What's in the input/output distinction?

Alexei Grinbaum

CEA-Saclay/LARSIM

Game of 20 questions

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

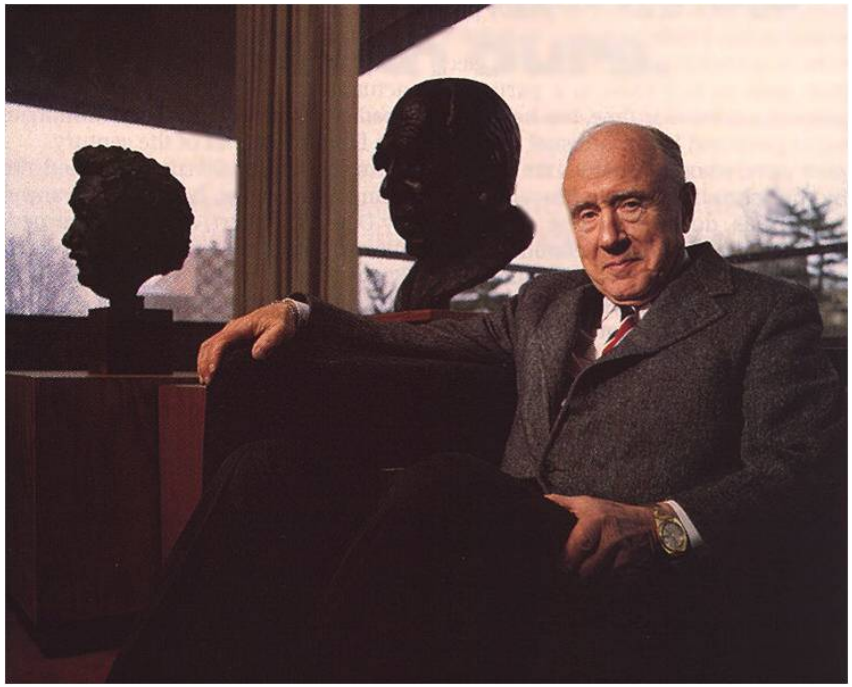
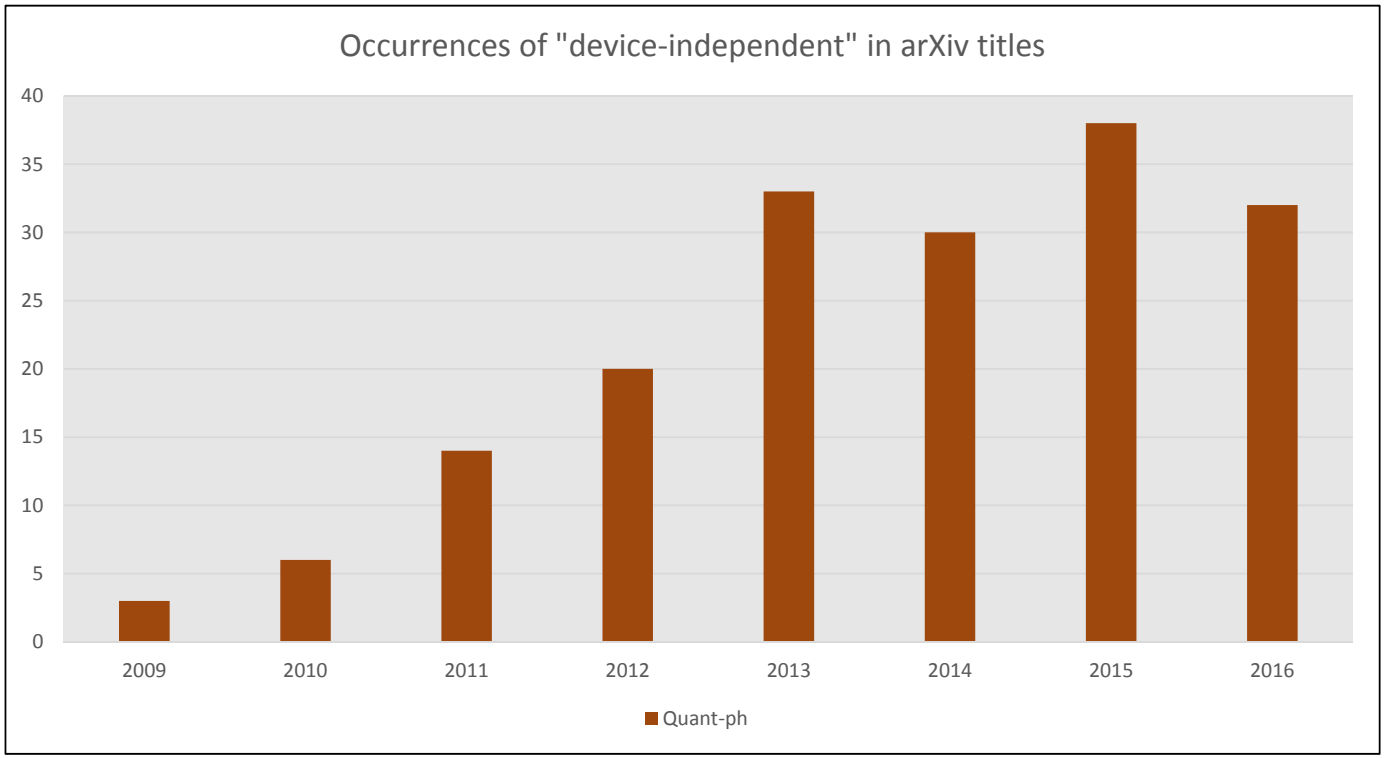


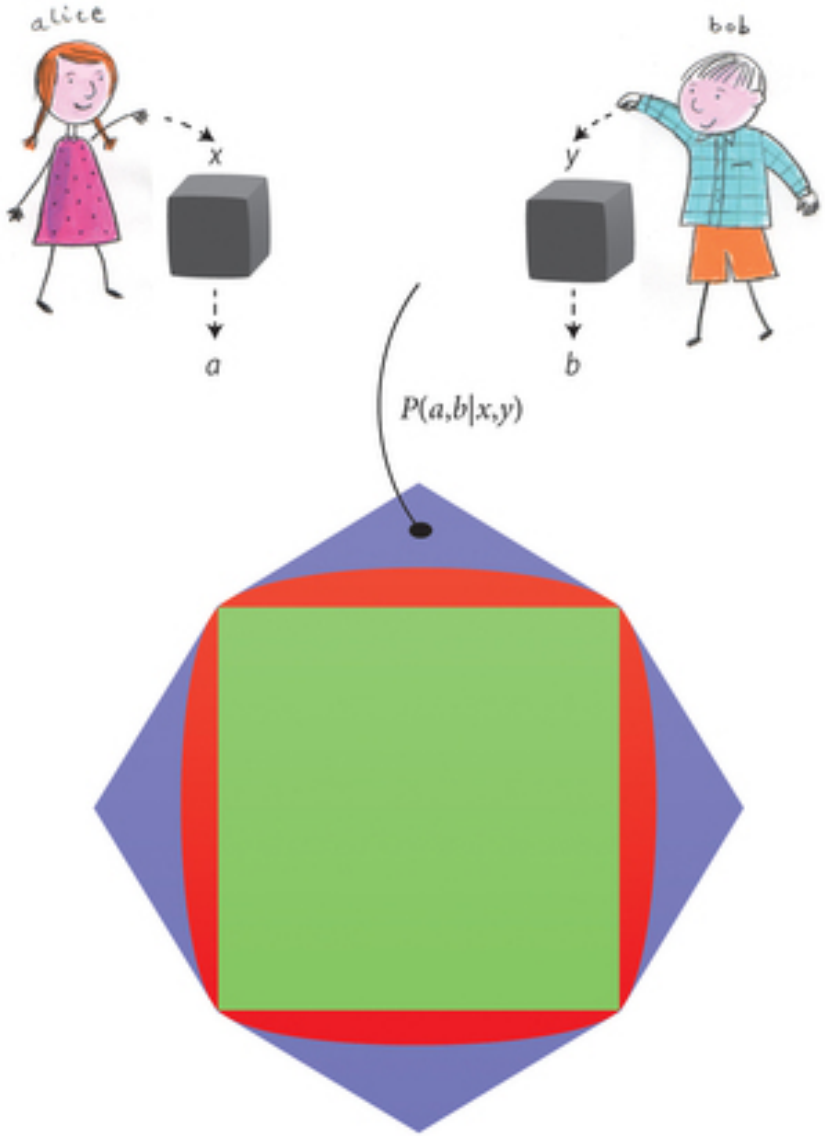
Figure: John Wheeler (1911-2008) with Bohr and Einstein.

Device-independent physics



Problem of trust.

Physics without systems?



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.

"For Alice (respectively for Bob), an experiment is a process or black box to which she feeds an input x from the alphabet $\mathcal{X}$ and from which she receives an output a from the alphabet $\mathcal{A}$. Alphabets $\mathcal{X}, \mathcal{Y}, \mathcal{A}, \mathcal{B}$ are of finite cardinality." Lang, Vértesi and Navascués, *J. Phys. A: Math. Theor.* 47 (2014) 424029.

A theory of languages. AG, *Found. Phys.* 45 (2015) 1341; *Studies in the History and Philosophy of Modern Physics* 58 (2017) 22-30.

"Observers are the nexus between experience and the account thereof. Whether this account can be formalized – that is, exhaustively represented in a formal language – can be doubted." Hansen and Wolf, arXiv:1810.04573.

Physical and philosophical consequences?

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.

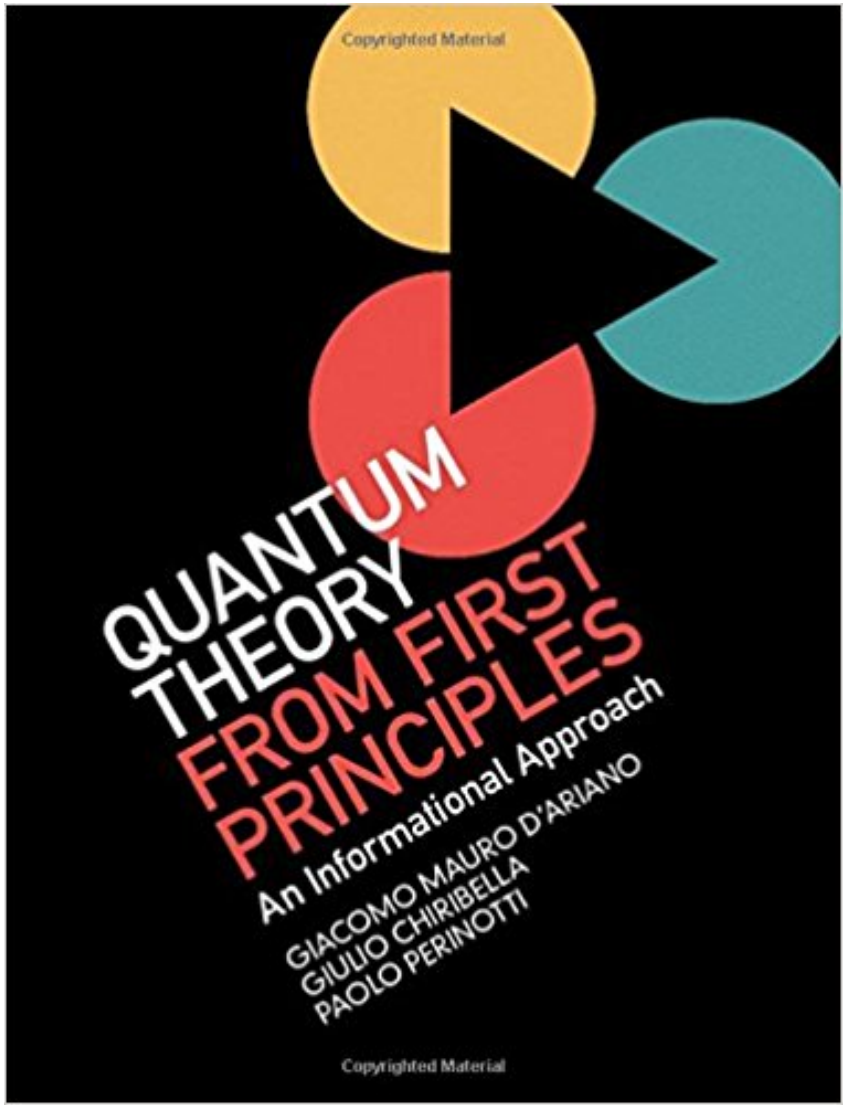
Interpretation of quantum theory

Reconstruction of quantum theory

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

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."


Copyrighted Material
QUANTUM THEORY FROM FIRST PRINCIPLES
An Informational Approach
GIACOMO MAURO D'ARIANO
GIULIO CHIRIBELLA
PAOLO PERINOTTI
Copyrighted Material

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.

Continuity makes things quantum

Holland Superposition principle for pure states. Ample unitary group.

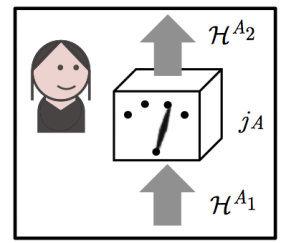
Landsman Two-sphere property: a certain algebraic structure is isomorphic to a sphere.

Hardy There exists a continuous reversible transformation on a system between any two pure states of that system.

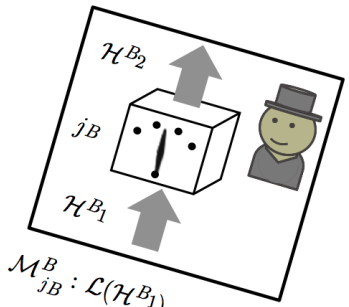
Brukner and Zeilinger Homogeneity of parameter space.

Dakić and Brukner Between any two pure states there exists a continuous reversible transformation.

Process matrix framework



$\mathcal{M}^A_{j_A} : \mathcal{L}(\mathcal{H}^{A_1}) \to \mathcal{L}(\mathcal{H}^{A_2})$



$\mathcal{M}^B_{j_B} : \mathcal{L}(\mathcal{H}^{B_1}) \to \mathcal{L}(\mathcal{H}^{B_2})$

Probabilities are bilinear functions of the CP maps:

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

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

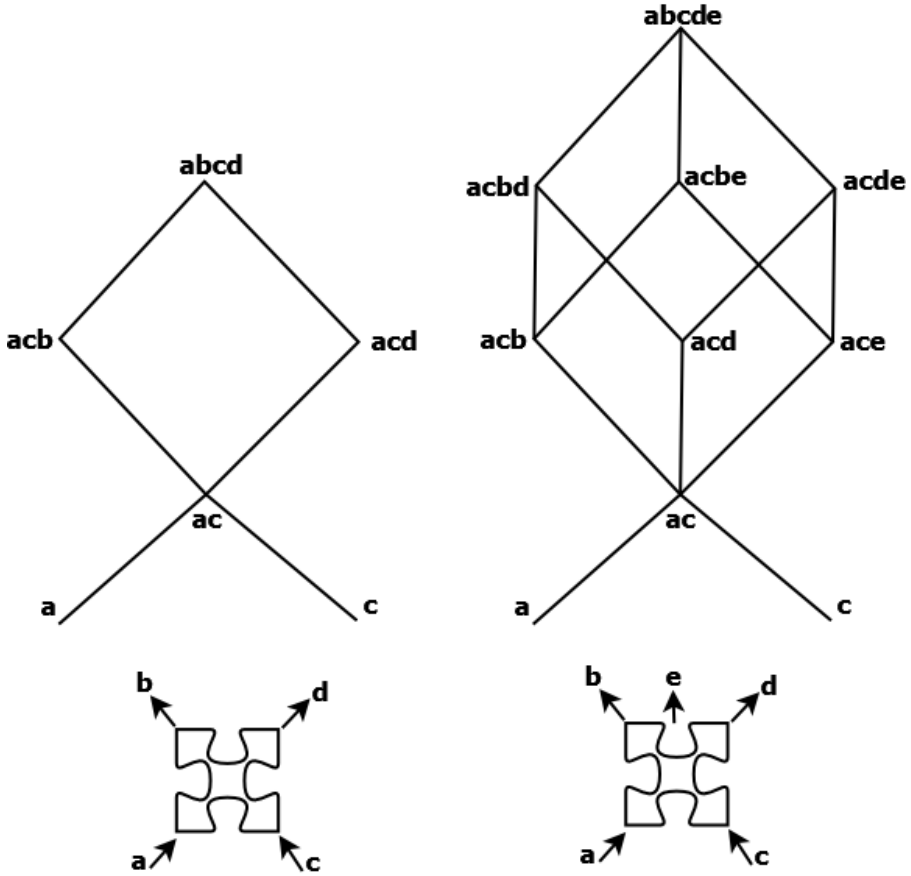
How to characterize the most general probability distributions allowed by quantum mechanics?

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

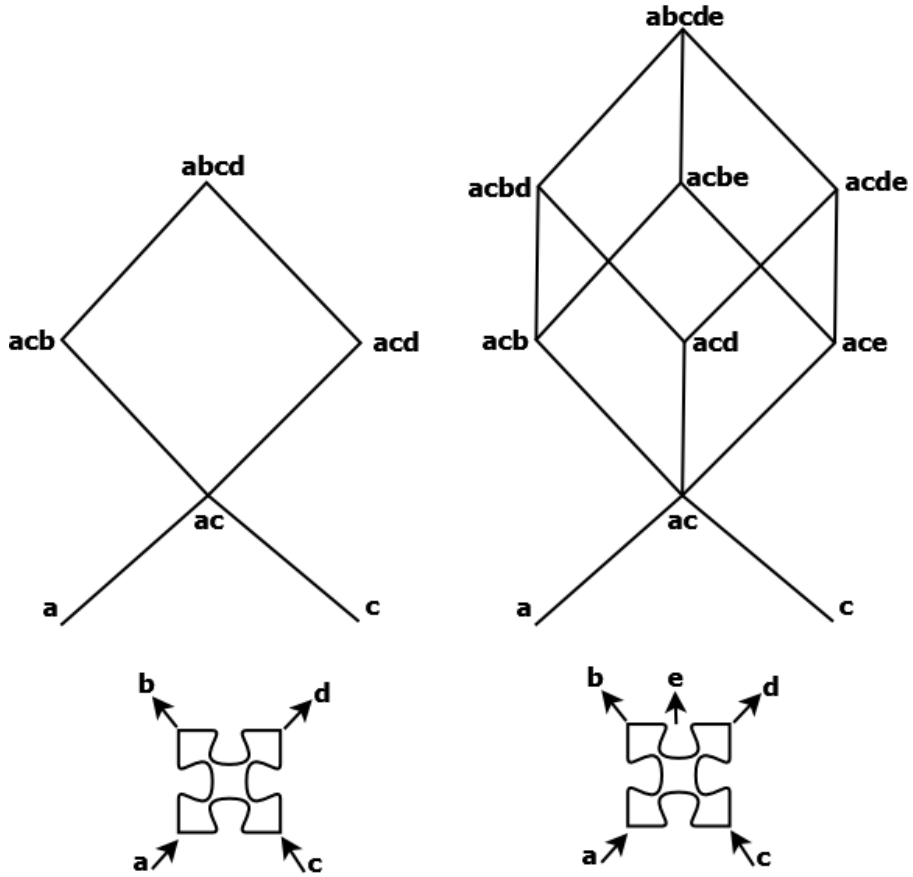
- "Correlations can be established in such a picture by physical systems that may be shared or exchanged by different parties, and which may be used to communicate or convey causal influences. It is well known, however, that this view is challenged by quantum correlations."
- "Alice and Bob both open their lab, let some physical system in, interact with it and send a physical system out, only once during each run of the experiment."
- "Alice and Bob are given some classical inputs labeled by x and y, and return some classical outputs a and b, respectively."

Branciard, Araújo, Feix, Costa, and Brukner, arXiv:1508.01704

- 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.

New CHSH and Klyachko bounds

- Discrete, not continuous. Finite field, not complex numbers.
- Computable, because defined in a finite alphabet.
- Linear codes.

Strings a and A are computable concatenations of all inputs and outputs over the runs.

$$I_H(A:a) = \kappa(a) + \lim_{N\to\infty} \frac{\Delta K^N}{N},$$

where $\Delta K^N = K(A^N) - K(A^N, a^N)$ and $\kappa(a)$ is the complexity rate of the input string.

ΔK^N corresponds to the decrease in complexity of the output string when the input string is adjoined to it. This decrease is due to a lawful connection that exists between the inputs and the outputs.

Using Kolmogorov complexity and algebraic coding theory:

	Classical	**This model**	**Quantum**
CHSH	2	$2 + h(1/4) \simeq 2.8113$	$2\sqrt{2} \simeq 2.8284$
Klyachko	2/3	0.6531	0.6366

Binary entropy $h(p) = -p\log(p) - (1-p)\log(1-p)$.

Adding continuity: CHSH $\simeq 2.8254$.

AG, *Found. Phys.* 45 (2015) 1341, arXiv:1501.02710

Experimental results

Quantum theory	$2\sqrt{2} \simeq 2.8284$
2015 continuous model	2.8254
This model	2.8113
Measured value	2.8117 ± 0.0032

Experiments: M. Smania, M. Kleinmann, A. Cabello, M. Bourennane, arXiv:1801.05739

- If the inputs only determine the sign of the correlator: three times a plus and once a minus,
- if this is all mutual information,
- and if the inputs are independent and uniformly selected,

then this mutual information is equal to $h(1/4) = 0.8113$. Adding two independent bits per run gets us 2.8113.

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.

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

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