QSEC Quantum Science & Engineering Center

Welcome to Quantum Pathways

George Mason University

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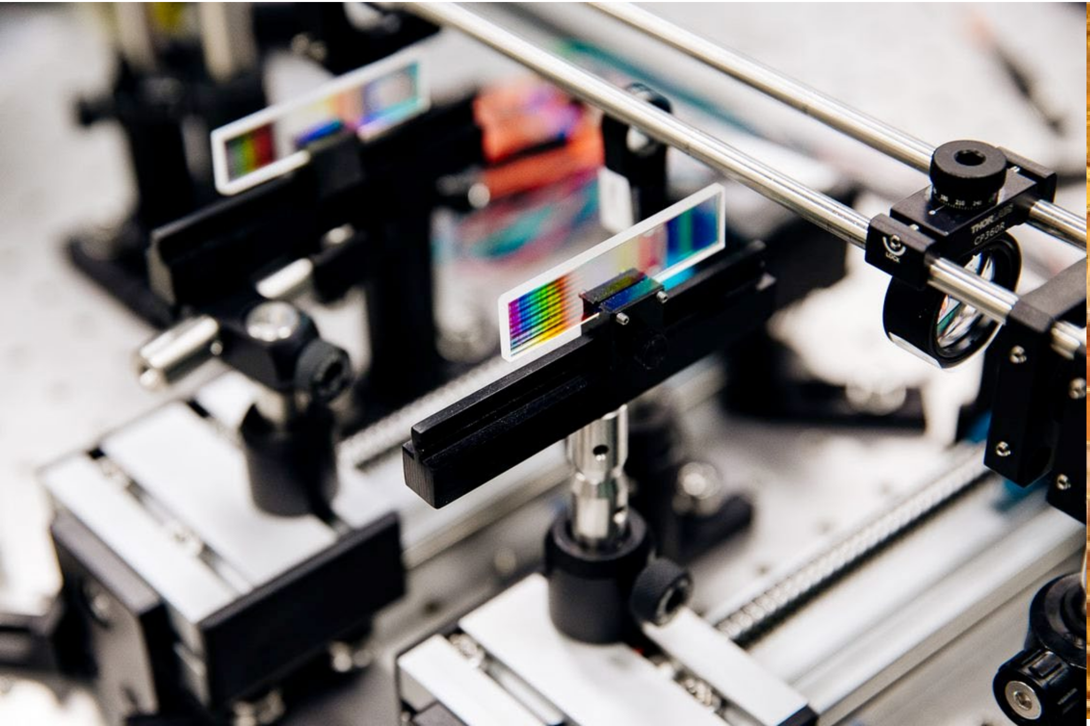


2:00 – 2:15	Welcome and introductions
2:15 – 2:30	Quantum Questions
2:30 – 3:15	Introduction to Quantum
3:15 – 3:30	Break
3:30 – 4:00	Path from classical computing to quantum computing
4:00 – 4:45	Industry panel
4:45 – 5:00	Wrap up

Introductions

In pairs (with someone you don’t know) introduce yourself to one another.

You will have ~5 minutes to learn about one another and then you will introduce your partner to the group.

Questions to consider discussing (come up with your own as well):

- Name, degree program
- Why are you here?
- What is your favorite hobby or sport?
- If you could work anywhere in the world, where would it be?
- What is the most recent song you listened to or movie/show you watched?

Quantum Questions

In your group, come up with 10-12 questions about quantum and quantum careers you hope to learn more about:

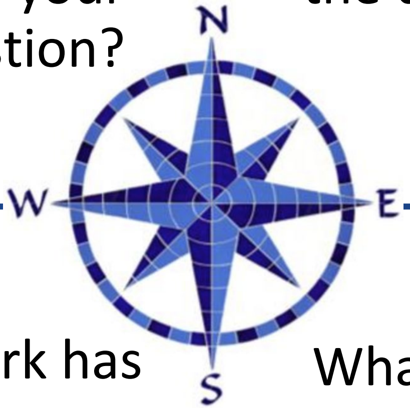
- *Why…?*
- *What if…?*
- *What is the purpose of…?*
- *How would it be different if…?*
- *Suppose that…?*
- *What if we knew…?*
- *What would change if…?*

Compass Points

In your group identify one question to dig into further. Use the prompts below to explore your question. Capture your response on the poster paper provided.

What else do you **N**eed to know or find out to explore your quantum question?

What do you find **E**xciting about the quantum question?



What **W**ork has been done by researchers or industry to explore this question?

What **S**teps can you take to explore this question further?

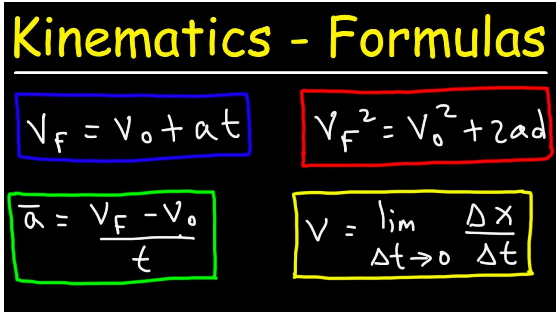
Classical Mechanics

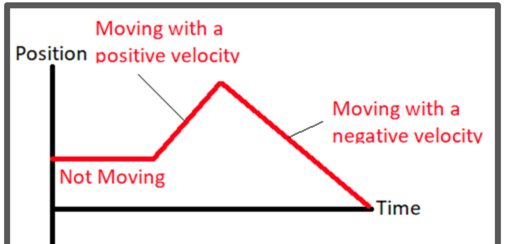
What is the object's position?

What is the velocity?

What forces are acting on it?

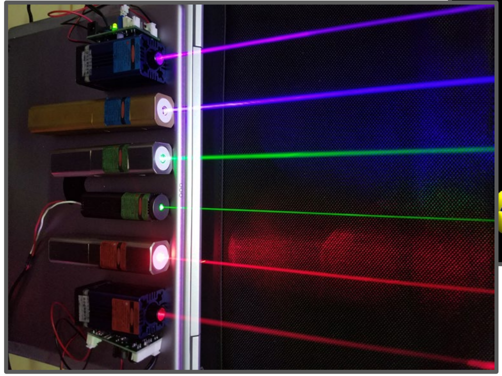
What will happen next?

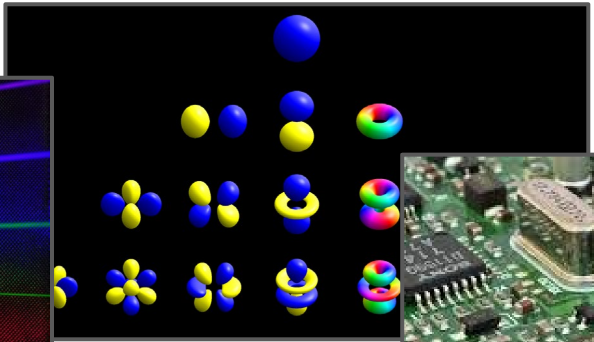


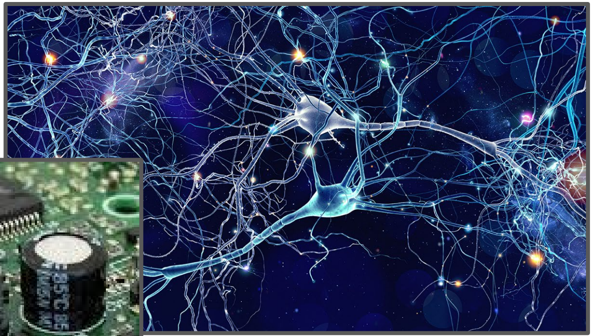


Quantum Mechanics

Instead of describing the state of a system with definite values of position, velocity, etc., we describe it with **probabilities**, and we can predict how these probabilities change over time.



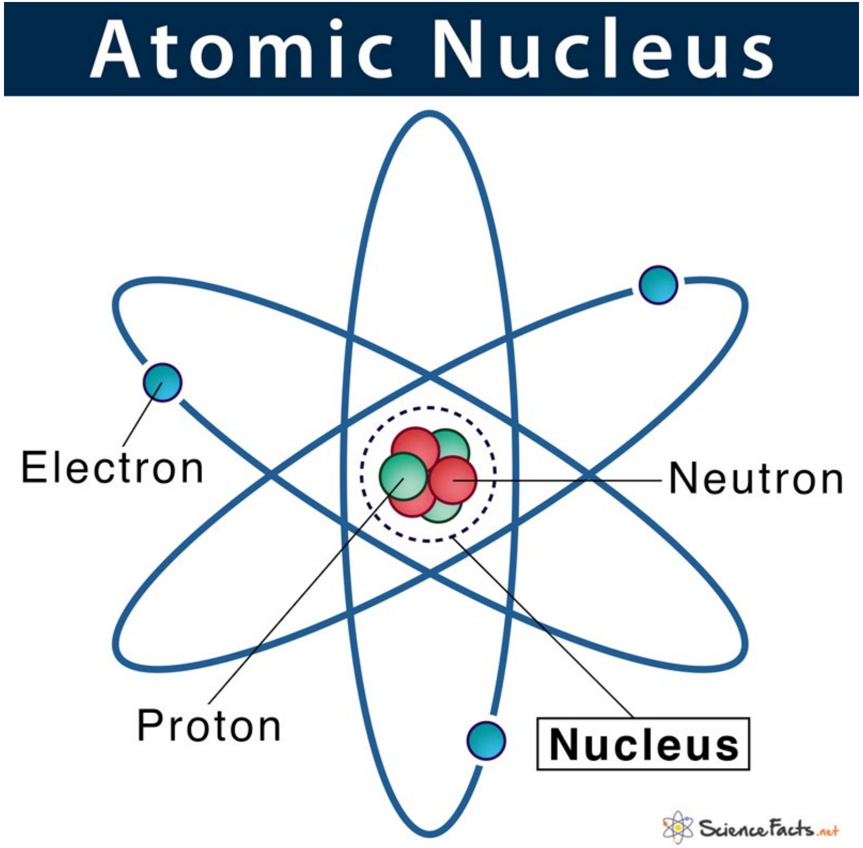


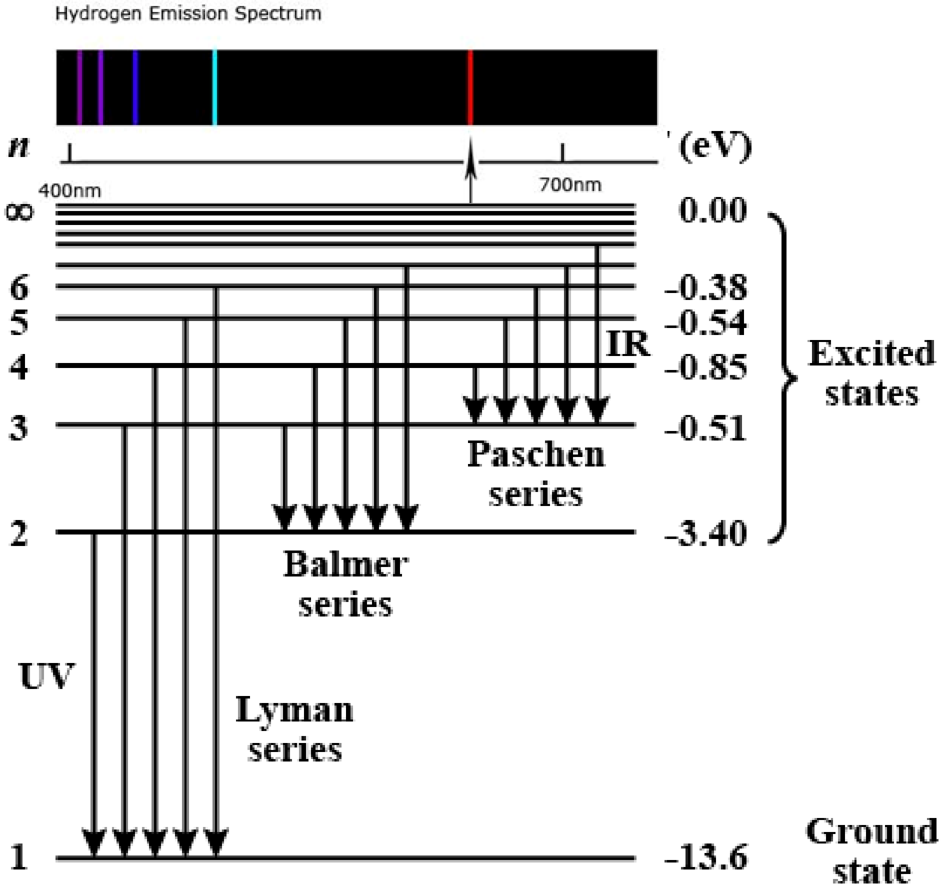


At larger scales, the results are the sa nics, but at smaller scales we need quantum mechanics.

Classical Physics	Quantum Physics
Classical physics explains most physical behaviors in our everyday life **Deterministic:** Position, velocity, and momentum can be *precisely predicted* using equations of motion **Measurement:** Tells you the “state” of an object (that it was already in). Measurement doesn’t change anything	Quantum physics explains behaviors at the sub-atomic level **Probabilistic:** Precise values for position, velocity, & momentum of an object *cannot* be predicted. They are described by *probabilities* **Measurement:** In quantum, taking a measurement determines the value – thereby changing the “state” of the object.

Atoms and Energy Levels

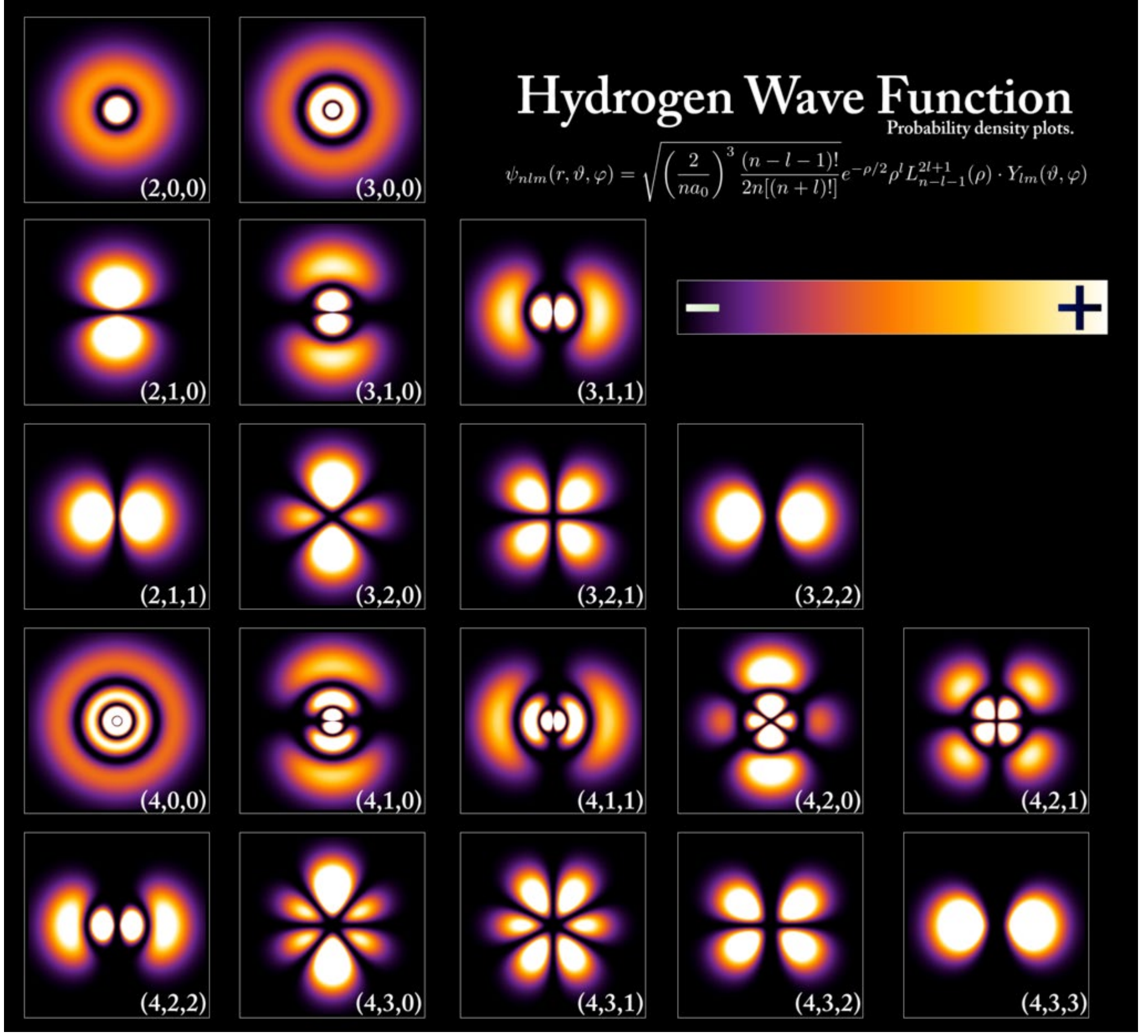




Quantum States

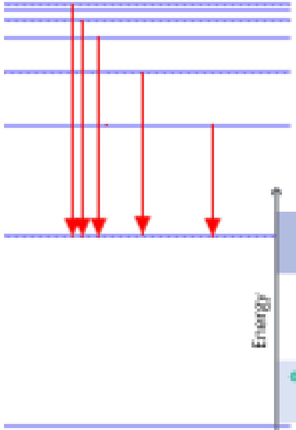
- **A mathematical representation of a physical system**, such as an atom

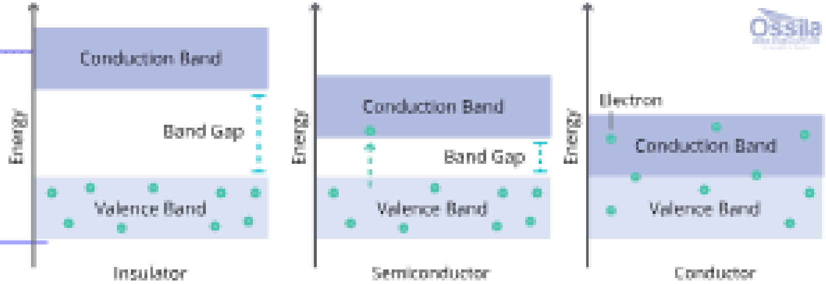
- Quantum states are properties of the system

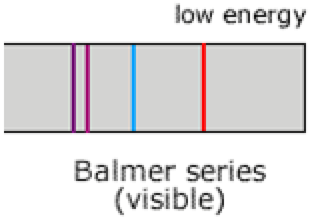


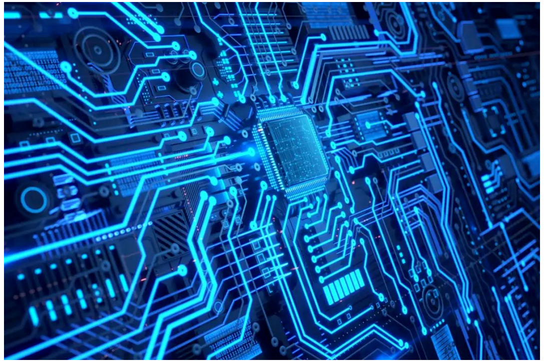
Probability densities for the electron of a hydrogen atom in different quantum states.

1st Quantum Revolution





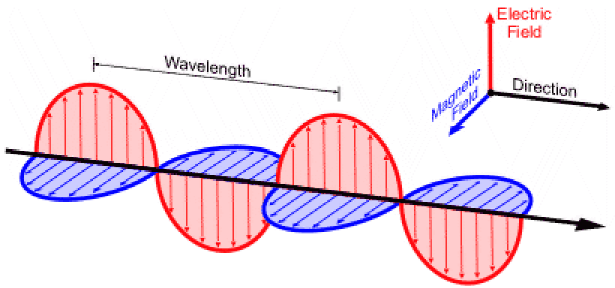


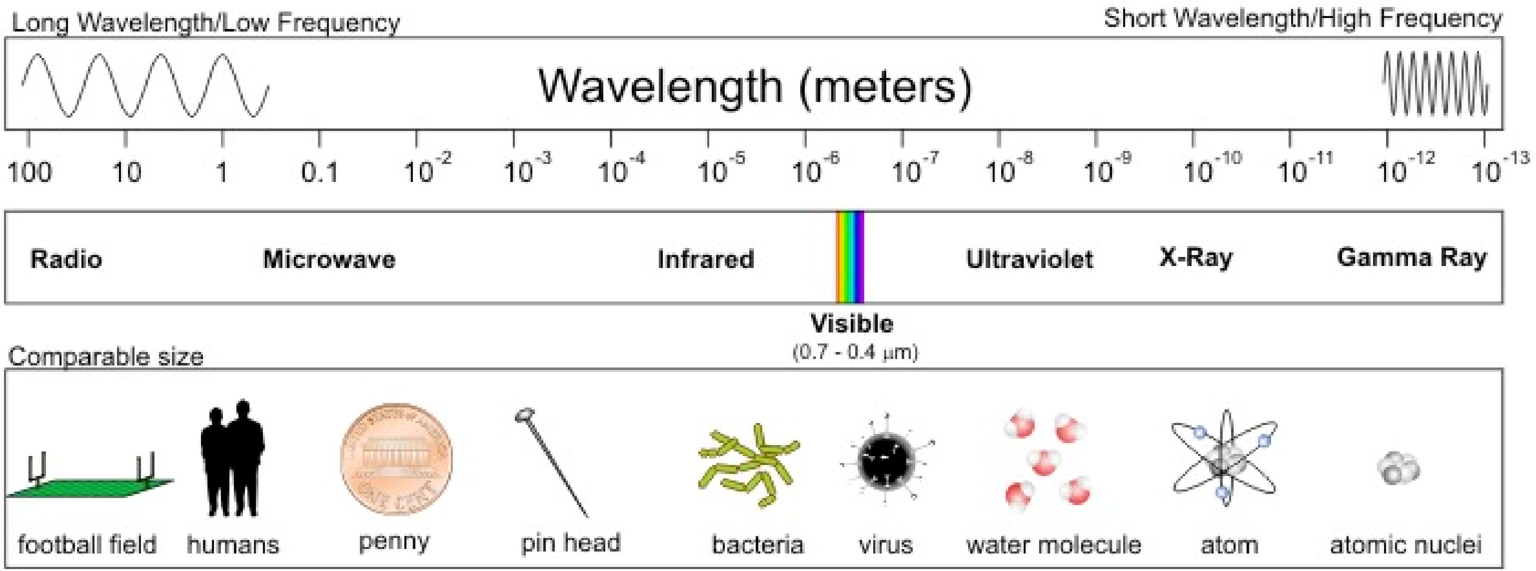


What is Light?

Light is wave combination of electric and magnetic fields

Wavelength is key property of light





Credit: David Babb

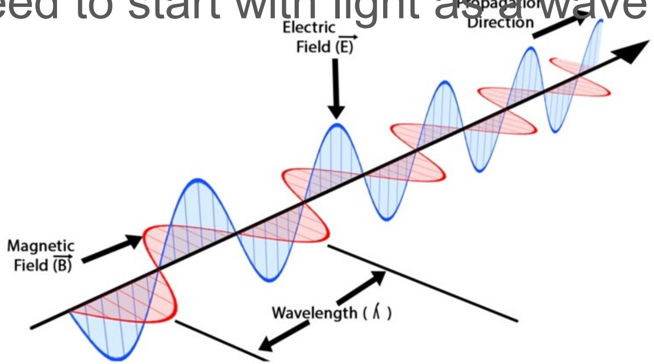
Is there a tangible example of Quantum?

You may have heard that *Light is Polarized*

You might have polarized sunglasses.

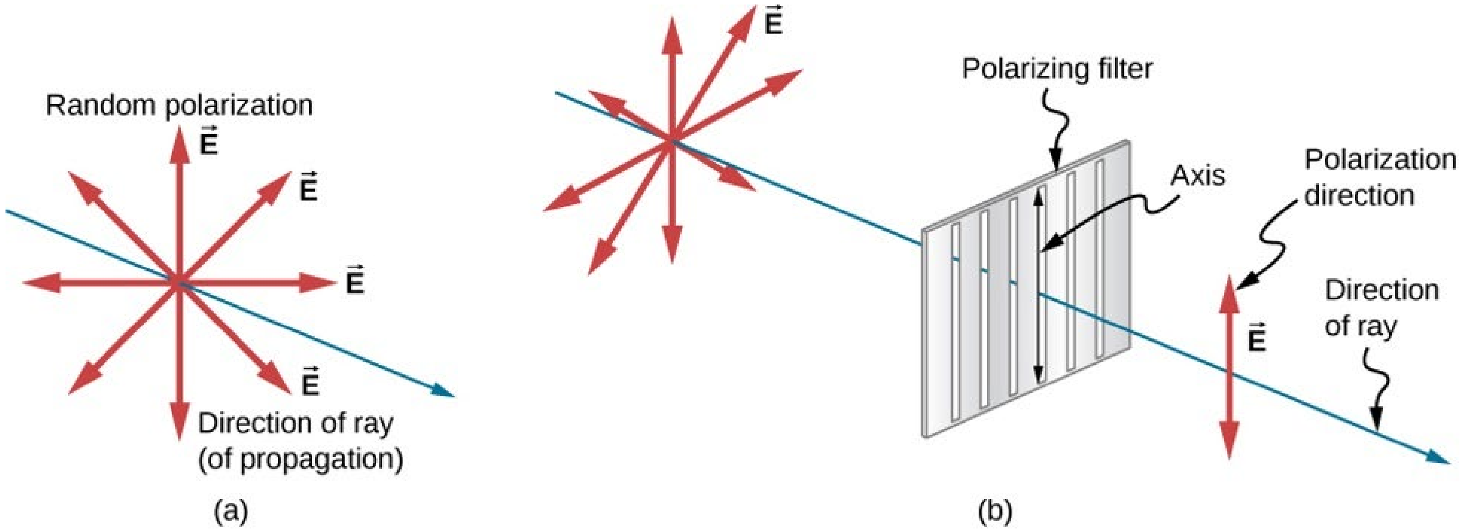
What is polarized light?

Need to start with light as a wave



Polarized Light

- Sunlight is ***UN**polarized* light
- The waves that compose the light are all jumbled and vibrate in all directions.
- A polarizer filters out all the light except the light that is vibrating in the orientation of the polarizer



Let’s take a look at what happens with polarizers:

A fun (quantum) experiment with polarizers

What do you predict will happen when you look through one of the polarizers?

Take one polarizer and look through it - what do you notice?

Let’s take a look at what happens with polarizers:
A fun (quantum) experiment with polarizers

What do you think will happen when you look through 2 polarizers?

Now look through two polarizers

- What do you notice?
- What happens as you rotate the polarizers with respect to one another

Let’s take a look at what happens with polarizers:
A fun (quantum) experiment with polarizers

What do you expect to happen if you add a polarizer between the first two?

When two polarizers are oriented to block the light, insert a third polarizer between them - what do you notice?

A fun (quantum) experiment with Polarizers

Polarizers perform ***quantum measurements***

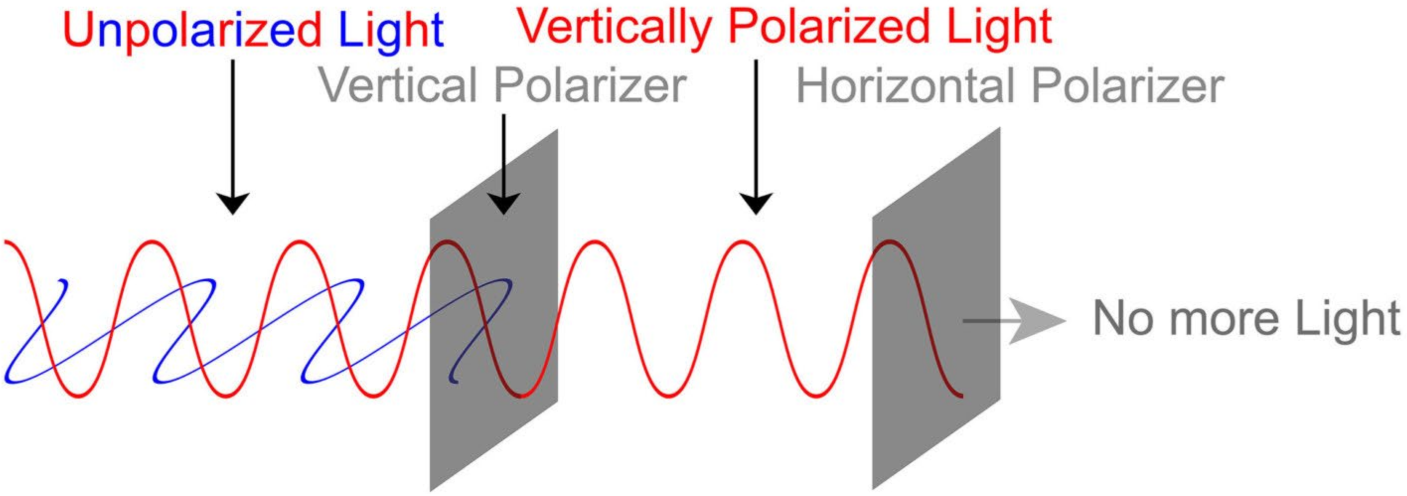
We can think of measurement as asking a question

How much of the incoming light is polarized in the same direction as the polarizer?

Using the concept of ***measurement***, can you explain why the two polarizers in the video blocked ALL the light when the first one was vertical and the second was horizontal?

A fun (quantum) experiment with Polarizers

Using the concept of measurement, can you explain why the two polarizers in the video blocked ALL of the light when the first one was vertical and the second was horizontal?

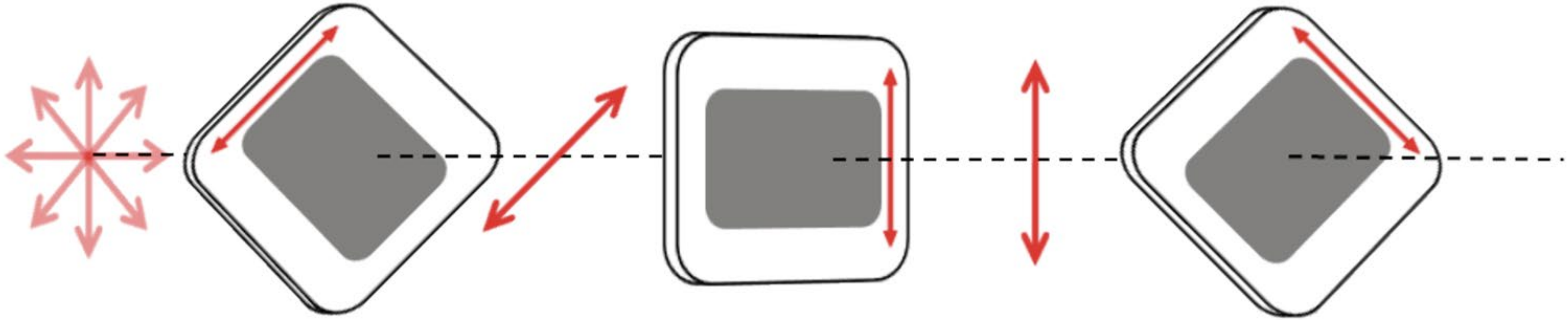


Also note that measurements can't be reversed!!

A fun (quantum) experiment with Polarizers

A bit harder question…

Using the concept of measurement, can you explain why some light makes it all the way through if you use ***THREE*** polarizers like in the video?



A fun (quantum) experiment with Polarizers

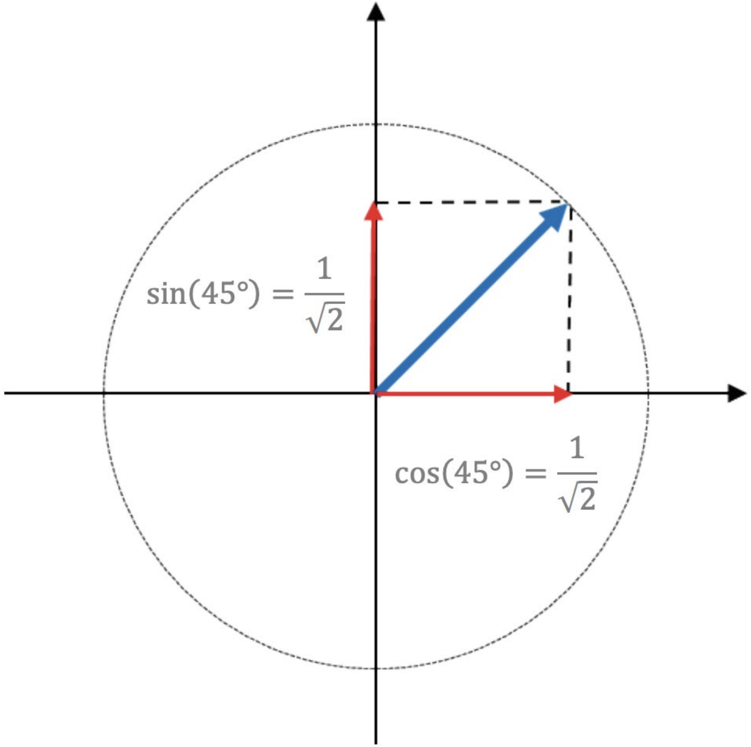
Some new vocabulary…

A horizontal polarizer and vertical polarizer form a ***measurement basis***.

Horizontal and Vertical are ***mutually exclusive***

We can use Horizontal and Vertical States to build ***superposition states***.

How much of the (diagonal) blue line is in the Vertical or Horizontal direction?

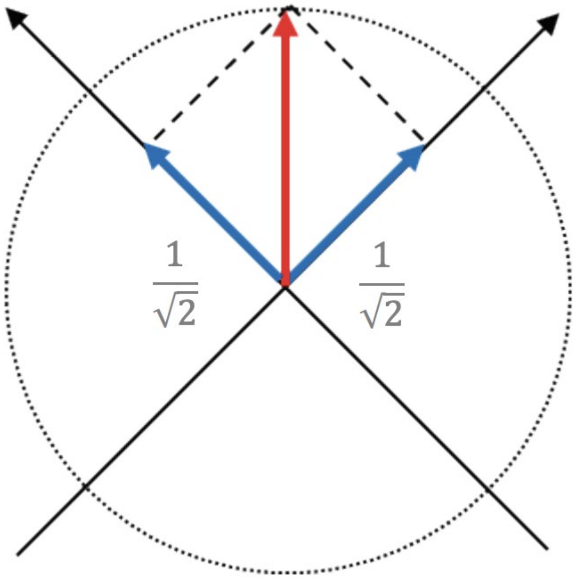


A fun (quantum) experiment with Polarizers

Diagonal polarizers also form
a *measurement basis*.

We can consider vertically polarized
light to be a superposition of
Diagonal and ***Anti-Diagonal*** Polarization

How much of the (vertical) red line is in the
diagonal or anti-diagonal state?

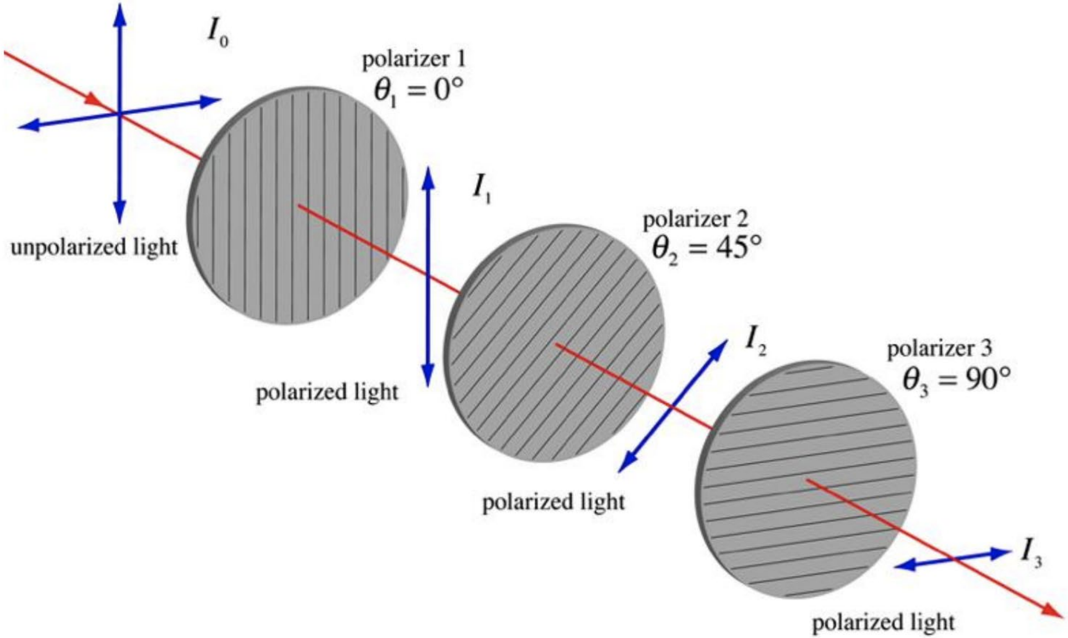


A fun (quantum) experiment with Polarizers

First vertical polarizer sets state by measuring in the H/V basis

Second diagonal polarizer sets state by measuring in the D/A basis

Final polarizer sets state by again measuring in the H/V basis

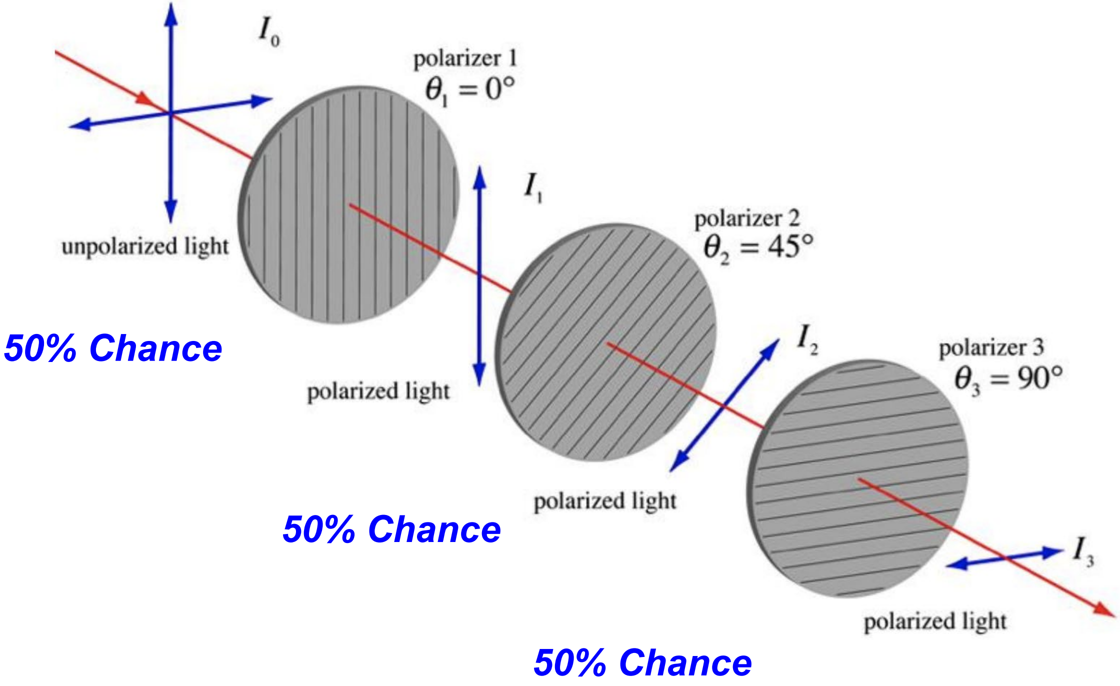


What would happen if you switched the order of the 2nd and 3rd Polarizer?

A fun (quantum) experiment with Polarizers

But wait…
Light is also a particle!
(***wave-particle duality***)

When a photon passes through a polarizer it has a *probability* of passing through that is proportional to the angle between polarizers

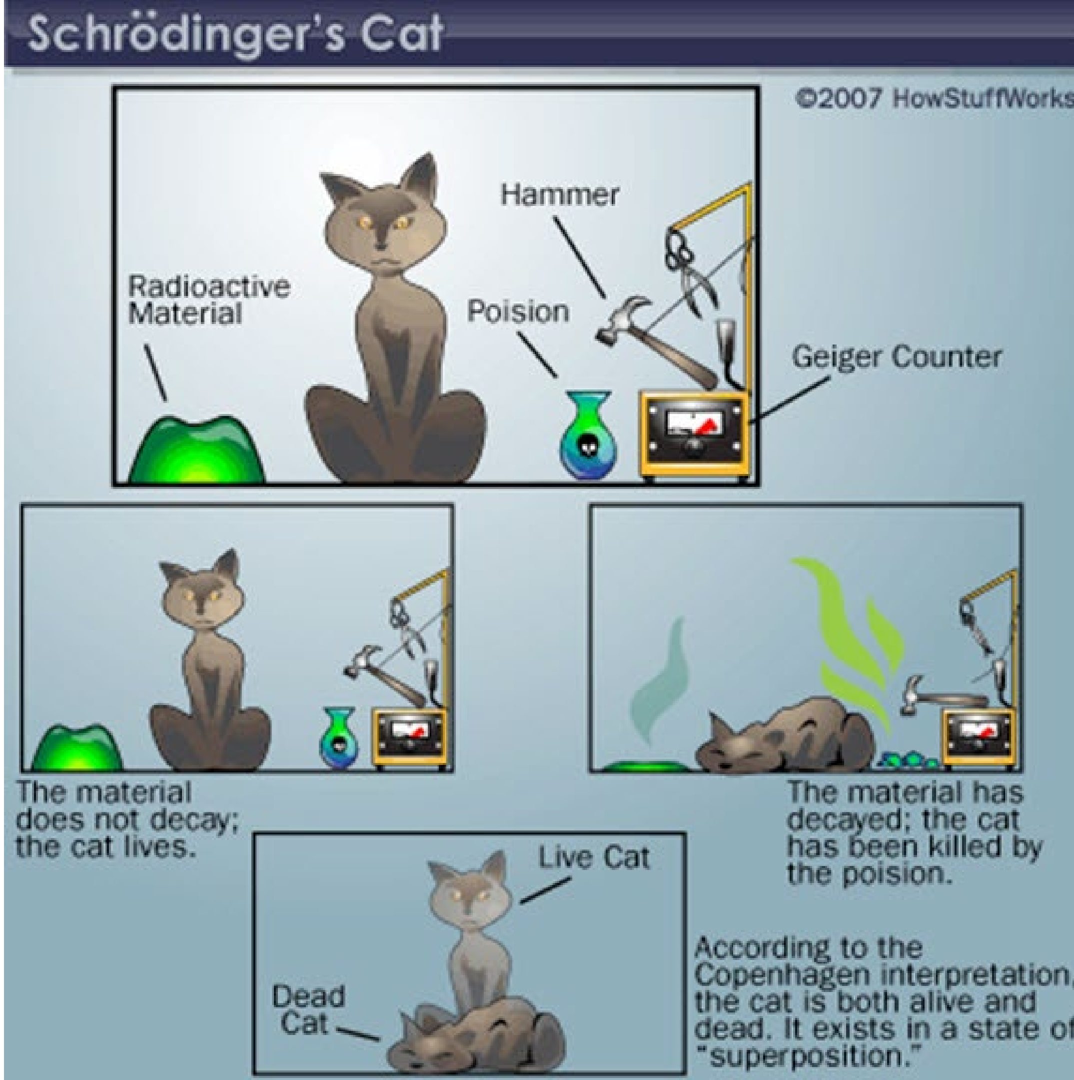


Superposition

Quantum systems can exist in more than one quantum state at the same time.

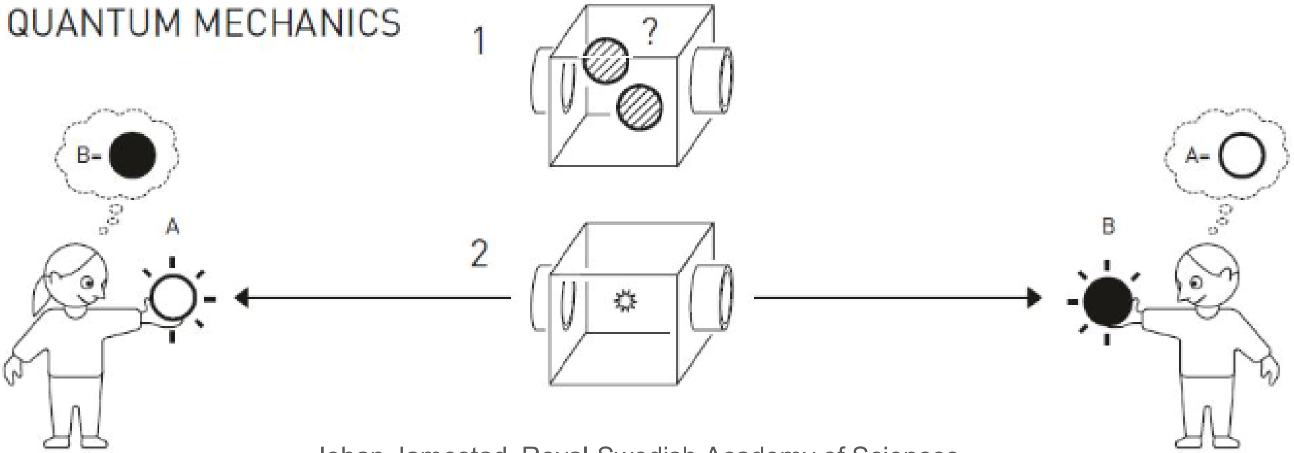
For Schrodinger's cat, the cat is both alive and dead until you "look" or **measure** its state

https://datavizblog.com/2014/02/25/quantum-computers-and-schrodingers-cat/



Superposition, Entanglement, and Measurement

- Two balls start in a **state** that is a **superposition** of black and white
- In the cartoon version, the balls are sent to the two people
- When one **measures** the state of their ball to find out the color, they know the color of the other ball no matter where it is in the universe
- The ball is not black or white until it is measured



Johan Jamestad, Royal Swedish Academy of Sciences

Key Concepts To Take Away

Superposition

A quantum object can be in a superposition of multiple states at once or in a pure state of a measurement basis.

Measurement

The act of measuring the superposition will collapse it and change the state.
The outcome of the measurement is probabilistic and depends on the measurement basis that is being used.

Probability

Quantum measurements are not deterministic, they are probabilistic. Each time a measurement is taken, the outcome is independent of all other previous measurements

Entanglement

If two quantum particles are entangled then if you measure the state of one, you know the state of the other

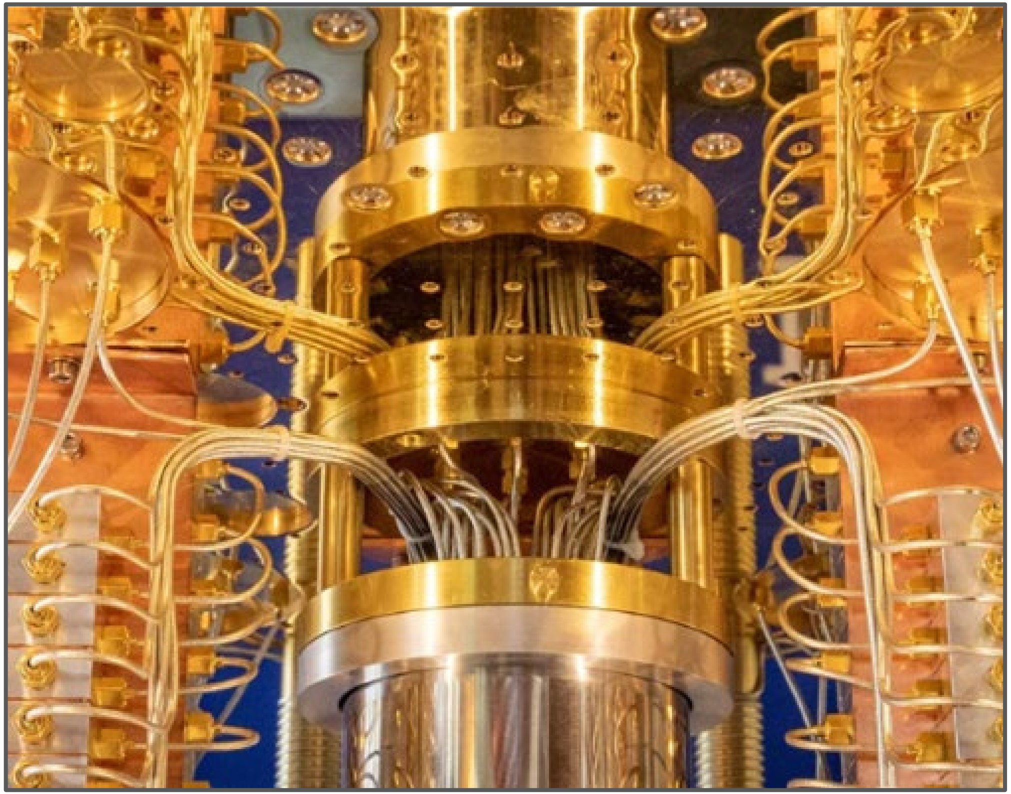
Break

https://jqub.ece.gmu.edu/categories/QPaths/

Why is this Quantum Weirdness important?

We are starting to be able to build devices to manipulate this weirdness to our benefit:

- Quantum sensing
- Quantum communication and cryptography
- Quantum computing



Quantum Domains

Quantum Computing	Quantum Communications & Cryptography
Quantum Sensing	Quantum Materials

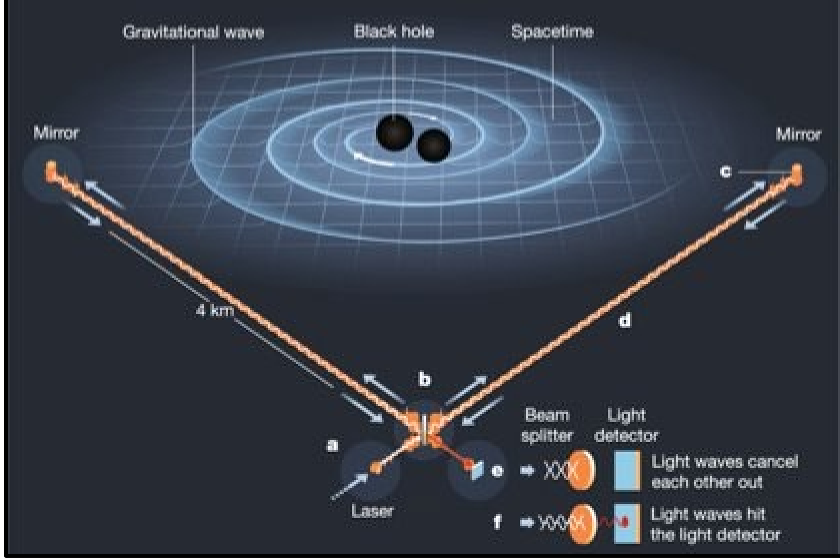
Quantum Sensing

Can be used to measure in wide variety of environments:

- Magnetic fields
- Electric fields
- Temperature

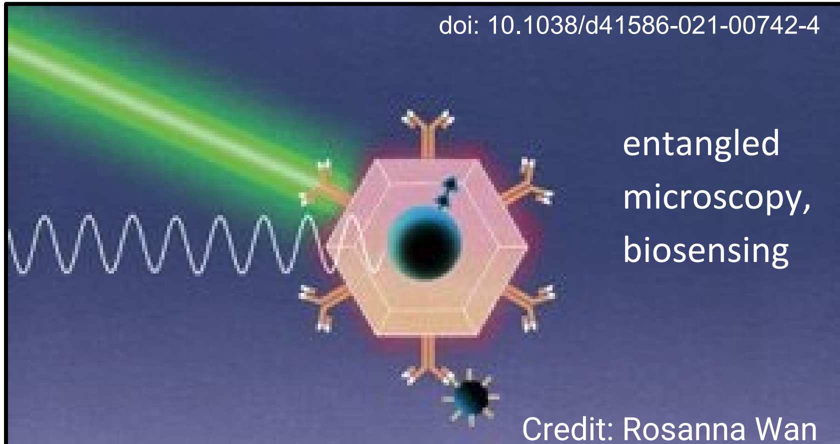
Uses (just a few examples):

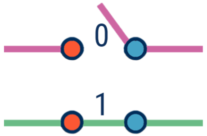
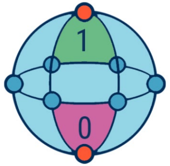
- Oil prospecting
- Improve MRI resolution
- Temperature inside cells
- Detection of viruses and cancer cells in the blood
- Detection of gravity waves



doi: 10.1038/s41586-019-1129-z

Gravitational Wave Discovery with LIGO



Classical Computing	Quantum Computing
 Calculates with transistors, which can represent **either 0 or 1**	Calculates with qubits, which can represent **0 and 1 at the same time** 

From https://research-assets.cbinsights.com/2020/12/22124918/Quantum_computing_classical_qubit_infographic_122020.png

Classical Bit vs. Quantum Bit

Classical Bit

- 2 basic states — 0, 1 (OFF or ON)
- Mutually exclusive

$$X = 0 \ \textbf{\textit{or}} \ 1$$

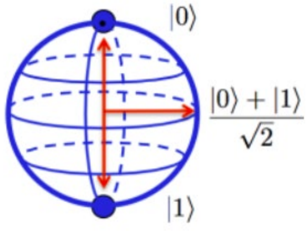
Classical Bit

Quantum Bit (Qubit)

- 2 basic states — $|0\rangle$, $|1\rangle$ (ket 0, ket 1)
- Uses **superposition** of both states with "quantum" effect store information.
- Thus, it represents both $|0\rangle$ and $|1\rangle$ at the same time.

$$|\psi\rangle = |0\rangle \ \textbf{\textit{and}} \ |1\rangle$$

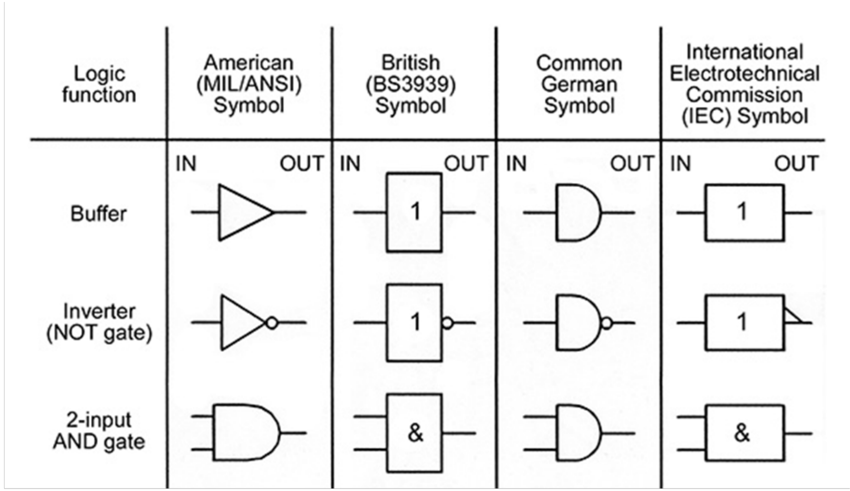
Bloch Sphere

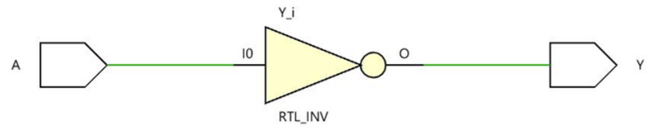


Qubit

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \rightarrow \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

Computation: Logic Gates vs. Quantum Logic Gates

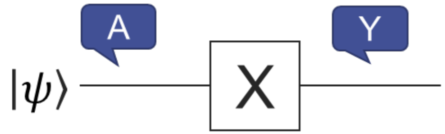




$$Y = \bar{A}$$

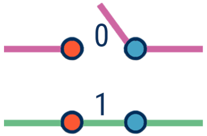
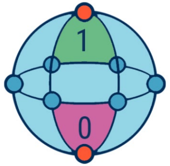
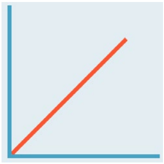
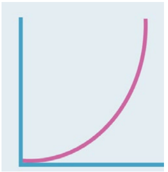
A	Y
0	1
1	0

Operator	Gate(s)		Matrix
Pauli-X (X)	X	$\oplus$	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)	Y		$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
Pauli-Z (Z)	Z		$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
Hadamard (H)	H		$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
Phase (S, P)	S		$\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$



$$|Y\rangle = X \times |A\rangle$$

$$\text{Y} \begin{pmatrix} y_0 \\ y_1 \end{pmatrix} = \text{X} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \times \text{A} \begin{pmatrix} a_0 \\ a_1 \end{pmatrix}$$

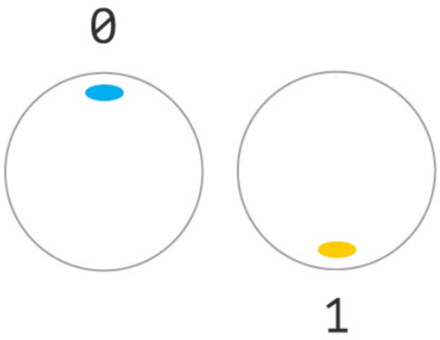
Classical Computing	Quantum Computing
 Calculates with transistors, which can represent either 0 or 1	Calculates with qubits, which can represent 0 and 1 at the same time 
 Power **increases in a 1:1 relationship** with the number of transistors	Power **increases exponentially** in proportion to the number of qubits 

From https://research-assets.cbinsights.com/2020/12/22124918/Quantum_computing_classical_qubit_infographic_122020.png

Multiple-Qubits

2 Classical Bits

00 **or** 01 **or** 10 **or** 11

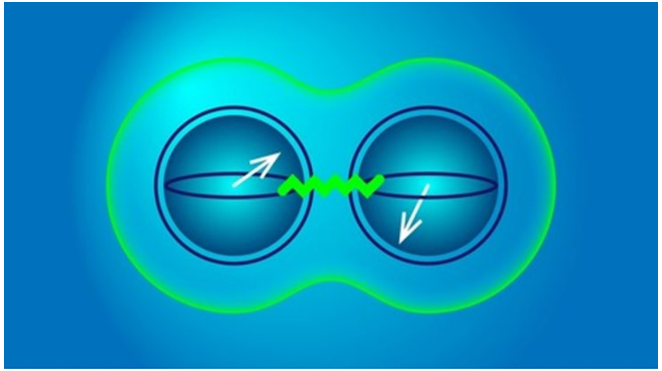


n bits for 1 value

$x \in [0, 2^n - 1]$

2 Qubits

$c_{00}|00\rangle$ **and** $c_{01}|01\rangle$ **and** $c_{10}|10\rangle$ **and** $c_{11}|11\rangle$



n bits for 2^n values

$a_0, a_1, a_2, \cdots a_n$

Operations on Multiple-Qubits (Extremely High Parallelism)

$$A_{N,N} \times B_{N,1} = \frac{1}{2} \times \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \times \begin{bmatrix} c_{00} \\ c_{01} \\ c_{10} \\ c_{11} \end{bmatrix} = \begin{bmatrix} d_{00} \\ d_{01} \\ d_{10} \\ d_{11} \end{bmatrix}$$

Matrix multiplication on classical computer using 16bit number

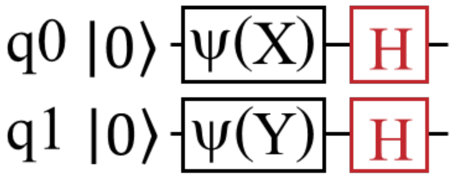
$$A_{N,N} \times B_{N,1} = C_{N,1}$$

Data: $(M \times M + 2 \times M) \times 16bit, \quad M = 2^2$

Operation: Multiplication: $\boldsymbol{M \times M}$

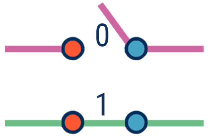
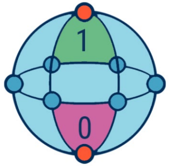
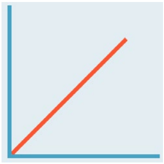
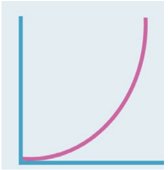
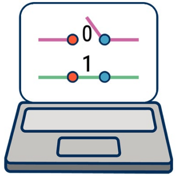
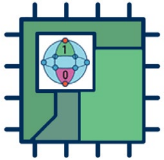
Accumulation: $\boldsymbol{M \times (M - 1)}$

Special matrix multiplication on quantum computer



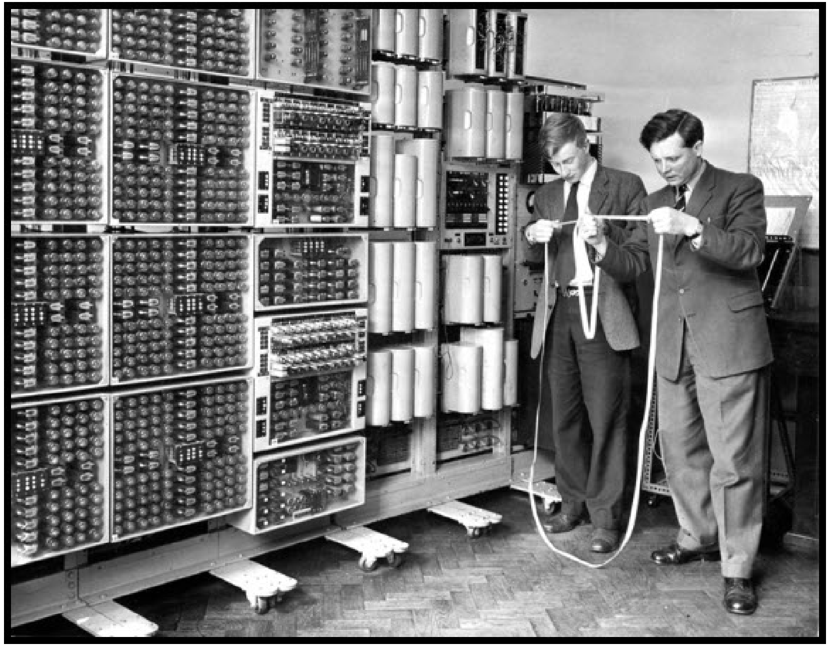
Data: **K** Qbits, **K = logM = 2**

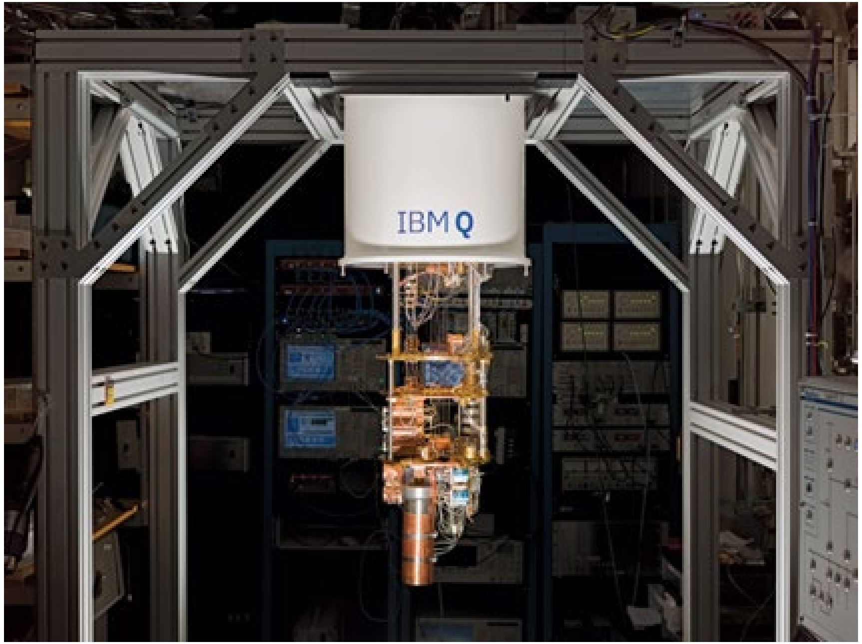
Operation: **K** Hadamard (H) Gates

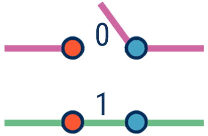
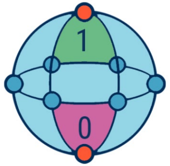
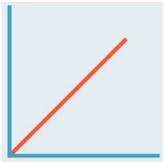
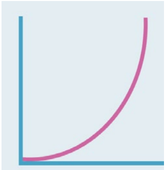
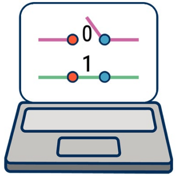
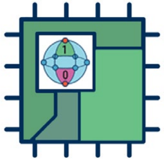
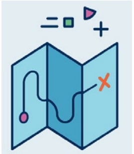
Classical Computing	Quantum Computing
 Calculates with transistors, which can represent either 0 or 1	Calculates with qubits, which can represent 0 and 1 at the same time 
 Power increases in a 1:1 relationship with the number of transistors	Power increases exponentially in proportion to the number of qubits 
 Classical computers have a **low rate of errors** and work well at **room temperature**	Quantum computers have **high rate of errors** and must be kept **ultracold** 

From https://research-assets.cbinsights.com/2020/12/22124918/Quantum_computing_classical_qubit_infographic_122020.png

Big Refrigerator for Quantum Computer to Cool Down!





Classical Computing	Quantum Computing
 Calculates with transistors, which can represent either 0 or 1	Calculates with qubits, which can represent 0 and 1 at the same time 
 Power increases in a 1:1 relationship with the number of transistors	Power increases exponentially in proportion to the number of qubits 
 Classical computers have a low rate of errors and work well at room temperature	Quantum computers have high rate of errors and must be kept ultracold 
 Most everyday computer work is best handled by classical computers	Well suited for tasks like optimization problems, data analysis, & simulations 

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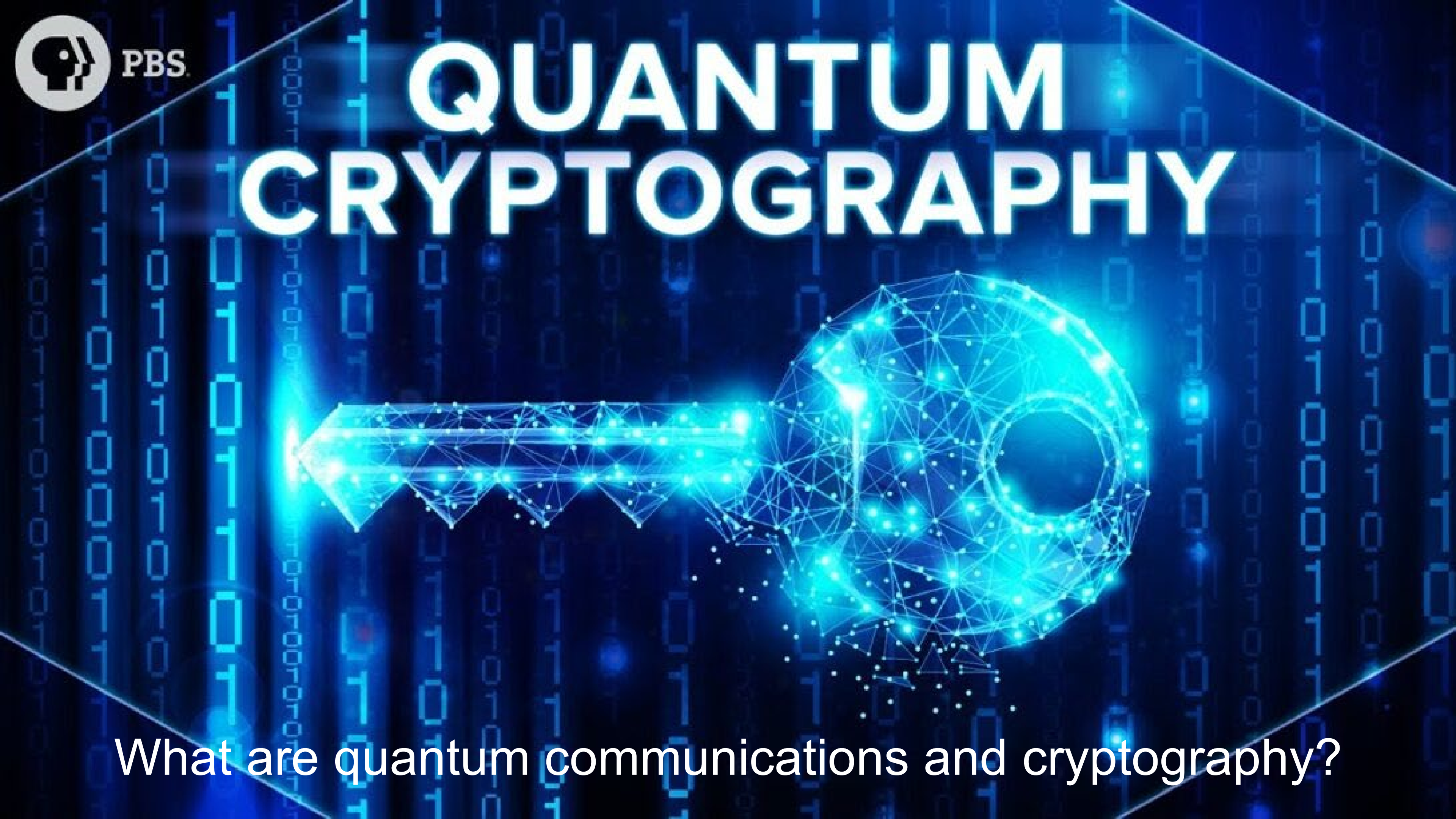

What are quantum communications and cryptography?

Quantum Communications and Cryptography

We are constantly sending information from one place to another and often use some form of encryption (scrambling of the data that requires a key to unscramble) to keep it safe in transit.

Post-quantum cryptography: Algorithms developed to encode data that are thought to be secure against an attack by a quantum computer

Quantum cryptography: using the principles of quantum mechanics to send secure messages in a manner that is truly unhackable.

Thank You!

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