Is there an invisible tug-of-war behind bad hearts and power outages?

June 17 2013

Systems such as a beating heart or a power grid that depend on the synchronized movement of their parts could fall prey to an invisible and chaotic tug-of-war known as a "chimera." Sharing its name with the fire-breathing, zoologically patchy creature of Greek mythology, a chimera state arises among identical, rhythmically moving components—known as oscillators—when a few of those parts spontaneously fall out of sync while the rest remain synchronized.

Whether chimera states exist in the real world has remained an imminent question since their discovery in theoretical studies 10 years ago. Now, researchers from Princeton University and Germany's Max Planck Institute for Dynamics and Self-Organization (MPIDS) report the first purely physical experimental evidence that chimera states can occur naturally and under a broad range of circumstances.

They report in the journal *Proceedings of the National Academy of Sciences* that a surprisingly simple experiment demonstrated that chimera states naturally lay at the crossroads of two types of synchronized motion—in-phase and antiphase. Imagine two groups of pendulums that swing in the same direction at the same time—that's in-phase. Under antiphase, the pendulums move at the same pace, but one group goes left as the other goes right.

Furthermore, the researchers found through mathematical models that the phenomenon can strike any process that relies on self-emergent synchronization, or the natural tendency of components to fall into the same rhythm. A range of things that swing, blink or pulsate share this quality, including clock pendulums, lightning bugs and heart cells.

Shashi Thutupalli, co-corresponding author on the paper and a postdoctoral research fellow in Princeton's Lewis-Sigler Institute for Integrative Genomics, explained that chimera states have recently been the topic of a lot of study and numerous computer models explore them. Nonetheless, there was a lack of experimental investigations into how they occur, and whether chimera states need specific conditions in order to crop up, Thutupalli said.

"We hope this will prompt scientists to look for chimeras where they haven't before," Thutupalli said. "Our experiment captures elements such as friction and inertia, the direct analogs of which occur in a wide range of natural systems. There may be many processes that are chimera-like. We just don't recognize them and so don't know how to control them."

Daniel Abrams, a Northwestern University assistant professor of engineering sciences and applied mathematics, said that these findings are significant for researchers exploring the applications and natural occurrences of chimera states. Abrams, who is one of the first researchers to identify chimera states in theory, is familiar with the Princeton-MPIDS research but had no role in it.

Possible systems susceptible to a chimera state include electric-power grids, which rely on synchronized generators to avoid breaks in power transmission, Abrams said. Also, certain patterns of intense heart-tissue contraction—known as "spiral waves"—in certain types of heart attacks have been observed in simulations of chimera states. Forms of chimera state may also be connected to large-scale synchronization patterns of neurons that have been observed during seizures, Abrams said.

"A better understanding of the behavior of coupled oscillators could be useful for understanding a variety of biological activity," Abrams said.

Yet, two obstacles have long hindered the physical observation of a chimera state, Abrams said. On one hand, before the state's theoretical discovery, scientists didn't think that a hybrid of synchrony and asynchrony could exist—chimera states were dismissed as an anomaly, Abrams said. Secondly, it was not clear until this latest work that they could exist in a simple system.

"The big point of the paper—that chimera states can occur in simple systems that have not been explicitly designed to find them—is an important one," Abrams said. "Before this work, the only experimental examples of chimera states were in fairly complicated systems with computers in the loop. Here the authors have constructed an extremely simple mechanical system that shows a chimera state."

The Princeton-MPIDS researchers developed an apparatus made of two swings, each fitted with 15 metronomes. A spring connected the swings so that they moved together. The research was largely conducted at MPIDS, and included first and co-corresponding author Erik Martens, now a postdoctoral researcher at the Technical University of Denmark; Antoine Fourrière, a postdoctoral researcher at Max Planck; and Oskar Hallatschek, now an assistant professor of physics at the University of California-Berkeley.

The device was inspired by the work of Dutch physicist Christiaan Huygens, who in 1665 observed that the pendulums of two clocks suspended on a beam would automatically synchronize their motion, Martens said. "We drew inspiration from this classic experiment, but we took it quite a few steps further," he said. "This allowed us to find a system based merely on swings, springs and gears that displayed these mysterious chimera states."

Similarly, as the swings on the researchers' apparatus were set in motion, the metronomes would start moving willy-nilly then eventually move together. If the spring connecting the swings was taut the metronomes on both swings moved with in-phase synchrony, i.e., left and right in unison. If the spring was loose, antiphase movement developed so that metronomes on one swing moved left as the others moved right, yet always in time.

A chimera state arose when the spring's tensity was in between. The symmetry spontaneously broke so that the metronomes on one swing stayed in lockstep with one another while the metronomes on the other swing moved erratically. The researchers used mechanics equations to develop a mathematical model and simulate various scenarios under which a chimera state arose.

More information: The paper, "Chimera states in mechanical oscillator networks," was published online June 12 by the *Proceedings of the National Academy of Sciences*.

Provided by Princeton University

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