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Information Theory After Shannon

Purdue University's Science of Information Center seeks new principles to answer the question 'What is information?'

IN A SENSE, Claude Shannon invented the Internet. An electronic engineer at Bell Labs, Shannon developed information theory in "A Mathematical Theory of Communication," a landmark paper published in 1948. By quantifying the limits to which data could be compressed, stored, and transmitted, he paved the way for high-speed communications, file compression, and data transfer, the basis for the Internet, the CD and the DVD, and all that they entail. Now scientists at Purdue University, with a $25 million, five-year grant from the U.S. National Science Foundation, have created the Science of Information Center with the goal of moving beyond Shannon. They aim to develop principles that encompass such concepts as structure, time, space, and semantics. These principles might help design better mobile networks, lead to new insights in biology and neuroscience, drive research in quantum computing, and even aid our understanding of social networks and economic behavior.

"Whether we will build a new theory or not remains to be seen," says Wojciech Szpankowski, professor of computer science at Purdue University and leader of the project, which includes some 40 researchers at nine universities. "It's definitely time, after 60 years, to revisit information theory. It's basically communication and storage today, but we need to go beyond that."

In Shannon's theory, information, which consists of bits, is that which reduces a recipient's statistical uncertainty about what a source transmitted over a communications channel. It allows engineers to define the capacity of both lossless and lossy channels and state the limits to which data can be compressed. Shannon theory ignores the meaning of a message, focusing only on whether the 1s and 0s of binary code are being transmitted accurately. It doesn't care about the physical nature of the channel; information theory is the same for a telegraph wire or a fiber optic cable. And it assumes infinite delay, so a receiver has all the time it needs to receive and recognize a signal.

Wojciech Szpankowski, project leader for the Science of Information Center at Purdue University, is revisiting Claude Shannon's information theory with a team of some 40 researchers.

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A growing challenge for information theory is the field of quantum information and quantum computing.

Szpankowski argues that information goes beyond those constraints. Another way to define information is that which increases understanding and that can be measured by whether it helps a recipient to accomplish a goal. At that point, semantic, temporal, and spatial factors come into play. If a person waiting for a train receives a message at 2 P.M. saying the train leaves at 1 P.M., the message contains essentially no information. In mobile networks, the value of information can change over the time it takes to transmit it because the person receiving it has moved; instructions to make a left turn are pointless, for example, if the driver has already passed the intersection. And there's no good way to measure how information evolves on the Web. "We cannot even understand how much information is transmitted on the Internet because we don't understand the temporal aspect of information," Szpankowski says.

Sergio Verdu, an electrical engineer at Princeton University and a co-principal investigator, is trying to find the fundamental limits of compression and data transmission. The math is easy if engineers focus on signal-to-noise ratio, but that turns out to not be the best measure of fidelity in audio and video. The human brain is very tolerant of visual noise in general, but less so of particular types of noise; for instance, sharp edges are much more important to identifying an image than color. It's not just a question of how many bits have to be received to deliver a comprehensible message, but which bits. "In lossy compression, the bottleneck has been to come up with measures of distortion that are relevant in the real world," says Verdu.

It's also difficult to find the limits of compression for structural information, says Szpankowski. Proteins behave differently and transmit different information depending on their shape, and scientists would like to build computer models that would help them better understand how structure contributes to cell development or the rise of diseases. But the math becomes complex, because structural elements such as edges and vertices can add several dimensions to an equation. So far, Szpankowski says, no theory exists to provide a metric for how much information is embedded in structure. There's not even a good way to quantify complexity; we can say a car is more complex than a bicycle, but how much more?

Shannon theory works well for point-to-point transmission or in systems with several transmitters and one receiver. But once there are two transmitters and two receivers, the problem of cross-talk arises, where a receiver can pick up a signal from the wrong transmitter. With the growth in mesh networks and mobile communications, and even high-frequency transmissions turning old copper wires into miniature antennas, the point-to-point solution isn't adequate. "We still don't know what are the ultimate, fundamental limits to how much information we can send robustly in the presence of noise," Verdu says.

Quantum Information

A growing challenge for information theory is the field of quantum information and quantum computing. Classical information has always been understood as a collection of bits, says Madhu Sudan, principal researcher at Microsoft Research New England (now on leave from Massachusetts Institute of Technology) and a co-principal investigator. Quantum information, by contrast, is a continuum; the qubits used in quantum computing can have a value of 1 and 0 and any of the infinite possible values in between simultaneously. In such a circumstance, Sudan asks, "What does it even mean to be in-

NSF Science and Technology Centers

The U.S. National Science Foundation (NSF) selected the Purdue University's Science of Information Center as one of the Science and Technology Centers (STCs) to receive funding in 2010. The purpose of the NSF's ambitious STC program is to "support integrative partnerships that require large-scale, long-term funding to produce research and education of the highest quality." In their quest to launch the next information revolution, the Purdue scientists will collaborate with colleagues at Bryn Mawr College; Howard University; Massachusetts Institute of Technology; Princeton; Stanford; University of California, Berkeley; University of California, San Diego; and University of Illinois at Urbana-Champaign.

NSF funded four other STCs. The Center for Dark Energy Biosphere Investigations, headed by the University of Southern California, will explore sub-surface life in deep mines and aquifers and below the ocean floor and how they influence global energy cycles. The Center for the Study of Evolution in Action, based at the University of Michigan, will develop computer models to study complex biological questions that can't be studied in nature. Emergent Behaviors of Integrated Cellular Systems, led by Massachusetts Institute of Technology, will try to engineer biological machines. And the Center for Energy Efficient Electronics Science, led by the University of California, Berkeley, will try to develop technology that can could eventually reduce power consumption in electronics by a millionfold.

Technology

Social Media Trends

The use of social networking is becoming more prevalent worldwide, with people from countries of varying economic development increasingly accessing the Internet to participate in networking sites. In addition, cell phone ownership has increased significantly in 16 countries (for which trends are available) over the last three years, from a median of 45% in 2007 to 81% in 2010.

These are among the findings of a new survey by the Pew Research Center's Global Attitudes Project. The survey, "Global Publics Embrace Social Networking," examined technology usage in 22 countries, with 24,790 people surveyed either face-to-face or by phone. Social networking is especially widespread in the U.S., Pew says, with 46% of the U.S. survey respondents saying they use social networking sites. Other top-ranking countries are Poland (43%), Britain (43%), and South Korea (40%).

Pew notes that while involvement in social networking is relatively low in less economically developed nations, this is largely due to the fact that many in those countries are unable to access the Internet, rather than having a disinterest in social networking.

"In middle- and low-income countries, when people go online they also tend to participate in social networking," says Richard Wike, associate director of the Pew Global Attitudes Project. "In places like Poland, Russia, and Brazil, the vast majority of Internet users also use social networking sites. If you look at the two sub-Saharan African nations we surveyed, Nigeria and Kenya, relatively few people use the Internet, but among those who do, social networking is very popular."

For the most part, the study shows, men and women tend to engage in social networking at about the same rates. The U.S. is the only country in which women (52%) are significantly more likely than men (41%) to use social networking.

—Bob Violino

formation? What does it mean for you to send me information?"

Many differences exist between classical and quantum information, Sudan says, notably that classical information can be copied and quantum information, by definition, cannot. Sudan is not merely interested in discovering fundamental principles; he wants to figure out which ones have practical importance. "The next level is going to focus on 'How do I understand this information? Where did it come from? And how can I manipulate it in ways that are convenient?' " he says.

Researchers are hoping to apply information theory to fields beyond communications and computing. Christopher Sims, an economist at Princeton, applies Shannon's insights about channel capacity to how consumers respond to economic information. In theory, if the central bank alters interest rates or the money supply, prices should change quickly, but in reality they don't. Sims says that's because people have limited physical capacity to process all the data, so they usually don't act on the information until it crosses some threshold, such as appearing on the Yahoo! homepage. They're striking a balance between the cost of processing information and the reduction in uncertainty—the payoff in tracking small interest rate fluctuations isn't worth the effort it takes to react to them. Sims has dubbed this strategy "rational inattention."

"We cannot even understand how much information is transmitted on the Internet," says Wojciech Szpankowski, "because we don't understand the temporal aspect of information."

Sims is hoping to combine information theory with control theory, which looks at the behavior of dynamic systems, and come up with new economic insights. Perhaps, he says, some of those insights will feed back into engineering. "There's a long way to go here, and we've only just begun to get information theorists interested in what we're doing here," Sims says. "We're still using information theory in a relatively primitive way."

"I'm hoping in the first five years we'll make some advances," Szpankowski says. "We will at least formulate the right questions." C

Further Reading

Goldreich, O., Juba, B., and Sudan, M.
A theory of goal-oriented communication, Electronic Colloquium on Computational Complexity TR09-075, Sept. 17, 2009.

Konorski, J. and Szpankowski, W.
What is information? *Zeszyty Politechniki Gdanskiej*, 5, 2007

Shannon, C.E.
A mathematical theory of communication, *The Bell System Technical Journal 27*, July and October, 1948.

Sims, C.A.
Rational inattention: a research agenda. Deutsche Bundesbank Spring Conference, Berlin, Germany, May 27, 2005.

Verdu, S.
Fifty years of Shannon theory, IEEE *Transactions on Information Theory 44*, 6, October 1998.

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Biology

Algorithmic Entomology

Network software engineers have long found inspiration in ant colonies, whose collective wayfinding strategies have shed light on the problems of routing data across a busy network. In recent years, ant colony optimization has emerged as a proven algorithm for network optimization, one of several swarm intelligence models based loosely on the behavior of nature's social animals.

Now, a recent study from the University of Sydney suggests that ant colonies may possess even greater problem-solving abilities than previously thought. The study, "Optimization in a Natural System: Argentine Ants Solve the Towers of Hanoi," published in *The Journal of Experimental Biology*, demonstrates an ant colony's ability to adapt its navigational "algorithm" in response to changing environmental conditions. The findings may help open up new research avenues for optimizing the flow of traffic across data networks.

The international team of researchers enlisted a colony of Argentine ants to solve the famous Towers of Hanoi problem in which participants must find an optimal solution for arranging disks of varying sizes onto a set of three rods.

Translating the logic of the puzzle into a maze with 32,768 possible pathways to a food source, the researchers turned the ant colony loose for one hour, then abruptly blocked some of the pathways. In response, the ants swiftly recalibrated their methods, and soon found an optimal new route to the food supply.

The ant colonies' ability to rapidly adapt took the researchers by surprise. "Even simple mass-recruiting ants have much more complex and labile problem-solving skills than we ever thought," says lead author Chris Reid, a Ph.D. student at the University of Sydney.

The ants' successful rerouting holds potentially important lessons for network software developers. Traditionally, networking algorithms have focused on optimizing solutions to rigid, pre-programmed formulas. These approaches, while effective, also tend to constitute a brute-force response to computational challenges. "Although inspired by nature, these computer algorithms often do not represent the real world because they are static and designed to solve a single, unchanging problem," says Reid.

To survive in the wild, ant colonies must do more than just follow a set of rules; they must sense, respond, and adapt to the world around them. "Nature is full of unpredictability and one solution does not fit all," says Reid, whose research suggests that ants may have more to teach us about how to thrive in a changing environment. "Are they fixed to a single solution," he asks, "or can they adapt?"

—Alex Wright