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PROFESSOR: Today, big announcement. Wednesday, no lecture. Instead, Celebration Part 2. And I'm going to say a few words about it. There is the room assignments. I think they're the same as last time. If you miss the exam because of illness, there will be a make-up test on November 4th during class. There's no weekly quiz tomorrow. I'll be available for office hours 4:00 to 5:30 this afternoon over here at 8-205.

So a couple of things. I'm going to say few words about the quiz, the test, rather. The celebration. So the coverage is going to go starting from the time of the last celebration up through now, but I think in view of the fact that we started defects on Friday, and my thanks go to Professor Demkowicz, who jumped in the breach and lectured in my place so that I could get drawn into some of the activities associated with the visit of the President.

You will not have had the time to go through your recitation cycle on this new material. So I'm not going to put anything on defects on the exam, all right? So we'll go up through the end of the unit on x-rays right up through Bragg's Law, indexing crystals. So that starting Friday, defects. I'm not going to teach you Friday, teach you Monday, examine you Wednesday and Tuesday. Tomorrow I expect you're going to have all sorts of review-oriented activities in your recitation. So I don't want you torn between trying to master a lot of this new material, which is quite different from what you had in high school, and at the same time trying to have a catch up on capturing all that material since the second test.

So that having been said, I'm going to remind you. I'm going to basically say the same thing I said before the first celebration, but we need to be reminded. So what's the purpose of the test? The purpose of the test is to give you a status report and send you a message. And there's really only two answers here that we're looking for. You're either going to get a smiley face or you're going to get a frowny face. That's all it's about.

I don't care whether it's a 78 or a 75, but hard 50 is a pass. And if you're not mastering the material, I intend to tell you so and then invite you in so that we can figure out how to get you through. Because everybody in this room has the intellectual apparatus to pass this class. Some of you just are not managing your time well and you need to be told that. So we will tell you that. With one of these. That's going to be the message.

Go to the right room. Bring five things with you: Periodic Table, table of constants, your age sheet, calculator, and a pen, something to write with. You'll write on the question paper. No wireless devices. Shut them off. Don't even bring them. What do you need your cell phone for? Don't need it during a test.

We're going to start at 11:05 promptly and stop at 11:55. What's the strategy? Read the entire paper. Try every question. You know this. You get part marks if you write something. If you don't write anything for the question, you get a zero. So try every question. And start with the easy one. The easy one for you may not be the easy one for your neighbor, but how do you know what the easy one is? I just put them down as they came out of my mind. I didn't put them down in ascending order of difficulty, chronological order, topical order. They're just-- they're there.

Leave tracks, tell us how you got to the answer, Work parametrically. Don't start plugging in numbers on the first line, because if you make a computational error on the first line and drag it through the entire derivation, you'll make a mess of things. You'll have wavelengths, size of distance here to Chicago, light moving at ten times its normal speed and stuff like that. It's no good.

Focus on the question. Don't just say, oh, it's something to do with x-rays, just give me some stuff that you memorized about x-rays, some stuff you wrote down in your age sheet about x-rays. If it's not about the question that we asked, I'll give you a zero. I don't care how much you write. Write on the topic.

And refer to electronic structure. When you don't know what to say, start talking to me about electronic structure. That's the theme of chemistry. electronic structure dictates behavior. So talk to me about electronic structure.

Do your own work. And lastly, it says something here, oh, good luck. That's what it says. Good luck.

So last day, Professor Demkowicz got to the line defects. He was talking to us about line defects and how they have an impact on behavior. So I wanted to pick up the treatment there.

So what's the whole issue behind line defects? Well, what line defects do is they explain this anomalous behavior where the measured value of yield strength-- so I'm going to write  $\sigma_y$ ;  $\sigma$  is the symbol for strength. the yield strength as measured is on the order of only about 1/10 of the theoretical value. It's only about 1/10 of the theoretical value for the yield strength.

You might, say, wait a minute. How do you get that theoretical value?

You can calculate this. Not too badly. If I take a look at a system of atoms, and this could be a metallic crystal, you could argue that there are metallic bonds between all of these atoms. And if what I wanted to do to shear something-- so this is the yield strength for shear-- if I wanted to shear the top plane of atoms versus the bottom plane of atoms, can you see that to a first approximation, the energy required would be the energy to break each one of these bonds? Because I have to break the bond to release the plane and then move it.

So if you make an estimation on the basis of bond strength-- so you take individual bond strength times bond

density or bond concentration. When I say density, I don't necessarily mean mass per unit volume. I could mean bonds per unit area. You saw your homework questions. How many atoms per unit length? And we said what's the linear density?

And some people were saying, but density is mass per unit volume. No, I'm counting atoms per unit length. Open your mind, OK?

So bond strength, what's bond density? That's atoms per unit area. So we can calculate this and we're way off. We're way off by about a factor of 10. So it was the dislocation that allowed us to explain why this happens. And it was the work of two scientists, one by the name of Orowan in Hungary and Taylor in the UK.

Orowan, after World War II, went to the UK and then ultimately came to MIT. And he spent most of this later part of his career here in the Mechanical Engineering Department, from which he retired. And actually, he's too modest to say it, but Professor Demkowicz, his PhD was for Professor Argon, and Professor Argon was one of Orowan's students. So this is direct lineage. This is all very clear, so he was the appropriate person to introduce dislocations.

So what did Orowan do? Orowan came up with this idea of an interruption. And how did he get it? It shows how to look around and, in the world, see analogies.

Now, we didn't have the powerful electron microscopes then that we have today. This was in the 1930s, so people didn't even agree on an atomic view of things. So people were thinking, thinking, thinking.

So this is the dislocation. You can see. Here, we have three rows of atoms, now there's two rows of atoms. The middle row stops there. And I'll show you what the consequence of that is in terms of being able to shear the crystal of lower values of applied stress. So that's the dislocation. You can see here. If you break this bond and then propagate that through, you don't have to shear them all. You break them one at a time.

So Orowan came home one day in Budapest, and the cleaning woman was moving the runner on a hallway, the story goes, and she was about to move the runner. And Orowan came up the stairs and offered to help her, and she told him, get out of the way. Academic.

And what she did, instead of pulling the rug, she did what we see in the cartoon here. She put a little kink in the rug, snapped her foot and propagated the kink and moved the rug a half a foot down the hallway with minimal energy. Instead of having to pull the rug with it's coefficient of friction over three, four meters, all she had to do was come up with enough energy to make the kink and then stamp the foot.

This person's really doing it the hard way. I don't know. This guy must have taken classes in chemistry or

something. But see, all you've got to do-- once you get that kind you just push and it'll go by itself.

So Orowan said could this be a metaphor for what's going on at the atomic level? And that's where it came up with this idea of the dislocation. So there we have it.

So where do we find the dislocations? Where do we find them? So what is it? The dislocation-- I keep talking about it, what is it? The dislocation, this is, if you like, it's a line defect. It's a line defect formed by misregistry of atoms. And with the misregistry, that leads to a reduction in bond density. And that broken bond is like the hole, if you like, in the valence band. It can propagate very easily.

We're going to learn a little bit later in the lecture where we find dislocations and how they contribute. But I want you to hold that in near-term memory.

OK. So we're going down the list of the different types of defects. Oh here, I found this off a coffee table book that's indicating-- I think this is a crummy analogy. It shows this caterpillar moving by. Instead of moving all of its legs, it causes this thing-- I think this is a bad analogy. Just look down here. You see, you breaking this. And once you break this, you just keep moving it along. Propagate the single broken bond instead of breaking them all at once. I don't think the caterpillar moves that way, anyway. It's cute, but it's wrong.

This is a dislocation. I don't think it has anything to do with mechanical behavior, but it's a misregistry. So you can-- these guys, they write the books and they come up with this stuff and you study it, and you're going, I don't get it. You know what? You shouldn't get it. Because this is crummy. It doesn't make any sense.

How does that impact the yield stress of the corn? Someday you could write a book. Better one than this.

All right, so now we're going to go to two-dimensional defects. Let's go to two-dimensional defects. So two-dimensional defects, there's a couple types. The dislocation is one dimensional.

Two-dimensional defects. There's two types. One is the free surface. We're going to call the free surface a defect, and I'll explain why in a second. And then internal surfaces. Internal-- I'm going to use surface in quotation marks-- they're interfaces. And there's different types of them, OK? An interface. There's an interface inside the thing.

So what's the physics here? Surfaces are high-energy regions. Why? Because when you're inside the crystal, you have the prescribed number of nearest neighbors. Let's say you're in an FCC crystal. You're an aluminum atom. So you're an aluminum atom and you've got 12 nearest neighbors because you're FCC, except if you're at the free surface. If you're an aluminum atom at the free surface you don't have 12 nearest neighbors. Because if I look down I've got aluminum atoms all over. If I look up, I've got nothing.

So axiomatically, I've got a different number of bonds. Why do we form bonds? We form bonds in order to lower the energy of the system. But axiomatically, the ones at the top can't form the same number of bonds, so they are not in the same low energy state. So once you get the connection between lower number of bonds, higher energy state, then any place, free surface, internal surface, is going to be relatively high energy. Relatively higher energy than atoms in the matrix.

Matrix. What do I mean by matrix? In the middle of a crystal. In the matrix, OK?

So that means that it's not quite as tightly bound, so the consequence of this is if they're high-energy regions, so high-energy implies higher reactivity. And that can be good or it can be bad. It can be good if you're trying to design a catalyst. And it can be bad in the case of corrosion. Where do you think corrosion occurs? Not deep inside the crystal. It occurs at the surface along the grain boundary.

So here's a cartoon that shows different regions within the crystal. And Professor Demkowicz showed you on Friday-- and I'll cut to the thing in a second, the Atomix. but here we see atoms. So this is a simple cubic, this is simple cubic, this is simple cubic. But when they meet they don't line up. They don't line up because this formed from solidification from the melt. So there might have been a seed here and it grows outward. A seed here and it grows outward. A seed here and it grows outward. And when they grow outward they impinge, but they're not all growing with the same orientation.

You already know what the planes are. And they could even be the same plane, but they're starting from a different point. So there's this misregistry here. But it's not a misregistry like the dislocation. It's a two dimensional misregistry.

Actually, let's cut to the document camera. Dave, could we do that please?

OK, so here's Atomix. This was, as explained, an object of art made by Francois Dallegret in Quebec in the '60s. So it's kinetic. It's supposed to be after the artist, see? You know, you, too. You pick it up on a coffee table, you put it down, now you have become the artist. You become the artist. Postmodernism. After the death of the artist. See? I'm an artist. Look. I'm an artist. One of my best works.

So a couple of my professors at the University of Toronto were at a cocktail party one night and they saw this thing on a table. Must've been a wild party because they kept looking at this thing. Finally decided to write a paper about it. And as Professor Demkowicz said, I bet Francois Dallegret sold more of these to professors of material science than he sold to art collectors.

So it's 200 ball bearings strategically placed between two plates of plexiglass. And as he pointed out on Friday, you can't get everything to go away in terms of dislocations, but now you can see misregistry-- pardon me,

vacancies here. Here's a stacking fault and so on. And now here you see grain boundaries. There's the free surface. Here's the vapor phase. Everything. We're having a lot of fun, here.

So we can look at it again. We can change. We'll try to anneal it. So how do we anneal it? You put it in an oven and you eat it. This is the mechanical equivalent of annealing. I'm tapping it, for those of you in the back. Now, I'm going to put it down and you see I have a much more refined structure.

So now you can see a large section here of a single crystal. Each one of these is called a grain. A grain is a zone that is a single crystal with some defects. You can see the vacancies. And then look at the grain boundary here. See this is a nice crystal, this is a nice crystal. So one grain, two grains, and there's the grain boundary where these don't line up with those. Because they started from a different angle so they can't impinge and blend.

There's grain boundaries here, here, here, and there's beautiful stuff. You can see dislocations. Everything. And I know he showed you at the end the Bragg bubble wrap. And you could see--

[SOUND EFFECT]

PROFESSOR: --dislocations zipping. When people were trying to compress the bubble wrap, the way the bubble wrap was compressing the bubbles didn't all get flat. The bubbled glided over one another, and the dislocations relieved the stress.

See what I'm telling you here? What I'm telling you here is something that you don't get in a Gen Chem class anywhere else. If I told you about the chemical origins of reactivity, you'd go, yeah, that's chemistry. But what are we talking about here? We're talking about the chemical origins of mechanical behavior. Now that's different.

The chemical origins of mechanical behavior: only in 3.091. And why shouldn't we? Because at the end, everything is chemistry. Everything is chemistry. The rest is stamp collecting. So the grain-- make sure we know where the grain is. The grain is like, I want to call single crystal. The grain is like a single crystal. And the grains are separated by grain boundaries. So by managing grain boundaries, control of grain boundaries, or if you like, management a grain boundaries, this has an impact on mechanical properties. This is called grain boundary engineering. How we control mechanical properties. Grain boundary engineering.

So for example, if we want high strength-- and I just told you that the dislocations will allow the atoms to glide. Can you see that if the dislocation is present in this large grain on the bottom here and the dislocation, just as in the bubble wrap movie, is zipping across, what happens when it gets to the grain boundary? The misregistry of atoms stops that dislocation dead in its tracks.

So if I want high strength, do I want a large number of grain boundaries per unit area? Or a small number of grain

boundaries per unit area if my goal is to stop the dislocations? I want a high number. High strength means fine grain structure. Fine grained means small grain size. Fine grain structure.

You can think of it as like a river. You know, you're running, running, running-- all of a sudden, you stop because you've got to ford the river.

On the other hand, if you want high ductility-- why would you want ductility? For example, you want to make a beverage container. How do you make a beverage container? Not by casting. You take a sheet of aluminum and you punch it and you cause it to deep draw. That's atoms sliding over atoms.

So do I want to facilitate that process or do I want to impede the process? Well, to facilitate the process, I want to make it as easy as possible for those atoms to glide over one another. So high ductility means coarse grain structure. Coarse grain means large, if you like, large grain diameter. Fine grain structure means small diameter.

So there we go. That's the beginning. And there's a lot more to it, but I just wanted you to see that there is something. And David, may we cut back to the slides, please?

OK, I think the next one shows. All right, so this is a-- oh, we don't want to hear that. Whoops! Well, I've got music embedded in this one. This is Philip Glass.

[MUSIC PLAYING]

PROFESSOR: Because we're going to talk about glasses later. Koyaanisqatsi. It's beautiful. Can you feel the bass? There's the subwoofer right here. You stand right here. It's like a message. Low frequency, of course.

All right, so here's this. But this is a piece of copper. Now, this was the advent of modern materials characterization when Sorby, in the late 1800s, figured out that if you polish the piece of metal supersmooth-- that's good, huh? Maybe we better turn the volume down. I can't compete with these. There's more of them than me. I can't compete. That's called the mute button.

[MUSIC ENDS]

PROFESSOR: So what did he do? He polished the copper and then he etched it. And what happens with an acid etch? It will etch at different rates because the different grains have different atom densities. You see, if I take a piece of metal and I polish it super, super bright and I shine a light on it and look at it in a microscope, what am I going to see? I'm going to see my eyeball, right? I'll blind myself.

So the key was to etch. And then when you etch, you differentiate the different grains. So that's what you're looking at-- the grain boundaries. And this is now the same thing, only under a field ion microscope. This is a

bicrystal of tungsten. It's hard to see, but this is all one. This looks like a lolly pattern, doesn't it? You can see the symmetry here. I don't know if you can see right here. There's a line, sort of v-shaped here. And that's the second crystal. So there's one crystal here, a second crystal here. So this two-dimensional defect is now characterized. And we'll get to that later.

OK. So now we want to do three-dimensional defects. What are the three-dimensional defects? Three-dimensional defects are important. And they have beneficial and they have harmful consequences. Three-dimensional defects. The dominant mechanism here is coalescence. So three-dimensional defects formed by coalescence. And you can coalesce two things. You can coalesce voids, or you can coalesce-- actually, you can coalesce void, and you can coalesce-- I'm going to use Democritus talk here. You can coalesce void, or you can coalesce being.

What do I mean by that? Well, void, this could be a vacancy cluster. So if you have a large number of vacancies coalescing, you'll actually end up with a hole, a blow hole inside the material. And as you can imagine, that has the mechanical strength of nothing. That's bad.

And being? This could be impurity clusters. And there's two types of impurities, as we've learned. There are good impurities, such as dopants, and there are bad impurities such as contaminants. And what can they do to the mechanical properties if they are bad?

So what I like to say is impurity clusters-- so we've got, for example, there are good ones that are managed. The ones that are managed can be used to our advantage. So I'm going to say the managed ones get a smiley face, and the ones that are uncontrolled-- I'll give you a vivid example of that at the end of the lecture. Uncontrolled, they get a frowny face, and they can lead to major disasters.

So for example, you're really talking about clusters that exsolve as a separate phase. So these things exist as a separate phase. So they're no longer dissolved. And these precipitates, some of these impurity clusters, if they're managed, we can call them precipitates.

I'll give you an example of precipitates. Some of you might be going home at some point in the not too distant future, maybe for Thanksgiving. And if you're flying on an airplane, the airplane is made of an aluminum alloy. Aluminum copper. And one of the precipitates that you can form is various copper-aluminum compounds. And these form precipitates that the volume of copper-aluminum  $2$  is greater than the volume of the constituents.

So if you take a copper atom and two aluminum atoms in the lattice and they react to form copper-aluminum  $2$ , there's a volume increase. And so that works to give you constituents. Isn't that great? I left you in suspense there as to rest of the word. So what happens? This works a little bit the way carbon does in iron, where carbon atom is



bigger than the interstitial void space in iron, and that force fit leads to a strengthening. This leads to a strengthening, oK? So that's good.

So this is called precipitation hardening. I'm just going write precipitation pptn, precipitation hardening. Very important in metallurgy. Whereas carbon in iron is called solution hardening. Because it doesn't exist as a separate phase. The carbon atom is sitting on an interstitial site so it's a force fit, but it's still within the lattice, whereas the copper-aluminum actually exists as a precipitate outside the lattice. So there we go.

In order to give you a little bit more, I said we're going to talk about the chemical origins of mechanical behavior. And I want to show you how this all leads to strengthening, strengthening in terms of the yield. So let's talk about deformation and the relationship to chemistry.

There's two types of deformation. And this really accounts for the importance of metals in the history of man. Why? Because they have this unique property. Until the modern era, when we discovered plastics. But until modern era, metals are deformable. They can deform without breaking. That's what made them so desirable as materials of construction.

So I'm going to talk about deformation, how we deform them. So really, metallurgy consists of-- really, there's two major divisions of metallurgy. The first part is chemical, chemical metallurgy, and that's called dirt to metal. That's the conversion. This is the intensive chemistry. And then the second part is called physical metallurgy, which is what I'm going to talk about next. Physical, which is change of shape. That relies on the ductility.

So deformation. There's two types of deformation. The first one is called elastic deformation. And it is reversible. So it is strain only under stress. Or if you like, displacement only under applied force. So this is Hooke's Law. Hooke's Law applies.

So let's take a look. I'm going to draw a little curve here. You've seen this before. I'm going to draw one of these energy curves. So this is interatomic separation, which we might use the lower case  $r$ . And this is the potential energy that's stored between two atoms. Remember, when they're far apart, they want to attract. When they get too close together, their electronic shells repel.

So we've got-- time for colored chalk-- we have the attractive component, which looks like this. And then we have the repulsive component, which looks something like this. And then we put the two of them together, and I think we did this for ions, but there's an analogous one for other materials, and so you add the two of these, and you eventually end up like this, where this is  $r_{\text{naught}}$ .  $r_{\text{naught}}$ , the optimum separation. Here's attraction, this is repulsion, et cetera, et cetera. So this is  $e_{\text{minimum}}$ .

We've seen all of that before. Now what's this have to do with mechanical behavior? Well, I'll take it just a little bit farther. And so I'm going to take the derivative of that and look at the force. All right, so now I'm going to take the first derivative of that. So this is going to be force, which is equal to  $de/dr$ . Force is the derivative of energy.

And what do I find? Well, look. If I take this derivative, below  $r$  equals  $r_0$ . I've got a negative slope. Above  $r$  equals  $r_0$ -- I have a positive slope. And at  $r$  equals  $r_0$ , zero slope. So I'm going to put that down here. So it's zero right at  $r$  equals  $r_0$ , and above  $r$  equals  $r_0$  it's positive, and below  $r$  equals  $r_0$  it's negative. Not to scale. But one thing is certain. It is positive above  $r$  equals  $r_0$ , negative below  $r$  equals  $r_0$ , and to a first approximation, I can linearize about  $r$  equals  $r_0$ , or  $r = r_0$ .

So what's the real shape of this thing? You could use a Taylor series if you want. And just take the first-- what's the first term of a Taylor series? Constant. Second term, linear. Third term is squared, da, da, da, da. So neglect higher order terms. You get a straight line.

And what does this mean? It means that if I try to disturb the atoms from one another and move them away from their rest position, there's a force that pulls them back, and the force is proportional to the displacement. If I move the atoms farther apart by a distance  $r_1$ , I get a certain force. If I move them apart by  $r_2$ -- 2 times  $r_1$ -- I get twice the force. It's linear.

Now let's go over here. Now let's draw another analogy. So here I've got something that's pegged. And now I'm going to put a spring onto this secure wall. So here's my spring, and I'm going to hang a mass on the spring. Now I'm going to bring this into Hooke's Law. I'm going to show you that what you know to be Hooke's Law is a direct consequence of this. The atomic origin.

So what's the force on this? There's a force on this, and that's equal to product of the mass times the gravitational constant. And if there were no mass, this spring would be compressed and it might be sitting here. I will call this  $x_0$ . And now that I put the spring here I'll measure, say, this point. And this point here is now at some value  $x$ . So this is the displacement, isn't it? This is the  $\Delta x$ .

So Hooke's Law is simply  $f = k \Delta x$ , isn't it? If I double the  $\Delta x$ , requires double the force. Well, that's this. This analogy goes right down. And if I remove the mass it springs back, which is what I meant when I said it's reversible. This is not permanent. No stress, no strain. Strain is the deformation. No deformation, no force. If I put a force, non-zero force, non-zero deformation.

By the way, Hooke-- little bit of culture-- Hooke announced Hooke's Law in 1676. Here's how Hooke's Law was first published. It's an anagram and it's in Latin. And it was in a book entitled *A Decimate of the Centesms of the Inventions I Intend to Reveal*, which is English for, This is a Tenth of the Hundreds of the Inventions I Intend to

Reveal. He did not suffer from an overabundance of modesty. Actually, Hooke and Newton sparred. They hated each other's guts. They fought bitterly. Two giant egos.

Anyway, so here's the thing. So in 1679 he published a book called *De Restitutiva. On The Spring*. Very presumptuous. *On The Spring*. And here it is in its unraveled, *ut tensio, sic vis*. As the extension, so the force. Nice, huh?

This is u. That's why the u, but it's really v. Vis. We get the English word vim from this. This is the accusative form of vis. The Romans didn't care between the u and v. In fact, if you go on the steps of 77 and you come up, it says Massachusetts Institute of Technology, you ever notice this? Yeah. I always thought that that's because the Romans, they couldn't-- no. And I thought, well, maybe it's because it's hard to make a u, but then it says Institute of-- I figure if you can make one of these, you should be able to make one of these. So if you can tell me why they do it that way, I might be able to find another Periodic Table beach towel. So that's another thing.

All right. So that's the elastic deformation. And now we want to look at the other type of deformation, and that's called plastic deformation. And that's permanent. It's a permanent shape change. So let's get that up here. Permanent shape change. And this requires ductility. Because otherwise you'll have fracture. If you take something that has no ductility and you apply a super critical force, you just crack everything. So ductility allows for the atoms to glide over one another. So what is the mechanism? The mechanism for plastic deformation? Plastic deformation in crystals, we're talking about here, not liquids. It's called slip. Atom's slip over one another.

So time for one more cartoon. So I'm going to say, well, what happens if I start again with this? I'm going to put a thin wire, a thin wire of metal. Make it an FCC metal, let's say it's copper, and I'm going to put a mass here-- a honking big mass-- it's going to give me a force, and the force is great enough that it is actually going to cause the wire to elongate. That is permanent shape change.

So what's going on? Well, let's take this and blow it up. When we blow it up, we have what's on the screen. We have grains of different size. And I'm just going to show atomic planes. And that's why we have grains, right? Because the atomic planes don't line up. There's a misregistry along here.

So now I want to go down to the atomic level. So now I'm going to take this and blow it up. And what do I see here? I see atoms like so. I'm going to use that hard-sphere, close-packed model. So here's the force. The force is vertical, agreed? We've got the mass and it's pulling straight down according to gravity. So what's going on at the atomic dimension? Because ultimately, this is what we're working with. So what happens? One possibility, and don't laugh-- this was actually suggested-- when you cause extension in this manner, you actually take some of these and you can turn them into elongated atoms. No, no. That's no good.

What in fact happens is slip. So the force-- in fact, let me be more specific-- the applied force is resolved at atomic level. So what happens is that the atoms slip over one another because they can slip along the planes that have the least bonding between them, right? The chain is as strong as its weakest link. So what will happen here is that in order to affect the elongation, these will move relative to one another along this slip plane. This is resolved at the atomic level along slip planes.

I'll write that larger for the people way, way up in the back. I haven't forgotten about you.

And what's the slip plane? How do I determine which is the slip plane? The slip plane it's going to be the plane that's strongest because it retains its integrity. So which plane will be the strongest? The one with the most bonds. And which plane has the most bonds? The plane with the highest number of atoms per unit area. And that's why we study this stuff. Because now we know, in an FCC crystal, which plane will slide.

So in FCC, the high-intensity plane is  $1\ 1\ 1$ . So the  $1\ 1\ 1$  planes do the sliding one over another. And they'll zigzag the way you saw in the bubble wrap movie. They'll zigzag down, across, across, across, But from a distance, it appears as the thing is elongating. But at the atomic level, it's zigzagging along the close-packed planes. Now I'm in a close-packed plane.

By the way, if I have the highest density in the plane of the floor, can you understand that orthogonal to the plane on the floor, I must have the weakest density?

All right, now I'm in the plane. Which direction in the plane? Any direction? I'm going to push, I'm going to push some pasta. I'm going to push uncooked pasta or cooked pasta? Do you want to push on a rope? Do you want to push on a broom handle? The stiff.

So how do I determine, within the plane, which direction is the stiffest direction? The one with the most atoms, which is the close-packed direction when I'm in the plane. So if I'm in the  $1\ 1\ 1$  plane, which direction? The  $0\ 1\ 1$  direction. So this is direct line of sight from the original crystallography.

So that's how we get the slip. And in BCC the highest density plane is  $0\ 1\ 1$  and so on. And the close-packed plane simply means  $1\ 1\ 1$ , because FCC is the closest-packed structure, so that's a close-packed plane.

Otherwise, they're planes of highest density. It's a trivial-- forget the last column-- it's pedantry. Forget it. I'm sorry I have it up there.

So this is the slip system. So the slip system is the combination of close-packed plane-- or closest-packed plane-- close-packed plane and the close-packed direction. They all have close-packed directions because we've got atoms touching. Close-packed direction.

That's how it deforms. And then if I get a dislocation in a close-packed plane, vroom! Away they go. 1/10 of the applied shear stress theoretical. So if you want to get it down to a simple phrase, you can say, what causes slip? Atoms slip, dislocations glide.

But please don't think for one minute-- listen to me carefully-- a lot of students come away from this and they say, oh, I know why we have deformation. Because of dislocations. No, no, no, no. Atoms will slip no matter what. It's just that you're going to pay a lot more to cause the deformation. The dislocations allow you to have slip at lower cost.

Yeah, this is good. And I think we're probably at the point where I can show you the enormous consequences of a three-dimensional defect. Why did the Titanic sink? It's a story of three-dimensional defects and human greed.

So this Tim Fecke at the National Institutes of Standards and Technology with an optical microscope and a rivet from the Titanic. And what I'm going to show you in the rivet is a three-dimensional defect that took the boat down.

So this is the microstructure and what they're doing is they're showing you a blow up of this section of the rivet. Now, the rivet is made of steel. Before I can explain to you what's going on there, I have to show you--

[MUSIC STARTS]

PROFESSOR: Oh, shut up.

[MUSIC ENDS]

PROFESSOR: All right, so this is how they made steel. Imagine this area the front of 10-250 as an open-hearth furnace, and I'm up to about my knees in liquid iron. And on top of the liquid iron is a slag made of silica, calcia, and alumina. It's the stuff when it solidifies it makes something not too different from window glass. But we use it for refining to get some of the impurities out of the metal. And those impurities go up into the slag phase. And to keep this thing it about 1,300 degrees Centigrade, you've got burners. Two. One at each end like dragons--

[SOUND EFFECT]

PROFESSOR: --blowing flame into here for about 12 hours. 12 hours. And that's what it took to make a heat of steel back in 1910. This was made in Ireland, which was, at that time, part of the United Kingdom.

So on that day that they made the heat of steel that ultimately was shaped into rivets, evidently somebody became greedy, and instead of waiting long enough for the slag to phase separate and form a film on the surface of the metals, much like oil and water don't mix, but you can shake them up in your salad dressing application tool device and then pour it on quickly. But if you let it sit they phase separate. Well, somebody didn't allow this to

phase separate. They were told, pour the heat anyways. So now you have globs of what is the precursor to silicate glass in the metal. And now we take the metal and we cut it into little billets and the billets are extruded to form rivets. And then the rivets look like this, where you have glass stringers. Three-dimensional defects, impurity clusters, uncontrolled.

What are the mechanical properties of steel? Strong. Ductile. Tough. What does toughness mean? Impactability. When you say someone is tough, it means they know how to take a hit, whereas hardness means it takes enormous strength to cause deformation. They're very different. You know? You say someone is tough, you mean one thing. You say they're strong, it's different. You can be strong and yet not tough. You can be strong and brittle, so you can't take a hit. I know a lot of people like that. That can't take a hit.

Anyway, so enough about the people.

So here are the stringers. So what happened? What do you think the mechanical strength of this is? If you have an impact like so, instead of having the toughness to absorb the impact, these things broke. This is like perforations on a sheet of postage stamps.

And so these rivets were on the hull. And when the ship hit the iceberg, what should have happened is there should have been a small hole, the water would've taken, who knows, a day or two to fill up, and there was plenty of time to get rescue vessels. Instead, these rivets were brittle, thanks to this. And so they just unzipped. Just pop, pop, pop, pop, pop, pop, pop. Opened up a giant hole and then took on the water.

Now, did nobody check? Along the way, no inspection of the steel? Nobody looked? The guys that we're doing the riveting, they must have known the rivets were acting strange. They must have broken a lot of them just putting them in. But hey, it's not my job. Not my job. Not my job. No testing anywhere along the way.

What's shocking is not human greed. That's as old as humanity. What's shocking is there was no checks. So we have a different way to make vessels like this today. But that's the story, right there.