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Quantum theory from one simple symmetry

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What is quantum theory, anyway?

1. Physical *systems* are described by Hilbert spaces; physical *states* are described by normalized vectors in Hilbert spaces.

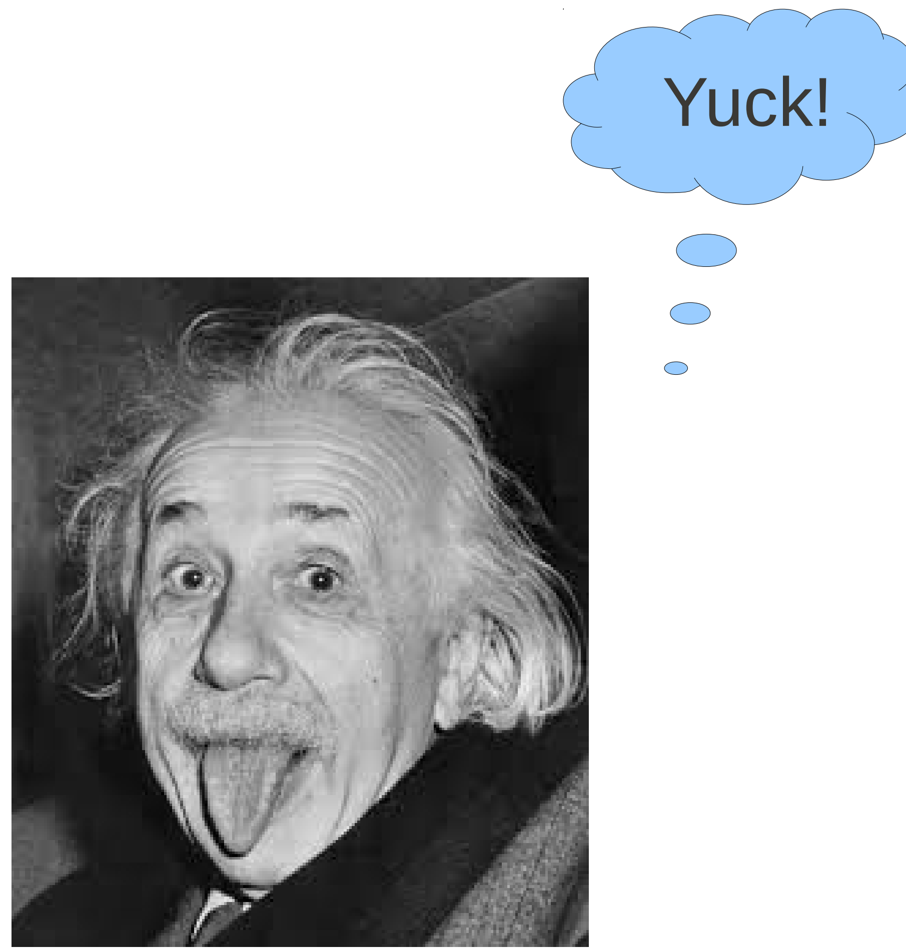
2. Closed quantum systems evolve by unitary transformations (i.e. by the Schrödinger equation).

3. Measurements are described by positive operator-valued measures (POVMs) defined on Hilbert spaces.

4. The state space of a composite system is the tensor product of the state spaces of its subsystems.

---Nielsen & Chaung, *Quantum Computation and Quantum Information*, 2000, Ch. 2.

“Spooky action at a distance …”



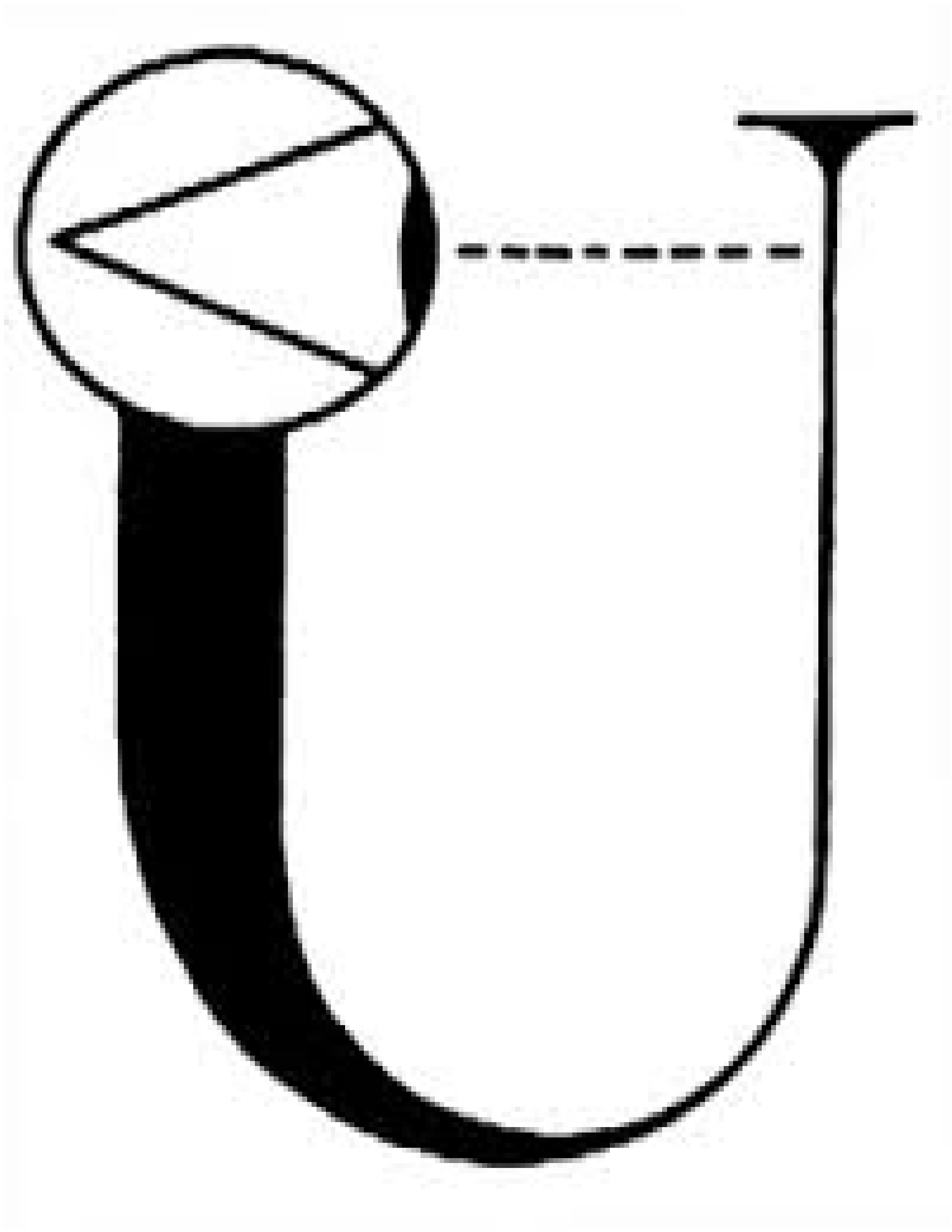

ENTANGLEMENT

"If you think you can talk about quantum theory without feeling dizzy, you haven't understood the first thing about it."

Shut up and calculate!

$$\partial\Psi/\partial t = -(i/\hbar)H\Psi$$

$$(|AB\rangle \neq |A\rangle|B\rangle)$$



“A participatory universe ...”

Goals for today:

1. See that quantum theory is simple and familiar - just “classical physics done right.”

2. Understand its implications for time and memory.

3. See that the ideas of an “isolated system” and a “system-specific information channel” are what are *really* counter-intuitive and problematic.

Fundamental claim:

All of quantum theory follows from *one* symmetry:

Addition is associative, so for a Hamiltonian H:

$$H_U = H_1 + (H_2 + H_3) + (H_{12} + H_{13}) + H_{23}$$

or alternatively,

Multiplication is associative, so for a state space $\mathcal{H}$:

$$\mathcal{H}_U = \mathcal{H}_1 \otimes (\mathcal{H}_2 \otimes \mathcal{H}_3)$$

“Decompositional equivalence”

Quantum theory:

“The physics doesn't care where you put the parentheses.”

Not in the Hamiltonian,

Not in the state-space decomposition.

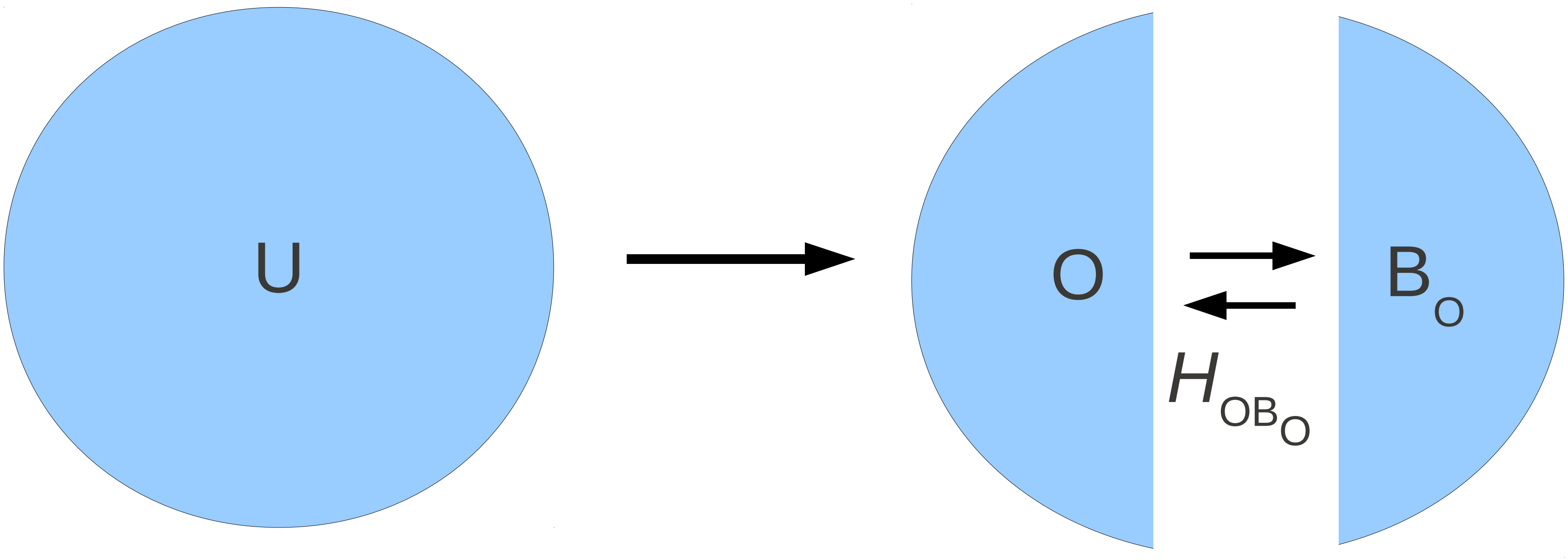
Note that this is also true in *classical* physics!

The problem is, *we* care …

It's *hard* to move the parentheses!

So quantum theory seems counter-intuitive.

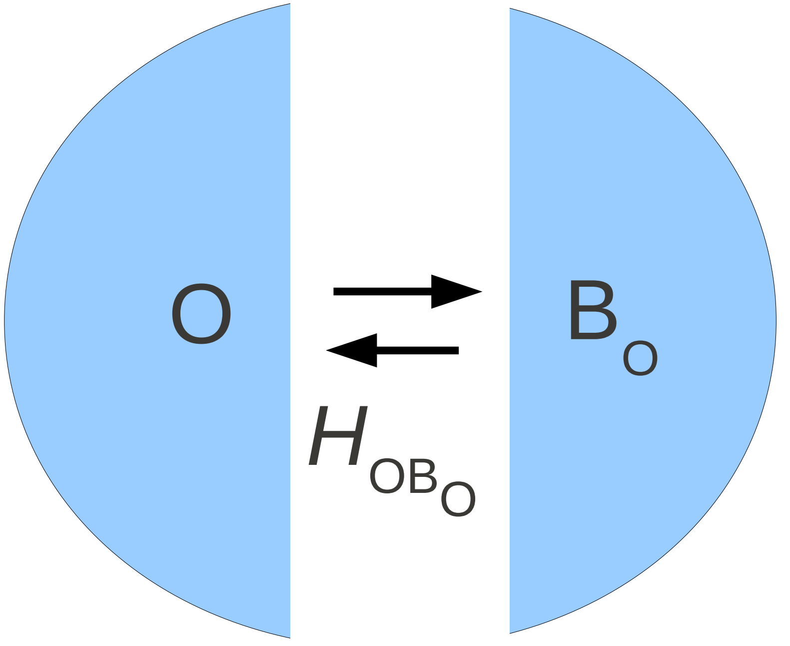
Start with a closed U ("everything") and make an *arbitrary* partition into two components:



Call O the "observer."

What can O learn about B_O from finite observations at finite resolution?

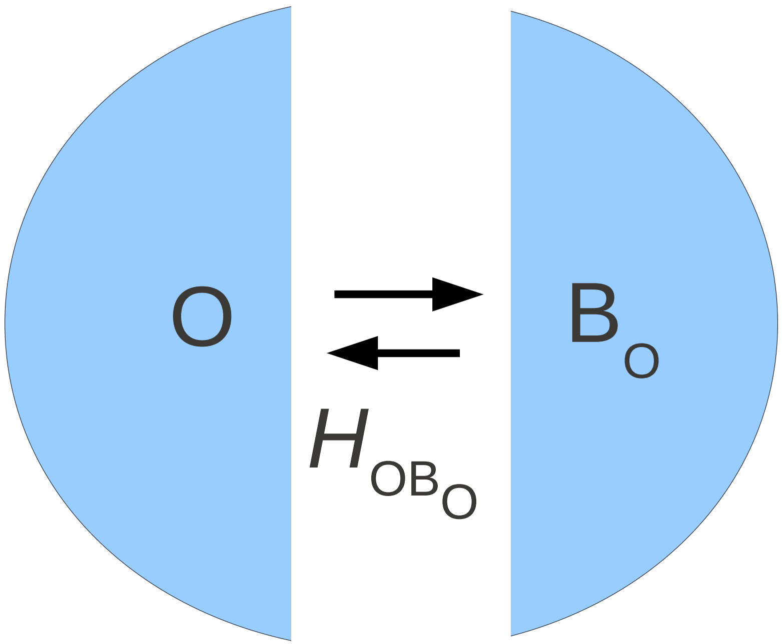
$$H_U = H_O + H_{B_O} + H_{OB_O}$$



H_{OB_O} can only transfer information about the state $|B_O\rangle$!

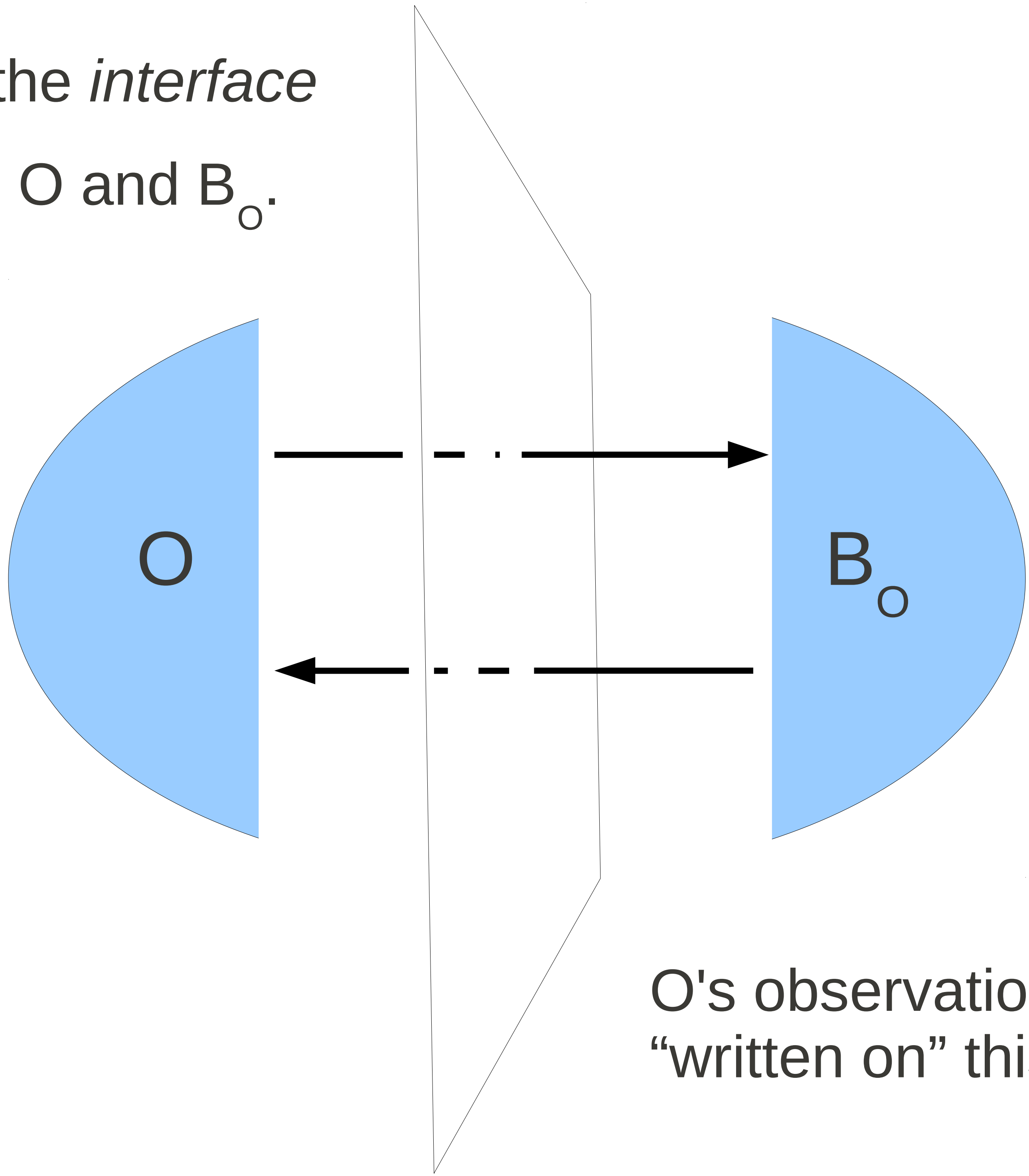
H_{OB_O} is invariant under arbitrary further decompositions of B_O. So O can learn nothing about the internal structure or dynamics (i.e. H_{B_O}) of B_O.

For O, B_O is a *black box*.



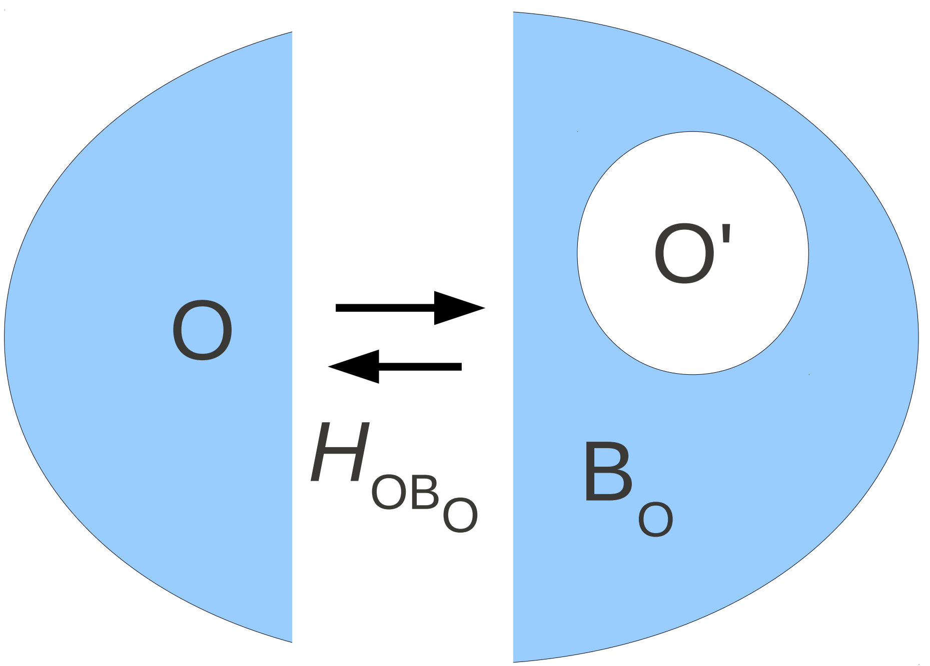
No sequence of finite observations allows O to limit the degrees of freedom or dynamic complexity of B_O.

H_{OB_O} is the *interface* between O and B_O.



O's observations are "written on" this interface.

Now consider a “second observer” O' embedded in B_O.
Can O and O' exchange classical information?



No. H_{OB_O} is invariant under arbitrary redefinitions of O' within B_O and hence of the interaction between O' and the “rest” of B_O.

No-signaling theorem:

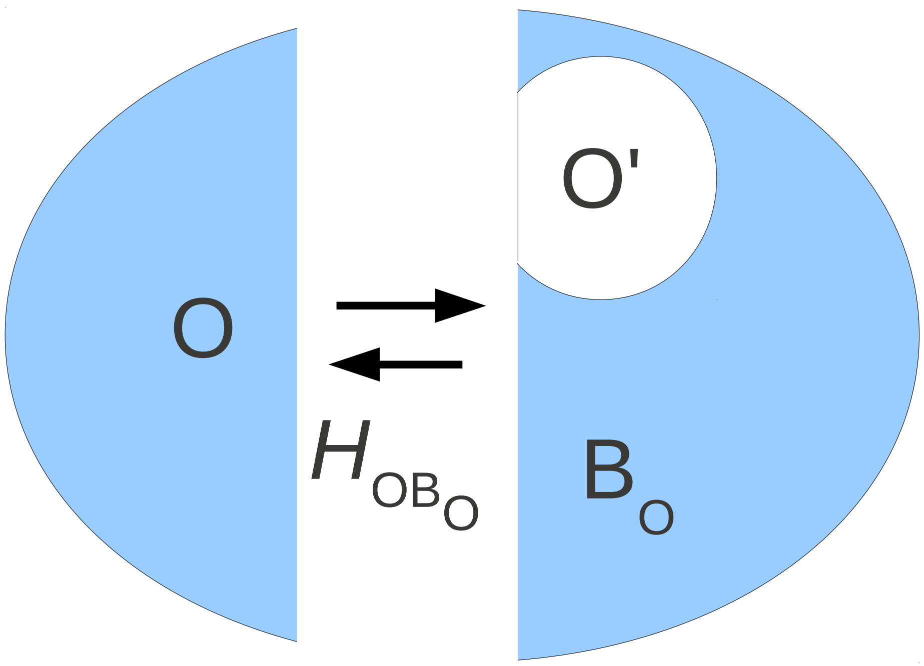
A shared black box cannot serve as a classical information channel.

Compare to the quantum no-signaling condition:

A shared quantum system cannot serve as a classical information channel.

This suggests that “black box” and “quantum system” may mean the same thing.

What about this situation? Here O and O' are not spatially separated.



They still can't exchange information: H_{OB_O} is still invariant under arbitrary redefinitions of O' and of its interaction with the “rest” of B_O.

Stronger no-signaling theorem:

If O and O' share a black box, $H_{OO'}$ does not implement a classical information channel.

Corollary:

O' cannot be a quantum reference frame for O.

In particular,

O' cannot be a *clock* for O.

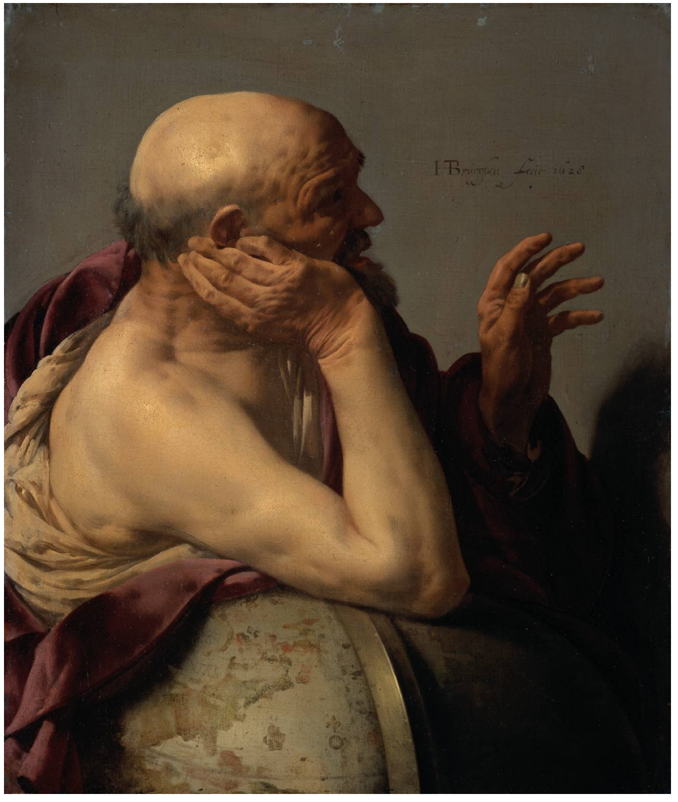
And also,

O' cannot be a *memory* for O.

What this means physically:

O cannot encode information in part of U using H_{OB_O} and then retrieve that same information from that same part of U using H_{OB_O}.

I knew that in 500 BCE!



Let's take stock of the story so far:

Just assuming an additive Hamiltonian, and hence even in *classical* physics, we have:

1. O's “world” B_O is a black box.
2. No signaling, so compatibility with special relativity.
3. No cloning, so compatibility with quantum information theory.
4. No objective clocks, so no objective time.

Now add some thermodynamics …

Assume O undergoes a physical state transition when an observational outcome is received from B_O – so assume that O *records* each outcome.

We can then consider O to be a counter and hence a clock with a period Δt. Information transfer being a *physical* process (Landauer's Principle) then requires:

$$0.7NkT\Delta t = \int_{\Delta t} H_{OB_O}\, dt$$

for N bits,where T is an effective “temperature” of the interaction.

We can calculate this action:

Minimal action to acquire 1 bit = $0.7kT\Delta t$.

Assume one photon can transfer one bit. Rhodopsin requires ~200 fs to absorb a photon at 37 C, so:

Minimal action (1 bit) ~ 0.7kt * 200 fs at 37 C
~ $6.0 * 10^{-34}$ Js.

Planck's constant h = $6.6 * 10^{-34}$ Js. So h is the minimal action to acquire 1 bit.

The rest is easy …

Invariance of HU under decompositions ⟶ unitarity.

Strong no-signaling ⟶ Bell's theorem.

Strong no-signaling ⟶ complex phases for “states” of subsystems of B_O.

But the interesting question is: What is the *physics*?

The parentheses we see ...

… aren't really there.

Our classical assumption that we can observe and manipulate individual, time-persistent systems is very useful.

The empirical success of quantum theory tells us that it's wrong.

Thank you.

Questions?