PHYS 220 B Lecture 5:
Spin, Entanglement and Bell's Test

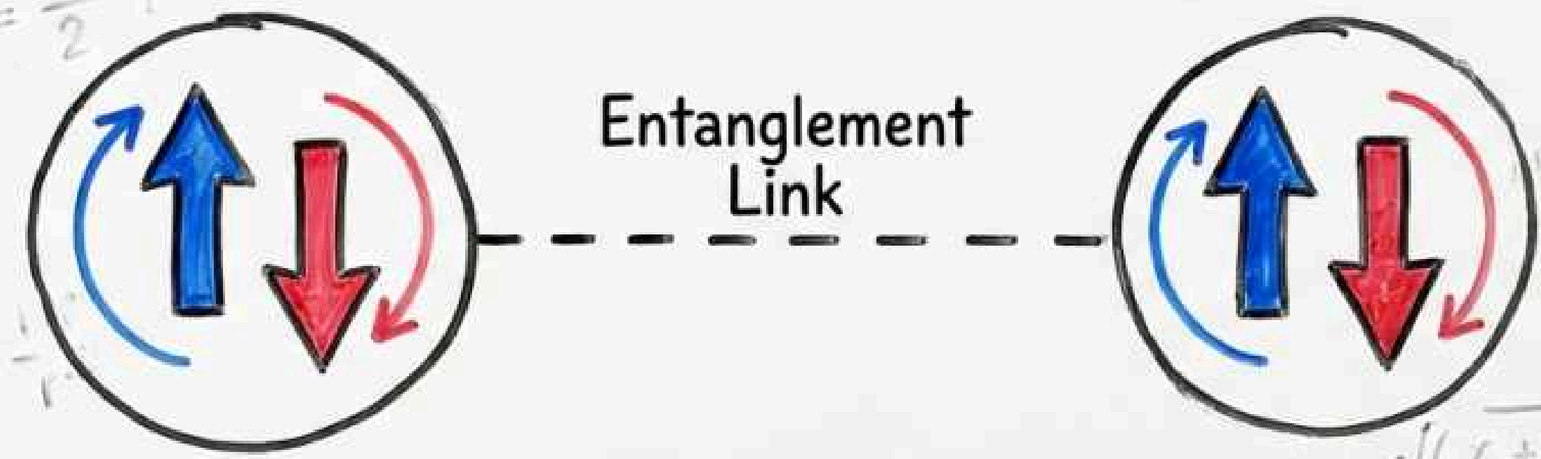
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A visual distillation of quantum mechanics' strangest properties.

$$E = hf$$

$$\lambda = \frac{h}{p}$$

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$$



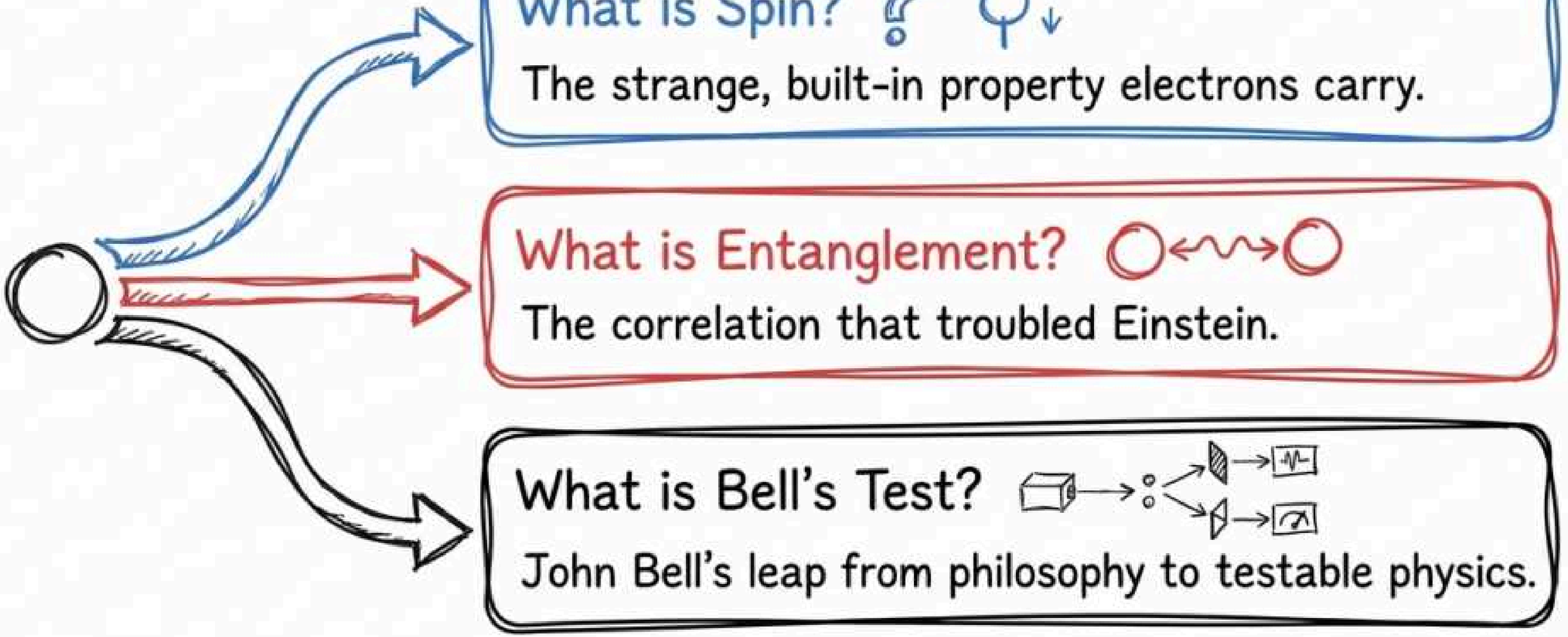
$$\hat{H}\psi = E\psi$$

$$\hat{H}\psi = E\psi$$

$$S_z = \frac{\hbar}{2}\sigma_z$$

Three fundamental questions rewrite our understanding of reality

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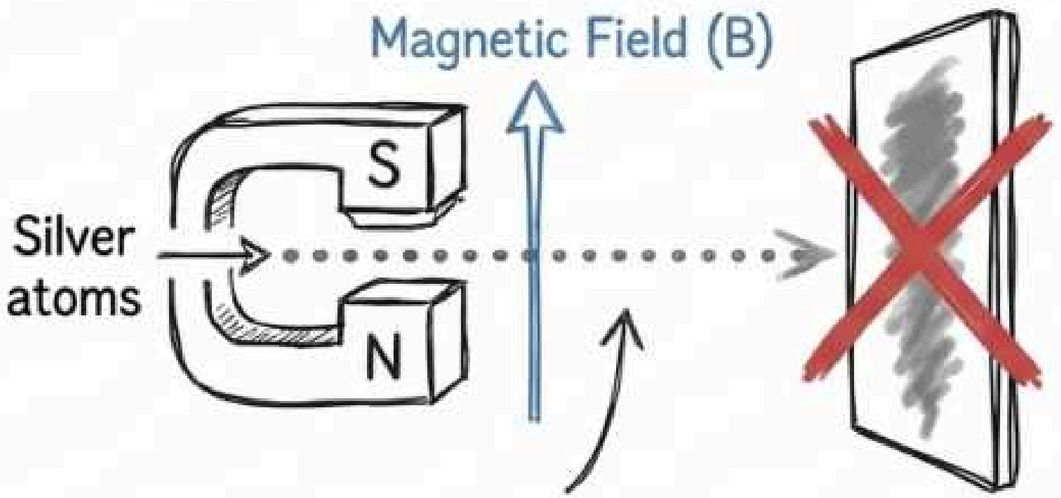


[Para 5.2]

The 1922 Stern-Gerlach experiment defied classical magnetism

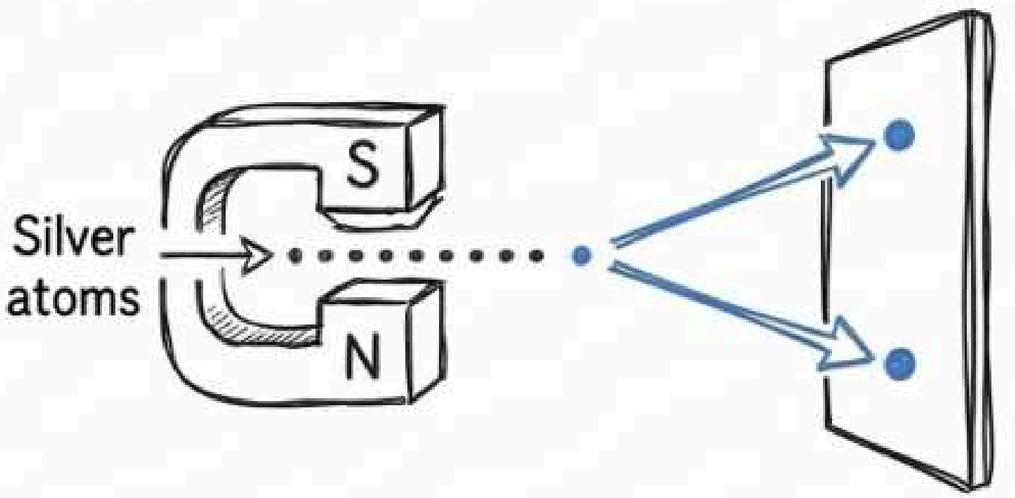
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Classical Expectation



Expected: A continuous smear.

Quantum Reality



Actual: A clean split.
Magnetism takes only two values.

Otto Stern & Walther Gerlach (1922) discovered this baffling effect.

[Para 5.3]

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Spin is a built-in quantum property, not a literal spinning ball

The Myth



If an electron-sized ball spun this fast, its surface would move faster than light.

The Reality



$\hbar/2$

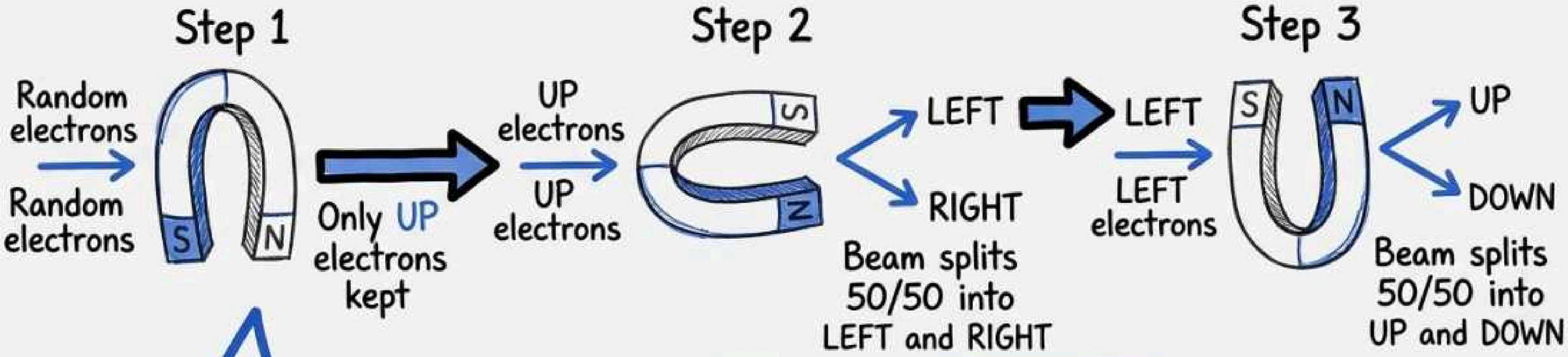
Spin is a fundamental built-in property like electric charge, shared by protons and neutrons.

George Uhlenbeck & Samuel Goudsmit (1925)

[Para 5.4]

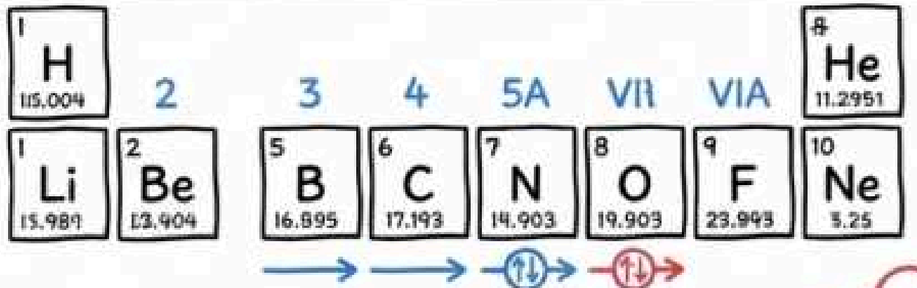
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Measuring spin along a new axis wipes out previous information

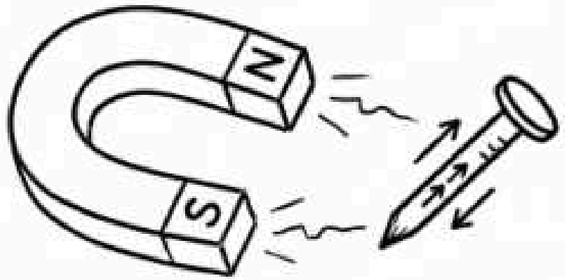


The horizontal measurement destroyed the vertical memory. Position/momentum and Spin axes cannot be sharply defined at once.

[Para 5.5]
Spin dictates the structure and behavior of the physical world



Shapes the Periodic Table.
Pauli Exclusion limits 2 electrons (opposite spins) per orbital.



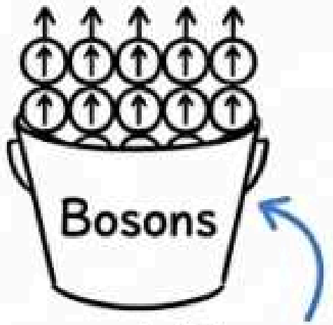
Magnetism. Lined-up spins in iron make it magnetic.

$$\gamma^\mu \partial_\mu \psi + \cdots$$

1928: Paul Dirac merged QM and Special Relativity; spin emerged naturally.



Divides the universe into Fermions
(matter, half-spin, exclusion)



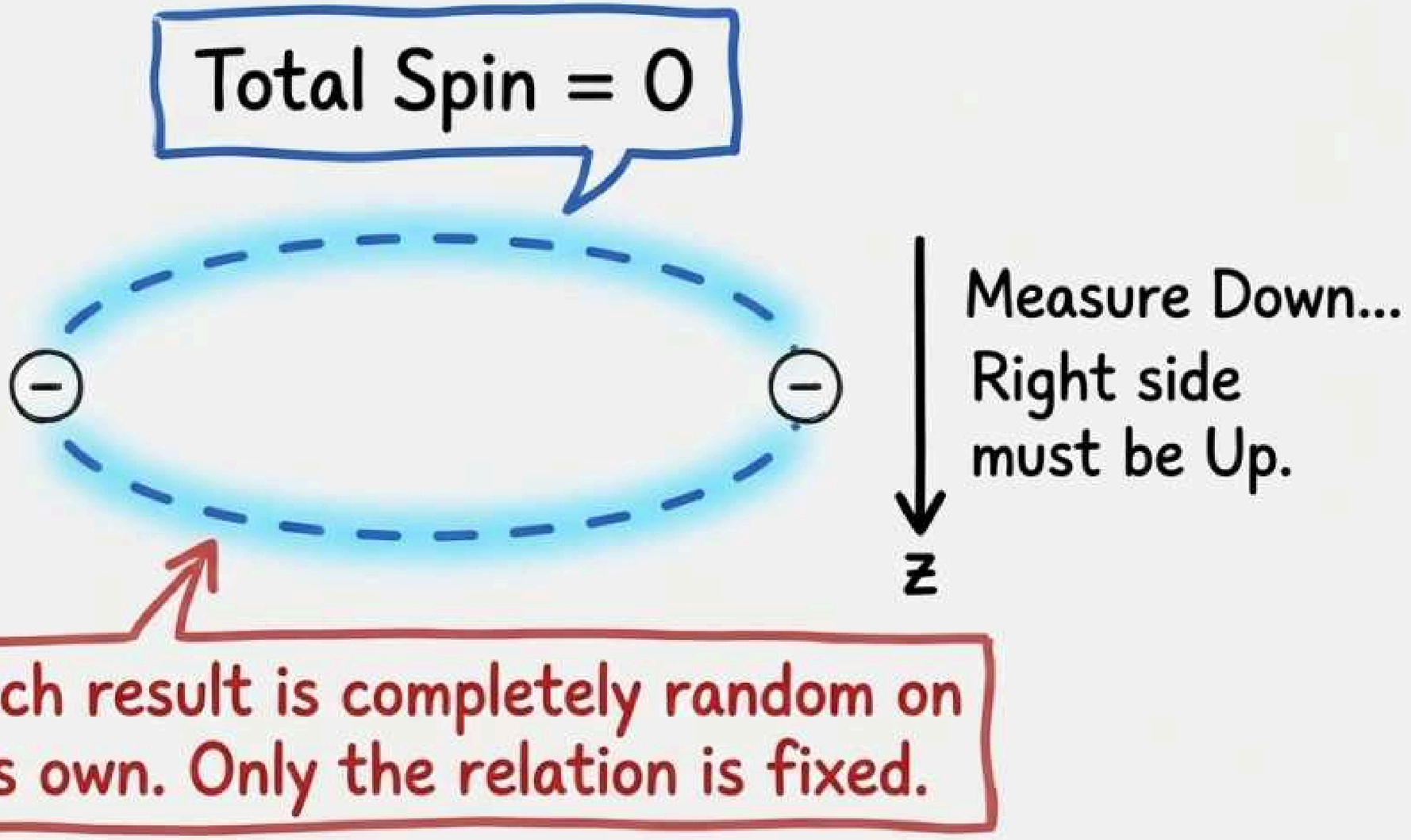
and Bosons
(light/lasers, whole-spin, crowding)

[Para 5.6]

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Entanglement links particles in a single, inseparable joint state

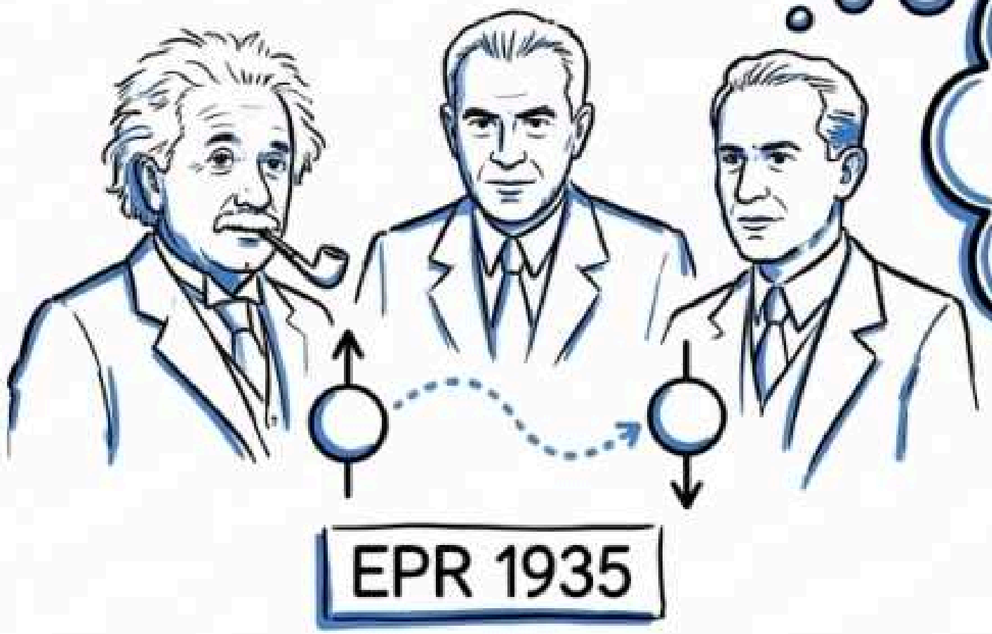
Schrödinger (1935) coined the term Entanglement



[Para 5.7]

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The EPR paradox argued that quantum mechanics must be incomplete

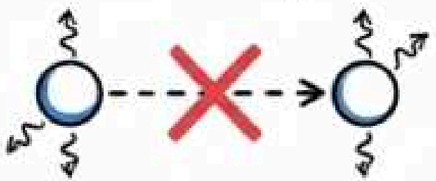


EPR 1935

If we can predict the distant result without touching it, the answer must have been real and fixed all along.

The Locality Assumption

What happens here cannot instantly affect what happens far away.

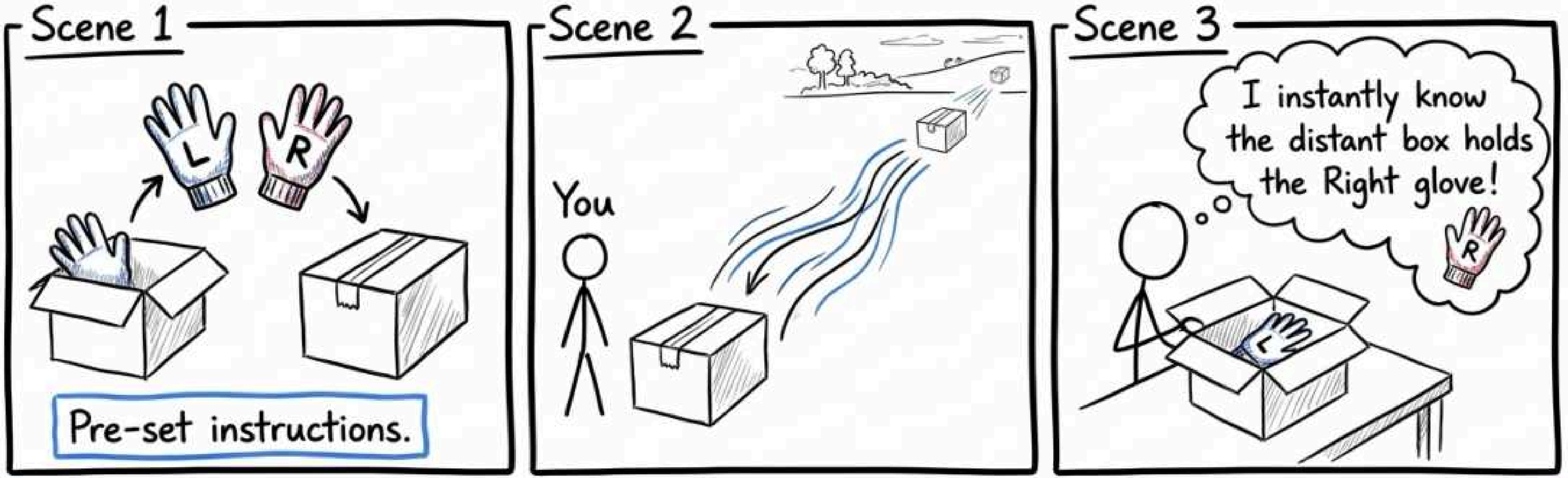


Therefore, Quantum Mechanics is missing hidden elements of reality.

[Para 5.8]

The Glove Analogy: Classical correlation through hidden variables

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Nothing traveled between the boxes. The answer was set at the start. Einstein believed entangled particles worked exactly like this (Local Hidden-Variable Theories).

[Para 5.9]

John Bell transformed a philosophical debate into a physics experiment



A **Philosophy**

Is reality local?

B **Physics**

We can test this.

Bell proved that ANY local hidden-variable theory (glove analogy) has a strict mathematical limit on correlation.

Quantum Mechanics predicts breaking that limit.

$$E(a,b)\cdot E(a,c) - E(a,b)\cdot E(b,c) \leq \dots$$
$$E(a,b)\cdot E(a,c) - E(a,b)\cdot E(b,c) \leq$$
$$= 2a\cdot E(a,b)\cdot E(a,c)\cdot E(b,c) \leq \dots$$
$$= K\,E(a,c) - E(l,b)\cdot E(b,c) \leq \dots$$



John Bell at CERN

[Para 5.10] The CHSH Test pits the Classical Limit against the Quantum Prediction

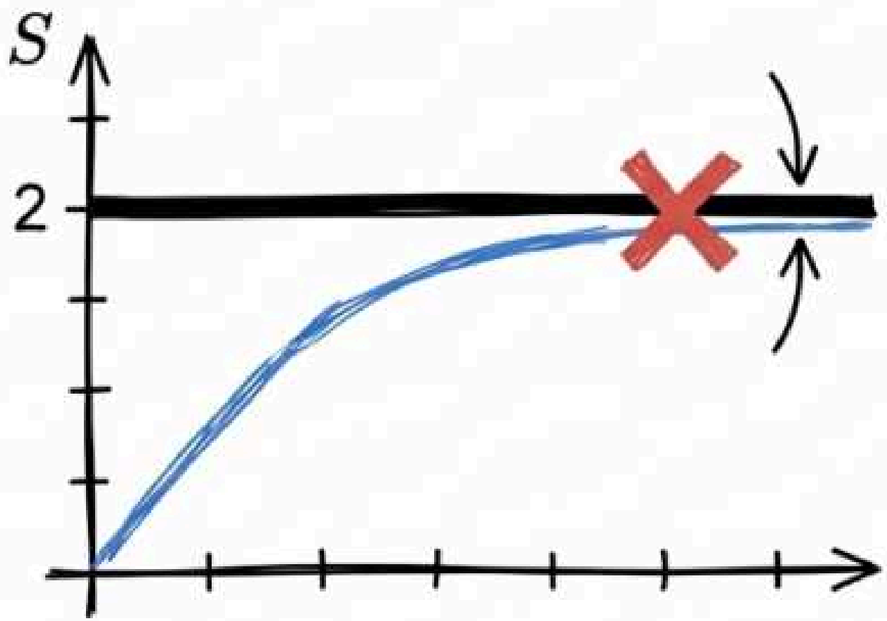
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Context: Random measurement directions for each pair are combined into a single correlation number, S.

Clauser, Horne, Shimony, Holt (1969)

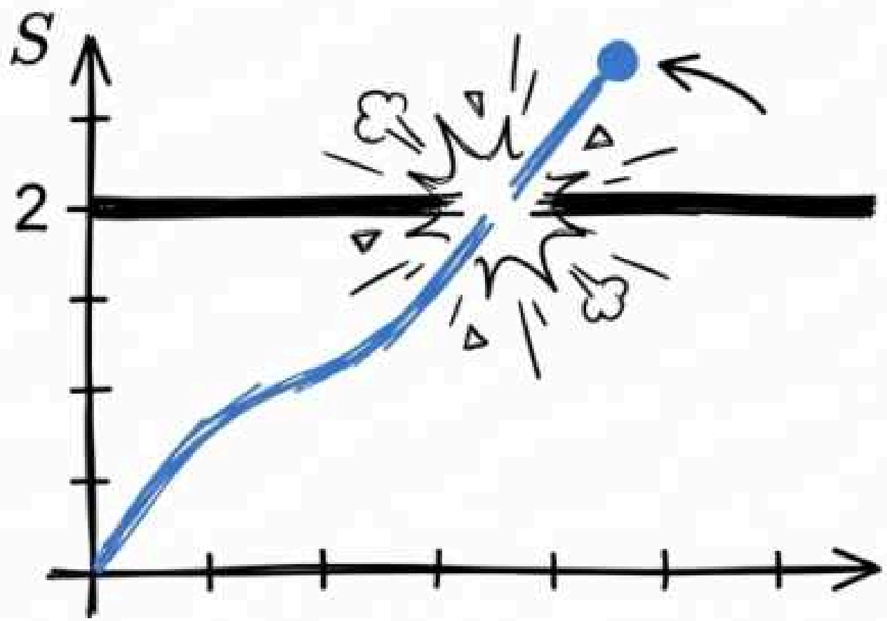
Local Hidden-Variable Theory

$$S \leq 2$$



Standard Quantum Mechanics

$$S = 2\sqrt{2} \approx 2.83$$



[Para 5.11]

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Decades of experiments consistently proved the quantum prediction

1972

Freedman & Clauser: First violation of Bell's limit using entangled photons.

1982

Aspect et al.: Measurement directions switched rapidly while photons were in flight to close communication gaps.

2015

Delft, Vienna, & Boulder: "Loophole-free" tests closed the final remaining gaps simultaneously.

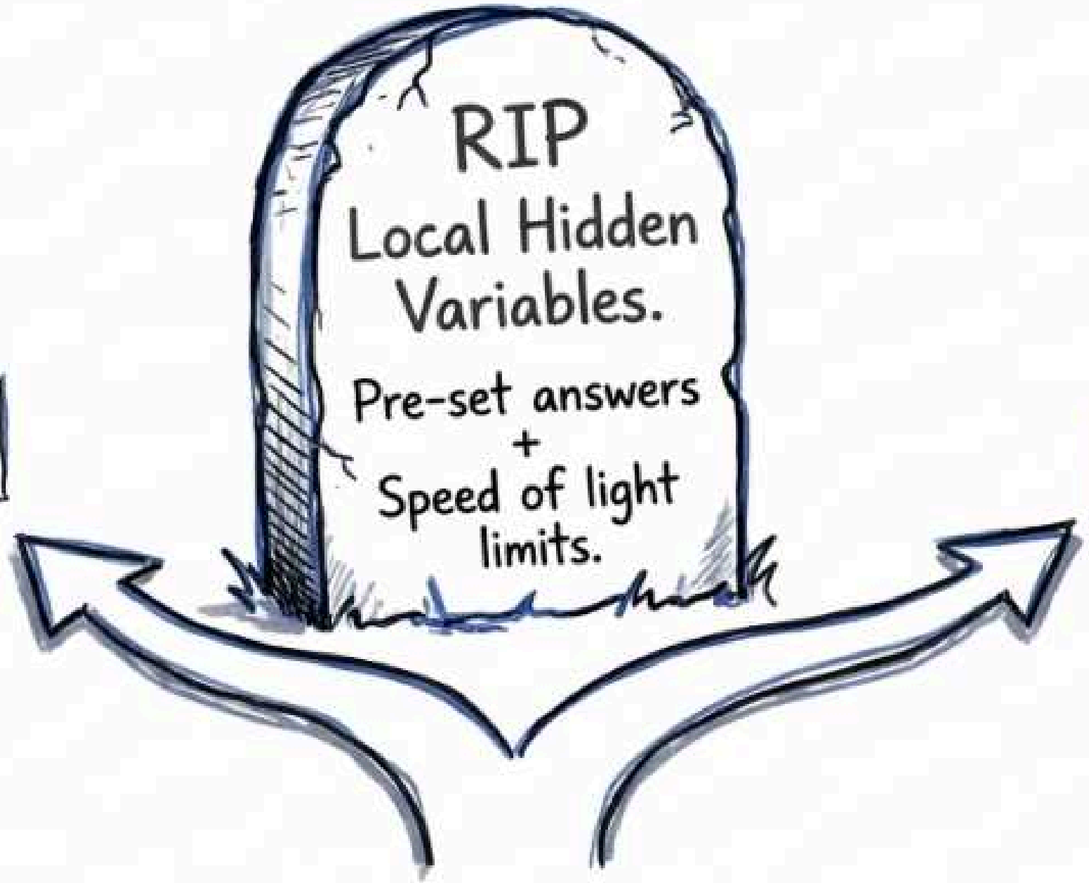
2022



All data firmly points to $S \approx 2.83$. The 2022 Nobel Prize in Physics awarded to Aspect, Clauser, and Zeilinger.

[Para 5.12] The fallout: At least one classical assumption about reality must go

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Pilot-Wave Theory

Keep pre-set answers, but accept non-local (instant) influences.

Many-Worlds

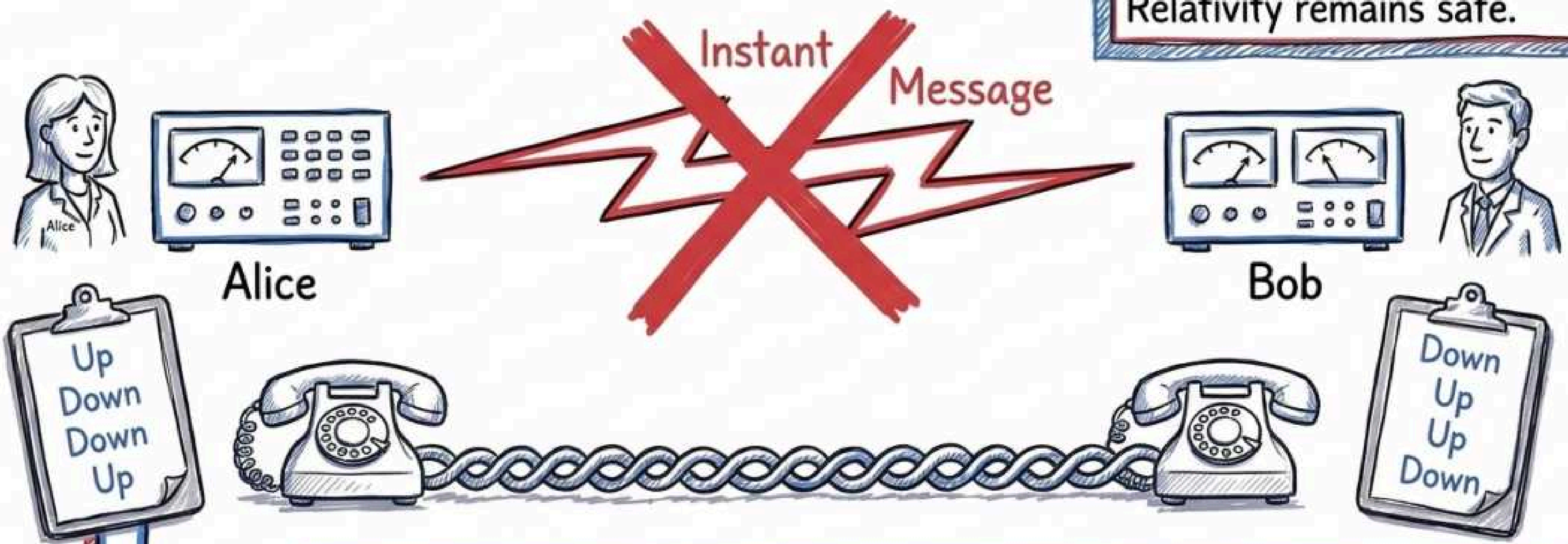
Deny that each measurement yields only one outcome.

Nature cannot be described by local pre-set instructions.

[Para 5.13] Entanglement cannot be used to send messages faster than light

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The No-Signalling Property: Relativity remains safe.

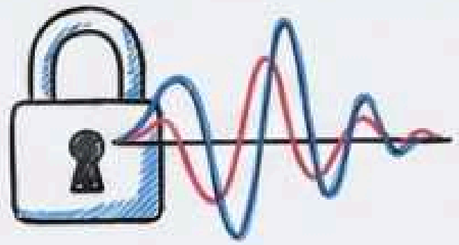


Correlations only exist when both lists are brought together via classical, slower-than-light communication.

[Para 5.14] Entanglement has become a resource for next-generation technology

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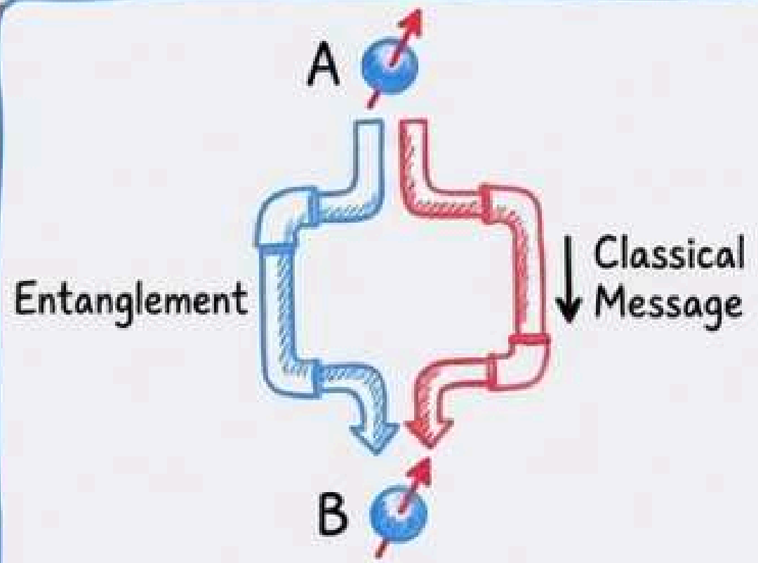
Entanglement



Quantum Key Distribution (QKD): Eavesdropping inherently disturbs the state, revealing the spy.



Satellite Comm: In 2017, the Chinese satellite Micius distributed entangled photons to stations >1000 km apart.



Quantum Teleportation: Transfers the state, but nothing material travels faster than light.

[Para 5.15] Separating sci-fi myths from the fragile reality of entanglement

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Sci-Fi Myths

Entangled particles are joined by an invisible physical string.

↓

They enable human telepathy.

↓

They allow instant, faster-than-light communication.

Quantum Reality

Entanglement is a shared mathematical state, not a physical tether.

↓

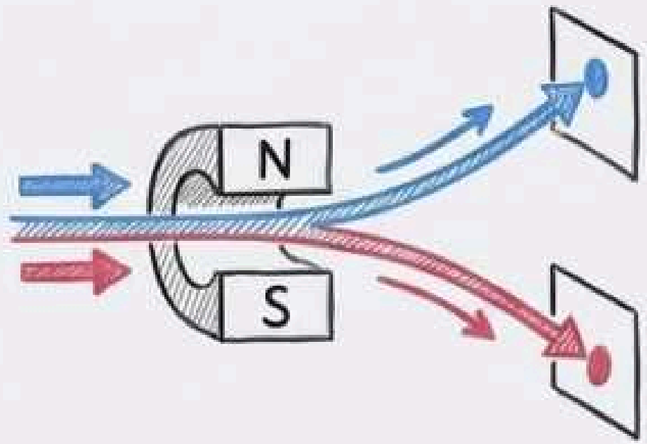
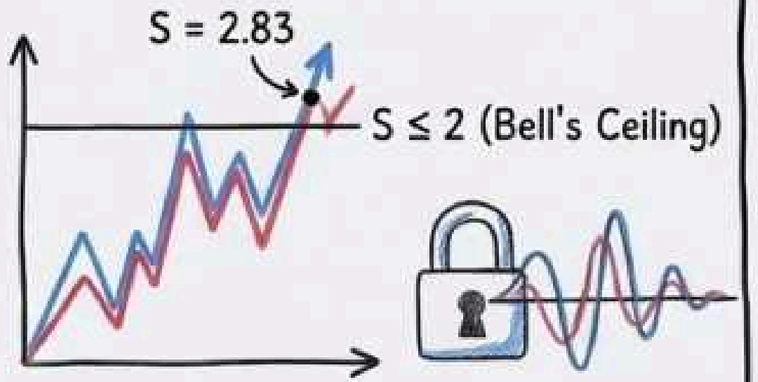
It is incredibly fragile. Contact with the environment (Decoherence) washes it away almost instantly.

↓

Requires extreme isolation—which is exactly why building quantum computers is so difficult.

[Para 5.16] Lecture 5 Synthesis: The journey from Spin to Quantum Tech

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Spin Revealed	The EPR Challenge	Bell's Verdict
		
Recap: A built-in, two-valued property of nature, dictating the structure of matter.	Recap: Entanglement posed a paradox: did particles carry hidden, local instructions?	Recap: Bell and experimenters proved local reality is false. Today, this strangeness powers quantum cryptography and teleportation.