While considering how best to approach the subject of communication for a recent Santa Fe Institute Annual Business Network Meeting and Symposium, SFI Research Professor David Krakauer contemplated orders of magnitude. What would it be like to approach the subject of communication networks from the most vast expanses, such as space, to the most minute, such as quantum mechanics? Thus, the structure of the Symposium was set, taking members on a journey of discovery through many fields of research, and revealing that although the networks may differ greatly, some principles remain generally applicable: whether examining communication between planets, between primates, or within cells in a human body, understanding the flow of information is key.

Krakauer set the stage by defining many models of communication networks, both traditional and innovative, including the canonical information theoretic principle of a sender (or node) giving specific information to a receiver (another node) through a channel or link. What complicates the situation, though, is that in most cases, multiple nodes are in fact sending and receiving information simultaneously, which necessitates integration over multiple channels and filtering out different sources of noise. This problem becomes even more complicated when communicating through multiple networks, as is common in biology and social systems. Furthermore, in some networks, most nodes are equally effective, while certain “key” nodes, if they were disrupted, would drastically change communication throughout the network. The meeting aimed to emphasize the need for a new, non-equilibrium network information theory applicable in many research areas.

Krakauer explained that because the problem of integrating across multiple information sources is common in many types of communication networks, be they natural or engineered, the conference should explore networks by common structure and function, rather than by discipline. To further emphasize this, the presentations were arranged according to network scale, illustrating the important property of self-similarity, such that no matter how large or small the networks, many of the fundamental properties persist. This way, he explained, representatives from different areas of expertise could converge on the subject, making contributions and applying new insights to their respective fields.

**Somewhere Out There**

The first presenter, Seth Shostak, from the SETI (Search for Extraterrestrial Intelligence) Institute began by addressing the topic of interstellar communication. He explained that SETI has worked to develop ways to detect sentient life on other planets by looking for signs of radio or optical communication. In order to do so, SETI has used a large radio telescope in Puerto Rico, an optical telescope at the Lick Observatory, and is currently developing an array of 350 radio telescopes in California.

Discussing the likelihood of life existing on other
planets, Shostak explained that most scientists in his field agree that statistically life probably does exist out there somewhere. In fact, he noted, there are more stars in our galaxy alone than grains of sand in North America, that many are not unlike our sun, and that more than 130 planets have already been detected. However, even though planets with biology—even very old ones—could be common, the matter of whether or not there is intelligent life on them is, of course, a separate question. “It’s not entirely clear that if I give you a bit of time, you get intelligence,” joked Shostak.

Shostak explained that our ideas about what extra-terrestrial intelligent beings might be like are probably rather naive. Given the fact that the Sun is a relative newcomer to the galaxy, other intelligent life forms, if they exist, could very well have mastered artificial intelligence and produced thinking machines. Any aliens that we might get a signal from, could, in fact, be machinery, not protoplasm.

Shostak emphasized that sending information between stars is relatively easy, and therefore by eavesdropping on the communication networks throughout the galaxy, scientists might detect advanced life if it’s really out there. “We’re not trying to figure out what E.T. is saying,” he said. “We’re just trying to see if the transmitter is on.”

Also discussing large-scale networks, Chris Wallace, of Northrop Grumman Mission Systems, presented the audience with a glimpse of the satellite communication systems around the planet and how they are used. This network of communication has layers in space, within Earth’s atmosphere, on the ground, and in the water. Each layer has many capabilities. For instance, with data from some of the space satellites (in the upper layers of the system), it is possible to view the Earth clearly enough to identify different species of trees.

Wallace showed how networks of satellites communicate with networks of aircraft, which then pass information to networks on the ground—which could include individuals in the military. Wallace described the use of coordinated systems in military operations and even showed the Symposium participants examples of how this information could be of use to soldiers on the ground in Iraq. He explained that soldiers in one area are able to use satellite information to locate soldiers in other areas (not visible to them) and to monitor and communicate about each group’s position. Naturally, one of the key components in this network is that not all nodes are privy to the information, and that it must be kept secret, especially from the enemy.

**Power Structures in Communication—“Knocking Out” a Primate**

Another type of communication discussed was status-signaling interactions among nonhuman primates. Jessica Flack, a postdoctoral fellow at SFI, explained the role of communication in the “organizational mechanics” and robustness of animal social organizations. Flack is interested in how power structures, which emerge from status-signaling interactions, influence intra- and inter-organizational heterogeneity in conflict management performance and style, and how conflict management mechanisms, in turn, influence social network structure.

Using ethological techniques that include video and voice-recording of primate social interactions in large, captive groups of macaques (monkeys found mainly in Asia) and chimpanzees (apes found in west, central, and east Africa), Flack collects data on status signaling interactions, conflicts, interventions by third parties, reconciliation, and pro-social behaviors including grooming and play. It turns out that the macaque social group studied by Flack and her colleagues has a log-normal power distribution, in which a few individuals receive many status signals from many individuals. These individuals are responsible for a large majority of effective conflict management. This conflict management, called policing, occurs when third-parties impartially intervene into ongoing disputes among group members, thereby terminating the conflict. Although policing is relatively rare, occurring in only about 15 percent of disputes, Flack hypothesized that it plays an important role in organizational robustness. To test this hypothesis, Flack and colleagues performed a “knockout” study. Knockout studies are common in the field of developmental genetics, where researchers infer the function of genes by disabling them and assessing changes to organismal phenotype following knockout.

Using this same logic, Flack temporarily and repeatedly removed powerful individuals responsible for effective policing and asked how social network structure and social system variables, like levels of aggression and reconciliation, changed when the policing mechanism is disabled. In the absence of policing, aggression increased, pro-social behavior decreased, and social networks fragmented—indicating that the presence of powerful policers plays an important role in organizational plasticity and robustness by promoting positive interactions among relatively unfamiliar individuals and maintaining network structures that...
How Cells Communicate

Further down the spatial scale of the networks, David Krakauer discussed his work with External Faculty member Walter Fontana, of Harvard’s Systems Biology Institute, on networks of communication within cells. These networks, which typically consist of modified proteins, are not only essential to the cells’ ability to communicate with each other, but they also make up the primary mechanism by which a message that reaches a cell can then be transmitted to the nucleus within the cell. These signals frequently induce DNA to express copies of genes that will be translated into proteins, which modify communication networks or perform more general functions for the cells. The two types of regulatory networks Krakauer discussed were signal transduction networks (protein-protein interactions) and gene regulatory networks (protein-gene interactions).

In describing how signal transduction pathways function, Krakauer explained that in response to a stimulus, proteins floating in a cell are able to spontaneously come together to create a network or pathway. This is in contrast to engineered networks that typically exist as a fixed topology. The self-assembling property of biological regulatory networks presents new theoretical challenges in biological information theory. One example is the cascade network, in which a set of proteins work as a relay of connections in order to pass a message from the exterior of a cell to the nucleus. The cascade circuit has been observed to have many computational properties, including amplification, filtering, and integration. In contrast, ionic signaling pathways occur when a protein (or ligand) attaches to the outside of the cell causing the release of charged particles that then affect many different proteins within the cell. The ionic interactions are more diffuse, which Krakauer likened to the systemic modulation of nerve cells by circulating hormones, as opposed to the precise connections between nerve cells in the brain. The ionic signals are like a cloud, and the cascade is a network.

The importance of these cell communication pathways can be illustrated through examining certain diseases. For instance, the protein interferon is produced by HIV-infected cells to warn other cells (by binding to a receptor upstream of a signaling pathway) to enter into a virus-activated state, thus making them less susceptible to infection. However, there can be substantial variation in this response. For example, some people have large amounts of interferon and are thus less likely to get HIV, and males and females vary in their interferon pathways. Viruses can attack these signaling pathways, disrupting the flow of information and crippling the host response.

Another example of the importance of cell communication has been found in cancer research. It is understood that certain signal pathways are disrupted in cancerous cells with mutations to proto-oncogenes. These pathways are normally used to induce a cell to proliferate, but in cancerous cells they are prevented from turning off, causing the cell to proliferate uncontrollably. Conversely, it is normal for cells to be regularly signaled to commit suicide and die, termed “apoptosis” (especially when defective), but in many cancer cells, the pathways that instruct the cell to enter apoptosis are disrupted and the cell immortalized. The disruption of these networks can be likened to memory loss in the nervous system, whereby adaptive states are erased through the action of mutations, and hence disease becomes a form of molecular network amnesia.

Quantum Communication

Carlton Caves, of the University of New Mexico, captivated the audience with a discussion of quantum information theory and quantum key distribution. As mankind continually advances its methods of communicating, through satellite and computer networks, one of the biggest challenges continues to be security of the communicated information. Secret information, such as issues of national security or even bank account details, is constantly being transmitted. To protect this information from the prying eyes of hackers, communication is encrypted; the sender and receiver share a security code or key used for encryption, without which decryption is practically impossible. However, this merely changes the emphasis of the security. Caves addressed the question: how are the security keys, packets of information themselves, kept secure when transmitted over open networks?

Caves used the example of secret communication between two parties, Alice and Bob, to illustrate concepts of quantum key distribution. Essentially, Alice...
wants to send information to Bob so that they can share a secret code. The scheme proposed uses lasers to create individual photons, which Alice can send through two channels. The photons represent binary information (0 or 1)—characterized by their polarization. This is done in two ways, vertical-horizontal polarization or diagonal left-to-right and right-to-left polarization. When Bob receives the photons in the first channel, he measures the polarization of each, using a randomly selected coordinate set, sometimes vertical-horizontal, and sometimes diagonal. Alice will then send, through the second channel, the correct orientation of the coordinate set used to generate the polarization of the photons, but not their digital values (0 or 1). Comparing results, Bob can discard measurements where the incorrect coordinate set was used, therefore leaving the correct digital values. This digital sequence becomes their secret key, and can be used as a “one-time pad” to send secure information.

The crux of this encryption scheme is the use of individual quantum objects, photons, to transmit the information. Quantum mechanics dictates that an observation cannot be made without perturbing the state observed. In the case of photons, they cannot be seen without being absorbed (or destroyed), thus only Alice and Bob share the key and can determine if someone is trying to eavesdrop. Furthermore, once they have a secret key, Alice and Bob can send data back and forth using the key to encrypt it.

Caves explained that although this technique is still very much a theory, there are some products already available to help individuals create secret keys. Traditionally, research efforts have been based upon quantum information being transmitted with lasers, computers, and fiber optic cables; however, research (including some at the Los Alamos National Laboratory) is now being conducted to try sending these keys through the atmosphere.

Other conference speakers included Peter Monge, of the University of Southern California, who explored the theory of communication networks. Some celebrities also visited the proceedings. James Surowiecki, writer for The New Yorker and author of The Wisdom of Crowds – Why the Many Are Smarter Than the Few and How Collective Wisdom Shapes Business, Economies, Societies and Nations, spoke on collective reasoning. Also on hand was New Mexico Governor Bill Richardson, who presented a few points about communication in politics and declared November 5th as “Santa Fe Institute Day” in New Mexico.

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