[SQUEAKING] [RUSTLING] [CLICKING]

PROFESSOR: OK so let's start here. So what I will do here is I will discuss a little bit about the devices people have actually been able to make using this kind of phase change materials. The first example here obviously is a bit outdated. I don't know if any of you still use CDs, DVDs. But the technology actually behind this kind of rewritable CD and DVD is exactly this kind of phase change alloys.

So what I'm showing here is like a laminate structure of if you actually look into what rewritable DVDs, this is what it looks like. They always have a substrate made of polycarbonate, basically just a plastic. That's the material you use to actually make the disk. On top of that, you then have a layer of these phase-change materials sandwiched between the two dielectric layers that provide essentially a protection to prevent essentially oxidation, and also prevent any kind of harmful interactions of the [INAUDIBLE] materials with the plastic substrate.

Because keep in mind, when you actually switch these materials, especially when you amortize them, you have to heat them up to pretty high temperature, usually around 600 degrees Celsius to melt it. And then you quickly quench down to get the amorphous state. So you don't want that process to actually harm your plastic substrate.

Now one thing I want to notice here is that for this particular application, the material we're using here is not a typical GST. It's a little bit modified composition over indium antimony telluride, or what people call AIST. So you can think of the AIST essentially as a variant of essentially antimony telluride. It's the base composition is basically antimony telluride. People add still over and indium to basically modulate the crystallization kinetics. It really doesn't play that much of a role. So it's basically indium telluride-based materials.

And then on top of that, you then actually have a metal reflective layer. The reflective layer serves to essentially try to capture as much optical power as possible into the phase change material layer. So it literally lowers the power requirement for writing. And then finally, on top, there's another layer of raising. And then there's actually another polycarbonate. So that's what the disk structure looks like.

So when you're actually doing a data recording, you then use a focused laser beam to deliver the power that's needed to either crystallize it or to amortize it. And you change the duration of the laser pulse so it's a longer pulse, lower power. This is how you actually induce crystallization, very short pulse, but very intense. You then melt it. And you amortize it.

So when you actually switch the crystalline structure of the material, as we have mentioned before, there is a very large change in terms of the refractive index, and hence the reflectance. Crystalline state is more reflective. And more first state is less reflective. So then based on that, you can then actually impact laser intensity writing and then use that to actually record digital information ones and zeros.

Now this is the first technology where this fancy new material was applied in the data storage domain. Obviously, as I said, this is an outdated technology. I don't think anyone really even use it. I don't even have a CD-DVD slot on my laptop. So, however, it doesn't mean that this phase change material is completely out of favor. So the other technology where they have been used here is called phase change memory. For short, it's also PCM. So it can be either Phase Change Materials or Phase Change Memory.

What I'm showing on this slide here is just a little bit of historic context, how this technology was developed over the past few decades. It all started back in about in the 1960s, where the scientist Ovshinsky, he discovered a unique phenomenon called threshold switching in [INAUDIBLE] compounds. We are going to talk about it in the next slide about what this is. But it's basically a phenomenon that really enables the operation of this kind of phase change material devices.

And that's why a lot of these cautionary-based phase change devices, sometimes they are also called ovonic devices, oh-von-ic. This is really just named after the person who discovered this phenomenon here, Ovshinsky. All right. Then a couple of years later-- actually, Gordon Moore-- so he's the same person from Intel that proposes Moore's law. So he was actually the one that actually developed the first phase change memory device.

The first device can storage up to 256 bits of information. Now you wonder how much that is. Each English letter is 8-bit. So basically what I'm putting in this box here, 256-bit phase change memory demo. That's right, about 256-bit. That's about how much information you can store in that entire memory unit. Now at the time, probably you will wonder, why is that even useful to store just a few words?

But fortunately, what we know is that a lot of these electronic devices, semiconductor devices, they are density follows exponential growth, known as Moore's law. Same thing happens, actually, with memory units. And I don't know who said it, but I think they said exponential growth is the most powerful force in the universe. So after a few decades, you can imagine that you actually get devices that can store lots of information, hundreds of gigabytes of information.

All right. So the next milestone comes in the 1980s. This is from a group in Japan, Yamada's group. They first discovered this GST competition decomposition along the pseudo boundary line, essentially pseudo boundary between germanium telluride, and [INAUDIBLE]. And they discovered that this combination uniquely exhibit this very fast and also reversible switching behavior that enabled the whole field application.

So starting from about 1990s, early 2000, several big companies started to deliver essentially commercial modules. They actually offer memory operation. So now in this next slide, I'm showing you a quick schematic about the essential structure of this kind of phase change memory. So the core of it is really pretty simple. The most simple version basically has two metal electrodes with a layer of this phase change material sandwiched in between.

So you can use those metal electrodes to essentially apply current, pass it directly through a phase change material-- which then generate joule heating-- and use the joule heating. You can use that to actually change the structural state of the material. At the same time, you also want to be able to read out the structural information, all the digital information encoded in the structure. So for this kind of memory, this is done through measuring the electrical conductivity.

So the crystalline state, because of the delocalization of the electrons in this kind of resonance bonding structure, it tends to be a lot more conductive compared to the amorphous state. It's several orders of magnitude more conductive. So then these two's the same pair of electrodes that you use to inject current can also be used to essentially read out the resistance by essentially setting a much lower voltage so it doesn't disrupt the structural material. But then you measure the current through it. So then from that, you actually know whether it's 0 or 1 or it's amorphous or crystalline.

So there's a pretty simple design here. I mean, the more state of the art efficient memory, they have different kind of architect architectures, more like a mush-- what they call mushroom design. But the basic idea is the same. Essentially, you still have two electrodes. And paths come directly through it. Now one challenge, however, is that in order to be able to pass current through it-- so to generate enough power to switch the face-- if you think about the-- look at the IV diagram here,

We have two lines here. If you focus on this two solid lines, this line, this is basically the crystalline state. The line at the bottom here, this one is amorphous state. Now, of course, amorphous state is electrically almost insulating. So that's why it has a very small slope. But then one of the challenge to immediately come up is that you still need to pass a lot of current through amorphous state to crystallize it. If it's insulating, how do you even actually pass current through it?

So that's where the threshold switching behavior comes in. So in these [INAUDIBLE] materials exhibit this kind of very unique behavior. If you apply an amorphous state, high voltage, once you pass some kind of threshold voltage, the material suddenly becomes electrically conductive. Now this electrical increase of electrical conductivity is different from crystallization in that the microstructure, if you look at atomic arrangement, it still remains the same.

In fact, when it goes to a conductive state, that's why you see voltage suddenly drop, current suddenly increases, if you decrease the voltage again, it goes back to the initial amorphous structure. As long as you don't go into this very high current regime where you start introducing material modification. So fundamentally, it basically says that this kind of so-called threshold switching behavior, it's purely electronic in nature. It doesn't involve atomic rearrangement.

So to explain what happens, we can take a look at this, a very schematic electronic tectonic structure diagram there. So what I'm showing you here, this will be conduction band, valence band. This is the band gap in the amorphous phase change material.

So later on in the semester, we're going to discuss more in details about the electronic structures of amorphous semiconductors. But for now, it suffices to say that unlike crystalline materials, where in the band gap you have zero density of states. For amorphous materials, there are still some localized states within the band gap. So you have electronic states.

And the Fermi level typically will still populate somewhere within the band gap. And below the Fermi level, obviously, the states are filled. Above the Fermi level, the states are empty. So from your solid-state physics, you may have learned that if it's off your state, it doesn't conduct electricity because electrons are fermions. You cannot move around. If it's empty, obviously, there are no [INAUDIBLE]. You cannot buy electricity.

So this kind of well-defined Fermi surface essentially says that this system is electrically insulating. It's very difficult to conduct electricity. So what happens when you actually start to apply a large voltage across it to trigger threshold switching? Once the voltage reaches a certain level, the electrons and holes, they start to get enough energy so that you can start to cause intermixing of the states around the Fermi surface.

And as soon as you have intermixing of these states, then you essentially create essentially still empty states below the Fermi level and fewer states above the Fermi level. And those are the states that now account for this increase of electrical conductivity. This is, as I said, this is purely electronic in nature. So that's why it's fully reversible. If you now remove the field, then it essentially goes back to the same amorphous structure, same insulating state. But practically what this allows you to do is now it allows you to apply large current through this normally insulating amorphous structure.

So if you continue to increase the current, then you can go to the set regime, where essentially now, there's large enough joule heating, the material is above its crystallization temperature. The atoms start to move around, start to rearrange themselves. You then crystallize it. So now if you go to this kind of gray zone here, and then you start to decrease the voltage again, instead of retracing this kind of amorphous curve here, it now goes into this crystalline curve. So you basically start from amorphous here.

You apply the voltage. You cause threshold switching, goes over here. You stay here for a little bit of time to allow crystallization to happen. And then when you come back, it now follows this kind of open square symbols. On the other hand, if it's in the crystalline state, you want to amortize it. That's quite straightforward. You just directly apply current through it. It's conductive. You bring up to this regime here. And you quickly cool it down. Then you go to the amorphous state. So this is just basically a mechanism that enables the operation of these devices without having to use excessively large bias.

All right. So that's basically how this efficient memory actually works. Before I go into some specific examples, I want to show you this table here that basically compares these phase change memory against some other so-called non-volatile or emerging memory techniques. Now when I'm talking about this non-volatility, this is one very important characteristic of this kind of phase change material. So non-volatility essentially means that after you remove the power, the data is still maintained.

This is different from DRAM in your computer. The DRAM in your computer is basically semiconductor based. So you need to essentially plug into power in order to maintain the data. As long as you unplug it, data is gone. In phase change materials, on the other hand, because the data is actually encoded in the material's microstructure and you don't need to continuously supply energy to maintain that microstructure state, so that's why it's called non-volatile.

A lot of the memory technologies I'm comparing here, these are essentially considered non-volatile memory technologies. So some examples I'm listing here-- Memristor, this essentially uses a conductance change in oxide materials, essentially the movement of ions to form essentially a conductive path and then use that to essentially recall information. You have a spin transfer torque random access memory. This is essentially using spin in magnetic materials. And the three columns on the right-hand side, these are more traditional memory.

DRAM, this is the internal memory you have on your computer. Flash, this is basically a solid-state drive, and then hard drive, essentially-- hard disk. So I like to keep this slide here. This chart is actually a bit outdated. It's more than 10 years old. So if you actually download a slide from Canvas a few days ago, I had actually replaced it with a more recent version. But then I decided to revert back to the old version because this was actually a good example to show how this table sometimes can be misleading.

OK, so if you look at this table, first question for you, who do you think made the table? I mean, I'm not asking about specific names. But what would be the technical background of the person that actually made the table?

AUDIENCE: The memristors?

PROFESSOR: Obviously. That's why everything is green for memristors. Well, this try is actually made by HP. So HP, 10 years ago, it was a big proponent of memristors. They give it up later on. So I think this is one of the things you have to be very, very careful. You often see these kind of tables comparing different competing technologies and papers, whatever publications. You have to be careful here because number one, you tend to be more familiar with the technology you're actually working on. You know about the latest and greatest, about what you actually develop.

But when you're trying to compare against other technologies, you should always keep in mind that you are actually comparing against moving targets in most cases, other technologies that are evolving, as well. So you should be aware about also what's the latest advances in other fields to draw a fair comparison.

You should also understand where you're seeing, for example, red boxes here, is it because some fundamental limitation that the technology simply just cannot overcome? Or is it just because people just haven't done it yet? So those are the things that may actually impact eventually the selection of the technology. So, for example, let's specifically look at this table here.

If you look at this column with respect to phase change materials, there are several figures of merit that are essentially quoted here. So density, this actually increases. Every generation of memory actually increases. So it's not really a fundamental limitation. If you look at energy per bit, this actually dictates essentially the energy efficiency. So it's quite important.

For PCM, as we mentioned, it does have this drawback. It tends to have very high energy consumption because you need to heat up the material to fairly high temperature to crystallize it or amorphize it. So that's one limitation of PCM technology. Read time-- this quoted number is quite outdated. State of the art phase change memories, they usually go with single digit, like two nanoseconds, for example, real time.

So it can be very, very fast because all you need to do is to send a very short electric pulse, measure electrical conductance. very low voltage pulse. So it's very, very straightforward. There's no fundamental limitation. It cannot be fast. Write time, I would say it's more close to the shorter end.

For GST, the kinetics is limited by crystallization. Amplification is faster. So for crystallization, the crystallization time is of the order of 50 nanoseconds. So it's off the lower end. But people have come up with other alloys that can actually crystallize a lot faster than GST. So it's potentially possible to get down to a even sub nanosecond operation time. Retention, it can go about above 10 years. Endurance, at least in literature, people are reporting endurance up to 10 to 11, 10 to 12 cycles.

So this also highlights one thing, though. When you're comparing some of these parameters, are you comparing a lab prototype with something that people is already commercially making? Or should you be comparing, essentially, a more mature technology with a mature technology? So making sure that you're actually comparing apples with apples, not apples with oranges. This is one of the pitfalls that lots of people actually falls in when they're doing this kind of comparison there. And that's why I want to list of as an example.

Now last slide, 3D capabilities. This is important for also increasing the memory density. Essentially, you want to stack many layers of this kind of memory together so that you can pack more information density in one given area. So you put a node here for PCM. Well, I'm going to show you an example how people actually stack PCM memories. All right.

So this is a technology that was actually developed by Intel about 10 years ago, exactly 10 years ago, 2015. Five years later, they actually developed second generation. They actually realized this 3D stacking of the memory there, it's called 3D XPoint. Now before I go into more details, I actually want to show you a little video here. And you can now watch the video. And keep in mind, they are also comparing this technology memory technology with some existing storage or memory technologies. So when they are talking about comparison, they are 1,000 times better. Be aware of what they're comparing against.

[VIDEO PLAYBACK]

- Forget all the big buzzwords. [INAUDIBLE] is so slow. Chances are your storage device is the problem, --to your processor's data requests and causing it to work at a fraction of its potential. Eliminating that bottleneck requires memory that is fast, dense, and non-volatile, so your data doesn't go away when your power does. DRAM memory is great because it's very fast. But it's volatile. And unlike many silicon components, DRAM density isn't doubling every two years. So it's hitting a wall.

On the other hand, NAND memory found in today's SSDs, is both dense and non-volatile. And while it's fast compared to other storage technologies, it's still much slower than DRAM. But get ready. We're about to shatter today's rules in a very big way.

[LAUGHTER]

- --we've been working on. Now for the first time ever, we'll be able to equip computers with memory that's faster than NAND and more dense than DRAM and non-volatile. Intel Optane technology combines a next generation non-volatile memory called 3D XPoint Memory with Intel's advanced system memory controllers and interface hardware and software enhancements to bring amazing new computing possibilities to a variety of markets.

So how do we do it? To make 3D XPoint Memory dense, we packed lots of capacity into a tiny footprint. We started by slicing submicroscopic layers of materials into columns.

PROFESSOR:

By lithography and etching.

- And then we connected those columns using an innovative XPoint structure consisting of perpendicular wires that enables memory cells to be individually addressed by selecting one wire on top and another at the bottom. We can stack these memory grids three dimensionally to maximize density.

And whereas DRAM requires a transistor at each memory cell to access or modify the cell, making DRAM big and expensive, each memory cell can be written to or read by simply varying the voltage sent to its selector, completely eliminating the need for transistors. This simple, stackable transistorless design enables us to deliver greater capacity than DRAM in the same space.

When it comes to memory performance, low latency is the key, especially for today's demanding workloads. Intel Optane technology's latency is much shorter than NAND memory, eliminating a significant portion of the performance penalty for each data request. This makes Intel Optane technology ideal for all devices, applications, or services requiring fast access to large sets of data. There you have it, a truly disruptive memory technology designed to change the face of computing with an unparalleled combination of speed, density, and non-volatility.

Get ready to unleash your processor's true potential and realize possibilities we thought were decades away. So be sure to stay tuned for upcoming announcements on Intel Optane technology.

[END PLAYBACK]

PROFESSOR: OK, so now you can count how many big buzzwords they use in there. OK, comes back here. Now tell me, they talk about a few different performance metrics. When they talk about latency, what are they comparing against? Or speed, essentially? There are basically two things. There's speed. There's also capacity.

AUDIENCE: Speed requires [INAUDIBLE].

PROFESSOR: The other one, actually. It's the solid-state drive, SSD. So NAND, NAND is basically like flash, essentially. So flash has very large capacity. All your flash drives are huge. But the bottleneck that is relatively slow in terms of read and write. On the other hand, DRAM is what's actually the internal memory of your computer. Those are extremely fast. But they are volatile. And also they do not store nearly as much information as your flash drive.

So the initial point of this Optane technology was that they tried to put something actually essentially in between, combine the best of both worlds. You have the capacity of flash or SSD. But at the same time, you also have the speed benefit of DRAM. So we'll get into a bit later and today actually really fulfill that promise. But for now, let's look at some technical details about how they realize it. Now, first thing you notice here is that I put a "likely" with a question mark there, because Intel actually never officially admitted that this is made out of PCM.

In fact, a couple of cases, they essentially denied that it is made of PCM. But there are actually people going there and do reverse engineering. So this group of people, they actually go in there. They actually get the memory. They slice it open using focused ion beam. And then they did elemental composition looking at the structures there. And they find, of course, germanium, antimony, tellurium. So what do you expect? It's a phase change memory technology. That's the consensus.

Now if you look at the structure here, this cross-section of memory, the bottom here, these are actually the metal wires. You see essentially a forest of the metal wire that provides interconnect. On top, this very thin layer there, this is actually the memory unit cell. In this particular module you see two stacked layers. In both layers you have a memory. And the memory is sitting on top of a selector.

And then this is actually the XPoint structure across it. So now, about why you actually need a selector. So if you look at this what they call XPoint technology, I mean, this is really just essentially-- in the community, people call it crossbar. So this is not really anything new. People know about this architecture for a long time.

But the idea is that you have two sets of metal wires. They are residing in two separate planes. You have the horizontal wires at the bottom, the vertical wires on top. And then at each cross point of wire, you have essentially a memory cell there where you can then pass current through. So normally it seems pretty straightforward. For example, if I were to operate this cell-- for example-- then I essentially apply a bias across this horizontal wire and across this vertical wire. Then you have current passing through it. That seems straight and simple forward.

However, there's one caveat. There is a so-called sneak path current you have to overcome-- sneak path. So if we apply bias across these two wires here, instead of going through this particular memory cell, the current can also go this way. We can go from here, for example. We can come to this one. It then goes up, move up, then goes into vertical line here. Once you get to this point, it goes down again.

And when it's coming over here, it goes back up again. And it goes up. So what you're seeing here is that instead of passing through one memory cell, in this case you pass through a total of three memory cells. So it's lower voltage. But it adds up. If you doing anything, if you think about huge network, there are tons of this three paths current. So they add up together will consume all the power.

So that's why to solve it, one way to do it is you put a little transistor next to each of these memory cells. A transistor is basically a switch. You can individually control each switch to ensure that you're actually reading the right memory cell. Downside is that transistor obviously is more complicated, takes more footprint. So that's what the video is actually alluding to.

Now what about a selector? A selector, in this particular case, is just a piece of [INAUDIBLE] compound. So, again, these people, they are doing reverse engineering. They look at it. They found essentially the selector is made of an alloy of germanium, arsenic, selenium. So it's a [INAUDIBLE] compound that also exhibits threshold switching.

So why is threshold switching good? So think about what you want for selector. So if you think about the IV characteristics for selector, IV, current voltage, ideally you want a selector to turn on if you are directly going through one memory cell. But it will remain off if you have three memory cells in series.

So the difference here is the voltage. For this one, this is the whole bias against essentially one cell. This is the bias distributed over three cells. So if you have an ideal selector that exhibit this kind of IV characteristic, it's like a step function.

So if your voltage exceeds a certain value, it suddenly turns on. Otherwise, it remains off. So as long as you set your operating voltage to be larger than this threshold here but at the same time, smaller than three times the threshold, then you will be able to turn on selectively only this particular cell, not all the other in the current path.

So now you already see this is what, exactly, threshold switching does. So threshold switching exhibit this kind of voltage characteristic, essentially. Beyond some threshold voltage, it suddenly turns on, allows you to go to large current. So as long as you set your threshold voltage correctly with respect to your operating voltage, that selector that allows you to pick out the right cell that actually is under operation.

And this is actually quite a neat concept here, because if you look at how they actually make it together, they just simply stack the memory cell directly in series with the selector. So they are just connected in series. And because they are all [INAUDIBLE] compounds, they are both [INAUDIBLE] compounds, it's quite straightforward to make them in the same manufacturing process. It's basically a multilayer deposition followed by pattern etching. So that's one quite neat technology actually apply in this process here to enable this technology.

So that's about the basics of this kind of a 3D XPoint technology. Now as I mentioned, the originally entails intention was they will fulfill, essentially, the need. They fill in the gap between typical computer memories with respect to solid-state storage devices. In terms of technology wise, this is a huge feat, lots of exciting advances. But from a market perspective, it's very hard to say that this is actually a successful product.

In fact, Intel-- so they started in 2015, when they first developed the technology. They partnered with Micron. Micron is actually the company that actually developed, originally, the phase change memory technology. In 2020, they developed second generation with increased density. The market reception has always been lukewarm. So they decided to wind down the business, starting 2022. You can still buy these memories. But they are not in active production anymore.

Some other companies continued the trajectory to develop technology like Micron, maybe Samsung. But it is not anymore Intel. So why is that? A few reasons here. So you remember when I was talking about this technology comparison chart? I said that you should always be aware that your competitors are moving targets. They don't sit still and wait for you to catch up. So same thing applies here.

When they're comparing against DRAM and SSD, what happens over the past few years is that DRAM becomes cheaper. So it's easier to get high-capacity DRAM. At the same time SSD, the bottleneck for SSD has always been speed. Latest version of SSD is a lot faster compared to previous versions. So this cuts the space where the [INAUDIBLE] technology can actually thrive.

And on top of that, there are also other limitations there. I mean, their manufacturing never really reached the capacity they want. So it's actually the product always has been too expensive, compared to other memory technologies. So it eventually become question about how much people want to pay for the added performance.

The other problem here is actually ecosystems. So when Intel designed these memories, they have to work with specific chipsets and specific hardware frames. And, again, that would obviously limit the adoption of technology. People also never really picked up, at least passing like 10 years ago. There were not much software that was specifically optimized for non-volatile memory. It's a great feature. But ecosystem simply wasn't there.

So it doesn't mean that non-volatile memory is out of favor. People are still developing it. And now people are starting to take advantage of that on the software side, as well. But it was a bit too early for this technology. And finally, there are also some business decisions. You know about all the turbulence that happened around Intel recently. They have been trying to focus on their foundry business over the past few years. They cut down a lot of other businesses. This is one of them. So that's why.

So takeaway message, you always should be very, very careful when deciding on what technology you want to work on. You should always be an expert, not just only technology you are focusing on, but also at least be aware of the latest and greatest of your competitors, as well, in order to make a fair assessment. All right. So that's about electronic memories.

Now, I also want to mention the other area where these phase change materials is getting a lot of traction is in the area of optics. No, I'm not talking about the old rewritable CD-DVDs. I'm more talking about essentially optics that can be integrated using state of the art semiconductor technologies for essentially photonics. So the basic property that all this optical application builds on is the fact that there's a huge optical property contrast when you switch the material from amorphous to crystalline state. And this is actually very unique.

I'm giving you here one example. This is basically silicon, very common material. I'm comparing here, again, now three different states of silicon. You have single crystalline silicon. You have polysilicon. This is actually, in this case, I believe it's more like nanocrystalline silicon. And then the last one, this is amorphous silicon. Now what you notice here, if you look at the refractive index, especially in this region-- this is where silicon actually become transparent-- it's basically the same. It differs by maybe up to 0.1 or 0.0 or something.

So for most materials, this is actually the case. If you change the arrangement of atoms, it's still the same atoms. So you expect more or less the same electronic polarizability ability for the material. So this is what really makes phase change material so unique. As I mentioned in previous lectures, because when you change atomic arrangement, you also change the bonding configuration. You go from covalent bonding to this kind of resonant or method of bonding. As a result, this increases the polarizability and therefore significantly enhances the refractive index.

So if you look at this classical GST 225 alloy, this is refractive index, amorphous crystalline. There's a huge jump. It's like index change by 3. It's like totally two totally different optical materials. At the same time, you also notice here that the absorption-- so extinction coefficient essentially gives you the absorption as a function of wavelength. You notice that the absorption also increases, going from the amorphous to crystalline phase.

Now this is also understandable because the crystalline phase is electrically conductive. Anything that's very electrically conductive is always optically absorbing, because free electrons can respond to essentially an incoming oscillating electromagnetic field. They can polarize. And in that process, they actually dissipate energy. This is what's causing optical absorption.

So that's why, going from amorphous crystalline, you increase the refractive index. And you also increase the optical absorption. So this is the behavior that people use now to develop, essentially, optical memories. Again, I'm not talking about rewritable CD or DVDs. These are actually optical memories integrated on the photonic circuits. So what I'm showing you here-- this is an example-- well, you basically have optical waveguide.

Optical waveguide is basically photonic wire. It's basically a strip of high-index material embedded or surrounded by a low-index material. So the light can get trapped. And they propagate along the high-index material through total internal reflection, similar to optical fibers. But this is made essentially on silicon wafer.

Now you can put a little chip of this GST material on top of this waveguide here. So this is actually your SEM image. You see a little patch of GST. When you switch this GST between this amorphous and crystalline state-- again, crystalline state is absorbing. Amorphous state is more transparent. So then this actually gives rise to a difference of the transmitted light intensity. You can then encode this digital information in the transmittance of the cell here.

So there's actually some data here. What they were able to realize, this actually, essentially, vertical axis is basically the intensity transmitted through a device. And you can see that a horizontal axis is basically like time. You can see they can switch between several discrete levels, in this case eight different levels, so 3-bit. So you can store 3-bit of information in one cell by essentially changing the fraction of crystalline versus amorphous state.

I mean, a few years later, the same group were able to actually push it to even more levels. In this case, this one is actually 32 levels. I believe they were also able to do 64 levels, so up to six bits within just one single unit cell. All right. So now you may wonder, why do you care about this optical memory here? One of the applications that actually attract lots of attention is actually in so-called optical analog computing.

So the big background there is that everyone is talking about AI. And for AI, it turns out the conventional computer architecture is very inefficient. Conventional computer architecture builds on so-called Von Neumann architecture there. In Von Neumann architecture, you have two separate units in computer. You have your central processing unit, or CPU. You have your memory.

When you do this kind of computing, they're like deep learning. It requires lots of data exchange between CPU and the memory. So the connection, the interconnect between these two units, is actually the bottleneck. It's not so much about CPU or the memory itself. It's about the data transfer in between them. So to resolve this kind of bottleneck, people come up with lots of paradigms.

And in particular, one promising pathway is to the so-called in-memory computing. You essentially have the memory itself as the computing unit. By doing so, you can avoid a lot of data transfer because you essentially-- data all resides in nowadays' computing memory there. And this kind of what I have referred there, this optical memory is one way to actually realize this kind of in-memory computing.

So just to give you one example how this in-memory computing can be executed, let's think about one very simple example here, which is basically matrix multiplication Now matrix multiplication, while this looks very straightforward, it's actually very relevant for AI applications. If you think about deep learning, it's all about big matrices, huge matrices multiplied together. This is actually how you do your training of your neural networks.

So big matrix multiplication is quite inefficient if you use computer-computer, again, because there's lots of data transfer that's needed So that's why people are looking for ways to do this so-called matrix multiplication and accumulation, MAC. So what I'm showing here is basically a simple vector-by-vector multiplication. A matrix multiplication essentially is a duplication of this task many, many times.

So to do it optically, this is one scheme that people can do it. There are other schemes. So you start out by essentially sending light of different wavelengths, Initially, they all have the same intensity. You combine all the light into one waveguide, and so that each wavelength is essentially more or less propagate independently. You then pass through these memory cells here. There's a cascade of this memory cell here that I'm labeling with different colors.

Each of these memory cells essentially interacts with one particular wavelength So I have labeled the number here W. So W is basically the transmission coefficient of each of the optical memory So, for example, W1, suppose you come in here. The light intensity is actually x1. You encode essentially the input vector using the intensity in the input light at different wavelengths.

So for the first wavelength of light, it goes in here. And x1, when it transmits through this little memory here, it light will then come out from the other waveguide that we labeled as drop. But the transmission coefficient is W1. So the light intensity coming through is going to be x1 times W1, same thing. The next one, this is a second wavelength. The intensity is going to be W2 times x2. So then all the wavelengths then again get combined in this second drop waveguide here.

If you have detected at the end, you can detect all the intensity adds up together. Then that will give you essentially immediately the sum of the product or the product of two vectors there. So what we are doing here, this is called analog computing because that's actually, you are not using digital processors. You're not using transistors to perform computing. You're essentially leveraging the fact that you can encode this analog information in terms of the memory state, optical transmittance state, and use that to directly perform the summation.

So the advantage here is that this can be extremely fast, especially when you go to very large matrices because the technology is, in essence, scalable, as long as you can provide a large number of wavelength. And then you can generate all of these filters and all of these memories and program them appropriately. The addition process is done automatically. You just have one single photodetector collect all the lights, essentially does the summation automatically.

And that's actually what the people have done. Let me see. Oh, OK. I'm actually missing a slide there. But basically, people have actually implemented, essentially, using these cells, based on essentially using the phase change memory elements I have mentioned in the previous slide. And then that allows you to essentially perform this kind of a computing. People have demonstrated prototypes of analog optical computers using this kind of phase change memory materials.

So that's one application where this kind of material has found a lot of traction there. Now the other useful aspect where this could also be used is what we have now, essentially, is a reconfigurable optical media. If you think about conventional optical devices like lens, prism, or whatever, once it's made, it's made. If you have a lens, if it's fabricated, the focal length is fixed. So there's nothing you can do to really change it.

But now with this kind of new material, it gives you essentially additional knob that allows you to tune the properties of optical systems post fabrication. So that's quite useful to realize different kind of reconfigurable optical devices. For example, optical switch, you can use that to essentially steer light towards different directions.

Now this is another interesting example here. What people have shown in this case is that if you deposit a very thin layer of this phase-changing material on top of some dielectric stack, by controlling the light interference at different wavelengths you can actually get different colors when you switch from amorphous to crystalline. Amorphous is like pink. Crystalline becomes more like yellowish. So what can you use this technology for? You can actually change the color of a thin film media. You can do displays.

So this is actually a demonstration first demonstrated by a group in Oxford. What they were able to show is that by essentially switching the material between these two states, they can essentially realize color displays. What they would do is they deposited the material, a thin film. They then define small pixels, where each pixel can be individually switched between amorphous and crystalline states. And by essentially interlacing different kind of pixels corresponding to different colors together, they were then able to demonstrate that they can actually realize color displays in this case.

OK, so these are actually some actual patterns like this logo of Oxford. This is actually written in this kind of phase change materials. So the advantage of this kind of display is that this is a little bit different from the display you have on your laptop. It relies on light reflection rather than the light emission. Normal displays essentially emits light of different color. But this is actually purely based on reflection. So this is more like a electronic paper.

The more exact analog of this kind of display is not your laptop, but rather Kindle. Have you used Kindle from Amazon?

AUDIENCE: Yeah.

PROFESSOR: Yeah, like e-readers. So the way Kindles work is also reflective display. They have essentially little spheres with two sides, black and white. By electric field they can actually control orientation of those spheres, whether it's black or white, and then train the reflectance. The advantage of this kind of electronic paper display, like Kindle, is that they are extremely power efficient because they are non-volatile.

Once you have absorb the state of the sphere, you do need continuous power supply to maintain it. So that's why your Kindle can last way longer than your laptop lasts, for days, months, rather than a laptop just a few hours. OK, so same idea here. Again, this feature, here, they are non-volatile. So the hope there is that they can utilize this non-volatile reflected display, but in color rather than just in black and white, just like in Kindle. OK, yes.

AUDIENCE: Is it still restricted to what colors it can use because the amorphous and crystalline states aren't specific?

PROFESSOR: Not really. Basically, the idea there is that even though you have the same material with fixed optical constants, you can train the layer structures. If you put it around different dielectric layers with different thicknesses, it changes the interference of light at different wavelengths. So you can encode essentially one pixel, for example, a switch between, say, black and red. The other ones switch between black and gray, the other one, black and blue. Then by combining the three together, you can actually get essentially [AUDIO OUT].

AUDIENCE: So each pixel can be layered with different--

PROFESSOR: In principle, at least. Yeah, you can design it so that you actually get full-color display.

AUDIENCE: In color. Those are really expensive.

PROFESSOR: So, no. Last example here, I just want to mention that for the efficient mirror I mentioned before, GST, you notice that when you switch from amorphous crystalline, you introduce larger refraction exchange. You also cause a very large absorption change, as well. The [INAUDIBLE] is optically absorbing. This is considered as a potential drawback because of a lot of optical devices, you imagine that you want something that's transparent, rather than absorbing.

So a few years back-- this is actually from my group-- we actually discovered that you can actually make a phase-changing material that switch between two transparent states, rather than one absorbing and one transparent state. So the material, this is actually the material. Again, I'm not going to go through details, JSSD. But if you look at optical constants, it still shows a very large change in refractive index. But the absorption, which is labeled by extinction coefficient here, is mostly zero across the entire infrared range for both crystalline and amorphous state.

So now you can imagine there's a whole lot of applications we can actually now explore in this kind of bi-state transparent phase change materials. This is actually something we have done a few years back. We demonstrate that by essentially patterning this material into these little subwavelength structures. And by designing that appropriately when you actually switch between amorphous and crystalline state, you can change the phase of light. Not phase, not in terms of material structure. I'm talking about the oscillation of the phase, sine, cosine phase of the light.

So you can change the phase of light at different locations. And therefore, you can actually change. For example, in this case, this is a lens that actually can shift the focus by just simply switching between amorphous and crystalline states. So there are quite some interesting applications you can now explore using these new materials there, now they are actually transparent.

So just to summarize what I have discussed here, this is a list of further readings if you're interested in this topic. I have already included here the Google Book link and this one. If you have an MIT certificate, you can actually download this book for free. I have also included a couple of papers here. This is a very nice review that discusses about, essentially, the phase change memory specifically for electronic applications. And then the last one here, this is the more recent publication.

I consider it as a very nice paper that talks about the different strategies people use to engineer the material, how to combine material science and use that to actually make informed decisions about how to actually make better devices, how to tailor material competition, for example, to get faster crystallization, faster speed, low energy consumption. They talk about all the material design considerations in that particular paper. All right.

So any more questions about phase change materials before we proceed to talk about the next topic? So we move on to the next, our fundamental science topic here. The next topic here is about viscosity of glass. Now specifically for this particular topic, we are going to try to address this question. Is glass considered a liquid? Or is it considered a solid?

Now, you may already have answered from the first lecture. You know that glass is very different from supercooled liquid. They have different thermal expansion coefficient. They have different heat capacity. So fundamentally, they are very different, two different states of matter. Well, that's not the answer I'm looking for. I'm looking more from rheological perspective. Does glass flow, basically?

Now your immediate intuitive answer may be that, well, glass doesn't really flow. You don't see a flow. Now let me give you a counter example just to confuse you a little bit. Think about pitch, or asphalt. It will be considered as solid. That's why people use them to pave roads. However, it's actually a liquid, just with very, very high viscosity.

So in this long-term experiment there, what they did is they actually put some pitch there in this funnel. And then they just basically wait. And over time, this pitch slowly flows. And eventually, you can collect the droplets at the bottom here.

So the most famous version of this experiment was started-- this is almost 100 years ago. And now they have how many jobs? Let's see. I think they only have something like eight to nine jobs fail. I don't recall the number. But you can go on Wikipedia. They make it a pretty big deal. Every time one job falls, it's like there's a celebration around it. All right. So takeaway message number one, if you're considering going to grad school where you're looking for a PhD thesis topic, this is probably a terrible choice.

Well, to be real. Now the main takeaway message here is that the boundary between solid and liquid is not so well defined. How do you tell whether something is actually solid, or something which is extremely high viscosity? Now coming to the specific case of glass, some of you may have heard this urban legend.

If you look at the color windows in medieval churches, if you look at them closely, you probably notice that a lot of these window panes, they tend to be a little bit thicker at the bottom compared on the top. And that's why some people claim that that's because over centuries of time, glass flows slowly. It's just a liquid, basically, with high viscosity. So that's why it gets thicker at the bottom. Is it true?

Some of you are already shaking your head. Well, that's a correct answer. Well now, just to confuse it a little bit more, let's think about this press release. So this is from Hitachi. What they were able to develop, essentially, is a new memory technology. It's somewhat similar to optical disks. But it's a more advanced version. You basically have silica glass. You can use laser to essentially locally modify the material structure and change optical properties so that you can then later on use. Essentially, you can read it out by looking at optical property contrast.

The advantage there is that you can read it at very high density, unlike optical disk. It's basically one layer that can do many, many layers. And that's why they have high information storage density. And it's also very stable. That's why it's getting attractive. People are trying to use it as a backup media to backup everything you have on the cloud.

Microsoft is also working on the technologies. But what they claim is that you can now store the information for 300 million years. So if you search for that press release and see the comments people post under that press release, people were like, well, this is-- OK, yes. Over millions of years, glass is going to flow like liquid. Nothing is going to be kept. Is that true? Now we're not talking about a few hundred years. There's millions of years, million years.

OK, well, that's what we're trying to address in this class here. Let's see if it's true. Before we go into more specific details, now we need to first essentially look at some basic properties about viscosity. And I'm trying to draw a comparison here between viscosity and elasticity. So you are all aware of elasticity. That's very simple for mechanics. You can approximate lots of materials essentially as a who can media.

So the strain and stress, they follow this very simple nice linear relation. This is for normal strain and stress. This is for sheer strain and stress. But essentially, strain is proportional to stress. And I put it here. They are instantaneous and transient. What that means is that if you have elastic media, ideal elastic media, you try to deform it, apply a force. You immediately see elastic deformation.

If you remove the force, it immediately recovers. That's why this trend is directly proportional to stress here. There's no time dependence. Everything is instantaneous.

Now viscous is the opposite. This viscous flow is always time dependent. If you look at the governing law here, this is more Newtonian fluid. What it basically says is that the shear stress is proportional to the shear strain rate. It's not proportional to shear strain, but shear strain rate. So first thing I want to mention there is therefore essentially for viscosity, you don't have normal stress. Normal stress is exclusive for elastics.

For liquid, if you try to compress it, you get the same behavior. You get elastic deformation, similar to solids. When you talk about viscous flow, this always happens due to shear motion. You have one pass of liquid. They try to flow past the other part, try to move past the other part. So only shear motion is involved. Two is that because this is shear rate, what it means is that you don't need a constant force to sustain the shape deformation.

So suppose you already have some sheer deformation, here epsilon. But it's not changing with time. The corresponding shear force is 0. And that's intuitive because liquid, it can hold any kind of shape. So as long as definition happens, as long as you don't confuse, deform it, you don't need to apply any force. So in this regard, viscosity is sort of like internal friction. Only when you're trying to deform the liquid actively, that's when you actually see the viscous force coming into play.

So the first thing you try to deform it, the more this friction is going to be. All right. So now in terms of glass, the answer about whether glass is liquid or solid, it really depends on lots of factors, most dominantly temperature. So we know that obviously if you go to high temperature when you go to supercooled liquid, it is liquid, no argument. If you go to a low temperature, like room temperature, you can go to the glassy state.

And as I will show you later, real logically, a lot of this glassy state is practically solid. It doesn't flow. The viscosity is so low that it's negligible, even over like millions of years of timescales. But then in between, you have the glass transition regime, where this material actually exhibits a combination of properties from both solid and liquid.

So later on, we'll have one chapter dedicated to it, just talk about so-called viscoelasticity of glass materials, which, judging from its name, is a combination of viscous properties and elastic behavior. All right. So now let's start by taking a look at some of the microscopic origins of elasticity and viscosity, for elasticity is quite straightforward. When you're trying to compress or stretch a material, you're changing it into atomic spacing.

So when you change it into atomic spacing, you're changing the relative magnitude of the attractive and repulsive forces. If you try to compress it, repulsive force becomes larger. So that's why you see essentially a resistive force resisting this kind of deformation, and vice versa.

Viscosity, on the other hand, this comes from internal friction or relaxation, as I call it. Essentially, when you have viscous deformation, you're changing geometric configuration of the material. You need to move some molecules or atoms past the others. That's the whole idea. And this can be realized with different kind of microstructure mechanisms, depending on different kind of materials.

If you think about polymers, if you think of long polymer chains, they can have different conformations. They can be twisted. They can be folded. They can be stretched to a straight line. So when you're changing in between these different conformations, you change the overall shape of the material. So that's a kind of viscous flow. If it's a material like glass, or maybe even like ceramics or metal under a high temperature, they can creep. Essentially, they deform plastically.

In that process, you have essentially viscous information coming in. And the underlying mechanism would be for things like vacancy diffusion or dislocation motion. That's how you induce plastic deformation in disordered materials.

So one key takeaway point here is that these different kind of mechanisms, they may have very different relaxation time scales. So they may or may not come into play, depending on the strain rate. Faster strain rate, you may have faster deformation mechanism coming into play, and vice versa. Also the rule of thumb is that if you have a stronger intermolecular interactions or inter atomic interactions, the materials tend to be a stronger resistance to deformation. And therefore, they will usually exhibit a higher viscosity. Again, quite intuitive there.

So what I'm showing on this plot here, because viscosity is actually a parameter that is very less intuitive, I'm actually showing you a little chart that should compare some of the common liquid with on the viscosity scale. So the unit of viscosity is in a Pascal second The other unit people also use often use here is called Poise. So the Si unit is Pascal's second. And then you can also use Poise.

I think it's a 0.1 Pascal second equal to 1 or equal to 1 poise, or maybe vice versa. You can Google up on wiki to find out exactly. But basically, they are trivially connected by a factor of 10. So what we see here is that for some liquid like water or acetone, they just flow easily. So that's why they tend to have low, essentially, viscosity here.

But then if you go to something like ketchup or syrup or even like toothpaste, they're a lot more difficult to deform. So they have a higher viscosity. The glasses actually has a viscosity spending much wider scale than what I'm showing on the previous slide. OK I'm going to show that later. So now the next thing I also want to discuss about here, this is actually quite important is the temperature dependence of this differential phenomena.

This is quite important for glass processing, especially so for elasticity. This is actually relatively straightforward. In this plot, I'm showing you how the elastic constant of silica glass is going to change as the temperature. Now clearly over this extremely wide temperature range this is like over 1000 degrees Celsius huge span of temperature. The compressibility or less constant change like 30%, barely. So it's a very, very small, very, very weak dependence on temperature.

Now this is also understandable because if you think about the nature of this kind of elasticity, it comes from, essentially interatomic interactions. What this tells you is that this interatomic interactions in terms of attractive and repulsive forces, they are just simply not very strong function of temperature. As you heat up, you may get a little bit of thermal expansion. You change the spacing of atoms a little bit, but you are not changing the nature of the force. They interact in between them. So that's why elasticity tend to exhibit a very weak dependence on temperature.

Now viscosity is different because viscosity, as we mentioned, it involves the relative motion of molecules. Some part of it has to move past the other parts. So any mechanism that involves molecular motion tend to be thermally activated. High temperature usually allows you to expect expedite the process exponentially. So we can formulate logically, essentially describe it using the Arrhenius equation there.

And I have shown you at the bottom here, this is essentially some activation energy values for different materials. So you notice here for silica, it tends to have a pretty high activation energy. Germania is a little bit lower because silica and germania, they have the same structure. Germania is basically GO2. It's the same structure. But germanium is a larger atom.

Larger atom has a weaker interaction between the nucleus and outer shell electrons. So they tend to form weaker chemical bonds. Weaker chemical bonds means weaker interactions. And therefore you tend to have a less activation energy barrier for this kind of process there. So if you go to a other kind of solids there with even weaker chemical bonds, you see that the activation energy continue to decrease.

Now the other thing you probably also have noticed here for silica, I have actually quoted two different activation energy values for different temperature ranges. So that means that this activation energy, in general, is temperature dependent. So the original law is not perfectly obeyed in a glass melt or in this kind of liquid here.

So you can discard this kind of Arrhenius behavior of glass materials in terms of viscosity, which this is a well-known so-called angel plot. So let me explain what angel plot is. So for an angel plot, the horizontal axis is basically inverse temperature It's normalized with respect to TG. So again, TG, TG is glass transition temperature. And in the context of glass viscosity, we are always defining it as corresponding to a viscosity value of 10 to the 12th Pascal second.

That's why, if you look at this horizontal axis here, this point is basically glass transition temperature. And that's why if you look at it here-- all the data-- by definition, all of these different curves corresponding to different glass competition, they all converge at one single point. This is by definition. A glass transition temperature, the viscosity should be 10 to the 12th Pascal second, or 10 to the 13th poise. So now you know which one is which.

So 1 plus a second equals to 10 poise. We have conclusive answer here. So that's why all the curves converge at this point. Now the vertical axis is basically viscosity here in logarithmic scale. So if you see a straight line here, it essentially indicates that the viscosity follows exponential dependence with respect to temperature. So any straight line is basically Arrhenius behavior.

Now if you look at this plot, clearly there are two big categories of this glass melts. You get something like silica or germania. Again, we see that the activation energy changes a little bit, but not too dramatically. They still more or less follow the straight line here. You also get some other solids. You have this kind of ionic compounds. You get this organic or molecular solids. You see that they have this kind of very large change of the activation energy with respect to temperature.

So we call these two kinds of behavior-- this is called a strong liquid for silicon, germanium, where it follows Arrhenius behavior. No Arrhenius behavior, this is called the fragile liquid. Now first thing you want to know is that this strong and fragile have nothing to do with mechanical properties of liquid. Again, liquid is liquid. You cannot describe, basically, like the strong or fragile. You cannot even use that to label liquid. You can use that to label solid. You cannot use that to label liquid. So it has nothing to do with mechanical behavior.

All it says is how the viscosity depends on temperature, whether or not it follows Reynolds' law. That's what's shown. Fragile says. OK. Now they can be engaged quantitatively by this so-called fragility parameter here. It looks complicated. But basically all it says is that it's the slope of the curve in your plot, right at this point here. And it's quite straightforward. If you have a smaller slope, it goes along this line. This is basically strong. Your large slope, it goes here. This is basically fragile. So fragility parameter, just gauges there.

Now I wonder why that matters? So from a practical perspective, fragility is quite important when it comes to glass processing. So question for you, which one do you think is more preferred for glass processing? Do you wants fragile liquid or do you wants strong liquid?

AUDIENCE: Stronger liquid.

AUDIENCE: What [INAUDIBLE]?

PROFESSOR: Oh, that's a great way to get the answer. Which is correct? What happens there is that later on we're going to talk about specific viscosity windows where we actually process the materials.

The viscosity window actually falls somewhere around here, like this regime here. So in this regime, what you notice here is that for fragile liquids, its viscosity changes a lot more dramatically with respect to temperature. And viscosity is a key process parameter. It controls how the liquid flows and how you deform it. So if you have a liquid where its property becomes very sensitive to temperature, it means that your process control has to be a lot more precise in order to get the desired results. So it has a much higher process sensitivity.

Any temperature excursion is going to lead to much larger deviation. So practically, that's why it's important. Having a strong liquid can be beneficial in that case. Now fundamentally, from a microscopic perspective, the fact that you have the activation barrier can be a function of temperature. It essentially means that at different temperature regimes, the deformation, or the flow mechanism is different.

So for a strong liquid like silica, you have strong chemical bonds. Those chemical bonds essentially retain this connection, even at high temperature. So that's why its activation energy doesn't really change with temperature, because the microscopic deformation is the same. You still get the same essentially atomic network. But for this kind of fragile liquid, basically what it says is that as you go to high temperature, the cluster of the molecules that essentially move past each other, the size is changing.

As you go to high temperature, you tend to have smaller clusters. And smaller clusters are a bit more mobile. And that's why the activation energy barrier essentially becomes lower. The specific mechanism depends on the specific type of material we're talking about here. But the general trend is the same. As you go to high temperature, you have essentially smaller cluster, more flexible structures. And that's why you get the low viscosity. That's why you get this kind of strong and fragile behavior difference.

To describe this kind of behavior quantitatively, there are a few equations people use here. For strong liquid, it's quite straightforward. You just use a Arrhenius equation. Maybe you add a little modification here so this delta EA is slightly temperature dependent. But that's about it. And as I've shown you in previous slides, this usually applies to covalent glass-forming liquids that has strong chemical bonds, like silicon or germanium. So the connection mechanism, or microscopic motion mechanism, doesn't change as a function of temperature. That's when you get this kind of strong liquid.

Now, one thing I also want to just very quickly mention there is that the fragility, as I said, often exhibit a minimum at the rigidity percolation threshold, which, again highlights the fact that topology has very important impact on the glass property. OK, just a quick point there. All right.

Now fragile liquid, so you cannot use Arrhenius equation. So what people do is they introduce a new set of equations here. And depending on who you talk to, this equation, same equation, has two different names. Glass scientists call it a vocal fracture equation, VFT equation. If you talk to a polymer scientist, they will tell you this is called Williams-Landel-Ferry equation. They are exactly the same. It just basically means that there are two communities. Historically, they don't talk to each other. They independently develop these equations without knowing that someone else is doing exactly the same job.

But if you look at the equation here, it's a modification of the Arrhenius equation. You add, essentially, this additional term here, TVFT. Then that allows you, this additional parameter now allows you to capture this temperature dependence of the activation energy barrier. So this applies mostly to liquids with relatively weak atomic interactions like ionic liquid or molecular liquids, sometimes some glasses, like, if you have, say, a lot of network modifiers, you put a lot of network modifiers into glass network, they also tend to become a little more fragile when they go into liquid state.

So if you look at this equation, it's actually obviously flawed. It's more of a semi-empirical equation. It's quite easy to see why it's flawed. If you go to low temperature, when the temperature starts to approach this VFT temperature there, the whole equation diverges, which is unphysical.

So that's why for a long time, people have always been trying to look for a better equation to replace VF equation, and also to yield more insight into the microscopic mechanism of viscous flow. Well, that equation actually exists. So this was about 15 years ago, when a group of scientists actually developed this new equation here, derived from first principles, using statistical mechanics principles, which is quite remarkable. This is one of the few examples where you start from very basic first principle all the way to equation that can vary the precise view you can experiment.

This equation is called a-- I'm not going to read all the names-- it's called MYEGA equation. Now you have five letters. This is showing the trend in the scientific community that author names is increasing over time. We'll see what happens in a few decades, how long we have to name equations.

But what's remarkable about this equation in itself is that it only contains three fitting parameters, exactly the same as the VFT equation. If you look at VFT, you have this pre-commercial vector. You have this, basically, the activation energy barrier. And then you also get this VFT temperature, three parameters. This new equation also contains three parameters here, the pre-exponential factor, K, and C. And that's it.

Now it's quite remarkable that they also get excellent agreement. They are trying to fit essentially this equation to the viscosity of different glass-forming liquids. And the solid line is basically what's predicted by this equation there. And the dotted line obviously is the experimental data. So you see remarkable agreement that can explain the liquid viscosity behavior across different fragility.

So the specific derivation of this equation is obviously outside the scope of this class. But I have listed this very remarkable landmark paper here, if you're interested. You can take a look at it. So we are almost out of time. We still have three minutes. I guess I will just quickly talk about one last topic here.

So we have discussed about this difference. We have fragile. You have strong liquid. Turns out there are actually some anomalous compounds that can actually switch between these two behaviors, with water being one of the examples.

So the most common liquid actually exhibit an underlying liquid-to-liquid phase transformation. So if you look at, for example, let's see which one is water. So this one is water. So the open red circles, if you look at the viscosity behavior of water, initially it seems to be residing somewhere here, photo fragile behavior. But as you go to lower temperature, it starts to actually come up. It actually follows more like a strong liquid.

So people are actually looking into this a little bit further. They were investigating essentially how the property actually changes upon this inflection point here. They noticed that a lot of the properties actually go to divergence when they approach this specific point. This is a clear signature of a high-order phase transition. A lot of the properties should diverge.

So without going into too much detail, suffice it to say that some liquids actually exhibit a liquid phase transformation. In the liquid phase, at different temperatures, they can switch from a fragile liquid to a to a strong liquid. It's a high-order phase transition. So you don't see an abrupt jump of extensive thermodynamic parameters. But you do see the divergence for some of this, for these parameters there.

And besides water, the other example where you have this kind of transition there, is this phase change material. Germanium telluride is actually one of the phase change materials. You see this very clear signature. You see this inflection point here that indicates a fragile two-stroke liquid transformation.

And that's actually quite important practically, it turns out, because now, remember, we were talking about these kind of phase-change memories. We said that they can switch extremely fast at high temperature. But the data can be kept for decades at room temperature. Why? Because of the high activation energy. I said that activation should have a quotation mark there, because what I'm really referring to is this part, the strong part.

The fragile part, obviously you cannot describe it using Arrhenius equation. So it doesn't make sense to describe it using essentially activation energy barrier. But for the strong part, it does exhibit very high activation energy. You have a very steep slope.

So that's why you can have essentially a fast crystallization. That's why you can have fast crystallization at high temperature and also, essentially, good data retention at room temperature. Also, it has a fragile behavior. This is useful at high temperature because we want to promote viscous flow to ensure you have high crystallization speed. But you don't want the fragile behavior at room temperature, because it turns out you can correlate fragile behavior into structural relaxation.

A fragile liquid tend to have more structural relaxation at low temperature. For memories, that's problematic because it leads to essentially a drift. You switch to some state. But its conductivity actually changes over time. So at some point, you lose the ability to tell the 1 bits from the 0's bits.

So the fact that it's transitioned into a strong liquid at low temperature means that this phase change material can also have very good data retention without drift. So anyway, that's the basic idea there why this kind of transition can be useful. I have also included the reference here, if you want to look for more information specifically about phase change materials and other liquids that exhibit this peculiar behavior.

All right. We are right on time here. Any last minute questions? All good? All right. Thank you, and see you tomorrow.