Schrödinger's position - superposition!

Dominik Przywara

sopra steria

Agenda

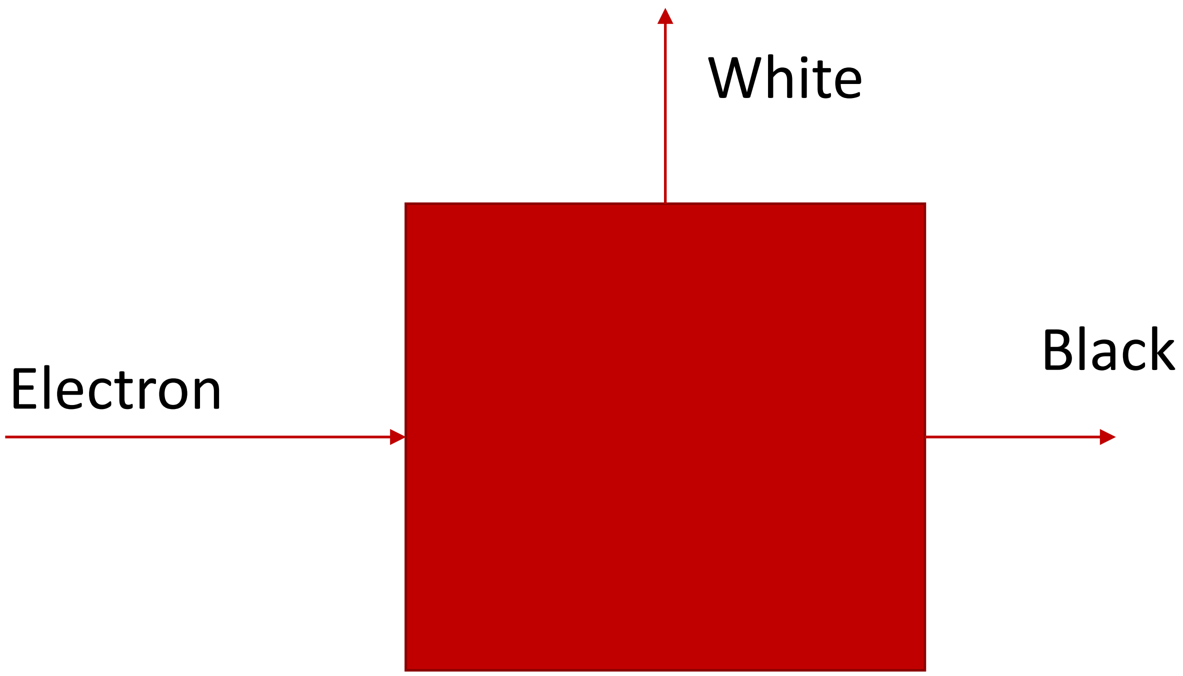
- Physics
- Maths
- Demo in Q#
- Teleportation
- Mind probably blown off

Quantum

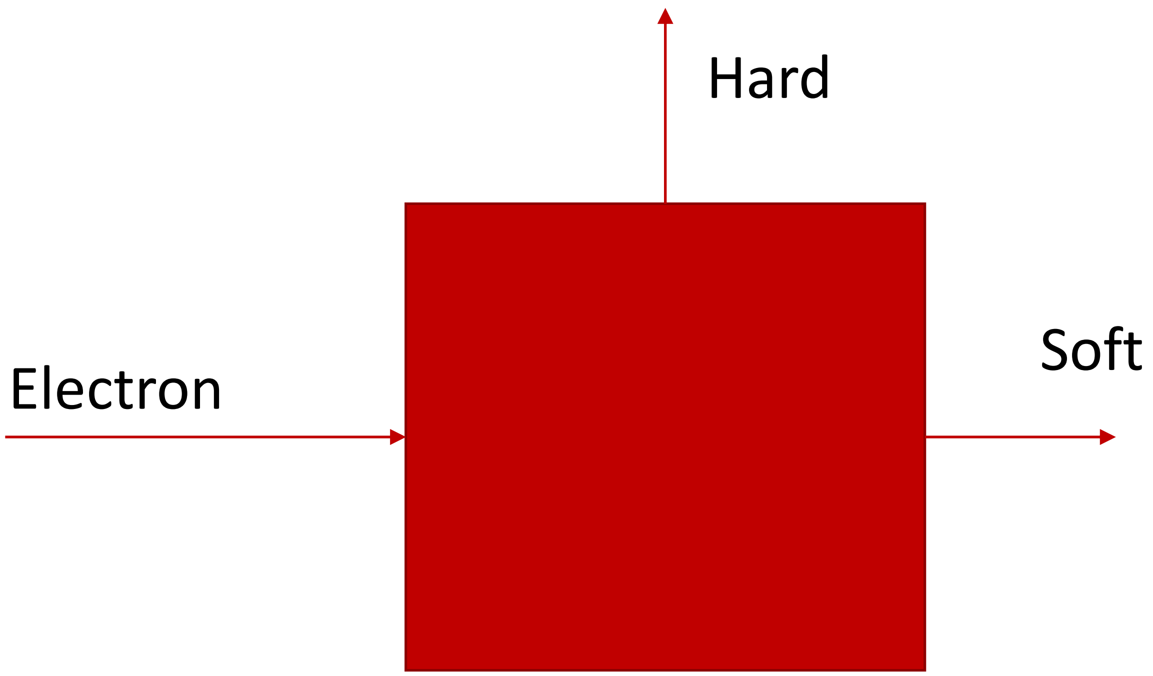
- „In physics, a quantum (plural: quanta) is the minimum amount of any physical entity (physical property) involved in an interaction.”
  - (wikipedia.org)

Mental experiment

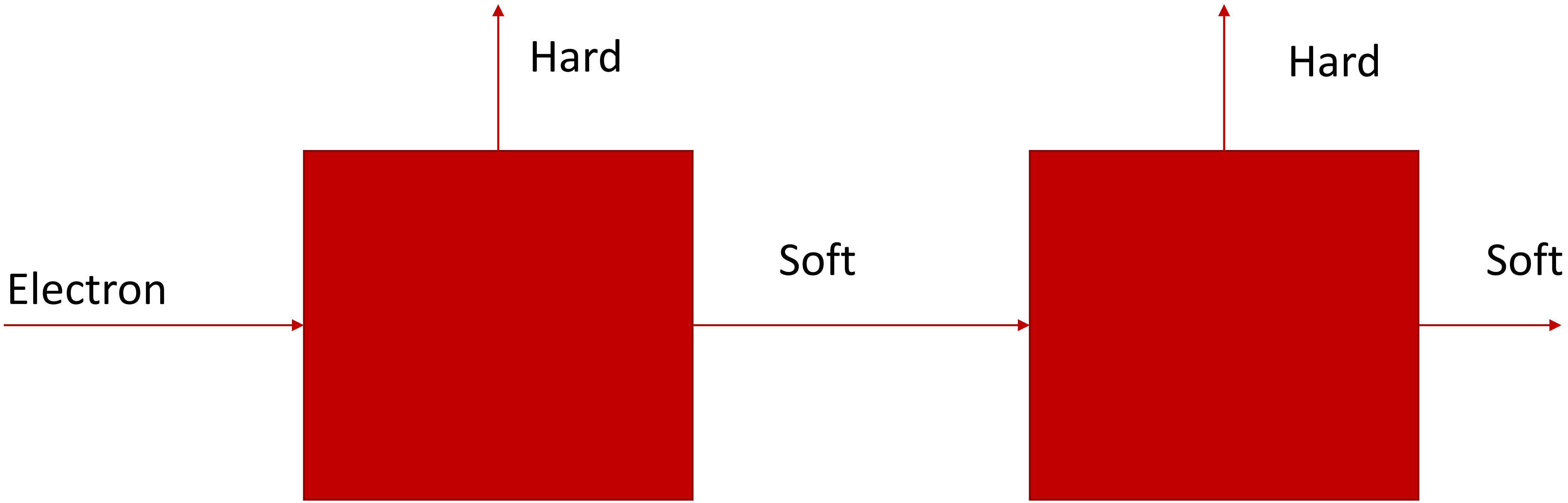
Mental experiment



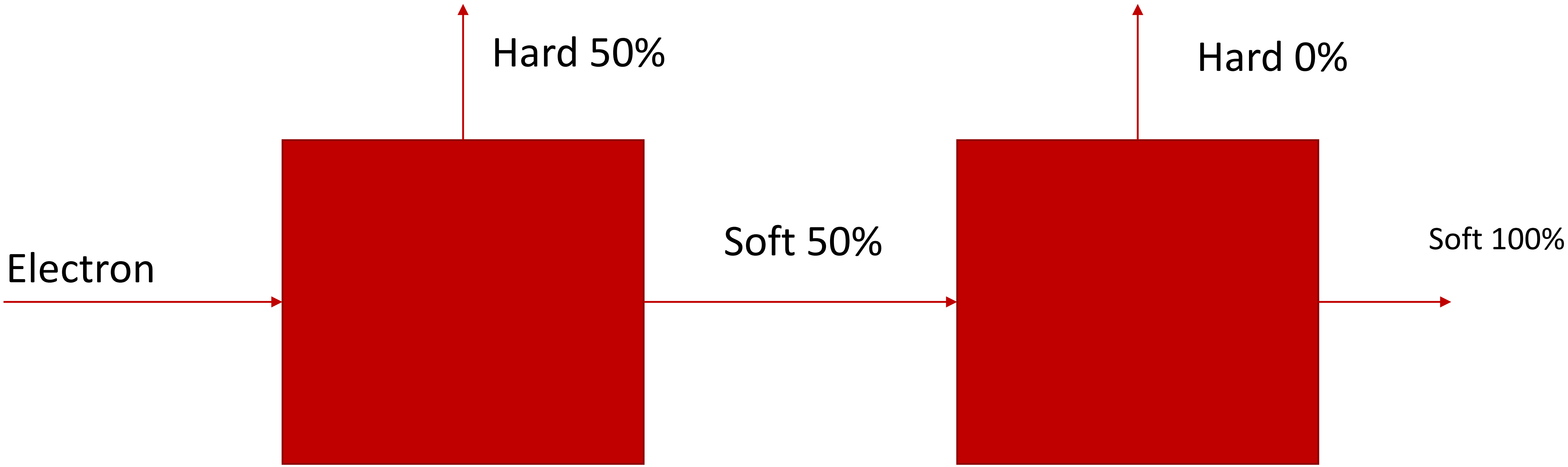
Mental experiment



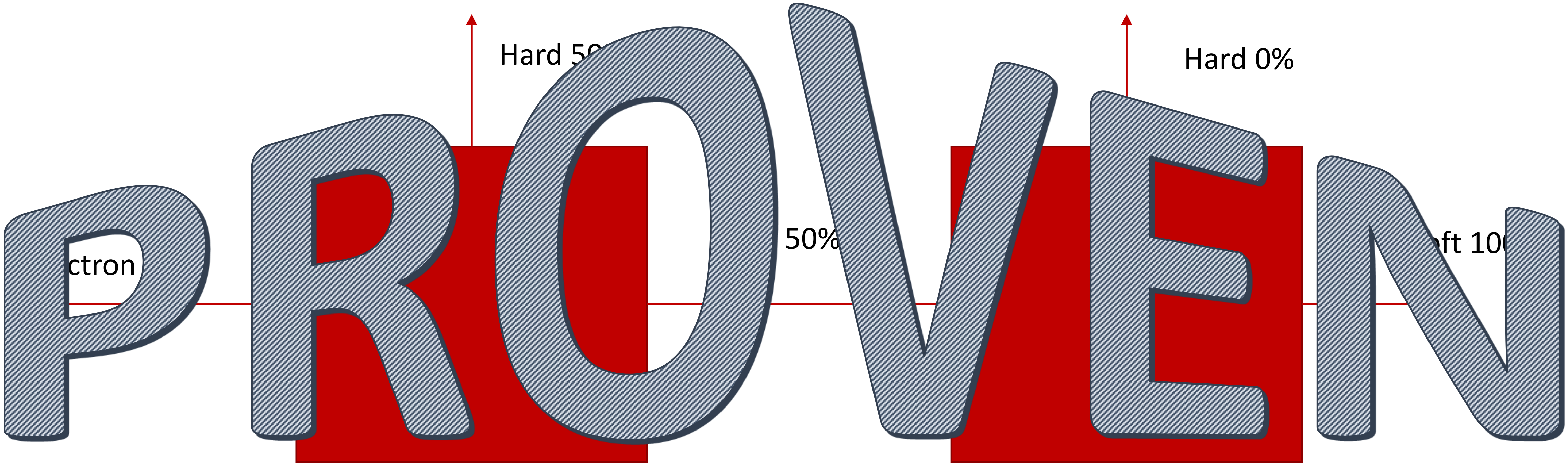
Mental experiment



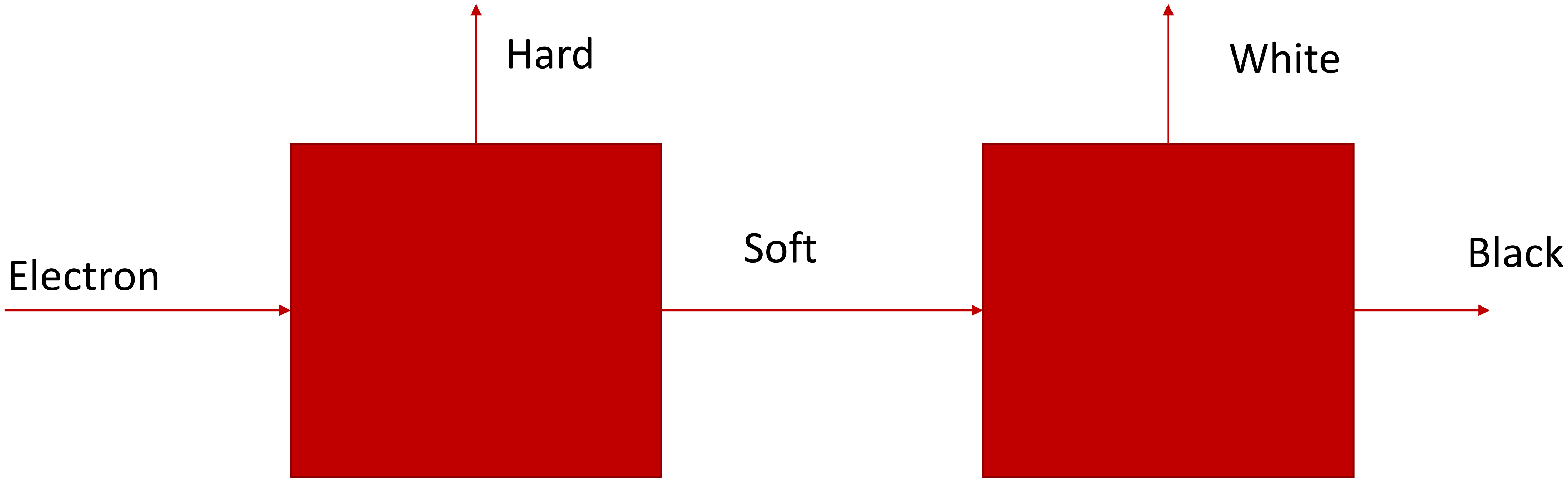
Mental experiment



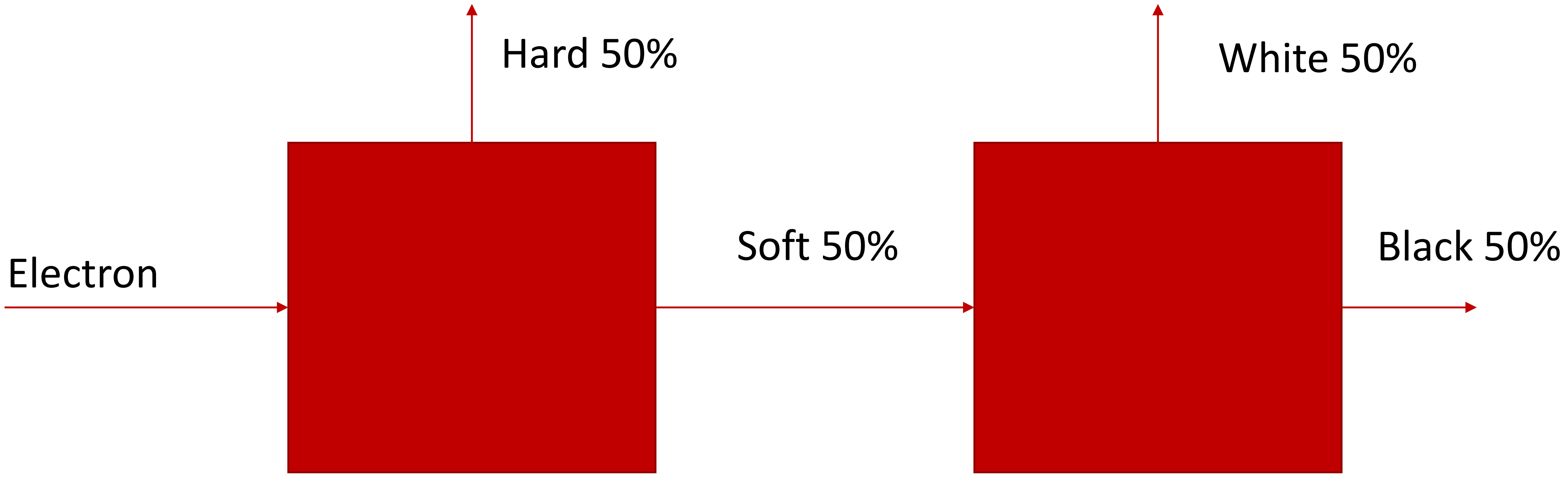
Mental experiment



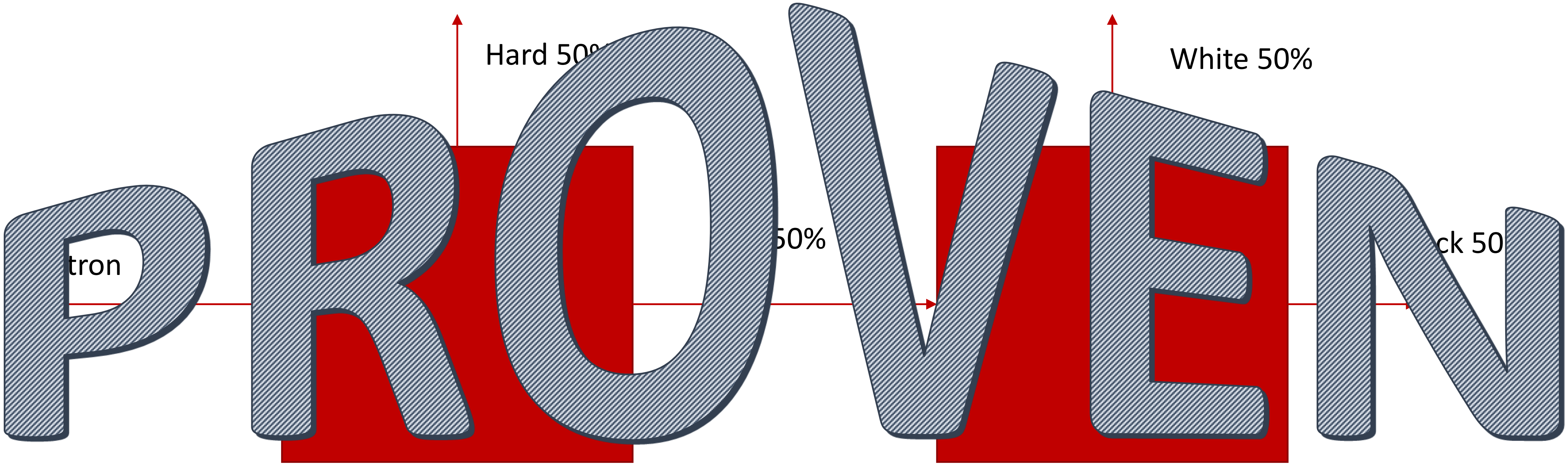
Mental experiment



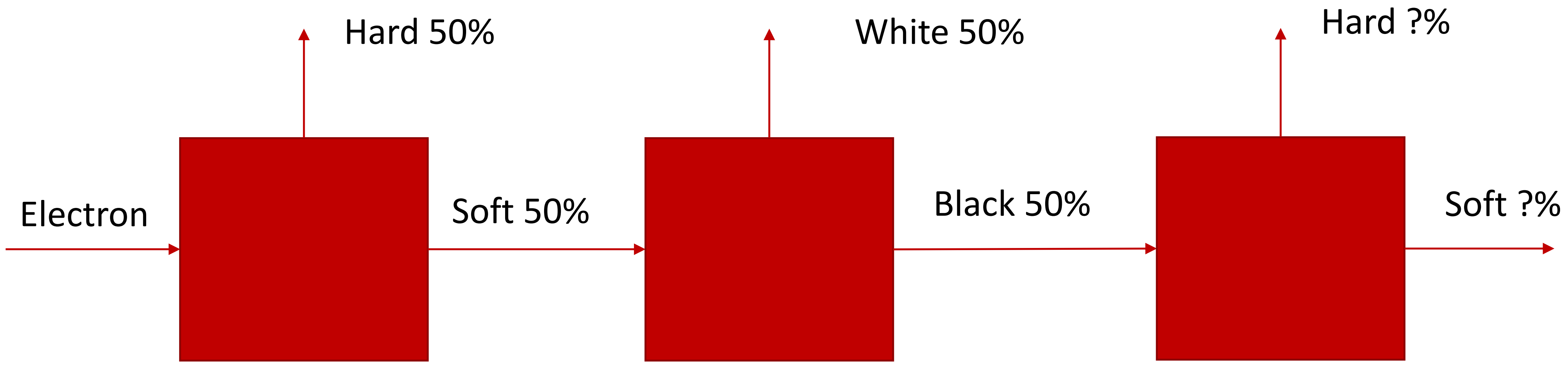
Mental experiment



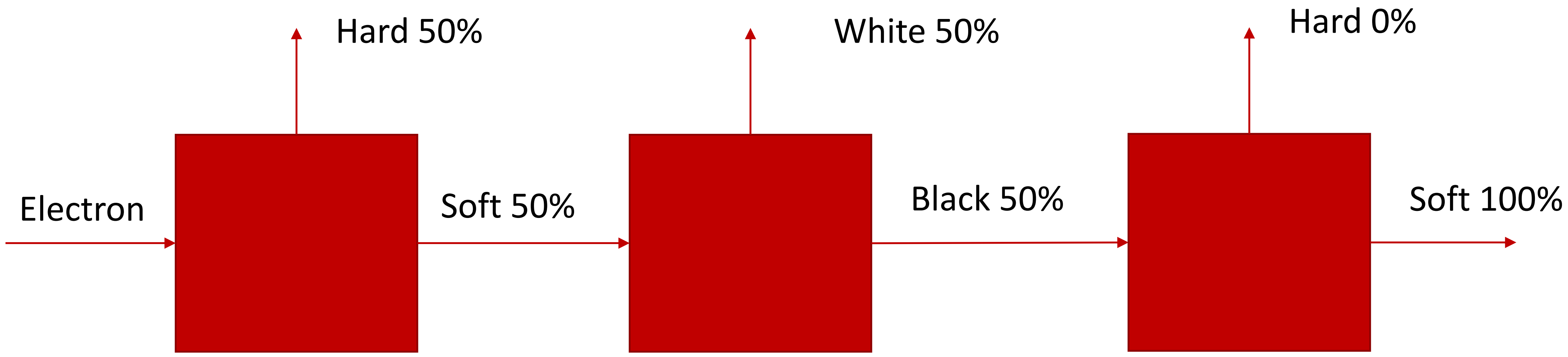
Mental experiment



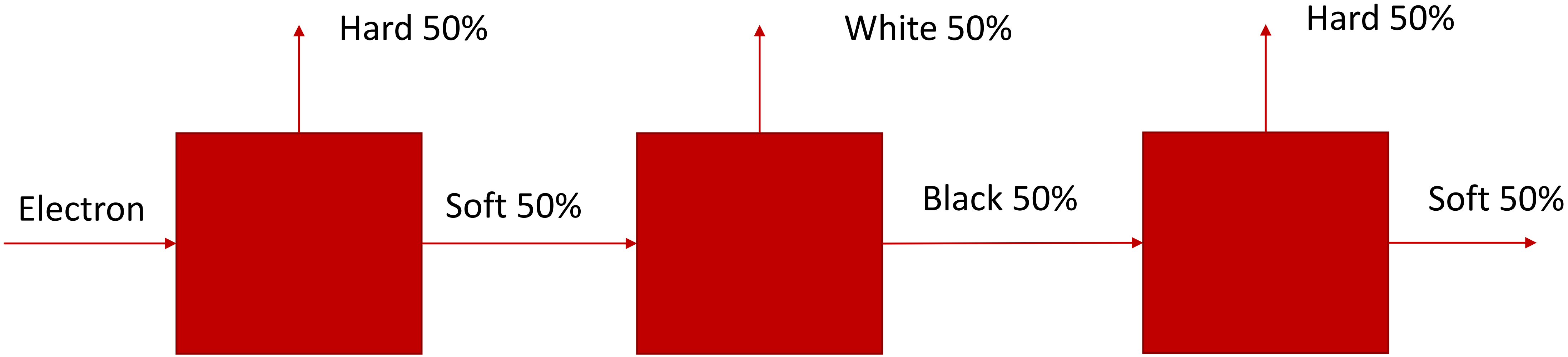
Mental experiment



Mental experiment



Real-life experiment



https://www.youtube.com/watch?v=zcqZHYo7ONs

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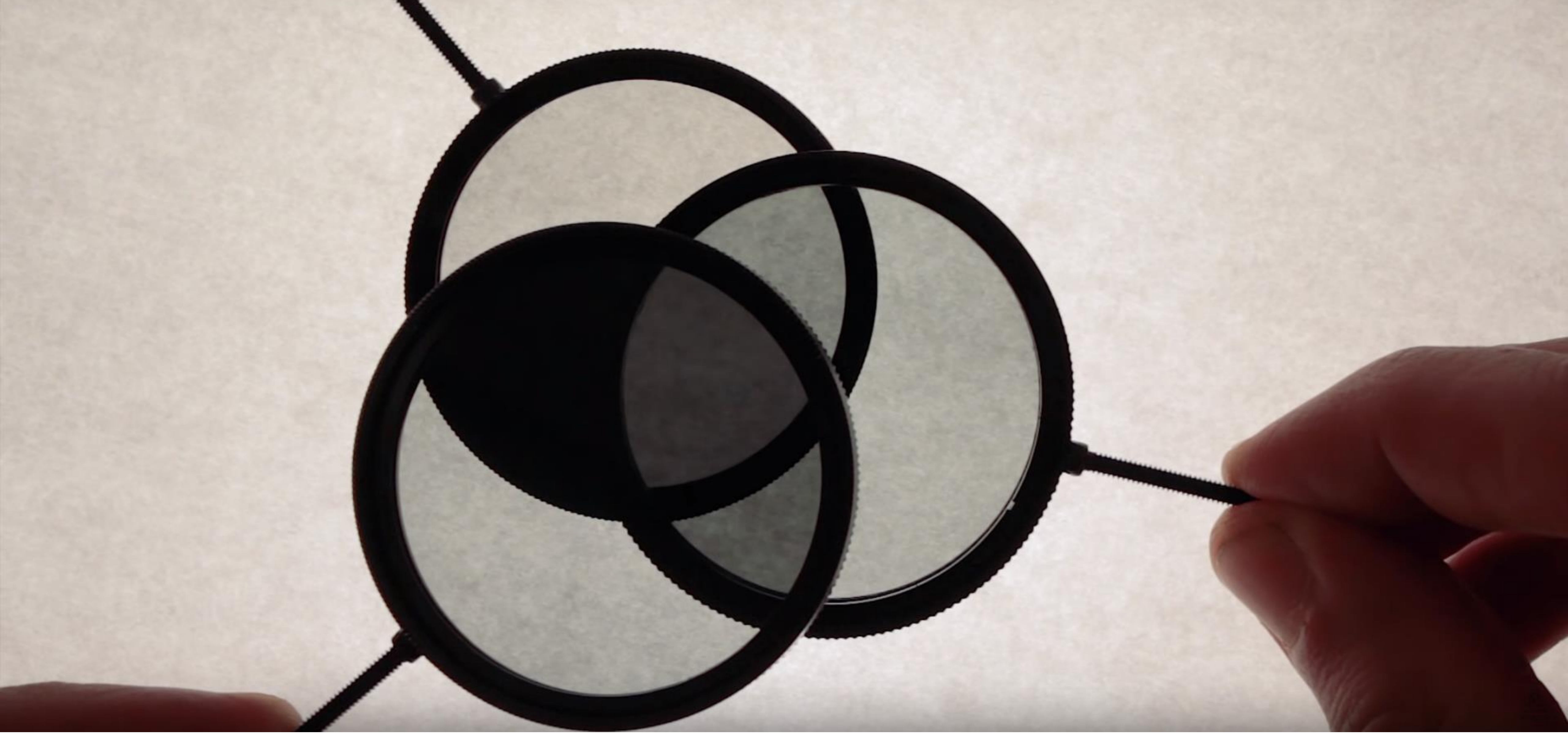
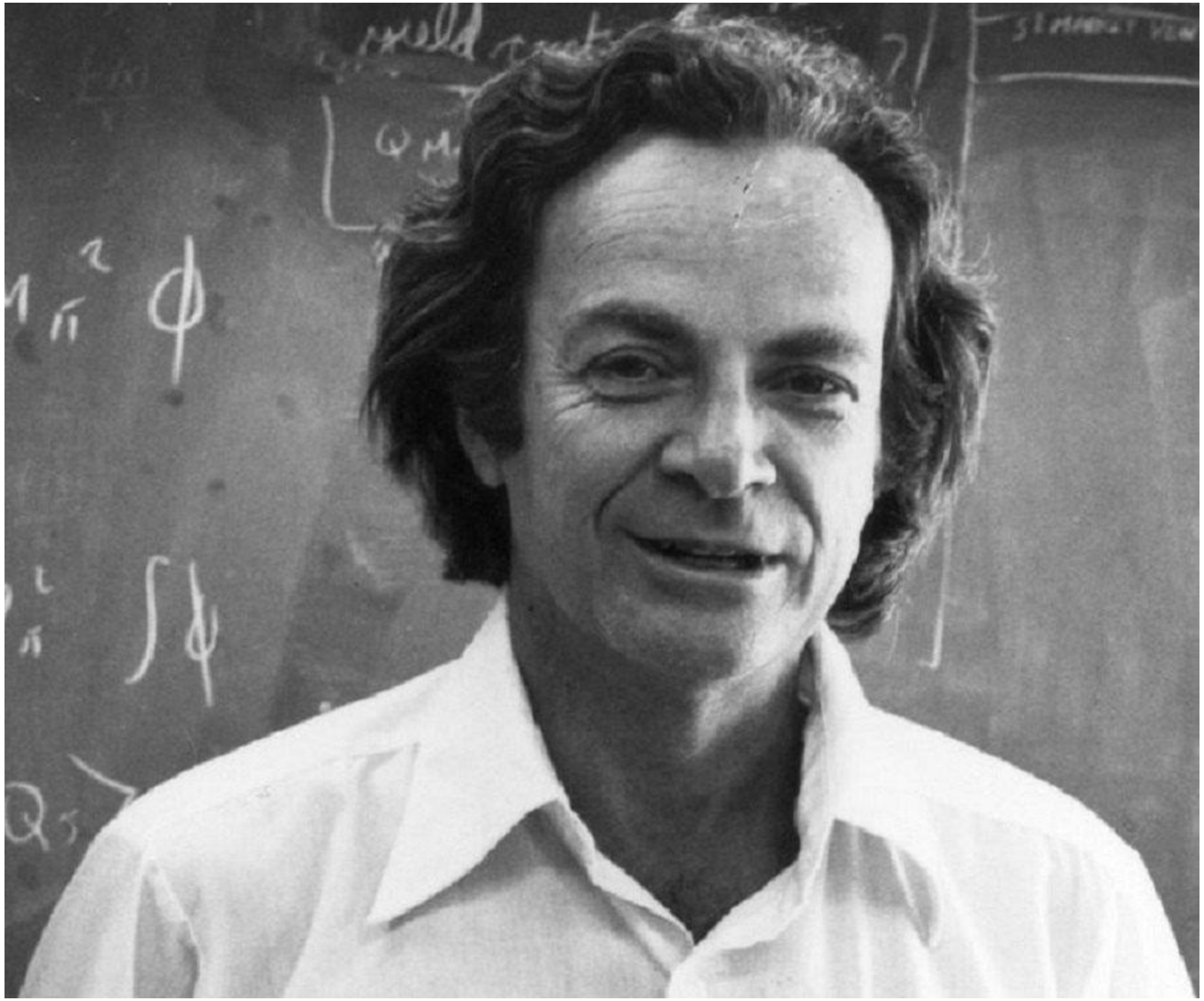


https://www.youtube.com/watch?v=zcqZHYo7ONs

Cbit vs Qubit

https://www.12voltplanet.co.uk/user/products/large/ON-OFF_toggle_switch_20A@12V_decal_1.jpg

http://pacificsource.net/wp-content/uploads/2016/02/free-shipping-led-light-dimmer-switch-220v-led-bulbs-dimmer-dimmer-switch-for-led-lights.jpg

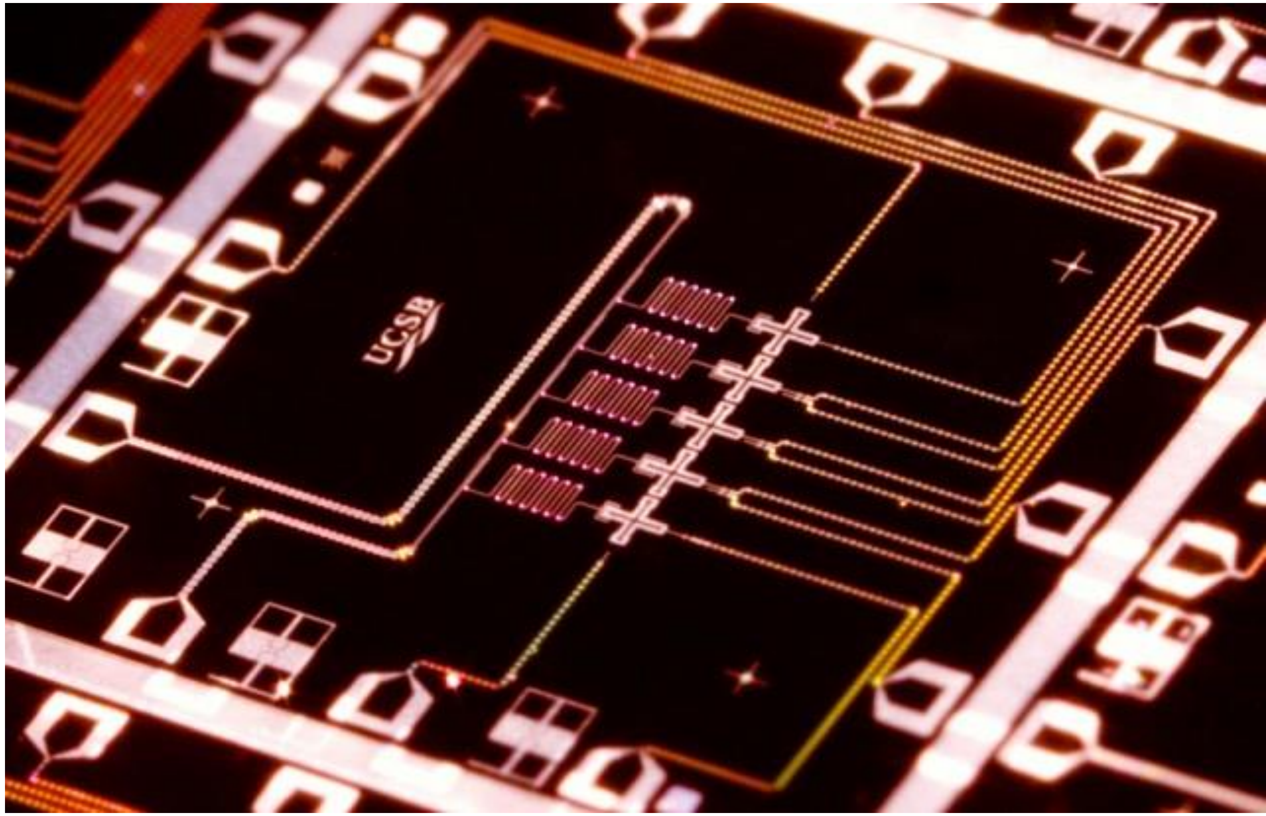


https://www.thefamouspeople.com/profiles/images/richard-feynman-1.jpg

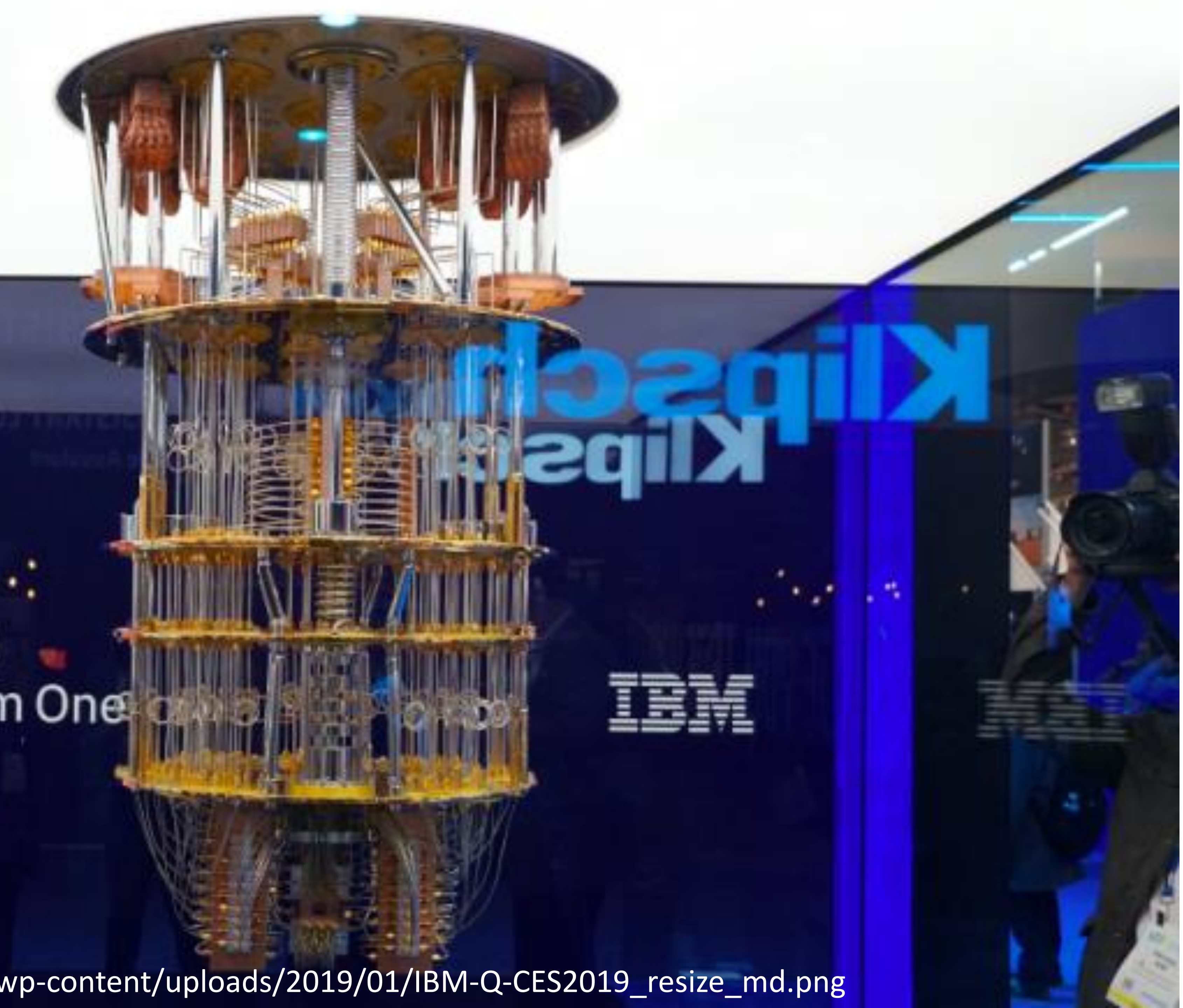
But how to get a Qubit?

- Electrons (spin)
- Photon (light)
- Ions with magnets
- **Superconducting materials (electricity)**

Quantum chip



https://www.extremetech.com/wp-content/uploads/2014/09/Qubit-architecture-640x411.jpg



wp-content/uploads/2019/01/IBM-Q-CES2019_resize_md.png

Application + Software

Cryogenic Computer Control ~3K

Quantum Chip ~100mK


IBM Q
IBM Q

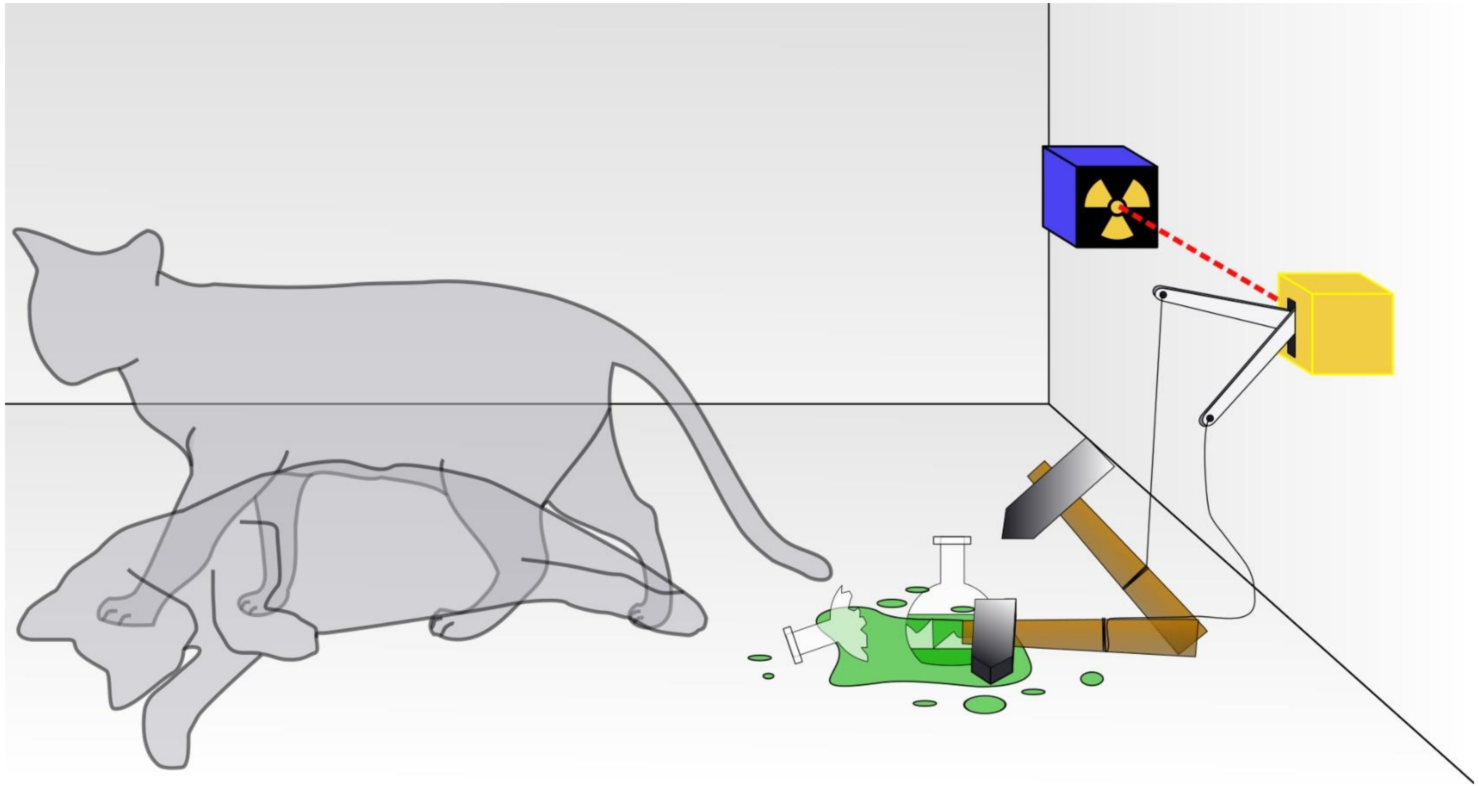

IBM
IBM Q
System One

It’s **„just”** a Coprocessor

Superposition

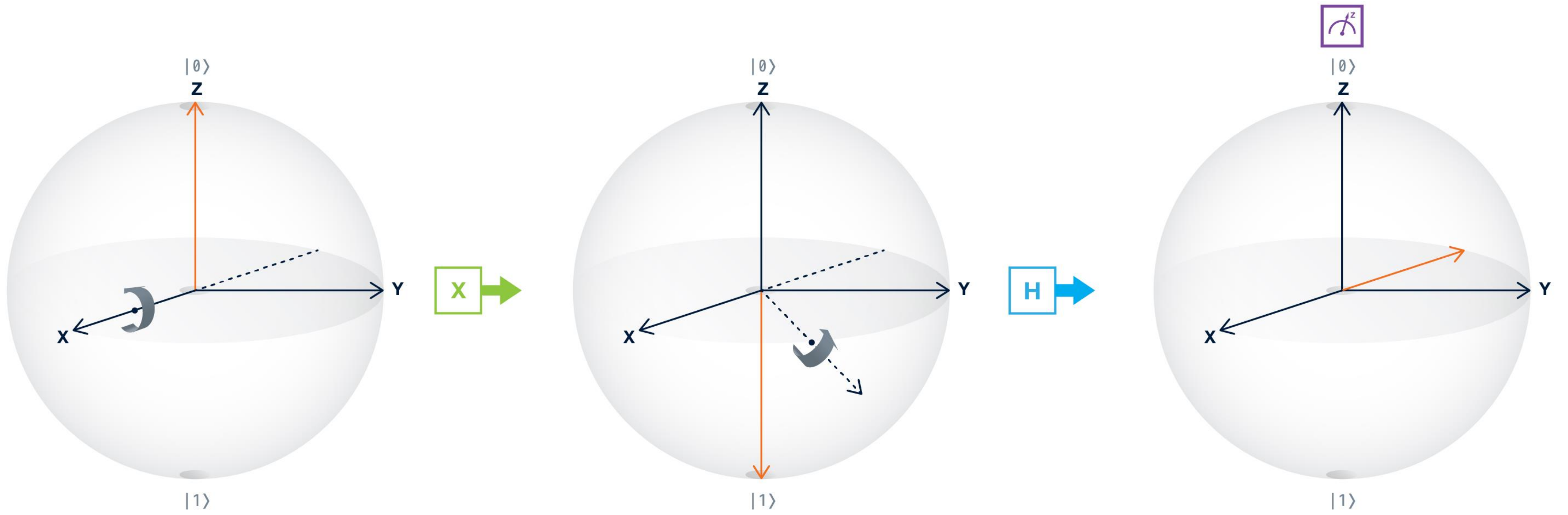
http://pacificsource.net/wp-content/uploads/2016/02/free-shipping-led-light-dimmer-switch-220v-led-bulbs-dimmer-dimmer-switch-for-led-lights.jpg

Schrödinger's cat



- Source: wikipedia.org

Measurement collapses superposition



https://quantumexperience.ng.bluemix.net/proxy/tutorial/beginners-guide/005-Single-Qubit_Gates/002-Creating_superposition.html

Measurement collapses superposition

https://quantumexperience.ng.bluemix.net/proxy/tutorial/beginners-guide/005-Single-Qubit_Gates/002-Creating_superposition.html

Quantum Darwinism

No cloning theorem

It’s all about vectors, matricies and probability

$$Q_s = \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$

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$$|\alpha|^2 + |\beta|^2 = 1$$

It’s all about vectors, matricies and probability

$$Q_s = \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$

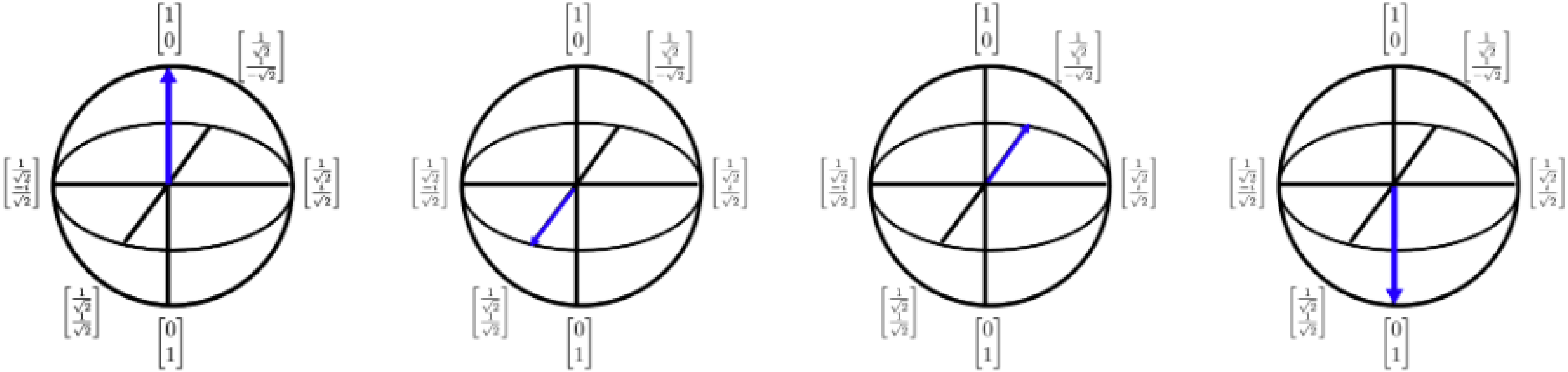
$$|\alpha|^2 + |\beta|^2 = 1$$

$$\begin{bmatrix} 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix}, \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{-1}{\sqrt{2}} \end{bmatrix}, \text{and} \begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{i}{\sqrt{2}} \end{bmatrix}$$

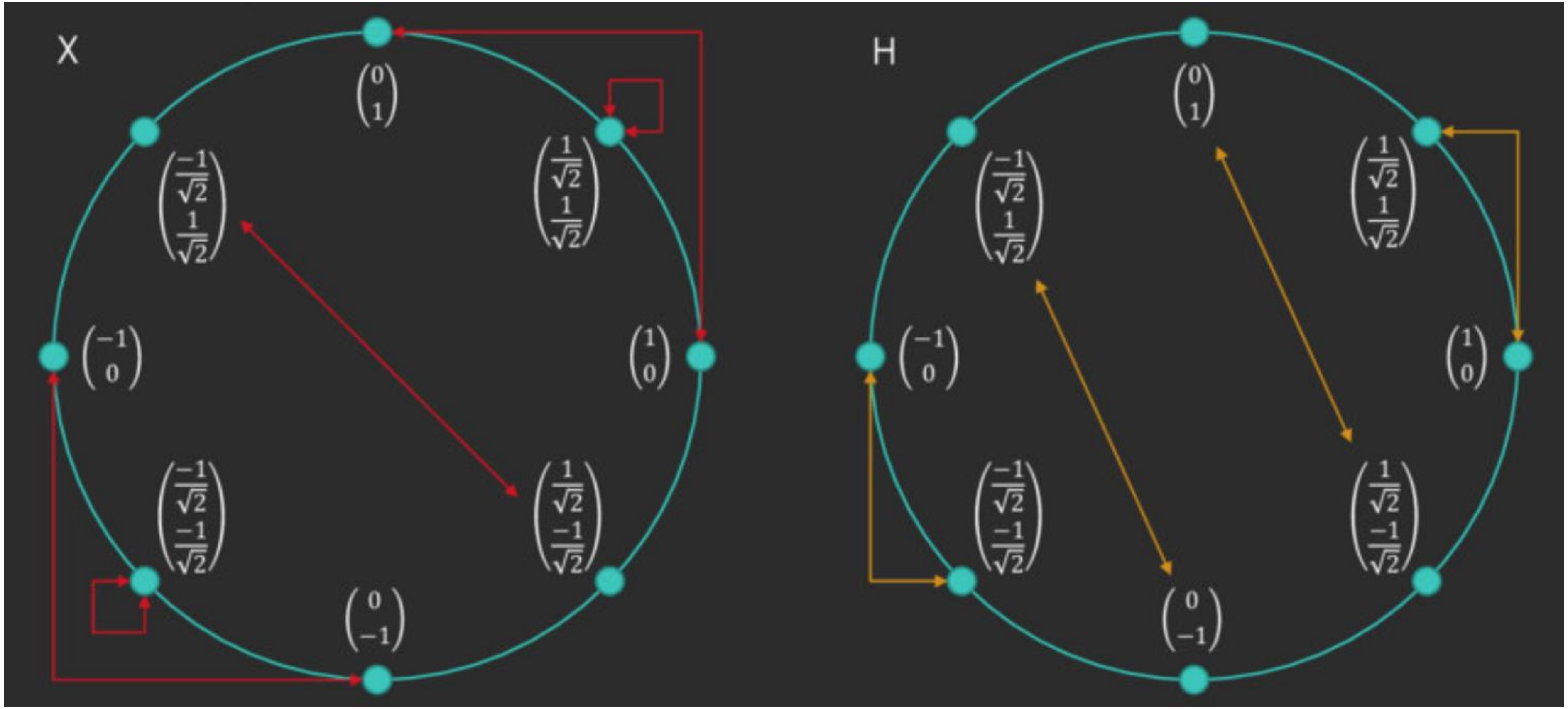
It’s all about vectors, matricies and probability

$$0 \equiv \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \qquad 1 \equiv \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

Bloch sphere



Unit cricle state machine



https://speakerdeck.com/ahelwer/quantum-computing-for-computer-scientists?slide=20

Dirac Notation

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

Dirac Notation

$$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix} = \mathrm{H}|0\rangle = |+\rangle = (|0\rangle + |1\rangle)$$

$$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix} = \mathrm{H}|1\rangle = |-\rangle = (|0\rangle - |1\rangle)$$

Representing Two Qubits

$$00 \equiv \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}1\\0\\0\\0\end{bmatrix}, \qquad 01 \equiv \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = \begin{bmatrix}0\\1\\0\\0\end{bmatrix},$$

$$10 \equiv \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}0\\0\\1\\0\end{bmatrix}, \qquad 11 \equiv \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = \begin{bmatrix}0\\0\\0\\1\end{bmatrix}$$

Representing Two Qubits

$$\begin{bmatrix}\alpha\\ \beta\end{bmatrix} \otimes \begin{bmatrix}\gamma\\ \delta\end{bmatrix} = \begin{bmatrix}\alpha * \gamma\\ \alpha * \delta\\ \beta * \gamma\\ \beta * \delta\end{bmatrix} \Rightarrow \; 2^n, where\ n = number\ of\ qubits$$

$$|\alpha|^2 + |\beta|^2 + |\gamma|^2 \; + |\delta|^2 = 1$$

$$0{,}25 + 0{,}25 + 0{,}25 + 0{,}25 = 1$$

Dirac Notation Two Qubits

$$00 \equiv \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}1\\0\\0\\0\end{bmatrix}, = |00\rangle, \qquad 01 \equiv \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = \begin{bmatrix}0\\1\\0\\0\end{bmatrix}, = |01\rangle,$$

$$10 \equiv \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}0\\0\\1\\0\end{bmatrix}, = |10\rangle, \qquad 01 \equiv \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = \begin{bmatrix}0\\0\\0\\1\end{bmatrix}, = |11\rangle$$

Dirac Notation Four Qubits

$$|0100\rangle = \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}0\\0\\0\\0\\1\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\end{bmatrix} \begin{array}{l}0000\\0001\\0010\\0011\\0100\\0101\\0110\\0111\\1000\\1001\\1010\\1011\\1100\\1101\\1110\\1111\end{array}$$

And going on…

$$|01000\rangle = \begin{array}{c} 00000 \\ 00001 \\ 00010 \\ 00011 \\ 00100 \\ 00101 \\ 00110 \\ 00111 \\ 01000 \\ 01001 \\ 01010 \\ 01011 \\ 01100 \\ 01101 \\ 01110 \\ 01111 \\ 10000 \\ 10001 \\ 10010 \\ 10011 \\ 10100 \\ 10101 \\ 10110 \\ 10111 \\ 11000 \\ 11001 \\ 11010 \\ 11011 \\ 11100 \\ 11101 \\ 11110 \\ 11111 \end{array} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

And going on…

$$|010000\rangle = \begin{array}{c} 000000 \\ 000001 \\ 000010 \\ 000011 \\ 000100 \\ 000101 \\ 000110 \\ 000111 \\ 001000 \\ 001001 \\ 001010 \\ 001011 \\ 001100 \\ 001101 \\ 001110 \\ 001111 \\ 010000 \\ 010001 \\ 010010 \\ 010011 \\ 010100 \\ 010101 \\ 010110 \\ 010111 \\ 011000 \\ 011001 \\ 011010 \\ 011011 \\ 011100 \\ 011101 \\ 011110 \\ 011111 \end{array} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\left[\begin{array}{c}0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\\0\end{array}\right]\begin{array}{l}100000\\100001\\100010\\100011\\100100\\100101\\100110\\100111\\101000\\101001\\101010\\101011\\101100\\101101\\101110\\101111\\110000\\110001\\110010\\110011\\110100\\110101\\110111\\111000\\111001\\111010\\111011\\111100\\111101\\111111\end{array}$$

Simulation - memory restrictions

Number of qubits	5	10	20	21
Memory Usage (state vector)	512 B	16 kB	16 MB	32 MB
Memory Usage (operation matrix)	16 kB	16 MB	16 TB	64 TB

Numerical Linear Algebra Methods is the most general technique for simulating the time evolution of a quantum system based on solving the Schrödinger's equation. For this purpose, it exploits methods such as matrix diagonalization, Chebyshev Polynomial Algorithm, Short-Iterative Lanczos Algorithm [26], or Suzuki-Trotter Product-Formula Algorithm [47]. These methods are reviewed and compared in [40]. Depending on the method, it requires from $O(2^n)$ to $O(2^{2n})$ memory. The latter, with memory and computational complexity of $O(2^n)$, is used by `Quantum Computer`

https://www.researchgate.net/publication/275258051/figure/tbl1/AS:667895277293570@1536250051176/usage-of-quantum-computing-simulation-system-based-on-matrix-vector-representation.png

Copenhagen interpretation

Einstein vs Bohr – EPR paradox

- Einstein believed that there has to be „hidden local variable” we don’t know yet and the quanutm mechanics is „incomplete”
- To show the silliness of Bohr’s idea, they stated, that we have to abbandon the principle of locality – fundamental principle to Einstein’s relativity theorem – that would break the assumption, that there cannot be anything faster than the speed of light

Entanglement

„Spooky action at a distance”

Bell Inequality

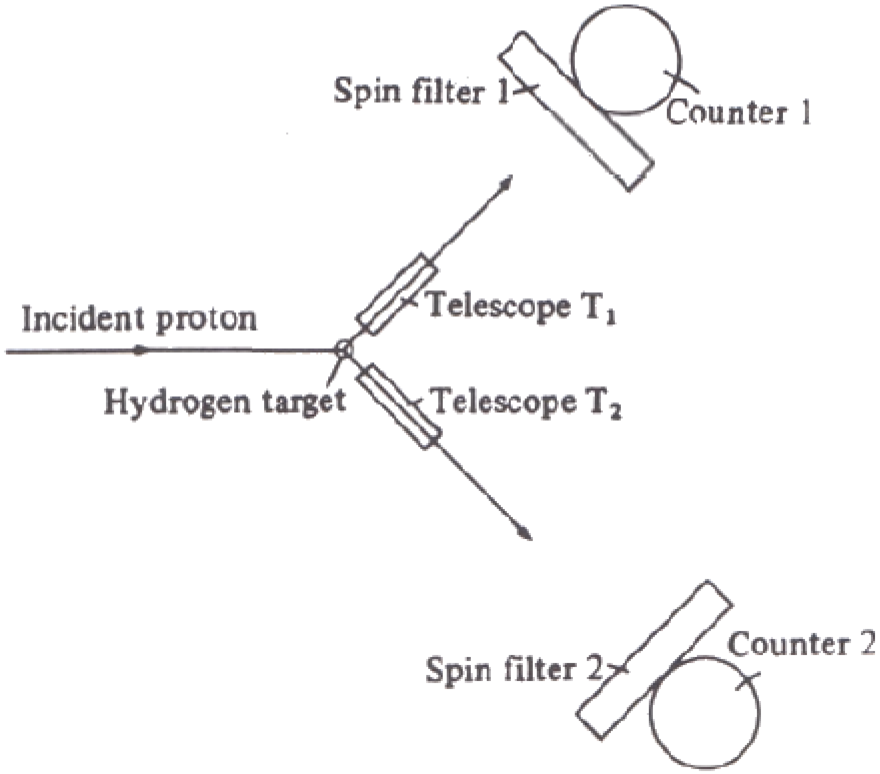
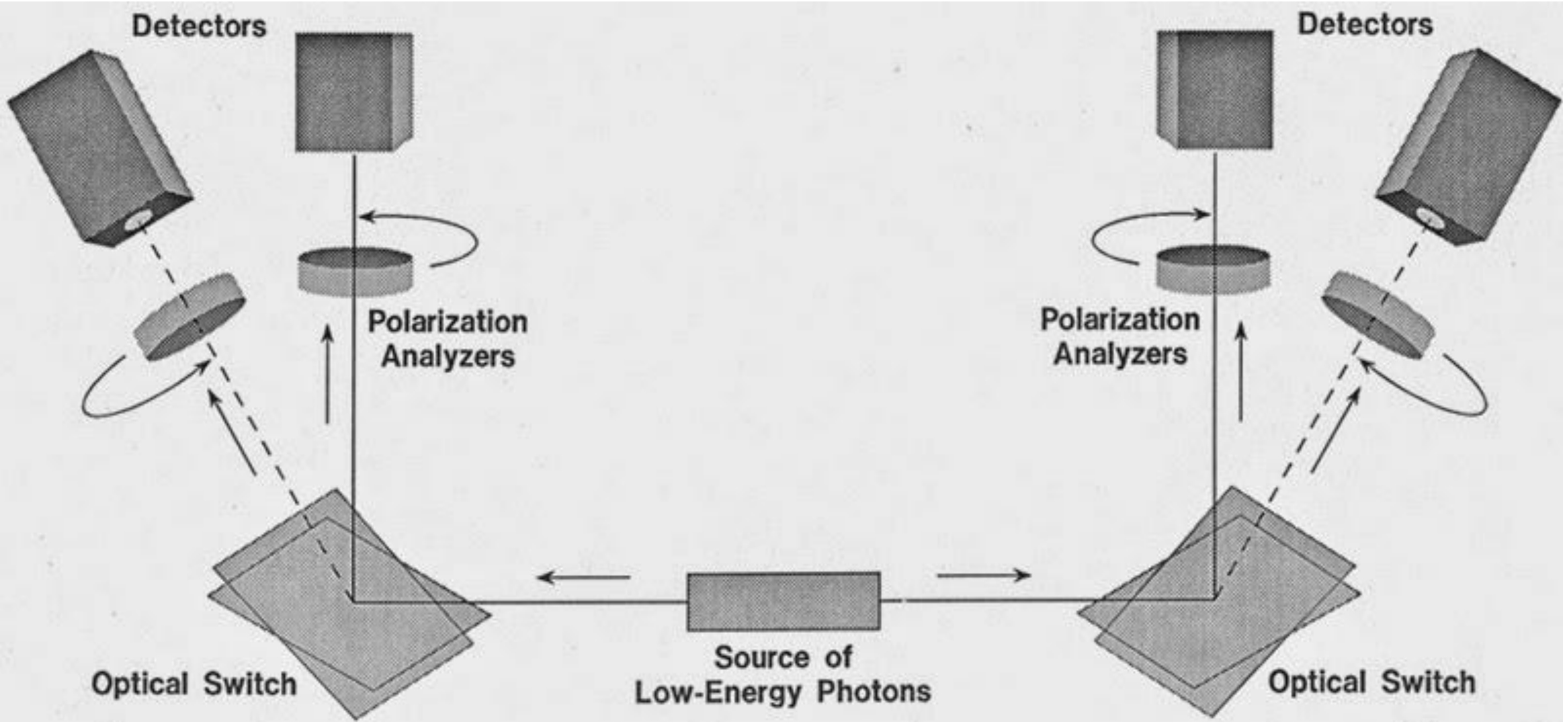
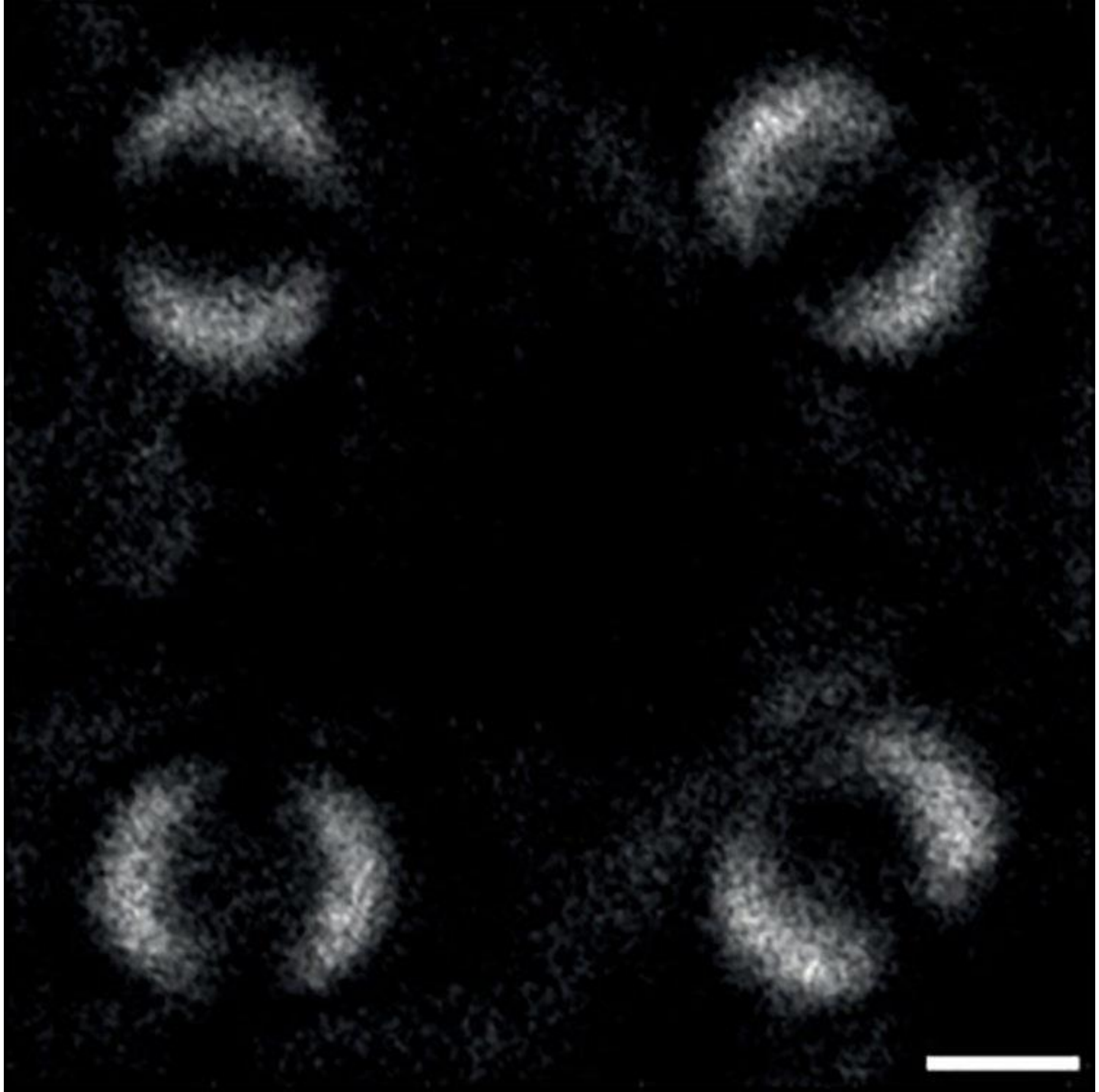


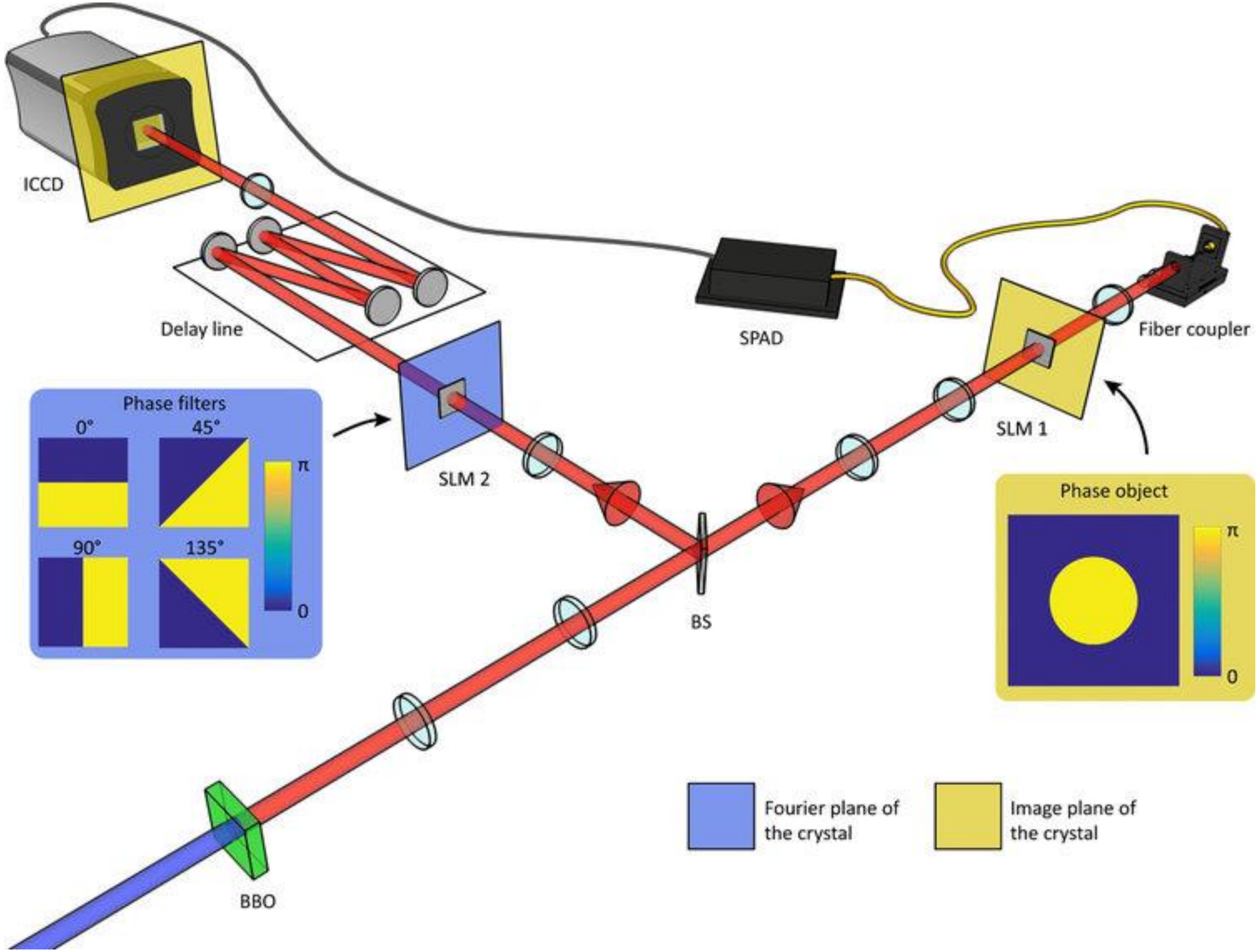
Fig. 1. Proton–proton scattering gedanken experiment.

Bell Inequality and Alain Aspect Ph.D. thesis





https://www.businessinsider.com/quantum-entanglement-einstein-first-picture-2019-7?IR=T



https://www.businessinsider.com/quantum-entanglement-einstein-first-picture-2019-7?IR=T

Gates & operations

U1 — The first physical gate of the Quantum Experience. It is a one parameter single-qubit phase gate with zero duration.

QASM Matrix

U2 — The second physical gate of the Quantum Experience. It is a two parameter single-qubit gate with duration one unit of time.

QASM Matrix

U3 — The third physical gate of the Quantum Experience. It is a three-parameter single-qubit gate with duration 2 units of gate time.

QASM Matrix

id — The identity gate performs an idle operation on the qubit for a time equal to one unit of time.

QASM Matrix

X — The Pauli X gate is a π-rotation around the X axis and has the property that $X \to X$, $Z \to -Z$. Also referred to as a bit-flip.

QASM Matrix

Y — The Pauli Y gate is a π-rotation around the Y axis and has the property that $X \to -X$, $Z \to -Z$. This is both a bit-flip and a phase-flip, and satisfies $Y = XZ$.

QASM Matrix

Z — The Pauli Z gate is a π-rotation around the Z axis and has the property that $X \to -X$, $Z \to Z$. Also referred to as a phase-flip.

QASM Matrix

H — The Hadamard gate has the property that it maps $X \to Z$, and $Z \to X$. This gate is required to make superpositions.

QASM Matrix

S — The Phase gate that is $\sqrt{Z}$ and has the property that it maps $X \to Y$ and $Z \to Z$. This gate extends H to make complex superpositions.

QASM Matrix

$S^\dagger$ — The Phase gate that is the transposed conjugate of S and has the property that it maps $X \to -Y$, and $Z \to Z$.

QASM Matrix

+ — Controlled-NOT gate: a two-qubit gate that flips the target qubit (i.e. applies Pauli X) if the control is in state 1. This gate is required to generate entanglement and is the physical two qubit gate.

QASM Matrix

T — The Phase gate that is $\sqrt{S}$, which is a $\pi/4$ rotation around the Z axis. This gate is required for universal control.

QASM Matrix

$T^\dagger$ — The Phase gate that is the transposed conjugate of T.

QASM Matrix

The barrier prevents transformations across this source line.

QASM Matrix

Measurement in the computational (standard) basis (Z).

QASM Matrix

if — Conditionally apply quantum operation

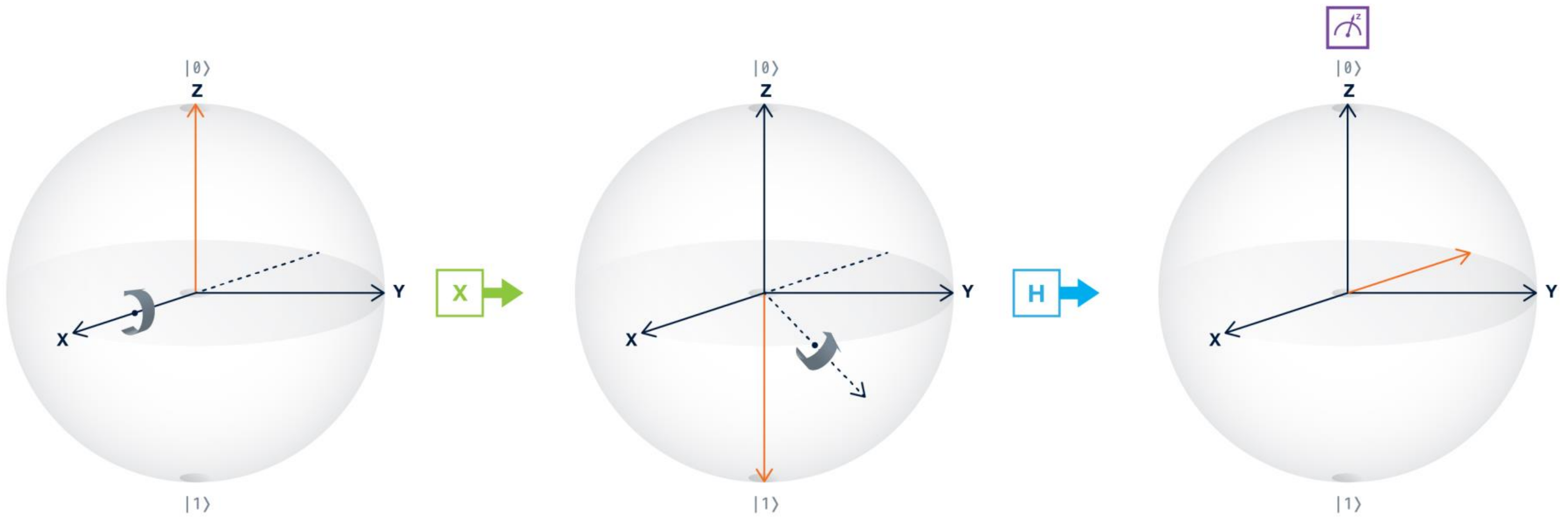
QASM Matrix

$|0\rangle$ — Prepare qubits in the $|0\rangle$ state.

QASM Matrix

https://quantumexperience.ng.bluemix.net/qx/editor

Bloch sphere after applying gates



https://quantumexperience.ng.bluemix.net/proxy/tutorial/beginners-guide/005-Single-Qubit_Gates/002-Creating_superposition.html

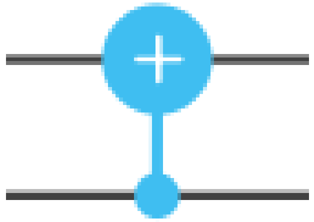
Gates & operactions

Controlled-NOT gate: a two-qubit gate that flips the target qubit (i.e. applies Pauli X) if the control is in state 1. This gate is required to generate entanglement and is the physical two qubit gate.

https://quantumexperience.ng.bluemix.net/qx/editor

CNOT

$$\mathrm{CNOT} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}.$$

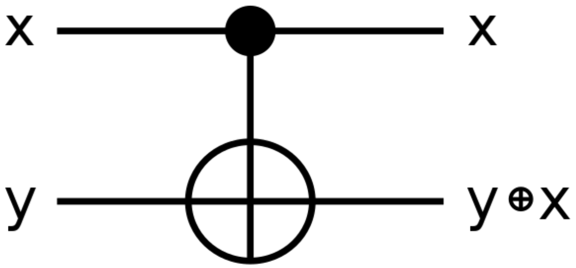


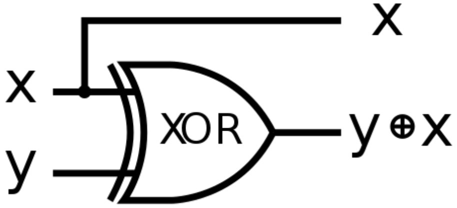
Before		After	
Control	Target	Control	Target
$\|0\rangle$	$\|0\rangle$	$\|0\rangle$	$\|0\rangle$
$\|0\rangle$	$\|1\rangle$	$\|0\rangle$	$\|1\rangle$
$\|1\rangle$	$\|0\rangle$	$\|1\rangle$	$\|1\rangle$
$\|1\rangle$	$\|1\rangle$	$\|1\rangle$	$\|0\rangle$

https://quantumexperience.ng.bluemix.net/qx/editor
https://en.wikipedia.org/wiki/Controlled_NOT_gate

CNOT

$$\mathrm{CNOT} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}.$$



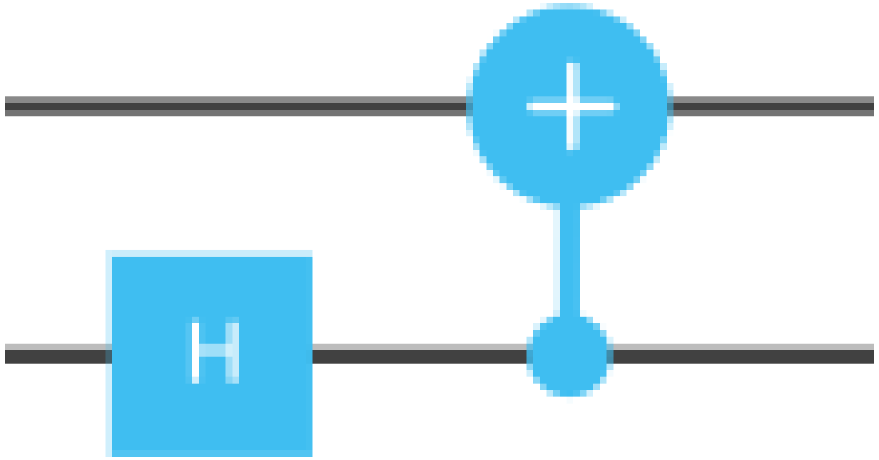


input		output	
x	y	x	y+x
$\|0\rangle$	$\|0\rangle$	$\|0\rangle$	$\|0\rangle$
$\|0\rangle$	$\|1\rangle$	$\|0\rangle$	$\|1\rangle$
$\|1\rangle$	$\|0\rangle$	$\|1\rangle$	$\|1\rangle$
$\|1\rangle$	$\|1\rangle$	$\|1\rangle$	$\|0\rangle$

input		output	
x	y	x	y+x
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0

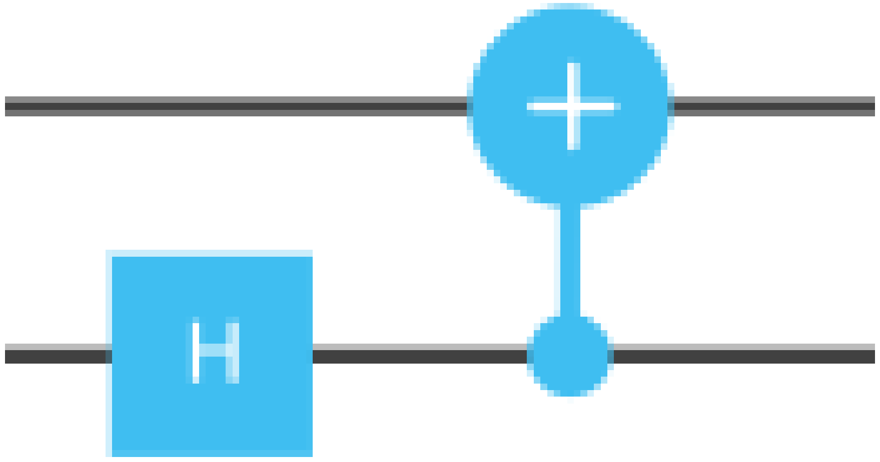
https://quantumexperience.ng.bluemix.net/qx/editor
https://en.wikipedia.org/wiki/Controlled_NOT_gate

CNOT



https://quantumexperience.ng.bluemix.net/qx/editor
https://en.wikipedia.org/wiki/Controlled_NOT_gate

CNOT

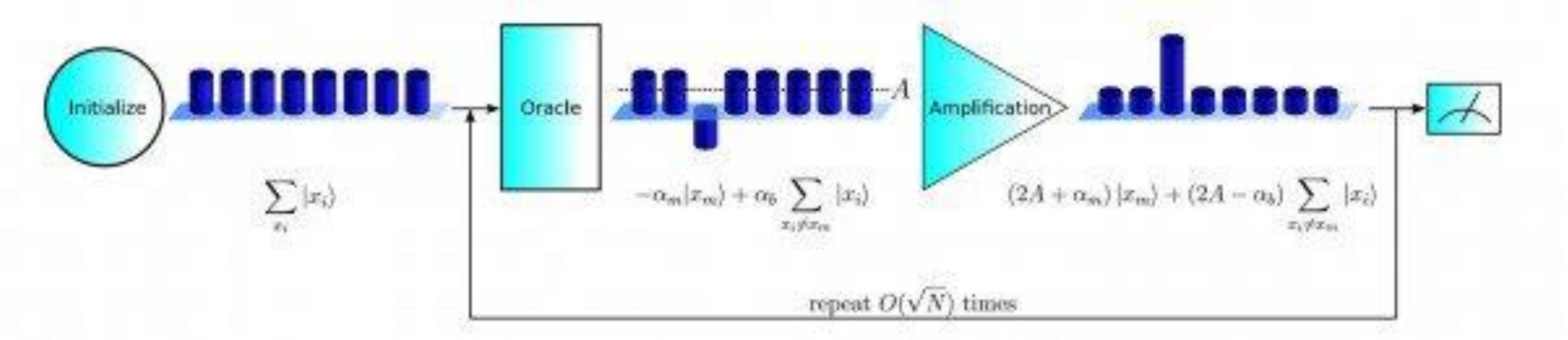


= Entanglement =

$$\begin{bmatrix} \frac{1}{\sqrt{4}} \\ \frac{1}{\sqrt{4}} \\ \frac{1}{\sqrt{4}} \\ \frac{1}{\sqrt{4}} \end{bmatrix}$$

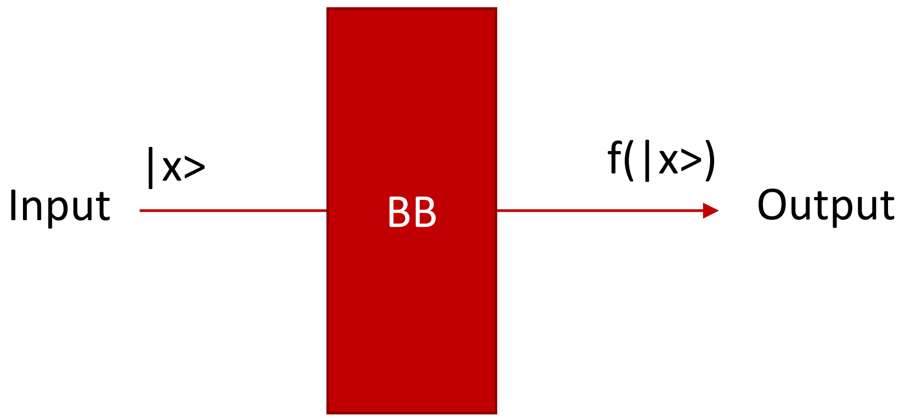
https://quantumexperience.ng.bluemix.net/qx/editor
https://en.wikipedia.org/wiki/Controlled_NOT_gate

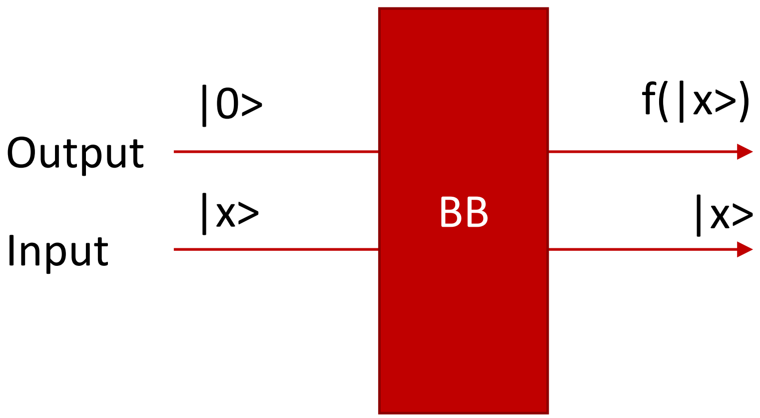
Oracles



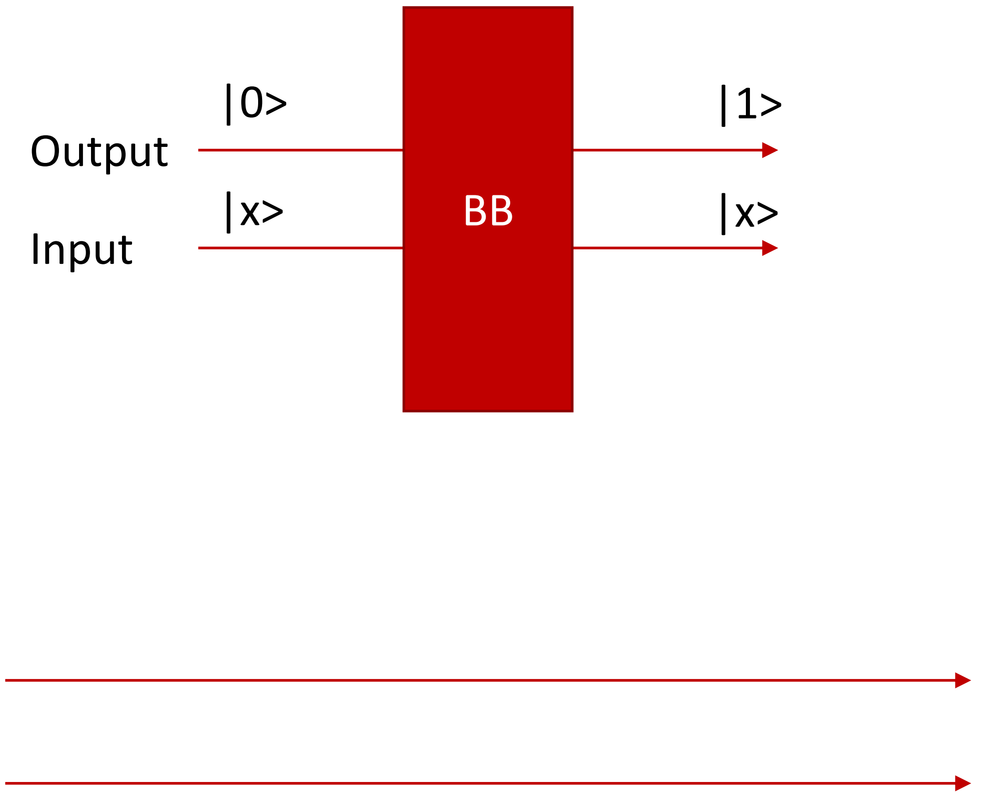
https://cdn.technologyreview.com/i/images/grovers-algorithm.jpg?sw=600&cx=0&cy=0&cw=2036&ch=451

Deutsch Oracles

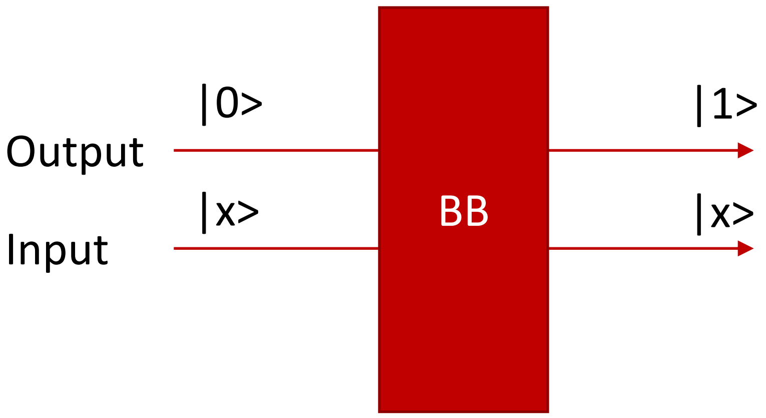


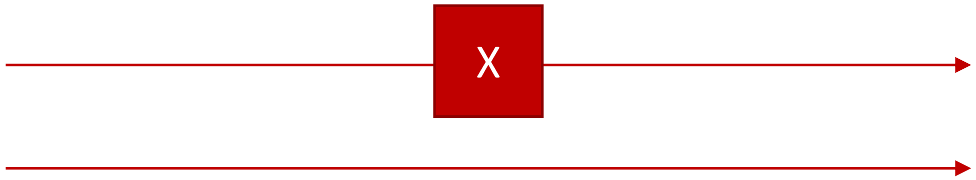


Deutsch Oracles

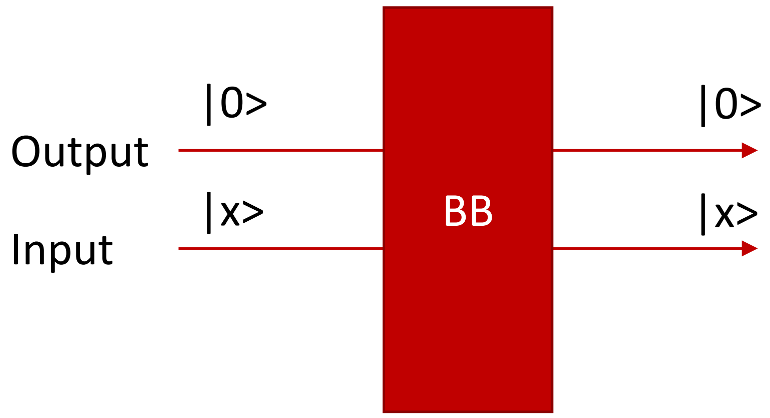


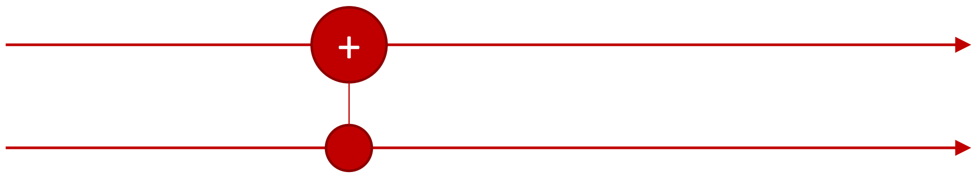
Deutsch Oracles



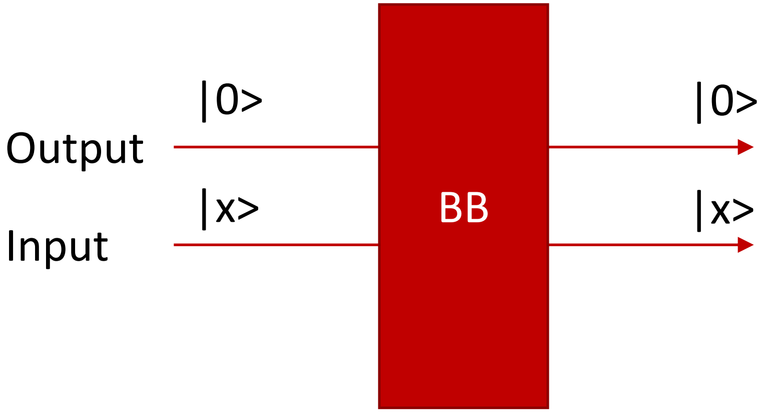


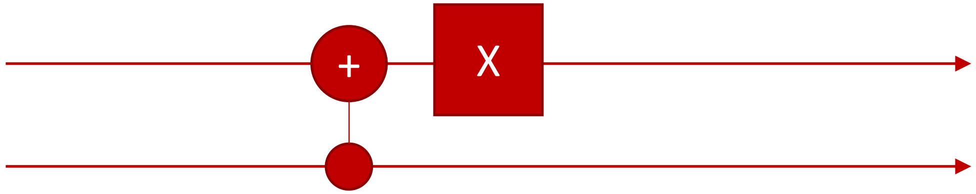
Deutsch Oracles

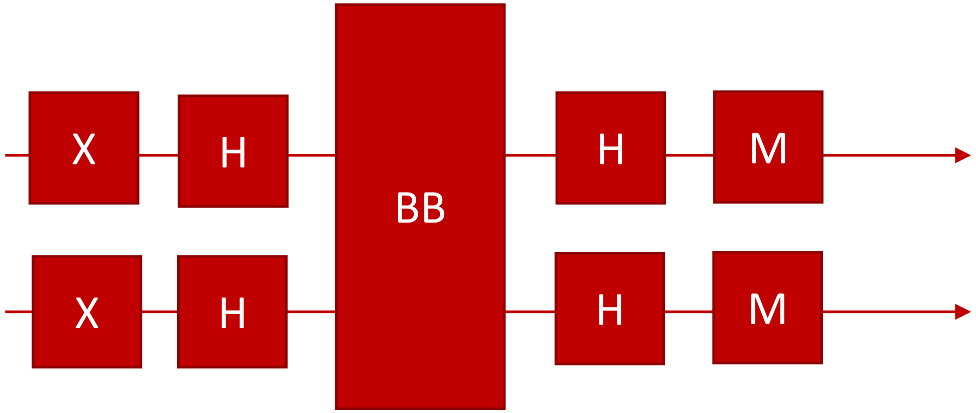




Deutsch Oracles



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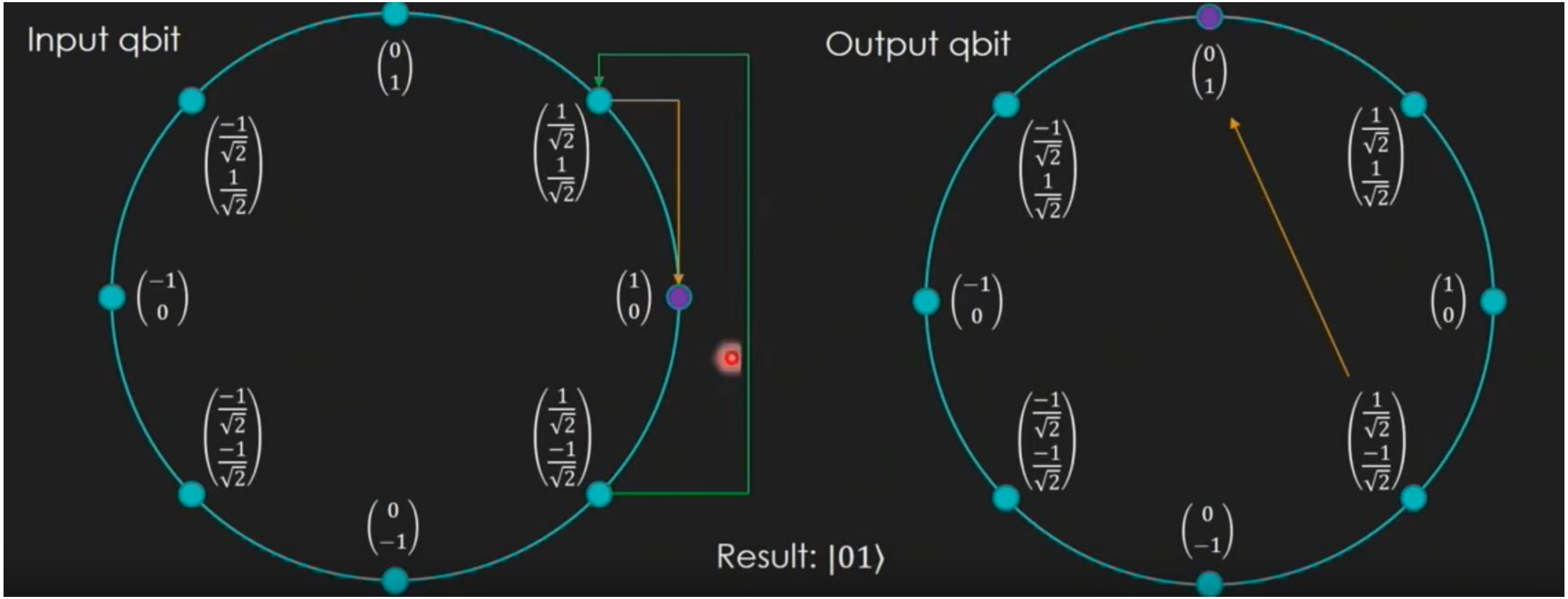


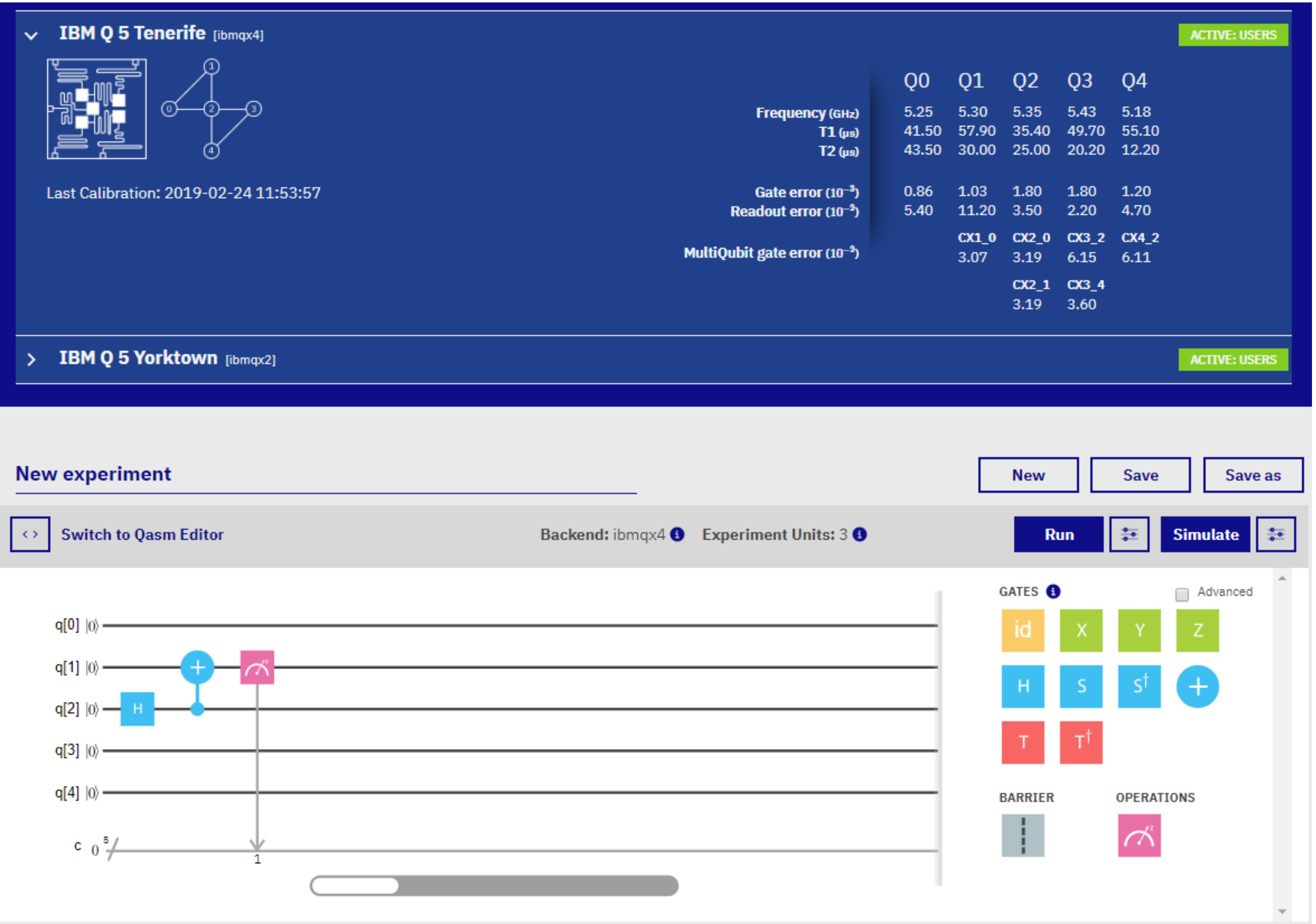
https://speakerdeck.com/ahelwer/quantum-computing-for-computer-scientists

$$C\left(\begin{pmatrix}\frac{1}{\sqrt{2}}\\ \frac{-1}{\sqrt{2}}\end{pmatrix}\otimes\begin{pmatrix}\frac{1}{\sqrt{2}}\\ \frac{-1}{\sqrt{2}}\end{pmatrix}\right)=C\begin{pmatrix}\frac{1}{2}\\ \frac{-1}{2}\\ \frac{-1}{2}\\ \frac{1}{2}\end{pmatrix}=\frac{1}{2}\begin{pmatrix}1&0&0&0\\0&1&0&0\\0&0&0&1\\0&0&1&0\end{pmatrix}\begin{pmatrix}1\\-1\\-1\\1\end{pmatrix}=\frac{1}{2}\begin{pmatrix}1\\-1\\1\\-1\end{pmatrix}=\begin{pmatrix}\frac{1}{\sqrt{2}}\\ \frac{1}{\sqrt{2}}\end{pmatrix}\otimes\begin{pmatrix}\frac{1}{\sqrt{2}}\\ \frac{-1}{\sqrt{2}}\end{pmatrix}$$

https://speakerdeck.com/ahelwer/quantum-computing-for-computer-scientists

Intro with examples – Q#

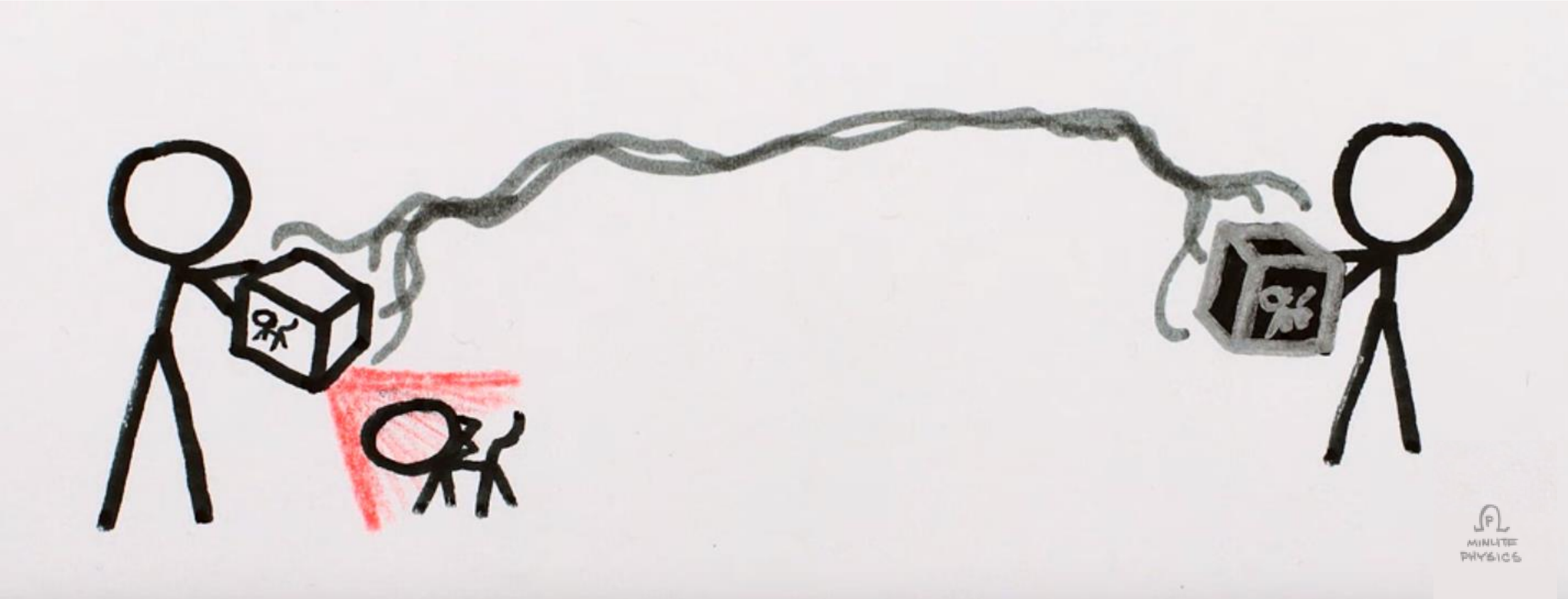
You can play with real quantum computer!



https://quantumexperience.ng.bluemix.net

Teleportation (simplified)

Teleportation (simplified)



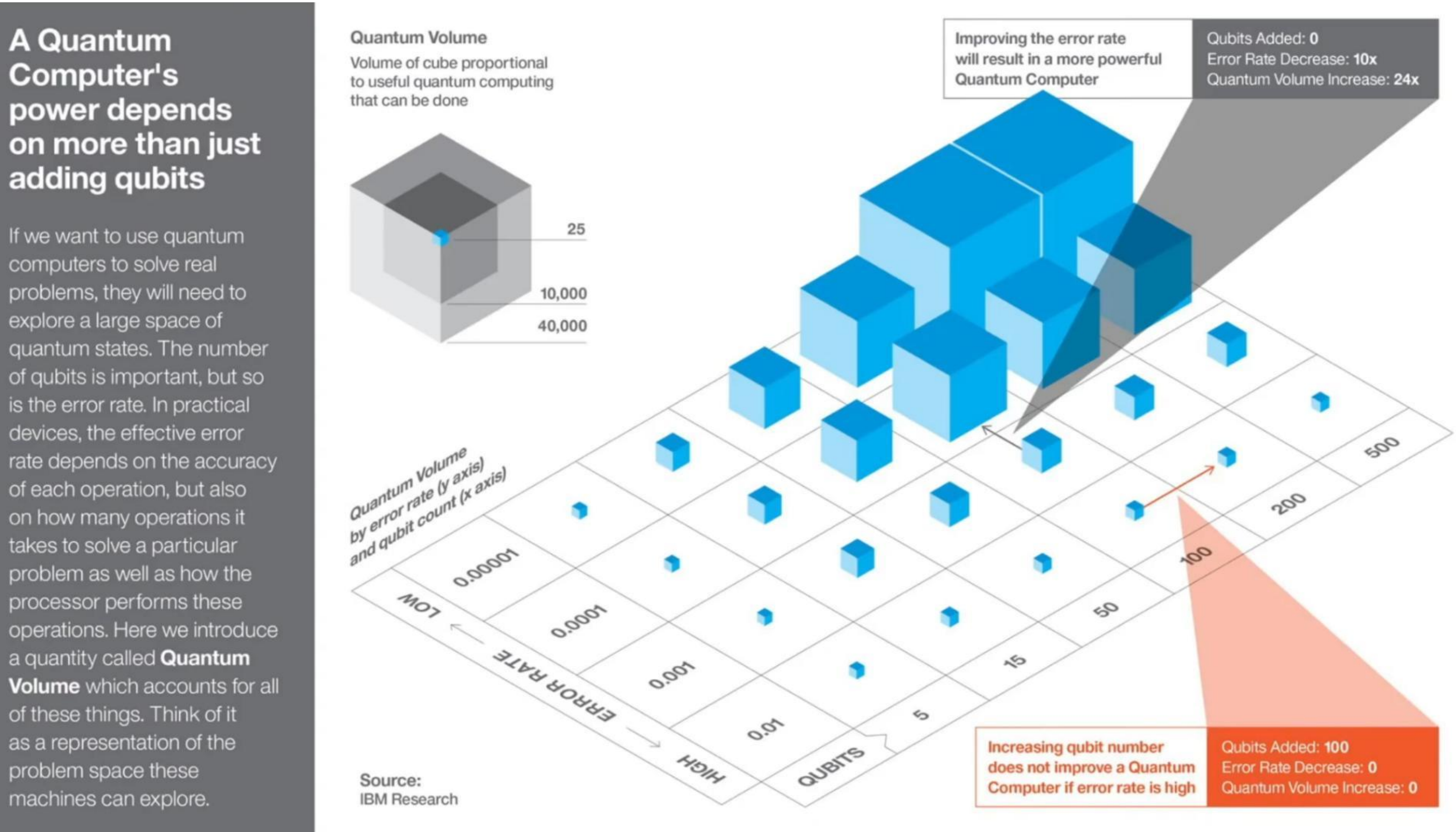
https://youtu.be/DxQK1WDYI_k?t=224 ->
Channel: minutephysics
Video: How to Teleport Schrödinger's Cat

Teleportation – Q# example

Qutrit teleportation == more with less

Our biggest enemy - Error corretion

https://i.stack.imgur.com/ekkrL.jpg



True power of quantum

- Chemistry
- Materials science
- Financial
- Machine learning
- Biology
- … and many, many more

Summary

- There is no magic in here, only probability. You can calculate everything on paper using vectors and matricies.
- It’s difficult to design algorithms
- It’s Coprocessor
- All we do is computing probability and we have to recompute it multiple times to get the best solution
- Classical computers aren’t going anywhere
- We just started this journey – there’s a lot things to discover, understand and improve

https://github.com/microsoft/qsharp-compiler

More information

- https://docs.microsoft.com/en-us/quantum/for-more-info?view=qsharp-preview
- https://quantumexperience.ng.bluemix.net/qx/tutorial?sectionId=full-user-guide&page=introduction
- Microsoft Research YouTube channel
- Microsoft Mechanics YouTube channel
- MIT OpenCourseWave YouTube channel - MIT 8.04 Quantum Physics I, Spring 2013

About me

- Lead Software Engineer at Sopra Steria
- Co-Founder of Silesian Microsoft Group

https://github.com/dominikprzywara

Questions?

https://github.com/dominikprzywara/QSharpExamples

Thanks!