In search of lost memories

In 1980, the physicist David Bohm published a book entitled *Wholeness and the Implicate Order*, in which he speculated about hidden structures that might somehow lie behind the mystery of quantum entanglement — the weird linking together of distant and apparently independent systems. As a suggestive analogy for the kind of structures he had in mind, Bohm referred to a famous memory effect in fluids. Place a blob of ink into a viscous liquid confined in the narrow gap between two cylindrical walls, and start rotating the inner cylinder. Shearing in the fluid will smear the ink out into increasingly fine ribbons, which eventually vanish. The ink is apparently gone, leaving only a featureless expanse of fluid.

But the ink spot in fact remains, only in a hidden or 'implicate' form. Rotate the inner cylinder again in the opposite direction and the spot eventually reappears. The example demonstrates the persistence within the system of hidden relationships storing precise details of its prior state. For Bohm, the idea was a useful analogy. Perhaps, he wondered, interactions between particles re-order space–time in some way that leaves a permanent memory of their interaction, no matter where they go. Unfortunately, he was never able to develop the idea much further for quantum physics.

Similar memory effects occur in myriad physical and biological systems, and memory always involves a storing of information, regardless of how much it may be transformed. Quantum physics aside, physicist Nathan Keim and colleagues in a recent review explore how this theme offers a novel and potentially very useful way to organize thinking about systems out of equilibrium (Kiem, N. C. et al. *Rev. Mod. Phys.* https://go.nature.com/2IyJgOe; 2019). As they argue, the various memory effects that arise show a surprising tendency to fall into classes of quite similar behaviour, even though they occur in very different physical systems.

There are no memory effects in equilibrium, as the description of an equilibrium state does not require any historical account. In contrast, systems out of equilibrium allow the persistence of delicate relationships — correlations in space or time, or material variables — reflecting prior conditions. In one of the simplest memory phenomena, a material remembers the direction in which it was most recently driven — the obvious example being digital magnetic storage systems, which use strong magnetic fields to write 0s or 1s into the polarities of magnetic domains.

As Keim and colleagues note, however, the same phenomenon occurs in macroscopic settings too. Take a pair of interacting gears. Rotating one gear to drive a second adjacent gear always requires overcoming some frictional resistance. Stop the rotation, and then resume again, the resistance comes back immediately. However, suppose the first gear rotates a certain amount, stops, and then reverses direction, driving the gear in the opposing direction. Now the resistance does not appear for a brief moment, because gears only work if they have a tolerance — if the teeth of one gear, when reaching into the indentations of the other, leave small gaps. Hence, the precise arrangement of the gears — the location of the gaps — records the last sense in which the gears were rotated. A geared mechanism may superficially look to have one unique resting state, but it doesn't.

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As Keim and colleagues describe, similar effects occur in systems of suspended colloids under rotation, or the electrical driving of charge density waves in some solids. Despite physical differences, in all such systems the simple direction of a past driving leaves an indelible trace revealing the system history.

Another common memory effect stores not the direction of last driving, but the maximum value of driving over some historical period. Take a ball of crumpled paper held inside a piston, with a mass M resting atop the piston. Leaving the mass in place for a long time 'trains' the crumpled paper, and after 'training', one can explore how the height of the piston changes under new applied masses. For masses less than M, one finds that the measurements all fall onto a simple reproducible curve. But if the mass used exceeds the training mass M, the relation between applied mass and height changes, even for masses less than M.

In effect, the original training load M leaves a memory in the ball's structure, reflecting the largest load it has borne. Future loadings follow a reproducible curve, unless they exceed the previous training load. This causes new inelastic changes in the ball, putting a new lasting memory in the structure of the system. Similar effects occur in many other natural systems under forcing, including rubber samples under stretching and the compaction of soil.

Another curious effect is shape memory, dramatically illustrated by a nickel titanium wire in a tangled shape at room temperature, which abruptly adopts the highly ordered shape of a paper clip when heated sufficiently. In this case, the memory is the result of a basic structural phase transition. For this alloy, the stable crystalline phase at high temperatures is a simple cubic lattice (austenite), whereas at lower temperatures the material adopts a lower-symmetry phase (martensite). Formation of the ordered paper clip phase under high-temperature conditions makes this the preferred shape for the austenite crystal. Heat it up, that's what you get.

When the paper clip cools down, however, it microscopically goes from austenite to martensite. Remarkably, it can then be distorted into many different shapes. The lower-symmetry martensite phase exists in alternating orientations, which are mirror images. Under stress, the orientation of any martensite region can flip to its mirror image, so large deformations do not cause any change in the network of atomic bonds. Deform as you like, it stays that way. But if heated, it remembers its birth. When the wire is heated, the microstructure returns to the austenite phase, which again adopts the paper clip form. This effect, the authors note, has been used in clever medical applications, such as a stent activated by body temperature to expand inside a blood vessel.

These and other memory effects share a great deal with the ink dot in the viscous fluid — information appears to be lost due to material treatment, but is actually only put into a hidden state from which it can be retrieved. Keim and colleagues' review ranges far beyond the few examples mentioned here, including more complex memory effects in systems under ageing or cyclic forcing, and where a system's dynamics store a sharp memory of an initial condition. Of course, most real-world materials are storing such memories all the time. It's only in the simplest cases that we can follow the process in detail. ❐

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