

[SQUEAKING]

[RUSTLING]

[CLICKING]

**RAFAEL
JARAMILLO:**

So thank you for waiting. So this lecture is an introduction to some basic principles in thermodynamics, is meant to be fun. Normally, I lecture on the board. This is much more interactive. You're all holding the text for today, which is *Statistical Physics for Babies* by Chris Ferrie, and then two demos, an instant hot pack and an instant cold pack that we'll use. So wait until I tell you, and we'll all pop those hot and cold packs in the context.

So I want to start by reading from the text. So I'll just read this to you, and you can read along with me. This is a great book. All right. So this is a ball. This ball is on the left. Now it's on the move, so we gave it some thermal energy. So it's moving. Now it's on the right, so it moved over here. So now we have six balls. All right. So we have six balls here and a space that's divided by a dashed line in two. So it's clear that they can go left and they can go right. And we gave them some thermal energy, so now they're on the move. So they're bouncing around.

So sometimes, you might find more on the left, and sometimes you might find more on the right. But you'll almost never find them all in one side. That would be pretty surprising. It doesn't seem impossible, but it'd be surprising if things are random. We all agree with that? So we normally find them like this. It looks pretty evenly distributed around the space. So now that was the first 10 pages. Now to I'm going to lecture a little bit on that.

So let me give you a slightly more scientific explanation of what we just read. No, chalk was right there. So just for today, when I have slides, I get squished over to the right hand side board. Normally, I lecture on the board right in the middle. So I apologize today. These lecture notes are going to be posted-- they are already posted to Stellar if you have trouble seeing. So what we're going to do is we're going to draw a cartoon of noninteracting gas molecules in a box.

So I'm going to start like this. We're going to have a box, and the box has a divider. On the right hand side is vacuum and the left hand side are six gas molecules. And I'm going to give them some thermal energy. So they have a finite temperature. They're zooming around, and they don't interact with each other. They just bounce off the walls. So the first thing we're going to do is we're going to remove the partition.

So I'm going to draw a dashed line where the partition was. And at the instant we remove the partition, there's still over here on this side bouncing around. So remove partition. So we remove the partition. Now, what's going to happen? So this is what's going to happen. So what I'm going to say is the next step is we just wait. We don't do anything. We just wait. And we probably don't have to wait very long. We don't have to wait very long before the gas molecules are randomly distributed around the space, zooming this way and that.

So you all buy this? So let me tell you what happened in thermodynamics speak.

So this is a key word in thermodynamics. This happens spontaneously. The volume of the system here at this moment, when I removed the partition was small, and spontaneously, without us having to do anything, it got bigger. So all we had to do is wait. It was a spontaneous process. So you could say the volume spontaneously adjusted within the limits that we imposed, that is the box is still there, to increase the amount of disorder in the system.

So now I'll ask you a question. Why?

STUDENT: Because the probability is higher than the number of combinations is but is greater number of [INAUDIBLE] atoms. The atoms are [INAUDIBLE].

RAFAEL JARAMILLO: That's exactly where we're heading. Let me rephrase that. That was the correct answer. Because the more disordered state is more likely. So we're using a frequentist definition of statistical likelihood. All right. Back to the book. So now he does a better job explaining this than I did, so let's go back to the book. All right. So now we're on page 11, where the balls now have different colors.

So now we have six balls. Now, each ball is a different color. So there's only one way you can have all the balls on one side. That way is have all the balls on one side. What if we want to put five balls on the left and one ball on the right? How many different ways can we do that? Six different ways. The ball on the right can be the red, yellow, blue, orange, green, or purple ball. So there are six ways to do that. Now,

If we started counting up the different ways to have two balls on the right and four balls on the left, you would find there are 15 different ways to do that. But what was the most likely situation? Three and three. It was sort of even. So if you count up all the different ways you can have three balls on the left and three balls on the right, you'll find that there are 20 ways. So it was 1, 6, 15, 20. So that seems too simple, right? But that's the answer.

The reason why this is the expectation, this is our expectation from everyday life, is because it's more likely. There are more different combinations that look like this than any other type of state. And in this case, this has a one combination like this and 20 combinations like this. So you would say there's something like a 1 in 20, roughly 5%, chance of finding all the balls on the left. That doesn't sound that small, right? You can take odds on that.

But when you start doing this calculation for a mole of atoms or a mole of molecules, you'll find that the likelihood is geometrically small. Meaning it's never going to happen. So we later on in the course, much later, we're going to come back to these concepts and do calculation with something like, what is it that good of finding all the air in this room suddenly over here? All right. None of us would be very happy about that. Fortunately, the likelihood is so small, you'd have to wait many, many, many ages of many universes long, and you still probably would never see it happen.

So OK with that. So physicists-- but I should say scientists because this book was written by a physicist, so there's an implicit bias in here-- physicists call the number of different combinations entropy. So that's what entropy is. So a state with a low number of combinations is a low entropy state, like a state with all the balls on the left is a low entropy state. A state with a high number of combinations is a higher entropy state.

So even if the balls, all started on one side, as in my example, they're going to end up here because this is more likely. It's an increase in entropy. So the second law of thermodynamics says that things move from low entropy to high entropy. We'll rephrase that later on in a couple of weeks. I'd be a little more technical about it, but that is one form of the second law, that entropy always increases in the universe, never decreases. So that explains why we see these more likely scenarios.

You can, if you like, push all the molecules back into the left, but the key word there was push. To do that would take some work. So you can do work on a system and decrease its entropy. You can clean a room. So you can decrease the entropy of a finite system, but in so doing, you're still increasing the entropy of the universe. You're just shifting it around. So things naturally go from organized to messy, just like my kids' rooms, and now statistical physics.

So do you feel like you know statistical physics? I love this book. Now we're going to fill in some of these concepts on the board. Any questions on the reading? The theory is now. So if anyone didn't get, I think I owe. How many people did not get a copy? 1, 2, 3, Thomas, 4. Anyone else? All right. So we'll get more copies for you. Now we're going to talk about solutions. So yes, [INAUDIBLE].

STUDENT: Are we doing the mean [INAUDIBLE]

RAFAEL
JARAMILLO: So we'll cover this in a couple of weeks, but the quick answer is that the entropy of a system left alone never decreases. It either stays the same or increases, but if a system is not left alone, if it actually can interact with its surroundings, entropy is something that can be exchanged. So I can actually-- if I were a system, I could lower my entropy by giving some to you, or you could decrease my entropy by taking some. That's--

STUDENT: So when you pull down the [INAUDIBLE] where with [INAUDIBLE]

RAFAEL
JARAMILLO: When you work?

STUDENT: When you clean your room, [INAUDIBLE]

RAFAEL
JARAMILLO: The work you're doing generates heat. You cool off. That generates entropy. The most famous example of this is Maxwell's demon. It's a thought experiment. You can fall down quite an internet rabbit hole, or a textbook rabbit hole, reading philosophical style treatise on Maxwell's demon. Maxwell's demon is a little demon that sits in between this box and only lets gas molecules go to the left. And so Maxwell's demon is like a little turnstile for gas molecules.

And it's called Maxwell's demon because it was thought of as a thought experiment to disprove the second law. And there have been a hundred plus years of physics papers showing that, for example, there's an information theory approach to Maxwell's demon that Maxwell's demon has to know that the molecule is approaching. Therefore, it has to receive at least one photon, and you can calculate the physics of the entropy generation of that photon generation and absorption by the demon. So we can make the decision to open the gate. Can't get around the second law, so we'll get there.

I don't know if that exactly answered your question, but it was a little-- we'll get there again with more time to spare in a couple of lectures so. Just Google Maxwell's demon. It's kind of fun. So now we're going to talk about solutions. So here comes the first demo, maybe the last demo. Done a lot of demos in this class, but this one is so easy. I did the same demo in 3001. So many of you were in 3001. So I'm sorry I'm ripping myself off here, but it's topical. All right.

So there is water. There's water in the dish. You can't see it. So what I'm going to do is I'm going to make a solution. I'm going to mix two substances. One substance is food coloring, which is, of course, also water, but pretend this is like some other substance. It's water, like it's some dye molecule solvated, so insulation, and the other substance is water. So I'm going to mix them, and you can see what happens. So let's see. So while this is going-- you guys know what's going to happen, right?

I find kind of fun and calming to watch it happen. All right. So over here, we're going to talk about solutions. So we're going to talk about solutions for the case of noninteracting molecules. So I'm going to draw some pictures. All right. So let me say 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15. So here's the starting condition. We have some uniform material. It's made of some molecules. I don't know.

All right. So here it is. Here's the uniform material in a box, and these are the molecules that make up the material, and its properties are uniform. So now what we're going to do is going we're going to label certain molecules. Can you guys see that? Barely. We're labeling certain molecules. So what's one way you could label molecules? Physically. Yeah.

STUDENT: [INAUDIBLE] position.

RAFAEL JARAMILLO: Mhm, no. What I mean is we're going to make a physical change to the molecule, so it's carrying a label.

STUDENT: [INAUDIBLE] little fluorescent tag.

RAFAEL JARAMILLO: Some kind of fluorescent tag. You could make it a different isotope. There's different ways to label, or just as a thought experiment. You just go in and you take, let's say, five of these molecules and color them blue to pick a color. Kind of what we're doing, 1, 2, 3, 4, 5. So I went in and I labeled those molecules, and now I'm going to wait. What do I expect to happen? Yes please.

STUDENT: [INAUDIBLE]?

RAFAEL JARAMILLO: Yeah, you expect it to even out. So the case of noninteracting molecules. Initially, everything looked even, and then we did something. We made it uneven, and now you expect it to even out. So I'm going to draw again, 15. And you expect the label molecules to spread out, maybe like that. They're not on one side anymore. You get it. I didn't want to spend all day up here drawing circles. It's more convincing if I do like 20 or 30 circles, but I decided to stop at 15 circles.

So what's actually happening-- I mean, you understand that, and you believe that. I'm just going to describe that in thermodynamics language. So what happens is that diffusion-- so the process by which this concentrated area of labor molecules becomes diffuse is diffusion. And it happens spontaneously.

I don't have to go over there with my atomic tweezers and move the blue food coloring molecules until they all look even. I think by the end of this course period, it will be uniformly blue. Takes about half an hour or so at the temperature of an overhead projector. So that's the diffusion process. And again, that word spontaneously, it's happening spontaneously, and it's mixing the label of molecules.

So what can you say about the entropy of this situation? Is the entropy from the second frame to the third frame, is it going up or down? It's going up. Something's becoming more disordered. That's true. The entropy is going up. There's more different configurations that look like this, all mixed up, and configurations that look like this, everything on one side. So it's more likely, it's more entropy.

All right. So now I'm going to erase this board and redo it for the case of molecules that now are going to interact with each other. Yes please.

STUDENT: [INAUDIBLE] spontaneously I thought before when we're talking about the [INAUDIBLE] indicate instantaneously or--

RAFAEL No, it doesn't mean instantaneously.

JARAMILLO:

STUDENT: [INAUDIBLE]

RAFAEL Exactly. That's right. It does not mean instantaneously. There are many good examples of this, of systems that are out of equilibrium that are slowly relaxing. If you go to very ancient cathedrals, you'll see that the windows appear to be pooling at the bottom of the window frames. They're slowly flowing. Things seem static.

JARAMILLO:

In the case of gas molecules, it'd be about hundreds of nanoseconds in a reasonable space. So the timescales might vary. But it's a good question. It doesn't mean instantaneous. It just means without outside influence. Thank you.

So now let's do the case-- my favorite example here is-- there's something called the Tar drop experiment. And this is a university in Australia, where they took some tar and they put it in a vessel. And they poked a hole in the bottom of the vessel, and they put a video camera on it. And it's been running for decades. And I don't remember, but once every eight or nine years, you get a drop. There's a webcam for this thing. You can go and watch it. So spontaneously, it's dripping, but it's pretty slow.

So now we're going to do the case of interacting molecules. So the previous example and the example you're watching over there, there's effectively no interaction between the labeled molecules and between the labeled molecules and the unlabeled molecules. There's not a lot of intermolecular forces in between the blue dye, and, let's say, a distant water molecule, or between two distant blue dye molecules, not a lot of interaction.

So what about when there is interaction? Let's do the cartoon case, and then we'll start-- this is how we get through with the hot and cold packs. So we have a uniform material, all right, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15. All right. So we're starting again with the uniform material, and now I'm going to-- let's see-- label some. So just as before, I'm going to label some. This time, the ones I'm going to label are--

All right. I'm going to label them in a way that is more like what you expect from the equilibrium situation for the noninteracting particles. Label some. So now I've labeled them. I've labeled them as quasi randomly, and now I'm going to make a caveat, label some so that they attract.

So I've labeled these with some sort of a molecular tag that likes to be close to other like molecular tags. So there's an attraction here. So now we're talking about forces and interactions between molecules. So what happens if I label these so that they interact and then I wait? What do you expect to happen?

STUDENT: They only attract themselves?

RAFAEL JARAMILLO: Yeah, they're only attracting. So it would be as if the blue dye molecule were attracted to other blue dye molecules in that case.

STUDENT: Then I'd assume separation.

RAFAEL JARAMILLO: So if they're attracted to each other and there's no other forces in this-- let's see-- you might expect after waiting for some time, that now the molecules have clustered. So in this case, inter atomic or molecular-- if these were atoms, I would talk about inter atomic forces. If they're molecules, I'll say intermolecular forces, same thermodynamics-- inter atomic or molecular interactions cause spontaneous unmixing.

All right. So we talked about mixing, and now it's on mixing. So this can happen too. And there'll be plenty of examples. Maybe you're already familiar with some. And you can also-- I won't draw this-- so you can also consider the case of repulsive interactions. So let's say that those molecules, instead of attracting each other, were repelled from each other, think about how you sit in a lecture room when it's an exam and we told you not to sit next to anybody, do you become completely disordered or more ordered?

STUDENT: More ordered.

RAFAEL JARAMILLO: More ordered. You become more ordered, because if I have a person, I know that I only have to go to two chairs over to find another person and I go two chairs over to find another person. That's order. So is that increase in entropy or decrease in entropy?

STUDENT: Decrease.

RAFAEL JARAMILLO: That's a decrease on entropy. So from this central frame to the right hand frame, is that an increase in entropy or decrease in entropy?

STUDENT: Decrease.

RAFAEL JARAMILLO: Decrease. It's a decrease in entropy. And the case of the students taking an exam in a lecture hall, that's also a decrease in entropy relative to, say, right now, where you look more disordered than that. There's some clusters. There's some lone people. It's more disordered. Yes please.

STUDENT: So then would the balance in entropy, like you said how everything always have to increase, would that come from doing work to label some molecules [INAUDIBLE]?

RAFAEL Not quite, but balance is the key thing. We're heading exactly towards this idea of balance. But thank you for saying balance. So now everyone-- let's see. So you got this idea of disorder and a basic notion of entropy, and now we've started to introduce the fact that molecules can interact with each other, and an interaction is typically characterized by an energy of an interaction. So there's energy involved. And I think these are concepts which you're already familiar with.

So we're going to now review endothermic and exothermic reactions in this context. So who's here heard of endothermic and exothermic? Everybody raised their hand, except for [INAUDIBLE.] All right. So now we get to play with the hot packs, but wait till I say you play with the hot packs. All right. So we're going to start with endothermic process, endothermic process, endothermic example.

So an example of an endothermic process is ammonium nitrate dissolving in water. So I'm going to draw it like this, n moles of ammonium nitrate plus n moles of water are going to react, and the reaction product is going to be a solution. So even though this just looks like you dissolved or you just mixed, you can still talk about it as a reaction. So this over here is pure solid.

So this is what we call in thermodynamics a pure material. And it's in a standard, state ammonium nitrate. Will sit in a jar. It's solid at room temperature and atmospheric pressure. All right. And this over here is a pure liquid. So this is a pure solid and this is pure liquid. And what's this on the right hand side?

STUDENT: Mixture?

RAFAEL It's a mixture. It's a liquid solution. In thermodynamics-- and this is something-- is this terminology you have to get used to it-- the word solution and the word mixture are basically interchangeable. Solution to us does not mean it's a liquid. Solutions can be liquid, gas, or solid. In fact, in this class, usually, they're solid. So just get used to it. There's no way around it. So this is a-- but this is a liquid solution. In this case, it's a liquid solution, or mixture, I feel like, liquid solution.

So I need to get more board space here. So this process absorbs a finite amount of heat from the surroundings. It's an endothermic process. So it absorbs an energy, Q -- this is in unit of joules, it's an energy-- from the surroundings. Sometimes this is called the heat of solution.

Later on in this class, we'll show that this is related to the enthalpy of solution. We'll start using the word enthalpy, but for today's lecture, it's enough to think about heat and energy. So in going from left to right, does the energy of the system increase or decrease?

STUDENT: Increase?

RAFAEL It increases because it's endothermic. It got energy from the surroundings. Does the entropy increase or decrease?

STUDENT: Increase.

RAFAEL It increases. And it's OK if you didn't have an intuition for that now. The reason it increased is because on the left hand, you had a solid phase, and then every n moles of that solid went into a liquid phase. And liquids tend to have much higher entropy than solids. They're more disordered. A solid is like everyone at every other chair. A liquid is somehow more disordered. So that was right.

So in this case, the energy and entropy, both increase. So before, we learned that nature likes to increase the entropy of the system. So that would seem to drive the reaction to the right, but if you've taken a physics class, you were probably told that nature likes to decrease the energy, which would drive the reaction to the left. All right. And both of those things are true in the right context. So what gives? All right. So we're going to find out what gives.

So take your instant cold packs, which is the-- not the one that says warm relief, the one that's blue. All right. So this is a Dynarex Instant Cold Pack. This is a snapshot from the Safety Data Sheet, Dynarex Instant Cold Pack. If you're ever looking for your first choice for gloves, I guess it's the Tillotson Health Care Corporation. All right.

So this is the SDS, and this is telling you that it's made of ammonium nitrate pellets surrounded by a small ruptured plastic bag filled with water. So we're going to figure this out. Does this reaction stay on the left hand side or does it go spontaneously at the right hand side? So what do you think?

STUDENT: To the right side.

RAFAEL Everyone who thinks it's going to go to the right, shout or raise your hand. Hey, hey. So squeeze together here.

JARAMILLO: So here we go. I'm going to squeeze together. Aah, cold. All right. So is it cold? Yeah. So is it spontaneously went to the right or the left? Where does it go? It goes to the right. So it's absorbing heat from your hands. You feel cold. All right.

So in this case, entropy-- it spontaneously went to the right, which means entropy increased, but the energy also increased. So it's like we weren't sure what was going to happen, but in this case entropy drives-- I'm being really sloppy here so-- entropy drives the reaction. It's the entropy consideration. Nature thinks about it, figures out the right balance, and say, entropy is going to win. We're going to make a solution.

So now we're going to do the opposite case, which is exothermic process. That was satisfying, right? I like that. So exothermic process, for example, crystallization of sodium acetate from a solution. So we're starting with a solution, and we're going to crystallize sodium acetate. So CH_3COONa . Let's see.

The way I wrote this was like this, x , H_2O , see, reacts, the reaction is like this. It goes with some heat, Q , and it becomes CH_3COONa , I'm going to put a little solid there because it came out of solution, formed a solid crystal, and then CH_3COONa x minus y H_2O .

So someone tell me-- well, so I told you this is the solution. This is a solution. It's a liquid solution of x moles of sodium acetate into z moles of water. All right. What is-- someone repeat for me. What is this material? What is this phase?

STUDENT: Solid sodium.

RAFAEL Solid sodium acetate. All right. And what is this material over here, this phase?

JARAMILLO:

STUDENT: Liquid.

RAFAEL It's a liquid. Is a pure material?

JARAMILLO:

STUDENT: Still solution.

RAFAEL JARAMILLO: A still solution. So we have solutions on both sides, but they have different concentrations. We've conserved moles. We haven't created a destroyed matter. So this is a liquid-- it's a liquid solution, but in the hot pack we're about to use, it's super saturated.

So ask me questions in a minute about what that means. We'll come back to that concept later in the class. It's a supersaturated liquid solution, so it's non equilibrium. Then over here, we have a pure solid, and over here, we have a liquid solution. And what do you think would be the right term to characterize this liquid solution? A liquid solution in equilibrium with the solid solute is a--

STUDENT: Saturated?

RAFAEL JARAMILLO: Saturated solution, saturated. So if that didn't come to your tongue right away, that's fine. That's a concept which we're going to cover in detail in a number of weeks from now. All right. So we start with a supersaturated solution, and we get a saturated solution.

So I told you this was exothermic, so I'm not going to ask you what's the sign of Q. This process releases heat energy Q to the surroundings. all right. So would you say the energy of this system increases or decreases as it goes from left to right?

STUDENT: Decreases?

RAFAEL JARAMILLO: Decreases, exothermic. It lost energy. So energy-- all right. What about the entropy of the system? Does it increase or decrease from left to right?

STUDENT: Decreases.

RAFAEL JARAMILLO: Decreases, right? It decreases. You started with all the sodium acetate in a liquid state, and then you took some of that and made it a solid. And I told you before that the solids tend to have lower entropy. So the entropy decrease. So energy and entropy, they decrease. Key is that they both decrease. All right. So nature likes to maximize entropy, but it also likes to minimize energy. So what's going to happen?

So demo number two. So grab your instant hot pack. Let's see. There we go. So this is instant hot pack from Danyang Rapid Aid Hot and Cold Therapy Product Company Limited, and it is made up of sodium acetate and water. That's what's in here. So I'll tell you what's actually-- I'll show you a video of what this might look like in a minute, but let's test it. Let's do the experiment. Let's figure out if it goes left or right. So I did this the other day. It's like, fold top to bottom to pop inner fluid bag and shake.

So I'm folding the top to the bottom. Certain amount of strength required to be in this class. Aah, there we go. Oh it's like it's hot. This is like a PE credit. I should PE credit for this. All right. Who's got popping? I hear some popping sounds. Gets hot, right? So what's going on? So what happened? Some people are still struggling. It's actually really tricky. Those of you whose bags popped, can you tell me what happened? Somebody tell me what happened.

STUDENT: It warmed up.

RAFAEL It warmed up. It got hot. So did the reaction-- where's equilibrium here? To the right or to the left?

JARAMILLO:

STUDENT: To right.

RAFAEL To the right. So it's weird, right? Entropy decreased. So in this case, unlike the previous case-- so in the previous case, entropy seem to win. Nature got to increase its entropy, but in this case, energy seems to win. Nature got to decrease its energy. So the balance was different.

JARAMILLO:

Let me show you a video of what these look like. All right. So we've seen two examples, and we've done two experiments. And we've seen that in one example, entropy seems to rule the day, win the day, but in the other example, entropy or energy seem to rule it. I forgot which one I said first.

So on the one hand, we have entropy or disorder, and on the other hand, we have energy, or what we will more commonly use in this class, which is enthalpy. They're not identically the same thing. So we'll cover enthalpy in plenty of detail in later lectures, but for today, we can use them interchangeably. So on the other hand, we have energy or enthalpy, and this question of balance is everything.

So here's a plank, and there's a fulcrum. And this is basically thermodynamics. Thermodynamics is nature's way of balancing entropy with enthalpy. And so what we're going to do is spend a semester learning how to calculate the balance for all sorts of different physical situations, mostly with solids but also reacting chemicals, liquids, solid gas, systems, and systems of interest, rates, and modern material science.

So what happens when we get the final answer? So I'm going to move on. I have a couple of slides to share now to introduce you to the concept of phase diagrams, which is the way that we communicate with each other in material science what the answer is, what's the balance. Before I move on, do we have any questions about these hot and cold packs, endothermic, exothermic processes?

So you might not know in advance the balance. One chemical system we just showed you, room temperature and atmospheric pressure preferred to maximize entropy, the other system, at the same set of conditions, prefer to minimize energy. So fortunately, there's a rigorous theoretical framework to calculate the balance, and that's what we're here to learn. Once you've calculated the balance for a given material, you want to communicate that answer to other people. And this is where phase diagrams come in.

Phase diagrams are the visual tool by which within material science, we communicate what that answer is, what nature will prefer at a given set of conditions. So I want to show you some examples of phase diagrams. If I have one deliverable in this class to you when you walk out of here in December, it's that you know how to use phase diagrams and you know where they come from. That's the core of thermodynamics and material science, unlike, let's say, mechanical engineering.

So this is the water phase diagram. Let's see. I assume that most people have seen the water phase diagram before. What's cool about this water phase diagram is that it covers a very large range of pressure. So this is pressure in the y-axis, and the x-axis is temperature. And the colors here show you what the right balance is between enthalpy and entropy.

So for example, at a given pressure, let's say atmospheric pressure-- where is that? Here. When you heat up, you go from ice, which is a low entropy state, to water, which is a medium entropy state, to-- came down here-- to vapor, which is a high entropy state.

On the other hand, it turns out pressure goes the other direction. Pressure, we haven't talked about volume, but increasing pressure favors smaller material. It makes sense, right? So as you go from the vapor to this solid, and then these other phases of ice, which you might find in the core of distant planets, the volume per mole becomes smaller. Crystal structure becomes different. There are different materials. So this kind of neat. You have 11 phases of ice. I think there are 12 known now. They're labeled with these different Roman numerals.

And so this is one thing that we get used to in thermodynamics, is that there are many different solid phases of a material. They're in a sense different phases. They're different materials. They behave differently. They have different structure, and therefore, they have different properties.

I was just speaking with one of my Europe advisees who-- she spent her summer at JPL testing the mechanical properties of drill bits on different phases of ice. Why? Because they're going to land a rover on Europa, and they want to drill through-- they want to go ice fishing. They want to drill through the ice core of Europa to get to the liquid underneath.

And they might expect different phases of ice than the normal terrestrial ice that we're familiar with. And they will have different properties, and therefore, it will wear the drill bit differently. And they have to know where the drill bit. You'd hate to fly all the way to Europa and have something like the drill bit failure ruin the mission. So it's kind of interesting. She just told me about this just before this class. So here's another example. Here's a binary phase diagram. Here, the y-axis is temperature, and what's the x-axis?

STUDENT: [INAUDIBLE]?

RAFAEL
JARAMILLO: I heard something like concentration, which is about right. It's composition. So this is a complicated diagram which you're going to know the back of your hand when you walk out of this class. So this is the copper-zinc system. This is called the liquidus line. Above this line, the system is a uniform liquid mixture. Below this line, there's a slew of solid phases, alpha, beta, gamma, delta, epsilon, eta. Which phase or combination of phases-- this region, I know is a mixture of alpha and beta, you'll learn that.

How the system behaves depends on where you are in temperature, pressure, and composition. And that's something-- this is an equilibrium phase diagram, well established because that's brass. It's an important metal, alloy. And we'll learn how to calculate these phase diagrams. There's a lot more. So the types of phase diagrams, that's a binary phase diagram, a classic eutectic tactic. Phase diagrams don't have to be composition temperature and pressure. They can be electrical potential and pH.

So a pourbaix diagram, like we would use to predict corrosion or to optimize a battery, gives you the phase that you might expect as a function of aqueous solution pH and electrochemical potential, or electrical potential, relative to a standard electrode. Here's a ternary phase diagram. So here, instead of two elements or pure materials, we now have three, titanium, tungsten, and carbon. So this is going to be all sorts of high performance titanium, tungsten, alloys in there.

Here, there is no more room left on the page to do temperature and pressure, so those are in some sense in the third and fourth dimensions, but they're there. And this is something that's near and dear to my heart because I work on a lot of oxide and sulfide electronic materials.

This is a Richardson-Ellingham diagram, which isn't quite a phase diagram, but it does tell you whether nature predicts the metal or the metal oxide as a function of temperature and oxygen partial pressure. So this is very useful if you are, for example, making a transistor. You have to know how to control the oxidation process of silicon, or if you're smelting or any number of other interesting processes that are important.

So we're going to learn how finds this balance, and we're going to learn how to interpret these phase diagrams. But in practice, calculating one of these phase diagrams would take you a really long time, and you'd get a paper out of it. And you'd feel very accomplished, but what if you're out there in the world and you have to make engineering decisions and you have 7 minutes before your boss tells you, what percentage carbon do we want in this deal? All right. You don't go to the blackboard. You go to computerized tools.

So the idea that you could calculate phase diagrams with a computer, that idea is called CALPHAD. It's kind of funny that that idea would have an acronym, but it does. It's called CALPHAD. And there are many CALPHAD software packages out there. What they do is they take materials data from databases, which often are proprietary, and they calculate the balance for a given temperature or pressure or composition or a pH or electric field or what have you, and they tell you the answer.

So these are really indispensable once you leave here and you go off to your next position, whether it's in research or industry or what have you. And so we're going to spend a little bit of time in this class getting familiar with one of these, Thermo-Calc. The reason why we're going to get familiar with Thermo-Calc is because they have a free educational version, and it's relatively user friendly.

So you have a thick a couple of weeks until we're actually asking you to use Thermo-Calc in your p sets, but if you want to just download this on your computer, install it, get ahead of any problems-- it tends to work well on both PCs and Macs-- and play around a little bit.

So the thermodynamics section of this course basically has three parts. The first seven lectures are introducing the concept of equilibrium. That is this balance. How does nature determine the equilibrium situation, the most balanced situation for any given set of conditions? And then we're going to apply that concept. We apply the concept of equilibrium to increasingly complex physical systems to calculate these phase diagrams to figure out how to where they come from, how to make them, how to read them, how to use them.

And then at the very end of the course, we're going to come back to some foundational material. We're going to come all the way back to statistical physics for babies and do some slightly more sophisticated analyzes of entropy and how it relates to, let's say, configurations of molecules, do some foundational work. We might even mention Carnot cycles at the very end of class.

I already told you about the resources online. So I'll leave you with this. So Arnold Sommerfeld is one of the fathers of quantum mechanics. The point is that he was a smart person, no dummy when it comes to science. And this is a very famous quote. There's a website devoted to quotes about thermo by the way, but this is the one that gets most often related.

So I'll read it. He said, "Thermodynamics is a funny subject. The first time you go through it, you don't understand it at all. The second time you go through it, you think you understand it, except for one or two small points. The third time you go through it, you know you don't understand it, but by that time, you're used to it. So it doesn't bother you anymore."

And this is consistent with most people's experience of learning thermal. This is a bit of a disclaimer because this is the first time you go through it. So this is a tricky subject, and you shouldn't feel badly about yourself if you leave this course thinking that, I know how to use a phase diagram, Thermo-Calc, that's neat, but what just happened? All right. That's perfectly natural.