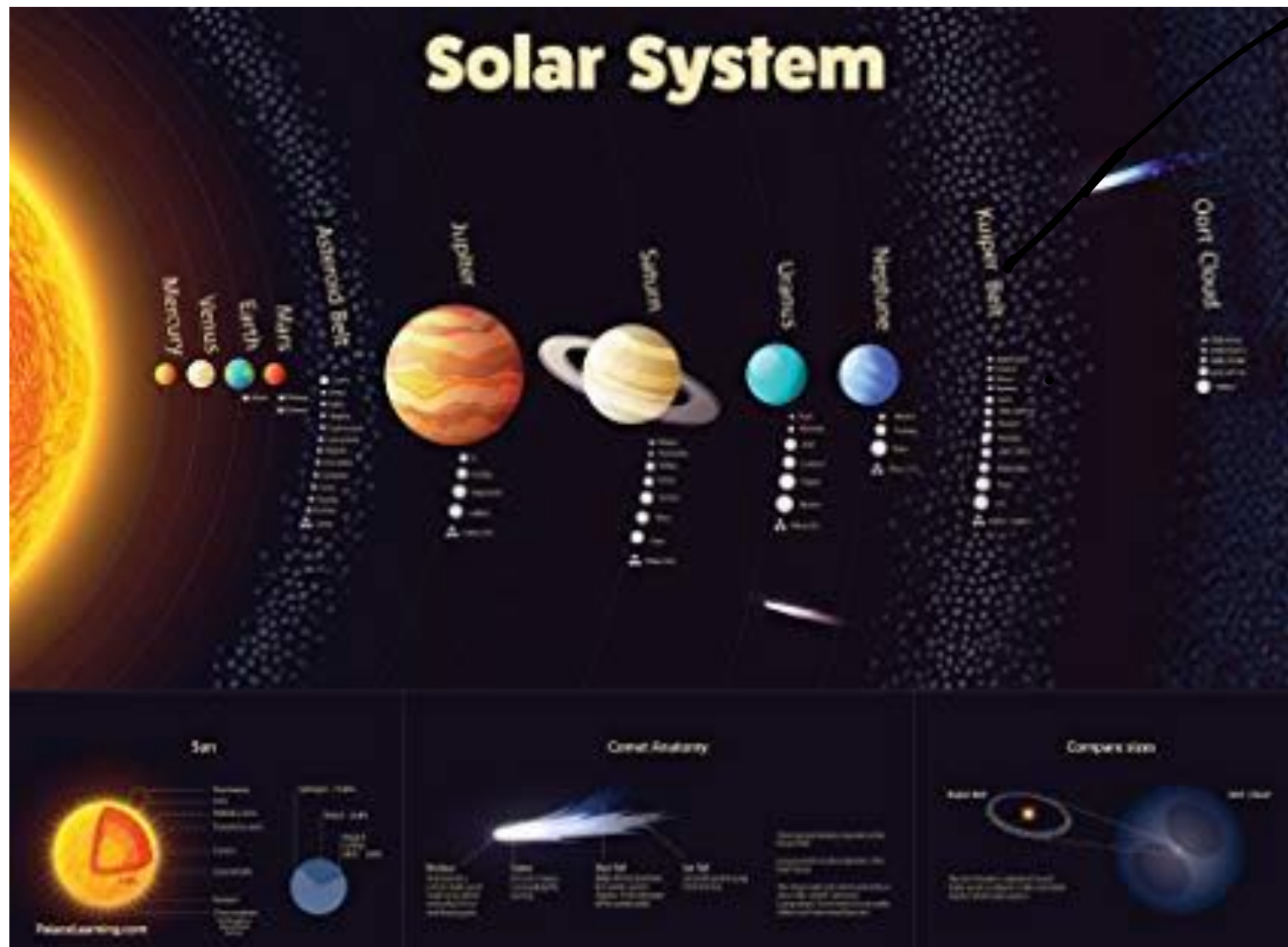


The background is a vibrant blue digital landscape. On the left, a portion of a globe is visible, showing continents and oceans. The foreground is dominated by a grid of binary code (0s and 1s) that recedes into the distance, creating a sense of depth. On the right side, there are dynamic, glowing light trails and a bright light source that creates a lens flare effect, suggesting high-speed data or quantum processes.

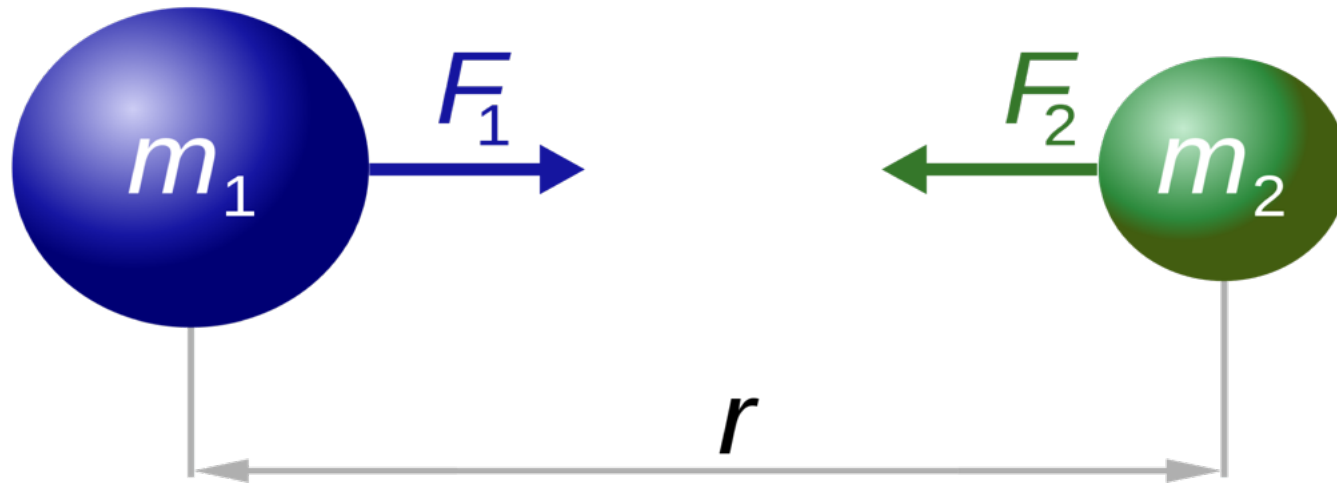
The Quantum World: Information, Communication and Computing

Arnold Sommerfeld Lectures (Munich 2023)

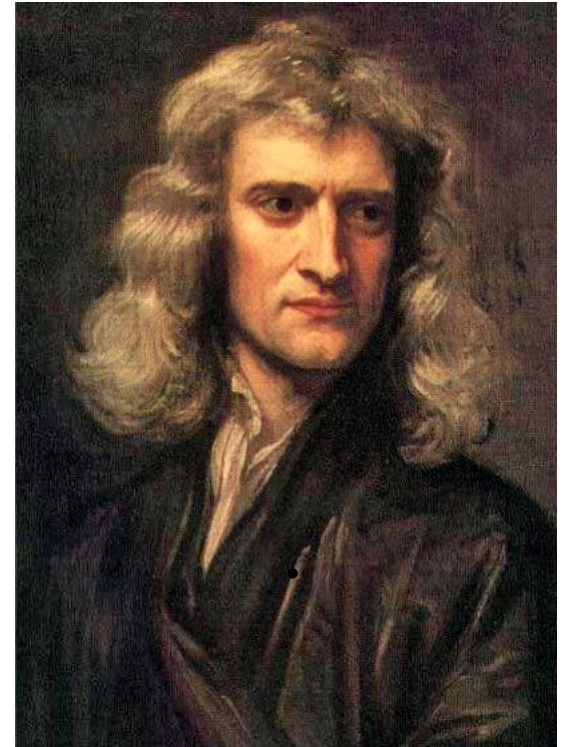
The Classical World



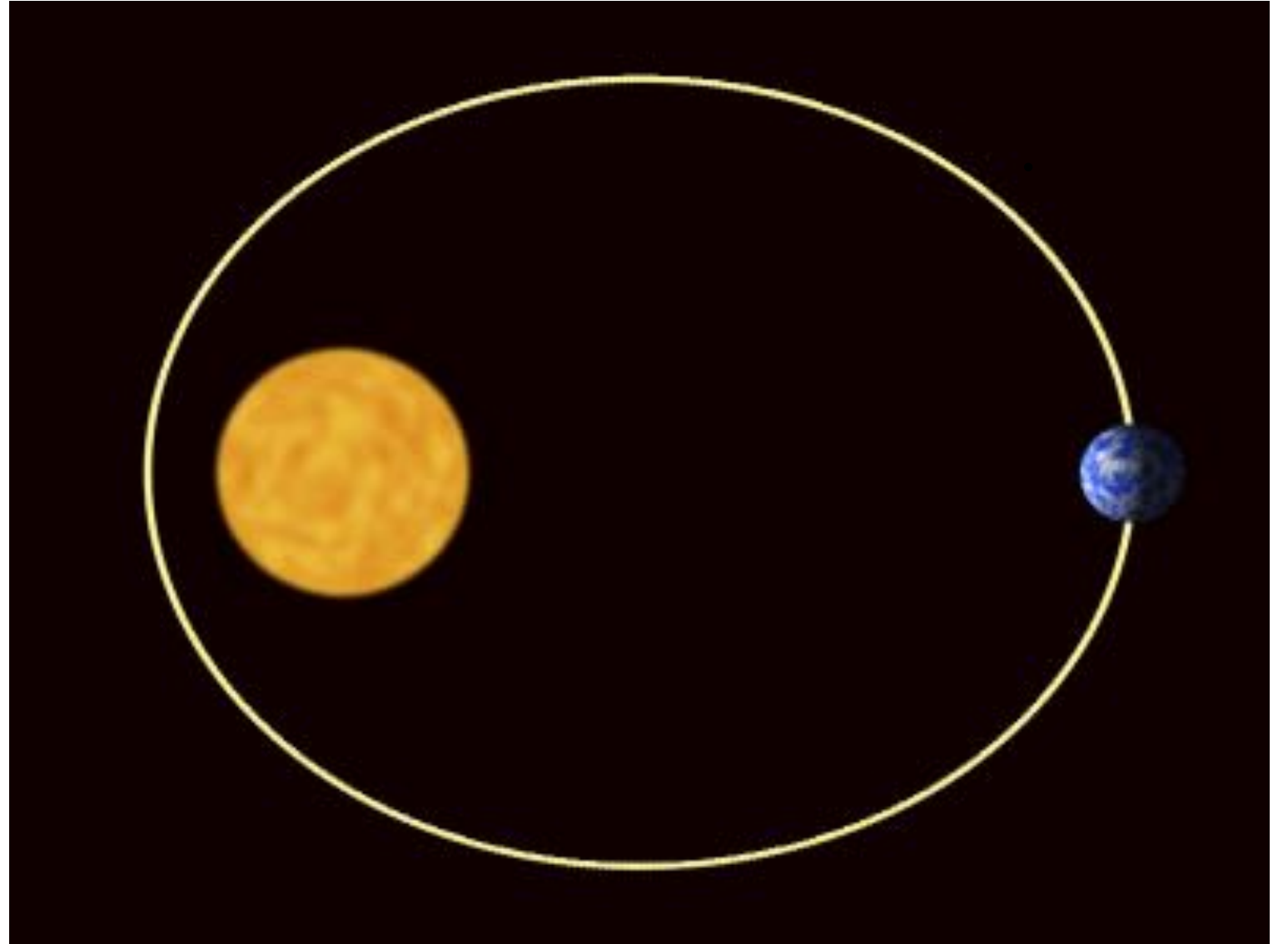
Newton Law of Gravitation



$$F_1 = F_2 = G \frac{m_1 \times m_2}{r^2}$$



The Two Body Problem



Determinism



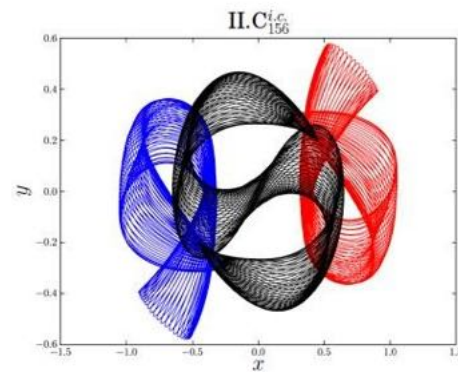
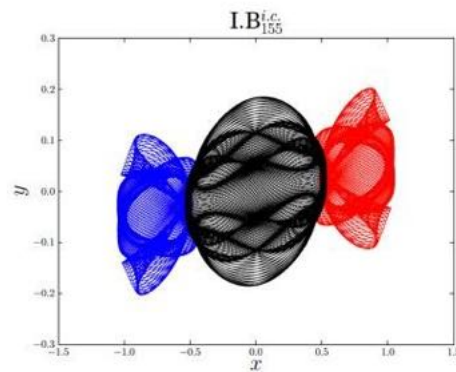
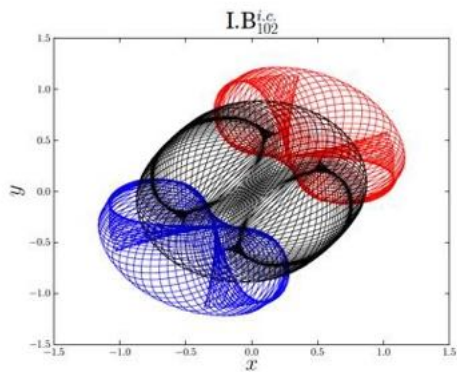
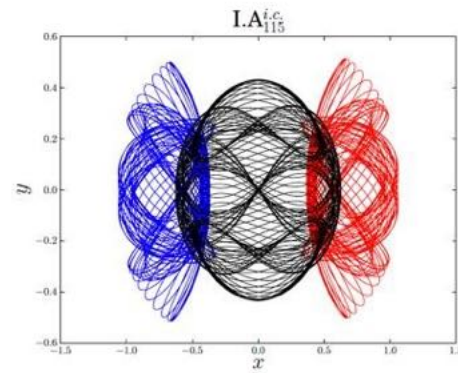
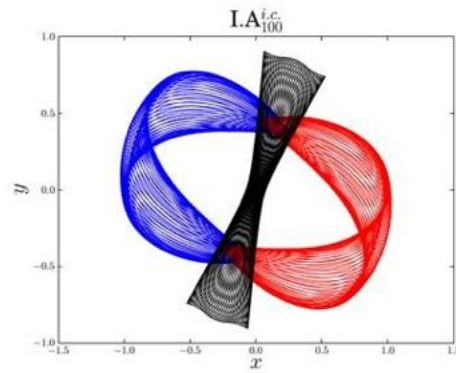
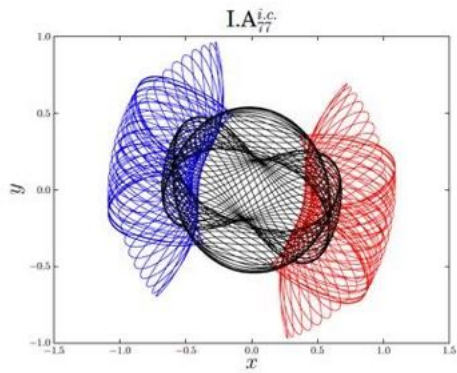
Pierre Simon Laplace
1749 – 1827

“An intelligence knowing all the forces acting in nature at a given instant, as well as the momentary positions of all things in the universe, would be able to comprehend in one single formula the motions of the largest bodies as well as the lightest atoms in the world, provided that its intellect were sufficiently powerful to subject all data to analysis; to it nothing would be uncertain, the future as well as the past would be present to its eyes”

Three Body Problem

In 1890 Poincare showed that trajectories of three-body systems are generically no-periodic. Sensitivity dependence of initial condition: chaotic dynamic systems:

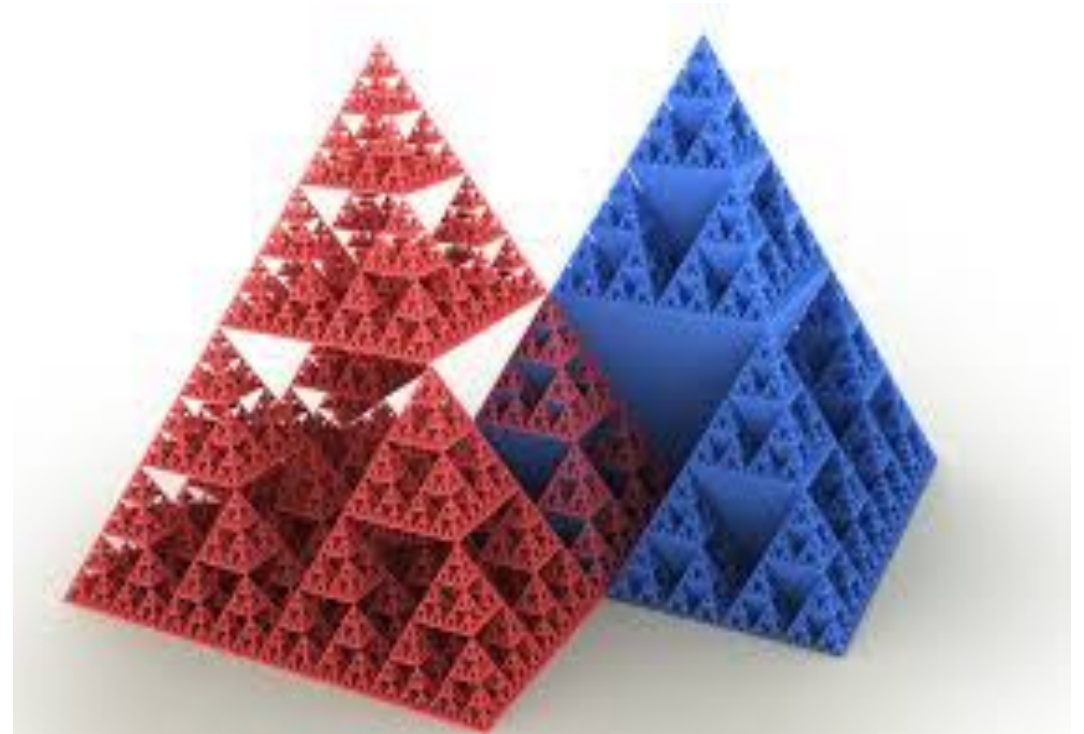
1854-1912



Characteristics of Chaos

The present determines the future, but the approximate present does not approximately determine the future.

Self-organized structures



The Butterfly Effect



"Remember that hurricane a thousand miles away? That was me!"

What Do We Know Today ?

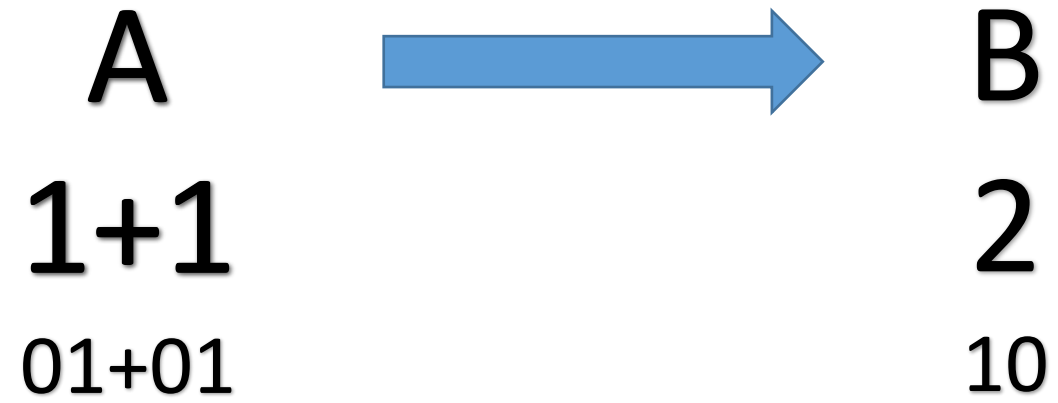
Most of the calculations agree that eight million years from now all of the planets will still be in orbits very similar to their present ones.

After a few tens of millions of years, calculations using slightly different parameters begin to diverge.

Shifting the pencil from one side the desk to the other today could change the gravitational forces on Jupiter enough to shift its position from one side of the Sun to the other a billion years from now.

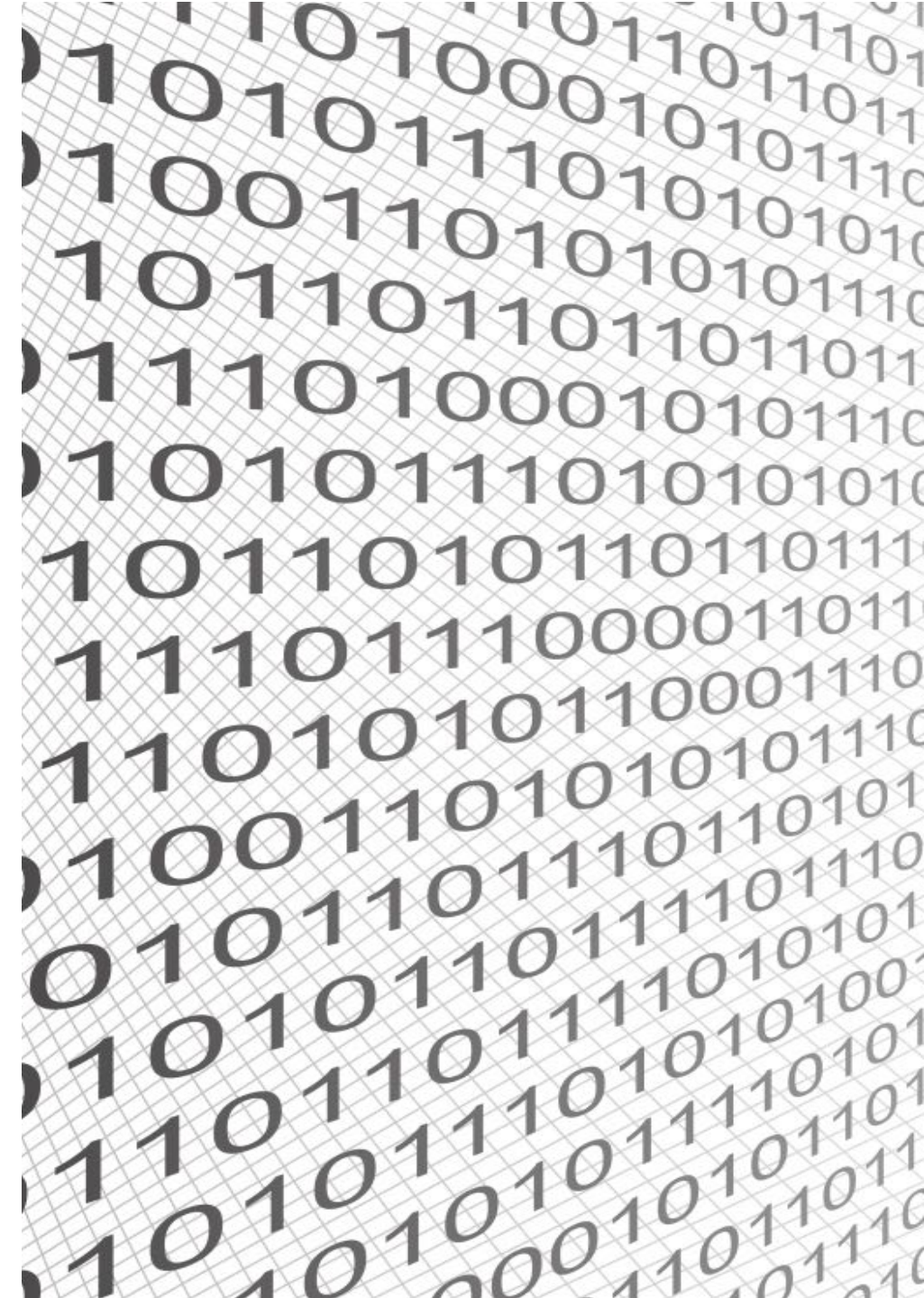


Classical Calculation

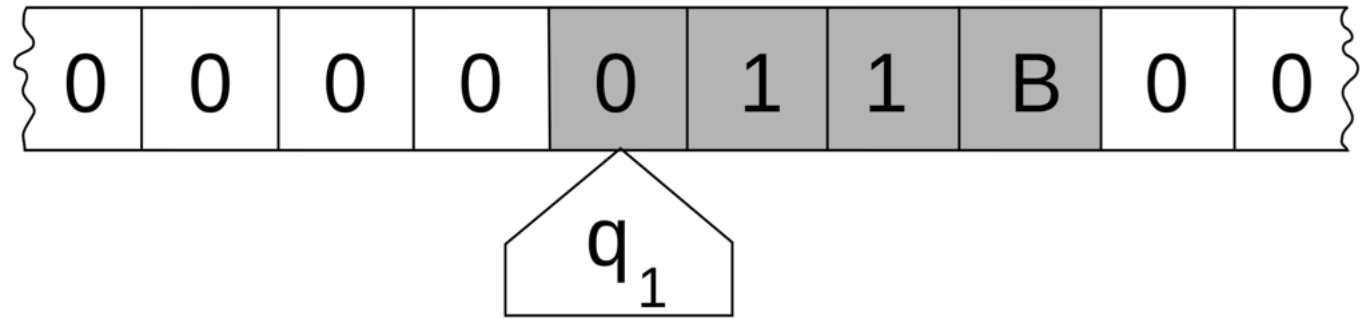


Classical Calculations

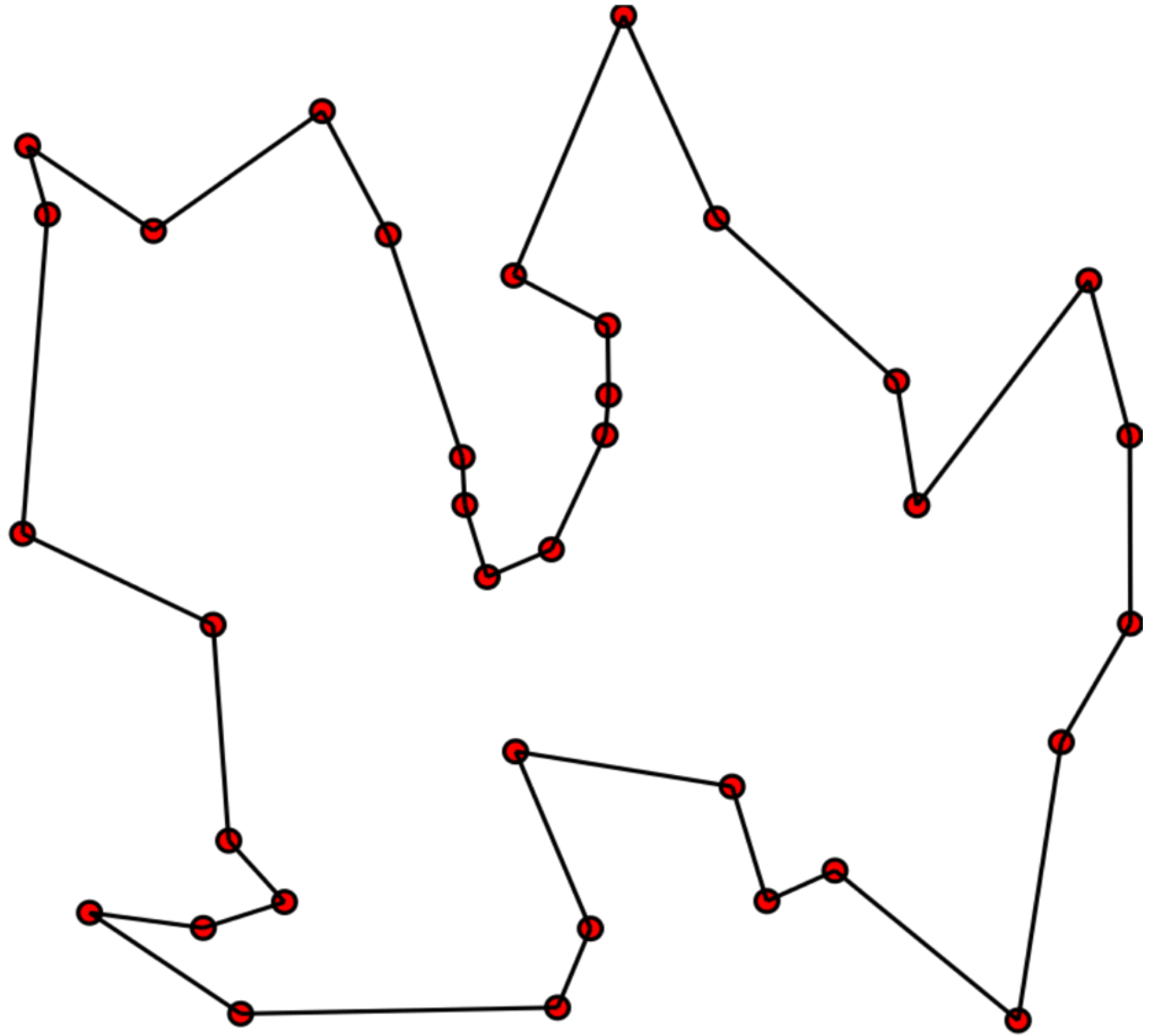
- Classical mathematical operations are done with classical gates.
- A classical computer uses bits to represent the values it is operating on. A bit can either be 0 (off) or 1 (on).
- A particular state of a classical computer is given by a collection of zeros and ones: 1000111000....



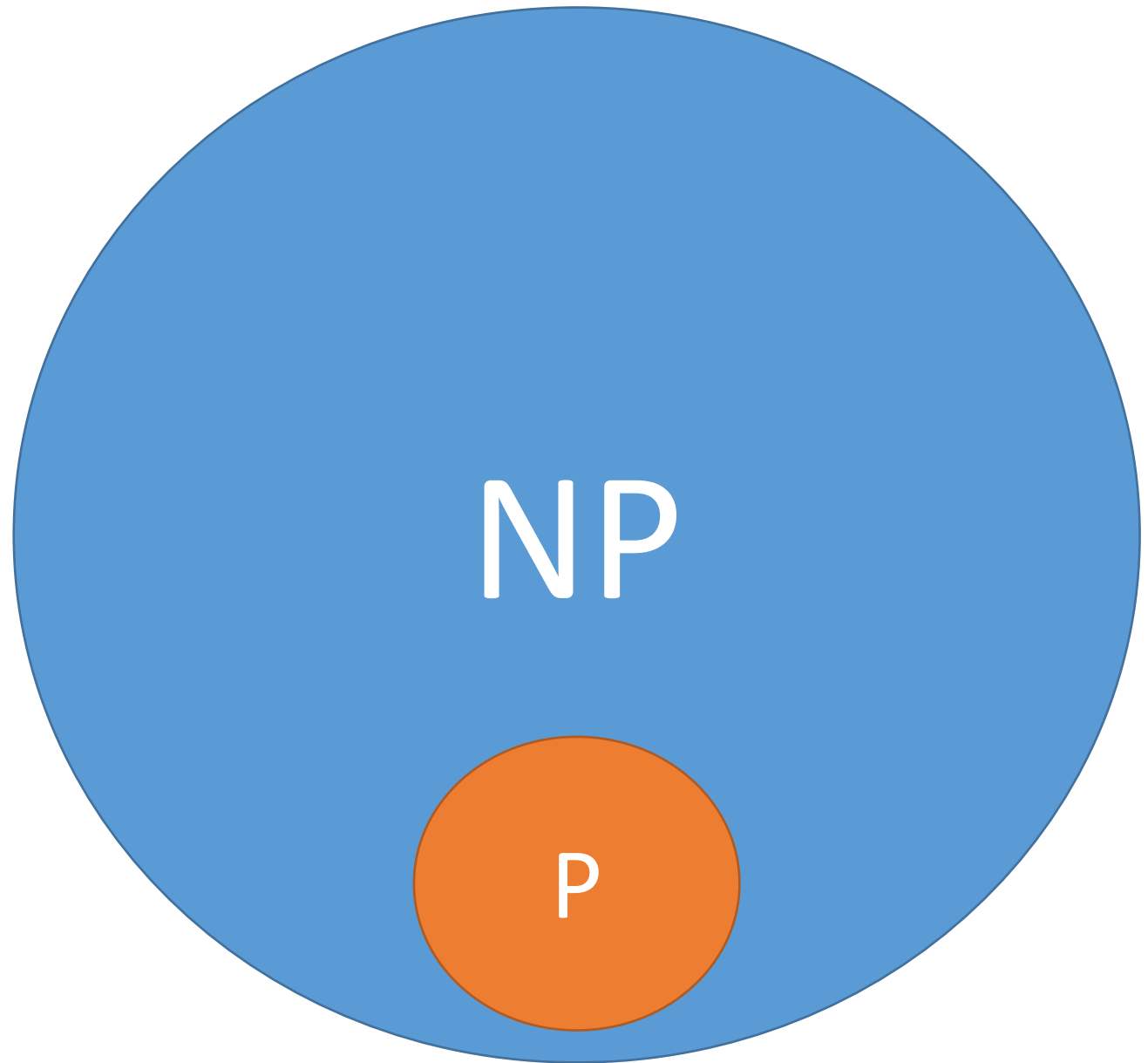
Turing Machine (1948)



Hard Problems



P versus NP



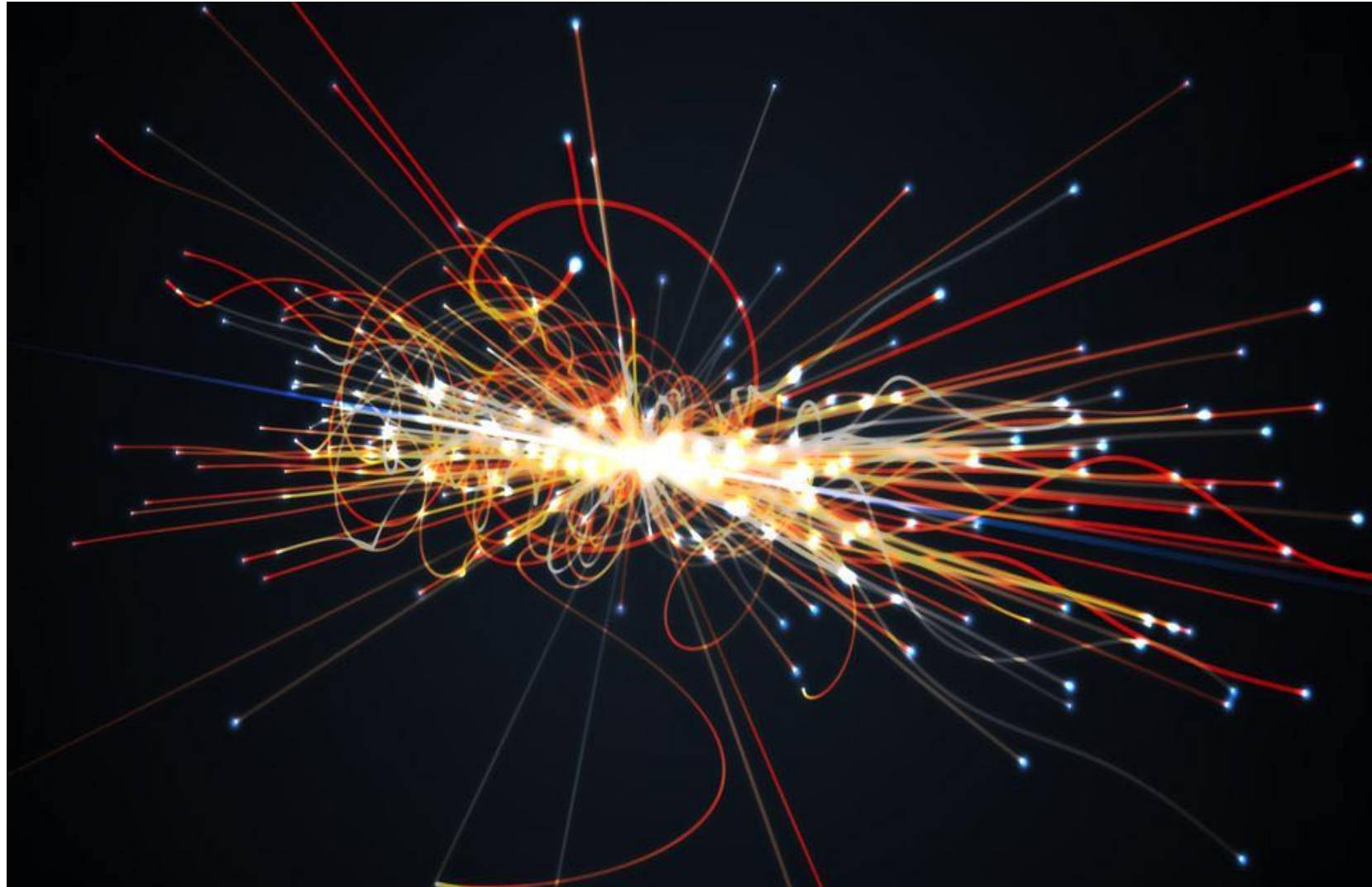
3-SAT PROBLEM

$(x \text{ OR } y \text{ OR } z) \text{ AND } (x \text{ OR } \bar{y} \text{ OR } z) \text{ AND}$
 $(x \text{ OR } y \text{ OR } \bar{z}) \text{ AND } (x \text{ OR } \bar{y} \text{ OR } \bar{z}) \text{ AND}$
 $(\bar{x} \text{ OR } y \text{ OR } z) \text{ AND } (\bar{x} \text{ OR } \bar{y} \text{ OR } \bar{z})$

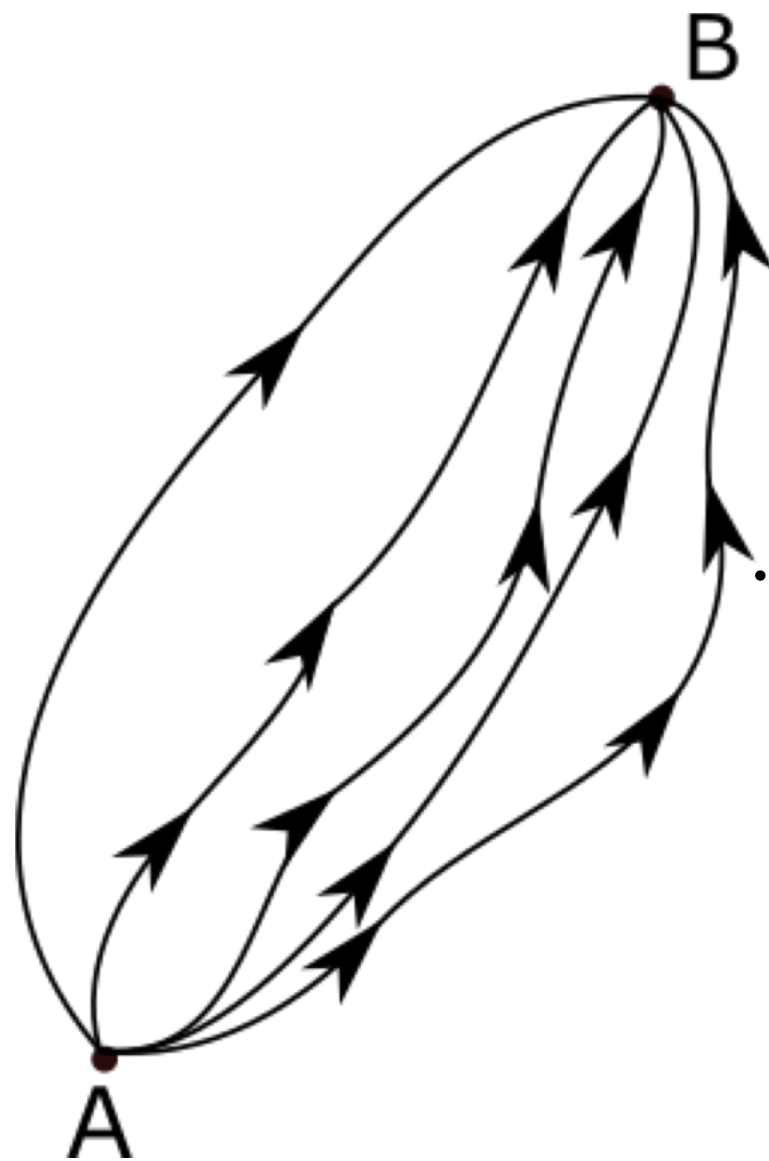
Quantum Mechanics

The physical theory that describes the dynamics of tiny particles such as electrons and photons (light particles).

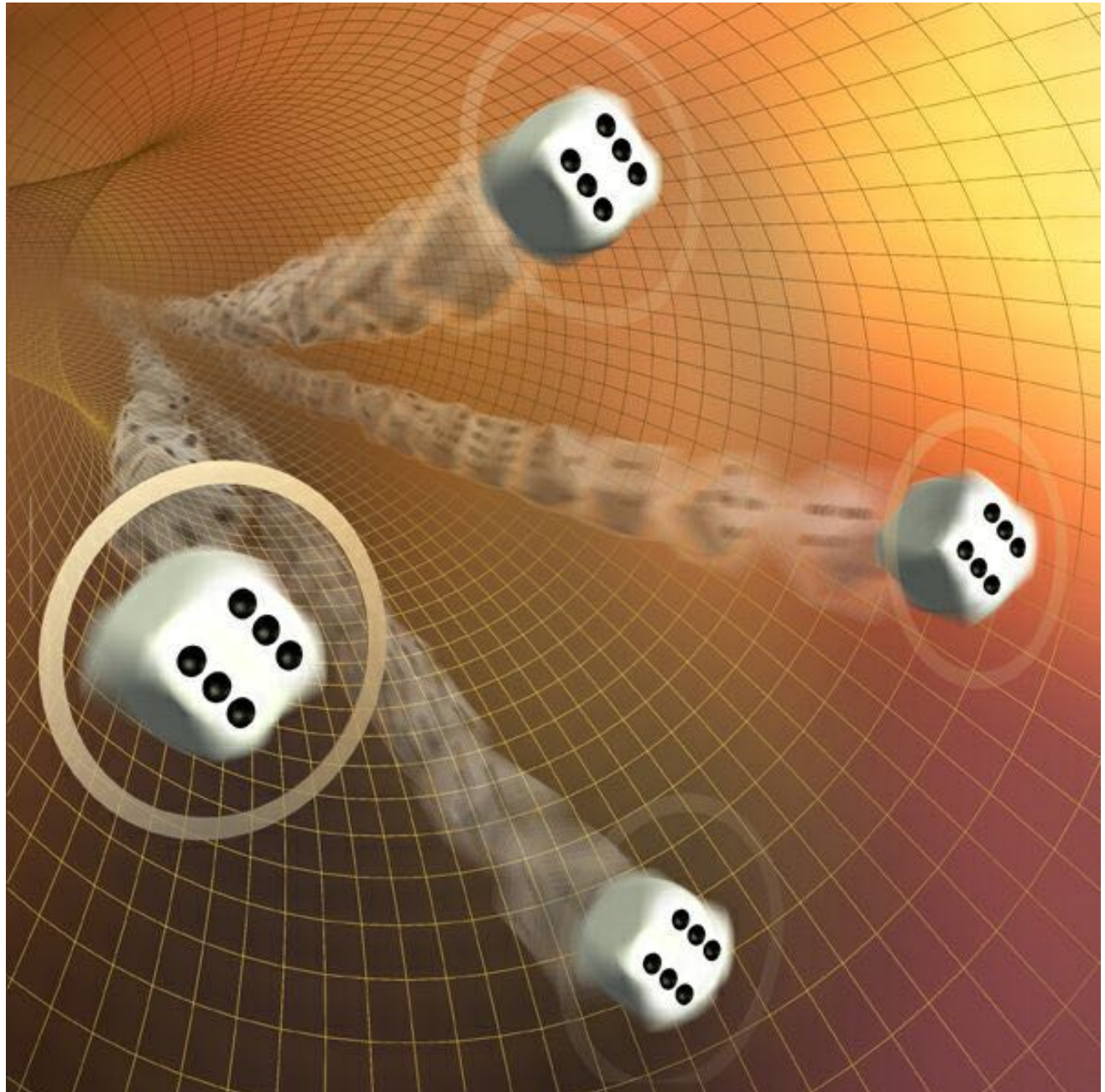
Quantum mechanics is a statistical theory. This is the true nature of our universe.



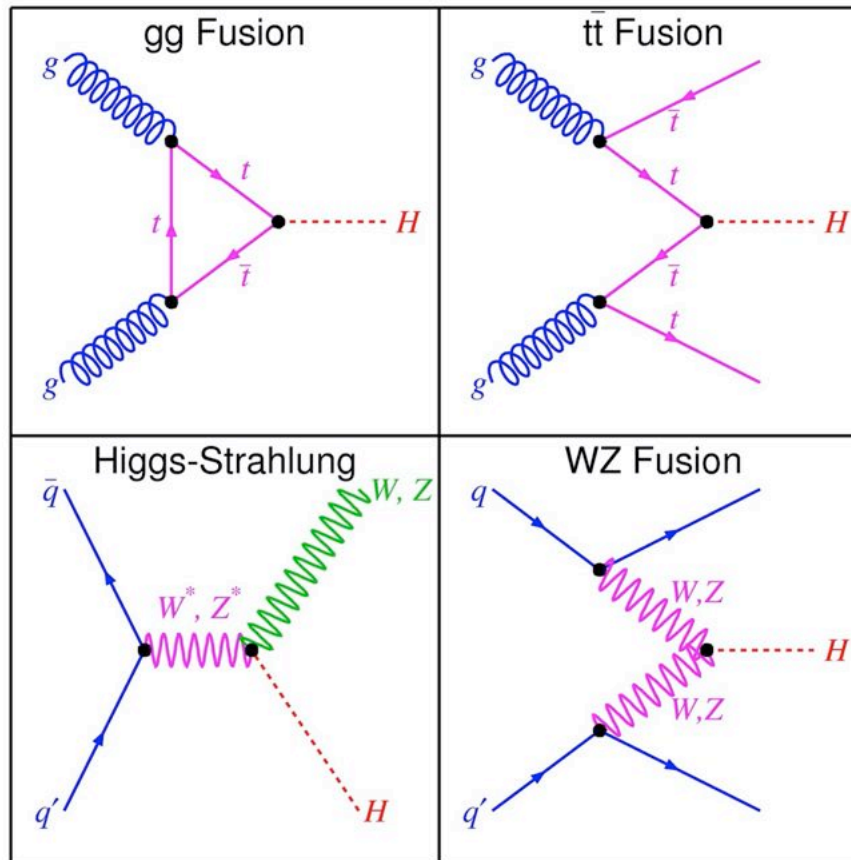
Sum Over Paths



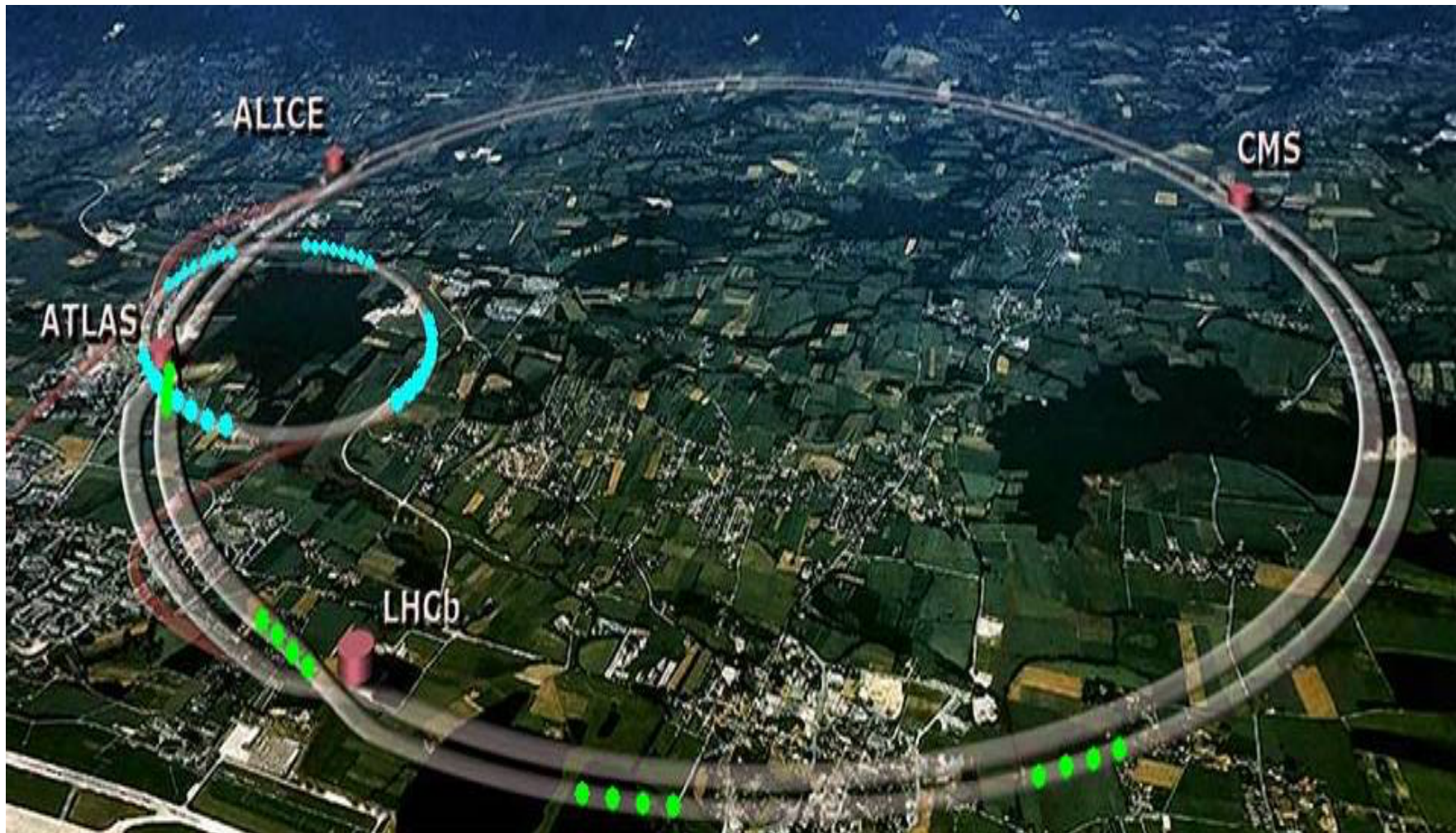
Each Path Has
A Probability
Amplitude



Quantum Field Theory



Large Hadron Collider



Quantum Black Holes

God sometimes throws dice where they can't be seen





The universe is a huge quantum computer

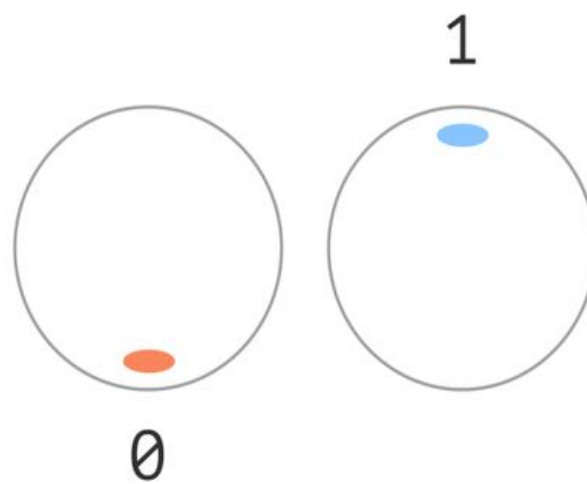
History

Quantum Computing has been proposed in 1982 by the physicist Richard Feynman as a different computational framework in order to analyze quantum physical systems.

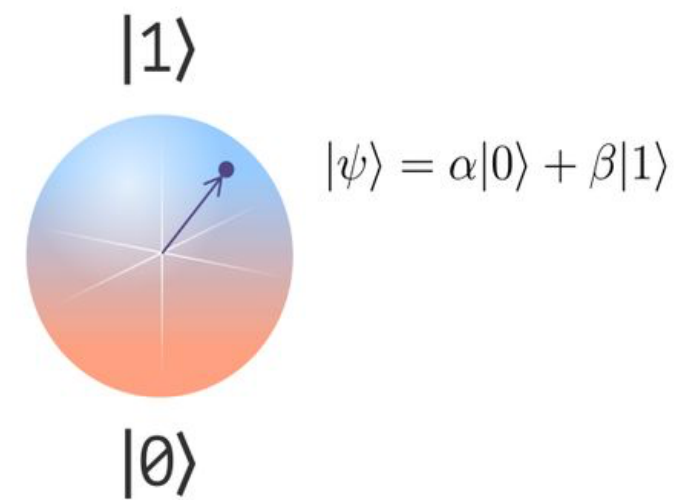


Bits and Qubits

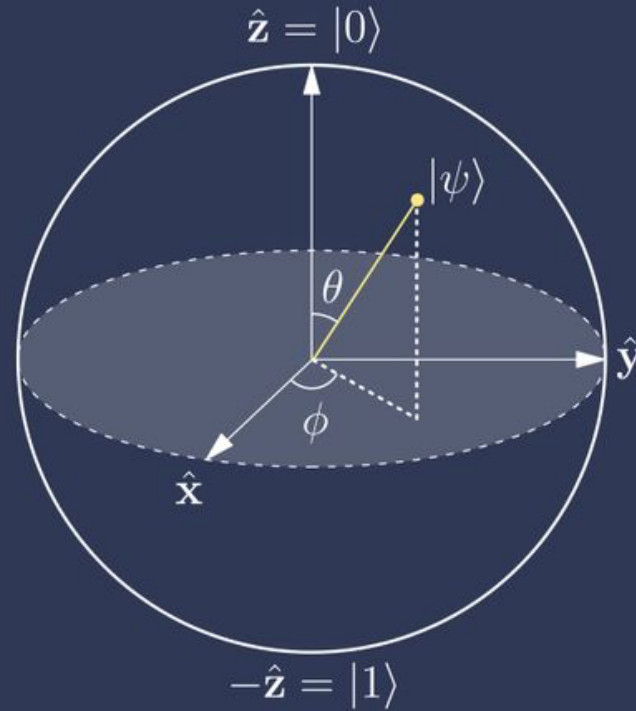
Bit



Qubit



A quantum computer uses quantum bits called Qubits



Qubit

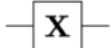


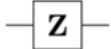

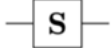
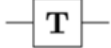
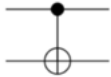
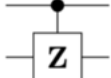



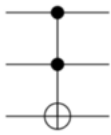
/'kju:ɪbɪt/

Basic unit of quantum information

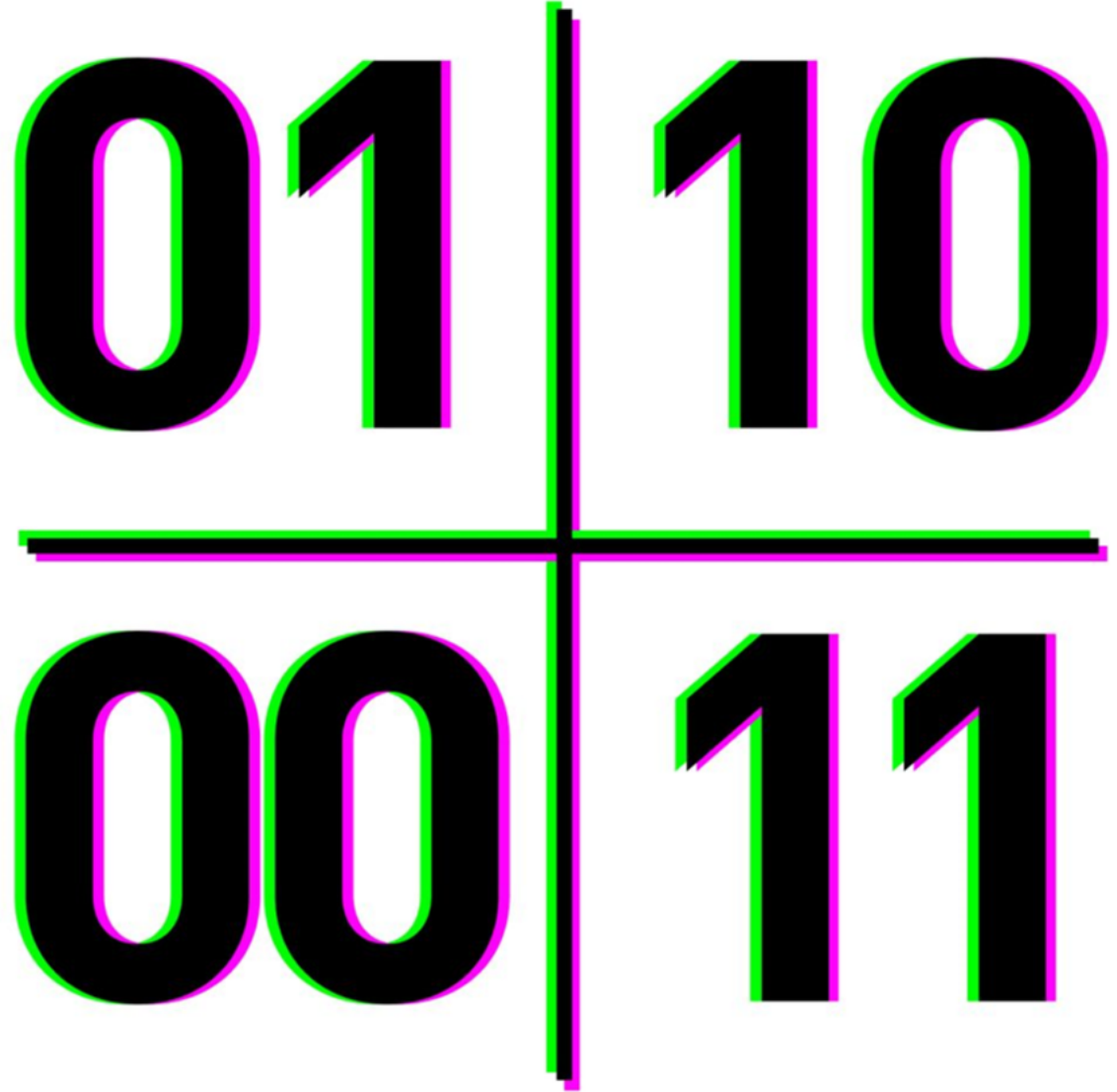
Quantum Gates:
Analogy to Qubit
Manipulation:
Moving On Earth



Quantum Gates

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)		$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$

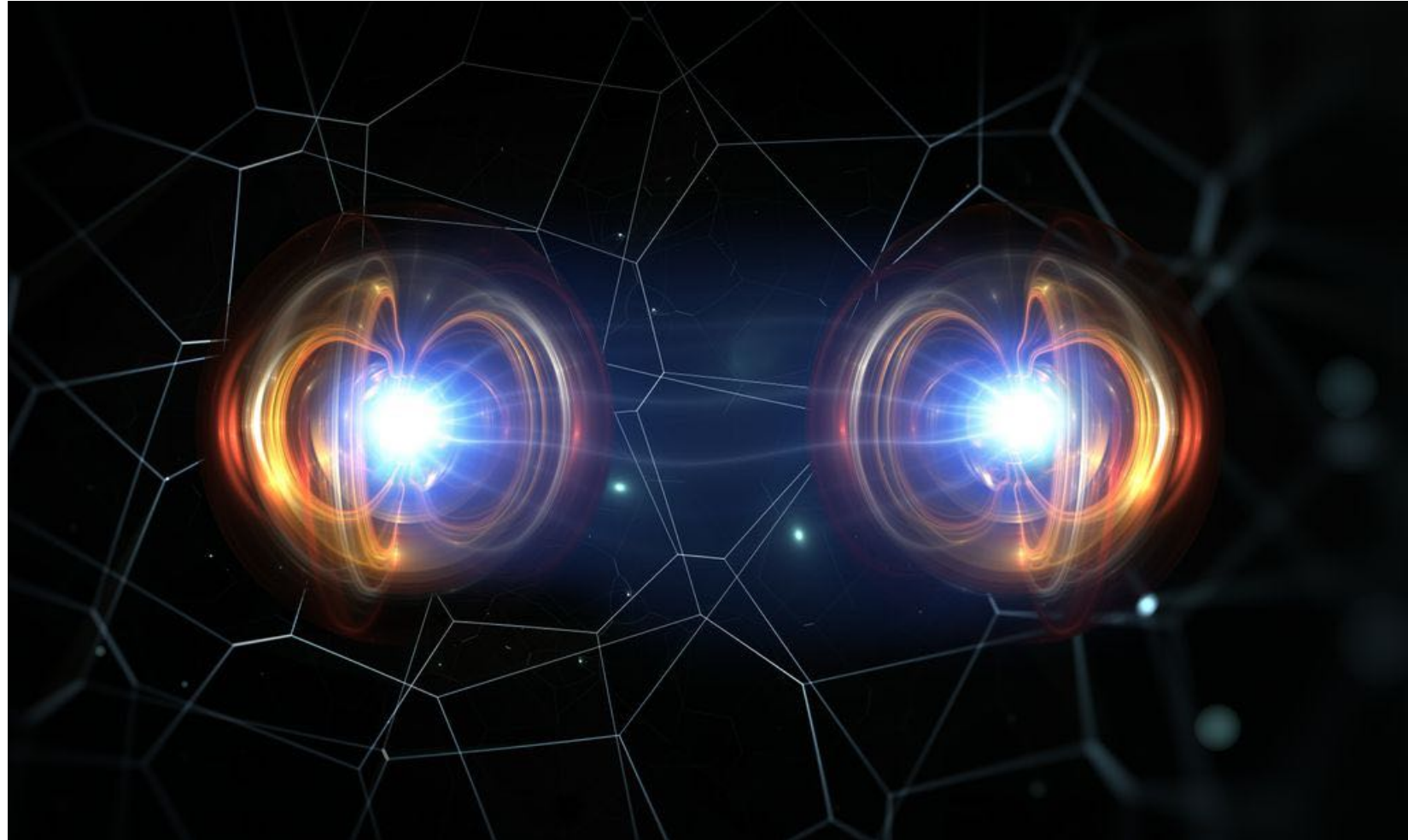
Two-Qubit
State:
Superposition



Data Storage:
The Hilbert
Space is
Exponentially
Large



Entanglement



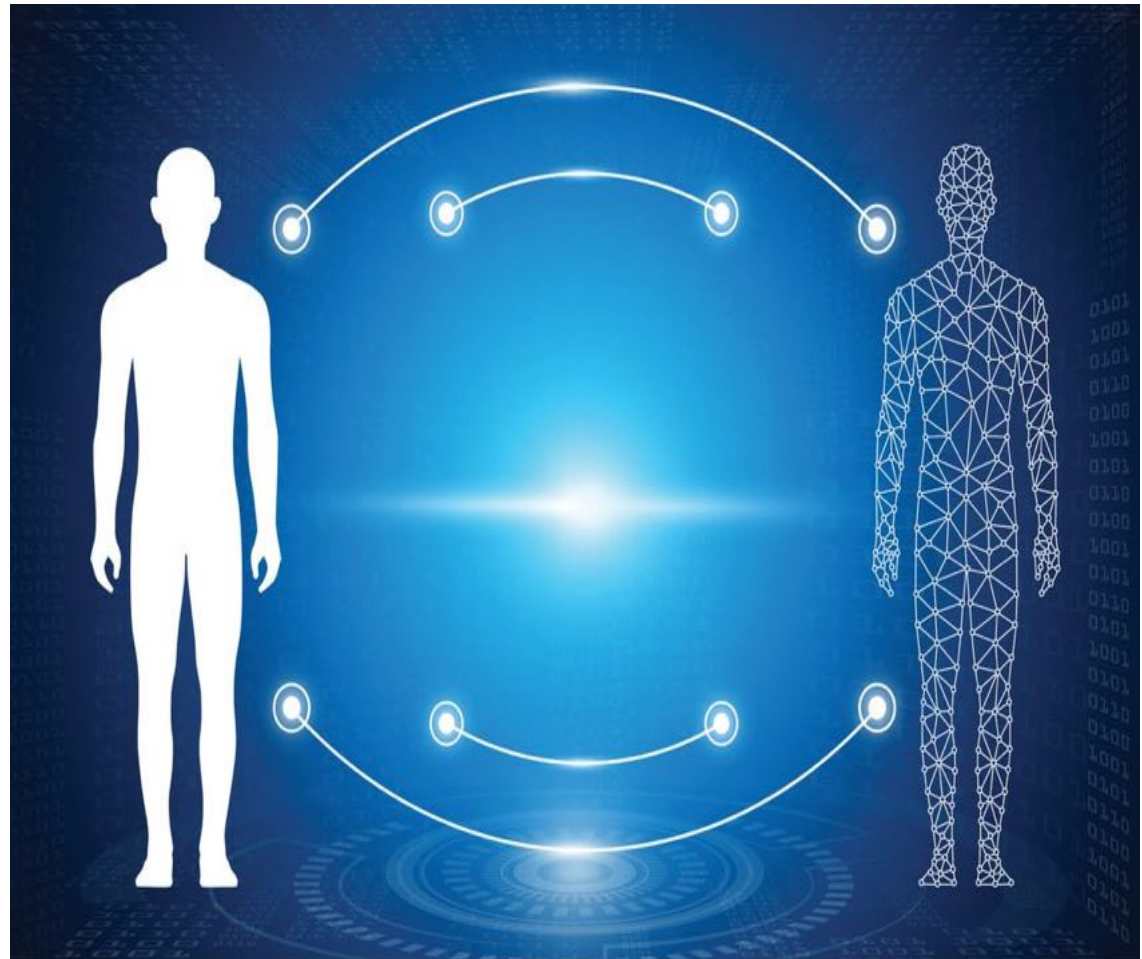
Dirac Notation

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

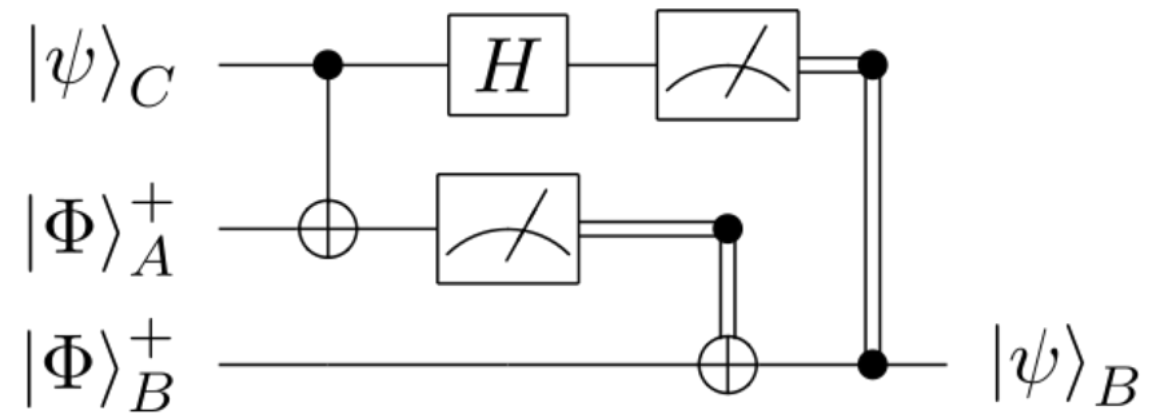
$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

No Cloning

It is impossible to make a copy of a quantum system (law of Nature called no-cloning).



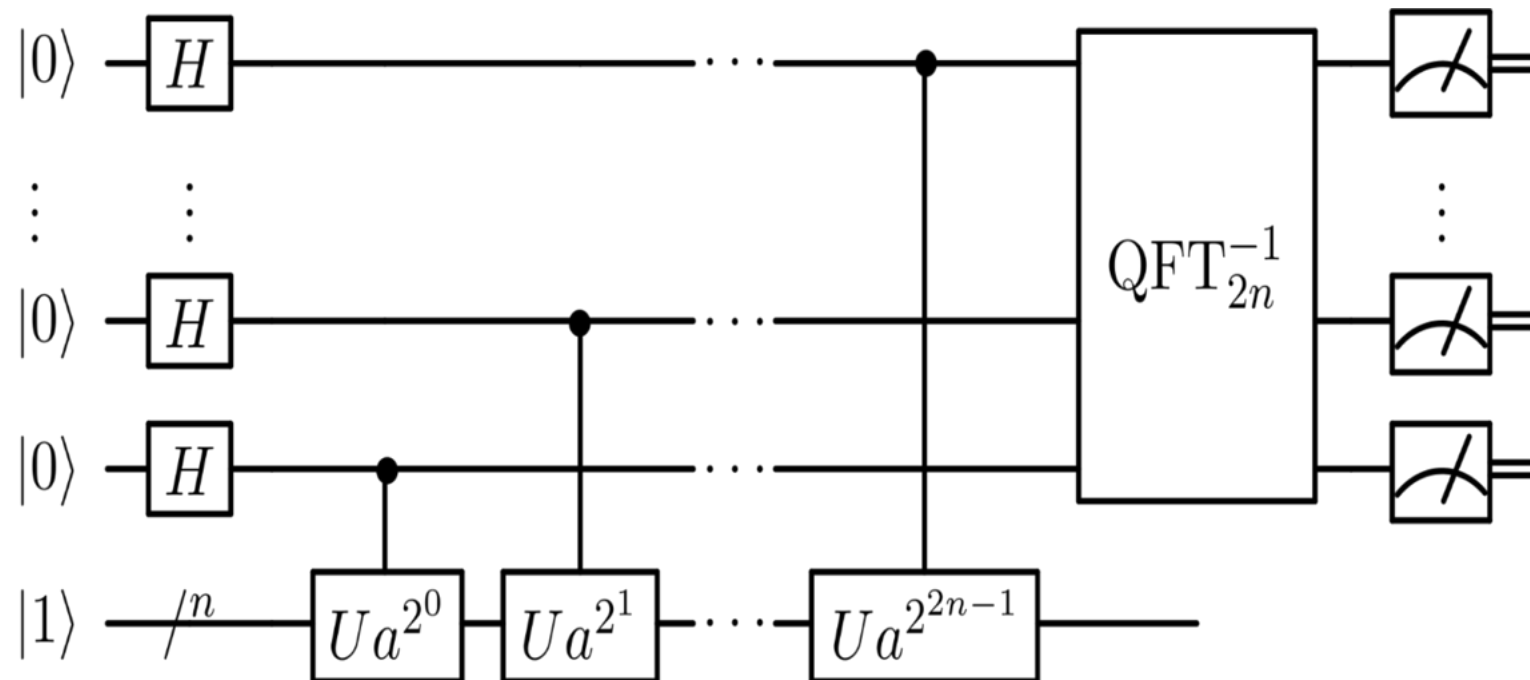
Quantum Teleportation

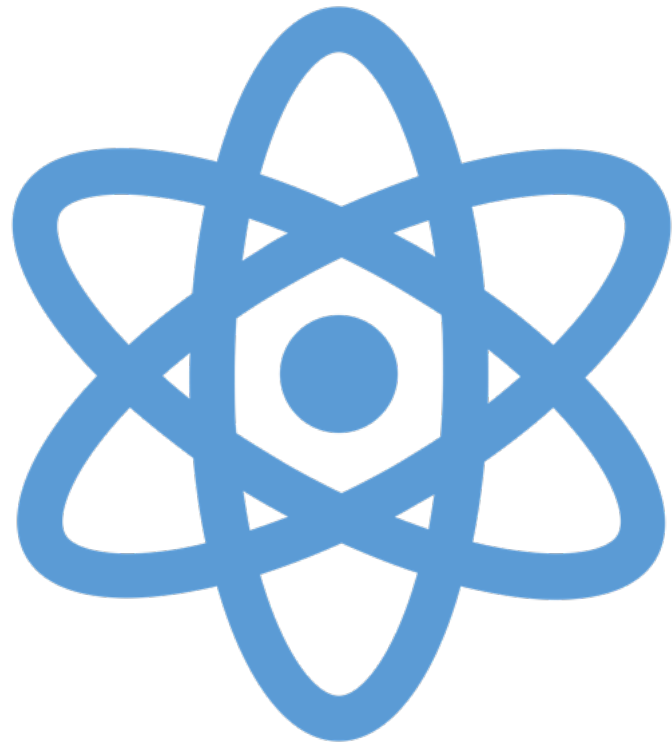


Factoring Integers

$$N = PQ$$

Quantum Algorithm (SHORE)

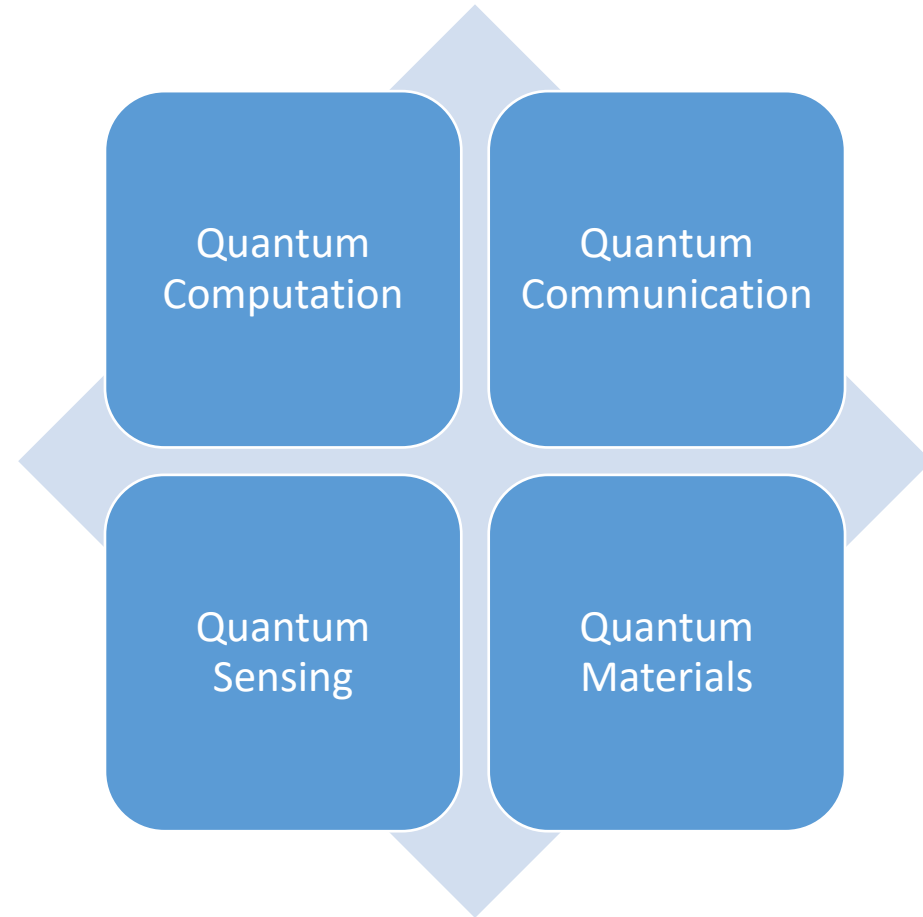




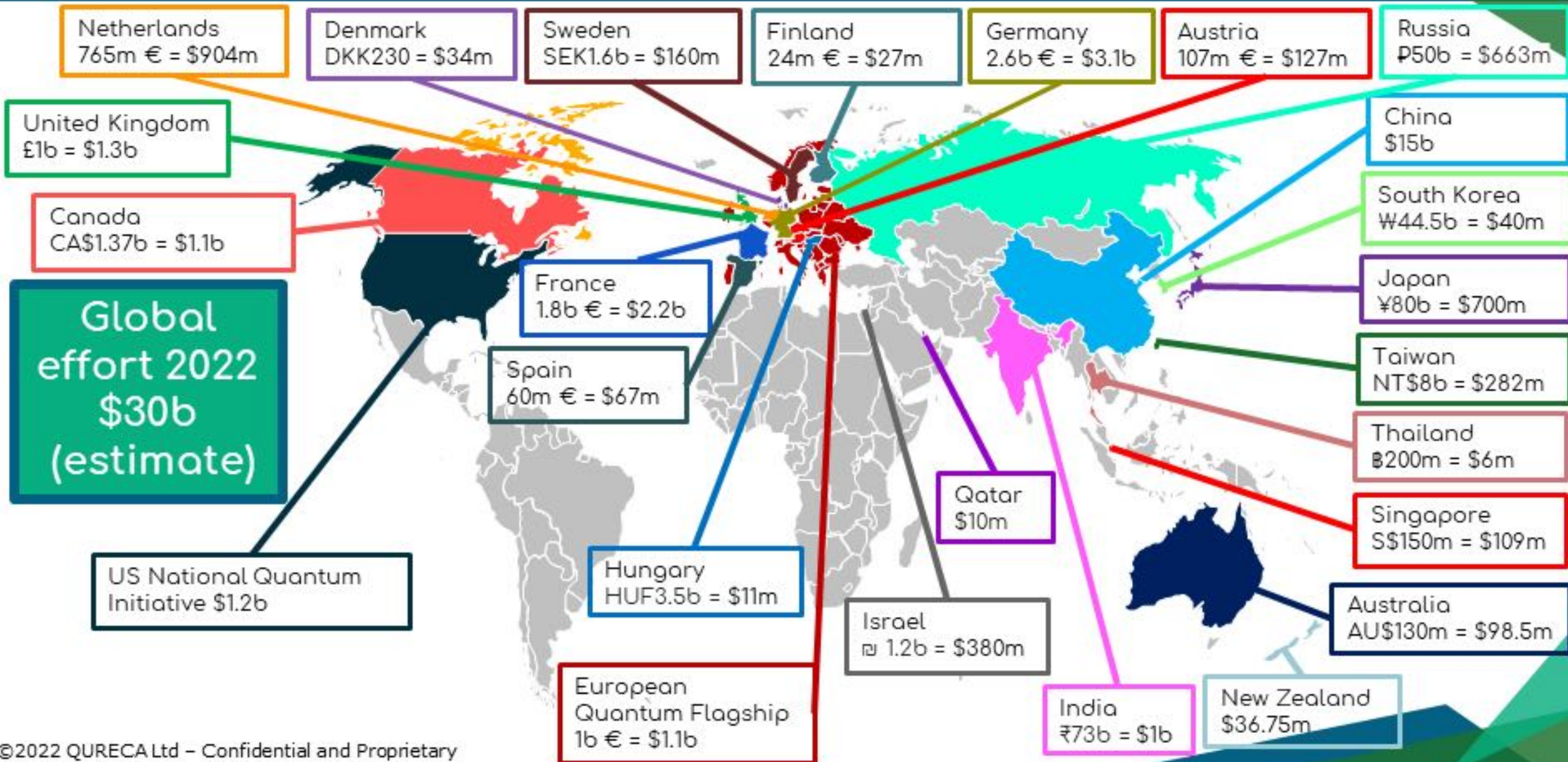
No one “understands” quantum mechanics.
What’s in there for us technologically ?

Quantum Technology

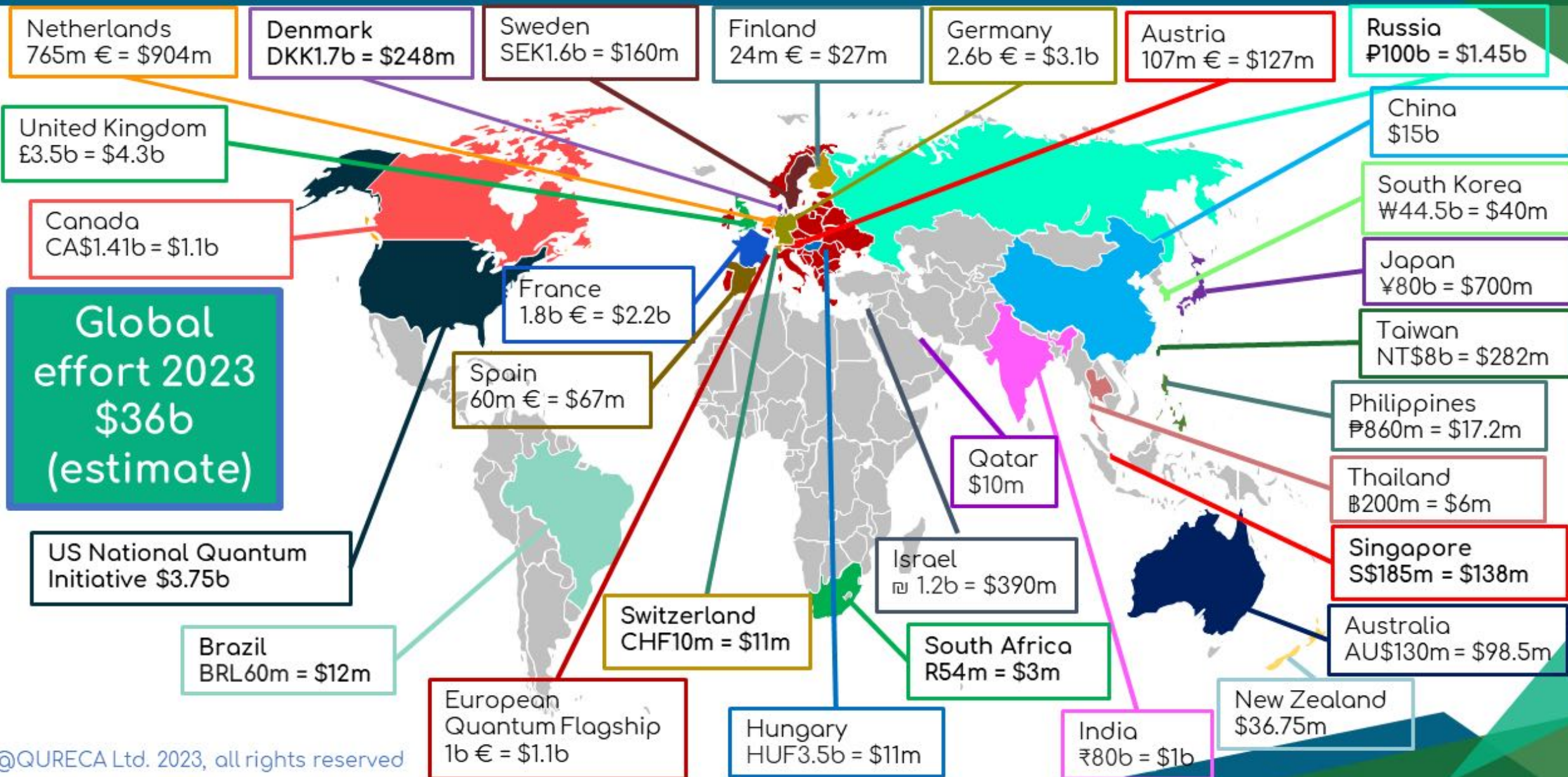
Quantum Technology



Quantum effort worldwide



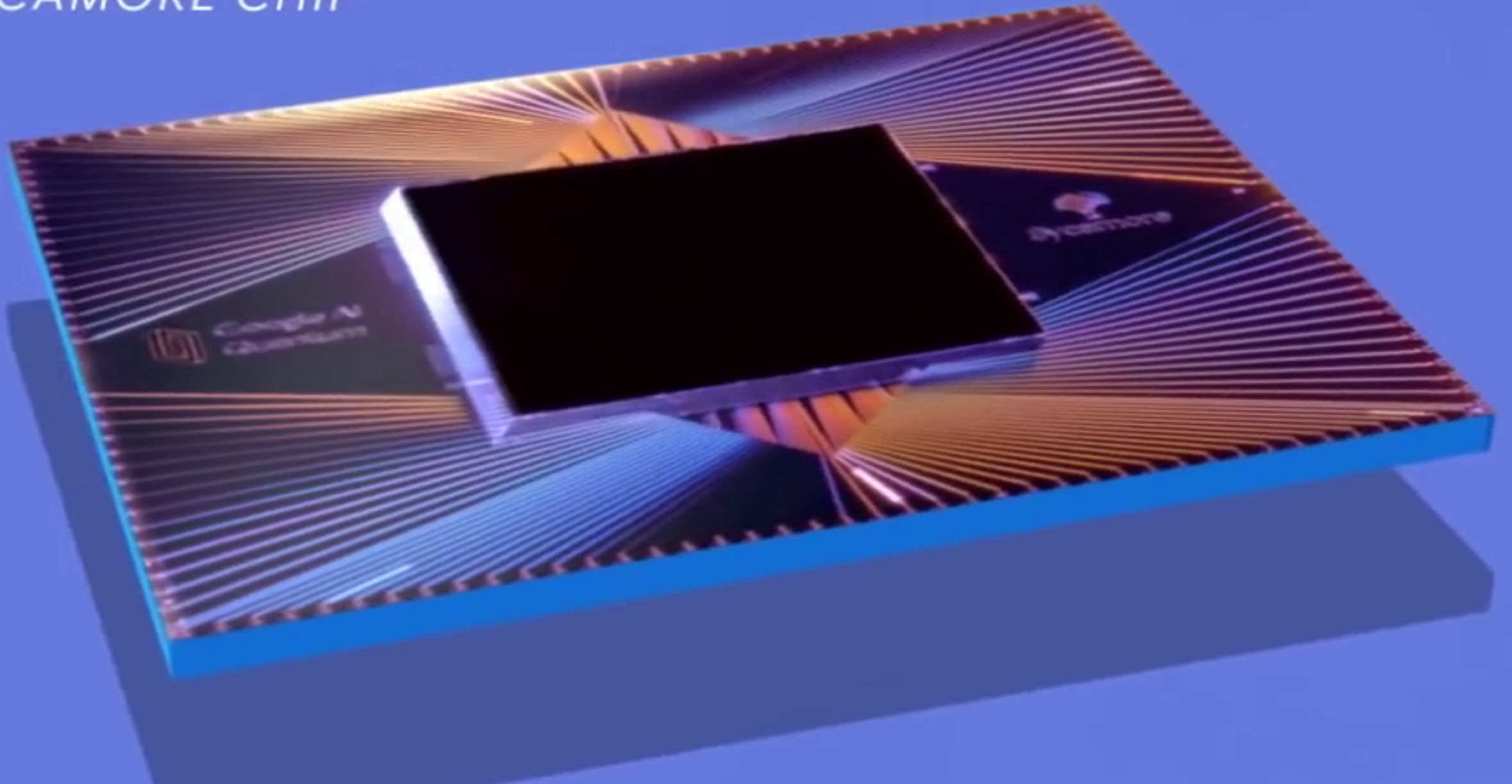
Quantum effort worldwide



Quantum Computers

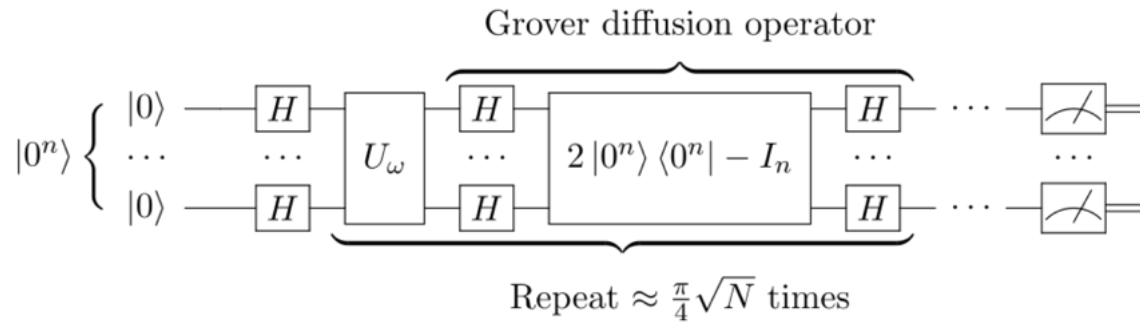


SYCAMORE CHIP

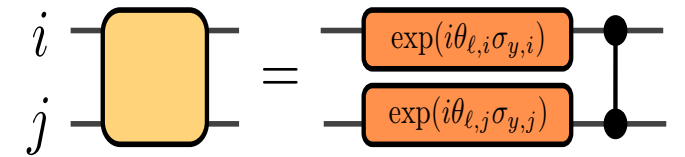
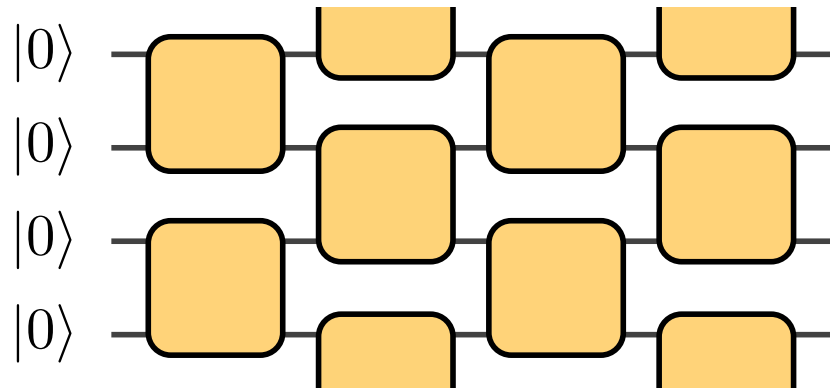


By Google, CC BY 3.0, <https://commons.wikimedia.org/w/index.php?curid=109155716>

Data Analysis



Quantum Machine Learning and Optimization



Noise

Noise is a huge issue for quantum computers.

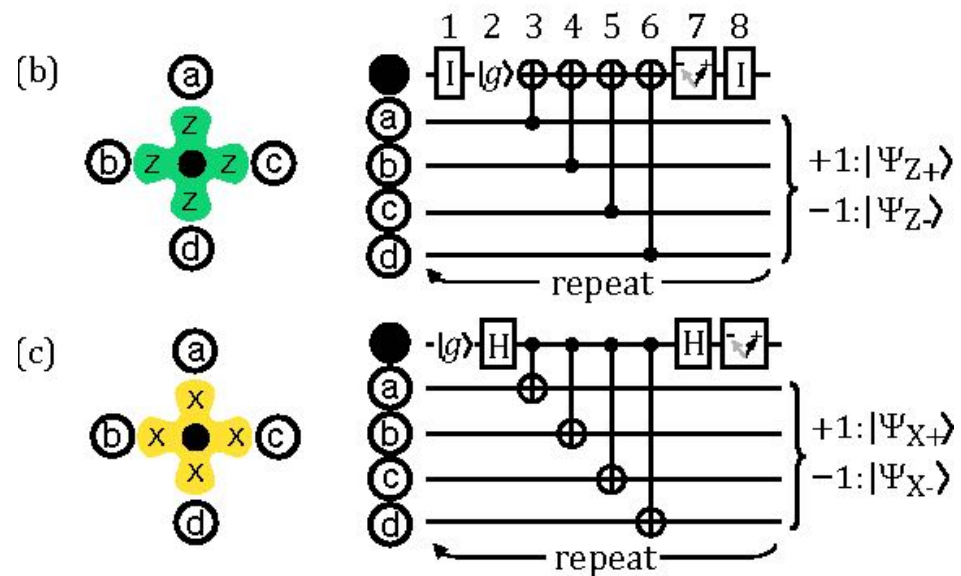
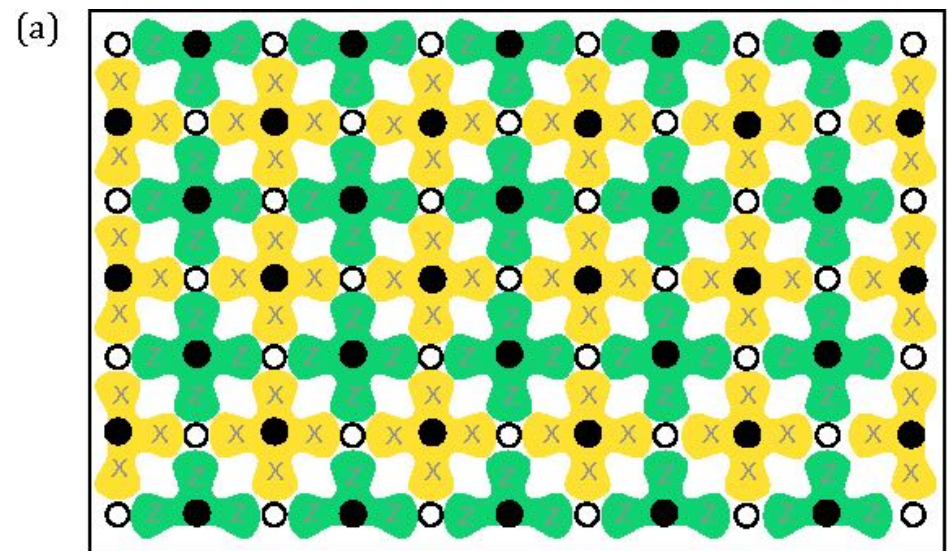
A classical bit is either one or zero. A noise can flip the bit.

Quantum systems are extremely delicate: qubit phase errors, gate errors, decoherence.

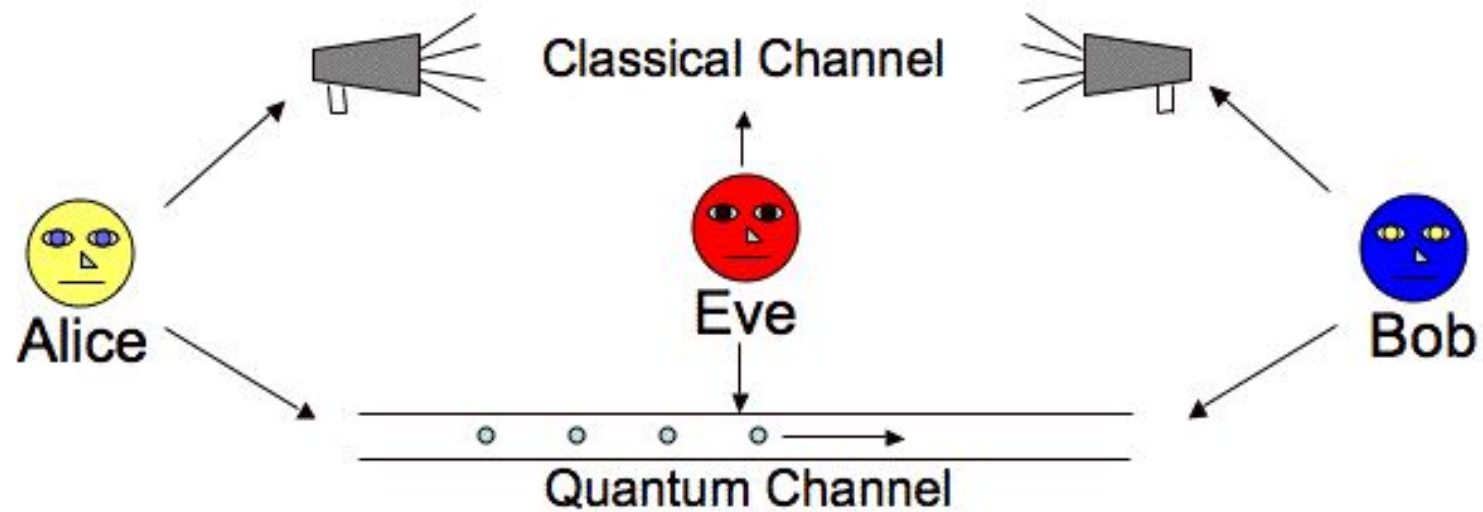
Error correction algorithms cannot use duplication and need to rely on encoding the information in entanglement correlations.



Surface Code



Quantum Key Distribution



Alice's bit	0	1	1	0	1	0	0	1
Alice's basis	+	+	X	+	X	X	X	+
Alice's polarization	↑	→	↖	↑	↖	↗	↗	→
Bob's basis	+	X	X	X	+	X	+	+
Bob's measurement	↑	↗	↖	↗	→	↗	→	→
Public discussion								
Shared Secret key	0		1			0		1

QKD

- <https://www.cse.wustl.edu/~jain/cse571-07/ftp/quantum/>

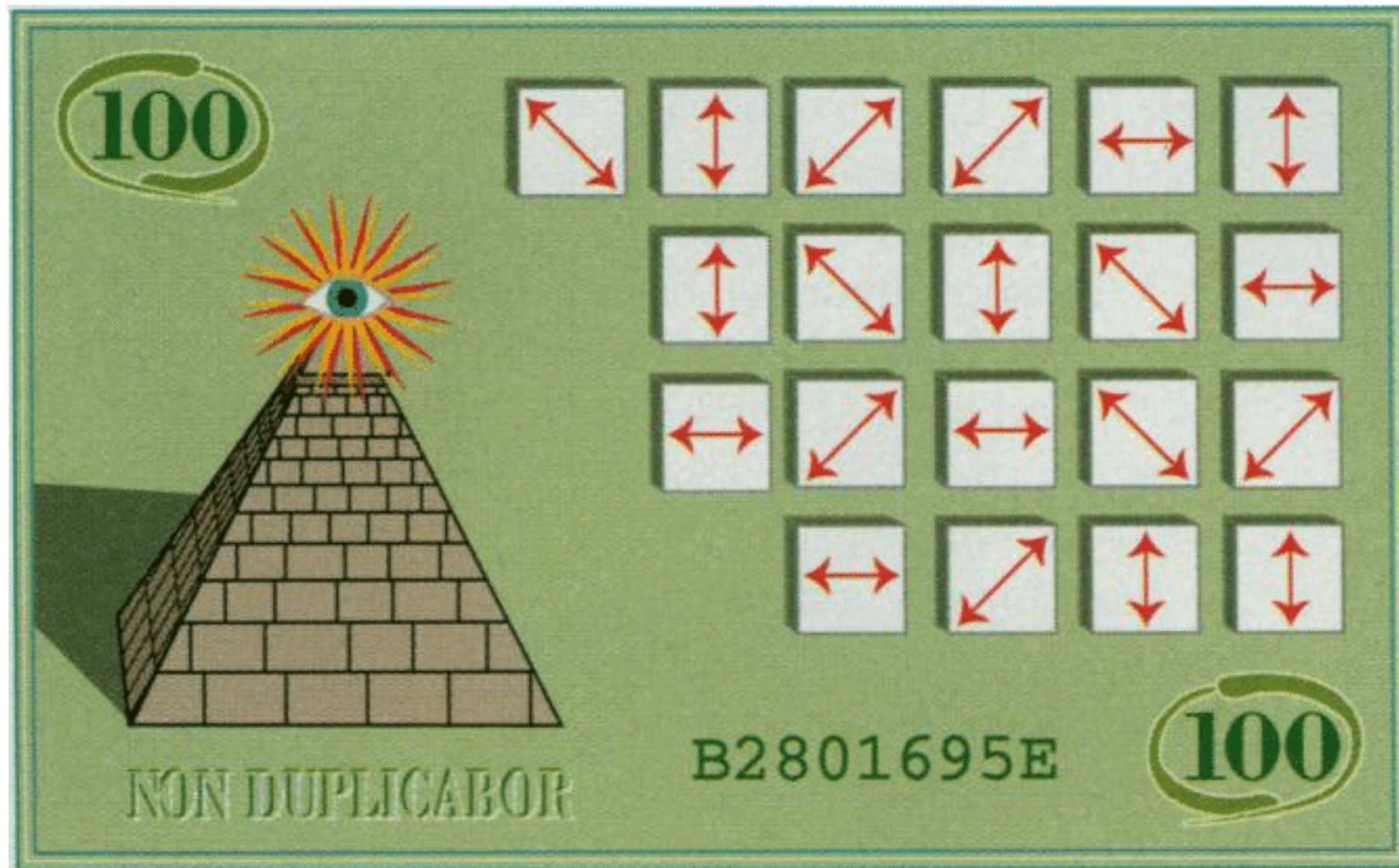
Quantum Communication



TAU Ground Station



Quantum Money



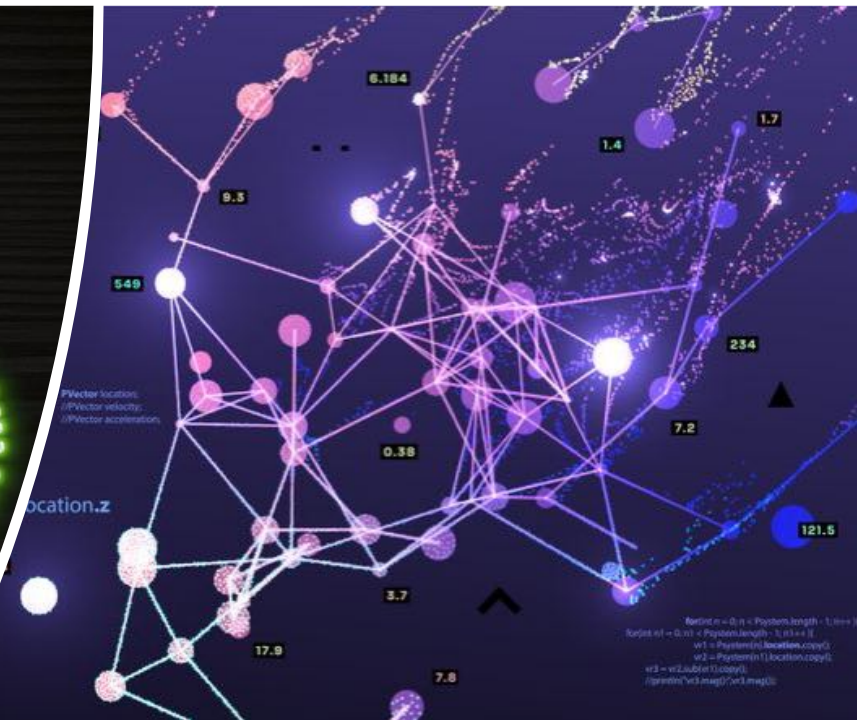
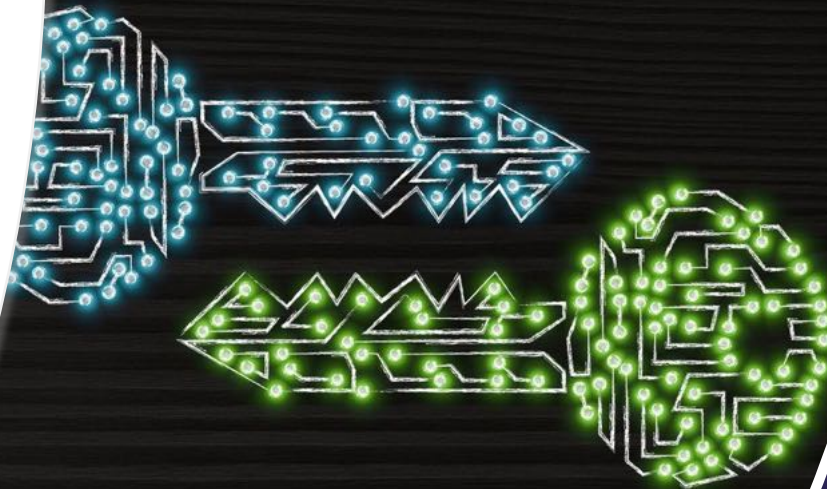
https://www.researchgate.net/figure/Quantum-banknote-in-Wiesners-quantum-money-scheme-with-20-qubits-as-depicted-by_fig11_321748972

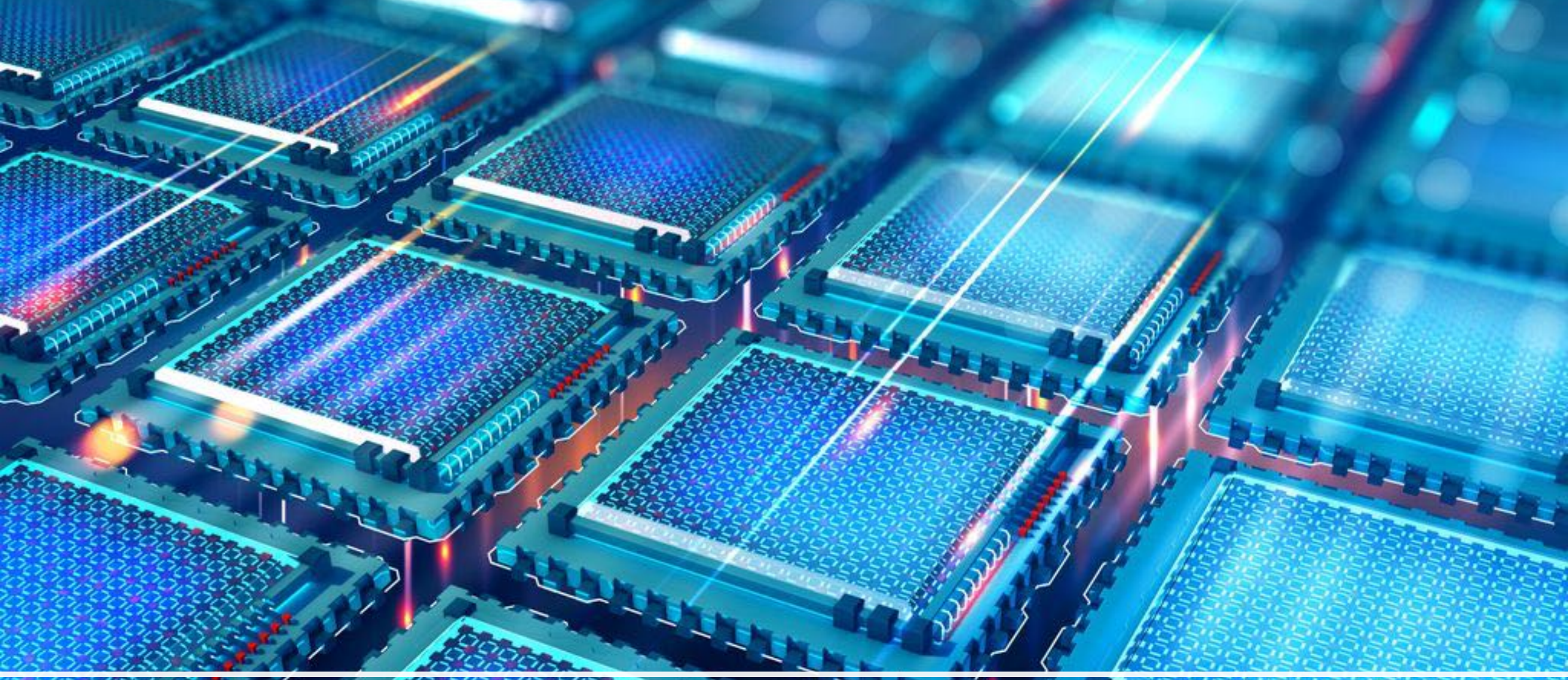
BLOCKCHAIN

T E C H N O L O G Y



Secure Ledger
Quantum Cryptography
Quantum Networks
Quantum Internet





Thank You

