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About Thought Leader Forum | 2003 | Past Forums

Search Investment Banking

Go

Thought Leader Forum > 2003 > Steven Strogatz

- Introduction
- Presenters
  - Juan Enriquez
  - Eric Bonabeau
  - Alph Bingham
  - Anita McGahan
  - Steven Strogatz
  - Paul DePodesta
  - Brooke Harrington
  - Dan Schrag
- 2003 Concept Cards

Steven Strogatz

Sync

I may be a bit of a fish out of water here, but I will avoid the biggest mistake that I could make. I won't tell you about your business. I will talk about my business instead, which is the game of trying to understand self-organization in nature. Specifically, I study how so many things in nature manage to get themselves in sync.

Some of my friends and family do not quite understand why I've spent 20 years studying this subject. We don't have intuition about these questions. It is difficult to think about sync in a precise way because it comes so easily to us. We can easily clap in unison, stomp our feet together, or do the wave. Another puzzle is that we find it fun to be in sync. We like to sing together, and even being together is pleasurable for us. We dance together. We march together-talk about a dumb activity!

Given how easily sync comes to us, we really don't understand what it requires. For instance, is there a threshold of intelligence required? Can only primates do this, or can insects synchronize as well? Can sperm cells synchronize when they swim towards the egg? Do you even have to be alive? Can planets synchronize their motions with each other? Can things like electrons and photons also sync with each other at a subatomic scale? The answer is yes to all of these questions.

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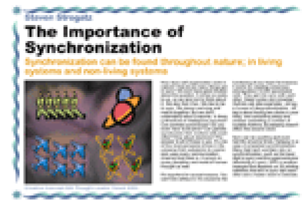
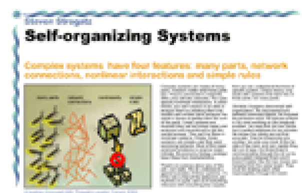
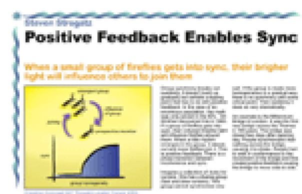
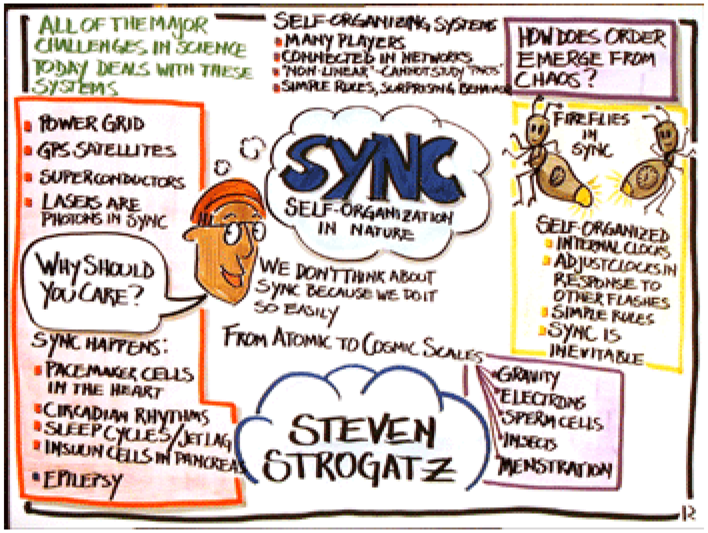
Concept Cards









Sync is one of the most pervasive drives in the universe. It extends from subatomic to cosmic. It uses every communication channel that nature has invented. Astronomical things synchronize through the force of gravity. Sperm cells synchronize the beating of their tails—a kind of primordial synchronized swimming—through pressure fluctuations in the fluid. The fireflies that you will see on the cover of my book synchronize through light. Crickets use sound.

Women who synchronize their menstrual cycles with their roommates communicate through pheromones in their sweat. It was a long time before we learned what the communication channel was between women. In fact, for many years male researchers refused to believe that it was a true phenomenon.

There was a remarkable experiment done that was published and is therefore apparently true. A woman named Genevieve Switz (which is remarkably close to the Yiddish word for "sweating") found that whenever she went home in the summer, her sister's menstrual cycle would lock onto hers within the first month and stay that way.

To test whether Genevieve was some sort of compelling synchronizer, the researchers had her wear cotton armpads to collect her sweat every day. They then ground those pads in an alcohol solution to create an "essence of Genevieve," and then put daps of this solution on the upper lips of women far away who had never met her. These women sensed her secretion somehow, and within a few months, these women had their periods within a few days of Genevieve. A control group with just alcohol started their periods at random.

Any way that things can communicate in nature, they will do it and synchronize. This phenomenon takes place is every discipline. You have to take this into account in the physical and chemical sciences and possibly in the world of finance and economics. This is a thrilling subject, and I hope you'll buy the book.

Why is sync important? A practical reason is that you cannot live without it. Sync is crucial to the function of your heart. Within your heart is a specialized region called the sinoatrial node that triggers the rest of the heart to beat. It sends out signals to your ventricles to get them to beat and keep the rest of your body alive.

How does this natural pacemaker work? Is there a master cell that makes the rest of them beat? That would not be a very robust system because that cell could die. What nature has chosen to do is make a consensus out of 10,000 cells, each of which is a competent oscillator, each of which would have a rhythm of electrical discharge on its own. Now there's a problem—they must come to some agreement about who's setting the pace. They all get into sync with each other for every second of your life for one and a half billion beats during your lifetime. If they didn't do that, you would get different signals to your ventricles and you would suffer from pretty serious heart disease.

Another case of sync that we take for granted involves sleep cycles. My baby wakes up very regularly at 5:25 A.M. every morning—not a time when I want to wake up on my professor lifestyle. It is very awkward that she is so well synchronized to this time of day. When you have jetlag, you are experiencing desynchronization. Maybe you don't realize that two different clocks are involved.

Some people claim to not experience jetlag because they sleep on the plane. This demonstrates a fundamental misunderstanding of jetlag. Jetlag is not about sleeping at the wrong time. Jetlag is about two different clocks in your body—one controls your sleep and one controls all of your internal rhythms of hormone secretion, body temperature, alertness, cognitive function, and memory. It is this circadian pacemaker that controls all of these functions that is left behind in your old time zone. Even if you sleep on time, your internal pacemaker is still desynchronized from your local time zone. We need to understand more about sync in our own bodies. Another example that you may not have focused on is the secretion of insulin in your pancreas only happens when the beta cells in the eyelet are electrically synchronized.

It is sometimes hard to understand why this tendency occurs. Why do we see this behavior in all mammals? There is some evidence that in other species that share nursing duties (like rats), their pups turn out to be healthier than those of female rats who are going it alone. Being in sync with your trusted friends seems to be good.

Not all sync is good for you. Epilepsy is a form of sync in which billions of brain cells conspire to fire at the same time that should not. The rhythmic convulsions that we associate with epilepsy are caused by this rhythmic discharge of billions of cells in the brain that shouldn't be synchronized.

Many high-tech wonders also rely on sync. The laser exploits light waves in sync. The light being generated here is by atoms that are excited and emit light when they drop down to lower energy levels. Those are not laser beams. Those atoms are no different than the atoms in a laser, but in a laser the atoms are choreographed to do their dance exactly in step. Without having light in sync, we would not have laser eye surgery, CDs, check-out scanners, etc. Superconductors are the electrical versions of the same thing. Instead of light waves in sync, this is electricity in sync.

This may become economically interesting someday—the magnetically levitated trains in Japan depend on the currents that you can generate using superconductors. The Global Positioning System has been so important in Iraq and in helping us find our way in unfamiliar towns. This depends on 24 orbiting satellites that are perfectly synchronized with each other and with a master super-clock in Boulder, Colorado. It is only because of this synchrony that we are able to do this triangulation on earth.

The power grid also works because of sync. What is supposed to happen in the grid is that all of the generators in all of the plants are rotating at 60 cycles per second, and they have to be in step or the grid doesn't work. The concept of sync, then, is important for all kinds of reasons in our world.

I want to talk today about a more philosophical question that transcends any practical application—where does order come from? How does order emerge out of chaos? Let's begin with the case study of fireflies. If you are familiar with fireflies in this part of the world, you will know them as independent, spirited, and they do not care about each other. They flash independently of each other, and they are not cooperative.

In contrast, fireflies in Asia are known to be extremely cooperative. The first Western travelers to Malaysia or Thailand noticed that there were unbelievable spectacles along miles of riverbank of fireflies flashing in perfect time. These travelers came home to report their experiences, but no one would believe them.

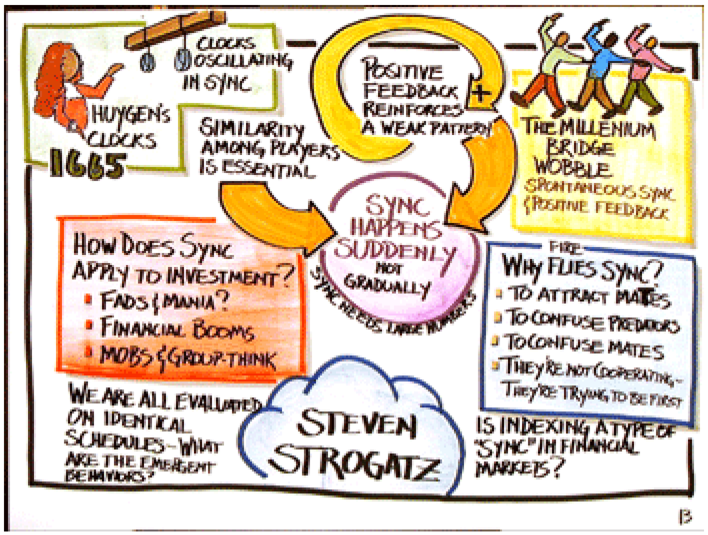
There was a raging debate in the pages of *Science* magazine between 1915 and 1935. *Science* was the preeminent science publication in the U.S. There were twenty-some articles published about whether or not fireflies could synchronize. One author said, "Some twenty years ago, I saw or thought I saw a synchronal flashing of fireflies. I could hardly believe my eyes because such a think is contrary to all natural laws." Insects could not possibly do this. I don't know what natural laws he means, but he is probably referring to the Law of Entropy.

Systems left to their own normally get more disordered and random—this is what we're taught in thermodynamics, although there's always the caveat that you're talking about a closed system. Closed systems always get more disordered and move towards greater entropy. They don't spontaneously create order.

The writer continues, "The apparent phenomenon was caused by the twitching of my eyelids. The insects had nothing whatsoever to do with it." This is the Twitching Eyelid theory of firefly synchronization.

There were other theories as well. The theory that many people come up with is that there is a firefly leader, or a maestro. This might sound ridiculous, but there is such a thing as a queen bee, so it's not unheard of for insects to have leaders. There has never been any evidence to support this theory.

Other people have theorized that this was related to the weather—that this only happened on very calm nights, or dark nights, or nights with no humidity. Someone proposed that it had to do with lightning—a flash of lightning would startle the fireflies, and they would all start flashing at the same time. Unfortunately this phenomenon happens in all kinds of weather, so these explanations don't work. On scientist who had lived in Thailand for twenty years stated that some of the explanations for this were more remarkable than the phenomenon itself.



How do thousands of these creatures get in sync? There is a great clip of this phenomenon in David Attenborough's video, "Trials of Life: Talking to Strangers." In the video, not all of the fireflies are in perfect sync—the original claims were probably exaggerated. Individual trees are well synchronized, but over the scale of a riverbank, the flashes actually propagate like a wave. If the flashing were totally random, you would not see this kind of pattern. The fact that you can see some organization shows that the fireflies are communicating in some way.

So, how do these fireflies organize? Today, we believe that they organize themselves—there is no lightning flash or leader. In the early 1900s, this was an unthinkable explanation. The evidence for this comes mostly from John Buck at the NIH and his collaborators. First, each firefly is rhythmic—they do not flash randomly. They have an internal clock that helps them keep a very regular tempo. There must be some kind of rhythm generator somewhere within its body.

Second, there is evidence that they not only emit light, but also are sensitive to light. When they see the light of another firefly, it resets its own clock. The rule for the resetting depends on the species—some species move their clocks forward, other species will advance or retard depending on when they see the flash. In each case, there is a simple rule for how to respond to an incoming flash. Out of the chaos and the repeated action of these simple rules, sync arises spontaneously, no matter what the original conditions were.

This moves us out of the realm of biology and into the realm of math. Can we really understand how these rules give rise to inevitable sync? As a mathematician, I don't like to believe that the "simulation is the explanation," as Eric Bonabeau asserted. To say that the simulation is the explanation is to give up, to admit that certain systems are too complex to understand.

I'm in the business of explaining this kind of system. If a system is this complex, then why bother even simulating it? Just watch the real system. Still, simulations can give rise to prediction, even if you do not discover insight or explanation. I would like to see if I can derive the group behavior of the fireflies from the simple rules. We were able to prove that sync was inevitable, given some assumptions about the rules.

So, who cares about fireflies? We don't care about them, except that they're an exemplar of a self-organizing system. Many self-organizing systems have similar features. They are made of many parts (heart cells, species, firms, etc.) —there are many players. They are connected with intricate networks—not everyone is connected to everyone. The rules for behavior in the systems are nonlinear. "Nonlinear" means (roughly) that you cannot expect to analyze a system by breaking it into smaller and smaller parts. The classic method of reductionism will not work in these systems because the whole will be more or less than the sum of the parts.

Linear systems are the ones that we teach throughout college because we have a completely developed theory for them. Linear systems are modular and can be broken into parts. If you took linear algebra, you learned a word called eigenvector. If you took physics, you learned about "normal modes." Those are the words that we use to refer to parts. You can then analyze those parts separately, and when you put them back together, you will find the right answer. In a nonlinear system, there is no eigenvector decomposition and there are no linear modes. You cannot take the thing apart without losing its essence. You have to analyze these systems all at once, and they have many complex parts and elaborate networks. And even simple rules give rise to complicated and surprising behavior.

What is the state of the theory for understanding self-organizing systems? You hear about lots of exciting claims about discoveries. It is a very exciting subject, but there is a lot we don't understand about these systems. We are spending a lot of time studying this subject because most of the major unsolved problems in science today have this character. This is what makes nature hard to predict, the economy inscrutable, and the effect on our ecology of species going extinct. You can be thoughtful and reasonable on both sides of these issues because there is very little science about them yet. We just don't understand how to think about these complex systems.

We do understand a very simple subclass of these systems. They have two distinctive features. If everyone is rhythmic (like a firefly or a heart cell) and if everyone interacts equally with everyone else, then we can understand this system. It has taken us decades because of the nonlinearity. We don't have the math to describe this complexity. Chaos theory was an attempt to describe the nonlinear science of systems with two or three parts. That's why it was such a joke when someone wrote a book about chaos in the capital markets—capital markets have far too many parts for chaos to be applicable. Chaos theory cannot tell you anything about complex systems. We need new theories to talk about complex systems with many parts. We are getting there in cases where the parts are rhythmic.

The granddaddy of all complex systems was developed by Christian Huygens in the 1600s. He serendipitously discovered sync between inanimate objects. He invented the pendulum clock. He was in a room with two pendulum clocks, trying to solve the longitude problem. One solution for the longitude problem required the use of an extremely accurate clock. Take this clock on board your ship, and compare the time on this clock to the time of day where you are (based on the sun's position). The time difference between you home time and the time where you are will tell you how far east or west you are from home. This is a kind of primordial global positioning system.

Huygens was developing such clocks, and he suspended two identical clocks from a beam in his room. While he was in his room "with a slight indisposition," he noticed that the clocks were swinging in perfect antiphase to each other. It lasted for over fifteen minutes, and Huygens knew that his clocks could not maintain that level of accuracy. He could see that the two clocks were influencing each other—they were communicating, but he could not tell how. He put one clock on the far side of the room, and the clocks fell quickly out of step. Clearly the clocks were communicating, but how? He thought it might be through air currents, so he put a plank between the two clocks (moved closer together). They stayed in sync, so air currents were not the answer. He realized that the communication was taking place with imperceptible vibrations through the beam over which they were suspended.

I tell this story in my book, and I also had the occasion to tell this story on "Scientific American Frontiers" with Alan Alda. He is personally interested in how fads work, and he thought that sync might be a way to understand fads. He asked me if there is a limit for what kinds of things will synchronize. Alan had tried to get his grandfather clock to keep better time by placing a loudly ticking electric clock on top of it. (The grandfather clock continued to gain five minutes per day.) There is a limit related to diversity. The two clocks will only sync with each other if they are well enough matched, as Huygens' clocks were. In the case of large populations of oscillators (like the fireflies), the math to solve these problems was only developed in the 1960s. This math is still under development today.

The insight that comes from Art Winfree's work is that synchrony breaks out suddenly. It does not build up gradually. It breaks out in a tipping-point, or phase-transition fashion. It has to do with positive feedback.

Art was an undergrad at Cornell, and wrote his senior thesis on this topic. His work is very enduring. He later won a MacArthur Genius Award, and he won awards for his work on biological rhythms, cardiology, and applied math. He was one of the great geniuses of the last half-century. He is the hero of my book.

Positive feedback will be the focus of the rest of my talk. If a few fireflies happen to get in sync by chance, they will exert a stronger influence on everyone else because they're coherent. Their light combined will be brighter. If I asked everyone in this room to tap one finger on the table softly, we could quickly get the whole room to tap in sync. We don't know when to start or how fast to tap, but most people use a basic rhythm that's about the speed of a heart beat. When a certain rhythm emerges among a part of the group, it will continue to grow stronger through positive feedback. This is a kind of a herd effect once some sheep head in one direction, more sheep join them which makes the effect stronger, which makes more sheep head in that direction. This is the same mechanism that accounts for group synchrony.

A less intuitive result is the phase transition. Imagine running clubs, now, instead of fireflies. These running clubs will vary in their diversity. A running club with high diversity shows a broad bell-shaped curve of natural speeds. Some are very fast and some are very slow. In such a diverse group, you will have no synchronization—they will not run around the track as a pack.

If I make the running club gradually more homogeneous, will I gradually get more and more synchrony? No. In fact there will be absolutely no synchrony until you reach a critical point. You can keep making the system more and more uniform, and it won't synchronize. Then all of the sudden, it will synchronize dramatically. Sync takes off suddenly and dramatically. After this phase transition, adding greater homogeneity will only gradually increase you level of sync. This is real science backed up by rigorous math and observations.

Let me finish with an example of this kind of positive feedback in humans. This was a very unexpected example, and very unwanted. This event took place a few years ago at London's beautiful new Millennium Foot Bridge. This bridge opened on June 10, 2000, and was supposed to be the pride of London. It was the first new bridge over the Thames in over 100 years. It was a symbol of rebirth in the city, connecting some of the poorest parts of London to the financial areas. Everyone was very excited about this bridge and there was a huge turnout of people on opening day. The bridge was closed two days later because of what happened. What happened was an unintended human synchrony caused by positive feedback.

People synchronized their walking across the bridge, giving it a terrible case of the shakes. The more that the bridge shook, the more people walked in step with each other, which caused the bridge to shake even more. People did not deliberately walk in step, but they had to walk that way to conform to the movement of the bridge.

These were civic-minded pedestrians minding their own business, and the bridge started to move in sync for some reason. The bridge starts to move side to side (not up and down), and in order to keep from falling down, people had to adopt a weird, side-to-side gait, which served to reinforce and strengthen the side-to-side movement of the bridge.

Normally these sideways forces that people are exerting on the bridge would be generally cancelled out by each other because people are walking on the bridge at random. When a part of the group gets in sync, however, then they are exerting a positive force on the bridge which will cause it to move, which causes more people to lose their balance and adopt this side-to-side gait, which will cause the bridge to move even worse.

This is the positive feedback effect. The footage of people walking across this bridge is dramatic and shocking, with hundreds of people rocking side-to-side with the bridge. This effect can be simulated with a very few people on a smaller version of the bridge. In these conditions, sync just happens.

Are there implications that should be of more direct concern to the financial community? I don't know for sure, but here are some possibilities. Fads, manias, and stock market bubbles are possible examples of sync. Should we be thinking about these situations in terms of sync? Probably not. The theories that we have developed so far are only for very simple, rhythmic processes. I'm not so sure that these models apply when you have more intelligent decision-makers and more complex decision rules. I think we may need a deeper branch of the theory of self-organizing systems to explain these phenomena.

Are mobs an example of sync, either old-fashioned mobs or the newer flash mobs? We like to think that there are a lot of independent thinkers in the marketplace, but investors sometimes follow each other and develop a kind of groupthink—they all evaluate things in the same way. How should we value risk in this environment? The old assumptions about investing do not allow for sync, and sync may lead to more volatility. I don't know the answers to these questions, but they are worth pursuing.

I would like to conclude by saying that Art Winfree was not just a great hero of this subject, but also my mentor. He was a great help to me in every stage of writing my book. I was planning his 60th birthday party when I got a phone call from his wife to tell me that he had developed a malignant brain tumor. He did not live to see the book published. I dedicate this work to Art.