2022 Physics Nobel prize

Getting entangled

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Nobel 2022

John F. Clauser
USA
1942

Alain Aspect
France
1947

Anton Zeilinger
Austria
1945

"for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"

Bell inequalities as quantum games

The GHZ game: Greenberger Horn Zeilinger)

	Alice	Bob	Charlie	
Q_1	X	X	X	1
Q_2	Y	Y	X	-1
Q_3	X	Y	Y	-1
Q_4	Y	X	Y	-1
	1	1	1	?

	A	B	C	
Q_1	-1	-1	-1	lost
Q_2	-1	-1	-1	-1
Q_3	-1	-1	-1	-1
Q_4	-1	-1	-1	-1
	1	1	1	?

winning probability 3/4

Can't satisfy table with ± 1

Classical winning probability $\leq 3/4$

GHZ entangled state

Unreasonable quantum correlation

$$|GHZ\rangle = \frac{|000\rangle + |111\rangle}{\sqrt{2}}, \quad |0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

- $\underbrace{X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad Y = i \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}}_{Pauli}$
- $X|0\rangle = |1\rangle, \; X|1\rangle = |0\rangle$

  $Y|0\rangle = i|1\rangle, \; Y|1\rangle = -i|0\rangle$

$$X \otimes X \otimes X |GHZ\rangle = +|GHZ\rangle$$
$$X \otimes Y \otimes Y |GHZ\rangle = -|GHZ\rangle$$
$$Y \otimes X \otimes Y |GHZ\rangle = -|GHZ\rangle$$
$$Y \otimes Y \otimes X |GHZ\rangle = -|GHZ\rangle$$

Always win with the help of an entangled state

The X and Y questions instruct ABC what observable to measure

- A, B & C share $|GHZ\rangle$
- Measure X for question X
- Measure Y for question Y
- Always win

	A	B	C	
Q_1	X	X	X	1
Q_2	Y	Y	X	-1
Q_3	X	Y	Y	-1
Q_4	Y	X	Y	-1
	1	1	1	?

No local hidden variables

No values assigned to questions not asked

Observed values are not predetermined

Correlations do not transfer information

No signaling

Alice Bob and Charlie win but remain ignorant

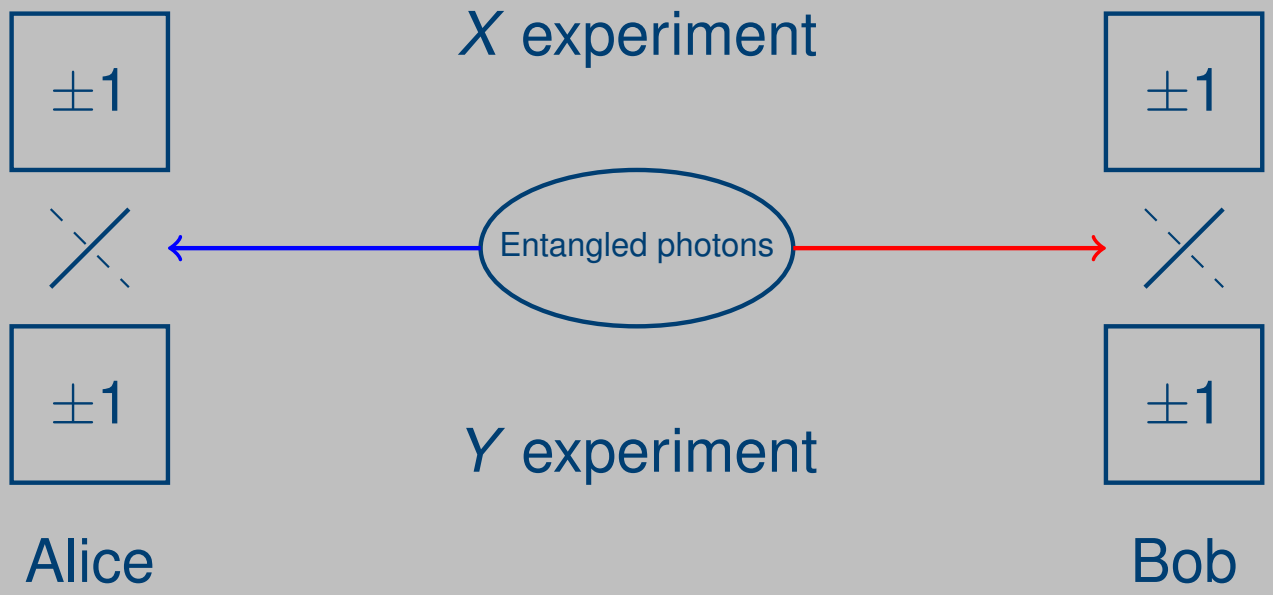
- Alice does not learn what question B & C were asked

Quantum correlations do not signal

- Quantum mechanics is consistent with relativity

Closing the communication loophole

Aspect experiment



Alice and Bob

- Choose randomly experiment X or Y
- Choice is made during photons transit

Clauser, Aspect, Zeilinger

Improved sources of entangled photon pairs

- Clauser:
  - 1969: CHSH inequality
  - 1972: Testing a Bell inequality (w. Freedman)
  - Entangled photons: Atomic cascade & lamp
- Aspect
  - 1982: Alice and Bob could not communicate
  - Entangled photons: Atomic cascade & laser
- Zeilinger
  - 1997: Teleportation
  - Entangled photons: Down conversion

What is Entanglement?

Pure states

Product

$$|\Psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle$$

- Being products is basis dependent

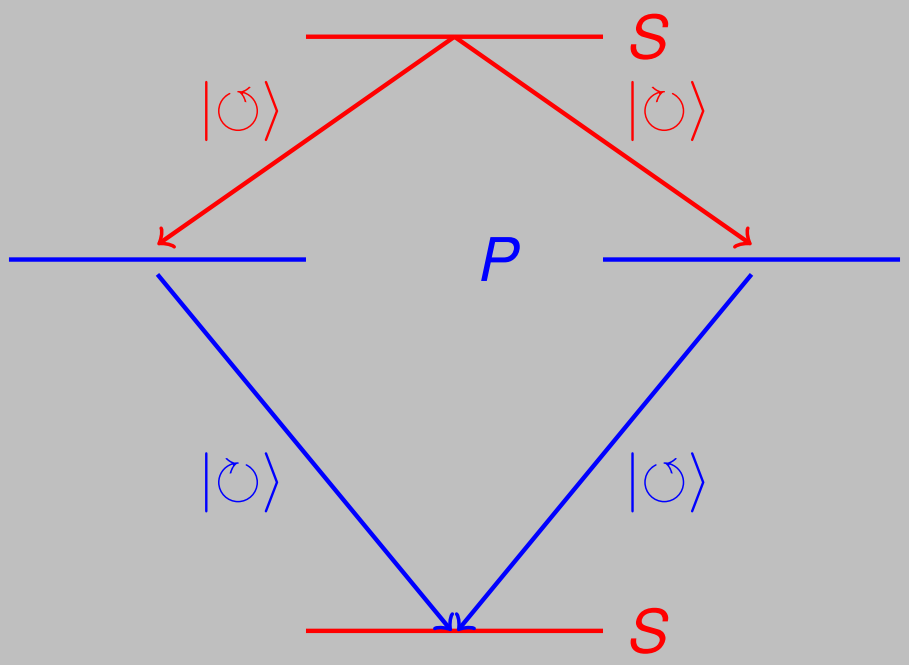
$$\underbrace{|00\rangle + |01\rangle + |10\rangle + |11\rangle}_{\textit{superposition}} = \underbrace{(|0\rangle + |1\rangle) \otimes (|0\rangle + |1\rangle)}_{\textit{product}}$$

Entangled pure states

$\nexists$ basis where $|\Psi\rangle$ is a product

Entanglement =Which path ambiguity

Atomic cascade of polarized photons

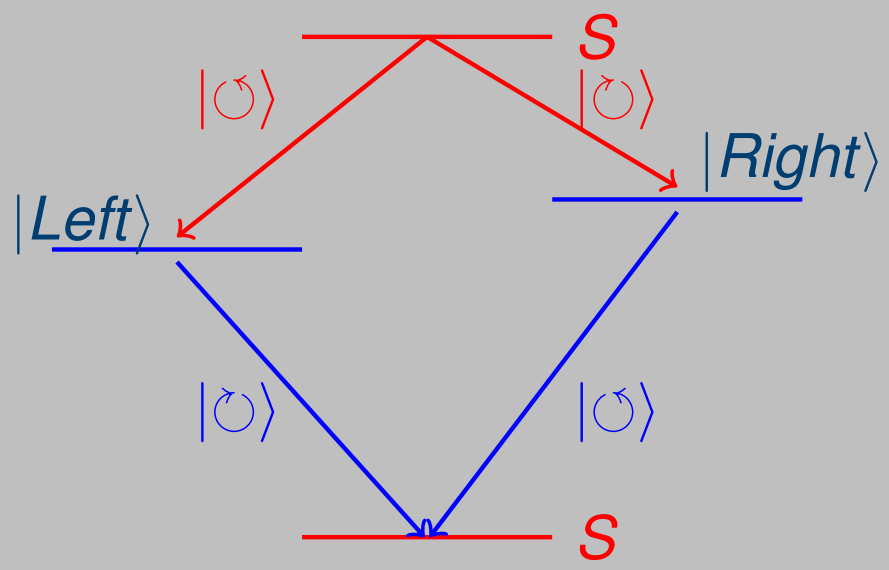


Alice is red and Bob is blue

$$|\beta\rangle = \frac{|\circlearrowleft\rangle \otimes |\circlearrowright\rangle + |\circlearrowright\rangle \otimes |\circlearrowleft\rangle}{\sqrt{2}}$$

Which path witness kills the entanglement

Spies everywhere



$$|\psi\rangle = |\circlearrowleft\rangle \otimes |\circlearrowleft\rangle\,|Left\rangle + |\circlearrowright\rangle \otimes |\circlearrowright\rangle\,|Right\rangle$$

The split degeneracy betrays the path

Entanglement killed by which path information

Spookhaft vernwirkung

Entanglement allows for remote operations

Maximally entangled states

$$|\Psi\rangle_{AB} = \sum |a\rangle_A \otimes |a\rangle_B , \quad \langle a|a'\rangle = \delta_{aa'}$$

Everything Alice can do, Bob can

$$M \otimes \mathbb{1} \, |\Psi\rangle_{AB} = \sum M_{ab} \, |b\rangle_A \otimes |a\rangle_B = \mathbb{1} \otimes M^t \, |\Psi\rangle_{AB}$$

No cloning

Can't copy an unknown quantum state

A known quantum state:

A classical preparation protocol.

An unknown quantum state

Output of a quantum computer

- Alice doesn't know how $|\psi\rangle$ was prepared
- Extracting information on $|\psi\rangle$ is destructive
- Alice can't make copies of $|\psi\rangle$

Bell states

The 4 mothers of entangled states

- 4 Bell states:

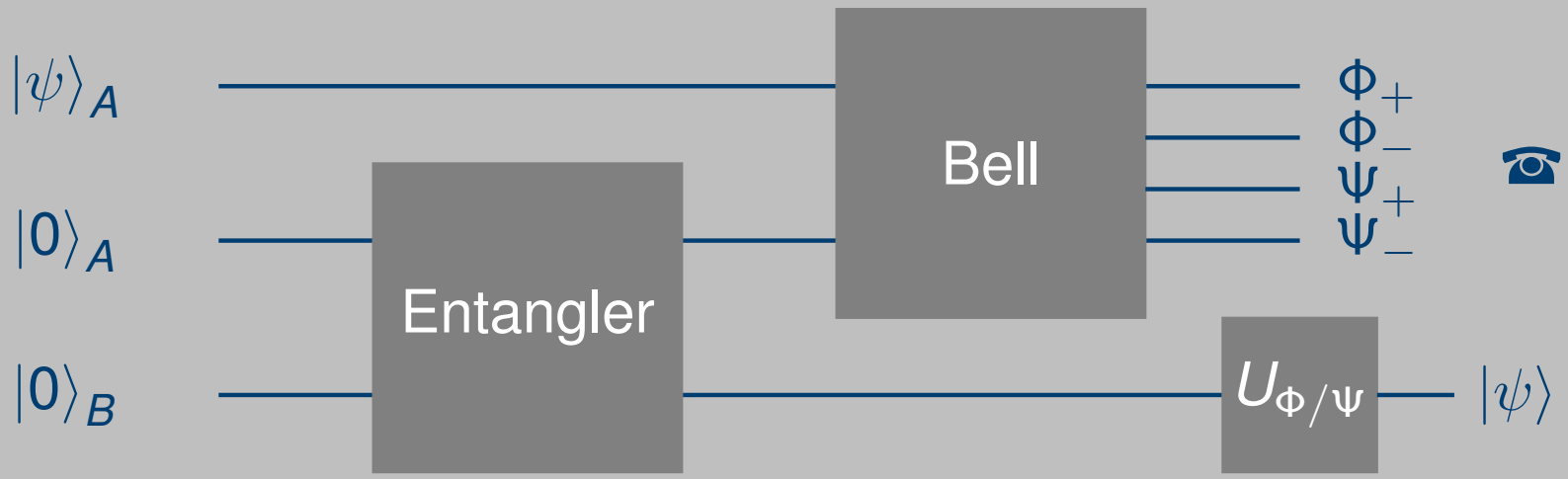
$$|\Phi_{\pm}\rangle = \frac{|00\rangle \pm |11\rangle}{\sqrt{2}} \qquad |\Psi_{\pm}\rangle = \frac{|01\rangle \pm |10\rangle}{\sqrt{2}}$$

- Mutually orthogonal
- Span 2-qubits Hilbert space

Teleportation

Setting and protocol

- Alice has 2 qubits & Bob has 1 qubit
- Alice's qubit 1 is in an unknown state $|\psi\rangle$
- Alice's qubit 2 in entangled with Bob's



The teleportation identity

Moving $|\psi\rangle$ from Alice to Bob

- Pauli matrices

$$X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad Y = i\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}, \quad Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Teleportation identity

$$2\,|\psi\rangle_A \otimes |\Phi_+\rangle_{AB} = |\Phi_+\rangle_{AA} \otimes |\psi\rangle_B + |\Psi_+\rangle_{AA} \otimes X\,|\psi\rangle_B + |\Psi_-\rangle_{AA} \otimes Z\,|\psi\rangle_B + |\Phi_-\rangle_{AA} \otimes XZ\,|\psi\rangle_B$$

The six fathers of teleportation

Jozsa, Wootters, Bennett, Brassard, Crepeau, Peres

1993

Experimental quantum teleportation

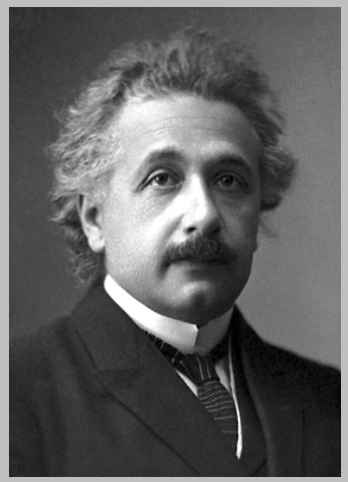
Dik Bouwmeester, Jian-Wei Pan, Klaus Mattle, Manfred Eibl, Harald Weinfurter & Anton Zeilinger

Institut für Experimentalphysik, Universität Innsbruck, Technikerstr. 25, A-6020 Innsbruck, Austria

Quantum teleportation—the transmission and reconstruction over arbitrary distances of the state of a quantum system—is demonstrated experimentally. During teleportation, an initial photon which carries the polarization that is to be transferred and one of a pair of entangled photons are subjected to a measurement such that the second photon of the entangled pair acquires the polarization of the initial photon. This latter photon can be arbitrarily far away from the initial one. Quantum teleportation will be a critical ingredient for quantum computation networks.

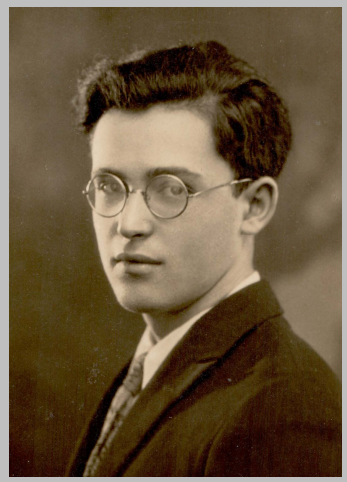
The lingering discomfort with QM

From EPR to Everett and Penrose



?

Podolsky



Rosen

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

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)

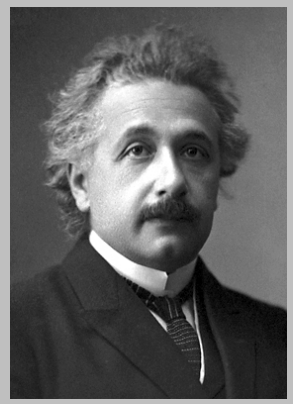
In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In

quantum mechanics 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

Lingering discomfort

Measurements do not reveal a pre-existing values

- Physics is about what nature is (Einstein)
- $|\psi\rangle$ is about what is possible (Bohr)



Is there a more fundamental theory behind QM?

Where is the classical/quantum boundary?

What about the consistency of QM with GR?

The end

Thanks: Arad, Behar, Gershoni, Kenneth, Lindner, Rohrlich, Vaidman