Synchronization: An introduction for a General Audience

(Summary of *Cluster Synchronization and isolated desynchronization in complex networks with symmetries, Pecora et al.)*

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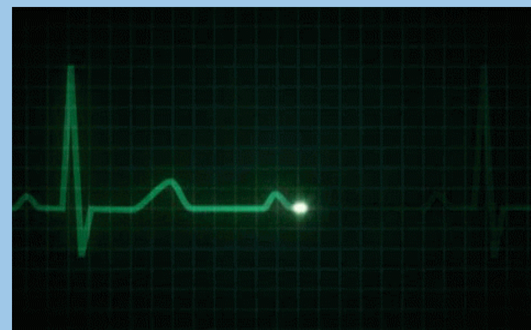
What is synchronization?

When multiple objects seem to acting in the same way, they are said to be *synchronized.* Synchronization is a widespread phenomenon appearing in both natural and manmade systems. These systems include the networks of neurons in mammalian brains, the chirping of crickets, and turbine rotation in power grids.

There are two minimal requirements for synchronization: Multiple *oscillators* and some[1] form of *coupling*. An oscillator can be roughly defined as an object which repeats some process in time. A pendulum swinging under a large clock or the periodic tick of a metronome are two such examples, however oscillators are ubiquitous in everyday life.



Oscillators are everywhere. Not only are they the foundation of time, but they also keep us alive. Human hearts are oscillators. They beat periodically producing our pulse. Bottom: A pendulum keeps time in a grandfather clock. Top: An electrocardiogram (ECG) records the electrical activity of a heart. The pulses are periodic in time.

Coupling refers to the interactions between oscillators changing their behavior. For a quick example picture this: You are at your local track running at your own comfortable pace. Suddenly your friend arrives and begins running at *their* own pace. You would like to catch up to your own friend for a chat, and vice versa. Thus, depending on where you are along the track, you speed up and your friend slows down until you're both running next to each other at the same pace. Congratulations, you and your friend are now synchronized oscillators! Your periodic laps around the track will now match those of your friend, even though you both naturally run at different paces. This is the phenomenon of synchronization. You and your friend altered your speeds to run together, a result that indicates two oscillators being coupled.

Synchrony governs more than just the ability to chat, however. Synchrony is a *necessity* for systems such as power grids, where small differences in speed among turbines can cause massive power outages. Neurological diseases such as epilepsy are

[1] I write 'some' here because there are specific coupling schemes required for synchronization of oscillators.

characterized by the synchronized firings of neurons. With implications such as these, it is crucial to understand under what conditions oscillators can synchronize.

A network is a series of objects, typically called 'nodes', connected to each other in an arrangement. Connections are referred to as 'edges'. Pictured above: A rendition of the World Wide Web. The edge between one point and another symbolizes a data packet being sent from one router to another.

When does synchrony occur?

Until recently there has been relatively limited understanding of the conditions which contribute to synchrony. However, Pecora et al. have developed a framework which describes the precise setting needed for synchronization to occur.

In order to understand these conditions we must first understand what clusters are: a *cluster* is one or more synchronized oscillators. Large networks coupled oscillators can have multiple clusters of synchronized oscillators. Oscillators in group A are synchronized, as are oscillators in group B, but an oscillator in group A is not synchronized to one from group B. Global synchrony occurs when all oscillators in a given network are synchronized.

Recent studies have found a connection between the appearance of clusters and *symmetry* in the network. Roughly speaking, a symmetry exists in a network if the structure (i.e. coupling) of one node in a network resembles another node in that same network. This means that if you switched the connections between to nodes, the behavior of the network would be exactly the same.

Pecora et al. developed a quantitative approach from the mathematical field of computational group theory to identify symmetry in networks and predict precisely when synchronized clusters will emerge based upon the coupling of the network. This theoretical underpinning provides us with an explanation of when synchronization occurs. The theory is only a model, however. Like all trusted theories, an experimental verification is needed, or else we haven't *physically* proved its validity.

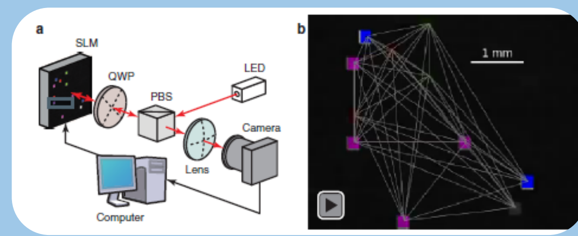
An experiment in synchrony.

Pecora et al. demonstrate their newly developed technique using a *spatial light modulator* or SLM. The spatial light modulator is a 32x32 arrangement of pixels. When light hits a particular pixel on the SLM its phase is shifted according to a programmed amount. Each pixel can have its own phase shift. The SLM receives input from a light emitting diode (LED). The LED's light beam is split and polarized. The SLM then returns the phase shifted light in the direction it came from, back through the beam splitter and into a camera. The camera is connected to a computer which then programs the SLM. Thus the SLM exhibits *self-feedback*: It receives input from its prior output. This self-feedback causes each pixel to oscillate. Because the SLM is programmable, each pixel is digitally coupled. Hence we have the two requirements for synchrony. Each pixel acts as an *optoelectronic oscillator*. An optoelectronic oscillator is an oscillator that involves both light and electricity. Typically, a laser is shined onto a photodiode, which converts light waves to electric signals. Then the electric signal is used to somehow modify some property of the light.

Just as theoretically anticipated, synchronized cluster arise out of network symmetries calculated by computational group theory. This work has given great insight into why synchronization occurs and will likely be considered in future engineering applications and design.

Frontiers in Science

Network science is a relatively new and rapidly expanding field studying the properties of networks. Several brilliant minds are constantly pushing the boundaries of knowledge into the unknown properties of these complex structures. The discoveries in this field have deep implications in the ubiquitous systems present.



Left: A diagram of Pecora et al.'s experimental setup. The PBS is a partial beam splitter which sends the incoming light to both the camera and the SLM. The QWP is a quarter wave plate which polarizes the light moving to and fro the SLM. Right: A close view of the SLM module. Pixels identical colors are synchronized oscillators. The grey lines represent the coupling between each pixel.