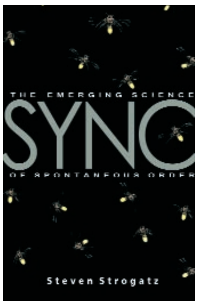
Decoding the Science of Synchronization

Sync: The Emerging Science of Spontaneous Order

Steven Strogatz
Hyperion, New York, 2003. $24.95, (338 pp.). ISBN 0-7868-6844-9

Reviewed by Nigel Goldenfeld



After a prolonged and difficult adolescence, the science of complex systems has finally come of age. No longer dismissable as being long on hype and short on results, the field boasts some remarkable and genuinely wide-ranging discoveries that are starting to make an impact across the spectrum of scientific endeavor—from mathematical physics to cell biology, genomics, and even social science. The recent developments are especially notable because they are detailed quantitative analyses or predictions, clearly moving beyond the grandiose collection of aphorisms and paradigms that, to some, characterized the field's early days and drew the ire of skeptics.

Advances in the characterization of networks are arguably the most fundamental insights that have arisen in recent years. How can one describe the structural complexity of networks? How do networks evolve? What new features emerge when dynamical systems are strongly coupled into complex networks? These questions would be a fruitless line of inquiry if the answers exhibited sensitive dependence on the specifics of the networks. But remarkably, it turns out that some generic applicable principles permit useful idealization, classification, quantification, and even insight. Answers to these questions are relevant to a whole host of real-life systems, such as food webs, microbial communities, metabolic and gene networks, the power grid, the Internet, and social or affiliation networks.

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Two network phenomena are of special interest to researchers: synchronization and connectedness. Synchronization refers to the way in which networked elements, due to their dynamics, communicate and exhibit collective behavior. Connectedness describes the architecture of networks. For example, are there just a few highly connected "hubs" (think airline route maps) from which lots of short hops are made? Or is everything connected to everything else in a way that has no recognizable, simple structure? Connectedness is an important aspect of networks that determines, among other things, their efficiency and their vulnerability. We now know that many real networks are not random collections of nodes and links. Real networks are connected in special ways that have functional significance. Perhaps no one has been closer to the epicenter of the recent progress than Steven Strogatz, the author of the smart, carefully written, and fascinating account that is *Sync: The Emerging Science of Spontaneous Order*.

Sync is a collection of vignettes about spatially-extended dynamical systems that fall (or fail to fall) into synchronization—often in spectacular ways. The captivating opening chapter describes the massive displays of synchronized firefly flashing that are observed in Southeast Asia. The chapter then moves rapidly into the synchronization of cells in a beating heart and the general problem of the effect of pulse coupling on a set of identical nonlinear oscillators. In a beautifully simple explanation that faithfully captures the elements of his rigorous proof, Strogatz shows that, regardless of the initial conditions, the oscillators will inevitably become synchronized.

Indeed, the first section sets the tone of the book, which has crystal clear explanations of mathematical proofs—often geometrical or topological—that are enlivened by thumbnail descriptions of the key protagonists. Strogatz uses a discussion of entrainment and Christiaan Huygens's discovery of the synchronization of pendula to launch a fascinating chapter on the examples of synchronization in everyday life, such as lasers, power grids, computer chips, global positioning systems, and orbits of celestial bodies. Strogatz even finds examples of quantum synchronization in superfluidity and superconductivity, especially in the phenomena associated with Josephson tunneling.

But this is not merely a book about mathematical results on idealized models. Strogatz clearly describes experimental observations, sometimes putting into perspective the mathematics that is his central interest. For instance, a lengthy account of the sometimes grueling experimental exploration into the sleep cycle suddenly segues into Strogatz's graduate work at Harvard University. His research helped provide firm evidence in the circadian cycle of forbidden zones during which sleep onset has a very low likelihood.

One of the many nice things about *Sync* is its disarmingly frank account of the personalities and careers of some of the people whose work has, in some sense, been related to synchronization. Most affectionately recalled is Arthur Winfree, a brilliant and unconventional thinker who has had a profound influence on many people. I will never forget my own excitement when I corresponded with Winfree in the early 1980s. He was kind enough to send me my own Belousov–Zhabotinsky reaction kit, which I treasured until all the reagent was used up. Perhaps the most difficult chapter, on scroll wave patterns in three-dimensional chemical reactions, is enlivened by Strogatz's personal account of his summer work with Winfree. The work involved trying to model the sought-after wave forms with pipe cleaners, dental floss, and modeling clay. The eclectic array of brilliant and sometimes quirky thinkers who also make an appearance in the book include Brian Josephson, Norbert Wiener, Yoshiki Kuramoto, and Charles Peskin. Strogatz evidently is fascinated by his colleagues and paints their portraits in ways that are generous and true to life yet refraining from judgment.

To my surprise, only at the end of the book does Strogatz devote a slightly short chapter to what is perhaps his most widely recognized work: the field of small-world networks. The prime example is known as "six degrees of separation," which refers to the parlor game in which one tries to link a given actor to a target (historically actor Kevin Bacon) through the smallest chain of movies sharing common costars. Strogatz describes how small-world networks are intermediate between regular and random networks. A few shortcuts that link random points in a regular network have a drastic effect on the connectivity: The average path length goes down significantly, while the local order in the network is hardly affected. Small-world networks have been found in numerous situations, such as in the nervous system of the worm *C. elegans*, the US power grid, and the Internet. But their influence is not always benign: Viruses and epidemics, for example, can easily spread globally.

Sync is one of those rare books that can profitably be read and enjoyed by both experts and laypeople. It comes with a very complete set of notes that provide detailed literature citations and technical comments. The book could even serve as an excellent reading assignment for an introductory course on complexity. So go read *Sync*. And if you like it, tell all your friends about it.

On second thought, don't bother. I already have.

The Discovery of Global Warming

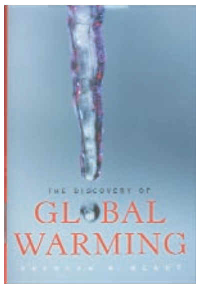
Spencer R. Weart
Harvard U. Press, Cambridge, MA, 2003. $24.95 (228 pp.). ISBN 0-674-01157-0

Two mountain villages, one Swiss and the other French, are neighbors and only a few miles apart. What divides the communities is the snowy roof mass of Mont Blanc, western Europe's highest mountain, in the French Alps; so visits between the villages are uncommon. But during the 18th century, as Spencer Weart recounts in *The Discovery of Global Warming*, both settlements were eager to share experiences when they saw the coarse, glacial ice sheet—always a grim sight for the towns—slowly move nearer their homes.

The elders recalled from village lore how disappointed the people were when their rare exchanges disclosed the threat to every visible wall of shelter on both sides of the mountain. The ice ignored every human appeal, even prayer; only patience and hope offered a defense. The climate was changing, not merely the weather. Climate includes the locally expected weather, such as the valley heat or mountain snow. That a reliable climate also can change may sound like a paradox: Isn't climate the steady part of changing weather?

Global warming is a worldwide summertime and an unexpected discovery. Of course, ice ages have long belied a fixed climate. At least several millennia ago, mountainous ice caps gripped the world through several cycles. Climate itself has gone through profound, repeated change.

Ice ages have long been recognized as cosmic phenomena caused by interplanetary gravitational interactions that transform any simple elliptical orbit like Earth's into rosettes. A well-verified astronomical dance creates small but long-lasting deviations in the distance between Earth and the Sun. Sunshine that hits Earth dims and brightens time and time again. The deviations correspond with the main classical epochs of ice-age glaciation. Astronomical in origin, this climate-change puzzle was solved by means that depend on the effects of times and distances so great as to be irrelevant to everyday weather.



Detailed facts about global warming can be found in countless research tables, graphs, maps, and other such records. Yet *The Discovery of Global Warming*, a thorough history of the subject, has only four graphics in more than 200 pages. But those few graphics are compelling. First, the data in the book stamp a vivid label on one variable: the abundance of carbon dioxide. The large variations in levels of carbon dioxide, which is found in only a few parts in 10 000 of Earth's atmosphere, are strikingly coherent. The data reveal changes in carbon dioxide content in Antarctic air measured at different locations over almost 50 years. One set of data show, in two years, continent-wide variations of carbon-dioxide levels, from Antarctica's icy coast to its far-off South Pole station. Another graph records carbon-dioxide levels from 1958 to 2002 at the high Hawaiian plateau of Mauna Loa. Each year resolves a repeated seasonal rise and fall, with an overall change of 30% in levels of the gas.

Weart is the director of the Center for History of Physics at the American Institute of Physics. His deep engagement with the history of physics informs the book's guiding summaries of the climate pioneers: Benjamin Franklin, Joseph Fourier, John Tyndall, Svante Arrhenius, John Von Neumann, and Guy Callendar. It was Callendar, an engineer, who cut right to the chase in his 1938 paper to the Royal Meteorological Society about the causes of climate change so decisive in our own history. Callendar advanced data to support his argument that human-made fires in the 20th century generated sufficient amounts of carbon dioxide to raise global surface temperatures. Callendar's research introduced reasons behind global warming but did not bring clarity to the events overall.

Halfway into the book's history on global warming, Weart presents a plot of surface temperatures around the world. Described in the book as "the first entirely solid and comprehensive global analysis of average surface temperatures," the graph reveals a dozen big peaks from global temperature records from 1880 to 1980. The warmest three years, according to a 1986 study of a 134-year record, had all occurred in the 1980s. But cooler weather was what most people recalled during the first years of the warming period.

The disparate details of the climate problem set a tough course for the public. Weart's figure 3 is a graph that, although somewhat marred by scientists' reconstruction of old temperatures, documents a swift, strong, credible upturn from the circumstances of the last century. Familiar instruments and complete, meticulous records were valuable to climate scientists and helped bolster their credibility as "the greenhouse gases and the temperature soared."

The next pages of the book include a metaphor so apt that it seems all but unfair to debate it: "The global climate system," said geochemist Wallace Broecker in the 1990s, "is an erratic beast, and we are poking it about with a sharp stick." Insightful and eloquent, Broecker had introduced in his own doctoral thesis 30 years earlier a bold proposition for rapid climate change.

The closing paragraph in Weart's book sums up the public struggle with the unprecedented changes of climate—changes supported by a rapid increase, from 1900 on, of data, memories, and forecasts from researchers.