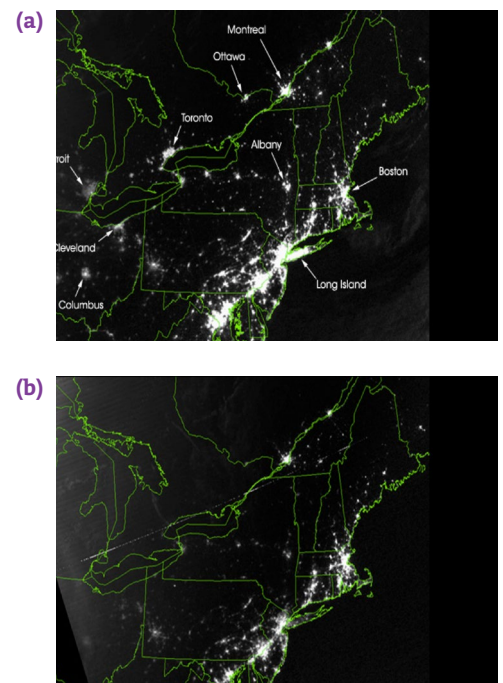


# VULNERABILITY DUE TO INTERCONNECTIVITY

At a first glance the two satellite images of [Figure 1.1](#) are indistinguishable, showing lights shining brightly in highly populated areas and dark spaces that mark vast uninhabited forests and oceans. Yet, upon closer inspection we notice differences: Toronto, Detroit, Cleveland, Columbus and Long Island, bright and shining in (a), have gone dark in (b). This is not a doctored shot from the next Armageddon movie but represents a real image of the US Northeast on August 14, 2003, before and after the blackout that left without power an estimated 45 million people in eight US states and another 10 million in Ontario.

The 2003 blackout is a typical example of a cascading failure. When a network acts as a transportation system, a local failure shifts loads to other nodes. If the extra load is negligible, the system can seamlessly absorb it, and the failure goes unnoticed. If, however, the extra load is too much for the neighboring nodes, they will too tip and redistribute the load to their neighbors. In no time, we are faced with a cascading event, whose magnitude depends on the position and the capacity of the nodes that failed initially.

Cascading failures have been observed in many complex systems. They take place on the Internet, when traffic is rerouted to bypass malfunctioning routers. This routine operation can occasionally create denial of service attacks, which make fully functional routers unavailable by overwhelming them with traffic. We witness cascading events in financial systems, like in 1997, when the International Monetary Fund pressured the central banks of several Pacific nations to limit their credit, which defaulted multiple corporations, eventually resulting in stock market crashes worldwide. The 2009-2011 financial meltdown is often seen as a classic example of a cascading failure, the US credit crisis paralyzing the economy of the globe, leaving behind scores of failed banks, corporations, and even bankrupt states. Cascading failures can be also induced artificially. An example is the worldwide effort to dry up the money supply of terrorist organizations, aimed at crippling their ability to function. Similarly, cancer researchers aim to induce cascading failures in our cells to kill cancer cells.



**Figure 1.1**  
**2003 North American Blackout**

- (a) Satellite image on Northeast United States on August 13th, 2003, at 9:29pm (EDT), 20 hours *before* the 2003 blackout.
- (b) The same as above, but 5 hours *after* the blackout.

The Northeast blackout illustrates several important themes of this book: First, to avoid damaging cascades, we must understand the structure of the network on which the cascade propagates. Second, we must be able to model the dynamical processes taking place on these networks, like the flow of electricity. Finally, we need to uncover how the interplay between the network structure and dynamics affects the robustness of the whole system. Although cascading failures may appear random and unpredictable, they follow reproducible laws that can be quantified and even predicted using the tools of network science.

The blackout also illustrates a bigger theme: *vulnerability due to interconnectivity*. Indeed, in the early years of electric power each city had its own generators and electric network. Electricity cannot be stored, however: Once produced, electricity must be immediately consumed. It made economic sense, therefore, to link neighboring cities up, allowing them to share the extra production and borrow electricity if needed. We owe the low price of electricity today to the power grid, the network that emerged through these pairwise connections, linking all producers and consumers into a single network. It allows cheaply produced power to be instantly transported anywhere. Electricity hence offers a wonderful example of the huge positive impact networks have on our life.

Being part of a network has its catch, however: local failures, like the breaking of a fuse somewhere in Ohio, may not stay local any longer. Their impact can travel along the network's links and affect other nodes, consumers and individuals apparently removed from the original problem. In general interconnectivity induces a remarkable non-locality: It allows information, memes, business practices, power, energy, and viruses to spread on their respective social or technological networks, reaching us, no matter our distance from the source. Hence networks carry both benefits and vulnerabilities. Uncovering the factors that can enhance the spread of traits deemed positive, and limit others that make networks weak or vulnerable, is one of the goals of this book.

# NETWORKS AT THE HEART OF COMPLEX SYSTEMS

*“I think the next century will be the century of complexity.”*

*Stephen Hawking*

We are surrounded by systems that are hopelessly complicated. Consider for example the society that requires cooperation between billions of individuals, or communications infrastructures that integrate billions of cell phones with computers and satellites. Our ability to reason and comprehend our world requires the coherent activity of billions of neurons in our brain. Our biological existence is rooted in seamless interactions between thousands of genes and metabolites within our cells.

These systems are collectively called *complex systems*, capturing the fact that it is difficult to derive their collective behavior from a knowledge of the system's components. Given the important role complex systems play in our daily life, in science and in economy, their understanding, mathematical description, prediction, and eventually control is one of the major intellectual and scientific challenges of the 21st century.

The emergence of network science at the dawn of the 21st century is a vivid demonstration that science can live up to this challenge. Indeed, behind each complex system there is an intricate network that encodes the interactions between the system's components:

- (a) The network encoding the interactions between genes, proteins, and metabolites integrates these components into live cells. The very existence of this *cellular network* is a prerequisite of life.
- (b) The wiring diagram capturing the connections between neurons, called the *neural network*, holds the key to our understanding of how the brain functions and to our consciousness.

## BOX 1.1

### COMPLEX

[adj., v. kuh m-pleks, kom-pleks; n. kom-pleks]

- 1) composed of many interconnected parts; compound; composite: a complex highway system
- 2) characterized by a very complicated or involved arrangement of parts, units, etc.: complex machinery
- 3) so complicated or intricate as to be hard to understand or deal with: a complex problem

Source: *Dictionary.com*

- (c) The sum of all professional, friendship, and family ties, often called the *social network*, is the fabric of the society and determines the spread of knowledge, behavior and resources.
- (d) *Communication networks*, describing which communication devices interact with each other, through wired internet connections or wireless links, are at the heart of the modern communication system.
- (e) The *power grid*, a network of generators and transmission lines, supplies with energy virtually all modern technology.
- (f) *Trade networks* maintain our ability to exchange goods and services, being responsible for the material prosperity that the world has enjoyed since WWII (Figure 1.2).

Networks are also at the heart of some of the most revolutionary technologies of the 21st century, empowering everything from Google to Facebook, CISCO, and Twitter. At the end, networks permeate science, technology, business and nature to a much higher degree than it may be evident upon a casual inspection. Consequently, *we will never understand complex systems unless we develop a deep understanding of the networks behind them.*

The exploding interest in network science during the first decade of the 21st century is rooted in the discovery that despite the obvious diversity of complex systems, the structure and the evolution of the networks behind each system is driven by a common set of fundamental laws and principles. Therefore, notwithstanding the amazing differences in form, size, nature, age, and scope of real networks, most networks are driven by common organizing principles. Once we disregard the nature of the components and the precise nature of the interactions between them, the obtained networks are more similar than different from each other. In the following sections we discuss the forces that have led to the emergence of this new research field and its impact on science, technology, and society.



**Figure 1.2**  
**Subtle Networks Behind the Economy**

A credit card selected as the 99th object in *The History of the World in 100 Objects* exhibit by the British Museum. This card is a vivid demonstration of the highly interconnected nature of the modern economy, relying on subtle economic and social connections that normally go unnoticed.

The card was issued in the United Arab Emirates in 2009 by the *Hong Kong and Shanghai Banking Corporation*, known as HSBC, a London based bank. The card functions through protocols provided by VISA, a USA based credit association. Yet, the card adheres to Islamic banking principles, which operates in accordance with Fiqhal-Muamalat (Islamic rules of transactions), most notably eliminating interest or riba. The card is not limited to muslims in the United Arab Emirates, but is offered in non-Muslim countries as well, to anyone who agrees with its strict ethical guidelines.