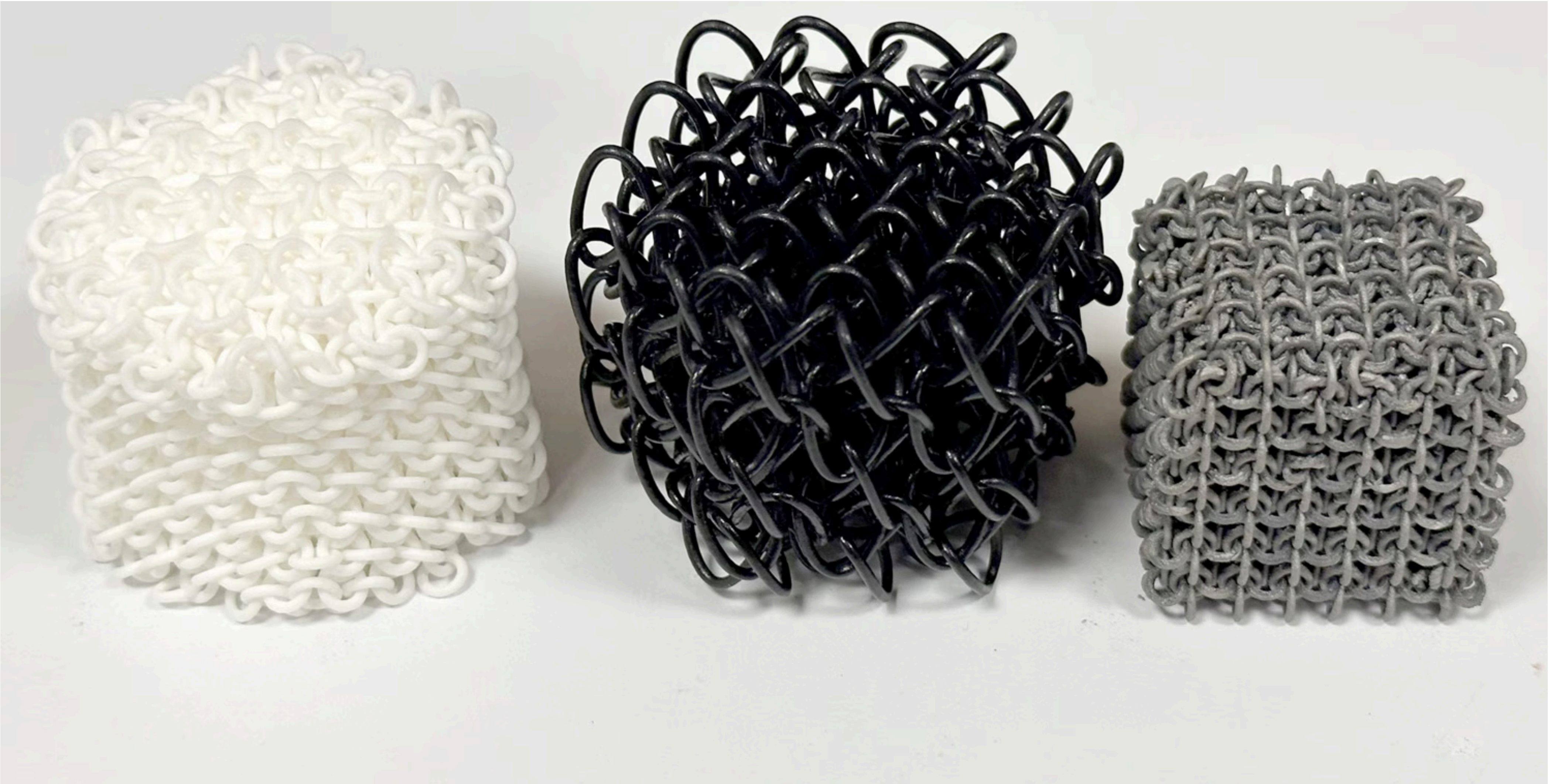
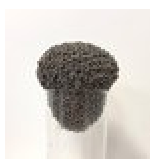
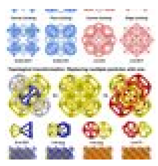
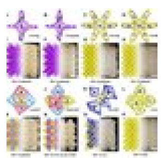


Reimagining Chain Mail: 3D Architected Materials That Adapt and Protect

January 17, 2025

PAMs in Action

Credit: Wenjie Zhou and Peter Holderness/Caltech

Experiments from the Caltech lab of Chiara Daraio, G. Bradford Jones Professor of Mechanical Engineering and Applied Physics and Heritage Medical Research Institute Investigator, have yielded a fascinating new type of matter, neither granular nor crystalline, that responds to some stresses as a fluid would and to others like a solid. The new material, known as PAM (for polycatenated architected materials) could have uses in areas ranging from helmets and other protective gear to biomedical devices and robotics.

PAMs are not found in nature, though their basic form is known to us through the millennia-old manufacture of chain mail: small metal rings linked together to form a mesh, most often used as a flexible form of armor. PAMs, however, are like chain mail on steroids. Following the basic principle of interlocking shapes, like those found in a chain, PAMs are made up of a variety of shapes linked together to form three-dimensional patterns whose configurations are almost unimaginably variable. The resulting materials, which Daraio and her colleagues have rendered using 3D printers, exhibit behaviors not found in other types of materials.

Wenjie Zhou, postdoctoral scholar research associate in mechanical and civil engineering, has been working on these types of materials for two years in Daraio's lab. "I was a chemist, and I wanted to make these structures at a molecular scale, but that proved too challenging. In order to get answers to the questions I had about how these structures behave, I decided to join Chiara's group and study PAMs at a larger scale."

The PAMs that Daraio's group created and studied were first modeled on a computer and were designed to replicate lattice structures found in crystalline substances but with the crystal's fixed particles replaced by entangled rings or cages with multiple sides.

These lattices were then printed out three-dimensionally using a variety of materials, including acrylic polymers, nylon, and metals. Once the PAMs could be held in the palm of one's hand—most of the prototypes are 5-centimeter (2-inch) cubes or spheres with a 5-centimeter diameter—they were exposed to various types of physical stress. "We started with compression," Zhou explains, "compressing the objects a bit harder each time. Then we tried a simple shear, a lateral force, like what you would apply if you were trying to tear the material apart. Finally, we did rheology tests, seeing how the materials responded to twisting, first slowly and then more quickly and strongly."

In some scenarios, these PAMs behaved like liquids. "Imagine applying a shear stress to water," Zhou says. "There would be zero resistance. Because PAMs have all these coordinated degrees of freedom, with the rings and cages they are composed of sliding against one another as the links of a chain would, many have very little shear resistance." But when these structures are compressed, they may become fully rigid, behaving like solids.

This dynamism makes PAMs unique. "PAMs are really a new type of matter," Daraio says. "We all have a clear distinction in mind when we think of solid materials and granular matter. Solid materials are often described as crystalline lattices. This is what you see in the classic ball-and-stick models of atomic, chemical, or larger crystalline structures. It is these materials that have formed our conventional understanding of solid matter. The other class of materials is granular, as we see in substances like rice, flour, or ground coffee. These materials are made up of discrete particles, free to move and slide relative to one another."

PAMs defy this binary classification. "With PAMs, the individual particles are linked as they are in crystalline structures, and yet, because these particles are free to move relative to one another, they flow, they slide on top of each other, and they change their relative positions, more like grains of sand," Daraio explains. "PAMs can be very different from one another. You can print them in squishy materials or hard ones. You can change the shape of each particle, and you can change the lattice that you use to connect these particles. Each of these parameters affects the behavior of the resulting material. But all of them show a characteristic transition between fluid and solid-like behavior. This transition may happen under different circumstances, but it always happens."

"Architected materials have been a significant subfield in material science and engineering for the past 20 to 30 years," Daraio says. "But as hybrids between granular materials and elastic deformable materials, PAMs are exciting and new. We have theories to describe granular matter and theories to describe elastic deformable matter, but nothing that captures these in-between materials. It's a fascinating frontier that promises to redefine what materials are and how they behave."

At this point, potential uses for PAMs are largely speculative but nevertheless intriguing, Daraio says: "These materials have unique energy-absorption properties. Because each element can slide and rotate and reorganize relative to each other, they can dissipate energy very efficiently," making them better candidates for use in helmets or other forms of protective gear than the currently used foams. This property makes them similarly attractive for use in packaging or in any environment where cushioning or stabilization is required.

Experiments with microscale PAMs have shown that they will expand or contract in response to applied electrical charges as well as physical forces, suggesting possible uses in biomedical devices or soft robotics.

Co-author Liuchi Li (PhD '20), now assistant professor of civil and environmental engineering at Princeton University, is enthusiastic about the future of PAMs: "We can envision incorporating advanced artificial intelligence techniques to accelerate the exploration of this vast design space. We are only scratching the surface of what is possible."

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