PROFESSOR: OK, Let's get down to business. Last day we started study crystallography. And we were looking at ordered solids. And we recognized the crystal structure is the sum of the combination of a Bravais lattice, which is the way that points are identified in space, plus the basis. And we saw that we could put a variety of elements at the corners of the Bravais lattice. And this is taken from the archival notes where we see the simple, single atoms at the various lattice points. And we recognized last day that we could put clusters of atoms and so on, and even proteins will crystallize in this form.

And actually, to make a point, about five years ago, a group of students came to my office after the final exam, and recognizing that I drink Fresca during the lectures, they came to me with this body-centered Fresca unit cell. So this just makes the point that you can put anything at the lattice point. So there it is.

Oh, here's the point. This is me at a conference in Copenhagen. This is outside the Admiral Hotel. And just to show you I'm always thinking about 3.091, I came outside-- and this is a colleague of mine from France, Marcelle Gaune-Escard. How do we know she's French? She's got a cigarette. She's a scientist. She's a woman. And she smoking. And it's fantastic. And she's a great gal.

Anyways, so there we are out in front of the Admiral Hotel. And I notice these cannon balls. And what do you notice about the cannon balls? They are sitting in one of the Bravais lattices. So I couldn't resist having my wife take this picture. Because I knew that this would come back to 3.091.

So here we are with the individual cubic lattices where we're going to focus. And we started looking at the properties of cubic lattices. And I started working through this table. And we got down to nearest neighbors, and so on, and this relationship between the lattice constant and the radius. And I just wanted to show this last point here about packing density. Because it comes up considerations of properties of elements. And so I wanted to go through the packing density calculation.

And so the way we handle the packing density, remember we're looking at a unit cell here. This is the cube that's the repeat unit. And it has a lattice constant of dimension a. And then depending on where we put atoms, I want to show that we've got three different options here, simple cubic, body-centered cubic, and face-centered cubic. And the last line of that slide shows that the densest packing of atoms-- this is hard spheres, the cannon balls-- the densest packing is face-centered cubic.

And I wanted to show the derivation of that where if we face-centered cubic where the atoms are big enough to touch. If we have 4 atoms at the corner touching on the face diagonal and then continuing through the cell, we want to get packing density as the ratio of the volume occupied by the atoms-- and here we're modeling the atoms as hard spheres-- divided by the volume of the cell itself.

And so that's pretty straightforward calculation. We're modeling the atoms as hard spheres. And we saw last day that if we take the fraction of the atom, 1/8 times 1/8, and 6 times 1/2, we have 4 atom equivalents per unit cell. And each of these has a volume of 4/3 pi r cubed. And then we divide that by a cubed. And then we know the relationship between a and r. This is 4r and that's root 2 a. So we can say root 2 a equals 4r. Either eliminate a or eliminate r. We eventually end up with this dimensionless group, which is pi divided by 3 roots of 2. And that is 74%. And that's the densest package.

If you go through the same calculation for body-centered packing, you'll find it's 68% packing. And for simple cubic it's 52% packing. That's the highest density that you can have. So I urge you to spend some time. If you work the homework, you'll work your way through that chart.

So now I wanted to take a few minutes and talk about crystallographic notation. Because we need to know this in order to describe various features of a cell. So I'm going to start with a Cartesian coordinate system that obeys the right-hand rule. So we'll put down x, y and z. And then we'll put up a unit cell here with edge a. So we have a on the x, y and z coordinate. And we know that a equals b equals c. That's the unit vectors here. There's a little a here, a little b here, and a little c here. These are all equal to the lattice constant value a. And all of the angles are 90 degrees. This is what defines the cubic system.

So I'm going to put several positions here. So here is the origin. And the origin we designate as 0, 0, 0. I'm going to put a position up here, a. And you just use the same notation as you'd use mathematics. Only crystallographers don't put parentheses around it. So what I'm really teaching is notation. You already know the math. So a up here is what? It's 0 units on the x-axis. It's 1 unit on the y-axis, and 1 unit on a z-axis. So that would make it 0, 1, 1. And I'm going to put a b out here. B is out 1 unit on the x-axis. It's 0 units on the y-axis. And it looks like it's up at about 1/2 unit on the z-axis. So that makes 1, 0, and 1/2.

And so now what I want to do is show you how we designate directions and planes. You use a slightly different notation from what you used to in math. So this chart will be posted at the website. Move the coordinate axes so the line passes through the origin, define a vector from the origin to the point on the line, and choose the smaller set of integers.

So let's do a simple one here. Let's do from origin to b. So o to b. That's this vector here. So how would we do that

one? Well we're already at the origin. So that's trivial. o to b, so we're going from here out to here. And then what does it say? It says choose the smallest set of integers, no commas, clear fractions. So that's going to take us out to 1 0 1/2.

But the crystallographers don't like fractions. So you're supposed to clear the fractions. You clear the fractions by multiplying through. So make that 2 0 1. It's the same direction. See if I came out two units here, I'd end up being one unit here. So it's the same direction. It really is the same direction. Don't put any commas. And put brackets around it. So that's the 2, 0, 1 direction, which is o b.

And I want to do a different one. I'm going to go this way, a to o. So let's look at that one, a o. And what happens on a o? Well now I'm going to put the origin at a. I'm going to go to 0 in the x-axis. I'm going to go minus 1 in the z-axis, and minus 1 in the y-axis. So that gives me 0 minus 1 minus 1. But see they don't use commas. And so this looks kind of goofy. Because you get these minus signs in here. So what the crystallographers do is they put the minus sign on top of the number. So this becomes 0 1 with a macron it. If you'd studied Latin, you'd know this thing is a macron, a line over a vowel. So 0 1 bar 1 bar. And that's the direction a o. So that's the macron acting as the minus sign. So that's the a o direction

And then furthermore, we can designate families. This is just the 0 1 bar 1 bar. If you want to be a hipster with crystallography, you call this 0. You say it's 0 1 bar 1 bar. But if you're a nice chemistry student, you'll say zero, minus 1 minus 1. No we don't do that in 3.091, 0 1 bar 1 bar.

Now suppose I wanted to describe all of the faces, every face. So what I could do, is I could say I want the set of all face diagonals. Well, that's a face diagonal. But what I can do is in a compact notation, I could write 0 1 1 and use the carat. This is called the carat. So if I enclose in carats, this means the set up all 0 1 1 type planes. And so what that means is I can unpack that, and write 0 1 1, 0 1 1 bar, 0 1 bar 1, et cetera. And what I'll end up doing is describing the set up all face diagonals.

So if I want to talk to you later when we're studying x-ray diffraction, I want to talk about face diagonals, I don't use that word. We're quantitative here at MIT. I say look at the 0 1 1 planes. So you go face diagonals. That's the compact notation.

If we want to look at all cell edges, what's the cell edge? Here's the cell edge. This is an edge here, isn't it? It's right on the edge of the cell. So it's 0 on the y, 0 in the z. It's 1 in the x. So the set of all cell edges would be 0 0 1. And you could write 1 0 0, that's OK too. Or you could write 0 1 0. That's OK. But if you want to be a hipster in crystallography, put the zeroes out in front. So the set of 0 0 1 directions is all the cube edges.

And then lastly, if we wanted to get all the diagonals that starts from here and goes up, we'll have all cell

diagonals, all, if you want to call it, body diagonals, not face diagonals, body diagonals. Body diagonals is 1 1 1. And the mathematics imitates reality. How many combinations are there here? I've got 0 1, and I've got minus 1. So I have 0 0 1, 0 0 1 bar, 0 1 0, 0 1 bar 0, 1 0 0, 1 bar 0. There's 6 And how many edges are there? 6. Mathematics imitating reality, what a concept. That's great. OK. So that's good.

Now we want to look at planes. Let's look at planes. Now planes are a little bit different. This is basically what you know from math with a little bit of notation It's basically the same thing. Planes are quite different. So let's go to the planes. So you know the equation of a plane. It's x over a plus y over b plus z over c equals 1. And a b and c are the intercepts at the x, y z axes.

Well, in order to make this notation compatible to what we have here for lines, a British meteorologist by the name of William Hallowes Miller in 1839 said let's define h, k, and l as the reciprocals of these intercepts. And now we'll write the equation of a plane as hx plus ky plus lz equals 1. And we'll use those values of h, k, and l as the indicators of a plane.

So here's an example. So again, I've got the right-handed rule coordinates. And here's the plane. And you can see that it cuts the x-axis and a. It cuts the y-axis at b. And it's parallel to the z-axis. So if we were just to use the old mathematics notation, and put the a, b and c, you'd have 1/2 here. You'd have 1 here. And you'd have infinity here. And that looks goofy.

So instead what we want to do is use the Miller indices, which are the reciprocals. So now the reciprocal of 1/2 is 2. The reciprocal of 1 trivially is 1. And the reciprocal of infinity is 0. And so now you have something that makes sense. And you put no commas in between. And you put the whole thing in parentheses. So that's the 2 1 0 plane.

And there's a really cool property here. And that is, using this same formulation I just showed you for directions, the 2 1 0 directions-- you see 2 1 0 with square brackets, that's a direction. 2 1 0 with parentheses is a plane. The 2 1 0 direction is perpendicular to the 2 1 0 plane. And that's one of the advantages of using Miller indices notation with the classical notation for direction.

Here's another one. This is 0 1 0. This is the x, y, and the z. So this cuts at 1, 0 1 0. This is 0 2 0. An 0 1 0 directions are perpendicular to 0 1 0 plane. 0 2 0 directions are perpendicular to 0 2 0 plane. Oh here's 1 1 1. That's cool. See it cuts it at 1 1 and 1. And 1 1 1 direction cuts through the 1 1 1 plane perpendicular.

This is an interesting one. See the origin. The plane cuts through the origin. Now what do you do? What do you do? You move the origin. Because we don't know where the origin of the universe is. It's just a unit cell. It doesn't matter. So we move the origin up here. And now what do we have? We have 1 1 and minus 1. And just as before, we put 1 with a macron over it. That's 1 1 1 bar plane. And there is the 1 1 1 bar direction. It doesn't matter. It'll

always give you perpendicular. It's really cool. All right.

And we can also specify a set of planes. So instead of using parentheses, we use brace brackets. And if we use brae brackets, we get families of planes. So for example, we could say if we wanted a particular face so that the face in the xy plane, facing the xy plane would be 0 0 1. Right, because it cuts the z. So this is 0 0 1.

But what if I wanted to say in a compact way, all faces of the unit cell, all of the faces. So this is the particular plane. If I wanted to say all faces I would write 0 0 1. But I can't use any of these containers. So I'll use brace brackets. So 0 0 1 in brace brackets means the whole setup, 0 0 1, 0 0 1 bar, 0 1 0, 0 1 bar 0, 1 0 0, and 1 bar 0 0. So there's only 6. And there's 6 faces. Again mathematics imitating reality. What a concept. Make the math work for you. You don't work for the math.

All right and just to make the point about the h k l plane, is perpendicular to the h k l direction. So that's good.

And the last thing I want to show you that comes out of the use of the Miller indices for planes, is that another property that we'd like to know is the interplanar spacing. What's the spacing between like planes. So interplanar spacing, that is to say the distance between like planes, adjacent planes identical index. I'm going to write it to be specific to say Miller index, h k l in parentheses.

And the property that comes out of this-- and you don't have to derive it. Somebody worked this out for you about a 150 years ago-- is that the distance between adjacent planes with the index h k l is given by the ratio of a, which is the lattice constant, this is the cubed edge, divided by the sum of the squares of h, k, and l taken to the power of 1/2, So the square root of h squared plus k squared plus l squared divided into the lattice constant, gives you the value of the spacing in between. And this is the a just to be clear about it.

So for example, I think I've got some cartoons up here that show this. So here's 0 1 0. It's trivial. What's the distance here? The d 0 1 0 is just day. How about here? This is 0 squared, 2 squared. 0 squared, this is d over 2. So this is a 0 2 0 plane. But if the distance between 0 2 0 planes is 1/2 a, well, then that's an 0 2 0 plane. Then this is an 0 2 0 plane. So point of fact, every 0 1 0 plane is an 0 2 0 plane. But every 0 2 0 plane isn't an 0 1 0 plane. You can see that some planes have multiple names.

Here's another one. Look, this is the distance between adjacent 1 1 1 planes. It's a over root 3. So as the index goes up, as h k l goes up, the distance between successive planes goes down. And the angle between the planes goes up. The easiest one is orthogonal. OK, that's good. That's good.

All right. I think that's a good place to stop. I dread these kinds of lessons. And I'm sorry that the parents ended up here on a day like today. But there's a little bit of this notation and taxonomy that they have to know. And so we suffer through it. And then we get on to the meat. Now we're ready for some meat.

Now that we can describe crystal structure, we're ready for physical measurement of crystal structure. So what I want to start today is the characterization of crystal structure by x-rays. How do we measure? How do we know that gold is fcc. We use x-rays.

So today what I want to do is start as I always do on new unit with history lesson. We'll start with the discovery of x-rays. And we'll get into the underlying physics. And the next day we'll look at applications including x-ray diffraction.

So first of all, what are x-rays? They're a form of electromagnetic radiation. And they have the property of that. They have very short wavelength. How short? It's on the order of about angstroms. So strictly speaking, it goes from about 1/100 to 100 angstroms. So centered at about 1 angstrom is the center of the x region of the spectrum.

And because they're a form of electromagnetic radiation, their energy is given by these equations, hu equals hc over lambda or hc u bar. Those equations that you've seen over and over again apply for the energy of an x-ray, because an x-ray is identical to a photon of wavelength somewhere down at this level.

Why do we care about this? Because this is atomic dimensions. If I want to measure the dimension of the human hair, I don't use a yard stick. I use something that is of the human hair dimension. If we want to get into the characterization of atomic structure, we need a measurement tool that is on the order of that blank scale. And that's why we're going to use x-rays.

Now other property, I said very, very short wavelength. But because of this inverse relationship between wavelength and energy, I want to draw attention to these superbly high value of energy. So let's plug in the energy for lambda equals 1 angstrom. When lambda equals 1 angstrom, we end up with 12,400 electron volts per photon.

Now what's that mean, just to put it in perspective? Look up here at the table I've shown. We know the ionization energy, the lone electron in hydrogen is 13.6 electron volts, which is 14 to 2 significant figures. And then we go to helium. You pull these off the periodic table. This is the first ionization energy. And they're down around somewhere about 10 electron volts. Look at. This is 12,400.

So let's go down to the 1 electron atom. So this is helium plus. This is lithium 2 plus. And we see a set of numbers here that follow this sequence 1 4 9 16, which is nothing more than the sequence you would expect for a series of 1 electron atoms. It's K, which is 13.6 times the square of z/ So z here is 2, z here is 3, z here is 4, and so on.

But even so, this is the last electron of nitrogen. The most tightly bound electron of nitrogen, 668 electron volts.

That's a huge amount of energy. But that pales in comparison to 12,400 electron volts. So this is clearly ionizing radiation writ large. What do I mean by ionizing radiation? It has the capacity to ionize everything. Every electron will be blown away. This is called knocking the stuffing out of the electron structure. So that's what we're dealing with.

So now let's go to the origin of x-rays. So how did we discover x-rays? Well, it was a dark and stormy night, not unlike the weather today, apropos of the lesson. It was November 8, 1895. And it was at the home and laboratory of a professor. Of course it's a professor, Professor Wilhelm Roentgen. And he was a professor of physics at the University of Wurzburg in Bavaria, now part of Germany.

And he was doing research, as many people were in the 1890s, on the properties of gas discharge tubes. He was studying gas discharge tubes. And he had a special interest in gas discharge tubes. Remember Lorentz? He like to put the gas discharge tubes in a magnetic field. Stark liked the put them in an electric field. And what was Roentgen's pet project? Roentgen loved high voltage. He loved high voltage an low pressure. He was focused high voltage, low pressure, near vacuum.

And so let's have a drawing of what he used. And here's an image of the museum that is literally in the house that was occupied by him. So the apparatus is sitting right there on the table. And here's the heart of the apparatus. I'm going to go to a fresh board because I need a little extra room here.

So we know what the gas discharge tube looks like. It's a glass tube, sealed. And we've got feedthroughs for electrodes at both ends. And this goes down to a power supply. And the power supply that he used was batteries of chromic acid. And they were open beakers. And they were down in the basement two floors below. And he had wires going from the basement up to the second floor. And he was able to generate about 20 volts. So he had a number of these in series. Because this is roughly a 1-volt system. So round numbers, you got about two dozen of these things in series. And I'm going to write here, in the cellar.

Now how did he get the high voltage? He put in here something that we wouldn't recognize today as an inductor. He called it a choke coil. And what the choke coil did, is it would charge up until it got to 35,000 volts. When it got to 35,000 volts, it would discharge and send a current at 35,000 volts to the cathode here. And with 35,000 volts, the cathode would send electrons boiling off the cathode, heading towards the anode with the kinetic energy associated with 35,000 volts. And this discharged at about eight times a second. So I'm going to write 8 hertz here. So eight times a second this thing, bam, bam, bam, bam. And the electrons go firing off here. And this to make sure he had really low pressure, he had the cell open actually. And this went to a vacuum pump. He had almost no gas molecules in here.

Now, the way he did the experiment is, he'd set this thing up, started it going, and this was after dinner. So on a Friday night after dinner, he was upstairs. And he wanted to measure emissions here. And so what he had, you either get graduate students to sit there and you exploit their labor, or what you do is you put up a detector here which was a screen. So this is either a sheet of paper or a sheet of cloth. So we call this a screen.

And so you're going to look here. All right you're looking at this, seeing what's coming out of this gas discharge tube. And it was a screen up paper or fabric. And it had been painted with a chemical that would glow if it were struck by a particle, or by a photon of a given energy. And they used in this case, coated with the chemical barium platinocyanide, so cyanide four times.

So you make an aqueous paste of this stuff. And you gob it on to the screen. And when the screen is hit by something, it sparks. And the latin word for spark is scintilla. Have you ever heard of someone being described as a scintillating conversationalist? It means they are a sparkling conversationalist. So this is called a scintillation screen, a scintillation screen. And so presumably, every time there's an event, the screen glows.

And so Roentgen starts the experiment. And it's raining outside. There's thunder. There's lightning. There's a street light as you can see right there. There's windows. And the thing is glowing. And he really can't detect what's going on here. So he decides to cover the tube.

So he puts a wooden box around the gas discharge tube. So now the gas discharge tube is enclosed in a box. And he continues the experiment. And what he sees is glowing on this scintillation screen. The scintillation screen is glowing even though the gas discharge tube is in a box.

There was another observation he made. The student earlier in the day, who had painted the screen with the barium platinocyanide. I guess he was practicing his calligraphy. And he left a paper towel on the edge of the bench. And he painted the letter A on the paper towel. And the paper towel was glowing with the letter A. And this thing is enclosed in a box.

So he's saying what's going on here. So he decides that there's some kind of an interaction between the screen and something going on in here. So the first thing he does is he says, well maybe it's electromagnetic. Maybe it's charged particles. So he takes a magnet. And he moves a magnet around. And nothing changes. He kills the power to the gas discharge tube. Everything stops. So it's definitely inspired by 35,000 volts of energy going into the tube.

So then he says, OK I'll take a piece of black paper. And he puts the black paper in between. And the screen continues to glow. So then he takes a book. And he puts the book in front. And he sees the shadow of the book. And he's standing here like this. He sees the shadow of the book. And he can see the shadow of the bones of his

hand. So he says, you know I don't think it's particles. I think it's radiation. I think it's radiation. And maybe it's something like that radiation that Hertz has been talking about. It's some kind of radiation. But I don't know exactly what it is. It's mysterious. And x is the letter of mystery. I'm going to call it x-radiation.

So he's discovered this mysterious form of radiation. Does he rush to publish? No. He's not going to risk his scientific career by announcing that he's discovered a form of radiation that can see inside the human body. That would be professional suicide. So he continues to repeat the experiments through November and December of 1895. And in January of 1896, he finally publishers. And it takes the world by storm.

By the way, how did he record this stuff? He used photographic plates. And he stored the photographic plates in his lab in a wooden file cabinet. And so many of the plates were fogged even before he got them to the experiment. Because of the x-ray, they were going everywhere in the lab. And he was working there the whole time.

So what happens? What's the world's reaction? January 16, 1896, *New York Times* reports radiation that can see through matter and peer inside the human body. Peer inside the human body, you say. Well, why is that? What's the big deal? Well, in London, immediately there was a market response. A manufacturer claimed to be a purveyor of x-ray proof lady's undergarments.

I mean if you can see inside the human body, it's Victorian England. How modest can you be? This is a calamity. In France, of course, they don't care about such things. So they had a different response.

Remember this is where Daguerre invented halide photography. So there it's very deep. It's very existential. Somebody claimed that with x-rays he could irradiate and get a picture of the human soul. How French. But I'm sorry to say it, the wackiest comes from guess where? The United States. No lesser an institution than the New York City College of Physicians and Surgeons. They proposed to use x-rays to project drawings from text books of anatomy onto the brains of students thereby creating, and I quote, an enduring impression. In Iowa, we plumb new depths. There was a group out there claiming that they could turn copper pennies into gold. So this was the response.

But the thing that makes it so fantastic is we take it for granted that if I want to exercise power and exert a force on that can, I don't necessarily have to make physical contact with it. We accept this as given that you an either have direct mechanical contact, or indirect contact, magnetics, what have you. But in 1896, this wasn't given. So the notion that I could exert a force on something from a distance was very fresh. It wasn't so easy.

But there were benefits of the x-radiation already in middle of 1896. There was a seamstress who had a broken needle in an industrial accident in Scotland buried into her hand. This is trivial. Look, all you need is low pressure

in a gas tube, and you can set this up in high school. It's nothing. People had this set up in dentist offices. It's nothing. So this surgeon was able to find where the needle was, and then use precision to go in and take the needle out of the injured person's hand. In eighteen 1899 they were already using radiation in treatment of cancer.

So what is the relevant physics? what's the relevant physics here? Let's look at the relevant physics. Well, when we're talking about 35,000 volts, and we're talking about energies in the vicinity of tens of thousands of electron volts, you know that this can't come from emission from an excited electron in a gas molecule. The gas binding energies are way lower than that. This must come from the solid. The electron leaves the cathode, and it crashes into the anode. Here's the smoking gun. There's something going on here when the electron crashes into the anode and then gives rise to the radiation.

So let's look inside the anode. So what's the energy level diagram? Let's say the anode is made of copper. So what's the energy level diagram look like? So we know up here we're going to have energy is 0. And the energy quantum state is infinity. Down here is the ground state. And the energy is the ground state energy. And we know this is up in the tens of thousands of electron volts. And then up here there's an E2 for state 2. And up here is an E3, energy 3. Then maybe an E4 for energy 4, et cetera. And I'm going to write not to scale. This is just to give you a sense.

And so the ballistic electron with, in this case, 35,000 volts of energy, comes crashing in to the anode. And this is one of these mixed metaphors. So this is a Cartesian drawing of an electron. All right? This is the incident electron. And its energy is given by the charge on the electron, which is E, and the plate voltage, which is 35,000. So it's got 35,000 electron volts, which turns into 1/2 mv squared. It goes crashing into this thing. And it's got enough energy it can kick out top level electrons, mid-level electrons, and in the extreme, it an eject ground state electrons in 1s.

By the way, the spectroscopists, they don't like numbers. Remember, this is K. This is L. This is M. This is N. So we can eject K shell electrons. What happens if we create a vacancy down here? all? Of these electrons above are unstable. If its copper, there's 29 of them. Now there's 28 with a vacancy. And they fall down. And when they fall down from N equals 2 to N equals 1, there's a photon emitted. And that photon emission is in the x region of the spectrum.

But we don't just get one wavelength. We get a plurality of wavelengths. n equals 2 to n equals 1, we get a photon. There's a possibility to go for n equals 3 to n equals 1. We'll get a photon of even higher energy or a lower wavelength. Well, heck, if you've got enough energy to kick out an electron from n equals 1, you've certainly got enough energy to kick out an electron from n equals 2. So you can get a cascade from 3 to 2, which gives us a

photon, or from 4 to 2, which gives us a photon.

Can you see that you're going to get an entire set of lines? We're going to label them because we don't have a single line. So what do we label them? We label them on the basis of the destination shell and how far they traveled. So this line here is known as a K alpha line. Why is it a K? Because that's the nf. That's the n number of the final state.

And why is it alpha? Because the delta n equals 1. It came from 1 shell away. What's this one? It's gotta be a K line, because we ended at n equals 1. But the delta is 2. It went from n equals 3 to n equals 1. So this is called K beta. So there's a K beta line and a K alpha line. This ends at n equals 2, which the spectroscopists call L. So we call this L. Delta is 1 L alpha. This is L, but delta is 2. So this is L beta.

And what I can do, is I can plot all of this on a curve showing the spectrum of this particular element. And what do I expect to see? I expect to see a spectrum that plots intensity versus some energy coordinate. It could be wavelength in this direction, which means that energy increases in that direction. And which has the highest energy? The highest energy up here is K beta, n equals 3 to n equals 1. So there's K beta. And then close to it is K alpha.

And why do I put the K alpha line higher than the K beta line? I don't know what the relative amounts should be. But I suspect that if there's a vacancy, it's like musical chairs. If there's a vacancy in n equals 1, and an electron only has to go from n equals 2 versus n equals 3, the chances are the journey from n equals 2 to N equals 1 is easier, and therefore more frequent than the journey from n equals 3, even though n equals 3 to 1 is greater energy. But 2 to 1 is more likely. And intensity reflects frequency. The wavelength reflects the energy. And then over here is L alpha L beta.

Now there's one more piece here. The precise value here is determined by the identity of the element in the anode. If it's copper-- and I had to do this as a junior at the University of Toronto. I spent a whole year doing x-ray crystallography. And I will know on my death bed the wavelength of copper K alpha radiation is to five significant figures, 1.5418 angstroms.

Now if someone had fallen asleep in this lecture and open their eyes right now, and looked at the wavelength of this line as 1.5418 angstroms. And I erase the letters Cu. You take one look at that, and you say copper. Because only copper has a K alpha wavelength of 1.5418, which means I can use x-ray analysis to determine the identity of a unknown specimen.

And furthermore it's additive. So if I had a brass, which is copper and zinc, the zinc K alpha line is over here. And I will have both lines. And the relative intensities of the lines are related to the relative concentrations of the copper

in zinc. So now I have a tool for chemical analysis. All of this from going upstairs after dinner and horsing around with the gas discharge tube. OK, so we're going to end the formal lesson here. But we have a few more minutes. So everybody is instructed to not make a lot of noise and just sit quietly. So let's take a look. This is an image. This is an image of Bertha. This is Roentgen's wife. This is her hand. He invited her into the lab. And she stood for a full 15 minutes in front of this tube. And in that 15 minutes, got a lifetime's worth of radiation.

But what we're looking at here, and what I'm going to point out to you in the last several minutes here, Roentgen was a prissy physicist, a really prissy guy. And he was German, which meant that the German academics had no contact with industry whatsoever. On the night of November 8, 1895, he invented three modern technologies. This is Bertha's hand. It represents the birth of medical radiography.

Is there anybody in this auditorium who has never had an x-ray, a dental or body x-ray? It's very rare. We see them all the time. We use them all the time. This morning I had one taken about 9:10, right here. And I'm OK. So that's radiography, medical radiography.

Roentgen had a balance in his laboratory. The justice, and she's got the torsion balance. So you put the unknown on one side, and then you put weights that are calibrated. These are made of brass. And they're in a wooden box. And so Roentgen has already covered the tube with a wooden box. And so he took the emission from this, and he radiating his box of weights. And what he see? He saw dark regions where the weights were. Because metals have a different electron density, because they've got a greater atom density than wood. Wood is a more open structure. And so by contrast, he could see inside the box. This is the basis for airport security.

Roentgen had a gun. He was not holding up convenience stores. He was a hunter. He went into the woods. And he x-rayed the gun. Now why did he x-ray the gun? Now the gun is made of steel. But deep inside the steel, there could be a flaw. There could be a crack. There could be a blowhole. The surface of the steel looks beautiful. But inside is a crack. And that crack could lead to failure under pressure. So Roentgen irradiates. And we already know from this that different electron densities give different shading, which means if there were a crack right here, you might see it in the radiograph.

And this we use for certification of pressure vessels today. Certain pressure vessels that have to be welded, have a specification that requires that every inch of the weld be inspected by radiation, to be certain that there are no cracks deep inside the weld that under high pressure could open up, have an explosion, and cause injury, or in the worst case, death.

So what's the outcome of it all? In 1901 when the Nobel Prizes were offered for the first time, Roentgen by unanimous vote of the selection committee was the first recipient of the Nobel Prize in Physics. So on that occasion, he was invited to come from Wurzburg and to deliver a lecture in Stockholm. I've been to the place, it's

a spectacular hall, gilded, beautiful champagne reception, elegant dinner. And he gives a lecture.

And what's his lecture on? The discovery of x-rays. He received a huge amount of money at the time in prize money. And he returned to Wurzburg What did he do with the prize money? he? Donated it to the University to be used for scholarships for students studying physics. And to this day, students who study physics at the University of Wurzburg are beneficiaries of the generosity of the first winner of the Nobel Prize in Physics. Such was his humanity.

I hope you have a great weekend. We'll see the students back here on Monday.