Close Connections

It's a small world of crickets, nerve cells, computers, and people

By IVARS PETERSON

Throughout much of North America, warm summer evenings resound with the synchronized chirps of snowy tree crickets. The loud, high-pitched trills of these insects repeat at regular intervals that shorten as the temperature increases.

This nocturnal chorus presents a puzzle. How do widely scattered crickets coordinate their musicmaking without a conductor to keep them together?

While trying to develop a mathematical model to describe interactions in a tree full of crickets, Duncan J. Watts, then a graduate student at Cornell University, pondered how the arrangement of links between members of a network—whether crickets, nerve cells, computers, or people—might affect the entire system's behavior.


The Kobal Collection

By appearing together in films, movie actors are members of a vast, small-world network.

Watts, who is now at Columbia University, ended up focusing on a particularly intriguing type of network—one in which each member has a direct link to just a few other members. When some of those links involve members that would otherwise be widely separated, such a web can be described as a small-world network. Each member is then only a modest number of intermediaries away from any other member.

A small-world network underlies the popular notion of "six degrees of separation"—the idea that everyone in the world is connected to everyone else through a chain of at most six mutual acquaintances.

"If you happen to have one friend who knows everybody in the world, then through him or her, you're just one degree of separation away from everybody in the world," explains Carson C. Chow of Boston University. If, more realistically, each person knows a random assortment of 100 to 1000 people, six degrees of separation encompass the world's population.

Because most people belong to small, interconnected groups of acquaintances, however, connections tend to be strongly clustered rather than random. Nonetheless, as Watts and Cornell mathematician Steven H. Strogatz report in the June 4 NATURE, even members of networks characterized by strong clustering are generally only a small number of steps away from any other member.

"I think the small-world phenomenon is ubiquitous," says mathematical biologist Simon A. Levin of Princeton University. The work of Watts and Strogatz provides a potentially powerful framework for tackling such issues as the spread of disease, the diffusion of goods and services, and the transmission of information, he notes, adding that it also has important implications for environmental management.

Networks pervade biology and society. "The brain is a network of neurons," Watts says. "Organizations are networks of people. The global economy is a network of national economies, which are themselves networks of markets, which are themselves networks of interacting producers and consumers."

In the past, researchers found it convenient to model these systems as either regular or random networks. Mathematicians represent a network with what they call a graph, which consists of a collection of points, or vertices, and a set of lines, or edges, joining pairs of points. The points stand for members and the lines reflect the members' connections.

In a regular network, each point has the same number of links, and those links usually join a small number of neighboring points in a specific pattern. In a sparse random network, each point is haphazardly connected to a few other points that can lie anywhere.

Most real-world networks appear to occupy some sort of middle ground between regular and random, Strogatz says.

To study what happens in this intermediate regime, Watts and Strogatz scanned a range of connection patterns between one extreme and the other. They started with an example of a regular network, represented by a ring of points, each one connected only to its neighbors. For some points, they then replaced links to neighbors with links to randomly selected points elsewhere in the network.

"We just rewired the network," Strogatz says. "The number of edges stayed constant." As more links changed from neighborhood to random long-distance, more disorder appeared in the arrangement of network connections.

To characterize the resulting networks, Watts and Strogatz computed two parameters. The characteristic path length is the smallest number of links required to connect one point to another, averaged over all pairs of points. The clustering coefficient measures the fraction of a point's links that go to other points in its immediate vicinity. According to these measures, regular networks have longer characteristic path lengths and larger clustering coefficients than random networks.

Surprisingly, when just a few random, long-range connections replace neighborhood links in a regular network, its characteristic path length abruptly decreases—producing the small-world effect.

"The first bit of random rewiring has a huge impact on the path length," Watts says. "The clustering, however, hardly changes."

Examples of Small-World Networks

	Characteristic Path Length		Clustering Coefficient	
Network	**Actual**	**Random**	**Actual**	**Random**
Movie Actors	3.65	2.99	0.79	0.00027
Power Grid	18.7	12.4	0.080	0.005
Worm Neurons	2.65	2.25	0.28	0.05

This table compares the characteristic path length and clustering coefficient of each network to that of a random graph with the same number of points and average number of edges per point. The movie actor data is based on a graph containing 225,226 points, representing actors, and edges connecting actors who appeared in the same movie. In the power grid, the points represent 4,941 generators, transformers, and substations; the edges stand for high-voltage transmission lines. The nematode's neural network consists of 282 cells; edges correspond to information-transmitting connections—synapses and gap junctions.

The random shortcuts connect points that would otherwise be much farther apart in terms of links, shrinking the distance not only between those two points but also between points in both of their immediate neighborhoods.

"You get a dramatic transition to a small-world effect with very few new connections," Chow says.

At the same time, people who belong to a small-world social network might not recognize it as such. "You tend to know which of your friends know each other, but you don't usually know who else they know," Watts explains. If one of your friends happens to know someone in a foreign country, you (and everyone you know) would have a close connection to people in that country—often without being aware of the link.

To determine whether real-world networks fit the small-world category, Watts and Strogatz looked for examples of networks in which all the links are known.

"Our [theoretical] results suggest that just a few connections amongst very many can turn out to be important, so it's no good doing [the analysis] unless you're pretty sure you've got everything," Watts says.

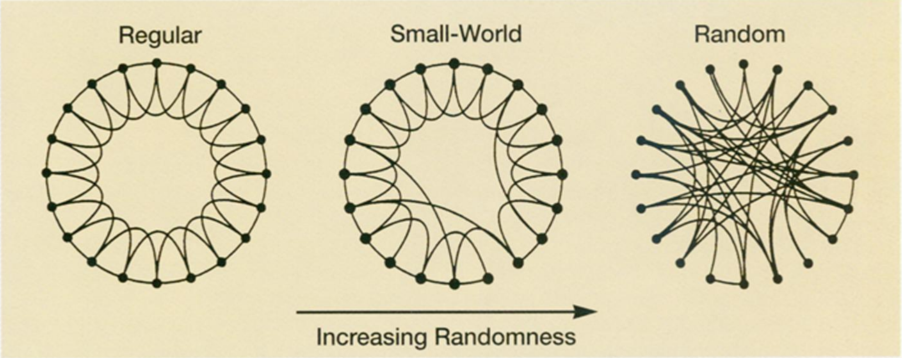
The researchers came up with three very different examples for which they had all the data necessary to compute the characteristic path length and clustering coefficient: the neural network of the nematode worm *Caenorhabditis elegans*, the electric power grid of the western United States, and a vast database showing which actors appeared together in different movies.

The film database has become the basis of an amusing Web-based pastime in which participants name an actor and learn how many steps away that actor is from well-known star Kevin Bacon. About 90 percent of all actors in the entire history of film are four steps or fewer away from Bacon.

"These instances had the advantage that the whole network is known, so we could use a computer search to figure out the shortest paths," Strogatz says.

Measured against comparable random networks, all three examples display similarly short characteristic path lengths but much stronger clustering (see table). So, they appear to be small-world networks. "That says something about the way the world is," Watts says.

"We didn't pick these networks *because* they were small-world networks," he insists. "We basically took the data we could get our hands on, and they all just turned out that way."



In this example of random rewiring, the graph consists of a ring of 20 points. Initially, each point is connected to its four closest neighbors to form a regular network (left). Changing a few neighborhood links to long-distance connections turns the graph into a small-world network (middle). Rewiring all the links produces a random network (right).

Watts & Strogatz

Strogatz says that their work "also makes the point that the small-world phenomenon can occur over a wide range of scales and a wide range of settings." Why that should be so isn't clear, however.

Mathematicians working in the field of graph theory have already made efforts to pin down some of the phenomena characteristic of small-world networks, especially for application to communication networks.

Early on—going back to the days of the telegraph and the first telephones—engineers tried to minimize delays in signals sent via cable networks. In many cases, that objective had to be balanced against limitations set by the number of cables or telephone lines available.

In recent decades, mathematicians have used graphs to represent such networks. Fan R.K. Chung of the University of Pennsylvania in Philadelphia and her colleagues have proved rigorously that specific types of graphs show roughly the same sort of behavior observed in computer experiments by Watts and Strogatz.

The mathematicians focus on a quantity they call the graph's diameter, which is closely related to the characteristic path length. In models of communication networks, a long diameter is associated with delays in passing messages through a network. "To minimize delays, you want the diameter to be small," says Chung. "You want to know how far you need to reach out to touch everyone."

One example of a graph with a large diameter is a regular graph in which each point is connected to two other points and the set of points forms a single, continuous chain back to the starting point. In this case, a message passed along the chain could take a long time because it may have to pass through many intermediate points to get to its destination.

Adding a small number of links between randomly selected pairs of points in that graph, without removing any links, changes its diameter. In 1988, Chung and her collaborators proved that this change creates a network with the same small diameter as a comparable random graph.

Mathematicians have since proved other theorems that suggest how networks may be modified to improve data flow. Because Watts and Strogatz haven't yet rigorously and precisely defined what constitutes a small-world network and how it behaves as a whole, the earlier findings lend credence to their observations.

"What we've done is a first step, and much remains to be done," Strogatz admits.

Nonetheless, says James J. Collins of Boston University, the findings not only open up new areas for mathematical investigation but also suggest a variety of potential applications in data networks and elsewhere.

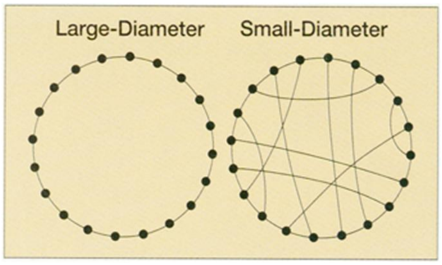
Small-world social networks have important implications. "If you need to spread information through a network quickly and reliably, this may be a good architecture," Strogatz says.

For example, creating shortcuts by sprinkling a few diversely connected individuals throughout a large organization could dramatically speed up information flow between departments.

On the other hand, because only a few random shortcuts are necessary to make the world small, subtle changes to networks have alarming consequences for the rapid spread of computer viruses, pernicious rumors, and infectious diseases, Strogatz notes.

The standard assumption in most models of disease transmission is that every individual has an equal probability of infecting every other individual. That's clearly flawed, Levin says.

"It is especially bad for sexually transmitted diseases, for which most individuals have few contacts and a few have many," he argues. "Those so-called superspreaders shorten the median distances among individuals, essentially making the world a small one and dramatically increasing propagation rates."



A graph consisting of points connected in a ring is said to have a large diameter because a message may have to pass through many intermediate points to get to its destination (left). Mathematicians have proved that adding links between randomly selected points creates a network (right) with the same, small diameter as a comparable random graph.

Subtle differences in connections may also have a significant effect on the ability of networks of interacting members—whether people, nerve cells, or crickets—to coordinate behavior.

In networks of neurons, for instance, the cells sometimes display waves of activity and at other times synchronized behavior. Synchrony is characteristic of networks with high connectivity, Chow says. Indeed, researchers modeling neural networks typically assume that every neuron is connected to every other neuron.

Assuming complete connectivity, however, may be an unnecessary simplification, he notes. The behavior of small-world models suggests that changes in just a few links within a mainly regular network might be enough for regions of the brain to switch from waves to synchrony or vice versa.

Collins hopes to look at synchronization effects across a network by using about 100 students, each one working at his or her own computer terminal. "Each screen would show two circles that move along a line," he says. One circle would be controlled by the user of the terminal, and the other would represent the average position of all the circles. The goal would be for each student to make the circles overlap.

"We would change the coupling, going from a regular network through a small-world network to a random network, to study the effect of network architecture on synchronization times," Collins says.

In the meantime, Watts hasn't returned to his work on crickets. "I'm like a kid in a candy store," he says. "This work has relevance to so many different areas."

In more ways than one, it truly may be a small world after all.

Biomedicine

Drug prevents herpes return to the eye

About 400,000 people in the United States suffer from a potentially blinding herpes infection of the eye that tends to recur. A new study suggests a way to thwart the herpes simplex virus and prevent loss of vision.

Kirk R. Wilhelmus of the Baylor College of Medicine in Houston and his colleagues studied 703 people who had reported a previous herpes infection of the eye.

Although the immune system may clear the initial disease, it often doesn't kill the herpes simplex virus, which can remain in hiding for months or even years—causing another round of disease when it revs up again.

The virus can also infect the mouth or genital region. The drug acyclovir prevents recurrence of herpes disease there. Could acyclovir block a flare-up of the disease in the eye as well?

To find out, the researchers gave approximately half the study participants 400 milligrams of acyclovir twice a day for a year, while the controls received a placebo pill. Herpes infections to the eye were recorded.

The researchers observed that acyclovir reduced the recurrence of herpes infection of the eye by 41 percent during the year of treatment. After the acyclovir treatment ended, the number of recurrences increased to match that of the control group. Wilhelmus and his colleagues report their findings in the July 30 New England Journal of Medicine.

The team also noted that the therapy lowered by about 50 percent the risk of a return of the most severe form of the disease, stromal keratitis. Stromal keratitis occurs when the virus invades the inner layer of the eye's cornea where it can lead to scarring and loss of vision.

The study detected no side effects that could be attributed directly to the drug.

The findings suggest that people who have had stromal keratitis should consider taking acyclovir over the long term, perhaps even for life, to prevent a recurrence, says Scott Whitcup of the National Eye Institute in Bethesda, Md. —*K.F.*

More babies sleep safely

The public health message telling caregivers to put babies to sleep on their backs has paid off: A new study reports that between 1992 and 1996 the frequency of babies being put to sleep on their stomachs dropped by 66 percent.

Previous research had suggested that babies who sleep on their stomachs face a greater risk of sudden infant death syndrome, or SIDS. It is the leading cause of death for U.S. infants between the age of one month and one year.

Marian Willinger of the National Institute of Child Health and Human Development (NICHD) in Bethesda, Md., and her colleagues interviewed about 1,000 caregivers of infants annually.

The team found that infants were placed on their stomachs by 70 percent of caregivers in 1992—before the American Academy of Pediatrics recommended that babies be put to sleep on their backs or on their sides. In 1996, just 24 percent were putting infants to sleep on their stomachs, the team reports in the July 22/29 Journal of the American Medical Association.

However, Willinger's study and two others that appear in the same issue indicate that greater educational efforts may be needed. A study by Ruth A. Brenner, also at NICHD, discovered that about 40 percent of low-income, inner-city mothers put their infants to sleep in the hazardous stomach position.

Moreover, Samuel M. Lesko of Boston University reported that almost 30 percent of 7,796 mothers across a range of income levels had switched their babies from the back to the stomach sleeping position at about 3 months, an age when they are still vulnerable to SIDS. The younger moms were more likely to change their baby to the less safe position. —*K.F.*