CATHERINE DRENNAN: OK. We're going to take 10 more seconds. OK. Does someone want to explain how they got the right answer? We have a Faculty of 1,000 research bag for them. Do you want to hand that up and the bag, too? We're just--

AUDIENCE: So the theme of light gives enough energy for the electrons to be ejected. And the amount of energy for that is 4.3 eV. And then it also has kinetic energy of 7.9 eV. So you just add the two. So 4.3 plus 7.9 is 12.2 eV.

CATHERINE DRENNAN: Thanks. Let's bring it back. OK. Thank you. All right. We'll have lots more practice with this today, and we'll get the hang of doing these problems. So let's just jump in and get started. We're still continuing to think about the photoelectric effect, and think about light as a particle. So we're going to finish up with the photoelectric effect, and we're going to have a little demo on that in a few minutes.

Then we're going to go on. If light is, in fact, quantized, and you have these photons, then photons should have momentum. And so we'll talk about that. Then we've talked about white as a particle. And most of you are probably pretty OK with matter being a particle. But what about matter being a wave? So we're going to talk about matter being a wave.

And if we have time at the end, we're going to start on the Schrodinger equation, which we're going to continue with on Friday. So I'll just say that sometimes, I am a little overly ambitious, and I put things on the handout that I'm not really sure I'm going to get to. Just because I've never gotten into it before doesn't mean that I won't get into it this time. So if I don't finish everything on a handout, bring your handout to the next class, and we'll just continue from there. And there'll be a new handout then as well, so just a heads up on that. All right.

So let's continue with the photoelectric effect and get good at doing these kinds of problems. So let's look at these particular examples. We have three different examples here. We have the energy of an incoming photon must be equal or greater to that threshold energy or that work function, in order for an electron to be ejected. So in this case, the energy is greater than the work function. So tell me whether an electron will be ejected or will not be ejected. And you can just yell it out. What do you think?

AUDIENCE: Will.

CATHERINE DRENNAN: Yes. So an electron is ejected. It will be ejected. What about this scenario over here, where the energy is less than that threshold energy? Is or is not ejected?

AUDIENCE: Is not.

CATHERINE DRENNAN: Yes. OK now we have another scenario. We have three photons, each of which have half of the energy needed, half of that threshold energy. But you have three of them. So will an electron is or is not ejected?

AUDIENCE: Is not.

CATHERINE DRENNAN: Is not. OK. So three photons each that have half the energy does not add up. You cannot add it. It will not eject an electron. So let's just think about it for a minute.

Suppose the threshold knowledge for passing an exam is answering three specific questions correctly. Suppose over here, we have the answer to one of the questions, but not to the other two. Over here, we have an answer to the middle one, but not the first or the second. And over here, we have the answer to the third, but not the first or the second. So everyone knows the answer to a different question. Will there be the threshold energy, a threshold knowledge, to pass this test? No.

Everyone needs to have the threshold knowledge themselves to be able to pass. Everyone has to overcome that critical amount of knowledge to be able to pass the test. So that's the same thing here. You can't add it up.

Now, with the test here at MIT, if everyone has that threshold knowledge, and a really high level of the threshold knowledge, everyone can get an A. So the more people with the threshold knowledge, the more tests that are passed, and the more the course is passed by people.

So the more photons coming in with that threshold energy, the more electrons being ejected. But you can't add up if you have photons that don't have enough, if they're not greater than, the threshold energy. You won't eject an electron. So everyone needs to meet that threshold criteria. You can't add things up. OK.

So here's just some useful terminology for solving problems on this problem set. And there will also be problems on problems set two related to this topic. So photons-- also called light, also called electric magnetic radiation-- may be described by their energy, by their wavelength, or by their frequency. Whereas electrons, which are sometimes also called photoelectrons, may be described by their kinetic energy, their velocity, and, as you'll see later, by their wavelength.

So you'll be given problems where, given different pieces of information, you have to think about how you're going to convert it. You've got to think about am I talking about a photon? Am I talking about an electron? And you also want to think about units. You'll sometimes be told about energy in eVs and sometimes be told about energies in joules.

So this is a conversion factor. All conversion factors are given to you on the exam. You do not need to memorize any kind of conversion factor. But you need to be aware, when someone said joules, what's that a unit for, or eV, what's that a unit for. All right.

So now we're going to do and in-class demonstration of the photoelectric effect. But before we actually do the experiment, we're going to predict what the experiment will show. Always dangerous to do that, so we'll hope it works after we do the prediction. All right. So we're going to be looking at whether we're going to get an injection of an electron from a zinc surface. And we're given the threshold energy, or the work function, of zinc. Every metal-- this is a property of metals. They're different, as we saw last time.

So this is 6.9 times 10 to the minus 19th joules. And we're going to use two different light sources that are going to have different wavelengths. And we'll predict whether they have enough energy to meet this threshold to go over the threshold and inject an electron.

So the two different sources, we have a UV lamp with a wavelength of 254 nanometers and a red laser pointer with a wavelength of about 700 nanometers. OK. So before we do the experiment, let's do some calculations to see what we expect. So first, we want to see what the energy, or calculate what the energy, of the photon will be that's a emitted by the UV lamp. And I will write this down.

So what do we know? We know a bunch of things already. We know that energy is equal to Planck's constant times the frequency. We also know that the frequency is related to wavelength by c, the speed of light. And then we can put those two things together to say the energy, then, is also the Planck's constant times the speed of light divided by the wavelength.

So we can use that last equation to do a calculation, and figure out the energy that's associated with that particular wavelength of light. So here we have energy. We're going to write in Planck's constant, 6.626 times 10 to the minus 34. And the units are joules times seconds and the speed of light, 2.998 times 10 to the 8 meters per second.

And we want to divide this, then, by the wavelength. So we have the wavelength here that we're using first is a 254 times 10 to the minus 19 meters. Oh sorry-- 9 meters. Thank you. I wrote down 19. I'm like, wait a minute. That's not right. OK. OK.

So then we can do the calculation out. And here is where I got excited about 19. We have 7.82 times 10 to the minus 19 joules. And if we look at the equation, we'll see that the meters are going to cancel. The seconds cancel, and we're left with joules, which is good, because we want an energy. So joules is a good thing to have.

So there, we can do a simple calculation. And we can look and say, OK, if the energy, then, associated with that wavelength is 7.82 times 10 to the minus 19th joules, then we ask, is this greater or less than the threshold energy? And it's greater than that. So it does have enough energy. It should eject an electron. So we can try that out and see.

Now we can look at what happens with the red laser pointer and see whether that should have the energy that's needed. And so I will just write these things down here instead of writing it again. So that was our UV. So now our red light, we have 700 times 10 to the minus 9 meters, or 700 nanometers. And so here is our answer for the UV. And our answer for the red light should be 2.84 times 10 to the minus 19 joules. And I'll move this up a little so people can see that.

So does that have enough energy to eject an electron?

AUDIENCE: [INAUDIBLE]

CATHERINE DRENNAN: No, that should not work, because that's less than the threshold energy that's needed. All right. So we'll do one more calculation just for fun. And then we'll do the experiment. So the last calculation we'll do is we'll think about the number of photons that are emitted by a laser in 60 seconds if you have an intensity of one milliwatt. And a milliwatt is equal to 10 to the minus 3 joules per second.

So we can just do that calculation over here. So we have 1.00 times 10 to the minus 3 joules per second, 1 photon, and here, this is for the red laser. So we'll use the number that we just calculated over here. So we have 2.84 times 10 to the minus 19th joules for the red laser and times 60 seconds. And we should get 2.1 times 10 to the 17 photons. So that's how much photons, if we hold it for 60 seconds, that were going to be shooting at our metal's surface.

So these are the kind of calculations that you'll be doing on these kind of problems. And now let's see how well the experiment works. So we're going to bring out our demo TAs, who are going to tell you about this demo. And we're going to try to do some fancy stuff with this document camera to project it on the screen. So this is all very exciting.

Oh, I guess I should put that down, the number, in case you couldn't see it-- 2.1 times 10 to the 17. All right. So let's bring-- you've got the mic.

GUEST SPEAKER 1: OK. So we've got our metal plate here that Eric's got in his hand. And what he's doing right now is he's rubbing it with a little bit of-- what is that, actually?

ERIC: It's just steel wool.

CATHERINE DRENNAN: Steel wool.

GUEST SPEAKER 1: OK. So that's just going to get the aluminum oxide, because sometimes-- you guys will get to it. But sometimes you can get a reaction of aluminum with the moisture in the air, and that's going to cause aluminum oxide. So he's getting get rid of that.

And now we've put this on a-- what is this?

ERIC: [INAUDIBLE].

GUEST SPEAKER 1: What do you call it? A detector of some kind. So basically, when he charges this, what's going to happen is that you have this plate, and you have this joint. And they're both going to be electrically negative, because you've introduced some electrons. And they're going to repel each other, because they're both negative. Two negative charges repel each other. So you're going to see some space develop as Eric's done.

Now, what he's doing is he's got a plastic rod here that he's charging with the fur. And he's introducing those electrons onto the plate. So now we've got a negatively charged plate, and you can see that by the fact that you see some repulsion between that rod and the rest of the detector, which is actually working out pretty nicely. So once--

CATHERINE DRENNAN: So say this experiment is very weather-dependent. If it's really humid or too dry, it doesn't work nearly as well. But today, today's good weather. Today's good weather for this experiment, not so much good for sunbathing outside, but good weather for this experiment.

GUEST SPEAKER 1: Although we have UV lamps, so maybe.

CATHERINE DRENNAN: That's true.

GUEST SPEAKER 1: OK. So now we've got a charge.

CATHERINE DRENNAN: That's the green laser pointer. Let's get the red.

GUEST SPEAKER 1: It's underneath here, I think.

CATHERINE DRENNAN: Oh, yeah.

GUEST SPEAKER 1: OK. So now--

CATHERINE DRENNAN: We could do the calculation for the green. If you want to do the calculation for the green, we can try it later.

GUEST SPEAKER 1: Eric's got a red laser pointer in his hand. He's going to shine it. And we're going to see that nothing happens, because as we calculated, the energy of these photons is not enough to get over the threshold of this particular metal.

CATHERINE DRENNAN: So if electrons were being ejected, you should see it move.

GUEST SPEAKER And we'll do that one more time. Maybe the green one will work. It doesn't.

1:

CATHERINE DRENNAN: All right. Well, now we have to see if the UV-- we built it up. The UV should--

GUEST SPEAKER 1: So hopefully this works.

CATHERINE DRENNAN: --work. Let's see.

GUEST SPEAKER 2: [INAUDIBLE]

GUEST SPEAKER 1: OK. So oh-- maybe--

AUDIENCE: [INAUDIBLE]

CATHERINE DRENNAN: Oh.

GUEST SPEAKER 1: Oh, well, I guess it worked.

CATHERINE DRENNAN: It did work. You could sort of see that.

GUEST SPEAKER 1: So maybe we can charge it up again while I talk about it.

CATHERINE DRENNAN: Yeah, sometimes the charge [INAUDIBLE].

GUEST SPEAKER 1: The UV lamp, obviously, has enough energy in each of these photons. So when you shine that light at the metal, you have the electrons on the surface, which are being ejected. And if those electrons get ejected, then the whole system becomes neutral. If the systems become neutral, then that rod can go back and is no longer feels a repulsion, because the two parts are no longer negative. So once we charge this up again, maybe we can go to the other side and-- I think it's good. It's good.

CATHERINE DRENNAN: Yeah, that's good. Oh--

GUEST SPEAKER 1: It will be fine.

GUEST SPEAKER 2: Wavering.

CATHERINE DRENNAN: OK.

GUEST SPEAKER 1: OK. Now we're just going to try it again. And yay.

CATHERINE DRENNAN: Yay.

GUEST SPEAKER 1: We got it.

[APPLAUSE]

CATHERINE DRENNAN: OK. Great. We can just leave this here. All right. And I think he held it for 60 seconds, so you know how many photons were coming off, too, if you want to do that calculation.

So again, the photoelectric effect was really important at this time in understanding the properties that were being observed, to help us understand about this quantized energy of particles, that light had this particle-like property. It had this quantized energy. And you needed a certain amount of it to eject an electron from a metal surface.

So we all know that light is a wave. But now there's this evidence that, even though it's pretty much this massless particle, that it still has particle-like properties. So light is a really amazing thing. This doesn't really show up very well. It's a view of the Stata Center. Stata Center always has some really spectacular sunlight coming around it sometimes. All right.

So now, if this is true, that means that photons that have this quantized energy should have momentum as well. And so Einstein was thinking about that. And so he reasoned that this had to be true. There had to be some kind of momentum associated with them. And so momentum, or p, here is equal to Planck's constant times the frequency divided by the speed of light, c. And since the speed of light is equal to the frequency times the wavelength of the light, then the momentum should be equal to Planck's constant divided by the wavelength.

So this is really-- we're talking about momentum in terms of wavelength, this inverse relationship here. This was just a kind of a crazy idea to be thinking about momentum, when you're talking about light. And this really came out of the photoelectric effect. And also, there were some experiments done by Arthur Compton that also showed that you could sort of transfer this momentum. And so that's again the particle-like property. So it's a really exciting time. OK.

So we're going to now move to matter. So we've been talking about light and how light has this dual, particle, wavelike properties. But what about matter? So we accept that matter has particle-like properties. But what about as a wave? So enter de Broglie into this area.

And so he was following what Einstein was thinking about. And he said, OK, so that's pretty cool. If you have momentum is equal to Planck's constant divided by wavelength, if you could think of things that have wavelengths as having momentum. And he said, or I can rewrite this equation, that wavelength equals Planck's constant divided by momentum.

And we know something about momentum. We know that momentum is often associated with something's mass times its velocity. So therefore, I should be able to rewrite this equation again in terms of wavelength being equal to Planck's constant divided by a mass and a velocity. And here, we are expressing wavelengths in terms of masses. So this was really something.

And this was basically his PhD thesis. I think it maybe had more pages than that, but this would have probably been enough, this sort of cover page. This is my PhD thesis. And Einstein said that he had lifted the corner of a great veil with really just manipulating what was known at the time and rearranging these equations and presenting relationships that people hadn't really put together before. So he ended up winning a Nobel Prize, basically, for his PhD thesis, which is a fairly rare thing to have happen. But this was really an incredible time.

OK. So if this is true, if you have equations that relate wavelengths to mass, and particles have wavelike properties, how come we don't see this? How come this isn't part-- how come no one noticed the particle going by and this wavelength associated with it? So why don't we observe this wavelike behavior if, in fact, it is associated with particles?

So let's think about this a minute. And we can consider why, when you go to Fenway Park-- and you should, because it's fun-- and you watch someone throw a fastball, why you don't see a wave associated with that fastball. So we can consider a fastball and that the mass of a baseball is about 5 ounces, or 0.142 kilograms. And the velocity of a fastball is around 94 miles per hour, or 42 meters per second.

And so we can do a little calculation and figure out what the wavelength associated with that ball should be. So wavelength should be Planck's constant over the mass times the velocity of the ball. And we can plug in these values. And here's Planck's constant again.

And now you'll note I did something with the units. So instead of joule seconds, I substituted joules with kilograms meters squared seconds to the minus 2. And that's what's equal to a joule. And I'm going to do that so I can cancel out my units. And again, all of this will be provided on an equation sheet. You do not need to remember all of these conversions.

And so over the mass of the baseball and the velocity of the baseball-- and we're going to put the velocity in meters per second so our units can cancel out. And so I'll just cancel units out. So we're canceling our kilograms. We're canceling one of the meters, and canceling all of the seconds. And we have one meter left, which is good, because we're talking about wavelengths. So that's the unit we should have.

And the wavelength is 1.1 times 10 to the minus 34 meters. That is a really small number times 10 to the 34. And it is, in fact, undetectably small. OK. So now why don't you try your hand at this, and we'll try a clicker question.

Yeah, it's very tiny. All right. Let's take just 10 more seconds. Oh, or five seconds. OK. Awesome. It went away. That's OK. So they're in-- 97%. I like 97%. That's a good number.

So again, you want to think about this and just realize the relationship, the equation, involved. And so thinking about-- oops, I switched pointers. I like the green better. So think about the relationship between the velocity of the ball and the wavelength. And so Wakefield, who was an knuckleballer, is the winner here, with the longest wavelength.

But still, the number for this is 1.4 times 10 to the minus 34. And so this is still undetectably small. So of course, no one had noticed this property before. But it still, it still exists. So when you're talking about a baseball, the wavelength is really not very, relevant to you, because it is this incredibly small, undetectable number.

But if you're talking about an electron, it's entirely different. So now, if we think about a gaseous electron traveling at 4 times 10 to the 6 meters per second, and so that's associated with an eV of about 54. So we have this electron traveling with this velocity. And now, if we do this calculation, so if we use Planck's constant divided by the mass of the electron-- and that's known, in another great experiment-- and its velocity, now we can calculate out the wavelength. And it's 2 times 10 to the minus 10, or about two angstroms.

Now, 2 angstroms is a relevant number, when you're talking about an electron, because an electron is in an atom. And atoms tend to be-- you have diameters 0.5 to 4 angstroms. So now the wavelength is on the same scale as the size of the object you're talking about. And so when that's true, all of a sudden, the wavelength-- the wavelike property becomes super important to thinking about this. So for an electron that is a particle, it's really important to think about its wavelike properties.

And so people were saying, OK, if electrons are waves, then maybe we should see other wavelike properties, such as diffraction. Diffraction, we talked about last time, is an important wavelike property of constructive interference, destructive interference. So people looked to see whether there were diffraction-like properties, and in fact, there are.

So we had observed, then, the first was observing diffraction of electrons from a nickel crystal. And then JP Thomson showed that electrons that pass through gold foil again produced a diffraction pattern. So again, this was a wavelike property.

So you might think Thomson, that sounds a little familiar to me. Didn't she just talk about that last week? And yes, here there are two important Thomsons in this story. And this is a father and son team. And so JJ Thomson won a Nobel Prize in 1906 for showing that an electron is a particle. He discovered an electron.

And then in 1937, his son wins a Nobel Prize for showing-- son just had to be like, Dad, I'm going to show you're wrong. An electron is, in fact, a wave. But I think they were both happy. I think they both got along, no father-son rivalry. I think this is one of the cooler stories in science, how this father, son both had kind of opposite discoveries, which both ended up being true, and really changed the way we thought about matter. All right.

So we have light as a particle and as a wave. We have matter, particularly electrons, as particles and waves. And now we are ready for a way to think about how to put this together. So before we move on and talk about the Schrodinger equation, I just want to take a break from history for a minute, because some of you are like, OK, well, this is really cool for the father and son team, but what about today? What's happening today?

So let's take a break from history for a second and talk about why you should care about small particles. Small particles of special properties, if they're on the subatomic scale, their properties are different. If you have very, very few atoms, versus many atoms, the things with very few atoms have special properties.

So why should you care about that? Why should you care about the energies that we can get out of the Schrodinger equation? So why should we care about the Schrodinger equation or quantum mechanics?

So there are many reasons, but I will share one with you. And this is a segment in their own words. So you're going to hear from Darcy, who was actually a former TA for 5.111. So she is associated with this class. She actually just got her PhD in the spring from MIT, and she now works at Google.

But in this short, she's going to tell you about research in Moungi Bawendi's Lab, and why you should care about quantum dots, which are small collections of atoms. So I'm going to try to switch over now and hope that our demo before didn't screw up the sound. But we'll see what we can do. And I think it should be good.

[VIDEO PLAYBACK]

- My name is Darcy Wanger, and I work as a graduate student in the Bawendi Lab at MIT. I work with quantum dots in my research. Quantum dots are really, really tiny particles of a semiconductor. So we're talking like 4 nanometers in diameter. In a particle that small, there are only 10,000 or so atoms, which seems like a lot of atoms if you're comparing to something like water, which only has 3 atoms in it. But if you compare it to something you can actually hold in your hand, which has a lot of atoms in it, 10,000 is actually a pretty small number.

So a particle this small has really strange properties. Different things start to matter when you get really small. And just like an atom, a quantum dot, or semiconductor nanocrystal, has discrete energy levels. So if an electron is sitting at this energy level, and it absorbs light, an electron can get excited to a higher energy level. And then, when that electron relaxes back down to the ground state, it emits light. And the energy of that light is exactly the difference between these two energy levels.

The difference between the energy levels is related to the size of the dot. So in a really small quantum dot, the energy levels are far apart. So the light it emits is higher energy, because there's a large energy difference between the energy levels. If we use a larger quantum dot, the distance between the energy levels is smaller, so the light it emits is lower energy, or redder.

People in our lab are working to make quantum dots bind to a tumor. So when a doctor goes in to remove a tumor, they can see the shining of the UV light on it, and see whether it's all gone when they've taken out the tumor. They can also use quantum dots to label other things other than tumors, like pH or oxygen level or antibodies or the other drugs that are treating the cancer tumor. Each of those can be different colors.

So if you shine a light on that whole area, you can see, oh, that orange spot, that's some cancer cells. Oh, and that green tells me that the pH is above 7.4. So it's pretty cool that we can use the idea of energy levels in something so applicable like surgery, where it can actually be used to track things and make it easy for doctors to see what's going on while they're doing a surgery.

[END PLAYBACK]

CATHERINE DRENNAN: OK. So that's an example for course 5 research.

[APPLAUSE]

And you can see all these credits online. I will mention that some of those nice animations were done by a former graduate student in the chemistry department. So these videos, even the art was done by chemists, which is a lot of fun.

OK. So let's introduce the Schrodinger equation. And we'll spend some more time on this as we go along, on Friday. So we needed now-- we had learned a lot about wave particle duality and about these subatomic particles. And we needed a way to think about it. We needed a theory to describe their behavior. And classical mechanics had some flaws in with respect.

So we needed a new kind of mechanism. We needed quantum mechanics. So here, if we're thinking about particles that are really small like electrons, we need to consider the wavelike properties. It's really important when you have a wavelength that is so similar to the size of the object that you're thinking about. So the Schrodinger equation really became to quantum mechanics like Newton's equations were to classical mechanics.

So what is the Schrodinger equation? So here's a picture of Schrodinger. And he looks so happy. I would be happy, too, if I had come up with this equation, I think. So here's the simplest form of the equation that you will probably ever see. And so we'll just define some of these terms.

So we have wave function, psi. And over here is the binding energy, and that's the energy of binding an electron to a nucleus. And then an H with a hat, we have our Hamiltonian operator. And in this course, you will not be solving this equation. We're just going to be talking about what sorts of things came out of this equation.

So I'm going to give you a little bit longer version of the equation now. And so again, you're thinking about the electron. It has these wavelike properties. And it's somewhere in the atom, not crashing into the nucleus. And it needs to be defined in three dimensions.

And it has momentum, so it's moving. So we need to think about this as an equation of motion in a three-dimensional space. And the equation is going to change. The math will change, depending on where the electron is located, which you won't know exactly.

So this is a very hard problem. But it's not totally without anything to do with classical mechanics. And if we write the longest version you'll see, at least in this course, for the hydrogen atom, I just want to show this to point out that there are some terms from classical mechanics in here. This is Coulomb's energy, also sometimes called potential energy. So we saw Coulomb's force before. Here is Coulomb's energy. So some of the classical mechanics is contained within this, but it expands from classical mechanics to consider the wavelike properties of the electrons.

So whenever I talk about this, I always feel like I want to have something better to say about really what this is doing and where it came from. In terms of what it's doing, how is solving this helping you? What are you learning from solving this?

So one thing you're learning from solving this is you're finding E. And that's really important, the binding energy of the nucleus and the electron. And we saw before that, if you just used simple classical mechanics, you have a positive and negative charge that are close to each other. Why don't they come and crash into each other? We want to know how they are bonded to each other, what's the real energy of that association.

We also saw, with the photoelectric effect, that it's not that easy to get an electron to eject from a metal surface. So it's bound in there. And what is that actual binding energy? So that comes out of the Schrodinger equation. This E here is the binding energy. And also, solving it will tell you about the wave function or, as chemists like to talk about, orbitals, where the electrons are, in what orbitals. So this is the information you get out.

And importantly, it works. It matches experiment. So chemists are experimentalists. We love experiments, and we see this data, and we want to understand it. And the Schrodinger equation helps us understand it. It correctly predicts binding energies and wave functions, and it explains why the hydrogen atom is, in fact, stable, where you don't have crashing or exploding of the hydrogen atom.

So where did this equation come from that works so well? How did Schrodinger come up with this? And this is always sort of the puzzle when I teach this. I feel like I should have something profound to say about where this came from.

And so I've done a little reading and looked, and I thought the best explanation for this that I ever saw came from Richard Feynman. And when he was asked how Schrodinger came up with this equation, he said, "it is not possible to derive it from anything you know. It came out of the mind of Schrodinger." And I thought that pretty much summed it up.

So sometimes-- after class last week, on Wednesday, someone came down and said, you know, the Thomson experiment, discovering the electron, why didn't someone else do that experiment? It seemed like it's not a cathode ray. And you have to have a little phosphorous screen. Why didn't someone else discover the electron?

And some of these other-- de Broglie rearranged some equations, did it in a way that no one else was thinking, but still. Or plot solving the equation of a straight line. No one else was thinking about it some way, using other people's data. They just sort of saw things in data that other people didn't. But you think why didn't someone else see that, too?

When it comes to the Schrodinger equation, the question is why didn't someone else or lots of people come up with it? I think the question really is, how did Schrodinger come up with it? At least, that's the question to me. And I have never really-- that's the best explanation I have. It just came out of his mind. OK.

So we're many years later. We've had the Schrodinger equation for a while. So this is an old story, right? Well, maybe for the hydrogen atom, but this is still actually a very active area of research. Oh, my startup disk is full. Thank you. Let's go back to that. All right.

So I just thought-- I always like to give you examples of current research on these areas. And so I know a number of you were interested in potential of being chemical engineering majors, undergrads. And I'll tell you about a new professor who started about a year ago, Heather Kulik. And her research group is really interested in using a quantum mechanical approach to study materials and to study proteins.

But when you get to things like proteins, there's thousands and thousands of atoms around. Forget multiple electrons, we're talking about multiple atoms with multiple electrons, huge complexes. How can you give a quantum mechanical analysis of things that are so large?

And this is really important. I mean, I think that one of the big problems moving forward is solving the energy problem and doing it in a way that doesn't destroy our environment, so new batteries, new electrodes, new materials. We need to understand the properties of different metals to understand what will make those good electrodes. And to really understand them, we need a quantum mechanical approach. But these are big areas. There's a lot of things to consider here.

So Heather is interested in coming up with improving algorithms, improving the computation, to really give a quantum mechanical analysis to systems that have a lot of atoms in them. So if you're interested in this area, you're not too late. You don't have to go back to the early 1900s. There's still a lot to do in this area. OK.

So very briefly now, let's just look at the Schrodinger equation we saw from the hydrogen atom. So we'll go back to understanding quantum mechanical analysis of photosynthesis-- amazing, don't understand how it works. That would be great if we did. That would really solve a lot of energy problems. But we'll just go to hydrogen atom, one electron back.

So if you solve the Schrodinger equation for this-- and I think I did this in college, not in freshman, chemistry, but somewhere along the line-- you'll come up with this term. So again, this is the binding energy. We just want to know about how the electron is being held by the nucleus.

And there are some terms in here. We have the electrons mass-- that's known, the electrons charge. We have a permittivity constant and Planck's constant. And if you look at this, you go, wait a minute. That's a constant. That's a constant. That's a constant. That's a constant. We can simplify that. And we will.

And that is the Rydberg's constant, 2.18 times 10 to the minus 18th joules. So now it doesn't look quite as scary. We can just substitute this RH. That makes us feel a lot better. It's one number that will be given on the equation sheet, so we don't even have to remember it. And now we can rewrite this in terms of the binding energy.

So again, the binding energy, this is a constant. So now this turns into minus RH over n squared. And n, what is n? n is a positive integer 1, 2, 3, up to infinity. And what's its name? What is n? You can you yell it out. Some of you know.

AUDIENCE: [INAUDIBLE]

CATHERINE DRENNAN: Yeah. The principle quantum number, that's right. So the principle quantum number comes out of the Schrodinger equation. And that's how we can think about it. And again, here are these ideas. The binding energies are quantized. This is a constant over here. So the principle quantum number comes out of the Schrodinger equation. All right.

So now, next time, we're going to think more about the Rydberg constant. And we're going to do a demonstration next Friday of the hydrogen atom spectrum to show that the Schrodinger equation, in fact, can explain binding energies. So that's on Friday, and that's our first clicker competition. So come. Be ready with your clickers. You can sit in recitations. You can share answers before clicking in. It's not cheating. It's teamwork. OK. See you Friday.