

# Local Reality, Experimental Falsifiability, and Bell's Theorem

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# Agenda

A Personal Rant on the Philosophy of Science

Foundational Experiments of Quantum Mechanics

- Photoelectric Effect
- Two Slits
- Stern-Gerlach

Uncertainty and Entanglement

EPR Paradox and Local Reality

Bell's Theorem, Tests, and (uncomfortably weird) Fixes

# Personal Story



Is interpretation of quantum mechanics science? No.

# What is science?

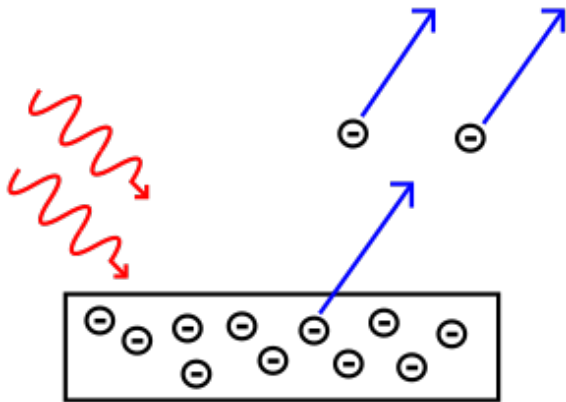
Mueller's idiosyncratic Karl Popper CliffNotes.

- Do an experiment.
- Create a formalism that predicts the results.
- Look for an experiment that breaks your formalism.

The best you can do is create a formalism that agrees with the experiments a future generation will use to try and break it.

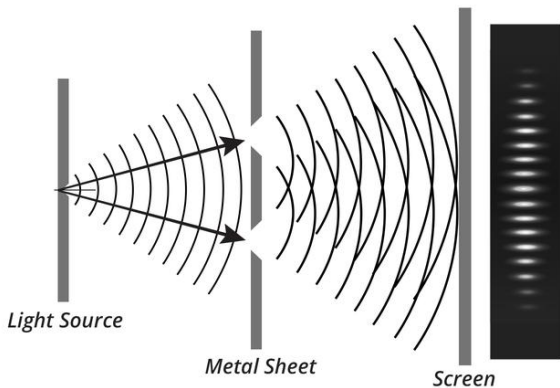
Quantum mechanics is where you can see that this sort of philosophical stuffiness starts to matter, and we actually often retreat into crypto-religious cafe argument to the expense of science (because in fairness it is sometimes more fun).

# Photoelectric Effect



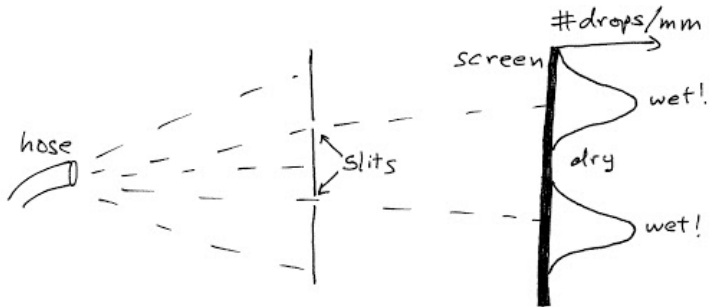
Patterns in absorption and readmission suggest that light exists in discrete packets (don't call them "particles") of particular size.

# Two Slits Experiment



What's going on with my discrete packets here? Odd...

## Two Slit Experiment: Water Droplets



This result is more in line with what one expects from discrete packets, in this case droplets of water.

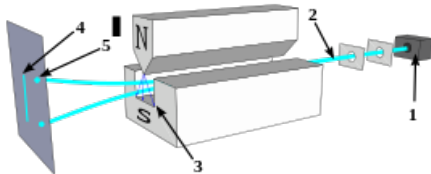
## Two Slit Experiment: Water



The result of my original experiment disturbingly resembles what I get when I try a similar experiment involving water.

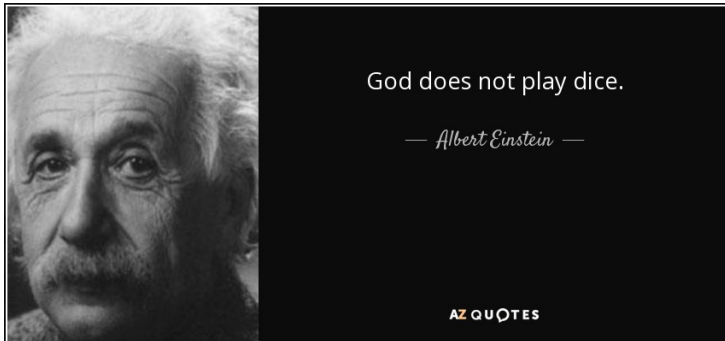


# Stern-Gerlach Experiment



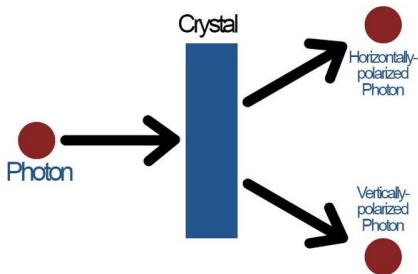
A charged *something* shot through magnets will be deflected like it is spinning but then this “spin” property is also being a weird little pill in the details.

# Naughty Scientists



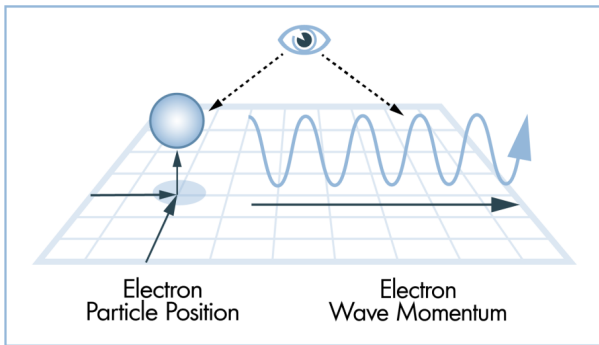
There are various temptations towards *interpreting* our two-slits experiment probabilistically, and suddenly everyone is a theologian who wants to argue about daydreams.

# Quantum Entanglement



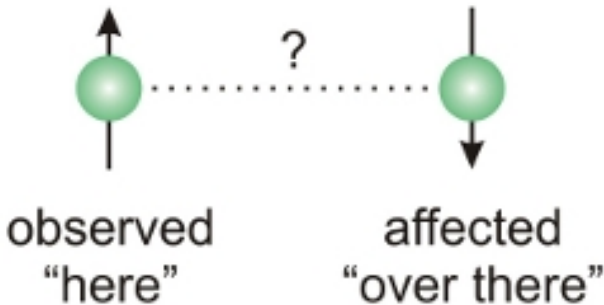
Various experimental methods exist for cooking up two photons with opposite, but not yet known, properties. These are called “entangled” photons.

# Heisenberg Uncertainty Principle



In the only mathematical formalism we have for this weirdness, the “spins” on perpendicular axes (or more commonly position and momentum) are incompatible observables - measuring one affects measurements of the other.

## EPR Paradox



Entanglement  $\oplus$  Heisenberg create a disturbing addition to our developing weirdness: measuring one photon's spin affects the statistical distribution of measurements we can expect measuring the spin of the other on a perpendicular axis.

# Locally Real Theories

Naughty scientists didn't like...

- Non-locality: measuring over here affects measurements over there
- Non-reality: things appear random and not predictable from previously measurable things

There was hope of a locally real theory of quantum mechanics, meaning hope of finding some previously unknown, local things to measure that deterministically predicted our weird results.

John Bell did right by Mueller and Karl Popper and thought up additional formalism and additional experiments to determine whether this was possible. **It's not.**

## Bell's Approach

Let's imagine we have your locally real theory...

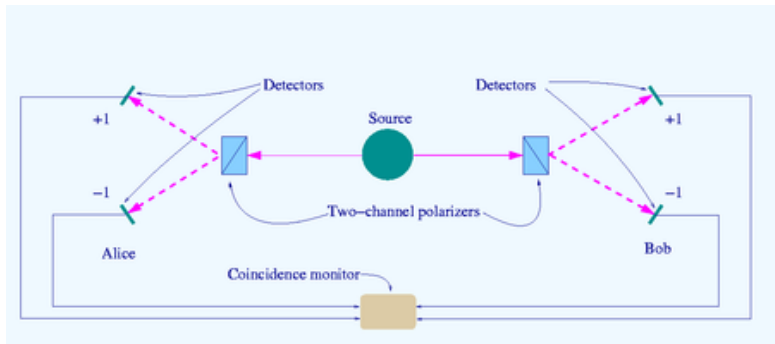
- its formalism would look like this
- we can do some formula pushing
- an inequality should be true

Bell's theorem is a proof that a locally real theory predicts a certain correlation in measurements of entangled photons.

$$C_h(a, c) - C_h(b, a) - C_h(b, c) \leq 1$$

For the moment, you need only know that  $C_h$  is a correlation measurement under suspicion of being equal to -1 while  $a, b$ , and  $c$  are (**arbitrary!**) experimental configurations, all testable in a laboratory.

# Bell's Test



The experiment suggested by the theorem has been performed many times and the inequality violated.

$(\text{local reality} \Rightarrow \text{inequality}) \iff (\neg \text{inequality} \Rightarrow \neg \text{local reality})$



## Escape from John Bell

Where does this leave us? Magicians or problematized choice.

- local is still ok
- reality (non-randomness) is still ok
- can't have both at once

Non-local hidden variable theories are permitted (and resembles various **occult ideas around correspondence**).

Particular **many-worlds -esque theories** are permitted (**only the wave function exists**, local but not real) but clash with everyday notions about definite events and choices.

One simple but subtly disturbing real but non-local escape is called **superdeterminism**, which is approximately the assertion that everything about all our experiments is pre-ordained.

## More on Superdeterminism

I don't think I quite understand superdeterminism, but I think I can manage some true statements about how radical and **incompatible with notions of free will** it is.

We spoke about an experimenter choosing an axis on which to measure spin, but superdeterminism requires that there is no choice and that physics only permits a particular pre-ordained measurement axis. **Experimenter choice is an illusion.**

One way of imagining lack of free will is that choice is determined deterministic processes in their brain. **This smells dangerously like local reality.** Superdeterminism is more like an **a-spatial, a-temporal universal lookup table** events, or some **amazing conspiracy of neural events** in our deterministic thoughts about experiments.

# Questions

Do you have any questions?

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