Engineers develop a computer that operates on water droplets

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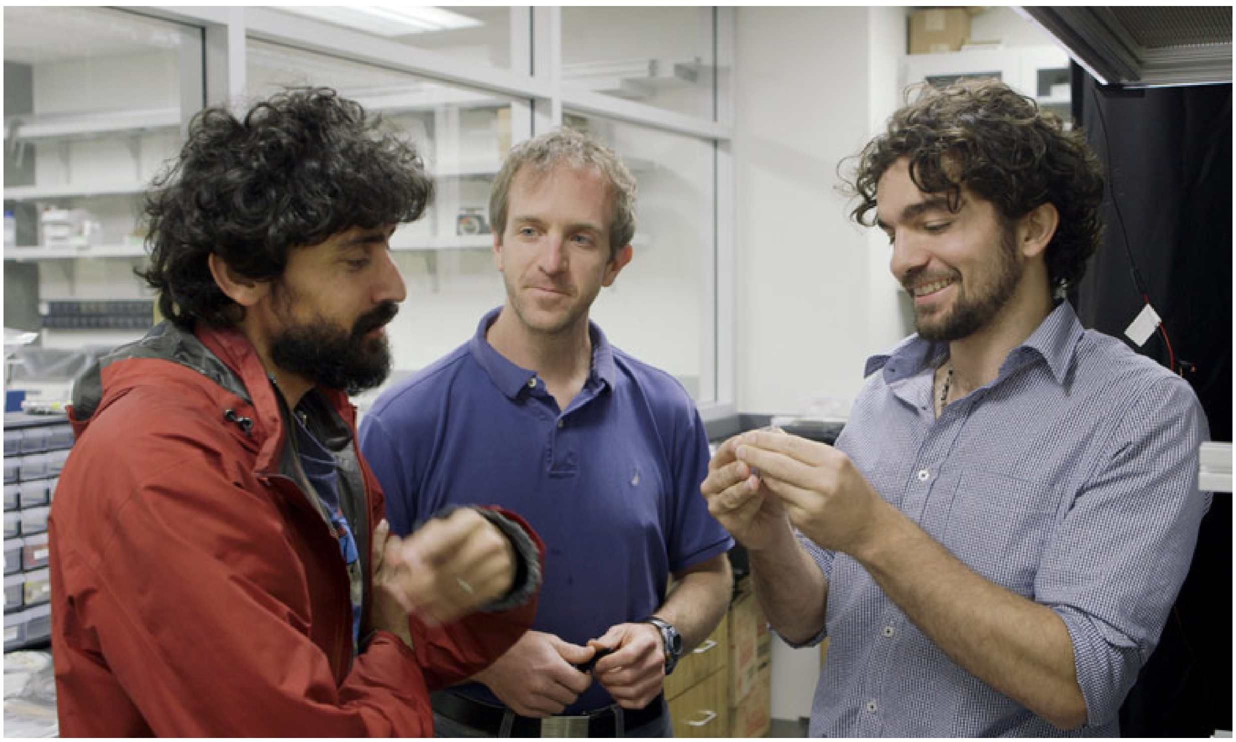

Stanford Assistant Professor Manu Prakash, left, and graduate students Jim Cybulski and Georgios Katsikis developed the water drop computer.

Computers and water typically don't mix, but in Manu Prakash's lab, the two are one and the same. Prakash, an assistant professor of bioengineering at Stanford, and his students have built a synchronous computer that operates using the unique physics of moving water droplets.

The computer is nearly a decade in the making, incubated from an idea that struck Prakash when he was a graduate student. The work combines his expertise in manipulating droplet fluid dynamics with a fundamental element of computer science – an operating clock.

"In this work, we finally demonstrate a synchronous, universal droplet logic and control," Prakash said.

Because of its universal nature, the droplet computer can theoretically perform any operation that a conventional electronic computer can crunch, although at significantly slower rates. Prakash and his colleagues, however, have a more ambitious application in mind.

"We already have digital computers to process information. Our goal is not to compete with electronic computers or to operate word processors on this," Prakash said. "Our goal is to build a completely new class of computers that can precisely control and manipulate physical matter. Imagine if when you run a set of computations that not only information is processed but physical matter is algorithmically manipulated as well. We have just made this possible at the mesoscale."

The ability to precisely control droplets using fluidic computation could have a number of applications in high-throughput biology and chemistry, and possibly new applications in scalable digital manufacturing.

The results are published in the current edition of *Nature Physics*.

The crucial clock

For nearly a decade since he was in graduate school, an idea has been nagging at Prakash: What if he could use little droplets as bits of information and utilize the precise movement of those drops to process both information and physical materials simultaneously. Eventually, Prakash decided to build a rotating magnetic field that could act as clock to synchronize all the droplets. The idea showed promise, and in the early stages of the project, Prakash recruited a graduate student, Georgios "Yorgos" Katsikis, who is the first author on the paper.

Computer clocks are responsible for nearly every modern convenience. Smartphones, DVRs, airplanes, the Internet – without a clock, none of these could operate without frequent and serious complications. Nearly every computer program requires several simultaneous operations, each conducted in a perfect step-by-step manner. A clock makes sure that these operations start and stop at the same times, thus ensuring that the information synchronizes.

The results are dire if a clock isn't present. It's like soldiers marching in formation: If one person falls dramatically out of time, it won't be long before the whole group falls apart. The same is true if multiple simultaneous computer operations run without a clock to synchronize them, Prakash explained.

"The reason computers work so precisely is that every operation happens synchronously; it's what made digital logic so powerful in the first place," Prakash said.

A magnetic clock

Developing a clock for a fluid-based computer required some creative thinking. It needed to be easy to manipulate, and also able to influence multiple droplets at a time. The system needed to be scalable so that in the future, a large number of droplets could communicate amongst each other without skipping a beat. Prakash realized that a rotating magnetic field might do the trick.

Katsikis and Prakash built arrays of tiny iron bars on glass slides that look something like a Pac-Man maze. They laid a blank glass slide on top and sandwiched a layer of oil in between. Then they carefully injected into the mix individual water droplets that had been infused with tiny magnetic nanoparticles.

Next, they turned on the magnetic field. Every time the field flips, the polarity of the bars reverses, drawing the magnetized droplets in a new, predetermined direction, like slot cars on a track. Every rotation of the field counts as one clock cycle, like a second hand making a full circle on a clock face, and every drop marches exactly one step forward with each cycle.

A camera records the interactions between individual droplets, allowing observation of computation as it occurs in real time. The presence or absence of a droplet represents the 1s and 0s of binary code, and the clock ensures that all the droplets move in perfect synchrony, and thus the system can run virtually forever without any errors.

"Following these rules, we've demonstrated that we can make all the universal logic gates used in electronics, simply by changing the layout of the bars on the chip," said Katsikis. "The actual design space in our platform is incredibly rich. Give us any Boolean logic circuit in the world, and we can build it with these little magnetic droplets moving around."

The current paper describes the fundamental operating regime of the system and demonstrates building blocks for synchronous logic gates, feedback and cascadability – hallmarks of scalable computation. A simple-state machine including 1-bit memory storage (known as "flip-flop") is also demonstrated using the above basic building blocks.

A new way to manipulate matter

The current chips are about half the size of a postage stamp, and the droplets are smaller than poppy seeds, but Katsikis said that the physics of the system suggests it can be made even smaller. Combined with the fact that the magnetic field can control millions of droplets simultaneously, this makes the system exceptionally scalable.

"We can keep making it smaller and smaller so that it can do more operations per time, so that it can work with smaller droplet sizes and do more number of operations on a chip," said graduate student and co-author Jim Cybulski. "That lends itself very well to a variety of applications."

Prakash said the most immediate application might involve turning the computer into a high-throughput chemistry and biology laboratory. Instead of running reactions in bulk test tubes, each droplet can carry some chemicals and become its own test tube, and the droplet computer offers unprecedented control over these interactions.

From the perspective of basic science, part of why the work is so exciting, Prakash said, is that it opens up a new way of thinking of computation in the physical world. Although the physics of computation has been previously applied to understand the limits of computation, the physical aspects of bits of information has never been exploited as a new way to manipulate matter at the mesoscale (10 microns to 1 millimeter).

Because the system is extremely robust and the team has uncovered universal design rules, Prakash plans to make a design tool for these droplet circuits available to the public. Any group of people can now cobble together the basic logic blocks and make any complex droplet circuit they desire.

"We're very interested in engaging anybody and everybody who wants to play, to enable everyone to design new circuits based on building blocks we describe in this paper or discover new blocks. Right now, anyone can put these circuits together to form a complex droplet processor with no external control – something that was a very difficult challenge previously," Prakash said.

"If you look back at big advances in society, computation takes a special place. We are trying to bring the same kind of exponential scale up because of computation we saw in the digital world into the physical world."

More information: "Synchronous universal droplet logic and control." *Nature Physics* (2015) DOI: 10.1038/nphys3341

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