Linked:
The New Science of Networks
By Albert-Laszlo Barabasi

Précis by Royce Holladay

"From a cocktail party to a terrorist cell, from an ancient bacterial to an international conglomerate—all are networks and all are part of a surprising scientific revolution." This beginning sentence from the jacket of Dr. Barabasi's book captures the diversity and commonality he describes in this discussion of networks. As a storyteller, Dr. Barabasi spins the thread of discoveries he and his team made in their quest to understand networks. As a scientist, he shares the spotlight with his colleagues as he describes each step of their process of investigation.

The First Link: Introduction – In his introduction, Dr. Barabasi uses physical descriptions of networks and their power. He talks about a computer virus that interrupted the Internet by overload and then shifts to the network formed by St. Paul and other early Christian followers. In showing similarities and differences between these two networks, this author points out that networks cannot be studied by taking them apart and studying the parts. His invitation to the reader is to join him as he recounts the journey he and his colleagues took in exploring networks to see what makes them work as they do.

The Second Link: The Random Universe – Barabasi starts his story in St. Petersburg in 1783, with the death of Leonhard Euler, one of the most prolific mathematicians of all time. In one of his many areas of interest, Euler was the initiator of a branch of mathematics known as graph theory, which has become the basis of current thinking about networks. Barabasi then jumps to the 20th Century and introduces the reader to Paul Erdos, who, along with Alfred Renyi, wrote eight papers that addressed the fundamental question of, “How do networks form?” In 1959, almost as an aside to their work on the mathematics of random networks, they published
their random network theory. While these two mathematicians didn’t focus on the practical applications of their theory, they did trigger further questions about the operations of real networks.

**The Third Link: Six Degrees of Separation** - Beginning with its first appearance in a little-known book of short stories by a Budapest author, people have been intrigued by the idea that any individual is actually linked by, at most, five links to any other individual. This is now referred to as “six degrees of separation” and has been the focus of a Hollywood movie as well as a game that names those connections from any actor in Hollywood to a particular actor, Kevin Bacon. Barabasi describes scientific studies to test and clarify that concept. In 1980, the idea of connecting all information stored on computers everywhere was a dream of Tim Berners-Lee, who wrote the first computer program to allow computers to do just that—link to one another. Through a number of examples, the author introduces “small worlds” where all information and all people are only a few links away from one another, both through the Internet and through personal contacts. He points out that in small worlds our ability to reach people has less to do with the physical distance between us, and more to do with the ways in which we are connected to one another. Discovering common acquaintances with perfect strangers on world-wide trips reminds us that, in social networks, people on the other side of the planet may be closer to us than those who live across town.

**The Fourth Link: Small Worlds** – Barabasi introduces the reader to Mark Granovetter, a researcher who first proposed the idea of strong and weak ties in a social network. He proposed that individuals have strong ties to those who are closest to them and weak ties to those who are further away. He also proposed that it is the weak ties that are responsible for social change and personal movement within the society. This is the first proposal of networks that are not, as Erdos and Renyi depicted, random. What he proposed, instead, was a world of complete graphs of strong ties, connected to other complete graphs by fewer and weaker ties—a picture that is not random. Duncan Watts began his studies in networks by trying to figure out how crickets synchronize their chirping, and ultimately produced further understandings of how networks work. He and Stephen Strogatz offered an alternative to the model of random networks, describing clustering within the random networks. However just about the time they published
their work, Barabasi’s own work on the Internet and the World Wide Web reflected actual networks that were very different from the work of both Erdos-Renyi and Watts-Strogatz.

**The Fifth Link: Hubs and Connectors** – What Barabasi and his colleagues found were that there were particular points in networks that had high levels of connections—they seemed to be the “connectors” for smaller points in the web. These connectors they came to see as hubs in their networks with the less connected points being the nodes in the network, and Barabasi uses examples from the Web and popular culture to help describe and clarify this concept. After a thorough discussion of hubs and their appearance, function, and contributions in our society, Barabasi ends the chapter by pointing out that they also follow strict mathematical laws that he and his colleagues have spent years trying to explain.

**The Sixth Link: The 80/20 Rule** – In this chapter, Barabasi introduces Vilfredo Pareto, an economist who spent the later years of his career turning economics into an exact science, describable by laws. The contribution that is important in this context is his observation that 80% of an outcome can be attributed to 20% of the input—80% of the peas in his garden came from 20% of the plants; 80% of the land in Italy was (at that time) owned by 20% of the population. This rule has come to be used in many facets of business life today. It also contributes to the understanding of how networks form and led to Barabasi’s discovery that networks follow power laws as they form—a few nodes (the hubs) carry the largest percentage of the connections, and those numbers always relate to each other according to a given exponent. Using the picture of an airline routing map, Barabasi describes these networks. The presence of the power law says that these networks are scale-free, and his research has shown that “most networks of conceptual importance, ranging from the World Wide Web to the network within the cell, are scale-free.” Physicists have found that power laws rarely emerge in systems dominated by randomness, and they generally signal a phase change from chaos to order. From this, he says, came the idea that the power laws are the patent signatures of self-organization in a complex adaptive system.

**The Seventh Link: The Rich Get Richer** – These discoveries and further study brought Barabasi and his colleagues to challenge two long-held assumptions about random networks. First they realized that the number of nodes is not fixed. Nodes emerge and disappear over the life of the network. Second, not all nodes are equivalent. Some nodes are more attractive to
others and continue to gain connections in increasing numbers while other node connections are static or increase slowly. What this means is that as networks grow, those that have the most connections attract more connections than others—the parallel to the statement that the rich get richer. They called this phenomenon preferential attachment and realized that this, along with growth, are the two governing laws of scale free networks and explain why hubs and power laws emerge as they develop. They have come to realize that networks are not en route from a random to an ordered state. Neither are they at the edge of randomness and chaos. Rather the scale-free topology is evidence of the organizing principles operative at each stage of the network formation process. These discoveries led to the question of how latecomers make it in a world in which only the rich get richer.

The Eighth Link: Einstein’s Legacy – In explaining why some late-arriving links can become as rich as those that are long-established, Barabasi describes “fitness.” Fitness is the ability of the node to “fit” its environment and the needs of the other nodes, to draw them to link with it. By extrapolating and testing against quantum theory, they found that, both mathematically and in actual networks, there are two categories. One is the “fit get rich” where the fittest node will inevitably grow to become the biggest hub, with the winner’s lead never becoming significant. In some situations, however, the fittest node grabs all the links, leaving very little for the rest of the nodes. Barabasi says that these networks are not scale-free, and they develop a star topology, in which all nodes are connected to the central hub. He uses the growth of Microsoft as an example of such a network.

The Ninth Link: Achilles’ Heel – In this chapter, Barabasi explores the potential for networks to be interrupted by failure or attack. He introduces the concept of “robustness” which describes the network’s ability to withstand failure, and explores what makes networks robust. What he shows is that networks that are well connected with many nodes can easily withstand the collapse of a number of those nodes. Using the example of airline traffic patterns again, he shows that several smaller airports (nodes) can be taken out, and the patterns adjust and keep flying. Similarly, in a computer network, several smaller nodes may be taken out by a virus or by an electrical outage, but the network can readjust and continue. This robustness is a factor of the interconnected nature of such networks. On the other hand, if the hubs of a network are attacked, it cannot withstand the loss of more than a small percentage of its hubs. If as few as
three or four of the major airports in the country were shut down at once, the impact on all traffic patterns would be profound. Thus, Barabasi describes the hubs as the network’s Achilles’ heel in any time of attack.

**The Tenth Link: Viruses and Fads** – The next challenge Barabasi and his colleagues faced was to examine what made some networks grow—what is preferential attachment about? Sociologists and epidemiologists developed a tool called the threshold model. This level of tolerance an individual has for new and different experiences is called the threshold, and it quantifies the likelihood that he or she will adopt a given innovation. People would have different thresholds for different items. One person may like to try electronic devices, giving them a low threshold in that area, while their aversion to new food experiences would make that a high threshold. Innovations have well defined spreading rates, representing the likelihood that it will be adopted by a person introduced to it. When this threshold is describing the point at which a fad takes over or an illness becomes an epidemic, this is called the epidemic threshold. However, there are some types of social phenomenon that spread faster and last longer than would be indicated by the threshold research. However, what was discovered was that in scale-free networks, the epidemic threshold vanishes. Because of the interconnectedness of the hubs in a scale-free network, the virus or cause of the epidemic can be spread so fast and so far that it becomes virtually unstoppable.

**The Eleventh Link: The Awakening Internet** – In this chapter, Barabasi reviews the frustrating career of Paul Baran. In 1959 this researcher at RAND was given the assignment to develop a communication system that would survive a nuclear attack. In a series of twelve memoranda to Rand, he proposed a system of communication that would overcome the vulnerabilities of those that existed at that time. He proposed the Internet. However, at the time neither industry nor the military were prepared or able to accept the changes he proposed. Over the following years, other groups took those steps and created the decentralized, massively entangled web of connections that is the Internet. Barabasi points out that the underlying network has become so distributed, decentralized, and locally guarded that even such an ordinary task as getting a central map of it has become impossible.
The Twelfth Link: The Fragmented Web – Through various research and projects, scientists have come to estimate that the size of the Internet is over one billion documents, and there are nineteen degrees of separation, suggesting that this is a small world. However, the fact is that from any page, an individual can reach only about 24% of all documents. This exists for a number of reasons. First the links of the web are directed, meaning they can only go one direction. Second the links and groups of links are disjointed from each other. He describes the map of the Internet as being continents, with some parts accessible from others and some not accessible from anywhere except within their own boundaries. He explores the nature of a network that is so large and that encompasses the earth, discussing legal issues, control issues and finally the issues of archiving all that has been on the web.

The Thirteenth Link: The Map of Life – Barabasi explores the networks that carry on the work of the human cells and systems. He and his colleagues assembled the full metabolic map for forty-three organisms. What they found was that each one displayed a clear scale-free topology. Each cell looked like a tiny web, with few molecules involved in the majority of reactions and most molecules participated in only one or two. They found that these cells are small worlds with three degrees of separation, on average, in both metabolic and protein interactions. He talks about the applications of this knowledge in studies of cancer. The Achilles’ heel of the network is the hub, in fighting off attacks, so identifying those hubs is critical in fighting such diseases. The first approach is to destroy those hubs, which is how some current cancer treatments work. However, the more effective goal is to work to restore full functioning of those hubs so that the cell can “heal” itself. As scientists are more able to map the cell, they are more likely to be able to pinpoint their drugs and predict exact influences in the cells. Barabasi claims that by 2020, this knowledge will have changed the entire face of medicine.

The Fourteenth Link: Network Economy – The author discusses the various ways in which this understanding of networks has influenced the economy. The push for organizations to get onto the Web and gain power there has made a huge impact on the economy. Organizational structures are moving from the traditional hierarchical structures to more web-like structures where information and accountability can be shared more effectively throughout the organization. Powerful individuals gain their power by the “networks” they build, with
themselves as hubs, connecting both to less active nodes and to other hubs throughout the network. Economists are beginning to pay close attention to what is being learned about networks. Not only do they have the power to build and exploit the riches in an economy, they are also vulnerable to the difficulties caused by the “crash” in one or more hubs. Barabasi describes how one property development company in Thailand failed to pay its interest, starting a cascading impact that ultimately brought down the economy in that region of the globe and caused significant challenges around the world.

**The Last Link: Web Without a Spider** – In this final chapter, Barabasi describes scale-free networks as webs without spiders. There is no real design behind these networks; they are self-organized and show how the independent actions of millions of nodes and links lead to spectacular emergent behavior. He even talks about the networks of terrorists, pointing out how difficult they will be to eliminate, simply because they do operate in scale-free networks. He proposes that the next step is to study complexity and come to understand and apply what is learned about networks to the issues that challenge society today.