PERSPECTIVES ON COMPLEX NETWORKS

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Summary

In this contribution we outlined the main contributions of the science of complex networks and we provide some ideas about its future evolution. This topic seems to embrace more than traditional technological application and it is likely to affect a large number of disciplines.

1. Introduction

Large and complex networks arise at many levels in the natural world. The world's ecosystems consist of species linked together within intricate food webs, just as our communities are complex webs of social ties. The living cell depends for its function on a staggeringly complex web of interactions among a great number of genes, proteins and other small molecules. We find complex webs of technology as well; the Internet, for example, is a vast network of computers linked by transmission lines. Again, the global economy functions through a vast network of trade links which bind the world's nations together.

Ten years ago, science had very little to say about the architecture of these networks, despite their obvious importance. A traditional perspective viewed them as mostly random; that is, as sets of elements linked together without any plan or organization, any pair being connected with equal probability. This understanding — or, rather, this admission of scientific ignorance — has been dramatically revised in the past decade, as seminal work by a number of researchers, notably in physics, has led to a far deeper understanding of the architecture of these complex networks [1, 2, 3, 4]. This work has revealed deep similarities between networks that have emerged in diverse settings and that would appear to have little in common. In particular, food webs, social networks, the Internet and the World Wide Web all share important topological properties. This research has also led to a growing understanding of the relationship between the topology of complex networks — their "wiring diagrams" — and their functional properties such as stability and information-processing efficiency.

The rapidly emerging science of complex networks is likely to be among the most important sciences of the 21st century. As one example, take molecular biology. Biologists increasingly know the "parts list" of molecular biology, as they have access to a virtually complete map of all the genes in the human genome, and in the genomes of many other species, and are aggressively assembling a similarly detailed knowledge of the “proteome,” the full collection of proteins encoded by those genes, and the “transcriptome,” the diverse set of mRNA molecules that serve as templates for protein manufacture. Even so, we still lack a deep understanding of how all these parts work together to support the complex and coherent activity of the living cell; how cells and organisms manage the concurrent tasks of production and re-production, signaling and regulation, in a fluctuating and often hostile environment.

What's lacking, in other words, is an understanding of how cells function as complex networks. Building a more holistic understanding of cell biology is the aim of the new discipline of systems biology, which views the living cell as a network of interacting processes and gives concrete form to the vision of François Jacob, one of the pioneers in the study of genetic regulatory mechanisms, who spoke in the 1960s of the "logic of life." Put simply, systems biologists regard the cell as a vastly complex biological "circuit board," which orchestrates diverse components and modules to achieve robust, reliable and predictable operation. Systems biology suggests that the mechanisms of cell biology can be related to the information sciences, to ideas about information flow and processing in de-centralized networks. With rapidly advancing technology, and new theoretical tools coming from physics, engineering and mathematics, systems biology is beginning to explore how such networks are highly efficient for biological information flows, often involving operations such as feedback, synchronization, amplification and error correction that are familiar to engineers.

This networks perspective is also well attuned to matters of the utmost social and political importance. Indeed, early in 2009 as the world endures the worst economic crisis for 70 years, tangled networks of financial interdependence among banks, hedge funds and other institutions have come to be seen as the primary cause of the crisis, and as the focal point for measures to prevent similar disasters in future. Even without the problems in sub-prime mortgages, many researchers suspect, instability in the global credit markets would have soon prompted a meltdown of some sort. The credit network had become so highly interlinked that each participant faced high risks from the possible collapse of their partners. Traditional central-bank controls and banking regulations just weren’t adequate to controlling such instability, for their focus on the health of individual institutions rather than networks of many institutions in interaction. The banking failure is, in many respects, a failure of economic science to have any well developed understanding of the financial system as a complex dynamical network. Rather than just looking at individual banks' lending practices to see if their risks are at acceptable levels, regulators will need to take a more holistic view, monitoring the nature of the links between institutions and the overall stability of the credit network.

In general, the new science of complex networks seeks to understand the various structures of complex natural networks, and how those structures influence the many processes taking place within. We clearly stand closer to the beginning of this science than to its end, but recent work has made major strides in elucidating key issues and at least identifying the most important problems to be tackling in the coming decades.

2. Complex Networks and the "Small World" Property

Many real-world complex networks have the so-called "small-world" property. In social networks, for example, as the Harvard social psychologist Stanley Milgram showed several decades ago, we do live in a very small world; it generally takes only about six "degrees of separation" to go from any one person on the planet to anyone else [5]. Our social world is surprisingly small. This idea has since then slipped into popular folklore, even though many people still wonder if it can possibly be true. But consider the social microcosm of corporate executives, linked by virtue of sitting together on some corporate board. Several years ago Gerald Davis and colleagues from the business school at the University of Michigan studied this network of interconnections, and discovered further evidence of the small world phenomenon [6]. As they concluded,

Corporate America is overseen by a network of individuals who—to a great extent—know each other or have acquaintances in common. On average, any two of the 6724 Fortune 1000 directors we studied can be connected by 4.6 links…

The same pattern turns up also in technology. Although the number of pages in the World Wide Web is now truly astronomical, it generally takes only about 20 clicks to navigate from one page to another [7].

What about the network of computers linked together by communication links of many sorts and making up the physical Internet? In a key study a decade ago [5], computer scientists and brothers Michalis, Petros and Christos Faloutsos approached this question by studying the number of links that a small piece of information – a portion of an email, for example – has to follow in going between one point on the Internet to another. When a computer in San Francisco sends e-mail to Hong Kong, or another in Helsinki tries to access information from a computer in Virginia, how many transmission lines are typically involved? As the Faloutsos team found, the answer is only about four, despite the immense size of the Internet. In fact, if you search throughout the Internet for computers that are especially difficult to link, the number is never more than about ten.

Studies of food webs, cellular protein-protein interactions networks, the nervous systems of elementary organisms and networks of many other kinds reveal a similar character – going from any one element to another requires only a handful of steps, even in networks comprised of an enormous number of elements. In technical terms, this property of complex networks — often called the "small world" property — is that the network “diameter,” the number of steps required on average to go from one element to another, grows very slowly (logarithmically) as the number of elements N increases.

But this is only one of the interesting properties researchers have recently discovered about our world's complex networks.

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Bibliography

A.-L. Barabási, R. Albert, H. Jeong, G. Bianconi, “Power law Distribution of the World Wide Web”, *Science* **287**, 2115 (2000) [A detailed analysis of the WWW].

A.-László Barabási, *Linked* Perseus, Cambridge, (2002) [the first book on complex networks].

A-L. Barabási and R. Albert “Emergence of scaling in Random Networks”, *Science* **286**, 509-512 (1999).

D. Watts, *Six Degrees* W.W. Norton, New York, (2004) [a dissemination book on small-world networks].

D.J. Watts and S.H. Strogatz “Collective Dynamics of small-world networks” *Nature* **393**, 440-442 (1998) [the first paper on small-world effect].

G. Caldarelli, (2007) *Scale-free Networks* Oxford University Press, Oxford, .[A textbook on the theory of complex networks]

G. Caldarelli, A. Capocci, P. De Los Rios, M.A. Muñoz (2002), “Scale-free networks from varying vertex intrinsic fitness”*Physical Review Letters* **89**, 258702 [the first paper that present a rule of growth different than the preferential attachment].

G. Davis, M. Yoo and W. Baker, *Strategic Organization*, **1**, No. 3, pp. 301-326 (2003) [An analysis of the interconnections in the world of finance].

H. Jeong, B. Tombor, R. Albert, Z. Oltvai, A.-L. Barabási, (2000)“The large-scale organization of metabolic networks” *Nature* **407**, 651-655 . [A paper on the modular structure of biological networks]

J. Travers, S. Milgram, “An Experimental Study of the Small World Problem” *Sociometry*, **32**, No. 4, pp. 425-443 (1969) [one of the first seminal applications of the concept of small-world].

J.B.C. Jackson, M.X. Kirby, W.H. Berger, K.A. Bjorndal, L.W. Botsford, B.J. Bourque, R.H. Bradbury, R. Cooke, J. Erlandson, J.A. Estes, T.P. Hughes, S.Kidwell, C.B. Lange, H.S. Lenihan, J.M. Pandolfi, C.H. Peterson, R.S. Steneck, M.J. Tegner, R. R. Warner, (2001) “Historical Overfishing and the Recent Collapse of Coastal Ecosystems” *Science*, **293**, 629-637 . [A study on a particular kind of complex network, that of the food web of fishery species]

L.A.N. Amaral, A. Scala, M. Barthélemy, and H.E. Stanley (2000) “Classes of small-world networks” *Proc. Natl. Acad. Sci. U.S.A.* **97**, 11149-11152 [The first study on the widespread presence of small world systems in the present world].

M. Faloutsos, P. Faloutsos and C. Faloutsos, “On Power-law Relationships of the Internet Topology” ACM SIGCOMM (1999) [The first experimental evidence of the scale-invariance of the Internet].

Mark Buchanan, *Nexus* W.W. Norton, New York, (2002) [a dissemination book on the subject of complex networks].

R. Albert and A.-L. Barabási (2002) “Statistical mechanics of complex networks”, *Review of Modern Physics* **74**, 47 [the first review paper on the statistical description of complex networks] 2002).

R. Albert, H. Jeong and A.-L. Barabási (2000) “Error and attack tolerance of complex networks”, *Nature* **406**, 378-382 [A paper on the fragility and systemic risk of complex networks]

R. Albert, H. Jeong, A.-L. Barabási, “The diameter of the World-Wide Web” *Nature* **401**, 130-131 (1999) [The first application of the ideas of complexity to the WWW].

R. Starr, J. Newfrock and M. Delurey (2003), “Enterprise Resilience: Managing. Risk in the Networked Economy” *Strategy + Business*, Spring issue [A paper on the structure and fragility of Companies].

Uetz, P., Giot, L., Cagney, G., Mansfield, T.A., Judson, R.S., Knight, J.R., Lockshon, D., Narayan, V., Srinivasan, M., Pochart, P., Qureshi-Emili, A., Li, Y., Godwin, B., Conover, D., Kalbfleisch, T.,Vijayadamodar, G., Yang, M., Johnston, M., Fields, S., and Rothberg, J. M “A comprehensive analysis of protein-protein interactions in Saccharomyces cerevisiae.”, *Nature* **403** 623-7 (2000) [one of the most cited papers on protein protein interaction].

Biographical Sketches

Mark Buchanan is an American physicist and author. He was formerly an editor with the international journal of science Nature, and the popular science magazine New Scientist. He has been a guest columnist for the New York Times, and currently writes a monthly column for the journal Nature Physics. He has been awarded in 2009 by Lagrange prize in Turin for his science writing in the field of Complexity.

Guido Caldarelli is currently Associate Professor in the Institute of Complex Systems in the Department of Physics of the University of Rome "Sapienza" Italy. The institute is part National Research Council (CNR) of Italy.

He got his degree in physics in the Department of Physics of the same University in 1992 working with L. Pietronero and A. Vespignani. He then moved to SISSA/ISAS in Trieste where he got the PhD in Statistical Physics in 1996 working on Self-Organized Criticality with A. Maritan. He has been postdoc in the Department of Physics in the University of Manchester with A. McKane and in TCM Group in the University of Cambridge with R. Ball. During his scientific activity in Rome he has also been visiting professor in the École Normale Supérieure in Paris, and in the Department of Physics of the University of Barcelona.

After the studies on fractal growth and self-organized criticality he moved his research on the analysis of scale-free networks. On this topic he published a textbook and he coordinated a European Project (http://www.cosinproject.org).