Understanding Network Complexity

Jeannette M. Wing
Assistant Director
Computer and Information Science and Engineering Directorate
National Science Foundation

11 March 2010

Our networks have evolved to be extremely complex and we do not understand them. The Internet, for example, is complex. In 1970 we could draw the four-node DARPAnet on a napkin. Forty years later, due to its scale and dynamic nature, the Internet is too complex to draw, let alone understand, model, or predict its behavior. The Internet is computer science's gift to society, but ironically we cannot even describe it.

In December 2007 NSF challenged the computer and information science and engineering community to address this fundamental question: Is there a science for understanding the complexity of our networks such that we can engineer them to have predictable, or at least adaptable, behavior? We urged the community to interpret "networks" broadly, to address multiple levels of abstraction, to tackle complexity issues that cross the different levels, and to work with social scientists and economists. At the lowest level, we continue to accommodate new technologies: we have evolved from phone lines, modems, and cables underground to our current diversity of communication media, including wireless and optical, and proliferation of devices, sensors, and actuators. At the highest level, we are witnessing an explosion of social and economic uses of our networks, from beneficial ones such as on-line banking and shopping, social networks, open courseware, and scientific collaborations, to detrimental ones such as spreading worms and viruses, spamming and phishing, and distributed denial of service. Most challenging is complexity in our networks due to one small device at the lowest level having an impact through all other levels, affecting, surprisingly or adversely, a user at the highest level—and vice versa. Complexity cuts through these abstraction levels in ways we do not fully understand.

The scientific challenge is clear: We need theories of our networks such that we understand their inherent and emergent properties. We need formal models of our networks such that we can assert guarantees of reliability or survivability, especially in the presence of disruptive events or malicious attacks. We need models of our networks such that we can accurately predict their performance. Are Poisson models, heavy-tail distribution models, chaos theory, game theory, or fractal theory unrealistic, overly simplistic, or good starting points? Maybe our networks are really different from anything anyone has ever seen (in nature) or built (by human) before. Maybe we need brand new mathematical theories and models. Consider these questions: Is there a complexity theory for analyzing networks analogous to the complexity theory we have for analyzing algorithms? What is the analogue to Shannon information theory for networks? Is there a way to measure the capacity of the Internet, especially as it is continuously changing? If we consider The Internet as a computer, what can be computed by such a machine (and do not forget the human element)? And this question, due to Jim Horning: What is the thermodynamics theory of complex networks, from which we can determine "bulk" properties of a

network, e.g., congestion and stability, without considering its components? More broadly, how does our understanding of networks inform the study of networks in other disciplines, such as biology and social science, and conversely what can we learn from networks found in natural and social systems?

The goal of the NSF program on Network Science and Engineering (NetSE) is to understand the complexity of our networks better so that we can evolve them in ways that can unleash unimaginable creativity and innovation—from new technologies, to new applications, to new users—and hopefully at the same time improve the overall trustworthiness of our networked systems.

I am delighted to see that this second workshop on Network Science for Communication Networks directly addresses this goal, by proposing and exploring new mathematical models of network behavior from the communications media level, such as wireless, to the application level, such as MySpace and YouTube. Best wishes to all participants for a productive and engaging workshop!

To appear in *Proceedings of the Second IEEE International Workshop on Network Science for Communications Networks*, San Diego, CA, March 19, 2010.