Title: Information is the key!

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Abstract: <p>Most physicists take it for granted that the experimental violation of Bell's inequality provides evidence that it is not possible to completely describe the state of a physical system in terms of purely local information when this system is entangled with some other system. We disagree. Provided we redefine appropriately what is the information-theoretic state of a quantum system, it becomes possible to recover the whole from the description of its parts. This is in sharp contrast with the standard formalism of quantum mechanics in which the density matrix provides all there is to say about the state of a system. According to our formalism, there is no need to invoke supernatural nonlocality in order to explain everything standard quantum mechanics tells us that we can observe. We show, however, that this is inconsistent with the usual belief held among Everettians that the universal wavefunction can be taken as the complete representation of reality. Inspired by Plato and Kant, we introduce and contrast the notions of noumenal and phenomenal states of physical systems: the former corresponds to the complete but unknowable state of the system and the latter to what can be perceived about it with the help of arbitrary technology. We exhibit an explicit epimorphism from the former to the latter, which explains the relationship between all that there is and all that can be apprehended. Joint work with Paul Raymond-Robichaud</p>

Information is the Key!

Gilles Brassard Paul Raymond-Robichaud
Université de Montréal

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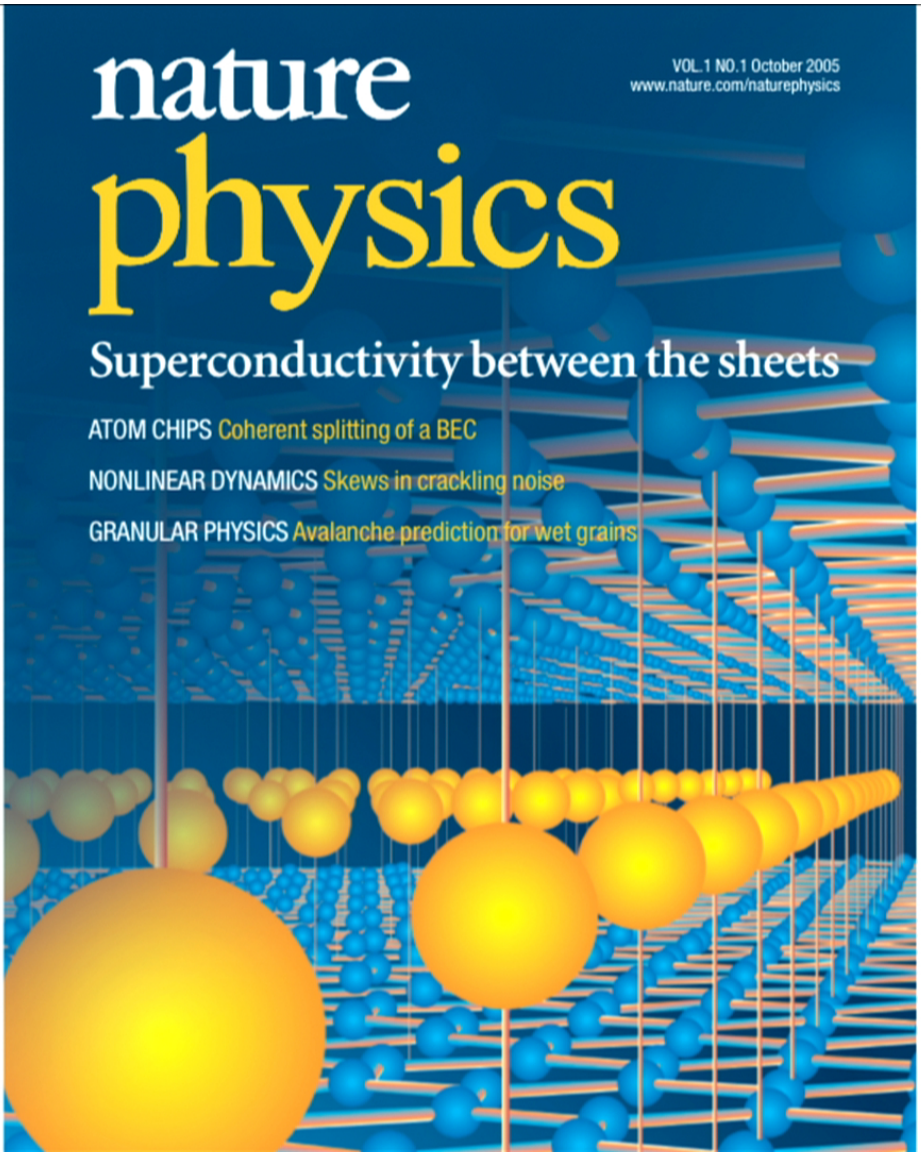
CIFAR
CANADIAN INSTITUTE FOR ADVANCED RESEARCH


nature
physics
VOL.1 NO.1 October 2005
www.nature.com/naturephysics
Superconductivity between the sheets
ATOM CHIPS Coherent splitting of a BEC
NONLINEAR DYNAMICS Skews in crackling noise
GRANULAR PHYSICS Avalanche prediction for wet grains

COMMENTARY

Is information the key?

GILLES BRASSARD

is in the Département d'informatique et de recherche opérationnelle, Université de Montréal, Québec H3C 3J7, Canada.

e-mail: brassard@iro.umontreal.ca

Quantum information science has brought us novel means of calculation and communication. But could its theorems hold the key to understanding the quantum world at its most profound level? Do the truly fundamental laws of nature concern — not waves and particles — but information?

This year marks the centenary of quantum mechanics. Despite earlier work by Max Planck, it was Albert Einstein's Nobel prize-winning 1905 paper[1] on the photoelectric effect that gave us what is arguably the greatest scientific theory of all time. Subsequently, the stones that make up the exquisite structure of quantum mechanics were laid out, one by one, by a stream of legendary giants such as Niels Bohr, Erwin Schrödinger and Werner Heisenberg — sometimes to the horror of Einstein. An almost inevitable consequence of this collective foundational effort over so many years is that quantum mechanics, for all its elegance, is built upon a rather disjointed, *ad hoc* set of axioms.

Quantum mechanics has forced us to rethink the nature of the physical world, its teachings often running counter to our misleading macroscopic experience. It is time to pause and reflect on what we've learned in the course of these 100 years. Alongside Christopher Fuchs[2], I contend that there is a fresh perspective to be taken on the axioms of quantum mechanics that could yield a more satisfactory foundation for the theory.

NEW HORIZONS

Quantum mechanics has changed our outlook on the world. The transistor, the laser, superconductivity, the atomic bomb — these early applications of the theory are but a few among those that have reshaped the way we live. The transistor made possible a dramatic increase in computation speed. However, given enough time, cog-and-wheels devices such as Charles Babbage's analytical engine are, in principle, capable of the same calculations. In a very real sense, the modern electronic computer is essentially a classical device. Could genuinely quantum-mechanical effects be harnessed for computing purposes?

In the early 1980s, it occurred to Richard Feynman[3] and David Deutsch[4] that a quantum computer could become so efficient that it would far outperform its classical counterpart. For example, an atom can be simultaneously in its ground and excited states. If we assign classical bit 0 to one state and bit 1 to the other (Fig. 1), this gives us a quantum bit, or qubit. If we string together ten qubits, they can be collectively in all 1024 classical states of ten bits, and we can compute using all those states in parallel. If we replace those ten qubits by one thousand, we obtain $2^{1,000}$ (roughly 10^{301}) simultaneous operations. This entails an amount of parallelism that could not be matched by a classical computer the size of the Universe, in which each elementary particle would be harnessed as a processing unit.

Quantum computing was at first regarded as a mere theoretical concept, but interest in it grew when Peter Shor discovered a way to use its capabilities to factorize large numbers efficiently[5]. Such a computer would threaten the public-key cryptographic schemes currently in use, in particular for the secure transmission of credit card numbers over the Internet. Electronic commerce in its current form is saved from a catastrophic collapse only because the construction of a full-size quantum computer is, for the moment, eluding our technological capabilities. And we can only shiver to think of the effect that such a collapse of classical cryptography could have on national security.

Even though the potential of quantum computers is mind-boggling, that does not change the theoretical notion of what is computable. The mathematical theory of computability is rooted in

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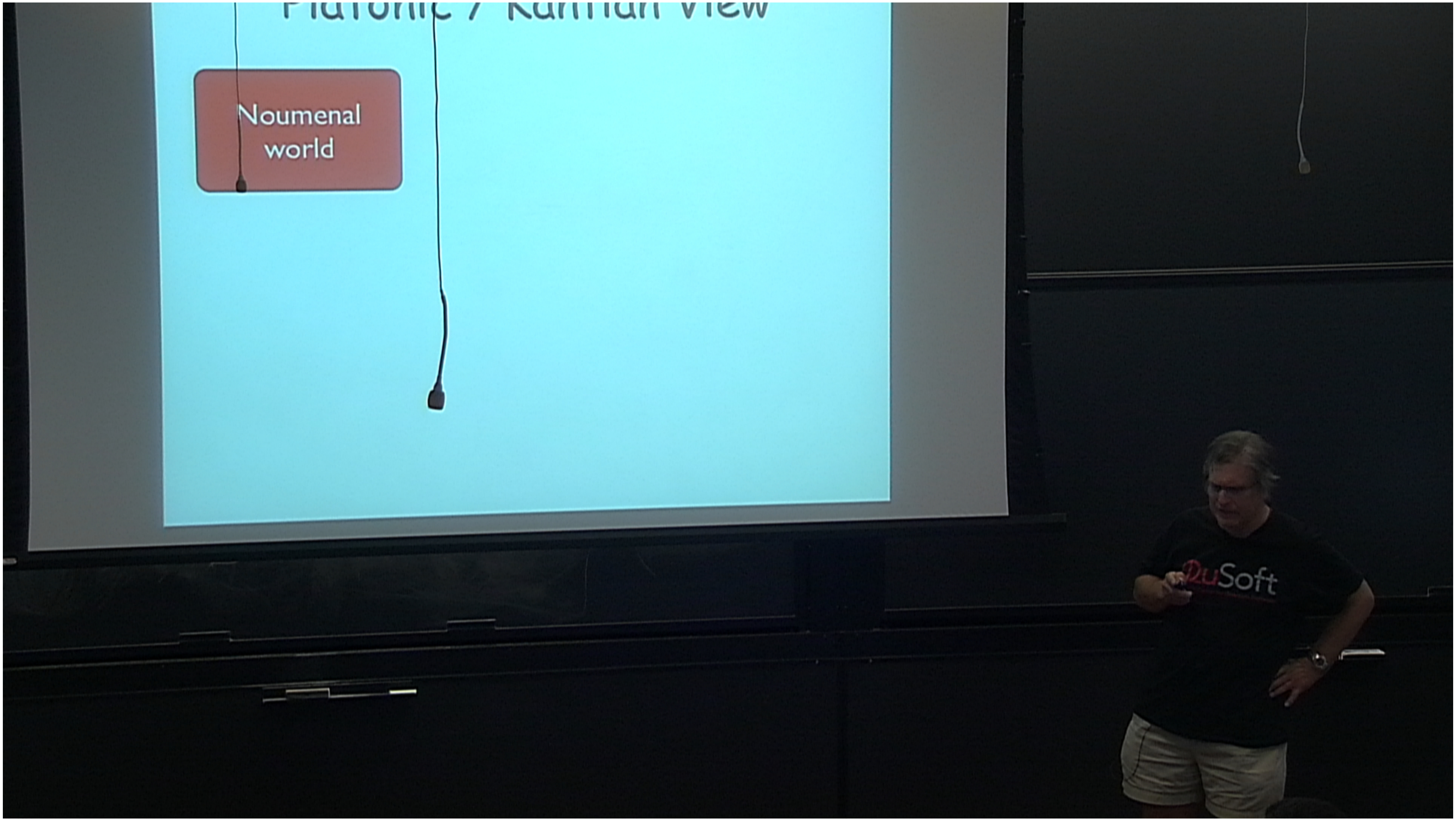
John Archibald Wheeler

By the late 1970s and onward, [...] to the best students who came asking for a research project, Wheeler would say,

"Derive quantum theory from an information theoretic principle".


Noumenal
world

Platonic / Kantian View

Noumenal world

All that there is
(*Ding an sich*)

Platonic / Kantian View

Noumenal world

All that there is (*Ding an sich*)

Kant: The noumenal world may exist, but it is completely unknowable through human sensation

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Phenomenal world

All that that can be apprehended
with help of unlimited* technology

Platonic / Kantian View

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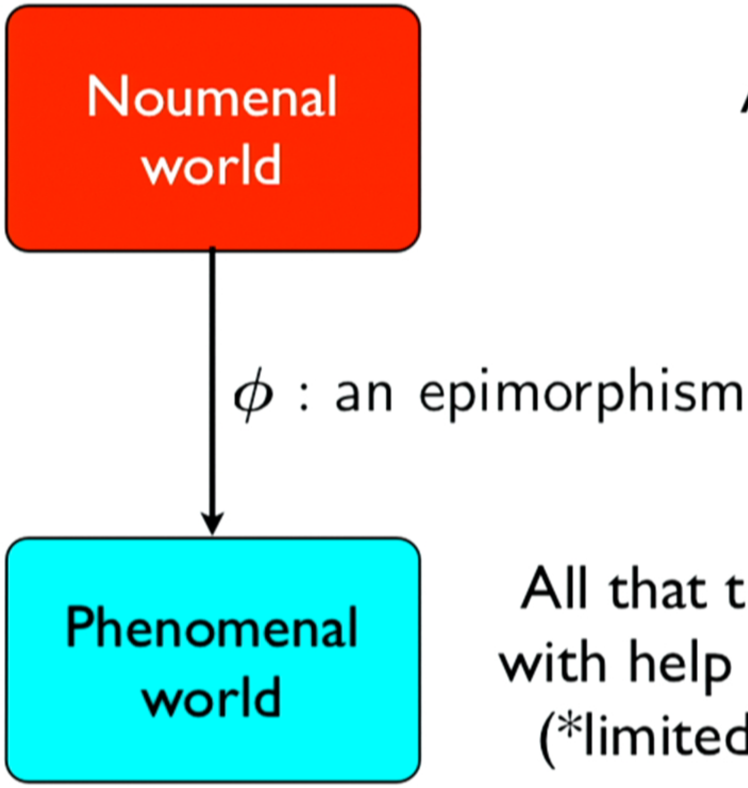
Platonic / Kantian View



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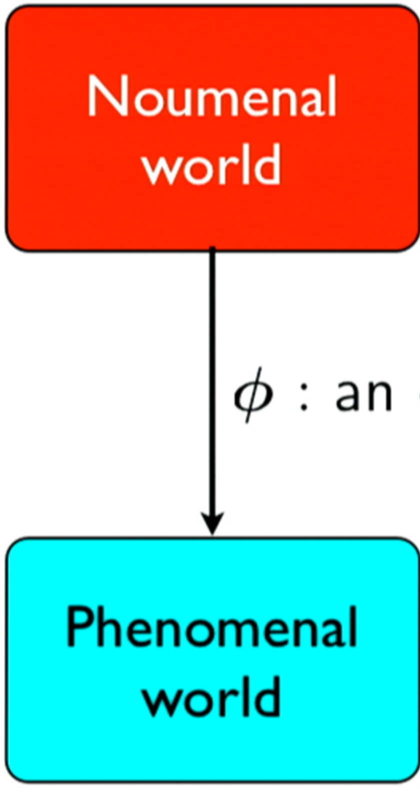
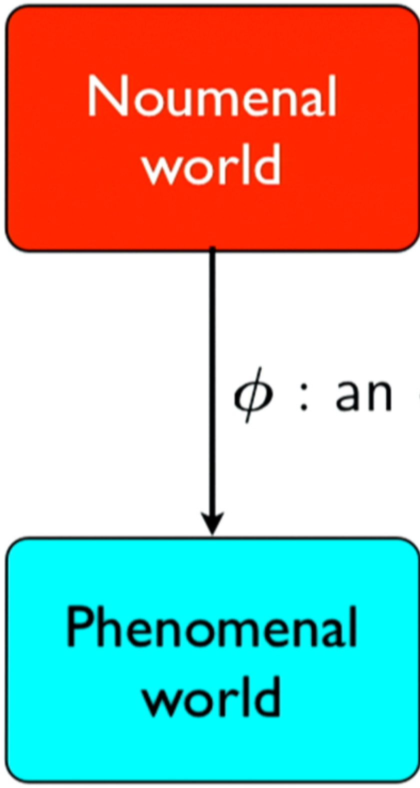


Why not "Ontic"?

ϕ : an epimorphism (cannot be one-to-one)

Platonic / Kantian View

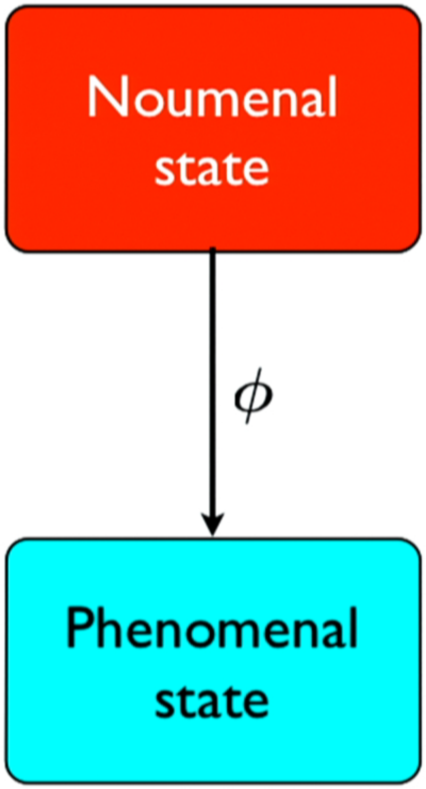


Why not "Ontic"?

ϕ : an epimorphism (cannot be one-to-one)

Because *this* is not "Epistemic"!
(and even less "Doxastic")

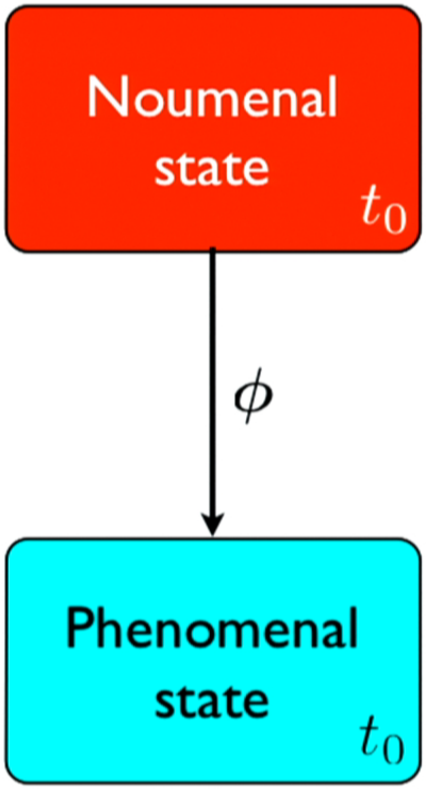
State of a System



All that there is

All that that can be apprehended with help of unlimited* technology (*limited by the laws of physics)

Evolution of a System



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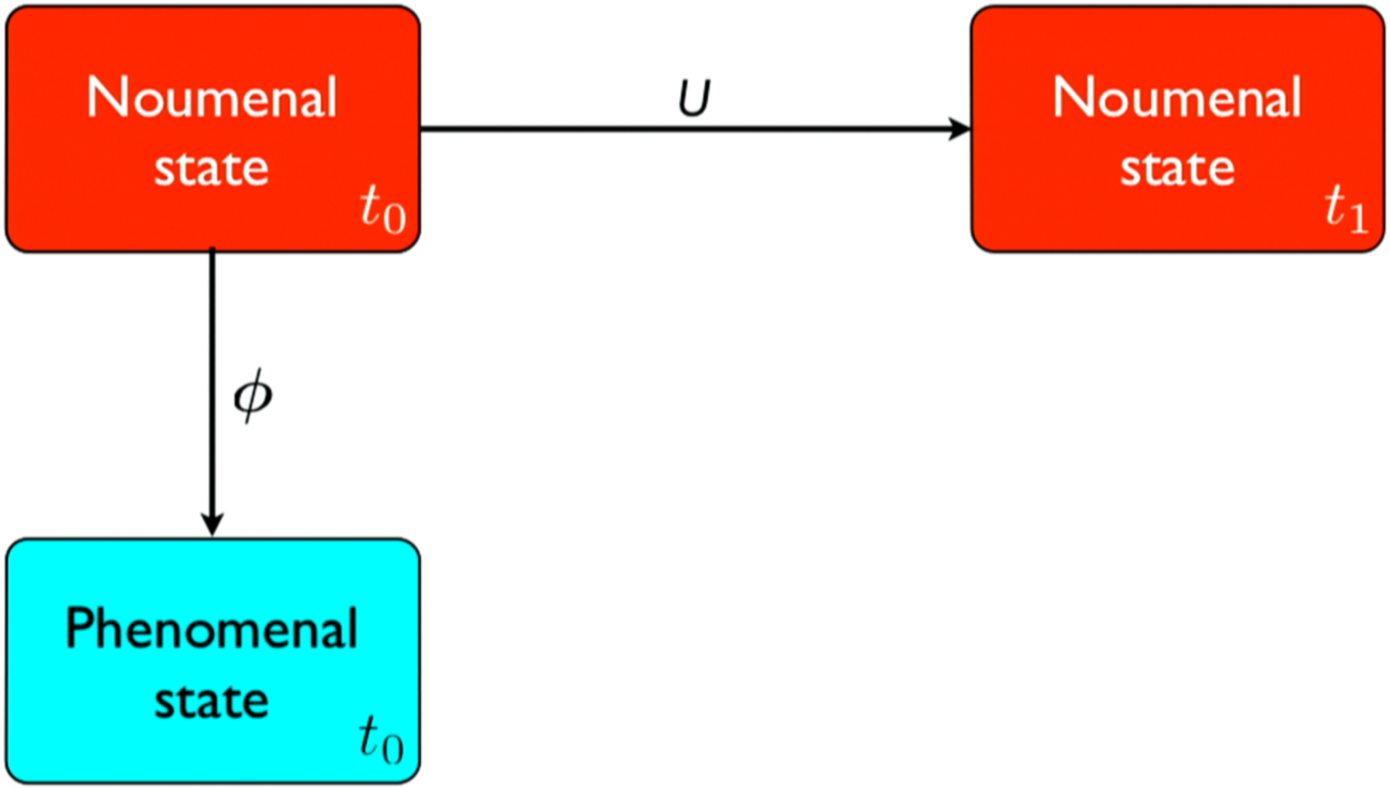

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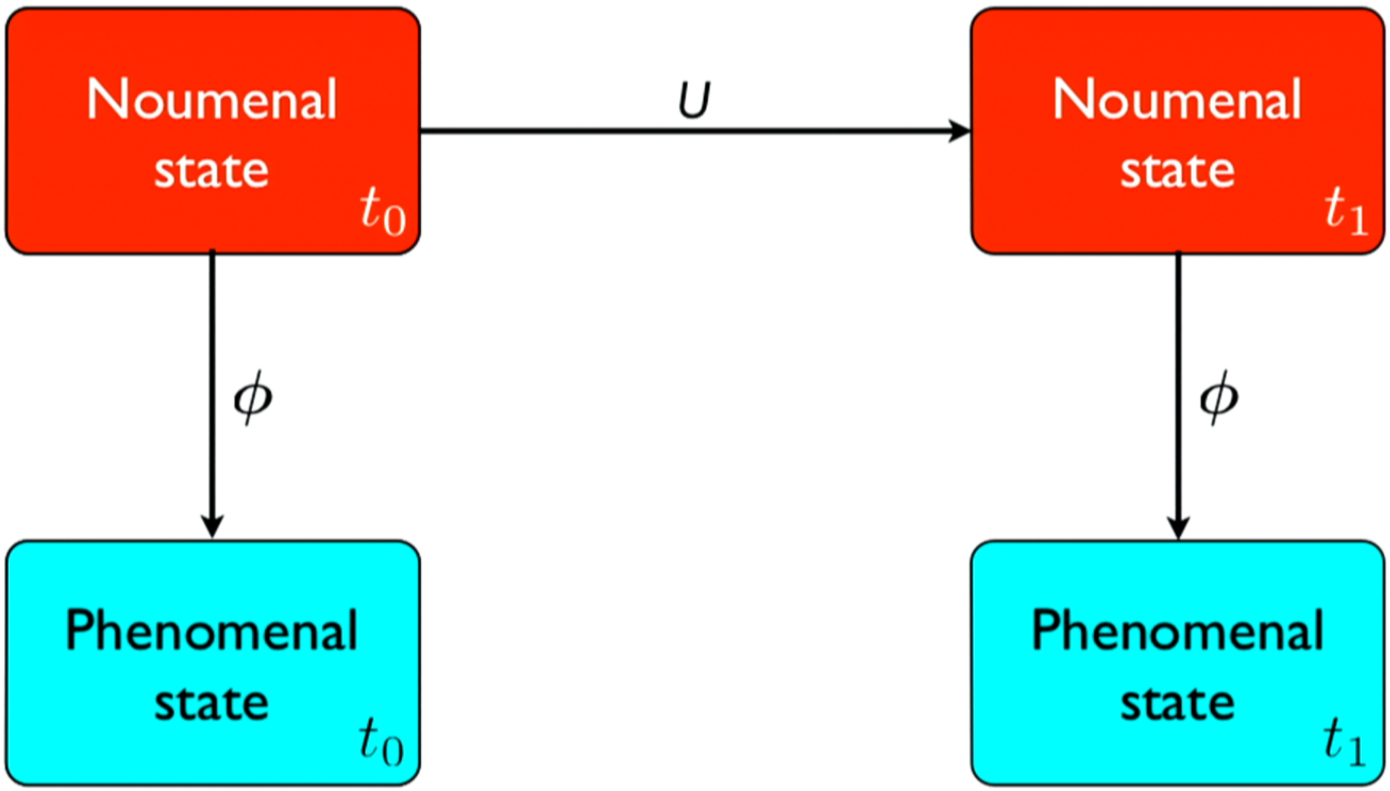

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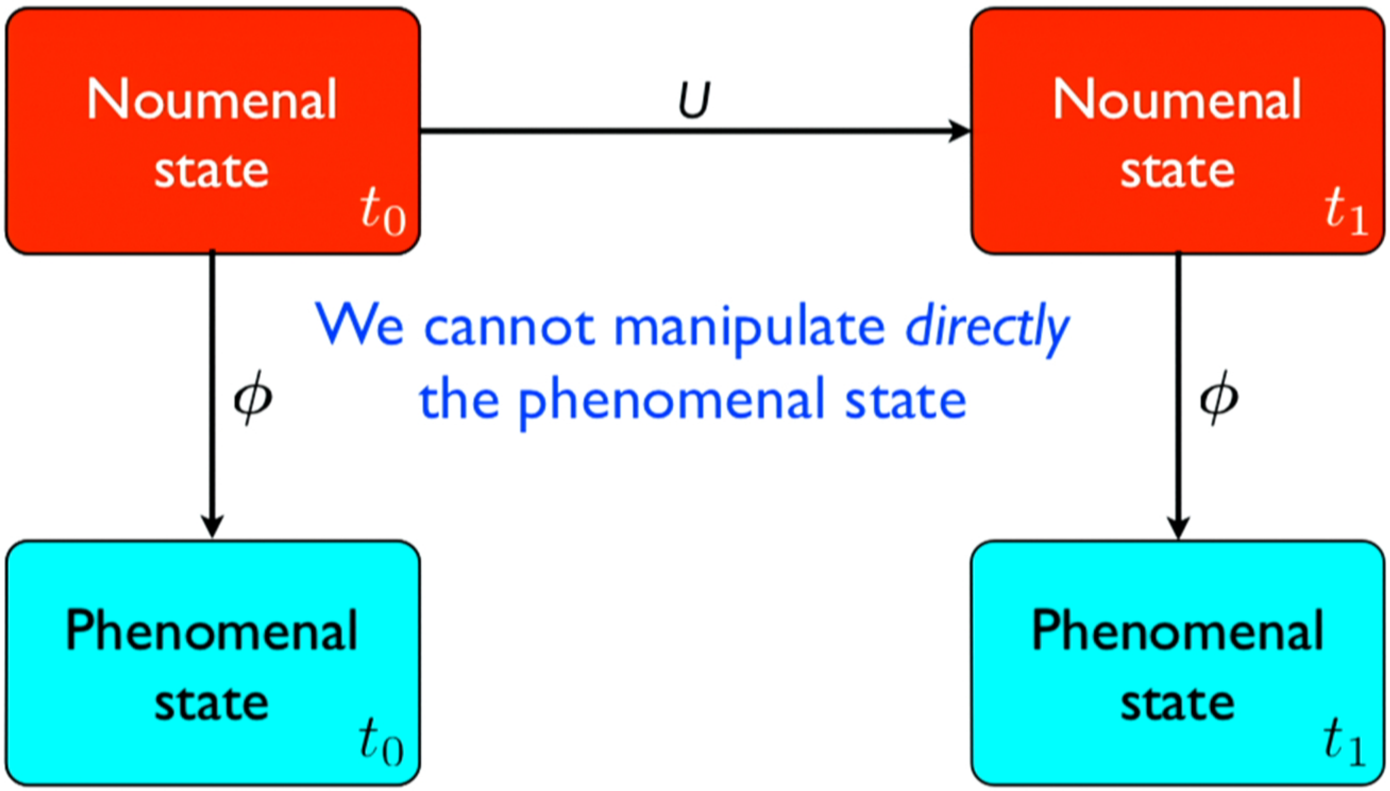

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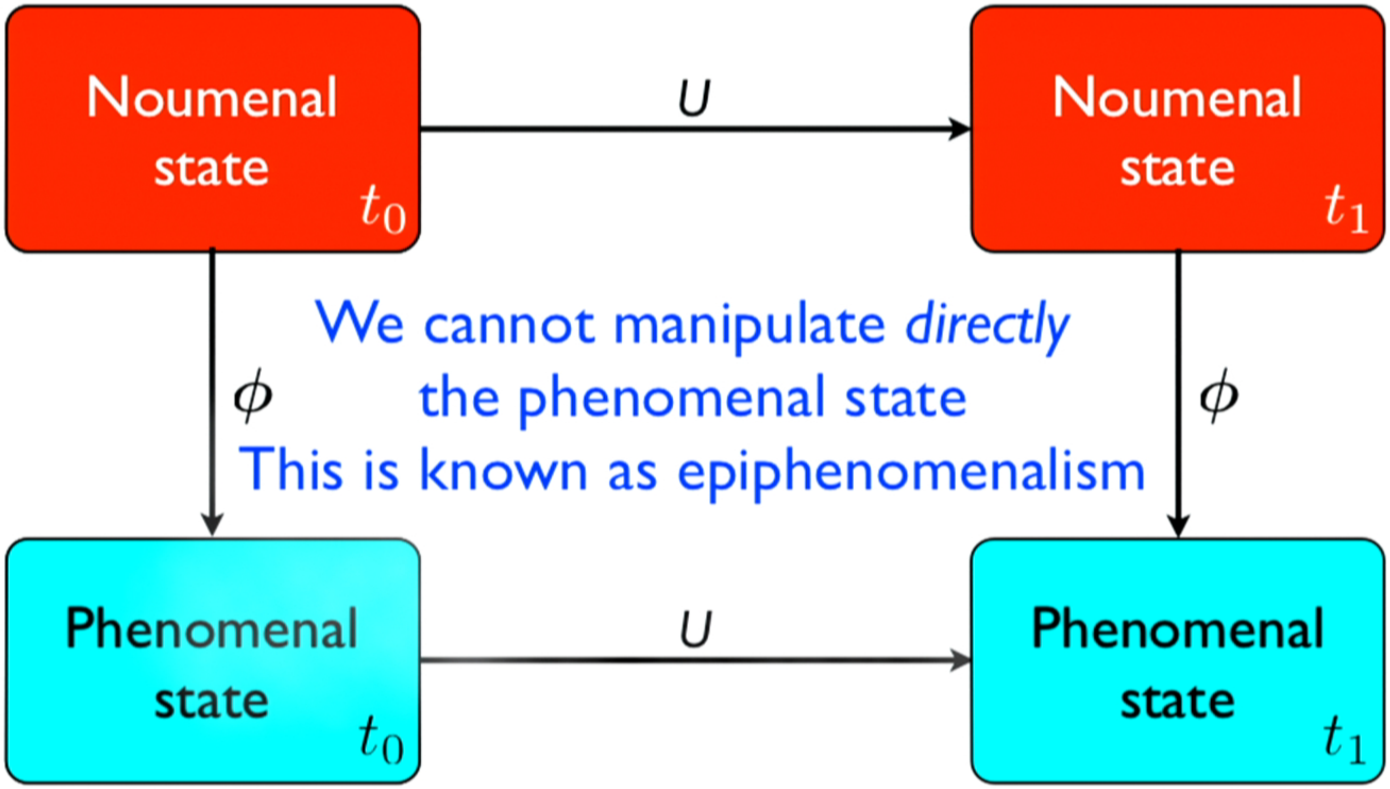

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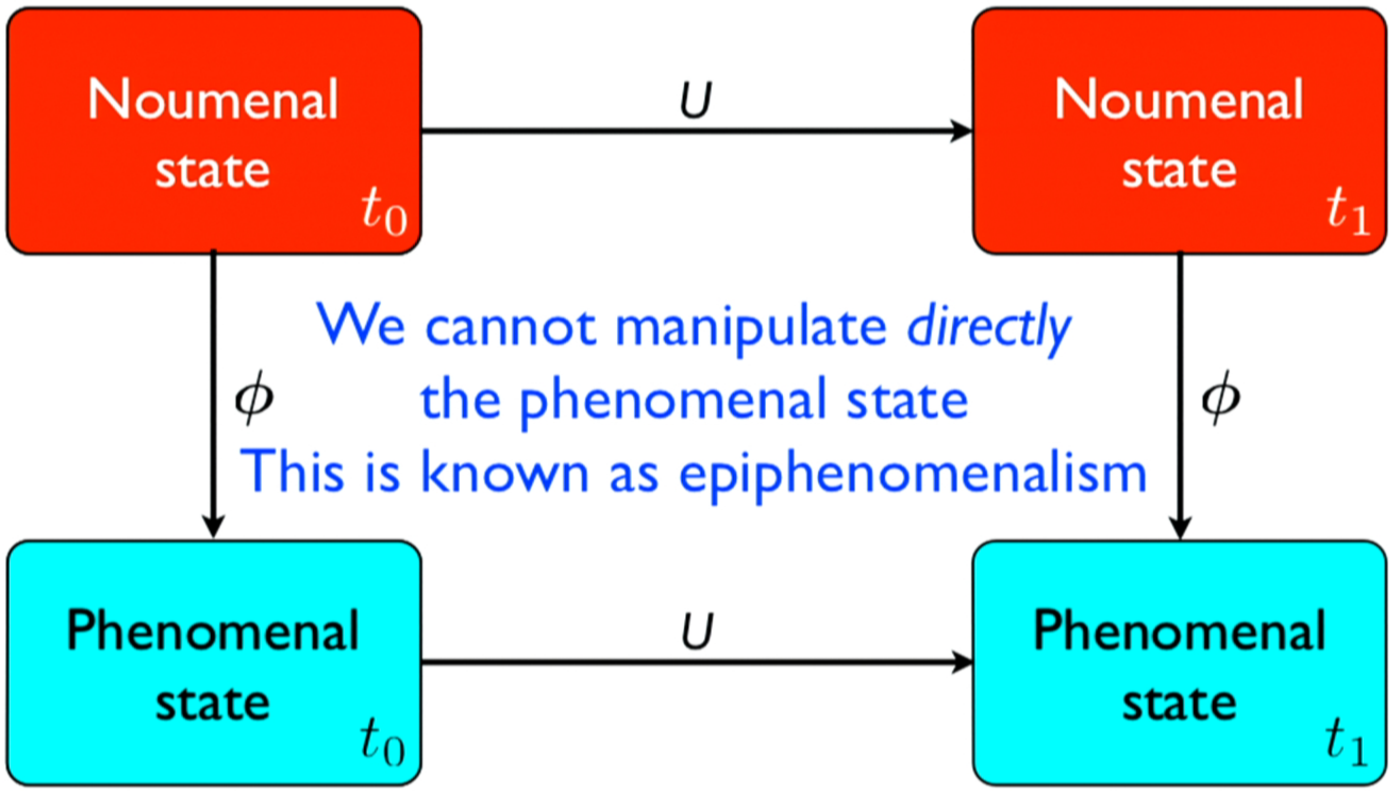

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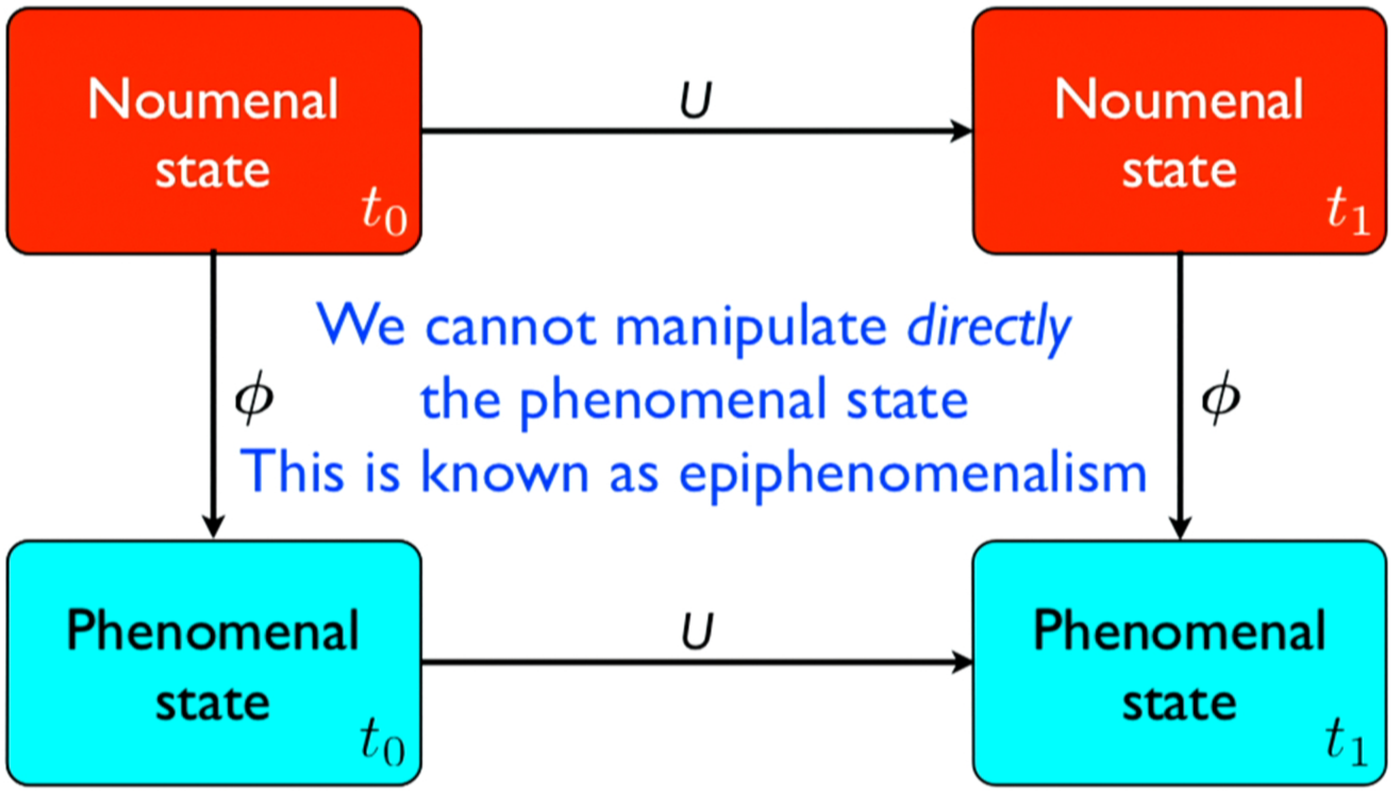

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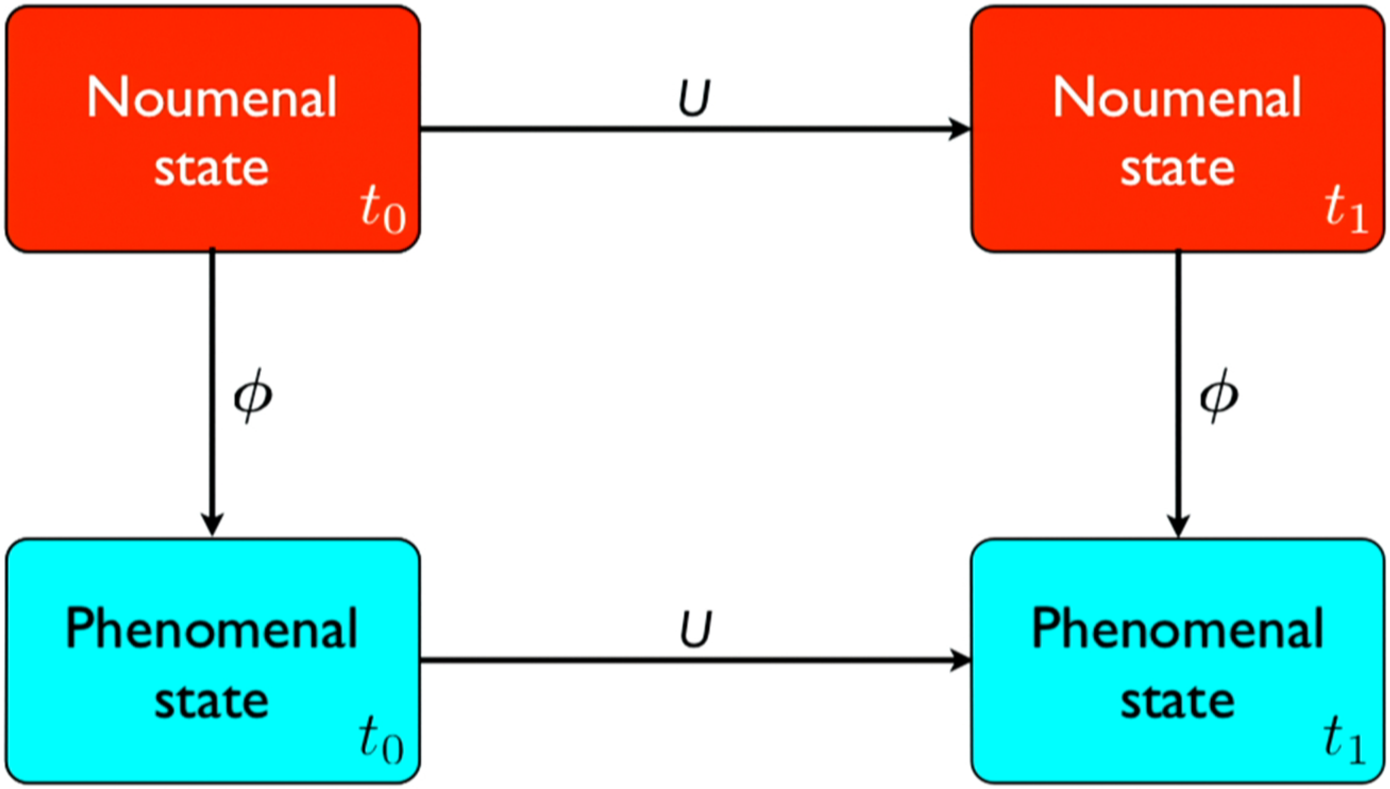
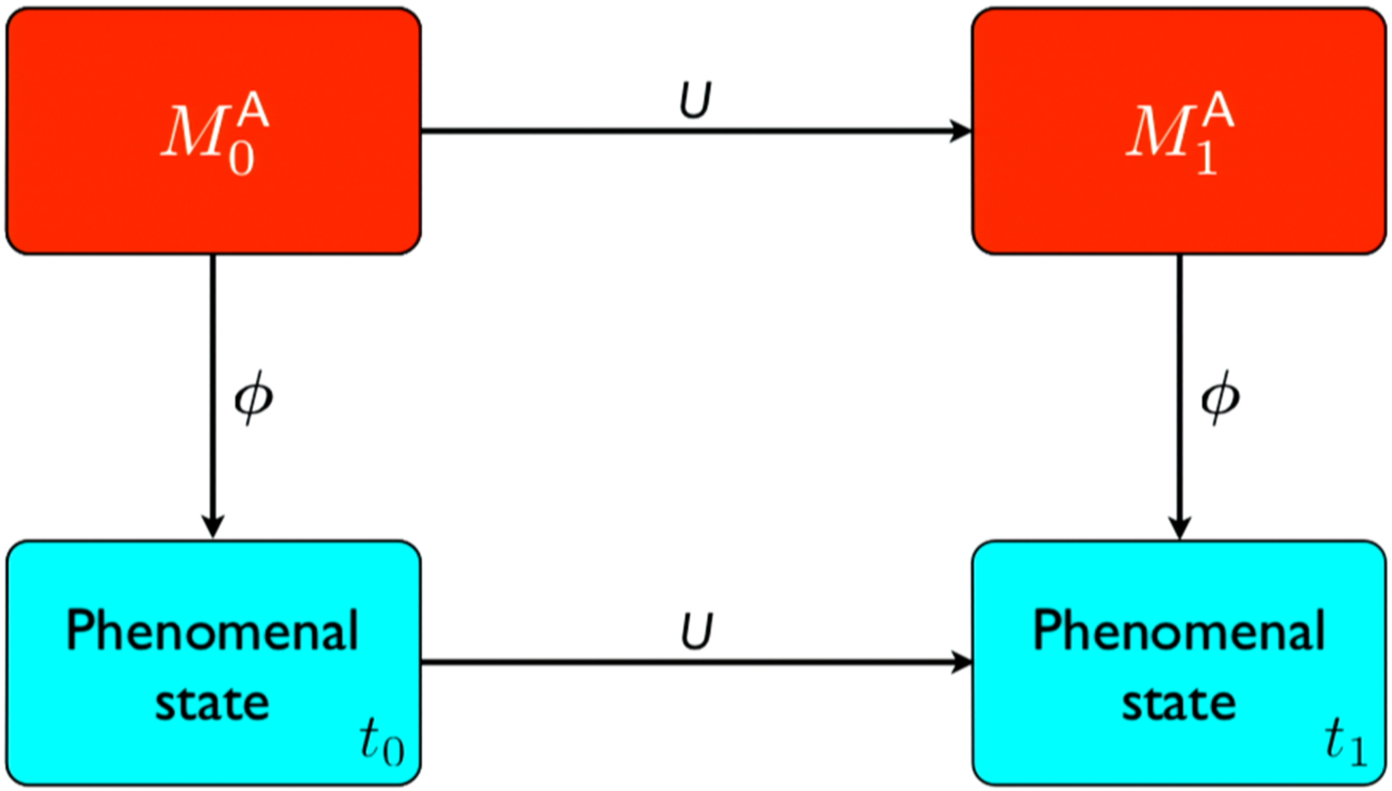
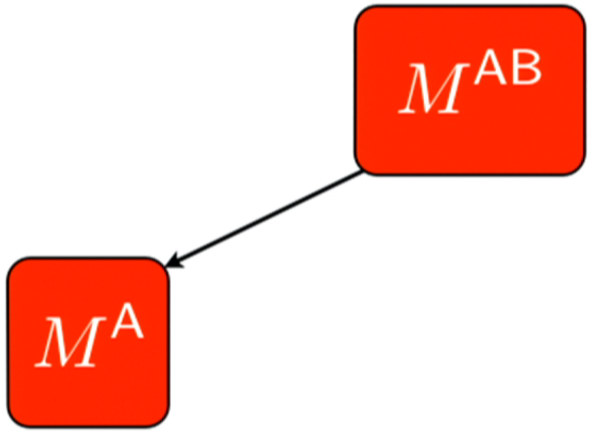


This diagram commutes

Evolution of a System A



Splitting of a System



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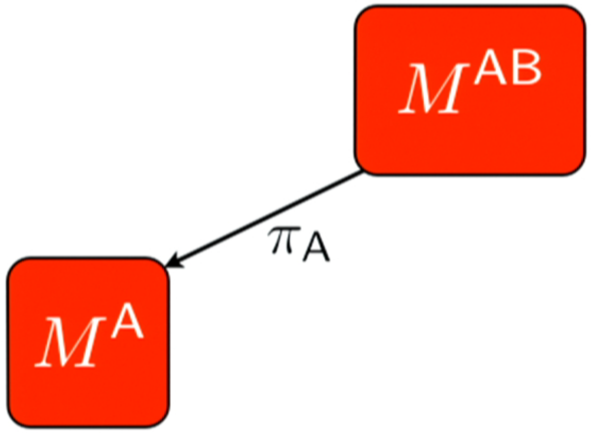

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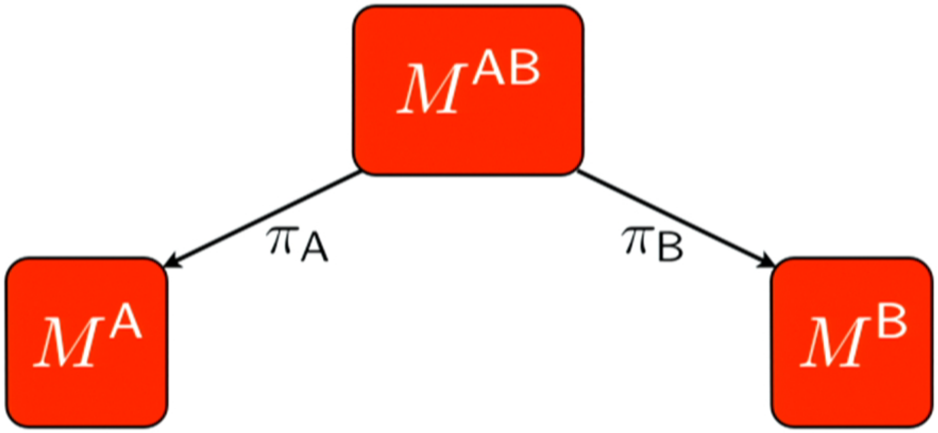

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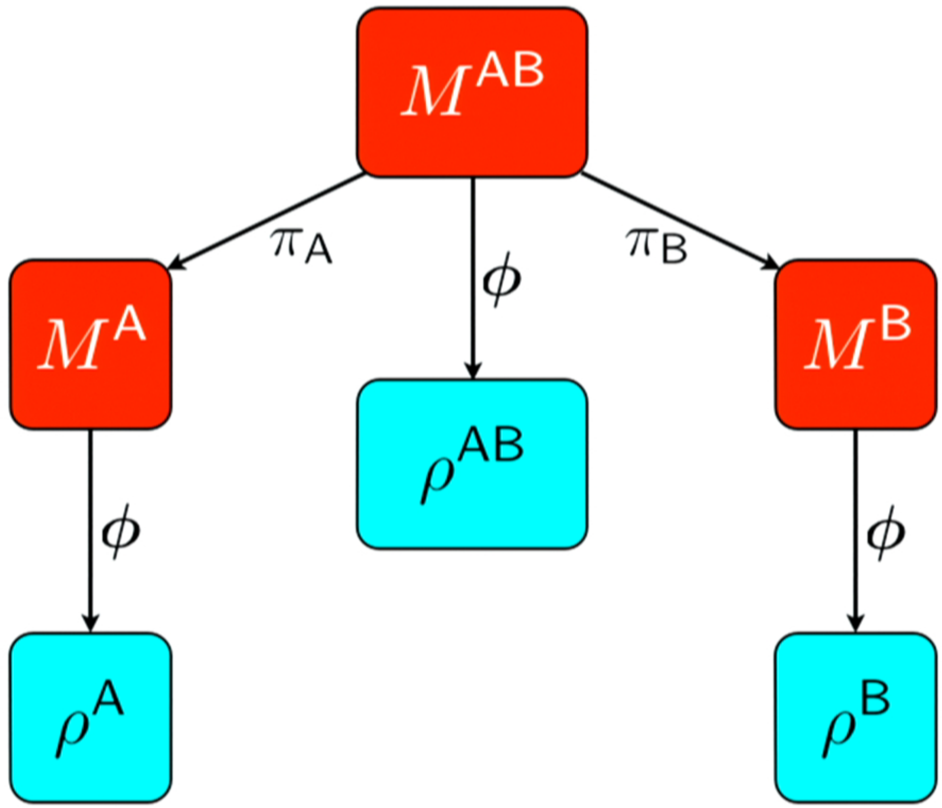

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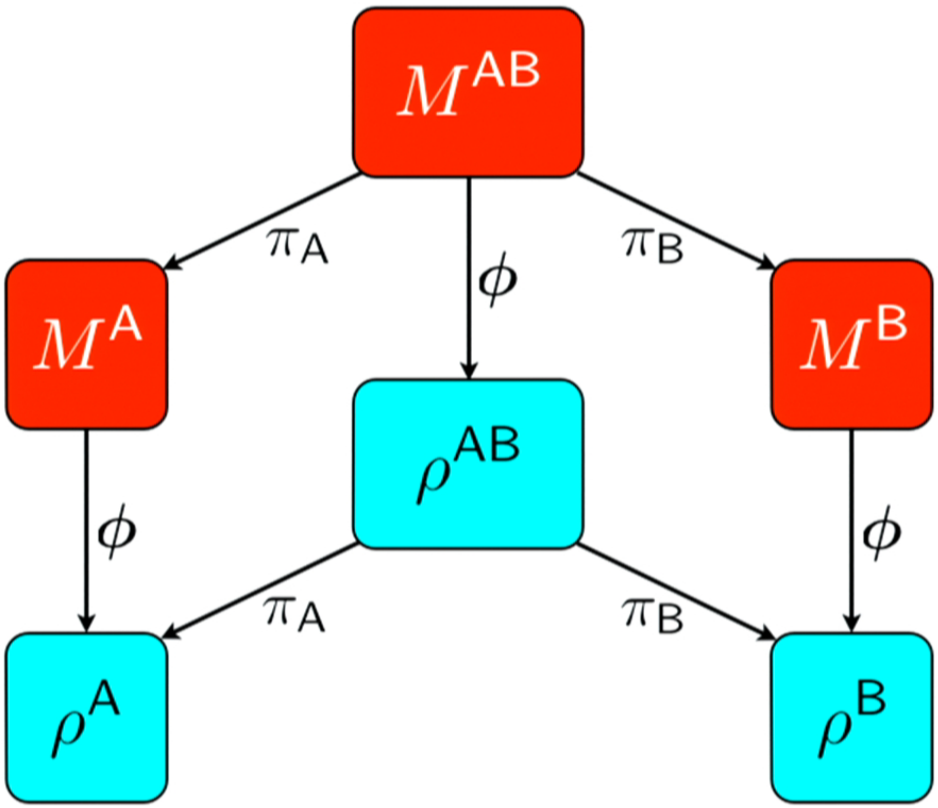

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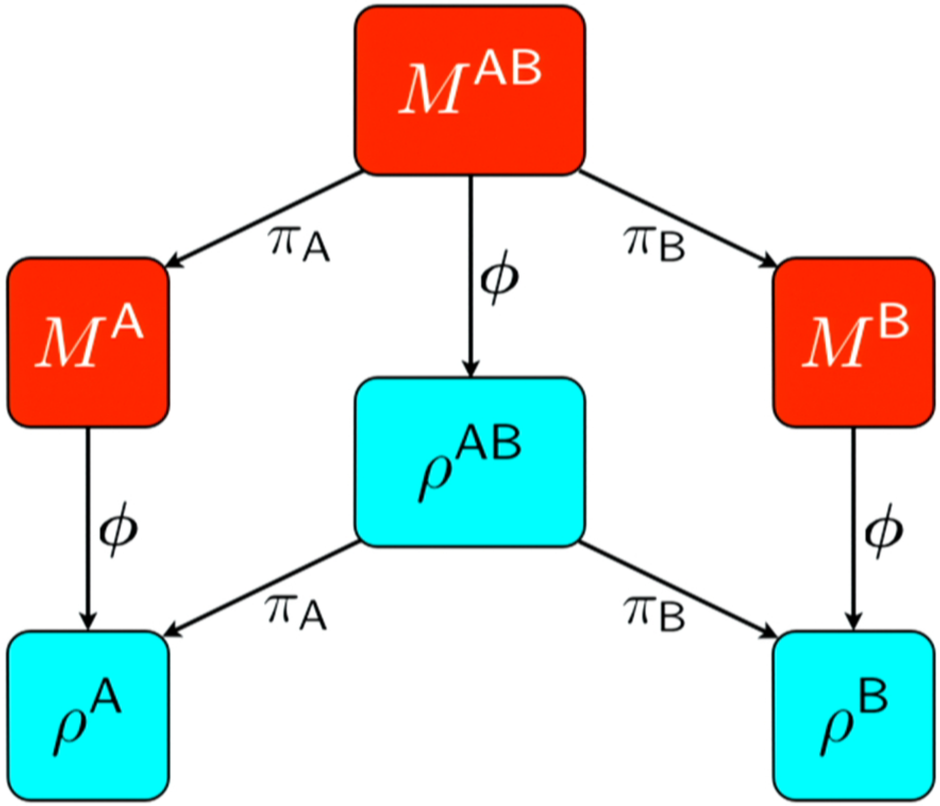

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Two Theorems

1) Local-realistic theories are non-signalling

2) Non-signalling theories
   can be *made* local-realistic
   with the proper choice of noumenal states

This includes quantum mechanics

as well as Popescu-Rohrlich nonlocal boxes

Foundations of Physics, Vol. 24, No. 3, 1994

Quantum Nonlocality as an Axiom

Sandu Popescu[1] and Daniel Rohrlich[2]

Received July 2, 1993; revised July 19, 1993

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REVIEW ARTICLES | INSIGHT

PUBLISHED ONLINE: 1 APRIL 2014 | DOI: 10.1038/NPHYS2916

nature physics

Nonlocality beyond quantum mechanics

Sandu Popescu

Nonlocality is the most characteristic feature of quantum mechanics, but recent research seems to suggest the possible existence of nonlocal correlations stronger than those predicted by theory. This raises the question of whether nature is in fact more nonlocal than expected from quantum theory or, alternatively, whether there could be an as yet undiscovered principle limiting the strength of nonlocal correlations. Here, I review some of the recent directions in the intensive theoretical effort to answer this question.

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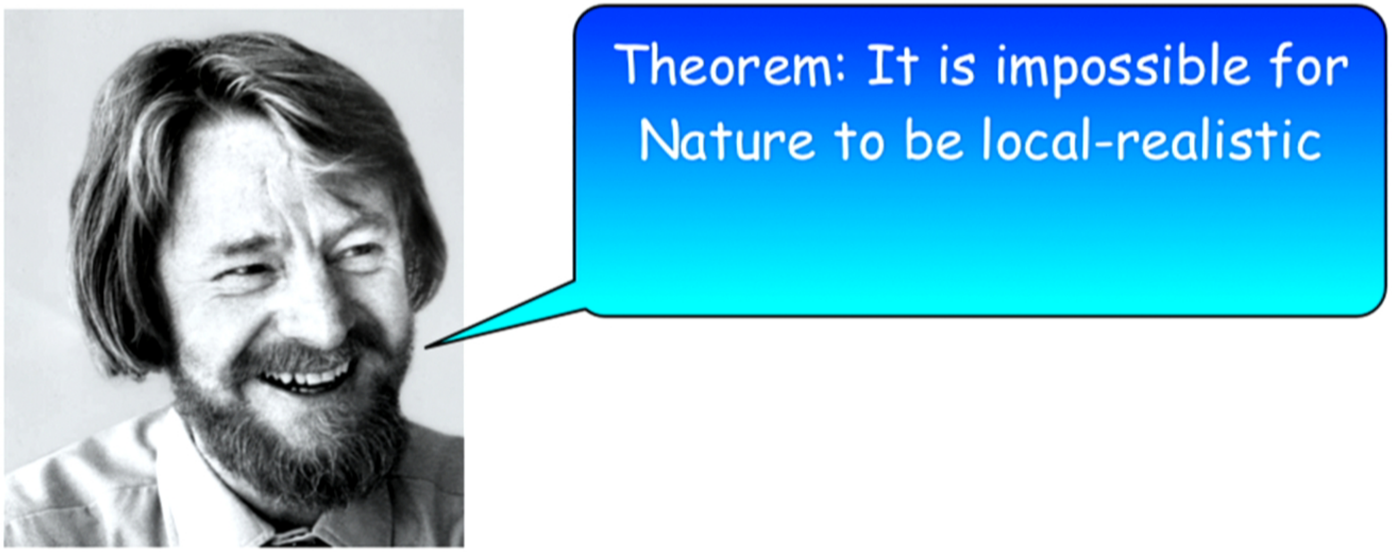
* There are technical caveats



Theorem: It is impossible for Nature to be local-realistic

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According to *Nouvelle Cuisine* (1990)
not his original 1964 paper

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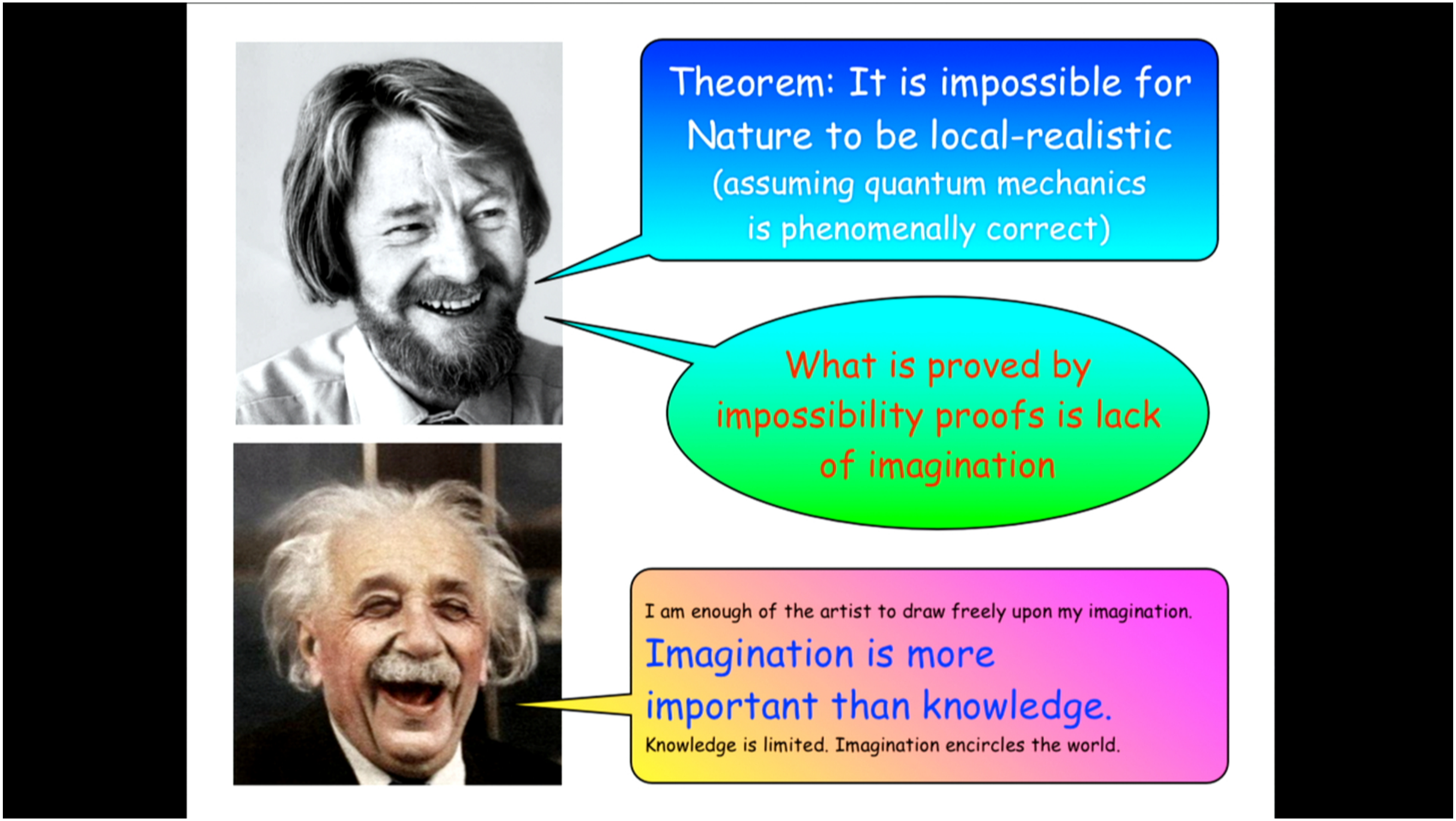
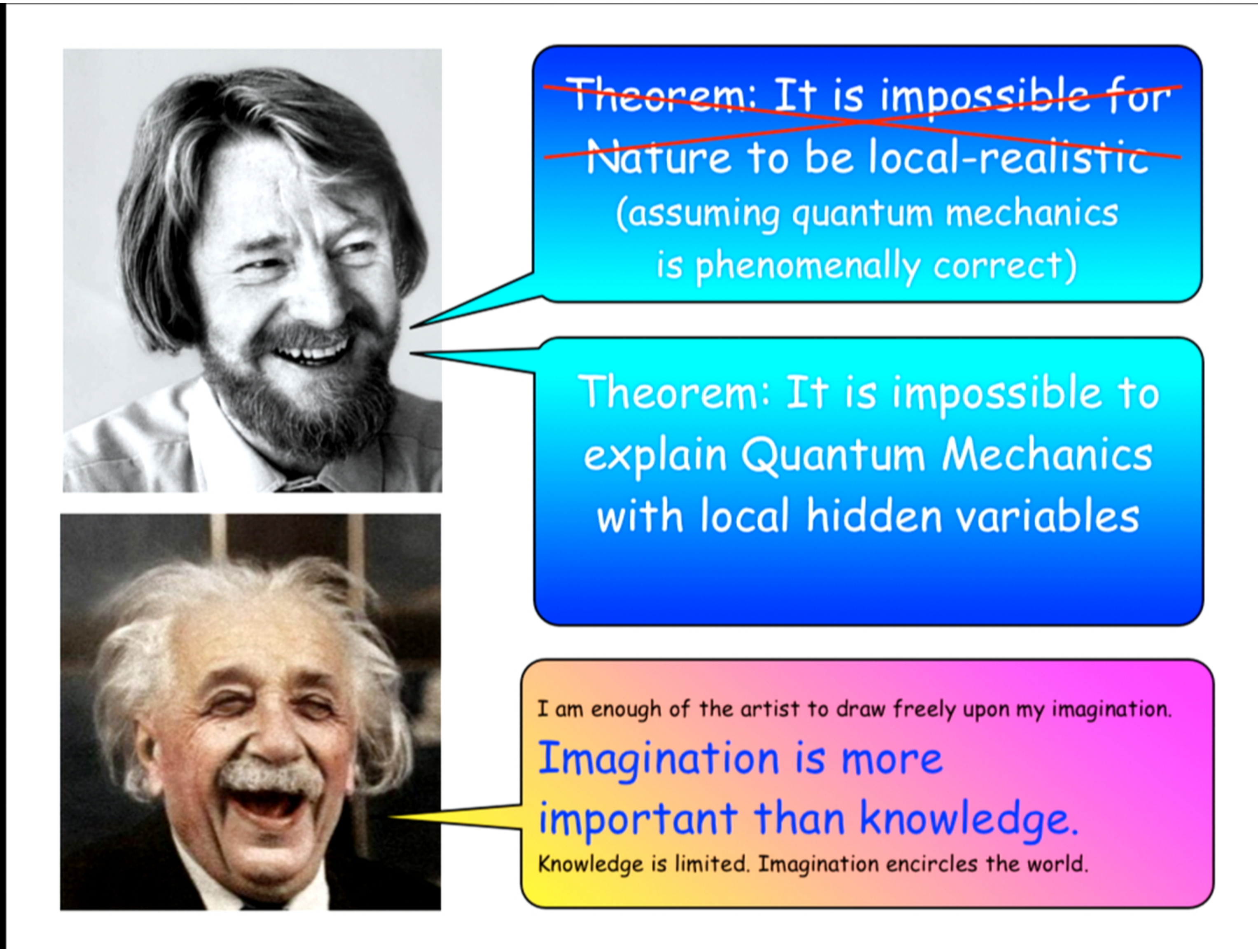
What is proved by impossibility proofs is lack of imagination


Theorem: It is impossible for Nature to be local-realistic (assuming quantum mechanics is phenomenally correct)
What is proved by impossibility proofs is lack of imagination
I am enough of the artist to draw freely upon my imagination.
Imagination is more important than knowledge.
Knowledge is limited. Imagination encircles the world.


~~Theorem: It is impossible for Nature to be local-realistic~~
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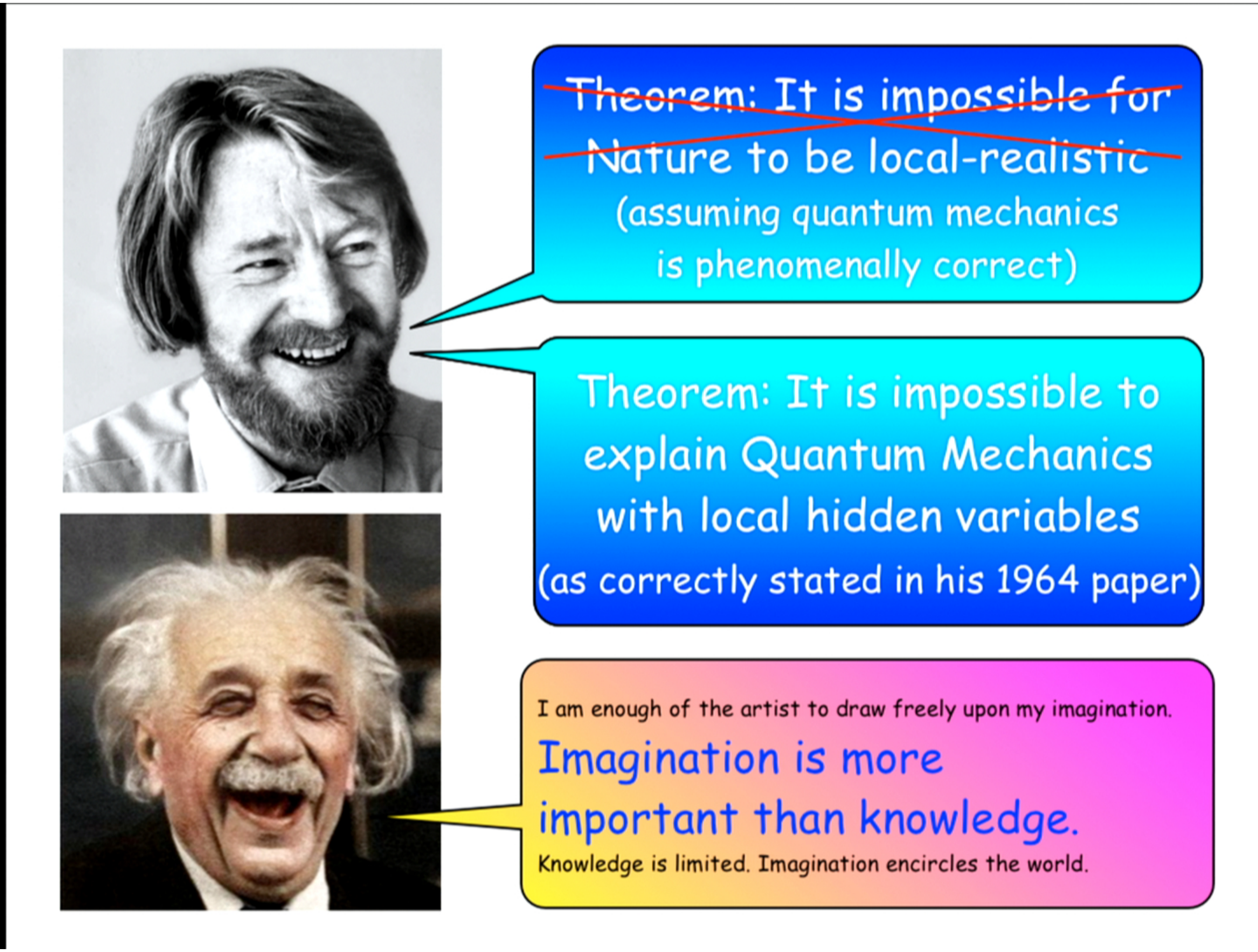

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(as correctly stated in his 1964 paper)
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Another Local-Realistic Way?

One that requires just a little more imagination!

Two keys towards a solution:

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Two keys towards a solution:

1) Tests of Bell inequality are not complete until Alice's and Bob's data are compared.

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This cannot be faster than the speed of light!

2) Measurement outcomes never have to become fixed and definite:
All possible results can occur simultaneously!

Popescu-Rohrlich Boxes

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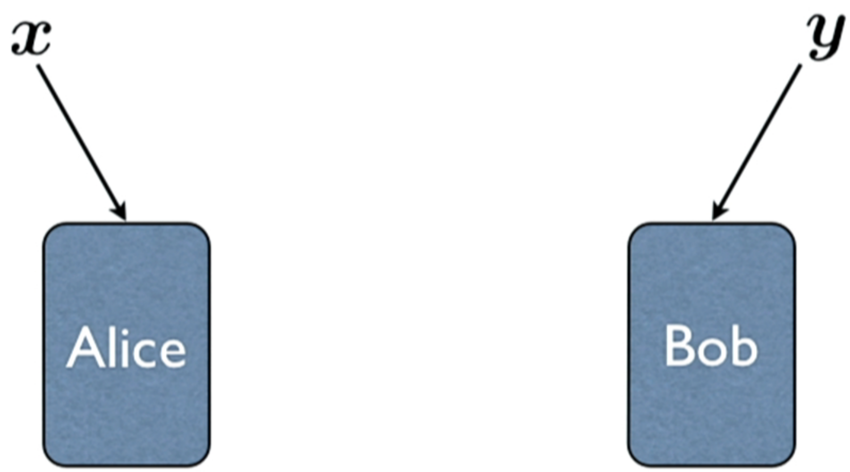

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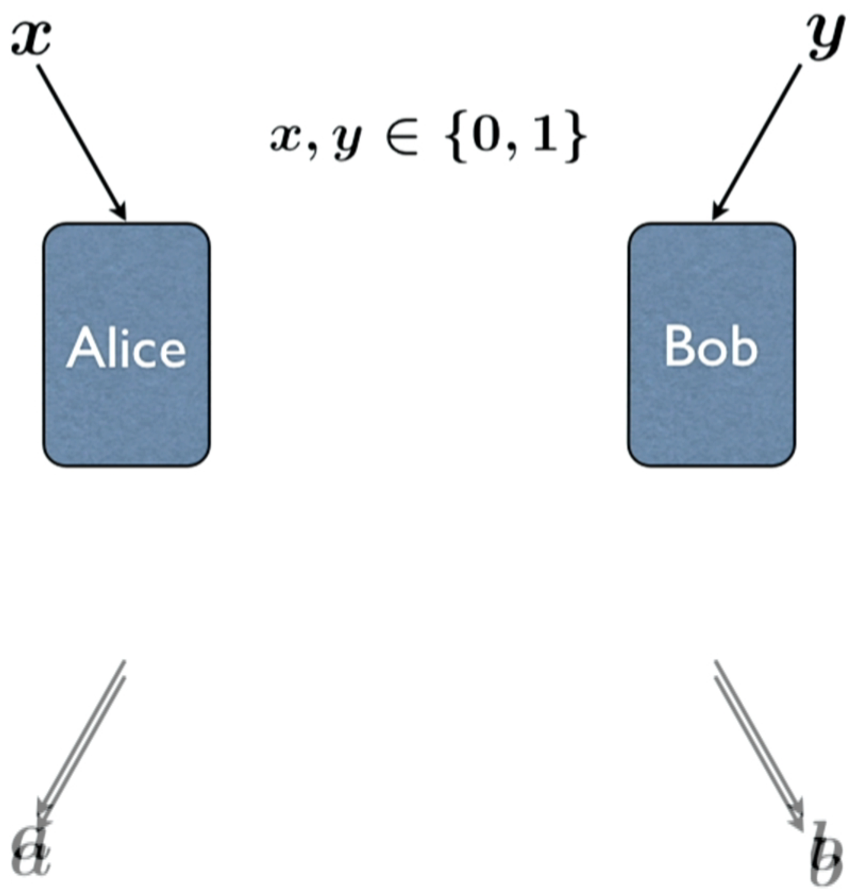

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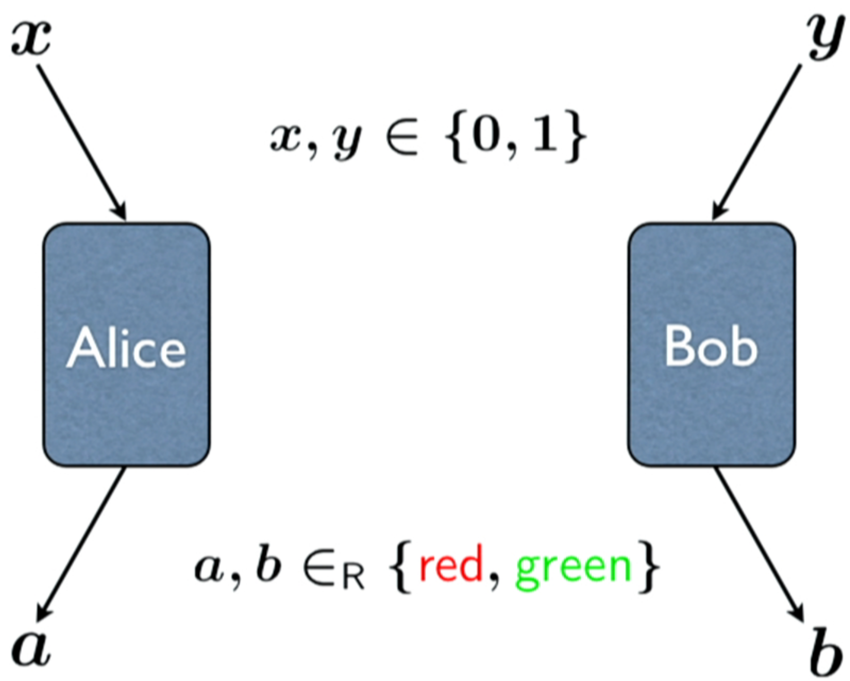

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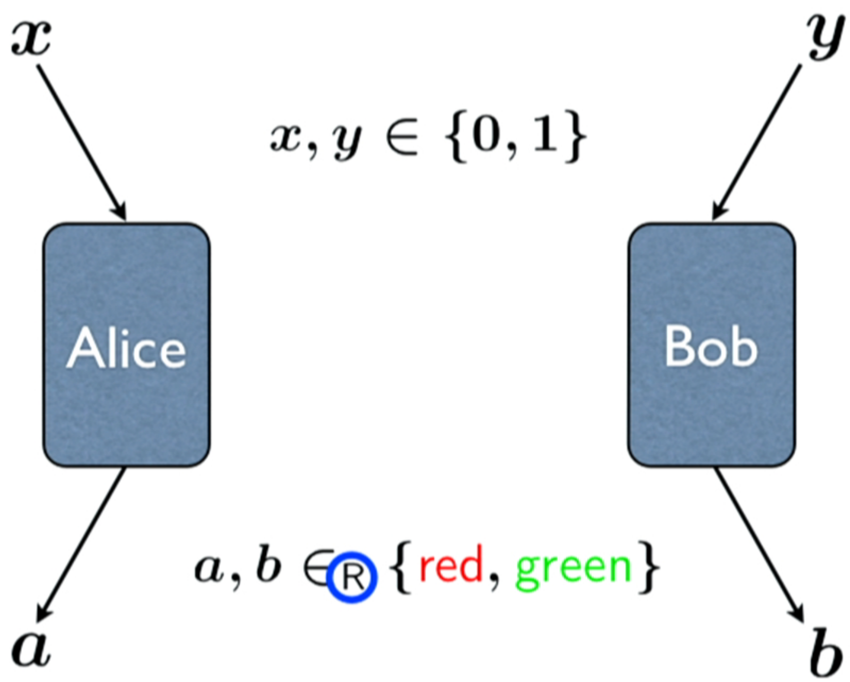

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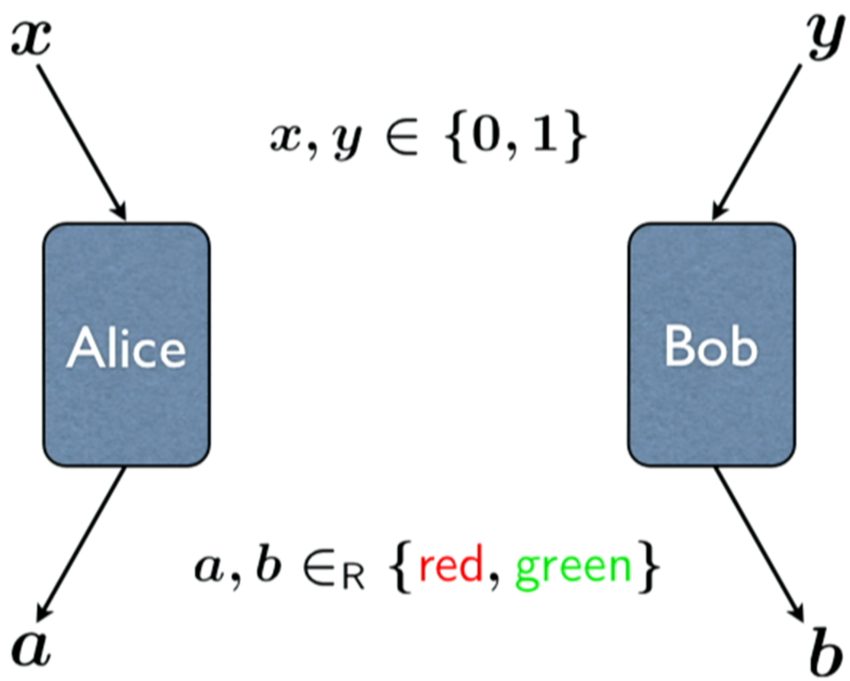
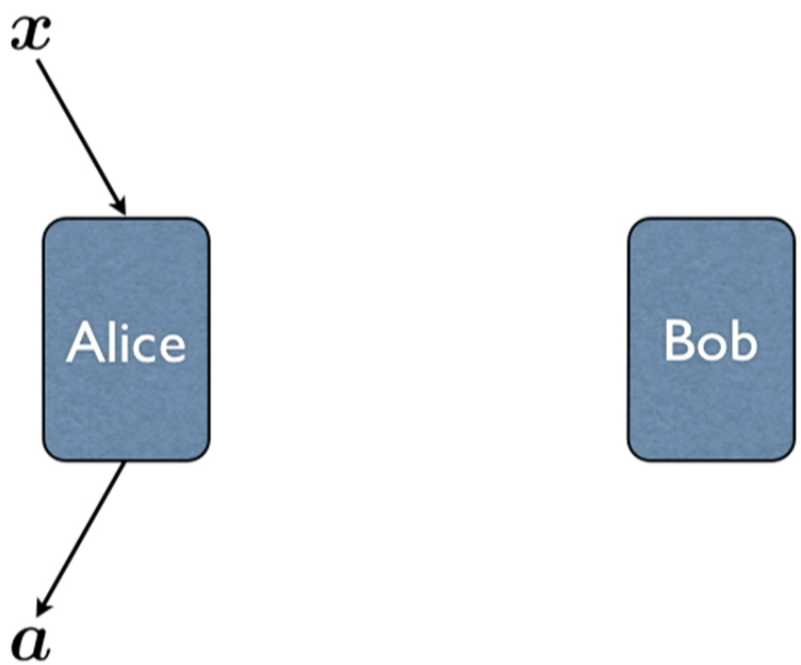


$$a \neq b \Leftrightarrow x = y = 1$$

PR Boxes are Atemporal



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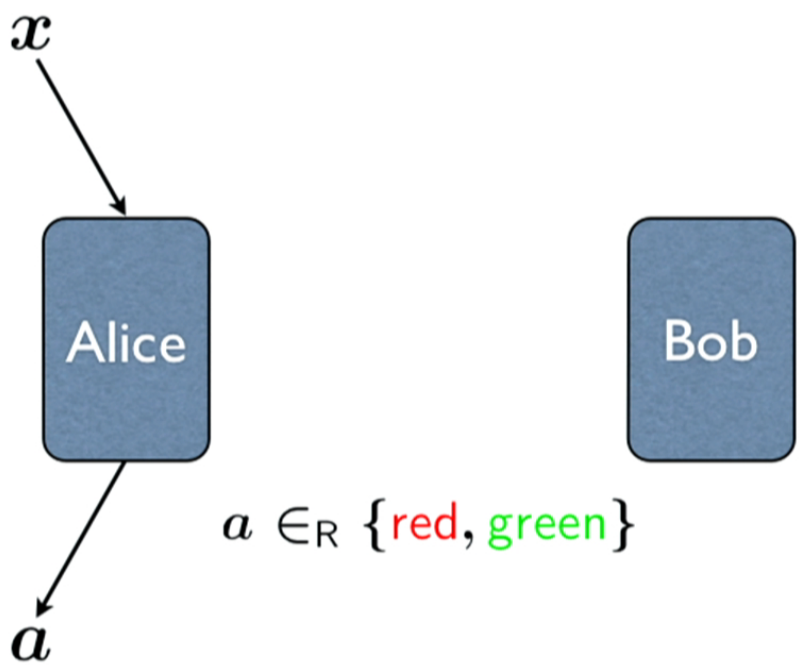
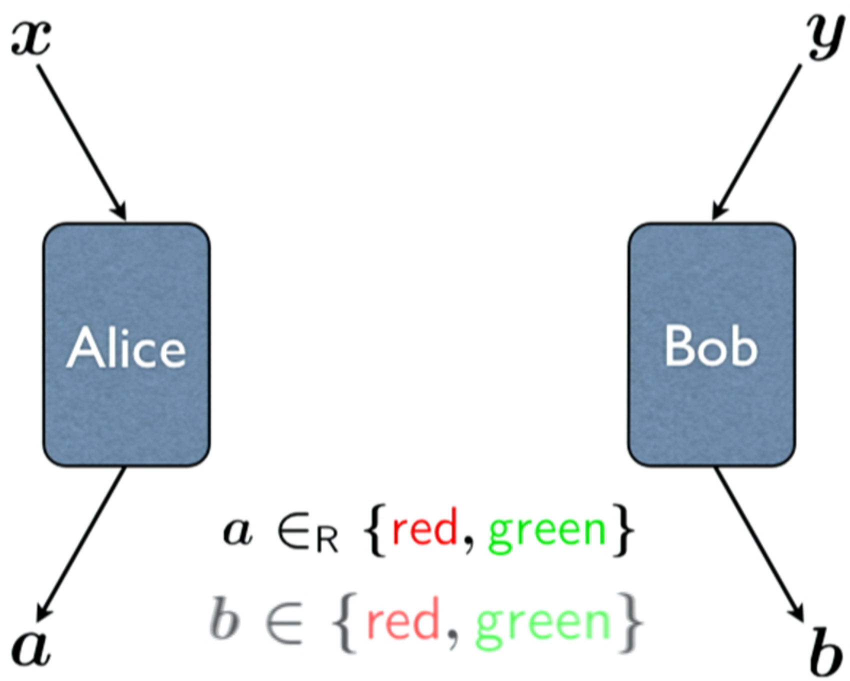


$a \in_R \{\text{red}, \text{green}\}$

PR Boxes are Atemporal



$a \in_R \{\text{red}, \text{green}\}$

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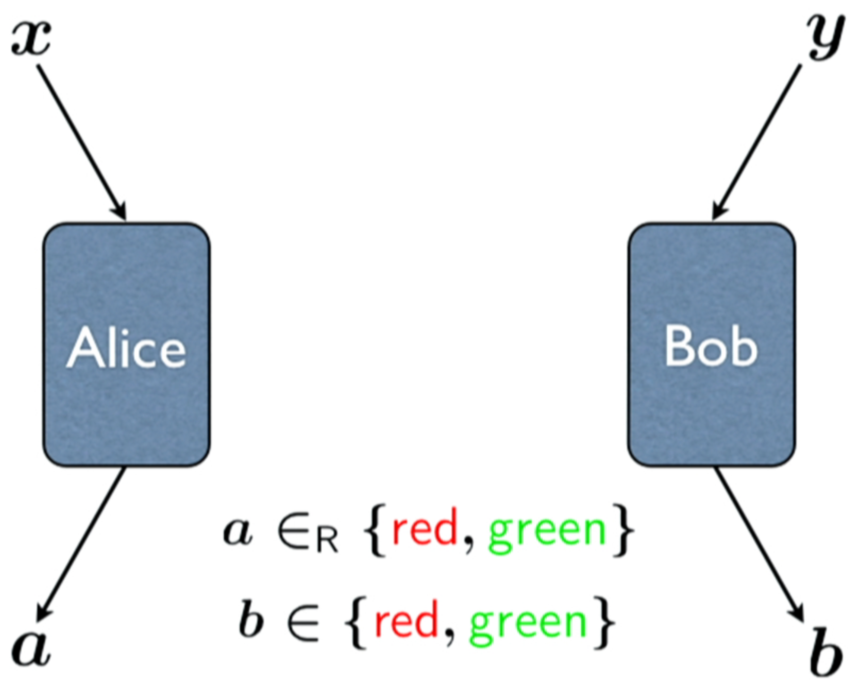

$$a \in_{\mathsf{R}} \{\text{red}, \text{green}\}$$

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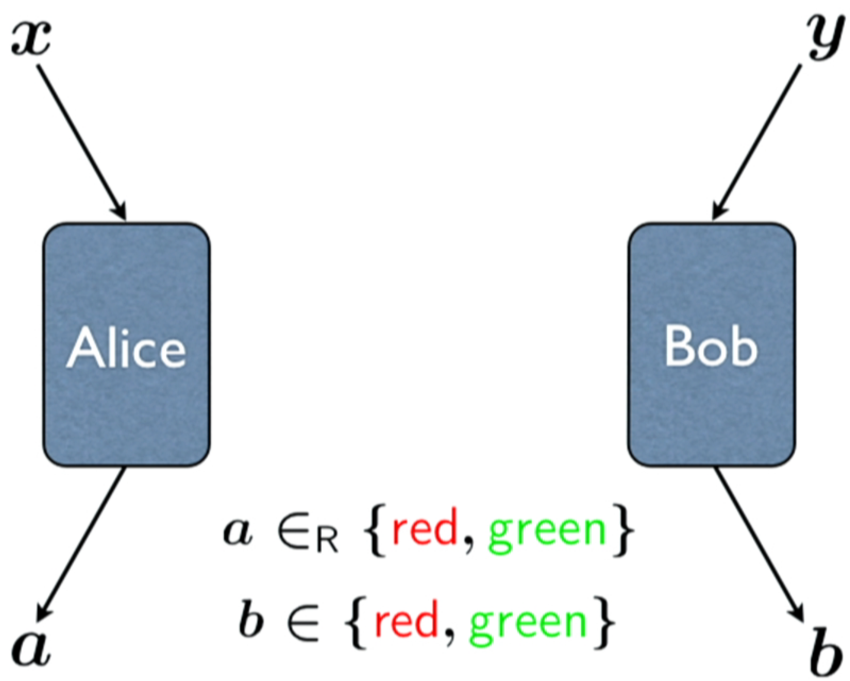

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* Can be simulated classically with probability 75% at best

Popescu-Rohrlich Boxes

* Cannot be used to communicate: They are causal and atemporal

* Can be simulated classically with probability 75% at best

* Can be simulated quantumly with probability $\cos^2 \frac{\pi}{8} \approx 85\%$ at best

Popescu-Rohrlich Boxes

* Violate CHSH Bell inequality more than Quantum Mechanics

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* Yet, they can be "implemented" in a local realistic toy universe

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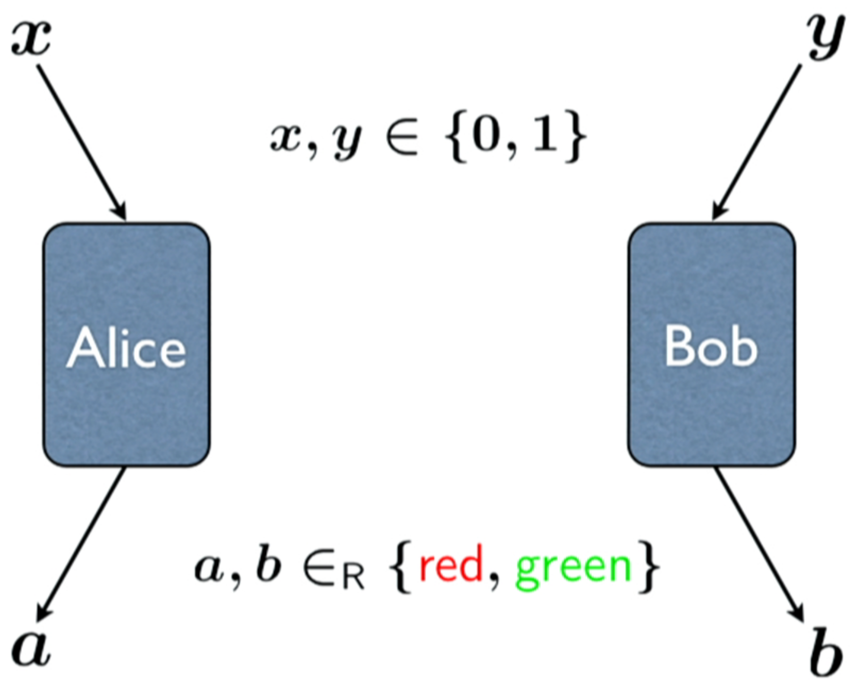
Popescu-Rohrlich Boxes

* Violate CHSH Bell inequality more than Quantum Mechanics

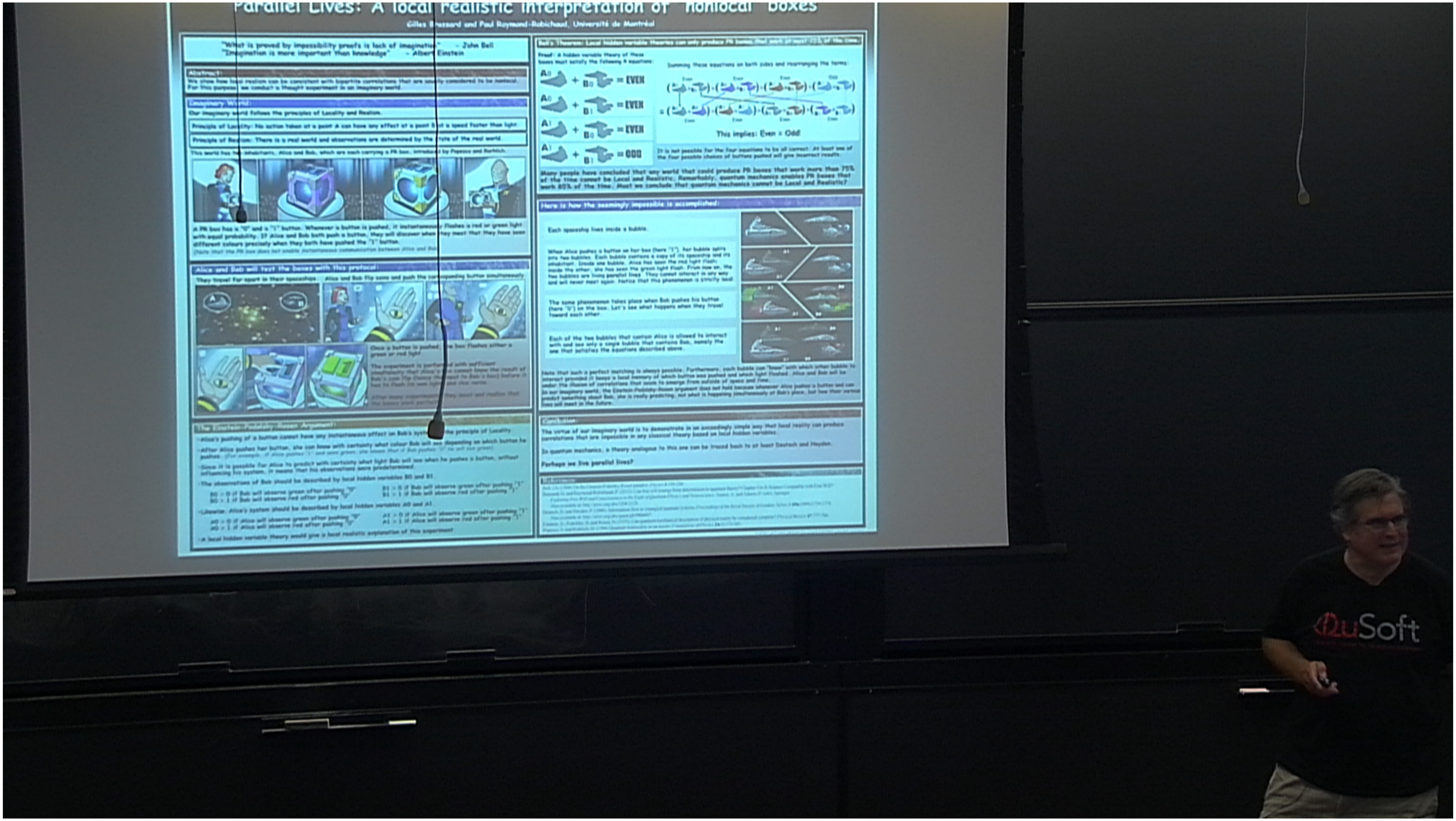
* Yet, they can be "implemented" in a local realistic toy universe

* Hence a violation of Bell inequalities is NOT a proof of nonlocality!
  This applies to Quantum Mechanics!

Popescu-Rohrlich Boxes



$$a \neq b \Leftrightarrow x = y = 1$$


Parallel Lives: A local realistic interpretation of "nonlocal" boxes
Gilles Brassard and Paul Raymond-Robichaud, Université de Montréal
"Imagination is more important than knowledge" - Albert Einstein
This implies: Even = Odd
QuSoft

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"What is proved by impossibility proofs is lack of imagination" - John Bell
"Imagination is more important than knowledge" - Albert Einstein

Abstract:

We show how local realism can be consistent with bipartite correlations that are usually considered to be nonlocal. For this purpose, we conduct a thought experiment in an imaginary world.

Imaginary World:

Our imaginary world follows the principles of Locality and Realism.

Principle of Locality: No action taken at a point A can have any effect at a point B at a speed faster than light.

Principle of Realism: There is a real world and observations are determined by the state of the real world.

This world has two inhabitants, *Alice* and *Bob*, which are each carrying a PR box, introduced by Popescu and Rorhlich.

A PR box has a "0" and a "1" button. Whenever a button is pushed, it instantaneously flashes a red or green light with equal probability. If Alice and Bob both push a button, they will discover when they meet that they have seen different colours precisely when they both have pushed the "1" button.

(Note that the PR box does not enable instantaneous communication between Alice and Bob)

Alice and Bob will test the boxes with this protocol:

They travel far apart in their spaceships. Alice and Bob flip coins and push the corresponding button simultaneously.

Once a button is pushed, the box flashes either a green or red light.

The experiment is performed with sufficient simultaneity that Alice's box cannot know the result of Bob's coin flip (hence the input to Bob's box) before it has to flash its own light, and vice versa.

After many experiments, they meet and realize that the boxes work perfectly.

The Einstein-Podolsky-Rosen Argument:

- Alice's pushing of a button cannot have any instantaneous effect on Bob's system by the principle of Locality.
- After Alice pushes her button, she can know with certainty what colour Bob will see depending on which button he pushes. *(For example, if Alice pushes "1" and sees green, she knows that if Bob pushes "0" he will see green)*
- Since it is possible for Alice to predict with certainty what light Bob will see when he pushes a button, without influencing his system, it means that his observations were predetermined.
- The observations of Bob should be described by local hidden variables B0 and B1.

  B0 = 0 if Bob will observe green after pushing "0"
  B0 = 1 if Bob will observe red after pushing "0"
  B1 = 0 if Bob will observe green after pushing "1"
  B1 = 1 if Bob will observe red after pushing "1"

- Likewise, Alice's system should be described by local hidden variables A0 and A1.

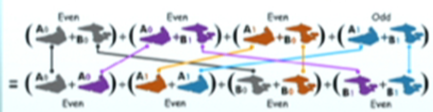
  A0 = 0 if Alice will observe green after pushing "0"
  A0 = 1 if Alice will observe red after pushing "0"
  A1 = 0 if Alice will observe green after pushing "1"
  A1 = 1 if Alice will observe red after pushing "1"

- A local hidden variable theory would give a local realistic explanation of this experiment.

Bell's Theorem: Local hidden variable theories can only produce PR boxes that work at most 75% of the time.

Proof: A hidden variable theory of these boxes must satisfy the following 4 equations:

Summing these equations on both sides and rearranging the terms:



This implies: Even = Odd!

It is not possible for the four equations to be all correct. At least one of the four possible choices of buttons pushed will give incorrect results.

Many people have concluded that any world that could produce PR boxes that work more than 75% of the time cannot be Local and Realistic. Remarkably, quantum mechanics enables PR boxes that work 85% of the time. Must we conclude that quantum mechanics cannot be Local and Realistic?

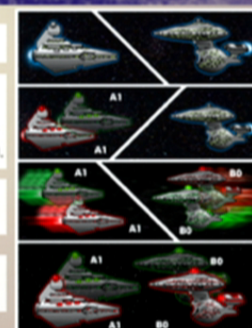
Here is how the seemingly impossible is accomplished:

Each spaceship lives inside a bubble.

When Alice pushes a button on her box (here "1"), her bubble splits into two bubbles. Each bubble contains a copy of its spaceship and its inhabitant. Inside one bubble, Alice has seen the red light flash; inside the other, she has seen the green light flash. From now on, the two bubbles are living parallel lives. They cannot interact in any way and will never meet again. Notice that this phenomenon is strictly local.

The same phenomenon takes place when Bob pushes his button (here "0") on the box. Let's see what happens when they travel toward each other.

Each of the two bubbles that contain Alice is allowed to interact with and see only a single bubble that contains Bob, namely the one that satisfies the equations described above.



Note that such a perfect matching is always possible. Furthermore, each bubble can "know" with which other bubble to interact provided it keeps a local memory of which button was pushed and which light flashed. Alice and Bob will be under the illusion of correlations that seem to emerge from outside of space and time.

In our imaginary world, the Einstein-Podolsky-Rosen argument does not hold because whenever Alice pushes a button and can predict something about Bob, she is really predicting, not what is happening simultaneously at Bob's place, but how their various lives will meet in the future.

Conclusion:

The virtue of our imaginary world is to demonstrate in an exceedingly simple way that local reality can produce correlations that are impossible in any classical theory based on local hidden variables.

In quantum mechanics, a theory analogous to this one can be traced back to at least Deutsch and Hayden.

Perhaps we live parallel lives?

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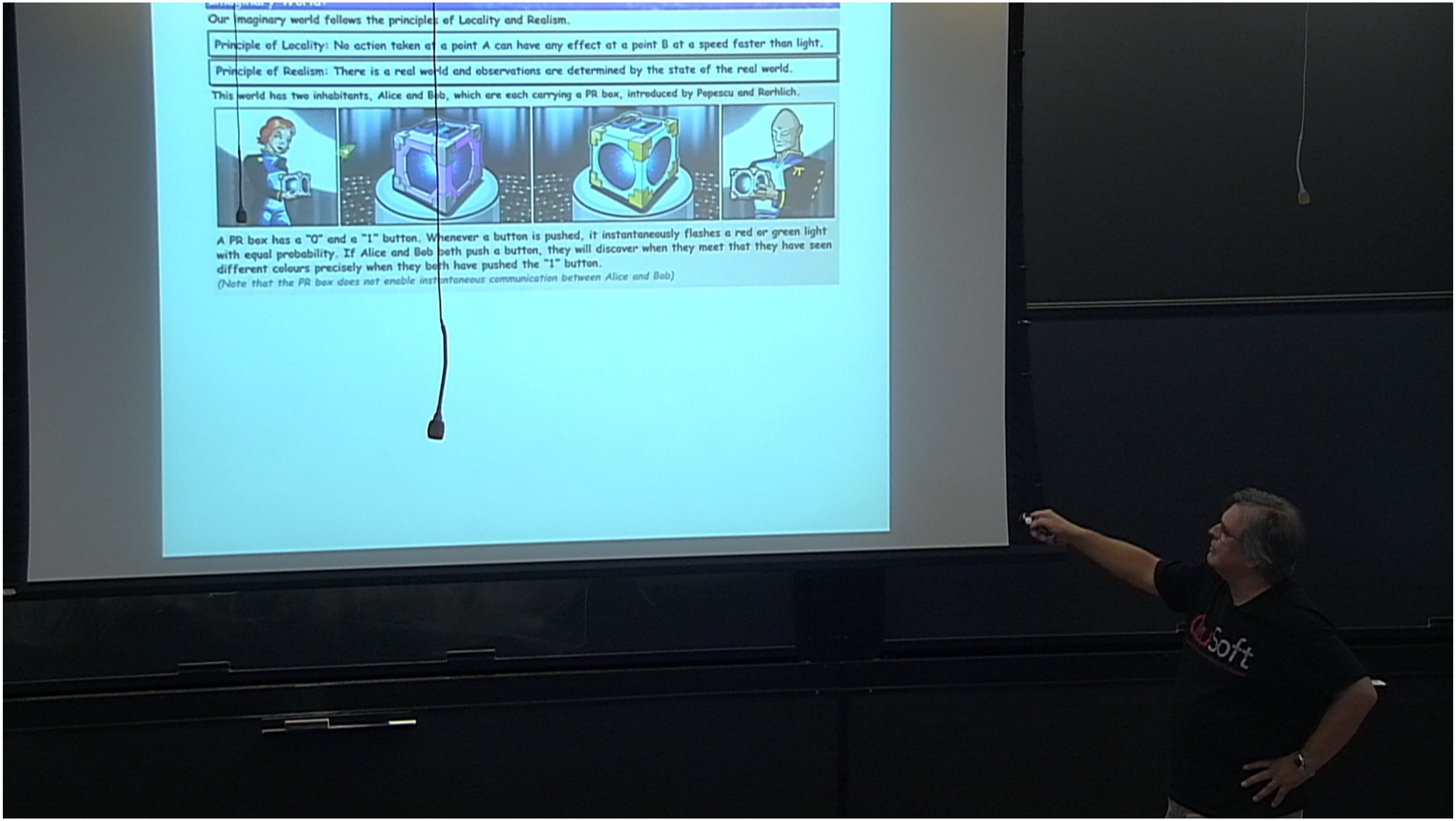
Poster art and design by Louis Fernet-Leclair (2012)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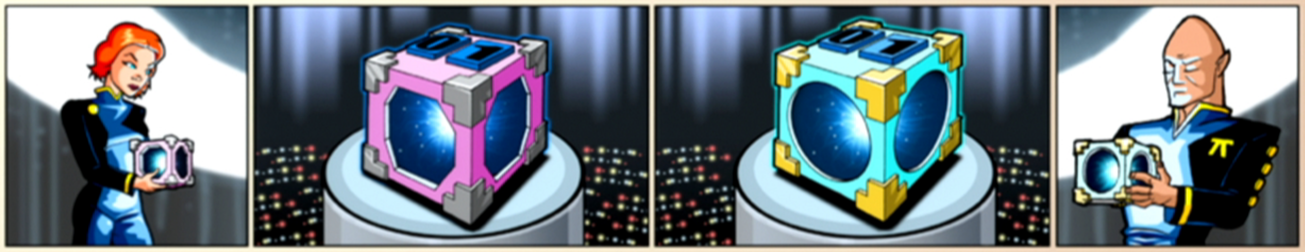

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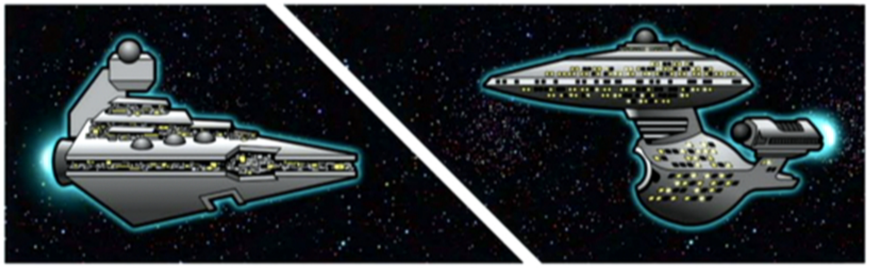

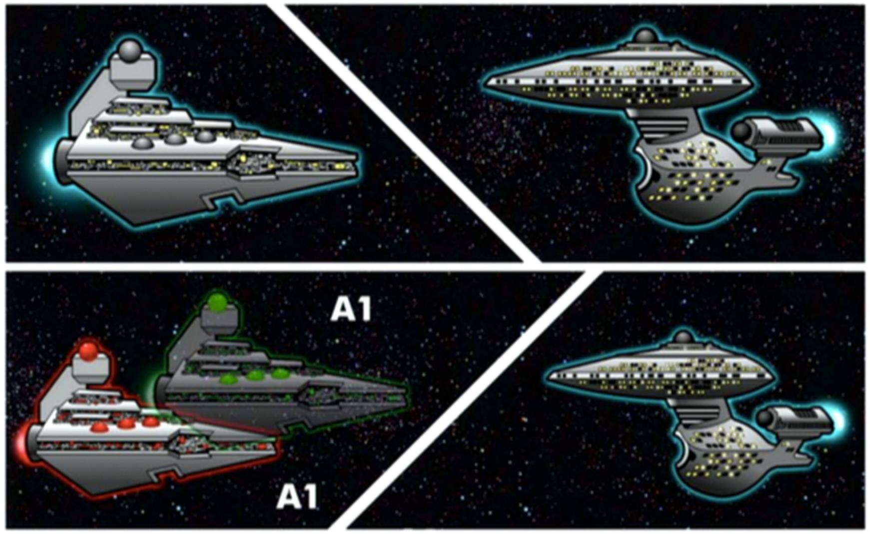
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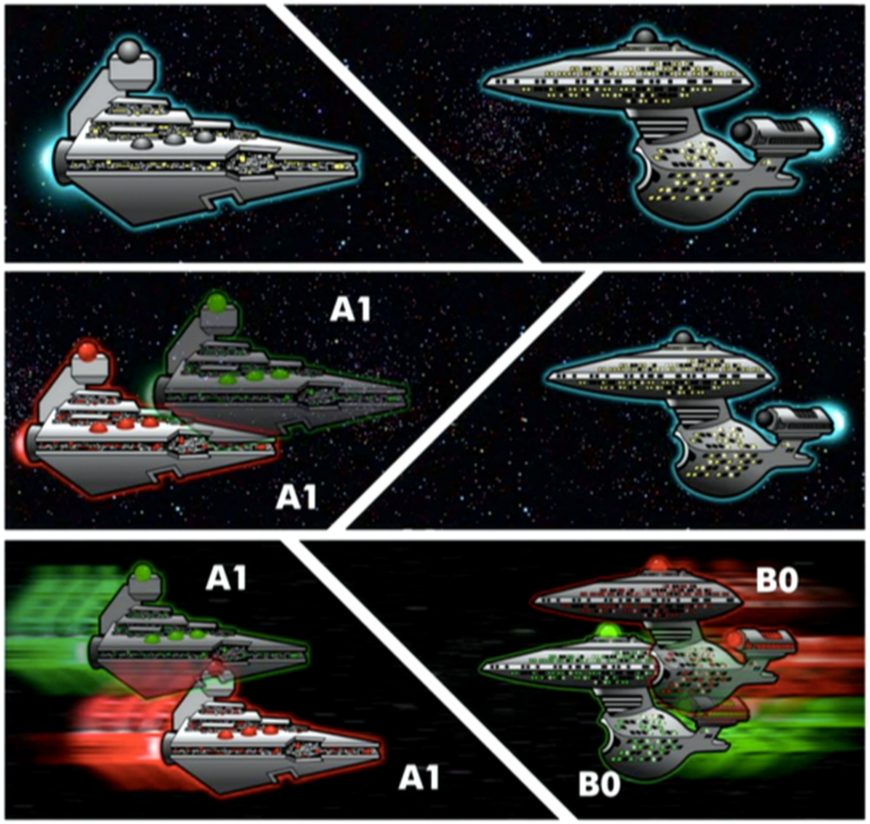
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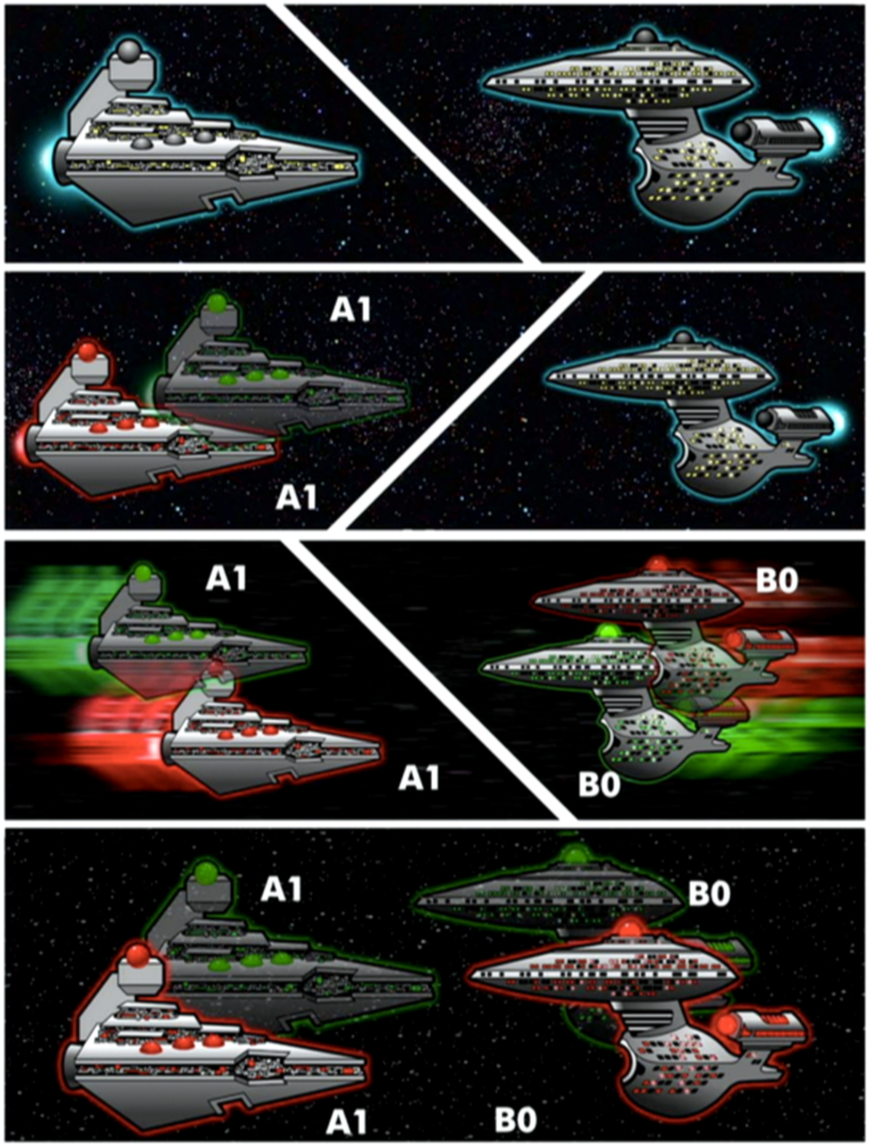
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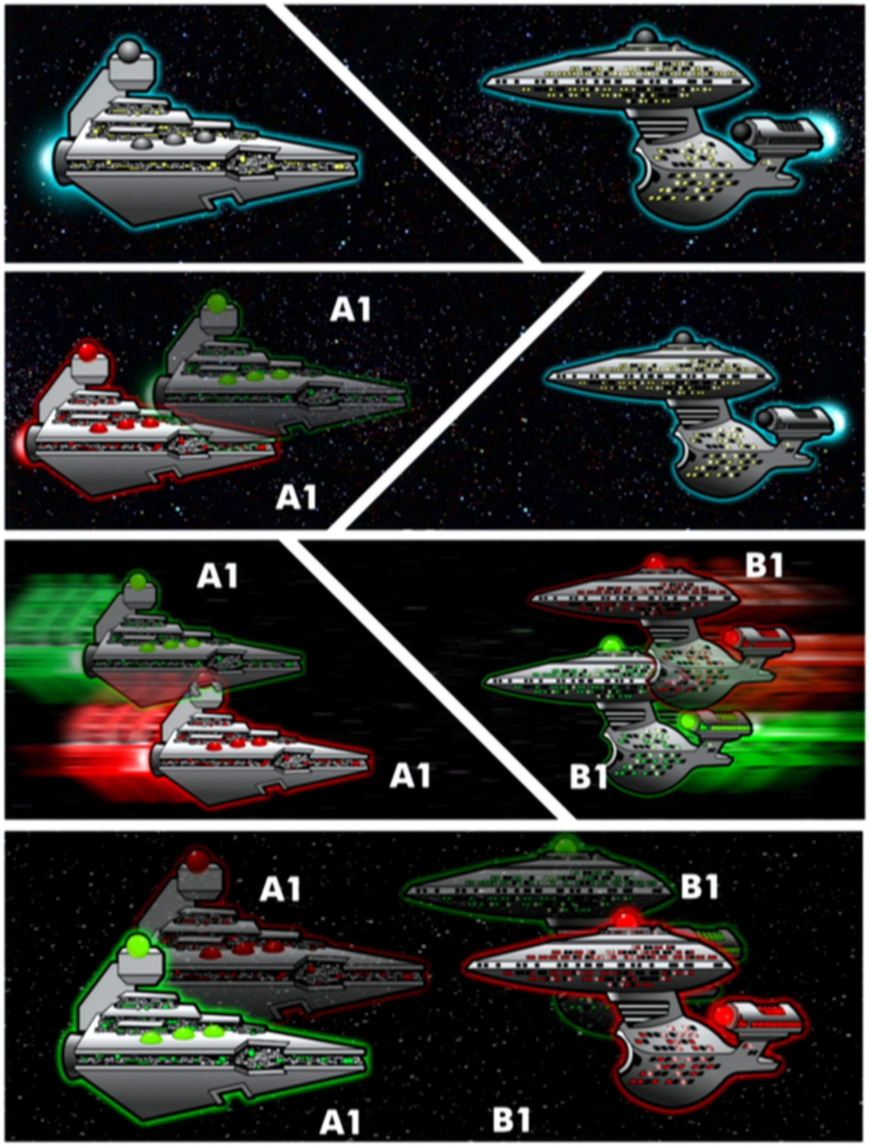
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In our imaginary world, the EPR argument does not hold because whenever Alice pushes a button and can predict something about Bob, she is really predicting not what is happening simultaneously at Bob's place but how their various lives will meet in the future.

This proves that

it is wrong to claim that

any world that violates
Bell inequalities
has to be nonlocal

How about Quantum Mechanics?

States

For a system A associated with a Hilbert Space of dimension n, its noumenal state M^A is formally defined by an *evolution matrix* $[W]^A$, which is an $n \times n$ matrix whose entries are matrices:

$$[W]^A_{i,j} \stackrel{\text{def}}{=} W^\dagger \left(|j\rangle\langle i| \otimes I^{\overline{A}} \right) W$$

for some unitary W on the global state, which corresponds to all that happened to the universe since the beginning of time.

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If we have a system A in state $\left[W\right]^A$ on which we apply a unitary operation U, the system evolves to

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Theorem

$$U\left[W\right]^A = \left[\left(U \otimes V\right) W\right]^A$$

for any unitary V acting on $\overline{A}$

Local Evolution

Proof

$$\left(U\left[W\right]^{A}\right)_{i,j} = \sum_{m,n} U_{i,m}[W]^{A}_{m,n}U^{\dagger}_{n,j}$$

$$= \sum_{m,n} \langle i|U|m\rangle \left(W^{\dagger}\left(|n\rangle\langle m| \otimes I^{\overline{A}}\right)W\right) \langle n|U^{\dagger}|j\rangle$$

$$= \sum_{m,n} W^{\dagger}\left(\left(|n\rangle \langle n|U^{\dagger}|j\rangle \langle i|U|m\rangle \langle m|\right) \otimes I^{\overline{A}}\right)W$$

$$= W^{\dagger}\left(\left(\sum_{m,n} |n\rangle\langle n|\; U^{\dagger}|j\rangle\langle i|U\; |m\rangle\langle m|\right) \otimes I^{\overline{A}}\right)W$$

$$= W^{\dagger}\left(\left(U^{\dagger}\,|j\rangle\langle i|\,U\right) \otimes I^{\overline{A}}\right)W$$

$$= W^{\dagger}\left(\left(U^{\dagger}\,|j\rangle\langle i|\,U\right) \otimes \left(V^{\dagger}I^{\overline{A}}V\right)\right)W$$

$$= W^{\dagger}(U^{\dagger} \otimes V^{\dagger})\left(|j\rangle\langle i| \otimes I^{\overline{A}}\right)(U \otimes V)W$$

$$= \left[(U \otimes V)W\right]^{A}_{i,j}$$

Separation

The noumenal state of system A can be obtained from that of system AB by a projection operation π_A defined as

$$\left(\pi_A \left[W\right]^{AB}\right)_{i,j} \stackrel{\text{def}}{=} \sum_k \left[W\right]^{AB}_{(i,k),(j,k)}$$

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$$\left[W\right]^{A} = \pi_A\left[W\right]^{AB}.$$

Proof

$$\begin{aligned}\left(\pi_A\left[W\right]^{AB}\right)_{i,j} &= \sum_k \left[W\right]^{AB}_{(i,k),(j,k)} \\ &= \sum_k W^\dagger \left(|j\rangle\langle i|^A \otimes |k\rangle\langle k|^B \otimes I^{\overline{AB}}\right) W \\ &= W^\dagger \left(|j\rangle\langle i|^A \otimes I^B \otimes I^{\overline{AB}}\right) W \\ &= \left[W\right]^{A}_{i,j}\end{aligned}$$

Merging

The state of a joint system AB can be obtained from the evolution matrices of systems A and B by the joint product $\odot$ defined as

$$\left(\left[W\right]^A \odot \left[W\right]^B\right)_{(i,k),(j,l)} \stackrel{\text{def}}{=} \left[W\right]^A_{i,j}\left[W\right]^B_{k,l}$$

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Theorem

$$\left[W\right]^{AB}=\left[W\right]^{A}\odot\left[W\right]^{B}.$$

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Proof

$$\left(\left[W\right]^{A} \odot \left[W\right]^{B}\right)_{(i,k),(j,l)}$$

$$=\left[W\right]^{A}_{i,j}\left[W\right]^{B}_{k,l}$$

$$=\left(W^{\dagger}\left(|j\rangle\langle i|^{A}\otimes I^{B}\otimes I^{\overline{AB}}\right)W\right)\left(W^{\dagger}\left(I^{A}\otimes |l\rangle\langle k|^{B}\otimes I^{\overline{AB}}\right)W\right)$$

$$=W^{\dagger}\left(|j\rangle\langle i|^{A}\otimes I^{B}\otimes I^{\overline{AB}}\right)\left(I^{A}\otimes |l\rangle\langle k|^{B}\otimes I^{\overline{AB}}\right)W$$

$$=W^{\dagger}\left(|j\rangle\langle i|^{A}\otimes |l\rangle\langle k|^{B}\otimes I^{\overline{AB}}\right)W$$

$$=\left[W\right]^{AB}_{(i,k),(j,l)}$$

Recovering the Phenomenal State

Let $|\psi\rangle$ be a vector in the Hilbert space of the universe.
We define $\rho^A \stackrel{\text{def}}{=} [W]^A |\psi\rangle$ by:

$$\left([W]^A |\psi\rangle\right)_{i,j} \stackrel{\text{def}}{=} \langle\psi| [W]^A_{i,j} |\psi\rangle$$

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Theorem

$$[W]^A |\psi\rangle = [W |\psi\rangle]^A$$

where

$$[W |\psi\rangle]^A \stackrel{\text{def}}{=} \mathrm{tr}_{\overline{A}}\left(W |\psi\rangle\langle\psi| W^\dagger\right) .$$

Recovering the Phenomenal State

Proof

$$
\begin{aligned}
\left(\left[W\right]^A |\psi\rangle\right)_{i,j} &= \langle\psi| \left[W\right]^A_{i,j} |\psi\rangle \\
&= \langle\psi| \left(W^\dagger \left(|j\rangle\langle i| \otimes I^{\overline{A}}\right) W\right) |\psi\rangle \\
&= \langle\psi| \left(W^\dagger \left(|j\rangle\langle i| \otimes \sum_k |k\rangle\langle k| \right) W\right) |\psi\rangle \\
&= \sum_k \left(\langle\psi| W^\dagger |j\rangle|k\rangle \right)\left(\langle i|\langle k| W |\psi\rangle \right) \\
&= \sum_k \langle i|\langle k| \left(W |\psi\rangle\langle\psi| W^\dagger \right) |j\rangle|k\rangle \\
&= \left(\mathrm{tr}_{\overline{A}} \left(W |\psi\rangle\langle\psi| W^\dagger \right)\right)_{i,j} = \left[W|\psi\rangle\right]^A_{i,j}
\end{aligned}
$$

Proportion versus Probability

The *proportion* of a system A, with evolution Matrix $[W]^A$ in state $|i\rangle$ is given by

$$\left[W\,|\psi\rangle\right]^A_{i,i}$$

where $|\psi\rangle$ is the reference vector.

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Separate evolution

Theorem

$$\left((U \otimes V)[W]^{AB}\right) = U[W]^{A} \odot V[W]^{B}$$

Commuting Diagrams

And indeed we have

$$
\begin{array}{ccc}
M^A & \xrightarrow{\quad U \quad} & U\left(M^A\right) \\
\Big\downarrow \phi & & \Big\downarrow \phi \\
\rho^A & \xrightarrow[\quad U \quad]{} & U\left(\rho^A\right)
\end{array}
$$

Commuting Diagrams

Theorem

$$U([W]^A |\psi\rangle) = (U[W]^A) |\psi\rangle$$

Proof

$$\begin{aligned}
&U\left([W]^A |\psi\rangle\right) \\
=&U[W |\psi\rangle]^A \\
=&[(U \otimes I) W |\psi\rangle]^A \\
=&[(U \otimes I) W]^A |\psi\rangle \\
=&(U[W]^A) |\psi\rangle
\end{aligned}$$

Commuting Diagrams

As well as

$$
\begin{array}{ccc}
M^{AB} & \xrightarrow{\pi_A} & M^{A} \\
\Big\downarrow \phi & & \Big\downarrow \phi \\
\rho^{AB} & \xrightarrow[\pi_A = \mathrm{tr}_B]{} & \rho^{A}
\end{array}
$$

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\end{array}
$$

Which means:

$$\left(\pi_A [W]^{AB}\right) |\psi\rangle = \pi_A\left([W]^{AB} |\psi\rangle \right)$$

Commuting Diagrams

Theorem

$$\left(\pi_A [W]^{AB}\right) |\psi\rangle = \pi_A\left([W]^{AB} |\psi\rangle \right)$$

Proof

$$\begin{aligned}
&\left(\pi_A [W]^{AB}\right) |\psi\rangle \\
&= [W]^{A} |\psi\rangle \\
&= [W |\psi\rangle]^{A} \\
&= \pi_A\left([W |\psi\rangle]^{AB} \right) \\
&= \pi_A\left([W]^{AB} |\psi\rangle \right)
\end{aligned}$$

Not a New Idea

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Some precursors who had enough imagination!

- It was prophecised by Hugh Everett (1955)

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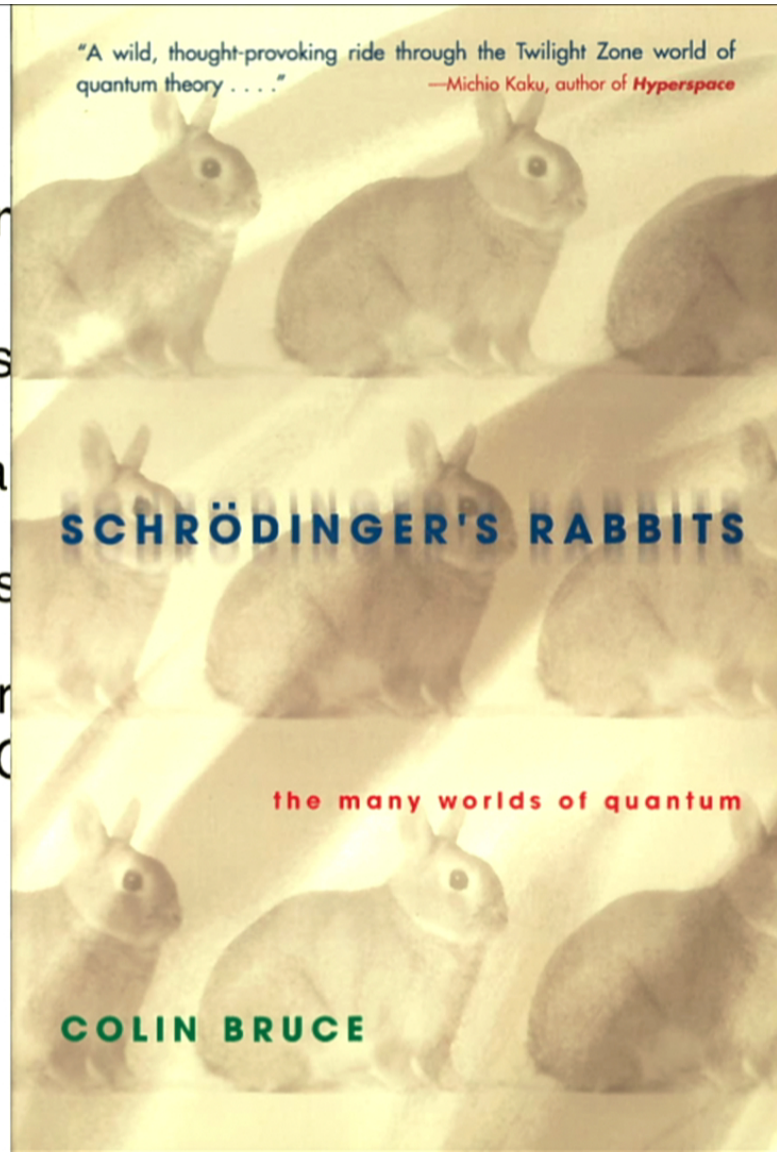
- Published by Deutsch and Hayden (2000)

Some pr  gination!

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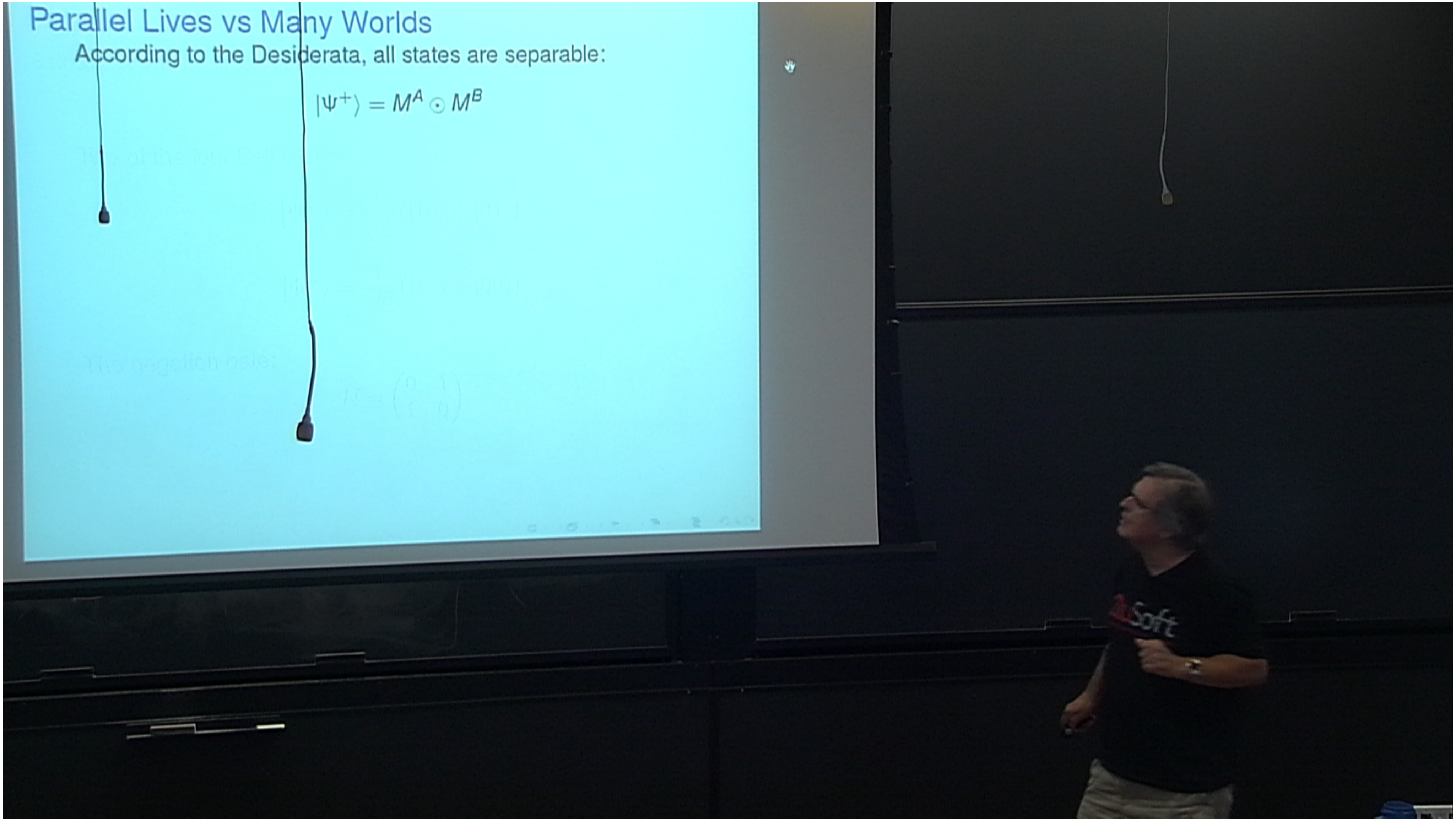
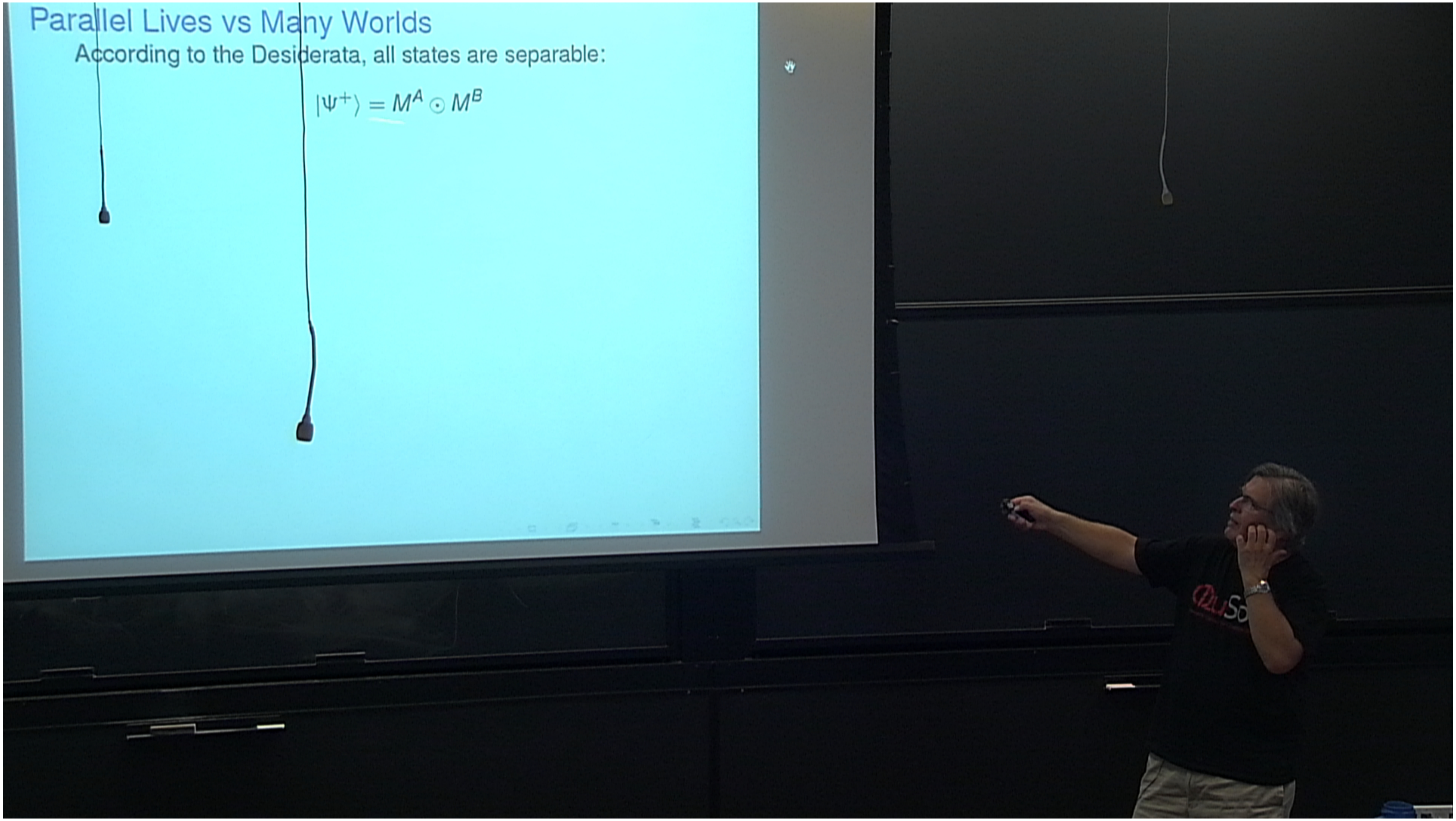
- We proved that the universal wavefunction *cannot* be a complete description of physical reality


Parallel Lives vs Many Worlds
According to the Desiderata, all states are separable:
$|\Psi^+\rangle = M^A \odot M^B$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By separate evolution:

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Since

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Since

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By tracing out B, we conclude

$$M^A = N\left(M^A\right)$$

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By separate evolution:

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A contradiction!