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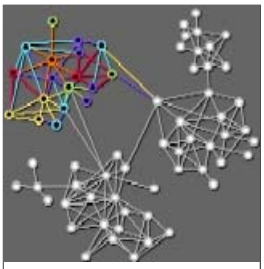

(National Science Foundation)

The Job Market

Tangled Webs: Careers in Network Science

In the age of Facebook, it's easy to grasp the idea of networks and of the endlessly variable and sometimes puzzling interactions that can occur among their members. It's also not hard to imagine that what binds you and your friends (and your "Friends") has analogs in ant colonies and beehives, tumor cells and the brain, terrorist groups and spam hosts, the Internet and the electrical power grid. But despite the current ubiquity of networks, it hasn't always been obvious to science that the connections *between* elements in any given network are, often, as interesting as the isolated network elements themselves, or that understanding one kind of network might shed light on others. These are the key insights of the emerging field of network science.

"It's still social science, but it involves a broader set of principles and analytic tools that fit into the physics literature." --David Lazer

Social scientists understood the importance of networks long ago and have spent decades developing quantitative tools to examine the dynamics of social groups: Who is friends with whom, who influences whom, who gets information from whom? Computer scientists also have a venerable history of studying networks.

(Courtesy, Albert-László Barabási)

Albert-László Barabási

But it's only in the last decade that network science has exploded, attracting scientists from disciplines including physics, applied math, engineering, economics, and the biomedical and environmental sciences. "The sheer volume of the field has increased dramatically in the last 3 to 5 years, so much so that I'm unable to keep up," says physicist Albert-László Barabási, director of the **Center for Complex Network Research (http://www.barabasilab.com/)** at Northeastern University in Boston.

"When I started working in the field about 10 years ago, there were probably only a dozen physicists interested in networks," says physicist Mark Newman of the **Center for the Study of Complex Systems (http://www.cscs.umich.edu/}{)** at the University of Michigan, Ann Arbor. "Now you go to conferences and there are hundreds." Network research has become mainstream, he notes. "Now you open the major journals, and you regularly find articles on network research."

Unifying principles

Modern network research is an extension of a long-established branch of theory that deals with a world of mathematical abstractions. But it's the messy real world that has fueled network science's recent growth. The sudden availability of massively complex data sources, including the Internet, e-mail, and mobile phone records, has spurred new questions about how networks function, even as vastly improved computational power has made it practical to analyze huge data sets. Jennifer O'Connor, a psychologist in the science and technology division of the Department of Homeland Security, says: "When I first came out of grad school, I used to shut down a mainframe on a regular basis. Now I can analyze those data on a laptop."

What unites the sociologists, physicists, biologists, and other scientists studying networks is the recognition that "whether they're networks of people, computers, genes, [or] neurons, they often obey similar mathematical rules and have similar properties," says **Nicholas Christakis (http://www.wjh.harvard.edu/soc/faculty/christakis/)** , a professor of sociology and of medical sociology at Harvard Medical School in Boston.

(Norman Johnson)

Mark Newman

That doesn't mean that the interactions within a honey bee colony are exactly like those of a metabolic pathway, a pandemic flu outbreak, or an air traffic–control system. But it does mean that the mathematical tools developed to study one phenomenon can yield insights into others. Physicist **Marta González (http://cee.mit.edu/gonzalez)** of the Massachusetts Institute (MIT) of Technology in Cambridge and colleagues, for example, are using mobile phone records to study people's travel patterns. By integrating methods of statistical physics, computational science, and geographic information systems with classical network theory, the researchers have been able to find patterns that could help address problems as diverse as urban traffic congestion and the spread of epidemics.

For more and more disciplines, 'This is us'

Network science has become an interdisciplinary undertaking, drawing on tools and ideas from at least two dozen fields. "Computer scientists and sociologists, of course, claim it as their own," says Barabási. "Biologists claim that networks are all about them. And then there are a lot of new areas, like engineering and informatics, that are recognizing this is important to them. There's a lot of passion within this community to say, 'This is us.' "

That interdisciplinary appeal is evident in the makeup of some of the most cutting-edge laboratories. Christakis, for example, will have four postdocs in the lab this year: a psychiatrist who also has a Ph.D. in economics, a computational biologist, a physical anthropologist, and a physicist.

The tools that different disciplines bring to the study of networks are varied because different disciplines are trying to answer different questions. For example, social scientists studying human group dynamics have focused heavily on research design and statistical methods that can uncover patterns of causation within a network, says political scientist **David Lazer (http://www.hks.harvard.edu/davidlazer/html/)** of Harvard University. "That's not been part of the sensibility of the physics

(Courtesy, Jennifer O'Connor)

Jennifer O'Connor

and computer science community because, historically, they have not studied human beings, who produce more ambiguous data than particles do," he says. On the other hand, social scientists typically have not needed the kinds of computer algorithms that computer scientists need to route a data packet from one place to another on the Internet.

These diverse methods converge around unconventional data sets, Lazer says. A sociologist trying to pick meaningful patterns out of records for millions of mobile phone calls can't rely only on the quantitative tools that were developed to probe friendship patterns among 100 or fewer people. Studies involving such massive data sets are "a whole different animal," he says. "It's still social science, but it involves a broader set of principles and analytic tools that fit into the physics literature."

Career trajectories

Tooling up to do cutting-edge network research requires, first, honing the quantitative and methodological skills from your discipline that are pertinent to network science. What those skills are and how scientists get them varies from one discipline to another. "That's not necessarily a good thing," says Newman, "but it's where things are right now at many institutions." Sociology, for which social network analysis is a subfield of its own, has standard textbooks and course sequences. In other fields, there is no established training trajectory. Statistical physicists studying networks focus on advanced mathematics, modeling, and computer programming. Network biologists follow still another path, taking courses on bioinformatics, biostatistics, and simulation techniques.

(Courtesy, Marta González)

Marta González

Interdisciplinary training has become more important as the field has matured. Some institutions offer multidisciplinary courses on complex systems. If your department doesn't offer such courses, take courses in other fields, or read the literature independently. One way to broaden your scope is through a postdoc in a different network-related discipline or a multidisciplinary lab. Some researchers have jump-started network-research careers by taking summer courses at the **Santa Fe Institute (http://www.santafe.edu/)** .

As network science has gained momentum, a number of interdisciplinary centers dedicated to network science have emerged--for example, at Northeastern University, the University of Michigan, Indiana University, the **University of Notre Dame (http://www.nd.edu/%7Enetworks/)** , and in nonuniversity settings such as the Santa Fe Institute and the Los Alamos National Laboratory. Similar facilities exist in Europe, at the International Centre for Theoretical Physics in Italy and Institute Para Limes in the Netherlands, to name two. Such centers are still few and employ only a small fraction of scientists trained to do network research. But they play an important role in training scientists and fostering the kind of interdisciplinary grounding that network research demands.

Few universities advertise faculty positions in network science per se; with some exceptions, network researchers are housed within disciplinary departments and must convince hiring and tenure committees that their work constitutes a significant contribution to their home field. Yet the demand for researchers who can do network research, especially those who have interdisciplinary skills and knowledge, is high. "The skills are so widely applicable, and so many fields need their expertise, that they really don't have much trouble finding employment," says Barabási.

Even so, where a network scientist will land can be hard to predict. After finishing a postdoc in Barabási's lab this year, González, a statistical physicist, got four job offers, only one of which came from a physics department. González, who ultimately accepted a tenure-track position in civil and environmental engineering at MIT, says her experience is not unusual, especially among physicists doing network science, few of whom end up working in physics departments.

Money is flowing

You don't often hear scientists say that there's plenty of funding for their field. But you do hear network scientists say it. "Right now just about everyone" is funding network science, says MIT sociologist Damon Centola, who studies how beliefs and behaviors--from religious extremism to vaccination--spread in large social groups. "It's a really good time to get into network science," he says.

(Courtesy, David Lazer)

David Lazer

The U.S. National Institutes of Health (NIH) has made major investments in network approaches in many areas, including cancer biology, cardiovascular and metabolic diseases, neurophysiology, and human genetics and genomics. The agency supports network science through individual institutes (for example, the National Institute of General Medical Sciences funds nine **National Centers for Systems Biology (http://www.nigms.nih.gov/Initiatives/SysBio)** , academic centers that emphasize network biology) and through agencywide initiatives (such as the **National Technology Centers for Networks and Pathways (http://nihroadmap.nih.gov/buildingblocks/technologycenters/)** , funded by the NIH Roadmap for Medical Research and the **recently announced (http://www.nih.gov/news/health/jul2009/ninds-15.htm)** Human Connectome Project, which aims to map the connections among the human brain's 100 billion neurons).

The National Science Foundation, too, has been increasing its support for network science, especially within the divisions dedicated to computer science and human social dynamics. There is also growing military support for network research, Barabási says, pointing to research programs funded by the Army, Air Force, Office of Naval Research, and Defense Threat Reduction Agency. "There's never enough money, of course," he says. "But we're seeing that many agencies are discovering that this is important, and they're putting their money where their mouth is."

Resources

- Connected: The Power of Six Degrees (http://ivl.slis.indiana.edu/km/movies/2008-talas-connected.mov) (video)

- Network Science (http://www.nap.edu/catalog.php?record_id=11516) (2005). National Academies Press

- David Lazer's **Complexity and Social Networks Blog (http://www.iq.harvard.edu/blog/netgov/)**

- Center for Complex Network Research (http://www.barabasilab.com/) (Northeastern University)

- Center for the Study of Complex Systems (http://www.cscs.umich.edu/) (University of Michigan)

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