3.091SC Introduction to Solid State Chemistry, Fall 2010
Transcript – Session 7

PROFESSOR: OK, a couple of announcements. Tomorrow will be the Periodic Table test. I provide the numbers, you provide the letters. Friday, the contest ends, 5:00 pm. Get the submissions to me, either over the internet or if you have something majestic, you have to cart it in with the riggers. Get it to my office. Last day, we had a lesson on the Aufbau principle. And the Aufbau principle gave us the--

There's still too much talking. Still too much talking. I will tolerate zero, zero talking. When you walk through that door, I'm assuming it's an act of free will. And when you walk through that door, we enter into a contract. The contract goes something like this: You have certain expectations of me. You expect me to come to class prepared. You expect me to treat you with respect, not to use vulgar language, not to say things that are insulting, insensitive. And I have certain expectations of you. I expect you to come to class prepared. I expect that you've done the reading. And I expect that you're going to sit quietly. Absolutely quietly. Because it's my duty to preserve a fertile learning environment. If you don't want to learn, I don't care. I don't care. But if you impair the ability of your neighbor to learn, I will take action. It's very simple. Very simple.

Where was I? I think I was talking about the Aufbau principle. And the Aufbau principle tells us what the filling sequence of electrons is in a multielectron atom, which ultimately we rationalized in terms of the four quantum numbers and the filling in ascending order of energy. And then we tried to understand what's behind the Aufbau principle.

And lastly, we took a journey through central Europe in the 1920s and 1930s. And we met de Broglie, who gave us the concept of matter waves. If matter has wave-like properties, the wavelength would be given by the ratio of the Planck constant to the Newtonian momentum. Heisenberg taught us that we can't deal with precision down to atomic dimensions, and there's a certain degree of uncertainty or indeterminacy. And it's given by this relationship here.

And then, lastly, we saw Schroedinger, who wrote the wave equation saying that if we have wave-like properties then let's model the atom as a wave, and he gave us this equation here, which is essentially the equation of the simple harmonic oscillator. The simple harmonic oscillator, which allows you to tell us what's going on with the plucked string. And it's essentially just this, the double derivative x double dot plus kx goes to some function. And the solution of that is a bunch of sines and cosines. And that's this equation, but dressed up for night-time. It's a little bit more sophisticated and gives us the three dimensions, eigenfunctions that ultimately, we can take and generate the pretty pictures of the orbitals.

So, today what I want to do is go a little more deeply into properties. And if you learn nothing else from me in 3.091, this is what I want you to retain. It's that electronic structure dictates properties. Electronic structure dictates properties. You know this on your death bed. It's that simple. Electronic structure dictates properties. Then we're going to take 14 weeks and describe electronic structure, right? But that's it. That's it.

So I want to go back to this. We got into this energy, Aufbau principle because we saw on the Periodic Table there's some problems here. If we just go in terms of quantum numbers, we see there's two elements in n equals 1 shell. There's 8 elements in n equals 2 shell. And, if we just kept going, we would expect to find 18 elements in n equals 3 shell, but instead we found only 8. And that's where the journey began.

Well, there's a way to sort of help remember what the filling sequence is. And that rule is encapsulated by the n plus l relationship. So for equivalent, n plus l values, for equivalent n plus l values, you fill in ascending n. Fill in ascending n. So let's take a look.

So, here's Aufbau. n plus l rule. Here's an example where we have 3d. d means l equals 2. p means l equals 1. s means l equals 0. So 5 plus 0 is 5. 4 plus 1 is 5. 3 plus 2 is 5. So what do I do?

Well, it's saying go in order of ascending n plus l. And so, you can snake your way through this n plus l, and get the filling sequence for the whole Periodic Table. So let's take a look.

We'll start with 1s. Well, that's easy. That's hydrogen and helium. Then we go next to 2s. There's lithium and beryllium. And then next goes 2p. I mean, nobody's going to try to stick 3s ahead of 2p. That's pretty straightforward. 2p, and that gets us all the way over to neon. And then we wrap around over here to 3s. That gets us from sodium to magnesium. And then we jump to 3p, gets us from aluminum over to argon. And then, we don't go to 3d, because 3p is 3 plus 1 is 4. 4s is 4 plus 0 is 4. So it says we fill in ascending n. So we go to 4s next. And that gets us potassium and calcium.

Then comes 3d. So that gets us scandium over to zinc. Then comes 4p, gallium to krypton. 5s. I'm having fun here, I'm going to keep going. 5s gets us over to strontium. Next comes 4d. Gets us all the way over to cadmium. 5p gets us to xenon. Now it's turn 6s cesium, barium. 4f. We've got to jump down here. Finally we're going to get to the f shell. See? The 4f is in here. Now, this is an item of convenience. Strictly speaking, lanthanum is 57, cerium is 58. So all of these elements belong in here. But if we were to put this to scale, the Periodic Table would be way over here. It wouldn't fit on a page. So people, over time, have gotten used to just putting it down here. But these elements are in the middle here. So you go 4d, 5p, 6s, then 4f. Finally we get over to the edge here, to erbium, and then we jump over here to hafnium, 5d, over to mercury, 6p, et cetera.

So the n plus l rule gives you the filling sequence in ascending order. That's good. So we've got a nice compact way of grabbing this e goes to n plus l. Now let's look at some properties. We said it's a table of the elements, but it's a periodic table. So let's see what this periodicity looks like. Now, here's a variation of first ionization energy. So here it is in kilojoules per mole, and here's my pet unit, the electron volt

per atom. Because here's hydrogen, of 1.6 megajoules per mole, but I like the 13.6 electron volts because I can remember 13.6. I can't remember 1312 megajoules per mole, kilojoules per mole, whatever it is. 13.6 electronic volts.

So here's hydrogen, there's helium. And then we drop down to lithium, and then we move across up to neon, and so on. So you can see 1s, we filled the 1s shell. Now, we're going to go to shell n equals 2. Here's 2s. And then we go to 2p. And you can even see, look, boron, carbon, oxygen, the ascending value of the first ionization energy. And then there's a little jog here at oxygen. Because here we've got the three unpaired electrons for nitrogen. And then there's the oxygen starts to pair, and we continue to neon, and so on. 3s, 3p, 4s. So you can see the relationship between that property, and the place, the element, in the Periodic Table.

So how do we measure these values? Well, I thought it might be a good opportunity to look at, revisit the whole question of gas dynamics, and also understand the measurement. Measurement of ionization energies. And the technique that's used is called photoelectron spectroscopy. Photoelectron spectroscopy.

All right. And it's got a three-letter initialization, PES. I want to show you a cartoon of how this works. Actually, I took one -- this is taken from the text we used to use. I like the text that we're using now better, but there are a few things in the other text that were good. So, we've scanned these few pages and posted them at the website if you want to go through and read this stuff. So let's jump over to that.

So here's an example of a terrible drawing. I look at this and I haven't got the faintest idea how this thing works. It's not the artist's fault. Somebody should have proofread this thing. What they should be doing is showing something like this. So, let's see what's going on. So what we're going to do is, we're going to bombard a specimen right here. Which they never show. I suppose this atom beam is supposed to be colliding with the photons. That would be quite an apparatus to build, let me tell you.

Instead, what you have is, you have the apparatus sitting so that you've got the material in the center of the chamber. And you irradiate with photons. And the photons have very, very high energy, and they dislodge electrons. When they dislodge electrons that's the ionization event. And then what we do is, we measure the velocity of those ejected electrons. And if we know the velocity, we know their energy. We know the energy of the incident energy and by difference, we calculate the binding energy of the electron and the atom.

So let's take a look. I'm going to draw a cartoon here that gives you a sense of what's going on. So, here's the n equals 1 shell, or the k shell. And then I'm going to show, say, a second shell here. One, two, three. So this is the l shell, or n equals 2. And you might say, gee, he's got that wrong. It's kind of simple, and so on. It's as complex as it needs to be for the explanation. Don't let accuracy trump clarity. The real accurate picture here is too detailed to convey what I'm trying to convey.

So, this is the specimen, right? Let's call this the specimen. And I'm going to irradiate the specimen with some radiation of high energy. And so, I generally indicate the photon by a squiggly line with an arrow. That's to indicate it's got wave-like properties. And I'll usually write h nu next to it, to indicate that it's a photon of energy h nu. So the photon comes in, and if the energy is high enough, it will

dislodge an electron. So this electron is dislodged. It's now ballistic. It's rendered ballistic. It's free. It's ionized. It's gone. It's gone.

And what we're going to do is, we're going to take an energy balance here. And at some point you may come back and learn some quantum mechanics. This photon is annihilated at this collision. So the photon doesn't act the way an incident electron does where it loses some of its energy. All of the energy is lost. So this photon's gone. All of the energy is given to this electron. So let's do an energy balance here. So I can say that the energy of the incident photon, the energy of the incident photon, is now going to be given to the electron. It's now got some kind of kinetic energy. E kinetic plus the energy it took to pull it out of the atom. Plus E, let's call it binding. E binding

And we know the incident energy of the photon because we're running the experiment. So we set the value of the incident energy of the photon beam. And then we send this to a detector. This goes to a detector. And the detector measures the velocity and ultimately gives us the energy of the scattered electron. This is called the dislodged electron, or photoelectron. It's the electron that was kicked out by the photon. So it's known as the photoelectron. Photoelectron. Pardon me, let's try that again. Photoelectron energy is measured at the detector. And then by difference, we get the binding energy. We get the binding energy. So this is h nu. This one here is going to be a 1/2 m b squared, and then by difference we get the binding energy.

And what kind of photon energies do we need? We need fairly high energies. And so typically, we might use wavelengths down around 1 angstrom, which then makes it an X-ray. And so, over here in Building 13, we have such instrumentation, and the material scientists would call this XPS. X-ray photoelectron spectroscopy. And if you don't want to blast all of the electrons out of the specimen and just get the most weakly bound, then you want a lower incident photon energy, which means a longer wavelength. You might come in at around 100 angstroms, which is ultraviolet. You know, people, the general public, is so afraid, they don't know science. If they hear X-ray they get all panicked. You know, it's radiation. Their children are going to die and all this kind of stuff. So, what people will do is, they'll say instead of soft X-ray they'll say hard ultraviolet. And then the public thinks, oh, as long I wear sunscreen I'm going to be OK. So if you use hard ultraviolet, it's called UPS. That's nothing to do with brown trucks. It's ultraviolet photoelectron spectroscopy. And collectively, this is known as PES-- photoelectron spectroscopy.

All right. So now, let's go back to this schematic. Now you can see how bad this schematic was that these photons are coming in as so. And striking the specimen here, ejecting the photoelectrons which then are focused and ultimately measured here at the detector. So there's the energy balance. The energy of the incident photon is distributed across the kinetic energy of the photoelectron plus the binding energy, and this is how we measure all of these quantities. Since you're using very, very high intensity radiation, there's nothing saying that you're going to eject only one electron. You can eject a plurality of electrons. And the different electrons have different binding energies. So you're going to get a set of binding energies, which means you'll get a set of lines. You'll get a spectrum of energies. So this is what the spectrum looks like, and this is, by the way, just a general way of looking at any spectrum so that you train you eye to know what to look for.

If I look at any spectrum, I'm going to have a plot of some kind of intensity, some kind of intensity unit versus some kind of energy unit, versus some kind of energy unit. And sometimes, energy increases from left to right. But sometimes they might put energy increasing from right to left as you see in these spectrum. But energy is along here. And intensity is related to population. All other things being equal, if I have a specimen that has two times the concentration of active species, I'm going to get twice the strength of the line. So the intensity measures population. The energy is related to the characteristic binding energy of a particular electrons, so the energy is related to the identity of the species. This is how we can identify certain species. I've already shown you if you walk in and you see those four Balmer series lines on a spectrum, you know that's characteristic of atomic hydrogen. Nothing else. So those are energies. And then, where do we go?

So we have a line here, but we know that real data have a little bit of a spread to them. So you don't see discrete lines; you'll see a spread centered at about the value. So let's look at these. These are highly stylized, but here you can see-- here's boron for example.

So these are the 1s electrons of boron, and they're held at a binding energy of about 19.3 megajoules per mole. And then this is 2s, and here's 2p.

Now there's a difference between 2s and 2p, but they're of the same order. They're roughly about a megajoule per mole. There's subtle differences. And this goes back to Sommerfeld, who said that even though there are s and p orbitals, there's a circular orbit and there's an elliptical orbit. But they're roughly in the same shell and that's what you see. But there's a huge difference in going from shell n equals 1 to n equals 2. This is not to scale. You see they got a little break there.

And now look, what's the electronic structure of boron? 1s2 2s2 2s1. There are two 2s electrons, but only one 2p electron. And this is trying to show that the height here is twice the height of the 2s peak. So you see that we've got two electrons here, one electron here, and it's easiest to pull out the 2p electrons first. And you go on, there's beryllium and so on.

So we see that we can build data in this fashion here. We keep going. Here's carbon, which is 2, 2, 2. And then oxygen has 2s2-- pardon me. 1s2, 2s2, 2p4. So this is two electrons, this is four electrons. Showing that the 2p height is twice the 2s height. And then finally, neon is 2s2, 2p6. So this is roughly three times the height of the 2p. But all of the 2p numbers are roughly of the same order of magnitude and decidedly smaller than what's going on at 1s. And what else do you see?

Well, the carbon has 6 protons, so the inner electrons of carbon are held not as tightly as the inner electrons of neon, which has 10 protons. All of this comes out. The data are all good.

So now what do we want to talk about? What's all this about? I said electronic structure leads to properties. The first thing we want to talk about is reactivity, chemical reactivity.

Well it's pretty clear from looking at these XPS data that those inner shell electrons aren't going anywhere. They're too tightly held. So first thing is the only electrons that we can even think about involving in chemical reactivity must be the electrons

in the outermost shell. These are called valence electrons. The outermost shell is called the valence shell. So let's get that down because that's probably important.

So chemical reactivity determined by only electrons in outermost shell. And we're going to term that the valence shell. And those electrons are called the valence electrons. And, these are the only ones that we expect to see involved in chemical reactivity. And we want to have a measure. You can see that there are subtle differences between the energies that hold the valence electrons of carbon as opposed the valence electrons of neon. And so what we can do is have a measure of the ability for valence electrons to react. That is to say, to participate in chemical activity. And that measure is called the average valence electron energy. And there's no special symbol for that, so we just call it AVEE. And it's just the values of the valence electron energies averaged.

So if I want to take the average valence electron energy for say, oxygen. So I can take it right off of there. I can see I'm going to need two times the ionization energy of 2s plus four times the ionization energy of 2p. And those data are up there. All divided by 6. 2 plus 4, the total number of valence electrons. And if I go through the math up there I get 1.91 megajoules per mole, which I prefer to expresses as 19.8 electron volts per atom.

And when we go through and calculate the values of average valence electron energies, we find trends. And here's what the trends look like.

So you have, first of all, following along with the ionization energies, very similar values. Pardon me. So here's the plot of average valence electron energy in bar heights arranged as the elements are found on the Periodic Table. So you have hydrogen here, helium on this scale would be way up. And then here's lithium, beryllium, boron. And so you see a monotonic increase as you move from left to right. And you see a monotonic decrease if you stay in the same column from low mass to high mass. So what's going on there? Why do we have that change?

We have similar electronics structures. We have similar electronics structures in a given column and lithium is s1, sodium is s1, potassium is s1, rubidium is s1. And let's put some values on here. Let's put some values.

For the majority of elements in the Periodic Table, we get values of average valence electron energy less than 11 electron volts. And when we have such values, we have the following properties: the valence electrons are weakly held. The valence electrons are weakly held. How do we know this? Because the binding energy isn't so strong. That means the electronic are weakly held. So we say that the element is a good electron donor. It's a good electron donor and we term this a metal. The property that makes an element a metal is that it has a low value of average valence electron energy and therefore, it is a good electron donor. And it turns out about 75% of the Periodic Table is made of metals.

At the other extreme we have high values of average valence electron energy. High values. So when the average valence electron energy is high, we have the complementary set of properties. So that means the valence electrons are tightly held. Valence electrons tightly held. Tightly held. And so the element is a poor electron donor. But complementary fashion, it is a good electron acceptor because when it gets near electrons it tends to grab them and hold on to them. So this is a good electron acceptor. And we term such a element a nonmetal. And so roughly,

about 25% of the Periodic Table is non-metallic. And I think I've got that shown here. And you see just a few elements off to the upper right.

And then in the middle, we've got this-- about a half a dozen elements and they have values of average valence electron energy intermediate between 11 and 13 electron volts. And so, they can behave either as electron donors or electron acceptors depending on who else is in the room. So if you put an element like silicon with a very strong metal, silicon will act as an electron acceptor. If you put silicon in the presence of something that's a very strong nonmetal, silicon can act as an electron donor. It has that dual property. And these elements are called semimetals or metalloids. And I think I've got some images to portray that.

There's the semimetals. And if you look carefully at the Periodic Table that you have, you'll see that there's this red staircase here. So there's silicon, arsenic, tellurium, antimony and so on that act as semimetals. They can behave in both fashions.

All right, so now with this classification scheme, let's start thinking about chemical reactivity. And seeing if we can, on the basis of where the elements are found on the Periodic Table, start to make some judgments.

Well I know one thing right off the bat that along the right-hand column, the noble gases are chemically inert. That much we know. Noble gases are chemically inert. I know there's a Nobel Prize out there for getting xenon to combine with fluorine, and the chemistry textbooks love to point out these exceptions. But by and large, the group 8 elements are chemically inert. So what do we know about their electronic structure?

They all have the same electronic structure ns 2, np 6. With the exception of helium. Helium, because it's 1s 2. There's no p. So beside helium, starting with neon, we've got 2s2, 2p6. Argon is 3s2, 3p6, and so on. n2 p6, it has 8 p electrons. It has a full valence shell. And because the last electrons are p electrons, this is termed octet stability. There's something about having a full shell that renders the system satisfied energetically. And it doesn't want to react anymore. So we say octet stability, and if you want to be a wise guy, parenthetically you whisper helium is due at stability. But you know, whatever.

All right, so let's make this octet stability a hypothesis and see how far we can go with it. So the next one I want to look at is sodium.

Now sodium, it's got the electronic structure 1s 2, 2s2, 2p6, 3s1.

Now, I really don't need to talk about anything up to n equals 3 because this is not valence electrons. I just put it up there for completeness, but this is all we have to worry about.

Now we know that sodium is a metal. It's a metal. It's got an average valence electron energy of about 5.2 electron volts, which happens to be the ionization energy. Because that's trivial; it's only got one electron, so the average valence electron energy is equal to the ionization energy. So it's a metal. So it's a good electron donor. But let's think about that.

If we could get rid of that electron in sodium, we could then turn it into something that has the same electronic structure as neon. And why do we want to do that? Well

because there seems to be an energy well there. If we can make something neon-like, then it's going to be happy. So let's do it. Let's write a reaction sodium to lose an electron and become sodium plus. And sodium plus now is this minus 3s1. So it's isoelectronic with neon, and neon has the octet stability. But charge neutrality forbids me to say, OK, lose an electron. It won't. The only way for sodium to lose an electron is to find an acceptor. So if you put a good electron donor in the presence of a good electron acceptor, then the donor can give an electron to the acceptor and both profit from the transaction.

So, where are we going to find a good electron acceptor? Well I just told you, the nonmetals are the really good electron acceptors. So let's go zooming over to the right-hand edge of that row and look at chlorine.

We need an electron acceptor. So choose just for argument's sake, chlorine. It's got an average valence electron energy way, way up there. So let's go. Chlorine, it has the electronic structure of neon plus 3s2, 3p5. So chlorine, if it could acquire an electron, would then become isoelectronic with argon. So imagine chlorine plus electron becomes Cl minus and Cl minus is isoelectronic with argon. So now I've got two elements. One that's one electron richer than inert gas structure, and one that's one electron poorer than inert gas structure. If I put them together, put them both together in the same reactor, they will react and electron transfer occurs via electron transfer. Chemical reaction occurs. Chemical reaction occurs through electron transfer.

And what's the purpose of electron transfer? It's to achieve full valence shell. Achieve full valence shell occupancy, if you like. Achieve full valence shell occupancy. So, now we've got it. But there's more. There's more.

What happens after the electron transfer step? We don't have neutral species anymore. The sodiums have given up their electrons to become sodium ions. And the chlorines have acquired electrons to become chloride ions. And these are free. Let's make this simple. Let's make it a gas phase reaction. So sodium vapor and chlorine gas have become sodium ion vapor and chloride ion vapor.

What do you know happens when you have charges of opposite value, opposite polarity? There's a coulombic force of attraction. So the sodium will attract the chlorine. So let's put the two together.

So sodium attracts chlorine, but it's not over. There's more sodiums, there's more chlorines. So chlorine attracts sodium, which attracts sodium. Which could attract more chlorines. Which could attract more sodiums.

And what do you see happening here? Well we're now starting with a gas phase and we're forming some giant atomic aggregate. This is a giant ion aggregate.

What's the state of matter going to be if this thing's honking big? It's going to be a solid. We're going to form a solid starting with those two gases: sodium vapor and chlorine vapor. And what about the solid? What do we see about the atomic arrangement here?

All the sodiums are the same size and all the chlorides are the same size. They have the same coulombic forces of attraction in between them. Can you see that they're going to form not just a solid, but they're going to form a solid consisting of atoms in

a regular array? This is going to be an ordered solid. And there's a plain Anglo-Saxon word for an ordered solid, it's called a crystal.

Now look at how far we've come. Look at how far we've come. 10 minutes ago we hadn't done anything about chemical reactivity. We made one observation. We had the tools of course. We were ready. We're ready for discovery. We had the tools. We had the average valence electron energy. We knew that helium, neon, argon, krypton, xenon, radon, et cetera, all have this inertness. We postulated that the octet stability was some-- as a sweet spot. And then we went with it. And operating with that one postulate, we get to electron transfer and we're concluding that if I take a really, really good metal-- see, I can generalize this now. There's nothing peculiar about sodium that makes it react this way and no other element will react this way. I could replace sodium with any other metal. I could say any metal, any metal will react with any nonmetal in order to achieve octet stability. So now you can take big pieces of the Periodic Table and conclude that entire sets of elements will act in this way to form ionic compounds, crystals, atoms of regular periodicity. That's a nice pun there, right? We started with the Periodic Table and now we have periodic spacing of atoms. I think that's beautiful. Obviously this view is not shared by the rest of the audience.

This crystal consists of ions. It's held together by what chemists like to refer to as bonds. This is called an ionic bond. And what you're witnessing here is ironic bonding via electron transfer. So we've now categorized the first form of primary bonding. Sodium chloride, magnesium oxide-- ionic bonding. And ionic bonding must give us solids at room temperature. If you've got ionic bonds and you don't have a solid, clearly you are at elevated temperature where at elevated temperature, the thermal energy is disruptive enough to break those bonds. Those are very, very strong bonds. And what we're going to do next day is look at the nature of those bonds.

So I think I'm going to stop the formal lesson at this point. And by the way, perhaps I failed to mention on the first day of the class. What I'm doing is I'm lecturing for, out of the 50 minutes, about 45 on hard core topics. And then, about the last 5, 7 minutes, I want to go to something related to these-- chemistry in the world around us. That's why you see this little break. But it doesn't mean that class is dismissed. There's a difference between changing topics and dismissing class. I don't know how people confuse the two. But somehow I've inadvertently communicated to you evidently. So we're not dismissing yet. We're going to try to apply this knowledge somehow.

So what I wanted to do was to show you what happens with these ionic solids in commerce. And in particular, I wanted to talk about metallurgy and the best form of metallurgy, which is of course, electrometallurgy. Which is the kind of research that I'm involved in. And electrometallurgy is quite pervasive. The aluminum beverage can is made by electrometallurgy, as is magnesium. So I'm going to talk to you a little bit about magnesium. This is a bar of magnesium. Obviously, it's magnesium because if it were steel, it would be so massive that I wouldn't be able to fling it around like this. The density of iron is 7.87, the density of magnesium is about 1.76. It's less than 2. It's 2/3 of the density of aluminum. It's lighter than aluminum.

Now perhaps some of you've been told that magnesium burns. Well, let's see what happens. There's a billet of magnesium and this is the key made of steel. We're OK. We're OK. It's not going to burn. That's a myth. Magnesium in powder form, magnesium in ribbon form will burn. The surface to volume ratio is so high that the

oxidation generates a lot of heat. But here the surface to volume ratio is so low that it's fine. In fact, I went to school at the University of Toronto. And at the time the department head was a man by the name of Pigeon who invented a process during World War II to make magnesium cheaply. And when he came into the classroom to lecture on the day that he would talk about magnesium, in those days they had lab benches at the front of the class with sinks and gas outlets. And he would put the magnesium billet on a stand and light a Bunsen burner under it. And of course, people in the class sort of leaned back, and he would lecture for 45 five minutes with the Bunsen flame burning the whole time. And then towards the end he would extinguish the flame, let the billet cool. And then pick it up and go back to his office with it to make the point.

All right, so how do we make these metals? Well, what we do is we reverse the electron transfer step. And we start with the cations and anions, and we force the electrons back onto the cations anions. Thereby, creating the neutrals again. This is called electrolysis. So cation plus electron gives us neutral. Anion minus electron gives us neutral. So in the case of magnesium, we start with magnesium chloride, which dissolves and forms magnesium cations and chloride anions. So, at elevated temperature-- in this case, at about 700 degrees Celsius, the ionic solid becomes an ionic liquid. And it's clear, colorless, and has the fluidity of water.

And this is a very simple schematic, so we've made the cathode of steel negative and on the negative electrode, magnesium ions are reduced to magnesium, which is a liquid at this temperature. And these are little bubbles of magnesium and they pool here. And we collect them and syphon them off. And on the other electrode, we're making bubbles of chlorine. And they rise and we collect them. So we reverse nature.

If you put chlorine in the presence of magnesium it wants to form magnesium chloride. Here we do the reverse. So electrolysis undoes the spontaneous electron transfer of ion formations. So I decided I better get something more authoritative than my little cartoon. So first I looked on the library website and I found that there was an article in this volume of Advances in Molten Salt Chemistry. And there's this article here, an authoritative article about chemistry and electrochemistry of magnesium production. And so I decided to turn to the article and let me read the first paragraph of this authoritative article.

A cubic kilometer-- what is a cubic kilometer? It's a cube, 1 kilometer on edge. A cubic kilometer of sea water contains approximately 1 million tons of magnesium. 1 million tons of magnesium as the salt magnesium chloride decahydrate dissolved in sea water. More than has ever been produced in one year by all the magnesium plants in the world. The world production of magnesium right now is about 600 million tons.

No, furthermore, sea water contains only 3.7% of the total magnesium present in the earth's crust. Clearly magnesium resources are ubiquitous and virtually inexhaustible. So when people tell you we've got to recycle because we're running out of resources, I read this-- I don't know. You might want to recycle for other reasons, but you can't make the case it's because of scarcity. This is magnesium that has been made by this electrolytic root. And what's the value of this? It can substitute for steel in automobiles. It's density is less than 2. Steel is about 8. Factor of 4 you lightweight the vehicle, which means per unit distance traveled, less fuel consumed. Fewer emissions. And less fuel, which means less dependence on

imported petroleum. So why aren't we doing this? Why aren't we lightweighting our vehicles with magnesium. Because the bonds are so strong the energy required to make this metal is so high that it's very costly.

If I give you a light bulb that costs three times what the other light bulb does and burns only twice as long, you won't buy it. If it costs three times as much and burns 10 times as long, then you're willing to pay the premium. So what we do in my research group, among other things, is study the electrochemical processes by which we make these metals in order to make the process more efficient. Thereby reducing the cost, making these lighter materials more competitive. Thereby, making the world a better place by electron transfer in service of humanity. And I invite you to do the same. But in order to do so, you have to learn the lessons of 3.091. Because after all, this is the most important subject you will take at MIT. All right, we'll see you on Friday.

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