SOCIETAL IMPACT

The impact of a new research field is measured both by its intellectual achievements as well as by its societal impact, indicated by the reach and the potential of its applications. While network science is a young field, its impact is everywhere.

ECONOMIC IMPACT: FROM WEB SEARCH TO SOCIAL NETWORKING

The most successful companies of the 21st century, from Google to Facebook, Twitter, LinkedIn, Cisco, Apple and Akamai, base their technology and business model on networks. Indeed, Google not only runs the biggest network mapping operation that humanity has ever built, generating a comprehensive and constantly updated map of the WWW, but its search technology is deeply interlinked with the network characteristics of the Web.

Networks have gained particular popularity with the emergence of Facebook, the company with the ambition to map out the social network of the whole planet. Facebook was not the first social networking site and it is likely not the last either: An impressive ecosystem of social networking tools, from Twitter to LinkedIn are fighting for the attention of millions of users. Algorithms conceived by network scientists fuel these sites, aiding everything from friend recommendation to advertising.

HEALTH: FROM DRUG DESIGN TO METABOLIC ENGINEERING

Completed in 2001, the human genome project offered the first comprehensive list of all human genes [5, 6]. Yet, to fully understand how our cells function, and the origin of disease, a full list of genes is not sufficient: We also need an accurate map of how genes, proteins, metabolites and other cellular components interact with each other. Indeed, most cellular processes, from food processing to sensing changes in the environment, rely on molecular networks. The breakdown of these networks is responsible for human diseases.

The increasing awareness of the importance of molecular networks has led to the emergence of *network biology*, a new subfield of biology that aims to understand the behavior of cellular networks. A parallel movement within medicine, called *network medicine*, aims to uncover the role of networks in human disease (Figure 1.5). The importance of these advances is illustrated by the fact that Harvard University in 2012 started the Division of Network Medicine, that employs researchers and medical doctors who apply network-based ideas towards understanding human disease.

Networks play a particularly important role in drug development. The ultimate goal of *network pharmacology* [7] is to develop drugs that can cure diseases without significant side effects. This goal is pursued at many levels, from millions of dollars invested to map out cellular networks, to the development of tools and databases to store, curate, and analyze patient and genetic data.

Several new companies take advantage of the opportunities offered by networks for health and medicine. For example GeneGo collects maps of cellular interactions from the scientific literature and Genomatica uses the predictive power behind metabolic networks to identify drug targets in bacteria and humans. Recently major pharmaceutical companies, like Johnson & Johnson, have made significant investments in network medicine, seeing it as the path towards future drugs.

SECURITY: FIGHTING TERRORISM

Terrorism is a malady of the 21st century, requiring significant resources to combat it worldwide. Network thinking is increasingly present in the arsenal of various law enforcement agencies in charge of responding to terrorist activities. It is used to disrupt the financial network of terrorist organizations and to map adversarial networks, helping to uncover the role of their members and their capabilities. While much of the work in this area is classified, several well documented case studies have been made public. Examples include the use of social networks to find Saddam Hussein [10] or those responsible for the March 11, 2004 Madrid train bombings through the examination of the mobile call network. Network concepts have impacted military doctrine as well, leading to the concept of *network-centric warfare*, aimed at fighting low intensity conflicts against terrorist and criminal networks that employ decentralized flexible network organization [11] (Figure 1.6).

Given the numerous potential military applications, it is perhaps not surprising that one of the first academic programs in network science was started at West Point, the US Army Military Academy. Furthermore, starting in 2009 the Army Research Lab devoted over $300 million to support network science centers across the US.

The knowledge and the capabilities offered by networks can be also abused. Such misuses were well illustrated by the indiscriminate network mapping operation by the National Security Agency [12]. Under the pretext of stopping future terrorist attacks, NSA monitored the

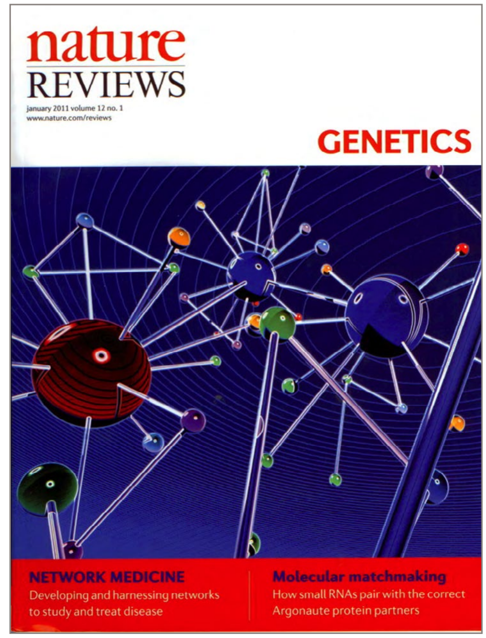


Figure 1.5

Network Biology and Medicine

The cover of two issues of *Nature Reviews Genetics*, the leading review journal in genetics. The journal has devoted exceptional attention to the impact of networks: the 2004 cover focuses on *network biology* [8] (top), the 2011 cover discusses *network medicine* [9] (bottom).

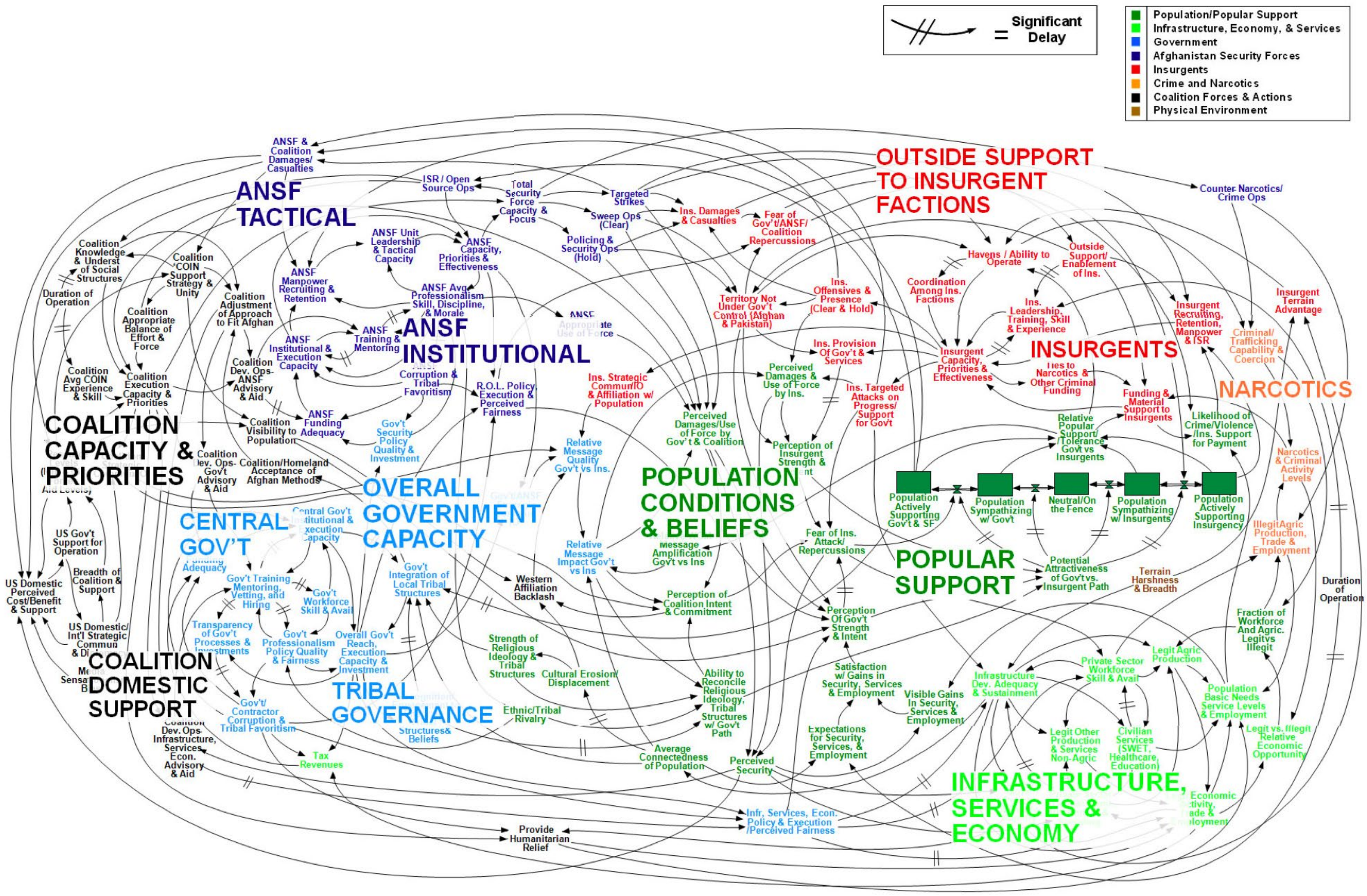


Figure 1.6

The Network Behind a Military Engagement

This diagram was designed during the Afghan war in 2012 to portray the American operational plans in Afghanistan. While it has been ridiculed in the press for displaying too much complexity and detail in one chart, it vividly illustrates the interconnected nature of a modern military engagement. Today this example is studied by officers and military students to demonstrate the power and utility of network models for decision-making and operational coordination. Indeed, the job of military generals is not limited to ensuring the necessary military capacities, but must also factor in the beliefs and the living conditions of the local population or the impact of the narcotics trade that finances the opearations of the insurgents. Image from New York Times.

communications of hundreds of millions of individuals, from the US and abroad, rebuilding their social network. With that network scientists have awoken to a new social responsibility: to ensure the ethical use of our tools and knowledge.

EPIDEMICS: FROM FORECASTING TO HALTING DEADLY VIRUSES

While the H1N1 pandemic was not as devastating as it was feared at the beginning of the outbreak in 2009, it gained a special role in the history of epidemics: It was the first pandemic whose course and time evolution was accurately predicted months before the pandemic reached its peak (Online Resource 1.1) [13]. This was possible thanks to fundamental advances in understanding the role of transportation networks in the spread of viruses.

Online Resource 1.1
Predicting the H1N1 Epidemic

The predicted spread of the H1N1 epidemics during 2009, representing the first successful real-time prediction of a pandemic [13]. The project, relying on data describing the structure and the dynamics of the worldwide transportation network, foresaw that H1N1 will peak out in October 2009, in contrast with the expected January-February peak of influenza. This meant that the vaccines timed for November 2009 were too late, eventually having little impact on the outcome of the epdemic. The success of this project shows the power of network science in facilitating advances in areas of key importance for humanity.

Video courtesy of Alessandro Vespignani.

Before 2000 epidemic modeling was dominated by compartment-based models, assuming that everyone can infect everyone else in the same socio-physical compartment. The emergence of a network-based framework has brought a fundamental change, offering a new level of predictability. Today epidemic prediction is one of the most active applications of network science [13, 14], being used to foresee the spread of influenza or to contain Ebola. It is also the source several fundamental results covered in this book, allowing us to model and predict the spread of biological, digital and social viruses (memes).

The impact of these advances are felt beyond epidemiology. Indeed, in January 2010 network science tools have predicted the conditions necessary for the emergence of viruses spreading through mobile phones [15]. The first major mobile epidemic outbreak that started in the fall of 2010 in China, infecting over 300,000 phones each day, closely followed the predicted scenario.

NEUROSCIENCE: MAPPING THE BRAIN

The human brain, consisting of hundreds of billions of interlinked neurons, is one of the least understood networks from the perspective of network science. The reason is simple: We lack maps telling us which neurons are linked together. The only fully mapped brain available for research is that of the C. elegans worm, consisting of only 302 neurons. Detailed maps of mammalian brains could lead to a revolution in brain science, allowing the understanding and curing of numerous neurological and brain diseases. With that brain research could turn it into one of the most prolific application area of network science [16]. Driven by the potential transformative impact of such maps, in 2010 the National Institutes of Health in the U.S. has initiated the *Connectome* project, aimed at developing technologies that could provide accurate neuron-level maps of mammalian brains (Figure 1.4).

MANAGEMENT: UNCOVERING THE INTERNAL STRUCTURE OF AN ORGANIZATION

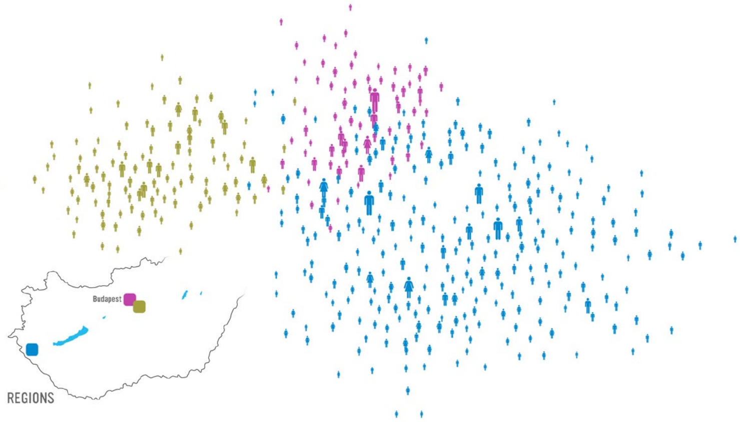
While management tends to rely on the official chain of command, it is increasingly evident that the informal network, capturing who really communicates with whom, plays the most important role in the success of an organization. Accurate maps of such *organizational networks* can expose the potential lack of interactions between key units, help identify individuals who play an important role in bringing different departments and products together, and help higher management diagnose diverse organizational issues. Furthermore, there is increasing evidence in the management literature that the productivity of an employee is determined by his/her position in this informal organizational network [17].

Therefore, numerous companies, like Maven 7, Activate Networks or Orgnet, offer tools and methodologies to map out the true structure of an organization. These companies offer a host of services, from identifying opinion leaders to reducing employee churn, optimizing knowledge and product diffusion and designing teams with the diversity, size and expertise to be the most effective for specific tasks (Figure 1.8). Established firms, from IBM to SAP, have added social networking capabilities to their business. Overall, network science tools are indispensable in management and business, enhancing productivity and boosting innovation within an organization.

Figure 1.7

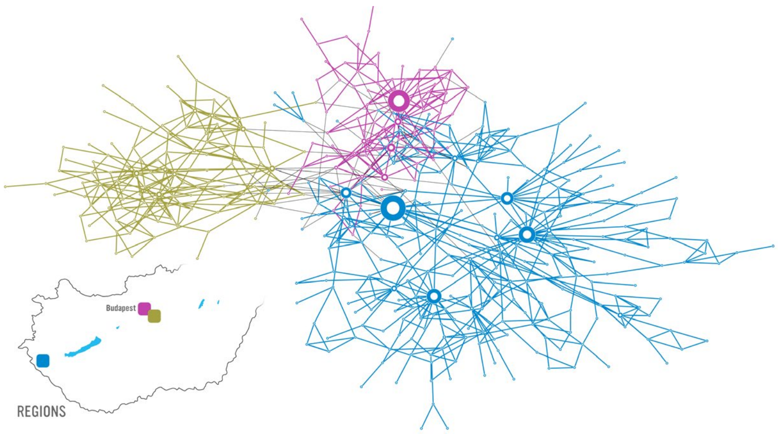
Mapping Organizations

(a)



(a) Employees of a Hungarian company with three main locations (purple, yellow and blue). The management realized that information reaching the workers about the intentions of the higher management often had nothing do to with their real plans. Seeking to enhance information flow within the company, they turned to Maven 7, a company that applies network science in organizational setting.

(b)



(b) Maven 7 developed an online platform to ask each employee to whom do they turn to for advice when it comes to decisions impacting the company. This platform provided the map shown in (b), where two individuals are connected if one nominated the other as his/her source of information on organizational and professional issues. The map identifies several highly influential individuals, appearing as large hubs.

(c)

(c) The position of the leadership within the company's informal network, nodes being colored based on their rank within the company. Note that none of the directors, shown in red, are hubs. Nor are the top managers, shown in blue. The hubs come from lower ranks: they are managers, group leaders and associates. The biggest hub, hence the most influential individual, is an ordinary employee, appearing as a gray node in the center.

(d)

(d) The links of the largest hub (red) and those two links away from this hub (orange), demonstrate that a significant fraction of employees are at most two links from this hub. But who is this hub? He is the employee in charge of safety and environmental issues. Hence he regularly visits each location and talks with the employees. He is connected to everyone except the top management. With little knowledge of the true intentions of the management, he passes on information that he collects along his trail, effectively running a gossip center.

Should they fire or promote the biggest hub? What is the best solution to this problem?

SCIENTIFIC IMPACT

Nowhere is the impact of network science more evident than in the scientific community. The most prominent scientific journals, from *Nature* to *Science*, *Cell* and *PNAS*, have devoted reviews and editorials addressing the impact of networks on various topics, from biology to social sciences. For example, *Science* has published a special issue on networks, marking the ten-year anniversary of the discovery of scale-free networks [18] (Figure 1.8).

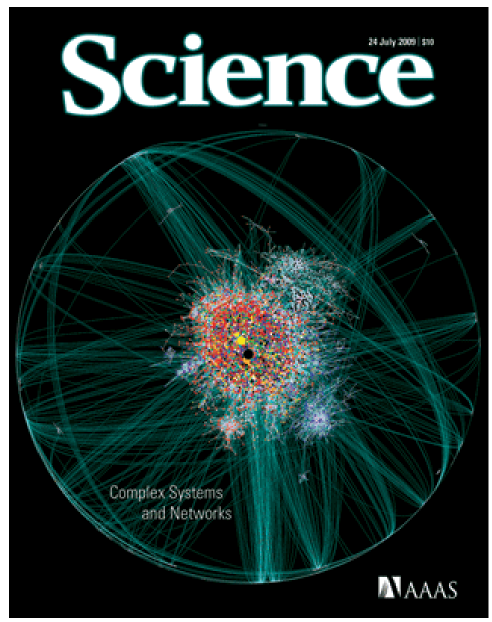


Figure 1.8
Complex Systems and Networks

Special issue of *Science* magazine devoted to networks, published on July 24, 2009, on the 10th anniversary of the 1999 discovery of scale-free networks [18].

During the past decade each year about a dozen international conferences, workshops, summer and winter schools have focused on network science. A highly successful network science conference series, called NetSci, attracts the field's practitioners since 2005. Several general-interest books have made bestseller lists in many countries, bringing network science to the general public. Most major universities offer network science courses, attracting a diverse student body, and in 2014 Northeastern University in Boston and the Central European University in Budapest have launched PhD programs in network science.

To see the impact of networks on the scientific community it is useful to inspect the citation patterns of the most cited papers in the area of complex systems. Each of these papers are citation classics, reporting classic discoveries like the butterfly effect, renormalisation group, spin glasses, fractals and neural networks, and cumulatively amassing anywhere between 2,000 and 5,000 citations. To see how the interest in network science compares to the impact of these foundational papers in Figure 1.9 we compare their citation patterns to the citations of the two most cited network science papers: the 1998 paper on small-world phenomena [19] and the 1999 Science paper reporting the discovery of scale-free networks [18]. As one can see, the rapid rise of yearly citations to these two papers is without precedent in the area of complex systems.

Several other metrics indicate that network science is impacting in a defining manner numerous disciplines. For example, in several research fields network papers became the most cited papers in their leading journals:

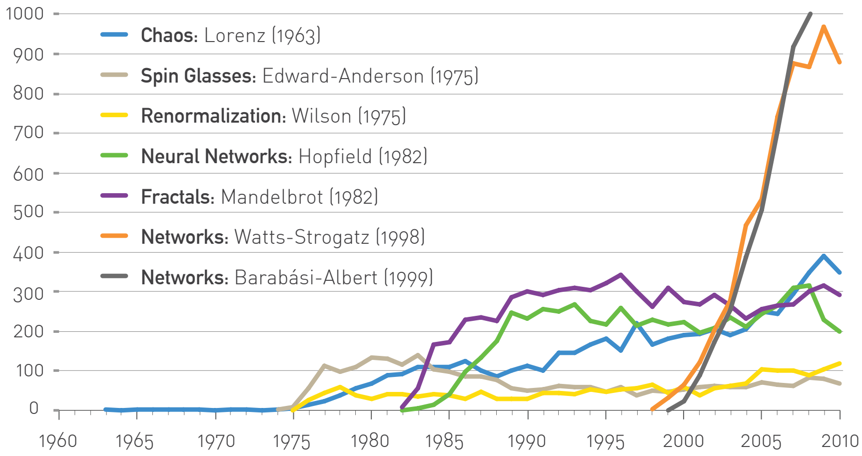


Figure 1.9

Complexity and Network Science

The scientific impact of network science, as seen through citation patterns, compared to the citations of the most cited papers in complexity. The study of complex systems in the 60s and 70s was dominated by Edward Lorenz's 1963 classic work on chaos [20], Kenneth G. Wilson's renormalization group [21], and Samuel F. Edwards and Philip W. Anderson work on spin glasses [22]. In the 1980s the community has shifted its focus to pattern formation, following Benoit Mandelbrot's book on fractals [23] and Thomas Witten and Len Sander's introduction of the diffusion limited aggregation model [24]. Equally influential was John Hopfield's paper on neural networks [25] and Per Bak, Chao Tang and Kurt Wiesenfeld's work on self-organized criticality [26]. These papers continue to define our understanding of complex systems. The figure compares the yearly citations of these landmark papers with the citations of the two most cited papers in network science, the paper by Watts and Strogatz on small world networks and by Barabási and Albert, reporting the discovery of scale-free networks. [18, 19].

(a) The 1998 paper by Watts and Strogatz in *Nature* on small world phenomena [19] and the 1999 paper by Barabási and Albert in *Science* on scale-free networks [18] were identified by Thompson-Reuters as being among the top ten most cited papers in physical sciences during the decade after their publication. Currently (2011) the Watts-Strogatz paper is the second most cited of all papers published in *Nature* in 1998 and the Barabási-Albert paper is the most cited paper among all papers published in *Science* in 1999.

(b) Four years after its publication the *SIAM* review by Mark Newman on network science became the most cited paper of any journal published by the Society of Industrial & Applied Mathematics [27].

(c) *Reviews of Modern Physics*, published since 1929, is the physics journal with the highest impact factor. Until 2012 the most cited paper of the journal was written by Nobel Prize winner Subrahmanyan Chandrasekhar, his classic 1944 review entitled *Stochastic Problems in Physics and Astronomy* [28]. During the 70 years since its publication, the paper gathered over 5,000 citations. Yet, in 2012 it was taken over by the first review of network science published in 2001 entitled *Statistical Mechanics of Complex Networks* [29].

(d) The paper reporting the discovery that in scale-free networks the epidemic threshold vanishes, by Pastor-Satorras and Vespignani [30], is the most cited paper among the papers published in 2001 by *Physical Review Letters*, shared with a paper on quantum computing.

(e) The paper by Michelle Girvan and Mark Newman on community discovery in networks [31] is the most cited paper published in 2002 by *Proceedings of the National Academy of Sciences*.

(f) The 2004 review entitled *Network Biology* [8] is the second most cited paper in the history of *Nature Reviews Genetics*, the top review journal in genetics.

Prompted by this extraordinary enthusiasm within by the scientific community, network science was examined by the National Research Council (NRC), the arm of the US National Academies in charge of offering policy recommendation to the US government. NRC has assembled two panels, resulting in recommendations summarized in two NRC Reports [32, 33], defining the field of network science (Figure 1.10). These reports not only documented the emergence of a new research field, but highlighted the field's role for science, national competitiveness and security. Following these reports, the National Science Foundation (NSF) in the US established a network science directorate and several Network Science Centers were funded at US universities by the Army Research Labs.

Network science has excited the public as well. This was fueled by the success of several general audience books, like *Linked*, *Nexus*, *Six Degrees* and *Connected* (Figure 1.11). *Connected*, an award-winning documentary by Australian filmmaker Annamaria Talas, has brought the field to our TV screen, being broadcasted all over the world and winning several prestigious prizes (Online Resource 1.2).

Networks have inspired artists as well, leading to a wide range of network-related art projects, and an annual symposium series that brings together artists and network scientists [38]. Fueled by successful movies like *The Social Network* or *Six Degrees of Separation*, and a series of science fiction novels and short stories exploiting the network paradigm, today networks are deeply ingrained in popular culture.

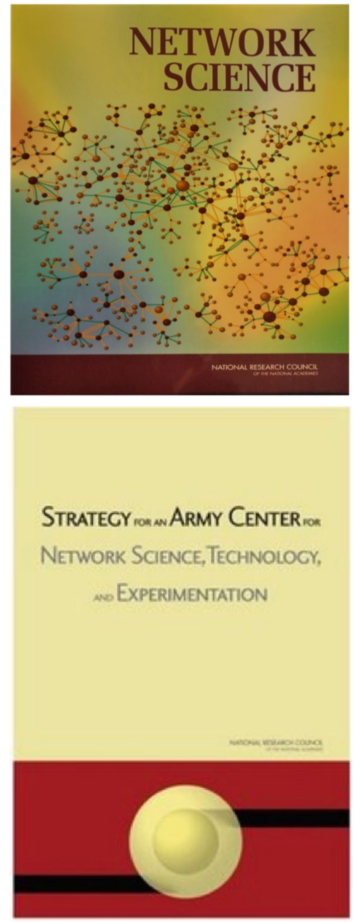
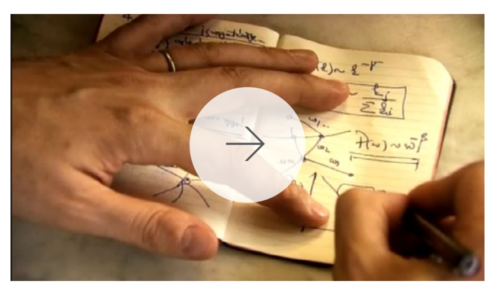


Figure 1.10
National Research Council

Two National Research Council reports on network science have documented the emergence of the new discipline and highlighted its long-term impact on research and national competitiveness [32, 33]. They have recommended dedicated support for the field, prompting the establishment of network science centers at US universities and a network science program within NSF.



Online resource 1.2
Connected

The trailer of the award winning documentary entitled *Connected*, directed by Annamaria Talas, offering an introduction into network science. It features the actor Kevin Bacon and several well-known network scientists.

Figure 1.11

Wide Impact

Four widely read books, translated to over twenty languages, have brought network science to the general public [34, 35, 36, 37].