AUTHOR COMMENTARIES - 2008

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Dr. Albert-László Barabási and Dr. Réka Albert

Featured Paper from *Essential Science Indicators*SM

According to Essential Science Indicators *from* Thomson Reuters, *the paper "Emergence of scaling in random networks" (Barabási AL, Albert R,* Science *286[5439]: 509-12, 15 October 1999) ranks at #5 among Highly Cited Papers in the field of Physics, garnering 2,708 citations between January 1, 1998 and August 31, 2008.*

The paper's authors are Albert-László Barabási and Réka Albert. Dr. Barabási is the Distinguished University Professor of Physics and the Director of the Center for Complex Network Research at Northeastern University in Boston, Massachusetts, and holds an appointment at the Department of Medicine, Harvard Medical School. Dr. Albert is an Associate Professor of both Physics and Biology at the Pennsylvania State University, where she is also a member of the Center for Infectious Disease Dynamics.

This month, ScienceWatch.com *talks with both authors about their paper and its influence.*

SW: What was your inspiration for this study reported in your paper?

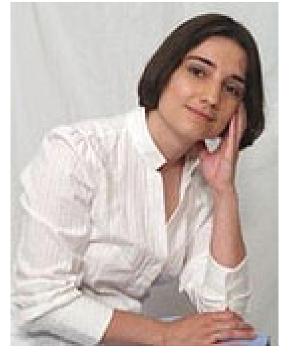
Our earlier study, published in the same year in *Nature* (Albert R, Jeong H, Barabási AL, "Internet—diameter of the World-Wide Web," *Nature* 401[6749]: 130-1, 9 September 1999), has shown that the World Wide Web is a not a random network, but the number of links per node, often called the degree distribution, follows a power law. This was rather unexpected, as earlier network models predicted only Poisson distributions in this context. Subsequently we found that not only the WWW, but other networks, like the actor network or the citation network, follow the same distribution. These different datasets together indicated that we are dealing with a potentially universal behavior, which might have a common explanation. This paper was intended to offer that missing explanation.

SW: How did you perform this study—what were your methods?

This is a theoretical paper, and its essence is a model that we proposed to explain the origin of the power laws seen in various complex networks. The model, based on the idea that networks grow by the addition of new nodes, and these new nodes have a tendency to link to more connected nodes (preferential attachment), was first simulated numerically, then we obtained an analytic solution, predicting the observed power law distribution.

SW: Would you sum up your findings for our readers?

The novelty of the proposed model was that for the first time it considered the network as a dynamical object, that evolves with the addition of nodes and links to the system, in strong contrast with the static models that dominated the literature before. As such it faithfully captured the emergence of real networks, predicting their large-scale topology relatively accurately.



Coauthor:
Réka Albert

SW: How was this paper received by the community?

At first the community was slow to pick it up, as the paper was not solving an established problem in a well-defined field with a strong preexisting community, but instead opened a new field. However, soon papers started to emerge in two areas: First, they provided evidence that many other networks are scale-free (which is the name of the network that our model generated), expanding the applicability of our results. Second, several investigators offered extensions of the model, showing that it can account for the structure of many real networks. Only about two years later the paper entered its "exponential" phase, an indication that the amount of work in this area exploded.

SW: Where have you taken your research since the publication of the 1999 paper?

In 2000 we found that the scale-free structure proposed in this paper applies to the cell as well, characterizing its metabolic network (Jeong H, *et al.,* "The large-scale organization of metabolic networks," *Nature* 407[6804]: 651-4, 5 October 2000) and protein interaction network (Jeong H, *et al*., "Lethality and centrality in protein networks," *Nature* 411[6833]: 41-2, 3 May 2001). We have also shown that scale-free networks, which due to the power law distribution are dominated by hubs, show a high degree of robustness to errors, but are fragile to attacks (Albert R, Jeong H, Barabási AL, "Error and attack tolerance of complex networks," *Nature* 406[6794]: 378-82, 27 July 2000).

"The novelty of the proposed model was that for the first time it considered the network as a dynamical object..."

Subsequently many other researchers have demonstrated a series of fascinating properties of these networks, finding not only that a very large number of real networks, from the Internet to social networks, are scale-free, but also that this scale-free topology fundamentally changes the system's behavior, affecting everything from spreading processes on networks (like the spread of infectious diseases) to cascading failures.

SW: What are your hopes for this field for the future?

Since 1999 a rather active highly interdisciplinary field was born, which a recent National Research Council report dubbed Network Science, bringing physicists, computer scientists, biologists, social scientists, and researchers from many other disciplines under the same umbrella. These days there are several conferences each year devoted to the topic, and several dozen books have appeared on the subject. Networks offer a mathematically rigorous formalism that is critical for understanding complex systems, explaining the reason why it has been so embraced by various communities.

The role of the statistical physics community has been particularly important, and we consider network science an integral part of statistical physics these days, as it is dominated by the tools of statistical mechanics, and has also led to many fascinating and challenging problems that have captured the physics community. We very much hope that this enthusiasm will continue, eventually leading to a rigorous treatment of networked systems, from cells to social systems.

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Albert-László Barabási and Réka Albert's current most-cited paper in *Essential Science Indicators*, with 2,708 cites:

Barabási AL, Albert R, "Emergence of scaling in random networks," *Science* 286(5439): 509-12, 15 October 1999. Source: *Essential Science Indicators* from Thomson Reuters.

Keywords: scaling, random networks, world wide web, internet, power laws, complex networks, scale-free networks, interdisciplinary research.

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