CATHERINE DRENNAN: Click in your response.

All right, let's just do ten seconds on the clicker question.

OK, so 82%. I like it when we get into the 90s, just FYI, for these. So since this is similar to one we did last time, it's just to remind you again of the first part of problem set one where we have this material that you need to learn how to cover.

So does anyone want to tell me how they got the right answer? And this is not going to be a great prize. There's going to be better prizes later. This is an American Chemical Society pen for this one, since we had a similar question last time. I should've told you it was going to be a better prize later. Now no one's going to-- everyone's going to wait.

See if that's turned on. No, I guess not.

AUDIENCE: So you find the limiting reactant by dividing the amount of moles for both by the molar coefficient. And you see that it's at the O. And then you just do 12 times the molar fraction, which is just one AL203 for every 3FEO and you get 4.

CATHERINE DRENNAN: Great. So if you haven't practiced these yet, go ahead and practice. Yeah!

[APPLAUSE]

CATHERINE DRENNAN: OK, so let's think about what we were talking about on Friday. We were talking about discovery of the electron and the nucleus, and realized through the experiments that the atom is mostly empty space. But there is this concentrated small part of the nucleus that can deflect alpha particles, or ping pong balls. And this is a really small concentrated part, so that would be like the head of a pin in a room somewhat bigger than this, or a pea in the size of a sports arena. The nucleus is very tiny compared to the atom. And the atom is, again, mostly empty space.

So this discovery was amazing of these subatomic particles and was really changing what people were thinking about. So at that time, they started to realize in doing these experiments and the experiments I'm going to tell you today that they needed a different way of thinking about matter. And to explain the observations that scientists were making at the time, they needed to think about the fact that radiation had both wave-like and particle-like properties. And matter had, also, wave-like and particle-like properties. And also that energy is quantized into these discrete bundles called photons.

So we're going to be talking about these new discoveries and the data that didn't fit today, and how we came up with this new mechanics that helped to explain the properties that were being observed. So we're going to start today with a wave particle duality of light. So we're going to talk about light as a wave. And we're going to first talk about the characteristics of waves, which is a little review. And then we're going to talk about light as a particle and get into the photoelectric effect, which was a really important series of experiments that help scientists understand what was going on.

So first we'll just have a little review about waves. So some of you come from places that probably don't have oceans nearby. You are now living in a place that does have an ocean nearby, so you can go take the blue line to Revere Beach. I always find doing a chemistry problem set is very relaxing on the beach. And you can watch the water level go up and down in this repeated periodic fashion. So if you haven't experienced water waves, you should absolutely do that.

So waves have this periodic variation. So you could have average water level, the water level will go up and then go down and go up and go down from high levels to low levels. This same behavior is observed for other types of waves, such as sound waves. So here you would have the average density, and the sound wave can go to higher density, lower density, higher density, lower density. And this same periodic behavior is also observed with white light or electromagnetic radiation is also a periodic function. But here you have this periodic variation of an electric field.

So we have, whether it's water waves or if we have sound waves or light waves, we always have this periodic behavior. And you can define this periodic behavior by a number of different terms, which we'll talk about now. Mostly we'll be focused on light waves today, but these terms can apply to other types of waves, as well.

So we have amplitude. And that's the deviation from the average level. So you can have a positive amplitude or a negative amplitude here. So this is the height of the wave. You also have wavelength where the abbreviation is lambda. And this is the distance between successive maxima, so the distance from this maxima to this maxima is one wavelength. We also have frequency of the wave, which helps to define it. Oh, I should say wavelength can be up here or down here. They should be exactly the same. So frequency or nu is the number of cycles per unit time.

So we talk about wavelength, amplitude, and frequency. And as you turn the page, we can also talk about the period of the wave. So 1 over the frequency is called the period, and it's the time it takes for one cycle to occur. So the time that you go from one maximum to the other maximum for one cycle is the period of the wave.

As with most things in chemistry, there are units, always think about your units. So units of frequency are cycles per second, and that's also called a hertz. So you will often just see per second, but sometimes you'll see hertz in these problems. So those can be used interchangeably. And one other term is intensity, which is equal to the amplitude squared.

So for all of these waves, there are these certain characteristics you think about. The amplitude of the wave, the wavelength, and the frequency, the period of the wave, and also the intensity of the wave. So now if we're thinking about light waves, which we will be most of the time, we can also think about the speed of that light that is traveling. And so at time 0 if we're thinking about the time it is going to take this little orange dot, to move this pink here that's labled, to move from here to here, move one wavelength. So it has moved to this second location.

The time it takes to do that is going to be 1 over the frequency. If we think about then the speed at which this will happen, that it'll go from here to here at time 0 to time 1 over the frequency or one period as we just defined, now we can fill out this equation. And see that the speed is going to be equal to the wavelength, lambda. So that's the distance traveled, the wave traveled one wavelength. And the time it took, the time elapsed was one period or 1 over the frequency, and then we can define one of the equations that you probably don't really need to have defined for you, which is that the speed of light is equal to the wavelength times the frequency. And this is in usually units of meters per second.

So most people already know what this speed of light, we're talking again about light here, is equal to. And it has a constant speed. So electromagnetic radiation has a constant speed, the speed of light. And the speed of light is abbreviated c, equals the wavelength times the frequency, which is 2.9979 times 10 to the 8th meters per second. So most of you have seen this before and are well aware of it. This also has some of the conversions on here.

Speed of light is quite fast and often people have the expression how fast [INAUDIBLE]. You're working at the speed of light. And that's a pretty valid thing to indicate that you're doing things very, very quickly, because that is fast. And in fact, if we had the earth here and the moon here, light would go like that. And it should take about 1.2 seconds to do that. So speed of light, very quickly.

All right, so what's also important in thinking about this is that the speed of light is a constant, which is going to mean that these terms are related. So first before we move on, let's do a clicker question. And you can all test out that your clickers are working again.

How are we doing? OK, let's do 10 more seconds.

OK, 92%, that's awesome. All right, does someone want to explain how they could eliminate one and two versus three and four and get this one right?

AUDIENCE: Sure, well it looks like this problem is asking us to look at two different things, the wavelength of these waves and the frequency. And you can look at the distance between the two peaks in both of the waves to see how short or long the wavelength is. Wavelength A has a much shorter distance between peaks than B does. And then you're also looking for nu, the frequency. So within a period of time you can fit more waves of A than B, so it has a higher frequency.

[APPLAUSE]

CATHERINE DRENNAN: So, this prize here is LEGO. And LEGO has decided to make girl chemists. So this is a little LEGO girl chemist that comes with pretty colored erlenmeyer flasks. So that's very special.

OK, yeah, so the trick of that question you just looked which was the longer wavelength. And then you could rule out that from the picture and also realize that there's connections because of the constant speed of light between the frequency and the wavelength.

So when you're talking about wavelengths of light, c is always equal to a product of the wavelength times the frequency. So they're not independent of each other. And if you know one, you will know the other. So this is something you'll come in very handy as you're doing these problems.

OK, so let's talk about light for a minute and look at these different colors of light. So we go from red at long wavelengths to violet at the shorter wavelengths. And so here the wavelength is decreasing. And then if we think about the corresponding frequencies, up here then if we have long wavelengths, what are we going to have in terms of the frequency? Yeah, so we will have lower or shorter frequencies going up to higher frequencies up here. So again, we have this relationship because the speed of light equals the wavelength times the frequency.

So you are not responsible for memorizing all of the wavelengths, but you should have a sense of the order of the wavelengths and certainly the relationship between wavelength and frequency. And there's going to be a number of problems later when we're talking about colors of light that are admitted from things or colors that are absorbed where it's really convenient to have the order of wavelengths memorized. So I thought I would just help you out with this by this nice little song from They Must Be Giants in Here Comes Science's album, which should help you always remember the order of the wavelengths. So let's just see if this will play.

MUSIC: R is for red. O is for orange. Y is for yellow. And G is for green. B is for blue. I for indigo. And V is for violet. And that spells Roy G. Biv. Roy G. Biv is a colorful man. And he proudly stands at the rainbow's end. Roy G. Biv is a colorful man and his name spells out the whole color spectrum. Roy G. Biv is a--

CATHERINE DRENNAN: OK, so I think you get the idea there. And it sticks in your head. And you may remember this for the rest of your life, even if you don't want to. That's a very catchy song. In fact, my six-year-old daughter learned it when she was about three, and then we get very upset if anybody drew the colors that were not in the appropriate order of the rainbow. And she would come around and correct their work. Anyway, it made her into a little bit of a holy terror but we're working on that.

So in addition to the visible light, which is actually a very small part of the range of waves and so we have visual light in here, we can also think about other waves that go from then long wavelength here and low frequency to short wavelength and high frequency. So we have radio waves on the long wavelength end and we have then microwaves. Microwaves are I think college students' best friends. And as I am teaching this course, since many of you are freshmen, I feel the need to compare my many years of experience at MIT with you. Point number one, just use the popcorn button on the microwave. Don't think about how long is it-- just use the popcorn button on the microwave.

I used to live in Simmons for a while. 3:00 AM fire drills or fire things because someone did not push the popcorn button on the microwave while making popcorn. Anyway, life lesson number one, microwaves. So molecules behave differently in these different kinds of waves. So you can rotate infrared, you're looking at vibrations. Of course here, visible light. We also have UV light. So when you go to the beach on the green line this weekend to do prom set number two and look at the waves, you'll want to wear your sunscreen because UV is, in fact, dangerous. So wear sunscreen, advice number two.

Then we have x-rays. Hopefully most of you do not know one of the uses to detect broken bones. And as you'll hear later on, x-rays can also be used to solve structures of molecules at atomic resolution. And then on the very short wavelength, then, we have gamma rays as well. So again, you're not responsible for memorizing all of these numbers, but you should have a sense of the order of these different types of rays of the electromagnetic spectrum, what's at short, what's at long wavelengths.

All right, so waves have other properties. And one of the most important properties of waves is that they can superimpose. So if you have two waves, one drawn up here, and one drawn down here, that are in phase with each other, which means that their troughs are at the same place, their peaks are at the same place, you can get constructive interference and that would look like this.

So you have these waves come together in phase and you get this much larger constructive interference. This property can be very important as we'll talk a little bit more about later. You can also have what's called destructive interference, so when you have out of phase waves. And the clicker, you can tell me what that should look like.

OK, ten seconds.

Now looks like it's back to being a darker color box in the corner. Just likes to vary it up on its own. OK, that's one second. Woo! All right, 98%. We don't have to explain that one. That one was pretty clear. So here you had they were completely out of phase. So you had total destructive interference. So that just looks like a straight line.

So the combination of constructive and destructive interference actually has a number of practical applications. So people who are very interested in constructive and destructive interference include people who are designing symphony halls or classrooms. Actually, this is one of the better classrooms in terms of the acoustics. And the Boston Symphony is actually, supposedly, the third best in the world in terms of acoustics. MIT students get nice discounts, go check it out.

Another practical application was in designing noise canceling headphones. I brought a pair if some of you have never tried them and you want to come down after class, you can give them a try and see what you think. These headphones, the Bose headphones, were developed by a former MIT professor. He passed away last year. He taught at MIT, taught acoustics, for many years. And he was riding on an airplane once and it was just so loud. And he was thinking, wow, I was wondering if there a way I can design some good headphones to cancel this noise. And he did and many billions and billions and billions of dollars later.

So as you are an MIT student, you get a discount on these headphones. So if you're going to buy them, buy them while you're here. Also, when he died, the majority share of his stock went to MIT. So you will buy them, get a discount, and you'll also be giving MIT money by buying these because we get a lot of money for this.

So I feel like this brings up a really important point that I just want to stress. And I'll probably mention a couple of times that the material that you learn in your classes here at MIT, and in this class, you will learn a lot of really useful things. Some of that will lead to money. And as you make lots of money, you should remember where you learned that and know that I take both cash and checks.

Another practical application is actually in my own research. So we have a series that I'm going to be using I mentioned to bring some different faces in. The first video I'm going to show you in this series is actually me. So it's not a different face. But when I asked other people to make videos about how they were using chemical principles in their research, they said OK, but you're going to do one, too, right, Cathy? So I was like, yes, I guess I'm going to do one. And that just happens to be the first one that I'm going to show.

So another practical use of constructive and destructive interference has to do with x-rays. And you can use constructive and destructive interference to determine the structures of very tiny things, protein molecules or nucleic acids in your body. So I'm going to try to run this movie now. We'll see, this as a demo. Good to try it out with me and see how this is going to work.

CATHERINE DRENNAN (VIDEO): My name is Cathy Drennan and I'm a Professor of Chemistry and Biology at MIT. And I'm also a Professor and Investigator with the Howard Hughes Medical Institute. And my lab uses the principles of diffraction in our research. A wave shoots through some kind of grating. You can have light, say light waves, shooting through. And when the light waves hit the metal lattice, they'll be diffracted. And some of those waves will be in phase with each other and will constructively interfere and you get a bright spot in a diffraction pattern. Other waves will be out of phase and they'll destructively interfere and you'll see nothing as a result of those waves.

From this pattern of spots and no spots, you can understand something about the structure of the grating that it went through. So if I had two different gratings, the diffraction patterns would be different for these. And so from looking at the diffraction pattern, you can figure out how the metal or whatever was arranged that generated that pattern. This property works whether it's a metal grating or a lattice that's made up of protein molecules.

Because the protein molecules are small and crystals are small, we use x-rays and short wavelength, high energy. But because everything is really tiny, we need really bright x-rays to do this. And I don't mean high energy bright, I mean intensity. So we need more photons per second. So we have to go to a place called the synchrotron, a research facility, that has really intense x-rays. And then we shoot those x-rays through our crystal, collect this diffraction pattern, and then figure out what the shapes of these molecules are.

The structure can tell you so much. I mean, there can be big questions of field about how something works. And all of a sudden, you see what the molecule looks like and you're like, ha, of course. Sometimes there's a problem with the DNA that then gets translated into a defect in the protein. But people often don't know why does it matter, why does it matter that the protein is this or that? But we can look at it and figure it out.

So we can compare what the protein structure looks like for a healthy individual with the protein structure from someone who has a mutation. All of a sudden you might see, wow, the vitamin that this protein needs can't bind anymore. So we can have a sense of what's wrong. And then sometimes you can figure out how to treat it once you know what the problem is.

Sometimes there'll be a protein molecule that everyone knows is important. Everyone wants to know what it looks like. But you might be the one who does it. You might be the one to figure out what it looks like. And you'll be the first one. You'll see these patterns, these diffraction patterns, and you'll build this model and all of a sudden you'll be like wow, that's not what people expected. And it'll just be this incredible discovery. So you're an explorer of the molecular world when you're a crystallographer.

[APPLAUSE]

CATHERINE DRENNAN: Thank you!

OK, so that's the first in the series. We're going to have another one this week, as well, because we have a lot of history. So we've got to counter it with a lot of current research. And so you'll be learning about quantum dots also this week. OK, so those are some of the characteristics of waves that are really important and we talked about light as a wave.

Now we're going to talk about light as a particle. Light as a wave is a little bit easier to grasp. Light as a particle is a little bit more confusing. And it took a while for people to really appreciate that light had particle-like properties, i.e. It was quantized. And this really came out of the photoelectric effect. So what were people doing? And this is around the time of the discovery of the electron and the nucleus. And what scientists were having fun doing were taking beams of UV light and hitting metal surfaces, and seeing if they could inject electrons, which have been discovered. It's like, let's get some electrons out of those metal surfaces. We know they're there, let's see them come off and characterize their properties.

So they found that if they had some UV light and the frequency of that UV light was below something, below a threshold that they referred to as the threshold frequency. So we have a new zero here. If the frequency was lower than this magic number for frequency, nothing would happen. But if they increased the frequency, if it was greater than or equal to this threshold frequency, then all of a sudden they would see something. They would see an electron being ejected. And the electron would come off with a certain amount of kinetic energy, K.E. And kinetic energy is equal to a half times mass times the velocity squared.

All right, so they decided let's characterize this. Lets very some parameters and see what happens. So they looked at constant intensity of this light and they changed the frequency. And then they looked at the number of electrons that were coming off. And so below this threshold frequency, no electrons came off. I just told you about that. Then when they were at the threshold, they saw electrons coming off and then they increased the frequency even more, but they weren't getting any more electrons.

Hm. OK, this was interesting. So they thought what else can we measure here. And they knew how to measure the kinetic energy. So it's like, let's start measuring the kinetic energy of these electrons that are coming off. So they plotted kinetic energy of the ejected electrons as a function of the frequency of the incoming light. And again, below the threshold, they saw nothing. But above the threshold, they saw the kinetic energy increase proportionally to the increase in the frequency of the light.

And this didn't really make any sense from what they knew at the time. They didn't have a way to relate kinetic energy and frequency. So they really weren't sure what this was about, but they were having fun doing experiments. It's like, let's keep going, let's vary more properties. So then they decided to look at how the kinetic energy of the electron was affected by changing the intensity of the light. And they thought that if you increase the intensity, you'd have more energy in your system, you should have more kinetic energy. But that did not seem to be the case.

They increased the intensity, the kinetic energy stayed the same. They were having trouble wrapping their head around it. But they said, all right, well let's collect some more data. So now they decided to look at the number of ejected electrons as a function of the intensity. And they really didn't think there should be much difference. Increase the intensity, number of electrons should be the same. But experiments showed otherwise. So when they increased the intensity, more electrons came off.

And this is where they were in the field. It almost seemed like everything they did was opposite of what they expected. It's a pretty exciting time actually in science when you're getting results that are unexpected. And some of this data sat around for a while. And then Einstein decided to take a little look at it and see what he thought of this data. And people were studying all sorts of things. They're taking different metals, you have a different metal, you have a different threshold frequency. And so people were characterizing different metals and figuring out the threshold frequency for all the different metals. And then plotting the kinetic energy of the ejected electrons as a function of the frequency.

And you look at this, you realize huh, there's different threshold frequencies for the different metals, but they all seem to have these straight lines that all seem to have the same slope. And sometimes when you look at the discoveries of really amazing people like Einstein, you're thinking well, basically what he did was solve the equation for a straight line. You realize hey, maybe I can contribute to science, as well. So we had a whole lot of straight lines here.

And when you have that, you can solve for the slope. So that's what he did, he solved for the slope. And he got this number, 6.626 times 10 to the -34th Joule seconds. And he saw that number and he's like, I've heard that number before. Planck came up with that number when he was studying black body radiation. So totally different phenomenon, but yet the number comes up again, Planck's constant, also known as h.

Now that seemed like a really strange coincidence. So there must be something to this number. So if you look at this plot, we can also think about what the y-axis is. So the y-intercept is minus Planck's constant times that threshold frequency. And when you have all of this, you can now write the equation for the straight line in terms of all of these variables. And so y-axis here is kinetic energy. So we'll solve that equation now in terms of kinetic energy. So kinetic energy is going to be equal. We have our x-axis here. The x-axis is frequency. And again, now, the slope of the line we know is Planck's constant, so that's h. And the y-intercept, or b, was -h times the threshold frequency.

And this is a very important equation. So just to define those terms again, we have the frequency here, Planck's constant. Planck's constant times the frequency is an energy. It is the energy of the incident light or the incoming light, e sub i. And on this side over here, we have that threshold frequency again. We also have Planck's constant. So Planck's constant times a threshold frequency is another energy term, which is called the threshold energy, or more commonly a work function.

So the kinetic energy equals the incident energy, the energy of the incoming light minus the work function, which has to do with the threshold frequency which depends on the metal in question. So this was a really important equation. And Einstein realized that the energy of light is proportional to its frequency and it's proportional by Planck's constant. And this really changed how people had been thinking about energy. And all of a sudden, a lot of those observations made sense.

Now, Einstein of course had many important discoveries in his career. But this one was the one that he personally felt was the most revolutionary. I don't know. People are always their worst critic, but even he realized that this was important. And in terms of units, because units are always important. Notice usually you'll see energy in joules or kilojoules. And Planck's constant has the units of joule seconds. And frequency is per seconds or hertz. So in this equation, your units work out.

So from this idea then we have this notion that light is made up of these energy packets which people call photons where the energy of that photon depends on its frequency. So we can go back to the photoelectric effect now and start thinking about those observations and try to rationalize now what we had been seeing. So here's this new model for the photoelectric effect where we can think about the energy of that incoming photon, or that incident photon. If it's greater than the work function, then you'll eject an electron from the metal. And any left over energy is the kinetic energy of that ejected electron.

So we can think about that here. That here we have the energy coming in of the incident photon. We have to get over that threshold frequency or overcome that work function. So you have this minus this, and the leftover is the kinetic energy. So we can also write it this way, that the kinetic energy equals the incident energy minus the work function.

So if you just have enough energy to do this, you have very small kinetic energy. But if you have a lot of extra energy once you overcome the work function, you'll have more kinetic energy. We can also write the equation this way, that the incident energy equals the kinetic energy plus the work function.

OK, so let's just try a clicker question on this. And we're going to go back and look at those graphs and think about what they mean.

All right, let's do ten more seconds.

Yeah, OK. So here the trick was to think about what the work function is and how much energy was coming in of the photon. But here the energy is lower than the threshold needed, so you're not going to get any electrons ejected. Let's try one more. Let's see if you can get up to 90%.

So now we've changed the energies. Or the energy, but not the threshold energy.

OK, ten more seconds.

Yeah, 98%. Yeah, so now we're over the threshold energy. So we need to subtract the threshold energy and the remaining is the kinetic energy. OK, so these are the kinds of questions we have on this. And now let's go back and think about these plots again. So we don't have these a second time in your notes, but you have them one time. And let's just think about how this makes sense now with the new equations that Einstein helped us achieve.

So in the top here, we have the surprising observation that when you increase the frequency of the light that the kinetic energy increase. Well, now this makes sense, because if you're increasing the frequency of the light, you're increasing the incident energy of the photons coming in. And so if you're increasing this frequency, so you're increasing the incident energy. And once you're above the threshold energy, you'll have more extra kinetic energy coming off as the frequency, or the energy of the incident light comes up. So that makes sense.

All right, what about intensity? We haven't really talked so much about intensity. So let's consider intensity for a minute and think about the number of electrons, as well. So both of these are about intensity. So let's think about the number of electrons ejected from a metal surface. We're going to come back to those plots in a minute, sorry to make you go back and forth in your notes.

And that's going to be proportional to the number of photons. So the more photons you have coming in, the more electrons are going to have coming out. That is, if the photons have the appropriate amount, if they're over the threshold frequency over the threshold energy, then you're going to have an electron ejected from the metal surface. So for each photon that has greater incident energy than the threshold, you'll have an electron being ejected.

So what is intensity? Well, the intensity is really the photons per second. So it's proportional to the number of photons being absorbed by the metal, and therefore, the number of electrons coming out of the metal. So intensity's units are often in watts. You also can do a conversion in joules per second. So the higher the intensity, the more photons with the appropriate amount of energy to overcome that work function, the more electrons coming off.

So now we can go back and think about these plots again. So here the relationship between intensity and kinetic energy was flat. And that was unexpected. But the kinetic energy doesn't change here since the intensity means more photons per second, not more energy per photon. So you're just increasing the number of photons. If none of the photons have the appropriate energy, you're not going to have any electrons coming off. But if you have more photons per second, and they have the appropriate amount of energy, then you are going to see these electrons coming off. So the number of electrons admitted does change since high intensity means more photons. More photons, more electrons.

So these things that Einstein helped us with, these equations, now made sense of the data that was being observed. So the photoelectric effect was really important in helping derive these relationships between energy and frequency. And so in particular, the really important points here is that light is made up of these photons, these discrete energy packages. And each one of those photons has to have enough energy in it to overcome the threshold to emit an electron.

So energy is proportional to frequency, which was a really new and exciting idea at the time. E equals Planck's constant times frequency. And the intensity of light has to do with the number of photons hitting per second. And if you keep these things in mind, you'll do really well finishing up a number of the problems on the photoelectric effect, which are in problem set one.

OK, see you on Wednesday. We're going to do a demo of the photoelectric effect.