[SQUEAKING]

[RUSTLING]

[CLICKING]

JUEJUN HU: OK. Thank you all for joining this semester's class, 3071 Amorphous Materials. So what I'll do in this lecture-- I will start by giving you a little bit of an overview, introduction of class and then proceed to talk about, essentially, the fundamentals of amorphous state, OK?

The way the lecture class is going to be organized is I will try to cover both fundamental science as well as practical applications based on the fundamental insights. OK? So later on, you'll see that I have essentially have one lecture focusing on the fundamentals and then one lecture to talk about what are the applications based on those scientific knowledge, OK? All right.

So here is just a quick introduction about myself. Some of you probably already know me. You can call me JJ. I will not try to ask you to pronounce my first name. That's the first homework assignment. No. Don't worry about it. You also don't have to call me Dr. Hu or Professor Hu. I have no connection whatsoever with BBC. Any of you have seen the BBC series, *Doctor Who?*

[LAUGHTER]

That's not me. OK? That's not me. In terms of what I do, in my lab, we work with light, just like that. OK? Now, for real, what we are doing-- we work a lot on new optical materials. And amorphous materials, of course, is something I work on. That's why this class is very dear to my heart. We use these materials for all types of applications, ranging from sensing, spectroscopy, to high speed communications, imaging, you name it. OK?

All right. Comes back to this class. We have a few reference texts, OK? These are not required because between the Google Books and MIT library, pretty much, you can get access for all these resources pretty much for free. OK? The main text we are going to use here is the *Fundamentals of Inorganic Glasses.* There are two versions-- 1994. A few years back, they actually have a newer version, an updated version. So either one is fine. All right?

I've included the Google Books links there. The other text we're also going to use is the *Introduction to Glass Science and Technology.* There are two versions, again. I've included a link for the 2005 version. You actually get free access through MIT for the 2005 version. 2020 version-- there's no electronic version you can access freely, but you can borrow it from MIT library. OK?

Another couple of texts here. This is another one here. This one is a bit older, but again, good reference. Now, the last one here-- this is a little bit of shameless self-promotion. Now, I put the text there not because I'm one of the editors. OK? A couple of reasons.

One is this actually a very comprehensive text. If you want to learn one specific area in amorphous materials with greater depth, this is actually a very good reference to go to. OK? As a matter of fact, this book is so comprehensive that I actually weigh it. It weighs 8 pounds.

So that's why normally, even for myself, I would just read the electronic version. You get free access through MIT library again for the entire book. You don't have to buy it, OK? In fact, I have a couple of copies of that book in my home because the publisher sent it to me. The main application-- my wife actually uses them as yoga blocks.

[LAUGHTER]

OK? I just read electronic version. All right. OK, so that's about the reference texts. Now, about this class-- we're going to have lectures. OK? We're also going to have a lot of in-class demos. We also have one joint session with the MIT Glass Lab. I will be talking about it, but we will have, essentially, some projects. And then we will have a few individual project meetings. There's a final project presentation. And I will talk about the pick-your-own-topic lectures. OK.

I have already posted all the course materials, including the lecture slides, on the Canvas website. You will also find, essentially, templates for project proposals, project reports, everything. It's all there. OK? All right, now, let me talk a little bit about these pick-your-own-topic lectures.

So normally, in a class, instructors will be giving you assignments. And then you go and complete it. I decided to do this in a little bit of an inverse manner. What I'll do is that I will leave, essentially, one lecture worth of time at the end of the semester where you actually propose a topic, like what you want to learn about amorphous materials.

I will actually go ahead, do the literature survey, look at the field, come back, essentially present to you about what I found out. OK? Now, in terms of topic selection, I want you to submit your topic proposal by April 15, the same time as you submit your tax forms. So don't forget that.

It should be relevant to amorphous materials, obviously. Also, think about the breadth and depth. It should be something that I can cover within about 1.5-hour lecture time. OK? And also, it should have some scientific depth, so we can dig a little bit deeper into actually what happens.

Now, I just want to give you some examples. I have been trying this for the last couple of times I offered this class. Back in 2021, we actually talked about how to apply deep learning into glass science, develop new glass materials. Now, in 2023, we actually have a far more interesting topic. Any of you have seen the TV series, *Squid Games?*

AUDIENCE: Oh, yeah.

JUEJUN HU: Anyway, there's one episode. There's actually one episode where they were actually talking about-- there's actually a glass bridge. And those participants of the Squid Game have to actually go across glass bridge. And it will break, depending on whether or not the glass is strengthened or not. OK? So we actually talked about that.

In the end, we actually did some calculations to show that the scene they depicted-- it would only work in the very idealized scenario. Most likely, it doesn't work. The mechanical strength contrast between the strengthened glass and unstrengthened glass cannot provide what they are doing in the TV. So anyway, if you're interested, I can send those slides to you, if you want to explore what ideas you can propose. OK? So you can start thinking about it, and just send me an email. Very simple. What's the topic you want to look at? Specific points. OK?

So I'm giving you here a few project examples. So for example, this topic can really come from your everyday life. For example, I read on the news about this here, the glass box. This is actually a glass box at the Willis Tower at Chicago. So Willis Tower used to be the tallest building in the world.

If you go over to Chicago, you can actually take the elevator, go all the way up to the top floor. It gives you a very nice view of the skyline of Chicago. OK? What happens there is that at one point, this glass box, which allows you to actually stand on top of the building there, actually cracked. The bottom cracked.

Scary, right? So now, the question is is that really safe? So you would essentially look into a little bit about how they actually strengthen the glass, what's the mechanism, why it actually cracks. You can also perform some calculations to figure out whether or not that's still safe. OK?

Second example I'm listing there-- there's a paper that actually discovered a method to essentially use the laser to engrave optical structures onto your cell phone screen. So you can potentially create photonic circuits, for example, on top of your cell phone screen so that it's not just a passive glass cover. It can carry some active optical functionalities.

Now, nobody has really figured out how that technology can be applied for-- what's an interesting application there. So if you have some interesting ideas, you may as well explore it and try to prove to yourself that this is something that's potentially viable. OK? Next one here-- starting 10 years ago, there has always been a rumor that iPhone is going to use liquid metal, basically, amorphous metal, for the iPhone casing, next generation iPhone casing. OK?

That has never really come true. All right. The obvious reason, actually, is that this metallic glass, like most metal, tends to be too expensive. So it's economically not feasible. So you can explore that topic. For example, do some techno-economic analysis, figuring out if it's not applicable for iPhone, maybe for iWatch, would that be feasible?

Would, again, the internal mechanical property potentially outweigh the much higher cost? OK? Or are there new processing technologies that are actually getting published over the past few years-- potentially allow much lower processing cost of these metals? OK?

Now, last one. We are talking about smart windows. Smart windows essentially refers to essentially window glass materials that can automatically change light transmittance as a function of wavelength. OK? And there can be different modes they can operate. For example, they can allow visible light and most infrared light to transmit through in a cold day like today. So you actually warm up the house, OK?

At night, you can essentially block the visible light transmission so it's dark. And then in the summer days, you may want to still let visible light transmit through, but completely reflect infrared radiation to keep the house cool. So the technology is already available. People have already published tons of papers on this topic over the past decade.

I don't think I have really actually seen the commercial products of that already. OK? Now, I have to mention that I'm actually not an expert specific to that technology, so I don't know exactly why. So you can go and find out. Is that because there's some fundamental technology barrier in terms of reliability or maybe in terms of performance that make it not viable? Or is it because of economic reasons? There's just some manufacturing issues they cannot get rid of. Open topic, OK? So that's why I hope that through this project, you can gain some new insights about what happens. OK?

Some more concrete examples about previous years' students, what they have done-- in the project proposal you're going to see, the example I put there, there are students looking into essentially modeling of the, essentially, breakage behavior of glasses. OK? Last year, one student actually used the breaker space to actually explore metallic nanoparticle precipitation when you're processing color glasses.

There's actually a color mechanism for all of these color glasses, OK? People are also looking to essentially 3D printing of sugar glass, candy, hard candy. Hard candy is basically a kind of glass. OK? You can actually use a 3D printer to print all kinds of funny shapes. So they actually look into actually putting together a 3D printer.

So there are lots of different things we can do, but as I said, when you have a project idea, we probably want to meet and discuss so we can actually make sure it's the right scope that you can complete within a semester while you also gain some new insights and have some fun. OK? Any questions about this? All right. No.

Of course, I also want to mention that if you want to propose a project that actually involves some experiments, we'll cover all expenses for you. OK? There are lots of facilities you can get access to at the Breaker Space. I'm more than happy to connect you with Justin or Professor Grossman so that you have access to this space if you don't already have.

If you need some assistance, potentially, I can also try to connect you, for example, with some experimental facilities on campus if you need to gain access to a specific piece of equipment. That's why I want to meet with you and discuss about the scope, ensure that I can be as helpful as possible.

All right. So now, let's talk about amorphous materials. Now, you're also going to hear about this, another term here, glass. In fact, lots of people use glass and amorphous solid or amorphous materials pretty much synonymously. They're not exactly the same. OK? What I'm showing you here is basically a diagram that shows you how these different materials fall into different categories. OK?

But before I give you a more scientifically rigorous definition of amorphous solids or glass, let's start with some descriptive terms. OK? So now, you can tell me some descriptive terms that you think should be associated with glass materials. OK? So for example, we can start with mechanical properties. What do you think is the typical mechanical property of glass? Yes.

AUDIENCE: Brittle.

JUEJUN HU: Very good. Brittle. Anything else? [LAUGHS] It is brittle. Everybody think about it, all right? Maybe let's move away from mechanical properties. Let's think about maybe optical properties.

AUDIENCE: It can vary from clear to opaque.

JUEJUN HU: Very good. So clear. It can be opaque. OK. Electrical properties?

AUDIENCE: Mostly insulating.

JUEJUN HU: Very good. So insulating. Let's see. What else? Chemical properties. Reactive? Is it--

AUDIENCE: Inert.

JUEJUN HU: --inert? OK. Soluble. Mostly inert. OK? All right. So we have a few descriptives here that capture what normally people will think glass is, OK? All right. So let's see if that's true. What I'll do next is then before I actually go into talking more specifically about the definition of glass and its properties, I'm going to show you a couple of YouTube videos. OK?

So this YouTube video's from Corning. Disclaimer-- I do not own any stock of Corning, nor do I have any significant financial interest, but it's a premium glass company. And of course, lots of relevant glass technology comes from Corning.

[VIDEO PLAYBACK]

[MUSIC PLAYING]

- Pop quiz. If you were able to look back on the present from deep in the future, what age would you say we're living in?

- Is this a trick question? I mean, I want to say Information Age, but it seems too obvious. Can I say more than one age?

- Yeah, I think it is safe to say that we are living in more than one age.

[BLOOP]

From the beginning of humanity, we've seen prevailing technologies marked with milestones-- the Stone Age, the Bronze Age, the Iron Age-- all occurring many thousands of years ago. Man's mastery of these materials has defined us, but by that metric, the last couple of hundred years have seen a flurry of ages-- the Steam Age, the Industrial Age, the Atomic Age, the Television Age, the Space Age, to name but a few.

[RADIO CHATTER]

But those are not the answers I was looking for.

- Is that a clue?

- Yes, it is. I think that this age could be classified as the Glass Age.

[MUSIC PLAYING]

- That's not what I was thinking.

- I know.

- So how are we in the Glass Age?

- Well, let me put it to you this way. Can you imagine a world without glass?

- Now, I don't want a cheeky answer. I want you to really think about it.

[MUSIC PLAYING]

- OK, no. I can't imagine a world without glass.

- Exactly. Glass is really quite extraordinary. Without it, many of our major accomplishments would never have happened. Glass has a deep and complex history. And as a material, it has properties and characteristics that we are only just beginning to understand. We look right through it and think of it one-dimensionally. Most of us think of glass as a fragile, brittle thing that, if not handled correctly, will break in a spectacular fashion.

- So you're going to break that to make a point?

- Indeed.

- Can I help?

- Yes, you can.

[CRACK]

And it's true. Our everyday common variety of glass is brittle, but it doesn't have to be that way. Glass has already altered our lives and is behaving in ways that is totally unexpected.

- Got it.

- Let's start with a history of glass.

- I think I can handle that.

[MUSIC PLAYING]

Glass as we know it is most commonly made of silica, the primary ingredient of beach sand. Mix silica with a couple of other key ingredients, heat it all up till it melts, and bang. You've got glass. Humans have been making glass since ancient times, starting with beads, vessels, and ceremonial accoutrements.

Glass-making techniques spread out from Mesopotamia, culture to culture, changing in incremental ways for much of the last 4,500 years or so. The Romans even had glass windows in their important buildings as early as the 1st century AD. Glassblowing was discovered around that time. And soon, inexpensive and ubiquitous glass became one of the hallmarks of the Roman Empire.

[CHATTER]

But no period has seen such growth in the development of glass technologies as in the last 150 years. We've been able to unlock the secrets of glass in ways that would have seemed like magic to our forebears.

[MUSIC PLAYING]

- Nice.

- Thanks.

- So tell me what's so special about the last 150 years.

- Well, several things. In that period, technology evolved at an exponential rate. With that came tools and processes that enabled advancement across all material sciences. The leader in glass material science was, and still is, an upstate New York glass company that started out in the mid-1800s-- Corning Incorporated.

One of their first products was a toughened glass lens for railroad signal lanterns that offered two radical improvements over any other lens of that time. It could be produced in a consistent color, and more importantly, it didn't break when rain hit the hot glass. This helped save lives by bringing down the number of train wrecks. But it also set a course for 160 years of innovation in glass. Of course, everybody knows about Corningware and Pyrex products, too. Those innovations came from Corning during the early part of the last century.

- You know, I have tons of this in my kitchen.

- Mm-hmm, but Corning no longer makes kitchenware. They've innovated way beyond that. Let's take a look.

[MUSIC PLAYING]

We'll start with this.

- Ah, optical fiber.

- Right, optical fiber. This does two things, both astonishing. The first one is this.

[MUSIC PLAYING]

- That right there is pure glass, a glass strand inside the cable, tightly wound around a pencil, And. Yet not breaking. When you stop and think about it, that is a mind-bender. OK, what's the second thing?

- Well, it's the way the light moves through the glass. When the glass is bent this way, you'd expect light to leak out and get weaker and corrupt the data that it carries. But that's not happening. Nearly all the light entering this optical fiber is coming out the other end.

- So it has a low attenuation?

- Yeah, exactly. Very low. In the late 1960s, Corning figured out how to limit the attenuation, or loss of light, as it travels through fiber, even when that fiber is bent.

- Nice.

- This discovery led to the practical use of fiber as a medium for voice and data communications over great distances, ushering in an era of low-cost, high-bandwidth communications, and ultimately, the internet as we know it.

- Wow. So just how much data can these optical fibers carry?

- This video playing back right here is sucking in data at around 20 gigabits per second.

- That is a lot of data.

- Yeah, this is ultra high definition raw video, but even in this case, the optical fiber is not anywhere near capacity. The bottlenecks are here and here, not here. The practical limit of data transport over optical fiber keeps increasing. Using today's technology, it's possible to transport more than a million gigabits per second, about a petabit. That would be like downloading 17,000 high definition movies from Netflix in a single second.

- That's amazing. OK, tell me about this stuff.

- Well, obviously it's an optical fiber as well, but instead of sending light through one end and out the other, it emits light throughout its entire length.

- Cool. What's it good for?

- I have no idea. OK, so I was able to seriously bend a strand of glass. Didn't break, but what do you think is going to happen when I try to bend a pane of glass?

- Uh--

- Rhetorical question. Check this out.

[MUSIC PLAYING]

[CRACK, SHATTERING]

- That doesn't look like it went very well.

- Well, that was soda lime glass, the normal stuff we see around us every day. But watch what happens next.

[MUSIC PLAYING]

- This? This is glass, too. It's called Willow glass, also made by Corning. And it's flexible.

- No way. I cannot believe that is glass.

- Well, it is. There's no trickery here. This is glass, but it's as flexible as paper.

- So what kind of applications does that have?

- Well, that's where it gets really cool. Check this out.

- All right. This looks like a piece of stainless steel. And what is this? Willow glass bonded to one side as a scratch-resistant coating?

- Yep.

- OK, but tell me this. How is the Willow glass anywhere near as durable as stainless?

- Well, that's a good question. Watch this.

[MUSIC PLAYING]

[BUZZING]

[MUSIC PLAYING]

- That is amazing. I cannot believe that the blade did not shatter the glass.

- It didn't. And that's just half the story.

[MUSIC PLAYING]

- All right, so what are we doing?

- Give me that.

- OK.

- Take this.

[MUSIC PLAYING]

- This is heavy, man. What do you want me to do with it?

- I want you to drop that right on that piece of stainless steel with the Willow glass on it.

- Seriously?

- Let's see what happens.

- Here we go. 3, 2, 1.

[PING]

No way.

[MUSIC PLAYING]

- It dented it, but it didn't break the glass.

- That is insane.

- And you can attach this to just about any solid surface.

- Bendy, flexible, durable glass-- impressive, and characteristics you wouldn't normally associate with glass, right?

- Right. I like this new Glass Age we're in.

[MUSIC PLAYING]

- Let's switch gears. Your smartphone-- you hold it in your hand, you put it to your ear, you keep it in your pocket or your purse. It's a great everyday use of glass that you might not think about.

- Till it breaks.

- Until it breaks. I myself have shattered over a dozen of these, but you might have noticed over the years that the display on your phone has been getting harder to break. Let's go back a few years.

[JINGLING]

[SCRAPING]

If you've done that to your standard 2008 phone, that's what would have happened.

- Not pretty.

- No. And that could easily happen just by keeping your keys and your phone in the same pocket. And if you then dropped that phone, well, the probability of the phone breaking was high.

- How high?

- Very high. Let me show you.

- Aren't you going to drop the phone?

- Well, sort of. Instead of dropping the phone, I'm going to drop something on the phone-- this steel ball.

- For consistency's sake?

- Exactly. In this way, my phone drops exactly the same way every single time. Here we go. 3, 2, 1.

[THUD]

[MUSIC PLAYING]

Oh.

- I've seen you do that so many times in real life.

- [SIGHS] Me, too, but that was then. This is now. Thanks to Corning, we have Gorilla Glass.

- I'm pretty sure that's what I've got on my phone.

- And it's on this phone as well. I'm about to do the same test a second time. Check this out.

[MUSIC PLAYING]

- No scratch.

- Not at all. Now, same drop test. Ready?

- Yeah.

- 3, 2, 1.

[THUD, CLATTERING]

- Wow. What a difference a few years can make.

- Actually, Corning came up with this method for strengthening glass long ago. Gorilla Glass evolved from that process and today is found on all the best small devices, like this. It's beginning to find its way onto larger-format displays, too.

[MUSIC PLAYING]

- Now, it's not unbreakable. If you set out to break it, you will, but as Corning figures out ways to unlock more secrets of glass, it will continue to get more resilient. It may even get to a state where devices such as these simply don't break anymore. Oh, and by the way, Corning has just come out with a new and improved version of Gorilla Glass.

- Really?

- Yeah. Let's go deeper. Watch this.

- Hot stuff.

- Yeah. This hot stuff is your basic, everyday, soda lime glass. There's nothing remarkable about it except that it's white-hot and molten. There we go. And I'm going to drop it in cold water. It's called a Prince Rupert drop.

- Who's Prince Rupert?

- Some Bavarian from the 1600s. He came up with this.

[MUSIC PLAYING]

OK, so there's a few things going on here. The cold water rapidly cools the exterior surface of the glass, hardening it almost immediately. The interior, still molten, cools more slowly. As it cools, it contracts and attempts to pull the surface in with it, but it can't-- well, not very much. The surface has already hardened, so it gets pulled in only a little, compressing it, while also creating an internal layer that remains forever under tension.

[WHISTLING]

It is this action that gives the glass its uncharacteristic strength. We call it compressive strength.

- Hmm. It sounds like the same principle as how an arch provides strength in structural engineering.

- Yes, kind of. Now, Jamie, I'm going to ask for your help. We're going to attempt to destroy this Prince Rupert drop. I just want you to tip that hammer past its center point. Go ahead.

[CLUNK]

[MUSIC PLAYING]

- I feel like we've been swindled.

- Swindled not. We have just experienced the power of compressive strength. It does, however, have an Achilles heel. Take those nippers right there, and nip the backside of the tail of this Prince Rupert drop, and watch what happens. Wait, wait, wait. Cue the high-speed camera. OK, here we go.

[SNAP]

Whoa!

[SNAP]

[LAUGHS]

That was even cooler than I thought it would be. That is what happens when you release the stress in compressive strength glass. The whole thing shatters.

- Spectacularly.

- Yes, well, at least in that example, it was. That's because the stress was so great between the outer compressive layer and the inner tension inattention layer--

- --that when released, it was a catastrophic result.

[SNAP]

[MUSIC PLAYING]

- This is Gorilla Glass. It has been refined over time, but like all Gorilla Glass variants that came before it, it is compressive strength glass, but it's not made in the same way as we just demonstrated, the rapid cooling method. No. Instead, Corning uses an ion exchange process.

To break it down simply, the surface ion particles that naturally form during the manufacture are replaced with larger ion particles. Once exchanged, the larger ion particles create the same sort of inward pressure that we see on the Prince Rupert drop. And with this method, they are able to control and manage the resulting tension.

- I think what you're saying with this process is that they're able to tune strength in the glass by dialing in the right balance between compression and tension?

- Yeah, that's a great way of saying it. That, and also, by adding in a few other tricks that change the molecular structure of the glass. Corning is steadily moving forward towards the Holy Grail.

- Thin, unbreakable glass for our mobile devices?

- Well, maybe not unbreakable, but yes, thin and very tough. And by the way, the applications for this tough glass go well beyond mobile devices. Let's go over this way.

[MUSIC PLAYING]

- Behold, the common automobile windshield made from regular soda lime glass. It's quite strong because it's very thick, and it's laminated, which means it's two pieces of glass bonded together using resin in the middle. And the resin does two things. It gives it added strength, and it holds the glass together on impact. You've probably seen broken windshields before. Lots of crazy cracked glass, but still mostly held together in the shape of a windshield.

- Like this.

[CRUNCHING]

That's pretty cool.

- Yes, it is. Windshields have been made of laminated glass for the last 100 years, and they've served us well. But there is a big drawback.

- I think I know what you're going to say. It's heavy.

- Yes, very heavy. And as we strive for more energy-efficient cars and trucks, the weight of all that glass can be a bit of a problem.

- I have a feeling you're about to show an alternative.

- Yes. Take a look at this.

[MUSIC PLAYING]

Now, this is also a laminate windshield, but it's not one you'd find in production. It's experimental, which is great because we're going to experiment with it. It has regular soda lime glass on its outside surface and resin in the center, like the other one, but this windshield has Gorilla Glass on the inside surface.

- Sweet. It looks thinner.

- Yes, it is, and a lot lighter, too. In fact, just by changing the one laminate, the overall weight is reduced by about 1/3. In a car, that adds up fast.

- Thinner, lighter. And let me guess, it's just as strong as windshield A.

- Well, maybe. Let's find out.

- Oh, goody.

- OK, wait, wait, wait. No, no, no, no. You don't need the sledgehammer for this one. Put that down. Instead, you're going to shoot this windshield with an air cannon.

- Cool.

- Now, don't get too excited. We're going to have to mount this, tie it down so it doesn't wobble. And we're going to simulate a pebble hitting this windshield at a super high speed.

- Good enough for me. When do I start shooting?

- Well, before we shoot the Gorilla Glass laminate, let's shoot the regular soda lime laminate, windshield A. This way. All right, here we go. Perfect. You want to do the honors?

- Sure.

- I'll count it in. 3, 2, 1, go.

[SHATTERING]

- Whoa.

- [CHUCKLES] That was a lot of damage.

- Can we see that in slow motion?

- The ball bearing hits the windshield at around 120 miles per hour. This could be a stone flicked up by another car. It penetrates the exterior glass. It stretches the resin. It's slowed down a bit, but it still has momentum to break the interior glass layer, causing small fragments of glass to spray out through the interior of the car.

[MUSIC PLAYING]

- Not good.

- So let's try windshield B.

[WHOOSHING]

The Gorilla Glass didn't appear to break. The foil is intact.

- Let's see it in slow-mo.

- The ball bearing hits the windshield at around 120 miles per hour, just as before. It goes through the front layer of soda lime glass, stretches the resin, but doesn't have enough energy to break the Gorilla Glass. It's not bulletproof. I'm pretty sure if we turned up the velocity, we'd breach the gorilla layer 2, but in this test, and all things being equal, it performed a lot better than the thicker, heavier soda lime laminate windshield. That's impressive.

[MUSIC PLAYING]

What we're seeing here is compressive strength at its finest moment.

[MUSIC PLAYING]

- OK, so it's lighter, thinner, and stronger. That's pretty good.

- Yes, it is.

- Can I get this on my car?

- Not today, but soon, I hope. Come on, though. After living through the Iron Age and the Bronze Age, you could wait a little longer. Actually, when you think about it, the application for this goes way beyond the car, doesn't it? Ah, yes. Feels good to be in the Glass Age. Come on.

- Don't touch me.

- Sorry.

[END PLAYBACK]

JUEJUN HU: OK, so now, what I actually have here-- I actually have brought with me a few pieces of Willow glass, which is the type of glass they mentioned that's actually flexible. It's actually a flexible sheet. I'm going to pass it around. It does break. Actually, it's stronger if you bend it one way than the other. I cannot really tell which side is which, but you can play around a little bit with it. Don't worry about it if you break it. Just don't hurt yourself, OK? I also have a thin sheet here. It's a bit easier to demonstrate how it bends. You can clearly see it does flex quite a lot.

AUDIENCE: I don't [INAUDIBLE]. is too much.

[WOBBLING SOUND]

[LAUGHTER]

- Good? OK. All right.

AUDIENCE: Sounds pretty good.

JUEJUN HU: Now, I also want to mention that this Willow glass-- it's actually developed more than a decade ago. It has a thickness of about 160 microns. So it's about the thickness of a thick sheet of paper. State-of-the-art, ultra-thin glass-- they can get down to a thickness of about 30 microns, which is less than 1/3 of a thin sheet of paper.

And those glasses-- they do flex, just like a piece of paper. In fact, I had the opportunity to actually visit one of the large glass plants that actually produce this kind of ultra thin glass sheets. They have a width of about 8 meters. They are transported on rollers. And they almost fly on the rollers because it's so thin, and has such a little weight, and they're mechanically flexible. So it's quite amazing to see how this glass is continuously being made on the big rollers that come out. OK?

OK, so that's about mechanical properties. So as the video already mentioned, you can already see properties that you normally would not associate with glass, OK? Glasses can be flexible, bendable as well. Now, what about some other properties? Let's start by looking at optical properties.

You have already mentioned that glasses can be transparent. They can also be opaque. Just to make the point, I also have with me here a piece of glass. Don't break this one. This one-- the mechanical property is not that good, OK? But I will pass it around. This is actually a chalcogenide glass. Instead of oxygen, It. Actually has sulfur in it. OK?

It's completely opaque. You will not be able to see through it. But later on in the semester, we are going to see is that this glass material is actually, despite being opaque in visible, it's actually very transparent if you go to an infrared wavelength range. You can actually see through it with infrared camera.

In fact, people use these kind of glasses to make lenses for infrared cameras. OK? And by the way, on that point, I also have to mention that when we talk about the definition of glass, Corning primarily focus on silicate glasses, the glasses made of SiO2. OK? So that's why they have been talking about, essentially, only silicate glass materials.

But glasses is a much broader family. It also includes things like chalcogenide, which doesn't even contain oxygen. OK? Later on in the semester, we're going to talk about the structural origins, why some glasses, like silicate glasses, they stay forever, billions of years, doesn't crystallize, versus for these kind of glass materials, they crystallize in a matter of a few hours. OK?

All right. So that's for mechanical optical properties. Now, we'll do electrical properties. You mentioned about most glass materials are insulating. There are actually some counterexamples here, what I'm going to show you. This piece is all glass. It looks like a sheet of metal, but this is a metallic glass. It's actually amorphous metal. In terms of electrical properties, it behaves pretty much like regular metal. It's electrically conducting. People mostly use it for their interesting mechanical and magnetic properties, which we are going to talk about later. OK?

Now, there are also glass materials, even oxide glasses, you can also make electrically conductive by putting in mobile ions so that they can essentially transport current, OK? And those glasses are actually very important when it comes to, essentially, solid-state batteries, for example. They are used as electrolytes or as electrodes. OK?

Chemical properties-- most glass materials-- they are pretty inert. That's why we don't have to replace our glass window every year, OK? However, people have actually come up with actually soluble glass. Now, you may wonder, why do I want soluble glasses?

They are actually called bioactive glasses. They are used in a lot of tissue engineering. So for example, if someone has a broken bone, conventional, essentially, bone fills-- essentially, they are not biodegradable. You have to actually take them out, OK? So that's another surgery.

If it's bioactive glasses, they can actually slowly dissolve in the body fluids. OK? And in the process, people have also engineered its microstructure so that you can actually essentially form micropores inside that selectively leech out in body fluids so that bone tissue can actually grow in those pores, and eventually, fill out the entire system there. OK? So they are actually very useful for these kind of medical applications.

Now, last descriptive term that you have not mentioned here is actually man-made. Now, you may think that glasses actually are man-made materials. Turns out there are also lots of natural glasses as well. What I have here-- a few pieces. This one is obsidian. This is a little obsidian arrowhead. You can see that's actually translucent glass. It comes from volcanic activities.

It's basically, what happens when you have lava. It actually cools down very quickly. It does not have time to crystallize. It becomes amorphous material. This one is tektite. It comes from a meteor's impact. Again, if a meteor's coming in here, high temperature, melt the mineral, quickly cools down, that's what you get. Same thing with lightning strike. You need lots of energy to melt it. This one is fulgurite. So these are all naturally forming glasses. OK?

Doesn't look like glass. The obsidian looks a bit more like glass. It's more translucent. And in fact, you'll find it not just on Earth. You can actually find it even on the moons of Jupiter or comets everywhere. OK? So glasses are really ubiquitous. They are everywhere.

Now, comes back in terms of application of glasses. Human beings have started to use glass actually way before we have written history. Talking about Stone Age. One question is what is the stone people used to actually make those tools? Turns out the stones they used are mostly either glassy or it's called a cryptocrystalline.

So this word is used to describe minerals that has very, very small fine grains. In a lot of cases, it's actually a mixture of amorphous matrix with crystalline precipitates, OK? So mechanically, they actually behave like glass, amorphous materials. Later on, we're actually going to talk about fractography of glass.

Glass actually break, or they fracture, in very specific manners. So if you know how they actually behave when you break, you can control it. And that's actually how our ancestors were able to make all these tools with very high quality. One fine example of these kinds glass tools or stone tools people were able to make-- let's think about Aztecs in Mesoamerica. OK?

You may have read in history books that Aztecs-- they live in the Stone Age, they use stone tools, OK? This does not mean that they don't know how to make use of metal. They can actually make bronze tools, but they choose to stick with stone tools. Why? They actually used obsidian, which is the thing I passed around over there.

They used obsidian to actually make these different kind of tools there. They have mastered the technology to actually process obsidian so that actually, for example, they can make knives. They are far more sharp. Or blades-- far sharper compared to what you can make using metal. OK?

So that's why people have actually commented. I have quoted some people, quoted here. "Obsidian is capable of producing an edge sharper than high quality steel razor blades. What need could there be for a replacement material? The Aztecs didn't develop the use of metal because they simply couldn't see beyond obsidian."

Because it's so good, they basically just did not actually develop metal further. OK? What I'm showing on this plot here-- actually, basically, what this Aztec warrior is holding is actually a saw made of obsidian. Now, it doesn't look like a normal saw, you will see, made of metal.

It basically has this big wooden shaft. And then you have pieces of very sharp blades made of obsidian put it on there, OK? The reason they constructed it that way, rather than a monolithic piece of big obsidian, is because obsidian, despite that it can be very sharp, just has one Achilles heel. It's brittle. OK? So it tends to break. So if you have a one big piece, if it cracks, then you lose the whole thing. But if you have these individual pieces, you can always replace it. So that's the technology they have developed. It's actually purely based on glass.

Now, let's fast-forward to today. Glasses are really amorphous materials that are really ubiquitous, OK? If you think about the phone in your pocket, there are tons of things that actually make use of these materials. You have the glass cover, all the camera lenses using optical properties. You have the thin film display, where from both the materials used to make transistors to the display itself, it's all amorphous.

You always involve amorphous materials, one or the other. Or dielectric materials and packaging materials-- they are mostly amorphous, OK? And finally, there are also some potential emerging applications people may one day also apply to consumer electronic devices, such as metallic glasses, new phase change memories, solid-state batteries. And we are going to talk about all of these different applications in the lecture here, OK? So we'll be covering structural, chemical, optical, electrical, transport properties, everything about glass materials. OK?

All right. Now, finally, this comes back about the definition of glass and amorphous solids. I want to show you this little, basically, screenshot. I quote from a paper there. Well, this paper was published in 2017, just eight years ago, where people were actually trying to actually give a glass material a more rigorous definition.

So what you see here is that this is a topic that still has quite some controversy there. People have not really converged into a consensus, even just 10 years ago. OK? It can be pretty complicated. You don't have to memorize it. What I want to do-- I will give you actually a working definition of glass, which is generally accepted by most glass scientists around the world. OK? All right.

So here you go. So let's go back to this plot here. This big circle represents all the solid matter, OK? Within it, it's our amorphous solids. Now, not all the glasses-- sorry, not all amorphous solids are glasses. OK? Amorphous solids refer to a solid material that's metastable and lacks long-range atomic order.

Now, in order for an amorphous solid to qualify as a glass, there's actually additional criteria. It needs to exhibit a glass transition. Not all amorphous solids exhibit glass transition. A lot of the metal oxides-- they can be amorphous, but they do not exhibit glass transition. OK? We're going to talk about some examples, for example, like amorphous silicon. It's amorphous, but normally, people normally don't consider it as a glass, but it has very important application in the electronic semiconductor field. OK?

Now, within that big circle of glass, we have a much smaller circle of silicate glass. This is what's referred to as glass in the video from Corning, but it's really only talking about glasses based on SiO_2 as a key backbone material. OK? We are going to see a lot more varieties of glass materials beyond just a very simple circuit. And finally, the glass as we know it every day-- this typically refers to so-called soda lime glass. It's one subgroup of silicate glass. OK.

So now, let's actually take a look at the definition here. OK? So for the definition, there are essentially a few key words here. You need to be a full glass. You need to be metastable. You need to lack long-range order. It also needs to exhibit glass transition. We're going to take a look at that three attributes, OK?

So first of all, let's start with metastable. So metastable can be illustrated by this plot here, where I'm showing you, essentially, this is basically a free energy of glass as a function of the structure. Now, as you probably already know, the thermodynamically stable state of a material is its crystalline state.

So because it's thermodynamically stable, it means that on this plot here, it must be a global minimum in terms of energy. Glasses, on the other hand-- it is metastable. So it means that it resides in a basin that represents a local minimum. And this local minimum is separated from the global minimum by some energy barrier.

So the height of this energy barrier actually dictates whether or not the glassy state is actually stable, OK? A glass is metastable means that with appropriate stimulus, it can always overcome this barrier and relax towards the thermodynamically stable state. This is called crystallization. OK?

Now, some glasses-- this process can take forever, like silicates. Some glasses-- this can be very, very fast. It all depends on the height of this barrier. You can also expedite this process by essentially giving it some energy, OK? You nudge the glass network a little bit, for example, by simply heating it up.

If all the atoms have more thermal energy, then you will be able to actually crystallize a lot faster. OK? Again, we are going to talk about the kinetics of crystallization later on in the semester, OK? But for now, you need to know that all the amorphous solids and glasses as well-- they always have to be residing in this local metastable state. OK?

Next attribute-- no long-range atomic order. So you have seen this in 3091, but what I'm trying to represent here is a fictitious 2D compound. It's some kind of atom, A, combined with oxygen, A_2O_3. OK? So A is basically plus 3, has a plus 3 valence state.

We can imagine that a plausible crystal structure for this A_2O_3 crystal is this 2-dimensional solid, where each of the A atoms here, these black dots, connect to 3 oxygen atoms. And 1 oxygen atom connects to 2 A atoms here, OK? Now, we say that for this crystal, it exhibits a long-range atomic order.

What do I mean by that? It's that suppose you know the orientation of this single crystal. And you know the location of one atom here. Then you'll be able to predict the specific coordinates of all the other atoms in this big single crystal instantaneously. OK? So you have this kind of spatial periodicity that's preserved over macroscopic distances.

On the other hand, if you look at its amorphous counterpart, the short-range order is still preserved, OK? When I talk about short-range order, I basically talk about local chemical environment. OK? So if you look at, for example, this amorphous structure here, look at A atom, it is still connected to 3 oxygen atoms there, OK? Each oxygen atom is still connected to 2 A atoms. So the basic structural unit to form this network here is basically this AO3 little cluster here. It stays exactly the same as in the case of an A2O3 crystal.

However, what is changing here is the bond length between the atoms, and so it's bond angle. Mostly, the bond angle. The bond length usually changes to a very, very small extent. Most of the time, it's just bond angle difference. Now, because of the variation of the bond angle, this structural disorder will accumulate as you move from one structural unit to another one.

So after passing through a few atomic interspacing, you quickly lose track of the orientation of your network there. OK? And that's where you essentially get this continuous network of an amorphous solid. So that's why sometimes, people are saying that if you are working in this amorphous glass network, you are working with an odometer, but without [INAUDIBLE]. Odometer means that the bond length still pretty much keeps constant, but the orientation of this structural unit becomes essentially random across the solid material. OK?

So one immediate consequence of this inherent structure disorder in glass network is that it actually lacks-- it's perfectly symmetric, and therefore, it's usually isotropic. OK? So unless you apply a specific external stimuli, most glass solids essentially exhibit isotropic properties. Its property does not depend on orientation. OK?

OK. So this picture, this glass, or these inorganic glasses-- they consist of this random network of atoms. This is called a Zachariasen's random network theory, first formulated by the scientist Zachariasen back in the 1930s. OK? This is a structural model that applies to inorganic glasses. OK? For metallic glasses, there's actually a different structural model. Later on in the semester, we're going to discuss about structural model of amorphous metals, OK? But this applies to, essentially, all the other inorganic glasses, OK?

All right. So just to take a closer look at the structural property of the glass material here, the most common way we use to actually characterize the structure of a solid is the X-ray diffraction. So what I'm comparing here is X-ray diffraction spectra of three different kinds of solid materials.

On top, you have basically silica glass, vitreous. Vitreous essentially means amorphous. OK? So it's amorphous silica. Here this is cristobalite. Basically, this is the crystalline counterpart of SiO2. All right? At the bottom, you have silica gel. Silica gel basically consists of many small, tiny nanoparticles of amorphous silica. They are stacked together, but there is actually an air gap in-between. There's nano voids in-between those amorphous solids. OK?

So if you look at, actually, the following structure, you see that silica gel and amorphous silica-- they are pretty similar. You have this broad bump there, the difference being that for silica gel, there's also this rising scattering intensity as you go to a small diffraction angle, OK?

So if you think about the Bragg's law, which basically says that lambda equals to 2d sine theta-- so if the wavelength is fixed in one particular experiment here, if you have small diffraction angle, essentially, what that means is you're looking at spacing that's actually larger. OK?

So in fact, what we are seeing here-- this is called low angle scattering. Low angle scattering usually is indicative that there are actually nano voids inside a solid material. OK? Those nano voids have a characteristic length scale much larger than inter-atomic spacing. That's why the diffraction peak tends to appear at a much smaller diffraction angle. So it's basically a nanoporous material. Now, the fact that for amorphous glass, there's no such low angle scattering indicates that there's no nano voids, or glass solids is not nanoporous. It's a continuous network. That's what I mean by continuous, OK?

OK. Next, we can compare this diffraction spectra with the crystalline cristobalite. OK? So if it's crystalline material-- you have already learned about X-ray diffraction from other glasses-- you're going to see a set of peaks that correspond to specific lattice spacing, OK?

You probably have also learned about this, called the Scherrer equation. So Scherrer equation allows you to actually predict the size of the crystalline grid by looking at the full width half maximum of these X-ray diffraction peaks. So you can actually apply this Scherrer equation onto this very broad diffraction peak of amorphous glass there.

If you go ahead and do the calculation, you will find out that the "crystalline grain," with a quotation mark, or the order region, has a dimension of about less than 8 Angstrom. Now, if you look at the unit cell size of a cristobalite, it's about 7 Angstrom. So what that tells you is that the whole concept of crystalline grain is completely inapplicable for amorphous materials.

Sometimes, you may hear people saying that amorphous solid is basically like a limit of nanocrystal material. If you have a nanocrystalline material, you made the grain very, very small. You then get amorphous solids. OK? What we're trying to argue is that that concept is at least flawed because all the regions inside glass material simply does not go beyond even just a couple atomic spacing. OK? So glasses-- you should not treat it as a collection of very small crystals. It's just a continuous amorphous network.

All right. So in this slide, I've shown you, essentially, qualitative analysis of actually differential fracture. We want to go a bit more quantitative. And that's what scientists have done, actually, back in-- this is almost 60 years ago. At the time, they didn't have advanced computer simulation tools.

So what they can do-- they can actually construct the atomic model of glass by stick model. Literally stick model. They actually use balls and sticks, put it together, OK? So they follow Zachariasen's model. They constructed this actual model. And then from that, they can then calculate, essentially, a structure factor, and therefore, the, in this case, radial distribution function of glass materials.

We're going to talk about this radial distribution function in the next few slides, OK? It's basically a parameter that characterizes the structure of this network here. But long story short, if you look at the comparison here, on top, you get the experimentally measured radial distribution function from actual diffraction spectra-- actually, differential spectra of glass.

At the bottom, this is the model, the radial distribution function from this ball and stick network. You see this striking similarity there that again indicates that this, Zachariasen's random network model, gives you a very precise description of the glass structure there. OK? All right.

Now, finally, I want to mention that seeing is believing. If you fast forward to just about 10 years ago, now, people have state-of-the-art electron microscopy that can actually resolve single atoms. So we will now be able to actually directly visualize the network structure inside glass. OK?

So the story behind it is that this is actually a group in Cornell. They were actually looking at some samples, some carbon samples. Then the grad student actually working on this noticed that there was actually something that looked like impurity on the sample here she's looking at [? NT ?] here, OK?

Instead of just simply discounting it as just this is contamination of the sample, she actually dug a little bit deeper, did some analysis, and found out that what she has there is actually a bilayer silica glass. OK? Now, to explain what bilayer silica glass looks like, we have to take a look at, essentially, the basic structural unit of silica glass.

If you think about, for example, quartz crystal, which is basically crystalline SiO2, the basic structural unit is this S, silicon, O4, SiO4, tetrahedra. You have silicon in the center. You have 4 oxygen atoms on the sides. They can then connect together to form the three-dimensional network.

Now, in the case of a 2D silica glass, what you have here is essentially 2 of these tetrahedra. They share one corner, and they connect to each other [INAUDIBLE] vertically. OK? So now, if you look from on top, they're actually aligned. So if you look on top, what you see here will be basically, you have 3 oxygen and 1 silicon. OK?

Then these units can connect to each other to form, basically, a two-dimensional network. That's what's called a bilayer silica glass. OK? So that's what I'm trying to show here, how, if you look from on top, you get a 2D projection of this silicon oxygen triangle here, which looks very similar, by the way, to the fictitious 2D model I had mentioned about this A2O3 glass. They look quite similar there from 2D projection perspective.

All right. Now, what I'm showing you here-- this is the actual image of this bilayer silica, OK? Left-hand side-- this is actually crystalline region. Right-hand side is actually the amorphous region. And they were able to verify that the structure they actually observed under [? TN ?] agrees perfectly with what Zachariasen had predicted almost 100 years ago.

OK? So this gives you a very strong belief that seeing is believing. Now, you can verify this theory with high confidence. And beyond that, turns out they also get into the Guinness World Record book. It's basically the thinnest glass you can ever make. And unlike other world records-- you have probably heard about people breaking the world record once in a while-- this is one of the world records that's going to stay forever because this is really the thinnest glass you can ever make. You can't make anything that's thinner than that, OK? OK.

So we still have about 10 minutes. Now, let's go to the last point here-- essentially, glass transition. So for amorphous solids, it needs to be metastable. It needs to exhibit this-- it needs to lack this long-range structure order. OK? So that's for amorphous solids.

In order for an amorphous solid to qualify as glass, it also needs to exhibit this very important property here. It needs to exhibit a glass transition. To explain what glass transition is, let's first take a look at the crystalline counterpart, OK? So if you have crystalline material, what I'm plotting here-- vertical axis is some macroscopic thermodynamic parameter.

It can be volume. It can be enthalpy. And what I'm showing here is how that macroscopic thermal parameter varies as a function of a temperature. If it's crystalline material, and assume you keep everything in thermal equilibrium, which means that you have to essentially heat up or cool down indefinitely slow, then everything stays in equilibrium, and you get the plot like this, which you probably have seen in your thermodynamics class.

Your crystalline material-- you heat it up slowly. You get to melting point. You get liquid. OK? Vice versa. You have liquid. You start to cool it down. As soon as you hit the melting point, you then go and transform into crystalline state. OK? There's a discontinuity there for this kind of an extensive parameter, OK? It indicates, essentially, there's a volume change between the solid and the liquid state or an enthalpy change, which gives you latent heat. OK?

So those are the characteristics of this first order solid liquid phase transition. OK? Now, in order to form glass, you have to go to an irreversible process. You have to cool down this liquid sufficiently fast. So you actually avoid crystallization. So now, starting from the melt, if you cool down quick enough so that kinetically, you don't allow this liquid to actually nucleate and grow, then what you end up getting here is then going to be, basically, a supercooled liquid. And if you continue to cool down, this supercooled liquid then transitions into glass, if you can suppress crystallization.

In-between here, this line-- this is the line that indicates glass, OK? Here, this is basically a supercooled liquid. In-between, there's this region here that's called glass transition, where the slope of this line actually changes. OK? Gradually changes. This is called a glass transition.

Now, a few important features about this glass transition. First of all, you see that this is a continuous change. Unlike melting or solidification, in a crystalline solid, you don't see a sudden jump of the extensive parameters, OK? So it's a continuous transformation. Essentially, liquid transitions into solid smoothly or continuously.

However, one thing I want to emphasize-- this is really important-- is that despite the glass and liquid-- they are connected together continuously-- glasses is different. They are fundamentally different from liquids. OK? Again, sometimes, you may hear people saying that glasses are basically frozen liquids.

That's actually not quite true because if you look at the property of glass, they are basically different from liquid. Now, simply put, think about the slope of this line. What is the slope of this line? It depends on what the vertical axis is. If it's volume, it's basically a thermal expansion coefficient, volumetric thermal expansion coefficient. If it's an enthalpy, it's basically a heat capacity.

So the thermal expansion coefficient essentially relates to a glass structure. The heat capacity relates to the degree of freedom the atoms can actually access in the solid state. So the fact that glass has a different heat capacity and volumetric thermal expansion coefficient compared to liquids means that fundamentally, glassy state is different from liquid state. You cannot just treat them as the same. So the glass transition, despite being continuous, is a real structure transition.

OK? Again, later, we are going into more details about what's your macroscopic and thermodynamic origin of the glass transition, but for now, you just need to know that essentially, you have to go through this smoothly region there that indicates that you are converting from liquid state to the glassy state.

And one useful concept I also want to introduce here is so-called fictive temperature, OK? So fictive temperature-- you can define it on this plot here by simply extending the glass line and the supercooled liquid line. Because they have different slope, they must cross over at some point. The crossover point corresponds to a temperature. This is what we call the fictive temperature.

Now, a couple of points about fictive temperature. First thing is that you probably have heard about another temperature called glass transition temperature, TG. So fictive temperature is close to glass transition temperature, but they're not exactly the same. We'll talk about that definition later. OK?

Fictive temperature, despite being a temperature, is actually usually used to characterize glass structure. Later on, you will see that this is actually treated as a structure parameter, here, OK? Different glass structures have different fictive temperature, all right? OK, just to prove my point here that different structures have different fictive temperature, quite obviously, if you start to cool down glass, for example, at different cooling rates, turns out you end up with different glassy states.

If you cool down at a faster cooling rate, this glass line is going to deviate from the supercooled liquid line at an earlier point. So you initiate glass transition actually sooner. And the resulting glass also has different thermodynamic properties that depend on cooling rate. On this plot here, we'll see that typically, if you cool down faster, you tend to get glasses with lower density.

There are exceptions, but most glasses, if you cool down faster, you tend to get lower density. Also, if you cool down faster, you always get a glassy state with higher enthalpy, always. There's no exception. OK? So if the vertical axis is enthalpy, then this plot always holds. If it's volume, they're actual volume anomaly, in some glasses.

So now, obviously, if you start to try to plot with the fictive temperature of these three different lines here, you draw your extension. What you'll find out almost immediately is that for the three glasses, glass 3 with highest cooling rate should have the highest fictive temperature. So the higher the cooling rate, the higher the fictive temperature.

And this is exactly because of this dependence of fictive temperature on the processing condition that people are actually using fictive temperature as a way to quantify glass structure. OK? So later on, again, we're going to talk about models, how this can actually be used to quantitatively, for example, predict glass relaxation that depends on structure. OK?

All right. Now, I also want to show you some peculiar behavior of the glass transition here. I've shown you how this line looks when you actually try to cool down the supercooled liquid. Now, what happens if you try to reheat it up? In a crystalline material, because it's a reversible process, if you do it slowly, whether heating or cooling, it always traces the same line.

But for amorphous solids, its property actually depends on the thermal history. So depending on whether you're cooling it down or heating it up, this line actually goes in different trajectories. So if you heat it up, most likely, we're going to see something like this. It goes down, and then goes back up. OK?

That's actually a sign of relaxation during the glass transition regime. And again, later in this semester, I'm going to give you a quantitative model that allows you to predict these kind of curves in glass materials. OK? All right. We are running out of time here, so I'll actually conclude this lecture. Any last-minute questions? All good? Crystal clear, not amorphous? All right, that's it. Thank you, and I will see you on Wednesday.