How device-independent approaches change the meaning of physical theory

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Game of 20 questions

Figure: What's wrong with the idea of quantum mechanical entities?

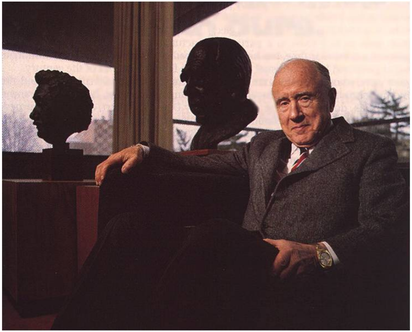
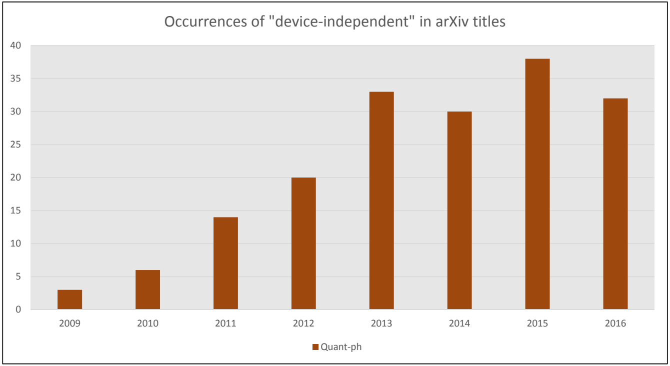


Figure: John Wheeler (1911-2008) with Bohr and Einstein.

Device-independent physics



Problem of trust.

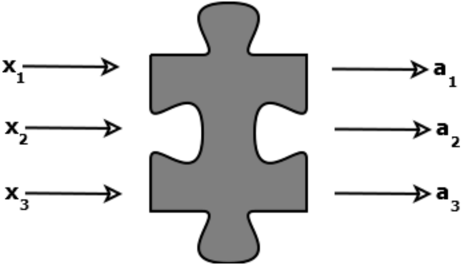
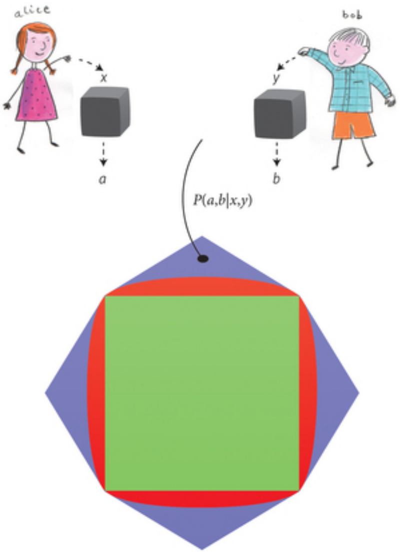


Figure: In the case of $n = 3$ parties, physics is fully contained in the probabilities $P(a_1 a_2 a_3 | x_1 x_2 x_3)$.



S. Popescu and D. Rohrlich, *Found. Phys.* 24, 379 (1994)
S. Popescu, *Nature Phys.* 10, 264 (2014)

PR boxes

	Classical	**Quantum**	**PR Boxes**
CHSH max value	2	$2\sqrt{2}$	4

PR box takes two inputs $x, y \in \{0, 1\}$ and produces two outputs $a, b \in \{0, 1\}$ according to the joint distribution

$$P(ab|xy) = \begin{cases} 1/2 : & a + b = xy \mod 2 \\ 0 : & \text{otherwise.} \end{cases}$$

Correlators: $E_{xy} = P(a = b|xy) - P(a \neq b|xy)$

CHSH: $CHSH = |E_{00} + E_{10} + E_{01} - E_{11}|$

No signalling: $P(a|x, y) = P(a|x)$ and $P(b|x, y) = P(b|y)$

S. Popescu and D. Rohrlich, *Found. Phys.* 24, 379 (1994)

Physical but unknown

Processes inside the box are:

- "of unspecified character"
- "of unknown nature"

A box captures unknown processes connecting inputs and outputs. They are assumed to be physical but not described by any known physical theory.

This is a new sense of "physical".

Historical precedent

New meaning of physical theory?

Similar to Einstein: unhappy about principle theories, wishing for a constructive theory that never came.

Wishing for more

Einstein, 1919: "When we say we have succeeded in understanding a group of natural processes, we invariably mean that a constructive theory has been found which covers the processes in question."

What if the knowledge/specification of physical system never came?

Einstein, 1911: “The principle of relativity is a principle that narrows the possibilities.” Principles act as constraints.

Interpretation of quantum theory

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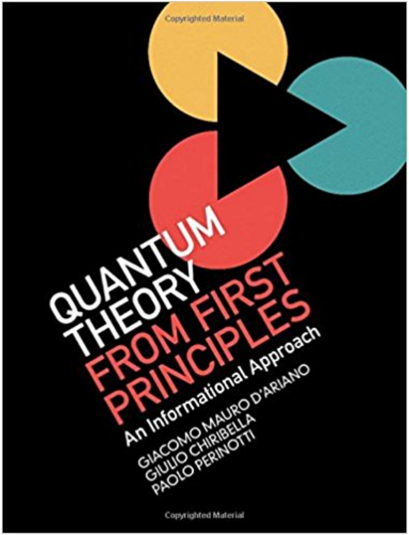
Reconstruction of quantum theory

AG, Reconstruction of quantum theory, *British Journal for the Philosophy of Science*, 58, 2007, pp. 387-408.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Rovelli in 1996

- "Quantum mechanics will cease to look puzzling only when we will be able to *derive* the formalism of the theory from a set of simple physical assertions ("postulates," "principles") about the world. Therefore, we should not try to append a reasonable interpretation to the quantum mechanical formalism, but rather to *derive* the formalism from a set of experimentally motivated postulates."

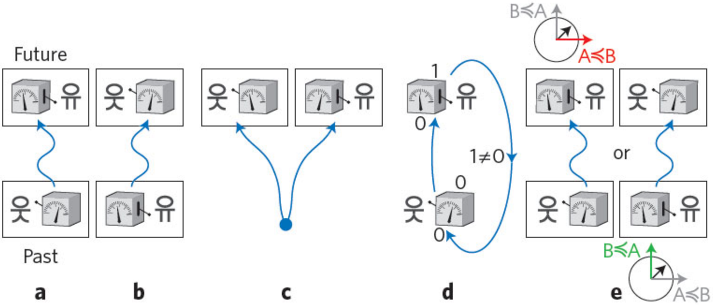
Principles for the Tsirelson bound

Linden et al., 2007 Non-local computation.

Pawłowski et al., 2009 Information causality for non-locality.

Masanes and Müller, 2011 Macroscopic locality for non-locality.

Cabello, 2013 Exclusivity for contextuality.

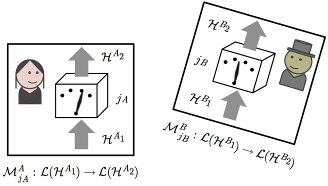


Č. Brukner, Nature Physics, 10, 159 (2014). G. Chiribella, Phys Rev A, 86, 040301 (2012).

Causal loops? Bipartite: no single or double loops. Different for three parties!

Macroscopic correlations locally compatible with classical probability theory exist that allow for deterministic signaling between three or more parties incompatible with any predefined causal order. Ä. Baumeler et al., *Phys. Rev. A* 90, 042106 (2014)

Process matrix framework



Probabilities are bilinear functions of the CP maps:

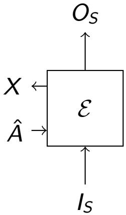
$$P(\mathcal{M}^{\mathcal{A}}, \mathcal{M}^{B}) = \omega(\mathcal{M}^{\mathcal{A}}, \mathcal{M}^{B})$$

$\omega : \mathcal{L}(\mathcal{H}^{A_1} \otimes \mathcal{H}^{A_2} \otimes \mathcal{H}^{B_1} \otimes \mathcal{H}^{B_2}) \mapsto \mathbb{R}$
positive normalized $\equiv$ a state.

How to characterize the most general probability distributions allowed by quantum mechanics?

O. Oreshkov, F. Costa, and Č. Brukner, Nature Communications 3, 1092 (2012)

A *party* $S = (\hat{A}, X, \mathcal{E})$ with $\mathcal{E} : \hat{A} \times I_S \rightarrow X \times O_S$, consists of an input random variable $\hat{A}$, an output random variable X, and a map $\mathcal{E}$ that maps $\hat{A}$ together with a physical system S that it receives from the environment to X and a physical system which is returned to the environment.



The environment "lies outside space-time" and is "described as a whole" by a process matrix.

Ä. Baumeler and S. Wolf, *New J. of Phys.* 18, 035014 (2016)
I. Ibnouhsein and AG, *Phys. Rev. A* 92, 042124 (2015)

Old and new modes of thinking about systems

Einstein's letter to Schrödinger, 19 June 1935:

> *The wavefunction ψ [should describe] the real state of the real system.*

EPR:

> *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.*

Dirac

Dirac, 1931:

> *The most powerful advance would be to perfect and generalize the mathematical formalism that forms the existing basis of theoretical physics, and after each success in this direction, to try to interpret the new mathematical features in terms of physical entities.*

If entity realism is rejected, why would systems remain?

New mode

Coecke et al., 2010:

> *Systems are "lines" or "wires" between "boxes" in symbolic diagrams connecting various operations on the observer's information — a conception that leads to "new modes of explaining physical phenomena".*

Examples: causal orders; almost quantum correlations.

Claude Shannon No semantics.

Niels Bohr There is a well-defined, unified and essentially unique formal symbolic structure to each complete physical theory which coordinates its descriptions of phenomena. (Hooker, 1991)

Bohr became "more and more convinced of the need of a symbolization if one wants to express the latest results of physics." (Jammer, 1974)

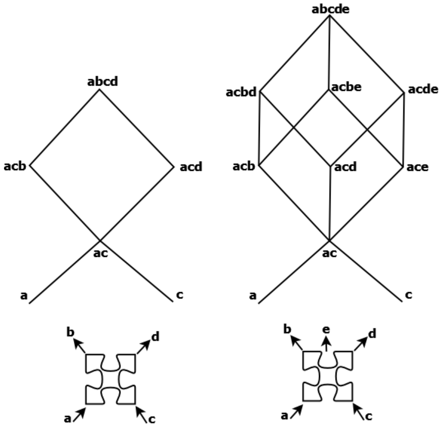
"The use of mathematical symbols secures the unambiguity of definition required for objective description." (Bohr, 1958)

Hugh Everett Observers possess memory, i.e. “parts... whose states are in correspondence with past experience of the observers”.

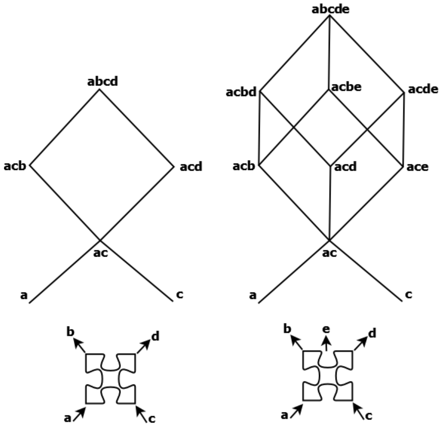
John Wheeler On this view physics is not machinery. Logic is not oil occasionally applied to that machinery. Instead everything, physics included, derives from two parents, and is nothing but cathode-tube image of the interplay between them. One is the "participant." The other is the complex of undecidable propositions of mathematical logic. . . .

The propositions are not propositions about anything. They are the abstract building blocks, or "pregeometry," out of which "reality" is conceived as being built.

- Strings $a, b, c, \ldots$ in a finite alphabet.
- Inputs: freely random. Singletons that are opens sets in a finite topological space.
- Other elements: not free, hence outputs.



Left: $\{a\}$ and $\{c\}$ are free random variables and open sets, while $\{b\}$ and $\{d\}$ are not. A loop means that the observer began with input a, then obtained information ac, followed by acb and $acbd$; then the observer's memory was erased in subsequent steps to return to the initial state a. N circular paths around the same loop correspond to N runs of the same experiment.



Right: Hasse diagram of a generalized box with two inputs and three outputs. Fundamental group $\mathbb{F}_2$. Loops of the first kind extend from the two-element set $\{ac\}$ to a four-element set, e.g., $\{abcd\}$, spanning three levels of the diagram. Loops of the second kind reach the five-element set $\{abcde\}$ and span four levels.

Conjecture Contextuality, in particular quantum mechanical contextuality, is fully captured by the properties of the fundamental group of a suitable discrete topological space.