A nonbiological system offers insight into biological synchronization

Porous microparticles suspended in a reagent solution can make the transition to synchronous activity in two ways—one gradual, the other sudden.

Many biological systems—from cells to tissues to whole organisms—exhibit rhythmic or oscillatory behavior. And those oscillations can synchronize: Fireflies can flash in unison, and neurons and heart cells operate in synchrony. To gain an understanding of how such synchronizations arise, biologists often look at populations of single-celled organisms that display collective oscillations in cellular processes like metabolism. But the complexity of living cells makes unraveling the synchronization mechanisms a challenge.

Now, researchers led by Kenneth Showalter of West Virginia University (WVU) have studied a nonbiological system of thousands of oscillators and found that the system undergoes two types of synchronization transition thought to occur in biological systems.[1] Their system is simple enough to be theoretically understood and mathematically modeled. Showalter and colleagues' work is relevant to populations of globally coupled oscillators—that is, systems in which each oscillator is linked to all the others, whether through a common electric potential, exchange of a signaling chemical with an external bath, or other means.

The two types of transition the researchers observed are a Kuramoto-type transition and a dynamical quorum-sensing transition. In the Kuramoto transition—named after Yoshiki Kuramoto, who developed much of its mathematical formalism—individual components of the system oscillate out of synchrony at low number density and gradually synchronize at higher number density. In the dynamical quorum-sensing transition, components do not oscillate at all at low number density, and above a threshold density they suddenly begin oscillating in near-perfect synchrony.

Chemical oscillations

The researchers used a form of the oscillating Belousov–Zhabotinsky (BZ) reaction based on the catalyst ferroin, which doubles as an indicator as it oscillates between its red, reduced form and its blue, oxidized form. The major features of the reaction are shown in figure 1. In one process in the oscillation cycle, shown in figure 1a, the so-called activator species $HBrO_2$ catalyzes its own production: A molecule of $HBrO_2$ reacts with a molecule of $HBrO_3$ (a reagent supplied to the system in abundance) to produce two BrO_2 radicals, which react with reduced ferroin to produce two more $HBrO_2$ molecules. The more $HBrO_2$ is present, the faster it is produced.

The newly oxidized ferroin then reacts with bromomalonic acid (BrMA, another abundant reagent), as shown in figure 1b. One product of that reaction is the inhibitor species Br^-, so called because it consumes $HBrO_2$ and shuts down its autocatalysis. When most of the ferroin is back in its reduced form, the production of Br^- slows, $HBrO_2$ levels start to rise again, and the cycle begins anew. The oscillations continue until all the initial $HBrO_3$ is consumed.

In the system the researchers studied, the ferroin was loaded onto porous cation-exchange particles 200 μm in diameter, which were placed in a solution containing the rest of the chemical species. On each particle, the reaction proceeded as described above; in the rest of the solution, $HBrO_2$ could not be produced (since that would require ferroin), but it could be consumed by reacting with Br^-.

The idea of looking at a BZ reaction with the catalyst immobilized on cation-exchange particles originated in Showalter's 1989 work with Jerzy Maselko.[2] The system was first used as a model of biological synchronization in a 2006 study by Annette Taylor of the University of Leeds, her student Rita Toth, and Mark Tinsley of WVU.[3] They found that when they stirred the reaction mixture, particles underwent a Kuramoto-type synchronization transition.

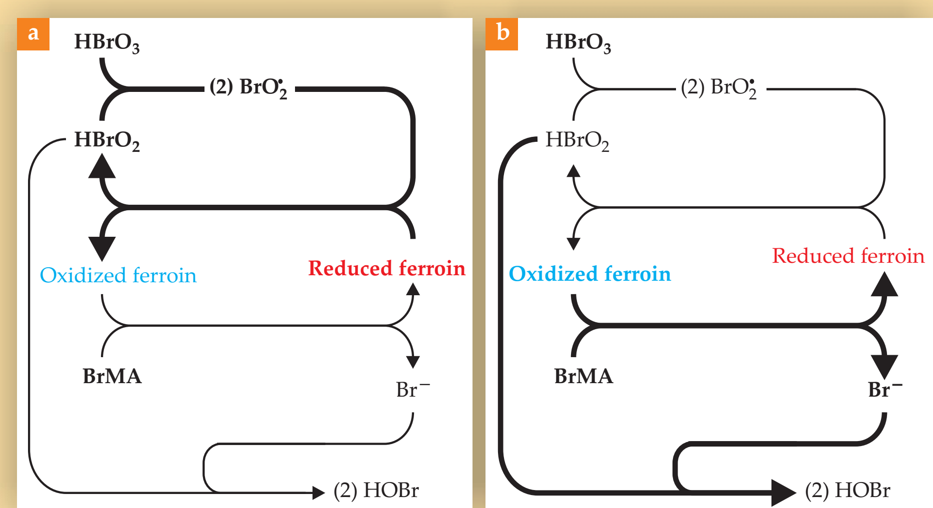

Figure 1. The major features of the Belousov–Zhabotinsky reaction, with the dominant reactions and chemical species shown in boldface for two processes in the reaction's oscillation cycle. **(a)** The activator species $HBrO_2$ catalyzes its own production from $HBrO_3$: Each $HBrO_2$ molecule produces two BrO_2 radicals, which go on to produce two more $HBrO_2$ molecules. In the process, the catalyst ferroin is converted from its red, reduced form to its blue, oxidized form. **(b)** When enough of the ferroin is oxidized, it reacts with bromomalonic acid (BrMA) to produce reduced ferroin and the inhibitor species Br^-, which draws $HBrO_2$ out of the system and thereby shuts off the autocatalysis. When the level of oxidized ferroin falls and Br^- production diminishes, $HBrO_2$ autocatalysis can begin again. In the experiments performed by Kenneth Showalter and colleagues,[1] the ferroin is loaded onto porous particles, and the other species are in solution.

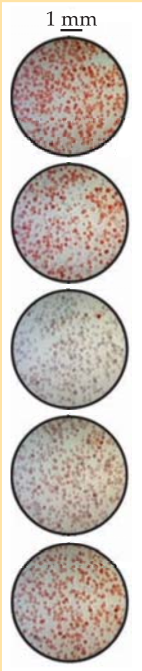

Figure 2. Frames from a high-speed video taken over the course of a nearly synchronized oscillation. (Adapted from ref. 1.)

In an unstirred mixture—or in a stirred mixture with few particles—each particle oscillated with a different period on the order of 30–60 s. But at higher particle densities, stirring caused an exchange of chemicals between each particle and the rest of the solution, allowing the oscillations on each particle to influence the others. As a result, the particles' oscillations aligned in both frequency and phase.

Kinetics

As chemical reactions go, the BZ system is complex—many more steps and species are involved than are shown in figure 1. But it is still simple enough that Toth, Taylor, and Tinsley were able to reproduce their experimental results using a kinetic model of the BZ reaction[4]—a system of coupled differential equations to describe the time-dependent behavior of each reaction step—that they modified to account for the exchange of chemicals between the particles and the solution. They parameterized the exchange using a rate constant k_{ex}; to fit their data, they set k_{ex} to a fairly low value. But they found that at higher values of k_{ex}, corresponding to faster stirring rates, their model predicted very different behavior from the Kuramoto-type transition they observed in their experiments. At high k_{ex} and low particle density, simulations showed that $HBrO_2$ was removed from the particles so quickly that it couldn't catalyze the production of more of itself, so the rate of ferroin oxidation never rose high enough to change the particles from red to blue. But in simulations at higher number density, so many particles were producing $HBrO_2$ that it accumulated in the solution faster than it could be removed by Br^-, which in turn slowed its loss from the particles and allowed it to accumulate on them. The simulated particles began to oscillate, suddenly and in near-complete synchrony. In short, the model predicted a dynamical quorum-sensing transition.

Showalter began a collaboration with Taylor and Tinsley to look for the quorum-sensing transition experimentally. Taylor went to visit WVU, where she and Tinsley continued their computational work and taught Showalter's students Fang Wang and Zhaoyang Huang some of the experimental methods. Together, the researchers captured images of the particles on high-speed video, as shown in figure 2, and monitored bulk oscillations by measuring the electrical potential of the solution. Says Showalter, "We were surprised and delighted to see both transitions in essentially the same system in both the experiments and the computational model."

Figure 3a shows the results of the model. The horizontal axes represent the exchange constant k_{ex} and the particle number density; the vertical axis and color scale show the amplitude of oscillations of the concentration of $HBrO_2$ in the solution, a measure of the coherence of the particles' oscillations. When the particles are unsynchronized or not oscillating at all, the amplitude is zero or nearly zero; when they are partially synchronized, the amplitude is low; and when they are fully synchronized, the amplitude is high. At low values of k_{ex}, the amplitude increases smoothly with increasing density, and at larger k_{ex}, the amplitude is zero at low density and jumps sharply at higher density.

Figure 3b shows a comparison of simulation to experiment as k_{ex} or the stirring rate is decreased while the density is held constant. The trajectory followed is the white line in figure 3a. At the initial, high rate of exchange, neither simulation nor experiment shows any oscillations. As the rate is decreased, oscillations arise via a dynamical quorum-sensing transition and gradually desynchronize via a Kuramoto-type transition.

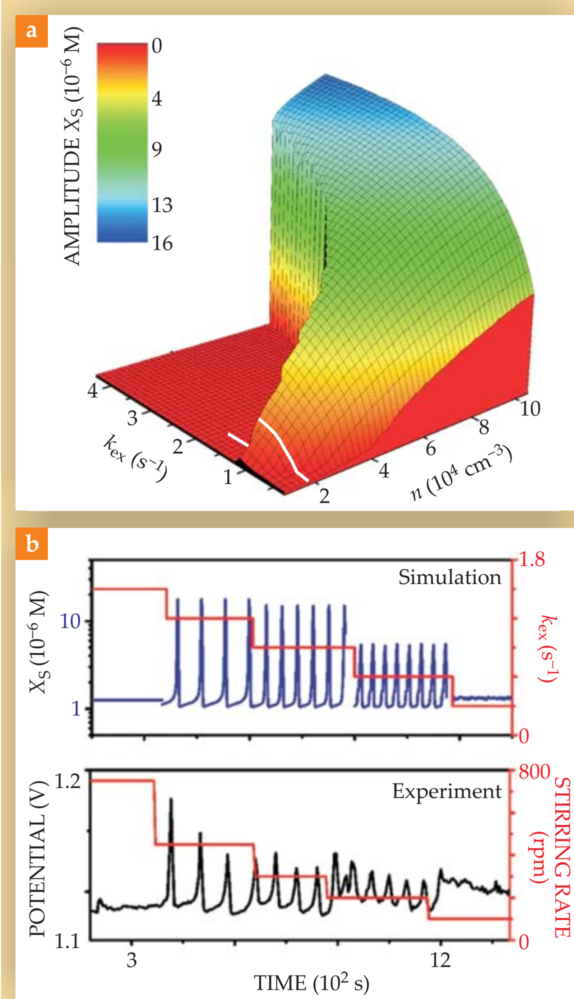

Figure 3. (a) Oscillations in X_S, the concentration of $HBrO_2$ in the solution, as a function of the exchange constant k_{ex} and the particle number density n. At low values of k_{ex}, the amplitude increases smoothly with increasing n as the particles undergo a Kuramoto-type transition from asynchrony to synchrony. At larger k_{ex}, the amplitude is zero at low density and jumps sharply at higher density. **(b)** Comparison of simulation to experiment as k_{ex} (or the stirring rate) is decreased and the density is held constant, following the path indicated by the white line in panel a. At the initial, high rate of exchange, neither simulation nor experiment shows any oscillations. As the rate is decreased, oscillations arise via a dynamical quorum-sensing transition and gradually desynchronize via a Kuramoto-type transition. (Adapted from ref. 1.)

Biological applications

The researchers hope that their study will offer insights into the dynamical nature of synchronization and quorum-sensing transitions in biological systems. In one recent study, researchers in France and Denmark found that in a stirred system of yeast cells, oscillations in the rate of a metabolic process synchronized via a dynamical quorum-sensing transition.[5] The BZ study suggests that biological systems such as stirred yeast cells might also undergo Kuramoto-type transitions, depending on the efficacy of the molecular signaling.

Showalter and colleagues have extended their study to look at catalytic particles in an unstirred solution, in which the coupling between particles is not global but local. They've found that spiral and bull's-eye patterns propagate over the surface of a layer of particles, but only when the group contains more than a critical number of particles—adding or removing just a few particles is enough to turn the behavior on or off. Says Showalter, "We are excited about this because there is a striking resemblance of the grouped particles to groups of bacteria."

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References

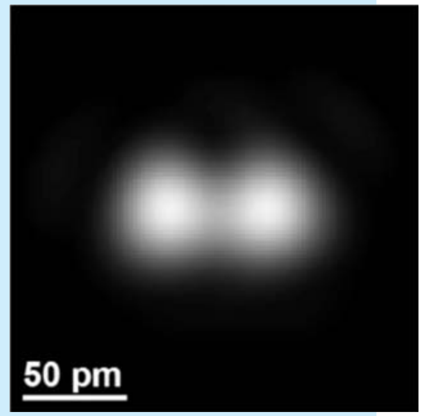
1. A. F. Taylor et al., *Science* **323**, 614 (2009).
2. J. Maselko, K. Showalter, *Nature* **339**, 609 (1989).
3. R. Toth, A. F. Taylor, M. R. Tinsley, *J. Phys. Chem. B* **110**, 10170 (2006).
4. A. M. Zhabotinsky et al., *J. Phys. Chem.* **97**, 7578 (1993).
5. S. De Monte et al., *Proc. Natl. Acad. Sci. USA* **104**, 18377 (2007).

physics update

These items, with supplementary material, first appeared at http://www.physicstoday.org.

Plasma waves and cosmic rays. With energies exceeding 10^{20} eV, the highest-energy cosmic-ray protons are as energetic as well-hit tennis balls. How does a proton become so energetic? Recent cosmic-ray data disfavor the notion that these ultra-energetic protons have exotic origins such as the decay of very massive particles as yet unidentified. So one must seek the proton acceleration mechanism in familiar astrophysical environments. The conventional suggestions—acceleration by relativistic shocks, spinning black holes, or flares on hypermagnetized neutron stars—each have problems accounting for the highest observed energies. Shock acceleration, for example, becomes increasingly inefficient at high energy because the inevitable trajectory bending causes severe synchrotron energy loss. Now theorist Pisin Chen (SLAC and National Taiwan University) and coworkers have demonstrated analytically and by computer simulation that so-called magnetowaves—electromagnetic waves with unusually strong magnetic components in magnetized plasmas—can drive plasma waves in their wake much as laser pulses in the laboratory drive plasma wakefields in experimental plasma-based accelerators (see PHYSICS TODAY, March 2009, page 44). The mechanism avoids synchrotron loss, and it provides strong accelerating gradients even at very high energy. Chen and company show that a proton surfing a stochastic succession of such plasma wakes can, with luck, be accelerated to 10^{21} eV. Magnetowaves are believed to be produced in the relativistic jets emanating from active galactic nuclei. And the "luck" required for the proton to catch just the right sequence of plasma waves in an AGN jet accords with the observation that ultra-energetic cosmic rays are extremely rare. That's why the detector arrays that study them cover thousands of square kilometers. (F.-Y. Chang et al., *Phys. Rev. Lett.*, in press.) —BMS

Electron microscope attains 50-picometer resolution. Ultimately, the resolution of an electron microscope is limited by the electron's de Broglie wavelength. For the 300-keV electrons typical in scanning transmission electron microscopy, that limit is about 2 pm, or 1/25th of the radius of hydrogen's 1*s* orbital. But STEM images are formed by focusing a billion or so electrons per second onto a sample. The spherical aberration of the electromagnetic lenses and the finite size of the electron source cause the electrons to lose phase coherence, lowering the resolution to about 100 pm, or about twice the distance between atoms in many crystals. Now, a team from Lawrence Berkeley National Laboratory in California has halved the STEM resolution limit to 50 pm. The boost in performance comes from two novel components: an electron source that emits copious electrons from a region just 25 pm across and a hexapole corrector that can compensate for phase aberrations up to fifth order. Using their new microscope, the LBNL researchers looked at a piece of germanium foil. According to x-ray crystallography, Ge atoms are arranged in rows of dumbbell pairs aligned end-to-end. Ordinarily, the dumbbells are too small to be resolved with STEM. But, as the accompanying figure shows, the LBNL microscope could resolve the 47-pm separation between two paired atoms. The resolution is so fine that the thermal jiggling of the atoms during the room-temperature measurement acts as an additional source of blur. (R. Erni, M. D. Rossell, C. Kisielowski, U. Dahmen, *Phys. Rev. Lett.* **102**, 096101, 2009.) —CD



Breathing Earth, venting cracks. The couplings between Earth's solid surface and atmosphere are a rich area for study. For example, it is known that soil "respiration" plays a large role in the global water cycle. Researchers have long assumed that diffusion is the dominant mechanism for transferring gases across the interface between air and soil or rock, enhanced somewhat by wind- and pressure-fluctuation-driven transport. But scientists working in Israel's Negev Desert have uncovered a surprisingly important new mechanism: In regions where Earth's porous surface has cracks, fractures, or other discontinuities, thermal convection can expel, on a daily basis, up to 200 times more gas than diffusion, depending on the surrounding conditions. The team from Ben Gurion and Oregon State universities