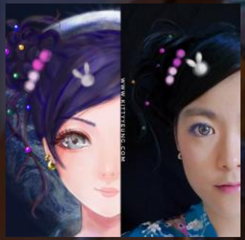
Introduction to Quantum Computing



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Creative Technologist + Sr. PM
Microsoft

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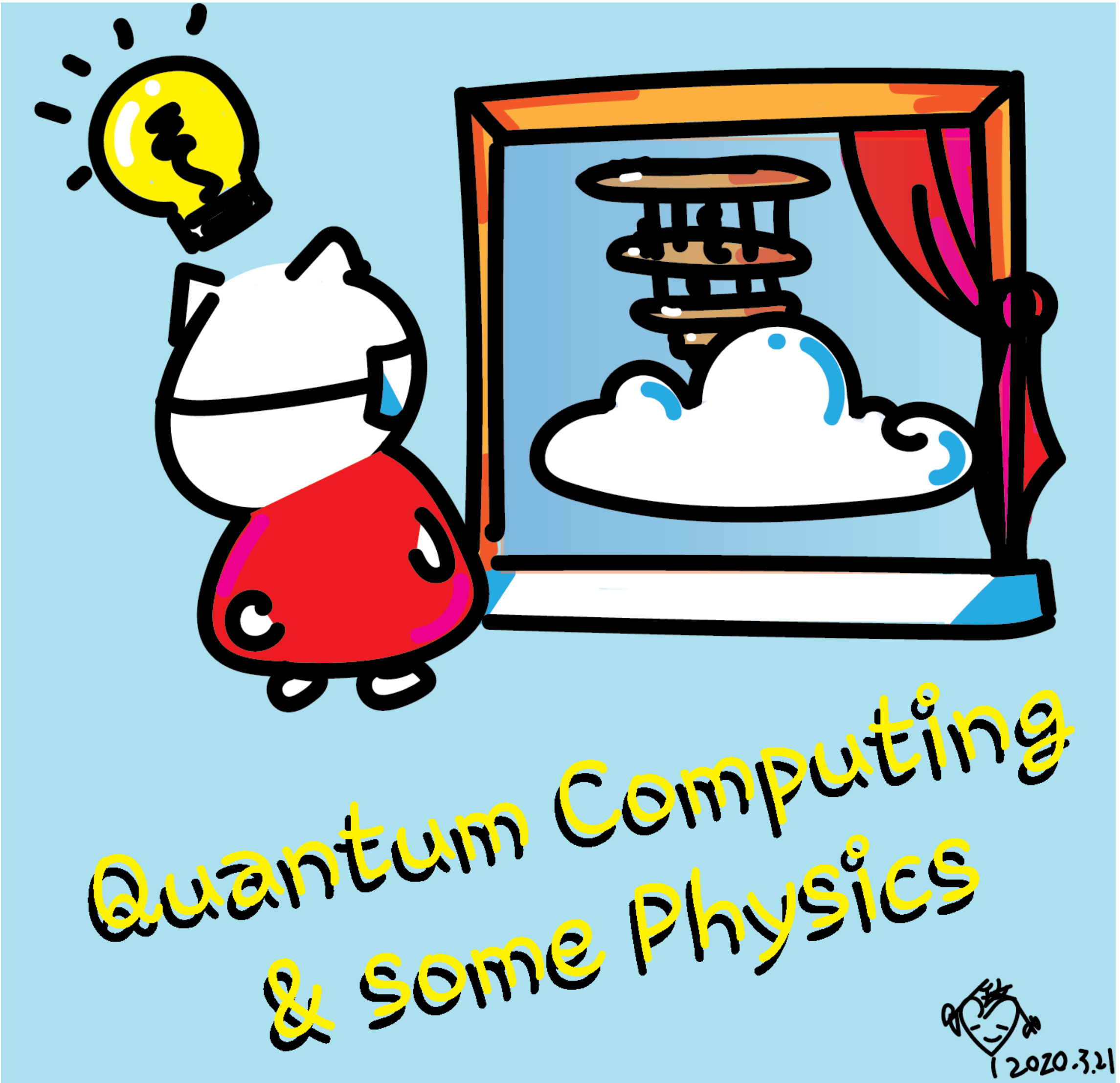
@artbyphysicistkittyyeung

May 31, 2020
Hackaday, session 9
Other communities, session 1

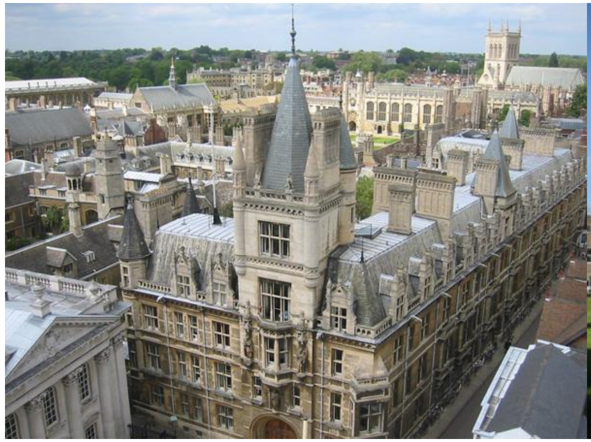
Class structure

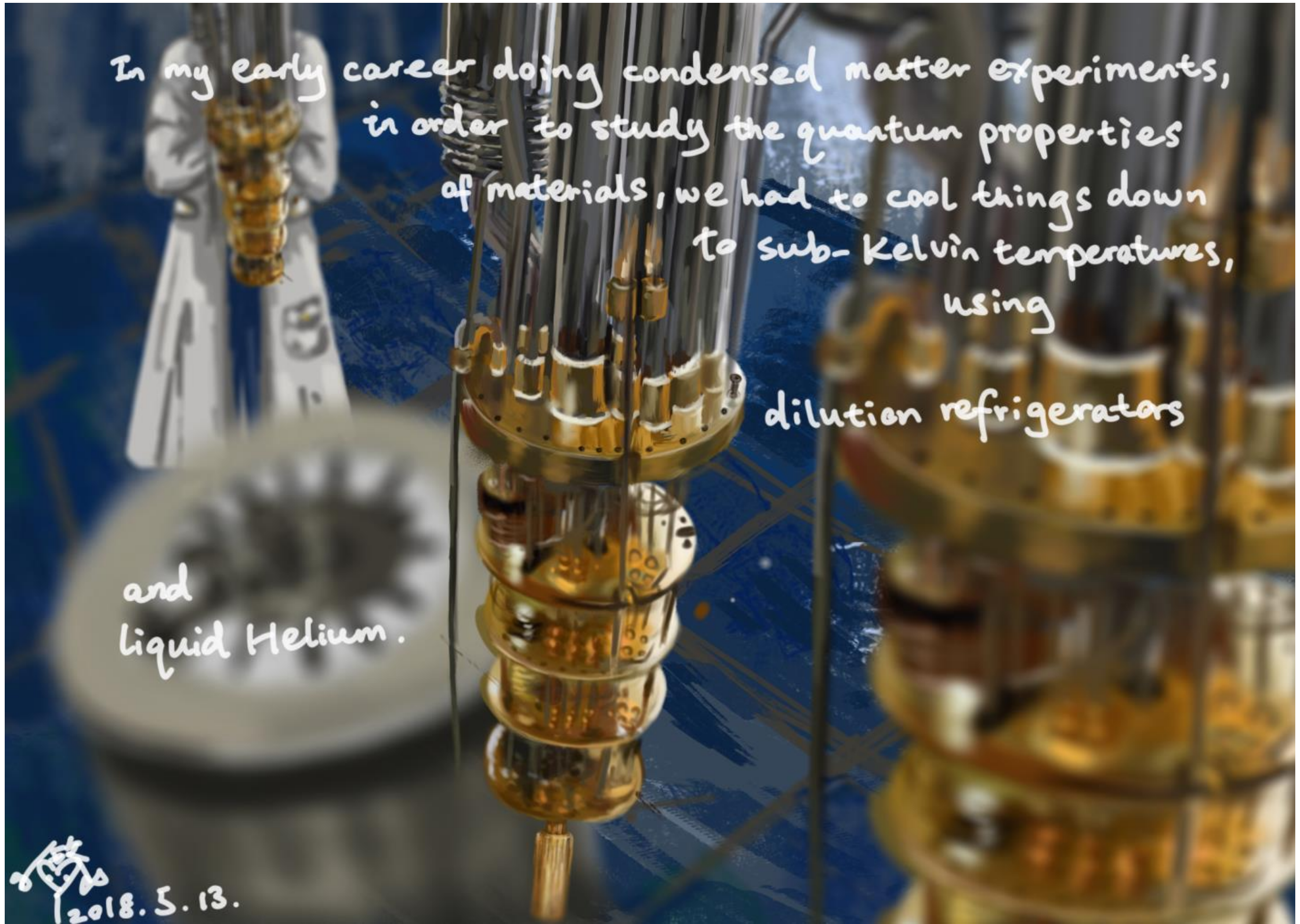
- Comics on Hackaday – Introduction to Quantum Computing every Sun
- 30 mins – 1 hour every Sun, one concept (theory, hardware, programming), Q&A
- Contribute to Q# documentation http://docs.microsoft.com/quantum
- Coding through Quantum Katas https://github.com/Microsoft/QuantumKatas/
- Discuss in Hackaday project comments throughout the week
- Take notes

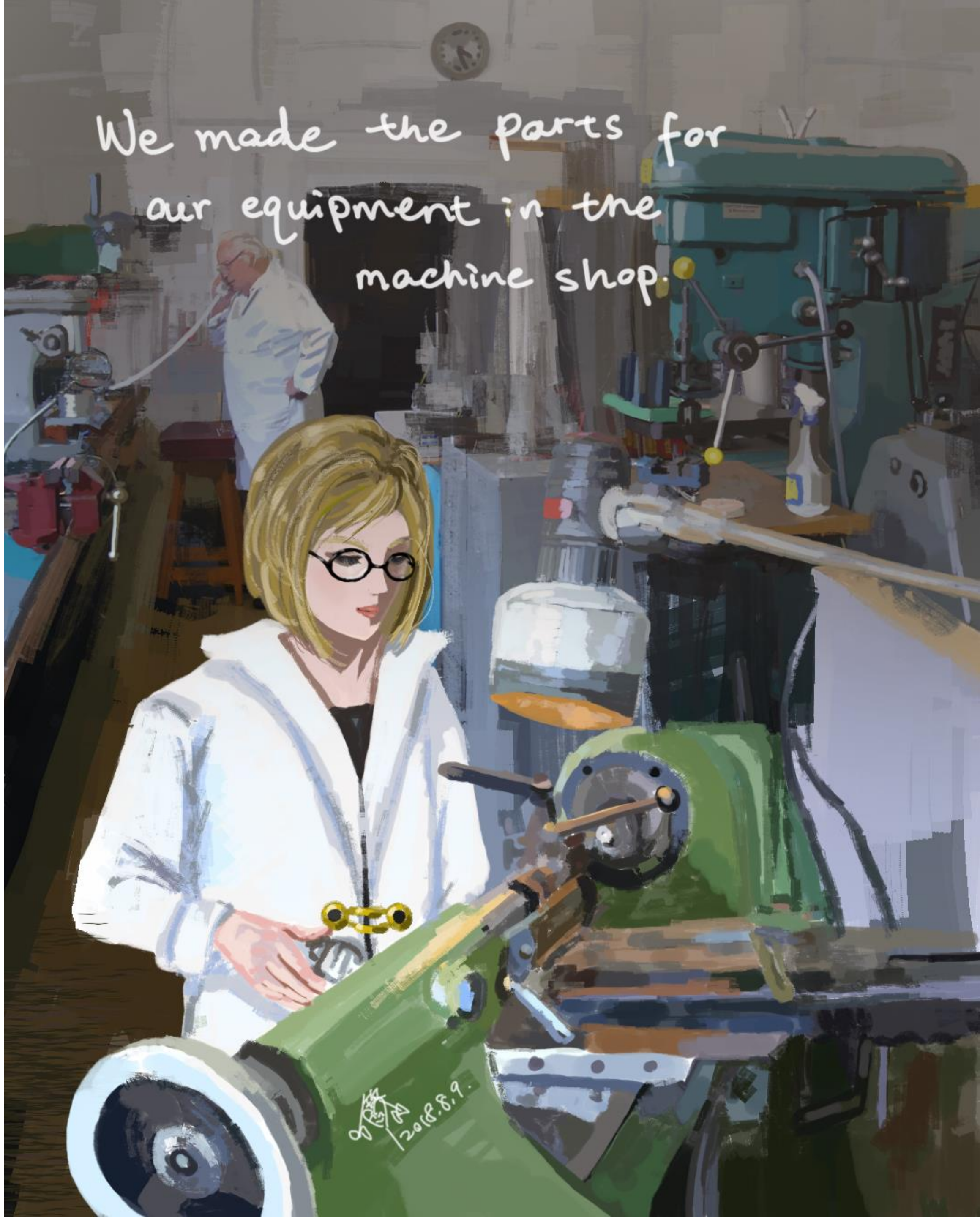


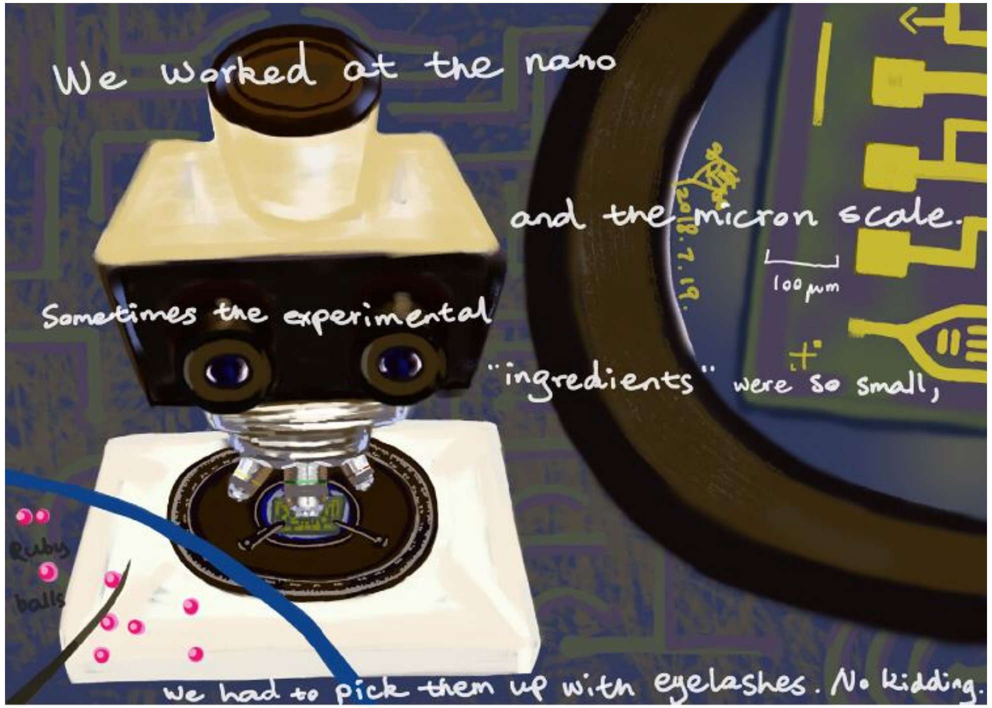
Welcome! & be safe

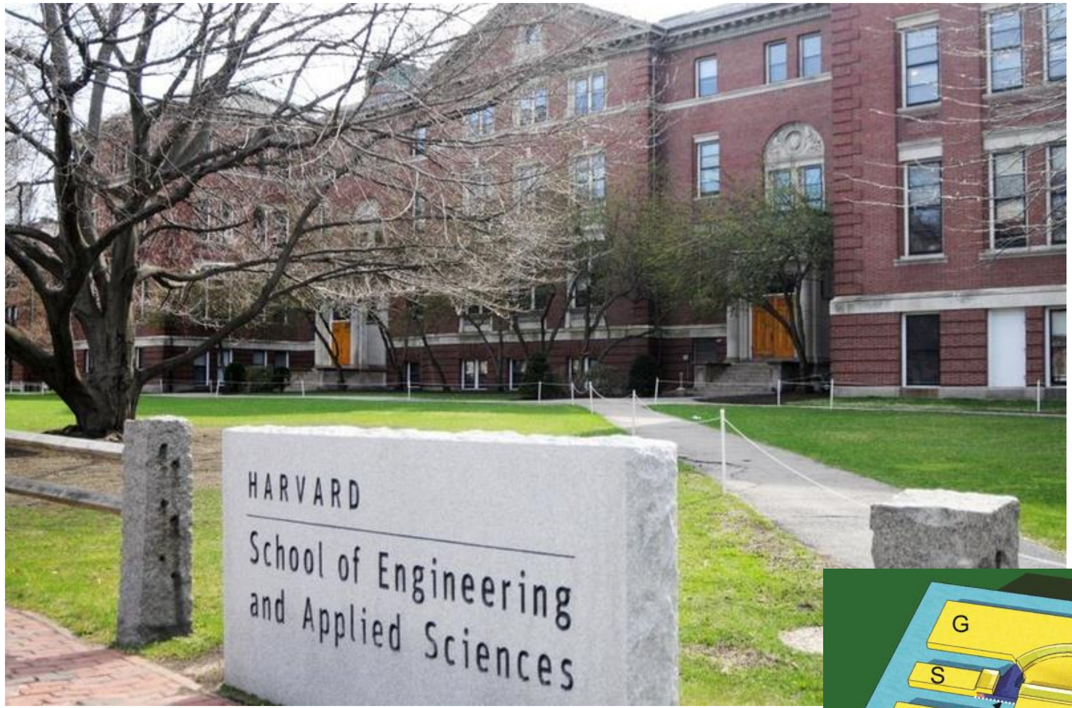
- Hackaday community
- Microsoft Reactor community
- Microsoft for Startups community
- Zen 4 Maker meetup group

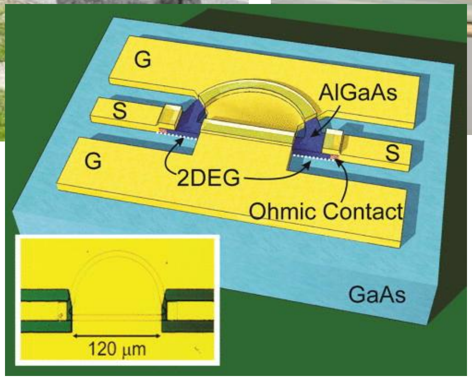



In my early career doing condensed matter experiments,
in order to study the quantum properties
of materials, we had to cool things down
to sub-Kelvin temperatures,
using
dilution refrigerators
and
liquid Helium.
2018.5.13.

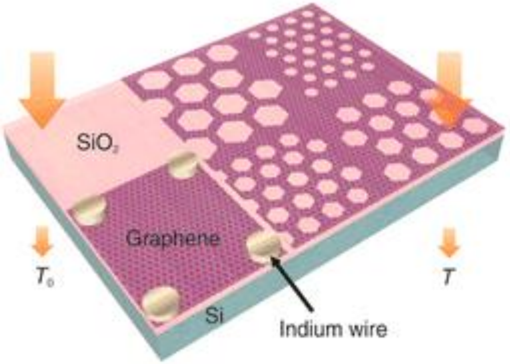

We made the parts for
our equipment in the
machine shop.
2018.8.9.

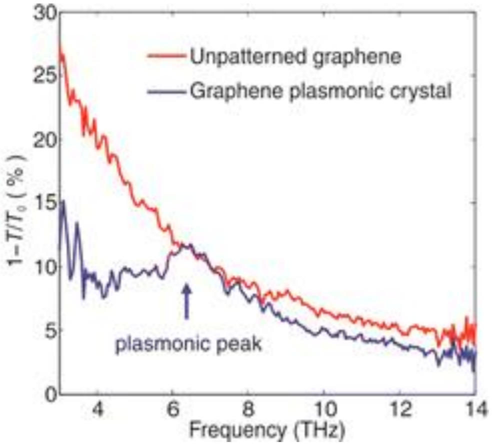

We worked at the nano
and the micron scale.
2018.7.19.
100 μm
Sometimes the experimental
"ingredients" were so small,
Ruby balls
we had to pick them up with eyelashes. No kidding.

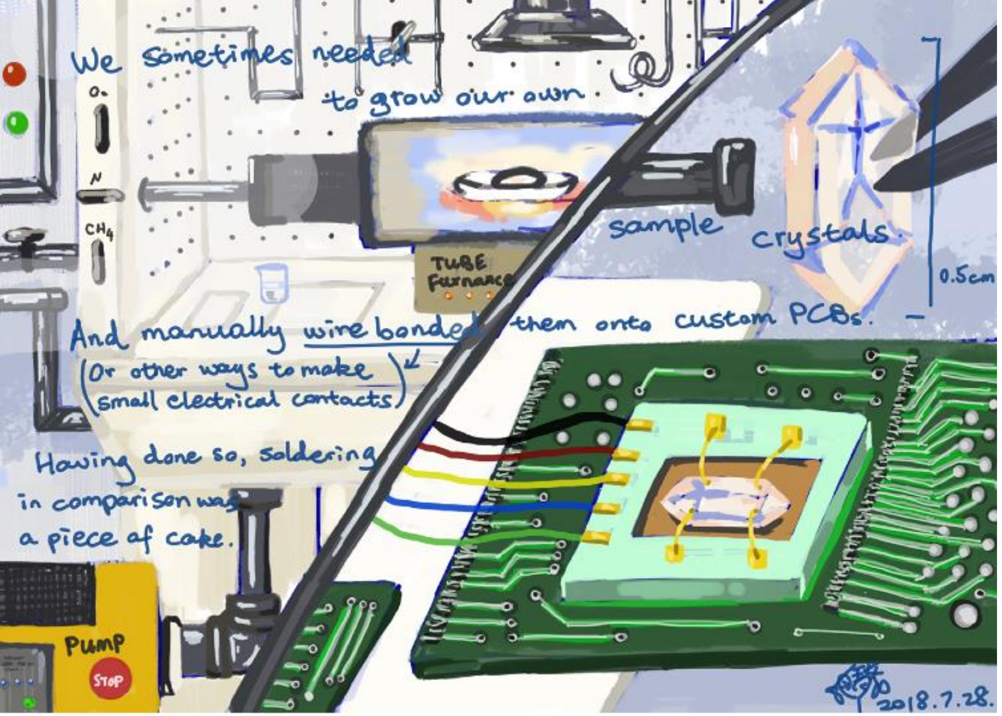

HARVARD
School of Engineering
and Applied Sciences


G
AlGaAs
S
S
G
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.


SiO₂
Graphene
Si
Indium wire
T₀
T


Unpatterned graphene
Graphene plasmonic crystal
1−T/T₀ (%)
plasmonic peak
Frequency (THz)
0
5
10
15
20
25
30
4
6
8
10
12
14

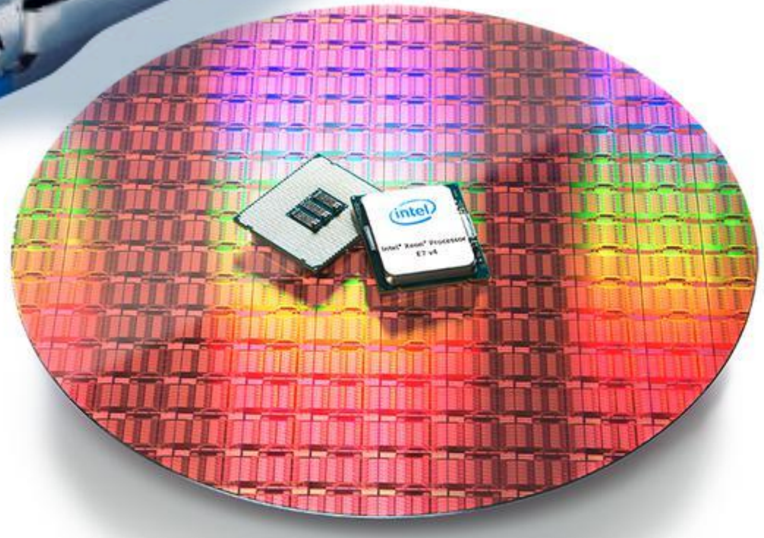


We sometimes needed to grow our own
sample crystals.
0.5cm
TUBE Furnace
And manually wire bonded them onto custom PCBs.
(Or other ways to make small electrical contacts)
Having done so, soldering in comparison was a piece of cake.
Pump
STOP
2018.7.28.

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

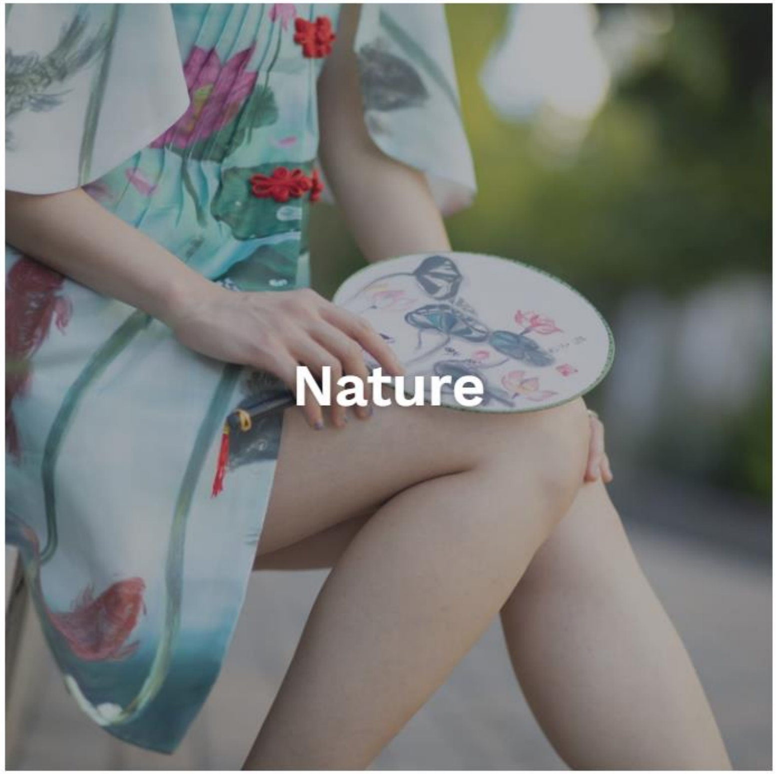
Science + Engineering + Design + Art

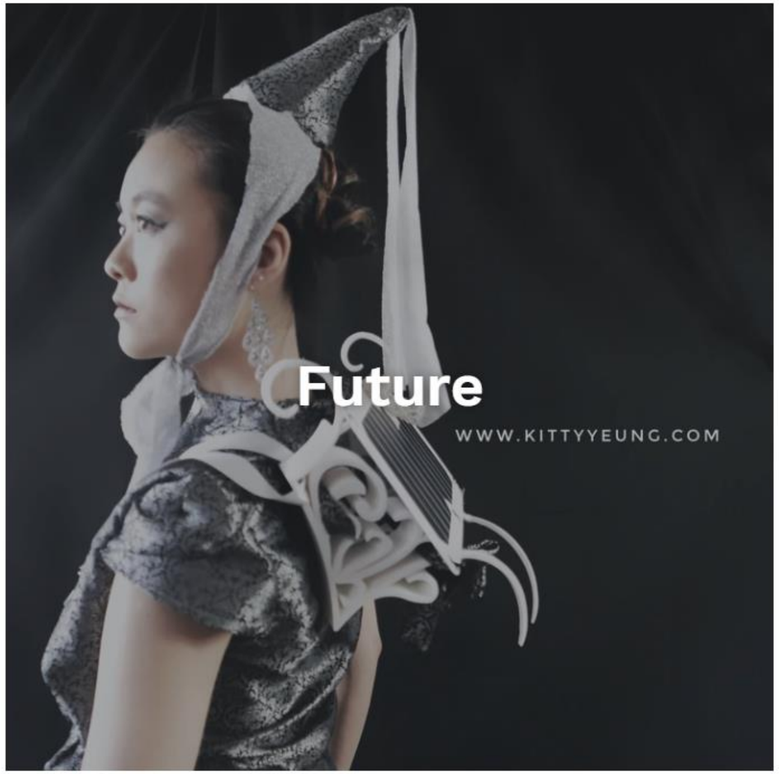
物艺

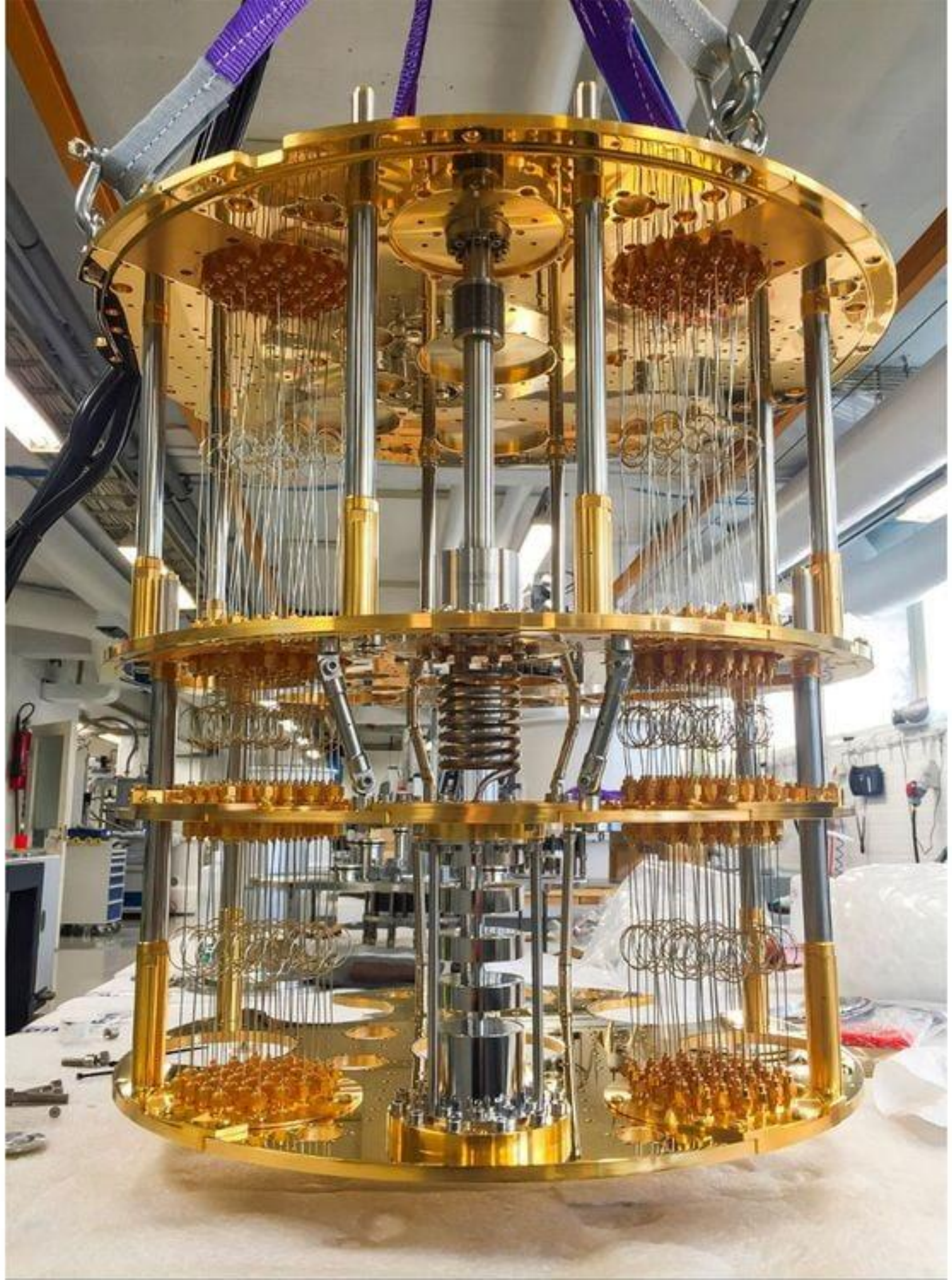
KtY

Art by Physicist

www.kittyyeung.com

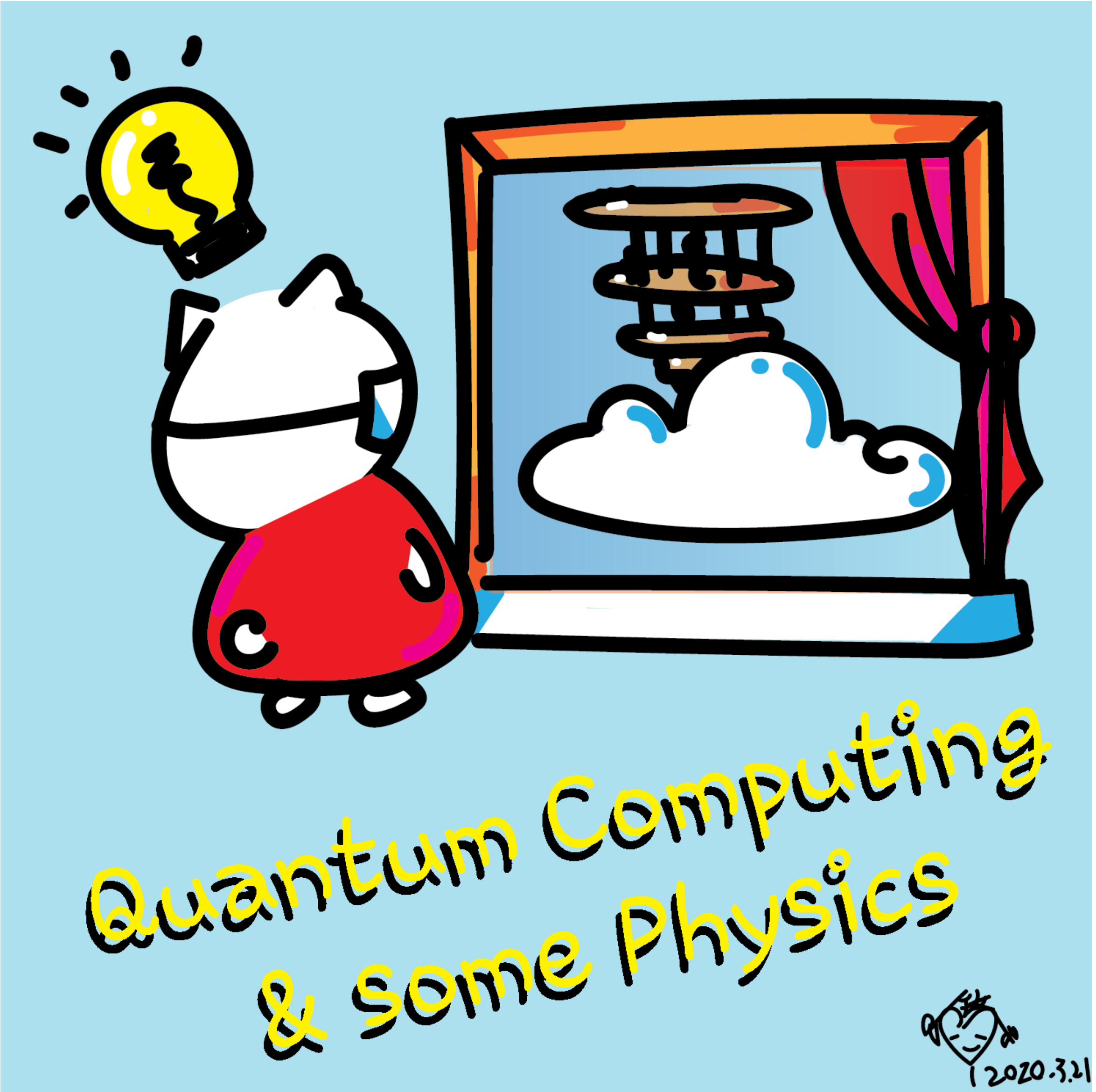


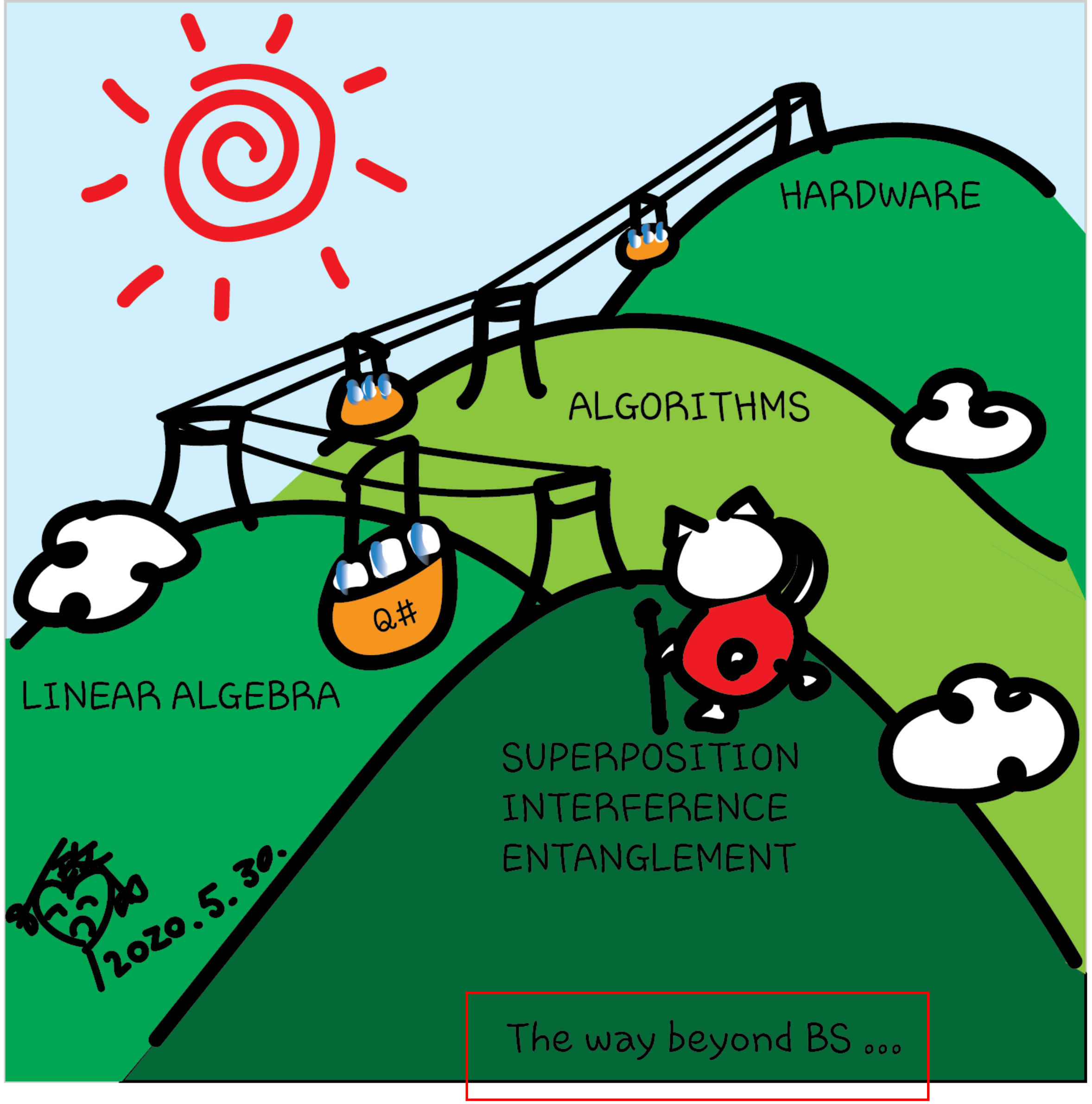




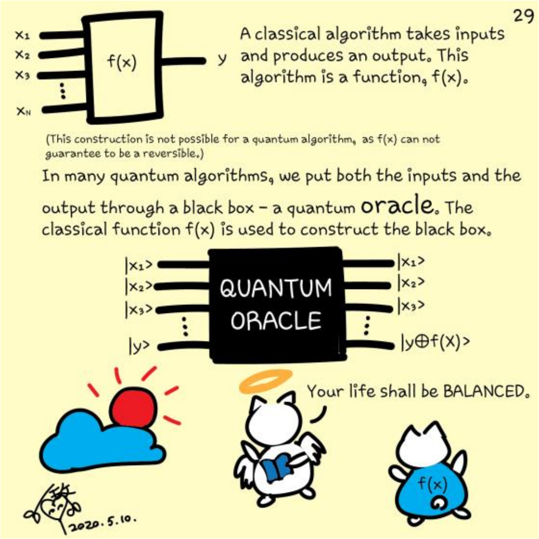

THE GLOBAL GOALS
For Sustainable Development
THE 17 GOALS
ACTION
NEWS
RESOURCES
SCHOOLS
THE 17 GOALS
In 2015, world leaders agreed to 17 goals for a better world by 2030. These goals have the power to end poverty, fight inequality and stop climate change. Guided by the goals, it is now up to all of us, 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

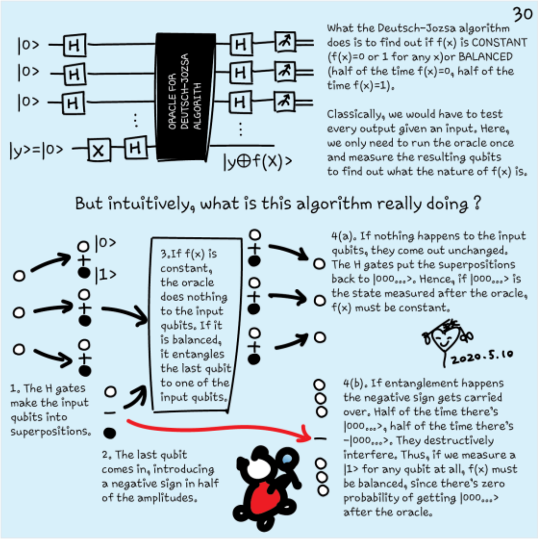
aka.ms/learnqc

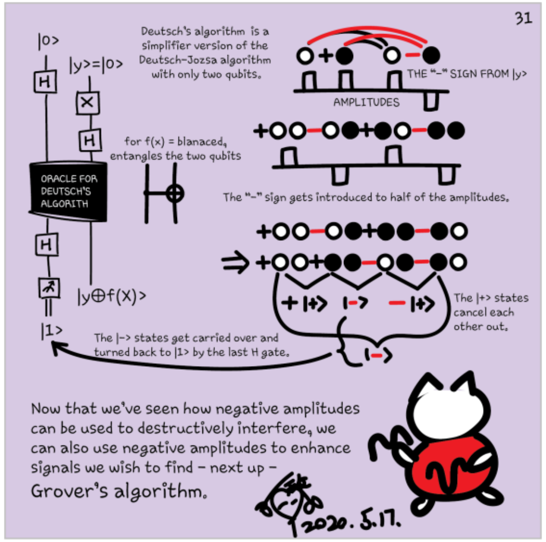

Quantum Computing
& some Physics
2020.3.21

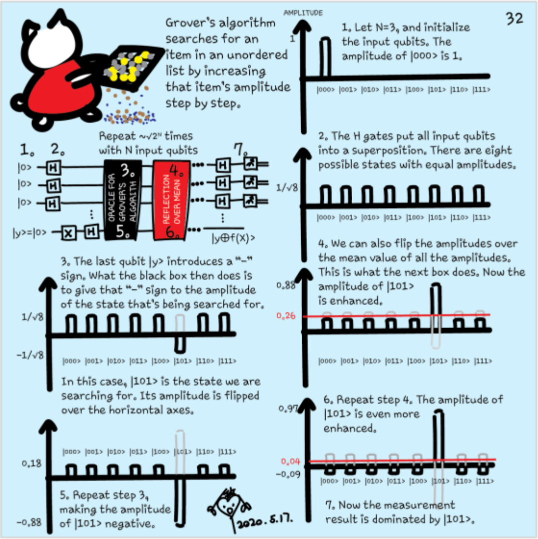

HARDWARE
ALGORITHMS
Q#
LINEAR ALGEBRA
SUPERPOSITION
INTERFERENCE
ENTANGLEMENT
2020.5.30.
The way beyond BS ...

Quantum algorithms

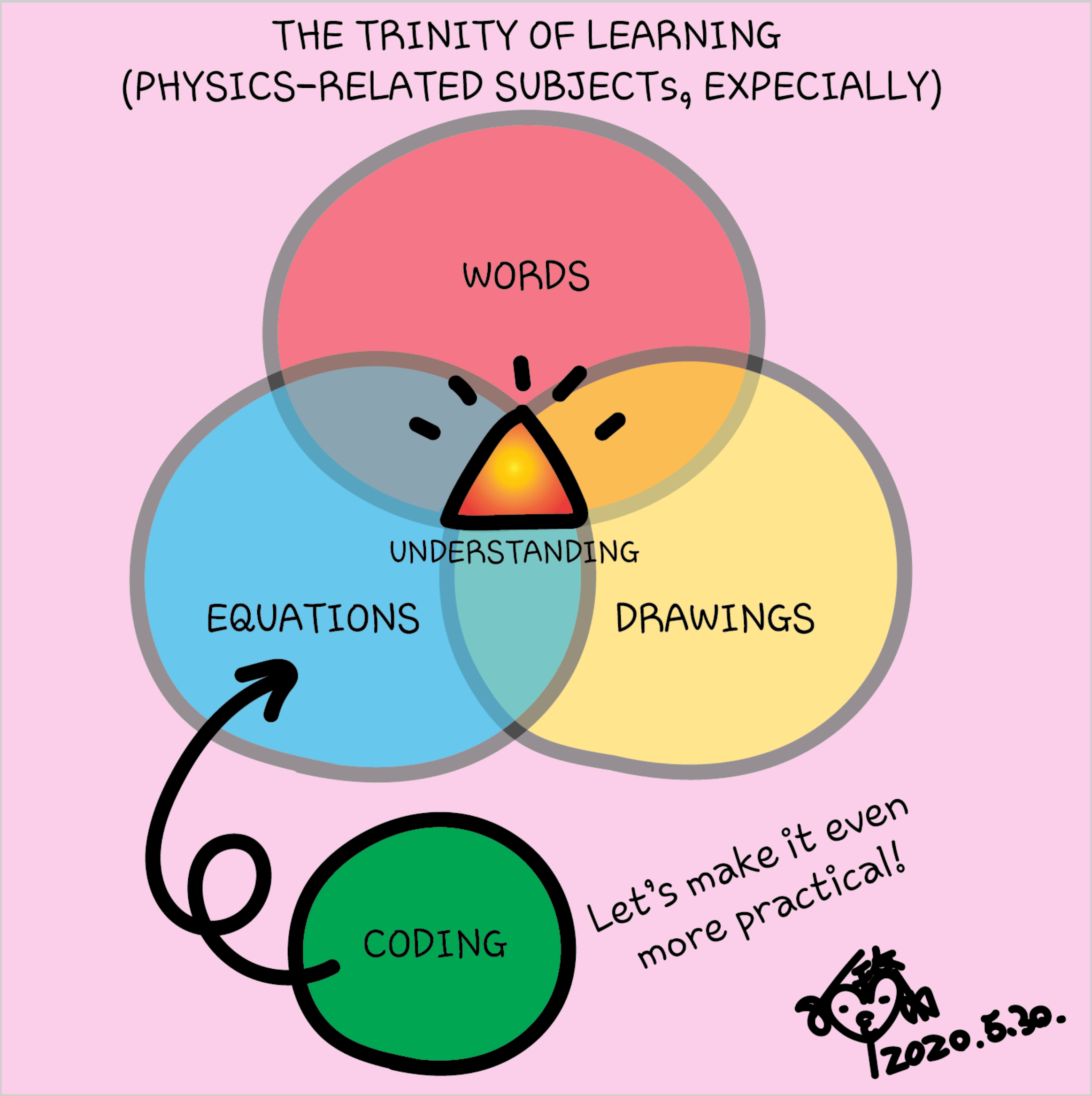


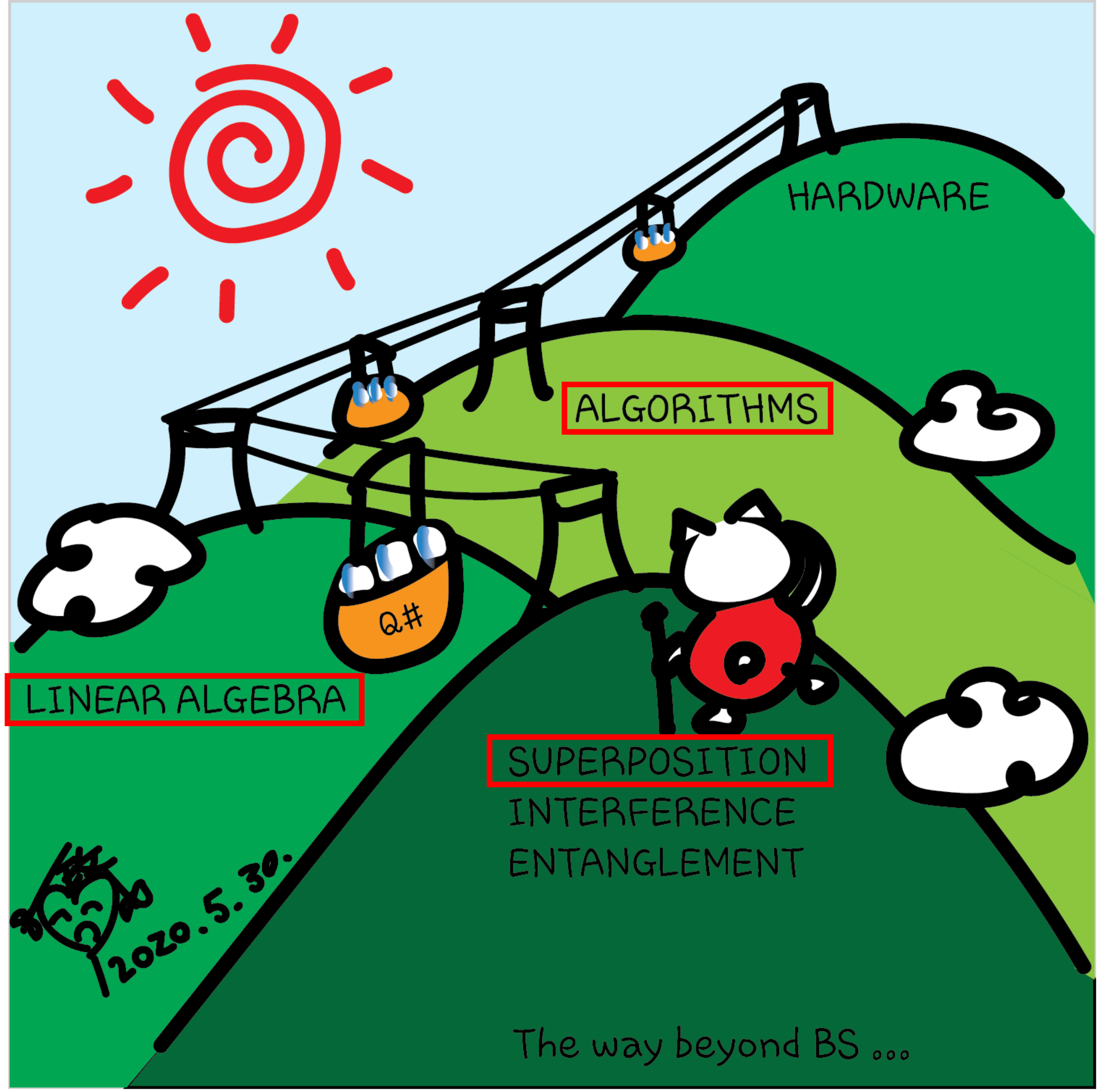






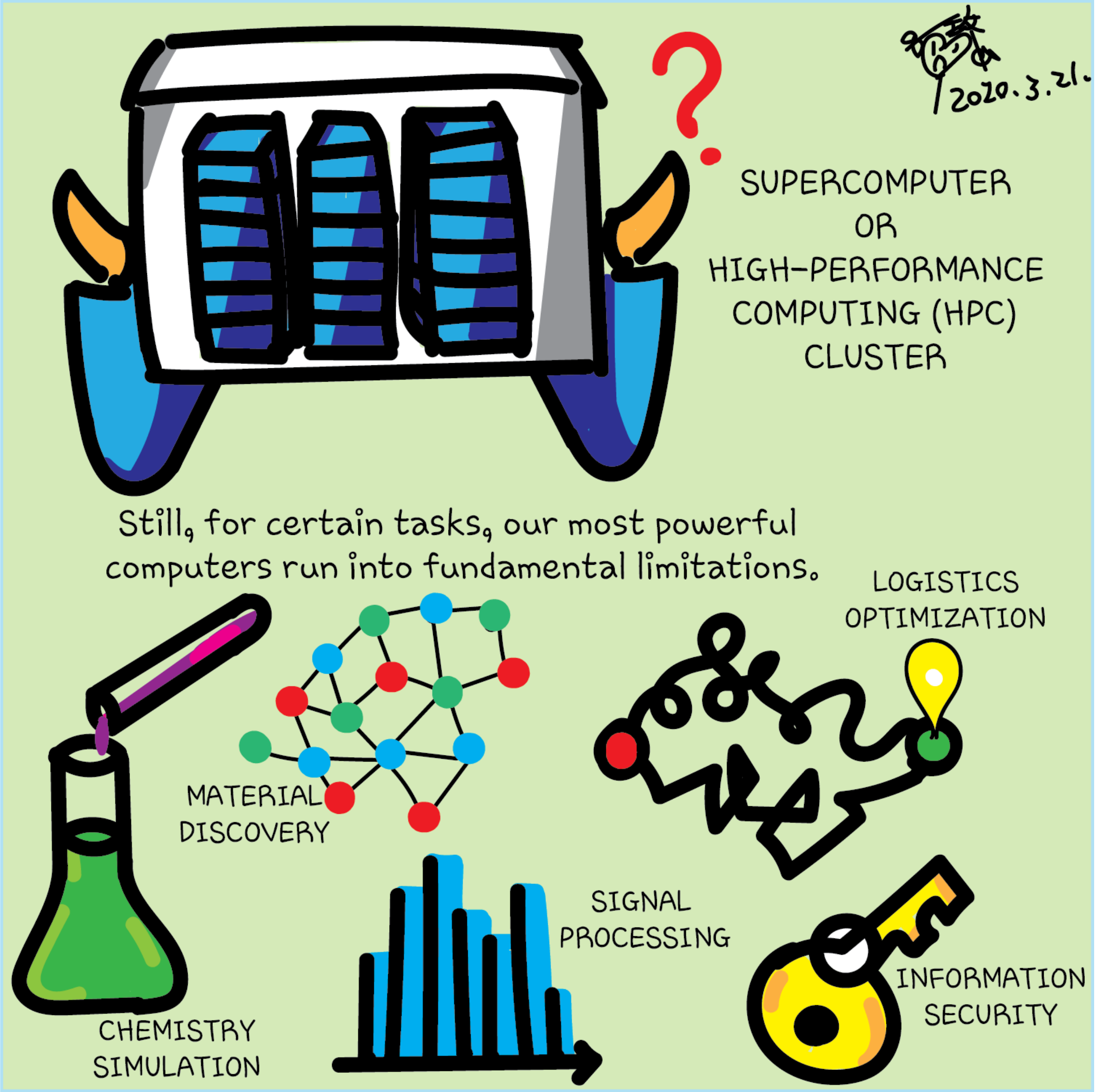
Shor’s algorithm
Chemistry simulations
Quantum machine learning
Quantum-inspired optimization
Program on hardware
…

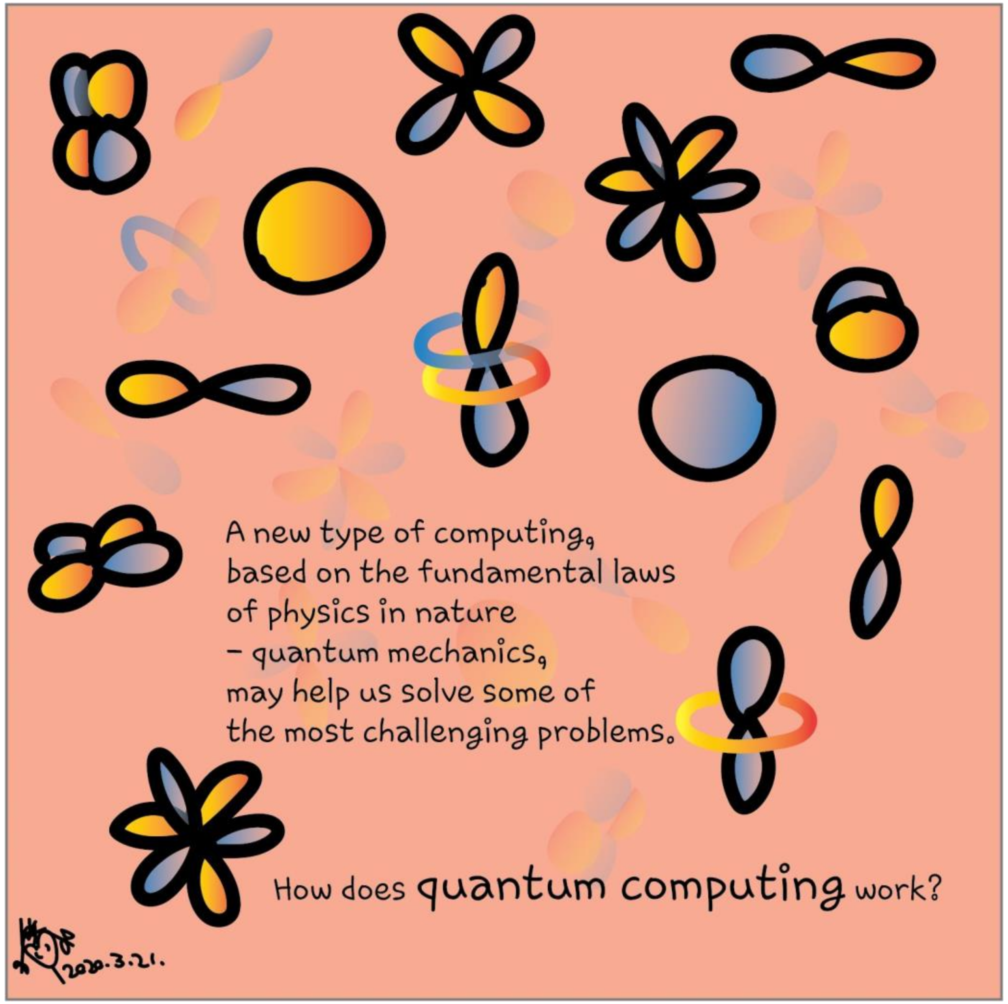

THE TRINITY OF LEARNING
(PHYSICS-RELATED SUBJECTs, EXPECIALLY)
WORDS
UNDERSTANDING
EQUATIONS
DRAWINGS
CODING
Let's make it even
more practical!
2020.5.30.

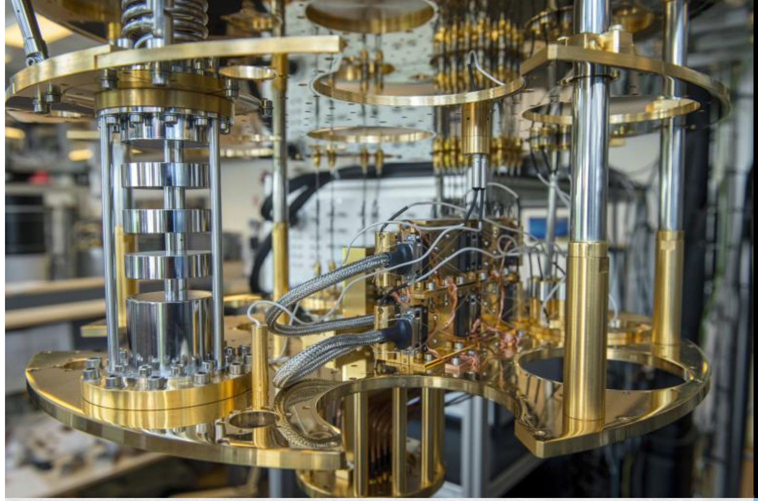


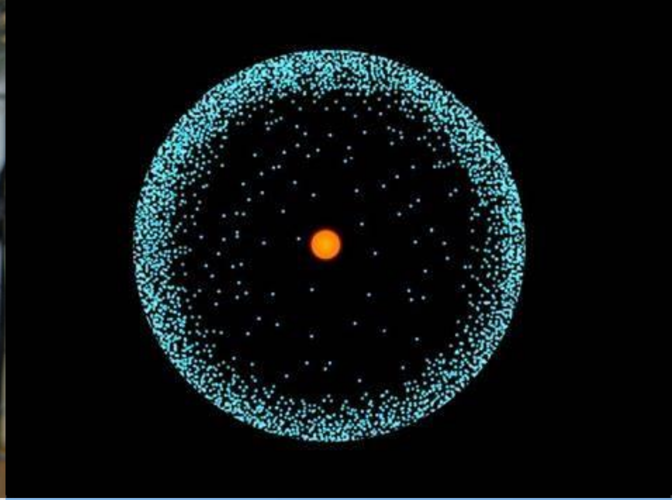
HARDWARE
ALGORITHMS
Q#
LINEAR ALGEBRA
SUPERPOSITION
INTERFERENCE
ENTANGLEMENT
2020.5.30.
The way beyond BS ...

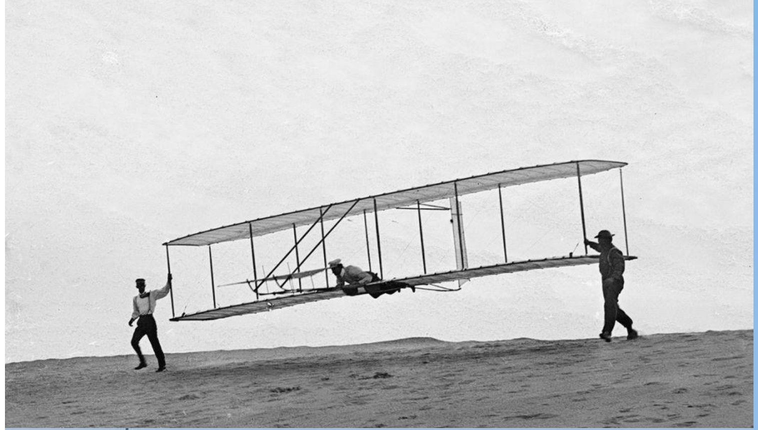

Our world now runs on computers
2020.3.21
– they are machines we task to carry out work more efficiently than we ever do manually.
DATA CENTER SERVERS
PUBLIC HEALTH
MOBILITY
EDUCATION
PRODUCTION
People and things are connected through the internet.

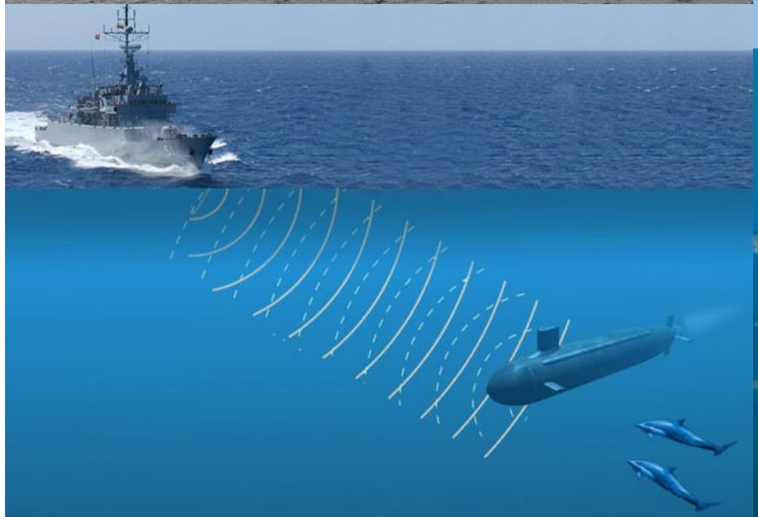

2020.3.21.
SUPERCOMPUTER
OR
HIGH-PERFORMANCE
COMPUTING (HPC)
CLUSTER
Still, for certain tasks, our most powerful computers run into fundamental limitations.
LOGISTICS
OPTIMIZATION
MATERIAL
DISCOVERY
SIGNAL
PROCESSING
INFORMATION
SECURITY
CHEMISTRY
SIMULATION

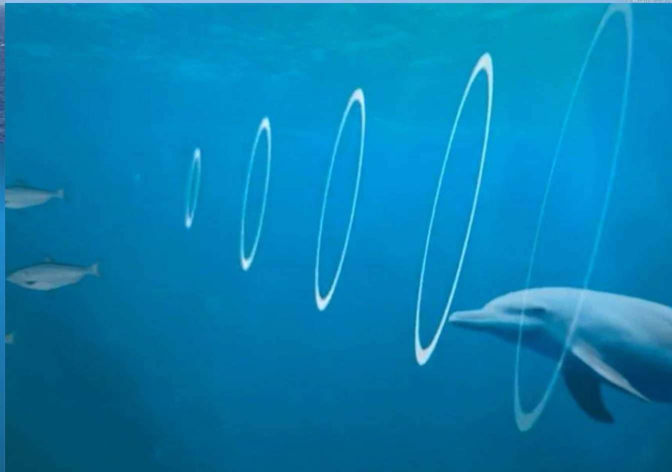

A new type of computing,
based on the fundamental laws
of physics in nature
– quantum mechanics,
may help us solve some of
the most challenging problems.
How does quantum computing work?
2020.3.21.

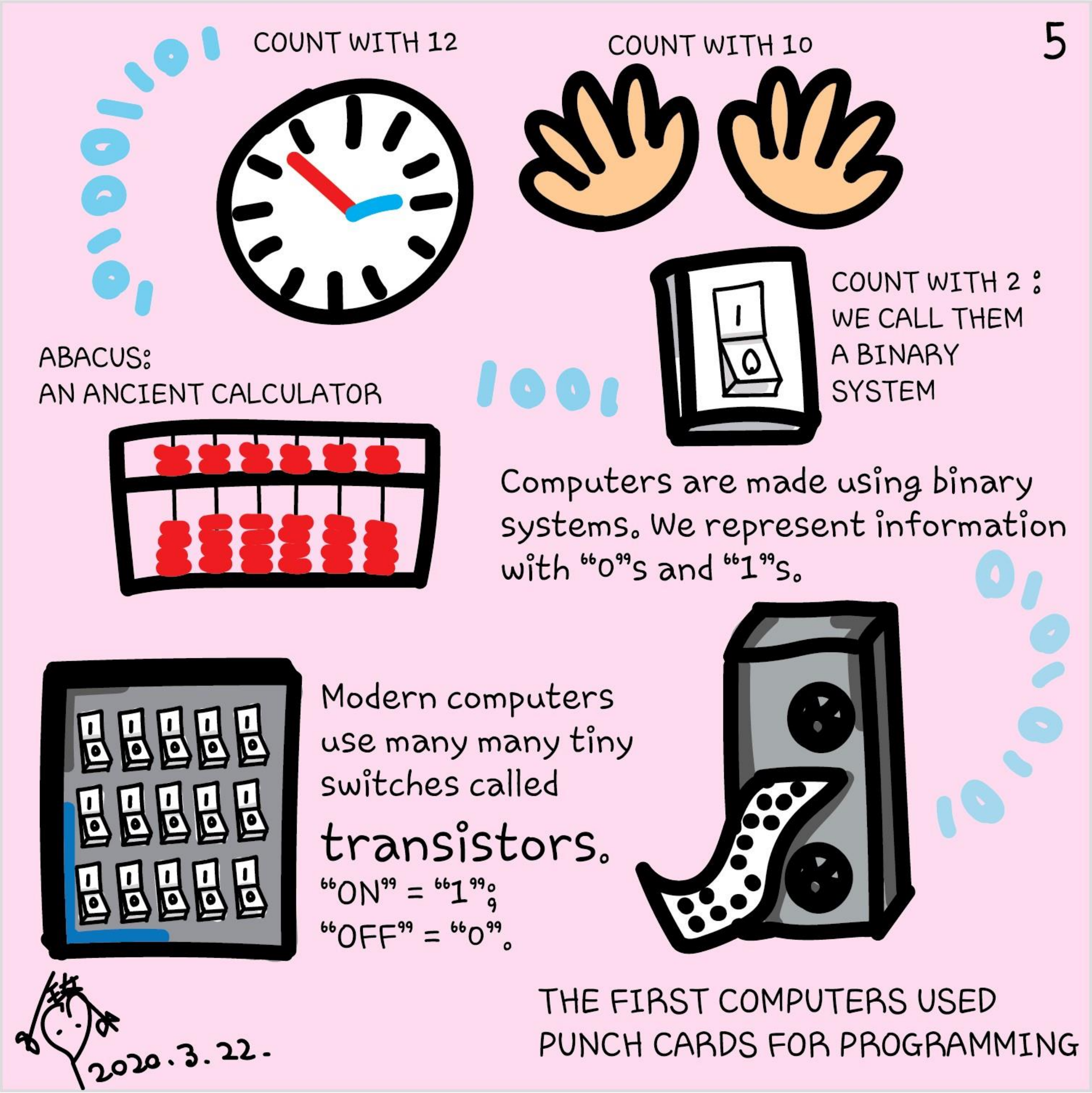






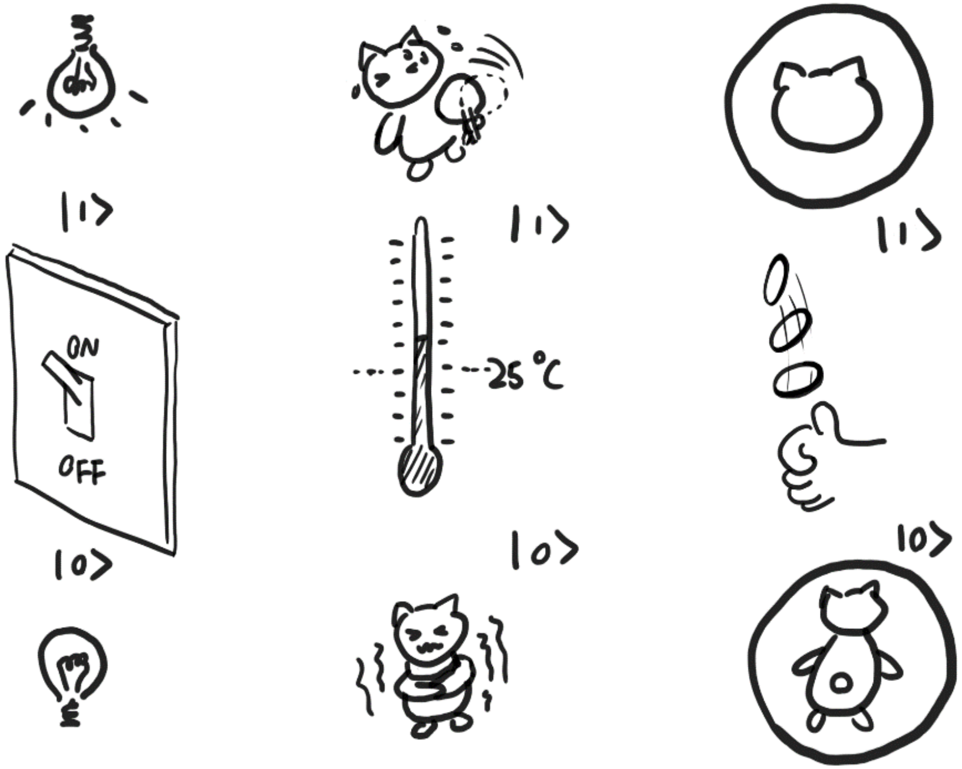





5
COUNT WITH 12
COUNT WITH 10
COUNT WITH 2 :
WE CALL THEM
A BINARY
SYSTEM
ABACUS:
AN ANCIENT CALCULATOR
Computers are made using binary systems. We represent information with "0"s and "1"s.
Modern computers use many many tiny switches called
transistors.
"ON" = "1";
"OFF" = "0".
THE FIRST COMPUTERS USED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

States – classical bits

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



MULTIPLE CLASSICAL BITS OF "0"s & "1"s.

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

$$|00\rangle = \begin{pmatrix}1\\0\end{pmatrix} \otimes \begin{pmatrix}1\\0\end{pmatrix} = \begin{pmatrix}1\\0\\0\\0\end{pmatrix}.$$

$$|01\rangle = \begin{pmatrix}1\\0\end{pmatrix} \otimes \begin{pmatrix}0\\1\end{pmatrix} = \begin{pmatrix}0\\1\\0\\0\end{pmatrix},$$

$$|10\rangle = \begin{pmatrix}0\\1\end{pmatrix} \otimes \begin{pmatrix}1\\0\end{pmatrix} = \begin{pmatrix}0\\0\\1\\0\end{pmatrix},$$

$$|11\rangle = \begin{pmatrix}0\\1\end{pmatrix} \otimes \begin{pmatrix}0\\1\end{pmatrix} = \begin{pmatrix}0\\0\\0\\1\end{pmatrix}.$$

Math insert - Tensor product--

How does tensor product ⊗ work?

$$\begin{pmatrix}x_0\\x_1\end{pmatrix} \otimes \begin{pmatrix}y_0\\y_1\end{pmatrix} = \begin{pmatrix}x_0\begin{pmatrix}y_0\\y_1\end{pmatrix}\\x_1\begin{pmatrix}y_0\\y_1\end{pmatrix}\end{pmatrix} = \begin{pmatrix}x_0y_0\\x_0y_1\\x_1y_0\\x_1y_1\end{pmatrix}$$

and

$$\begin{pmatrix}x_0\\x_1\end{pmatrix} \otimes \begin{pmatrix}y_0\\y_1\end{pmatrix} \otimes \begin{pmatrix}z_0\\z_1\end{pmatrix} = \begin{pmatrix}x_0y_0z_0\\x_0y_0z_1\\x_0y_1z_0\\x_0y_1z_1\\x_1y_0z_0\\x_1y_0z_1\\x_1y_1z_0\\x_1y_1z_1\end{pmatrix}$$

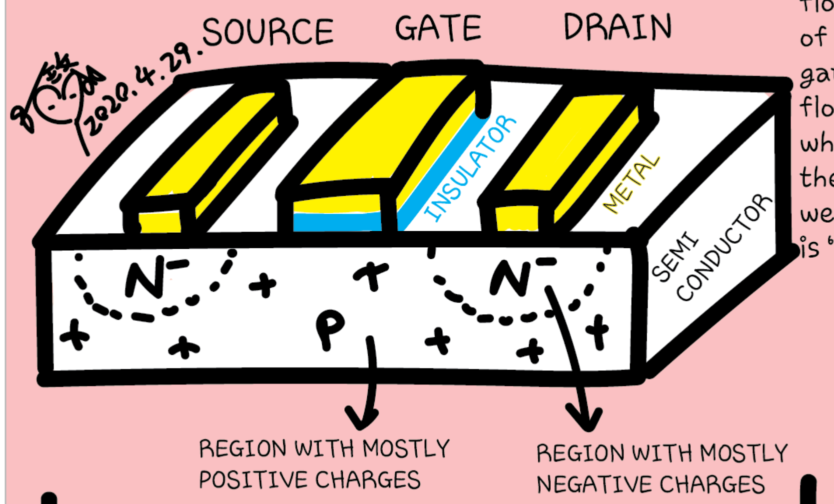
and so on.

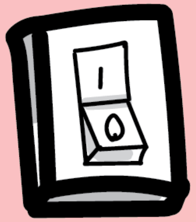
For example, the number 4 can be represented with a three-bit string 100. We can write

$$|4\rangle = |100\rangle = \begin{pmatrix}0\\1\end{pmatrix} \otimes \begin{pmatrix}1\\0\end{pmatrix} \otimes \begin{pmatrix}1\\0\end{pmatrix} = \begin{pmatrix}0\\0\\0\\0\\1\\0\\0\\0\end{pmatrix}.$$

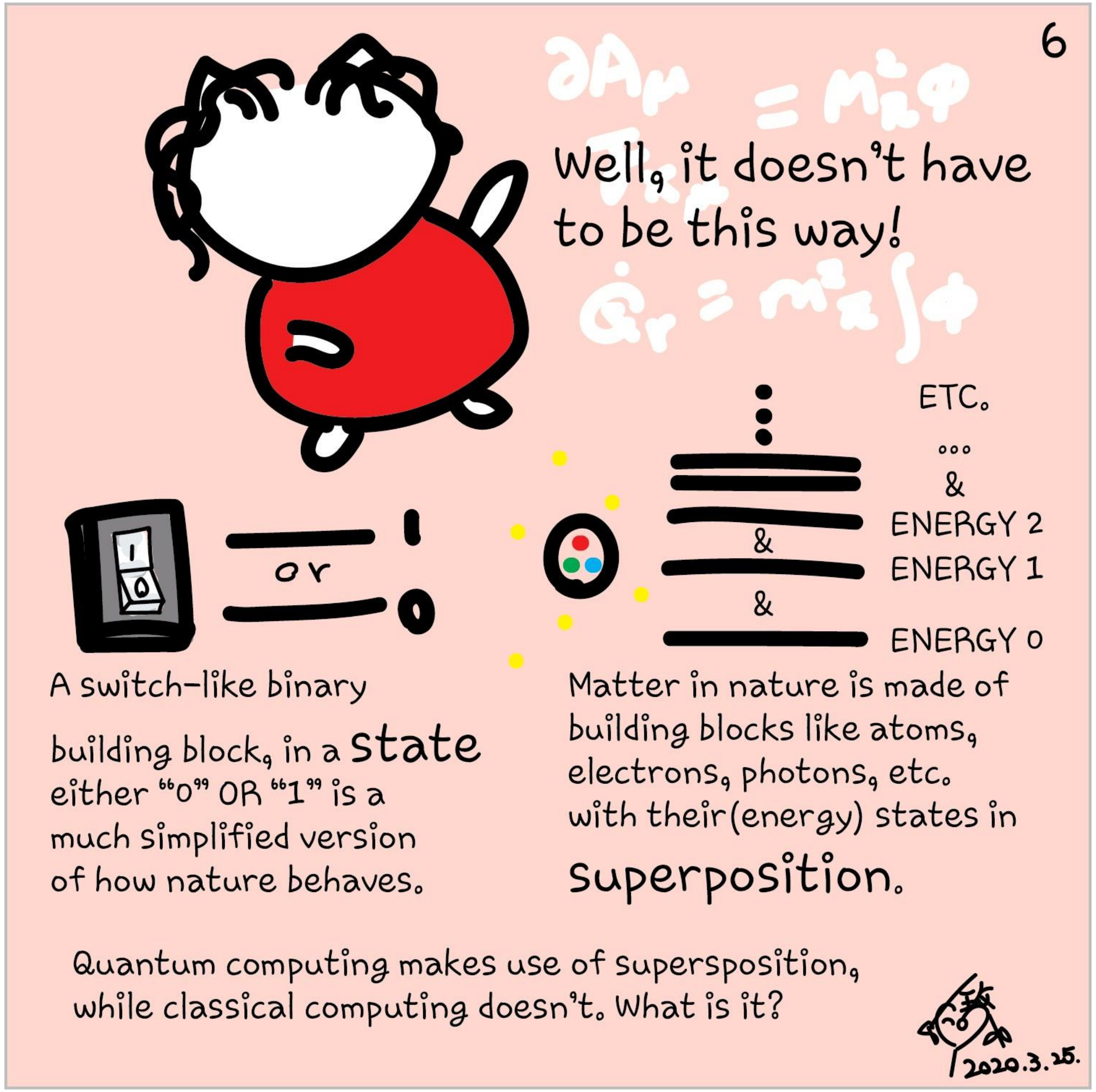
We leverage various properties of materials to make computing hardware.

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".

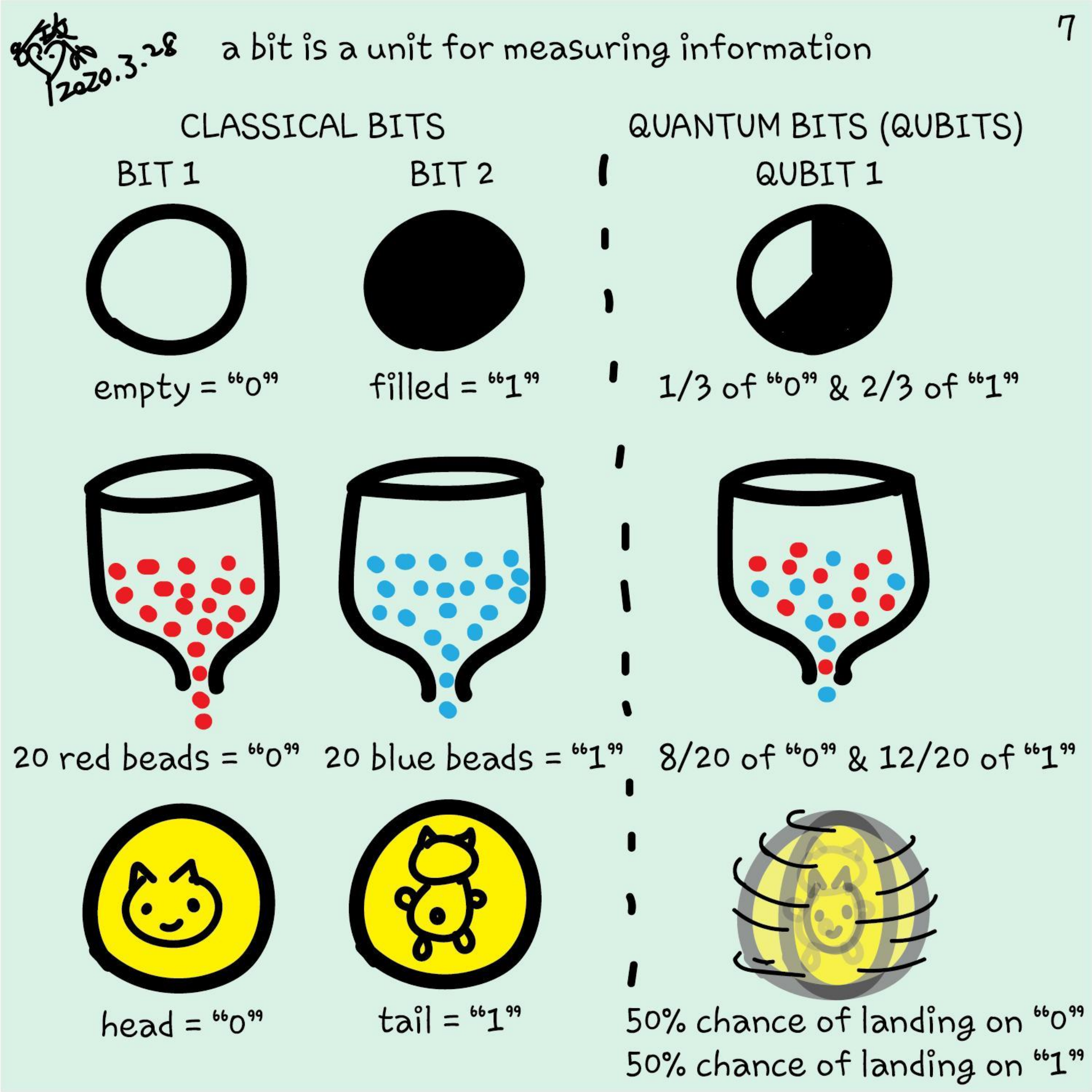




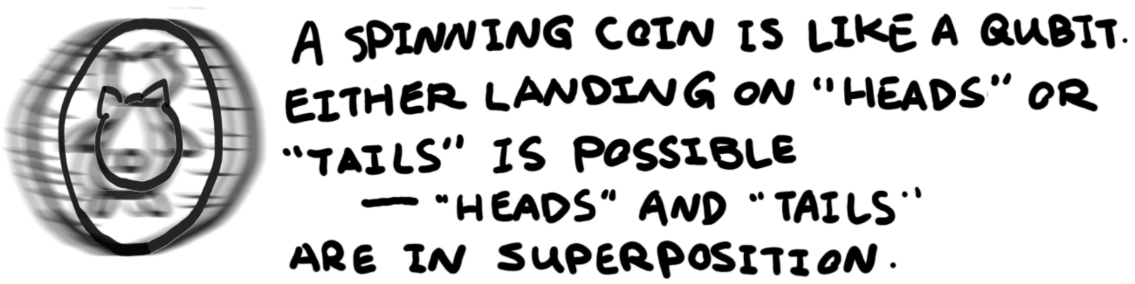
Transistors are nano- to micrometer switches.

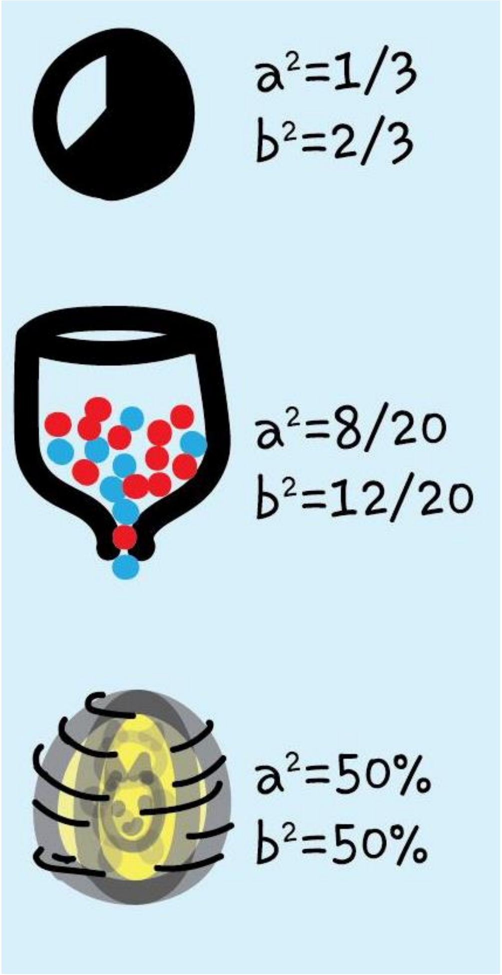


Discrete energy state: Quanta


2020.3.28
a bit is a unit for measuring information
7
CLASSICAL BITS
BIT 1
BIT 2
QUANTUM BITS (QUBITS)
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"

Quantum bits – qubits

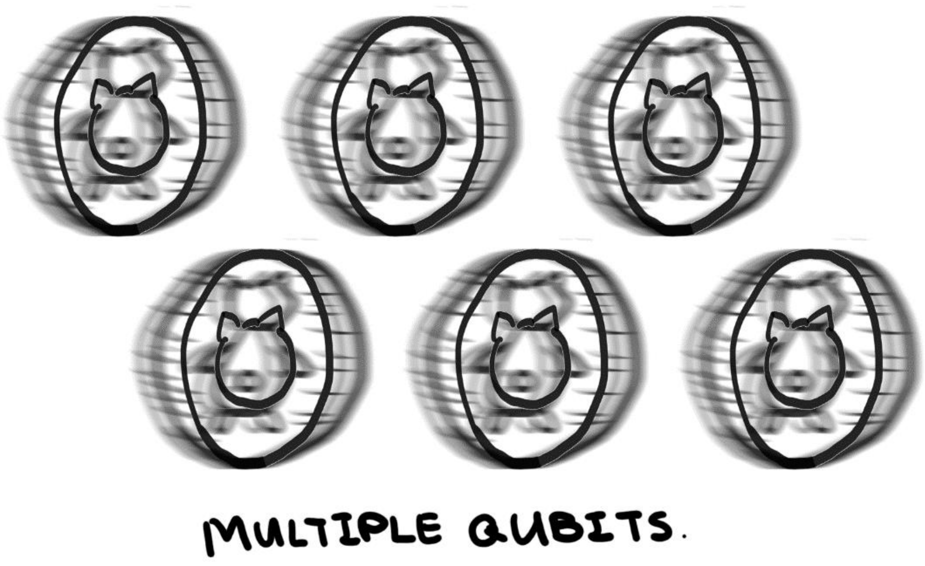




$$|\psi\rangle = \begin{pmatrix} a \\ b \end{pmatrix} = a|0\rangle + b|1\rangle$$

$$|a|^2 + |b|^2 = 1$$

Quantum bits – qubits



Two qubits:

$$|\psi\rangle = \begin{pmatrix} a \\ b \end{pmatrix} \otimes \begin{pmatrix} c \\ d \end{pmatrix}$$

$$= \begin{pmatrix} ac \\ ad \\ bc \\ bd \end{pmatrix}$$

$$= ac|00\rangle + ad|01\rangle + bc|10\rangle + bd|11\rangle$$

$$|ac|^2 + |ad|^2 + |bc|^2 + |bd|^2 = 1$$

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

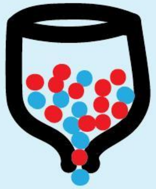
CLASSICAL BITS		QUANTUM BITS
BIT 1	BIT 2	QUBIT 1
$\|0\rangle$	$\|1\rangle$	$a\|0\rangle + b\|1\rangle$

(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 $|0\rangle$ and $|1\rangle$ 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 $|0\rangle$ and $|1\rangle$. Their squares, a^2 and b^2, are the **probabilities** of finding the system in the state $|0\rangle$ and $|1\rangle$, respectively.

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

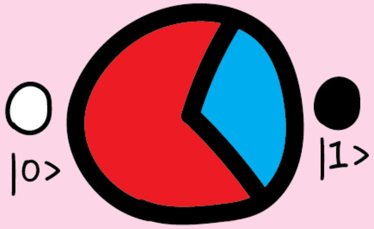
What do these lead to?

2020.3.28.

2020.3.28.

A qubit system is all the possible configurations in superposition.

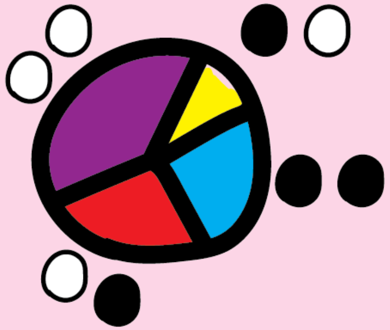
PIE CHART DENOTING PROBABILITY OF EACH CONFIGURATION



ONE QUBIT, TWO CONFIGURATIONS:

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

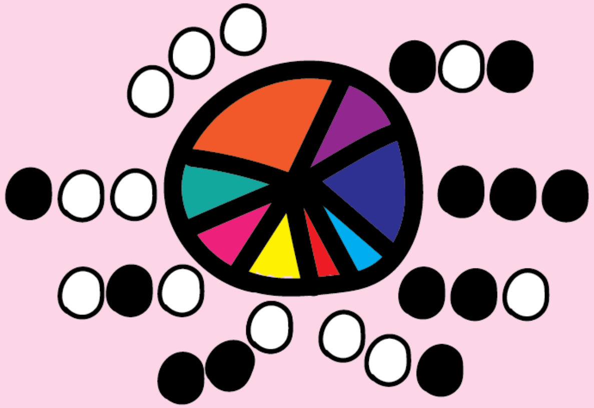
$a^2 + b^2 = 1$ (total probability adds up to 1)



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:

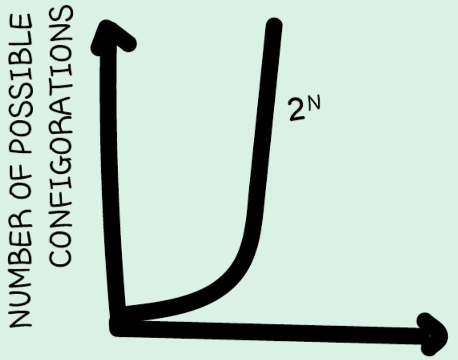
$a|000\rangle + b|001\rangle + c|010\rangle + d|100\rangle + e|110\rangle + f|101\rangle + g|011\rangle + h|111\rangle$

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

...

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

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



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

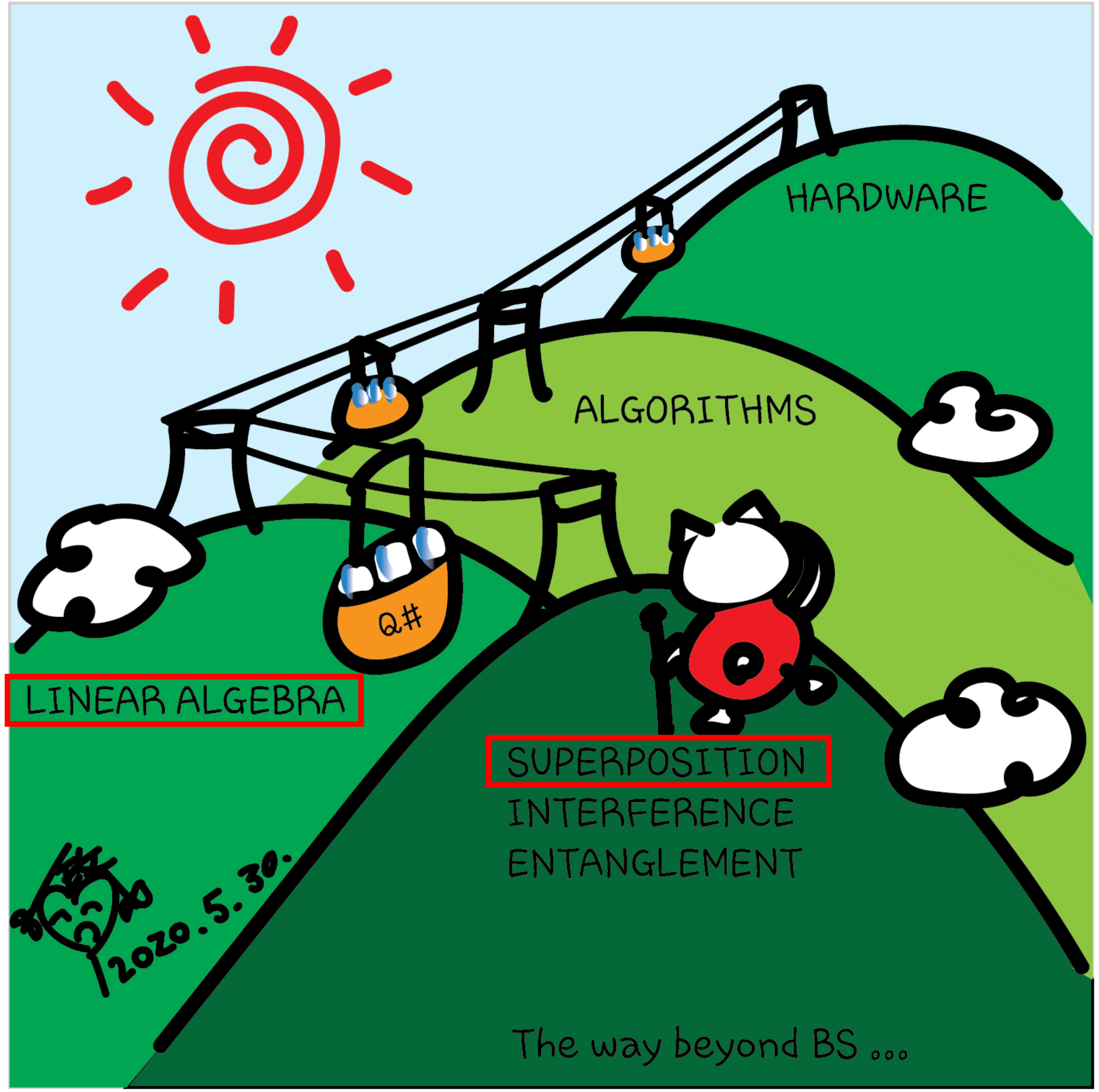
EACH POSSIBLE CONFIGURATION

NATURE DOES PLAY DICE!!!

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.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The way beyond BS ...

Quantum bits – qubits

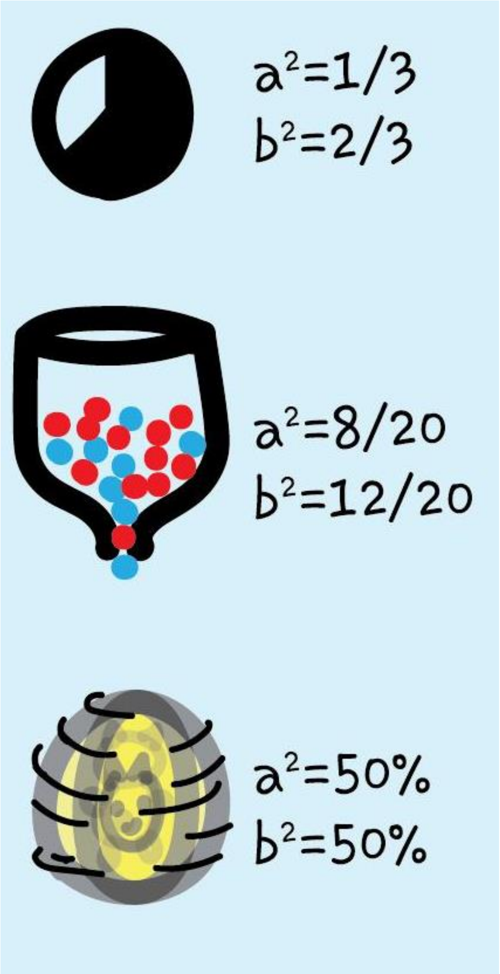
$$|\psi\rangle = \binom{a}{b} = a|0\rangle + b|1\rangle$$

$$|a|^2 + |b|^2 = 1$$

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

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

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



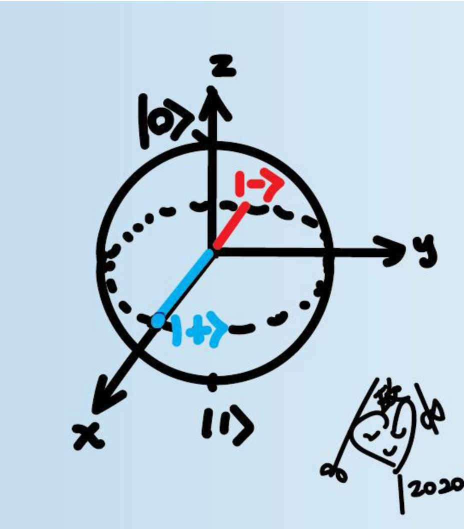
Hadamard H

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

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

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

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



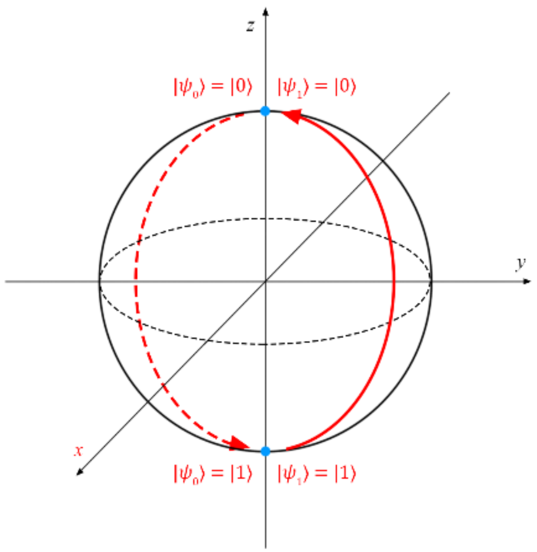
$$H|1\rangle = \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{bmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

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

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

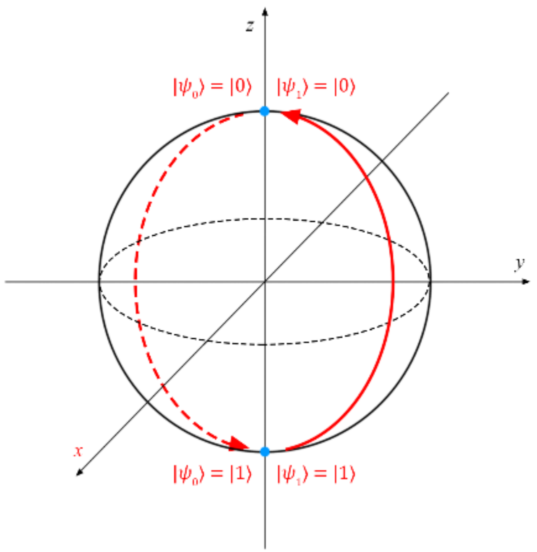
Pauli gates

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

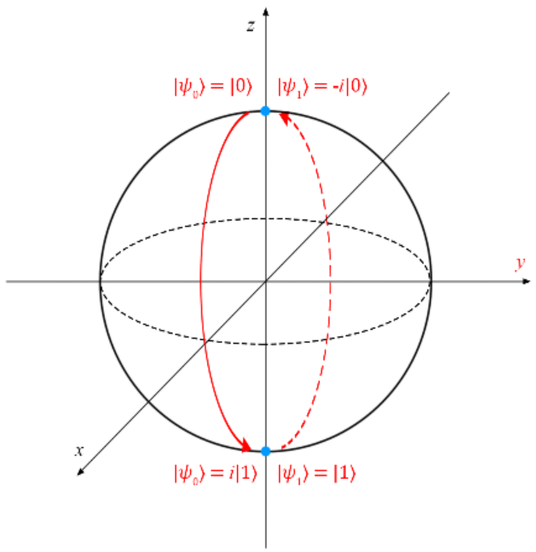
$$Y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$$

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

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



Pauli X



Pauli Y

Pauli gates

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

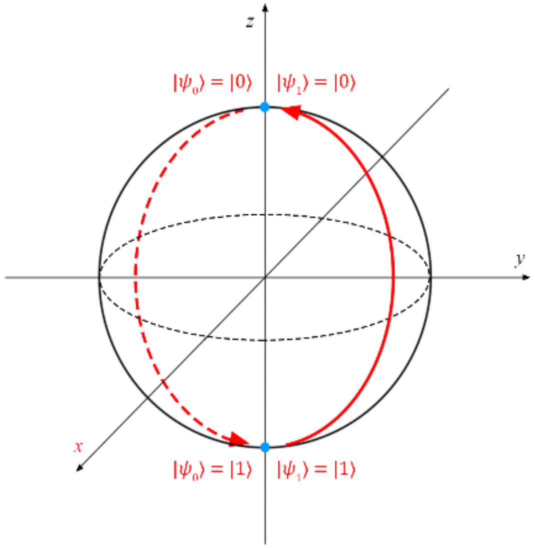
$$Y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$$

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

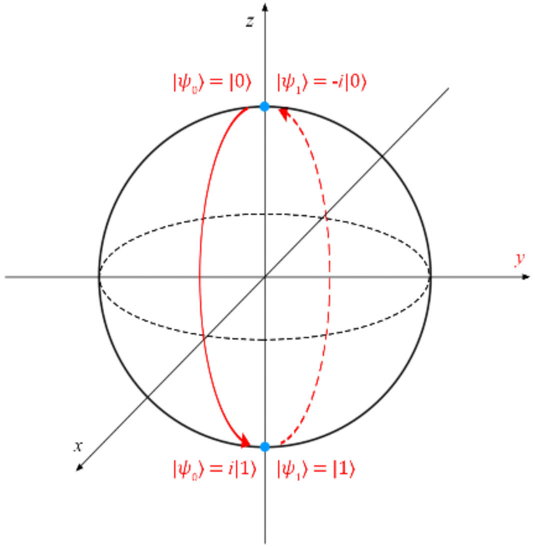
$$X\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \begin{pmatrix} \beta \\ \alpha \end{pmatrix}$$

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

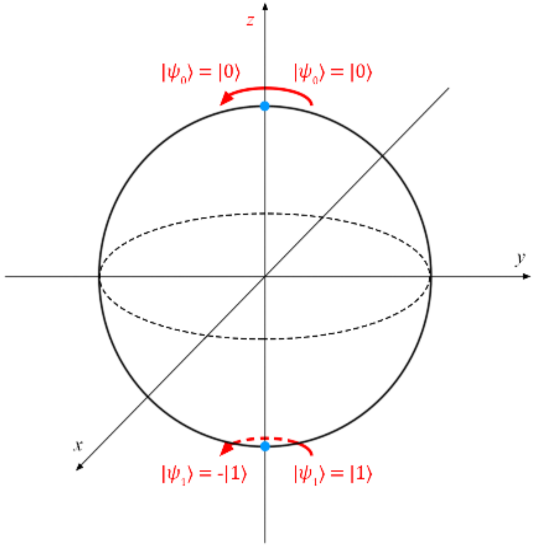
$$Z\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \begin{pmatrix} \alpha \\ -\beta \end{pmatrix}$$



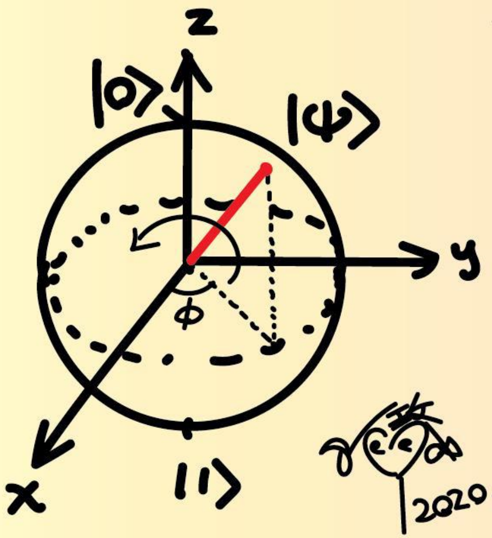
Pauli *X*



Pauli *Y*

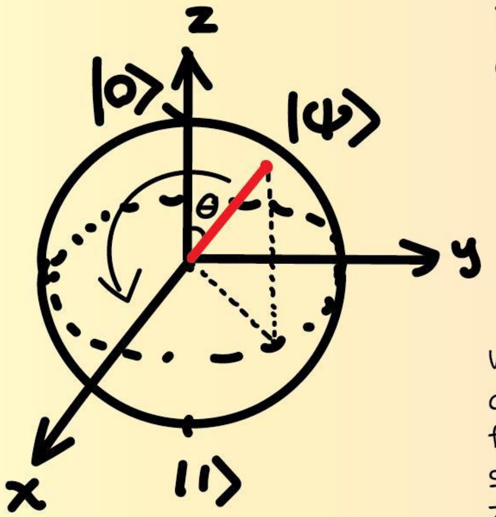


Pauli *Z*



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

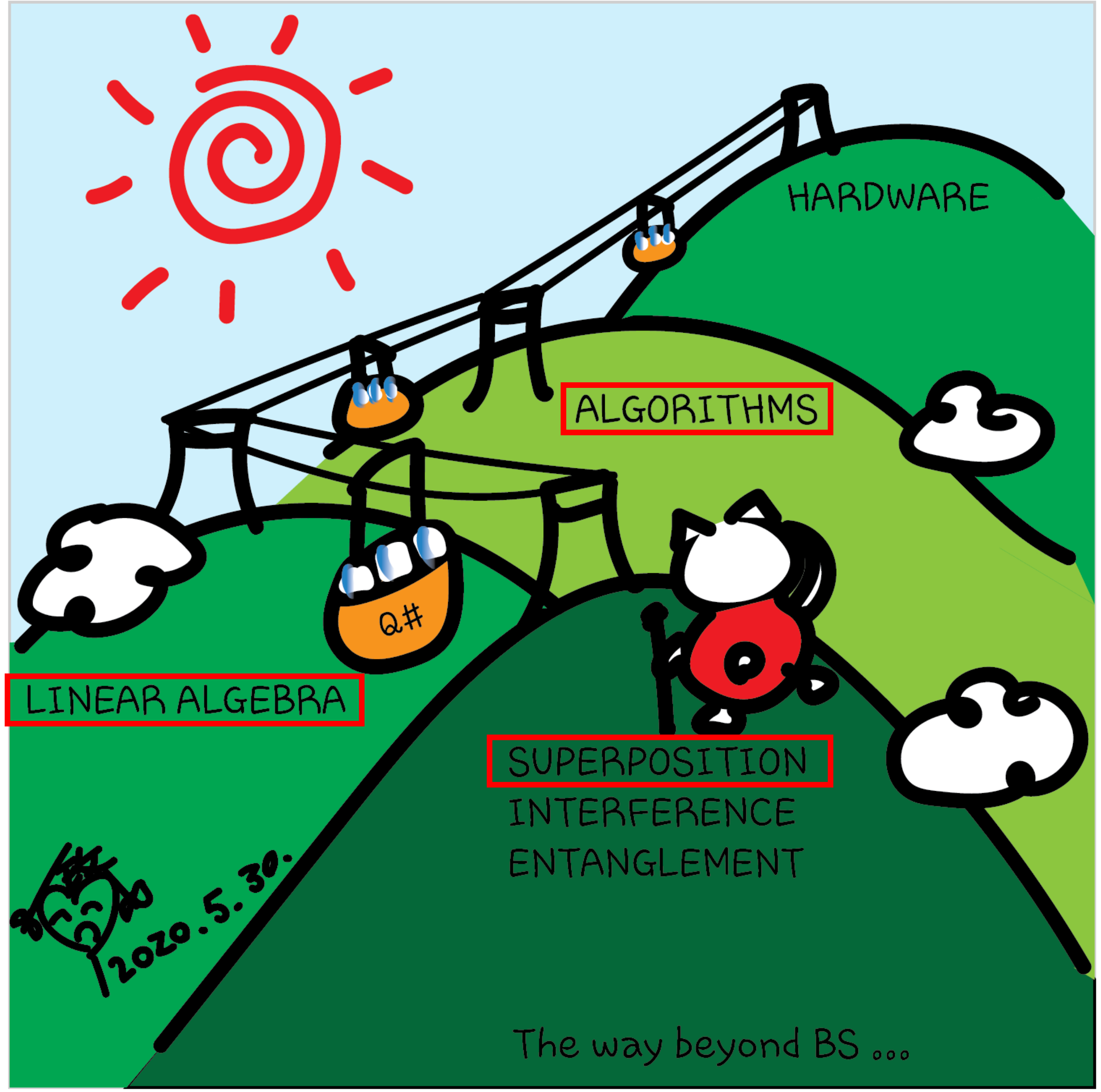
$$Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$



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.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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
- Superposition
- Tasks 1.1, 1.2, 1.3, 1.4?

Questions

- Post in chat or on Hackaday project https://hackaday.io/project/168554-introduction-to-quantum-computing

- Past Recordings on Hackaday project or my YouTube https://www.youtube.com/c/DrKittyYeung aka.ms/learnqc

https://www.microsoft.com/quantum/development-kit