MATERIALS SCIENCE

Synchronized tumbling particles

Magnetic particles have been made that undergo synchronized oscillations when suspended in liquid in a rotating magnetic field. This discovery links the fields of nonlinear dynamics and materials science. SEE LETTER P.578

SABINE H. L. KLAPP

In 1665, the Dutch scientist Christiaan Huygens discovered that two pendulum clocks mounted on the same wall synchronize with one another — their pendulums swing with the same frequency but exactly out of phase. The origin of this effect is weak coupling of the clocks mediated through the wall's vibrations. Since then, the seemingly old topic of synchronization has developed into one of the most actively studied phenomena, in such diverse contexts as coupled lasers in optics, firing neurons in the brain and people applauding at concerts. So far, however, it has mostly been of conceptual interest to scientists in the fields of applied mathematics, nonlinear dynamics and statistical physics. But with Yan and colleagues' report[1] on page 578 of this issue, the topic now enters the field of materials science. They describe the use of synchronization as a design principle for making micrometre-scale structures.

Figure 1 | Two-faced deity. The Roman god Janus has inspired materials scientists to prepare particles that have two distinct faces — such as the magnetic particles reported by Yan *et al.*[1] that exhibit synchronized behaviour.

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Yan *et al.* demonstrate their approach in a colloid — a liquid suspension of micrometre-sized particles. The authors' particles are capped on one side with nickel, a magnetically sensitive material, and so are described as magnetic Janus particles; the term Janus alludes to the Roman god who had two different faces on opposite sides of his head (Fig. 1), just as the colloidal particles have a magnetic and a non-magnetic side.

So how can magnetic Janus colloid particles synchronize their behaviour? One key feature of synchronizing dynamic systems is that each unit performs self-sustained oscillations[2]. Yan and colleagues induced oscillations of their Janus particles by placing them in a precessing magnetic field (in which the vector defining the field rotates about the field's directional axis). In this situation, a conventional (paramagnetic) colloidal sphere would acquire a magnetic dipole moment that slavishly follows the motion of the field. The authors' particles, however, are different, because their geometry induces a direction-dependent magnetic response to the field. This causes the axis of symmetry of each particle to undergo a persistent, oscillating motion that resembles the 'nutation' movement of a gyroscope[1]. Both the phase and the frequency of this oscillation are free (they are not determined by the field), so that the oscillation has adaptable degrees of freedom.

Consider now two magnetic Janus particles in a precessing field. Yan *et al.* observed that, if the spheres are far apart, their oscillations are essentially independent. But at closer distances, each particle is affected by the other's magnetic field. This leads to a dipole–dipole interaction between the particles; the presence of an interaction is the second main ingredient needed for synchronization. Moreover, unlike the oscillatory units in many conventional networks, the authors' magnetic particles can adjust their spatial positions, and so the coupling strength between them. As a consequence, not only do they synchronize their oscillatory phase and frequency, but they also arrange into a dimer-like cluster with 'phase-locked' motion of the magnetic caps — the caps move in such a way that the relative orientation between them does not change (see Fig. 1c of the paper[1]).

Yan *et al.* went on to investigate suspensions of many Janus particles, using a combination of state-of-the-art experimental techniques, computer simulations and theory. They consistently found that synchronization causes the particles to assemble into stable tubular structures (see Fig. 2b of the paper[1]), in such a way that the dynamics of particles inside the tubes is coherent and nutation-like. The phase dynamics of the entire tube can be described by the Adler equation of synchronization (which was first suggested by the Japanese physicist Yoshiki Kuramoto in one of the earliest theoretical descriptions of synchronized oscillators[3]). This is remarkable, because it implies that the complicated tumbling of all the particles in the tube can effectively be considered as a single-particle problem that involves only one phase.

Perhaps not surprisingly, however, Yan and colleagues' colloidal system is far more complex than conventional oscillators. For example, when the authors induced loss of synchronization by changing the field angle (the angle at which the magnetic field precesses about its directional axis), the tubes dissociated into loosely packed zigzag chains. Moreover, they observed that, by slightly varying the parameters of their system, they could select which of several different possible tubular structures forms.

It has long been recognized by materials scientists that complex colloids, such as Janus spheres, form excellent building blocks for nano- and microscale structures, including tubes[4]. However, such structures are traditionally generated by self-assembly processes at equilibrium — that is, the particles form ordered structures because of static particle–particle or particle–field interactions[5]. In these equilibrium systems, different self-assembled structures correspond to different configurations that simultaneously minimize the total energy of the system and maximize the entropy. By contrast, Yan and colleagues' tubular structures are generated by a self-organization process that is not at equilibrium. Their discovery forges a link between synchronization and self-assembly, and will certainly stimulate investigations of other condensed soft-matter systems, from the molecular to the microscale.

There has been enormous recent progress

in creating new colloidal building blocks[6], and it seems likely that many of these could be synchronized when placed in time-dependent fields or exposed to forces that dissipate energy (shear flow). This could open the way to colloidal assemblies relevant to materials science and engineering, including structures that are useful for fluid transport. Such behaviour can be seen in biophysical contexts — for example, the synchronous motion of oscillating organs such as flagella is known to be crucial for the self-propulsion of cells[7].

Another innovative possibility arising from Yan and colleagues' work is the idea that the dynamics of a colloidal system could be manipulated to form specific assemblies at will. This deliberate selection could perhaps be facilitated using ideas from control theory — a well-established framework in mathematics and engineering for manipulating the dynamics of nonlinear systems to obtain desired outputs or to stabilize specific states.

Finally, it would be interesting to explore how studies of nonlinear systems could profit from the development of analogous physical systems by materials scientists. For instance, Yan and collaborators' magnetic suspension can be broadly viewed as a network involving non-local coupling of particles. Such networks have been predicted[8] to spontaneously form 'chimaera' states (which contain domains exhibiting synchronized dynamics and others that have desynchronized dynamics). These states have been experimentally realized only recently in optical[9] and chemical systems[10]. An intriguing question, therefore, is whether Yan and co-workers' magnetic Janus colloids also form chimaera states. If such routes of research are productive, colloidal magnetic suspensions could become model systems for nonlinear behaviour, similar to their well-established role for proving concepts from equilibrium statistical physics[11]. ■

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PALAEOANTHROPOLOGY

Sharpening the mind

The discovery of stone tools dating to 71,000 years ago at a site in South Africa suggests that the humans making them had developed the capacity for complex thought, and passed this knowledge down the generations. SEE LETTER P.590

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The origin of human consciousness has historically been of interest to philosophers, clerics, linguists, psychologists and anthropologists. In the past decade, it has also become a key issue for archaeologists. Did the modern manner of human thinking emerge early or late in our species' history, and did it evolve gradually or suddenly? On page 590 of this issue, Brown *et al.*[1] report the discovery of minute stone artefacts that indicate that the bow and arrow was used by people in Africa as early as 71,000 years ago. The manufacture and use of this weaponry system strongly suggest that *Homo sapiens* had by this time already attained mastery of complex technology and ideas*.

Some researchers maintain that there is a disconnect between the appearance of modern human anatomy, which the fossil record shows was present in Africa by 200,000 years (200 kyr) ago[2], and the emergence of modern human behaviour, which they argue arose as late as 40 kyr ago[3]. A proposed explanation for this time lag is that a genetic mutation that affected cognitive capability occurred sometime between 50 and 40 kyr ago, and persisted thereafter[3]. However, I believe that modern cognitive capacity emerged at the same time as modern anatomy, and that various aspects of human culture arose gradually over the course of subsequent millennia[4]. Brown and colleagues' findings go some way to supporting this hypothesis.

Africa is vast and has been populated by humans and their hominin ancestors for more than 5 million years, yet only a small fraction of the continent has been explored systematically by archaeologists. The vagaries of the preservation of artefacts and fossils also affect what we can know about the past. So it is not surprising that a complete, continuous record of human activities has not been documented.

Even if the record were more complete, it would still be likely that many aspects of past behaviour would be represented patchily or not at all. But some scientists suggest that the gaps in the record are meaningful, reflecting the incomplete development of human cultural capacity[3], the isolation of small dispersed prehistoric populations, or the inherent variability of human adaptation. Certain types of evidence believed to represent modern thought are found repeatedly, but at sites scattered across Africa and dating to disparate times. Whether the discontinuities observed in the current record are simply a manifestation of an incomplete record or a real reflection of early *H. sapiens*' inability to maintain innovations and communicate them to others remains a topic of debate.

Another consideration is that the date for the appearance of modern human behaviour will, of course, depend on the criteria used to recognize it[5]. Researchers have employed a variety of measures for this purpose, but most recent discussions[6] have opted for artefacts with symbolic content, such as art or ornaments, as the defining benchmark for modern cognitive capacity. The reasoning behind this is that the production of such objects requires the ability to manipulate symbols, and this, by extension, indicates the presence of language. Some researchers include the use of pigment as a signal of symbolic thought[4,6,7], and the record shows that colouring materials may have been used as early as 200 or 300 kyr ago[4,8] (Fig. 1). Body ornaments, such as beads[9–12], and carved decorations on everyday objects[13,14] are almost universally accepted as evidence of symbolic thought, and such items appear in the African record between 100 and 60 kyr ago. But critics of these claims contend that the link between the material objects and the mode of thought is not well established[15], or that the dating of the objects or the context in which they have been found is suspect.

Brown and co-authors take a different approach. They argue that complex technology demonstrates the capacity for complex ideas and for transmission of these ideas, and hence for language. This reasoning stems from the authors' finding of small stone 'bladelets' (microliths) at Pinnacle Point Site 5–6 (PP5–6) in South Africa. The authors provide superb

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