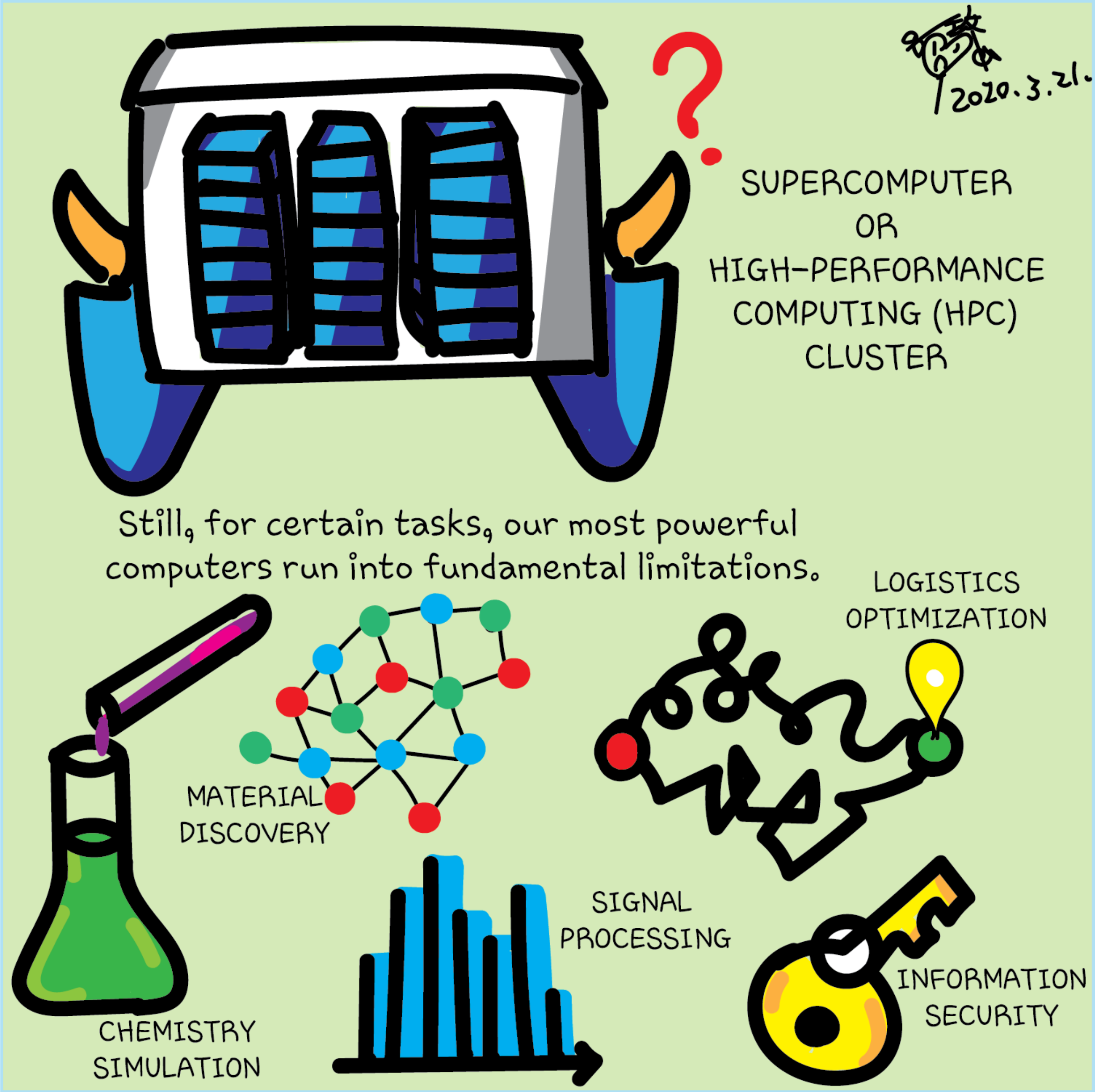


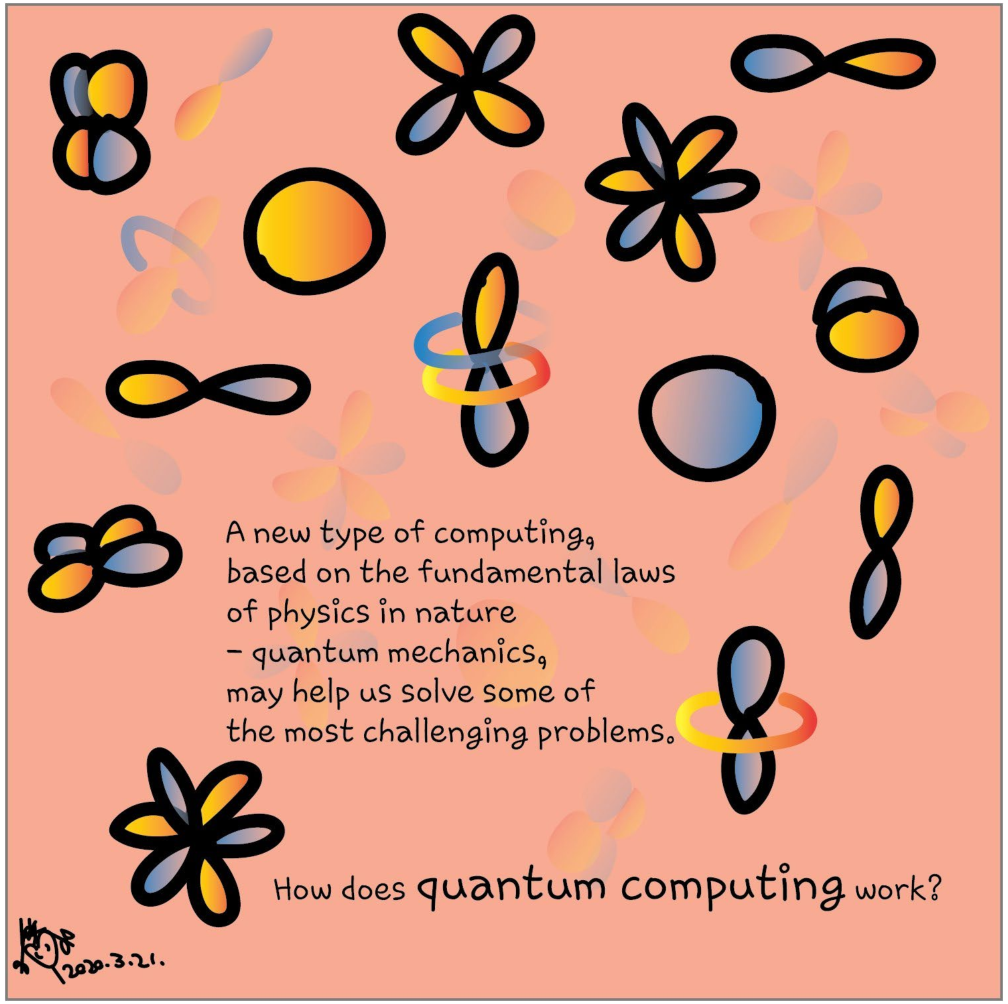


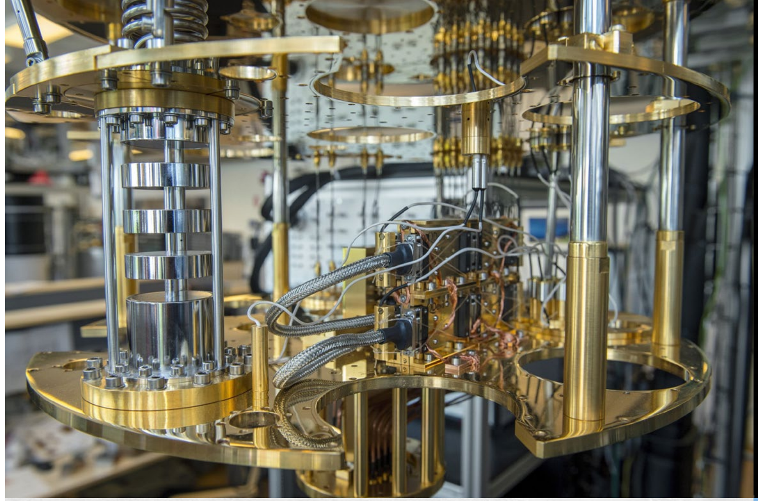

THE GLOBAL GOALS
For Sustainable Development
THE 17 GOALS
ACTION
NEWS
RESOURCES
SCHOOLS
THE 17 GOALS
In 2015, world leaders agreed to 17 goals for a better world by 2030. These goals have the power to end poverty, fight inequality and stop climate change. Guided by the goals, it is now up to all of us, governments, businesses, civil society and the general public to work together to build a better future for everyone.
1 NO POVERTY
2 ZERO HUNGER
3 GOOD HEALTH AND WELL-BEING
4 QUALITY EDUCATION
5 GENDER EQUALITY
6 CLEAN WATER AND SANITATION
7 AFFORDABLE AND CLEAN ENERGY
8 DECENT WORK AND ECONOMIC GROWTH
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
10 REDUCED INEQUALITIES
Reduce inequality within and among countries.
VIEW GOAL
11 SUSTAINABLE CITIES AND COMMUNITIES
Make cities and human settlements inclusive, safe, resilient and sustainable.
VIEW GOAL
12 RESPONSIBLE CONSUMPTION AND PRODUCTION
13 CLIMATE ACTION
14 LIFE BELOW WATER
HOW CAN I CONTRIBUTE?
The Global Goals will only be met if we work together. See how you can get involved here.
THE GLOBAL GOALS
For Sustainable Development
GET INVOLVED
The Bill & Melinda Gates Foundation
GOALKEEPERS 2019.
25-26TH OF SEPTEMBER.
WORLD LEADERS GATHER.
GO TO WEBSITE
15 LIFE ON LAND
16 PEACE, JUSTICE AND STRONG INSTITUTIONS
17 PARTNERSHIPS FOR THE GOALS

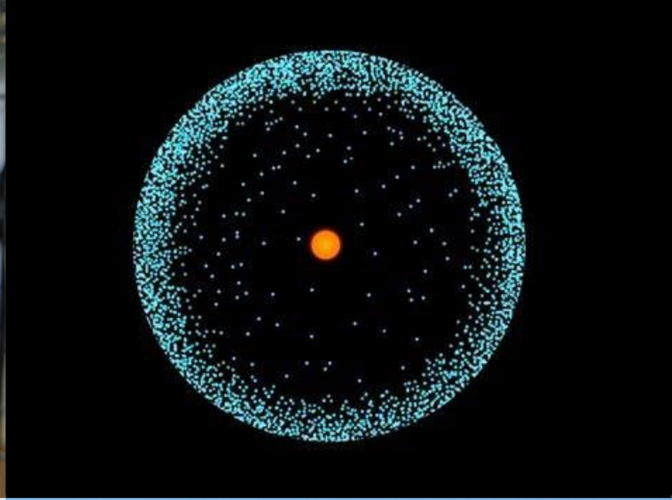

Science
Wonder
Art
QUANTUM MECHANICS
Science + Engineering + Design + Art

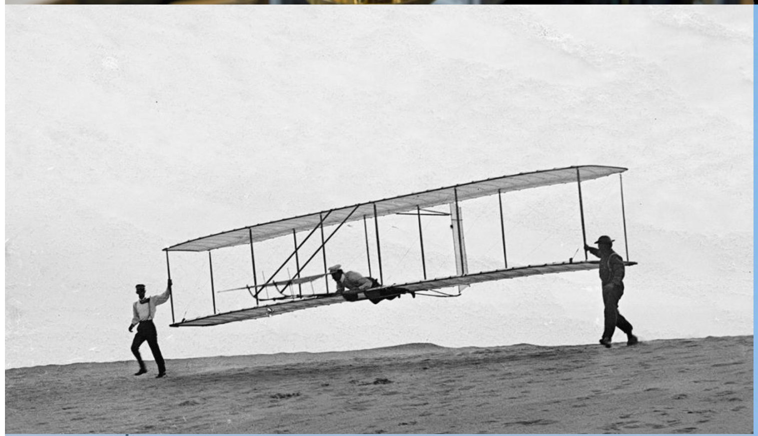
Our world now runs on computers
2020.3.21
– they are machines we task to carry out work more efficiently than we ever do manually.
DATA CENTER SERVERS
PUBLIC HEALTH
MOBILITY
EDUCATION
PRODUCTION
People and things are connected through the internet.

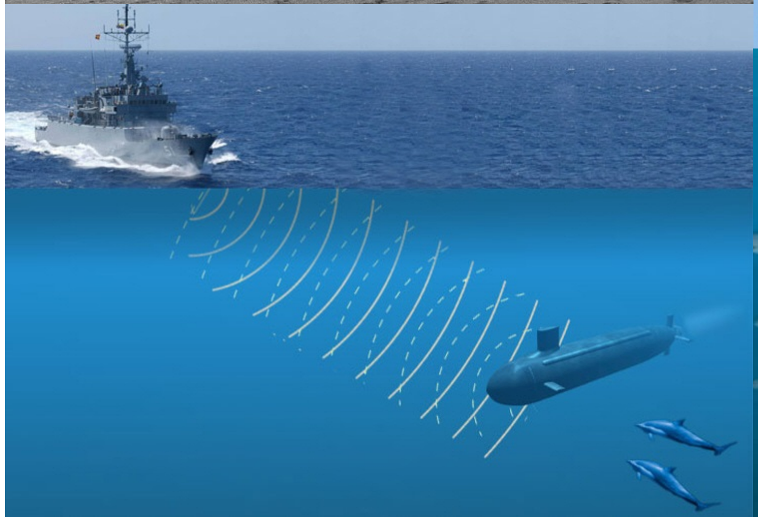

2020.3.21.
SUPERCOMPUTER
OR
HIGH-PERFORMANCE
COMPUTING (HPC)
CLUSTER
Still, for certain tasks, our most powerful computers run into fundamental limitations.
LOGISTICS
OPTIMIZATION
MATERIAL
DISCOVERY
SIGNAL
PROCESSING
INFORMATION
SECURITY
CHEMISTRY
SIMULATION

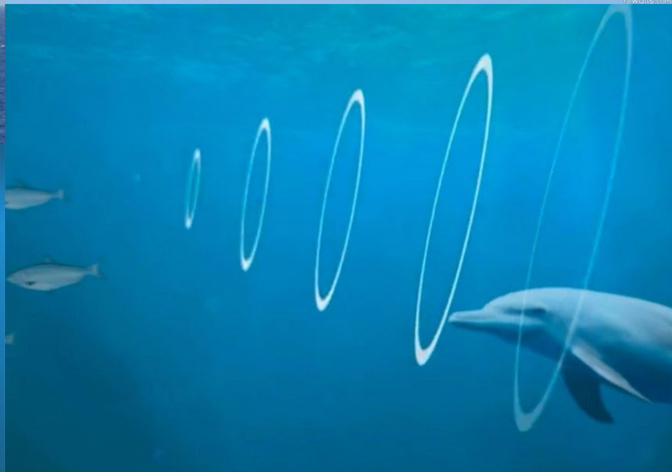

A new type of computing,
based on the fundamental laws
of physics in nature
– quantum mechanics,
may help us solve some of
the most challenging problems.
How does quantum computing work?
2020.3.21.

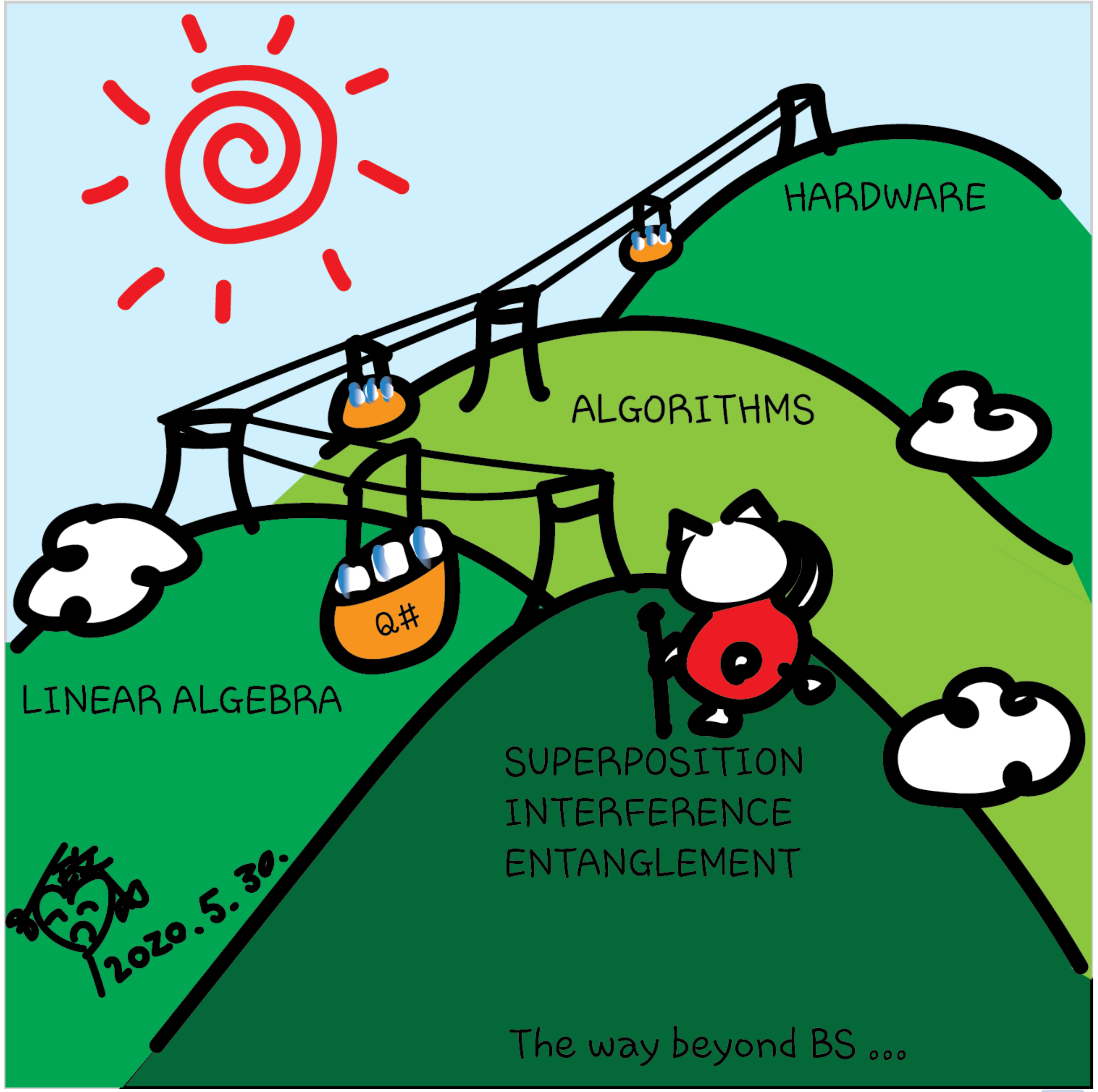


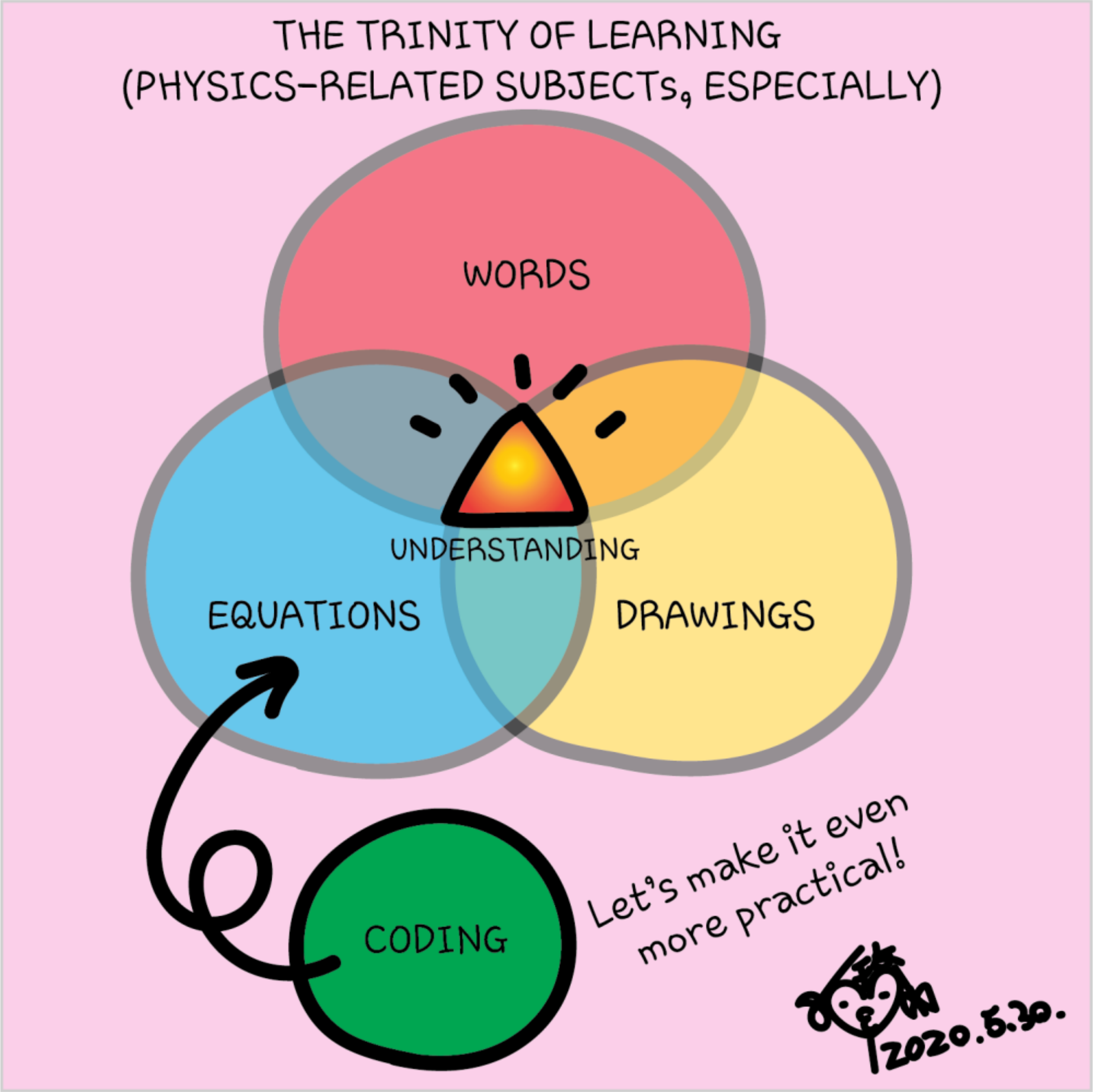


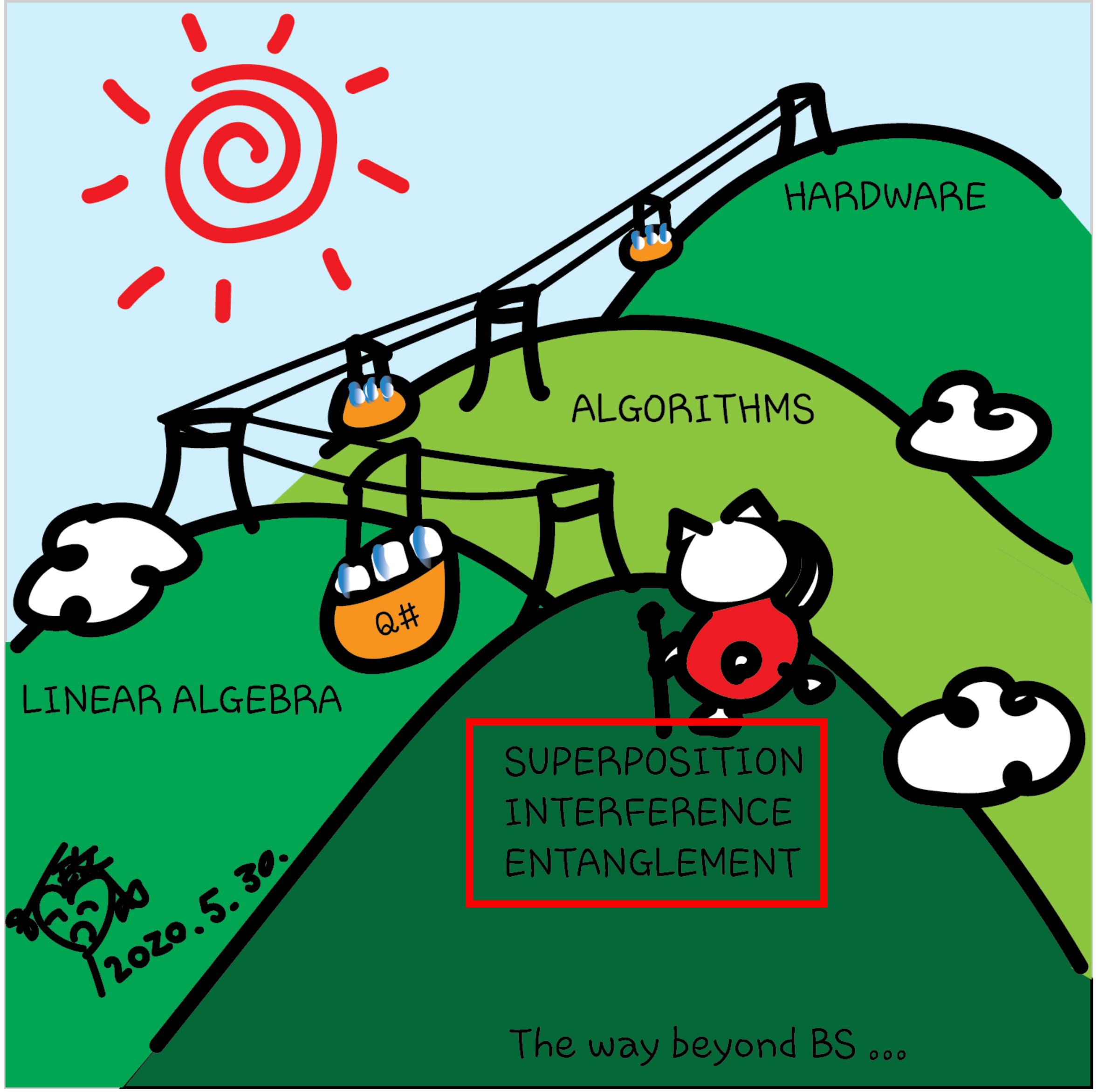


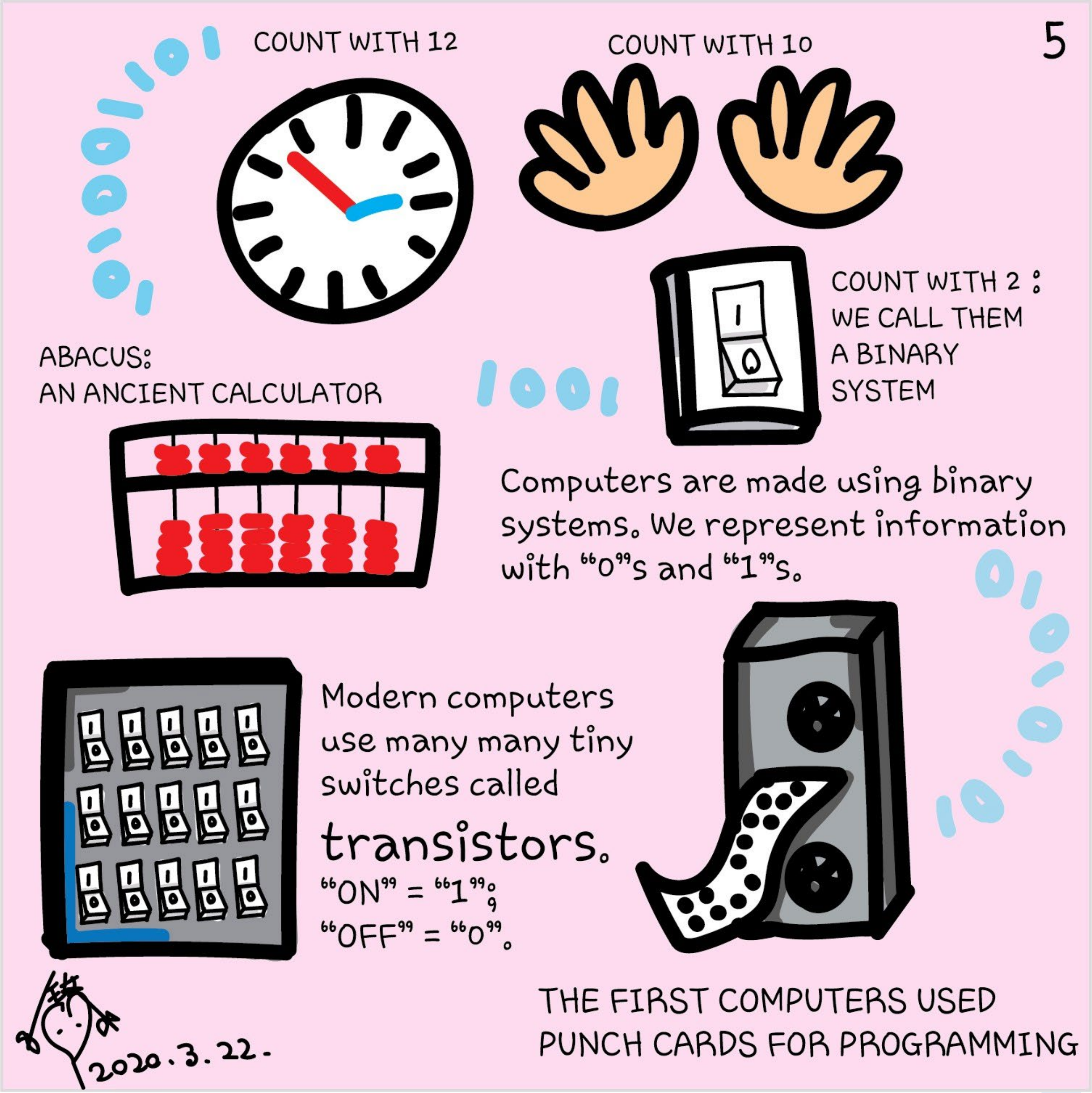





HARDWARE
ALGORITHMS
Q#
LINEAR ALGEBRA
SUPERPOSITION
INTERFERENCE
ENTANGLEMENT
2020.5.30.
The way beyond BS ...

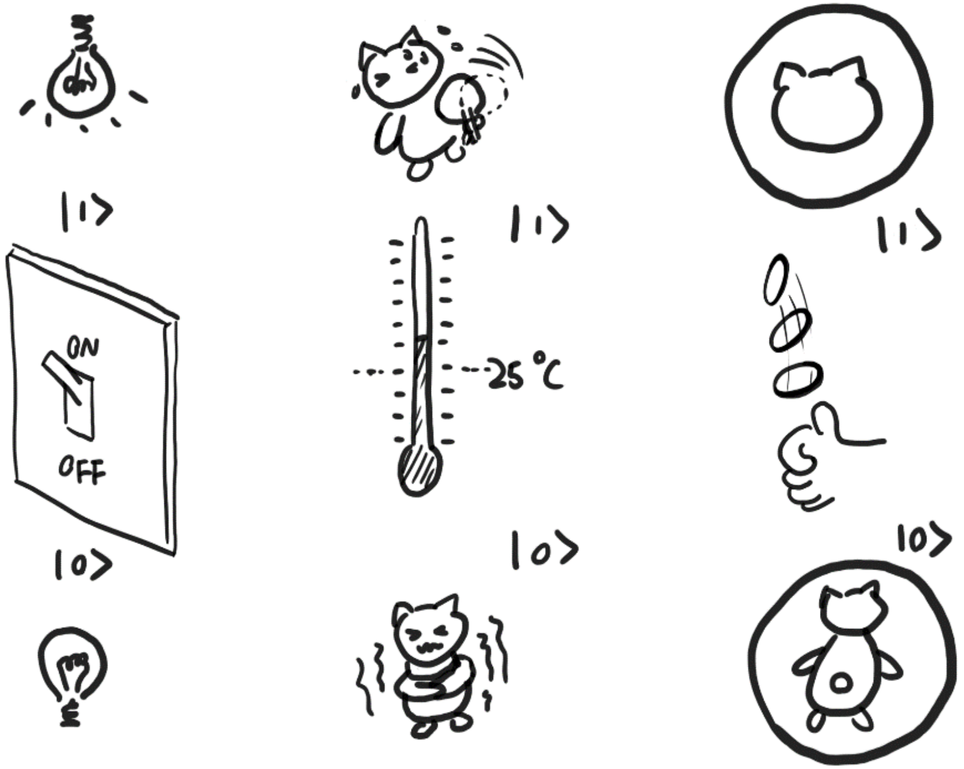

THE TRINITY OF LEARNING
(PHYSICS-RELATED SUBJECTs, ESPECIALLY)
WORDS
UNDERSTANDING
EQUATIONS
DRAWINGS
CODING
Let's make it even more practical!
2020.5.30.


HARDWARE
ALGORITHMS
Q#
LINEAR ALGEBRA
SUPERPOSITION
INTERFERENCE
ENTANGLEMENT
2020.5.30.
The way beyond BS ...

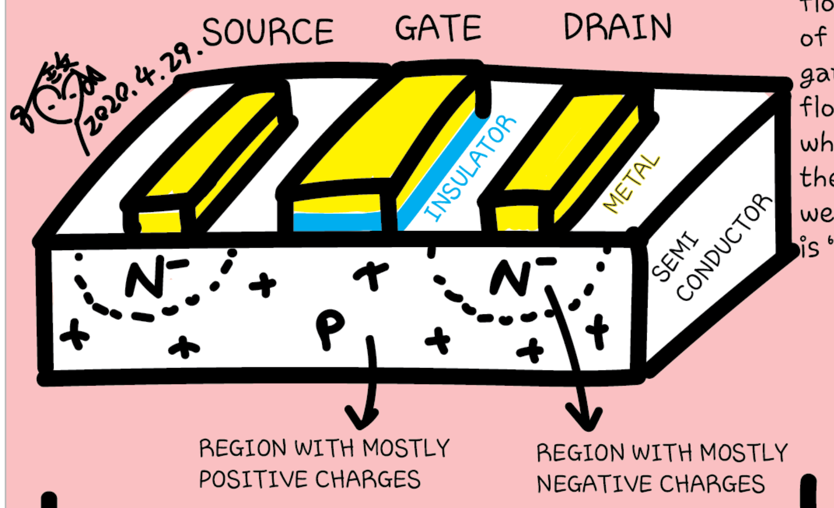

COUNT WITH 12
COUNT WITH 10
5
COUNT WITH 2 :
WE CALL THEM
A BINARY
SYSTEM
ABACUS:
AN ANCIENT CALCULATOR
Computers are made using binary systems. We represent information with "0"s and "1"s.
Modern computers use many many tiny switches called
transistors.
"ON" = "1";
"OFF" = "0".
THE FIRST COMPUTERS USED
PUNCH CARDS FOR PROGRAMMING
2020.3.22.

States – classical bits

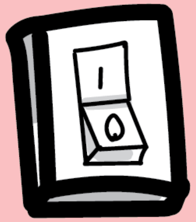
$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \qquad |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$



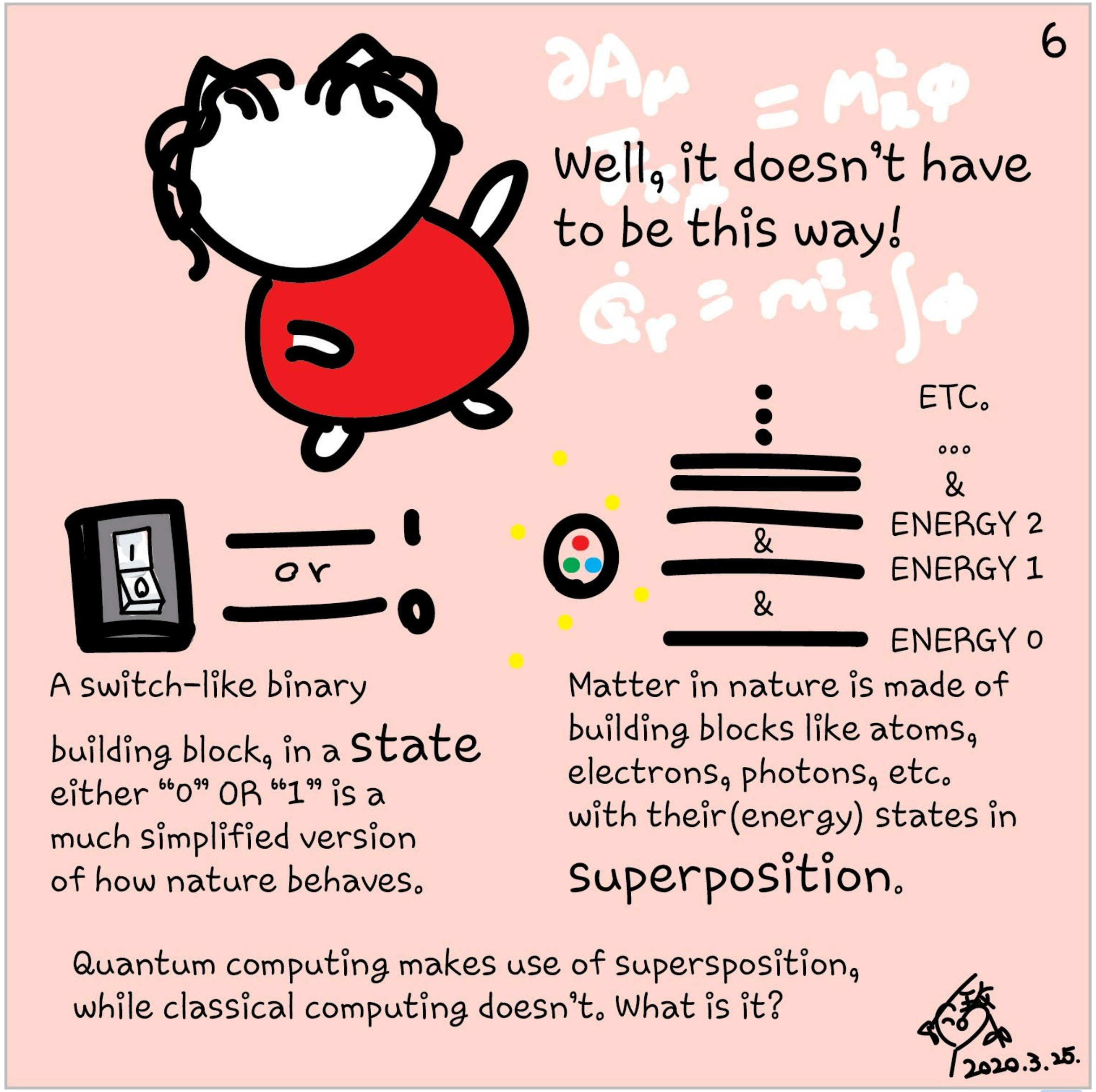
We leverage various properties of materials to make computing hardware.

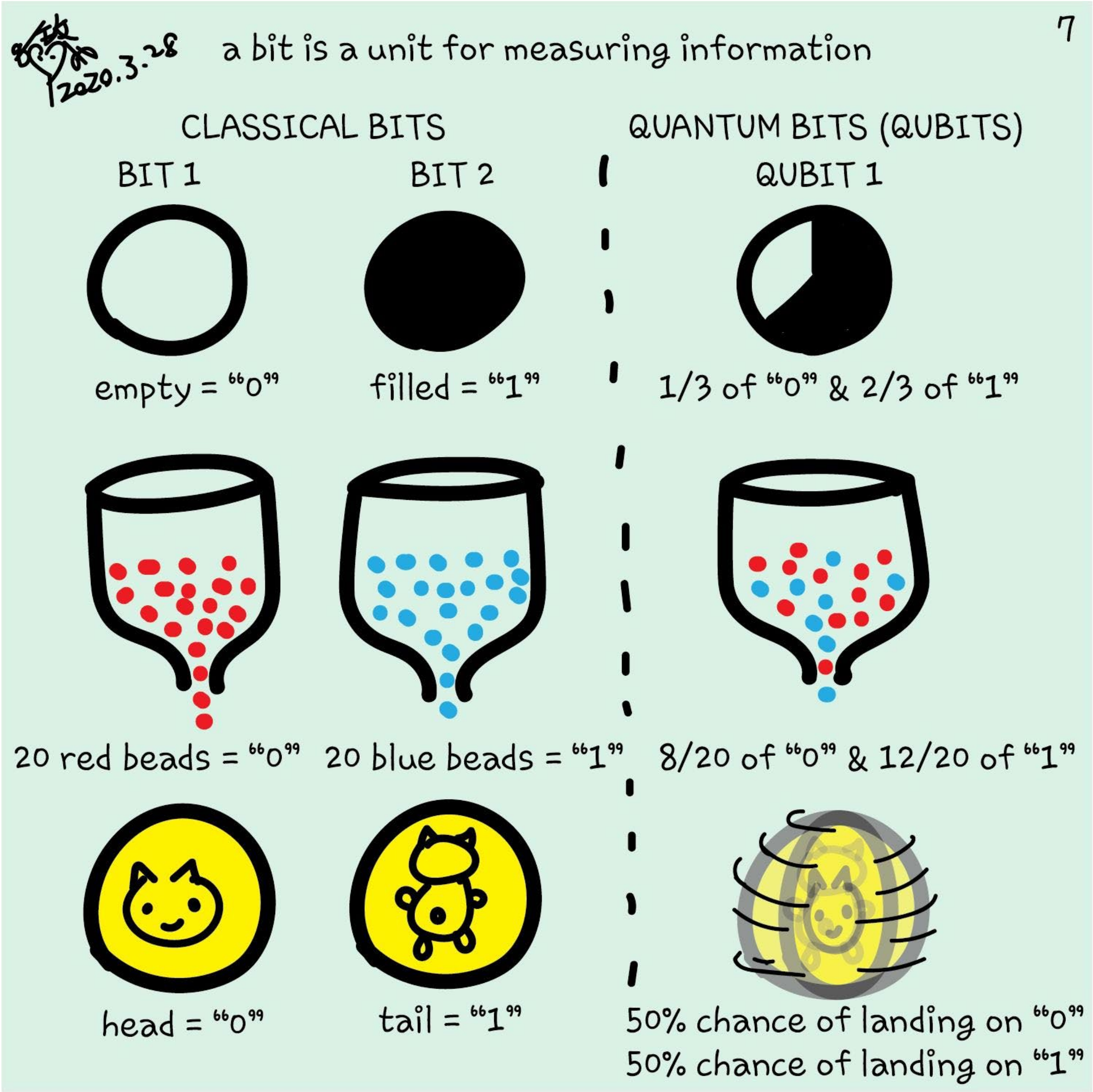


The gate applies voltage to control the electron flow from source to drain of a transistor. At a certain gate voltage level, electrons flow. This is the "on" state which we call "1". When there's no electron flow, we say the transistor is "off", or "0".



Transistors are nano- to micrometer switches.


6
Well, it doesn't have to be this way!
1
or
0
ETC.
...
&
ENERGY 2
&
ENERGY 1
&
ENERGY 0
A switch-like binary building block, in a state either "0" OR "1" is a much simplified version of how nature behaves.
Matter in nature is made of building blocks like atoms, electrons, photons, etc. with their (energy) states in superposition.
Quantum computing makes use of superssposition, while classical computing doesn't. What is it?
2020.3.25.


2020.3.28
a bit is a unit for measuring information
7
CLASSICAL BITS
QUANTUM BITS (QUBITS)
BIT 1
BIT 2
QUBIT 1
empty = "0"
filled = "1"
1/3 of "0" & 2/3 of "1"
20 red beads = "0"
20 blue beads = "1"
8/20 of "0" & 12/20 of "1"
head = "0"
tail = "1"
50% chance of landing on "0"
50% chance of landing on "1"

If we can represent the ideas with pictures, we can also represent them with numbers and symbols, i.e. MATHS!

CLASSICAL BITS		QUANTUM BITS
BIT 1	BIT 2	QUBIT 1
$|0\rangle$	$|1\rangle$	$a|0\rangle + b|1\rangle$

(This |...> symbol is called a Dirac notation. It means a state in ... We mentioned "state" in page 5.)

a and b indicate how much of |0> and |1> are in the system

In our previous scenarios:

$a^2=1/3$
$b^2=2/3$

$a^2=8/20$
$b^2=12/20$

$a^2=50\%$
$b^2=50\%$

In other words, a and b are **amplitudes** of states |0> and |1>. Their squares, a^2 and b^2, are the **probabilities** of finding the system in the state |0> and |1>, respectively.

The qubit, a|0>+b|1>, is represented as a linear combination of states |0> and |1>, equivalent of saying |0> and |1> are in superposition.

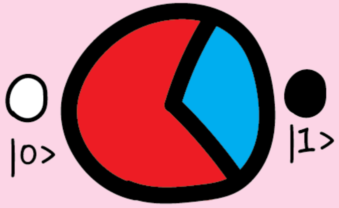
What do these lead to?

2020.3.28.

2020.3.28.

A qubit system is all the possible configurations in superposition.

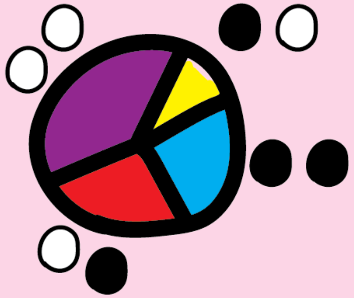
PIE CHART DENOTING PROBABILITY OF EACH CONFIGURATION



ONE QUBIT, TWO CONFIGURATIONS:

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

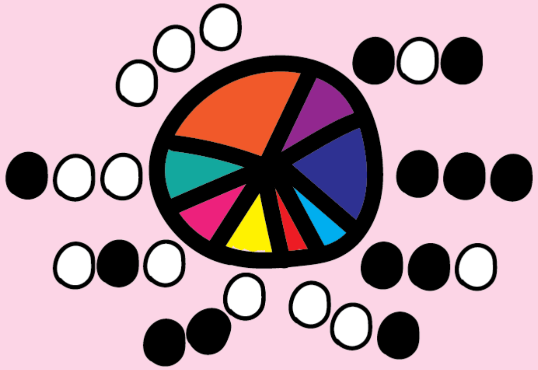
$a^2+b^2=1$ (total probability adds up to 1)



TWO QUBITS, FOUR CONFIGURATIONS:

$a|00\rangle+b|01\rangle+c|10\rangle+d|11\rangle$

$a^2+b^2+c^2+d^2=1$



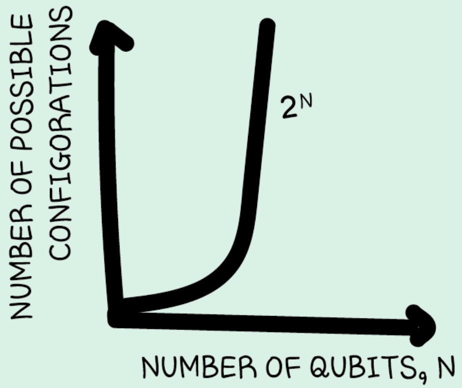
THREE QUBITS, EIGHT CONFIGURATIONS:

$a|000\rangle+b|001\rangle+c|010\rangle+d|100\rangle+e|110\rangle+f|101\rangle+g|011\rangle+h|111\rangle$

$a^2+b^2+c^2+d^2+e^2+f^2+g^2+h^2=1$

...

N qubits will have 2^N possible configurations in superposition!



Not only does the number of possible configurations grow exponentially with the number of qubits as 2^N, the number of possible combinations of amplitudes is infinite, as long as their squares – the probabilities – add up to 1.

THIS SYMBOL MEANS SUMMING ALL N TERMS FROM 1

$$|\psi\rangle = \sum_{i=1}^{N} c_i |\psi_i\rangle$$

AN N-QUBIT STATE

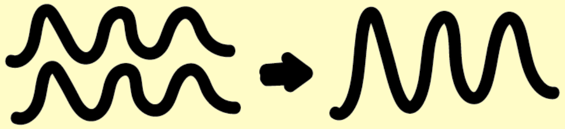
EACH POSSIBLE CONFIGURATION

The amplitude ci = a, b, c, d ...n
can be positive numbers 1, 1/2, 1/3, 1/4 ...n
or negative numbers -1, -1/2, -1/3, -1/4 ...n
(these are real numbers)
or imaginary numbers (+/-) i, 1/2i, 1/3i, 1/4i...ni
or 0.
In general they can be complex numbers
(with real and imaginary parts with
positive or negative signs)!

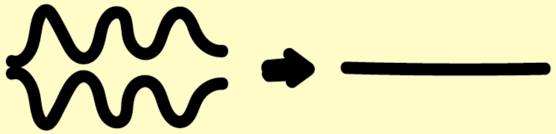
What's the consequence?

2020.4.1.

Our daily experience of amplitudes(like those of water waves, light waves, sound waves, etc.) has told us:

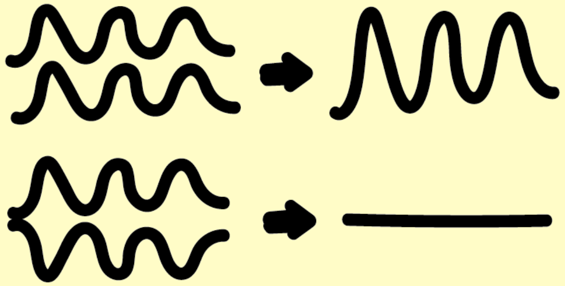


AMPLITUDES CAN ADD UP = CONSTRUCTIVE INTERFERECE



AMPLITUDES CAN CANCEL OUT = DESTRUCTIVE INTERFERENCE

Our daily experience of amplitudes(like those of water waves, light waves, sound waves, etc.) has told us:



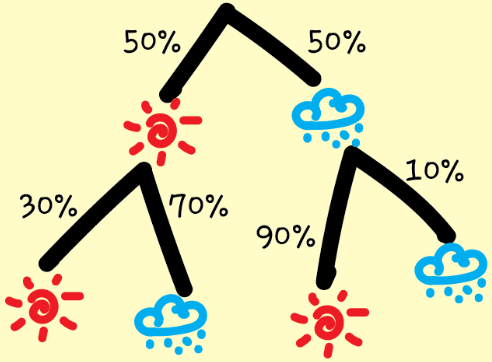
AMPLITUDES CAN ADD UP = CONSTRUCTIVE INTERFERECE

AMPLITUDES CAN CANCEL OUT = DESTRUCTIVE INTERFERENCE

How likely will it be sunny the day after tomorrow?

CLASSICAL

USES PROBABILITY DIRECTLY

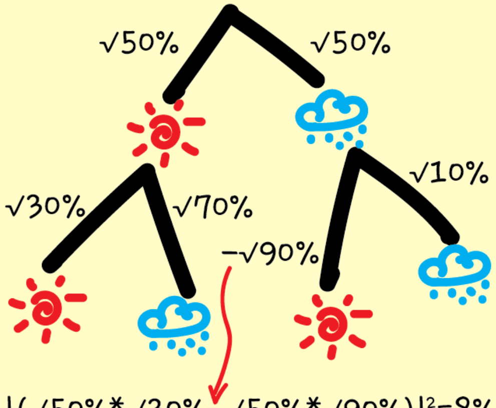


50%*30%+50%*90%=60%

Having more paths in classical case always leads to more likelihood.

QUANTUM

USES AMPLITUDE, AND CAN BE NEGATIVE



$|(\sqrt{50\%}*\sqrt{30\%}-\sqrt{50\%}*\sqrt{90\%})|^2=8\%$

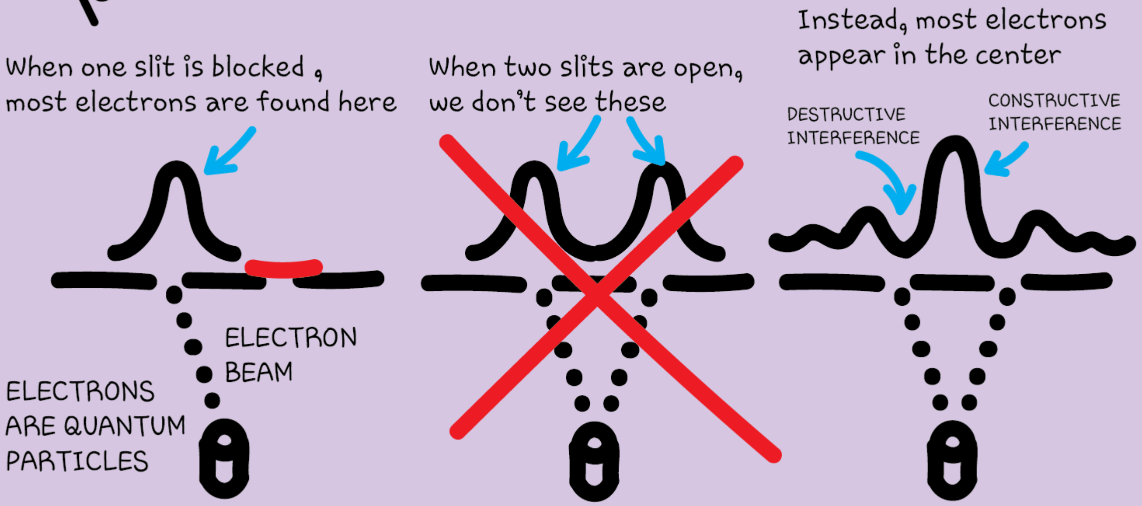
But in quantum case, the 2nd path of having a sunny day destructively interferes with the 1st one, making it less likely.

2020.4.4.

So, the things we observe (**measure**) are the results of interference. Possible results from constructive interference are more likely to be measured. The other possibilities cancel each other out through destructive interference.

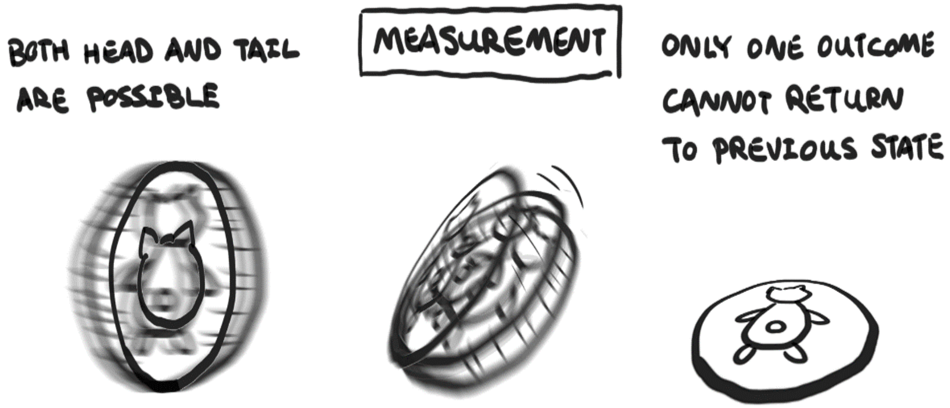
2020.4.5.

The famous double-slit experiment is a direct manifestation of quantum interference.



Interference is one of the "strange" behaviours of quantum systems enabled by superposition. What else?

Measurement



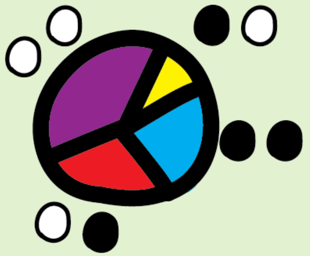
Not reversible

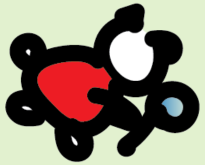
$$|\psi\rangle = c_{00}|00\rangle + c_{01}|01\rangle + c_{10}|10\rangle + c_{11}|11\rangle$$

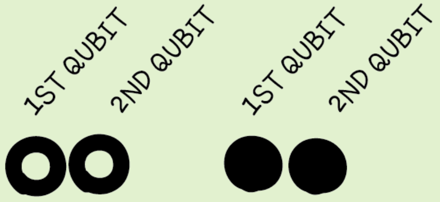
$$P = |c_{00}|^2 + |c_{01}|^2$$ If first qubit is 0

$$|\psi'\rangle = \frac{c_{00}|00\rangle + c_{01}|01\rangle}{\sqrt{P}}$$ After measurement

We've seen in page 9 that with two qubits, there are four possible configurations: both qubits in |0>s or |1>s, or one in |0> with the other in |1>. What if we make the |0>|0> case in superposition with the |1>|1> case? Or |0>|1> in superposition with |1>|0>?



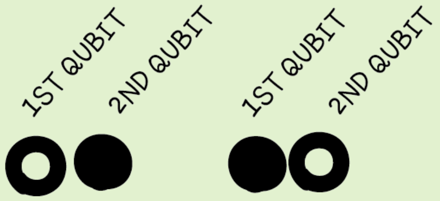




$a|0 \quad 0\rangle + d|1 \quad 1\rangle$

If we set the system to be in this case, we know that if we measure the first qubit and get |0>, the second qubit must be in |0>, without needing to measure it.

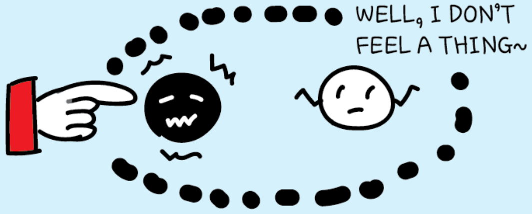
We can also measure the second qubit to know what the first qubit is without measuring it.



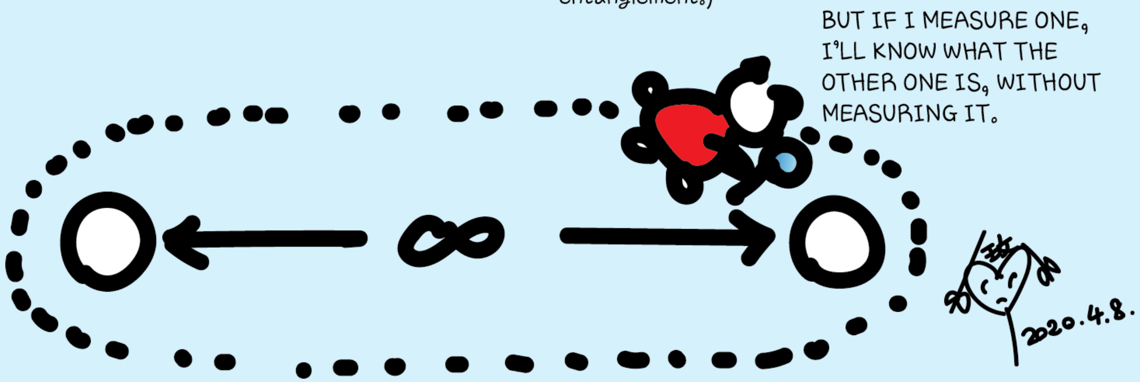
$b|0 \quad 1\rangle + c|1 \quad 0\rangle$

Similarly in this case, if the first qubit is |0>, the second qubit must be |1>. If the first is |1>, the second must be |0>.

The qubits are correlated. This is called "entanglement".



When we change one of the entangled qubits, the other qubit does not instantaneously change. (That would imply faster-than-light information transfer, which is prohibited. This is a common mistake people make when talking about entanglement.)



They can remain entangled even if they are separated infinitely far apart. There is no "spooky" interaction between them. All it means is that their measurement results are correlated. And entanglement simply does not depend on distance.

$1/\sqrt{2}(|00\rangle+|11\rangle)$ $\quad$ $1/\sqrt{2}(|01\rangle+|10\rangle)$

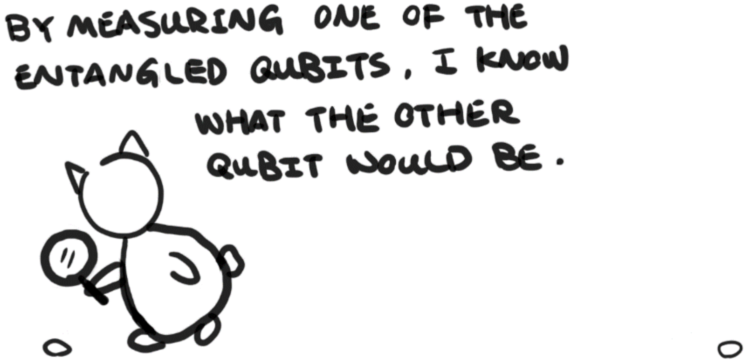
$1/\sqrt{2}(|00\rangle-|11\rangle)$ $\quad$ $1/\sqrt{2}(|01\rangle-|10\rangle)$

A special set of entangled two qubits is the four Bell states. We use them in every quantum algorithm.

Entanglement

Bell states

$$|\varphi^{\pm}\rangle = \frac{|01\rangle \pm |10\rangle}{\sqrt{2}} \text{ and } |\phi^{\pm}\rangle = \frac{|00\rangle \pm |11\rangle}{\sqrt{2}}$$



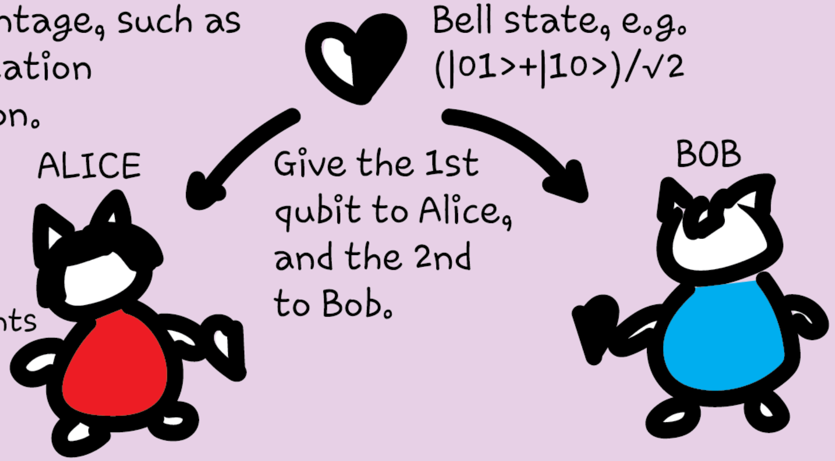
Take $|\phi^{+}\rangle$ as an example, upon measuring the first qubit, one obtains two possible results:

1. First qubit is 0, get a state $|\phi'\rangle = |00\rangle$ with probability ½.
2. First qubit is 1, get a state $|\phi''\rangle = |11\rangle$ with probability ½.

If the second qubit is measured, the result is the same as the above. This means that measuring one qubit tells us what the other qubit is.

We can use entanglement to our advantage, such as in communication or encryption.

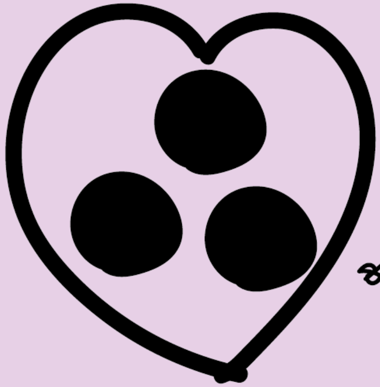
First prepare a Bell state, e.g. $(|01\rangle+|10\rangle)/\sqrt{2}$



Give the 1st qubit to Alice, and the 2nd to Bob.

If Alice measures and gets $|0\rangle$, she knows Bob will get $|1\rangle$. If she wants him to get $|0\rangle$, She'll ask him to flip his qubit.

Of course, entanglement can happen between any number of qubits. The multi-qubit counterpart of Bell states are called the Greenberger-Horne-Zeilinger (GHZ) states.



THREE QUBITS: $(|000\rangle+|111\rangle)/\sqrt{2}$

2020.4.11.

N QUBITS: $(|0000...\rangle+|1111....\rangle)/\sqrt{2}$
$=(|0\rangle^{\otimes N}+|1\rangle^{\otimes N})/\sqrt{2}$

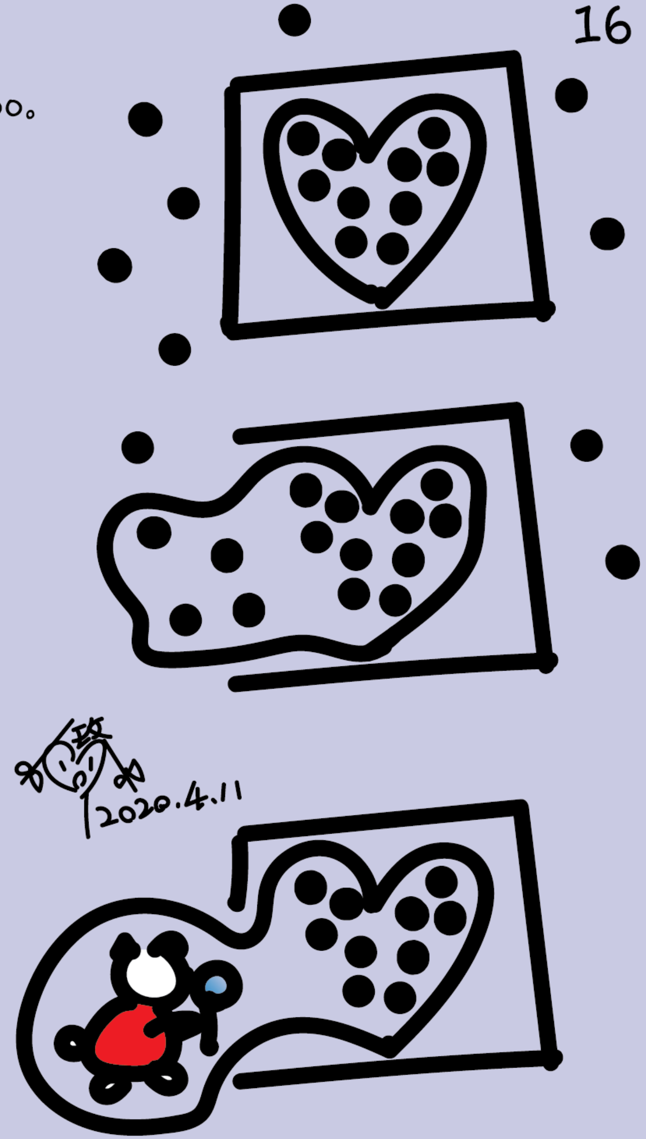
However, entanglement can be disadvantageous, too.

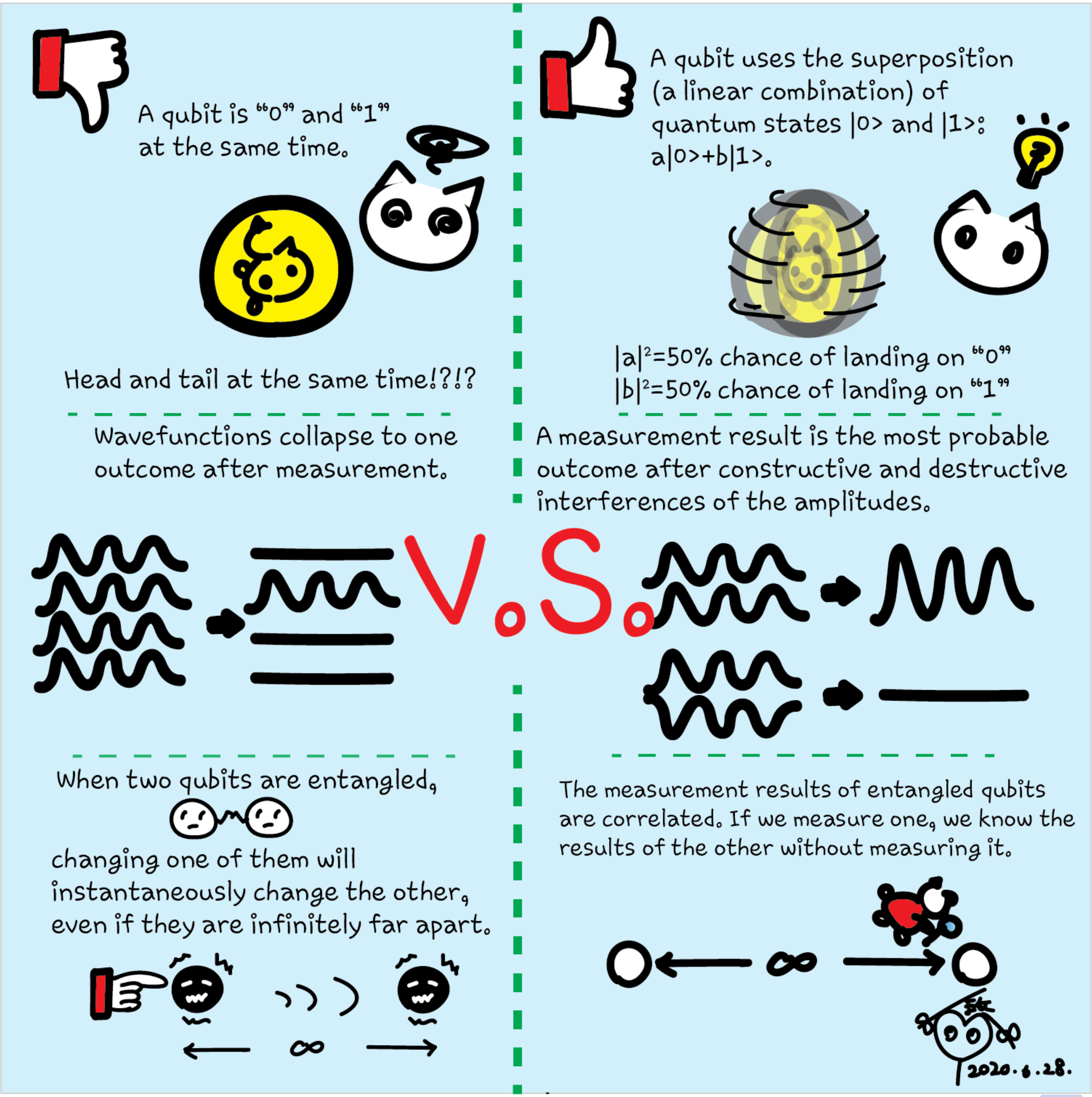
If the qubits are not perfectly isolated,

entanglement with their environment can easily happen, causing the qubits to **decohere** from each other.

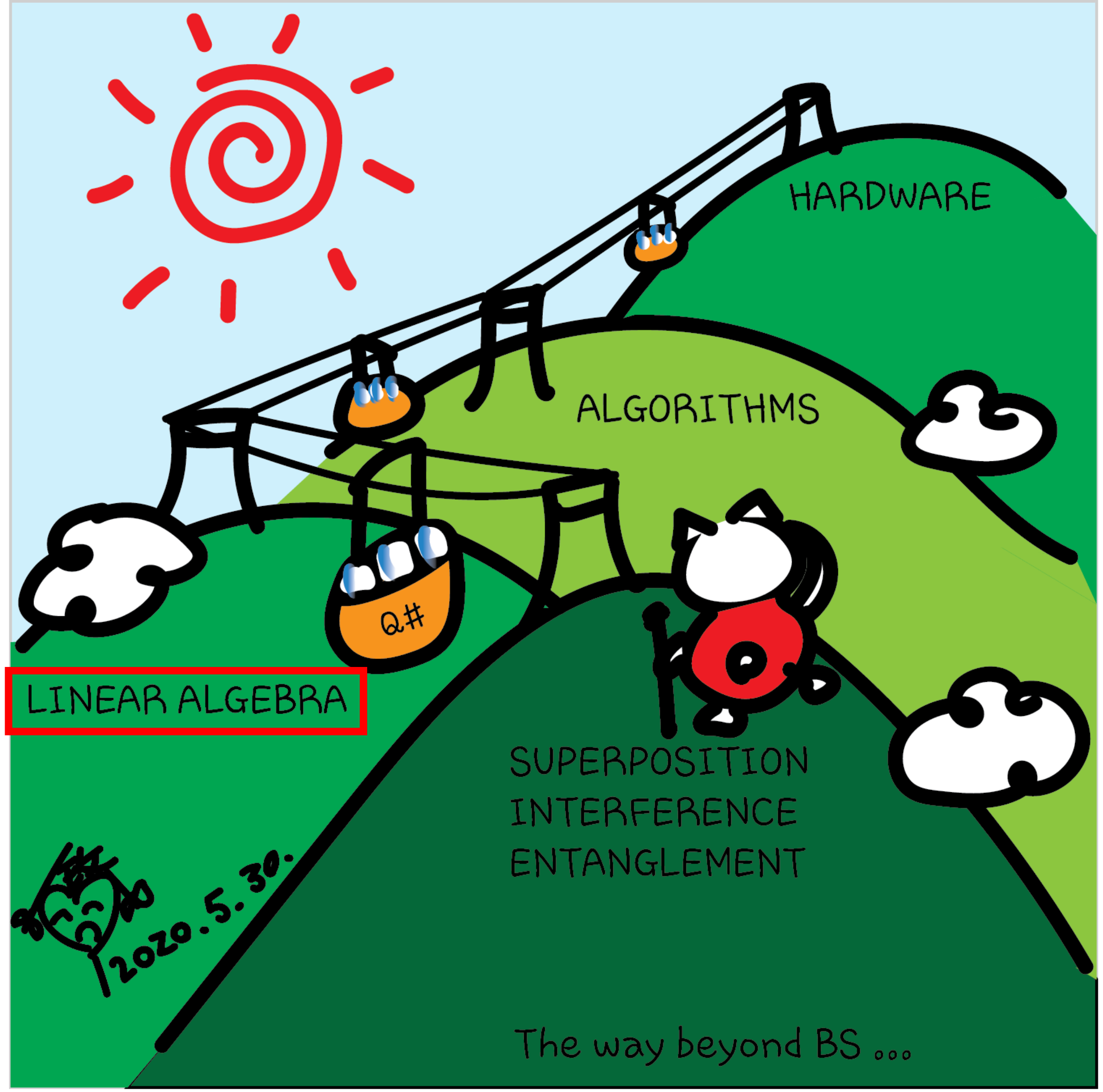
Measurements also cause decoherence, when the measuring device acts as the environment that entangles with the qubits.

Therefore, measurements must be delicately done. Otherwise, they cause errors.





https://quantumfactsheet.github.io/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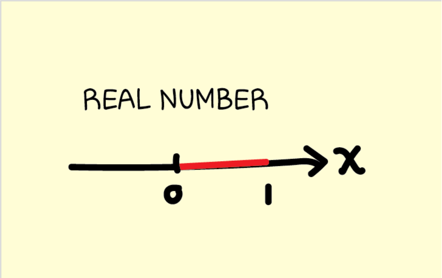
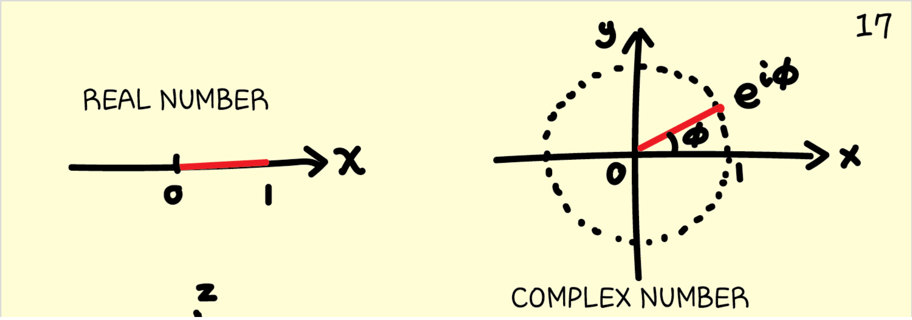
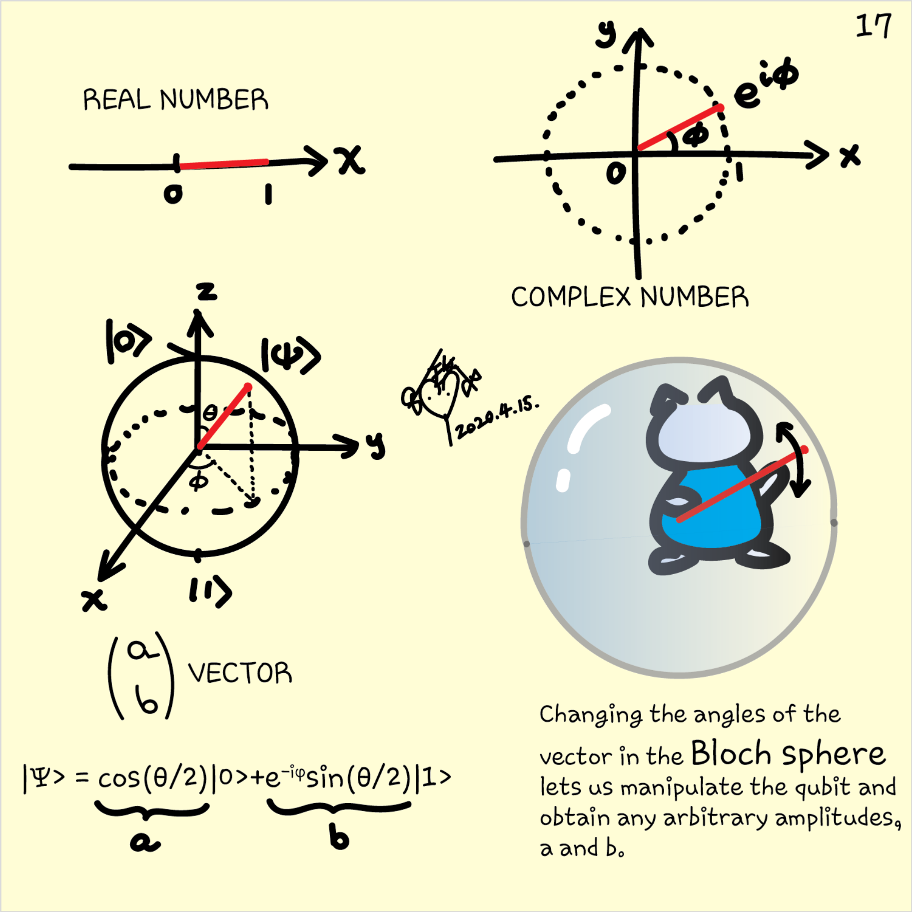
Graphic representation of a qubit



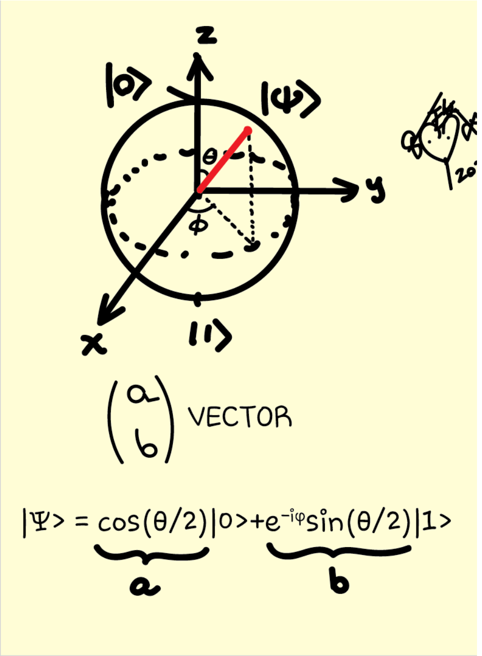
Graphic representation of a qubit

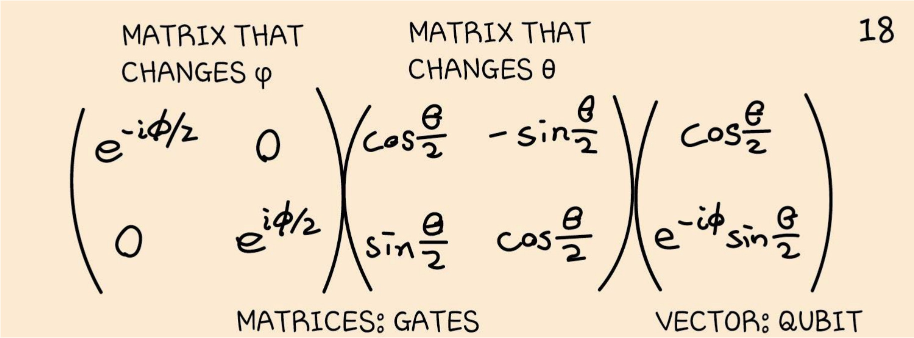


Graphic representation of a qubit



Gates (quantum operations)





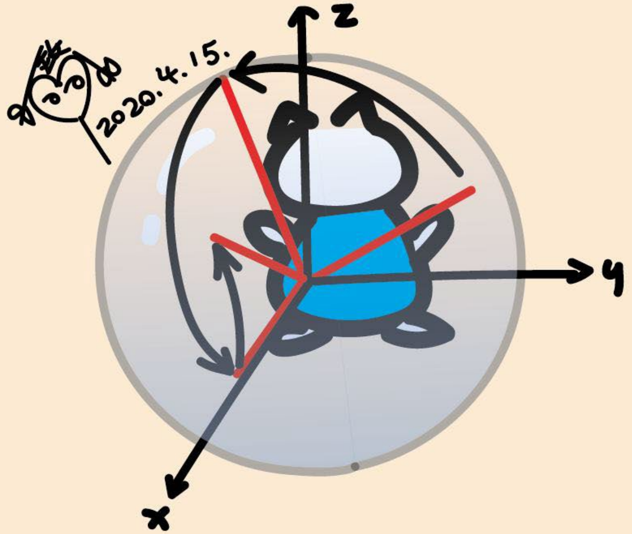
MATRIX THAT CHANGES φ

MATRIX THAT CHANGES θ

$$\begin{pmatrix} e^{-i\phi/2} & 0 \\ 0 & e^{i\phi/2} \end{pmatrix} \begin{pmatrix} \cos\frac{\theta}{2} & -\sin\frac{\theta}{2} \\ \sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{pmatrix} \begin{pmatrix} \cos\frac{\theta}{2} \\ e^{-i\phi}\sin\frac{\theta}{2} \end{pmatrix}$$

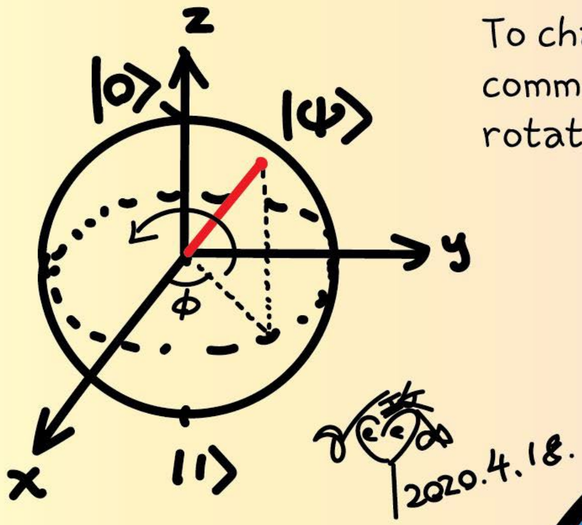
MATRICES: GATES

VECTOR: QUBIT



Like a set of coins, a combination of them can make up any number.

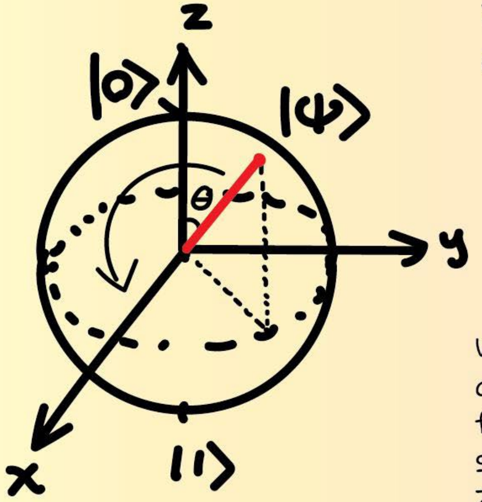
We can have a set of matrix operations (gates) that moves the qubit to anywhere on the Bloch sphere.



To change the phase φ, we have a commonly used gate, Z, which rotates about the z-axis by 180°.

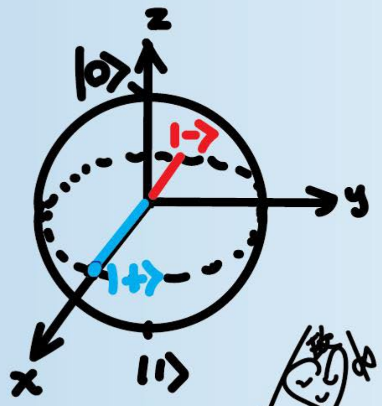
$$Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Similarly, the X gate rotates about the x-axis by 180°, rotating the angle θ e.g. X|0> = |1>, X|1> = |0>.



$$X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

We have seen in page 18 the two matrices for changing φ and θ in arbitraty amounts. They form a universal gate set - they can put a state anywhere on the Bloch Sphere. The gates Z and X are special cases of them.



Another important gate is the H (or Hadamard) gate. It changes states |0> and |1> and creates two new states in between them:

$$H|0\rangle = |+\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$$
$$H|1\rangle = |-\rangle = (|0\rangle - |1\rangle)/\sqrt{2}$$

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

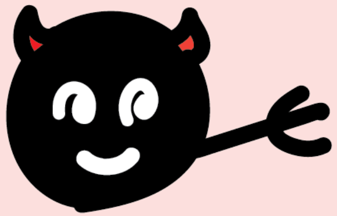
And some other commonly used gates:

$$S = \sqrt[2]{Z} = \begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}$$ Rotates about z-axis by 90°

$$T = \sqrt[4]{Z} = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix}$$ Rotates about z-axis by 45°

$$R8 = \sqrt[8]{Z} = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/8} \end{pmatrix}$$ Rotates about z-axis by 22.5°

But these are all for a single qubit. What about gates for multiple qubits?



CONTROL QUBIT :
YOU STAY THE SAME IF I'M |0>;
YOU CHANGE IF I'M |1>.

TARGET QUBIT :
OKAY~

PRESERVE

$$\text{CNOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

A 4X4 MATRIX

SWITCH

The controlled-not gate manipulates the target qubit based on the state of the control qubit.

$\text{CNOT}|00\rangle = |00\rangle$
$\text{CNOT}|01\rangle = |01\rangle$
$\text{CNOT}|10\rangle = |11\rangle$
$\text{CNOT}|11\rangle = |10\rangle$

TRY THE MATH!

There are other controlled gates for multiple qubits you should look up.
We highlight CNOT as it will be used in every(?) algorithm (sounds familiar?!)

Q# exercise:

No installation, web-based Jupyter Notebooks

- The Quantum Katas project (tutorials and exercises for learning quantum computing) https://github.com/Microsoft/QuantumKatas
- Superposition
- Tasks 1.1, 1.2, 1.3, 1.4?

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
- **BasicGates**
- Tasks 1.1-1.3
- Task 1.4, 1.5
- Task 1.6, Microsoft.Quantum.Intrinsic

https://review.docs.microsoft.com/en-us/qsharp/api/qsharp/microsoft.quantum.intrinsic

- Task 1.7 Microsoft.Quantum.Math
- Tutorial https://github.com/microsoft/QuantumKatas/tree/master/tutorials/SingleQubitGates

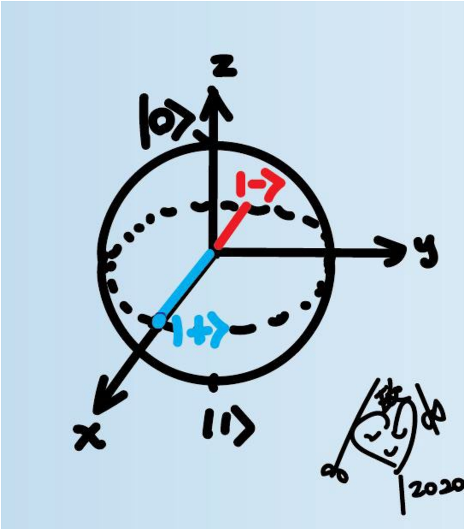
Hadamard H

$$H = \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{bmatrix}$$

$$H|0\rangle = \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{bmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$= \begin{pmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$= \frac{1}{\sqrt{2}} (|0\rangle + |1\rangle) \equiv |+\rangle$$



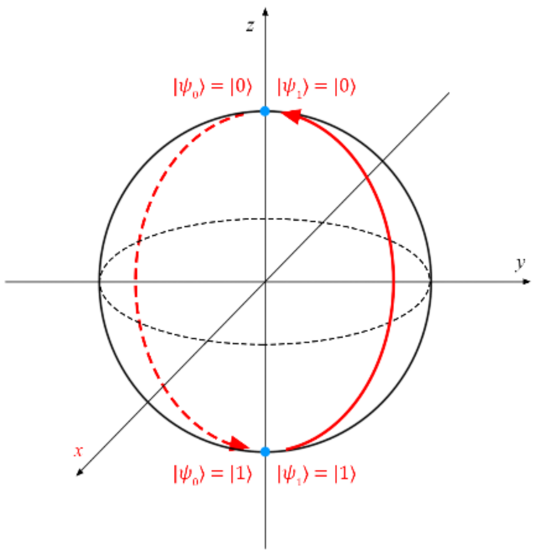
$$H|1\rangle = \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{bmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

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

Pauli gates

$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

$$X \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \begin{pmatrix} \beta \\ \alpha \end{pmatrix}$$



Pauli X

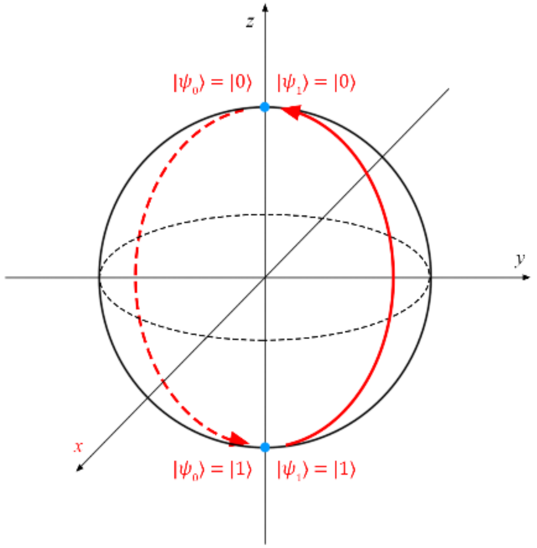
Pauli gates

$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

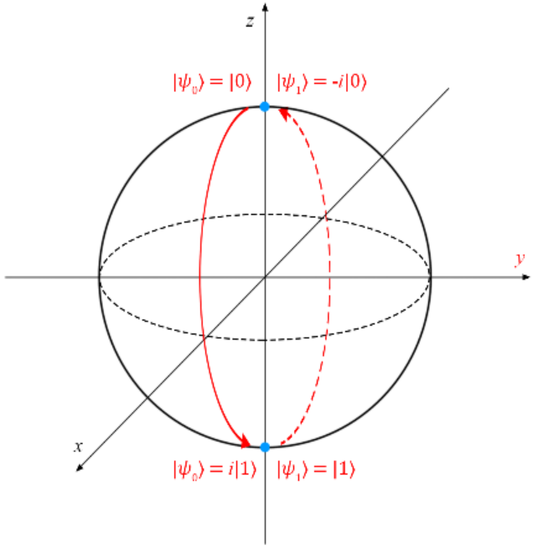
$$Y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$$

$$X \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \begin{pmatrix} \beta \\ \alpha \end{pmatrix}$$

$$Y \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = i \begin{pmatrix} -\beta \\ \alpha \end{pmatrix}$$



Pauli X



Pauli Y

Pauli gates

$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

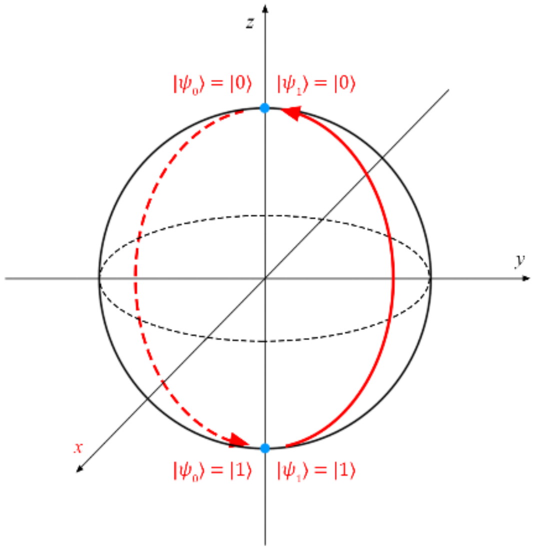
$$Y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$$

$$Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

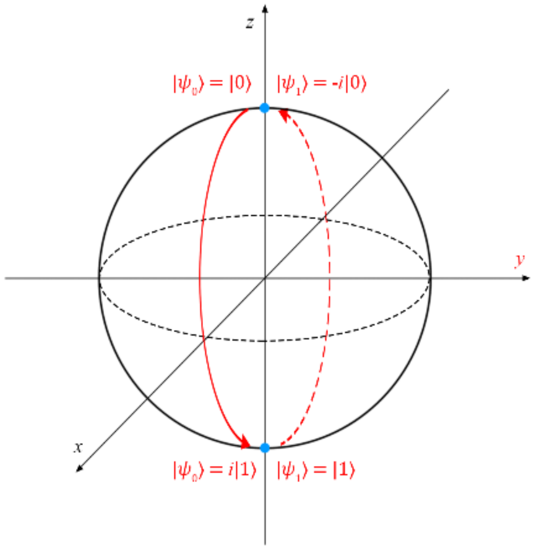
$$X\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \begin{pmatrix} \beta \\ \alpha \end{pmatrix}$$

$$Y\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = i\begin{pmatrix} -\beta \\ \alpha \end{pmatrix}$$

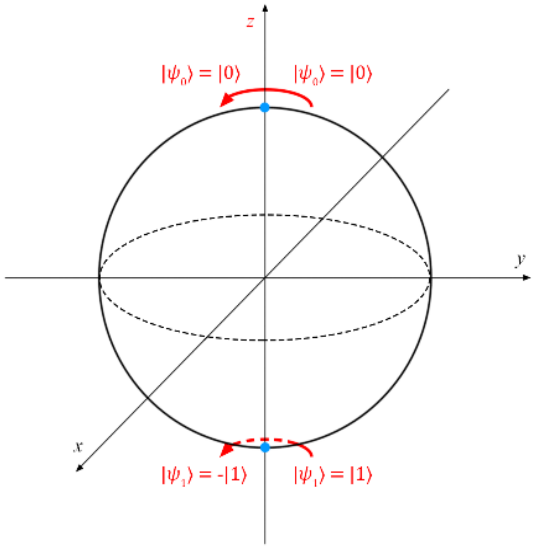
$$Z\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \begin{pmatrix} \alpha \\ -\beta \end{pmatrix}$$



Pauli *X*



Pauli *Y*



Pauli *Z*

General rotation

In general, rotation gates, R, about an axis can be described by the angles ϕ and θ:

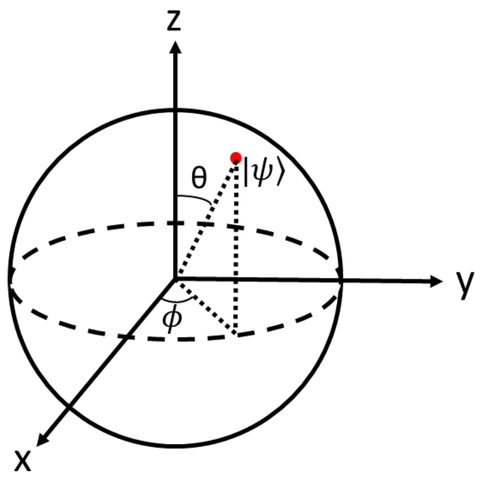
$$R_z(\phi) = \begin{bmatrix} e^{-i\phi/2} & 0 \\ 0 & e^{i\phi/2} \end{bmatrix},$$

$$R_y(\theta) = \begin{bmatrix} \cos\frac{\theta}{2} & -\sin\frac{\theta}{2} \\ \sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{bmatrix},$$

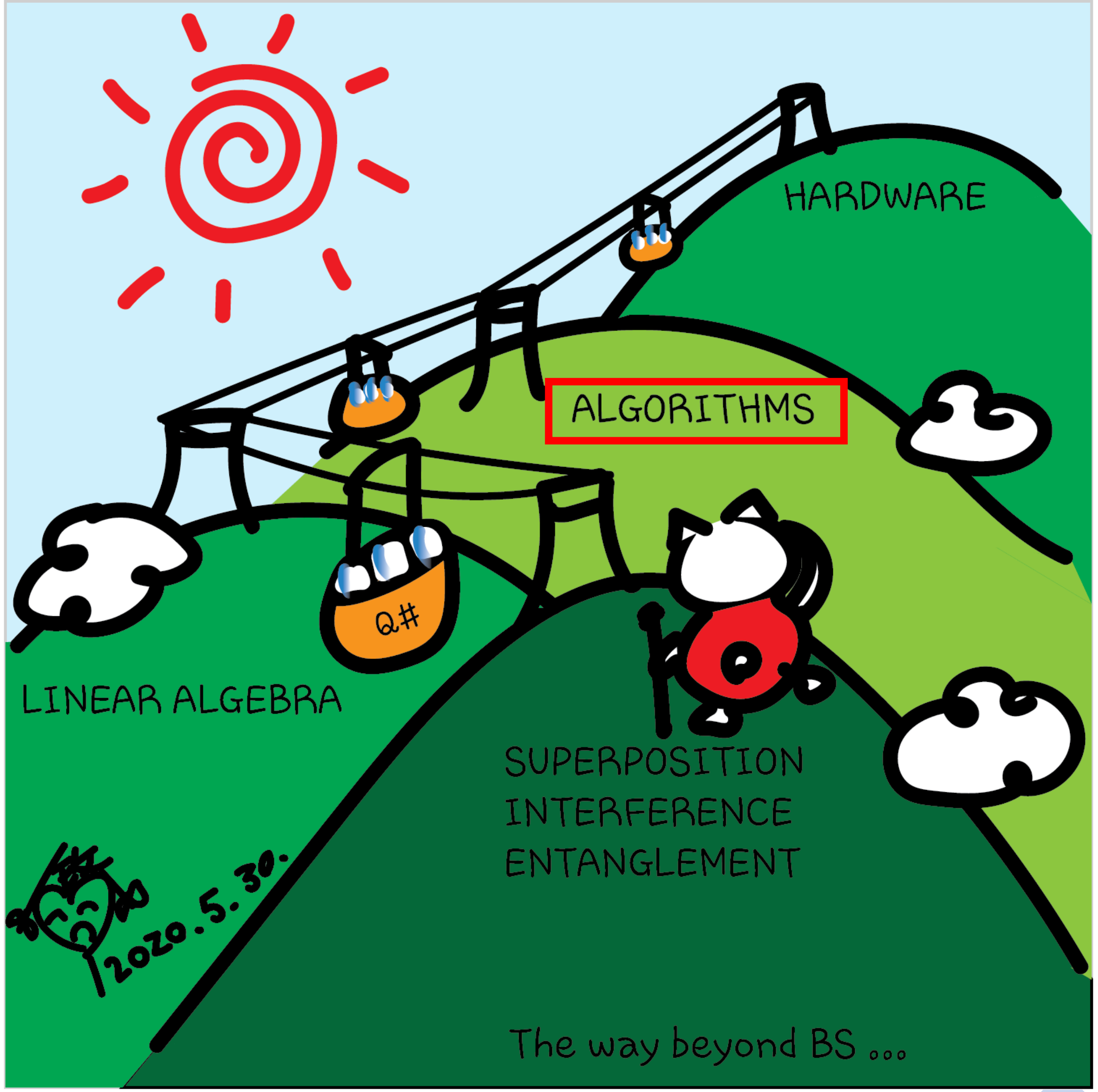
and

$$R_x(\theta) = \begin{bmatrix} \cos\frac{\theta}{2} & -i\sin\frac{\theta}{2} \\ -i\sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{bmatrix}$$

$$= R_z\left(\frac{\pi}{2}\right) R_y(\theta) R_z\left(-\frac{\pi}{2}\right).$$



https://review.docs.microsoft.com/en-us/quantum/concepts/the-qubit?branch=tensor-product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Quantum Algorithms

Performing calculations based on the laws of quantum mechanics

- 1980 & 1982: Manin & Feynman proposed the idea of creating machines based on the laws of quantum mechanics
- 1985: David Deutsch developed Quantum Turing machine, showing that quantum circuits are universal
- 1994: Peter Shor came up with a quantum algorithm to factor very large numbers in polynomial time
- 1997: Grover developed a quantum search algorithm with $O(\sqrt{N})$ complexity

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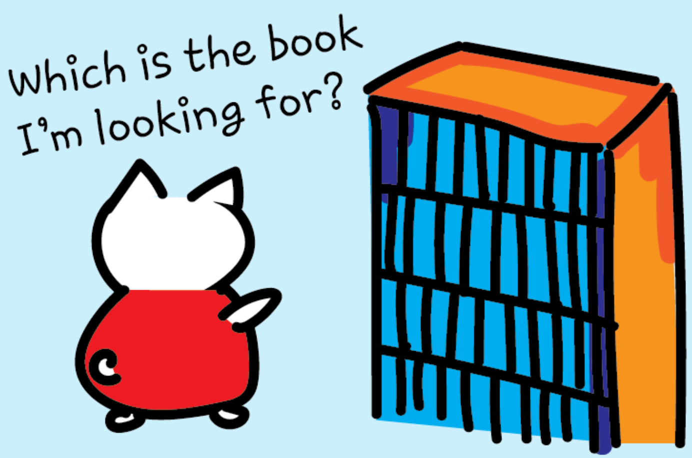
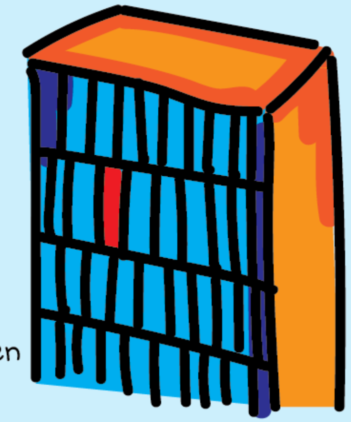


Classically need to look at each book. Grover's search feeds all inputs into the algorithm and output the answer. There is no "parallel computing", but interference between the possibilities.



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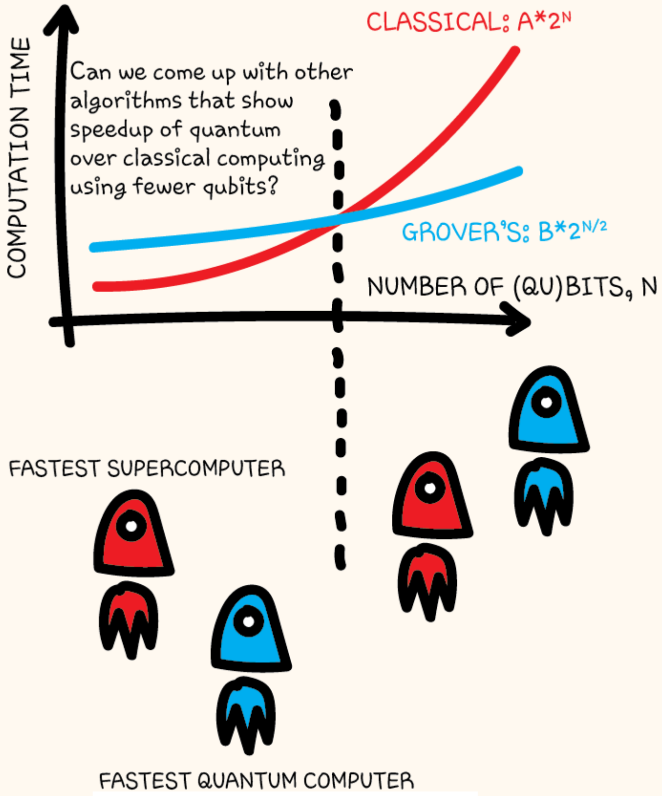
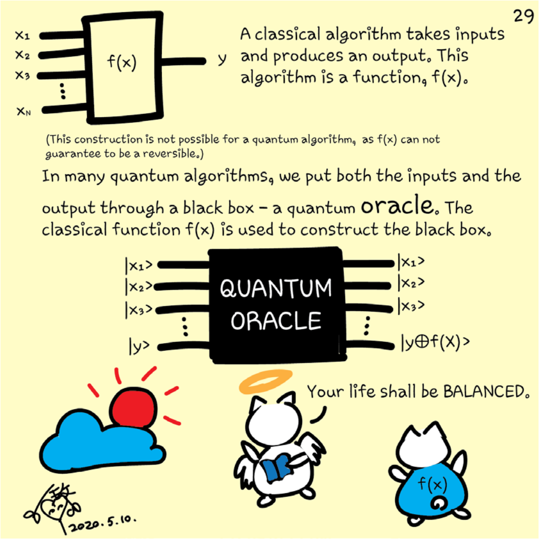
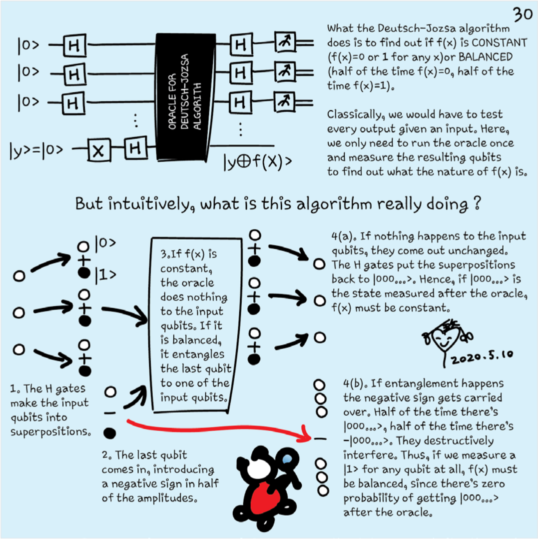


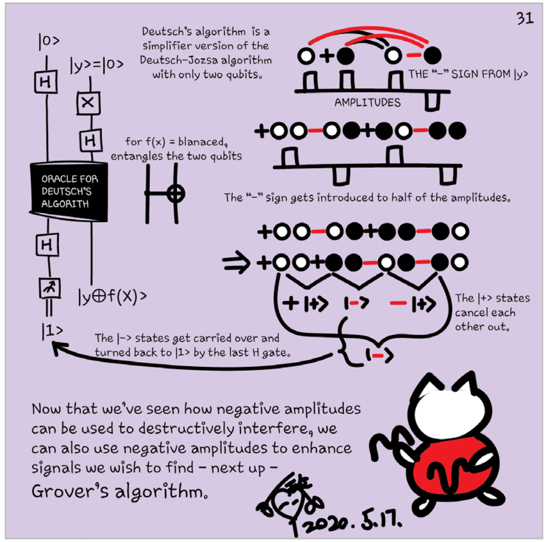
Grover's algorithm provides a speedup over classical algorithms for searching for an item in an unordered list (after a certain number of qubits are reached). A and B are factors that don't depend on N. (They describe how long it takes for the computers to complete the task for a fixed N).

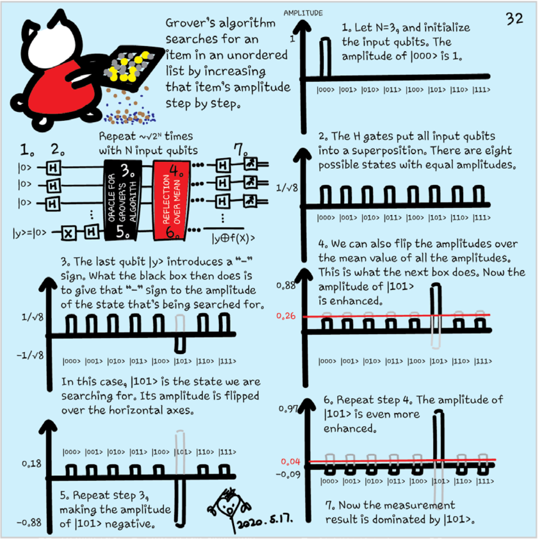
The reflection over the |000...0> state surrounded by H gates is the reflection over mean.

Quantum algorithms use interference and entanglement

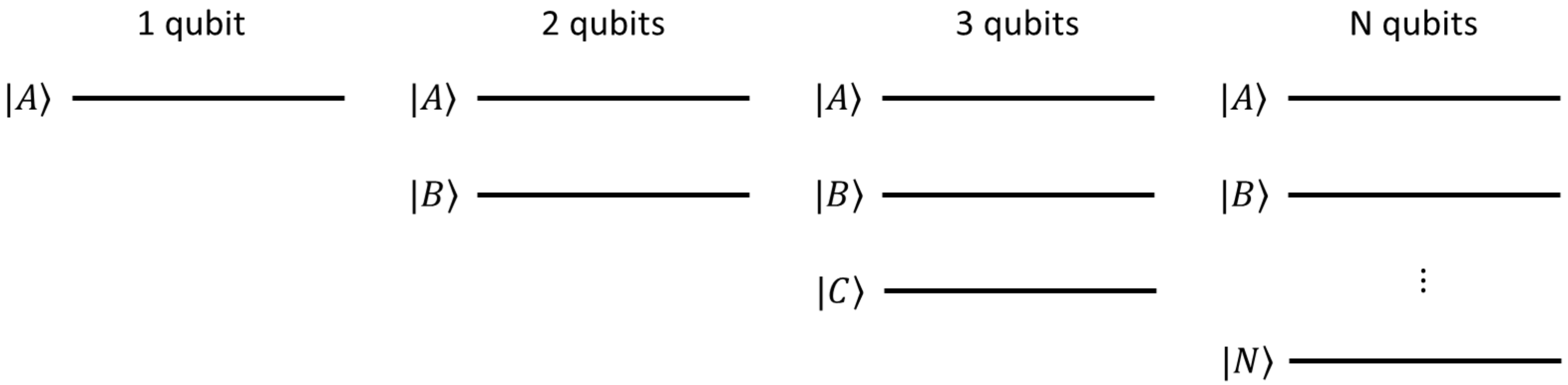


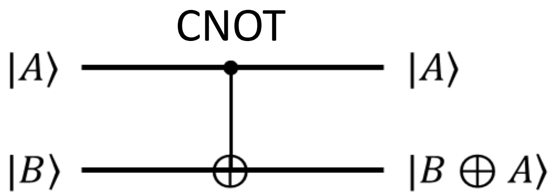




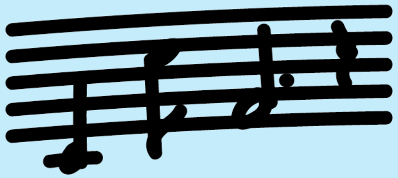


Circuit representation



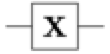
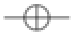
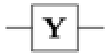
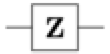
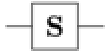
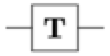
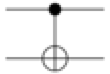
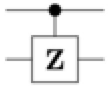
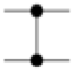
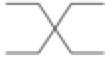
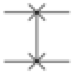
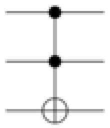


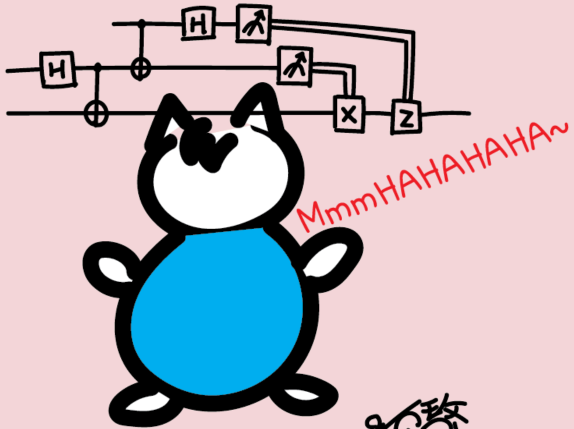
Target B controlled by A



The Bloch sphere is no longer useful when we look at more than one qubit. But we have another graphic representation to use for multi-qubit systems.

Similar to how the lines in music scores denote the time-evolving music, we can use lines to represent the time-evolving qubit states:

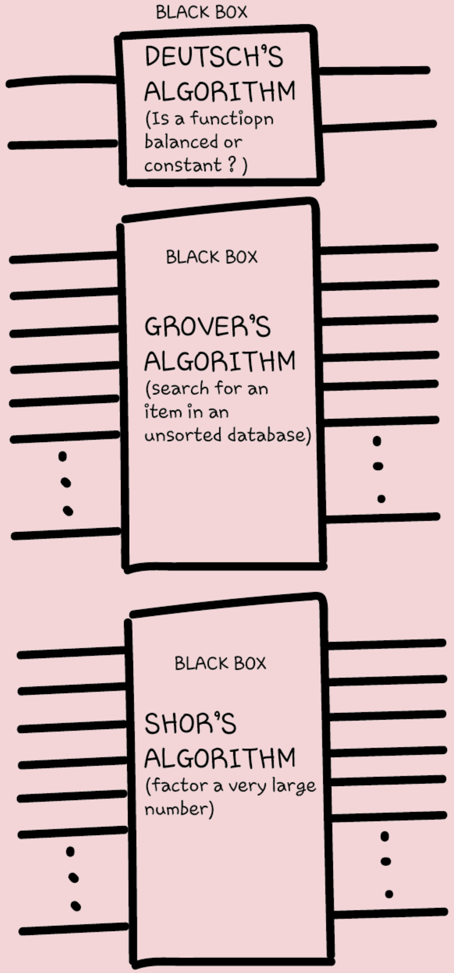
Operator	Gate(s)		Matrix
Pauli-X (X)			$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)			$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z (Z)			$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard (H)			$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Phase (S, P)			$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$
$\pi/8$ (T)			$\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$
Controlled Not (CNOT, CX)			$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$
Controlled Z (CZ)			$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$
SWAP			$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$
Toffoli (CCNOT, CCX, TOFF)			$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$



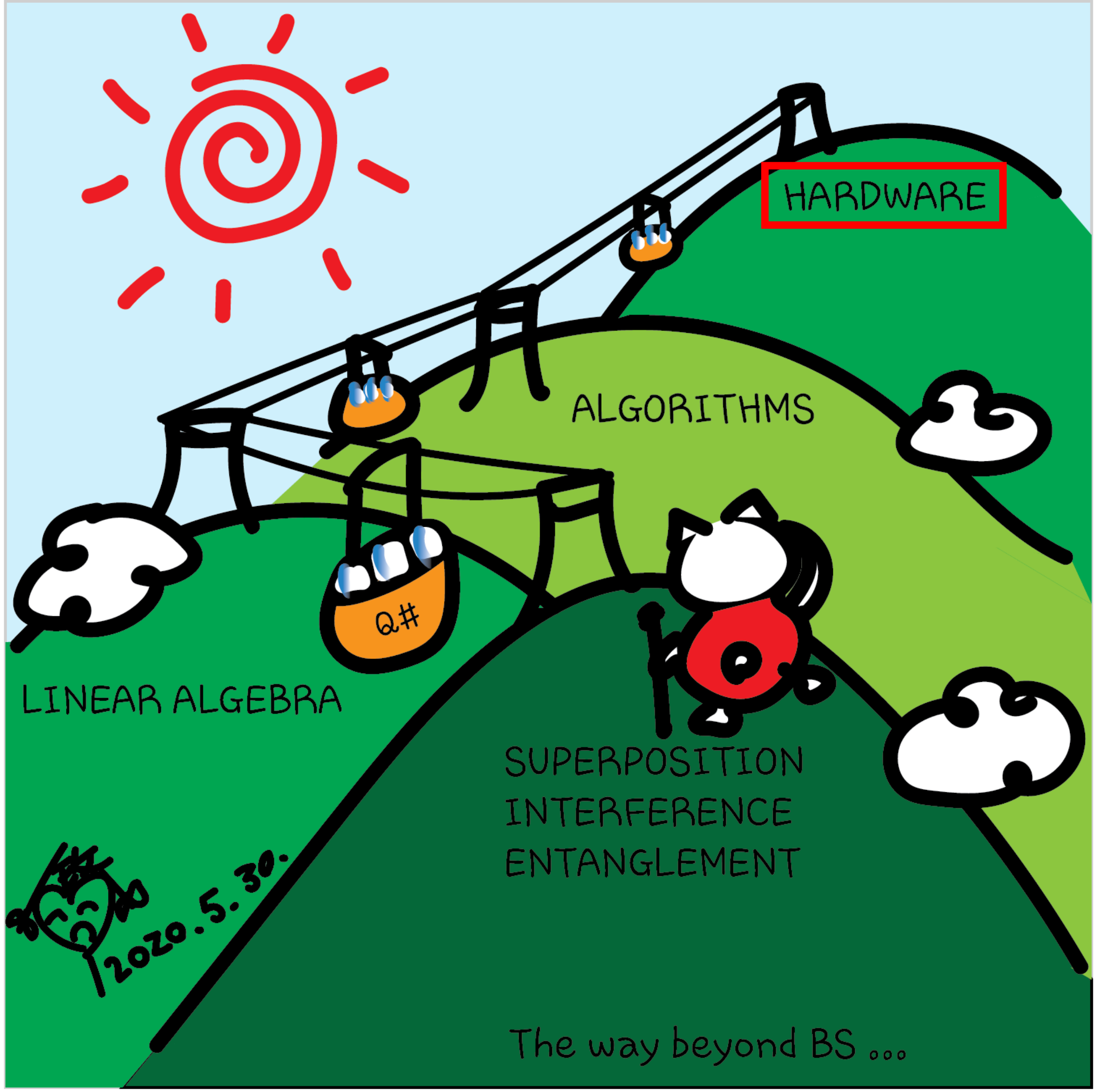
Some algorithms are neatly presented with circuits.

2020.4.25

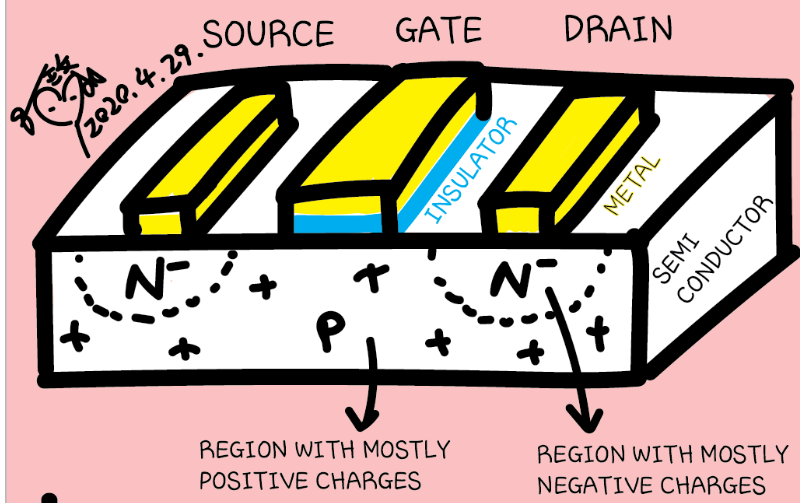
But as the number of qubits and complexity of algorithms grow, it's not feasible to always write down each qubit and construct circuits.



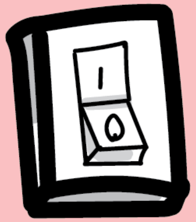
Just like we wouldn't describe each transistor in a classical computer when we write a program. We need a high-level quantum computing language to program quantum computers.


HARDWARE
ALGORITHMS
Q#
LINEAR ALGEBRA
SUPERPOSITION
INTERFERENCE
ENTANGLEMENT
2020.5.30.
The way beyond BS ...

We leverage various properties of materials to make computing hardware.



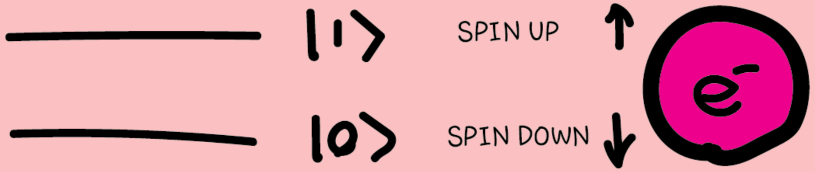
The gate applies voltage to control the electron flow from source to drain of a transistor. At a certain gate voltage level, electrons flow. This is the "on" state which we call "1". When there's no electron flow, we say the transistor is "off", or "0".



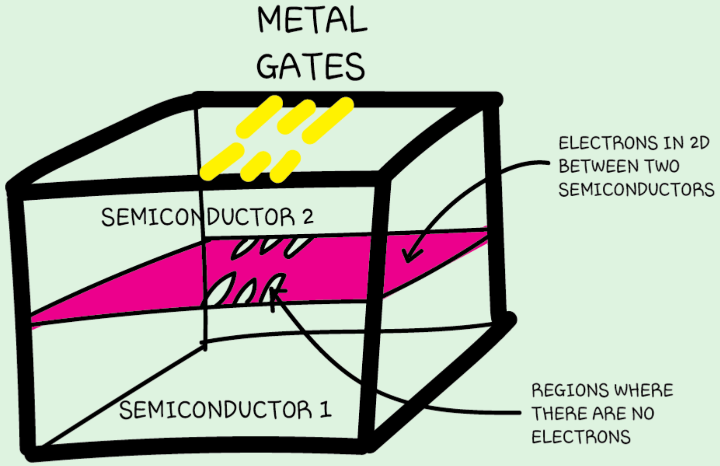
Transistors are nano- to micrometer switches.

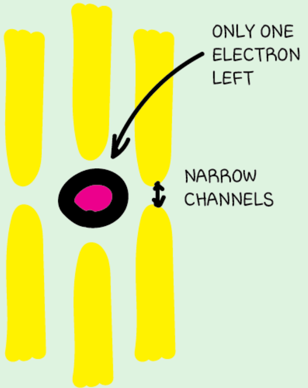
To make a qubit, we need a system with two states that can be in superposition.

The electron spin seems to be a natural candidate.

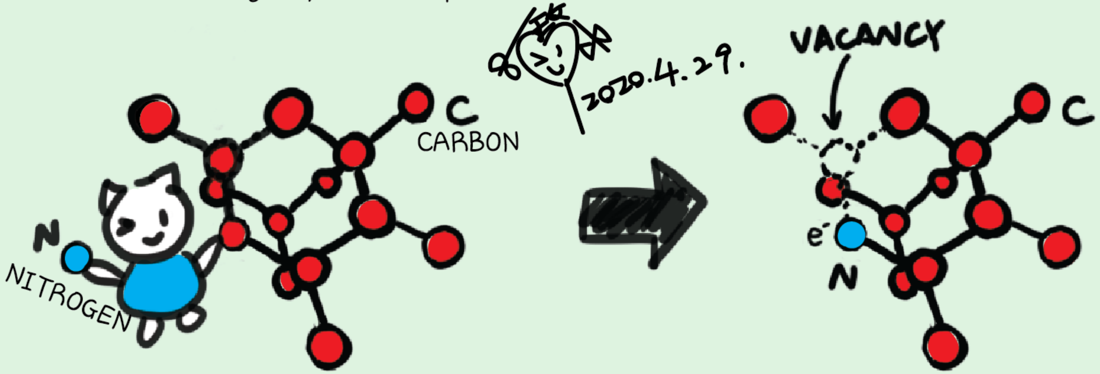


But how do we isolate and control electrons?



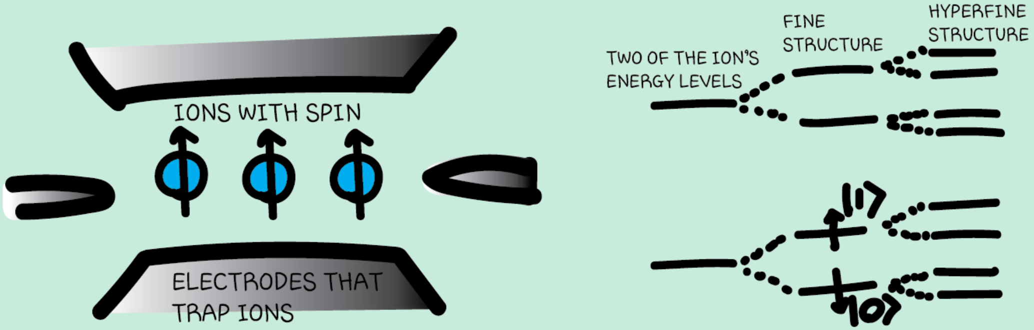


We can create a semiconductor stack. At the interface between the two semiconductors, electrons can be confined in 2D. By applying a gate voltage, the electrons underneath are removed, until there is only one electron left in a small region, called a "quantum dot".



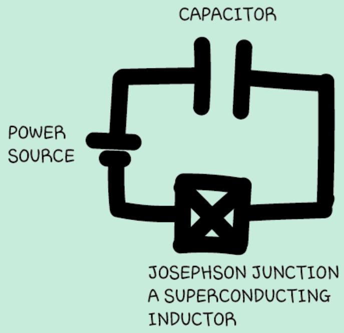
We can also use a crystal lattice, e.g. diamond. We can remove two carbon atoms (each has 6 electrons), replacing them with a single nitrogen atom (which has 7 electrons). The extra electron is bound to the nitrogen-vacancy region.

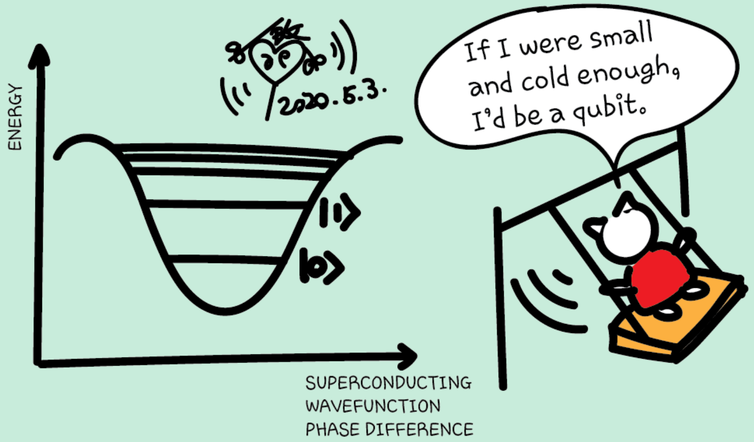
Although an electron can be conceptually the easiest qubit, it doesn't mean it is straightforward to control many electrons. There are other systems to explore.



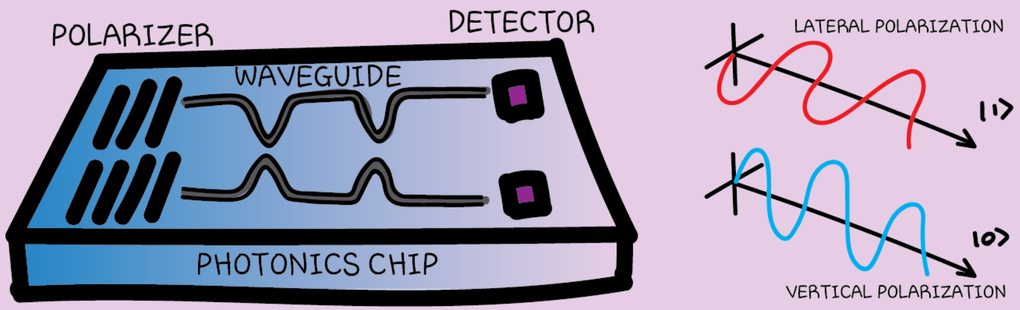
We can use two of an ion's electronic energy levels as the two qubit states. They can be the fine structure due to the ion's electron spins or the hyperfine structure due to electrons' interactions with the ion's nucleus.

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.

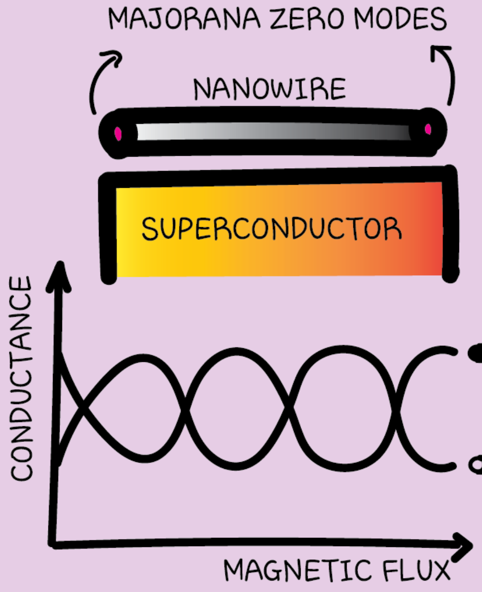




If we can use natural and artificial particles, such as electrons, ions or oscillating circuits, we can also try other types of particles and quasiparticles, and parameters other than energy levels.

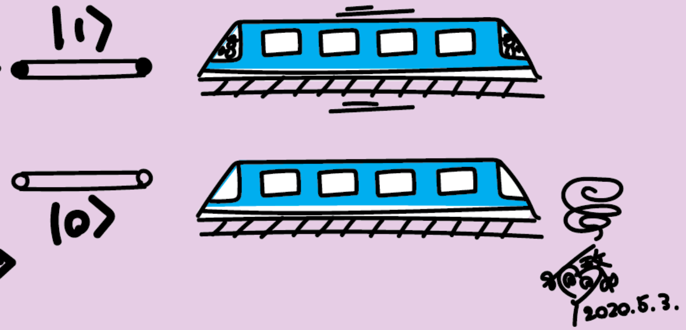


We can use photons' polarizations to encode qubit states.



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.



Class structure

- [Comics on Hackaday – Quantum Computing through comics](#) every Sun

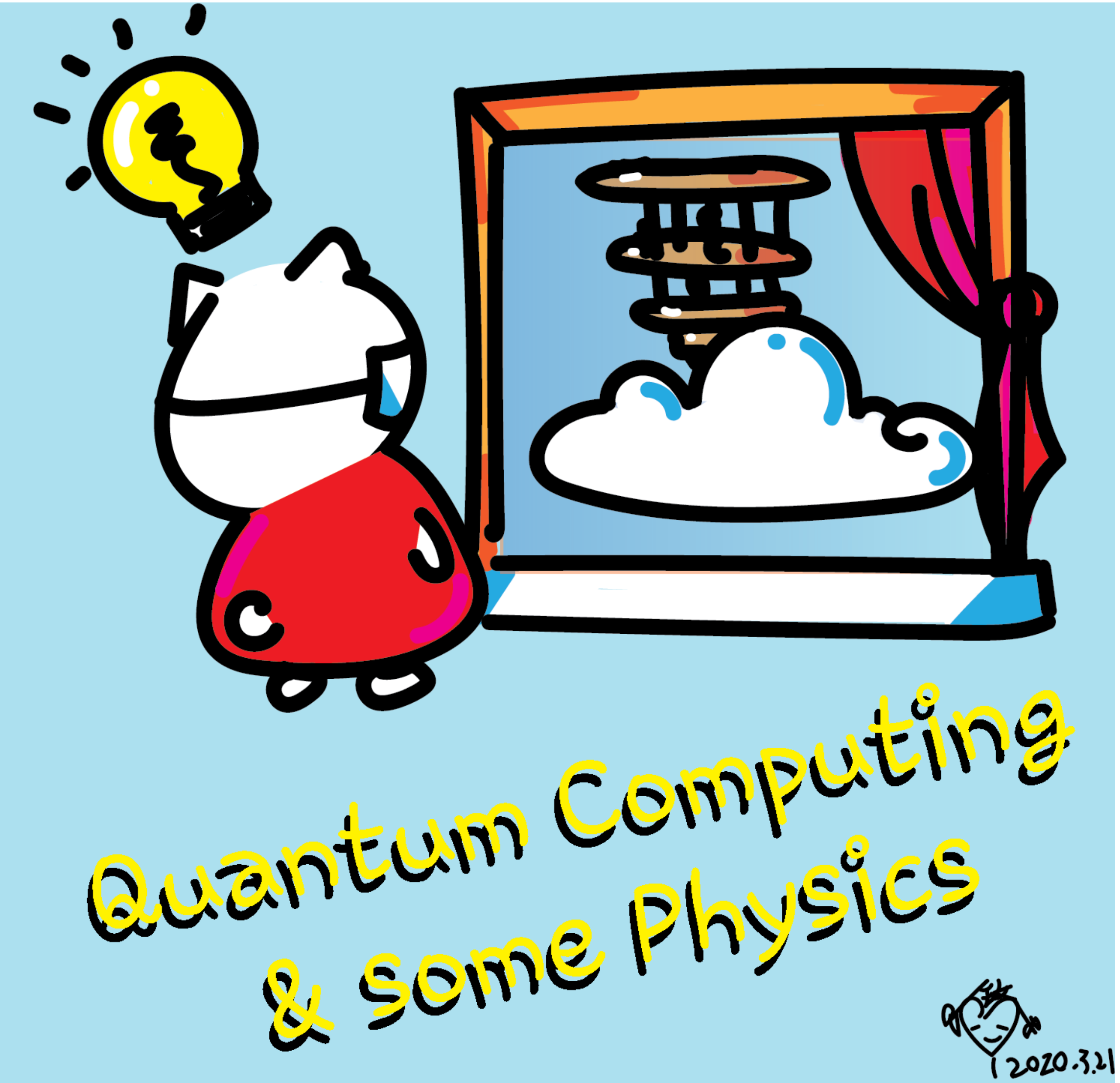
- 30 mins every Sun, one concept (theory, hardware, programming), Q&A

- 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

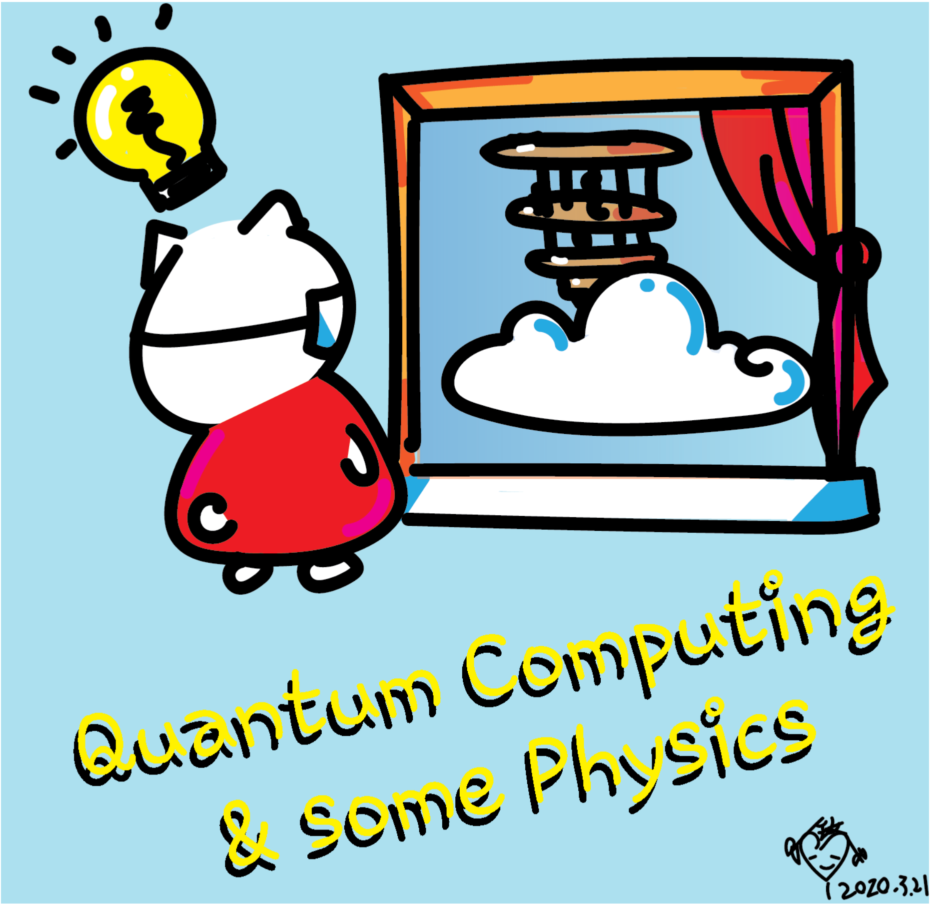
- Take notes



aka.ms/learnqc

Questions

- Post in chat or on Hackaday project https://hackaday.io/project/168554-quantum-computing-through-comics
- Past Recordings on Hackaday project or my YouTube https://www.youtube.com/c/DrKittyYeung



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