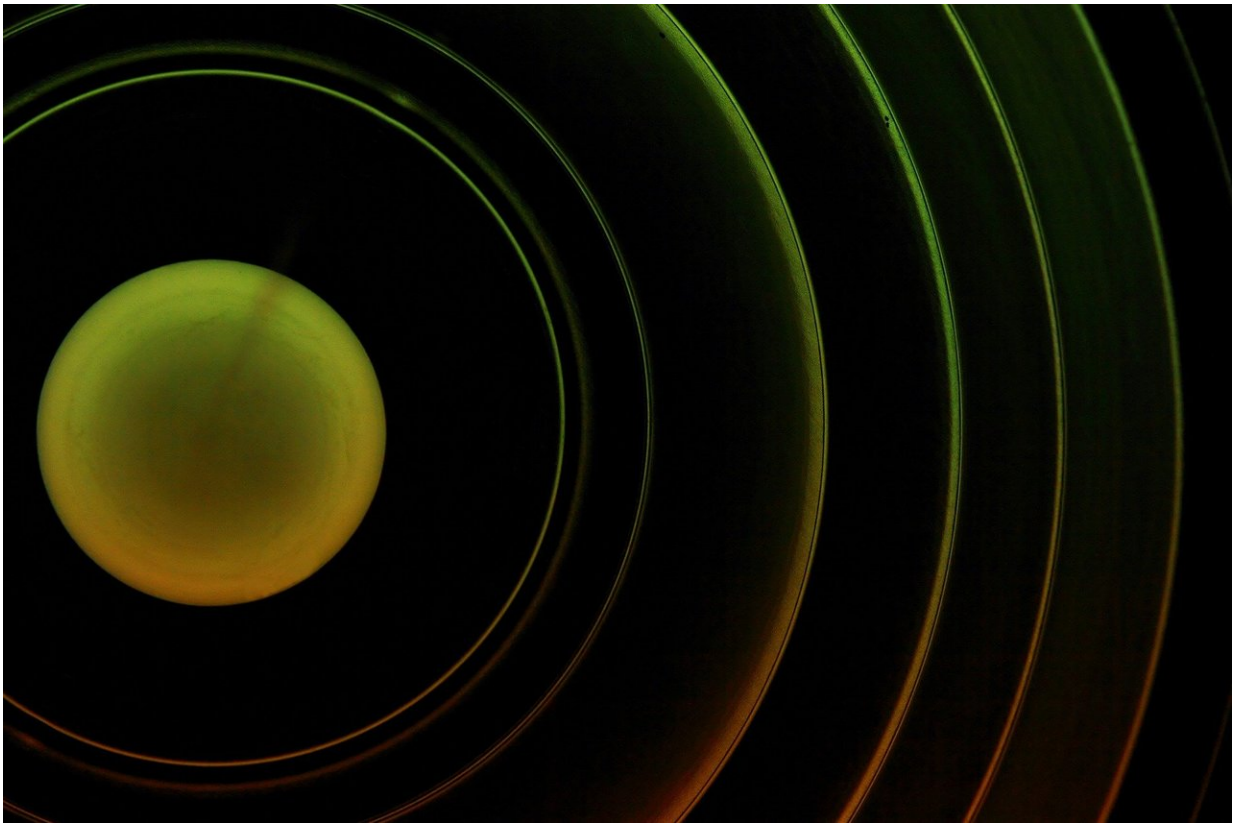


New laws of attraction: Scientists print magnetic liquid droplets

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Inventors of centuries past and scientists of today have found ingenious ways to make our lives better with magnets—from the magnetic needle on a compass to magnetic data storage devices and even MRI (magnetic

resonance imaging) body scan machines.

All of these technologies rely on magnets made from [solid materials](#). But what if you could make a magnetic device out of liquids? Using a modified 3-D printer, a team of scientists at Berkeley Lab have done just that. Their findings, to be published July 19 in the journal *Science*, could lead to a revolutionary class of printable liquid devices for a variety of applications from artificial cells that deliver targeted cancer therapies to flexible liquid robots that can change their shape to adapt to their surroundings.

"We've made a new material that is both liquid and magnetic. No one has ever observed this before," said Tom Russell, a visiting faculty scientist at Berkeley Lab and professor of polymer science and engineering at the University of Massachusetts, Amherst who led the study. "This opens the door to a new area of science in magnetic soft matter."

Jam sessions: making magnets out of liquids

For the past seven years, Russell, who leads a program called Adaptive Interfacial Assemblies Towards Structuring Liquids in Berkeley Lab's Materials Sciences Division, has focused on developing a new class of materials—3-D-printable all-liquid structures.

One day, Russell and the current study's first author Xubo Liu came up with the idea of forming liquid structures from ferrofluids, solutions of iron-oxide particles that become strongly magnetic, but only in the presence of another magnet. "We wondered, if a ferrofluid can become temporarily magnetic, what could we do to make it permanently magnetic, and behave like a solid magnet but still look and feel like a liquid?" said Russell.

To find out, Russell and Liu—a graduate student researcher in Berkeley Lab's Materials Sciences Division and a doctoral student at the Beijing University of Chemical Technology - [used a 3-D-printing technique](#) they had developed with former postdoctoral researcher Joe Forth in Berkeley Lab's Materials Sciences Division to print 1 millimeter droplets from a ferrofluid solution containing iron-oxide-nanoparticles just 20 nanometers in diameter (the average size of an antibody protein.)

Using surface chemistry and sophisticated atomic force microscopy techniques at the [Molecular Foundry](#), co-authors Paul Ashby and Brett Helms of Berkeley Lab revealed that the nanoparticles formed a solid-like shell at the interface between the two liquids through a phenomenon called "interfacial jamming," which causes the nanoparticles to crowd at the droplet's surface, "like the walls coming together in a small room jampacked with people," said Russell.

To make them magnetic, the scientists placed the droplets by a magnetic coil in solution. As expected, the magnetic coil pulled the iron-oxide nanoparticles toward it.

But when they removed the magnetic coil, something quite unexpected happened.

Like synchronized swimmers, the droplets gravitated toward each other in perfect unison, forming an elegant swirl. "Like little dancing droplets," said Liu.

Somehow, these droplets had become permanently magnetic. "We almost couldn't believe it," said Russell. "Before our study, people always assumed that permanent magnets could only be made from solids."

Measure by measure, it's still a magnet

All magnets, no matter how big or small, have a [north pole](#) and a south pole. Opposite poles are attracted to each other, while the same poles repel each other.

Through magnetometry measurements, the scientists found that when they placed a magnetic field by a droplet, all of the nanoparticles' north-south poles, from the 70 billion iron-oxide nanoparticles floating around in the droplet to the 1 billion nanoparticles on the droplet's surface, responded in unison, just like a solid magnet.

Key to this finding were the iron-oxide nanoparticles jamming tightly together at the droplet's surface. With just 8 nm between each of the billion nanoparticles, together they created a solid surface around each liquid droplet. Somehow, when the jammed nanoparticles on the surface are magnetized, they transfer this magnetic orientation to the particles swimming around in the core, and the entire droplet becomes permanently magnetic, just like a solid, Russell and Liu explained.

The researchers also found that the droplet's magnetic properties were preserved, even if they divided a droplet into smaller, thinner droplets about the size of a human hair, added Russell.

Among the magnetic droplets' many amazing qualities, what stands out even more, Russell noted, is that they change shape to adapt to their surroundings, morphing from a sphere to a cylinder to a pancake, or a tube as thin as a strand of hair, or even to the shape of an octopus—all without losing their magnetic properties.

The droplets' can also be tuned to switch between a magnetic mode and a nonmagnetic mode. And when their magnetic mode is switched on, their movements can be remotely controlled as directed by an external magnet, Russell added.

Liu and Russell plan to continue research at Berkeley Lab and other national labs to develop even more complex 3-D-printed magnetic liquid structures, such as a liquid-printed artificial cell, or miniature robotics that move like a tiny propeller for noninvasive yet targeted delivery of drug therapies to diseased cells.

"What began as a curious observation ended up opening a new area of science," said Liu. "It's something all young researchers dream of, and I was lucky to have the chance to work with a great group of scientists supported by Berkeley Lab's world-class user facilities to make it a reality," said Liu.

More information: X. Liu et al., "Reconfigurable ferromagnetic liquid droplets," *Science* (2019). science.sciencemag.org/cgi/doi/10.1126/science.aaw8719

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