From the book *Networks, Crowds, and Markets: Reasoning about a Highly Connected World*.
By David Easley and Jon Kleinberg. Cambridge University Press, 2010.
Complete preprint on-line at http://www.cs.cornell.edu/home/kleinber/networks-book/

Chapter 1

Overview

Over the past decade there has been a growing public fascination with the complex "connectedness" of modern society. At the heart of this fascination is the idea of a *network* — a pattern of interconnections among a set of things — and one finds networks appearing in discussion and commentary on an enormous range of topics. The diversity of contexts in which networks are invoked is in fact so vast that it's worth deferring precise definitions for a moment while we first recount a few of the more salient examples.

To begin with, the social networks we inhabit — the collections of social ties among friends — have grown steadily in complexity over the course of human history, due to technological advances facilitating distant travel, global communication, and digital interaction. The past half-century has seen these social networks depart even more radically from their geographic underpinnings, an effect that has weakened the traditionally local nature of such structures but enriched them in other dimensions.

The information we consume has a similarly networked structure: these structures too have grown in complexity, as a landscape with a few purveyors of high-quality information (publishers, news organizations, the academy) has become crowded with an array of information sources of wildly varying perspectives, reliabilities, and motivating intentions. Understanding any one piece of information in this environment depends on understanding the way it is endorsed by and refers to other pieces of information within a large network of links.

Our technological and economic systems have also become dependent on networks of enormous complexity. This has made their behavior increasingly difficult to reason about, and increasingly risky to tinker with. It has made them susceptible to disruptions that spread through the underlying network structures, sometimes turning localized breakdowns into cascading failures or financial crises.

Draft version: June 10, 2010

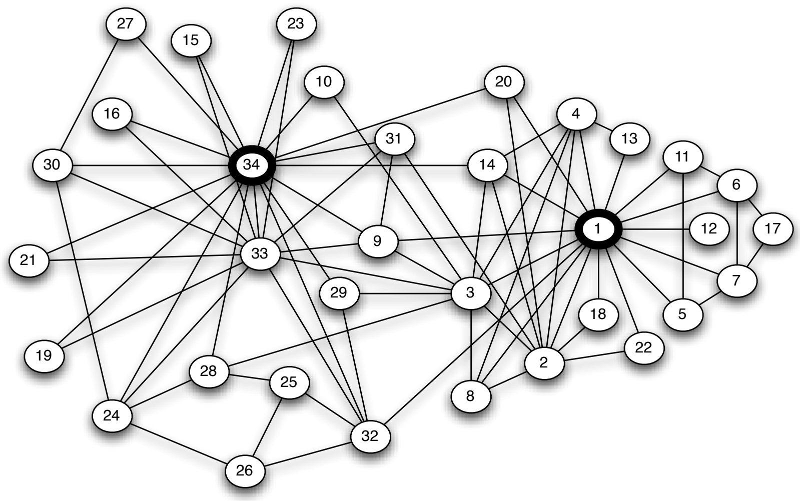

Figure 1.1: The social network of friendships within a 34-person karate club [421].

The imagery of networks has made its way into many other lines of discussion as well: Global manufacturing operations now have networks of suppliers, Web sites have networks of users, and media companies have networks of advertisers. In such formulations, the emphasis is often less on the structure of the network itself than on its complexity as a large, diffuse population that reacts in unexpected ways to the actions of central authorities. The terminology of international conflict has come to reflect this as well: for example, the picture of two opposing, state-supported armies gradually morphs, in U.S. Presidential speeches, into images of a nation facing "a broad and adaptive terrorist network" [296], or "at war against a far-reaching network of violence and hatred" [328].

1.1 Aspects of Networks

How should we think about networks, at a more precise level, so as to bring all these issues together? In the most basic sense, a network is any collection of objects in which some pairs of these objects are connected by *links*. This definition is very flexible: depending on the setting, many different forms of relationships or connections can be used to define links.

Because of this flexibility, it is easy to find networks in many domains, including the ones we've just been discussing. As a first example of what a network looks like, Figure 1.1 depicts the social network among 34 people in a university karate club studied by the anthropologist Wayne Zachary in the 1970s. The people are represented by small circles, with lines joining the pairs of people who are friends outside the context of the club. This is the typical way in which networks will be drawn, with lines joining the pairs of objects that are connected

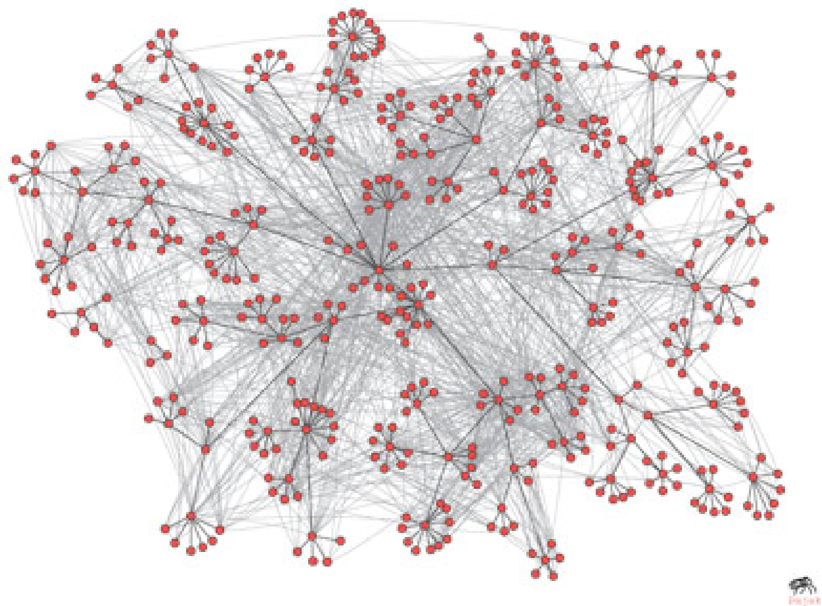

Figure 1.2: Social networks based on communication and interaction can also be constructed from the traces left by on-line data. In this case, the pattern of e-mail communication among 436 employees of Hewlett Packard Research Lab is superimposed on the official organizational hierarchy [6]. (Image from http://www-personal.umich.edu/ ladamic/img/hplabsemailhierarchy.jpg)

by links.

Later in this chapter we'll discuss some of the things one can learn from a network such as the one in Figure 1.1, as well as from larger examples such as the ones shown in Figures 1.2–1.4. These larger examples depict, respectively, e-mail exchanges among employees of a company; loans among financial institutions; and links among blogs on the Web. In each case, links indicate the pairs who are connected (specifically, people connected by e-mail exchange, financial institutions by a borrower-lender relationship, and blogs through a link on the Web from one to the other).

Simply from their visual appearance, we can already see some of the complexity that network structures contain. It is generally difficult to summarize the whole network succinctly; there are parts that are more or less densely interconnected, sometimes with central "cores" containing most of the links, and sometimes with natural splits into multiple tightly-linked regions. Participants in the network can be more central or more peripheral; they can straddle the boundaries of different tightly-linked regions or sit squarely in the middle of one. Developing a language for talking about the typical structural features of networks will be an important first step in understanding them.

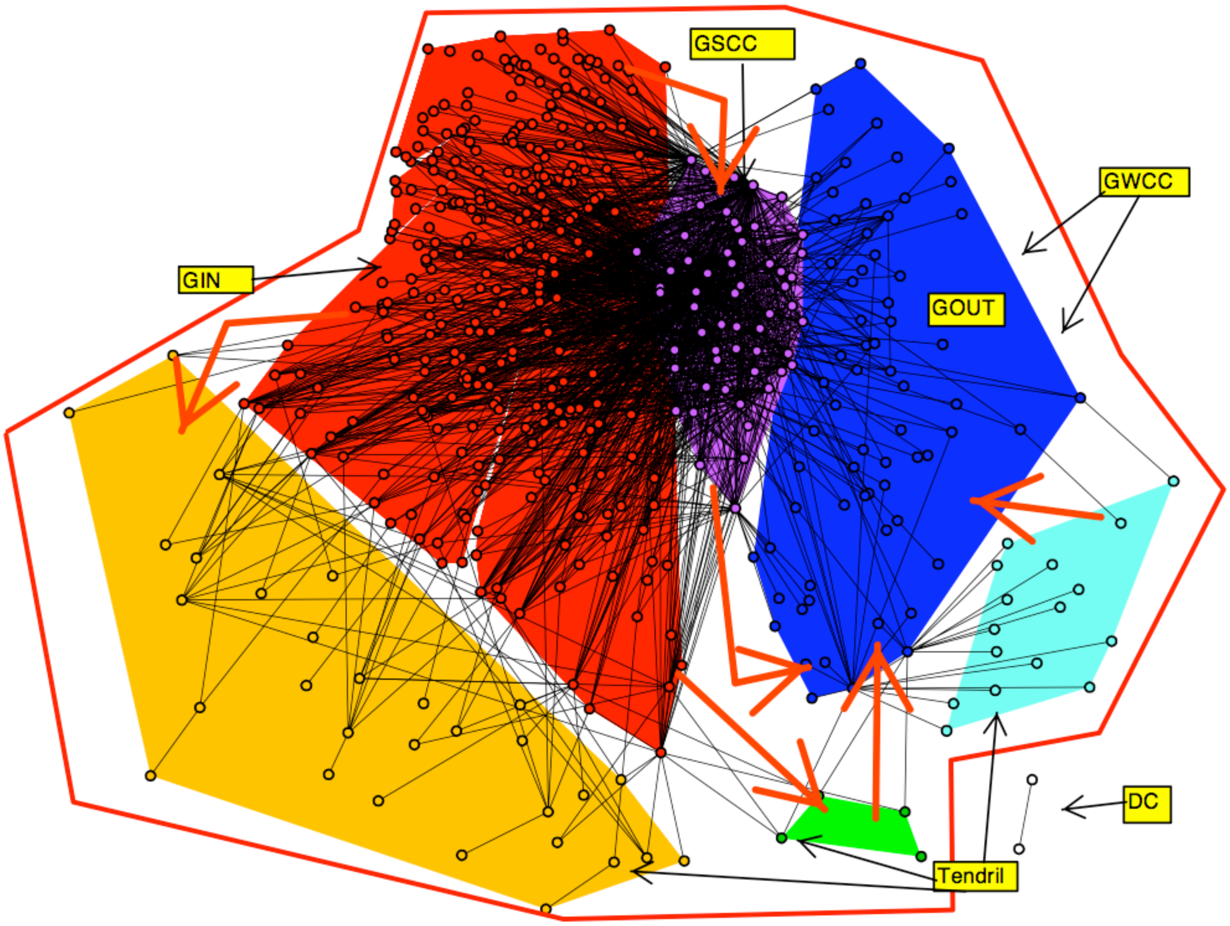

Figure 1.3: The network of loans among financial institutions can be used to analyze the roles that different participants play in the financial system, and how the interactions among these roles affect the health of individual participants and the system as a whole The network here is annotated in a way that reveals its dense core, according to a scheme we will encounter in Chapter 13. (Image from Bech and Atalay [50].)

Behavior and Dynamics. But the structure of the network is only a starting point. When people talk about the "connectedness" of a complex system, in general they are really talking about two related issues. One is connectedness at the level of structure — who is linked to whom — and the other is connectedness at the level of *behavior* — the fact that each individual's actions have implicit consequences for the outcomes of everyone in the system.

This means that in addition to a language for discussing the structure of networks, we also need a framework for reasoning about behavior and interaction in network contexts. And just as the underlying structure of a network can be complex, so too can the coupled behavior of its inhabitants. If individuals have strong incentives to achieve good outcomes,

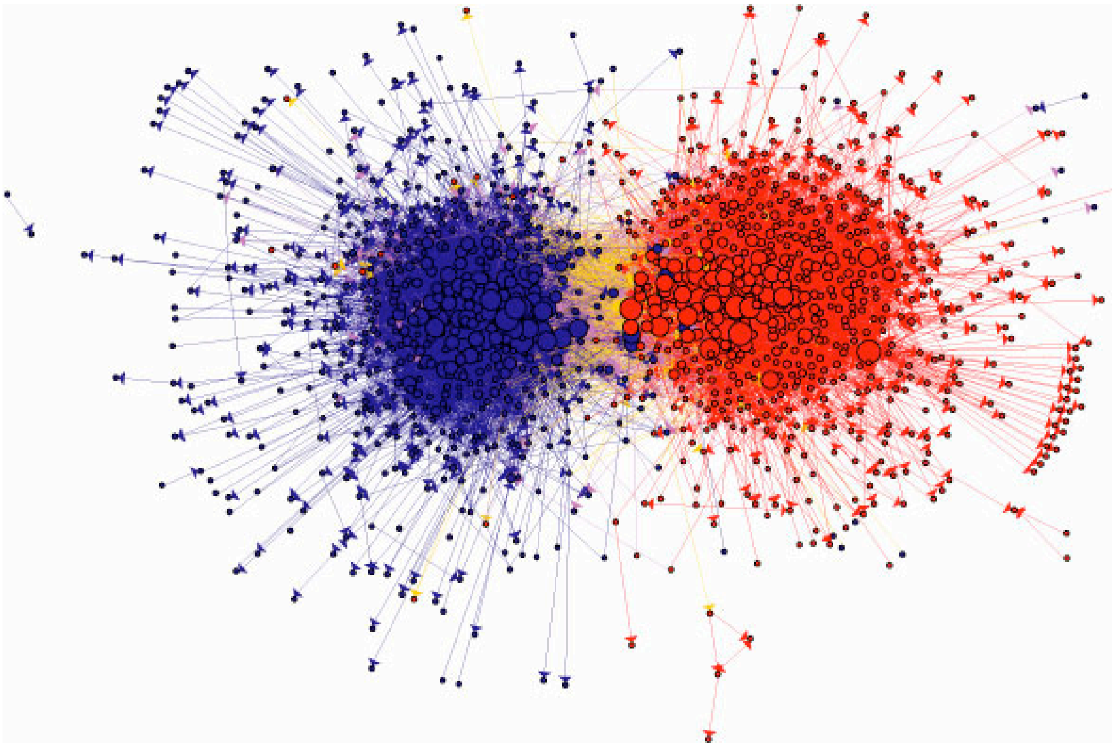

Figure 1.4: The links among Web pages can reveal densely-knit communities and prominent sites. In this case, the network structure of political blogs prior to the 2004 U.S. Presidential election reveals two natural and well-separated clusters [5]. (Image from http://www-personal.umich.edu/ ladamic/img/politicalblogs.jpg)

then not only will they appreciate that their outcomes depend on how others behave, but they will take this into account in planning their own actions. As a result, models of networked behavior must take strategic behavior and strategic reasoning into account.

A fundamental point here is that in a network setting, you should evaluate your actions not in isolation, but with the expectation that the world will react to what you do. This means that cause-effect relationships can become quite subtle. Changes in a product, a Web site, or a government program can seem like good ideas when evaluated on the assumption that everything else will remain static, but in reality such changes can easily create incentives that shift behavior across the network in ways that were initially unintended.

Moreover, such effects are at work whether we are able to see the network or not. When a large group of people is tightly interconnected, they will often respond in complex ways that are only apparent at the population level, even though these effects may come from implicit networks that we do not directly observe. Consider, for example, the way in which new products, Web sites, or celebrities rise to prominence — as illustrated, for example, by Figures 1.5 and 1.6, which show the growth in popularity of the social media sites YouTube

Figure 1.5: The rapidly growing popularity of YouTube is characteristic of the way in which new products, technologies, or innovations rise to prominence, through feedback effects in the behavior of many individuals across a population. The plot depicts the number of Google queries for YouTube over time. The image comes from the site Google Trends (http://www.google.com/trends?q=youtube); by design, the units on the y-axis are suppressed in the output from this site.

and Flickr over the past several years. What we see in these figures is a growing awareness and adoption of a new innovation that is visible in aggregate, across a whole population. What are the underlying mechanisms that lead to such success? Standard refrains are often invoked in these situations: the rich get richer; winners take all; small advantages are magnified to a critical mass; new ideas get attention that becomes "viral." But the rich don't always get richer and small advantages don't always lead to success. Some social networking sites flourish, like Facebook, while others, like SixDegrees.com, vanish. To understand how these processes work, and how they are realized through the interconnected actions of many people, we need to study the dynamics of aggregate behavior.

A Confluence of Ideas. Understanding highly connected systems, then, requires a set of ideas for reasoning about network structure, strategic behavior, and the feedback effects they produce across large populations. These are ideas that have traditionally been dispersed across many different disciplines. However, in parallel with the increasing public interest in networks, there has been a coming-together of scientific fields around the topic of network research. Each of these fields brings important ideas to the discussion, and a full understanding seems to require a synthesis of perspectives from all of them.

One of our central goals in this book is to help bring about such a synthesis, combining approaches that have traditionally been pursued separately. From computer science, applied mathematics, and operations research we draw on a language for talking about the complexity of network structure, information, and systems with interacting agents. From

Figure 1.6: This companion to Figure 1.5 shows the rise of the social media site Flickr; the growth in popularity has a very similar pattern to that of other sites including YouTube. (Image from Google Trends, http://www.google.com/trends?q=flickr)

economics we draw on models for the strategic behavior of individuals who interact with each other and operate as members of larger aggregates. From sociology — particularly the more mathematical aspects concerned with social networks — we draw on a broad set of theoretical frameworks for talking about the structure and dynamics of social groups.

And the overall picture can help fill in pieces that are arguably missing from the intellectual landscape of each of these disciplines. Economics has developed rich theories for the strategic interaction among small numbers of parties, as well as for the cumulative behavior of large, homogeneous populations. The challenge it faces is that much of economic life takes place in the complex spectrum between these extremes, with macroscopic effects that arise from an intricate pattern of localized interactions. Sociology has developed some of the fundamental insights into the structure of social networks, but its network methodology has been refined in the domains and scales where data-collection has traditionally been possible — primarily, well-defined groups with tens to hundreds of people. The explosion of new contexts where we find network data and network applications — including enormous, digitally mediated ones — leads to new opportunities for how we can pose questions, formulate theories, and evaluate predictions about social networks. Computer science, with the rise of the Web and social media, has had to deal with a world in which the design constraints on large computing systems are not just technological ones but also human ones — imposed by the complex feedback effects that human audiences create when they collectively use the Web for communication, self-expression, and the creation of knowledge. A fully satisfactory theory of network structure and behavior has the potential to address the simultaneous challenges that all these fields are encountering.

A recurring theme underlying these challenges is the way in which networks span many different levels of scale and resolution. There are interesting questions that reach from the

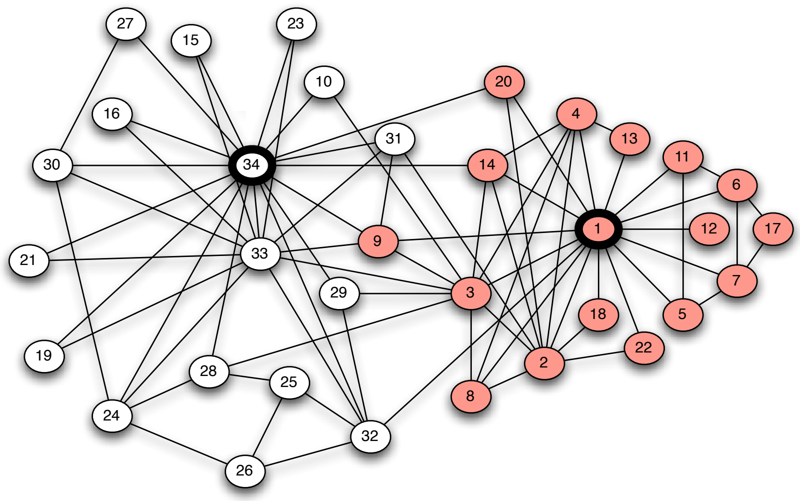

Figure 1.7: From the social network of friendships in the karate club from Figure 1.1, we can find clues to the latent schism that eventually split the group into two separate clubs (indicated by the two different shadings of individuals in the picture).

scale of small groups, such as the 34-person social network in Figure 1.1, all the way up to the level of whole societies or economies, or to the body of global knowledge represented by the Web. We will think of networks both at the level of explicit structures, like those in Figures 1.1–1.4, and at the level of aggregate effects, like the popularity curves in Figures 1.5 and 1.6. As we look at networks of increasing scales, it becomes correspondingly more appropriate to take aggregate models into account. But the ability to work with massive network datasets has also enriched the picture, making it possible to study networks with billions of interacting items at a level of resolution where each connection is recorded. When an Internet search engine identifies the most useful pages from an index of the entire Web, for example, it is doing precisely this in the context of a specific task. Ultimately, it is an ongoing and challenging scientific problem to bridge these vastly different levels of scale, so that predictions and principles from one level can be reconciled with those of others.

1.2 Central Themes and Topics

With this set of ideas in mind, we now introduce some of the main topics the book will consider, and the ways in which these topics reinforce the underlying principles of networks. We begin with the two main bodies of theory that we will be building on — graph theory and game theory. These are theories of structure and behavior respectively: Graph theory is the study of network structure, while game theory provides models of individual behavior in settings where outcomes depend on the behavior of others.

Graph Theory. In our discussion of graph theory, we will focus particularly on some of the fundamental ideas from social network analysis, framing a number of graph-theoretic concepts in these terms. The networks in Figures 1.1 and 1.2 hint at some of these ideas. In the corporate e-mail communication network from Figure 1.2, for example, we can see how the communication is balanced between staying within small organizational units and cutting across organizational boundaries. This is an example of a much more general principle in social networks — that *strong ties*, representing close and frequent social contacts, tend to be embedded in tightly-linked regions of the network, while *weak ties*, representing more casual and distinct social contacts, tend to cross between these regions. Such a dichotomy suggests a way of thinking about social networks in terms of their dense pockets of strong ties, and the ways in which they interact with each other through weaker ties. In a professional setting, it suggests a strategy for navigating one's way through the social landscape of a large organization, by finding the *structural holes* between parts of the network that interact very little with each other. At a global scale, it suggests some of the ways in which weak ties can act as "short-cuts" that link together distant parts of the world, resulting in the phenomenon colloquially known as the *six degrees of separation*.

Social networks can also capture the sources of conflict within a group. For example, latent conflicts are at work in the karate-club social network from Figure 1.1. The people labeled 1 and 34 (the darker circles) are particularly central in the network of friendships, with many connections to other people. On the other hand, they are not friends with each other, and in fact most people are only friends with one or the other of them. These two central people were, respectively, the instructor and the student founder of the club, and this pattern of non-interacting clusters was the most visible symptom of a conflict between them and their factions that ultimately splintered the group into two rival karate clubs, as shown in Figure 1.7. Later, we will see how the theory of *structural balance* can be used to reason about how fissures in a network may arise from the dynamics of conflict and antagonism at a purely local level.

Game Theory. Our discussion of game theory starts from the observation that there are numerous settings in which a group of people must simultaneously choose how to act, knowing that the outcome will depend on the joint decisions made by all of them. One natural example is the problem of choosing a driving route through a network of highways at a time when traffic is heavy. If you're a driver in such a situation, the delays you experience depend on the pattern of traffic congestion arising not just from your choice of route, but from the choices made by all other drivers as well. In this example, the network plays the role of a shared resource, and the combined actions of its users can either congest this

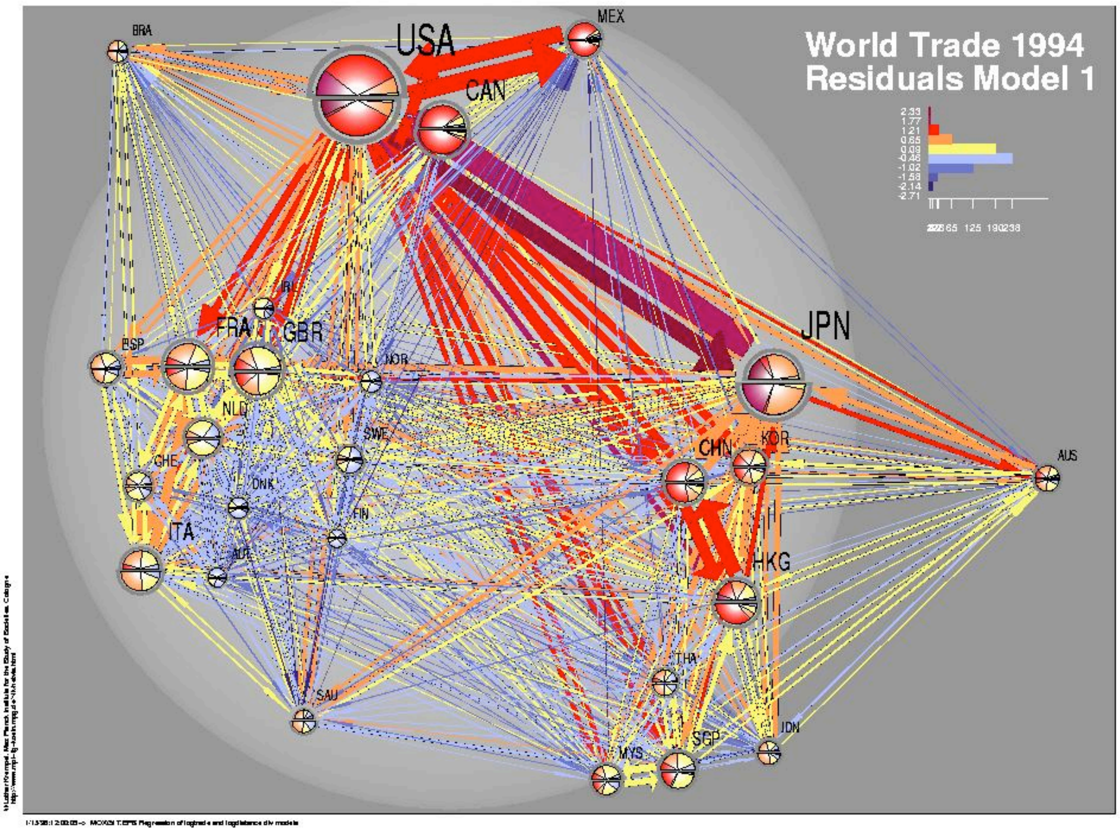

Figure 1.8: In a network representing international trade, one can look for countries that occupy powerful positions and derive economic benefits from these positions [262]. (Image from http://www.cmu.edu/joss/content/articles/volume4/KrempelPlumper.html)

resource or use it more efficiently. In fact, the interactions among people's behavior can lead to counter-intuitive effects here: for instance, adding resources to a transportation network can in fact create incentives that seriously undermine its efficiency, in a phenomenon known as *Braess's Paradox* [76].

Another example that will recur in several settings throughout the book is the problem of bidding in an auction. If a seller is trying to sell a single item using an auction, then the success of any one bidder in the auction (whether she gets the item, and how much she pays) depends not just on how she bids but on how everyone else bids as well — and so an optimal bidding strategy should take this into account. Here too there are counter-intuitive effects at work: for example, if the seller introduces more aggressive pricing rules into the auction, he can make the strategic behavior of the bidders much more complex, and in particular induce optimal bidding that offsets whatever gains he might have expected to make from the new rules. We will find that auctions represent a basic kind of economic interaction that can be

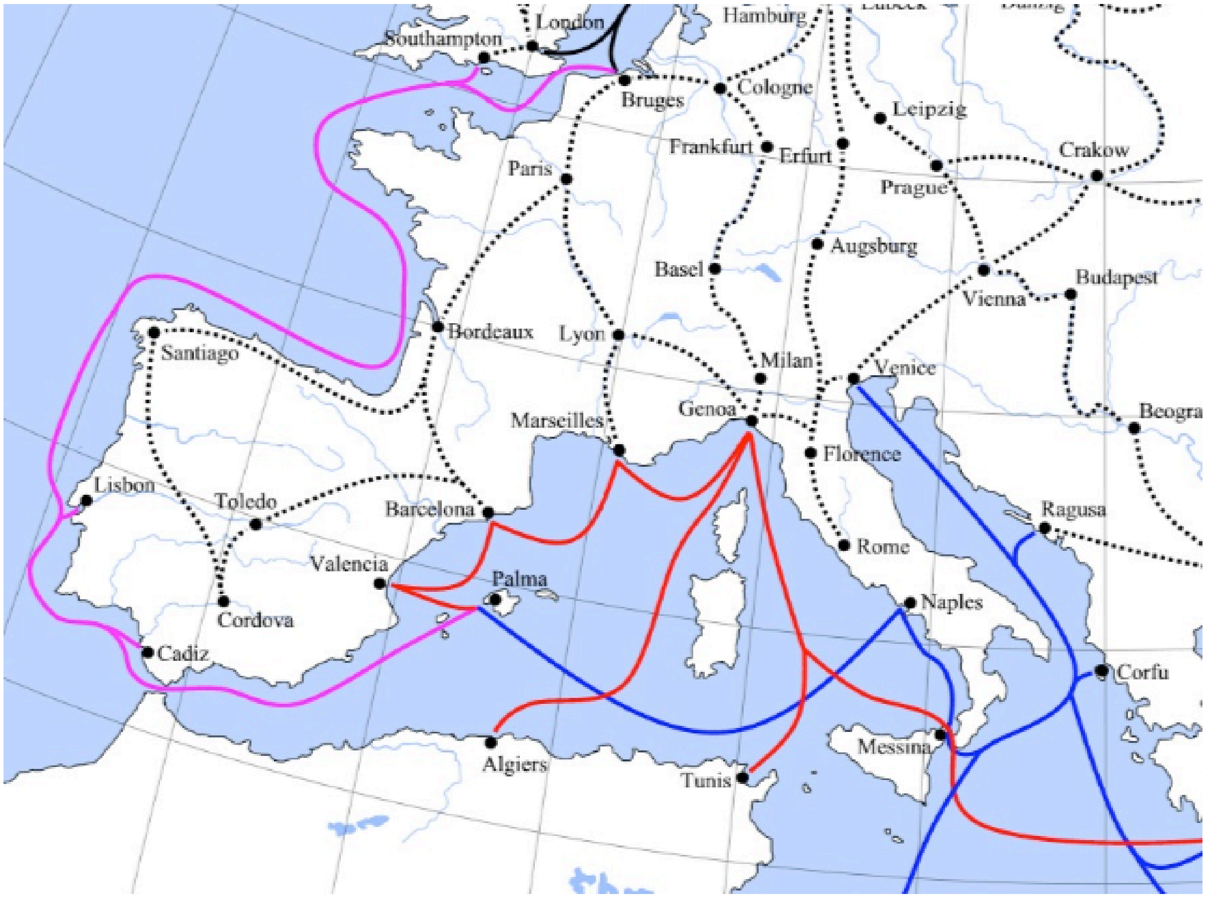

Figure 1.9: In some settings, such as this map of Medieval trade routes, physical networks constrain the patterns of interaction, giving certain participants an intrinsic economic advantage based on their network position. (Image from http://upload.wikimedia.org/wikipedia/commons/e/e1/Late_Medieval_Trade_Routes.jpg.)

directly generalized to more complex patterns of interactions on networks.

As a general part of our investigation of game theory, we will abstract such situations with inter-dependent behavior into a common framework, where a collection of individuals must each commit to a *strategy*, thereby receiving a *payoff* that depends on the strategies chosen by everyone. Interpreting our preceding examples in this light, the strategies available to a driver on a set of highways consist of the different options for routes he can take, and the payoff to this driver is based on his resulting travel time. In an auction, the strategies are the different choices for how to bid, and the payoff to a bidder is the difference between the value of the goods she receives and the price she pays. This general framework allows us to make predictions about how people will behave in a range of such situations. A fundamental part of this framework will be the notion of *equilibrium* — a state that is "self-reinforcing," in that it provides no individual with an incentive to unilaterally change his or her strategy, even knowing how others will behave.

Markets and Strategic Interaction on Networks. Once we've developed graph theory and game theory, we can combine them to produce richer models of behavior on networks. One natural setting where we can explore this is in models of trade and other forms of economic activity. The interactions among buyers and sellers, or pairs of counterparties to a trade or loan, naturally forms a network. In Figure 1.3 we saw an example of such a network, with links between banks engaging in a loan. Figure 1.8 shows another example: a network representation of international trade among 28 countries [262], with the size of each country depicting its total amount of trade, and the thickness of each link connecting two countries indicating the amount of trade between them.

Where do these networks come from? In some cases, they are the traces of what happens when each participant seeks out the best trading partner they can, guided by how highly they value different trading opportunities. In other cases, they also reflect fundamental underlying constraints in the market that limit the access of certain participants to each other. In modern markets, these constraints could be institutional restrictions based on regulations; in other settings, they could be based on physical constraints like geography. For example, Figure 1.9 shows a map of trade routes in medieval Europe: when the physical movement of goods is costly and difficult, the economic outcome for different cities can depend significantly on where they are located in the underlying transportation network.

In all these settings, then, the network structure encodes a lot about the pattern of trade, with the success levels of different participants affected by their positions in the network. Having a powerful position, however, depends not just on having many connections providing different options, but also on more subtle features — such as the power of the other individuals to which one is connected. We will see that this idea of network positions conferring power has been extended much more broadly, reaching beyond just economic exchange to suggest how power imbalances in many forms of social relationships may have their roots in the network patterns that the relationships form.

Information networks. The information we deal with on-line has a fundamental network structure. Links among Web pages, for example, can help us to understand how these pages are related, how they are grouped into different communities, and which pages are the most prominent or important. Figure 1.4 illustrates some of these issues: it shows a network of links among political blogs constructed by Lada Adamic and Natalie Glance in the period leading up to the 2004 U.S. Presidential election [5]. Although the network is too large here to be able to really see the detailed structure around individual blogs, the image and its layout does convey the clear separation of the blogging network into two large clusters, which turn out to closely correspond to the sets of liberal and conservative blogs respectively. From more detailed analysis of the raw linkage data underlying the image, it is possible to pick out the prominent blogs within each of these clusters.

Current Web search engines such as Google make extensive use of network structure in evaluating the quality and relevance of Web pages. For producing search results, these sites evaluate the prominence of a Web page not simply based on the number of links it receives, but based on more subtle aspects of its position in the network. For example, a page can be viewed as more prominent if it receives links from pages that are themselves prominent; this is a circular kind of notion in which prominence is defined in terms of itself, but we will see that this circularity can be resolved through careful definitions that are based on a kind of equilibrium in the link structure.

The interaction between search engines and the authors of Web pages is also a compelling example of a system where "connectedness" at the level of behavior produces interesting effects. Whenever a search engine introduces a new method for evaluating Web pages, deciding which pages to rank highly in its results, the creators of Web content react to this: they optimize what they put on the Web so as to try achieving a high rank under the new method. As a result, changes to a search engine can never be designed under the assumption that the Web will remain static; rather, the Web inevitably adapts to the ways in which search engines evaluate content, and search methods must be developed with these feedback effects in mind.

This inherently game-theoretic interaction existed in latent form even in the early days of the Web. Over time it became more explicit and formalized, through the design of markets for advertising based on search, with advertising space allocated by auction mechanisms. Today, such markets are a principal source of revenue for the main search engines.

Network Dynamics: Population Effects. If we observe a large population over time, we'll see a recurring pattern by which new ideas, beliefs, opinions, innovations, technologies, products, and social conventions are constantly emerging and evolving. Collectively, we can refer to these as social *practices* [382] (holding opinions, adopting products, behaving according to certain principles) that people can choose to adopt or not. As we watch a group or society over time, we'll see that new practices can be introduced and either become popular or remain obscure; meanwhile, established practices can persist or potentially fade over time. If we think back to Figures 1.5 and 1.6, they show the adoption of particular practices over time — the use of two very popular social media sites (taking the total number of Google queries for these sites over time as proxies for their popularity). Figure 1.10 depicts an analogous curve for the social-networking site MySpace, where we see a life cycle of rapid adoption followed by a slower period of decline, as MySpace's dominance was challenged by newer competitors including Facebook.

Figure 1.10: Cascading adoption of a new technology or service (in this case, the social-networking site MySpace in 2005-2006) can be the result of individual incentives to use the most widespread technology — either based on the informational effects of seeing many other people adopt the technology, or the direct benefits of adopting what many others are already using. (Image from Google Trends, http://www.google.com/trends?q=myspace)

The way in which new practices spread through a population depends in large part on the fact that people *influence* each other's behavior. In short, as you see more and more people doing something, you generally become more likely to do it as well. Understanding why this happens, and what its consequences are, is a central issue for our understanding of networks and aggregate behavior.

At a surface level, one could hypothesize that people imitate the decisions of others simply because of an underlying human tendency to *conform*: we have a fundamental inclination to behave as we see others behaving. This is clearly an important observation, but as an explanation it leaves some crucial questions unresolved. In particular, by taking imitation as a given, we miss the opportunity to ask *why* people are influenced by the behavior of others. This is a broad and difficult question, but in fact it is possible to identify multiple reasons why even purely rational agents — individuals with no *a priori* desire to conform to what others are doing — will nonetheless copy the behavior of others.

One class of reasons is based on the fact that the behavior of others conveys *information*. You may have some private information on which to base a decision between alternatives, but if you see many people making a particular choice, it is natural to assume that they too have their own information, and to try inferring how people are evaluating different choices from how they are behaving. In the case of a Web site like YouTube or Flickr, seeing a lot of people using it can suggest that these people know something about its quality. Similarly, seeing that a certain restaurant is extremely crowded every weekend can suggest that many people think highly of it. But this sort of reasoning raises surprisingly subtle issues: as many people make decisions sequentially over time, the later decisions can be based in complex ways on a mixture of private information and inferences from what has already happened, so that the actions of a large set of people can in fact be based on surprisingly little genuine information. In an extreme form of this phenomenon we may get *information cascades*, where even rational individuals can choose to abandon their private information and follow a crowd.

There is a completely different but equally important class of reasons why people might imitate the behavior of others — when there is a direct benefit from aligning your behavior with that of others, regardless of whether they are making the best decision. Let's go back to our examples of social-networking and media-sharing sites. If the value of such sites is in the potential to interact with others, to have access to a wide range of content, and to have a large audience for the content you post, then these types of sites become more and more valuable as people join them. In other words, regardless of whether YouTube had better features than its competitors, once it became the most popular video-sharing site, there was almost *by definition* an added value in using it. Such *network effects* amplify the success of products and technologies that are already doing well; in a market where network effects are at work, the leader can be hard to displace. Still, this type of dominance is not necessarily permanent; as we will see, it is possible for a new technology to displace an old one if it offers something markedly different — and often when it starts in a part of the network where there is room for it to take hold.

These considerations show how popularity — as a general phenomenon — is governed by a "rich-get-richer" feedback process in which popularity tends to build on itself. It is possible to build mathematical models for this process, with predictions for the distribution of popularity that are borne out by empirical data — a picture in which society's attention is divided between a small number of prominent items and a "long tail" of more obscure ones.

Network Dynamics: Structural Effects. As we've just seen, the question of how people influence each other's behavior is already quite subtle even when the actual structure of the underlying network is left implicit. But taking network structure into account provides important further insights into how such kinds of influence take place. The underlying mechanisms — based on information and direct benefits — are present both at the level of whole populations, and also at a local level in the network, between an individual and his or her set of friends or colleagues. In many cases you care more about aligning your own behavior with the behavior of your immediate neighbors in the social network, rather than with the population as a whole.

When individuals have incentives to adopt the behavior of their neighbors in the network, we can get *cascading* effects, where a new behavior starts with a small set of initial adopters, and then spreads radially outward through the network. Figure 1.11 shows a small example,

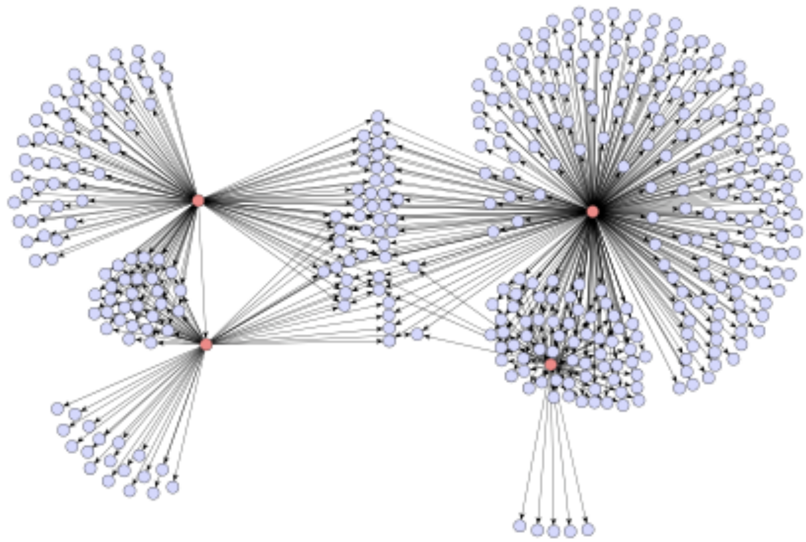

Figure 1.11: When people are influenced by the behaviors their neighbors in the network, the adoption of a new product or innovation can cascade through the network structure. Here, e-mail recommendations for a Japanese graphic novel spread in a kind of informational or social contagion. (Image from Leskovec et al. [271].)

in which e-mail recommendations for a particular Japanese graphic novel spread outward from four initial purchasers. By reasoning about the underlying network structure, we will see how it becomes possible for a superior technology to displace a universally-used but inferior one, if the superior technology starts in a portion of the network where it can make progress incrementally, a few people at a time. We will also find that the diffusion of technologies can be blocked by the boundary of a densely-connected cluster in the network — a "closed community" of individuals who have a high amount of linkage among themselves, and hence are resistant to outside influences.

Cascading behavior in a network is sometimes referred to as "social contagion," because it spreads from one person to another in the style of a biological epidemic. Figure 1.12 reinforces this analogy; it shows the beginning of a tuberculosis outbreak [16] and forms a visual counterpart to the social cascade in Figure 1.11. There are fundamental differences in the underlying mechanisms between social and biological contagion — social contagion tends to involve decision-making on the part of the affected individuals, whereas biological contagion is based on the chance of catching a disease-causing pathogen through contact with another individual. But the network-level dynamics are similar, and insights from the study of biological epidemics are also useful in thinking about the processes by which things spread on networks.

The act of spreading, which transmits both ideas and diseases, is just one kind of dynamic

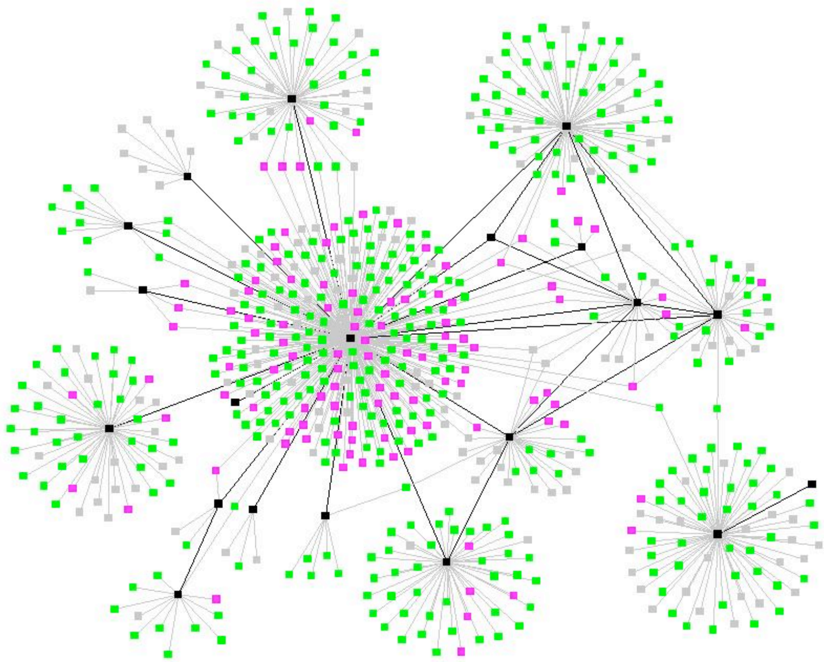

Figure 1.12: The spread of an epidemic disease (such as the tuberculosis outbreak shown here) is another form of cascading behavior in a network. The similarities and contrasts between biological and social contagion lead to interesting research questions. (Image from Andre et al. [16].)

process that takes place on networks. A different process that we also consider is *search* — the way people can explore chains of social contacts for information or referrals to others. The surprising effectiveness with which people are able to accomplish such tasks, confirmed both by experiments and everyday experience, suggests characteristic patterns of structure at the network level that help facilitate these types of activities.

Institutions and Aggregate Behavior. Once we have developed some of the basic forces underlying networks and strategic behavior, we can ask how the *institutions* a society designs can, in effect, channel these forces to produce certain kinds of overall outcomes. Our notion of an institution here is very broad — it can be any set of rules, conventions, or mechanisms that serve to synthesize individual actions into a pattern of aggregate behavior. We've already discussed particular examples of this process: for example, in the way in which a particular auction mechanism leads to bidding behavior and hence prices; or the way in which the Internet search industry has become a significant influence on how Web content is created.

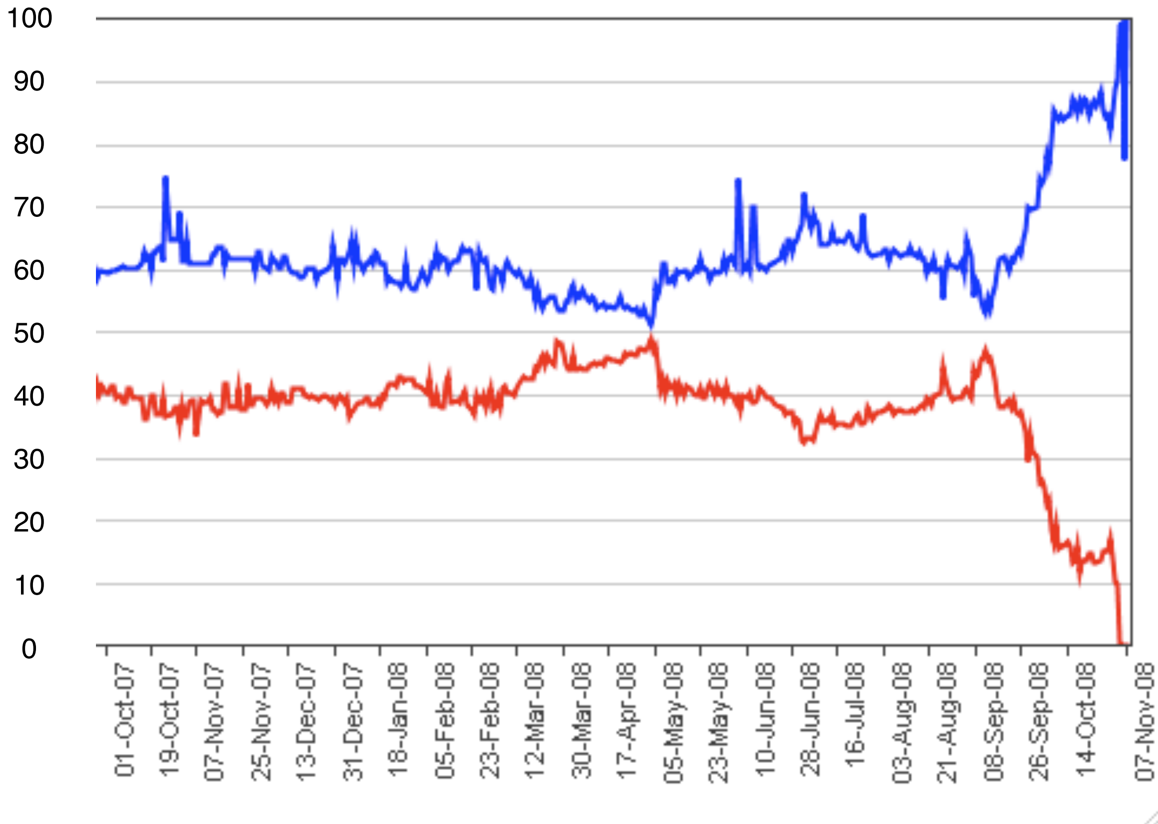

Figure 1.13: Prediction markets, as well as markets for financial assets such as stocks, can synthesize individual beliefs about future events into a price that captures the aggregate of these beliefs. The plot here depicts the varying price over time for two assets that paid $1 in the respective events that the Democratic or Republican nominee won the 2008 U.S. Presidential election. (Image from Iowa Electronic Markets, http://iemweb.biz.uiowa.edu/graphs/graph_PRES08_WTA.cfm.)

There are a number of settings in which this kind of analysis, applied to fundamental social institutions, can be very informative. One such setting is to think about markets and their role in aggregating and conveying information. In a financial market, for example, the market price serves as an aggregator of individuals' beliefs about the value of the assets being traded. In this sense, the overall behavior of the market serves to synthesize the information that is held by many participants; consequently, when people speak of what the market "expects," they are really referring to the expectations that can be read out of this composite of information.

How this synthesis works depends on how the market is designed, and on the kind of individual and aggregate behavior that results. Nor are such issues restricted to markets for financial assets such as stocks. Recent work, for example, has explored the design of *prediction markets* that use a market mechanism to provide predictions of future events such as the outcomes of elections. Here, participants in the market purchase assets that pay a fixed amount if a certain event takes place. In this way, the price of the asset reflects an aggregate estimate for the probability of the event, and such estimates have been found to be highly accurate in a number of cases — with the market's aggregate predictions often outperforming the opinions of expert analysts. Figure 1.13 shows an example from the 2008 U.S. Presidential Election: the upper curve depicts the price over time for an asset that paid $1 in the event that the Democratic Party's nominee won the election, and the lower curve depicts the corresponding price for the Republican Party's nominee. Note that the market was already functioning before the identities of these nominees were known, and it shows a clear aggregate reaction to certain events such as the contentious end of the Democratic primary process between Obama and Clinton (in early May) and the Republican National Convention (in early September), both of which brought the prices for the opposing predictions close to equality, before they diverged once and for all as the actual election neared.

Voting is another social institution that aggregates behavior across a population. While markets and voting systems both seek a synthesis of individual beliefs or preferences, there are some fundamental contrasts in the settings where they are generally applied. We have just outlined a view of markets as aggregators of beliefs about the probabilities of future events. In this view, each individual belief that forms an ingredient of the market's consensus will ultimately be confirmed as correct or incorrect, based on whether certain relevant future events actually happen or not. Voting systems, on the other hand, are typically applied to cases where each individual has a preference or prioritization over a set of arbitrary and subjective choices for which there may be no eventual way to say that any one is "right" or "wrong." The question is then to synthesize a cumulative social preference that reconciles, as well as possible, the conflicting priorities of the individuals in the population. In our analysis of voting, we will explore a long history of work showing that the task of producing such a social preference is fraught with unavoidable difficulties — results that formalize such difficulties began with work of 18th-century French philosophers, and came fully into focus with *Arrow's Impossibility Theorem* in the 1950s.

This perspective on institutions is a natural one for social systems that are highly interconnected. Whenever the outcomes across a population depend on an aggregate of everyone's behavior, the design of the underlying institutions can have a significant effect on how this behavior is shaped, and on the resulting consequences for society.

Looking ahead. Examples, phenomena, and principles such as these will motivate the ways in which we analyze networks, behavior, and population-level dynamics throughout the book. Understanding whether a principle holds across many settings will involve formulating and reasoning about mathematical models, and also reasoning qualitatively about these models and searching for their broader implications. In this way, we can hope to develop a network perspective as a powerful way of looking at complex systems in general — a way of thinking about social dynamics, economic interaction, on-line information, designed technology, and natural processes, and approaching such systems with an eye toward their patterns of internal structure and the rich feedback effects that result.