God Plays Dice

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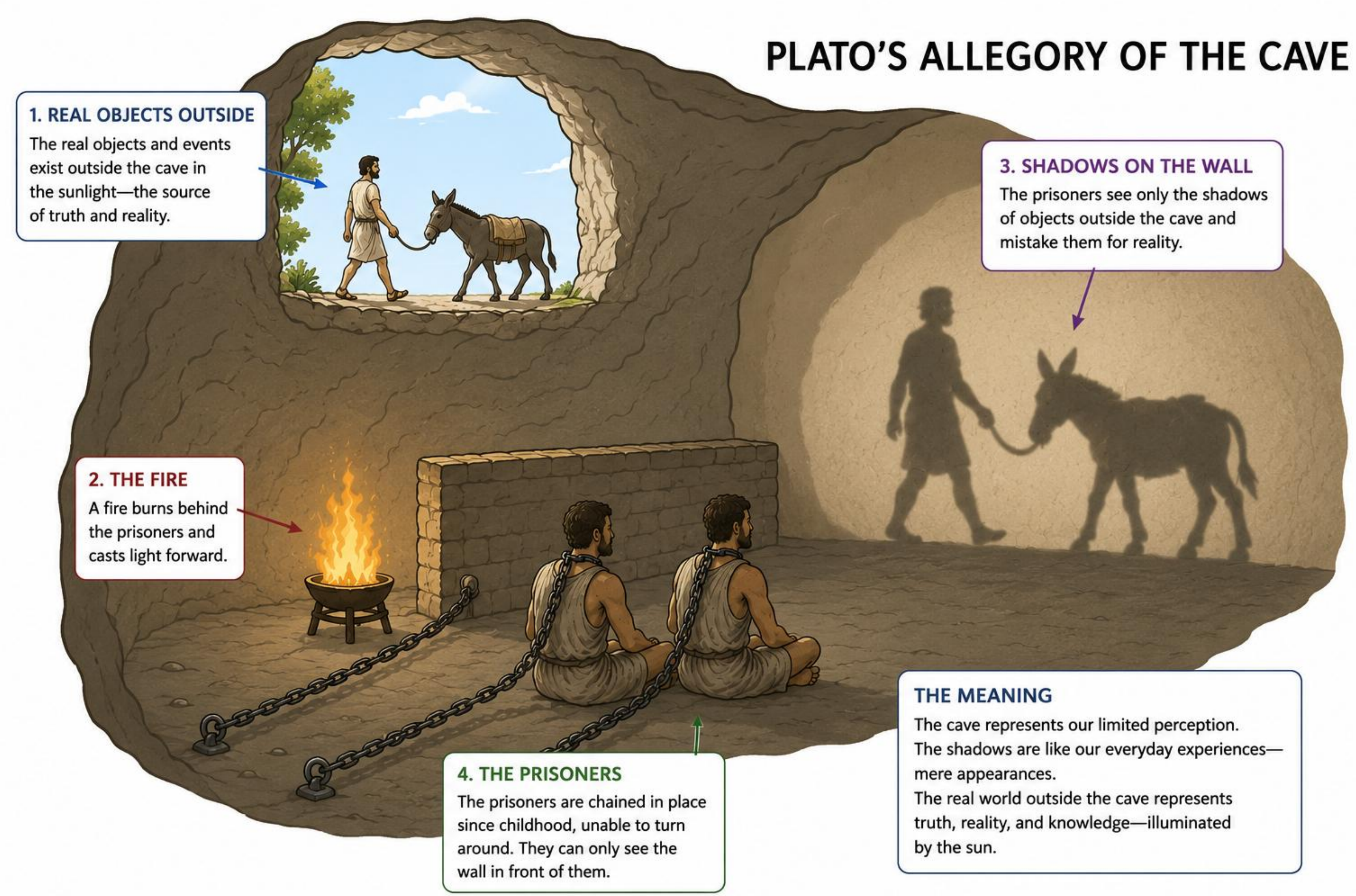
1926: in a letter from Albert Einstein to Max Born

“The theory yields much, but it hardly brings us closer to the Old One's secrets. I, in any case, am convinced He does not play dice.”

From Plato’s Republic Book VII



1935: Einstein, Podolsky and Rosen

"Can Quantum-Mechanical Description of Physical Reality be Considered Complete?"
Physical Review **47**, 1935

- EPR used the QM rules to conclude the rules were "incomplete".

  > "While we have thus shown that the wave function does not provide a complete description of the physical reality, we left open the question of whether or not such a description exists. We believe , however, that such a theory is possible"

- i.e. "…a theory with ***hidden variables*** is possible"

1964: Bell

"On the Einstein Podolsky Rosen Paradox“
Physics Physique Fizika **1**, 1964

- Abstract:

  “The paradox of Einstein, Podolsky and Rosen was advanced as an argument that quantum mechanics could not be a complete theory but should be supplemented by additional variables. These additional variables were to restore to the theory causality and locality. In this note that idea will be formulated mathematically and shown to be incompatible with the statistical predictions of quantum mechanics.”

- Conclusion:

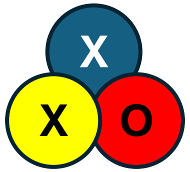
  “…Of course, the situation is different if the quantum mechanical predictions are of limited validity…”

- Bell’s theorem (a particular case):

  If a certain measurement, ***S*** is < 5/9, then hidden variables can’t explain quantum mechanics
  …and therefore, according to EPR, no **realistic** physical theory is possible.

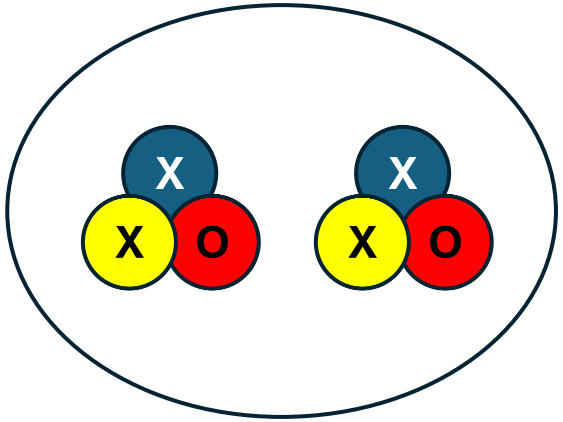
Experimental setup – “The Real World”

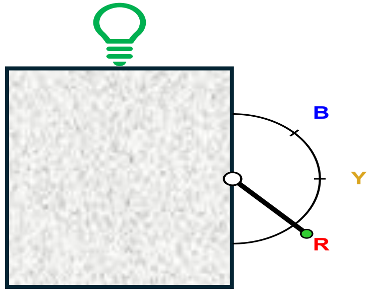
A “particle” is a triad of colored “balls”, one yellow, one red, one blue.



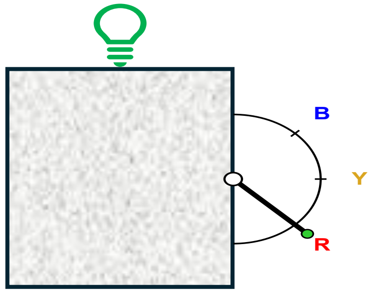
Each “ball” either has property **X** or property **O.**
Any configuration of X’s and O’s is allowed.

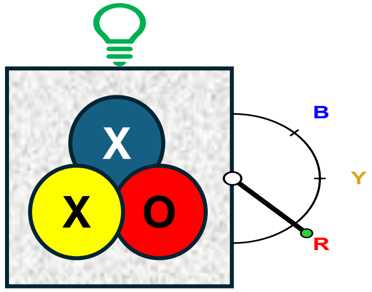
A particle-pair factory produces two pairs with identical configurations.



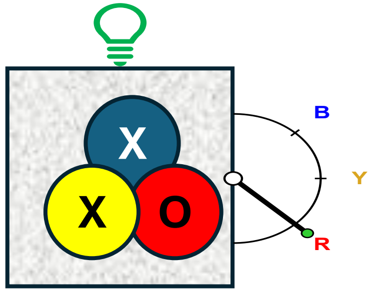


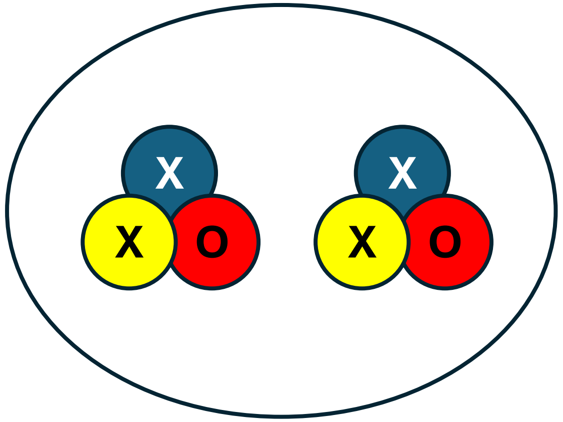
Then the two particles fly off in opposite directions towards 2 detectors





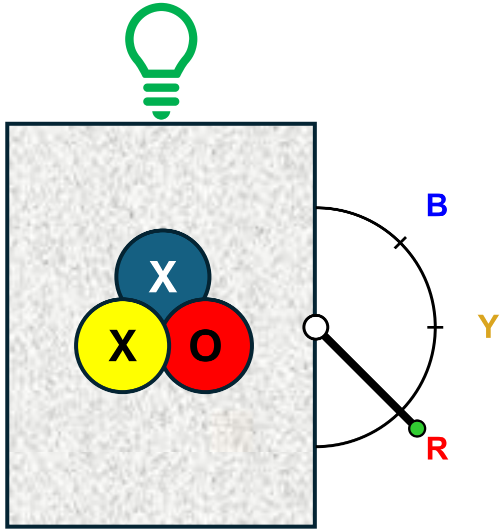
The detectors look at the colored balls corresponding to the settings of the levers





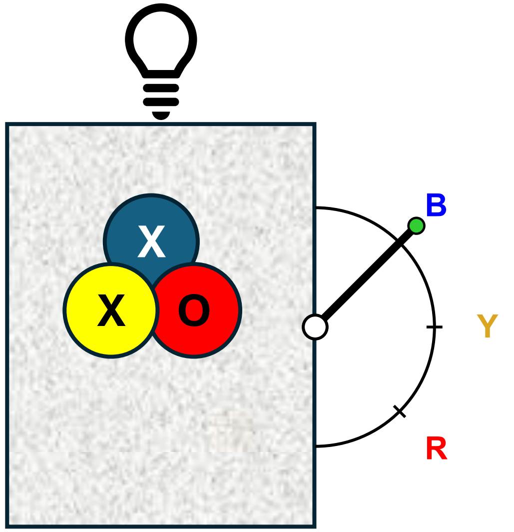
Configuration 1

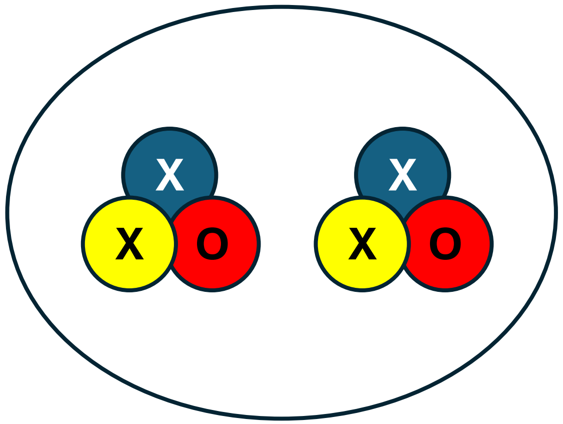
The light goes green for ***O*** and goes black for ***X***



	B	Y	R
B			*D*
Y			
R			

S = *"2 lightbulbs have same color"*
D =*"2 lightbulbs have different colors"*





Configuration 1

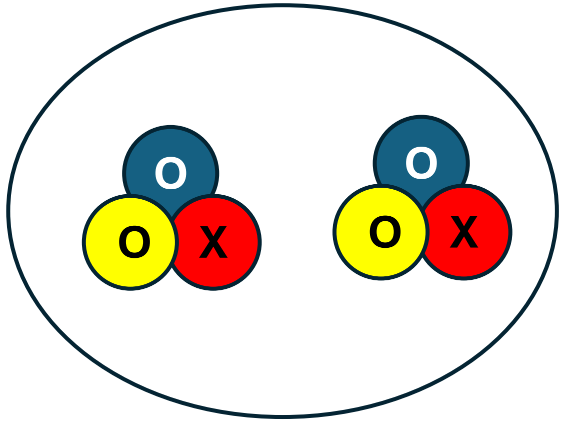
The light goes green for ***O*** and goes black for ***X***

	B	Y	R
B	*S*	*S*	*D*
Y	*S*	*S*	*D*
R	*D*	*D*	*S*

S = *"2 lightbulbs have same color"*
D =*"2 lightbulbs have different colors"*

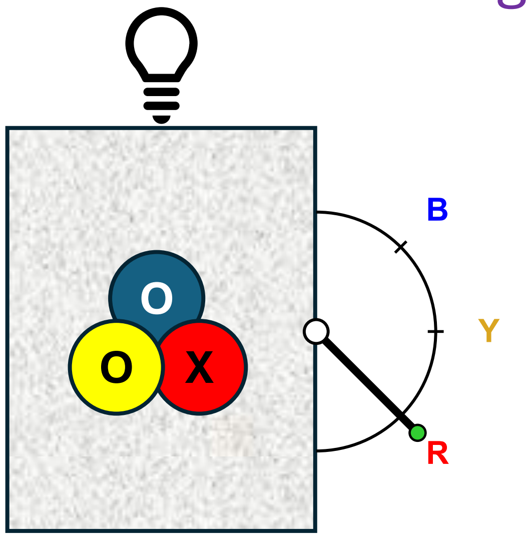
Score = (# of S's) /(Total)

*Configuration 1's score is **5/9***



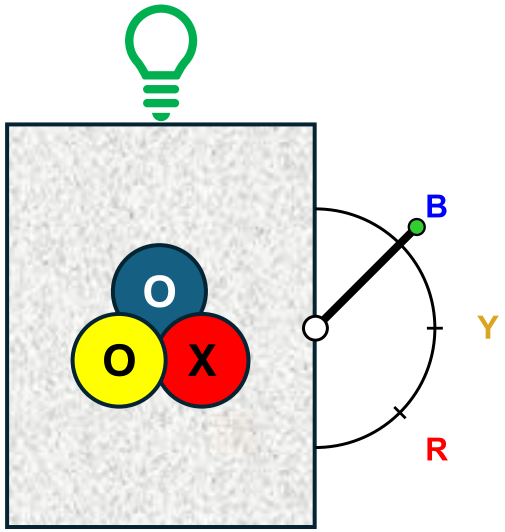
Configuration 2

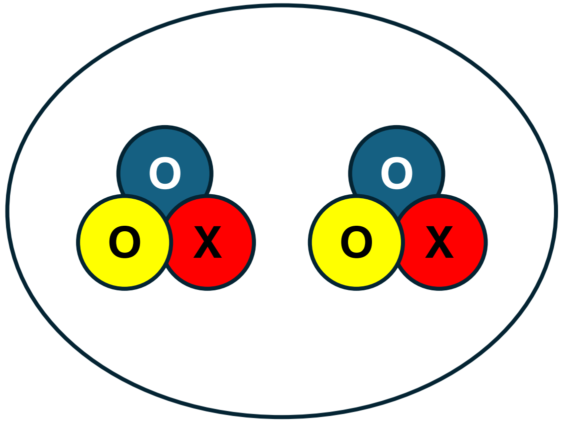
The light goes green for ***O*** and goes black for ***X***



	B	Y	R
B			*D*
Y			
R			

S = *"2 lightbulbs have same color"*
D =*"2 lightbulbs have different colors"*





Configuration 2

The light goes green for ***O*** and goes black for ***X***

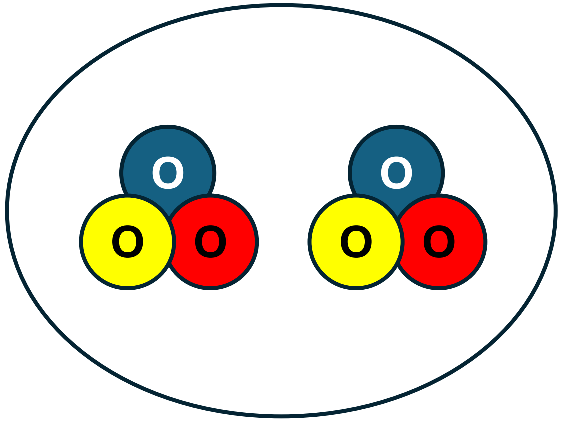
	B	Y	R
B	*S*	*S*	*D*
Y	*S*	*S*	*D*
R	*D*	*D*	*S*

S = *“2 lightbulbs have same color”*
D =*“2 lightbulbs have different colors”*

Score = (# of S’s) /(Total)

Configuration 2’s score is ***5/9***

T



Configuration 3

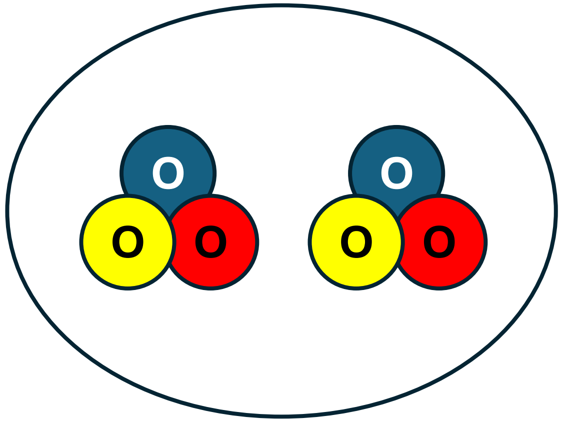
The light goes green for ***O*** and goes black for ***X***

	B	Y	R
B			
Y			
R			

S = “2 lightbulbs have same color”
D =“2 lightbulbs have different colors”

Score = (# of S’s) /(Total)

Configuration 3’s score is



Configuration 3

The light goes green for ***O*** and goes black for ***X***

	B	Y	R
B	*S*	*S*	*S*
Y	*S*	*S*	*S*
R	*S*	*S*	*S*

S = “2 lightbulbs have same color”
D =“2 lightbulbs have different colors”

Score = (# of S’s) /(Total)

*Configuration 3’s score is **9/9***

General Rule

- When all colors are the same, the score = 9/9
- When they aren't the same, the score = 5/9

Suppose we do the experiment **N** times (**N** is very large)

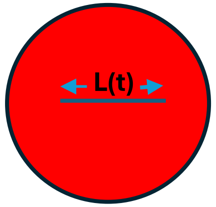
- Each configuration appears many times (some more than others)
- Each observer randomly chooses the lever-color each time
- ***Then for each configuration, each element of the chart is sampled approximately 1/9 of the time***.

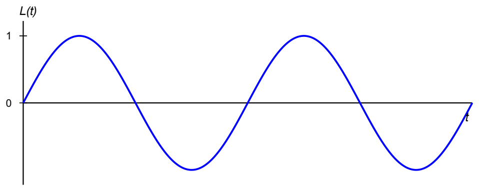
Therefore, the average Score for each configuration is 5/9 or 9/9.

Bell's Theorem: the average Score overall ≥ 5/9

Two "real world" sets of rules

- The ball factory produces
  - All-X particles 25% of the time
  - All-O particles 25% of the time
  - Mixed-value particles 50% of the time
  - Prediction: the <u>average Score</u> = 0.5*1 + 0.5*(5/9) <u>= 0.778</u>
- The ball factory doesn't mark balls with X or O. Instead, it prints a line of length L(t) = sin(t) on each colored ball
  - The detector-light goes green if L(t) < 0.5
  - The detector-light goes black if L(t) ≥ 0.5
  - Prediction: both-green 50% of the time, both-black 50% so <u>average Score = 1</u>

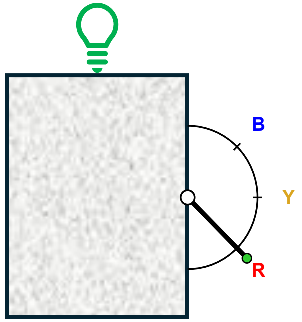




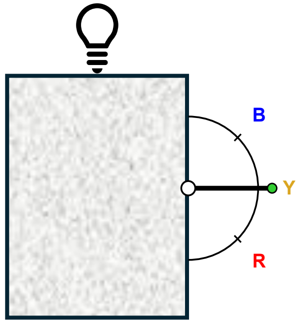
Notice: you can make average-Score predictions even without knowing details of the factory or detector

Black-box detectors – The "Shadow World"

Examples

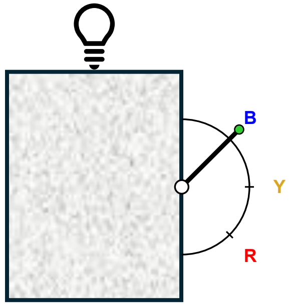


Press a button & choose levers

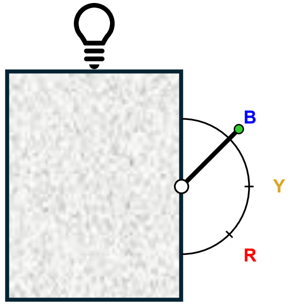


different-colored lights

The red property on the LHS differs from the yellow property on the RHS



Do it again



same-colored lights

The blue properties on LHS and RHS are the same. Ditto for red on both sides & For yellow on both sides.

Conclusions:

- There are 3 *different* variables, measured by the position of the lever (different levers, different-colored lights)
- Each variable has one of two properties (green light, black light)
- For each particle, the variables have **identical properties**
- ***Therefore the "real world" must resemble the previous slides and the Score ≥ 5/9.***

1981: Aspect, Grangier and Roger

"Experimental Tests of Realistic Local Theories via Bell's Theorem"
Phys. Rev. Lett. **47**, 1981

- Abstract:

  "…Our results, in excellent agreement with the quantum mechanical predictions, strongly violate the generalized Bell s inequalities, and rule out the whole class of realistic local theories…"

- Hidden variables are ruled out by experiment
- Nobel Prize 2022: Aspect, Klauser and Zeilinger

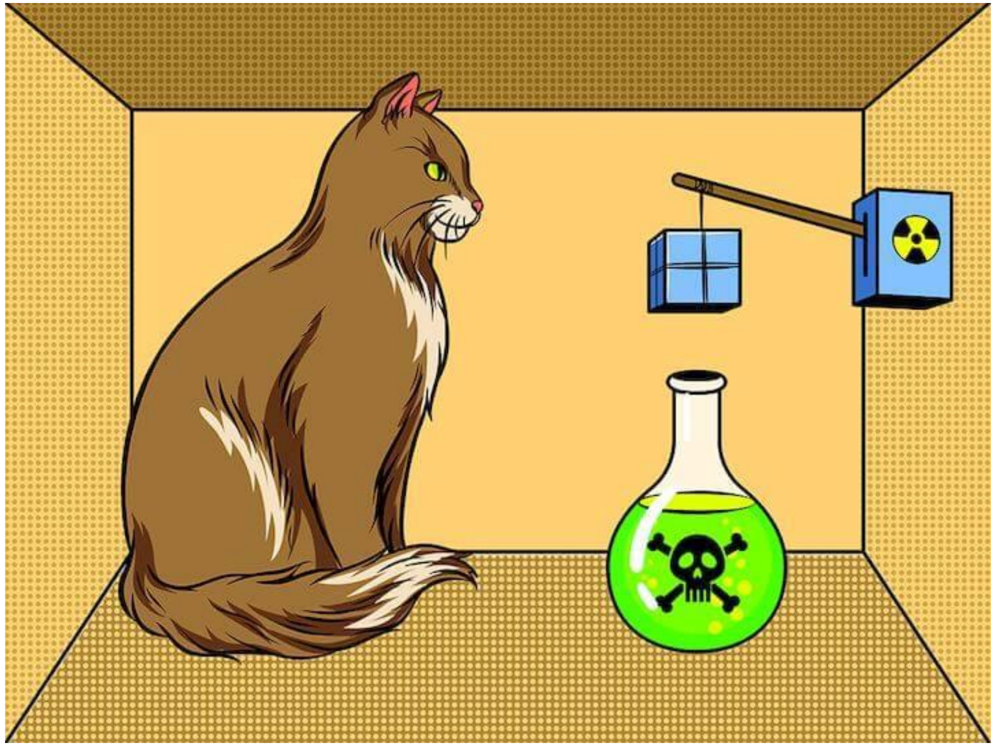
What is Quantum Reality?

It must violate Bell's theorem

- The two key assumptions of Bell's theorem – at least one must be violated
  1. It's meaningful to say that variables *have a property* (e.g. **X** or **O**)
  2. Two observers/detectors can't interact faster than the speed of light
- Assumption 1: Huh???
  - EPR: "If, without in any way disturbing a system, we can predict with certainty the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."
  - Metaphysical: Even God doesn't know if the variable is **X** or **O.**
  - Practical (Neils Bohr): Follow the rules and compute – stop trying to *picture* it.
- Assumption 2: Entanglement
  - Einstein, in letter to Max Born 1947: *"…spooky action at a distance…"* (*"spukhafte Fernwirkung"*)
  - Speed of light isn't relevant. Instantaneous action at a distance is inconsistent with cause/effect.
  - **Such a theory is also known as *nonlocal*.**

The Schrodinger Cat Experiment

Schrodinger: "The Present Situation in Quantum Mechanics" *Naturwissenschaften* **23**, 1935



- A cat in an opaque crate, along with a vial of hydrocyanic acid and a radioactive atom. If the atom decays radioactively, it tips the vial of acid, and the cat dies.
- Until the observer opens the box, the cat is neither alive nor dead.

Why this never helped me understand QM

- Suppose radioactivity was classical. There is some probability the cat is alive and some probability it is dead. When we open the box, we discover which it is.
- That's like saying the weather forecast is 50% rain. Until you open the shades, you don't know if it's raining or not.
- Schrodinger never intended for the cat to help us understand QM.
  - His goal was to reveal that the rules of QM are intuitively absurd.
  - But that's only manifest if you already think they are absurd.
- *For a fun attempt to illustrate dead/alive, see the Dybbuk scene of "A Serious Man" by the Coen brothers*

Quantum Computing: Harnessing Entanglement

- The Aspect experiment set up entangled states
- Quantum Computers use entangled states to solve problems more quickly than classical computers
- The Grover and Schor algorithms are the heirs of Bell’s theorem

A quotation from Richard Feynman

The Character of Physical Law 1964

"I think I can safely say that nobody understands quantum mechanics."

Another quotation from Richard Feynman

We have always had a great deal of difficulty
understanding the world view
that quantum mechanics represents.

At least I do,
because I'm an old enough man
that I havent' got to the point
that this stuff is obvious to me.

Okay, I still get nervous with it….

You know how it always is,
every new idea,
it takes a generation or two
until it becomes obvious
that there's no real problem.

I cannot define the real problem,

therefore I suspect there's no real problem,
but I'm not sure
there's no real problem.