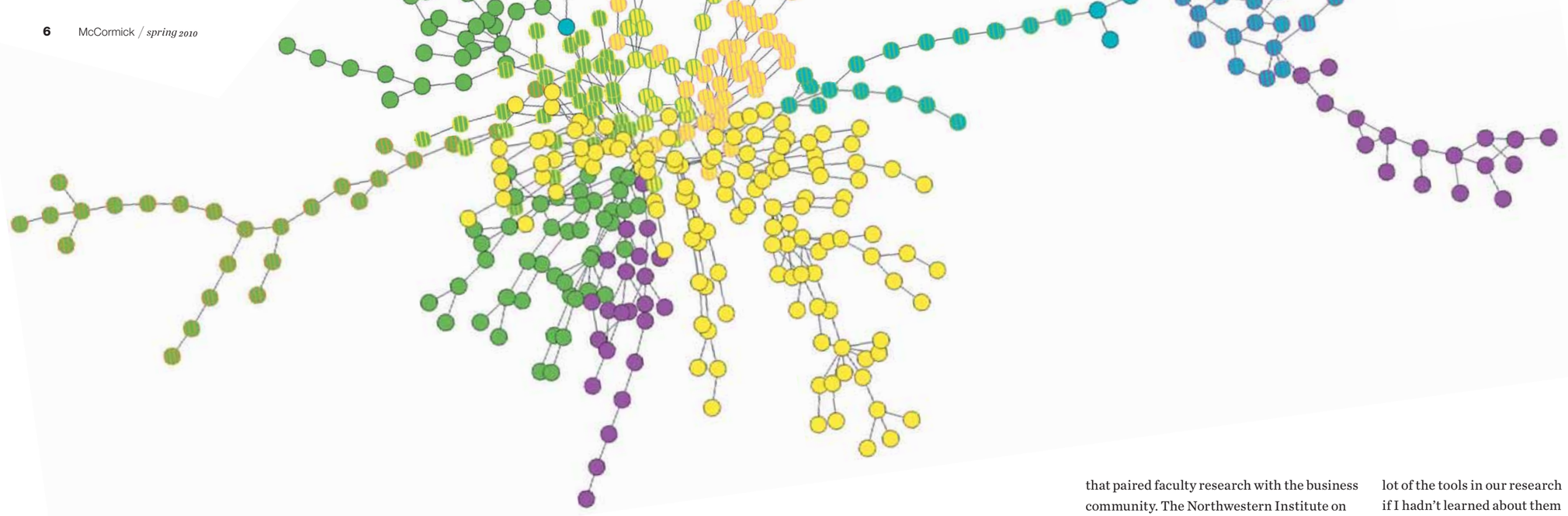


Left: Cartographic representation of the metabolic network of *E. coli.* Graphic by Luis A. N. Amaral and Roger Guimera. Below: NICO codirectors Brian Uzzi and Bill Kath

Network U

Connections enable research on complex systems

In many ways much of the progress in science has involved taking something complicated — a cell, a machine, an organization — and breaking it down to understand its basic building blocks and how they work together. But what if an understanding of the parts (neurons in the brain, for example) does not lead to an understanding of the whole (human consciousness)? What if knowledge of an object didn't come from an understanding of its parts but from an understanding of the connections among its parts? What if the object at hand is not just **complicated** but **complex?**

Over the past 10 to 15 years engineers and scientists have begun to view complex systems — such as traffic, power grids, social networks, and cells — as a series of connections rather than a collection of parts. Understanding these vastly intricate systems requires a new way of thinking and new types of collaboration. Northwestern has positioned itself at the forefront of this kind of research.

Nearly three dozen faculty members are now deeply involved in complex systems research at Northwestern. Working in research areas ranging from networks of neurons to social networks, faculty from McCormick are learning that the connections that they develop with each other are nearly as important as the dizzying networks they study.

Recognizing a need, starting an institute

Six years ago Julio M. Ottino, then a professor of chemical and biological engineering and now dean of McCormick, saw the growing interest in complex systems. His research on chaos and self-organization and the modeling of complex systems had earned wide attention, and a meeting with Daniel Diermeier, the IBM Distinguished Professor of Regulation and Competitive Practice at the Kellogg School of Management, sparked a cross-disciplinary collaboration. Although their work addressed different areas — Diermeier's research focuses on social and political phenomena — both professors realized that the theories and principles behind complex systems could be applied across disciplines.

"Complex systems were gaining more attention as an emerging research area, and we knew we were in a position to place Northwestern at the forefront of it," Ottino says. "Investigating how complex systems operate — looking at them as a whole and not just as the sum of their individual parts — is the only way to get an understanding and to make sensible decisions about them."

Ottino and Diermeier started pulling together faculty from across the University who were interested in the topic. What started as group meetings over lunch quickly expanded into a network of interdisciplinary teams, conferences, and a corporate outreach program that paired faculty research with the business community. The Northwestern Institute on Complex Systems (NICO) was born.

"It was the budding of a brand-new science," says Brian Uzzi, the Richard L. Thomas Distinguished Professor in Leadership at Kellogg, an expert in complex networks and now codirector of NICO. "Northwestern really got on at the bottom of the escalator."

At the heart of the center are weekly meetings where faculty members present their research and connect with each other. "People are just now figuring out the basic rules and tools by which you try to understand complex systems," says Bill Kath, professor of engineering sciences and applied mathematics and codirector of NICO. "We try to get people from across all kinds of disciplines to see if what you learn in one field can be translated into others. If you can get a little bit of insight into how a network works in one case, perhaps you can apply that to some other field."

Part of his research involves looking at the complex systems in biology. Kath works with Nelson Spruston, professor of neurobiology and physiology in Weinberg College, to understand how networks of neurons process information. Kath and Spruston's models have shown how neurons receive and integrate signals and how biological processes cause a neuron to fire. Studying how neurons behave in certain situations gives them a better idea of how the brain processes and stores information.

"We may never fully understand how the brain works," Kath says, "but we look for these key insights that help us understand what's happening. I wouldn't have thought to use a lot of the tools in our research if I hadn't learned about them from other faculty members in NICO."

Studying networks, from cells to students

The networks inside the body provide rich opportunities for research in what is called systems biology. Luis Amaral, professor of chemical and biological engineering, is primarily focused on building an equivalent to Google Maps for human cellular organization. (Amaral was named a Howard Hughes Medical Institute Early Career Scientist in 2009.) But he has also expanded his network research into other disciplines. Amaral has collaborated with Daniel Diermeier to study political prediction markets and consensus building and with Brian Uzzi on a project that will look at every scientific paper published since 1945 to come up with a more efficient way to rank academic departments.

Amaral is also collaborating with Uri Wilensky, associate professor of electrical engineering and computer science and of education and social policy, to look at networks among students in Chicago and Evanston. Amaral and Wilensky used surveys to find networks among the students, then used that data to determine the effects of school closings. Preliminary findings show that belonging to a group had a positive effect on how students performed at new schools. "We have been using network analysis and database modeling," Amaral says. "This was made possible by NICO. If you are like me and you like to work on many different things, you need to find people who can tell you what is known, what is not known, what could be challenging, and what is possible."

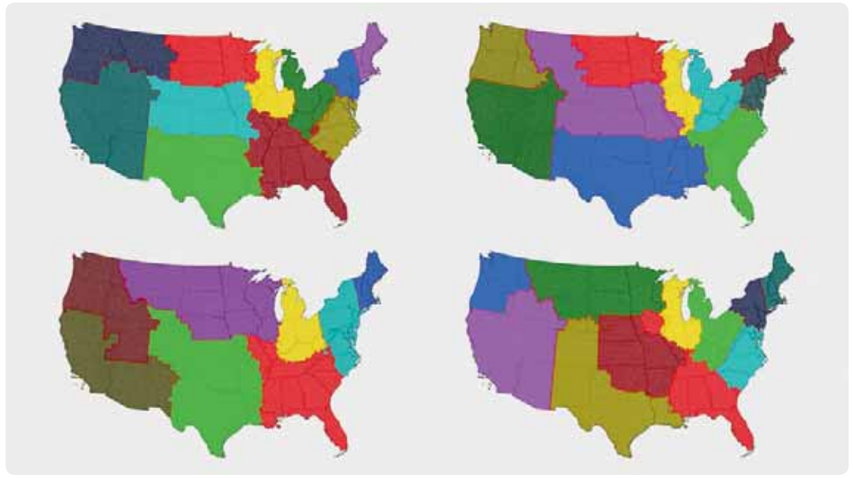
Changes in social network research

Social network analysis, an area once traversed only by sociologists, is undergoing a dramatic change. Previously, underfunded faculty members would hand out small-scale surveys, but in the digital age researchers use electronic information to understand human networks. "In the last five years we've gotten an unprecedented amount of electronic footstep data from e-mail, blogs, and Twitter," Uzzi says. "We now have an unbelievable amount of information on how people actually behave."

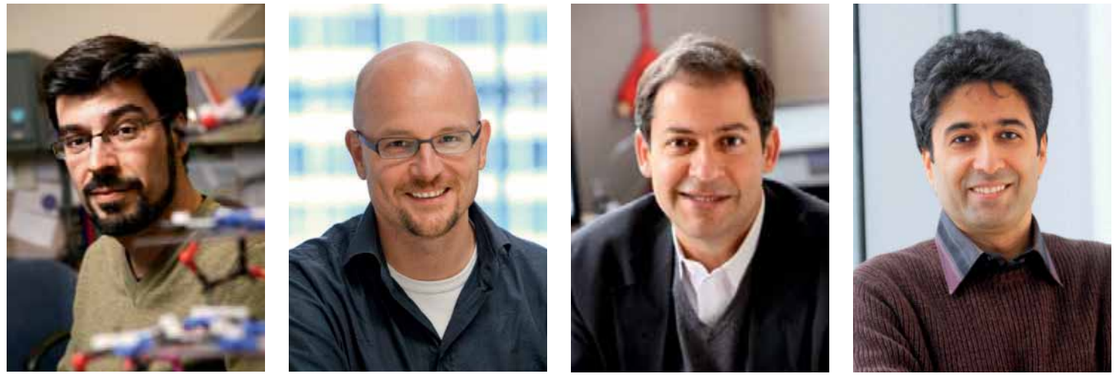
Uzzi, a sociologist by training, had always studied social networks. In one well-publicized paper Uzzi studied Broadway playbills from more than 2,200 productions to pinpoint how networks were involved in successful shows. In the NICO era, however, he has started studying large-scale networks.

"Sociologists have theories and models, but they don't really have methods to deal with large databases," Uzzi says. "NICO provided me with an opportunity to form collaborations with people who are trained in these methods."

Uzzi's collaborations with Amaral have led to new research on team science and science policy. "We are in a tremendously good position to take advantage of this new era in the social sciences," Amaral says.



Based on a human mobility network created with data from WheresGeorge.com, Dirk Brockmann and his research group have created maps of large-scale community boundaries in the United States. Graduate students Christian Thiemann and Daniel Grady created a video about the research called "Follow the Money," which won first place in the 2009 International Science and Engineering Visualization Challenge. Visit http://video.mccormick.northwestern.edu to see the video.



Among the network scientists at the McCormick School are (from left) Luis Amaral, Dirk Brockmann, Noshir Contractor, and Seyed Iravani. Their work with colleagues at the Northwestern Institute on Complex Systems (NICO) covers myriad disciplines, collaborations, and problems. It places the University at the forefront of this developing and highly influential field.

The impact of connecting

Using vast databases to get new perspectives on human behavior is also within the purview of Noshir Contractor, the Jane S. and William J. White Professor in Behavioral Sciences at McCormick and professor of communication studies. Contractor and his collaborators, who include scientists and engineers from around the country, are studying nearly 60 terabytes of data from EverQuest II, a massive multiplayer online role-playing fantasy game in which players complete quests and socialize with one other. The researchers analyzed this data along with a survey of 7,000 players, making it one of the largest social science projects ever to investigate virtual worlds.

Contractor is now looking at how players develop trust in virtual worlds. For example, in the online world of Second Life, players can assign other players different levels of trust, allowing them to see when they are logged on, for example, or allowing them to come into their online homes. By studying levels of trust, Contractor can create models of how people develop trust that can be used in real-life situations, as in emergency response situations where people have to work together but don't yet trust one other. Contractor is also working on a National Science Foundation project to analyze these large-scale networks using petascale computing.

"We have certain techniques to discern and understand the structural signatures of networks," Contractor says. "The techniques to accomplish these goals are very computationally intensive. We're exploring new algorithms that take advantage of high-performance computing, such as the recently launched petascale environments, to concurrently investigate disparate parts of these very large networks."

Contractor says that talking with faculty from across the University through NICO has given him theoretical and methodological insights into how networks can be understood and enabled across different disciplines. "It's incredibly valuable to me to find someone who is studying networks in one discipline and who has developed mathematical, computational, or statistical techniques that have not been discovered by those studying networks in other contexts," he says.

Human networks and new state boundaries

It was through NICO that Contractor met Dirk Brockmann, associate professor of engineering sciences and applied mathematics, who has used data from WheresGeorge.com — a site where users enter the serial numbers from their dollar bills in order to track the currency's travels — to discover the patterns that govern human mobility. That information has allowed Brockmann to reconstruct a comprehensive multiscale human mobility network for the United States that includes small-scale daily commuting traffic, intermediate traffic, and long-distance travel by air.

Using a framework based on this mobility network, Brockmann has modeled how diseases spread throughout the country and has created a map of large-scale community boundaries within the United States that differ from those defined by political boundaries. He is trying to understand the underlying rules of human mobility and the complex patterns hidden within multiscale human mobility networks.

Brockmann, whose collaborations with linguists and epidemiologists allow him to study everything from infectious disease to language, says NICO was one of the reasons he came to Northwestern a year and a half ago. "The critical mass of people at NICO who share the same philosophy about networks generates this interdisciplinary spirit," he says.

Optimizing the workplace

Social networks can be used to make businesses more efficient as well. That was a revelation for Seyed Iravani, associate professor of industrial engineering and management sciences, who, after learning about other faculty members' research through NICO, decided to apply their social network theories to his own work in operations management.

Iravani uses operations research methods and applied mathematics to determine how manufacturing and supply-chain companies can be more efficient and productive. When he read Brian Uzzi's paper on Broadway musicals, he realized he could use Uzzi's social network ideas in his own research.

His first project was to test social network theories in call center workforce management. A major issue for call centers is employee turnover. The high rate of turnover frequently forces call-center managers to decide whom to train or cross-train to answer different types of calls. Using concepts from social network theories, Iravani developed a model that helped managers quickly determine which employees to cross-train so that customers spend less time on hold.

> "If science is about great new discoveries, this area of network science is where those new discoveries are coming from. Northwestern is making that happen." BRIAN UZZI

"I was very excited because I was able to steal a concept from one discipline and bring it to another," he says. "I'm bringing the concept of complex systems and social networks to operations management, which hasn't been done enough."

Iravani also worked with a major auto manufacturer to examine the product development process. In a business where more than 10,000 engineers design more than 100,000 parts for a new car, engineers keep a paper trail of documents (called "engineering change orders") that can be used to track who talked to whom and when; when two or more engineers discuss something that affects parts they are designing, they all sign a document.

Iravani studied the more than 100,000 documents compiled during one vehicle's three-year design period. From that data he first created a complex network of the parts (how the parts of the vehicle are physically connected) and then a network of people (who talked to whom and how often). He then compared the two networks and asked, Did the connected engineers talk as often as their connected parts would have decreed?

"We could see where there was a lack of coordination," Iravani says. "If there was no connection, we could tell there would be a warranty problem later." And sure enough, Iravani was able to predict 7 of the top 10 warranty problems on the vehicle.

Iravani is no stranger to cross-disciplinary research: several years ago he conducted a study to show the collaborations of McCormick faculty members. "We showed that if you wrote a paper with someone from a different department, you got more citations and had more impact in the field," he says.

The future of NICO

Researchers who study networks are cognizant of their own networks, and NICO's are strong and growing. Its corporate arm provides executive education on complex systems and matches faculty members with businesses to collaborate on research. New links form among faculty members each week, and excitement about complex systems is growing on campus and beyond. The first-ever "Science of Team Science" conference, cochaired by Contractor and organized by several NICO faculty members, will be held in Chicago in April; participants will discuss what makes scientific teams succeed or fail.

"Northwestern is a leading institution in the study of team science," Uzzi says. "We continue to do some of the best work in the area of social networks. If science is about great new discoveries, this area of network science is where those new discoveries are coming from. Northwestern is making that happen."

The study of complex systems is daunting, but even small advances are changing our knowledge about previously inexplicable networks. "We may not fully understand everything," Kath says, "but every new insight enables you to make the system a little better." —*Emily Ayshford*