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This issue of THE BIOLOGICAL PHYSICIST brings you a feature interview with Cornell University's Steven H. Strogatz, well-known nonlinear dynamicist, applied mathematician, and author, as well as one of the originators of the idea of small world networks.

On another note, our readers may have noticed a paper copy of a condensed version of recent issues of THE BIOLOGICAL PHYSICIST landing in their mailboxes recently. Since some members of the Division of Biological Physics are "off line", we are now providing all members of the Division with occasional paper editions of the most important features and announcements from recent issues. We welcome your feedback on this expansion of THE BIOLOGICAL PHYSICIST into print. And your editor asks you, if you do not plan to archive the print edition, to please recycle!

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FEATURE

A Conversation with Steven Strogatz

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S. Bahar

Among many other achievements in interdisciplinary science and applied mathematics, Steven H. Strogatz, of Cornell University's Department of Theoretical and Applied Mechanics, is the author of a classic nonlinear dynamics textbook, and one of the originators of the idea of small world networks. Strogatz has recently published a popular press book, ***Sync: The Emerging Science of Spontaneous Order****, which discusses the dynamics of synchronization in biological systems. He talks with* THE BIOLOGICAL PHYSICIST *about small world networks, his early research with Art Winfree, the difference between writing for the "lay public" and a scientific audience, and the current state of interdisciplinary research.*

What led you into science?

As a first-grader, my two favorite books were "How Big is Big" and "The How and Why Book of Atomic Energy." I have no idea why they appealed to me. My parents grew up during the Depression and neither of them had a chance to go to college, so there were certainly no scientists in my family.

I never had a chemistry set or tinkered with radios, or anything like that. My mom wouldn't let me. She probably worried that I'd electrocute myself or blow something up. So my interests were always confined to the theoretical, even then.

Still, I wasn't truly hooked on math or science until much later, when two things happened. The first was a moment of truth that occurred one day at the beginning of my freshman year in high school. We did a little experiment in science class where we were asked to measure the period of a pendulum as a function of its length. As I plotted the fourth or fifth dot on my graph paper, and saw that parabola coming out—the same kind of curve I was learning about in algebra class—a shiver went through me. I suddenly understood what people meant by "a law of nature." In that moment I became aware of a secret world you could only see if you knew math.

The other decisive moment came a year later, when my pre-calculus teacher happened to mention a geometry problem: if two angle bisectors of a triangle are congruent, prove the triangle is isosceles. It sounded like all the other geometry problems, but then he offhandedly told us that he didn't know how to do it. In fact, he'd never seen *anyone* solve it. That was amazing—I'd never heard a teacher say something like that. And every day for months after that, I had images of angle bisectors in my head, distracting me during gym and French class and other inconvenient times. I couldn't stop thinking about the problem. It was my first experience with being entranced by a math problem, and feeling irritated by it at the same time – which of course I now recognize as the feeling of doing research. And when I finally got a proof that seemed to work, I called my teacher right away on the phone and he had me rush over to his house. It was a Sunday morning—his wife and kids were milling around the house, and I explained it to him in his pajamas. He checked it line by line, slowly, and eventually said, yes, that's a proof. After that I found myself making up math questions just for the pleasure of thinking about them.

Did you initially consider any other career paths? Did you begin as a mathematician, or a physicist?

I liked both subjects. When I started college I thought I'd major in math, but then I got wiped out by a very rigorous, abstract, proof-oriented course in linear algebra, taught by one of the worst teachers in the department—this was Princeton's way of weeding out the freshmen who thought they wanted to be math majors but who really shouldn't. So I turned to physics, and was excited by my E+M course out of Purcell's book, but was soon tugged back to math by a course in complex variables taught by Eli Stein. At that point I settled on being a math major. It was the right choice. I never enjoyed doing experiments and was thoroughly inept at them. Plus I always enjoyed the equation-solving aspect of physics the most, which should have told me I was a mathematician at heart.

As for careers, I always wanted to teach. There was never any doubt about that. Though for a very short time I considered being a science writer, and I even applied once to be a summer intern at various newspapers and magazines. But nothing came of it. *Time* magazine was the friendliest; they asked me to be a stringer for them, reporting from Cambridge, England (where I was then studying as a Marshall Scholar). It sounded good until my first assignment, when I wasted an entire afternoon sitting in Lord Dacre's office, waiting for a chance to ask him a few questions about "the social fabric" of England. That was enough of that. Whereas the *New York Times* instantly rejected my application with a zinger: "Even our copy boys have journalism degrees."

Describe some of your earliest research.

My first paper came out of my senior thesis in college. It was about the topology of DNA supercoiling—specifically, the linking number of DNA as it winds around the nucleosomes in the chromatin fiber. I'd gotten interested in biology during my junior year (when I was briefly pre-med, in response to some family pressure). The double helix made a big impression on me, especially how the rules of base pairing immediately suggested the way that replication must work. And I'd also taken a great course in differential geometry that same year, and wanted to find a way to combine those two fields, to do something about the geometry of life for my senior thesis.

I asked Fred Almgren to be my adviser. He was the closest approximation that Princeton had to an applied mathematician. He'd recently published a *Scientific American* article about minimal surfaces and the geometry of soap bubbles. As soon as I described what I was interested in, he suggested a problem about the supercoiling of DNA. This was long before the ideas of writhing numbers and linking numbers became fashionable. The whole project was a fantastic experience for me, especially toward the end, when I had a chance to collaborate with Abe Worcel, a brilliant, volatile molecular biologist and the resident expert on supercoiling. We ended up proposing a new model for the structure of chromatin, with the nucleosomes arranged in a zig-zag instead of a solenoidal helix.

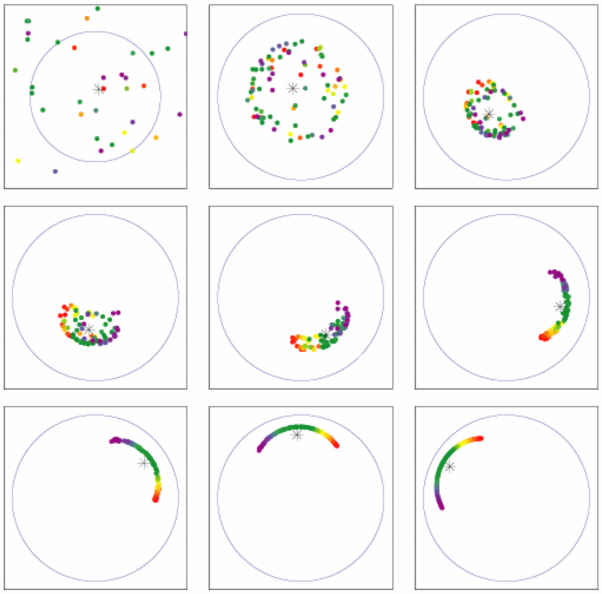

Figure 1. *Spontaneous synchronization in a network of coupled limit-cycle oscillators with distributed natural frequencies. The state of each oscillator is represented geometrically as a dot in the complex plane. The radius and angle of the dot signify the oscillation's amplitude and phase. Colors code the oscillators' intrinsic frequencies, running from slowest (red) to fastest (violet). As time progresses (from left to right, and top to bottom), the oscillators self-organize from a random initial condition and ultimately rotate as a synchronized pack. (Reproduced, with permission, from S. H. Strogatz, "Exploring complex networks," Nature 410, pp. 268-276 (2001).)*

How do you feel that your scientific work, attitude and approach have changed over the years?

The math I use has changed a bit. Initially I was interested in applying geometrical ideas to biology. That was the theme of the DNA supercoiling project, and it continued in my work with Art Winfree on the topology of scroll waves in excitable media. Those two summers with Winfree, in 1982 and 83, did a lot to shape my later tastes and interests. Winfree taught me about human sleep and circadian rhythms (which is what I worked on for my Ph.D.), and he introduced me to the mathematical topics that have occupied me since then: nonlinear dynamics, especially coupled oscillators and synchronization.

But in most ways (and I feel sheepish admitting it), my approach has stayed pretty much the same over the years. I've always liked thinking about everyday life, especially about phenomena that don't seem overtly mathematical, like love affairs or fireflies or six degrees of separation. I like simple, idealized models and the pleasures of analyzing them. And I care much more about problems than methods. What matters most is that the question should be captivating. Winfree taught me that strategy. When we were deciding what to work on, he told me the problems "must be things that irrationally grip you (and me) by the imagination, else nothing remarkable can be expected to happen."

You have written both textbooks and "popular science" books such as Sync. What major differences do you find in the process of writing for these different audiences?

The process of writing a textbook came much more easily. I had given a course in nonlinear dynamics three or four times before I started writing, so I had plenty of lecture notes, homework problems, and old exams to use. Plus I felt I knew who the audience was—I'd been teaching them. Of course there were a million little details to worry about, but that didn't bother me; I had just gone through a divorce, and was content to work every night and weekend, distracted only by my cat jumping on the computer every few hours.

Whereas writing *Sync* was an ordeal. I was completely unsure of myself at every turn. How much should I explain? Am I aiming this at the level of my relatives, or my old high school science teacher, or my colleagues in other fields? How much of my own life should I inject into the story? After all, I'm not Jim Watson writing the *Double Helix*, so what am I doing in the story at all? And on and on, self-doubts like I've never felt before. I never did figure out what level to pitch the book at—I just ended up trusting my editor, Will Schwalbe, who had no science background but a wonderful bedside manner, a keen eye, and a lot of reassuring enthusiasm for the book. He became the lay reader I was writing for.

With a book like Sync, what do you hope the "intelligent lay reader" will take from the book?

I wanted the reader to feel what it's like to be a scientist. The day-to-day fun of it, the frustrations, the sense of the hunt, dead ends and little breakthroughs, the journey from student to teacher, the feeling of being part of a huge, inspiring enterprise. And I know that people like stories about people, so I tell a lot of anecdotes about my colleagues and mentors and students, as well as all-time greats like Ed Lorenz, Brian Josephson, Christian Huygens, and Norbert Wiener.

Another thing is that the subject itself is so cool—there's something spooky about self-synchronizing systems, something almost mystical. I hoped I could convey that, in a scientifically honest way.

And finally, I very much wanted to convey what it's like to do research in applied mathematics. There have been very few books in which mathematicians try to explain what they do and why they love it so much, and the ones that do exist usually lean heavily toward pure math.

What do you hope a researcher in biological physics will gain from Sync?

A recognition of how ubiquitous synchronization is, and a curiosity about why that should be so.

"Everyone" says that we are in the midst of a great burgeoning of interdisciplinary science. Do you agree with that? How do you feel that interdisciplinary research has changed over the last couple of decades?

There have always been pioneers with the interdisciplinary spirit, but what's new is that "the establishment" is now behind them – at least, much more so than before. All the top universities are starting programs in systems biology, integrative biology, computational biology, functional genomics, and so on. It's becoming easier for students to get trained in these areas, and faculty are being given incentives to do this kind of work. I'm not sure that's a great idea, actually. Interdisciplinary work takes a certain kind of person, someone flexible and empathic, and with a flair for speaking different scientific languages.

Figure 2. *Steven Strogatz. (Photo by Dede Hatch.)*

Describe the genesis of the idea of small-world networks. How did you and Duncan Watts come to work on this topic?

Duncan's thesis problem was originally supposed to be about the chorusing of snowy tree crickets—how hundreds of them can end up chirping in unison. We saw that as a promising model system for studying collective synchronization more generally. But one summer night, while collecting crickets out in Cornell's orchards, Duncan got to thinking about how they might be interacting. Who was listening to whom? Did each cricket pay attention only to his nearest neighbors in the tree, or were longer-range interactions important too? And did it even matter how they were connected? That got him thinking about connectivity in general, and then, for some reason that can only be called creative, he remembered something his father had once told him, about how we're all just six handshakes from the president of the United States. He must have let the idea germinate in his head for a few months, because the first time he ever mentioned it to me was in January 1996. He asked what would happen if an oscillator network were connected in that way, with everyone just a few handshakes from everyone else. Would the system synchronize more strongly because of all the rapid communication channels across the network?

Before I could discourage him by reminding him how little was known about such things, and how hard they would be to solve, he barreled on and emphasized that the issue was big—much bigger than a question about coupled oscillators. It could have implications for all of science, since networks—and dynamical systems interacting on them—occur everywhere. Right away we both had a giddy feeling, a mixture of excitement and nervousness. On the other hand, neither of us knew anything about graph theory, and the whole project seemed risky and kind of flaky. So we decided to just play around with the idea for a few months; if it seemed we were getting nowhere, we'd go back to crickets.

Were you surprised by the amount of interest that has been generated in small-world networks over the last few years? Did you have any inkling that the field would take off so fast?

We thought there was a good chance it might catch on. There were so many interesting directions to pursue scientifically. You could do empirical work on real networks, like food webs, power grids, gene networks, and the Internet. You could make better models of complex networks and analyze them with graph theory or statistical mechanics. You could study dynamical systems on networks and ask how the topology affects the collective behavior. Also, from talking to our non-scientific friends, we could see these ideas would appeal to the general public. Networks were just starting to be in the air. The Web had exploded in 1994. The Kevin Bacon game was the biggest craze of 1996. So yes, when we were writing the 1998 Nature paper, we definitely felt the stakes were high.

But we also knew that it could end up being a dud. A few very smart colleagues couldn't see the point of our work. One dismissed it as just percolation and another thought it was just a question about the diameter of a random graph.

What do you think has been the most interesting and valuable application of small-world networks? What do you think has been the most outlandish?

There's been so much nice work that it feels unfair to single out just one contribution. Arbitrarily picking one that comes to mind, there was a computer science paper by Korniss et al. (*Science* 299, 677-679 (2003)) that struck me as very intriguing. They showed how to speed up massively parallel simulations by adding a few long-range links between the processors. The advantage of this small-world architecture, compared to purely nearest-neighbor connectivity, is that it keeps all the distributed computations moving forward in step, thereby avoiding data-traffic bottlenecks. As for outlandish applications, well, how about the paper that documented the small world of Marvel comic-book characters [Arxiv preprint cond-mat/0202174]? That was an imaginative one!

What advice would you have for a scientist just beginning a career in interdisciplinary science?

First, master the basics in as many fields of science and math as you can. Take undergraduate courses, even if you are a graduate student. Those fundamental courses will help you learn the languages and ideas you'll need to collaborate with scientists from other fields.

Second, don't be afraid to work in a completely unfamiliar subject. You can come up to speed amazingly quickly, if you have a collaborator in that field, and if you hang around his or her lab for a few weeks. And keep in mind that you bring many advantages as an outsider. You have a different set of tools. You will ask unusual questions. And you don't know what's impossible.

For more information:, the reader can visit http://tam.cornell.edu/Strogatz.html.

Selected recent publications include:

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(2) Abrams DM, Strogatz SH. Chimera states for coupled oscillators. Phys Rev Lett. 2004 Oct 22;93(17):174102.
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(9) Watts DJ, Strogatz SH. Collective dynamics of 'small-world' networks. Nature. 1998 Jun 4;393(6684):440-2.

PRE HIGHLIGHTS

Biological Physics articles from Physical Review E

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Assistant Professorships in Theory in Biological Physics and/or Theoretical Biochemistry

The Department of Physics & Astronomy and the Department of Chemistry & Biochemistry at Arizona State University seek candidates for two tenure-track assistant professorships in theoretical/computational biological physics and/or theoretical/computational biochemistry starting August 2006. Candidates will conduct and publish research, teach graduate and/or undergraduate courses, and perform appropriate service activities. In exceptional circumstances, an appointment at a more senior level may be made.

Applicants must have a Ph.D. degree in physics, chemistry, biochemistry, or a closely related discipline by the time of appointment, a strong demonstrated research experience, the potential to attract external funding, and a commitment to effective teaching appropriate to rank. Experience working in an interdisciplinary environment is desired. As part of its development plan, Arizona State University is expanding all aspects of interdisciplinary biological research, which includes the new Biodesign Institute and the School of Life Sciences. Research in this area spans the range from the most fundamental questions through biotechnology. Joint appointments as appropriate are encouraged involving departments, the Biodesign Institute, and the School of Life Sciences.

Applicants must send a résumé and a statement describing their current and future research interests, and arrange to have three letters of recommendation sent on their behalf. Initial review of applications will begin on November 15, 2005, and, if the position is not filled, will continue every two weeks until the search is closed. Further information about this position can be obtained from the chair of the search committee, Michael Thorpe (mft@asu.edu).

Please send application materials to: Theory Search, ATTN: Margaret Stuart, Arizona State University, Department of Physics & Astronomy, P.O Box 871504, Tempe, AZ 85287-1504 or email materials to biotheory@asu.edu. A background check is required for employment.

ASU is an equal opportunity/affirmative action employer, and actively seeks diversity among applicants and promotes a diverse workforce.

Postdoctoral Positions Available

The Applied Chaos Lab is seeking one or more postdoctoral fellows (for a period of up to three years) to work on various projects involving the application of dynamical systems to experimental biological and computational systems. In particular, we are interested in candidates with a strong grounding or interest in experimental nonlinear dynamics, biology, computing and medicine. Specific projects include the analysis and control of epilepsy, cardiac wave dynamics and the use of chaos to construct novel computing architectures in analog and digital VLSI circuitry. Ideal candidates would have both theoretical and experimental experience in dynamical systems, biological systems and/or novel computer architectures. Please email a current CV and the names and contact information of three references to: chaos@bme.ufl.edu, or to William Ditto, Applied Chaos Lab Postdoctoral Search, Department of Biomedical Engineering, 130 BME Building, University of Florida, Gainesville, FL 32611-6131.