PROFESSOR: So, moving to today's handout, we're going to talk about crystal field theory. And we're going to talk about how the shapes of those orbitals can explain the special properties of transition metals, like color and magnetism. And really, as I said, the transition metals have amazing properties that can be absolutely gorgeous. They can do incredible things. They're very, very useful elements. I like to think of them as the super heroes of the periodic table. They're doing all the really spectacular stuff.

So, today, we're going to talk about colors. And we're going to talk about whether things are magnetic, if they're paramagnetic, or diamagnetic. So, transition metals. I talked before about how they're useful in biology. They're also useful in terms of their beautiful colors. So, in the old days before you generated floor plans and drawings for buildings, on a computer you did blueprints for something. And the blue in the blueprint is actually a transition metal complex. And also, currently, it's an active area of research to design new imaging agents to use in MRIs, or to image the heart, or other things. And a lot of these also involve transition metal complexes.

And the reason why they're useful, say, in an MRI is because they can have magnetic properties. So, scientists see these beautiful colors. It's kind of obvious that the transition metals often have these incredible colors. And they can put the transition metals in something with a magnet and see that they have magnetic properties. So these things were obvious. And then chemists want to try to understand why it's true. Why this particular metal behaves this way, or this metal has this particular color. And they like to try to categorize them and come up with theories that help to explain what they're observing in nature.

And so, today, we're going to talk about one of those theories, which is Ligand field theory. And I'm also going to differentiate that-- or Crystal field theory and differentiate it from Ligand field theory. So both of these theories, again, are an attempt to explain the properties that we observe. And the idea behind it is pretty simple. You have a metal ion and a set of ligands around it. And if you compare the energy levels of that free metal ion-- so here's a free metal

ion-- with that metal ion in a coordination complex-- here is quite a pretty coordination complex-- the energy levels are different. That's really all these theories are getting at. That there's a change when you bring ligands in around a transition metal. It changes the energy levels of those d orbitals. And if we understand how those de-energy levels change, we can understand a lot about the properties of that particular metal in that coordination environment. So energy levels are altered.

So there's these two theories: Crystal field theory and Ligand field theory. Crystal field theory is the more simple one. It just considers the ionic description of the metal ligand bond. And so we talked about ionic bonds. And mostly you're just kind of thinking about them as these point charges. And you have plus, you have minus, and they attract each other. Covalent bonding is a bit more complicated. Start talking about hybridization and other things like that. So Crystal field theory is really simple. It just considers the ionic nature. And it does pretty well. It can explain a lot, but not everything.

Ligand field theory has the covalent and the ionic, so it's a more complete description of that metal ligand bond. But this is more of an advanced topic. I just want you to know that that exists. So if you take 503 here in organic chemistry, we'll talk more about Ligand field theory. In this class we're just going to do Crystal field theory. But I like Crystal field theory because I like it when something that's pretty simple theory can explain a lot. I think a lot of nature can be explained by this. So if you really want to understand particular properties of a specific compound, you probably want a more complicated way to think about it. But if in general you just want to say, why can some cobalt complexes can be so many colors? Crystal field theory works really well for that.

All right, so Crystal field theory. Very simple idea behind this. It's almost disappointing, I think. But it's OK. You can go, yeah we're studying, you know, Crystal field theory in class. Yeah, you don't have to tell people that it's a really, very simple idea. So the idea is that the ligands are negative charges. They're like this big blob of negativity. And those ligands, with their lone pairs, their negativeness or negative charge-- they got those extra lone pair electrons-- are going to be repulsive to those d orbitals. Negative point charges, you bring a d orbital, And a lone pair, and there's some repulsion. That's basically it.

Negative point charge repulsion. That's all that you have to think about with Crystal field theory. So it sounds really impressive to tell people you're doing Crystal field theory. And you can neglect to mention that it's just a really very, very simple idea that, sort of, negative

charges repel each other. That's really all it is. All right, so we're going to talk first about the octahedral case. And then we're going to get into some other geometries on Friday, so that's going to be exciting. But here's our octahedral molecule. And here we have it, here. And I can think about the metal in the middle, M to the N plus.

So this just indicates it's any metal and to the oxidation number. And the black balls, here, are the ligands and we can think of those as negative charges. So here, we have drawn sort of this octohedral shape around the metal in the middle. And we can think about these NH3 groups as these negative point charges. So these dots here are negative point charges. And so now if we think about the shapes of the d orbitals again, that we just looked at, we can look over here and say, wow, some of those ligands that are those negative point charges are basically right there up against that d orbital. Pointing directly toward the d orbital.

So that's going to be pretty repulsive. The point charge is right there next to the d orbital. This also has a point charge kind of right toward it along z. But these, the point charges, are on axis. Octahedral, you have your ligands along z, along x, and along y. But these sets of orbitals, the negative point charges, aren't pointing directly at the d orbitals. So one could think about the fact that these are not going to be not as much repulsion. This is a lot of repulsion.

All right, so let's go through orbital set by orbital set and consider how repulsive it's going to be compared to the other orbitals. OK, so if we look over here at the octahedral case-- and I have both, these drawings were on the first page of your handout. This is on the second page. But you can think about them. Here it's drawn more where they're all drawn kind of the same way. Here it's sort of moved a little so you can see better. So we can keep both of these in mind.

So, again, the negative point charges around the orbitals here. And on these drawings, I have these little negative signs pointing in to give you a sense of where those negative point charge ligands are coming. So we have our dz2 and we can see the negative point charge right toward this maximum amplitude along z. So that's going to be repulsive. Dx2, y2, same thing, point charges right toward these.

So the ligands point directly at dz2 and dx2 minus y2. So there's a large repulsion there. And, in this particular case, in the octahedral case, what turns out to be true, both of these are stabilized. And they're destabilized, actually, by the same amount. And so that means that they have the same energy, which we learned before, means that there-- you could say they're degenerate with respect to each other.

So both of these, big repulsion. Both are destabilized by those negative charges, by the same amount. And you have much more repulsion, and much more destabilization, for these two orbitals compared to the other set of orbitals. The ones that are 45 degrees off axis. So now, let's look at these and look at where the point charges are. So this is the picture in your handout. I just kind of put these up there, too, so you can think about where those point charges are for octahedral geometry.

So the ligands, again now, are not pointing right at the orbitals. They're off axis. Because of ligands are on axis, and the orbitals are off axis, and they're not directly pointing toward each other. And so this is a lot less repulsive than the other situation where you have the ligands and the orbitals, both on axis, pointing right toward each other. So now, this is why it's important to know which orbitals are 45 degree off axis because we, now, can think about the fact that there will be less repulsion in this case. So, we can say then, that the xy, xz, and yz orbitals are stabilized compared to dz2 and dx2 minus y2 orbitals. And they're also stabilized by the same amount. So these are also degenerate. With respect to each other, they have the same energy.

All right, so we have these now two sets of orbital types. Two orbitals that are destabilized, and three orbitals that are stabilized, compared to them. So now let's draw what's known as an Octahedral Crystal Field Splitting Diagram and think about what's happening. So, I have some over there. Ignore those for now. I'm going to draw one over here. So first, we have energy going up. And we have a situation we first want to think about. What would be the case, say, if you had ligands everywhere? Not just on the axis, not octahedral geometry, but just everywhere. So if you had ligands everywhere, you would have your 5 d orbitals, all would have the same energy. Because all of them-- there's ligands everywhere-- all of them would be experiencing the same amount of repulsion. So this would be the case for a Spherical Crystal Field.

And I like to think about this with this prop. I had this before as an s orbital. It's convenient for that as well. But, really, what it is, is a Hypothetical Spherical Crystal Field. Because these are all little ligands. And you can see these little ligands are completely symmetric around. And if you feel sort of the inside, there's something in there. Well that, of course, is a metal ion. And these ligands are completely around. So all the d orbitals are equally feeling the repulsive effects of these ligands. And so they all have the same energy in this hypothetical case.

I was so excited when I found this at CVS. And I went up and I was, like, wow, you sell hypothetical spherical crystal fields here. And the person was not amused. OK, so now what happens-- because this is not the case. This doesn't exist. This is just hypothetical. It looks like it exists, but it doesn't. This is what really exists. You have certain geometries. The ligands come together with the metal and form particular geometries. And we already talked about what those geometries are. There's not a whole lot of variation. We get the same kinds of geometries. And octahedral is the most common geometry for a transition metal complex. So what's going to happen here? So, the ligands will now split the energy of the d orbitals. And three of them are going to go down in energy. They're going to be stabilized compared to the two that go up in energy. So the three that go-- are stabilized again, are dxy, dyz, and dxz.

If you can't read this, it all should be in your handout. So it's OK, you don't have to read my handwriting. And just kind of-- just follow along in your notes. And then the ones that have the most repulsion are dx2 minus y2 and dz2 up here. All right, so two go up and energy. There's more repulsion. Three go down in energy.

And instead of writing all of those d's and x's and y's, they're little abbreviations that people use. So they call these two orbitals-- the eg orbitals. So those are the ones that are destabilized. And the ones that are stabilized are called t2g orbitals, which is going to make our nomenclature easier later on.

OK, these two again. Same energy I tried to draw a straight line between them. They're degenerate with respect to each other. These three of the same energy, again, degenerate with respect to each other. And then the difference of how much it's being split. This energy difference has a special name. It's sort of this delta sub o. And this is the octahedral. And that's the o. The o is octahedral. Crystal field splitting energy because it's the energy that shows the splitting of the crystal field. So that's at least a good name for it.

All right, now, overall this energy is going to be conserved. So the orbitals that go-- that are destabilized-- and two go up and three go down. So we can also put that the two that go up, go up by 3/5 times the octahedral splitting energy. And the three that go down-- are stabilized-- go down by minus 2/5 times the octahedral crystal field, splitting energy. So this is why I have it in your notes, because you can't really read my writing too well.

So two go-- are destabilized, up by 3/5. Three, or stabilized, down by 2/5 in energy. All right, so now what controls the overall size of this splitting energy? How do you know? Is it a small

splitting? Is this, you know, should I have drawn this, that they're just a tiny bit? Or is it, like, could it be a really large splitting? What determines the splitting? Or The magnitude of this splitting energy.

So what determines that are the nature of ligands. So some ligands are really repulsive. Big splitting. Others-- eh-- you barely notice they're there. Very little splitting. There's always some splitting. But it can be different. So the relative ability of a ligand to split the crystal field gives rise to what's known as the Spectrochemical Series. So it's the relative ability of common ligands to split the energies of these d orbitals. And this is what gives rise to these beautiful colors.

So all of those colors are possible from cobalt compounds. Every single one of them. Because different ligands will split the energy different amounts, giving rise to those different colors. So we have what's known as Strong field ligands. And as that name would suggest, Strong field ligands are going to have a large splitting. They're very strong. They split to a large degree. And we have Weak field ligands. Weak field don't cause much of a splitting. It's a small delta sub o, small octahedral crystal field splitting energy.

All right, so which common ligands fall into which categories? Here is the list that we talk about pretty much in this class. I don't think there are any other ones. So what I will put on your equation sheet-- your equation sheet for exam four is lots of cool, interesting things that were not in the other equation sheets. And I will tell you which are weak field, and which are strong field, but I will not tell you that weak field means that it's a small splitting. That's something that you need to know. Or that strong field means it's a large splitting. But I will tell you that your halides down here are weak field ligands. Water and hydroxide are sort of in the middle. And they can have all sorts of different colors when they're bound to coordination complexes. So they're sort of intermediate. And then your strong field ligands-- with your strongest being cyanide. Very strong field ligand.

All right, so, if your metal has a weak field, intermediate field, or strong field ligand, it can have very different properties. Especially very different colors. Also, it could be paramagnetic or diamagnetic, depending on this.

So let's take a look at two different iron complexes. We have iron with six waters, with a plus 3 charge, and iron with cyanide, with six cyanides and a minus 3. So the first thing we have to do is figure out the oxidation number of the iron and the d count. And that's our first clicker

question.

All right, let's just take 10 more seconds.

OK. There you go. There's the right one. A little more people say that. All right. So, let's take a look at this. And you will get used to thinking about what the charges are on the various ligands. So here, we know that the overall charge has to be the same as the overall charge on the complex.

Water is neutral. And so that means this iron has to be plus 3. Cyanide has a minus charge, and you may have noticed that in the list of ligands, that it was cn minus. That when I just showed you the strong field ligands. So there's six minus ones. And so it's also plus 3, to give you an overall charge of minus 3. And as you do these problems, and problem sets, you'll become very familiar with what the charges of the different ligands are. So overall, plus 3, 8 minus 3, is 5. Is a d5 system.

So the next thing we're going to do is we're going to draw our octahedral crystal field splitting diagrams and place electrons. And I already have, over here, a starting place for those. So we're doing here our d5 system. And we have a diagram with a small splitting and one with a large splitting. So with the small splitting, is that going to be a weak field or a strong field? That will be a weak field. And when we have a large splitting, that is a strong field

OK, so which of our two compounds is going to be the weak field compound? And which will be the strong? Let's do strong first. Which one has a strong field ligand? Cyanide one. So this one is going to be our cyanide complex because it has the strong field. And so this one would be the water. Water's intermediate. So you kind of have to see what the comparison is first before you decide. Oops, six bracket 3 plus. OK, so here we have water. There, we have cyanide. So a weak, or intermediate field, versus a strong field.

All right, now we need to put electrons in here. So I have to decide. I have five electrons I'm going to play with. And I could put them in here. Let's just start here. Do one, two, three. Now the question is, where am I going to put four? Am I going to put four down here? Or put it up here? And so, here, it depends on, if I put it down here on pairing-- and, you know, the seats on the bus-- people don't really want to sit together if there are empty seats. Now there are empty seats up here. So, the question is, is it going to take more energy to pair? Or more energy to put it up here?

Now, if this is a weak field, which it is, then that's not all that far away. You get on a bus and you see a seat in the back. You'd rather sit up front, but you're like, than you have to sit with someone, so you go to the back. So that's what happens with a weak field. The other energy levels are just not that far away, so you go up there. And if I kind of put this up-- move it up for just a second-- and then I'll say, so this rule here, and I'm going to kind of cover this up again. But maybe I'll just put it down here. This is in your notes. So here, the octahedral crystal field splitting energy is less than we call PE, which is pairing energy.

So, it's not that far away. Just put them singly, to the full extent possible, before you pair. So that's what happens with a weak field. And we also can think about how we're putting in our electrons parallel. We're not putting them in all sorts of different directions. And we're not-- if we do pair-- we're going to not pair-- we're going to pair. So one's up, one's down. So all the rules that we learned earlier are going to apply here. So this is good, good review.

So now, in this case, we can put in our first three electrons. And what do you think? Do you think I'm going to pair? Or do you think I'm going to go up there? What do you think? I'm going pair. Yeah, I'm definitely going to pair. So I'm going to put my other two over here. So in this case, the pair-- the octahedral crystal field splitting energy-- it's so much fun to say that so many times-- is greater than the pairing energy. And, so, in this case, there might be empty seats. But maybe it's a long train. And there is-- you can sit in car one with someone else, or carry all your luggage. Why did you bring so much? You're just going home for Thanksgiving. All the way, 23 cars later, to an empty seat in the back. You're just not going to do it. You don't have enough energy. You'd rather sit with somebody up front.

So how you put in electrons depends if it's a weak field or strong field. It depends on whether it takes just a little bit of energy, and it's worse to pair. Or takes a huge amount of energy. There's a big splitting, a really strong field. And in that case, you're going to pair first. And you're only going to put electrons up here when you're completely done here.

All right, so now we have placed our electrons. We've talked about pairing energy. And we've talked about the weak and strong fields. And now we can talk about some notation. Because there's always notation. So this is what we've done already. And now we're going to do step E, which is to our d to the n electron configurations. Every diagram, there's different configurations every time. So this one we do using those little kind of cool terms I told you about. So instead of writing, I have one electron in dxy, one electron in dxz, and one electron

in dyz, I can just say, I have three in the t2g set of orbitals that is a lot more convenient.

So you would just say t2g3. And I have two up here. So EG2. And that's how you would do this. I think this is our last configuration for electrons in a diagram that you're going to be learning. There's a lot of them. OK, so then over here, we would just say we have five, all in the lower energy set, all in our t2g.

All right, one other thing, part F that you can be asked about. Which is the crystal field stabilization energy. Not to be confused with the crystal field splitting energy. They both start with an s. So I don't know why you wouldn't be confused by that. But if you can try to remember it, that would be awesome. It's often abbreviated, CFSE. And this is the energy change that's due to going from this hypothetical spherical crystal field, where all the d orbitals have the same energy. And if you put your electrons in here, where they'd all have the same energy, to the diff energy difference, when you're placing energies-- when you're placing the electrons in lower energy orbitals or higher energy orbitals. So you're thinking about how much more stabilized is the system if all of the electrons are down here. That's going to be stabilized compared to where they were here. But if a lot of them are up here, then there'd be less stabilization due to this splitting.

All right, so let's look at how we would write that. So we have three electrons that are down in energy. And they are down in energy by minus 2/5 times the octahedral crystal field splitting energy. And that's because the overall energy is maintained. Three go down in energy, so that's minus 2. Two go up in energy, again, plus 3. And then we have two electrons up here. So 2 times plus 3/5, again times the octahedral crystal field splitting energy. And so overall, our stabilization is zero. There's no stabilization of this system, compared to the system here, because three electrons are down in energy, and two are up.

All right, so now you might imagine that this is going to have some extra stabilization. And you would be right. So we would write this like this. We'd say there are five electrons down. Stabilized in the lower energy orbitals. So five times minus 2/5, times the optic single crystal field splitting energy, minus 10/5 times the octahedral crystal field splitting energy. And sometimes you'll also see, kind of a little truth, that there's also some energy kind of due to this pairing. So you might see an indication that there's pairing energy for two sets of electrons. So sometimes that's included. Sometimes it's not. The questions were asked to indicate, you know, how many of sets of electrons ended up being paired for that stabilization?

All right, so we can think about, again, we have this nomenclature here. And we can think about the stabilization. So there's a big difference between these iron compounds. One, there's no stabilization due to the splitting. And the other one, there's quite a bit, because all the electrons ended down in the lower energy orbitals.

So now it's time to try some of these on your own. See if you got the rules down. And let's try some clicker questions. Clicker question one.

OK, 10 more seconds.

All right, yes. So the trick here is to remind yourself what weak field meant. And in this case, if it's a weak field, that meant that you place all the electrons singly-- there are seven of them-- to the fullest extent possible before you pair. You still have to pair. But here you put more-- you filled these up before you paired. And this is a strong field diagram where you put-- you paired all of them possible before you put any of them up here. And to make it harder, I made-- drew them the same. So you have to really pay attention to what weak field meant. But this would be the version of the strong field. And this is just wrong. So, you wouldn't have more electrons up in the higher energy orbitals for really any reason whatsoever.

OK, so let's try the next one.

All right, let's just take 10 more seconds and we'll mention high spin and we'll do this problem.

Yeah. People did very well with that. OK, so I forgot to mention that I ran out of room to draw. So I decided that was enough. So it's in your notes though, for here. And when you have a very small, weak field, and you end up putting all the electrons in singly, that is also known-- and I'll move this up a little bit-- as a high spin. And so you have a lot of unpaired electrons in this case. So that is the maximum number of unpaired electrons.

And it's easier to remember because, you know, you have these spins. There's a lot of spins. There are a lot of single spins and they're also high up. And this is a low spin case. When you have a strong field. Because you like to pair first before putting them singly. So this is going to give you the minimum number of unpaired electrons. So high spin, weak field. Low spin often comes from a strong field. So it's about whether you have maximum number of unpaired electrons, which you do with weak field, high spin, minimum number.

All right, so let's look at this one then. So it's a high field one. So that means that you're going to have the maximum number of unpaired electrons. So this would be diagram here. And I can put that over here. And so then you have to figure out how to write that. And so you would have three ones down in energy, minus 2/5 times the octahedral crystal field splitting energy. And you would have one electron, up by 3/5 times the octahedral crystal field splitting energy. So minus 6 plus 3 is minus 3/5 times the octahedral crystal field splitting energy. So this problem required you to know what high spin was, then correctly identify the weak field diagram, and then figure out the crystal field stabilization energy. So that was actually quite good. And maybe you'll remember the high spin, low spin definitions as well.

OK, so let's just do one more thing and then we'll-- because we've just been talking about high spin. So back to our compounds, we're going to talk about magnetism. And then we're going to come back next time and talk about color. And we have some cool demos for color which we'll do next time. But before we leave from this, our iron compounds, we want to think about whether they're paramagnetic, which is attracted by a magnetic field. Or diamagnetic, repelled by a magnetic field. And we've already talked about this in this class. So, based-- and here are our iron diagrams again. Based on these diagrams, would you expect these to be paramagnetic, or diamagnetic? Paramedic. And that was because it has what kind of electrons? Paired, right.

So here you just have to remember your definition of paramagnetic. It has unpaired electrons. Now, normally, things with a weak field, and a high spin, are going to be more likely to be paramagnetic, have unpaired electrons. Things that have a very strong field. And so you pair first, before you fill up. Minimum number-- low spin, minimum number of unpaired electrons are more likely to be diamagnetic. But in this case, we didn't have enough electrons, so they're still both paramagnetic.

All right, so we'll stop there. We'll come back and talk about the colors of those iron compounds. And more colors and cool demos on Friday. Don't miss Friday. Remember, Friday, double clicker competition. The team that comes in second is automatically in the playoffs.

Are you--

AUDIENCE: We're at 166, but it stopped.

PROFESSOR: OK, let's just take 10 more a seconds on the clicker question.

All right, let's quiet down. I'd like to see the 85% that's good. Of course it doesn't distinguish all that much for the clicker competition today. So if we can quiet down a little bit. People can just yell out. What would this have been the correct answer to? What should the question have said for that to be the correct answer? Low spin, right. So low spin-- shh-- is the minimum number of unpaired electrons. And so this is the low spin. High spin is the maximum number of unpaired electrons. So this is the correct diagram. And C is wrong. It's not correct for either high or low spin. Because we have two electrons here that would have the same four quantum numbers, which is not allowed.

OK, so let's continue on with the lecture. And we are talking about colors. So, we're talking-- we're talking about the colors of the two iron compounds that we had described before. And so let's continue. And when we talk about colors, we need to do a little review and think about what's happening when a substance gives off a color. And so, when a substance-- whether a substance is going to absorb a photon or not, to excite an electron to a higher energy level that then, when it falls back, will emit a beautiful light.

We can talk about whether a substance is going to absorb a photon or not. And it will if the energy of that photon is equal to the difference in that energy level. So we talked about this before. Exam one, exam two, somewhere around there. And so, we saw this equation a lot. That the energy equals Planck's constant, times the frequency of the light. And now we can take that same gorgeous equation and add a little thing to it. So we can add that that energy is going to be equal to the octahedral crystal field splitting energy.

And so, a substance, one of these transition metal complexes, will absorb a photon of light if the energy of that photon is equal to this splitting difference. And if it is, it can promote an electron between a lower and a higher state. So this is all the same kind of thing that we talked about before, but now we're just applying it to transition metals.

So, let's think about what's happening with our iron complex. And if we say, had a low frequency of light that was absorbed, what would be true about the wavelength? Would it be long or short? It would be long. And how do we know this? We know this from the fact that if you're talking about light, the speed of light equals the wavelength times the frequency. So if you have a low frequency, then you're going to have a long wavelength. So our long

wavelengths, then, are on this and over here, sort of our yellow, orange, red, with red being our longest wavelength.

So if, then, we have a high frequency of light absorbed, then the wavelength would be short. So it'll be short wavelength absorbed. And so, again, our short wavelengths are down here, with our shortest being the violet wavelength.

All right, and now, the color that you actually see is the one that is complimentary to the color that is of the absorbed light. So we're going to think about how big those energy differences are, whether that translates to high frequency, low frequency, long wavelength, short length-- wavelength for the absorb light. And then, the complimentary of the absorb light is the light that we see, the transmitted light.

All right, so let's think about the iron complexes that we talked about. And we had a high spin, or a higher spin, iron water complex. Water is actually kind of an intermediate field ligand. And it absorbs low frequency, or a longer wavelength of light. And so it's going to transmit on the shorter end of things. Again, water sort of an intermediate field. But in this case, it was less strong than our other one, which was cyanide, which is very strong.

And, actually, these iron water complexes can appear actually a variety of colors. If they're solid, they're more of this pale violet. So definitely a very short color wavelength that we're seeing. But in solution, and depending on the pH, they can be sort of yellowish, brownish color. But the strong field ligand, remember the other compound had cyanide on it. That's a very strong field ligand. And so that's going to absorb, then, a high frequency. So a strong field, so you have a big energy difference. So you have a big energy, high frequency, and therefore short wavelength. So it will transmit on the longer end of things. And this is actually a bright orange red color. So you have a very long, long wavelength that you're observing here. This beautiful red orange. It's a really brilliant color.

Now interestingly, I mentioned in terms of applications, as some transition metal complexes were used to color things-- and I mentioned the blue in blueprint-- and if you take this compound and actually add iron in a different oxidation state to it, and, form this complex that has iron plus 3, and iron plus true with cyanide, you actually get the blueprint blue. So the colors can be just dramatically different depending on what gets added to the system.

All right, so now let's think about-- it's a little sad-- but things without color. So what coordination complexes would be colorless? What would be true about the d orbitals If you

had a colorless thing? Yeah, what would be true?

AUDIENCE: [INAUDIBLE]

PROFESSOR: Yeah, they could all be degenerate, so there's no splitting at all. Which usually doesn't happen if there are any ligands around. That's their hypothetical spherical crystal field, which I brought with me again. Because I just love carrying this through the infinite corridor and have people look at me. But, if you do have the ligands around, it will happen. If all of your d orbitals are filled, or if the energy levels are basically out of the visible range. So the transitions are not in the visible range at all. So, if they're all filled-- so, there's no way that you can move an electron. Or, if you can. But it's outside the visible region

All right, so now let's think about some examples of what transition metals would fit into this. And I'll bring up my periodic table. And we'll also bring up a clicker question.

All right, let's just take 10 more seconds on this.

All right. So we can take a look at this. And with our periodic table, we have nickel and palladium, group 10 minus 2 is 8. Copper plus 2, gold plus 2, 11 minus 2 is 9. Zinc plus 2, cadmium plus 2, twelve minus 2 is 10. And so 10 would be the correct number for our field d orbitals. They can hold 10 electrons.

S if we, then, go and fill this in, examples would include: zinc plus 2, and cadmium plus 2, with our d10 system. And in fact, zinc plus 2 is a very common oxidation state for zinc. Many proteins require zinc. Many of you have zinc in vitamin tablets. Some people take extra zinc to make sure you have enough zinc plus 2 in your body. And a lot of times people who are studying proteins do not realize it's a zinc containing protein because they isolate the protein. And it's clear, so they don't think it has a transition metal in it. But zinc is hiding in that protein because it's colorless so you don't know it's there. If you purify a protein with color with other metals, it's really obvious that the metal is there. But zinc can be sneaky.

Cadmium can also be sneaky. Cadmium, for the most part, is a poison to us. And they used to use it to coat barbecue grills. Which is not-- you don't want to put a poisonous substance on a barbecue grill and then heat it up. That's a really bad idea. So if you go to a barbecue and you think, wow, that grill looks like it's, like, 70 or 80 years old, or something like that. It looks ancient. Maybe you don't want to eat from that barbecue grill. They don't do this anymore, but

old barbecue grills had cadmium on it. And I know someone who actually had cadmium poisoning. And it was a really pretty terrible thing because it's hard to diagnose that. But they finally got the right diagnosis. All right, so again, colorless things, you don't know that they're there, but they sometimes are.

All right, so what about cobalt plus 3? You can just yell this out. Would this be a colorless compound? No. So we have in our group 9, minus 3 would be sync -- would be 6. So it's not. Which vitamin contains cobalt? And you probably all know because we've been talking about it. Vitamin B-12. And I just thought I would share with you the colors of vitamin B-12.

And so this is crystals that contain vitamin B-12. And these are their actual colors of the crystals. So it's really fun to work with vitamin B12. It's absolutely brilliant. Except that it's also light sensitive. So you have to work in the dark, under red light. So everything, then, is red because you're under red light. But if you bring them out, and you expose them to light, they're really, really pretty.

All right, so we're going to continue on this cobalt theme. Because cobalt is one of the most spectacular transition metals when it comes to color. And I'm going to get you ready for a little demo. And you're going to help me first figure out what colors you should observe in this demo. All right, so, we're going to have a cobalt compound that has six waters with it. And you're given the octahedral crystal field splitting energy. So now we want to predict the color. And when we predict the color, we're asking about what sort of wavelength is going to be absorbed. So we can think about the wavelength that will be transmitted.

So we need to think about our equations. And we can combine these just like we did in many problems in the earlier part of the course. And so wavelength equals Planck's constant times the speed of light. Now, instead of just divided by any energy, we're dividing by the energy that's the octahedral crystal field splitting energy. And so we can put in our Planck's constant and our speed of light. And we can put in the octahedral crystal field splitting energy that we were given. But we want units in meters. And so we need our joules to cancel out. And in the bottom we're given the splitting energy in kilojoules. So we need to do some conversions. So first we need to get rid of this kilojoules. So we're going to convert it to joules. Then we can get rid of our joules.

We also have seconds. We don't want seconds in our wavelength. But that is going to cancel out here and here, so we're good. But now our answer, we have meters at the top, but we

have moles on the bottom. So we need to use Avogadro's number to cancel out our moles. And if you don't do that, you're going to get a really weird number for your wavelength that's not going to make sense. It's going to be off by something, like, a factor of 10 to the 23. That should remind you, you want to use Avogadro's number here to get rid of your per mole.

All right, so now we have a wavelength. And yes, on your equation sheet, we will give you this. We will give you the color spectrums. You don't have to memorize this. So about 500 nanometers is in our green region over here. So the color that should be absorbed, given this octahedral crystal field splitting energy, is green. So now, for green, what is the complementary color of green?

Yup, so it's going to be reddish. We have our little drawing over here. So the predicted color would be red. So let me just now tell you about this demo. And we're actually going to see some red color. But we're also going to see another color which is blue. So, in this demo, if you have, start with some copper chloride and add a lot of water. A lot, a lot of water. Hydrate it really well. You'll get this octahedral system that you just told me was red. But if you don't add a lot of water, just a little bit of water, you'll only display some of the chlorides. And then you're going to have a blue system.

So if you have a lot of water, red. And you're hydrated, red. If you're more dehydrated, you get blue. So we're going to now try this out and see if it works.

GUEST SPEAKER: Is it on? Yeah, it's on. Great. OK, so that's the cobalt flower. And as Cathy said, it's-- oh, we're going to put it under there. As Cathy said, it's got some cobalt. And it's got water ligands. And it's also got chlorine. And Eric's going to sprinkle it with water now.

PROFESSOR: So we're going to hydrate it.

GUEST SPEAKER: Hydrate it, as you do, when you have to water a flower. And it's turned, like, it's a pinkish, reddish color, right? Can they see that up there? Yeah.

PROFESSOR: It looks better with it. Hold it against this, too, I think.

GUEST SPEAKER: Right. So to show you that it was, in fact, the water that led to this color change, we're going to try to dry out the flower. Is it working? Am I on hot? Yes, I am. I know it's really slow. I'd just rather it go faster. And, well--

PROFESSOR: Yeah. Why don't you hold it under the document camera? I think you can kind of see it happening.

GUEST SPEAKER: So as-- there we go. That's working. As Eric continues to warm this thing up, the water is evaporating. And as that happens, it starts forming that hydrous chloride complex instead of up here, hydrous complex, and it's going back to emitting blue color instead of red. And hopefully we can see. Oh, there. It's working. Yea.

PROFESSOR: So some people give each other roses. But if your significant other is a geek, what's better than a flower that changes color on hydration? I don't know. I think this is a pretty good gift. Valentine's Day isn't quite coming up, but just keep it in mind.

All right, so we'll leave the flower here and we'll keep an eye on it as we go along. It will change back eventually. It depends a lot on the weather, but it's pretty dry right now in this time of year.