

SPOOKY CORRELATIONS AND THE DEATH OF LOCAL REALISM

The background features a dark, textured grid pattern. A large, translucent, blue and purple sphere is positioned in the upper right, with a smaller, bright yellow-green cone-like shape below it. A long, thin, translucent blue line extends from the lower left towards the center, ending near the sphere.

“FROM EPR TO BELL AND BEYOND”

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NIELS BOHR

THE FATHER OF QUANTUM THEORY



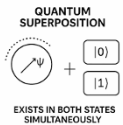
Reality
or
the state of a particle at the fundamental level
was not only unknown,
but unknowable,
until it was measured.

THE COPENHAGEN INTERPRETATION

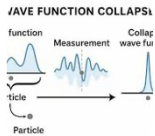
KEY POINTS



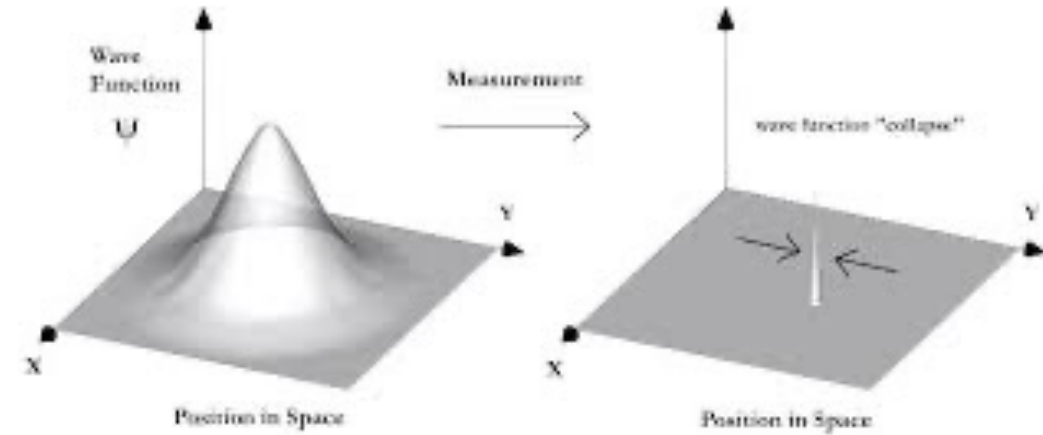
The **wavefunction** does not tell us exactly what a system is in reality. Instead, **probabilities of getting different results** when we measure it.



Before a measurement is made, a quantum system is said to exist in a **superposition** of possible states,

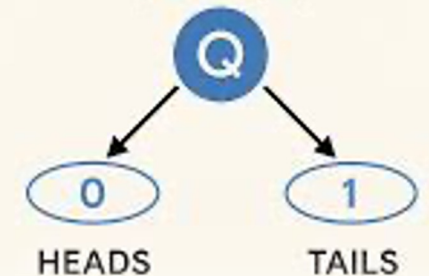


When a measurement occurs, the wavefunction **collapses** to a single outcome, and only then do physical properties become well-defined.



Quantum Superposition

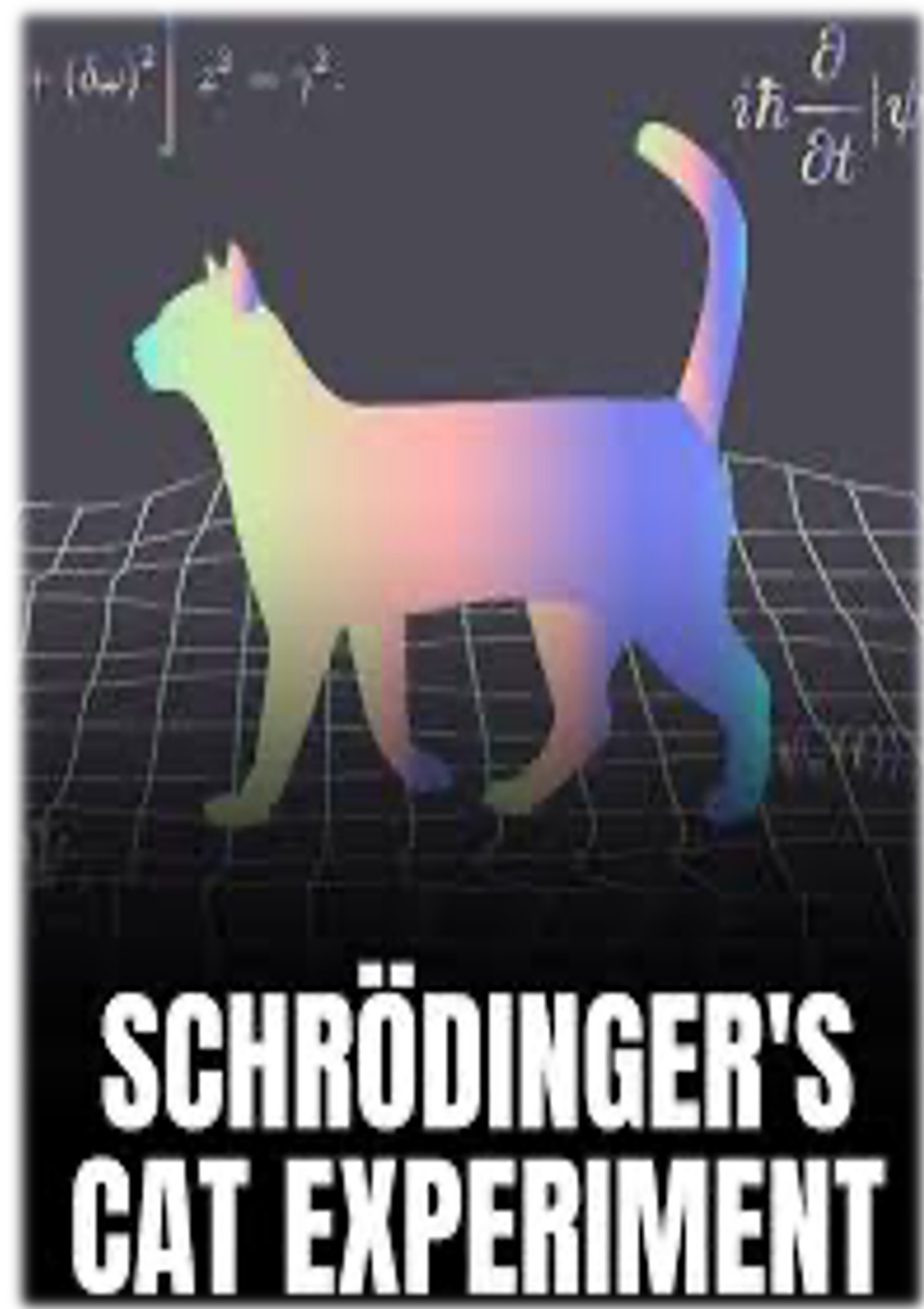
$$\alpha|0\rangle + \beta|1\rangle$$





superposition until measurement

Can it be applied from microscopic particles to everyday macroscopic objects





A radioactive atom may or may not decay

Detector triggers poison if decay happens; the cat's fate is linked to that quantum event

Before you open the box, the system is described by a superposition of "cat alive" + "cat dead."

When you open the box (measure), you observe one outcome: either alive or dead—this mirrors collapse in Copenhagen.

Schrödinger proposed it to show something feels wrong:

superposition seems reasonable for atoms, but absurd for a macroscopic cat.

Copenhagen's reply

In real life, a macroscopic cat cannot stay in a clean superposition. **The environment quickly destroys the coherence.** So we do not see a cat behaving like a neat quantum superposition.

- ❖ Albert Einstein disagreed with the Bohr's concept of reality
- ❖ He believed that **reality was knowable** and that probabilities could not completely define reality—that there had to be an **objective reality** out there, **independent of measurement**.

**“Do you really believe
the moon
only exists when you
look at it?”**

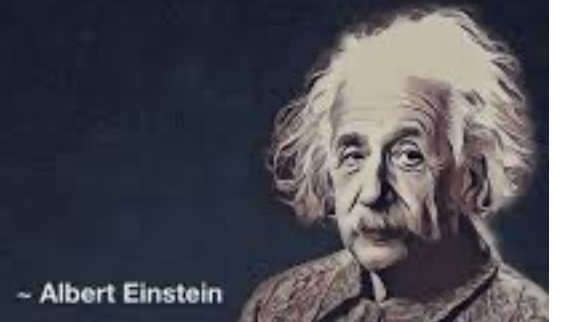
EINSTEIN ATTACKS QUANTUM THEORY

Scientist and Two Colleagues
Find It Is Not 'Complete'
Even Though 'Correct.'

SEE FULLER ONE POSSIBLE

Believe a Whole Description of
'the Physical Reality' Can Be
Provided Eventually.

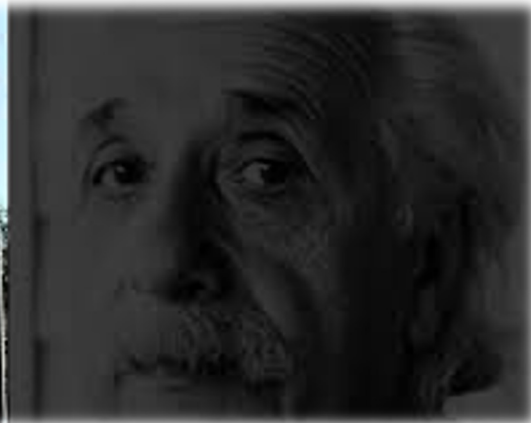
**God does not
play dice with
the universe.**



~ Albert Einstein

Einstein's Locality

- No influence can travel faster than light.
- What happens at one place cannot instantly affect something far away.
- Physics must respect special relativity.

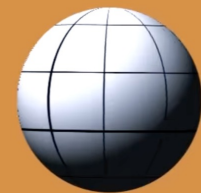


Einstein's Realism

- ❖ Physical properties exist before measurement.
- ❖ A particle has definite values (like position or spin), even if we do not measure them.
- ❖ Measurement reveals reality — it does not create it.

Realism:

particles have definite properties



$x = 0$
 $y = 0$
rotation $x = 0^\circ$
rotation $y = 141^\circ$

TOGETHER: LOCAL REALISM

REALITY IS DEFINITE AND INDEPENDENT.

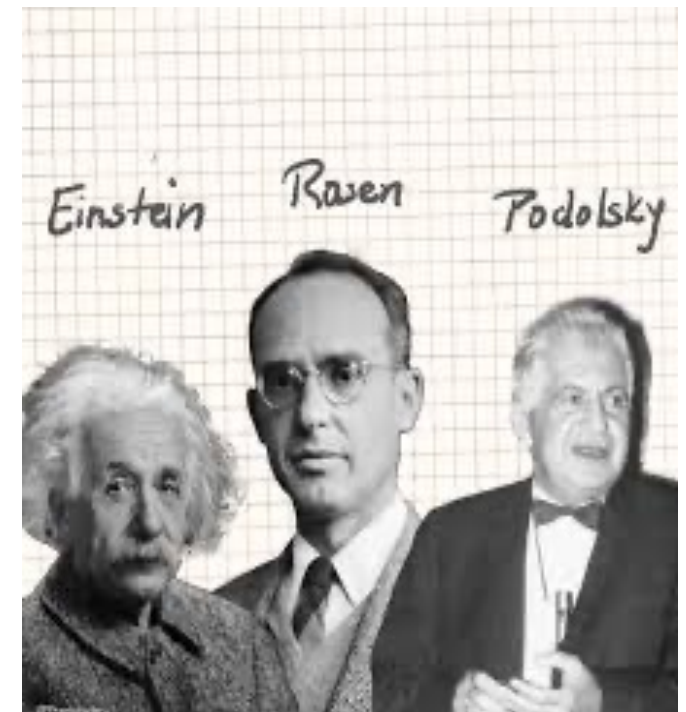
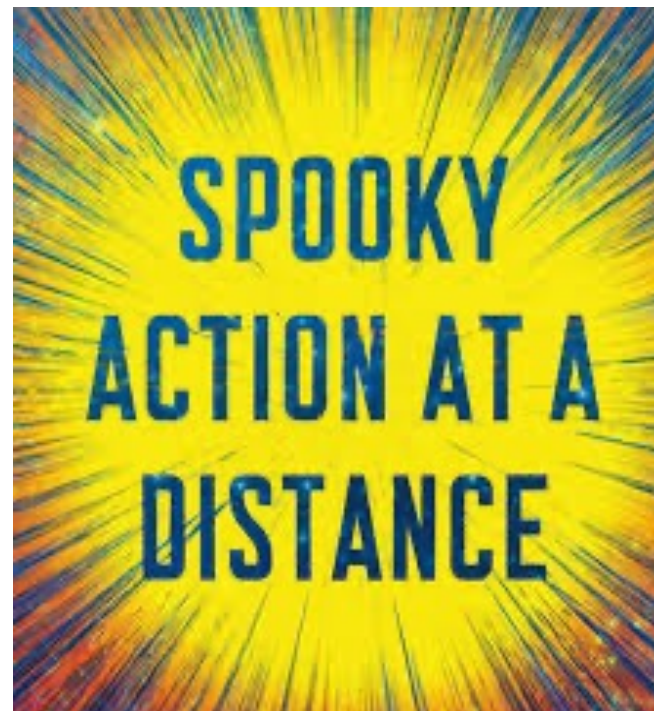
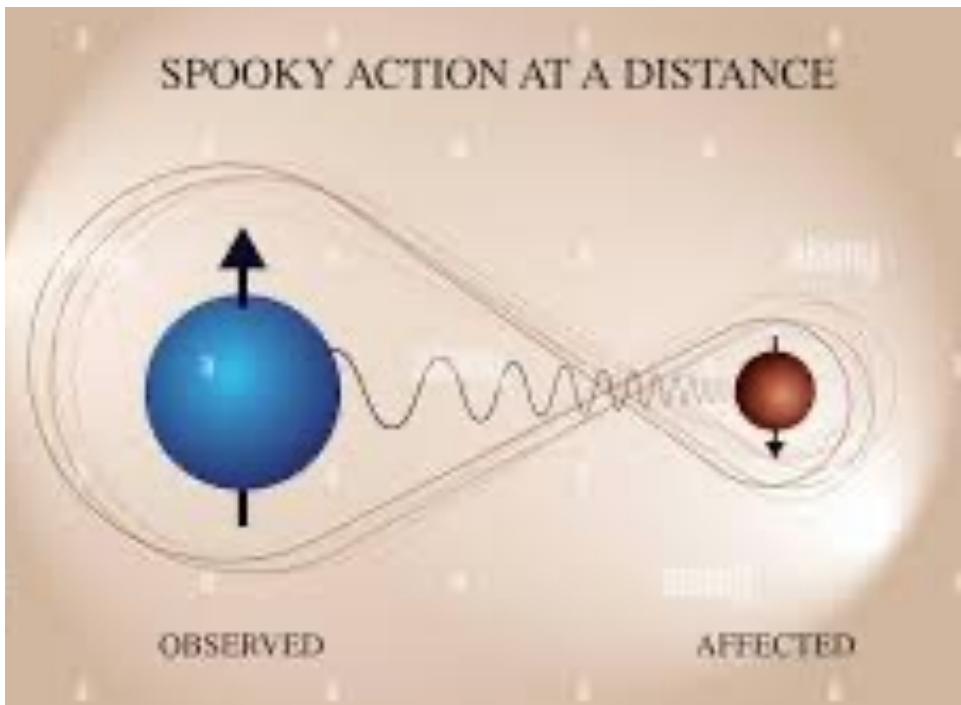
NO “SPOOKY ACTION AT A DISTANCE.”

EPR PARADOX

The EPR paradox (1935) was a thought experiment by Albert Einstein, Boris Podolsky, and Nathan Rosen arguing that quantum mechanics is an incomplete description of reality.

It highlights the strange implications of quantum entanglement, where measuring one particle instantly determines the state of a distant, entangled partner.

Einstein argued this implied "spooky action at a distance", suggesting hidden variables must exist to maintain local realism.



Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in

quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

1.

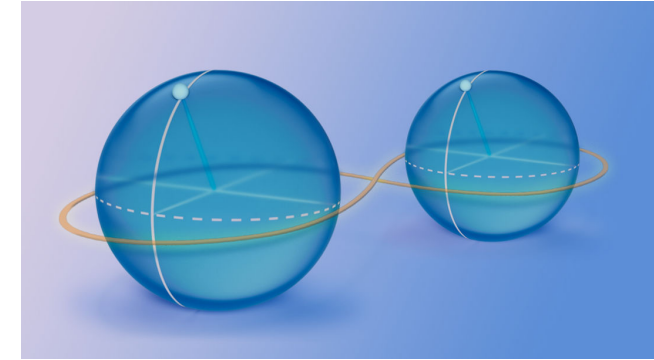
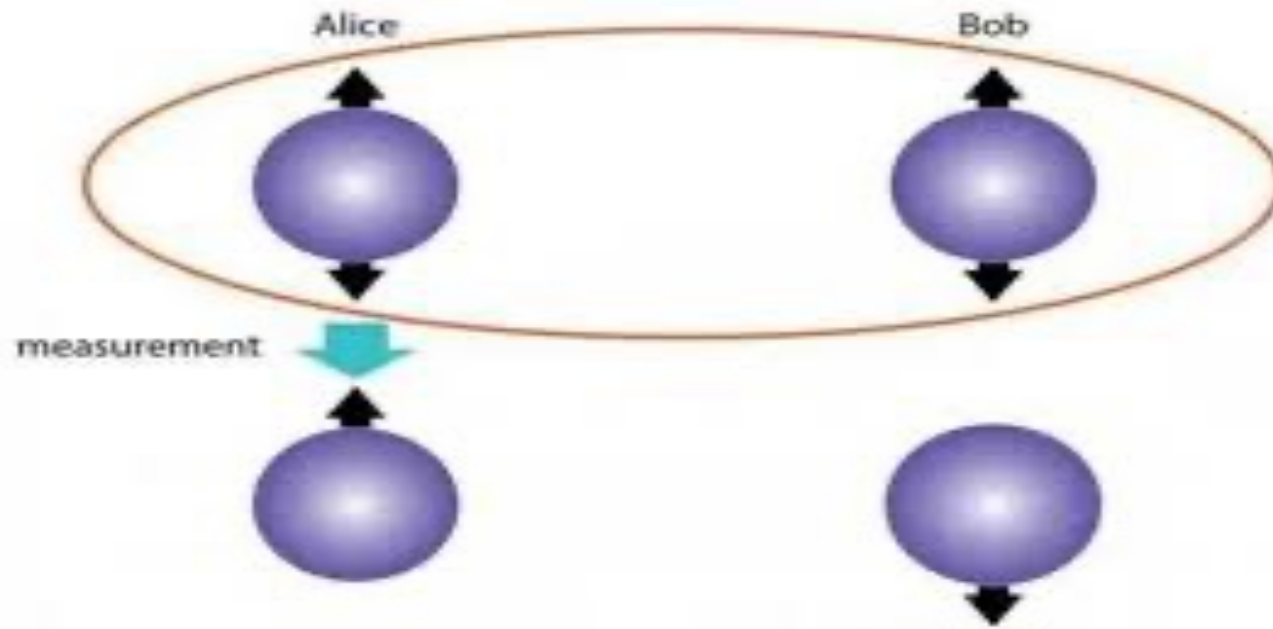
ANY serious consideration of a physical theory must take into account the distinction between the objective reality, which is independent of any theory, and the physical concepts with which the theory operates. These concepts are intended to correspond with the objective reality, and by means of these concepts we picture this reality to ourselves.

In attempting to judge the success of a physical theory, we may ask ourselves two questions: (1) "Is the theory correct?" and (2) "Is the description given by the theory complete?" It is only in the case in which positive answers

Whatever the meaning assigned to the term *complete*, the following requirement for a complete theory seems to be a necessary one: *every element of the physical reality must have a counterpart in the physical theory*. We shall call this the condition of completeness. The second question is thus easily answered, as soon as we are able to decide what are the elements of the physical reality.

The elements of the physical reality cannot be determined by *a priori* philosophical considerations, but must be found by an appeal to results of experiments and measurements. A comprehensive definition of reality is, however,

QUANTUM ENTANGLEMENT



QUANTUM MECHANICAL VIEW

EINSTEIN'S RESPONSE

Entanglement

Measuring particle **A** instantly fixes the result of **B**, even when far apart.

Appears as:

“Spooky action at a distance.”

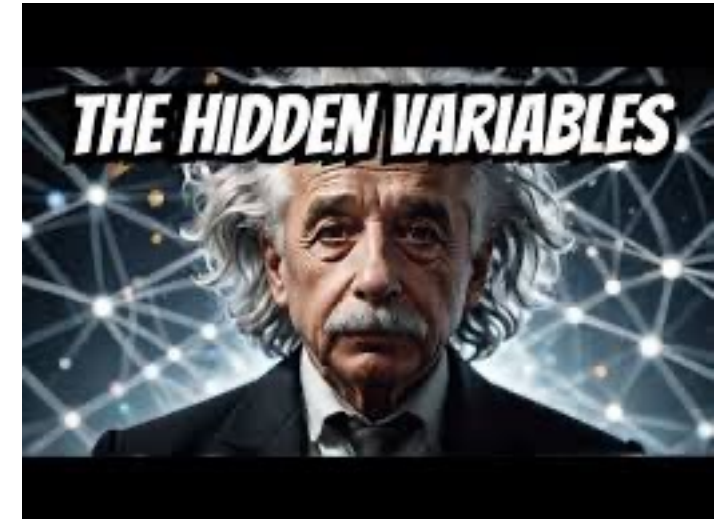
Locality

No real influence travels faster than light.

Realism

B must already have a definite value before measurement.

CONCLUSION



Quantum mechanics is incomplete.

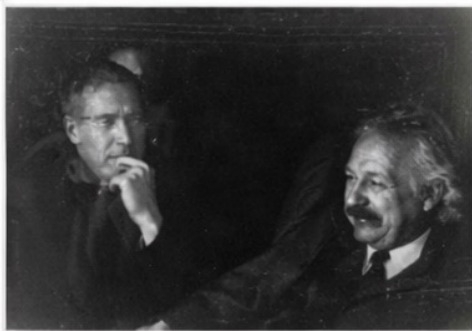
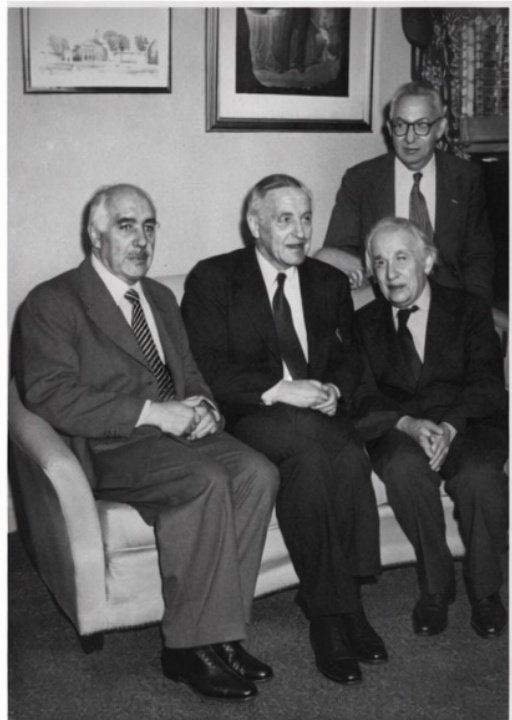
REALITY ??????

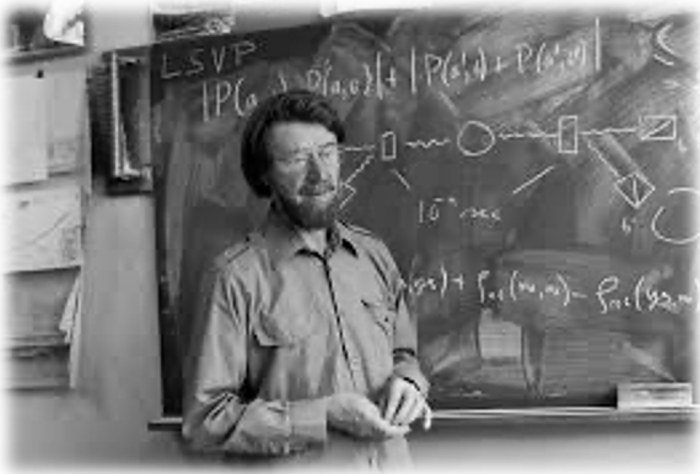
**LOCAL
REALISM**

**PROBABILITY
SUPERPOSITION
WAVE FUNCTION
COLLAPSE**



Two Brilliant Minds — One Question: What Is Reality?





In 1964, Irish physicist John Bell devised a way to prove whether Einstein's view of the local hidden variable theory was correct or incorrect.

Bell proved that any local-realist theory imposes strict limits on measurable correlations between separated particles—limits called Bell inequalities.

Quantum mechanics, however, predicts correlations that can exceed those limits.

In other words, Bell proved that quantum mechanics cannot be reproduced by any classical-style theory that keeps both locality and realism.

THE NOBEL PRIZE IN PHYSICS 2022



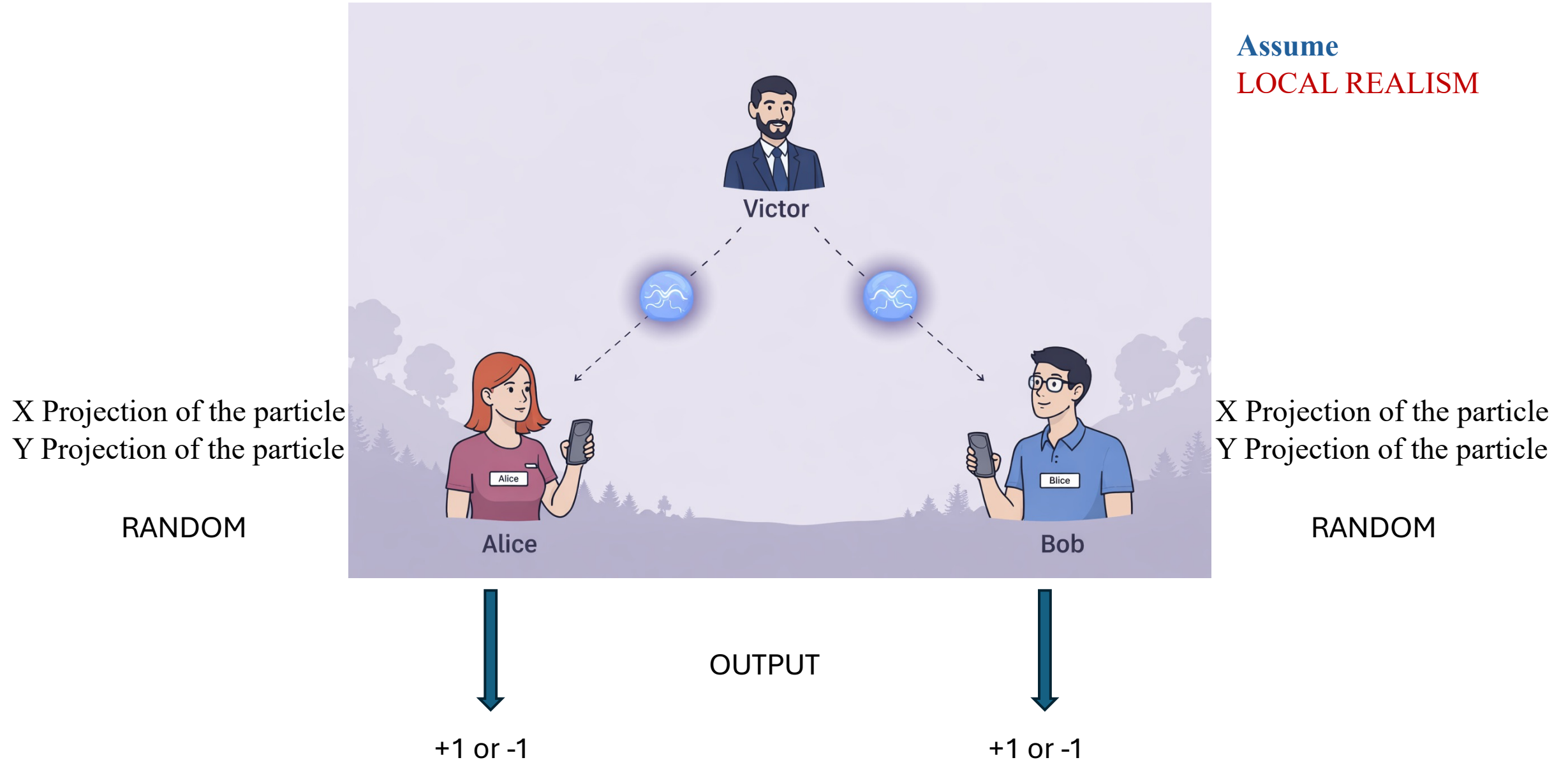
In 1972 John Clauser realized—
Bell's inequality
could be tested in
the lab

His first
experimental
version
demonstrated a
violation of Bell's
inequality, showing
that nature really
does behave the
strange way
quantum mechanics
predicts.

Between 1980 and
1982, Alain
Aspect carried out
more refined
experiments and
addressed
important
experimental
“loopholes,”
making the case
even stronger.

Anton Zeilinger then pushed these ideas
further into the realm of quantum
information science, including a landmark
demonstration of quantum teleportation - a
real method for transferring quantum
information using entanglement.

To understand the core idea behind Bell tests, let's focus on one commonly used version called the **CHSH inequality** (named after Clauser, Horne, Shimony, and Holt).



CHSH Value

$$A_X B_X + A_X B_Y + A_Y B_X - A_Y B_Y$$

$$= B_X (A_X + A_Y) + B_Y (A_X - A_Y)$$

CHSH

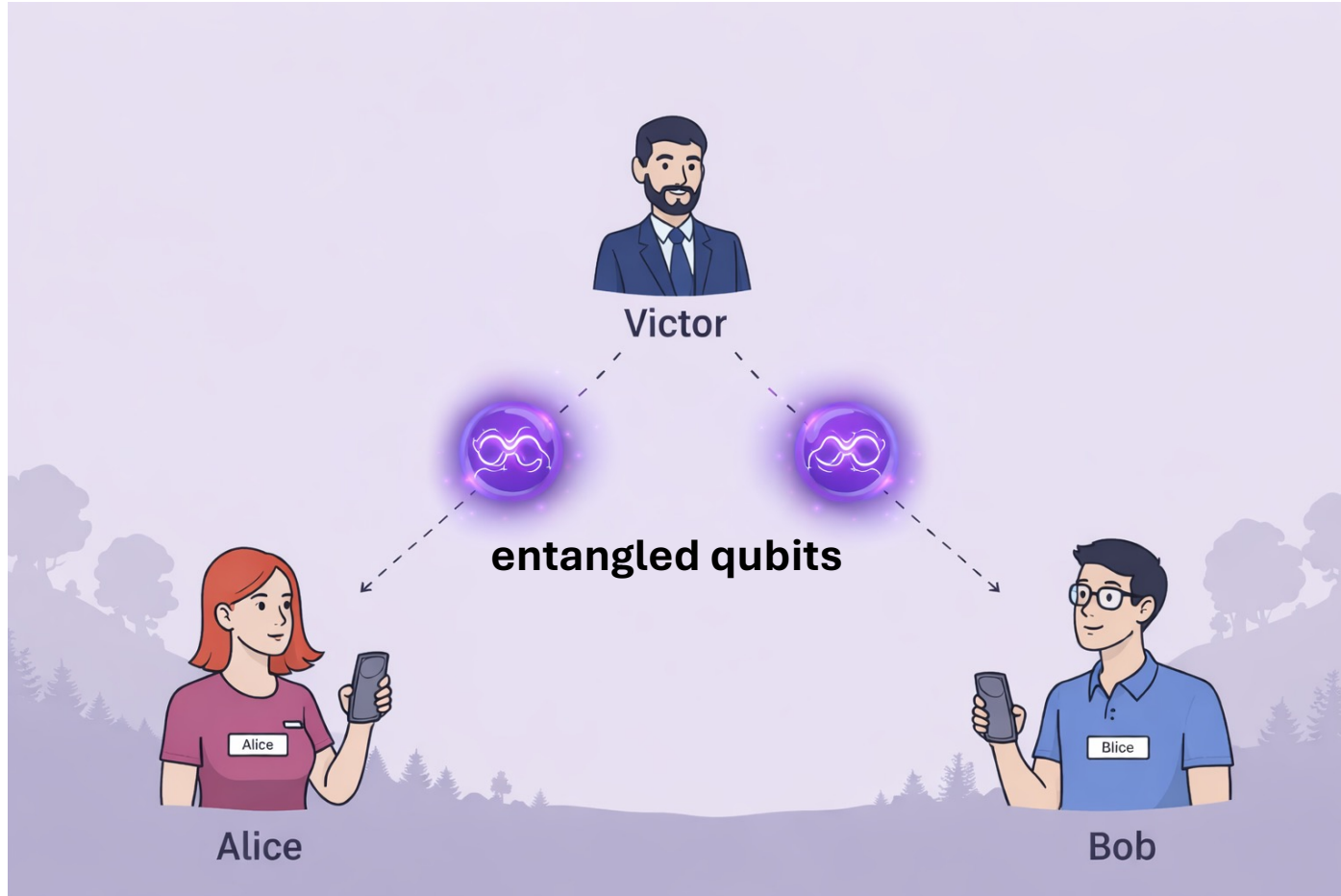


Max value =2

$$< A_X B_X > + < A_X B_Y > + < A_Y B_X > - < A_Y B_Y > \leq 2$$

REPEAT THE EXPERIMENT AGAIN

But when the particles are not ordinary particles—when they are **entangled qubits**—



If you run the experiment many times with properly entangled pairs and the right measurement choices,

The observed CHSH value can come out around:
CHSH ≈ 2.8

you can explore it yourself using a quantum computing simulator.

The real world violates the bound that local realism demands.

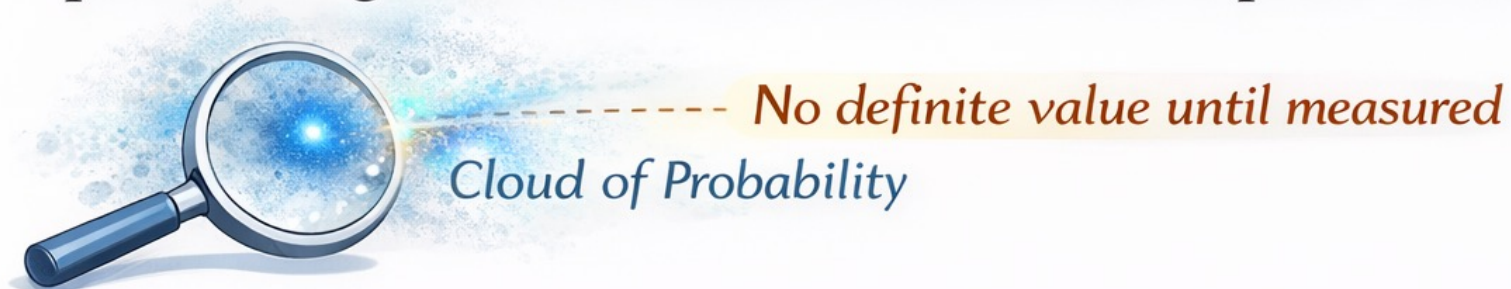


At least one of its two pillars must fail. Either:

- something like “locality” breaks down in a subtle way,



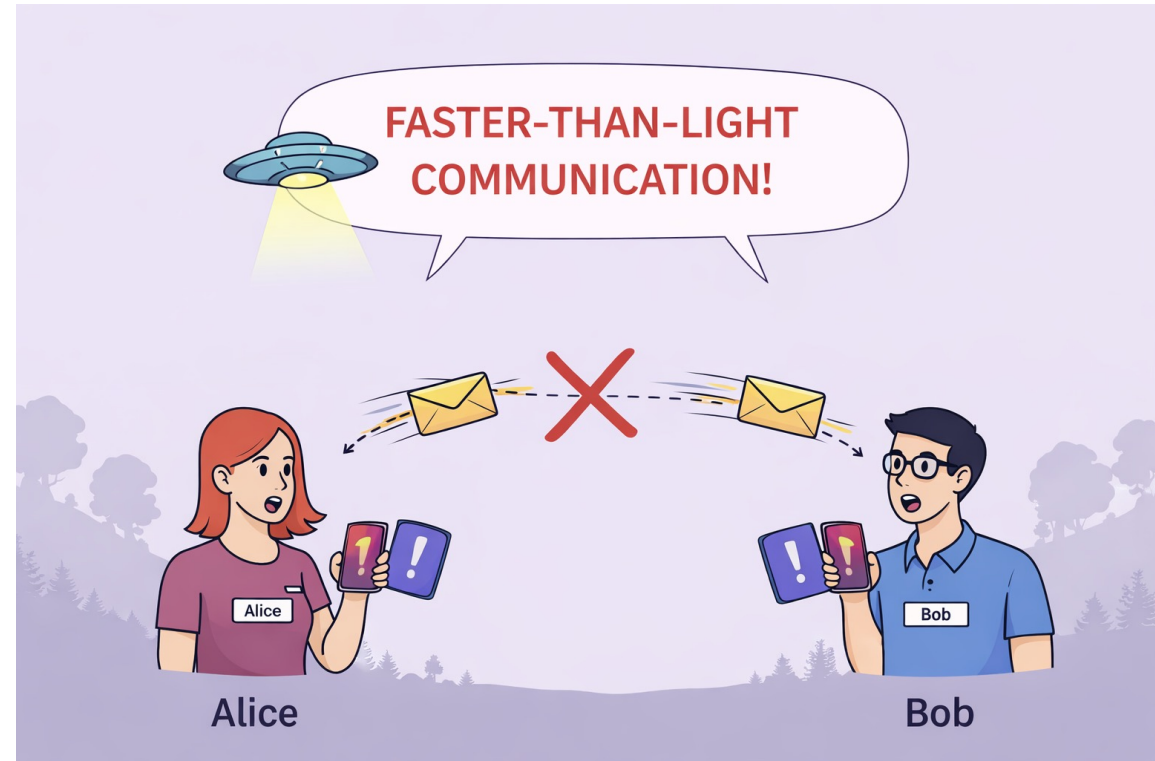
- “realism” fails—meaning the particle does not carry definite pre-existing values for those measurements prior to being measured.



Entanglement does not allow faster-than-light communication.

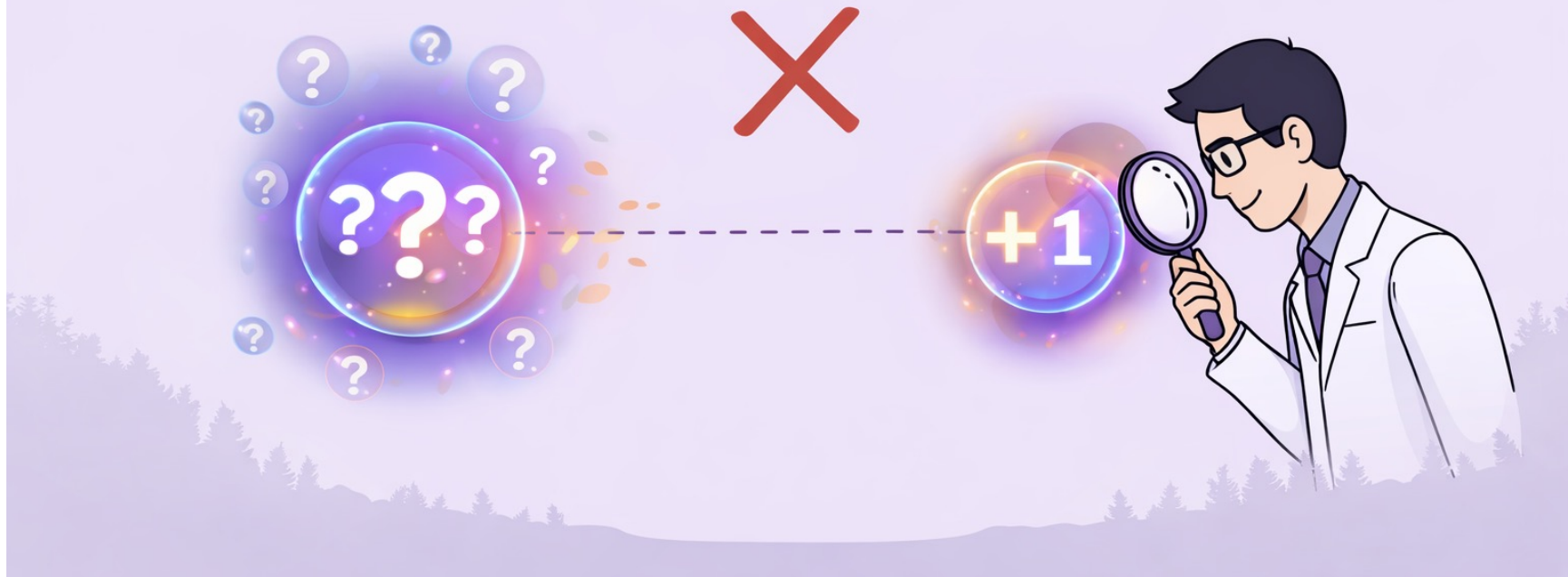
Although the results appear instantaneous, no usable information travels faster than light.

The correlations become visible only when the results are later compared through ordinary, slower-than-light communication



“realism” fails—

meaning the particle does not carry definite pre-existing values for those measurements prior to being measured.



Two brilliant minds asked what reality truly is.

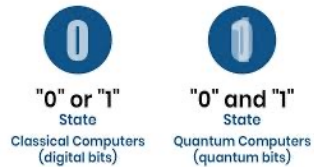
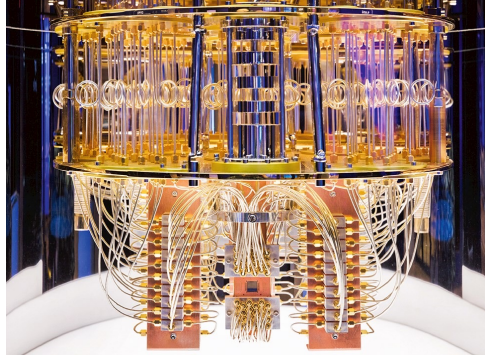
Bell gave us the test.

Experiments gave us the answer.

**The universe is not classical.
It is profoundly quantum.**

QUANTUM ENTANGLEMENT : APPLICATIONS

QUANTUM COMPUTERS



1

Faster computation: For certain problems—like factoring large numbers quantum computers can achieve exponential speedups compared to classical computers.

2

New materials: batteries, superconductors, catalysts, solar-cell materials

3

Optimization: faster planning for routes, supply chains, scheduling, portfolios

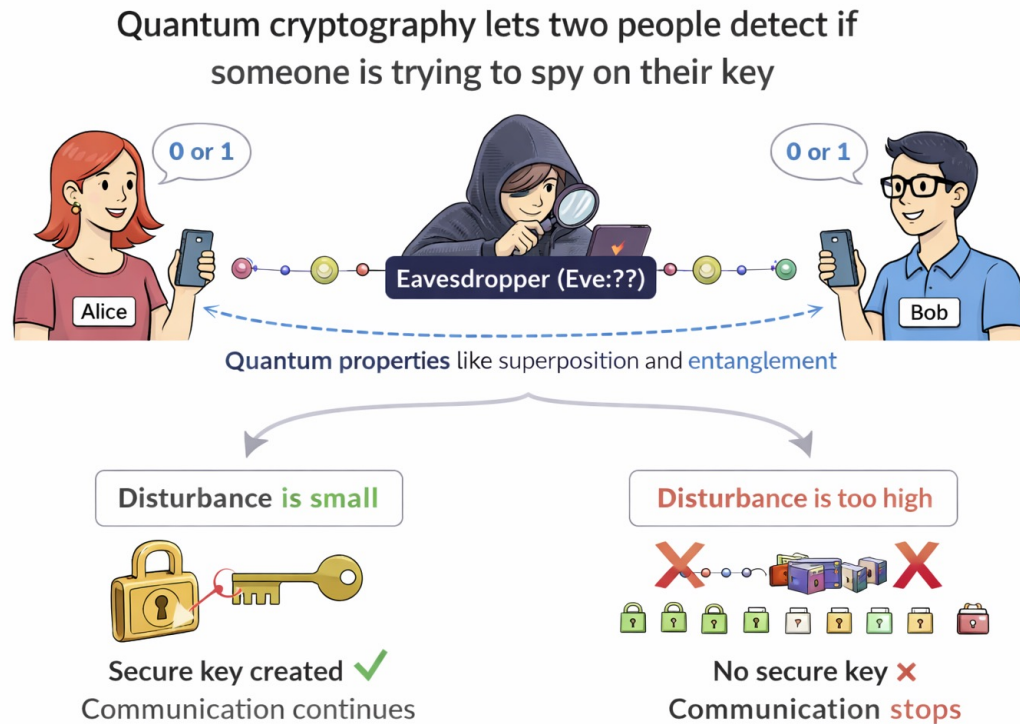
4

Drug discovery & chemistry: simulate molecules to design better medicines

5

Quantum sensing integration: using quantum processors + sensors for better signal processing/control

QUANTUM CRYPTOGRAPHY or QUANTUM KEY DISTRIBUTION



A special feature of quantum cryptography is that two people who are communicating can detect if someone else is trying to spy on their key.

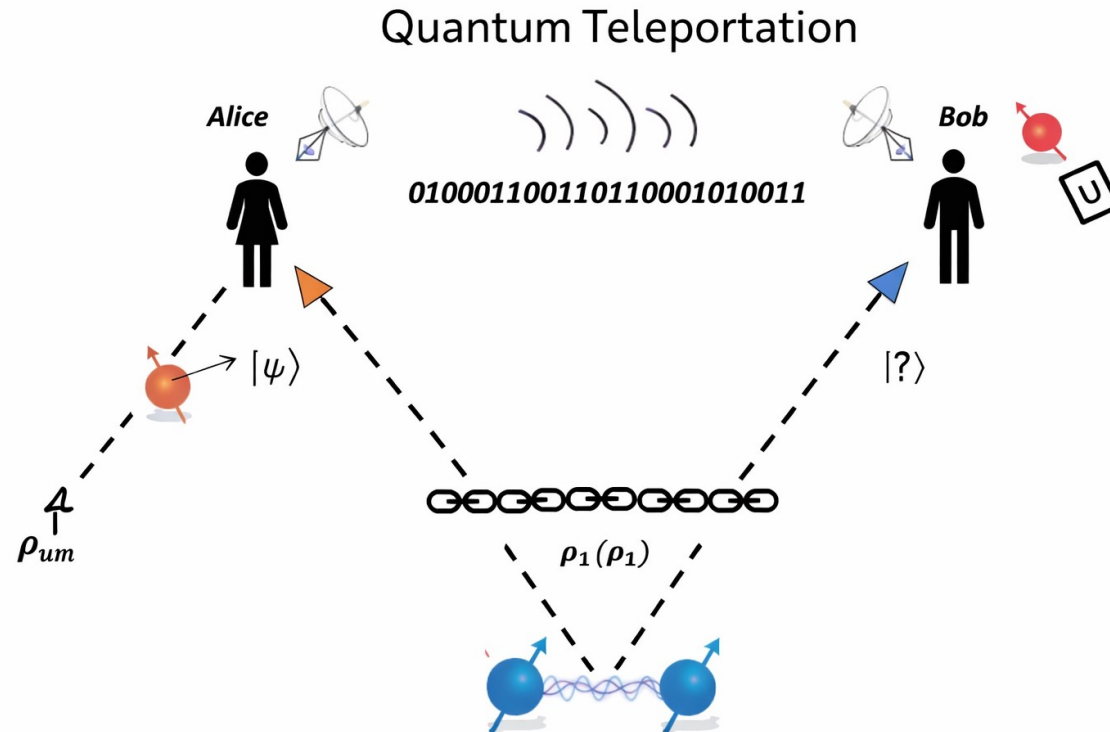
Uses quantum properties like superposition and entanglement to send information in the form of quantum states.

Because of this, any attempt to eavesdrop will disturb the system and can be noticed.

If the eavesdropping is small and below a safe limit, a secure key is generated and communication continues.

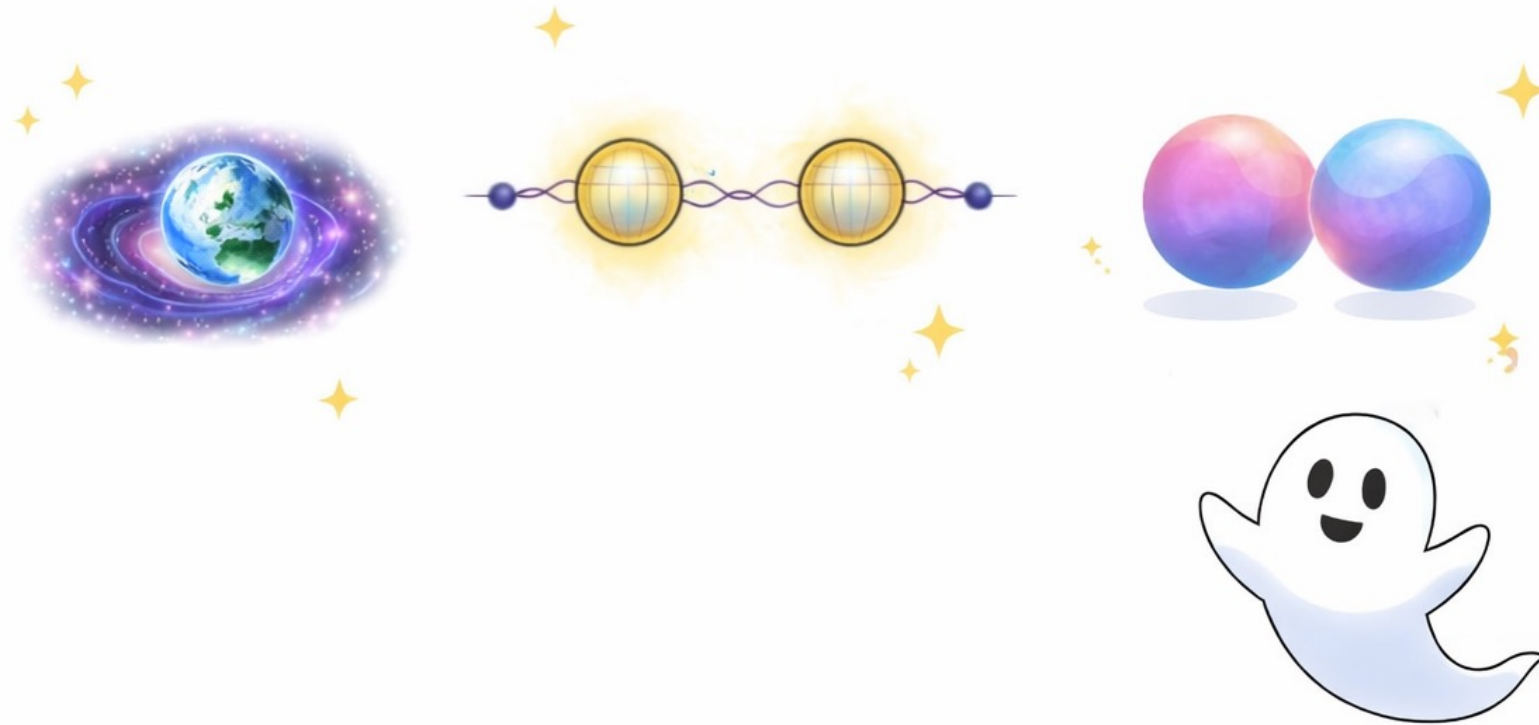
If the eavesdropping is small and below a safe limit, a secure key is generated and communication continues.

QUANTUM TELEPORTATION



Quantum teleportation of quantum states (moving a qubit state without moving the particle)

Hope you enjoyed exploring
the **spooky world of Quantum Mechanics!**



*From superposition
to entanglement,
from paradoxes
to real experiments —*

*Quantum mechanics continues to challenge
our intuition and expand our understanding
of reality.*

Thank You!



Ψ