From the Editor

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The name of our Society is "Circuits and Systems". For most of our members, "circuit" needs no explanation. However, the question of what a "system" is requires some further consideration. At random, I asked several individuals and received somewhat different albeit similar answers—a few even used the word "network" to describe "system".

Readers of this Magazine are mostly engineers without a linguistics background, so in the following discussion I will focus on insightful understanding and perspective, rather than offering a rigorous linguistic or philosophical definition of a "system" or a "network".

Actually, the word "system" is quite old, which dates back to the ancient Greek dictionary, $\sigma\upsilon\sigma\tau\eta\mu\alpha$, meaning a whole is composed of parts. One well-known monograph in the oldest Chinese literature is "I Ching", which refers to the world or the universe as a fusion of heaven, earth and humans; this already presented an earlier perception of today's "system". In Europe, pioneers of a more precise concept of a system were Johann Wolfgang von Goethe and Gottfried Leibniz, who were familiar with the Chinese philosophy. They were followed by several Western giant scientists like Jules Henri Poincaré, Norbert Wiener, John von Neumann and Claude Shannon. In particular, Wiener introduced the word "cybernetics", also from Greek, $\kappa\upsilon\beta\epsilon\rho\nu\eta\tau\eta\zeta$, which in modern language has a vague meaning of system, control and management.

Today's "systems theory" may be traced back to a general theory initiated by the Austrian biologist Karl von Bertalanffy in the earlier 20th century, although the book *The Principles of Scientific Management* published in 1911 by the American mechanical engineer Frederick W. Taylor already had some of the most basic ingredients of the modern systems theory. The term "systems engineering", on the other hand, perhaps resulted from the scientists and engineers of the Bell Labs in the 1940s, referring to an integration of design, development, production and operation of physical systems in technology and industry.

For quite a long time, the notions of systems science and systems engineering were fused together as an inseparable trans-discipline that studies various systems regarding their characteristics, dynamics and evolution, with applications to benefit the human society. Its basic components are control theory, information theory and systems theory, reaching out to cover many other disciplines in science and engineering such as operations research, game theory, automation, synergetics, dissipative structure theory, dynamics and catastrophe theory, fuzzy logic and artificial intelligence. In a sense, any subject that is "huge" and "complex" could possibly be studied under the framework of systems science and engineering, including many from species evolution in biology to aerospace structures in astrophysics, and from economic and military entities to social communities.

Networks, on the other hand, are also ubiquitous like systems. However, the concepts of "system" and "network" are similar but different. From one point of view, a network can be understood as a system. From another perspective, a node in a real-world network is typically a dynamical system, so a network is an assembly of many interconnected systems. Although such a network may be further considered as an even larger system, viewing it just as a network can clearly and conveniently lay the skeleton for the underlying structure and framework.

Graph theory is the scientific basis of physical and mathematical networks. In 1736, Leonhard Euler proved that the seven bridges problem of Königsberg has no solutions. This laid a foundation for modern graph theory in mathematics. The systematic theory of random graphs is attributed to Paul Erdös for his seminal work done in the late 1950s, which has dominated the main stream of research on graph theory through the past half a century to this day. It also finds extensive applications in circuits and systems as well as networks in engineering and technology. In fact, electrical engineers have successfully applied graph theory to formulate many electrical circuit problems, and a version of "network theory" for circuit analysis and synthesis has been developed since the 1950s. In the following thirty years or so, the term "networks" was commonly used to mean electrical circuits by electrical engineers. Even today most electrical engineering students are still learning their first course in "electrical networks" where graph theory is introduced to formulate independent Kirchhoff equations for electrical circuits. In the 1970–1980s, the advent of digital computation catalyzed the development of computer-aided circuit analysis software, in which graph theory played a pivotal role in the formulation of elegant and effective algorithms.

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In 1998, Duncan J. Watts and Steven H. Strogatz published an article in *Nature*, in which they introduced a new notion of small-world networks that could model and represent a wide spectrum between regular networks and random networks. A small-world network possesses high clustering, similar to that in regular networks, yet has a short average path-length like random networks. One year later, Albert-László Barabási and Réka Albert published another stimulating article in *Science*, showing that many networks have degree distributions in a power-law form. They are also referred to as scale-free networks for the independence of their degree distributions on the growing large network sizes. These two articles triggered a new wave of enthusiasm for networks research in almost all realms of science, engineering and technology. The *IEEE Circuits and Systems Magazine* subsequently published an overview article on the subject in the first quarterly of 2003, followed by a Special Issue on Complex Networks Applications in Circuits and Systems in the third quarterly this year. A 772-page monograph by Mark E. J. Newman, published also in this year, entitled *Networks: An Introduction*, summarizes the basic theory and methodologies of the new research direction. The book presents the state of the art in the field, in which it also describes the celebrated contributions of Jon M. Kleinberg who received the prestigious Nevanlinna Prize at the 2006 World Congress of Mathematics for his novel navigable small-world network model and its search method.

In today's scientific research terminology, a "network" typically means a "complex network". The adjective "complex" here has multifold meanings. First, it refers to the intrinsic connectivity of a topologically complicated network in comparison with the regular ones such as lattices and fully-connected networks. Second, it refers to the nontrivial dynamics of the systems as nodes in the network, which are usually higher-dimensional, nonlinear, and even chaotic. Moreover, it refers to the global behaviors of the large number of interconnected dynamical nodes, specifically adaptation, evolution, self-organization, self-synchronization and emergence.

Research on complex networks has been truly multi-disciplinary in the sense that the basic phenomenology and methodology are applicable across a multitude of applications and in different disciplines, including the Internet, communication networks, sensor networks, power grids, biological networks such as neuronal and gene networks, human dynamics and social networks, financial and economic networks, and language and music networks. Basic tools are computer simulation, graph theory, statistical physics methods, data analysis, and control theory. The main objectives are to understand and analyze the algebraic and geometric features of various networks, their formation and evolution, their modeling and characterization, and their dynamics and stability, among others. Important measures include node degree and degree distribution, clustering coefficient, average path-length, connectivity, coreness, betweenness, assortativeness, as well as their statistics, which altogether describe the topological and dynamical properties of complex networks.

Research on systems and networks share many common features: they are both based on physical principles and use mathematical means for modeling, identification, analysis and control; they apply localized and distributed strategies into the design, regulation, management and optimization; and they concern ultimately global and integrated behaviors such as convergence, synchrony, consensus, coordination, stability as well as adaptation, self-organization and emergence. Oftentimes, they both can be described by coupled differential equations in dynamical settings, where the adjective "coupled" emphasizes the connectedness of several sub-systems or sub-networks described by some sub-sets of dynamical equations.

However, networks differ from systems in their structure and behavior. Typically, systems theory emphasizes on integration and globalization while networks theory focuses more on local structures, especially multi-scale functions and behaviors. One typical example in point is that a local structure of a network affects the network connectivity, thereby considerably modifying the eigen-spectrum of its coupling matrix, which in turn changes the network synchronizability significantly. Yet this often has very little effect on the global statistical properties of the entire network. Usually, compared to systems the networks research is more interested in such topological features as community components, hierarchical layers, and their inner connections such as clusters, motifs, cores, hubs, assortative and disassortative structures. Furthermore, systems science often deals with global description, overall behavior, assembly design and integrated function, while networks science tries to manage local connectivity, internal reactions, sub-networks competition and cooperation, and inner evolution, self-organization, emergence and even cascaded catastrophe. In terms of methodology, traditional systems theory employs a unified approach based on the state-space theory and framework, while networks science utilizes graph theory as the norm. Generally speaking, networks science is more interested in the evolutionary process while systems science is more so in the asymptotic behavior and ultimate performance. Nevertheless, in many applications, the studies of networks and systems support each other. For instance, in electrical circuit analysis, graph theory is essential in identifying independent state variables of a given circuit (e.g., tree capacitor voltages and co-tree inductor currents) for the formulation of state equations, allowing the subsequent systems analysis to uncover the dynamical behavior of the circuit more visually effectively.

The research on both systems and networks has led the study of "complexity" to become more specific and more manageable. In his celebrated article "Scale-free networks: a decade and beyond", published in *Science* in July 2009, Barabási concluded by saying that "Interconnectivity is so fundamental to the behavior of complex systems that networks are here to stay." To my understanding, this implies that only if studying carefully the interconnectivity of a network and its impacts on the global performance can one better understand the complexity and the nature of a complex system.

The IEEE Circuits and Systems Society has in the past strongly supported research on systems science and engineering, and more recently also on complex networks. Progress and achievements notwithstanding, many important issues in complex systems and complex networks still remain today. While graph theory provides a unified mathematical tool for understanding a static network of nodes, is there a unified tool for the investigation of an evolutionary network of dynamic systems? How does the network structure affect its functioning, and vice versa? For a "network of networks", such as the conceptual "Internet of Things" that facilitates efficient communications through the Internet connecting to some fundamentally different networks such as transportation networks, power grids and military entities, how can we develop effective scientific research regarding such essential issues as modeling, analysis, management and control? "System on chip" and "network on chip" are other two of a kind. Our Society is facing many important new challenges in this territory that the name of the Society is here to stay.