Some everyday materials have memories, and now they can be erased

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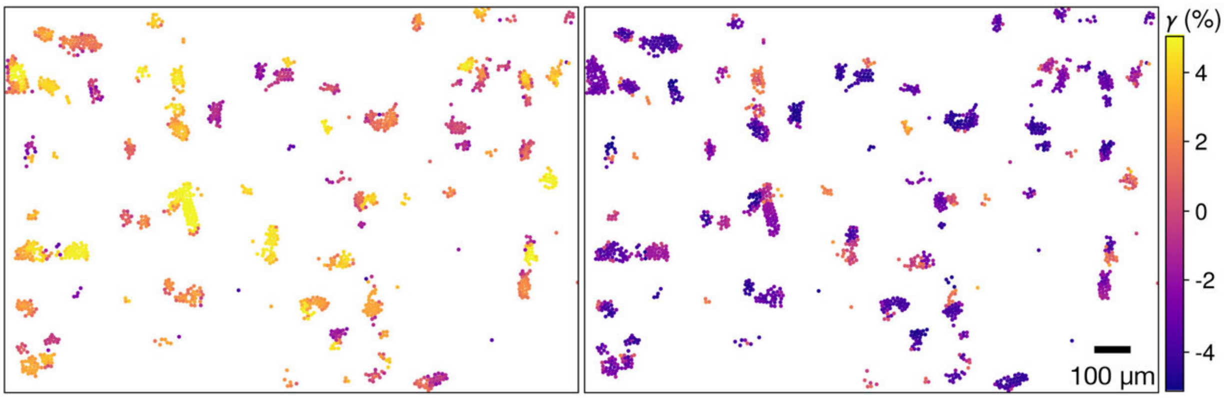

In this study, the research team tracked the locations of 25,000 tiny particles that make up a two-dimensional disordered solid. Groups of particles rearrange as the solid is deformed. This diagram depicts when particles are rearranged as the material is deformed in one direction (left) or the opposite direction (right). Particles with colors at the extreme end of the scale (yellow, blue) deform later in this process. Credit: Keim research group / Penn State

Some solid materials have a memory of how they have previously been stretched out, which impacts how they respond to these kinds of deformations in the future. A new Penn State study lends insight into memory formation in the foams and emulsions common in food products and pharmaceuticals and provides a new method to erase this memory, which could guide how materials are prepared for future use.

"A crease in a piece of paper serves as a memory of being folded or crumpled," said Nathan Keim, associate research professor of physics at Penn State who led the study. "A lot of other materials form memories when they are deformed, heated up, or cooled down, and you might not know it unless you ask the right questions. Improving our understanding of how to write, read, and erase memories provides new opportunities for diagnostics and programming of materials. We can find out the history of a material by doing some tests or erase a material's memory and program a new one to prepare it for consumer or industrial use."

The researchers studied memory in a type of material called disordered solids, which have particles that are often erratically arranged. For example, ice cream is a disordered solid made up of a combination of ice crystals, fat droplets, and air pockets mixed together in a random way. This is in stark contrast to materials with "crystalline structures," with particles arranged in highly ordered rows and columns. Disordered solids are common in food sciences, consumer products, and pharmaceuticals and include foams like ice cream and emulsions like mayonnaise.

"Preparation of materials often includes manipulating them in ways that change the arrangement of their molecules, bubbles, or drops, taking them from a higher energy state to a lower energy, more stable state," said Keim. "For some materials like glass, this involves carefully heating the material so its molecules are unstuck and can arrange themselves in a more organized way. But for some materials, like mayonnaise, heating has destructive or unappetizing side effects. So for materials where heating is not an option, we use a process called mechanical annealing to physically deform the material and bring it to a lower energy state."

Keim and colleagues previously investigated how mechanical annealing of disordered solids can allow a material to a form a memory of that deformation, impacting how it responds to future deformation. In a new paper appearing Oct. 5 in the journal *Science Advances*, the researchers provide a more refined understanding of how memories form in disordered solids and how existing memories can be "read" and even erased.

"We deform our material by shearing, which involves moving one side of the material relative to the other, like pulling the corner of a rectangle to the side so it becomes a parallelogram," said Keim. "By repeating this deformation at the same magnitude many times over, you can essentially inscribe a memory of the deformation, which subtly affects how it responds to deformation of other magnitudes in the future. We clarified the circumstances under which this memory forms in disordered solids and showed how to determine the magnitude of a previous deformation that had been inscribed."

The researchers also demonstrate a new method to erase memories in disordered solids.

"Some of the rules for memory in these materials look a lot like the rules for memory in ferromagnets, something that physicists have been studying intensely for over a hundred years," said Keim. "A refrigerator magnet carries a magnetization that is a kind of memory of magnetic fields that were applied at the factory. To erase these memories, you can apply a strong magnetic field and alternate its direction while you gradually make the field weaker. With our new method, which we call a ring down method, we apply smaller and smaller magnitudes of deformation until the memory has been removed."

Erasing a memory could provide an opportunity for materials scientists to essentially start from a clean slate and then prepare a material in the most advantageous way.

For this study, the researchers simulated a disordered solid using 25,000 tiny plastic particles located at the interface of water and oil in a dish—a setup developed by co-author Dani Medina, an undergraduate at California Polytechnic State University, San Luis Obispo, at the time of the research. The particles are electrostatically charged, repelling each other, and can be deformed with a needle moving along the interface in a controlled manner. The team used a microscope to track the arrangement of the particles in the material.

"Disordered solids are more alike than different, and the microscopic details of their structure —whether its oil drops or foam bubbles or grains or particles—doesn't seem to impact the overall behavior very much," said Keim. "This allows our experiments to provide insight into mechanical annealing and memory formation in many other materials. In the future, we'd like to verify these properties of material memory in three-dimensional disordered solids—the equivalent of mayonnaise or ice cream."

More information: Nathan C. Keim et al, Mechanical annealing and memories in a disordered solid, *Science Advances* (2022). DOI: 10.1126/sciadv.abo1614

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