TEACHING QUANTUM MECHANICS

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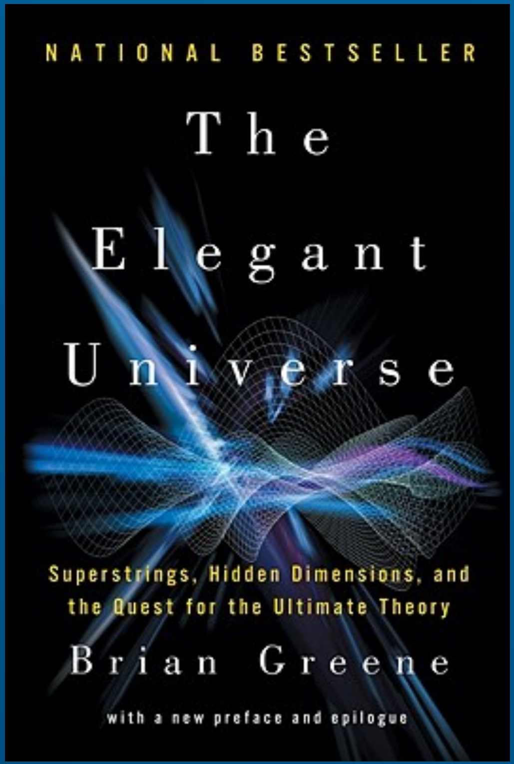
Illinois Mathematics and Science Academy – Friday, February 28, 2014

Why quantum mechanics?

- Quantum mechanics is essential to all fields of physics and many engineering fields (e.g., semiconductors and nanotechnology)
- The twentieth-century view of the universe necessitated by quantum mechanics is something non-physicists should know as well
- People are fascinated by modern physics concepts (e.g. *A Brief History of Time* or *The Elegant Universe*)
  - No one sells books about torque



Current events

- AP Physics B contains 10% atomic and nuclear structure – which means it has less quantum mechanics than AP Chemistry (20%)
- Serway's book spends about a sixth of the book on modern physics (often skipped, since it is at the end)
- NGSS has one relevant standard:
  - HS-PS4-3: Evaluate the claims, evidence, and reasoning behind behind the idea that electromagnetic radiation can be described either by a wave model or a particle model, and that for some situations one model is more useful than the other.

Lessons from IMSA

- Modern Physics offered as a one-semester class (with lots of quantum mechanics included)
- When the difficulty increased, enrollment also increased
- Students responded strongly:
  - "I had my mind blown every class"
  - "This is the most interesting class I've ever taken"
  - "ModPhys was the highlight of my day"
  - "Before this semester, I hated physics, but now, that hate has subsided and I actually find myself interested enough to pay attention, take notes, do my homework, and look up other resources in my free time."
  - Two students said they decided to become physics majors because of this class

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Quantum Mechanics

- Quantized energy levels of atoms in the Bohr model are the most applicable part of quantum mechanics, but:
  - They aren't that exciting
  - Chemistry already does that part
- Many students love the weirdness of quantum mechanics
- The most interesting part of quantum mechanics is not uncertainty
  - People are used to being unsure
  - We are not used to our observations changing the behavior of the universe

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The standard curriculum

(From Serway/Faughn, 7th edition)

- Blackbody radiation ← **Requires advanced thermodynamics**
- The photoelectric effect ← **Requires circuits**
- X-rays ← **Nothing to do with quantum mechanics**
- X-ray diffraction ← **Hard to explain**
- The Compton effect ← **Not useful for deeper understanding**
- Wave-particle duality ← **The important part!**
- The wavefunction ← **The important part!**
- Heisenberg's uncertainty principle ← **Poorly explained**
- Scanning-tunneling electron microscopes
- The Bohr model ← **Covered by AP Chemistry**
- The hydrogen atom
- Spin ← **The important part!**
- Semiconductors

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Proposal

- Why go in chronological order? We don't teach any other physics that way
- Skip the boring stuff – kids don't get it anyway
- Jump right into the interesting stuff:
  - The wavefunction and measurement
  - Compatible and incompatible observables
- Focus on the easiest QM systems:
  - The double-slit
  - Spin
- For students who like to talk about such things, spend some time on the philosophy

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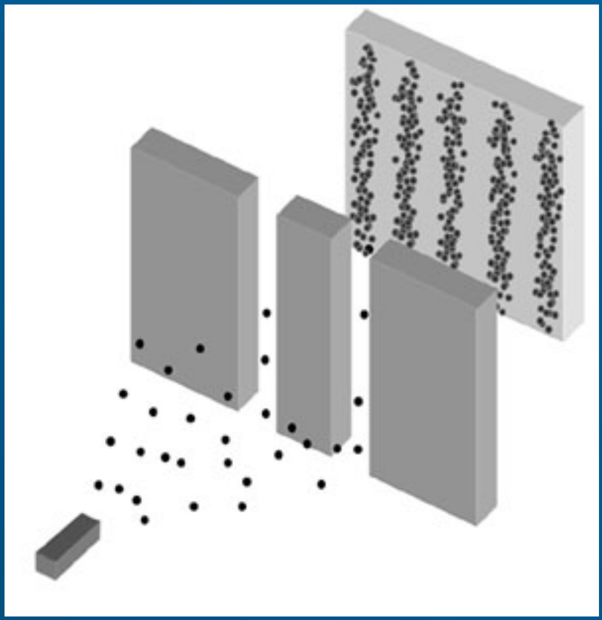
The double slit

- This example best explains the mechanism of quantum mechanics
  - Show that light is a wave with an interference pattern (lab)
  - Mention (or show, if you want) that Einstein found light is a particle
  - Ask: what happens if you shoot only one particle at a time at slits?
  - Show YouTube video of actual experiment
  - Discuss why this is weird
  - Add sensors to see which slit the particle passed through – show how interference disappears
- See attached talk at the end of this presentation



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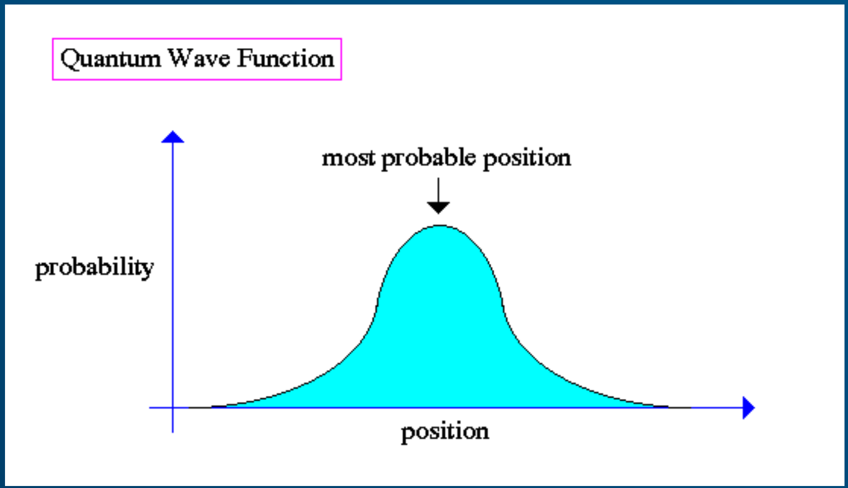
Wavefunctions and measurement

- The fundamental difference of quantum mechanics is that you cannot write any expression such as $x = 3$ m
- You can only give probabilities of being at a particular place
- The probabilities are represented by an (unobservable) wavefunction
- The strangest part – when we make a measurement, the wavefunction collapses to the value we measured, thus changing its behavior
- Our observation affects the behavior of the universe!



The fun part

- Classes who enjoy discussions can spend a long time on big questions:
  - How can our observation affect reality?
  - What is a measurement?
  - Is the universe fundamentally probabilistic?
  - Is consciousness necessary to induce a measurement?
- And, if you dare:
  - What implications does a probabilistic universe have for free will?
  - Is consciousness just a series of random quantum measurements that give the semblance of purpose?
  - Is it easier or harder to reconcile quantum mechanics with an intervening God?

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More advanced topics

- For those with the time and inclination, there is much more quantum mechanics that can be explored without any fancy mathematics.

Incompatible observables

- The center of the weirdness of quantum mechanics
- Measurements of two incompatible observables are mutually inconsistent – knowledge of one invalidates knowledge of the other.
- For example, if you measure the *x* spin of a particle, then measure the *y* spin, then measure the *x* spin again, you may get a different answer
- Position and momentum are incompatible observables – hence, the Heisenberg uncertainty principle

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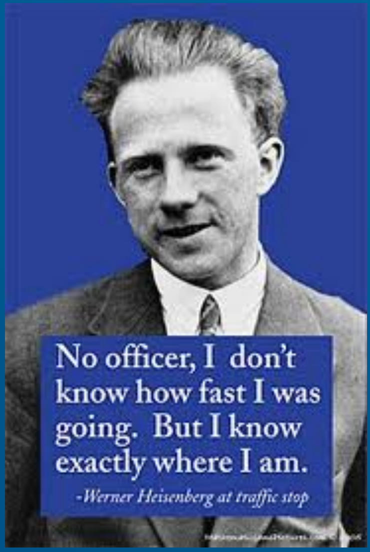
The Heisenberg uncertainty principle

- A fundamental result of quantum mechanics – nothing to do with experimental error
- There is a limit to how sure we can be of position and momentum *simultaneously*
- You can measure position as well as you want, and then measure momentum as well as you want
- However, if you then measure position again, it will likely be different from what you measured before



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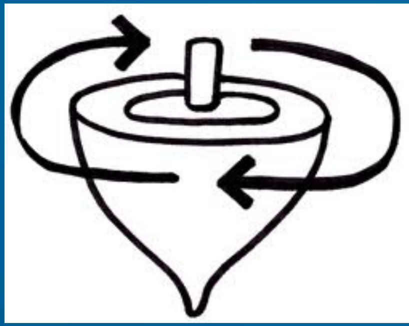
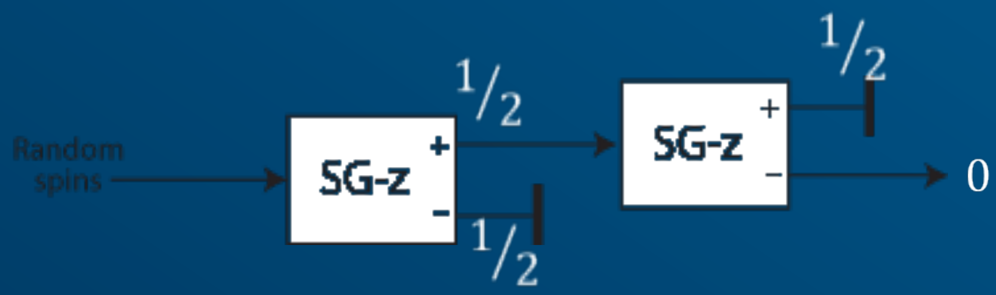
Spin



- A good illustration of incompatible observables
- A fundamental, quantized amount of angular momentum intrinsic to all particles
- Simplest example: spin-½
  - When you measure spin along a certain axis, it can only be up or down – nothing else
- Spin along one axis cannot be known at the same time as spin along any other axis
  - Suppose you measure *z* spin to be spin up
  - Then you measure *y* spin to be spin up
  - If you measure *z* spin again, you might get spin down instead of spin up (50% chance)
  - Measuring a spin "resets" the spins in the other directions

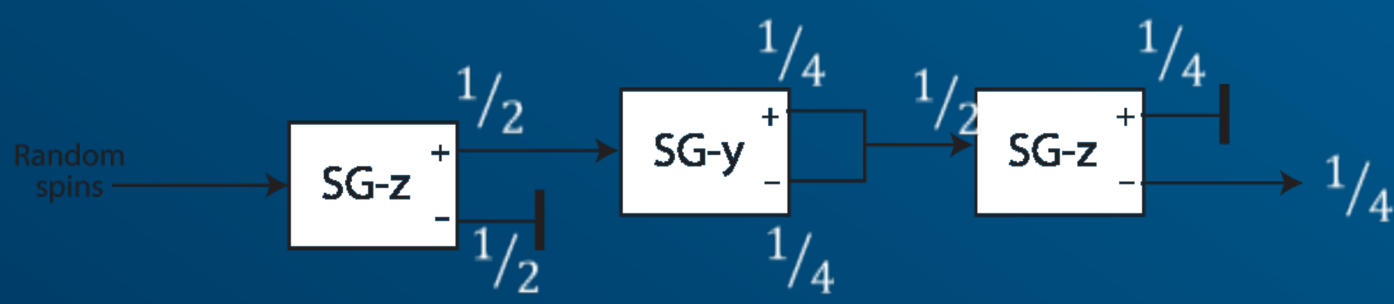
Stern-Gerlach devices

- One way (from Feynman) to discuss quantum mechanical principles is through Stern-Gerlach devices – devices which measure spin
- Thus, SG-z means that you measure the spin in the z direction
- As you can see, in this case you would have no particles coming out.



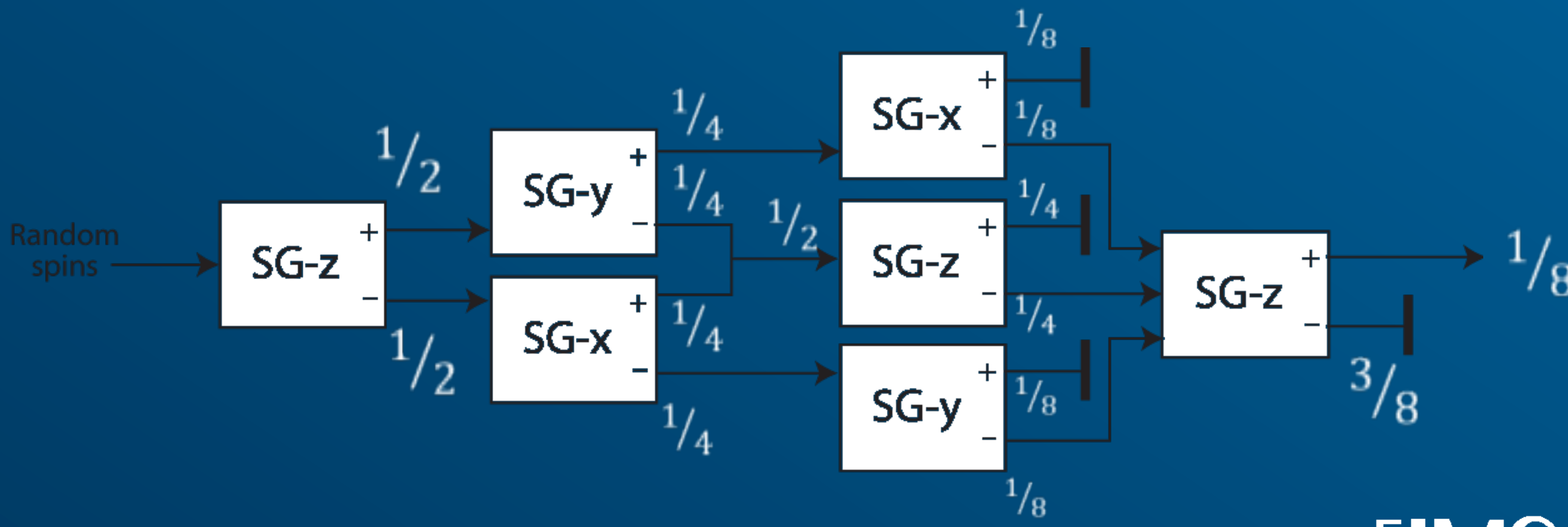
Stern-Gerlach devices

- However, a measurement of x spin, which does not commute with z spin, makes the previous measurement no longer valid
- Thus, our measurement changes the outcome.



Stern-Gerlach fun

- Many students enjoy working out larger, more complex Stern-Gerlach networks
  - These aren't too applicable to physics, but they can be fun



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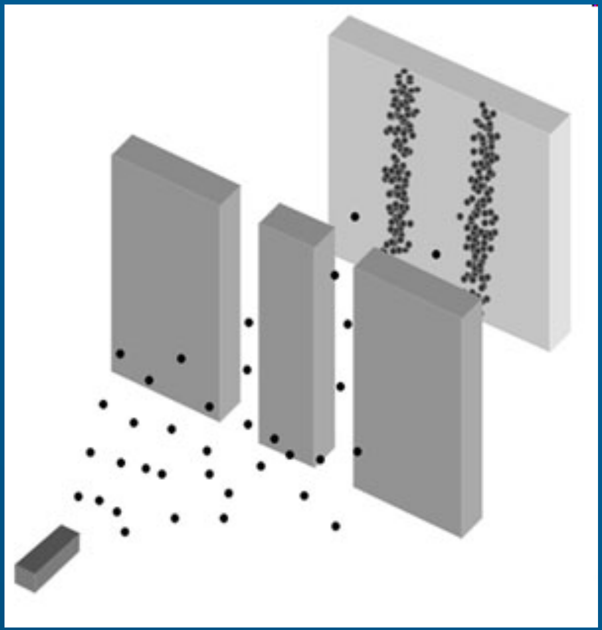
QUANTUM MECHANICS

What is quantum mechanics?

- The good news: Quantum mechanics is the only theory we have that explains our experiments
- The bad news: Quantum mechanics makes no sense

The double-slit experiment

- Suppose we shoot particles through two slits at a screen on the other side
- The particles will collect in two rows on the screen
- So far, so good



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The double-slit experiment

- Suppose we do the same thing with waves (e.g. water waves)
- Now waves from the two slits interfere with each other
- Get a series of light and dark rows on the screen

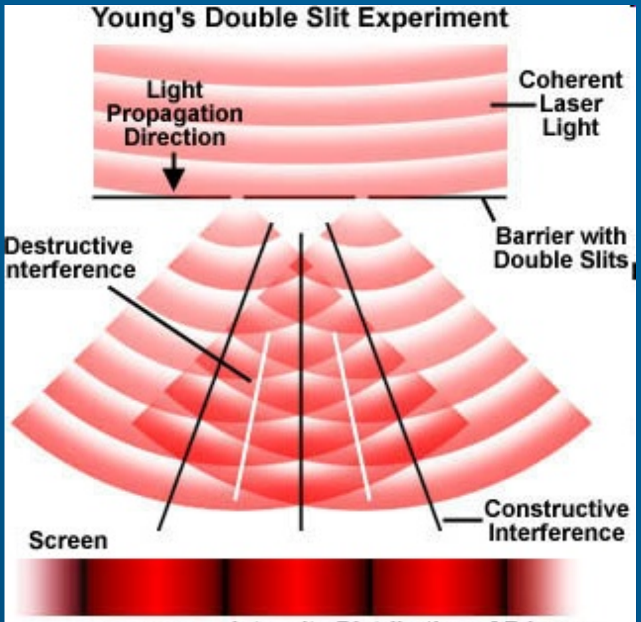

Figure 4

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Light

- Is light a particle or a wave?
- Thomas Young showed in 1801 that light has a double-slit interference pattern like a wave
- Albert Einstein showed in 1905 that light had to be composed of particles (photons)

The weird part

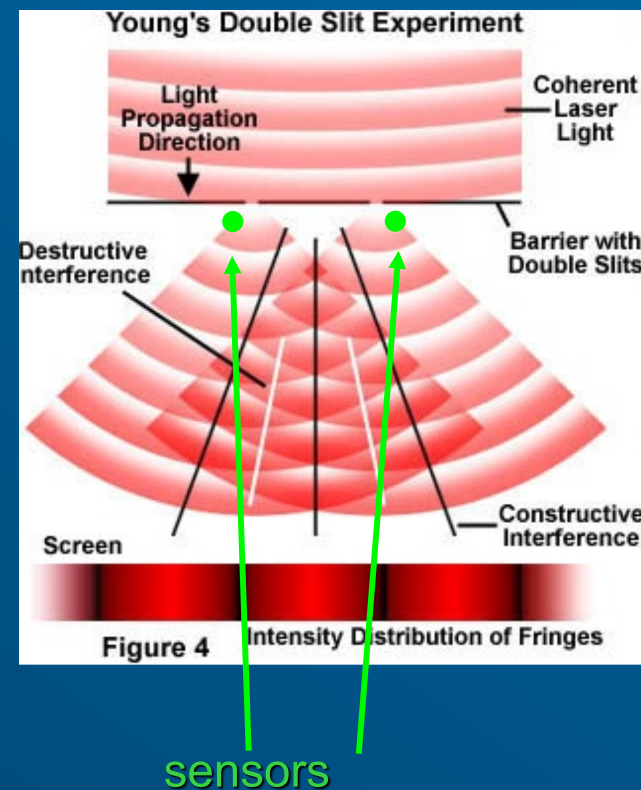
- What if we shot only one photon at a time through the slits?
- Should be impossible to interfere – should get two rows on the screen
- Here is a video of a real experiment.

Huh?

- Even though only one particle goes through the slits at one time, we still see interference!
- A photon interferes with itself?
- Each photon goes through both slits?

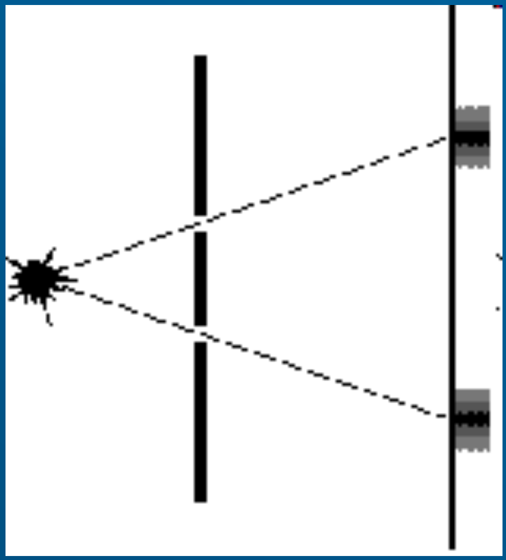
Trying to understand

- Okay, a photon can only go through one slit or the other
- Put sensors in to figure out which slit it went through



The even weirder part

- The sensors do their job: the photon shows up in only one slit or the other…
- But the interference pattern disappears!

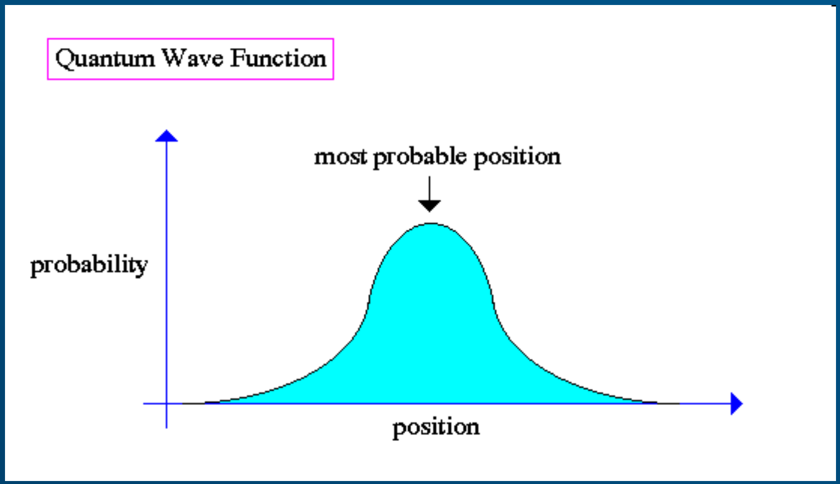


What?

- This means that our measurement changes the result of our experiment!

The Copenhagen interpretation

- A particle is actually not at a particular position; it has a wavefunction that gives a probability of being at a position
- When we make a measurement, we measure only one position, chosen at random



Wave-particle duality

- This means that:
  - Particles actually behave as waves
  - But we measure them as particles
- Or, if you prefer:
  - Particles propagate as waves but interact as particles
- Or, more simply:
  - Particles act like waves when we aren't looking

What this means

- A measurement is a fundamentally different physical process
  - No mathematical representation
  - The only truly random process
  - The only truly irreversible process
- What is a measurement, anyway?
  - The interaction of a microscopic system with a macroscopic one?
  - The transfer of information?
  - The intrusion of human consciousness?

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Measuring a measurement

- Can't we do an experiment to find out more about what a measurement is?
- Not easily – an experiment needs a measurement, and we can't take a measurement of a measurement
- We are asking about what happens before we measure it – can we ever know that? Does it even make sense to ask?

The end of science?

- Measurement is fundamental to the scientific method
- Thus, it’s not clear if science can tell us anything about measurement itself
- Quantum mechanics has at its heart the old question: if a tree falls in a forest…
- But who knows? We may figure something out

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