PROFESSOR: Hi. Welcome too Excitatory Topics in Physics. The last two weeks, I've talked to you all about one of the two major revolutions in physics in the 20th century. I talked about Einstein's theory of relativity and all of the strange, bizarre, wonderful consequences that it has in store for all of us. Space and time are much weirder than you might at first guess. Time travel is possible in some circumstances. It's certainly possible to travel to the future. There's no debate about that. Whether or not it's possible to travel to the past, it's more controversial. But the window of time travel is certainly opened by relativity.

Relativity, as I mentioned in the first class, was made necessary because there was this great dispute between Newton's mechanics and Maxwell's electromagnetism. And Einstein's theory of special relativity fixed all of that.

Well, quantum mechanics, which was the other achievement of 20th century physics fixes a lot of other problems. I mentioned and the first class that quantum mechanics fixes the so-called ultraviolet catastrophe-- that was a chalk catastrophe-- ultraviolet catastrophe. And this was simply the fact that with the current physics at the time, the physics that everybody had in the year 1900 or so, predicted that if you had an object like a microwave, just a simple way of putting it, if you had an object like a microwave, the only way it can exist is if there's an infinite amount infinite amount of energy inside of it.

And that's a problem that he talked about. And it was Max Planck who came up with a solution to the problem. And what he did was he proposed that the energy of light comes in individual chunks, discrete units. And he came up with the mathematical trick basically of fixing this problem. I won't go into detail of precisely how he fixed it. But he fixed this problem to get at the result we expected to be true about microwave, in particular that microwaves contain a finite amount of energy, which is what you'd exactly expect.

And it was Einstein later, a few years later I think, who made the bold guess that this mathematical trick of Planck's is actually a real physical actuality, a physical reality. And

Einstein was the one who came up with the idea of photons. Photons are these chunks, these bits of lights. Light comes in particles, which are called photons.

And this idea of the photon allowed Einstein to explain another problem which was unexplainable by classical physics. And this was the problem called-- well, it was an effect called the photoelectric effect.

And it turns out that if you've got some metal, like a cell phone, and you shine some light at it, it turns out that some electrons at the surface of it actually get kicked off by the light. The light actually kicks off the electrons. And these electrons just go flying away. That's called the photoelectric effect.

And according to the physics at the time, if you use the physics to make some predictions about what you'd observe, you get the wrong answer. According to the physics at it at the time, if I shined a bright enough light of any color at a metal, then electrons would be kicked off. But that turned out not to be true.

It turned out that there was a special frequency of light, below which shining light-- well, if you had light of a frequency below this certain frequency, then no electrons would get kicked off. Just to remind you all who might be unfamiliar with the frequency or wavelengths of light, light comes in many wavelengths.

Some of those wavelengths are the colors that we see-- red, yellow, blue. And some of those wavelengths are other things that we can't see, like microwaves and x-rays and gamma rays. And For. Each wavelength there's also a frequency associated with the wavelength.

You can think of a wave of light like this. And the wavelength is the distance between two crests of the wave. So it's some distance. It could be centimeters. It could be nanometers. It could be miles. That's the wavelength.

And the frequency is how many times in 1 second you get a wavelength. So how many times in 1 second you get a wavelength. Well, I need to be more precise about what I mean by that.

Well, so you can think of some traveling wave moving and you count how many times a crest passes you in 1 second and that's the frequency. That's the frequency. And so light comes in many frequencies, which each have their own wavelengths. Just some background info.

Now this photoelectric effect turned out to be the case that's shining light below a certain frequency would result in no electrons being kicked off. But if you got above that frequency, then electrons would be kicked off. And that was contrary to what the current physics predicted.

It was contrary to what's the idea of light being a wave predicted. So this was a big blow to many people who thought that light was a wave. So I'll just right down it was contrary to wave predictions, and it supported particle predictions. And I'll be more precise what I mean.

Now for a long time, up to the 20th century, there was a lot of debate among physicists over whether a light was a wave or particle. You've probably heard about this debate. Newton always thought that light was a particle. And he had lots of interesting reasoning for why that should be the case. This photoelectric effect was also support for light being a particle.

According to the particle theory, particles of light would simply come and kick off electrons. And that's not what you'd get if light were a wave. If light were a wave, you'd be able to kick off electrons with any frequency. But you get the wrong answer.

I don't want to go into too much detail about this because I really want to get to the main features of quantum mechanics. This is just some history, some history that is necessary to really appreciate it.

So the photoelectric effect was more support for the particle theory of light. But as I mentioned, there are many people that believe that light was a wave. And, well, why do they believe the light was a wave? Well, there were some experiments that showed that light was a wave, just like this shows that light is a particle. And probably the most important of all of these experiments is the so-called double slit experiment.

So for instance, I can imagine putting some screen in front of me with a couple of slits. That was three slits. I'm going to put two slits. No, that's-- how do you draw two slits?

AUDIENCE: One line.

PROFESSOR: One line, yeah. There you go. Those are two slits.

So let's say I've got this screen in front of me. There are two slits. One's right here. The other one's right there. And I'm behind it. And I shine some light through those slits.

So they're going to go through the slits. Those beams of light that I sent through the slits, they're going to go through the slits and they're going to reach the wall over there. So I'll draw the wall over here. OK, that's the wall.

And if you actually do this experiment, and you make these slits a suitable size, you can observe what's called an interference pattern on the wall, on this screen.

And here's what I mean by the interference pattern. So I've got one hole here. Let's see, I'll make a little line. I'll call this A. I've got another hole here, which corresponds to a point B on the wall-- that looks like a beta-- point B on the wall. And I can look at what I see. I can look at the brightness of the lights on the wall.

And I can plot the brightness on a graph. So if I put brightness here and, well, this would be a position, let's say that this corresponds to B. This corresponds to A. Then what I see is this. Also on this side. That's simply what I see. OK, that looks OK. That's simply what I see.

And to understand this-- you can understand this simply by thinking of water waves. If I were to do this experiment with water waves instead of light waves, then you can think of the ripples making a pattern like this. So let's say I've got a bunch of water waves coming from this way. What I see as they emerge from the slit? Well, I would see patterns like this. I would see these circular patterns.

Well, if I put two slits next to each other-- there you go-- I put two slits next to each other, then you add up two water waves, you add up these two sets of ripples, and you get an interesting pattern.

It's kind of hard to draw, but I'm sure you've all seen this in some way in a pond or something. You see certain points which look like they're higher than others. You see some certain points in the water which have maximum heights, certain points in the water which have a minimum height. And if you were to ask, what do the ripples look like over here, then the heights would look something like this.

I know I know it's kind of confusing to visualize, but you can imagine adding up ripples and getting some interesting pattern at the end. I meant to bring a cartoon showing this. But I'll send it to you all so you can better see how this works.

But this is a wave for now. You have water waves. You have these ripples that move in waves. And if you allow them to go through slits, you see something that looks like that.

And, well, if light were a wave, you'd also expect to see something like this. And this is precisely what you get when you do the experiment. You can actually do the experiment making this interference pattern.

It's called an interference pattern because these waves interfere with each other. You get constructive interference when the crests add up each add up with each other. And you get destructive interference when a crest adds with a trough and the two cancel out. That's how you get an interference pattern. That's how you get this pattern.

This pattern is not what you would expect to get if light were made up of particles. If light were made up of particles, you'd expect to get something much different.

So let's draw another couple of slits with the screen. Why can't I draw this? What's that?

AUDIENCE: It's right.

PROFESSOR: No, I was about to extend it all the way. That was going to be one slit. OK. And I have a screen here.

Imagine that I'm sitting on the other end of here, like I'm right here. Imagine I'm right here. And I'm simply throwing things, like chalks. Or I'm shooting bullets through these slits. I could be shooting bullets through these slits.

If I were to do that, then what would you expect to see on the screen?

AUDIENCE: Holes.

PROFESSOR: Suppose-- what's that? You expect to see bullets. Holes? OK, holes. OK, good answer. Good answer.

OK, suppose the screen were magnetic and attracted the bullets once they reach the screen, so that when the bullets arrive at-- sorry, when the bullets hit the wall-- when the bullets arrive at the wall, then they would stick. And then they would line up on each other. They line up on each other. They would pile up, getting higher and higher. But really, they'd be coming out this way. I mean, they're not going to fall down. What's that?

AUDIENCE: Have to be a strong magnet.

PROFESSOR: Yeah, it would have to be a pretty strong magnet, yeah. But suppose you did that, suppose you did it somehow. Then it's pretty clear what you expect to see.

So you shoot bullets. I'll just draw them. Suppose you have bullets. These are what bullets look like. Those are what bullets look like.

They go through this. Eventually they reach the wall. So if I were to draw, let's say, number of bullets as the height, and position here-- let's say this is A and this is B-- well, then I expect there to be a big pile over both A and B. They just fall down on top of each other like this. Yeah, something like that.

I mean I wouldn't expect to see all these extra humps. I mean, what's with that? Why should that happen? So this is what I expect to see bullets. And so this is what I expect to see for particles. I'd expect to see them all just falling on top of each other, creating piles like this.

Well, if light were a particle, then, yeah, we should see that. But that's not what we see. We see this. So light's a wave.

Well, how could light be a wave if it also acts in ways that particles act? If acts in ways that are consistent with the photoelectric effect and some other effects? I mean, there are some other experiments that you can do where you take an electron and you shine light at it. And the electron moves in such a way as if it were hit by a billiard ball. It moves in such a way that indicative of a particle hitting it. It moves in such a way that's indicative of light being made up of particles.

So how could light be both wave and a particle? Is that true? Is light both a wave and a particle? Or is it one or the other? Is it a wave or is it a particle?

This is something that people have thought about for a long time, for hundreds of years, until finally quantum mechanics answered the question. Finally, quantum mechanics answered the question. According to quantum mechanics light is neither a wave nor a particle. It's just this thing. It's just this thing that behaves in some ways that one associates with wave behavior, and it behaves in other ways that one associates with particle behavior. So light's just this weird thing.

But electrons, electrons are certainly particles, right? Right?

AUDIENCE: Right.

PROFESSOR: No, they're not. According to quantum mechanics electrons are just these things in some ways act particles and in other ways act as waves. I can do this experiment with bullets. And if I make the slits of a certain width, I'd see exactly that.

I can do this experiment with-- one second-- I can do this experiment with electrons. And if I make these widths a certain length, if I make the widths of these slits a certain length, then I'd see exactly that. I'd see the electrons piling up on each other.

But if I make these widths narrower, if I make these with smaller, then I no longer see this. I no longer see what you'd expect with the particle theory. Now, when I actually do the experiments, I see this. So now electrons have become waves.

I'm not making this up. You can actually do this experiment. You know, shoot electrons through a couple of slits and see what happens. Look at them in front of you. Look at the intensity of these electrons, the intensity pattern that these electrons make. Look at them on the wall and you see that.

You can also do this experiment with protons. And if you make the slits a certain width, then you see that. But if you make them smaller, then you see that. You can also do this experiment with larger molecules. And if you make the widths a certain length, you see that. And you make them smaller, and you see that.

In fact, people have done this experiments with molecules-- I don't know if you should even call them molecules now. But they've actually done it with viruses. They've done it with viruses and they don't see that. Well, you would see that if you made the slits narrow enough. But they've made them small enough so that you actually see this. You actually see the wave nature of viruses.

So if viruses can also have a wave nature then, what about larger things like chairs or people? What's that? Question?

AUDIENCE: Slits?

PROFESSOR: Well, in principle, you can arrange an experiment where you see an interference pattern like this with people, but no one's ever done that yet. But if you were to do that, then what would actually go through your mind? Because you can send through individual particles, and the individual particles will interfere with themselves. And so if you sent yourself, then what would it feel like to interfere with yourself? And this is maybe more a topic of philosophy than physics, so I'll just let you ponder that. Question?

AUDIENCE: So that's the brilliant solution of quantum mechanics, they just call everything that can't understood things?

PROFESSOR: OK, the question was that's the brilliant solution of quantum mechanics, we just call everything that can't be understood things? No, we can understand them. We just have to come up with better names for them. Particle is a bad name for things-- a particle is a bad name for light. Wave is a bad name for light.

AUDIENCE: But you use particle as a bad name for everything because it doesn't behave like a particle when it passes through small slits. So they just call everything-- they basically took particles away. And just called everything weird things.

PROFESSOR: In a way, yes. In a way, yes. They took away the title of particle and wave, and they just started to call them things. In practice, physicists actually do call electrons still-- they still call them particles. But we realize they don't behave as ideal particles in every way. Under some circumstances, electrons behave like particles. Under other circumstances, they behave like waves. And that's the same for every other type of--

AUDIENCE: So there are no particles because nothing behaves as a particle.

PROFESSOR: There are no ideal particles, yeah, that's true. And that's something that quantum mechanics has forced us to accept, as strange as it may seem. This is the so-called wave particle duality of not only light but also of electrons and neutrons and people.

So this is the-- well, I'll just write it-- this is the very confusing wave particle duality. The dual nature of light, particle and wave, the dual nature of electrons, the dual nature of people. Question?

AUDIENCE: But people jump through holes in walls all the time, but they don't move like a wave. What speed do you have to-- do you have to be traveling fast?

PROFESSOR: OK, the question is how can we arrange circumstances such that we can observe the wave properties of people or electrons or things like that? Well, there's this number called de Broglie wavelength.

Well, I'll just tell you. There's this length called the de Broglie wavelength. And any object in motion has a de Broglie wavelength. It's some constant divided by your mass divided your speed. That's your wavelength. You could calculate this number. And it turns out to be an extraordinarily small number for people, people just moving very slightly. It turns out to be an extraordinary small number.

Well, it turns out that if you make those slits approximately the size of the de Broglie wavelength, then you would observe your wave nature.

AUDIENCE: So if you made small enough, you wouldn't be able to pass through.

PROFESSOR: Well, if you make it small enough, then there's really a subtle interpretation of how we understand the word "you." It becomes confusing to think about you. I understand this is confusing stuff. And it's probably different from things you've thought about before. Time travel is confusing as you saw. Well, this is quantum mechanics. And it's confusing in its own ways, because it really asks us to rethink about-- well, we think about the nature of reality in ways that relativity forced us to but in different ways, perhaps more difficult ways.

So I said that's quantum mechanics resolves this question, is light a particle or a wave? Are electrons particles or wave? Well, the answer is neither. They're things.

But what specifically does quantum mechanics say? What explicitly does it say?

Well, in classical physics, the way that we think about objects is you have an object in front of you. You have an object in front of you, and I can say where it is. I can say how fast it's moving. And that's it. That's a complete and sufficient description of the states of the object. Of course, you can ask what is it made of, what are the objects made of, and how hard is it. You can also ask questions like that.

But in classical physics, it's easy to talk about the state of an object. It's easy to talk about its position and its speed.

So classical states of an object is simply the object's position. and it's speed. That's all there is to it.

Well, in quantum mechanics, the whole notion of position and speed are undefined for a particle-- well, are undefined-- I'll simply use the word particle when I mean electron or when I mean photon or something like that.

The whole notion of a position and a speed for a particle are undefined until you try to measure the object's position, until you try to measure the object's speed. It doesn't make any sense to talk about where something is until you make a measurement. And until you make a measurement, the object is in a mixture of many possible places. It's in a mixture of many possible speeds. It's in, in the language of quantum mechanics, a superposition of many possible states. And that sounds crazy. So I'll just write down what I mean before I talk a little bit more about it.

Now, quantum mechanics-- well, quantum states, position and speed, are meaningless until position or speed are measured.

You all have interesting looks.

Now, suppose I were to ask where is some electron in the universe? Where is it? Well, when I make a measurement of the position of the electron, I'll certainly get some position. I'll certainly get something somehow. I'll certainly get something.

Now, there are many possible places the electron can be. The electron can be in this room. The electron can be outside. The electron can be on the moon. The electron can be billions of light years away.

Now, until I've actually measured the electron, it's not that I don't know where the electron is. The electron is simply everywhere. It's in a mixture of every possible place. It's in a superposition of possible places. It's in a mixture. That's another way you can think of it. It's in a mixture of many possible places.

And similarly, I can ask what's the speed of the electron. Well, the speed could be this. The speed could be that. It could be 10 meters per second. It could be 50 meters per second. It could be a million meters per second. Well, until I measure the speed, it's in a mixture of all of those.

And this idea of objects being in a mixture of states, of being in a superposition of states-- that's the technical term-- of being in a superposition of states, this notion is completely unheard of in classical physics. We don't talk about a person being both here where I'm standing and the person also being there. We don't talk about people being both alive and dead. We don't talk about cats being both alive and dead in particular.

And some of you might be curious about my shirts, which on the front says Schrodinger's cat is dead and which on the back says Schrodinger's cat is not dead. And dome people asked me to explain it. Well, it has everything to do with the superposition principle. And I'll be more explicit what I mean by the superposition principle.

The superposition principle is a principle of quantum mechanics. It's a law of quantum mechanics.

And the principle says that it's possible for an object to be in many possible states at the same time. It's in a mixture of states,

Now, exactly which states are these? Well, there's a technical name for these states. They're only certain numbers which you'll get when you measure something. And when you make that measurement, that object will have the property of being, for example, over here or it will have the property of being in motion at 10 meters per second.

Now, those states, which are the states that you get once you make a measurement on an object, are called eigenstates, which is a lovely word. And these are states you get once you make a measurement of an object. So for example, there are position eigenstates. These are the states corresponding to various positions that you can measure. There are momentum eigenstates, or speed eigenstates, which is just the momentum divided by the mass of the object. There are also energy eigenstates. And these are the states that the particle is in or the object-- these are the states that the object is in once you measure its energy.

And these states are very special. These states are very special because these are the only states in which it's meaningful to talk about the position of the particle. These are the only states when it's meaningful to talk about the speed of the particle. These are the only states where it's meaningful to talk about the energy of the particle.

Now, measurement is actually a very weird process, because before you make a measurement, an object is in a superposition of many eigenstates. But once you make a measurement, the object is no longer in a superposition of many eigenstates. But it's now in only one eigenstate.

I'll let you think about.

OK, the superposition principle-- OK, let me write this down. Eigenstates are the states you get once you make a measurement. And the superposition principle is-- well, superposition is mixture of eigenstates.

Measurement is very fishing because it takes the superposition and destroys it. It destroys it. An object is in the superposition, and then it's only in one eigenstate. And this is called collapse, collapse of the quantum states. Shall I write that down? I'll write that down.

OK, now, I know this sounds extremely, extremely confusing, because first of all, I've been introduced a bunch of jargon. And second of all, I haven't given you very many examples of how to visualize these eigenstates and how to visualize the superpositions and how to visualize this collapse. And last of all, these are ideas that are completely unfamiliar to our intuitive minds. They're ideas that you don't expect to be true at all. You would have never guessed them to be true.

But it turns out that when you make predictions using these rules or you make predictions using this theory, they're completely right. They completely agree with experiments, completely.

Now, I mentioned that-- yes, question?

AUDIENCE: If an experiment in space of measurements, how do you ever measure or take into account a superposition?

PROFESSOR: How do you measure a superposition?

AUDIENCE: How do you ever take into account a superposition because any experiment you do is going to be based on some kind of measurement?

PROFESSOR: You mean, how do you prepare a certain superposition? I'm not exactly sure I understand.

AUDIENCE: If I want to try to say that you're this position, and you're half away around the and I haven't made a measurement, then I don't have any scientific evidence--

PROFESSOR: Oh, OK, so the question is, suppose an object is in a superposition of states right now. How do I know that? Because once I make a measurement on the object, then it's only going to be in one state. It's no longer going to be in a superposition. That's what you're asking, right?

OK, the way that you measure positions is by doing interference experiments. So what I can do is I can prepare some electrons to be in one type of superposition and I can prepare other electrons to be in another type of superposition. And then what I can do is I can send those electrons into specific superpositions, send those electrons through a couple of slits. And I could make them interact with each other in some way, in a way that I'll be able to make a measurement of the intensity of the electron, some type of intensity of the electrons, that's indicative of the type of superposition in which they were initially in.

So the only way you can really measure superpositions-- well, actually, I thought of another one. Sorry. OK, that's one way. That's one way you can measure superpositions. There are ways in which you can prepare superpositions, involving spins of atoms and things like that. But I won't get into that right now.

OK, where are we?

As I said, I know this is confusing to a lot of you. I hear a lot of people whispering probably. Maybe discussing Harry Potter, probably not. Perhaps discussing this confusing stuff. And I know it's confusing. It's weird. And it's hard to really get a grasp of it without getting mathematical.

But there are certain things that you can at least appreciate. You can at least appreciate this idea of the states, this idea of a mixture of states, this idea of collapsing into states, this idea of meaninglessness of the notions of position and speed. And we'll take a break right here.

So some of you have asked about what does my shirt mean. What is Schrodinger's cats? What does it mean for it to be dead and not dead?

Well, this is an extreme example of the superposition principle at work. Schrodinger was one of the founders of quantum mechanics. So Schrodinger was a person. I mean, I know it's a weird word. But Schrodinger was a person. Schrodinger was one of the founders of quantum mechanics.

There's a very famous equation named after Schrodinger called the Schrodinger equation. And it describes how the quantum state of an object changes in time. And it's a pretty complicated equation. So I won't write it down. I wrote it down for somebody, then I erased it because it scared some other people.

But Schrodinger was one of the founders of quantum mechanics. And he proposed a very interesting thought experiment to visualize the superposition principle. And it involved cats and it involved death.

So what he proposed was you get a cat, get a box, put a cat inside the box, but also get some radioactive poison and put that in the box too and close the box. So that when the box is closed we don't know whether the cat is alive or dead.

Well, OK, let's suppose there's enough air. Suppose there's a lot of air in the box. The only thing dangerous in the box is the poison.

Within a given hour, suppose that there's a 50% probability that the poison will decay and reach the cat and therefore kill the cat. So unless the poison decays and kills the cats, the cat's going to be alive. But until we actually open up the box and make a measurement on the cat, whether we measure it to be alive or dead, the cat is both in a superposition of alive and dead.

So in that sense, Schrodinger's cat is dead, and Schrodinger's cat is not dead. And it's a lovely way to think about things, because if we can think about super positions of things being alive and dead, we can think about a lot of different superpositions. You can think of superpositions of-- well, I mentioned you can think of superposition of me here or superstition of me there. You can think of a superposition of the chalk being both here and the chalk being on the moon.

But for some reason we don't observe those superpositions. Well, the reason we don't observe the superpositions has to do with the fact that many of our everyday experiences with states that are robust. And the way that they stay robust is kind of complicated and involves an idea known as quantum decoherence. And if any of you are interested about that, you can talk to me about it after class. Question? What's that?

AUDIENCE: The infinity.

PROFESSOR: Oh, about robustness? Yeah. Yeah, that's an important question. That's an important question. Why does the world look normal when I've just told you it's so crazy? Why does it look normal? Why does it look like what we would expect?

Well, it has to be true that quantum mechanics describes adequately the everyday objects. It has to be true that quantum mechanics makes correct predictions about how high a chalk if I threw it up and caught it-- if I did catch it. And it has to make predictions about everyday objects that are true.

Unfortunately, a lot of everyday objects are very complicated because they involve lots of atoms. There are lots of atoms in the chalk. There are lots of atoms in a person. And so actually describing everyday objects is extraordinarily difficult.

However, we have reason to believe that quantum mechanics should describe the objects, because quantum mechanics describes the very small. It describes electrons. It describes atoms. It describes molecules. It even describes viruses.

We simply don't have the experiments know how to test quantum mechanics on extremely large objects, but we suspect that it's still true, although we don't know for a fact if you were to go through a slit then interfered with another person. We don't know exactly what would happen or that to be the case. But quantum mechanics says that interference should occur. It says that many weird things should happen.

Now, I'd like to talk a little bit more about this collapse of eigenstate, this collapse of-- well, another word for quantum state is wave function. And you more often hear about collapsing of wave functions than you hear about collapsing of quantum states. So just to give you a little bit more words.

They're cool words too, because once you know what these words mean, you can make jokes about them. And you can wear T-shirts about them, like I am. And it's one of the pleasures of learning new terminology and learning new subjects, the fact that you get to make more jokes.

I'm not saying that that's the reason I've taken classes on relativity or taking classes on quantum mechanics, but it's a perk. It's a really cool perk. You can say lots of things interestingly with new language and new ideas. The space of jokes is enhanced by physics knowledge.

OK, but now, I'd like to talk more about this collapse of eigenstates. Now, there are certain states which correspond to positions that you can measure. We can measure a position to be here or there or there or there. But until you make a measurements, the object is in a superposition of those various states.

Let's talk about atoms. We know that atoms have a nucleus, which has some stuff in it, like protons and neutrons, maybe some other stuff. And we know that's surrounding these nuclei are electrons. Precisely how they surround them is a little complicated. But I can still discuss them. I can still discuss it in a certain way. I can still discuss an essential point that I've been trying to illustrate.

There are certain super positions that electrons and atoms can be in. And probably a lot of you have heard about these type of superpositions. In chemistry, they're called orbitals. You might have heard about S orbitals, P orbitals, D orbitals, F orbitals, G orbitals, H orbitals, and so forth. And these orbitals are really just types of superpositions that electrons can be in.

For example, an electron can be in what's called a 1s orbital. It can be in 1s orbital. That's a type of superposition.

It's in a mixture of various possible-- the electron is not at one point in space. It's in a mixture of various points in space. It's in a superposition of various points in space. But it's not an equal mixture.

There are some points in space where there is more weight. In particular, as you go closer to the nucleus of an atom, this weight becomes larger. And this weight actually has an interesting physical meaning, which I'll tell you in a moment.

So let's say I plotted position. I'll write down distance from the nucleus. And over here, I'll right down weight. It turns out that it has the greatest weights near the nucleus.

Now, when I say it has the greatest weight, that doesn't really mean anything to you yet. And what gives meaning to this weight is a probability interpretation of quantum mechanics where this weight is larger, an electron is more likely to be found once you make a measurement. If an electron is initially in a 1s state-- that's just a name of the state. It's just a weird name we've given to it. Well, not us. I mean, they did a long before we were born. But it's a weird name that people have given to this kind of superposition.

According to this probability interpretation of quantum mechanics, wherever this weight is larger, an object is more likely to be found in measurement. An electron is more likely to be found near the nucleus than it is to be found, say, a nanometer from the nucleus, anywhere at some distance from the nucleus.

But it's interesting, though, that this probability-- so I can right now probability, because this is the interpretation that we give to it-- probability. What's interesting is that this probability actually never reaches zero. I know I've drawn it to be zero here, and effectively it's zero-- I just made it bigger. I didn't mean to do that-- effectively at zero, but it never actually reaches zero.

So if I have an atom over here-- well, the chalk is made up of atoms. There are atoms in there. And if I try to measure the position of an electron in the atom, then there's a chance that I can measure the electron to be over here or over here or a mile away or 100 miles away. There's a chance I could measure to be a billion light years away. And this is something really weird that quantum mechanics simply predicts.

I can't really give you a whole lot of justification for it right now. But it's something that it predicts.

Quantum mechanics also has lots of things to predict about probabilities of events occurring. Not only is there-- can talk about probabilities of finding an electron at some place, but we can also talk about the probability that an electron will pass through my hand, or the probability that a chalk will pass through my hand or the fact that I will pass through the wall or something like that. And I did a very precise, sophisticated experiment in the first class. I don't know if you remember it.

But it took me it took like an hour to set up. And then I finally engaged in the experiments. I started preparing before class so I could do the experiment again. But I'll now test the experiment. The experiment is to test whether I can walk through a wall. And I'll just test-- well, there's a certain probability that I can walk to the wall. And I'll test to see if that's the case.

OK, it didn't work then. But it doesn't mean that there's a non-zero probability. It doesn't mean that there's a non-zero probability.

That took me an hour to set up. Took me an hour to set up, by the way. What's that? Why? Oh, well-- what's that?

AUDIENCE: We wanted to know why?

PROFESSOR: Why did it take me an hour to set up? Well, you can't actually see everything behind this experiment. There are lots of apparatuses stationed everywhere around the classroom to do it very precisely, to make sure things don't go wrong. To ensure the safety of you all, I had to take precautions. I have some charms that have cast upon you all. So it took a while to do that.

And this type of existence of non-zero probability arises from an effect known as quantum tunneling, which I think is one of the most fascinating predictions of quantum mechanics.

How much time do I have? OK, suppose I'm on my bicycle. And there's a hill in front of me, and I'm traveling at some constant speed. Let's say I'm traveling at 10 miles an hour on my bike.

So here's the landscape. It's flat, and then there's a hill, and then it gets flat again. And I start out here. I started here. I'm on my bicycle. I'm traveling at a constant speed. I start going up the hill.

And whether or not I can get over the hill depends on if I was traveling at a high speed, right? If I was traveling at 100 MPH, then probably certainly I would get over the hill. But if I'm only traveling at 1 miles an hour, then there's not a very good chance I'll get over the hill.

But according to classical physics, there is a certain energy that I have to have, a sort of kinetic energy that I have to get over this barrier, to get over this hill. And according to classical physics, there's a zero chance for me to get over the hill unless I have this certain kinetic energy. There's just no chance at all. There's no hope for me to get over the hill.

Well things are different in quantum mechanics. Things are very strange in quantum mechanics. And in quantum mechanics, there actually is a non-zero probability.

And the idea is that in a way-- well, because there's-- suppose I have some objects traveling at some speed moving across the landscape. That object is described by a certain probability distribution in position. And as the object moves, this probability distribution moves.

So for example, the probability distribution could start out looking like this. I don't know if you can see that. Can you all see it? No?

AUDIENCE: Yes.

PROFESSOR: Of course, you can see it. Well, I don't have an extra col-- I'll draw it larger. OK, let's say that this is the probability distribution of the position of this particle. So the particle's moving. And at a given instant in time-- suppose you stop time-- at a given instant in time, there's a certain probability that you'll measure the particle to be over here. There's a certain probability that you'll measure the particle to be over here. There's the high probability that you'll measure the particle to be here, and so forth.

Now, as the particle moves, this probability distribution moves. And it keeps moving as the particle moves.

Now, when the particle gets to near the top of the hill, when he gets, for example, to over here, the probability distribution might look this. If the particle didn't have enough energy, enough kinetic energy, to get over the hill according to the laws of classical physics. If they have enough kinetic energy to break this barrier, then according to quantum mechanics it might now have a chance of getting over the hill, because if you look at this probability distribution, there's now a non-zero probability that you'll measure the particle to be over the hill. There's a small probability, but it's still non-zero.

And this is a simple way of understanding how this tunneling phenomenon works. And we call it tunneling, because it's as if the particle tunnels through this hill. It doesn't actually get over the hill, but it goes through the hill in a certain way. It tunnels through the hill.

And this makes a lot of things possible, a lot of very interesting things possible. For example, ordinarily when I pull at this desk trying to lift it up, when I use the amount of force I'm using right now, the desk isn't going to lift up. But there's a chance that I can get it up even using that same amount of force.

There's a chance that air molecules around me can knock me over. There's a chance that they'll have enough energy to knock me over, enough energy as provided by this quantum tunneling phenomenon. So there's a chance that while talking to you all, I'll simply be knocked over. It can happen. The chance is very small. So you don't usually see it happening. And you probably never will see it happen ever in your whole entire life unless you live forever, in which case you'd see it happen infinitely many times, because if there's a non-zero probability that it will happen, then if you wait long enough, it will happen.

With this idea you can envision lots of possible worlds. You can envision magical worlds being possible being possible as a result of quantum tunneling. You can imagine people flying as a result of air molecules, pushing on them, giving them enough energy to surpass these barriers, to allow the air molecules to tunnel through these barriers.

And you can go further. You can say, well, let's say I want to punch one of the guys in the back row. Well, if I just do this, then I give a little bit of energy to these air molecules right in front of me. And those air molecules give a little bit of energy to those air molecules in front of them. And eventually, they can reach you and punch you with a very strong force.

So quantum tunneling can make possible, for instance, the force of Star Wars. I could choke one of you in the back. You can think of some very complex way that quantum tunneling can allow for air molecules to move and to have enough energy to surpass lots of barriers. You can let your imaginations run wild with this.

Pretty much any idea, pretty much anything that you can imagine, you can think of a way for it to happen. You can think of a very complex mechanism for it to happen. And if you can think of a mechanism for it to happen, then you can associate a probability for it to happen. And therefore, if you wait a long enough time, it will happen. But I don't know if you all have enough patient to use the force on people. Question?

AUDIENCE: Is there any record of quantum tunneling happening?

PROFESSOR: Oh, quantum tunneling. OK, so quantum tunneling has a very small probability of occurring for everyday objects like people. But, in fact, it's used in modern electronics all the time. For electrons and for other small particles, quantum mechanics, you can very easily see it work.

As I said, our only real experimental evidence for quantum mechanics is what we see in these experiments for very small objects in this very microscopic realm. We think it's true for macroscopic realm. But we don't exactly have a whole lot of experimental evidence for it. But why shouldn't it be true? Yes.

AUDIENCE: Does the same basic principle apply for things like spontaneous combustion.

PROFESSOR: Ah, no, no. It's kind of different. I don't have a whole lot to say about that, about spontaneous combustion. Sorry.

But this is one of the things that I love about quantum mechanics, the fact that it makes so many things possible, the fact that it gives you hope. I mean, if things are looking bleak, if you fall over a hill, for instance-- no, if you've fallen off a cliff. Things are looking bleak. It doesn't look like you're going to make it.

Well, quantum mechanics gives you hope. Quantum mechanics says that there is a chance that the air molecules can lift you up and lift you up to the heavens and save you, save your life.