QUANTUM ENTANGLEMENT!

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AGENDA

1. A Brief Introduction
2. History and Learning at the same time!
3. Applications of Quantum Entanglement

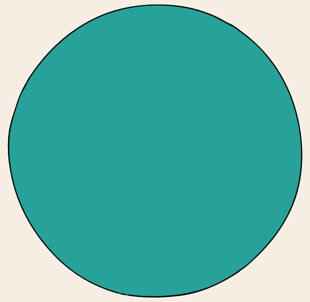
A BRIEF INTRODUCTION
QUANTUM ENTANGLEMENT

- Quantum: Regarding quantum particles
- Entanglement: Linking together and influencing each other

- **Definition of Quantum Entanglement**

Quantum entanglement is a phenomenon in quantum mechanics where two or more particles become linked together in a way that they share the same quantum state, regardless of the distance separating them

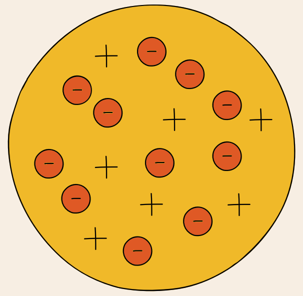
A BRIEF HISTORY



1935

EPR Paradox

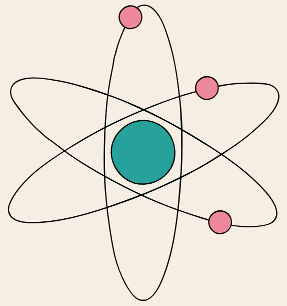
Einstein, Podolsky, Rosen



1935

‘Entanglement’

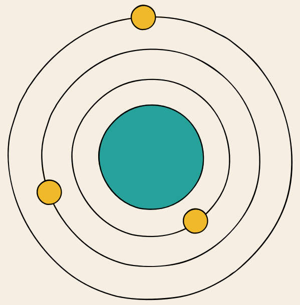
Schrödinger



1964

Bell’s Theorem

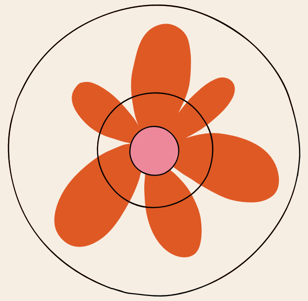
John Stewart Bell



1972

Experimental proof

John Clauser



1997

Quantum Teleportation

Anton Zeilinger

EPR PARADOX

EINSTEIN, PODOLSKY, ROSEN

1935

How did this come by?
When quantum mechanics first came by, the three scientists found out that it had some flaws

- It could only measure the probability and not the exact value of e.g. the time in which an atom emits a photon
- A complete physical theory should be able to predict every property of a system with certainty
- So they believed that quantum mechanics was incomplete with hidden variables

incomplete!

EPR PARADOX

EINSTEIN, PODOLSKY, ROSEN

1935

So they proposed a thought experiment:

- Suppose two particles' total momentum and position are linked (conserved).
- If you measure one particle's position, you instantly know the other's position, and the same for their momentum
- But this then leads to a paradox
- Quantum mechanics states that you cannot know the definite position and momentum of a particle before measurement (e.g. in the second particle)
- But measuring the first particle helps infer that of the second particle

WHAT DOES THIS SUGGEST?

- **EITHER**

(A) the second particle had these properties all along (hidden variables), meaning quantum mechanics is incomplete,

- **OR**

(B) measuring one particle somehow affects the other instantly, no matter the distance → which Einstein called “spooky action at a distance.”

'ENTANGLEMENT'

SCHRÖDINGER

1935

- In 1935, soon after the EPR paper came out, Erwin Schrödinger wrote a series of papers in response
- He agreed that the EPR paradox revealed something strange – but instead of calling it a flaw, he highlighted that this "strangeness" is actually a key feature of quantum mechanics, and thus introduced the term 'entanglement'

‘ENTANGLEMENT’

SCHRÖDINGER

1935

- To illustrate the weirdness of entanglement and measurement, he proposed the **Schrödinger’s cat** thought experiment
- A cat is placed in a box with a radioactive atom, a Geiger counter, and poison
- Quantum mechanics says the atom is in a superposition of decayed and not decayed
- So until observed, the cat is entangled with the atom – both alive and dead at the same time

BELL'S INEQUALITY

JOHN STEWART BELL

1964

- Bell showed that if the world worked like Einstein imagined (with hidden variables), then there would be a limit to how strong correlations between distant particles could be
- He turned this into a mathematical condition called a Bell inequality.
- However, it will be proven that quantum mechanics predicts stronger correlations than this limit, thereby violating Bell's inequality

- If experiments violate the Bell inequality, then the universe cannot be explained by hidden local properties – **entanglement is real and nonlocal**

BELL'S INEQUALITY

JOHN STEWART BELL

1964

- In simpler terms: Imagine two coins flipped at the same time, but far apart. If almost every time the two coins were flipped land on the same side (e.g. heads), this strong correlation proves that entanglement exists and this outcome cannot be due to hidden variables that do not have such a strong correlation

EXPERIMENTAL PROOF

JOHN CLAUSER

1972

- After Bell's inequality, the challenge was to test whether nature obeys local hidden variables or quantum entanglement
- In 1972, John Clauser (with Stuart Freedman) carried out the first experimental test of Bell's inequality using photons

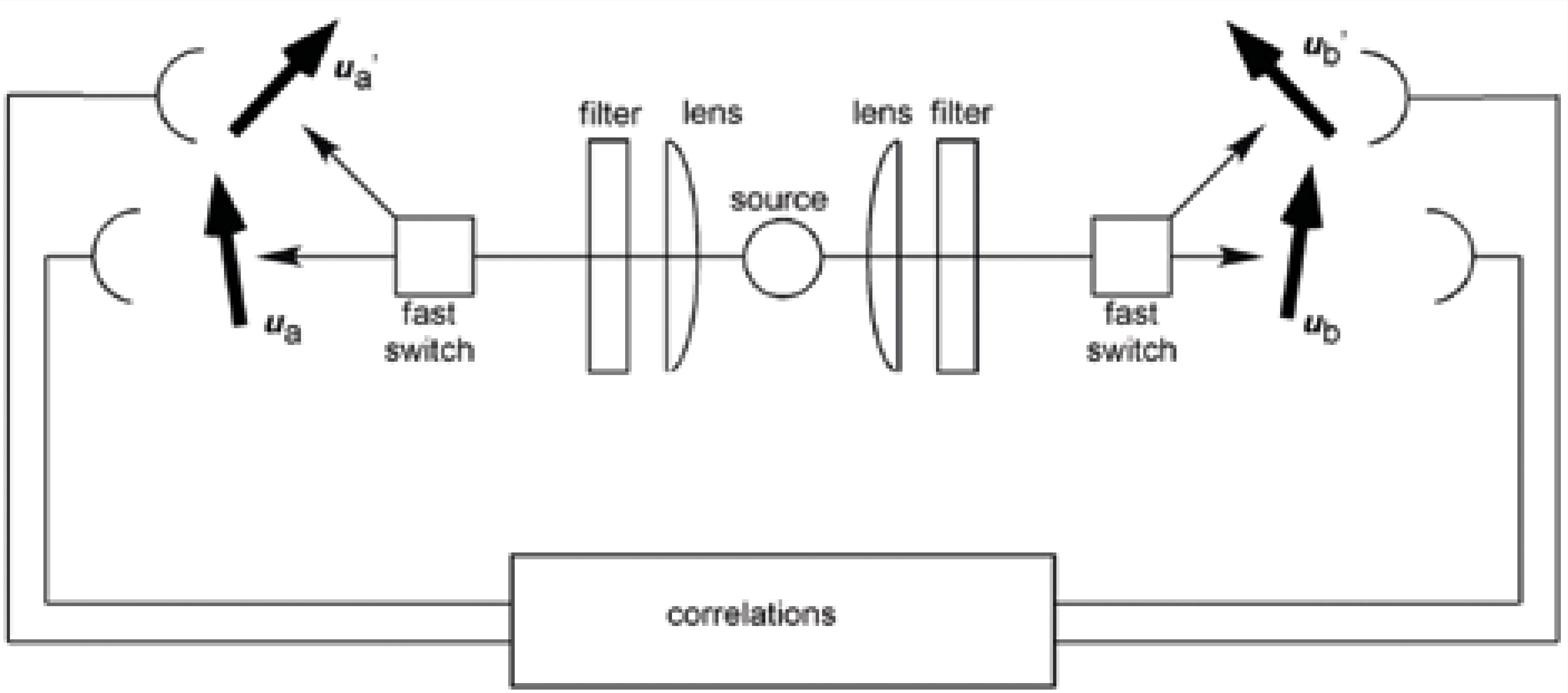
- Clauser and Freedman excited calcium atoms with lasers to create pairs of entangled photons
- The photons were sent to two detectors, each with a filter (polarizer) set at different angles
- They measured whether both photons "passed" their filters at the same time
- If the two photons were not entangled and just had hidden variables affecting them, the chance that both passed would only follow certain limits

- When Clauser rotated the filters to different angles, the photons still showed a very strong link
- The measured correlations were too strong to be explained by hidden variables – **they violated Bell's inequality**

EXPERIMENTAL PROOF

JOHN CLAUSER

A simple diagram to help visualise



AN EASIER ANALOGY

- Imagine two students are secretly told “answer Yes or No” to questions. If they had instructions in advance, their answers could only match so well. But Clauser found their answers matched better than any pre-written script allows → meaning they weren’t following instructions at all, but were somehow “linked” in the moment

- So Clauser’s experiment proved Bell’s inequality wrong and that **entanglement exists**

QUANTUM TELEPORTATION

ANTON ZEILINGER

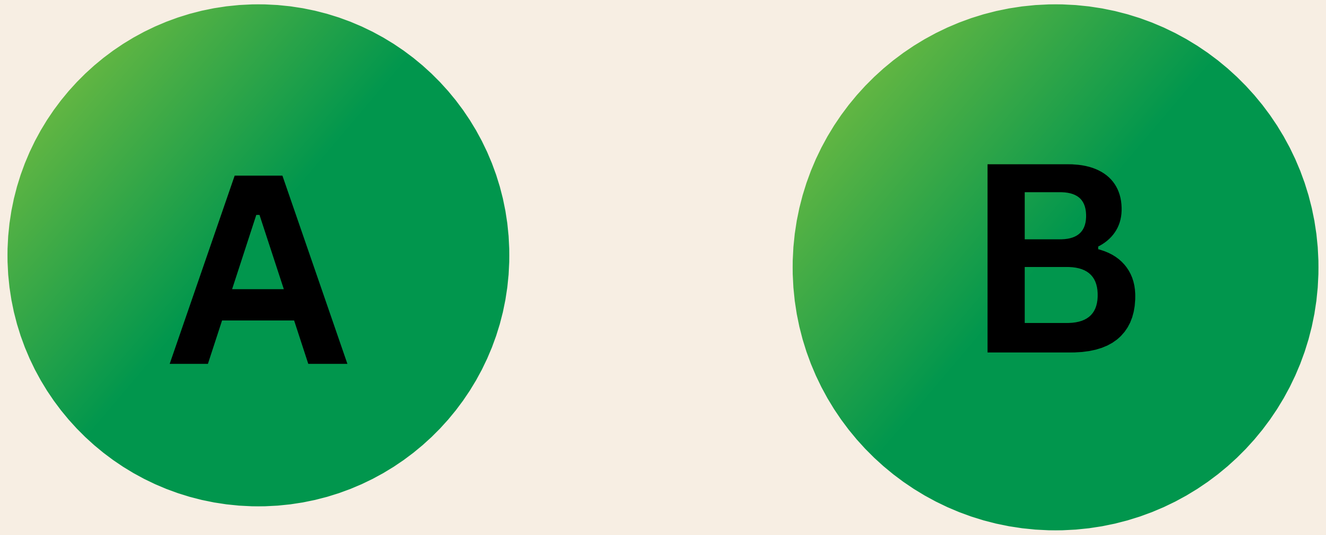
1997

- “Teleportation” here doesn’t mean moving a particle physically
- Instead, it means transferring the quantum state from one particle to another, using entanglement as the bridge

- Zeilinger’s team created a pair of entangled photons (Photon A and Photon B)
- Photon A was kept with Alice; Photon B was sent far away to Bob
- Alice also had another photon (Photon X) whose state she wanted to teleport to Bob
- She performed a measurement on Photon X together with Photon A (called a Bell-state measurement)
- This destroyed Photon X’s state locally but instantly changed Photon B’s state at Bob’s side to match Photon X’s original state

QUANTUM TELEPORTATION

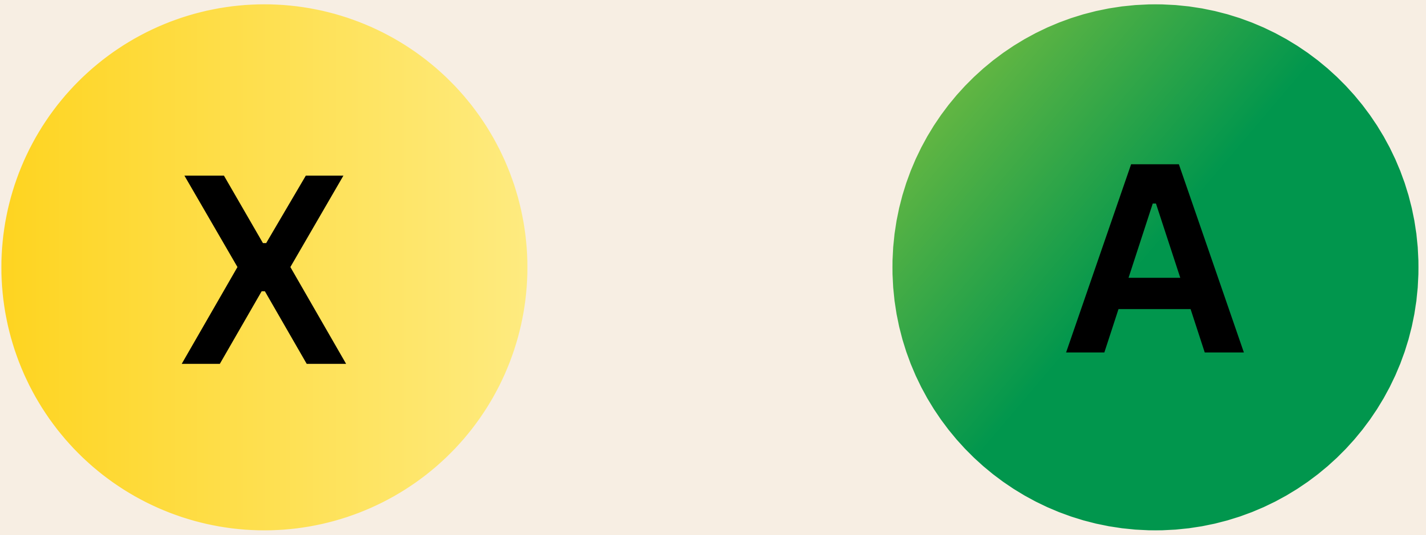
ANTON ZEILINGER



Photon A and B are entangled together and have the same quantum state (which is ever changing)

QUANTUM TELEPORTATION

ANTON ZEILINGER



The Bell-state measurement is performed on X and A

QUANTUM TELEPORTATION

ANTON ZEILINGER

X becomes entangled with A, and they share the same quantum state

QUANTUM TELEPORTATION

ANTON ZEILINGER

A **B**

Since A and B are entangled, the quantum state of A (or X) is transferred to B

QUANTUM TELEPORTATION

ANTON ZEILINGER

After measurement, X and A are destroyed locally, and no longer have their original quantum state, quantum state is transferred to B

QUANTUM TELEPORTATION

ANTON ZEILINGER

Overall

X ->> B

Quantim state of X is teleported to B

WHAT DOES QUANTUM ENTANGLEMENT MEAN FOR US? - APPLICATIONS

- We will be able to transfer information in ways not possible in classical physics

- Quantum teleportation is only an application of quantum entanglement, and there are many other uses of it, such as **quantum computing**

QUANTUM COMPUTING

- These quantum computers consist of qubits, which are in superposition (0 or 1), similar to the bits (0 or 1) of the modern computer
- Entanglement links multiple qubits together so their states are correlated
- Entanglement allows massive parallelism: a quantum computer with n entangled qubits can represent 2^n states simultaneously.
- This is what gives quantum computers an exponential advantage for certain problems
    - Factoring large numbers (important for cryptography)
    - Searching unsorted databases faster
    - Simulating complex quantum systems

QUANTUM COMPUTING

- Why can it represent 2^n states simultaneously?

Because each qubit is in superposition, so it is never definite. And with n of them, it represents 2^n possibilities of their combinations simultaneously.

- How does this give them an advantage?

They are able to run through all possible combinations simultaneously, instead of one by one like the modern computer

QUANTUM COMPUTING

CONTINUATION

How does this then give the correct answer?

- The quantum computer can interfere amplitudes of the 2^n states to favor correct answers
- Measurement at the end collapses the superposition into the correct solution with high probability

Then does this mean the quantum computer is single use?

- YES
- Quantum computations are usually single-use per run, but algorithms are designed so that the single measured outcome is likely the correct solution
- Multiple runs can be used if you need more statistical confidence

Simple Analogy

- Classical computer: opening one box at a time to find a prize.
- Quantum computer: opening all boxes at once in superposition, then using interference to make the prize stand out.

THANKS FOR LISTENING!

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