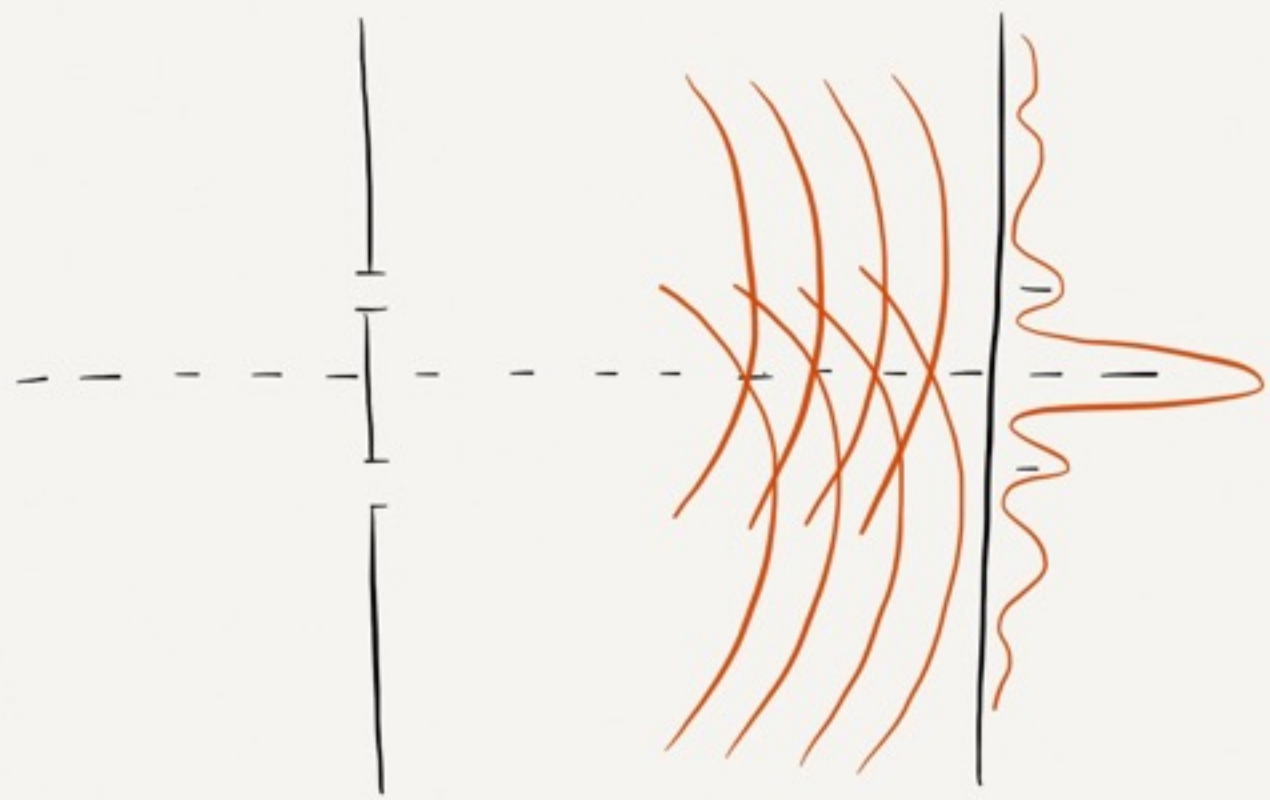
Hochschule Düsseldorf
University of Applied Sciences
HSD

09. Mai 2016

Quantenphysik



EPR, Verschränkung und die Bell'schen Ungleichungen

Einstein-Podolski-Rosen

1935

Einstein-Podolski-Rosen
1935

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 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

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

Einstein-Podolski-Rosen

1935

If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.

[…] when the momentum of a particle is known, its coordinate has no physical reality.

Furthermore, any attempt to determine the latter (state) experimentally will alter the state of the system in such a way as to destroy the knowledge of the first.

Einstein-Podolski-Rosen

1935

If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.

[…] when the momentum of a particle is known, its coordinate has no physical reality.

Furthermore, any attempt to determine the latter (state) experimentally will alter the state of the system in such a way as to destroy the knowledge of the first.

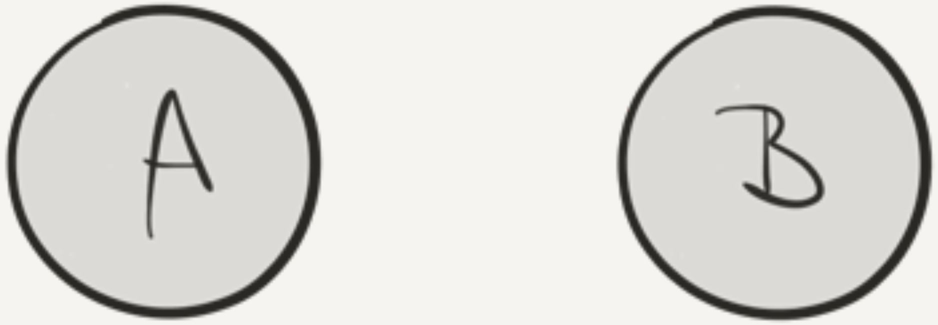
From this follows that either

(1) the quantum-mechanical description of reality given by the wave function is not complete

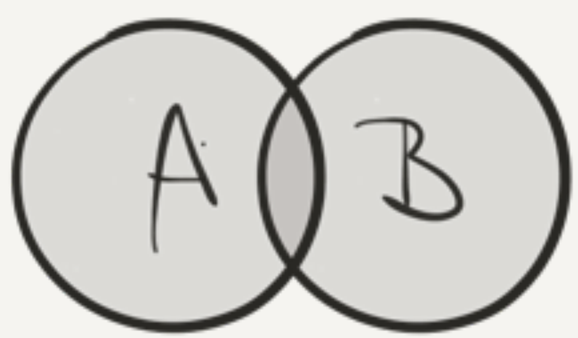
or

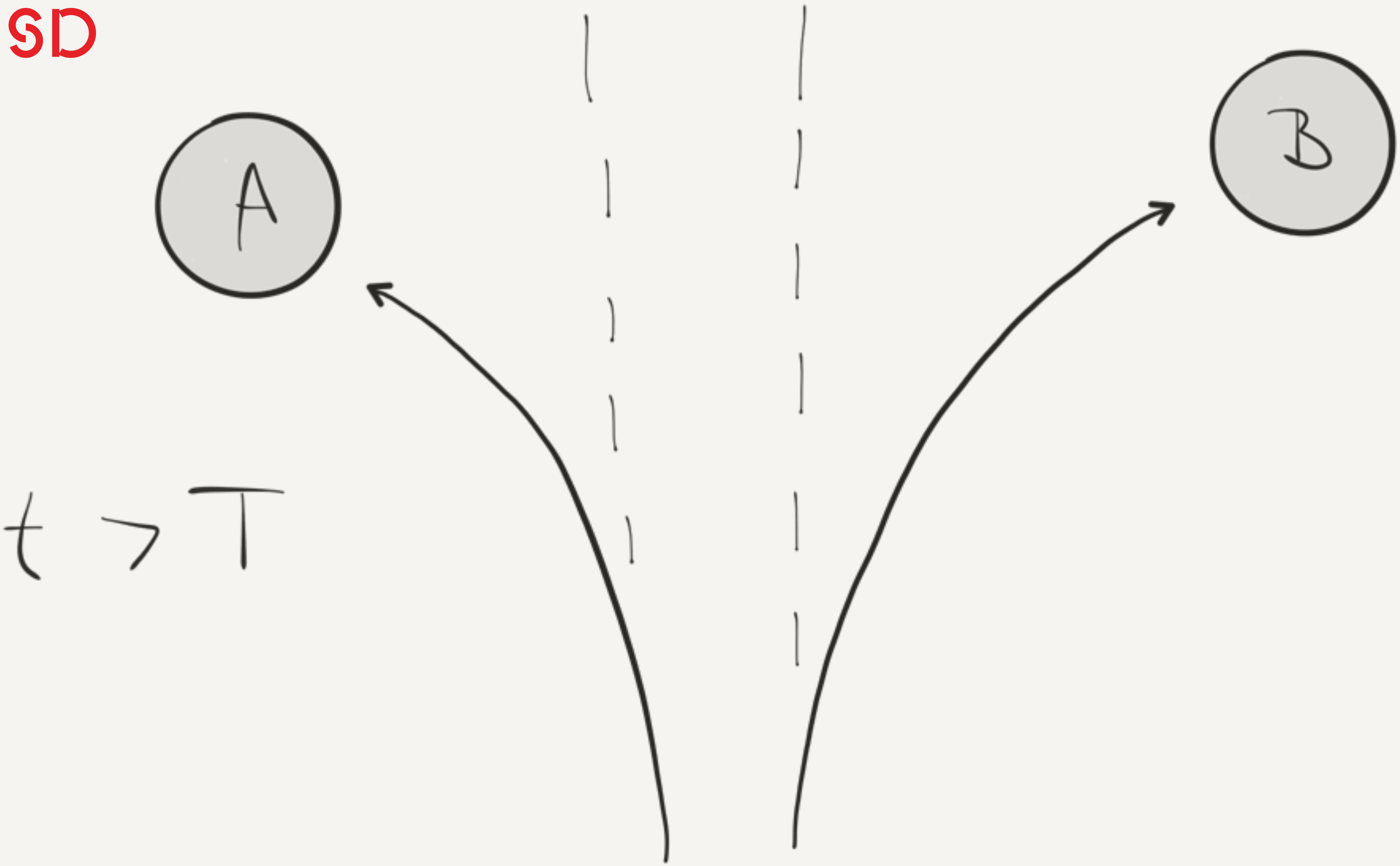
(2) when the operators corresponding to two physical quantities do not commute the two quantities cannot have simultaneous reality.

$t < 0$



$$0 \leq t \leq T$$





A und B werden getrennt und können nicht miteinander kommunizieren.

Messe ich Impuls, ist der Ort nicht real.

Messe ich Ort, ist der Impuls nicht real.

Weil die Systeme ‚**zusammen gehören**‘ macht B das was A macht.

Ohne B zu messen oder zu stören ist dann aber B in einem definierten Zustand, d.h. in einem ‚realen‘ Zustand.

Da ich aber mit A (raumartig getrennt!) aussuchen kann, ob Ort oder Impuls, müssen beide real sein.

„Lokal“ und „realistisch“

Lokal

Lokal bedeutet, dass sich keine Wechselwirkung (Einfluss, Zusammengehörigkeit…) schneller als Licht ausbreitet.

Realistisch

Real bedeutet, dass die Messergebnisse von bereits existierenden Eigenschaften des Systems abhängen und vor allem unabhängig sind von der Messung.

Verschränkung

Verschränkung
1935

- Einstein bezeichnet später (1947) diese Zusammengehörigkeit als „***spukhafte Fernwirkung***“.
- Schrödinger prägte noch im Jahr 1935 den Begriff ***entangled***. für dieses seltsame ‚zusammen gehören‘.
- Dies wurde als ***verschränkt*** übersetzt.
- Die Substantive sind ***Entanglement*** und ***Verschränkung***.

DISCUSSION OF PROBABILITY RELATIONS BETWEEN SEPARATED SYSTEMS

BY E. SCHRÖDINGER

[Communicated by Mr M. BORN]

[*Received* 14 August, *read* 28 October 1935]

1. When two systems, of which we know the states by their respective representatives, enter into temporary physical interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the same way as before, viz. by endowing each of them with a representative of its own. I would not call that *one* but rather *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought. By the interaction the two representatives (or ψ-functions) have become entangled. To disentangle them we must gather further information by experiment, although we knew as much as anybody could possibly know about all that happened. Of either system, taken separately, all previous knowledge may be entirely lost, leaving us but one privilege: to restrict the experiments to one only of the two systems. After re-establishing one representative by observation, the other one can be inferred simultaneously. In what follows the whole of this procedure will be called *the disentanglement*. Its sinister importance is due to its being involved in every measuring process and therefore forming the basis of the quantum theory of measurement, threatening us thereby with at least a *regressus in infinitum*, since it will be noticed that the procedure itself involves measurement.

Verschränkung

- Mathematisch ist Verschränkung sauber definiert.
- Teilsystem A lebt im Hilbertraum H_A, und B entsprechend in H_B.
- Der zusammengesetzte Hilbertraum (Tensorprodukt) erlaubt auch Summenzustände, die sich nicht sauber auf H_A und H_B aufteilen lassen (math.: in einen Produktzustand zerlegen).
- Verschränkung ist also eine **Superposition** von Wellenfuktionen, bei denen die beiden einzelnen Wellenfunktionen aus zwei Teilen bestehen.

A im Zustand 0

B im Zustand 0

$$\frac{1}{\sqrt{2}}\left(|0\rangle_{\mathrm{A}}|0\rangle_{\mathrm{B}} - |1\rangle_{\mathrm{A}}|1\rangle_{\mathrm{B}}\right)$$

Summe, kann nicht als Produkt dargestellt werden.

Die Bell'sche Ungleichung

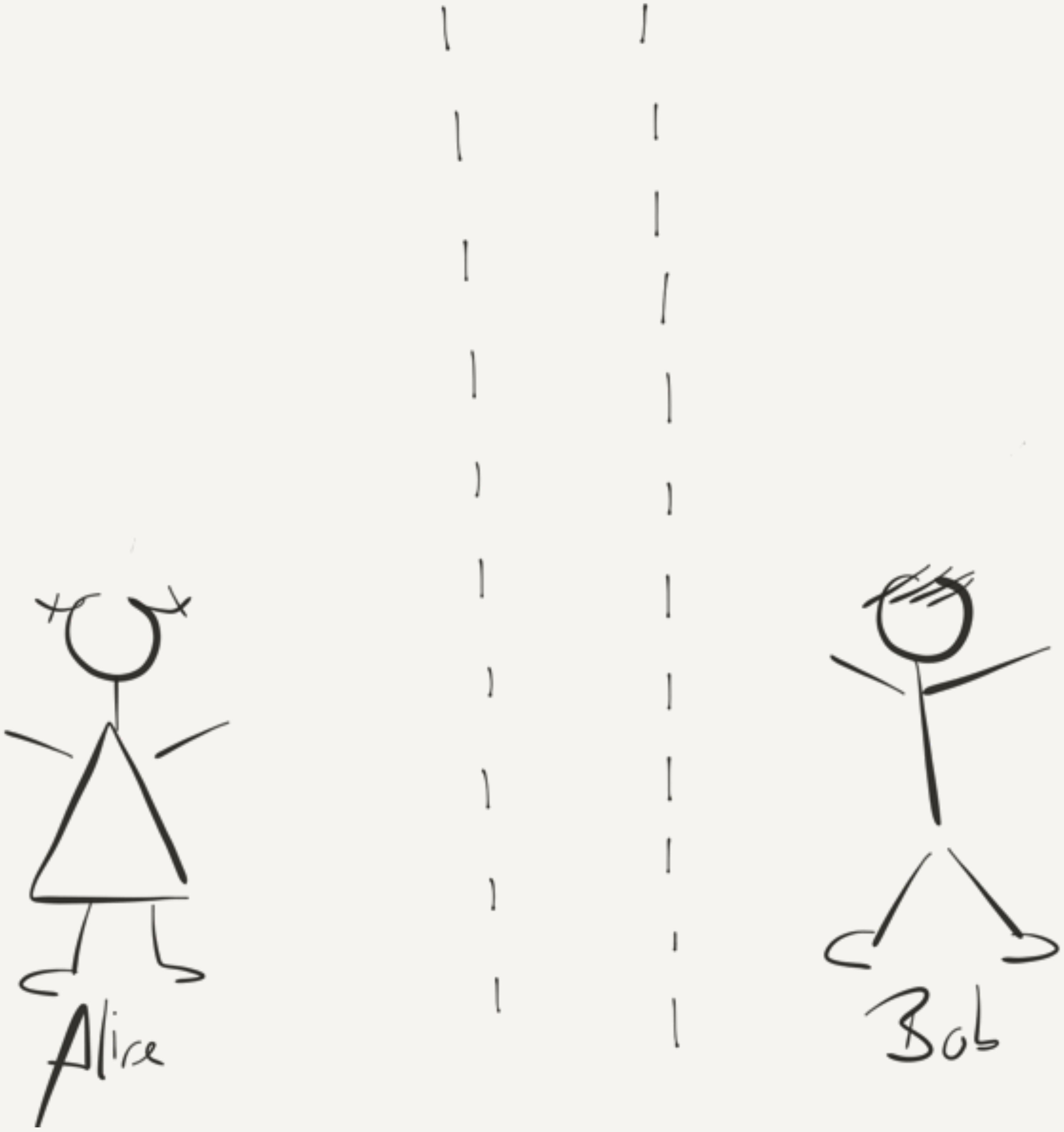
Die Bell'sche Ungleichung
1964

John S. Bell
1928 - 1990

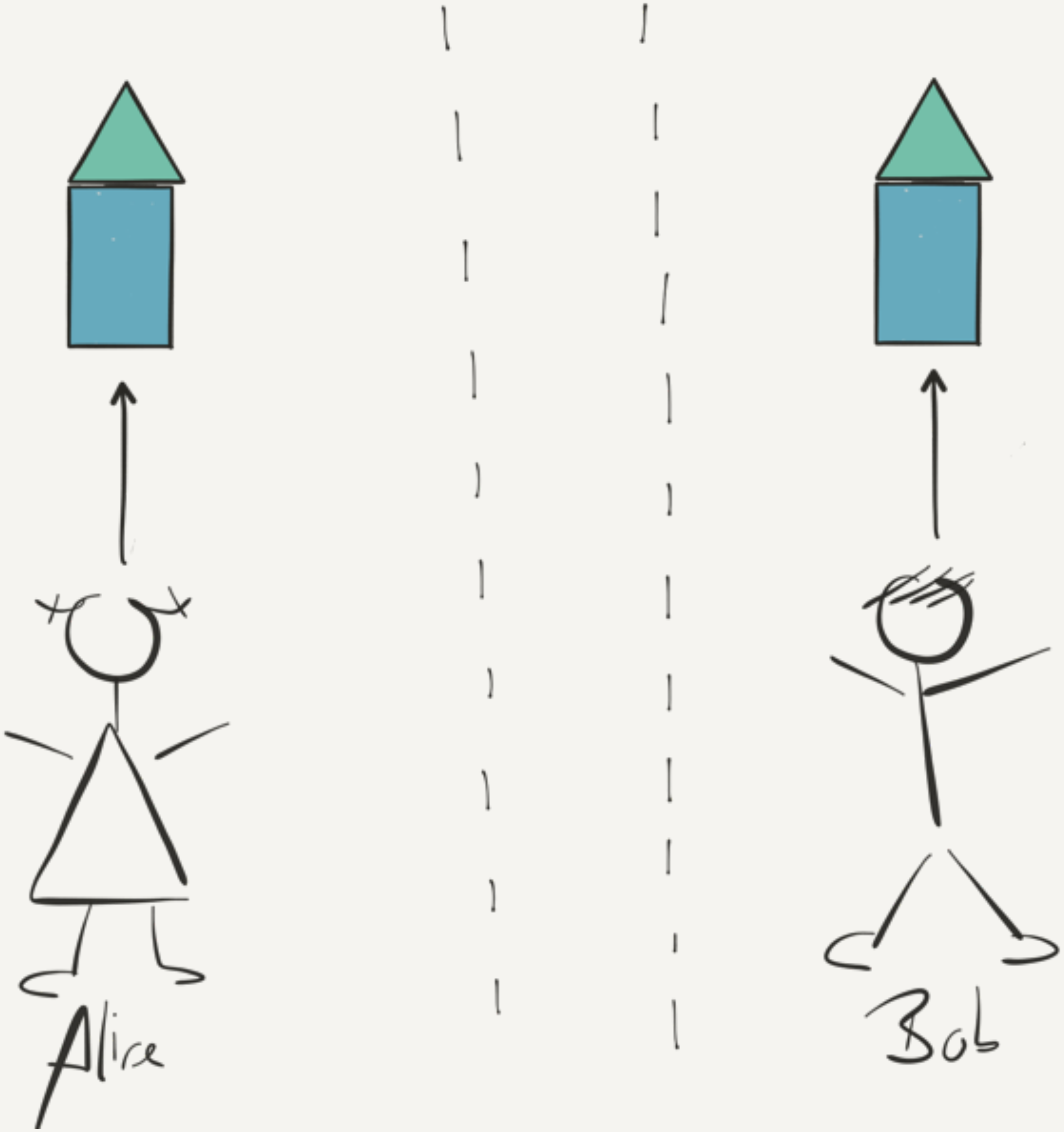
Quelle: Wikipedia

- John Bell griff das EPR-Argument auf und formulierte eine **experimentell überprüfbare Ungleichung** über Determinismus in der Quantenphysik.
- Demnach kann keine Quantentheorie gleichzeitig **realistisch *und* lokal** sein.
- Das gilt für **alle Zeiten** weil sonst nachfolgende Theorien aktuelle Messergebnisse verletzen müssten!

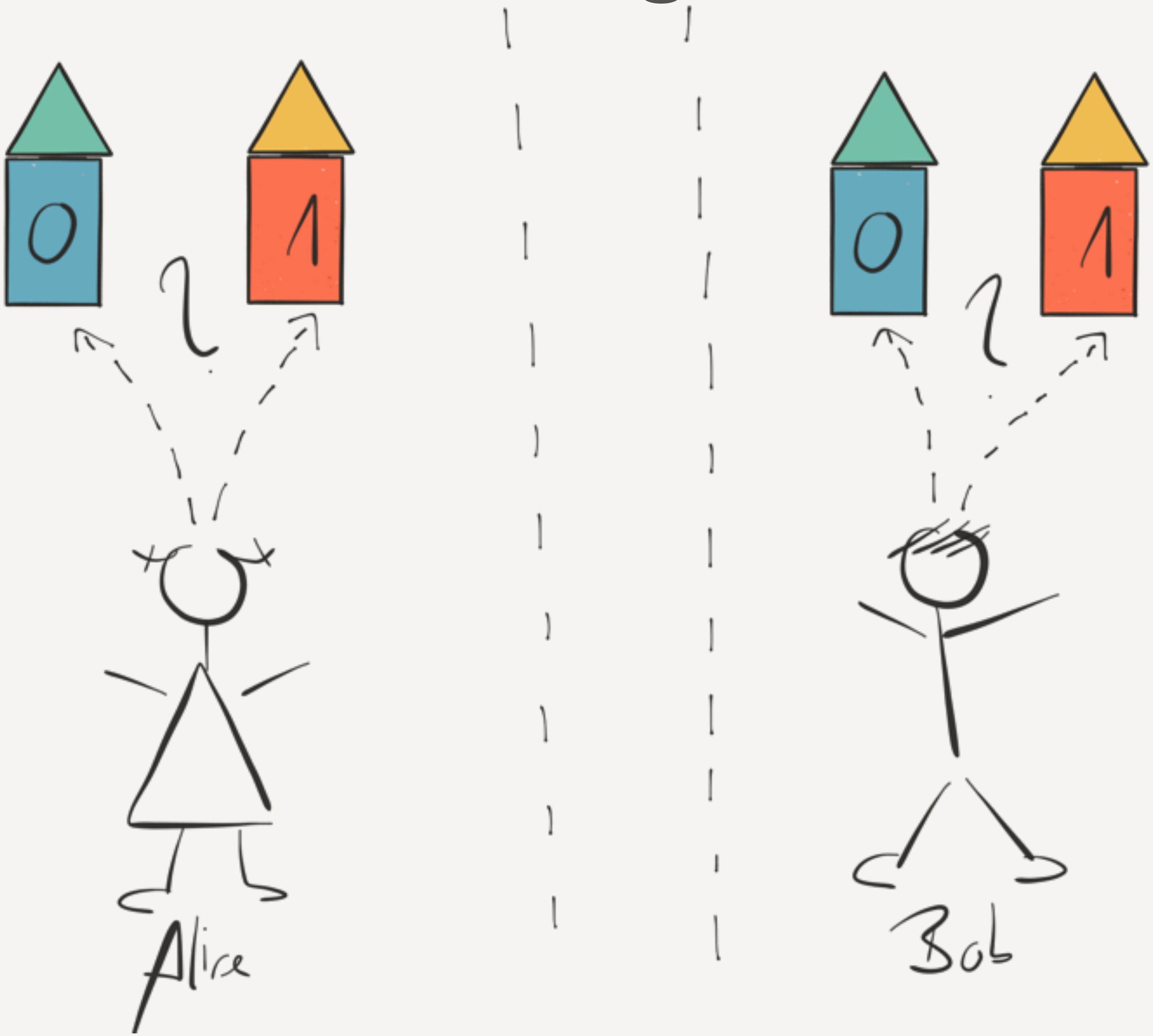
Korrelationen



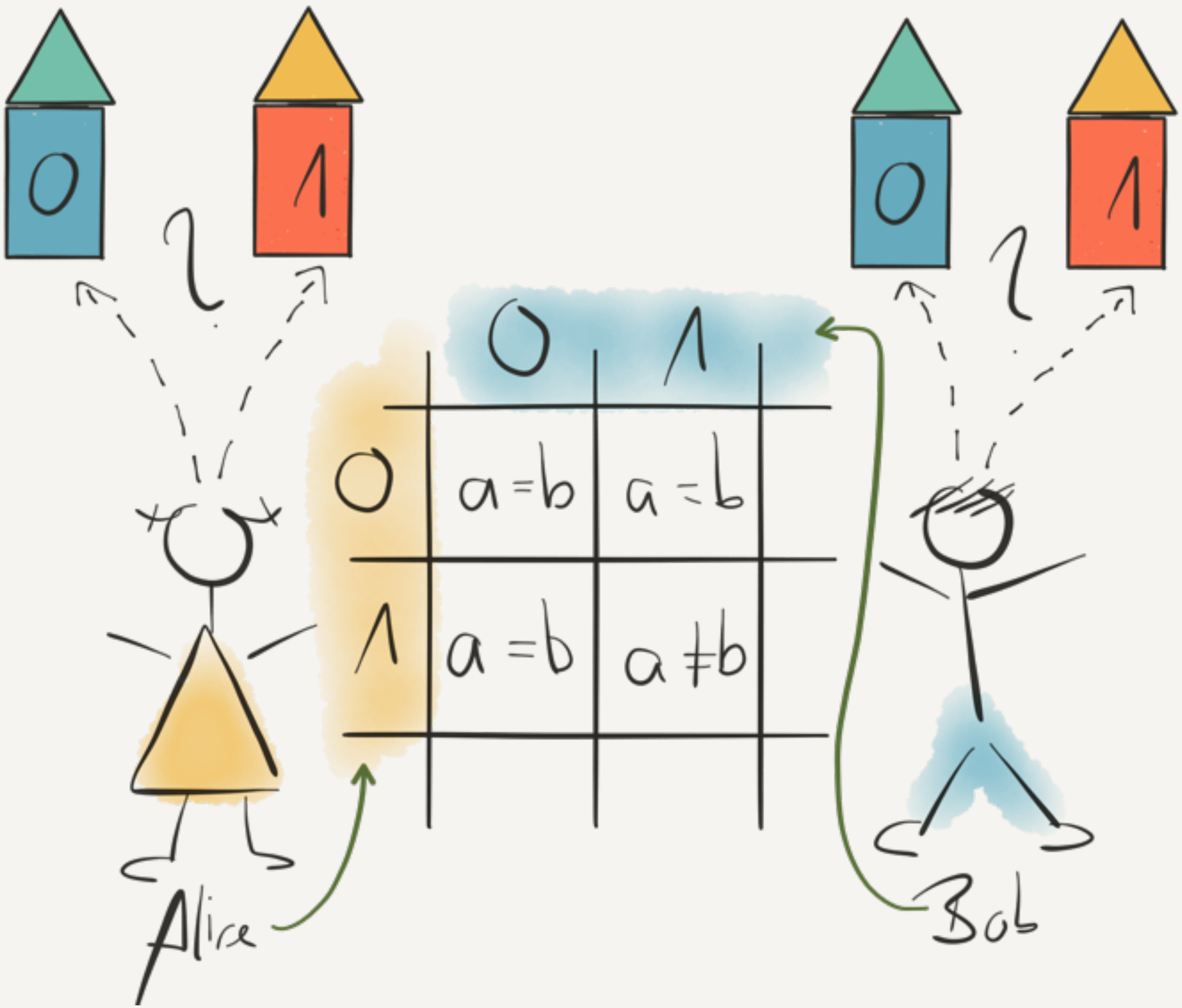
Korrelationen



Wahlmöglichkeit



Das Bell-Spiel



Alain Aspect
1982

Experimental Test of Bell's Inequalities Using Time-Varying Analyzers

Alain Aspect, Jean Dalibard,[a] and Gérard Roger
Institut d'Optique Théorique et Appliquée, F-91406 Orsay Cédex, France

(Received 27 September 1982)

Correlations of linear polarizations of pairs of photons have been measured with time-varying analyzers. The analyzer in each leg of the apparatus is an acousto-optical switch followed by two linear polarizers. The switches operate at incommensurate frequencies near 50 MHz. Each analyzer amounts to a polarizer which jumps between two orientations in a time short compared with the photon transit time. The results are in good agreement with quantum mechanical predictions but violate Bell's inequalities by 5 standard deviations.

PACS numbers: 03.65.Bz, 35.80.+s

Bell's inequalities apply to any correlated measurement on two correlated systems. For instance, in the optical version of the Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*,[1] a source emits pairs of photons (Fig. 1). Measurements of the correlations of linear polarizations are performed on two photons belonging to the same pair. For pairs emitted in suitable states, the correlations are strong. To account for these correlations, Bell[2] considered theories which invoke common properties of both members of the

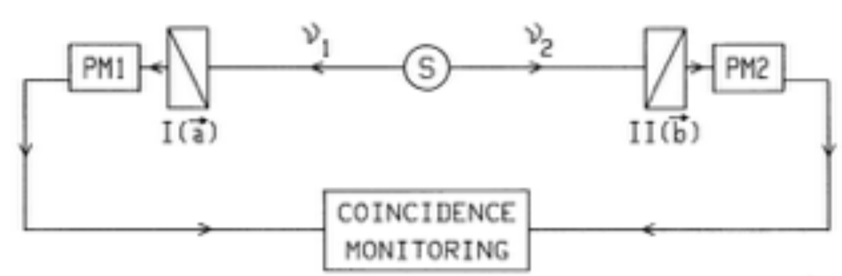


FIG. 1. Optical version of the Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*. The pair of photons ν_1 and ν_2 is analyzed by linear polarizers I and II (in orientations $\vec{a}$ and $\vec{b}$) and photomultipliers. The coincidence rate is monitored.

Locality-Loophole

Detector Loophole

Experimenteller Status

Lokalität
2008

- Lokalität wurde in vielen Experimenten ausgeschlossen, bei denen eine klare Verletzung der Bell'schen Ungleichung nachgewiesen wurde.
- Aktueller Status: $18\mathrm{km}$ Entfernung, eine lokale Wechselwirkung hätte mindestens die Geschwindigkeit $54.000c$.

Letter

Nature **454**, 861-864 (14 August 2008) | doi:10.1038/nature07121; Received 2 April 2008; Accepted 30 May 2008

Testing the speed of 'spooky action at a distance'

Daniel Salart[1], Augustin Baas[1], Cyril Branciard[1], Nicolas Gisin[1] & Hugo Zbinden[1]

1. Group of Applied Physics, University of Geneva, 20 Rue de l'Ecole de Médecine, CH-1211 Geneva 4, Switzerland

Correspondence to: Daniel Salart[1] Correspondence and requests for materials should be addressed to D.S. (Email: daniel.salart@physics.unige.ch).

Correlations are generally described by one of two mechanisms: either a first event influences a second one by sending information encoded in bosons or other physical carriers, or the correlated events have some common causes in their shared history. Quantum physics predicts an entirely different kind of cause for some correlations, named entanglement. This reveals itself in correlations that violate Bell inequalities (implying that they cannot be described by common causes) between space-like separated events (implying that they cannot be described by classical communication). Many Bell tests have been performed[1], and loopholes related to locality[2, 3, 4] and detection[5, 6] have been closed in several independent experiments. It is still possible that a first event could influence a second, but the speed of this hypothetical influence (Einstein's 'spooky action at a distance') would need to be

Realismus
2007

- Weiterführende theoretische Untersuchungen liefern eine Ungleichung, die gleichzeitig Lokalität und Realismus ausschließt.
- Diese Klasse der nicht-lokalen aber realistischen Theorien kann durch die Ungleichung von Leggett beschrieben werden.
- Diese Ungleichung wird hier experimentell verletzt.

Article

Nature **446**, 871-875 (19 April 2007) | doi:10.1038/nature05677; Received 22 December 2006; Accepted 13 February 2007

There is a Corrigendum (13 September 2007) associated with this document.

An experimental test of non-local realism

Simon Gröblacher[1,2], Tomasz Paterek[3,4], Rainer Kaltenbaek[1], Časlav Brukner[1,2], Marek Żukowski[1,3], Markus Aspelmeyer[1,2] & Anton Zeilinger[1,2]

1. Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Vienna, Austria
2. Institute for Quantum Optics and Quantum Information (IQOQI), Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 Vienna, Austria
3. Institute of Theoretical Physics and Astrophysics, University of Gdansk, ul. Wita Stwosza 57, PL-08-952 Gdansk, Poland
4. The Erwin Schrödinger International Institute for Mathematical Physics (ESI), Boltzmanngasse 9, A-1090 Vienna, Austria

Correspondence to: Markus Aspelmeyer[1,2]Anton Zeilinger[1,2] Correspondence and requests for materials should be addressed to M.A. (Email: markus.aspelmeyer@quantum.at) or A.Z. (Email: zeilinger-office@quantum.at).

Most working scientists hold fast to the concept of 'realism'—a viewpoint according to which an external reality exists independent of observation. But quantum physics has shattered some of our cornerstone beliefs. According to Bell's theorem, any theory that is based on the joint assumption of realism and locality (meaning that local events cannot be affected by actions in space-like separated regions) is at variance with certain quantum predictions. Experiments with entangled pairs of particles have amply confirmed these quantum predictions, thus rendering local realistic theories untenable. Maintaining realism as a fundamental concept would therefore necessitate the introduction of 'spooky' actions that defy locality. Here we show by both theory and experiment that a broad and rather reasonable class of such non-local realistic theories is incompatible with experimentally observable quantum correlations. In the experiment, we

▲ Top

Zusammenfassung

- Der experimentelle Status belegt, dass die Welt weder realistisch noch lokal ist!
- Es gibt keine verborgenen Variablen und kann diese auch in zukünftigen Theorien nicht geben, weil diese dann den aktuellen Messdaten widersprechen würden.
- Beim Kollaps der Wellenfunktion entsteht das Teil erst in der Realität. Die Wellenfunktion beschreibt eine Anzahl von Möglichkeiten der Realität.
- Vorher hat es keine definierten (realen) Eigenschaften, sondern der experimentelle Aufbau wählt aus welche Eigenschaft real wird.