Lecture 1: Introduction

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- 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
- 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

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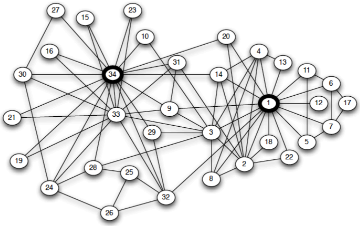

Figure 1.1: The social network of friendships within a 34-person karate club [421].

- It has made them susceptible to disruptions that spread through the underlying network structures, sometimes turning localized breakdowns into cascading failures or financial crises
- 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.

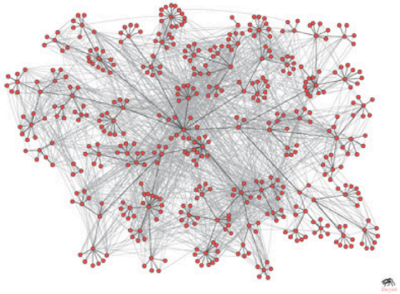

Figure 1.2: Social networks based on communication and interaction can also be constructed from the traces left by on-line data. In this case, the pattern of e-mail communication among 436 employees of Hewlett Packard Research Lab is superimposed on the official organizational hierarchy [6]. (Image from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

- 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

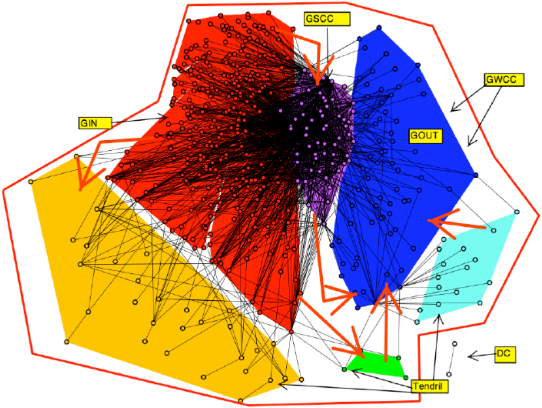

Figure 1.3: The network of loans among financial institutions can be used to analyze the roles that different participants play in the financial system, and how the interactions among these roles affect the health of individual participants and the system as a whole The network here is annotated in a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

- 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

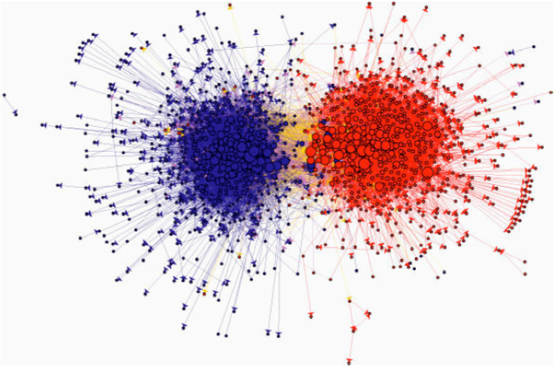

Figure 1.4: The links among Web pages can reveal densely-knit communities and prominent sites. In this case, the network structure of political blogs prior to the 2004 U.S. Presidential election reveals two natural and well-separated clusters [5]. (Image from http://www-personal.umich.edu/ ladamic/img/politicalblogs.jpg)

- 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, 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

- 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 and Flickr over the past several years

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.

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)

- 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
- 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
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- 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

- Graph theory is the study of network structure
- Game theory provides models of individual behavior in settings where outcomes depend on the behavior of others

- 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 are 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 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

- Once we have 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

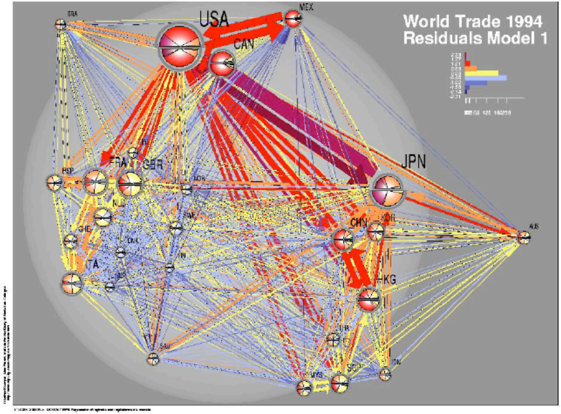


Figure 1.8: In a network representing international trade, one can look for countries that occupy powerful positions and derive economic benefits from these positions [262]. (Image from http://www.cmu.edu/joss/content/articles/volume4/KrempelPlumper.html)

- 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

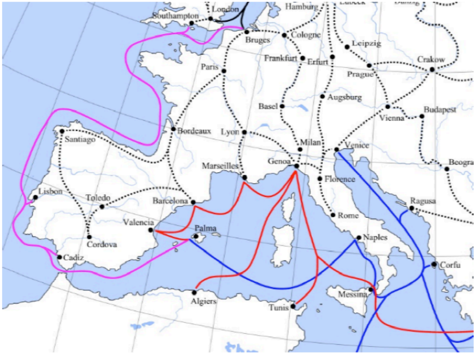
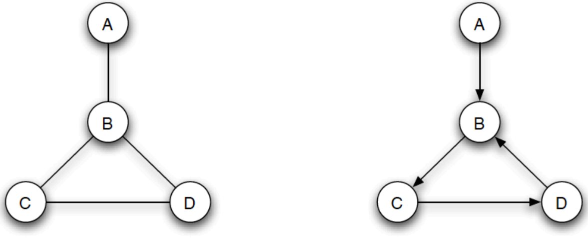


Figure 1.9: In some settings, such as this map of Medieval trade routes, physical networks constrain the patterns of interaction, giving certain participants an intrinsic economic advantage based on their network position. (Image from http://upload.wikimedia.org/wikipedia/commons/e/e1/Late_Medieval_Trade_Routes.jpg.)

- 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

- **Graphs: Nodes and Edges.** A graph is a way of specifying relationships among a collection of items
- A graph consists of a set of objects, called *nodes*, with certain pairs of these objects connected by links called *edges*
- We say that two nodes are *neighbors* if they are connected by an edge
- A *path* in a graph is a sequence of nodes with the property that each consecutive pair in the sequence is connected by an edge



(a) *A graph on 4 nodes.*

(b) *A directed graph on 4 nodes.*

Figure 2.1: Two graphs: (a) an undirected graph, and (b) a directed graph.

- We represent a transportation network by a directed graph: we consider the edges to be highways, and the nodes to be exits where you can get on or off a particular highway
- There are two particular nodes, which we will call A and B, and we will assume everyone wants to drive from A to B
- Each edge has a designated travel time that depends on the amount of traffic it contains

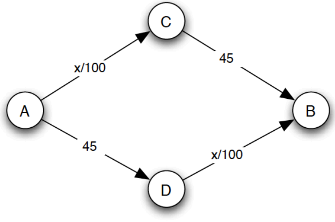


Figure 8.1: A highway network, with each edge labeled by its travel time (in minutes) when there are x cars using it. When 4000 cars need to get from A to B, they divide evenly over the two routes at equilibrium, and the travel time is 65 minutes.

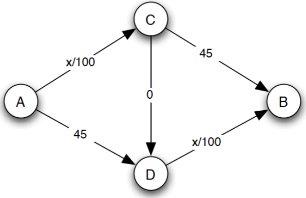


Figure 8.2: The highway network from the previous figure, after a very fast edge has been added from C to D. Although the highway system has been "upgraded," the travel time at equilibrium is now 80 minutes, since all cars use the route through C and D.