Book Review

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Linked: The New Science of Networks. Albert-László Barabási. (1st ed., hardcover, 2002, Perseus Books Group, 256 pages. Reissue ed., 2003, paperback, 2003, Plume Books, 304 pages.)

One of the alluring features of artificial life is the wide range of component disciplines from which it draws. Theoretical ideas in areas such as machine learning and soft computing sit alongside diverse applications, from economics to ecology.

In many studies of artificial life or complex systems in general, the properties of individual agents receive a lot of attention, while higher-level phenomena are allowed to emerge from simulations. Yet there is one powerful system-level methodology, the study of networks, that can tell us a great deal about what the emergent phenomena might be. Barabási's admirable book brings us right up to date on the role of networks in complex systems, a field in which his group has made substantial contributions in recent years.

The book loosely follows a historical path, with abundant illustrations interspersed with personal insights and anecdotes and snippets of biography. The author begins with random networks, proceeds through small-world to scale-free networks, and then takes up many of the technical and social issues to which network structure is relevant.

Although graph theory goes back at least to Euler in the 18th century, the network result most useful to complexity scientists came from Erdös and Rényi. They found a connectivity avalanche in random graphs. Researchers such as David Green established the importance of this result to other ideas, such as the edge of chaos, and to many practical systems.

But we now realize that many networks in real and virtual worlds are not best modeled as random networks. Watts and Strogatz' small-world models seemed to fit a number of social and biological phenomena where a small number of long-range connections could dramatically reduce the diameter of a graph. The notion of small world harked back to an early result from the 1960s, when Stanley Milgram showed that anybody could be reached from anybody else in a chain of usually six or fewer contacts. The book attends closely to historical detail, and Barabási points out that "five degrees of separation" was also suggested by Karinksy in a novel entitled *Chains* in 1929!

From small worlds we move to scale-free networks, where Barabási has made substantial contributions. Such networks have a power law distribution of connectivity, where the probability that a node has k connections is proportional to $k^{-\gamma}$. In the last few years these networks have been revealed in all sorts of places, from the World Wide Web and Internet servers to metabolic networks in a range of cells.

Power laws of this kind crop up frequently in physics at phase transitions, and usually symbolize long-range order. The book contains numerous interesting examples, developed in detail, of just how this manifests itself in our world. The spread of AIDS and other diseases may depend critically on a relatively small number of carriers, with powerful implications for disease control.

Such carriers are typical of the hubs (highly connected nodes) in scale-free networks. We are familiar with hubs from transport systems, particularly airlines, but they appear throughout economic systems, from the development of industrial clusters to the limited number of directors making up the boards of Fortune 1000 companies.

The stories make compelling reading, and it is immediately possible to apply these ideas to one's own area of interest. Culture and science exhibit hubs, often driven by a single individual such as

Niels Bohr in the Copenhagen school. It is interesting that Erdös, a peripatetic academic if ever there was one, held one of his few academic positions at the University of Notre Dame, where the scale-free network group now operates.

But the real message of the book is how important connectivity and network structure are to complex systems—"networks are by their very nature the fabric of complex systems," and "network thinking is poised to invade all domains of human activity." Many ALife practitioners will have spent many hours arguing over the problems with reductionism and should welcome such a holistic view. The artist Christo is used as an elegant metaphor in his philosophy of "revelation through concealment," discovering form though hiding details.

Barabási suggests that the 21st century will be the century of complexity. The powerful paradigm of network thinking promises to continue its role as a fundamental theoretical tool. This book is a timely and valuable overview of this burgeoning field.