The surprising

Three mind-bendy conversations about glass later,

Reprinted from *The Highlight by Vox*,
September 2023 issue,
Brian Resnick

There's a myth about glass you might have read about in high school: If you go to a church that's hundreds of years old and look at the glass windows, you'll find that the panes are thicker at the bottom of the frame than at the top. That's because, according to lore, glass is actually a liquid, just one that flows very slowly.

This is a myth for a lot of reasons. The simplest is that the thickness of glass at the base of the windows can be explained simply by how glass panes were manufactured in the olden days. Back then, flat windows were made by spinning a glass form into a flat disc, which left the finished product with uneven thickness.

But also, as a scientific explanation, the myth does not do glass justice. Glass is so much weirder than a very slow-moving liquid. In fact, even though glass is one of the most common, most useful materials in the world—lining our windows, covering our phones, delicately holding our stems of roses—scientists still have deep questions about what it fundamentally is.

"*It defies the very simple categories we have of liquid, solid, and gas,*" says Camille Scalliet, a theoretical physicist at the University of Cambridge. She's not the only scientist flummoxed by glass. All over the world, physicists, chemists, and other specialists are trying to unlock its secrets.

It's true that glass does have some liquid-like properties. But remarkably, rather than flow, glass doesn't move very much at all. In 2017, scientists analyzed the church glass myth in a paper, determining that, over a billion years, church windowpanes would flow a single nanometer. (That is one-billionth of a meter; it's infinitesimally tiny. A piece of paper is around 100,000 nanometers thick.)

And this finding gets us closer to the deepest mystery of glass. The question scientists grapple with isn't "*why does it flow*." Instead, "*we don't really know why it's solid*," Scalliet says.

The quest comes with some deep prizes. One prize would just be a better definition of one of the most common materials in the world. A complete understanding of glass would be satisfyingly sublime: It would teach us about how this material changes over billions of years and tell us about its final form. We could learn whether certain forms of it could be considered a new state of matter. Contemplating glass also forces us to consider the limitations of perceiving time on the scale of a meek human life span.

There are less heady prizes, too. If we understood glass better, "*you can really start creating materials that don't exist yet,*" Scalliet says. Glasses that are stronger or bendier, or have properties we can't yet imagine. "*But at the moment, we don't really have this knowledge*."

To explain the weirdness of glass, it's helpful to think about what typically differentiates between liquids and solids.

Solids and liquids are both made up of atoms and molecules. Temperature changes how these components are arranged. Cooler temperatures solidify molecules; warmer temperatures make them juicy.

The important differences are seen on the microscopic scale of molecules. In liquids, the molecules are very disordered; they move around each other and flow. "*If you could zoom in and see individual molecules, they would be packed randomly and they would be moving around very fast*," Scalliet says.

I think of a liquid like a crowd of people dancing at a club. They're energetic, packed in, vibing. They can move around each other, bump and grind, dancing to the music. If you took a snapshot of the dancers, it would look like a chaotic, jumbled mess. That's a liquid.

scientific weirdness of glass

I see the sublime in my windowpanes.

There's a myth about glass you might have read about in high school: If you go to a church that's hundreds of years old and look at the glass windows, you'll find that the panes are thicker at the bottom of the frame than at the top. That's because, according to lore, glass is actually a liquid, just one that flows very slowly.

Solids are much more tame. As we typically think of them, they are made up of crystals, which are structured, orderly patterns of molecules. When the temperature cools down, the atoms and molecules line up in a regular geometric pattern. In the dance club metaphor, instead of undulating past each other, these ravers stop dancing and sit down in concert seats. They can still squirm a bit in those seats (as long as the thermostat in the theater isn't set to absolute zero), but they're mostly locked in place.

So those are liquids and crystalline solids: simple and easily distinguished from one another. Glass is neither of those things—while still retaining some properties of each.

The simplest explanation for how glass forms is that it's a liquid that cools too quickly for those crystals to form. So the molecules get locked in place in a chaotic liquid-like arrangement.

Imagine you're in the crowded dance space, and you decide you need to use the bathroom. But when you try to get there, a lot of the dancers decide to stop moving. When that happens, it becomes harder and harder for you to navigate across the dance floor. "*If you're with your partner and you want to just trade places, you can't do it because you're so jammed, you need to get other people to move,*" David Weitz, a Harvard physicist, says. And when you can't move, it makes it harder for other people to move around you. So gradually, and then very suddenly, the whole dance floor seizes up. You're locked in place, and not in an orderly geometric pattern. It's a mess. It's glass. And you're not going to make it to the bathroom in time (again, it might take some billions of years to move just nanometers).

This is the basic definition of a glass: a liquid that has been locked in place. Or, in science-speak, an "amorphous solid." And it applies to a lot of materials, not just the silica-based glasses that hang in our windows or cover our phones.

"*When you think of glass, you think of a glass that you drink water from, or window glass*," Weitz says. "*But to me, it's so much richer. There's so many materials that behave glassy-like*."

Some plastics are considered glasses, as are natural materials like amber. And some parts of your cells are considered to be glass-like. Even foams like whipped cream can be described as glass-like, Weitz says. Finding out the underlying mechanics that connect all these forms of glass, that's "*the real challenge to me, the beauty of the whole science*."

The club scenario is the start of the explanation for why glass is solid, but for scientists, it's incomplete. The problem lies in the end result. If you take a picture of the molecular structure of a glass and the molecular structure of a liquid, they look the same. So why does one flow and another is locked in place?

"*There are currently different ways to explain this, why the glass is not moving*," Scalliet says. But no theory is universally agreed upon.

The various explanations involve some very math-heavy invocations of thermodynamics. But in short, scientists are in search of a deeper order to this system that we can't see just in a snapshot—something to explain glass's solidness like you could explain the solidness of table salt by pointing to its crystal structure. The secret is likely in the collective action of the molecules over time, and how they influence one another as the liquid seizes up.

But it's just such a complicated system to unravel. "*It's sort of a massively collective phenomenon where you look at a huge number of atoms and molecules*," Weitz says. "A *lot of the theory of glass is trying to understand how [the molecules] collect together.*"

[continued...]

In practical terms, it matters that scientists don't have a complete theory of glass. For one, it means they simply don't understand glass as well as they do crystalline solids.

With a crystalline solid, you can predict many of the properties of the solid just by looking at its simple crystal structure. Just by knowing the arrangement of the molecules in the crystalline solid, "*you can understand, for example, how the solid will absorb heat,*" Scalliet says, or "*where it will break*." But in the case of glass, "*you have basically an infinite number of arrangements. You don't have this well-known underlying structure*."

That means it's hard to predict the properties of glass. We learn how glass breaks by breaking it and how it holds on to heat by heating it. That leaves the manufacturing of new types of glass to be a bit of trial and error. But the lack of a complete theory also leaves scientists with some fundamental—even existential—questions about what glass truly is.

For one, it's hard to say exactly when a liquid stops being a liquid and starts being a glass. "*There's no clear boundary*," Scalliet says. "*At this moment, we basically have a very anthropocentric way to separate what's a liquid and what's a glass*."

That's because glass will still flow a tiny bit over millions and billions of years. If we lived for that long and experienced the passage of time more quickly, we might not think glass is very mysterious at all. We might think it was a liquid.

It could also be that, also over an immense period, glass will eventually crystallize and become a typical solid. In this light, glass is just liquid "*that's sliding on its way to being a crystal*," Mark Ediger, a chemistry professor at the University of Wisconsin Madison, says. But there's another exciting possibility here: that instead of crystallization, over very long periods, glass can inch closer to the state of "*perfect disorder*," as Ediger describes.

"*Let's suppose that you have boxes*," he says, "*many different boxes of different sizes and shapes, and you're trying to pack them all into the back of a U-Haul*." If you manage to squeeze all the boxes in the back of the U-Haul, with no possible room for any others, and there's only one possible configuration of the boxes that will allow you to do this, that's perfect disorder.

A glass that has achieved perfect disorder would be called an "*ideal*" glass, Ediger says. "*It's not ideal in the sense that it has the best composition to be on the front of your cellphone,*" he says. "*It's ideal in the sense it has the best possible packing of those constituent entities without crystallizing. If you wanted to make it any tighter, you'd have to start having crystals*."

The problem is that no one is sure if ideal glass can actually exist, let alone create it or use the material. Though it would be an exciting discovery, as Ediger says, the material would arguably represent an entirely new phase of matter. Ediger has done some experiments trying to make a glass as ideal as possible, packing molecules into a material one at a time. The problem is that "*the closer you get to the ideal glass, the longer everything takes*," he says. "*In terms of packing the U-Haul, we have one box left and it doesn't quite fit*."

That's because glass will still flow a tiny bit over millions and billions of years. If we lived for that long and experienced the passage of time more quickly, we might not think glass is very mysterious at all. We might think it was a liquid.

There are also studies of 100-million-plus-year-old pieces of amber to see if the material has evolved into a more "ideal" state over its long time on Earth. But the question remains unanswered.

If ideal glass exists, it could help scientists understand the more common kinds of glass better. The solidness of less-than-ideal glass could be explained, in part, by how close it is to being perfectly disordered. (That's because the closer a glass is to the ideal state, the less it's able to reconfigure itself, and the longer it takes to reconfigure itself. And a system that takes a long time to move is "*stiff*," as Ediger says—a.k.a. solid.)

The search for ideal glass is mostly an academic quest that flirts with sublime ideas; the researchers I talked to seemed to love the jigsaw puzzle nature of the problem. But discovering it could also lead to better predicting the properties of glass, and help with engineering new ones. "*If you can identify what this ideal packaging [of molecules] looks like, that's really telling you what the ultimate properties of glasses are,*" Ediger says. "*Now, if you don't make it that well, then you're not going to get those properties, but at least it tells you what you're shooting for*."

Any deeper insight into the nature of glass might help scientists engineer better ones. "*If you understand how physical properties emerge from a given [disordered] structure, then you can start making new materials*," Scalliet says. Like smartphone screens that are bendy, or less likely to break. Or making glass that can trap nuclear waste for longer and longer periods.

The future might be built on more advanced glasses. But for now, we can just appreciate glass for what it is: intensely useful, flowy like a dance floor but rigid like a gem. And deeply, beautifully unknown.

"*Look at this window*," Scalliet says. "*Like, there is this thing, It's everywhere. And we don't understand why it exists*."