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Solid or Liquid? Physicists Redefine States of Matter

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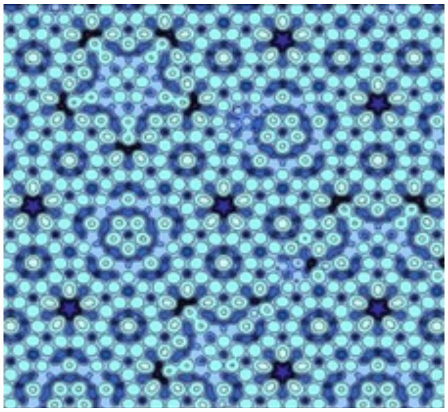
April 3, 2013

email print

The glass walls and floor of the Willis Tower Skydeck in Chicago behave like a solid but look more like a liquid at the atomic level. (Photo: Olga Bandelowa)

Why can you stand on a glacier but not the ocean?

The answer seems simple enough: Liquids flow. Solids don't. The atoms in liquids can slosh around. In solids, they fall lockstep into a crystal lattice. A crystal's endlessly repeating pattern is so stable that it takes a considerable infusion of energy to make the atoms break rank. Or so physics textbooks say.



The atomic patterns in quasicrystals like this model of an aluminium-palladium-manganese surface exhibit order, but never repeat. (Photo: J.W. Evans, Ames Laboratory, U.S. Department

But this long-accepted explanation for the rigidity of solids fails to account for quasicrystals — bizarre solids first discovered in the lab in 1982 and found in nature in 2009. Atoms in quasicrystals are arranged in patterns that never repeat, but the material is nonetheless rigid. So is glass, an amorphous mass of stationary atoms that behaves like a solid but, upon closer inspection, looks more like a liquid frozen in time.

"Glasses have been around for thousands of years," said Daniel Stein, a professor of physics and mathematics at New York University. "Chemists understand them. Engineers understand them. From the point of view of physics, we don't understand them. Why are they rigid?"

Even crystalline solids such as glaciers resist categorization, as their atoms can flow, albeit very

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slowly. And sometimes the reverse also seems true: The ocean feels rigid if you jump onto it from a tall enough glacier. What, then, is the difference between a liquid and a solid?

of Energy)

Physicists in France and the United States are proposing new answers to this fundamental question. As outlined in a March article in the Notices of the American Mathematical Society, the researchers have identified two characteristics of materials that dramatically change form at the intersections of temperature and pressure where liquids turn solid. These characteristics, the physicists say, could define the difference between the two states of matter.

Charles Radin, a mathematical physicist at the University of Texas at Austin, and his former student, David Aristoff, now a mathematician at the University of Minnesota, argue that the main difference between liquids and solids is the way they respond to shear, or twisting forces. Liquids barely resist shear and can easily be sloshed, whereas solids — regardless of whether they are crystals, quasicrystals or glass — resist attempts to change their shape.

The liquid/solid phase transition is not well understood mathematically. (Photo: Dmitry Valberg)

The liquid-solid phase transition, Radin and Aristoff reason, should therefore be marked by the “shear response” of a material jumping from zero to a positive value. And they observed just such a jump for a two-dimensional model material, in which atoms are represented by disks: At low densities corresponding to the material’s liquid phase, it showed no response to shear, but when the disks were densely packed, like the atoms in a solid, shear caused the material to expand. “The crossover where it shows this effect is exactly the density where the system becomes crystalline,” Radin said. “We propose this as a different way of understanding what a solid is.”

The shear response effect is usually obscured by the way physicists do their calculations. To identify the phase boundaries of a material (the curves across which it transitions from solid to liquid to gas), they must simplify their equations by pretending the material is so large that it virtually has no edges. Unfortunately, this simplification ignores the shape of the material, making it difficult to determine whether the shape will change in response to shear.

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Radin and Aristoff’s innovation was to calculate their 2-D model’s response to shear before treating the material as edgeless. This much trickier, reverse-order calculation has yet to be solved in general for all materials, but the approach “is very interesting and could potentially be very useful,” Stein said.

Meanwhile, the physicists in France took a different, but related, tack, reasoning that the difference between solids and liquids is the rate at which they flow. Glass, although it is a solid, is believed to flow very slowly. And the individual atoms in crystalline solids, even diamonds, can hop between defects, or empty spots in the lattice.

The researchers distinguished between the flow speeds of solids and liquids by comparing their viscosities, or responses to a shear that varies with time. (Honey, for example, is a more viscous liquid than water.) For a 2-D model of a crystalline solid, they found that as the shear gets very small, the viscosity of the crystal becomes huge. To see a diamond flowing under the pull of Earth’s gravity, “one would have probably to wait more than the age of the universe,” said Giulio Biroli of the Institute of Theoretical Physics at CEA in Paris.

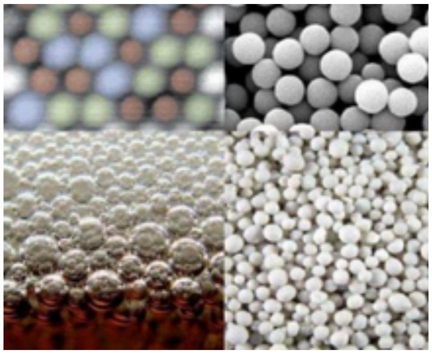
By contrast, ordinary liquids exhibit low viscosity even as the shear approaches zero.

The researchers hypothesized that glass would fall somewhere in between a crystalline solid and a liquid by exhibiting a large but finite viscosity under

small shear. Other physicists have since shown that the prediction is correct for a model glass system, though it has yet to be tested experimentally.

"Our ways are complementary," said Biroli, of the American and French approaches. "If we take both of them, I think we start to understand the difference between a solid and a liquid."

David Ruelle, a Belgian-French mathematical physicist and the author of classic textbooks on statistical mechanics, said a rigorous understanding of solids and liquids might be useful for predicting the behavior of novel materials such as metallic glasses, which have applications in electronics and nanolithography. But in a world where solids and liquids reign, "it is good simply to have a basic understanding," Ruelle said. "I would not say these things will bring you one million dollars very soon."



Many materials at a broad range of scales have a glass phase, including (clockwise from top left): alloys, colloids, fertilizer grains and beer foam. (Images: Courtesy of Giulio Biroli; alloy image from Sugimoto et al., 2007)

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