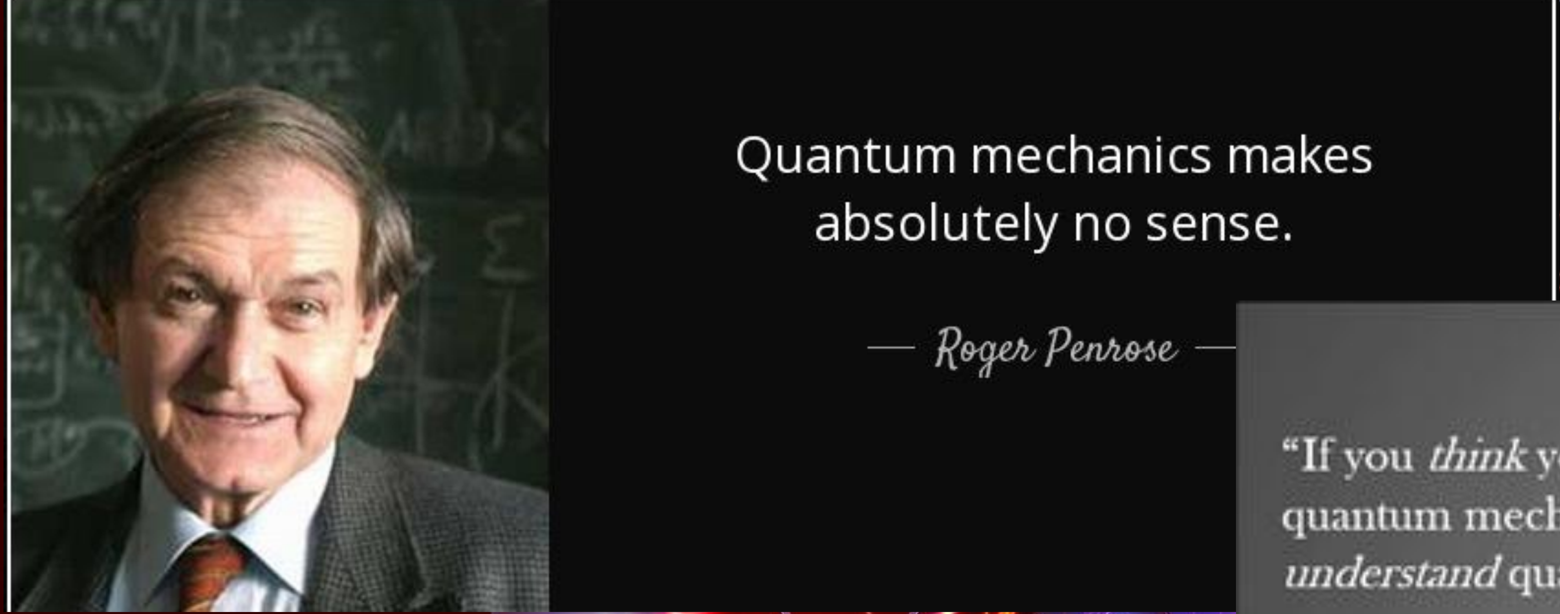
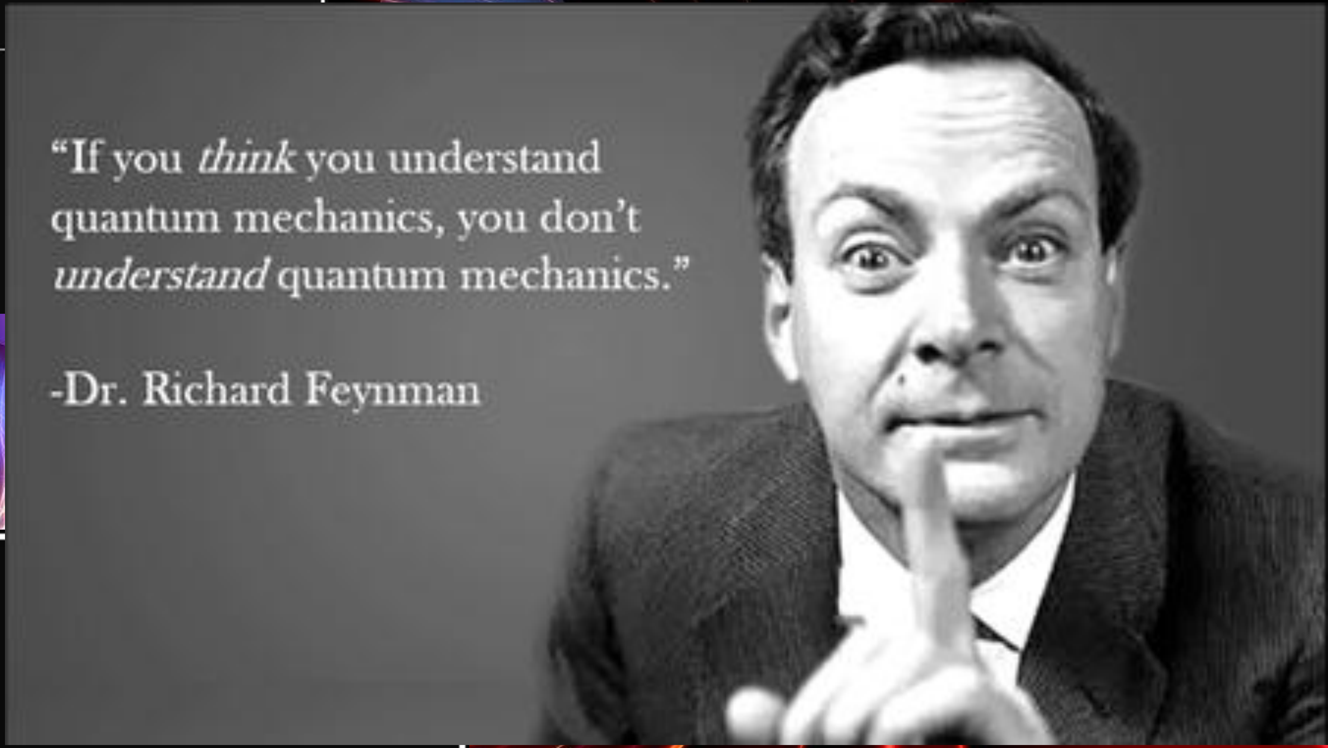
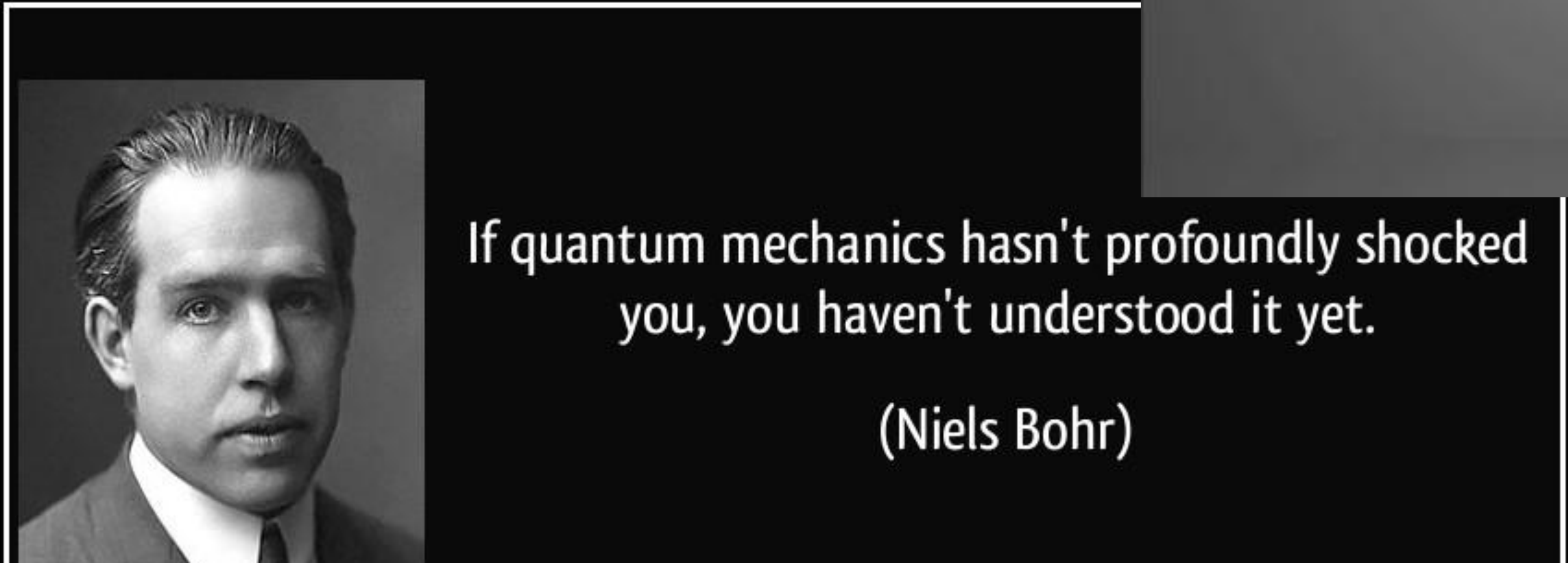
Quantum oddities: The revenge

Ambroise LAFONT


Quantum mechanics makes absolutely no sense.
— Roger Penrose —


"If you *think* you understand quantum mechanics, you don't *understand* quantum mechanics."
-Dr. Richard Feynman


If quantum mechanics hasn't profoundly shocked you, you haven't understood it yet.
(Niels Bohr)

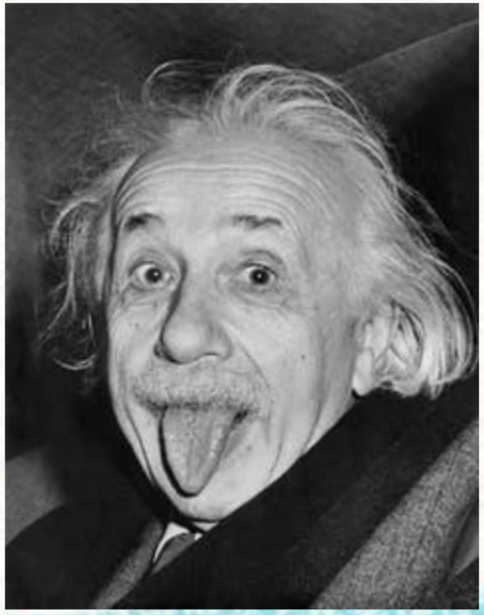
I. Bell’s theorem

- A gedanken experiment presented in the first page of

  “**The Best Version of Bell’s Theorem**”, Mermin 1995

- The outcome predicted by quantum mechanics challenges the **locality principle,** at the basis of Einstein’s relativistic theories

$E = mc^2$

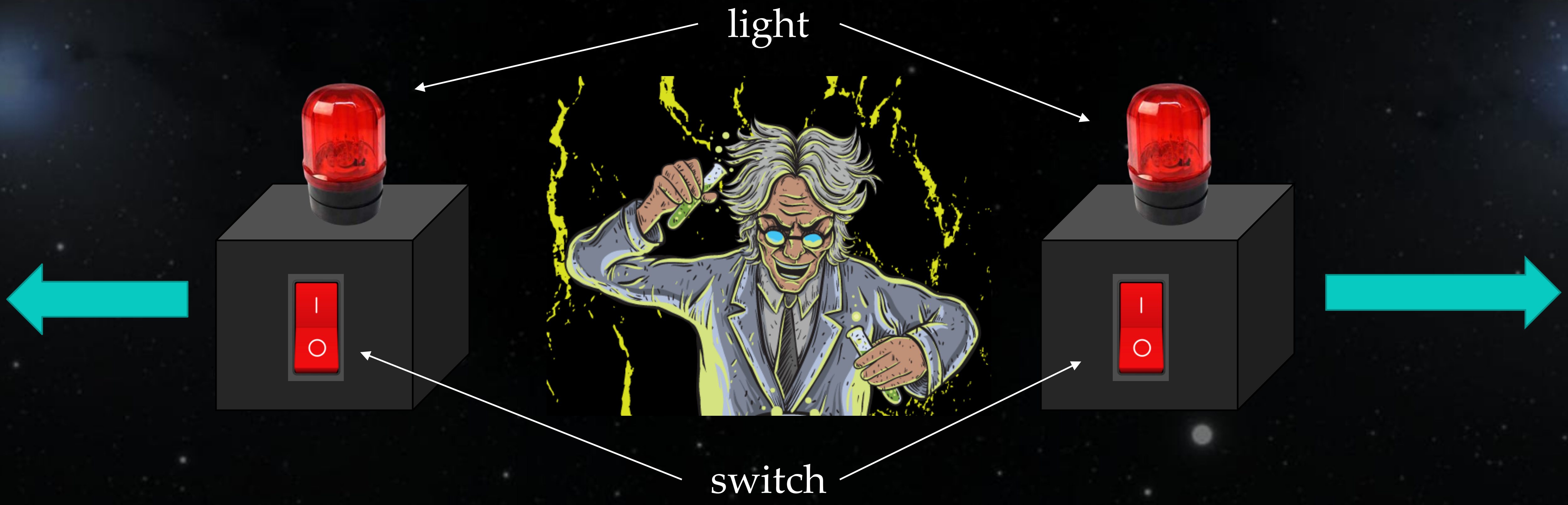


Causality has a maximal speed limit: the speed of light

What happens here cannot affect instantaneously what happens there.

A long time ago in a galaxy far, far away…

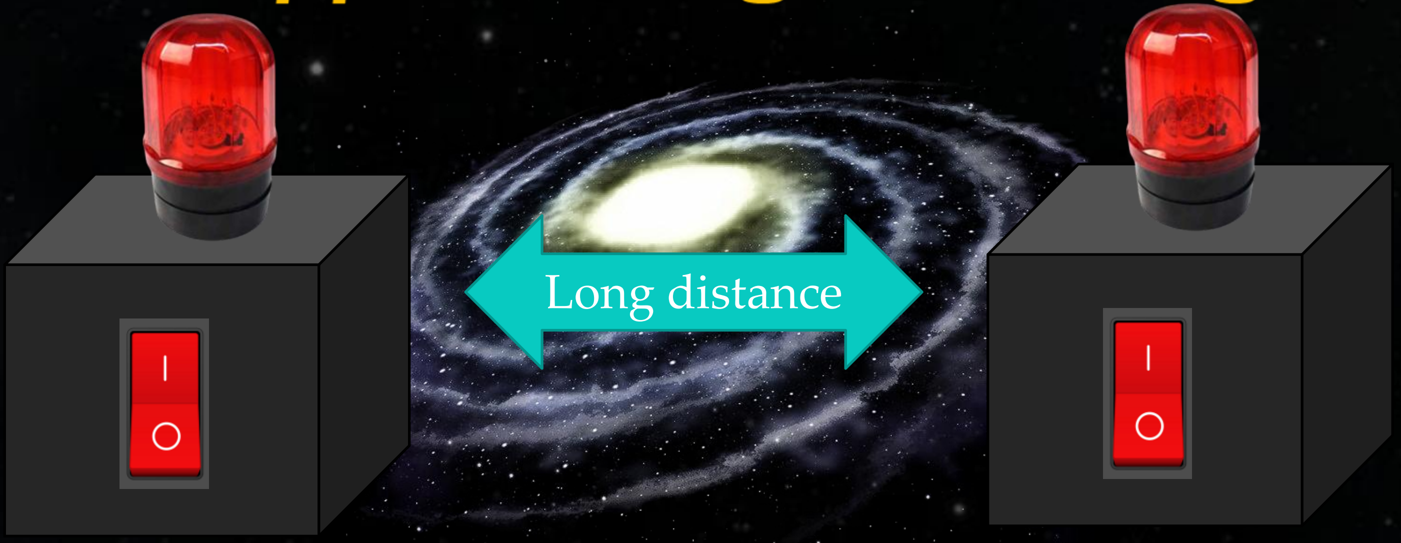
A crazy scientist prepares two mysterious « Bell boxes » and send them very far away from each other.

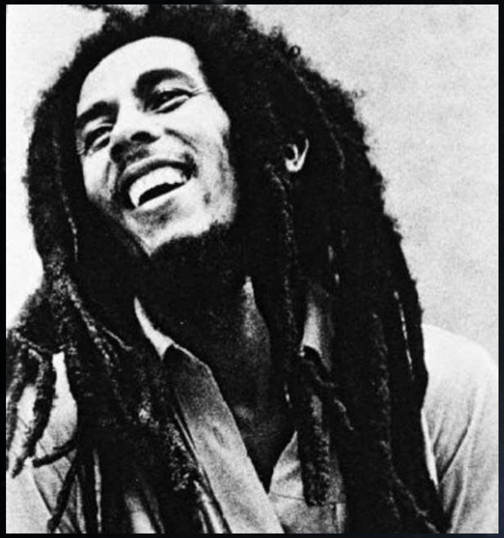


A long time ago in a galaxy far, far away…

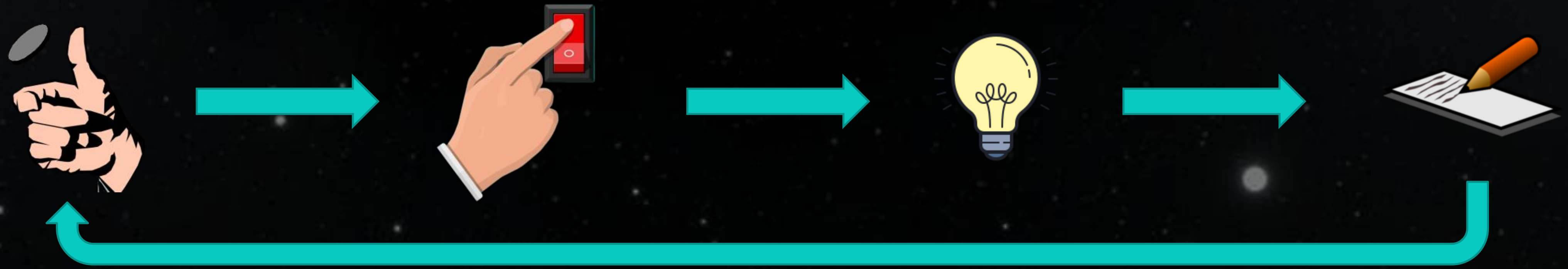
A crazy scientist prepares two mysterious « Bell boxes » and send them very far away from each other.

Alice and Bob Skywalker find the boxes at the opposite edges of the galaxy.

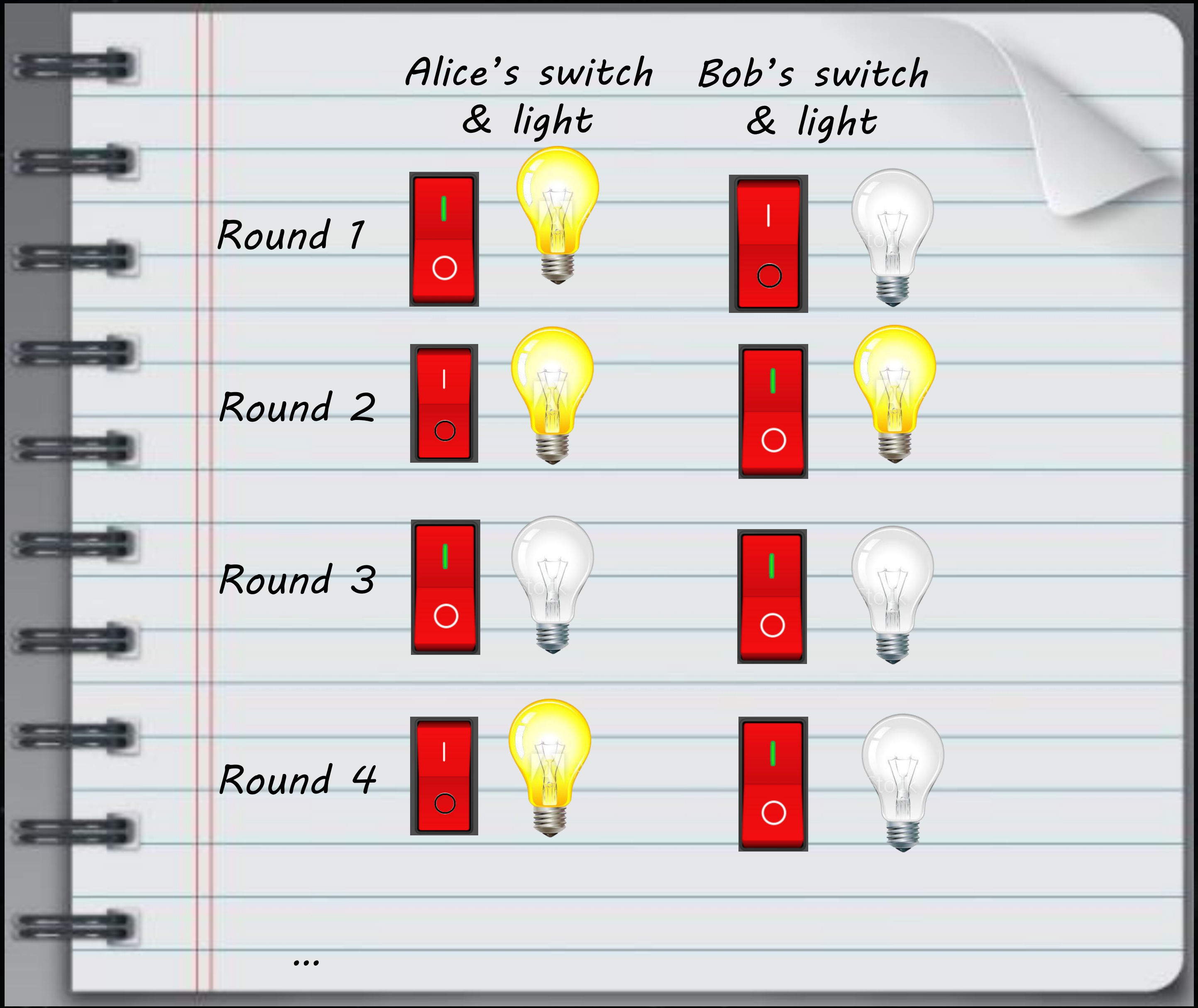


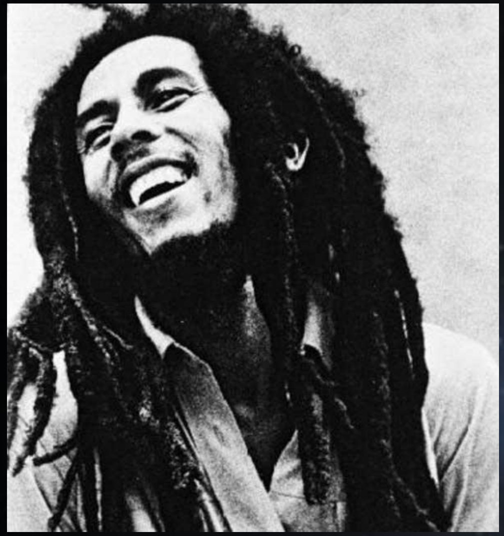


Inspired by the force, each second they simultaneously choose a random switch position, then record if their light is on.



Back at the jedi academy, Alice and Bob merge their records.





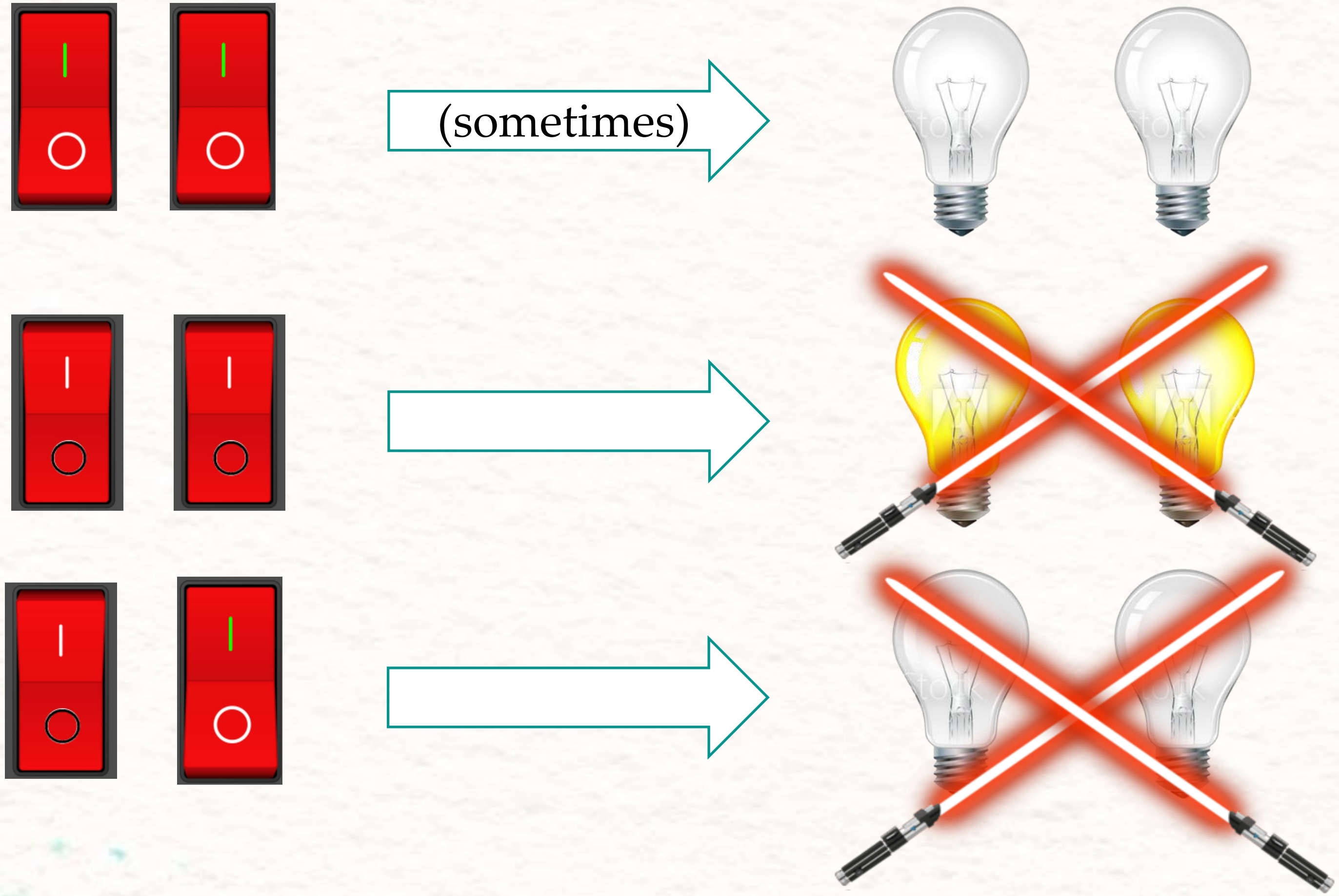
These black boxes do not behave like regular lamps

Yeah, looks random

Bell rules

- **Symmetric**
- Verifiable

Quantum mechanics allow to construct black boxes s.t.

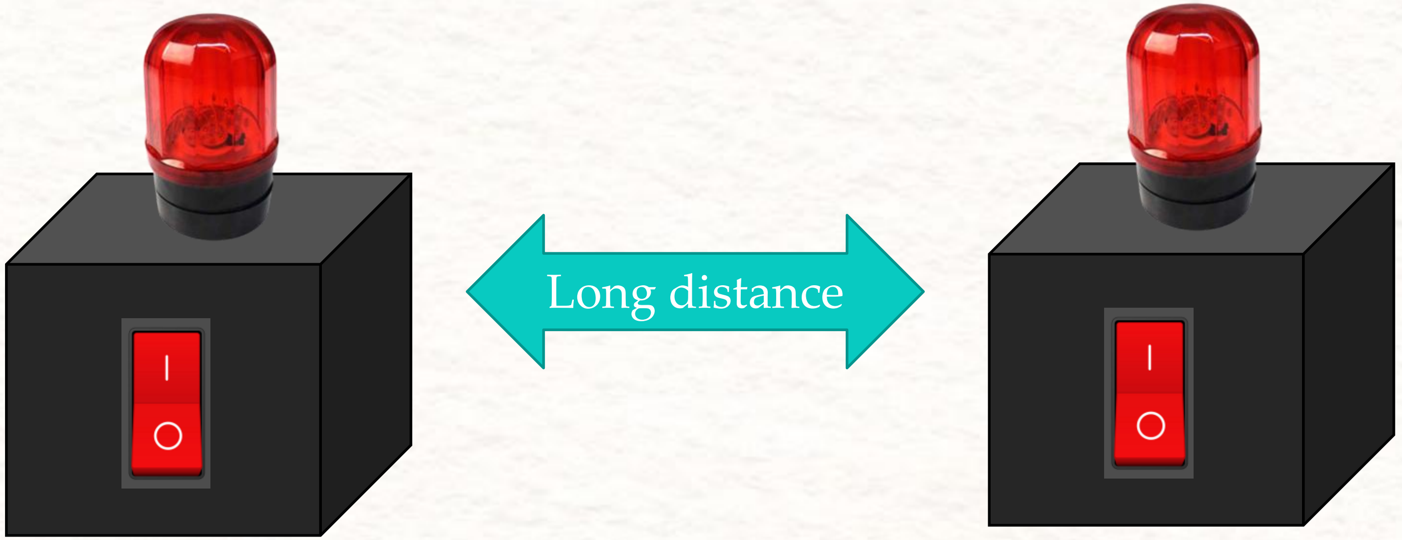


Both lights may be off even if both switches are on

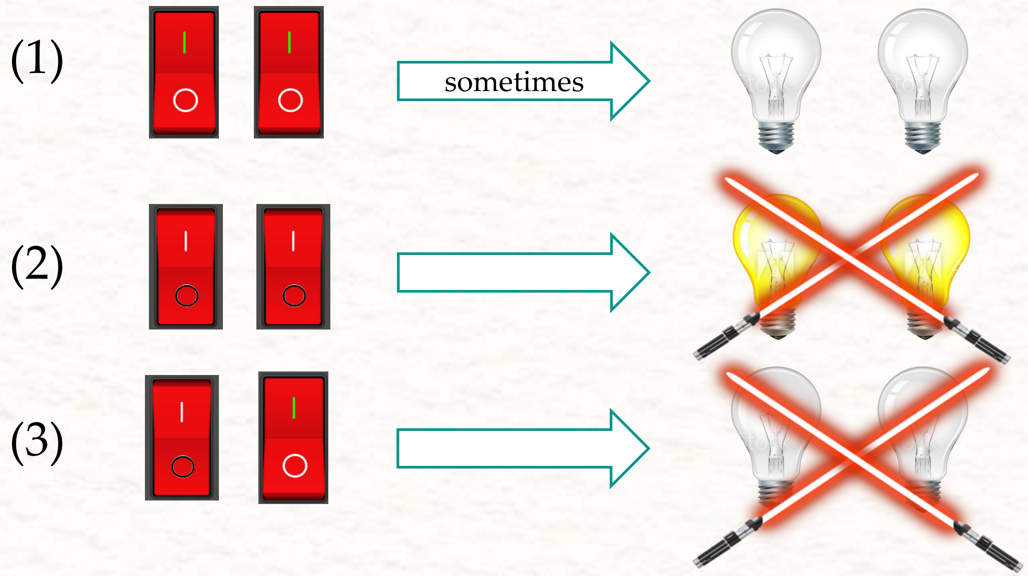
If both switches are off, at least one light is off

If exactly one switch is on, at least one light is on

Locality principle for Bell's boxes



If Bell's boxes are far enough from each other, the switch position of a box cannot affect the light state of the other box.



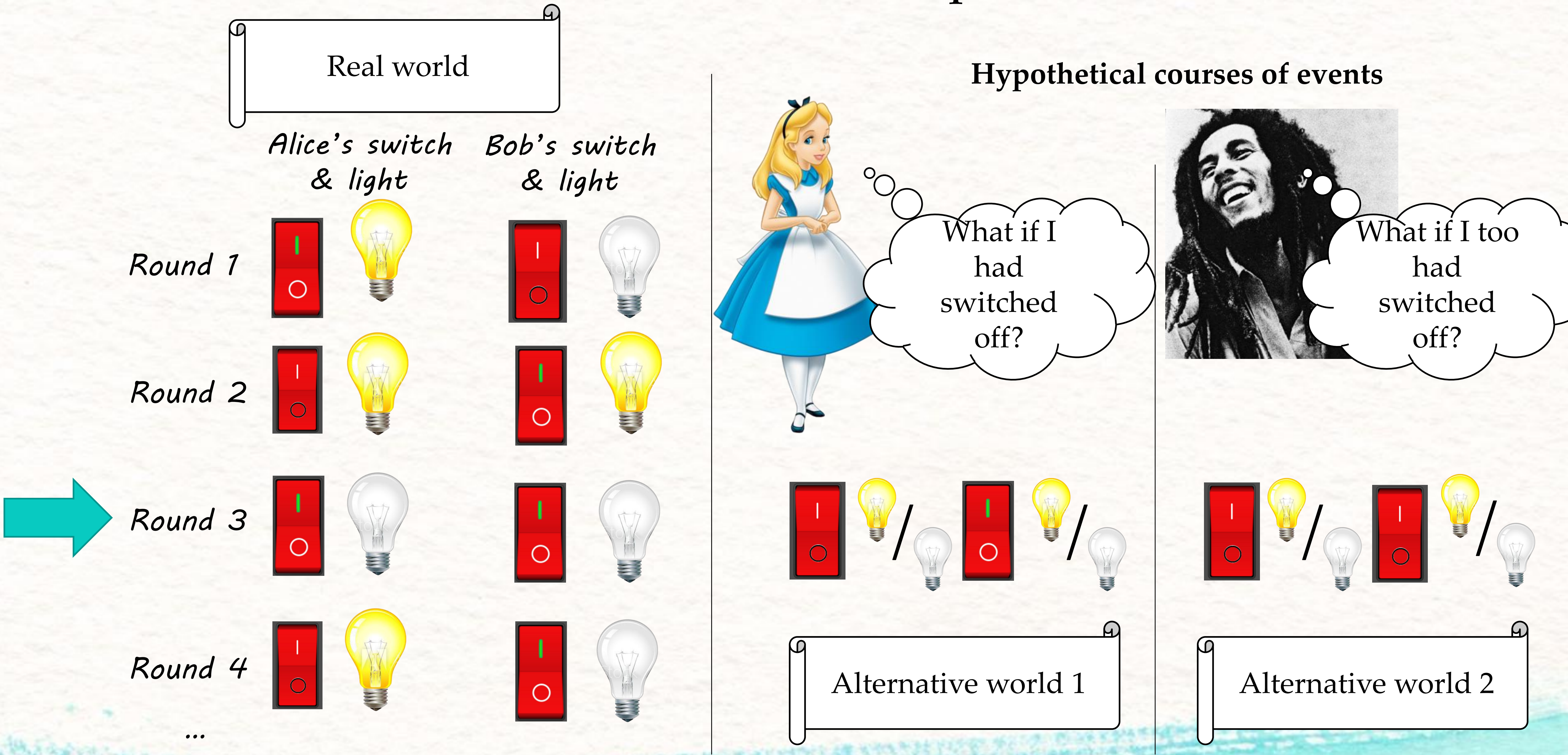
$\Rightarrow$ Contradiction

+

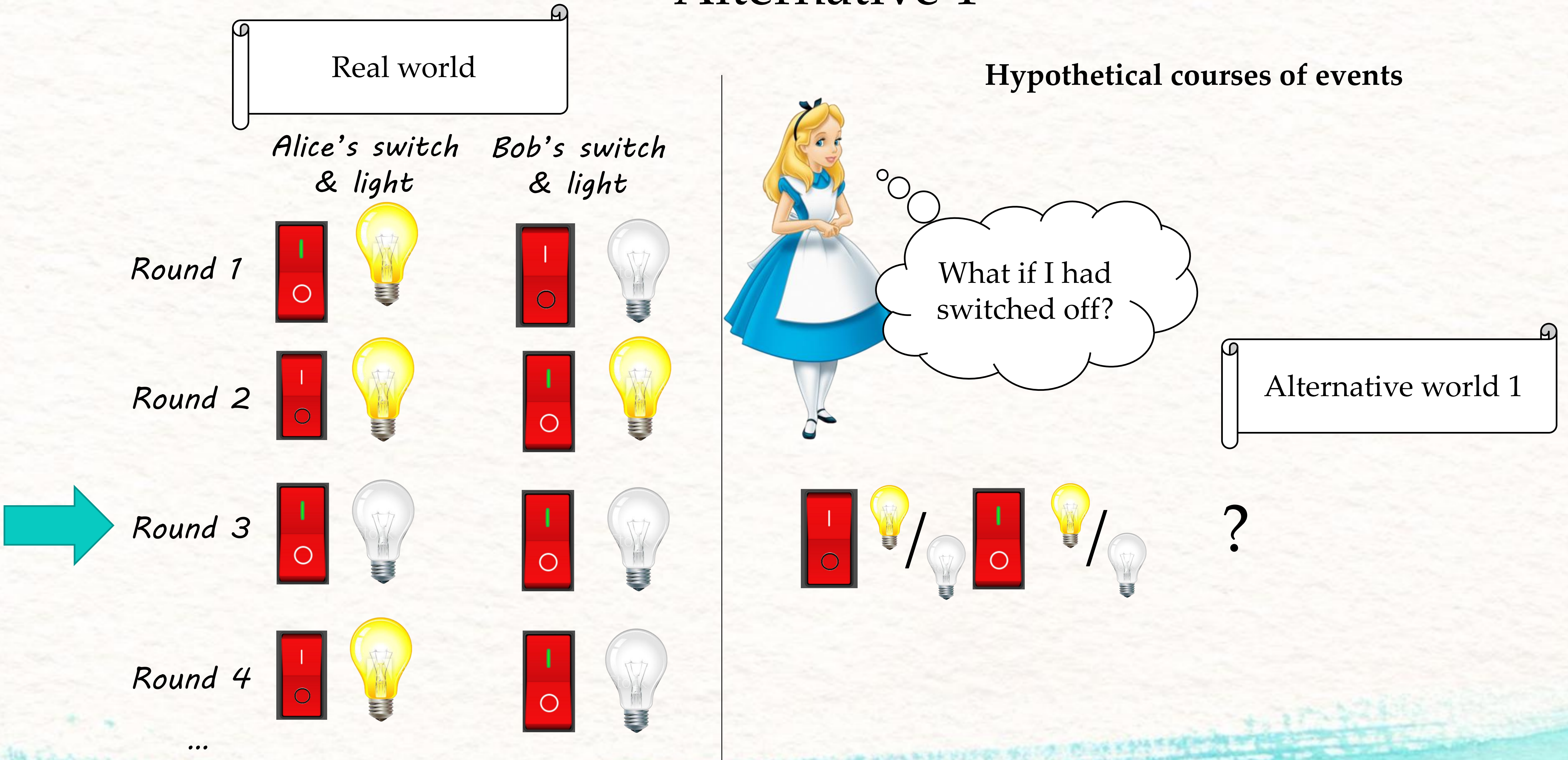
LOCALITY PRINCIPLE

Proof: next slides

Overview of the proof



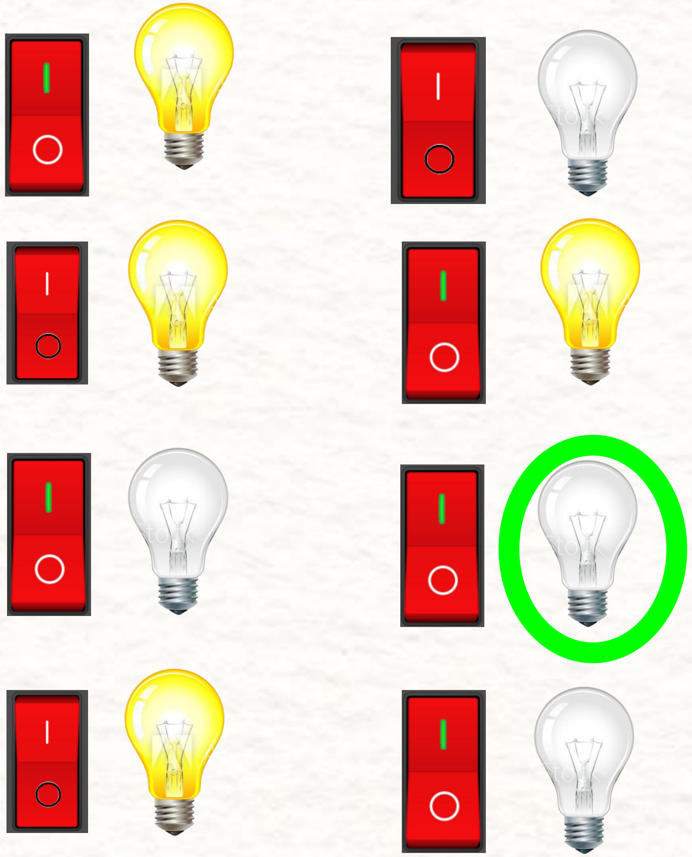
Alternative 1



Alternative 1

Real world

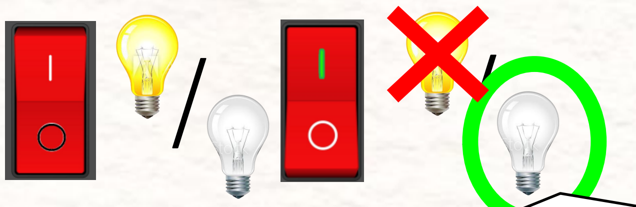
	Alice's switch & light	Bob's switch & light
Round 1		
Round 2		
Round 3		
Round 4		
…		



Hypothetical courses of events

What if I had switched off?

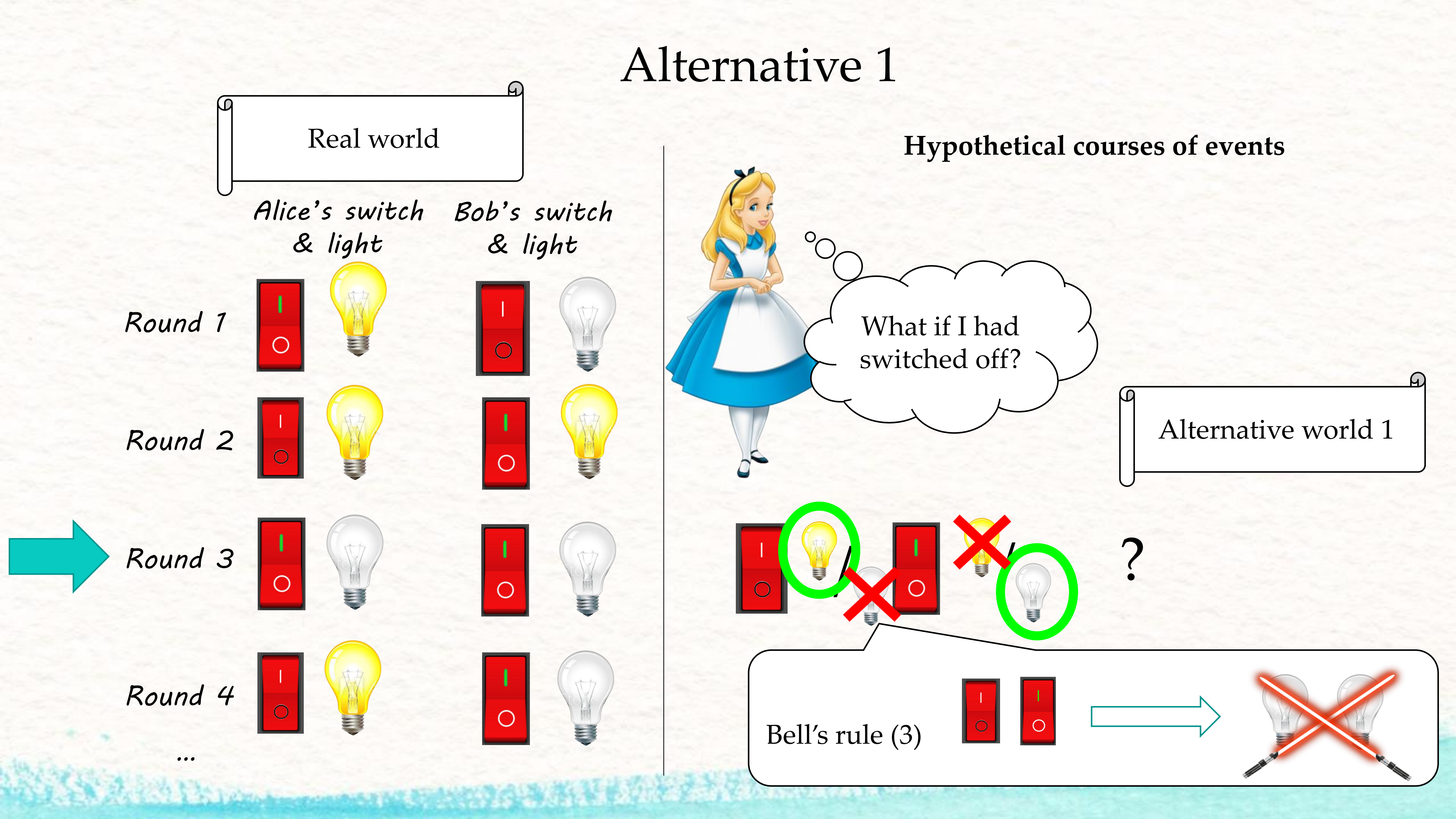
Alternative world 1



?

LOCALITY PRINCIPLE

I don't care about the other switch.



Alternative 1
Real world
Alice's switch & light
Bob's switch & light
Round 1
Round 2
Round 3
Round 4
...
Hypothetical courses of events
What if I had switched off?
Alternative world 1
?
Bell's rule (3)

Alternative 2

Real world

Alice's switch & light

Bob's switch & light

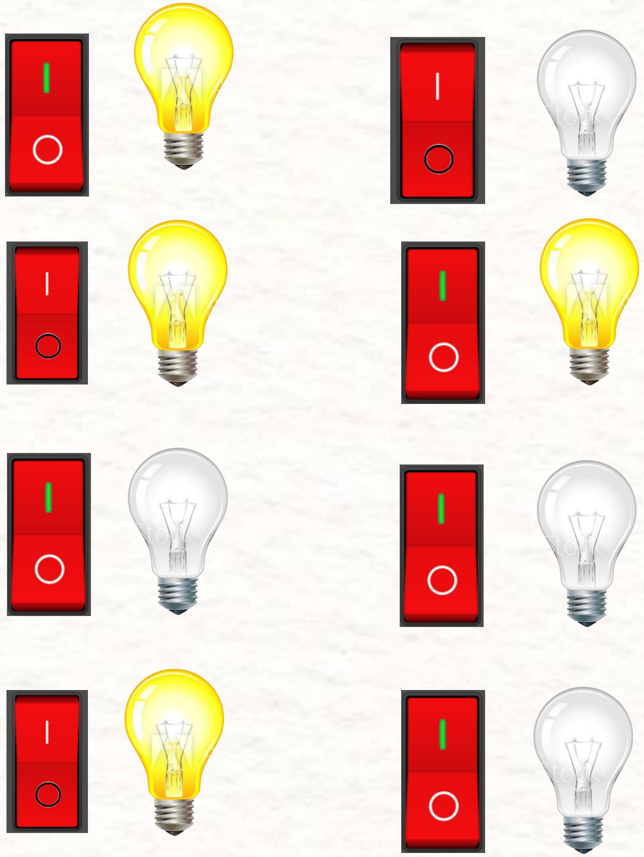
Round 1

Round 2

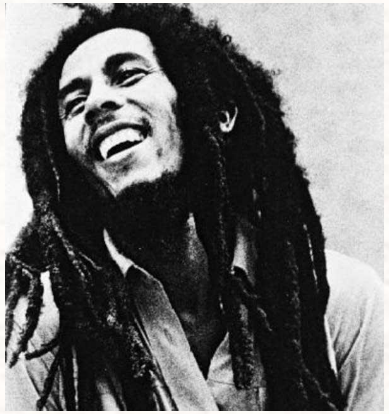
Round 3

Round 4

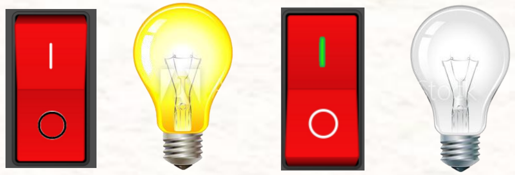
…

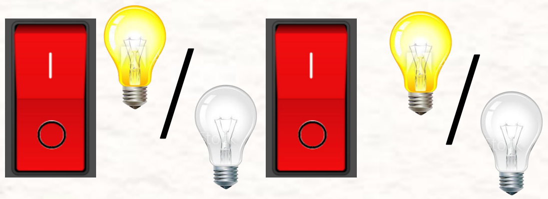


What if I too had switched off?



Alternative world 1





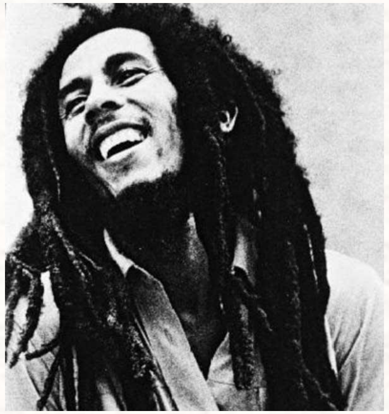
Alternative world 2

Alternative 2

Real world

	Alice's switch & light	Bob's switch & light
Round 1		
Round 2		
Round 3		
Round 4		
...		

What if I too had switched off?



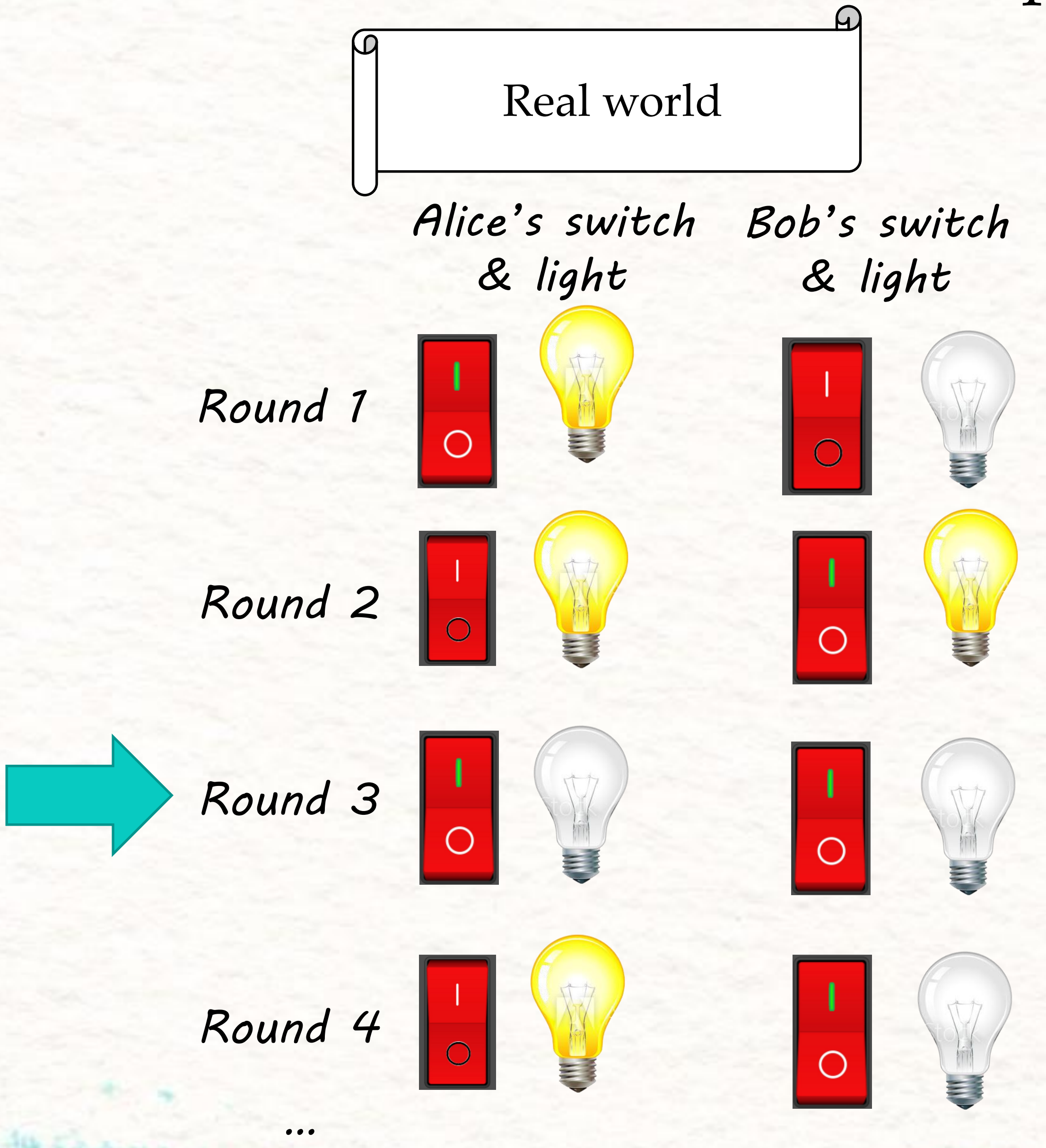
Alternative world 1

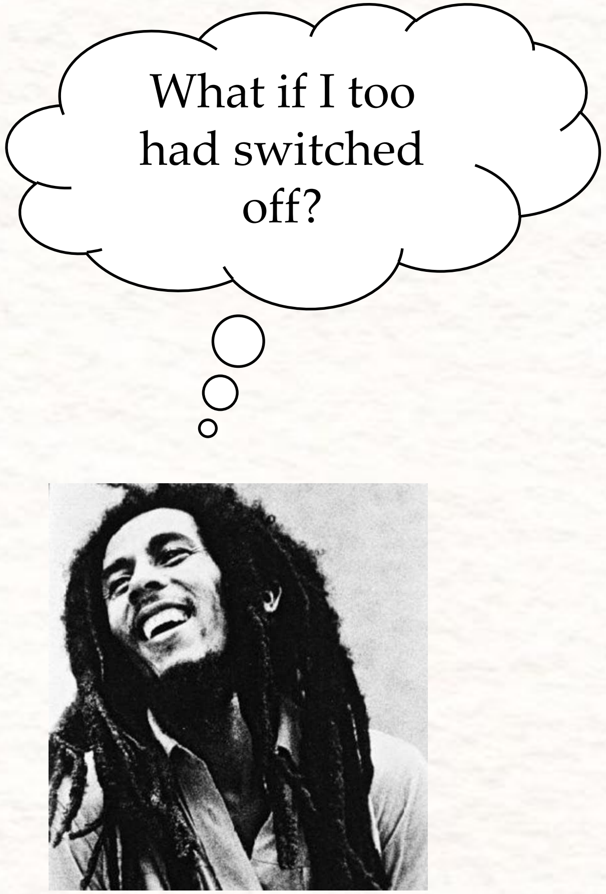
LOCALITY PRINCIPLE

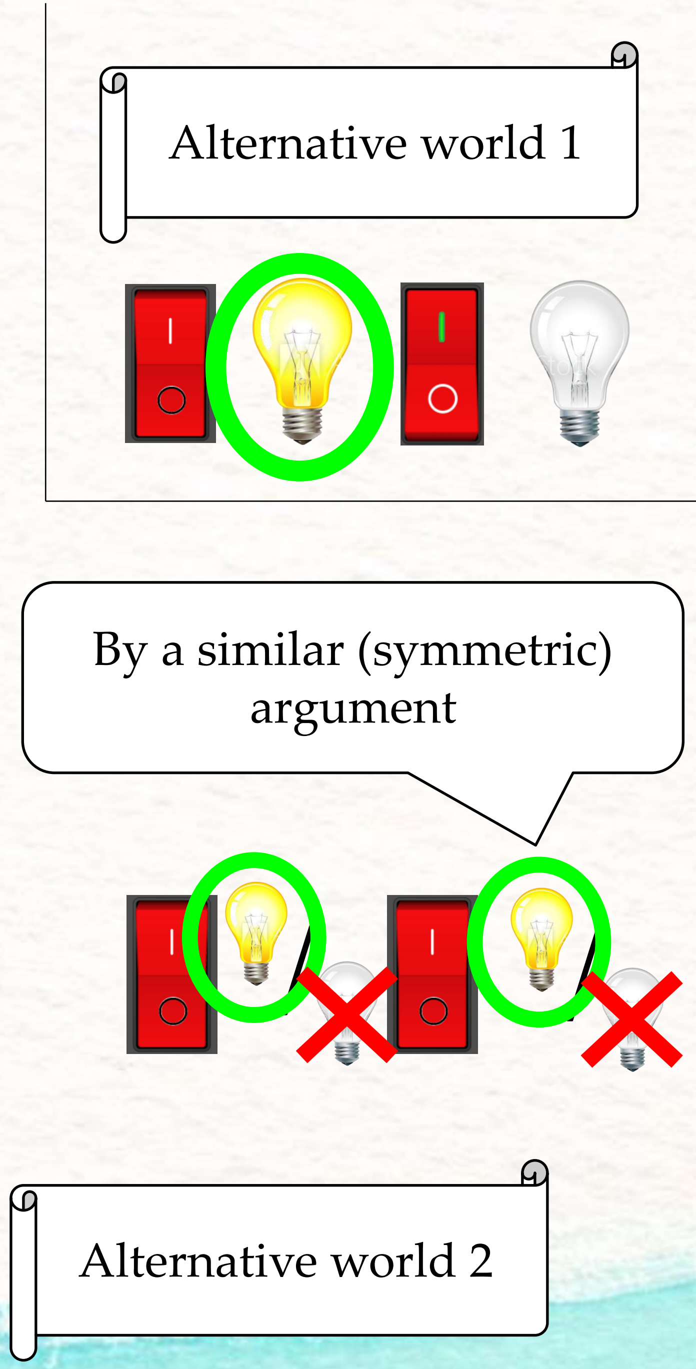
I don't care about the other switch.

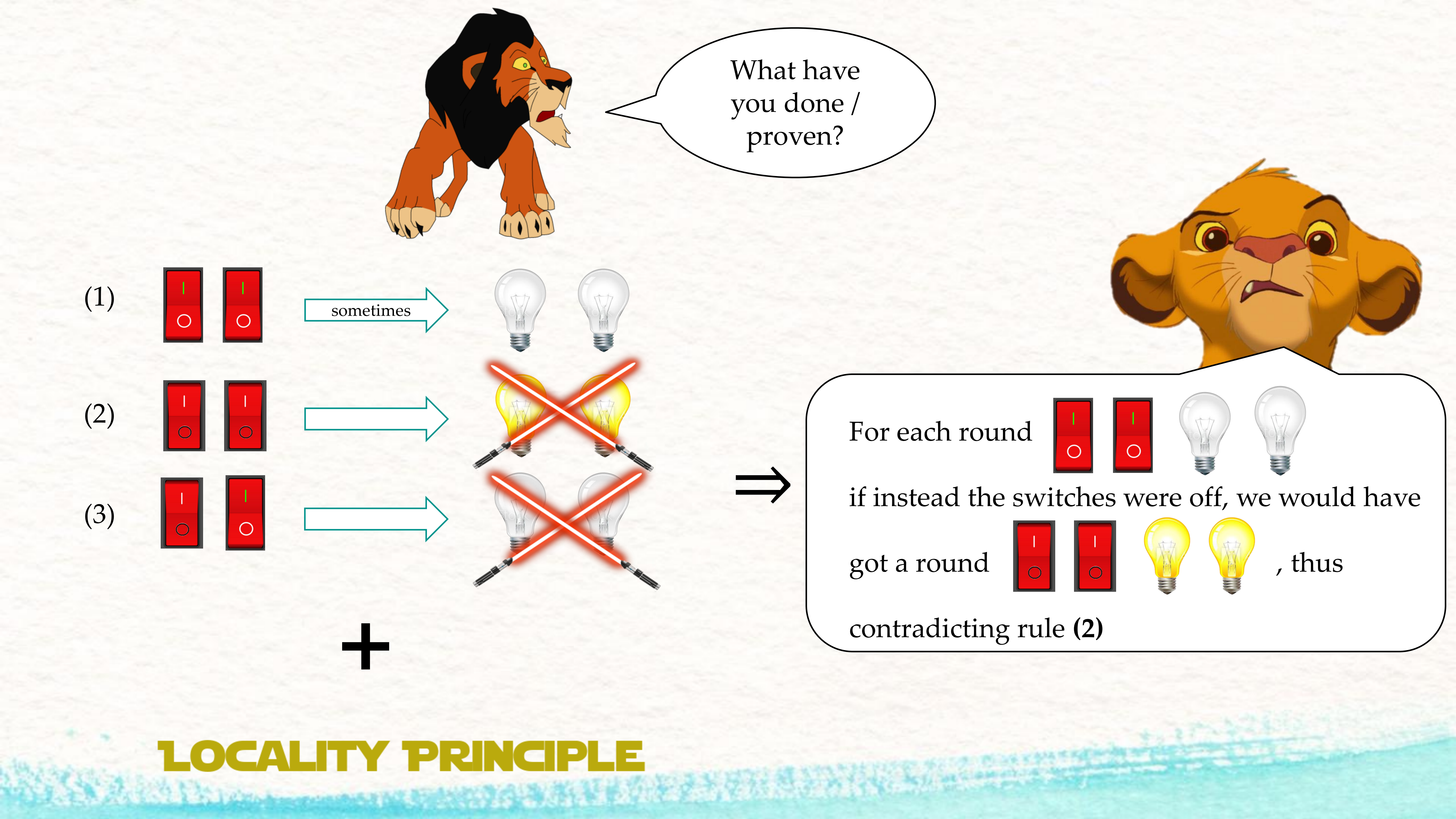
Alternative world 2

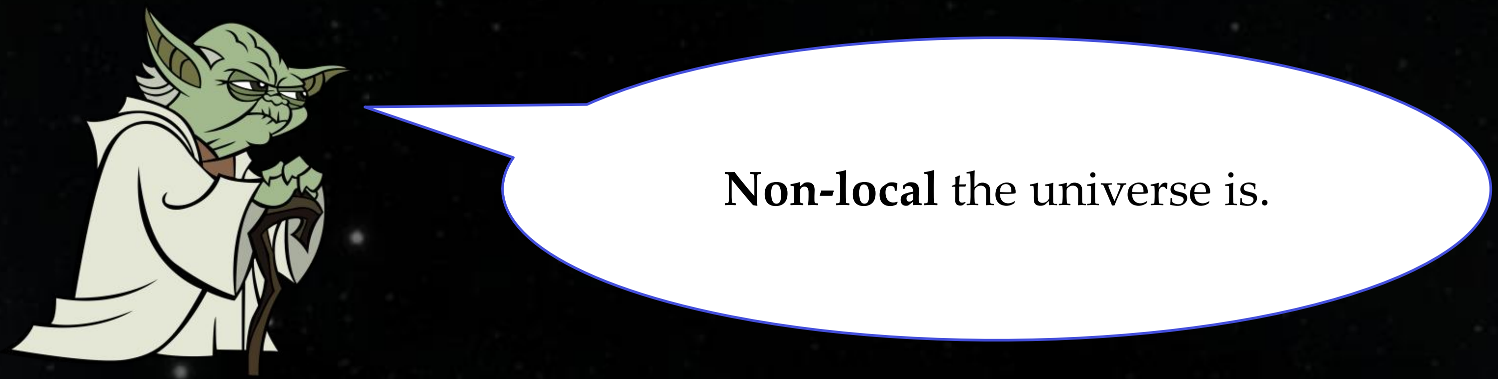
Alternative 2








What have you done / proven?
(1)
sometimes
(2)
(3)
For each round
if instead the switches were off, we would have
got a round
, thus
contradicting rule **(2)**
+
LOCALITY PRINCIPLE



BELL'S THEOREM

In 1964, John Bell suggested how to construct such black boxes using (intricate) quantum particles.

Wikipedia mentions 18 successful Bell tests performed between 1972 and 2018, all confirming the predictions of quantum theory against locality.

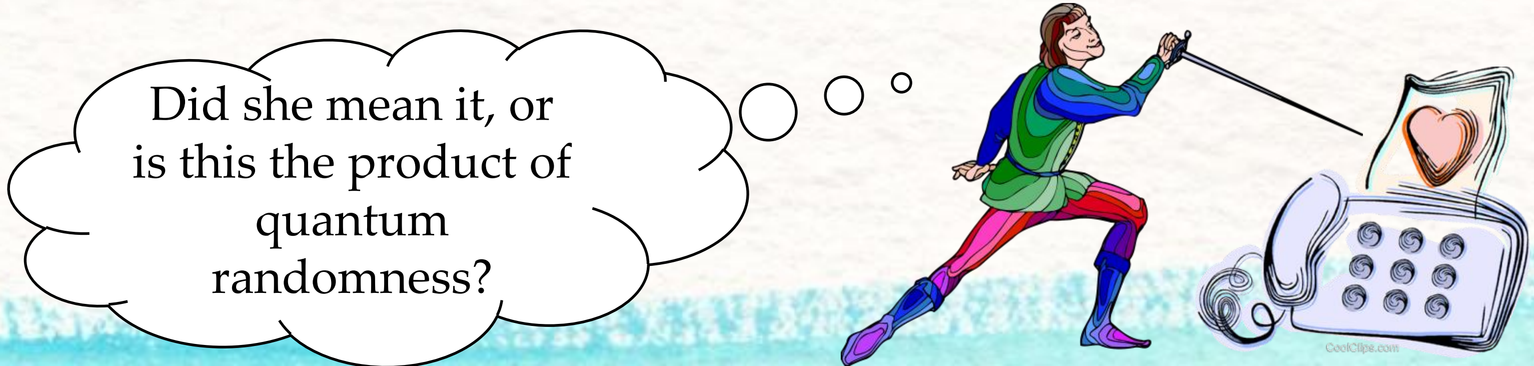
How useful is quantum non-locality?

Non-locality: In quantum mechanics, what happens at one place can instantaneously affect the state of a distant place.

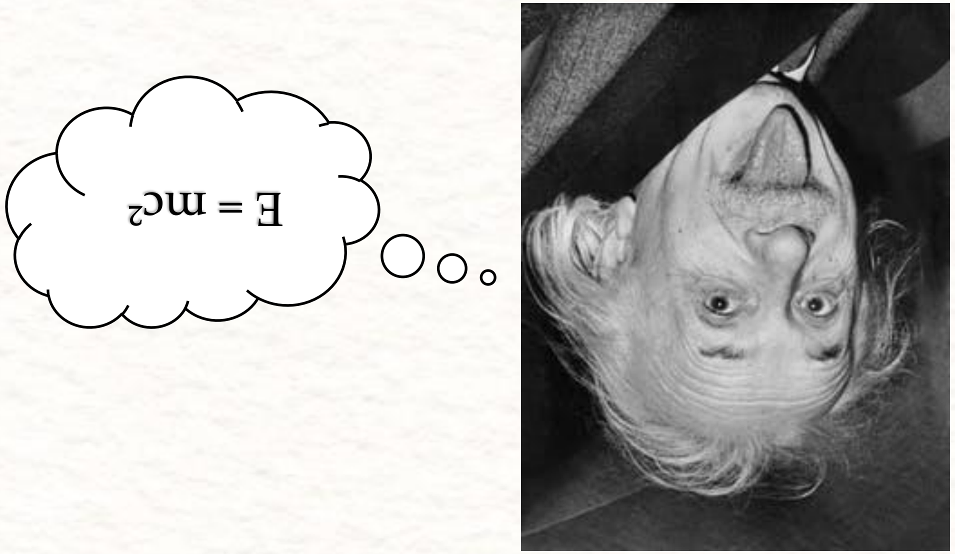
Yet,

No-communication theorem: quantum non-locality does not allow faster-than-light communication.

Idea of the proof: quantum indeterministic features blurs the message.



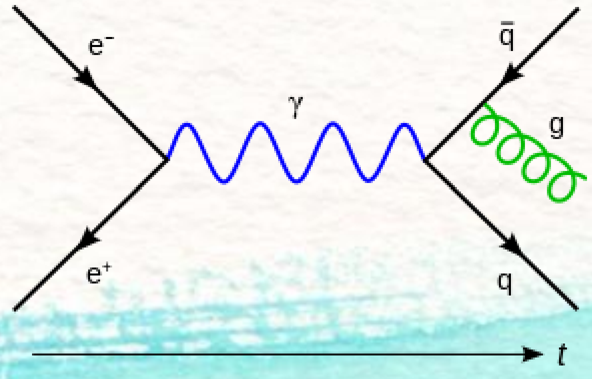
Is quantum mechanics compatible with relativity?



- locality principle: fundamental in Einstein's theory
- denied by quantum mechanics

- Is this why it is so hard to unify general relativity and quantum mechanics?
  - I don't know.

- **Quantum field theory**: (successful) adaptation of quantum mechanics to **special relativity** (= a particular case of general relativity).
  - Used to predict what happens in particle colliders (e.g., LHC)
  - Basis for our current « standard model » = catalogue of elementary particles (e.g. quarks)



Conclusion

- Our universe is not local.

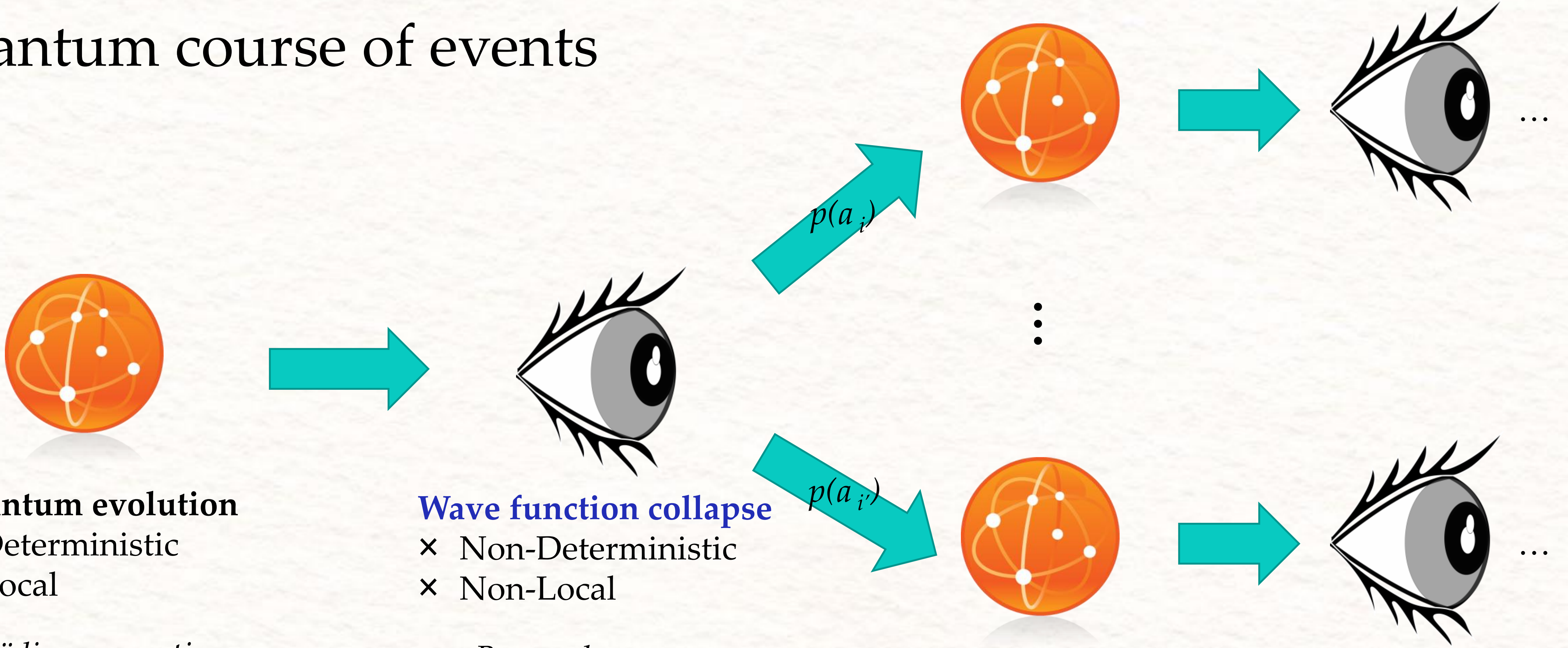
And since I have some time left...

THE MEASUREMENT PROBLEM

The measurement postulate is responsible for the indeterministic (and non-local) features of quantum mechanics.

« When a measurement occurs, the *wavefunction* of the observed system *collapses* ».

Quantum course of events



Quantum evolution
- ✓ Deterministic
- ✓ Local

Schrödinger equation

$$H(t)|\psi(t)\rangle = i\hbar\frac{d}{dt}|\psi(t)\rangle$$

Weird (quantum) states

Wave function collapse
- × Non-Deterministic
- × Non-Local

Born rule

$$p(a_i) = \left|\langle a_i|\psi_S(t)\rangle\right|^2$$

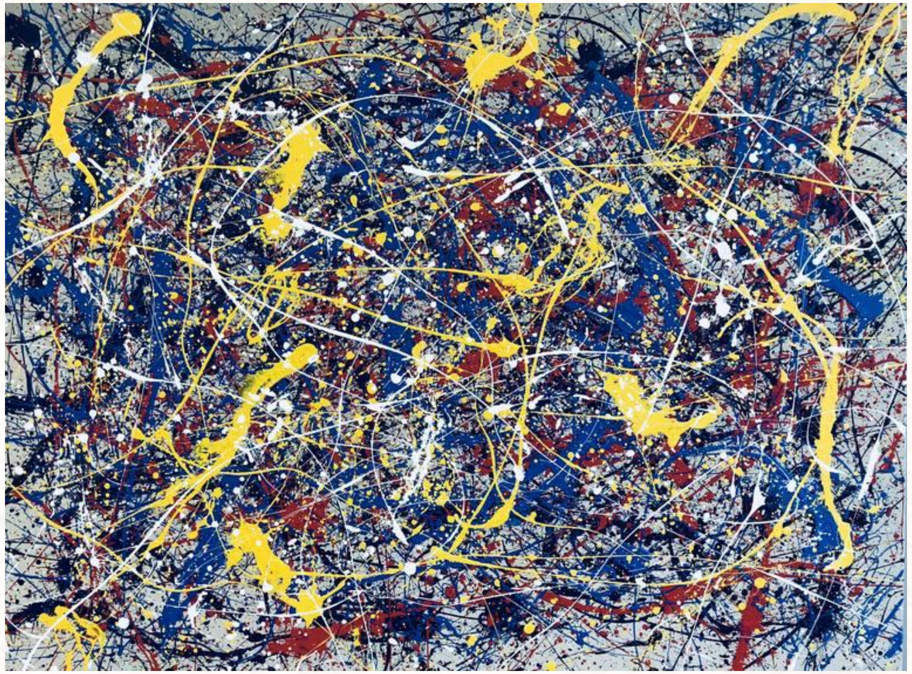
Classical states

Classical picture

Quantum picture

Before we open the eyes, the world is in a **quantum mess**

Such a tidy wardrobe



Wavefunction collapse

- Quantum superposition

- Things get definite properties (such as position)

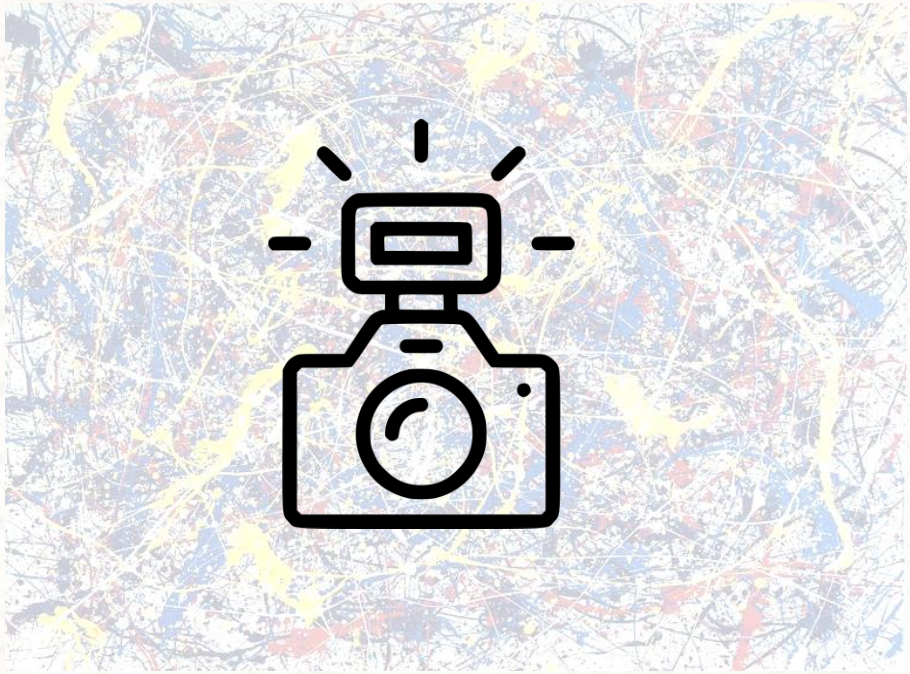
Quantum mess

- Quantum superposition: things may not have definite positions
- Not observable

Quantum mechanics was invented to model our observations, but it predicts some unobservable states...

- Not even representable!
  - Makes no sense to wonder what this state looks like

Disproving the quantum mess



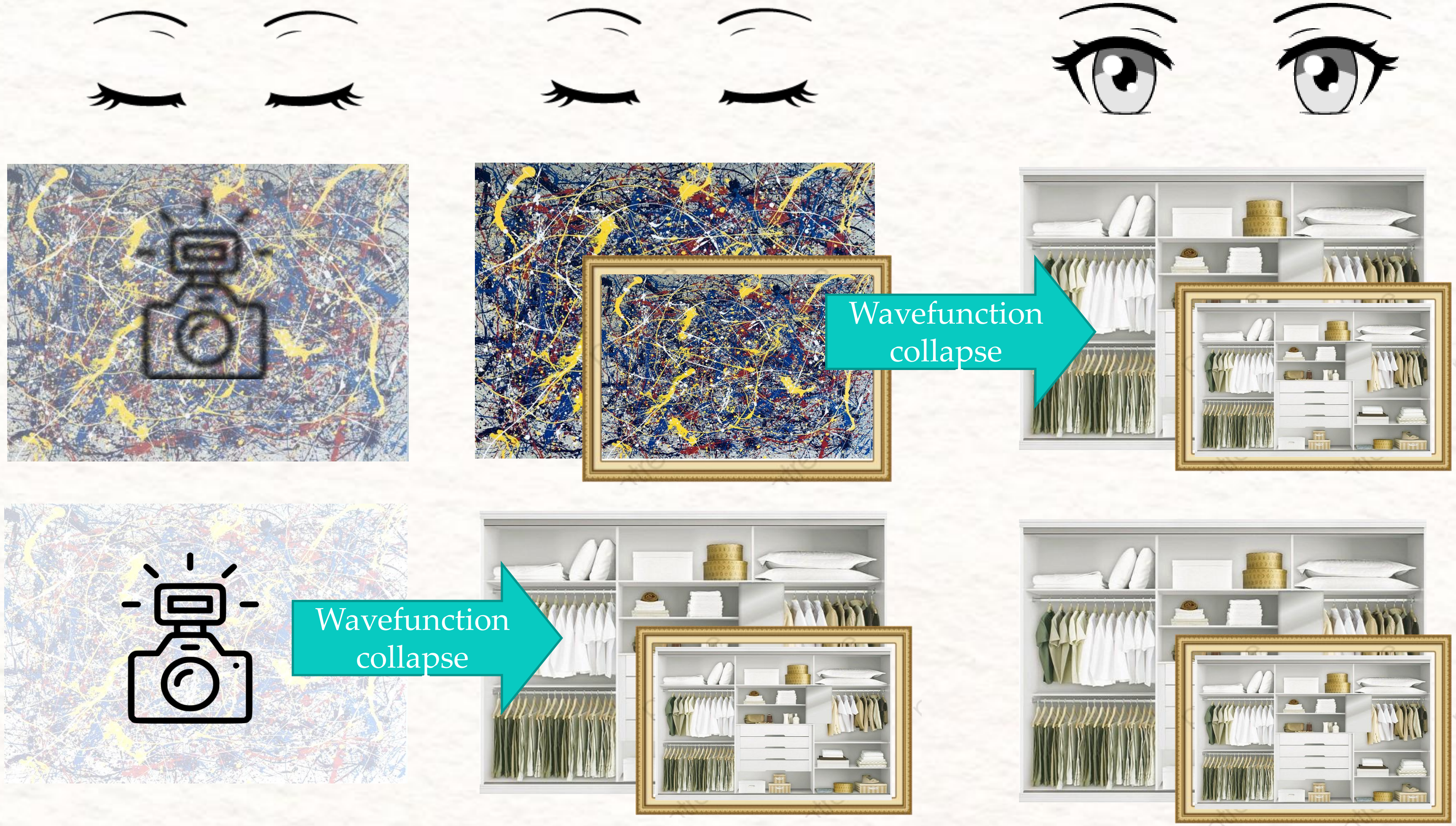
I take a photo, eyes closed.

The photo shows a classical wardrobe!

Some possible quantum accounts

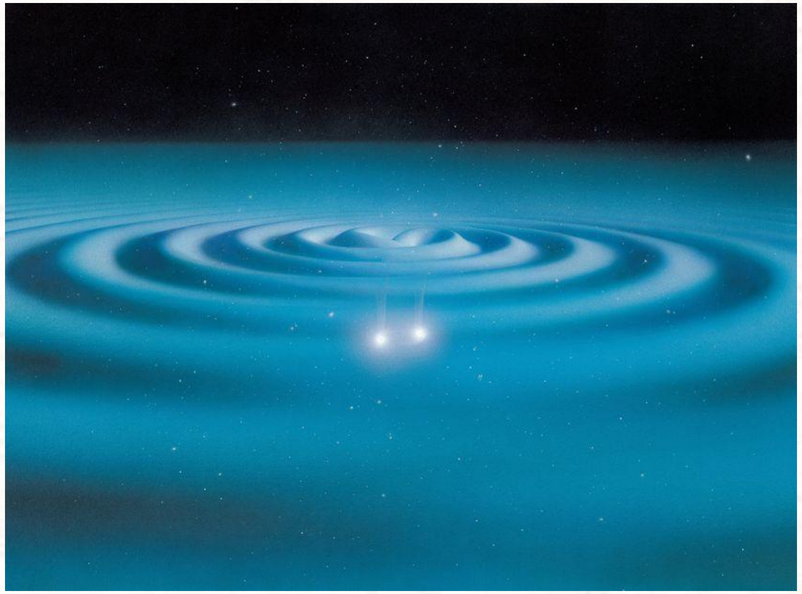
(1)

(2)



what counts as a measurement? The measurement postulate doesn't tell…

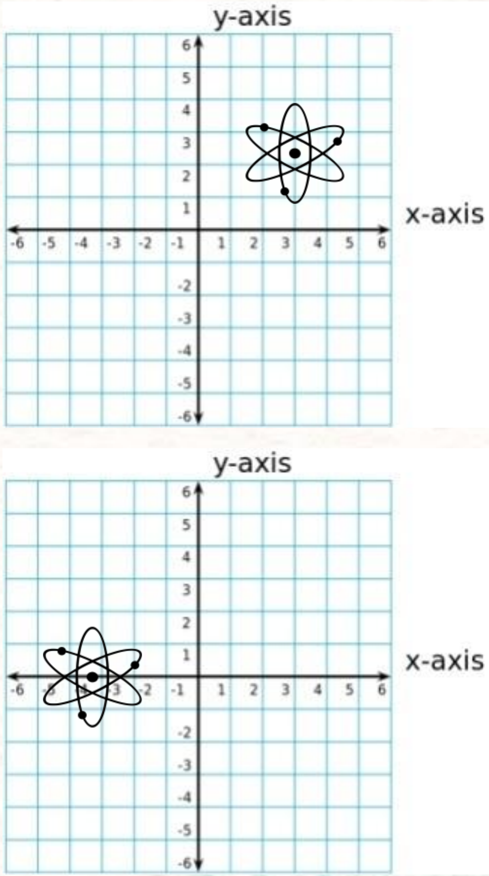
Wave/particle duality: indeterminism



The particle has no definite position

Wavefunction collapse

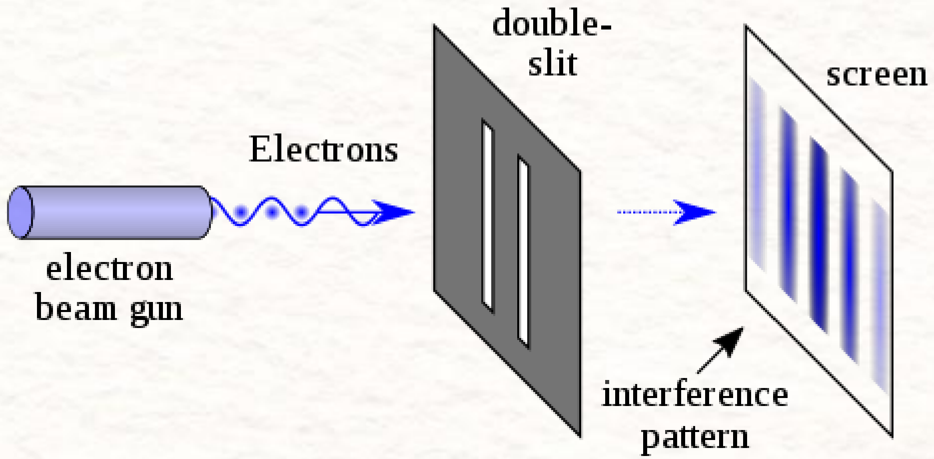
Wavefunction collapse



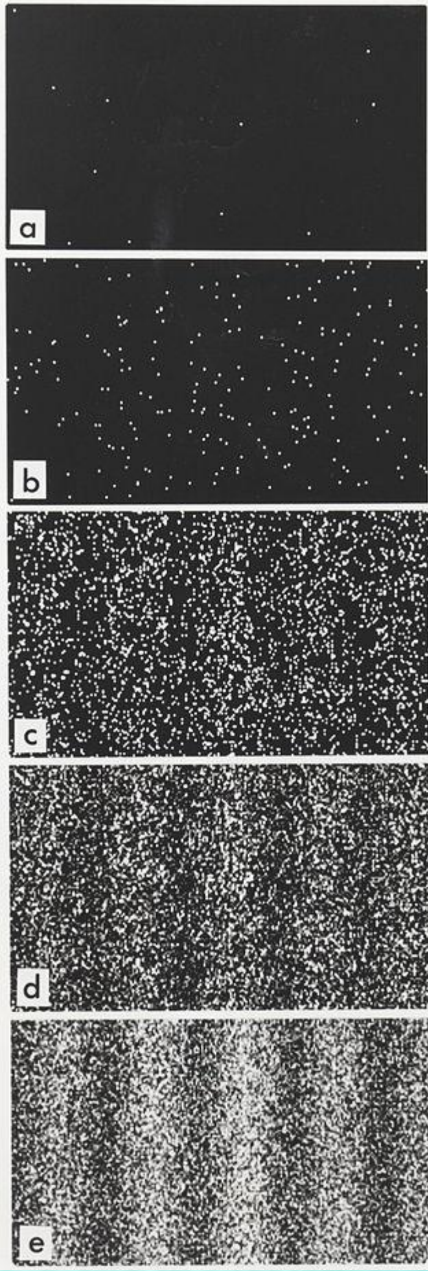
The particle gets a random definite position
(according to some probability distribution)

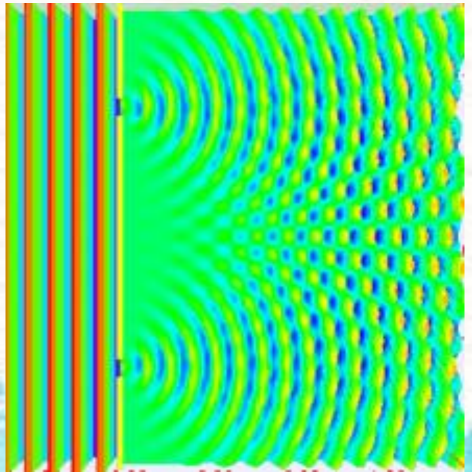
Proving the quantum mess: The double-slit experiment

- First experiment in 1801, by Thomas Young, for light



Electron buildup over time, on the screen



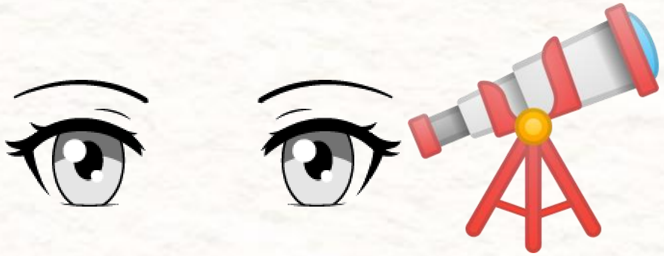


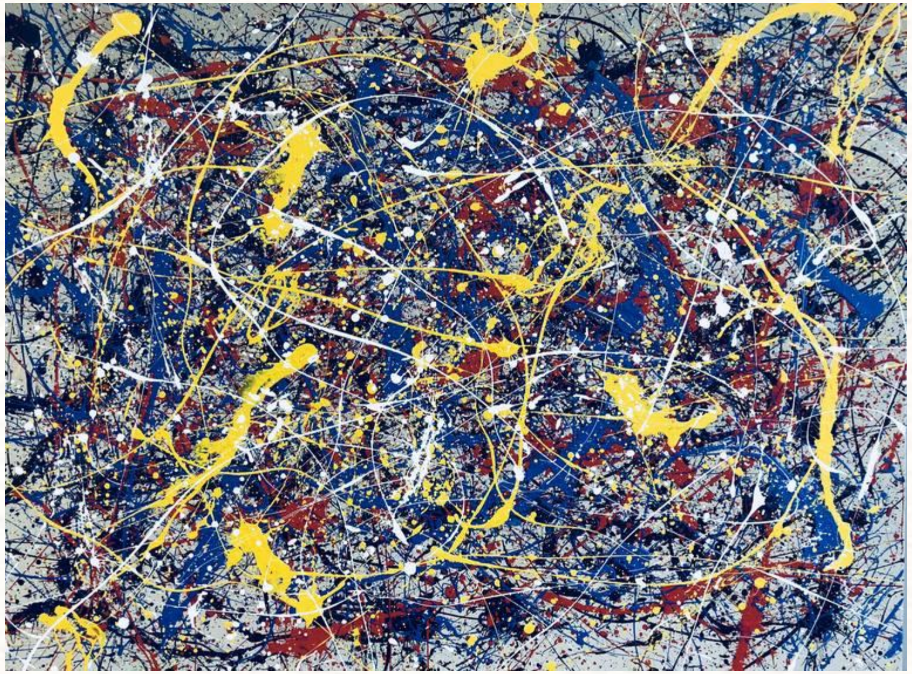
Until it is detected (hits the screen), the electron « behaves » like a wave:

before the wavefunction collapse, the electron « behaves » like a wave.

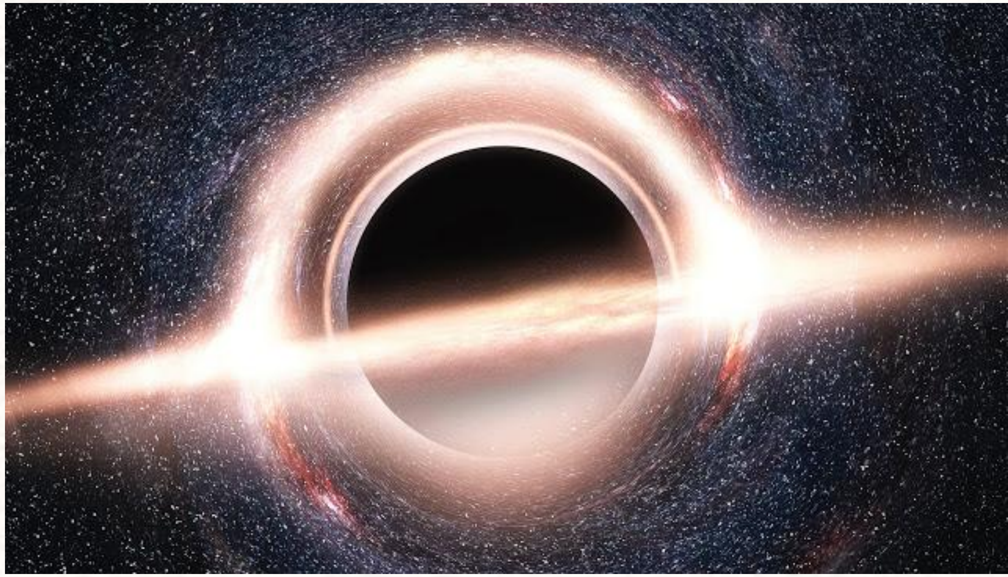
Non-locality

Before we observe distant stars, they are potentially in a **quantum mess**





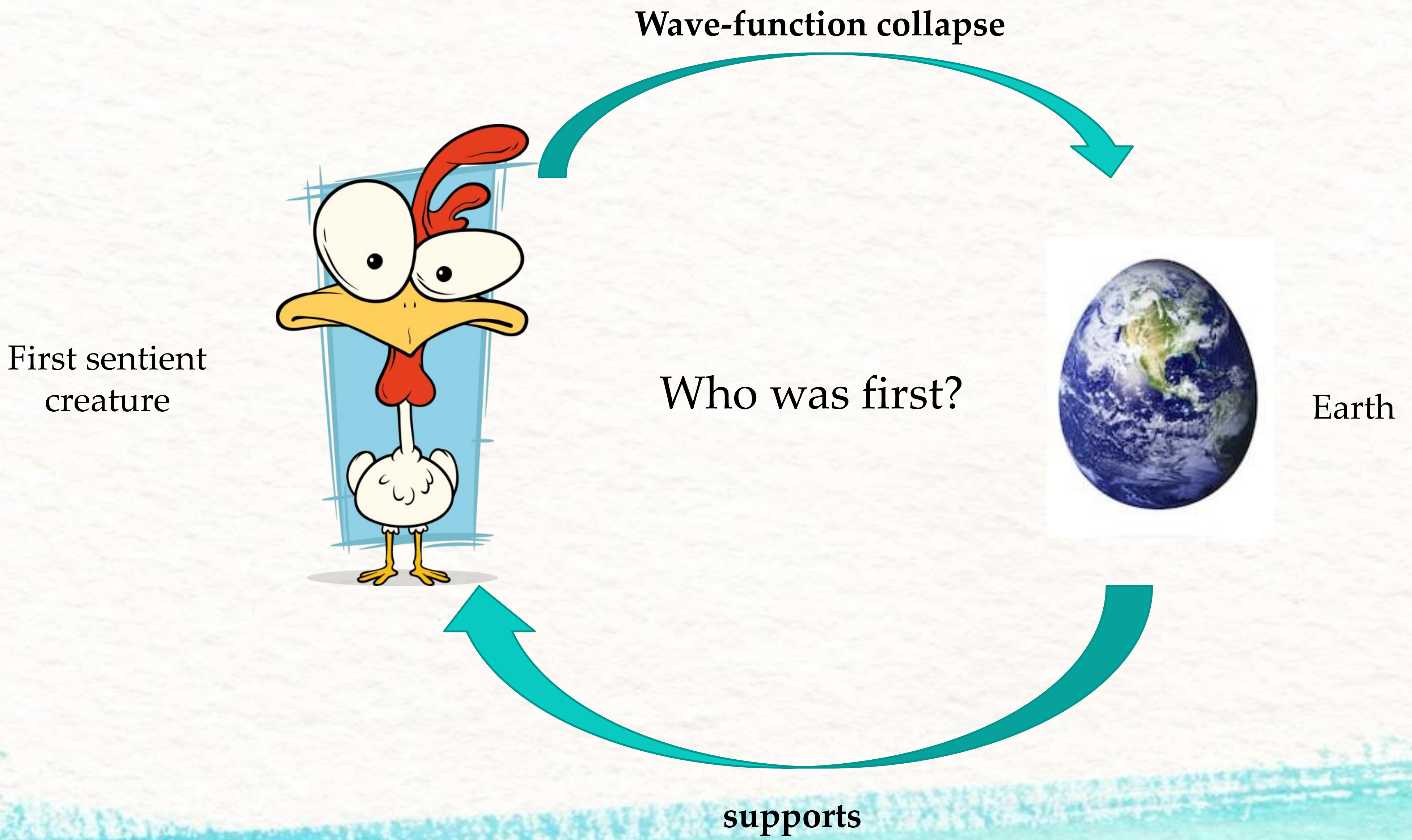
Wavefunction collapse



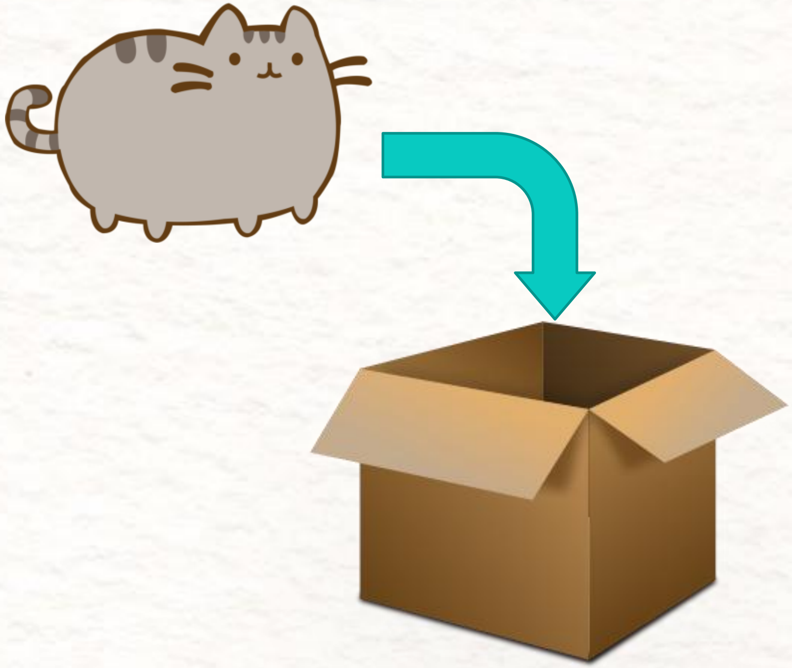
A gargantuan black hole

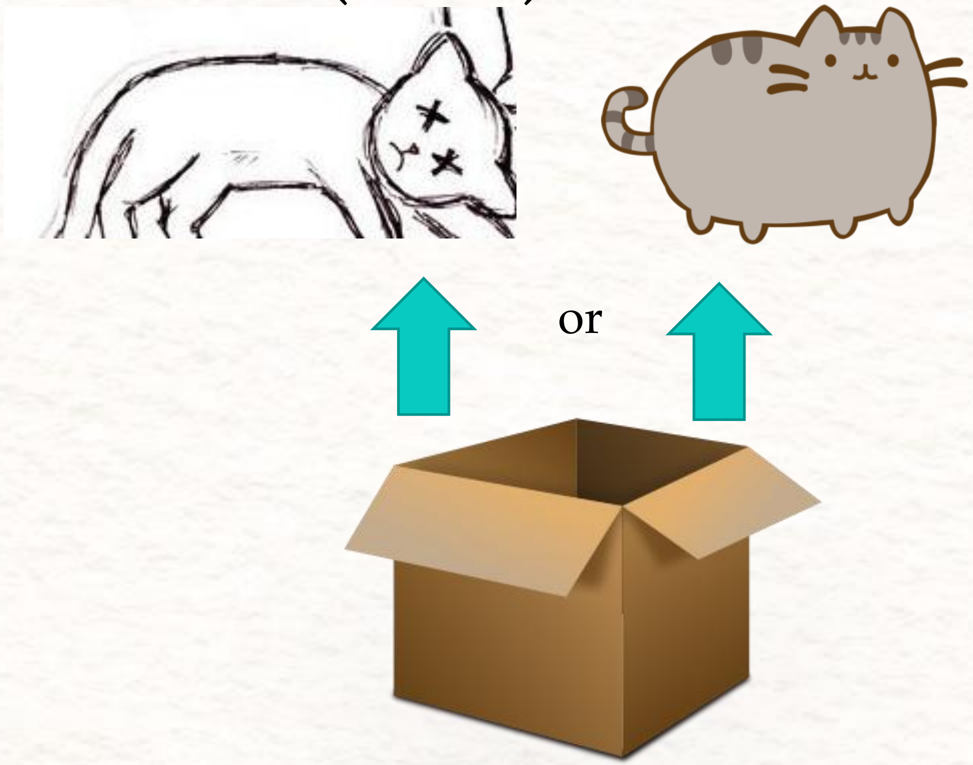
Paradox of ancestrality

How was the world before the first measurement?



The Schrödinger cat gedankenexperiment (1935)





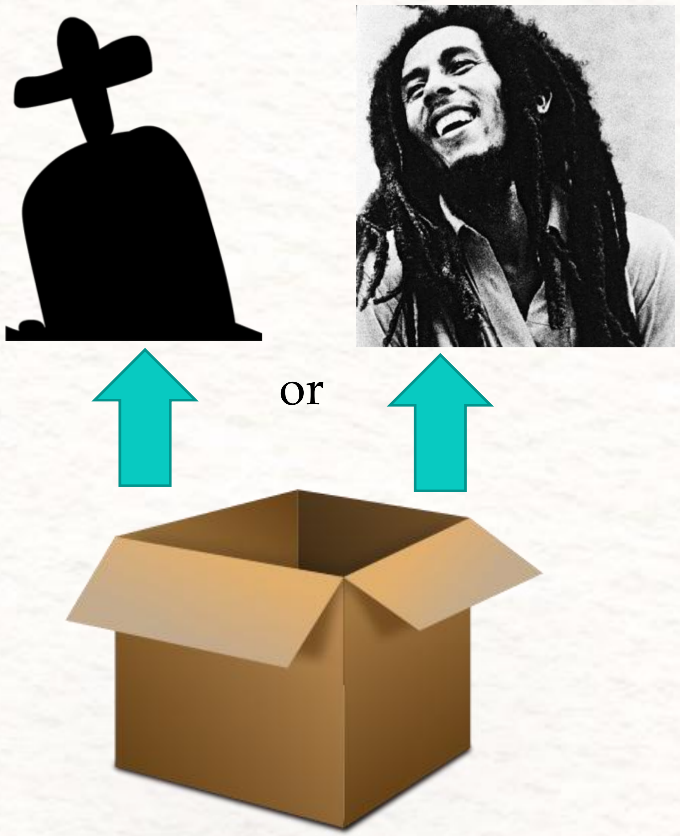
Episode 1
An alive cat is put in a prepared box

Episode 2: Quantum mess
Superposition of states
« alive/dead »

Episode 3: Measurement
The cat is found either dead or alive (non deterministically)

Meow! Why wouldn't I be able to « measure »?

Wigner's friend gedankenexperiment



Episode 1
Alice pushes Bob in a prepared box

Episode 2: Quantum mess
Superposition of states
« alive/dead »

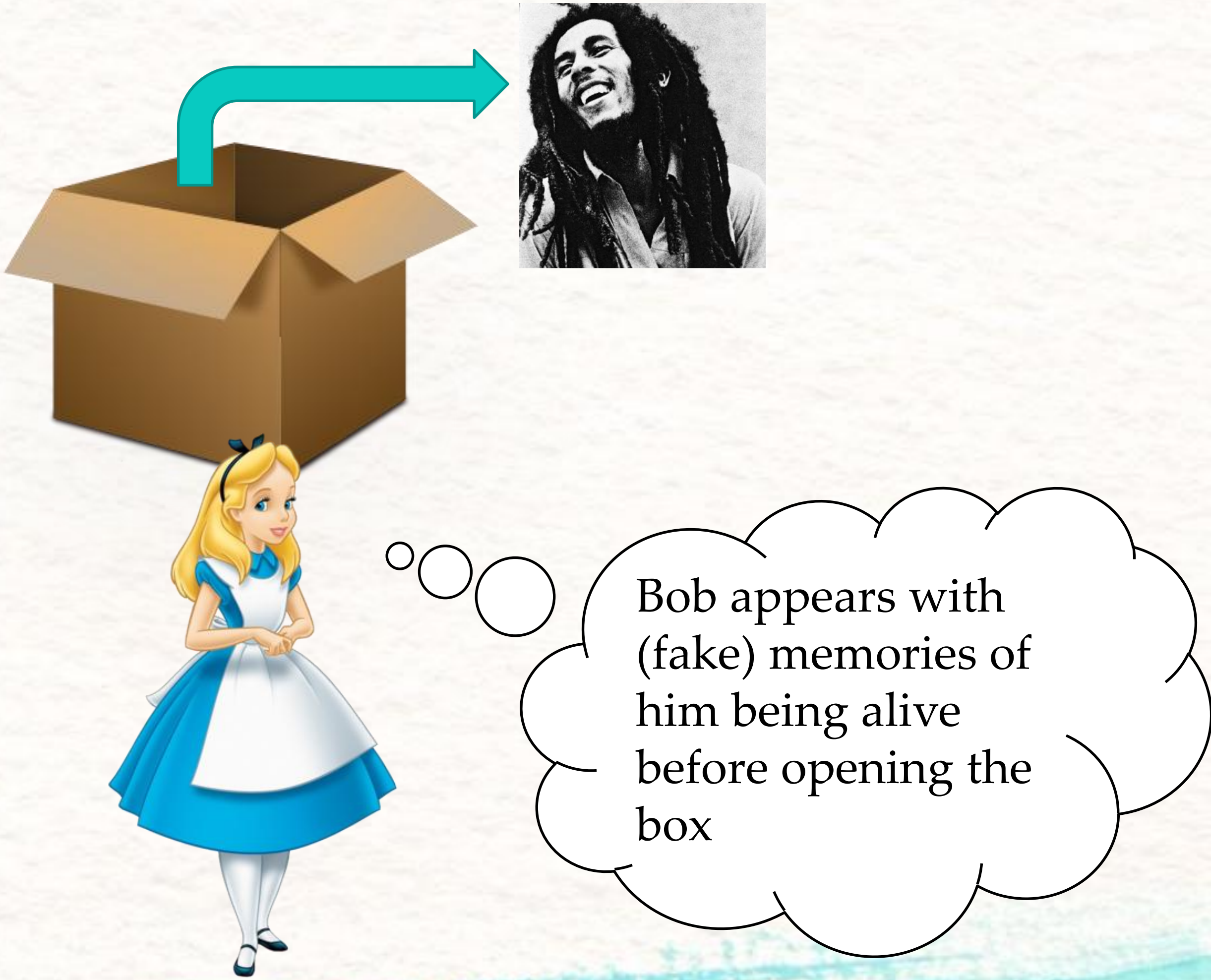
Episode 3: Measurement

- Introduced by Wigner in 1961
- Wigner's (controversial) point: consciousness is responsible for wavefunction collapse

Intersubjectivity?

Bob’s account

Alice’s account



(Relational interpretation of QM: this discrepancy is just the result of "changing the reference frame", similarly to what happen in general relativity!)

What is a measurement?

- The measurement postulate is very useful, but **it does not tells us what a measurement is!**
- It looks also dubiously subjective.
- If noone is there to read a measuring device, does the measurement postulate applies?

THE MEASUREMENT PROBLEM

$\Rightarrow$ multiple interpretations of quantum mechanics

Some popular solutions to the measurement problem

I don't understand

- **Copenhagen interpretation**: historically, the first mainstream one

I understand

I don't agree

- Explain when a **wavefunction collapses**, e.g.,
  - When involving « big » enough objects,
  - When a « mind » enquires about the world

I don't understand

I understand

- Remove the measurement postulate
  - **Multi-worlds**
  - ♥ **Bohmian mechanics**

Origin of indeterminism/non locality?

Not so popular because « very » non-local

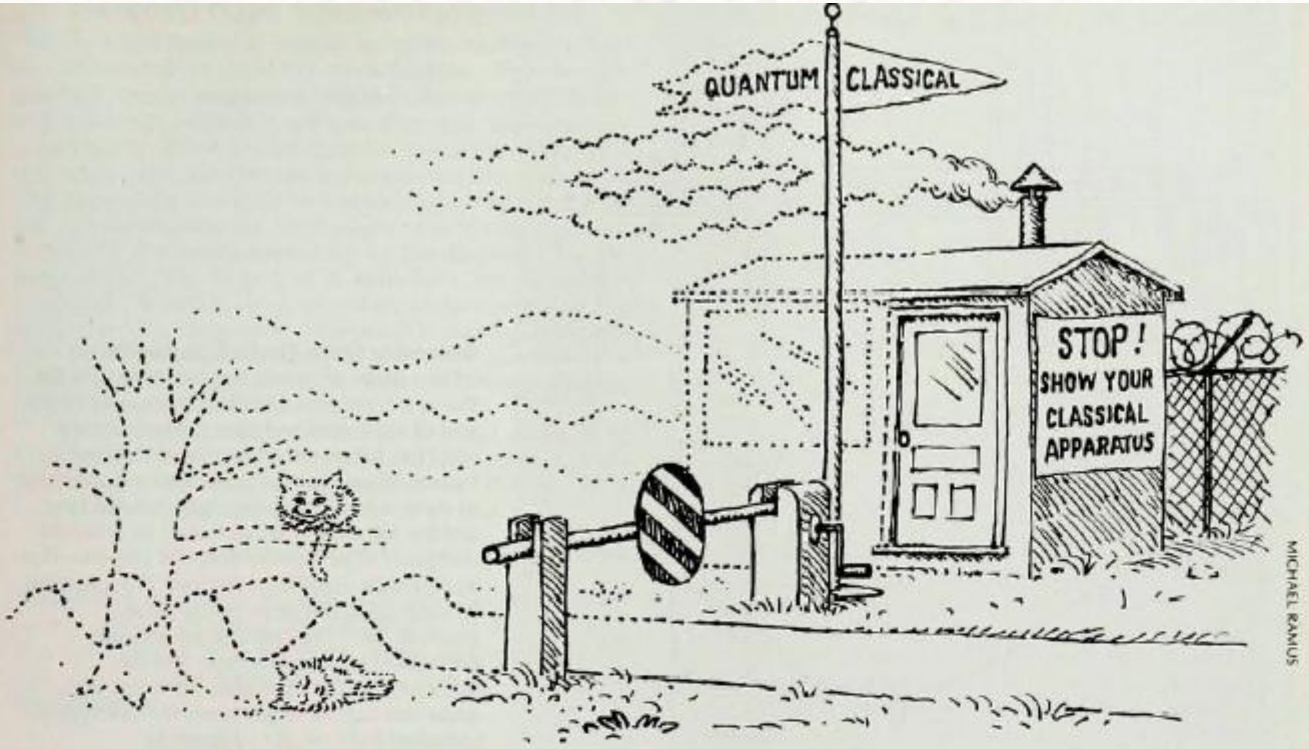
Copenhagen school

Bohr, Heisenberg, Pauli

Quantum mechanics with the measurement postulate, as I have described so far.

« Physics is about predicting the outcome of observations, nothing more. »

Spontaneous wave function collapse at large scale?



Delineating the border between the quantum realm ruled by the Schrödinger equation and the classical realm ruled by Newton's laws is one of the unresolved problems of physics. **Figure 1**

How big can an object be before the collapse?

Scientists supersize quantum mechanics

Geoff Brumfiel

Nature (2010) | Cite this article

Largest ever object put into quantum state.

A team of scientists has succeeded in putting an object large enough to be visible to the naked eye into a mixed quantum state of moving and not moving.

Letter | Published: 25 April 2018

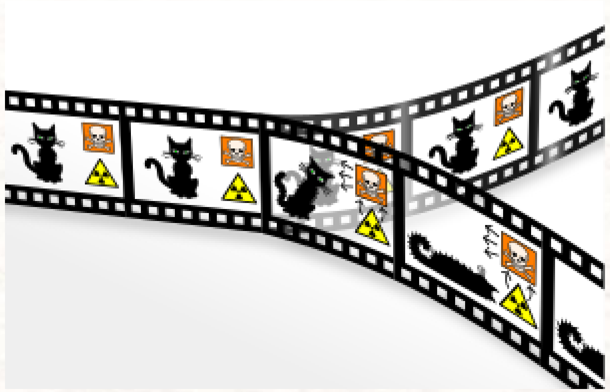
Stabilized entanglement of massive mechanical oscillators

The frontier between quantum and classical keeps being pushed up.

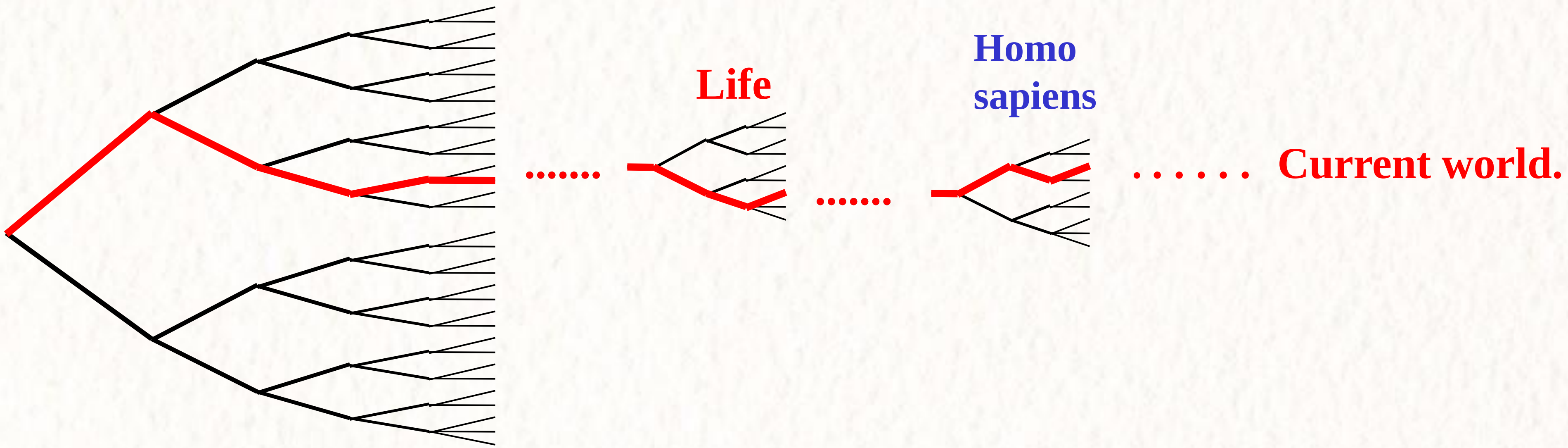
Many-world interpretation

- Originated in Everett's Princeton Ph.D. thesis "The Theory of the Universal Wavefunction", 1957

- No measurement postulate
- the world splits in as many worlds as possible outcomes each time a wavefunction collapse would have led to different outcomes



Universe – a bifurcations tree



"Probability" for **Life** → **Hom.sap.** → **Current world** extremely small.

All branches remain – **no collapse** of wave function

My concerns with the many-world interpretation

- Why am I aware only of this particular world?
- Where does the observable indeterminism come from, if not from the measurement postulate?
- How to explain the observed Born rule (observed probability distribution)?
  - Answer: Wallace, David (2009). "A formal proof of the Born rule from decision-theoretic assumptions"

Bohmian mechanics

Origin:
- **de Broglie**’s pilot wave theory in the 1920s
- in 1927, was persuaded to abandon it in favour of the then-mainstream Copenhagen interpretation

- **David Bohm**, dissatisfied with the Copenhagen interpretation rediscovered de Broglie's pilot-wave theory in 1952.

- widely deemed unacceptable by mainstream theorists, mostly because of its explicit non-locality

Features of Bohmian mechanics

- Remove the measurement postulate

Non-locality?
The Schrödinger equation is modified and becomes non-local

Indeterminism?
Observed indeterminism = ignorance of the initial state

No quantum superposition

Conclusion

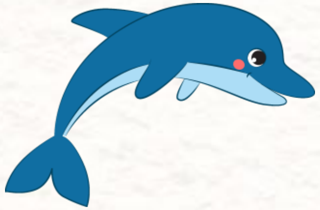
- The universe is non-local.
- Quantum mechanics is hard to interpret.
- I like Bohmian mechanics (although I don′t know the details)

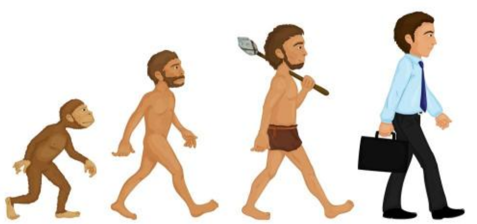
Paradox of ancestrality

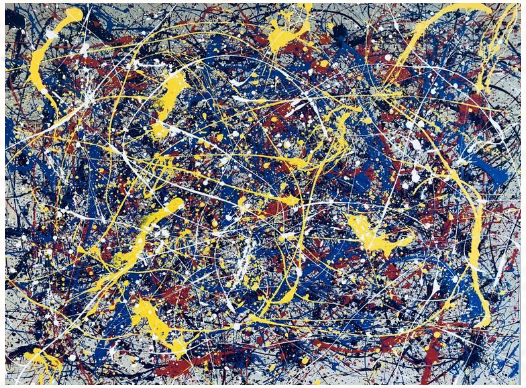
How was the world before the first measurement?

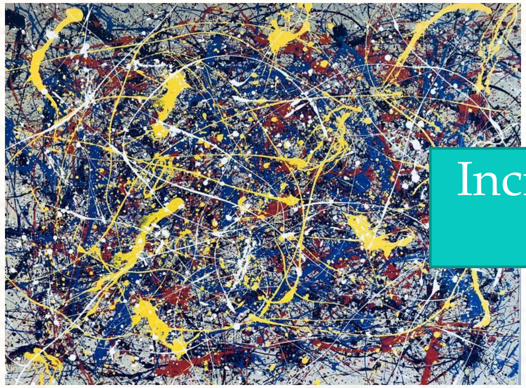
big 

More and more accurate « observers » come to life

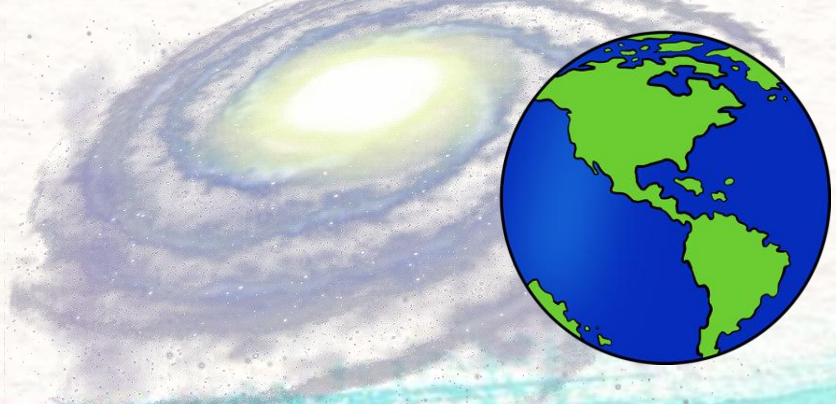








Increasing wavefunction collapses



- Earth did not exist before the first (earth) observer?
- Earth observer cannot exist before Earth?