# All together now

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## From wobbly bridges to new speech-recognition systems, the concept of synchrony seems to pervade our world. Steve Nadis reports on attempts to understand it, and the applications that may be on the horizon.

Steven Strogatz's curriculum vitae is more eclectic than most. He has investigated how crickets come to chirp in harmony, and why applauding audiences spontaneously clap in unison. The theme behind such studies — the way in which systems of multiple units achieve synchrony — is so common that it has kept him busy for over two decades. "Synchrony," says Strogatz, a mathematician at Cornell University in Ithaca, New York, "is one of the most pervasive phenomena in the Universe."

When a mysterious wobble forced engineers to close London's Millennium Bridge shortly after it opened in 2000, for example, an unforeseen synchronizing effect was responsible: walkers were responding to slight movements in the bridge and inadvertently adjusting their strides so that they marched in time. But synchrony can provide benefits too: researchers working on new radio transmitters and drug-delivery systems are harnessing the phenomenon to impressive effect. "It occurs on subatomic to cosmic scales and at frequencies that range from billions of oscillations per second to one cycle in a million years," says Strogatz. "It's a way of looking at the world that reveals some amazing similarities."

The study of synchronous systems cuts across the disciplines of modern science. But the underlying phenomenon was first documented over three centuries ago. In 1665, Dutch physicist Christiaan Huygens lay ill in bed, watching the motions of two pendulum clocks he had built. To his surprise, he detected an "odd kind of sympathy" between the clocks: regardless of their initial state, the two pendulums soon adopted the same rhythm, one moving left as the other swung right.

Elated, Huygens announced his finding at a special session of the Royal Society of London, attributing this synchrony to tiny forces transmitted between the clocks by the wooden beam from which they were suspended. But rather than inspiring his peers to seek other examples of self-synchrony, his study was largely ignored. The heir to Huygens' idea was not a seventeenth-century scientist, but Arthur Winfree, a theoretical biologist who began in the 1960s to study coupled oscillators[1] — groups of interacting units whose individual behaviours are confined to repetitive cycles.

### Jungle rhythms

The blinking of fireflies is one behaviour that Winfree studied. As night falls on the jungles of Southeast Asia, fireflies begin to flicker, each following its own rhythm. But over the next hour or so, pockets of synchrony emerge and grow. Thousands of fireflies clustered around individual trees eventually flash as one, switching on and off every second or two to create a stunning entomological light show.

How does such synchrony come about? In this case, each firefly has its own cycle of flashes, but that rhythm can be reset when the fly sees a flash from a neighbour. Pairs of flies become synchronized in this way, and the effect gradually spreads until large groups are linked. In general, oscillating units communicate by exchanging signals that prompt other units to alter their timing. Synchronization occurs if these 'coupling' signals are influential enough to overcome the initial variation in individual frequencies. "Below a threshold, anarchy prevails; above it, there is a collective rhythm," Winfree wrote in a review article published shortly after his death in November 2002 (ref. 2).

Winfree's attempts to create a detailed mathematical model of coupled oscillators were stymied by the difficulty of solving nonlinear differential equations — the mathematical tools used to describe such systems. But a crucial breakthrough came in 1975, when Yoshiki Kuramoto, a physicist at the University of Kyoto in Japan, produced a simplified model of the kind of system that Winfree was interested in. Kuramoto's system, in which the oscillators are nearly identical and are joined by weak links to all of the others, can be described by a set of largely solvable equations[3].

Kuramoto did not assume that his abstract model would necessarily relate to real physical systems. But that changed in 1996 when Strogatz, together with physicists Kurt Wiesenfeld of the Georgia Institute of Technology in Atlanta and Pere Colet, then at

**Cycling club: synchronizing systems in both natural and technological settings. Left to right: pedestrians make London's Millennium Bridge wobble; crickets and fireflies synchronize their chirps and flashes; an audience claps in sync; and the electric currents through Josephson junctions oscillate as one.**

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ABOVE LEFT, S. MAZE/CORBIS; ABOVE, H. VAN DER ZANT

the Institute of Material Structures in Madrid, produced a mathematical description of an array of superconducting devices called Josephson junctions[4]. These consist of an insulating layer, so thin that electrical current can actually cross it, sandwiched between two superconducting metals. Once the current across the junction exceeds a certain level, the direction of flow oscillates very rapidly, sometimes exceeding 100 billion cycles per second.

According to Wiesenfeld and his colleagues, an array of junctions will come to oscillate in sync as connections between the junctions nudge the devices into phase. Electrical engineers, who hoped that Josephson junctions could be used to drive a new breed of faster computers, were intrigued by the idea. What's more, in the same paper, the trio also showed that their theoretical description is equivalent, in mathematical terms, to Kuramoto's model. The finding kick-started interest in synchronized systems, capturing the attention of researchers from across the scientific spectrum.

John Hopfield, a theoretical physicist at Princeton University in New Jersey who pioneered studies of artificial neural networks, is one example. Computer simulations of networks of simplified model neurons are known to be well suited to certain tasks, such as pattern and face recognition. But Hopfield is now working with both real and simulated networks of units that behave more like actual neurons. Each neuron in his network emits voltage pulses at regular intervals, which are relayed to other parts of the network. Like the fireflies, a neuron's firing cycle can be reset by an incoming signal, allowing groups of neurons to synchronize their outputs.

In 2001, Hopfield described how this synchrony could be exploited to create a speech-recognition device[5]. He simulated a network of 650 biologically realistic neurons with only weak couplings between them, initially using conventional sound-analysis software to divide spoken words into 40 'channels'. Each channel corresponds to a particular range of sound frequencies and one of three key events: the time at which the sound of that frequency began, when it peaked, and when it stopped. Each thus has a time associated with it, which states when a particular frequency turned on, off or peaked. Neurons in Hopfield's network are connected to one or more of these channels, firing off a series of regular pulses when they receive the time signal. The frequency of this firing decreases with time, and although this rate varies between neurons, all eventually fall silent.

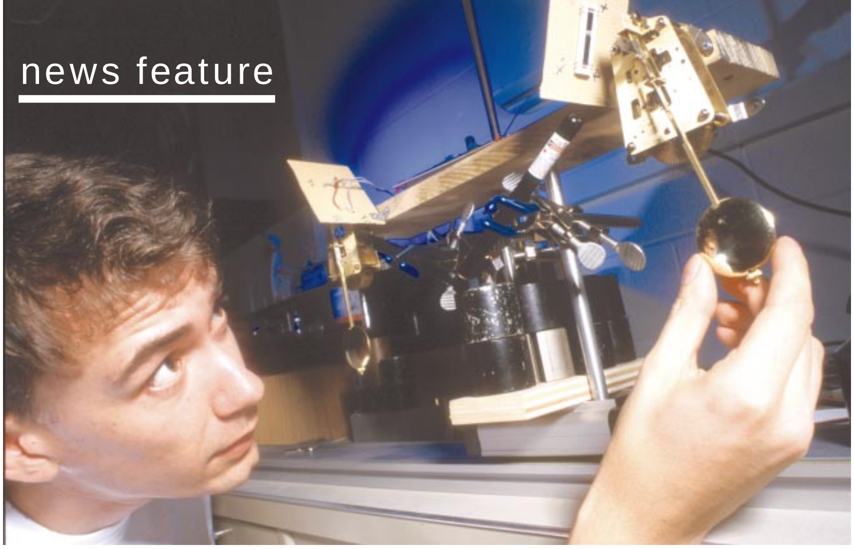
## One to think about

So how does such a set-up recognize sounds? Neurons are activated at different times, but because their firing frequencies fall off at different rates, some of them will momentarily fall into sync with each other before drifting out of phase again. In a first trial run, Hopfield fed the word 'one' into the network and tracked the firing of the neurons until he spotted a group that moved into phase. He then strengthened the coupling between these neurons. When the word 'one' was presented a second time, this coupling was sufficient to prompt a burst of synchronous and easily detectable firing when the neurons drifted into phase. Other words did not cause this subset of neurons to come into phase, and hence did not prompt synchronous firing.

The network could speed up speech recognition, as detecting synchronous firing is much quicker than identifying a word by analysing each channel. "If you take a system that can spontaneously synchronize, you immediately get an answer: it's in sync or it's not," says Hopfield. He suggests that the approach could be useful for answering questions in tasks such as face recognition, "where you have lots of information coming in and all you really want to know is yes or no".

At the University of Pennsylvania in Philadelphia, bioengineer Kwabena Boahen has created real systems, each consisting of a network of thousands of circuits that mimic the behaviour of neurons. Theoretical studies of these networks suggest that their synchronous firing could be put to good use[6]. Boahen's circuits can be trained to recognize a particular pattern of inputs. By measuring the proportion of neurons that fire in sync, an observer can judge the degree of certainty associated with the decision. An input that causes 90% of neurons to fire in sync, for example, is more likely to have been recognized that one that causes 80% to synchronize. "This shows you can answer more than just yes/no questions," Hopfield comments. "Instead, you can ask what is the degree of confidence that this face belongs to 'Joe'?"

While Hopfield and Boahen are pursuing computational methods inspired by neural circuits, other investigators hope to exploit synchrony at the level of genes and proteins. Nancy Kopell, Jim Collins and their colleagues at Boston University in Massachusetts are trying to construct a synthetic regulatory network in the bacterium *Escherichia coli* that turns genes on and off on a periodic basis. Last year, they described a theoretical



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**Swinging time: a Georgia Tech researcher recreates Christiaan Huygens' twin pendulum experiment.**

cell[7] that contains genes for two proteins, X and Y. X activates the genes that encode both itself and Y, and this positive feedback causes levels of X and Y to rise. But in the Kopell–Collins model, Y also degrades X, so that levels of X fall as Y builds up. This is turn reduces the activity of the gene for Y. With less Y around, X levels increase and the cycle repeats itself.

Each oscillating set of genes can be coupled by introducing a third protein, A, which diffuses between cells. The gene for A is activated by X, and A in turn activates X, so levels of A and X rise together. As these levels increase, molecules of A diffuse from the cell and boost levels of X in neighbouring cells. This resets the cycle of fluctuating X levels in neighbouring cells, bringing them into line with the cell from which A originally diffused.

Theoretical analysis of a population of 1,000 cells based on biologically plausible rates of diffusion suggests that they will all fall into synchronization within a matter of minutes, even when the simulation begins with cells distributed at random points in their cycle. In experiments set to begin later this year, the Boston University team will find out whether this idea holds up in the lab. If it does, the levels of one of the proteins produced by the cell will peak around once an hour, although this frequency could be adjusted. In the long term, they hope to use a similar strategy to produce therapeutic substances at regular intervals, to form part of a drug-delivery system for use inside the body.

Evidence that this approach could work in practice comes from a 2000 paper by theoretical physicists Michael Elowitz and Stanislas Leibler, then both at Princeton University. Elowitz and Leibler created an oscillating three-gene network in *E. coli* [8], in which the protein produced by the first gene suppresses the activity of the second gene; the second protein suppresses the third gene; and the third protein suppresses the first. In this way, levels of the three proteins successively rise and fall over a period of two to three hours. Collins and Kopell hope to build on this achievement, establishing oscillations such as this in many cells and then getting the oscillations to synchronize.

Other examples of research into self-synchronizing systems abound. Neuroscientists are debating how synchronous neural activity within the brain influences attention, and perhaps even consciousness. Studies of the breakdown of synchronous beating among heart-muscle cells could lead to a better understanding of cardiac arrhythmias. And in 2001, Wiesenfeld and his Georgia Tech colleagues repeated Huygens' experiment under more rigorous conditions[9], tracking the pendulums' movements with lasers, as a means of generating data for Wiesenfeld's theoretical studies of synchrony.

## Wider view

Meanwhile, Strogatz is interested in expanding the range of systems that are studied under the banner of synchrony. "We've gone far by limiting our focus to repetitive behaviour," says Strogatz, whose new book on synchronization will be published next month[10]. But the time is ripe to loosen the shackles of the Kuramoto model, he suggests, and entertain more general conditions.

The biological circuits studied by Kopell and Collins are one example, as the signalling between the cells is stronger than the coupling that Kuramoto built into his model. Work by Robert York, an electrical engineer at the University of California, Santa Barbara, represents another step away from simplified oscillator networks. York has constructed a string of ten radio transmitters[11] — the frequency of radio waves that each emits is determined by the oscillating current that is fed into it. The circuits that produce these currents are linked, and fall into sync with each other less than a nanosecond after they are turned on.

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**Steve Strogatz: it's time to study more systems.**

In York's system, each transmitter is coupled only to its nearest neighbour. But this doesn't prevent the array from synchronizing. What's more, it also allows York to control the frequency at which the array synchronized, simply by adjusting the oscillator circuits for the antennae at each end of the array.

A group headed by Brian Meadows, a physicist at the US Navy's Space and Naval Warfare Systems Command in San Diego, is scaling up this idea, preparing to build a square array of 900 radio antennae to see whether the same approach works in two dimensions. Such systems are attractive, as they are more flexible than a single large antenna and can be packed more tightly than a conventional array. If Meadows' array works, it could yield a wide variety of applications, such as compact system for ships, airliners and satellites. "Normally you can't put antennae too close, because coupling becomes a problem," says Meadows. "For us, this coupling is essential and we take full advantage of it."

But the biggest challenge may be understanding systems containing oscillators that are far from identical. "In physics, we're used to dealing with things like electrons and water molecules that are all the same," says Strogatz. "But no one knows how to deal mathematically with the tremendous diversity that biology presents." He wants to replace idealized oscillators with real biological elements such as genes and cells, but considers the task daunting. "Biologists are used to collecting as many details as possible," he says. "For someone like me, the trick is to see which details we really need. But there's no guarantee that simplification will work in our efforts to model cellular processes."

Strogatz is nevertheless convinced that such studies will one day bear fruit. "Virtually all of the major unsolved problems in science today concern complex, self-organizing systems, where vast numbers of components interact simultaneously, with each shift in one agent influencing the other," he says. Huygens had a similarly strong conviction that he had stumbled into something big, which was sufficient to rouse him from his sickbed, even if he could not have fathomed its full significance at the time. Only now are we getting a glimpse of how enduring his legacy may be. ■

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