From Hearts to Power Grids, Spontaneous Order Even Amid Chaos

Synchronization: A Universal Concept in Nonlinear Sciences

Arkady Pikovsky,
Michael Rosenblum,
and Jürgen Kurths
Cambridge U. Press, New York, 2001. $100.00 (411 pp.).
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Reviewed by Steven Strogatz

As budding physicists, we were all fed a steady diet of oscillators. Starting with the simple harmonic motion of a mass on a spring, we soon swallowed a large helping of electrical circuits and resonance, and washed it down with normal modes and beat phenomena. The same food group seemed to be offered at every meal for the rest of our education. Quantum mechanics dished out the harmonic oscillator again, though in barely recognizable form. Electromagnetic theory served up cavity modes; solid-state physics had phonons.

Fair enough. Harmonic oscillators are fundamental, and every physicist needs to master them. But relentless ingestion of purely conservative, purely linear oscillators is now recognized to be unhealthy, because such oscillators are so unrepresentative of many found in nature and technology. To understand the dynamics of lasers or Josephson junctions, or heart cells or neurons, one has to come to grips with oscillators that are both nonlinear and nonconservative. In particular, many real oscillators are self-sustained, meaning that they oscillate with a distinctive waveform at a preferred amplitude that reflects a balance between energy inflow and dissipation. (In contrast, harmonic oscillators can cycle at any amplitude, a decidedly nongeneric feature.)

When self-sustained oscillators are coupled, they behave very differently from harmonic oscillators. Instead of beating with an admixture of all the mode frequencies, they often lock onto a single frequency. In other words, they synchronize. For example, our hearts beat on command of the sinoatrial node, a natural pacemaker built out of about 10 000 cells, each an autonomous electrical oscillator. By exchanging ionic currents, all the cells manage to fire in sync and thereby trigger the rest of the heart to contract and pump blood. Inanimate oscillators can also synchronize spontaneously. As Christiaan Huygens discovered in 1665 (while lying ill in his bedroom), two pendulum clocks hanging from the same board will swing in perfect antiphase, thanks to the imperceptible vibrations they induce in their common support. The injection locking of lasers and the synchronous rotation of thousands of generators in the nationwide power grid are modern instances of the same principle.

For many years, the analysis of self-synchronizing systems was handled on a case-by-case basis, with little communication between the disparate fields in which those phenomena arise. *Synchronization* is the first book to treat this subject in a unified fashion. In an unconventional but excellent pedagogical choice, Arkady Pikovsky, Michael Rosenblum, and Jürgen Kurths begin in part 1 by discussing synchronization without resorting to equations. Using pictures, graphs, history, and conceptual explanations, they clarify its scientific importance through carefully chosen experimental examples from a dazzling array of disciplines. This part of the book is intended to be accessible to scientists in all fields. It succeeds brilliantly.

In part 2, the authors rework the same material from a more mathematical perspective. Again the treatment is clear and logical, organized in ascending order of structural complexity, from a single self-sustained oscillator driven by an external force, to two mutually coupled oscillators, and then on to the effects of noise, the dynamics of oscillatory media, and discrete populations of globally coupled oscillators, in which mean-field methods from statistical mechanics come into play. Much of this part reads like an extended review article, and a very good one at that.

Part 3 is about synchronization in chaotic systems, a hot research topic since 1990, when Lou Pecora and Tom Carroll of the US Naval Research Laboratory showed how to synchronize a pair of identical chaotic systems by driving one copy of the system with a small subset of signals from the other. Pecora and Carroll suggested that one could use such a pair in communication by adopting one system in the pair as a transmitter and the other as a receiver. As an additional benefit, the unique features of chaos (its random appearance and broad spectrum) could be used to enhance the privacy of an encoded message. Subsequent researchers developed that intriguing idea into a working technique in electronic circuits and optical communications, while others found ways to defeat the encryption. Very little of that story is discussed in part 3. I found the omission a bit surprising, given that the authors are experts in the area. Instead, they focus on the mathematics and downplay the applications of synchronized chaos. Fortunately, their treatment of the fundamentals is very well done and more readable than much of the original literature on this still-fashionable subject.

Steven Strogatz, *at Cornell University in Ithaca, New York, works on coupled oscillators and complex networks in physics and biology. He is the author of the forthcoming trade book* Sync: The Emerging Science of Spontaneous Order *(Theia/Hyperion, 2003).*

An Introduction to the Science of Cosmology

Derek Raine and Ted Thomas
IOP, Philadelphia, 2001. $50.00 paper (220 pp.).
ISBN 0-7503-0405-7

Teaching cosmology has always been exciting and yet difficult: exciting because cosmology is one of a few subjects that even "poets" want to learn, difficult because the general public and many students often have distorted perceptions of it. Cosmology is not about "wonders of creation." It is about physics: sometimes exotic, but always nontrivial, physics.

It is therefore commendable that Derek Raine and Ted Thomas undertook the task of writing a cosmology textbook for physics and astronomy majors, who constitute an often-overlooked category of students. Several acceptable textbooks are available for graduate students, and a sea of introductory astronomy textbooks treat cosmology with varying success. But the graduate texts are a small step above the level of most undergraduates, and introductory astronomy is useless for physics and astronomy majors. With *An Introduction to the Science of Cosmology*, Raine and Thomas have tried to cover that gap, and they deserve high praise for doing so, despite a few weaknesses in the book. Breaking new ground is always difficult.

I was especially pleased with the book's modest size, and with the brilliant idea of using brief overviews to cover topics. Most students will surely prefer this book's half-page chapters to five-page ones. Regrettably, my initial enthusiasm abated when I started reading the book. My first impression is that the book was written in a hurry. It looks as if the two authors wrote parts of it without talking much to each other, and the result is a disappointing lack of consistency.

Especially annoying is the inconsistency of units: one chapter may use SI units, and the next may switch to CGS. As a practicing scientist, I am used to unit conversion, but many a freshman will be totally confused and frustrated. Another worrisome feature of the book is its attempt at unifying cosmological notation. It is indeed true that cosmologists' notation is far from perfect, but trying to redefine Ω_0 will worsen the problem, not resolve it. Equally confusing is intermixing lower- and upper-case subscripts. Most graduate textbooks avoid the practice, so a student who continues in cosmology will have a hard time adapting between notations.

A few other things cry out for improvement. The quality of several figures is low even by journal standards. In a few places, frustrating physics mistakes creep in. For example, photoionized gas cannot emit x rays. I also found some of the problems uneven in difficulty. For example, calculating the number density of ionizing photons at recombination is a relatively simple exercise for an average undergraduate, but estimating the evaporation time for a galaxy requires a considerable knowledge of galactic dynamics.

The book is well organized and the format is well thought out. The few omissions and mistakes do not outweigh the strength of the book. Those mistakes can and should be corrected in the second edition, which I will gladly use in my upper-level undergraduate courses.

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The Measurement of Time: Time, Frequency and the Atomic Clock

Claude Audoin
and Bernard Guinot (translated from French by Stephen Lyle)
Cambridge U. Press, New York, 2001. $110.00, $39.95 paper (335 pp.). ISBN 0-521-80080-3, ISBN 0-521-00397-0 paper

Several essays, philosophical or scientific, exist on the concept of time. As its title indicates, this book by Claude Audoin and Bernard Guinot covers a practical aspect of the concept of time: its measurement. Among physical quantities, time can be measured with greatest accuracy: In fact, accuracies of a few parts in 10^{15} are routinely reached in the laboratory. In the International System of units (SI), time is a quantity whose representative unit (the second) is defined in terms of an atomic property: the hyperfine frequency of the cesium atom in its ground state.

A book about time measurement is a challenge, and because of their experience, the authors meet this challenge exceptionally well. Audoin formerly directed the Laboratoire de l'Horloge Atomique of CNRS and Guinot previously directed the Bureau International de l'Heure. Both authors, highly respected physicists, have been active in the field for more than 40 years.

The book contains historical background that describes how time measurements evolved from an astronomical to an atomic basis; it also describes how time scales were redefined as the understanding of underlying physical concepts evolved. The authors explain atomic and astronomical time in enough detail and interlace enough basic physics to make the information extremely useful to readers who know some basic physics but are otherwise unfamiliar with the accurate measurement of time.

The authors also have set the field of time measurement in its proper, general-relativistic context. They show that the basic conclusions of general relativity are required to define time scales properly and are also required in navigation by satellite—one of the most successful applications of time measurement. Neil Ashby's article (PHYSICS TODAY, May 2002, page 41) highlights the authors' theme. Unfortunately, many will find the general-relativistic framework difficult to comprehend. Toward remedying this problem, the authors have attempted to simplify the concepts. Chapter 3, although requiring serious effort to read, provides insight into the necessity of using general relativity. The authors, realizing the level of difficulty of the content, advise the daunted readers "*. . . to move directly to the summary at the end of this chapter*" (p. 17). The summary indeed helps readers to understand the parts of the book concerned specifically with time and time-scale definitions.

In chapter 5, which deals with the state of the art in frequency stability, the authors offer a good introduction to basic concepts and define a helpful set of parameters to characterize instruments and their measurements.

Any book about time measurement needs a description of the atomic clock—the key to the accuracy of modern measurements. In chapter 6, the authors not only describe these devices conceptually, but also discuss the inherent limitations of atomic-clock accuracy, the performance of current devices, and likely near-future improvements. A rather clear explanation of laser cooling reinforces the discussion in the same chapter 6.

A book of this nature would not be complete without providing readers with an understanding of the applications of accurate time measurement. In chapter 9, the authors list applications in sufficient detail to awaken a reader's curiosity, and provide a guide to readings in these applications. The chapter helps explain the need for greater frequency stability and accuracy, and hence the need for research in that direction.

Another book, P. Kartaschoff's *Frequency and Time* (Academic Press, 1978), covers the same field but is oriented mostly to engineering. Audoin and Guinot are essentially concerned with physical concepts basic to time measurement. Furthermore, Audoin and Guinot describe the present state of the art in the field. Both texts are fine complements of each other.

In all, *The Measurement of Time* is pleasant to read, and provides the basic information required for understanding the concepts of time measurement. It should guide the engineer involved in system design in which timing is critical, and should help the graduate student gain insight into the whole field. Finally, the text should be useful to anyone who wants to quickly