HSSP Philosophy of Quantum Mechanics
07/10/11
Lecture Notes

Outline:

0. Class intro
1. Uncertainty Principle intro
2. Lab 1: Stren-Gerlach (Incompatible Observables)
3. The Two-Path experiment and superposition
4. Position and Momentum (Uncertainty Principle conclusion)

Handouts:

1. Syllabus
2. Lab Intro
3. 3 lab group sheets: Persistence, Independence, and Three Boxes

Vocabulary

Macroscopic
Uncertainty Principle
Superposition
Incompatible Observables

You should be able to:

Explain why the Uncertainty Principle is *not* just about our measurements or instruments disturbing particles. Use the idea of incompatible observables.

Explain how the Two-Path Experiment leads to the idea of superposition.

The Macroscopic World and the Quantum World

"Classical" physics, or "Newtonian" physics, is useful when we're dealing with large objects (many particles), even though Quantum Mechanics is really the correct theory, because Newtonian physics is a *good approximation* when there are many particles. What counts as many particles? Imagine a spectrum, not a sharp line: Newtonian physics is very accurate for every-day situations, but worse when it comes to a few particles, and very bad when it comes to a single particle.

Myth: Uncertainty is caused by instrument interference

> **Uncertainty Principle (1):** We can never know both a particle's precise position and precise velocity at the same time.

Here's a *very common* explanation that non-physicists give for the Uncertainty Principle:

The way we know about a particle's position or momentum is by making a measurement with an instrument. Even the most theoretically simple measurement, like bouncing a photon off the particle, *disturbs* the particle. So, if you use a *collision* with a photon to learn the position of a particle, the collision gives it some energy (momentum) and so you no longer know the momentum of the particle.

This is true. Measurements *do* disturb the particles they measure. But that's not the explanation of the Uncertainty Principle. This explanation is about instruments and measurements, but there's also something going on with the *properties themselves.* We're going to discover that position and momentum are examples of **incompatible observables**.

<u>"What we can know" and "what's out there"</u>

Because this is philosophy, we have to be careful about how we say things. **Uncertainty Principle (1)** is *different* than

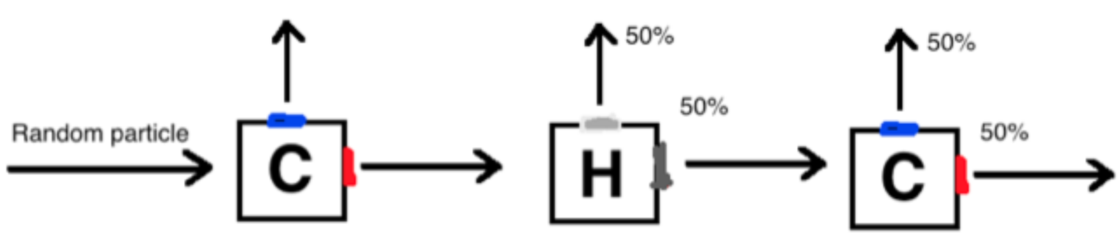
Uncertainty Principle (2): A particle doesn't have both a precise position and precise velocity at the same time.

(1) references people, observations, brains, knowledge. **(2)** is only about the properties of particles, or "what's really out there."

<u>Incompatible Observables (Stern-Gerlach Experiment)</u>
("Observables" is a fancy word for "properties")

To explore the idea of incompatible observables, see **Lab 1**. In Lab 1, particles had two properties: color (red or blue) and hardness (hard or soft). These are *just names*, abstractions. We can't really see the particles or touch them. The only way to know their color or hardness is to send them through boxes. Example: when a particle goes into a Hardness Box, if it comes out the side we say it is hard. If it comes out the top we say it is soft. Notice, then, that how particles come out of a hardness box *is the definition of hardness*.

Conclusions from Lab 1:
Group 3 saw the data below and concluded that some red particles changed into blue particles, maybe because of the hardness box in the middle. Group 3 suspects that color and hardness are *not persistent* (they change), and *not independent* (they affect each other).



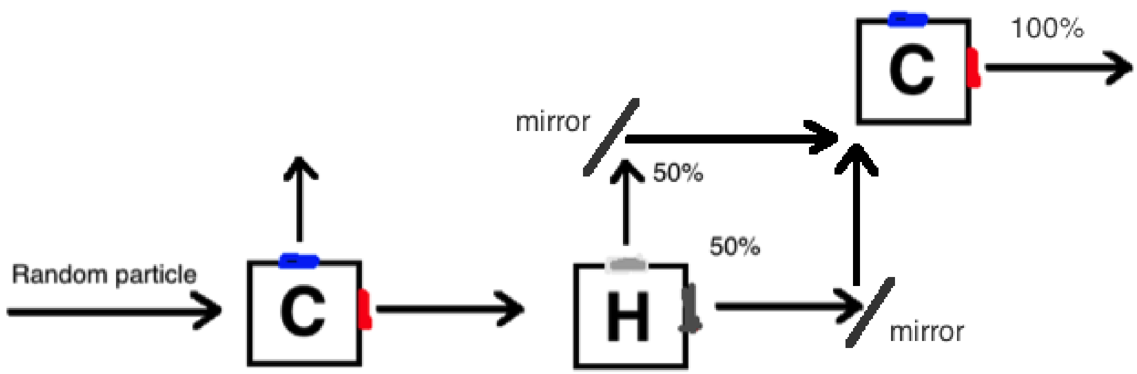
However, Groups 1 and 2 have different conclusions:
Group 2 saw that a stream of red particles comes out 50% hard and 50% soft. Same for blue particles. Hard particles come out of a color box 50% red and 50% blue. Same for soft particles. Group 2 concluded from this that color and hardness are *independent*: knowing one does not help you know the other. They proposed that 25% of particles in the experiment were red-hard, 25% red-soft, 25% blue-hard, 25% blue-soft.

Group 1 saw that particles going through a series of color boxes, and never changing color. Particles going through a series of hardness boxes never changed hardness. Group 1 concluded that color and hardness were *persistent*.

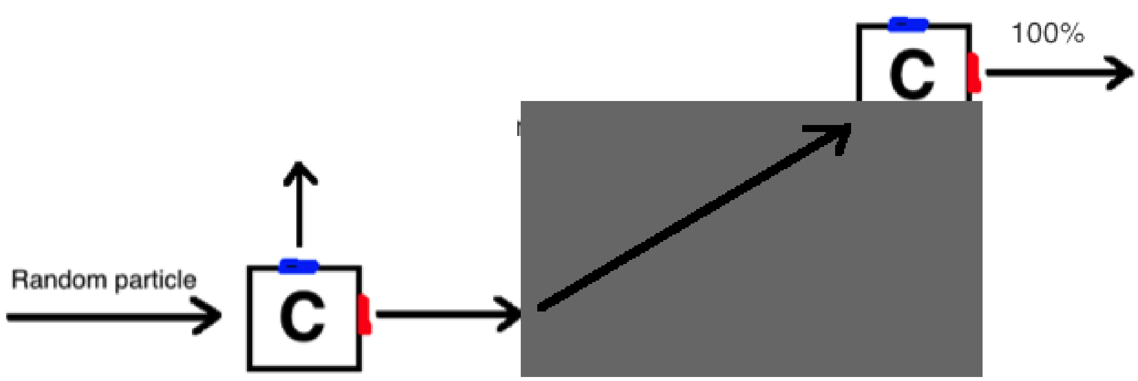
The conclusions of Group 3 did not fit the conclusions of Groups 1 and 2. But observations are observations. What's going on?

Hypothesis: "Something about putting a hardness box in the middle allowed red particles to change color and come out blue in the end," or "sending the stream through the hardness box *resets* its color." (A pretty reasonable guess.)

We tested this hypothesis on the board with the following setup:



This is just like Group 3's setup, except there are mirrors which recombine the "hard" and "soft" beams before going into the second color box. Mirrors (or any other material) don't by themselves affect the experiment. And if we move the color box to take just the hard particles or just the soft particles, they come out 50% red and 50% blue, like in Group 3's data. But with this "recombination" setup, all the particles come out red in the end! Just like Group 1's experiment, where there was nothing at all in the middle:



Q: “What is in between the two color boxes?”

A: “Nothing that affects the experiment.”

Hypothesis: “Sending the stream through a middle hardness box “resets” its color.

Conclusion: False. In this setup, particles were sent through a middle hardness box, but all of them came out red.

Hypothesis: “Maybe it has to do with the recombining. Maybe some combination of hard+soft = red.”

Test: We can send particles through *one at a time*. They still always come out red. So it can’t be about “recombining beams”.

Hypothesis: “Maybe even a single particle is getting split. It goes on both the hard path and the soft path and recombines to make a red particle.”

Test: If we *look at the experiment*, we always see the particle on one path or the other. Never both. (Of course, then we’ve stopped the experiment.)

So, when we send a single particle through this “Two-Path Experiment”, which path does it take? Let’s list all the possibilities: 1) the “hard” path 2) the “soft path 3) both paths 4) neither path (ex: it teleports). We have experimental evidence *against* each of these possibilities. The particle doesn’t take the hard path, because when particles take the hard path, they sometimes come out blue. For the same reason, it doesn’t take the soft path. It doesn’t take both paths or neither path because we never look in and see two particles, and we never look in and see no particles.

Let’s make up a new word to answer the question:

Q: “Which path is the unobserved particle on in the Two-Path experiment?”

A: “The particle is on a superposition of being on the hard path and being on the soft path.” This is *not* the same as “The particle is on both paths,” though non-physicists often say that in Quantum Mechanics particles can be “in two places at once.” This is a myth. Superposition is a new, 5th way to answer the question.

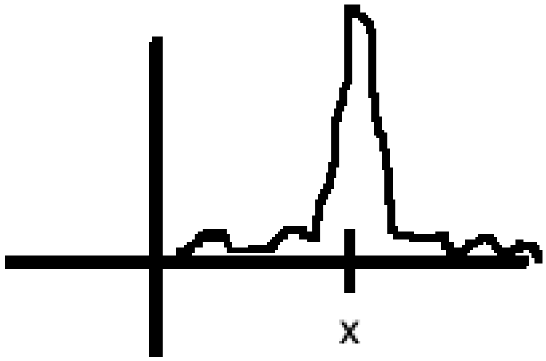
<u>Measurement (teaser)</u>

Maybe Group 3 should say that “making a measurement” “resets” the color of a particle. A hardness box in the 3-box experiment counts as “making a measurement”, but a the hardness box in the two-path experiment doesn’t count as making a measurement. So what counts as a measurement? Good question! We’ll be exploring that more in later classes.

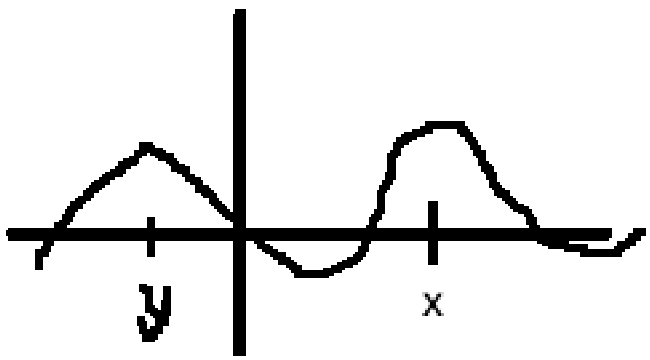
<u>Position and Momentum (True Uncertainty)</u>

Position and momentum are incompatible observables. How do we know? Because they behave like color and hardness in experiments. Also, here’s a way to visualize their incompatibility.

In quantum mechanics, we can mathematically picture a particle’s position as a *wavefunction*. (A fancy word for a squiggly line.) Pardon my terrible drawing, but here are some examples of wavefunctions. On the horizontal axis is space. On the vertical axis is probability.



A) Particle A has very high probability of being at approximately x. It has a pretty definite position.



B) Particle B does not really have a definite position. Look, it has about the same probability of being way over at y than of being at x. However, this wavefunction does have much more definite momentum, because momentum is measured using wavelength (the distance from peak to peak in a wave). The more a wavefunction has a definite wavelength, the more it has a definite momentum. Particle B has a much clearer wavelength than Particle A.

Conclusion: The more a wavefunction looks like a pointy mountain, the more definite its position, and the more uncertain its momentum. The more a wavefunction looks like a spread-out wave, the more definite its momentum and the more uncertain its position. A wavefunction (a particle) can't have both definite position and definite momentum at the same time, because it can't be like a pointy mountain and a spread-out wave at the same time.

So, what is this connection between wavelength and momentum anyway? It's called the deBroglie relation: wavelength = *h* / momentum. *h* is just a number, called Planck's constant. Or, frequency = Energy / *h*.

$$\lambda = \frac{h}{p} \qquad\qquad f = \frac{E}{h}$$

deBroglie discovered that everything, all matter, has some wavelength. But, as you can see, when things have a lot of momentum (like anything *macroscopic*: remember, momentum is mass times velocity) the wavelength is very small: much smaller than what we can easily detect. That's why we don't see that cars and people have wavelength.