ALSO BY MATTHEW O. JACKSON

Social and Economic Networks

Handbook of Social Economics

THE HUMAN NETWORK

How Your Social Position Determines Your Power, Beliefs, and Behaviors

MATTHEW O. JACKSON

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For Sally and Hal

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"How many valiant men, how many fair ladies, how many sprightly youths, . . . , breakfasted with their kinsfolk, comrades and friends, and the same night supped with their ancestors in the other world!"

—GIOVANNI BOCCACCIO, *THE DECAMERON,* 1353

The bubonic plague, or Black Death, spread across Europe, slowly but steadily, from 1347 to around 1352.

The culprit, *Yersinia pestis,* is a pathogen carried by fleas who ingest it when feeding on an infected host. It blocks the fleas' intestines causing them to become starved for nutrients, which leads them to feed voraciously and infect their subsequent hosts. Fleas are adept at living on rats, other animals, and humans; with some resistant hosts serving only as carriers and others quickly dying once bitten and infected. It is a horrifying disease: beginning like a flu with weakness and fever, but turning to extensive hemorrhaging. The dying tissues turn black, giving the plague its nickname of Black Death.

The sanitation of the era, a lack of understanding of contagion, and close proximity of humans and many animals meant that the disease was amazingly virulent in the growing cities of the Middle Ages.[1] It cut the populations of Paris and Florence roughly in half within a couple of years, with even larger death tolls in cities like Hamburg and London. It is believed to have made its way along the Silk Road from China to Constantinople, and later from Genoese trading ships to Sicily by 1347, where it quickly wiped out roughly half of the island's population. It continued to spread, hitting parts of Italy, and then Marseille, before spreading through France and Spain, and eventually getting to the northern countries a few years later. Overall, it is estimated to have killed more than 40 percent of Europe's population, as well as 25 million people in China and India before even reaching Europe.

What is remarkable from a modern perspective is how *slowly* and methodically it spread. Although the plague did make occasional long-range jumps, as in its travel along trading routes such as the Silk Road and via ships, its progression throughout Europe averaged only about two kilometers per day, slow even by the standards of foot travel at the time.[2] Even though the bubonic plague rarely transmits directly from person to person, the disease traveled alongside humans—via the fleas who fed on rats on ships, on farm animals, people, and in clothing—and so it made its way through the networks of humans and the various animals that accompanied them.

The slow movement of the plague tells us how limited the mobility and range of contacts of most humans was in the Middle Ages. Modern pandemics are quite different: they spread remarkably quickly, with diseases jumping continents typically within a matter of days or weeks. A measles outbreak among unvaccinated adults and children sparked via interactions at an American theme park in southern California in 2014 appeared in schools hundreds of miles away days later. Ebola was carried by health workers from Sierra Leone in 2015 to cities in Europe and North America within a week of their exposure.

In this chapter we will see how contagion and diffusion depend on the structure of our networks. Beyond immediate insights into the spread of diseases, this understanding will also serve as a starting point for comprehending the more complex spread of ideas, financial contagions, and inequality in employment and wages—topics of some of the following chapters.

Contagion and Network Components

Lycus: Is it contagious?
Pseudolus: Have you ever seen a plague that wasn't?

—BURT SHEVELOVE AND LARRY GELBART,
A FUNNY THING HAPPENED ON THE WAY TO THE FORUM

Although there are big differences between many of our networks and those of the Middle Ages, we can still learn much about the slow but relentless spread of the plague by looking at a particular type of modern network.

Figure 3.1 pictures a network of romantic and/or sexual relationships among teenagers in a U.S. high school. The students listed their liaisons over eighteen months.[3]

Even though a typical individual in the network in Figure 3.1 has only one or two interactions, the network still exhibits a "giant component": the large connected piece in the upper left of the figure in which 288 of the students are connected to each other via sequences of relationships.

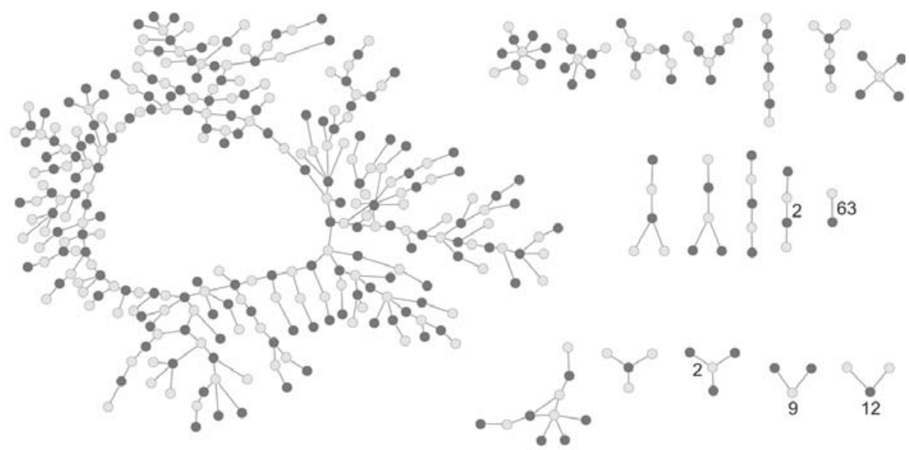


Figure 3.1: A network from a high school in the Midwestern United States from the Add Health data set. Nodes are students, colored by gender. A link denotes a romantic or sexual relationship during an eighteen-month period. The numbers by some of the components indicate how many times that component appears (e.g., there are sixty-three couples who only had a relationship with each other). Isolated students are not pictured. Just over half of the students are in one giant component on the left. The data in this figure were first analyzed and discussed by Peter Bearman, James Moody, and Katherine Stovel (2004).

"Components" are the pieces of a network in which each node can reach each other via a path of connections.[4] Just over half of the students in the figure are in the giant component, and the rest sit in many small components.[5] More than a quarter of the students reported no relationships (we all remember how lonely high school can be) and are not pictured.

This figure highlights how a sexually transmitted disease can infect a large fraction of the population, even though each individual has only a few interactions on average. Each link represents a potential for spreading a disease from one individual to another. If someone in the giant component were to become infected (for example, via an interaction with someone outside of the school), then the disease could spread widely within the giant component and thus within the school.[6]

As an example, HPV (the human papillomavirus) is sexually transmitted and can lead to several cancers, including cervical cancer. A danger with HPV is that it is often asymptomatic so that an infected person has no reason to believe that they are infected and so may continue to spread it to others. More than 40 percent of the adult population of the United States is estimated to have HPV, many unaware.[7] Most of those infected are not promiscuous; they just happen to be part of the giant component.

From Figure 3.1, it is easy to see how a disease could spread slowly, given the relatively low number of contacts per individual, but could still eventually lead to a high level of infection as it spreads throughout the giant component, just as it did with the bubonic plague.

We also see from this figure that a disease's spread is not dependent on the presence of highly promiscuous individuals or sex workers. High-degree individuals can amplify and accelerate the spread of diseases, but they are not necessary for a network to have a giant component. Simply having more than one interaction per individual is enough.

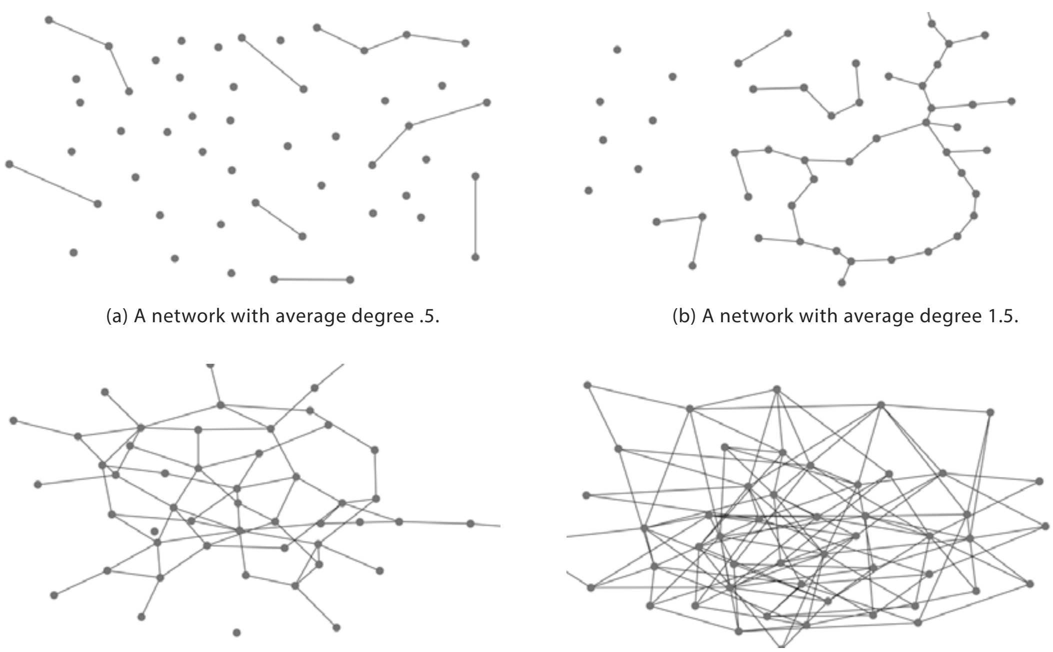
This network sits right at the juncture of connectivity at which widespread contagion becomes possible.

Phase Transitions and Basic Reproduction Numbers

The term "phase transition" is often used in thermodynamics to refer to changes in matter.[8] For instance, as water changes to ice or to steam it is said to undergo a phase transition.

Networks also undergo phase transitions, from being collections of isolated nodes and small components, to a network that has a giant component containing a nontrivial fraction of nodes, and then eventually to one in which all nodes can reach one another via paths in the network. Increasing the fraction of links present in a network is an analog of increasing the temperature and changing ice to water to steam.

The remarkable thing about phase transitions is how abrupt they can be. Just below the freezing threshold you are standing on ice and yet only a degree higher you are plunging into the water. Similarly, tiny changes in the frequency of links in a network have dramatic effects on its component structure. This is illustrated in Figure 3.2. As we move from one half of a friend per person on average (as in panel [a]) to one and a half friends per person (as in panel [b]), we transition from a network that is disconnected to one in which a majority of people can reach each other. Small further increases (panels



(a) A network with average degree .5.

(b) A network with average degree 1.5.

(c) A network with average degree 2.5.

(d) A network with average degree 5.

Figure 3.2: A comparison of networks with varying average degrees. With less than one connection per node, as in panel (a), the network is fragmented. Once there is more than one connection per node on average, as in panel (b), a giant component coalesces—the nontrivially sized group of nodes at the bottom of panel (b) in which all can reach each other via paths in the network. Slight additional increases in the connections per node lead the giant component to involve almost all nodes, as in panel (c), and eventually lead the network to become path-connected so that every two nodes have a path between them, as in panel (d).

[c] and [d]) lead the network to become "path-connected," or "con. nected" for short: each person can reach every other via paths in the network (panel [c] is just on the verge, with two nodes left out).

Phase transitions in networks are fundamental to fighting disease. A critical number associated with a disease and a network through which it might spread is known as the disease's "basic reproduction number." This tracks how many other people are newly infected by a typical infected individual. If its basic reproduction number is above one, then a disease spreads, while if it is below one, then the disease dies out.

The threshold of having a basic reproduction of one corresponds to the phase transition at which networks have a giant component, as in Figure 3.2. The idea behind this is simple but vital: with more than one new infection per infected individual, the contagion continues to expand, reaching more people with each new infection, and so can perpetuate itself. Below that level, the process dies off. In terms of the network, if each person has more than one friend, then a component tends to grow outward and expand to be a giant component, while with fewer than one friend on average, the network is a bunch of small disconnected components and isolated nodes. The analogy to reproduction is clear: if a society has more than one child per adult (who then survives to reproduce), then that society will grow; while having fewer than one child per adult leads a society to shrink.

It is easy to find examples of the extinction or near-extinction of a population as its reproduction dropped below one surviving offspring per adult, and where that reproduction number depends on circumstances. The American bison is thought to have numbered more than fifty million in the eighteenth century and was down to five hundred by the end of the nineteenth century. Their reproduction number plummeted after the U.S. Civil War, as new train lines brought more hunters to the herds and made it easier for them to transport their hides. Better guns also allowed hunters to kill animals at great distances without frightening a herd. For instance, the "Big Fifty" that was developed in the 1870s by Sharps Rifle had a reliable range of over a quarter mile (more than four hundred meters). The Plains Indians called it the gun that "shoots today and kills tomorrow."[9] The growing numbers of hunters, each killing more bison with improved rifles, and transporting them more quickly, led bison to be killed at a rate much faster than they could reproduce. The bisons' reproduction number abruptly dropped, and the existing population was all but eradicated in a few decades.

The basic reproduction number of a disease depends on how easily it spreads from one individual to another, as well as on with how many people each individual has contact. Since not every contact transmits a disease, the basic reproduction number is generally lower than the average degree of people in the network. Thus, reproduction numbers differ across diseases and locations.

Ebola's basic reproduction number (in the absence of intervention) has been estimated to be just over 1.5 in Guinea and Liberia, but closer to 2.5 in Sierra Leone.[10] This difference stems from differences in population densities, which affect the average number of people that a person has contact with per day, with Sierra Leone's being more than 60 percent higher than that in Guinea and Liberia.

The measles' reproduction number, in contrast, is much higher than Ebola's since instead of spreading via blood and saliva, it spreads via airborne particles and has a reproduction number from 12 to 18 depending on local population densities and interaction frequencies. Measles are very dangerous in unvaccinated populations. Diseases such as diphtheria, mumps, polio, and rubella, are intermediate, in the 4 to 7 range.[11]

The differences in these numbers correspond to different networks. HIV (human immunodeficiency virus) spreads via intimate contact, whereas one can catch the flu from a handshake or sitting near a coughing person on a plane or bus. That leads to many more interactions in the network of a flu, and fewer connections in the network of HIV. This does not mean that HIV does not spread: its reproduction number in some parts of the world and among some subsets of the population is well above one, and so it is still endemic among many communities around the globe.[12]

Reproduction numbers lie at the heart of vaccination policies. A vaccine does not need to be fully effective or to reach every individual in order to avoid widespread contagion, it just needs to bring the reproduction number below one. Vaccinating individuals not only keeps those individuals safe, but it also eliminates their connections from the network. Thus, it lowers the reproduction number of the society and helps protect the remaining population. If we start with a reproduction number of two, so that each infected person would infect on average two others, then vaccinating just over half of the individuals would drop the reproduction number to below one and limit the spread of the disease.

Unfortunately, the incentives that people have to vaccinate themselves are part of the reason that diseases are so difficult to eradicate. Those incentives are suboptimal because of what are known as "externalities."

Externalities and Vaccination

"Thousands of candles can be lighted from a single candle, and the life of the candle will not be shortened. Happiness never decreases by being shared."

—THE BUDDHA

"It may easily happen that the benefits of a well-placed light-house must be largely enjoyed by ships on which no toll could be conveniently levied."

—HENRY SIDGWICK,
THE PRINCIPLES OF POLITICAL ECONOMY, 1883

Henry Sidgwick was born in 1838 in Yorkshire, the year after Queen Victoria began her reign in England, and died in 1900, one year before Victoria. He was known for many things during his lifetime besides being one of the first to really pinpoint externalities.[13] He played a role in debunking psychics, including one of the more famous of the day—the medium Eusapia Palladino. Sidgwick was also the founder of Newnham College, the second college for women to be part of the University of Cambridge. He wrote essays in moral theory, which had many of its foundations laid during the Victorian era.

For us, however, Henry Sidgwick's legacy lies in his quote above, which illuminates the concept of externalities: *one person's behavior* *affects the well-being of others.*[14] In Sidgwick's quote it is a ship benefiting from the presence of a lighthouse that someone else built and maintains.

We have all experienced externalities in the small and large: having a neighbor learn to play drums, having someone kick our seat on a long plane ride, or sitting in a traffic jam. And, as climate change illustrates, externalities can even extend to people yet unborn—as future generations will experience a climate that is in part determined by our emissions.

Now that you are familiar with the concept, you will notice externalities everywhere. They make human interaction interesting and externalities prevent free markets from being a panacea. Externalities lie at the heart of moral and ethical quandaries, as well as many of the most pressing social and economic problems, ranging from freedom of speech to gun control and climate change. As externalities are fundamental to networks, they will keep reappearing in this book.[15]

When a worker in a coffee shop in an airport gets a vaccination against the flu, it not only helps him or her stay healthy, but also helps the many travelers who might otherwise have been infected if that worker caught the flu. The externality is that the worker's decision of whether to get a vaccine ends up affecting whether other people get sick. The worker might not fully take all those other people's potential suffering into account when making his or her vaccination decision. Stanford University, as do many organizations, understands this and tries to help people make the right decisions and so provides free flu vaccines for its staff and students. The vaccination of even a part of a community conveys benefits to the whole community. Governments pay special attention to the vaccinations of schoolchildren, teachers, health workers, and the elderly—categories of people particularly susceptible not only to catching but also to transmitting a disease.

It's not accidental that governments are heavily involved with vaccination. When there are externalities, free markets fail to align individual incentives with society's overall well-being. A parent weighing the costs and benefits of a vaccine for their child is not always thinking of the broader consequences of that vaccination to other people. These are markets in which subsidizing or regulating behavior can make everyone better off. The reason for requiring that a child be vaccinated before enrolling in school is not just to protect that child, but because each child's vaccination affects others via potential contagions. Small pockets of unvaccinated individuals can allow a disease to gain a toehold and spread more widely.

The biggest challenge in eradicating a disease is that externalities operate on a global scale. China was declared free of polio in the year 2000, but then in 2011 had an outbreak that appears to have made its way in from a neighboring country. Great strides have been made in the fight against polio, given that it was present in more than one hundred countries as recently as 1988. However, even having one country in which a disease is endemic is enough to keep it alive and allow it to resurge and spread again to other countries. Keeping a population vigilant against diseases that have seemingly disappeared is costly and challenging. It can be incredibly frustrating to have to keep vaccinating children around the planet year after year simply because a couple of countries are delinquent and keep incubating a disease.

Vaccination policies also have negative feedbacks: the more successful a vaccination effort is, the lower the threat of the disease and the lower the incentives for the population to remain vigilant. When a disease is running rampant, people pay attention and vaccinate themselves—not because of a concern about the externalities and others' health, but because they become scared for themselves. Deadly outbreaks of smallpox led to some of the first inoculations: centuries before vaccinations were formally developed, people in China were taking bits of dried pox from victims and either inhaling them or scratching them into their skin to gain immunity. However, once a disease subsides, people lose their fear and vaccination rates fall—leading the reproduction number to grow and allowing the disease to resurge.

This feedback effect can lead to especially strong cycles since many people fear vaccinations (more on that in Chapter 7) and so avoid vaccinations whenever a disease becomes less visible. Given the abrupt phase transition in a disease's reproduction number with small changes in vaccination rates, and the global scale of contagion networks, it becomes hard to eradicate any disease, and most tend to cycle over time. Smallpox is the only human disease that has been officially eradicated according to the World Health Organization (WHO). The last recorded wild case was in 1977 in Somalia, and in 1980 WHO said that the disease was eradicated. Fully eradicating smallpox was no small feat, as it involved decades of quick response to any observed new outbreak and then isolating patients and quickly vaccinating people in the area.

Well-Connected but Sparse

The good and bad news about human networks is that many of them are *well-connected:* having most people in a giant component. Although connected networks pose a challenge in controlling disease, they are vital in the spread of useful information, for instance, about a despotic government, an exciting new book or movie, or a valuable new technology.

Interestingly, human networks are well-connected even though they tend to be sparse at the same time. This sounds like a contradiction, but let me explain.

Consider Facebook. According to a recent Pew Research Center survey,[16] adult users on Facebook in the U.S. have an average of 338 friends and more than half of all adult users have over 200 friends. The numbers of friends among teen users are higher. This puts us well beyond the threshold of one friend per person at which networks begin to become connected. In that sense, human networks such as Facebook are extremely well-connected. Indeed, *99.9 percent* of Facebook's more than 700 million active users are in a single giant component.[17] So, except for a few isolated individuals and small groups, almost all Facebook users in the world can have information reach them from almost any other user via paths of friendships on the platform.

If almost everyone in the network is in one giant component, how is Facebook's network sparse? "Sparsity" refers to the fact that you could hypothetically have up to 720 million friends on Facebook, but you don't. We all know people who have thousands of friends on Facebook (don't forget the friendship paradox!), but nobody comes close to having even a percentage of all the possible friendships they could have. Having only hundreds of friends on average out of a potential hundreds of millions means that fewer than one in a million possible friendships on Facebook are actually present. The Facebook network has a minuscule fraction of its possible links present and hence is extremely sparse. Yet that tiny percentage of actual links is enough to bring almost all of the users into one giant component.

Beyond having almost all users in a giant component, despite the sparsity of Facebook's network, the paths between users are extremely short. Perhaps astoundingly, the average distance between any two active users is only 4.7 links.[18] This is known as the "small-world" phenomenon. It has a popular history via a Hungarian short story written in 1929 by Frigyes Karinthy, and later by John Guare's play *Six Degrees of Separation*. The small-world phenomenon is a robust feature of many random networks as discovered by a series of mathematicians in the 1950s.[19] It also played a starring role in an important book, *Small Worlds,* by Duncan Watts (1999).

The small-world phenomenon was beautifully illustrated in experiments conducted in the mid-1960s by psychologist Stanley Milgram. Milgram's starting subjects were people who lived in Witchita, Kansas, and Omaha, Nebraska, who responded to a letter Milgram sent out to residents asking them to participate in a study. Those people were asked to get a folder to some target individuals in Massachusetts. The targets were people Milgram had selected to help him with the experiment. One target was a stockbroker and the other was the wife of a divinity school student. The subjects in the experiments were told the targets' names and the towns in which they lived and a bit about them. The instructions to the subjects in the experiments were: "If you do not know the target person on a personal basis, do not try to contact him directly. Instead mail this folder . . . to a personal acquaintance who is more likely than you to know the target person . . . it must be someone you know on a first-name basis." Each person who received the folder read the instructions and added some of their personal information to the folder and then sent it along.

One folder started with a wheat farmer in Kansas. The farmer sent it to a minister in his hometown. The minister then sent it to a minister he knew in Cambridge, Massachusetts, who happened to know the target stockbroker directly. In this case, the folder went from its starting person in Kansas to the target across the United States in just three steps.

After collecting the folders from the targets, Milgram could see how many folders made it to their destination and how many steps it took each folder to reach the target. Out of the 160 folders that started in Nebraska, 44 made it to the final target—27.5 percent. The median number of steps was five and the range was from two to ten, with an average just above five.[20]

Given that all the people who had folders sent to them along the way were not volunteers for the experiment, but instead simply received the folder from an acquaintance, one might expect them to have a fairly low chance of forwarding the folders. Thus, the percentage reaching the final targets is impressive. However, the fact that participation was voluntary also means that the low number of steps of the folders that reached their target partly reflects a bias in the experiment. If a folder would have to take a longer path, involving ten people sending it along rather than five, then twice as many people would have to participate in order for it to make it. This makes it much more likely that paths with small numbers of intermediaries are successful and appear in the data, while ones that would have required more intermediaries are more likely to fail. Later experiments that correct for that bias find averages on the order of ten hops, double Milgram's results, but still relatively small.[21]

The results of the experiment are remarkable not only because of how few hops they took, but also because many letters made it at all despite the fact that people didn't have any map of the network to guide them in forwarding the folders. It would only be by the wildest chance that you would happen to know the shortest paths in the network between you and some stockbroker in Massachusetts, or, in later experiments, to a student in Beijing, or a plumber in London, and so forth. Thus, the fact that many of these folders were passed along fairly short paths suggests not only that short paths exist, but that many short paths tend to exist between any pair of people, and that people know enough to figure out how to pass something along fairly efficiently. How people are able to navigate a network is something that we will come back to in Chapter 5.

How is it that a network can be so sparse, having less than one in a million of its links present, and still require only a handful of links to get from any person to any other of the hundreds of millions of users?[22] Let us take the Facebook network as an example, and work with a typical user, say Diana, in terms of number of friends. A typical Diana would have a few hundred friends, and let's take the average at roughly 200 friends with whom she interacts at least occasionally.[23] Now let us count Diana's second-degree friends—people who it takes two links to reach from her. Let us suppose that each friend again has 200 friends that are not already Diana's friends.[24] Thus, by moving out paths of length 2 we have reached 200 × 200 = 40,000 users. Continuing, we reach 8 million people in three steps and 1.6 billion by the time we have gone out 4 steps. We have more than covered the full population of Facebook. Moreover, most of the users are reached at the later steps—most users are either 4 or 5 connections away from each other. This gives us the idea of why human networks have such small distances between people.

Our Ever-Shrinking World

"The pilgrims didn't know it, but they were moving into a cemetery."

—CHARLES C. MANN[25]

Let us compare this modern world network with one from medieval life. Suppose that instead of having 200 friends, we do the same calculation with 5 friends. After four steps we would have reached roughly 5 × 5 × 5 × 5 = 625 people instead of 1.6 billion. To reach the world population of the day would require more than a dozen steps instead of four or five.[26]

Nevertheless, the medieval world was still largely connected—as even a few friends put us above the reproduction number of one. And even the medieval world had a small-world aspect to it. Typical distances of a dozen or more links needed to get from one person to another are larger than the modern four or five, but still small compared to the hundreds of millions of people that were alive then. The greater distances of medieval times did lead to slower and more sporadic travel of germs and ideas than we see today. Yet the world was connected enough for long-range transmission and contagion, as we see from the relentless spread of a long list of diseases that made human survival a constant battle.[27]

Once global travel started to involve hundreds of thousands of people, the world began to see very fast and deadly pandemics. An eye-opening example is the 1918–1919 flu season. The flu of that season was a particularly nasty strain: it was unusually deadly among young and otherwise healthy populations, as it led to an overreactive immunity response that resulted in deaths of more than 10 percent of those infected. It became known as the Spanish flu, which was a disservice to the Spanish. The Spanish were being accurate in reporting infection and mortality rates, while information was being suppressed in other countries to maintain morale after the devastating world war of 1914–1918.[28] The news made it appear as if it was an epidemic coming from Spain, even though it was already widespread. The key to the spread of the flu that year comes from the end of the war, which led to mass troop movements around the world. Many soldiers were living in tight quarters and traveling great distances. This was coupled with a disease that has two features that enable it to spread quickly and extensively through human populations. One is that the flu can be communicated via small droplets that become airborne when someone sneezes or coughs and can travel from one person to another at a distance of over a meter, and can also be left on surfaces to be touched by someone else. The second is that people can be contagious for periods of over a week, sometimes beginning before symptoms emerge and ending after symptoms have subsided. The combination of a nasty flu, no vaccinations, and large masses of people moving around the world led to one of the largest flu pandemics in history and with deadly consequences. The flu infected on the order of a half a billion people (about a third of the world's population, and much more in urban Europe), and claimed somewhere between 50 to 100 million lives around the globe.

This example also points out that human networks are not constant in their connectivity. The mass troop movements of that year were unusual. They led to a smaller world than in previous years. Beyond occasional dramatic changes in human travel, there is a strong seasonality in how much people interact. For instance, the seasonality of school openings drives spikes in various diseases. This was first documented in 1929 by Herbert Soper, a statistician who studied the fluctuations of many diseases over time. He noted that measles outbreaks in Glasgow had patterns that could be explained by school sessions. When school is in session, many children who lack immunity to various diseases are in close proximity with each other, and so the connectivity of the network on a local level is quite high. In contrast, during times in which schools are closed, that local connectivity drops dramatically. However, longer trips and travel during breaks lead to increased long-distance connectivity.[29] Thus, networks of interactions change in more than one way depending on the season. Modern epidemiological models that are used to predict the spread of diseases, especially those such as the flu, take into account school seasons, travel patterns, interactions with health workers, and many other factors that affect the connectivity of the networks of transmission.

The deadliness of transported contagions was never more dramatic than the introduction of smallpox, measles, typhus, and influenzas to the Americas. It is estimated that those diseases ultimately have killed more than *90 percent* of the native population.[30] The native American populations were varied in their densities and the degree to which they interacted with each other and so it took time for the devastation to spread.

In Mexico, the arrival of smallpox on a Spanish ship from Cuba in 1520, via an infected slave, managed to devastate the majority of Aztecs in a matter of years. Within a decade it had made its way to eradicate most of the Incas in South America. Epidemics would also sweep through North America, killing large populations in the fertile zones in the East and Midwest, which were relatively densely populated. Some of the more remote and less dense populations in North America would last another century before their exposure, but none escaped. Native Americans in parts of the New England coastal area where the Pilgrims landed were devastated just a couple of years before the Pilgrims arrived. With much of the competition for land and resources decimated, the Pilgrims had a much better chance at survival than if they had encountered the denser native American population that existed just a few years prior.

Some of the last to be killed were the native Hawaiian populations, who lasted until the nineteenth century before they were eventually visited and then repeatedly battered by Eurasian diseases. The voyage of King Kamehameha II and Queen Kamamalu to London to negotiate a treaty led to their demise, as well as most of their party. They contracted the measles when they visited the Royal Military Asylum, which was full of soldiers' children.[31] Measles would eventually make their way to Hilo, Hawaii, in 1848 via a U.S. Navy frigate, the *Independence,* coming from Mexico.[32] Whooping cough and flus would make their way to Hawaii that same winter, starting a series of epidemics together with the measles that would eventually conquer roughly a quarter of the native population. The year would be called the "year of death" in the census. Before the society could get back on its feet, smallpox was delivered in 1853 via another ship, the *Charles Mallory,* which sailed into Honolulu from San Francisco. The ship was thought to be effectively quarantined and eventually sailed, but it had left the disease behind and within months thousands had died. When Captain Cook first arrived in Hawaii in 1778, the local population was estimated to be over 300,000; but fewer than 40,000 native Hawaiians made it to the 1900 census.

Modern medicine has greatly improved the understanding of contagion and the importance of sanitation and vaccination, and reduced the day-to-day threat of many diseases. Although we are far from eliminating pandemics, it is impressive that humans still survive despite the world becoming increasingly interconnected. The number of other people with which a typical individual in the industrialized world interacts is orders of magnitude larger than it was a few centuries ago, especially as we regularly rely on many others for our food and sanitation. Moreover, modern travel means that many interactions occur across large distances—with hundreds of thousands of people traveling internationally on any given day. Thus, potential contagion networks for many diseases have three big differences from the high school relationship network in Figure 3.1: they are denser, they include almost all nodes in the giant component, and they have shorter average distances between nodes. This means that the potential for many contagions to spread both rapidly and widely is much greater today than it was centuries ago, when such pandemics repeatedly wiped out millions. We can hope that science and the development of new vaccines continues to outpace the appearance of new diseases and the increase in the human network's connectivity.

Centrality and Contagion: The Downside of Popularity

The friendship paradox that we discussed in measuring centrality and influence also has implications for contagion and diffusion.

Being relatively overrepresented among people's friends not only gives someone high influence, but also high exposure. So, if you are at times jealous of your friends' high popularity, here's your silver lining. The most popular can be among the first to hear new news but also the first exposed to new infections.

A notorious example of this was a Canadian flight attendant, Gaëtan Dugas. A Centers for Disease Control study found that by 1983, out of the 248 people who were known to have HIV at that time, 40 had sexual contact with Dugas. Much was made about Dugas being "patient zero," and he was widely blamed for the epidemic that ensued.[33] With more data and hindsight, it is clear that AIDS had actually made its way into the U.S. by the 1960s, most likely via Haiti (and originally from Africa where it has even earlier roots), and that it would have become well-entrenched in the world without a promiscuous flight attendant. Nonetheless, Dugas helped stoke the most noticed early outbreak.

Similarly, it has been estimated that as few as 3 percent of people infected with Ebola may have spread more than half of the cases in an outbreak in Sierra Leone. Again, the outbreak would have occurred without highly connected people, but they are more exposed and can accelerate the spreading.[34]

To see why high-degree people are not vital for epidemics, it is enough just to look at a network. Again, revisiting our Figure 3.1, we saw a large giant component and yet the network has very few people with high degrees: only one person with degree 7, one with 6, and a handful with degree 5, and most nodes with degree 1 or 2.

This is important to stress, as it is a common misconception about networks. Hubs and connector nodes are not always *necessary* for a network to be connected and host contagions or diffusion. They may be more prone to be involved, and may provide early sparks, but many contagions would occur even without the most connected nodes. If we eliminated a few of the highest-degree nodes in the romance network, we would separate a few small bits from the giant component, but it would still be largely intact. The driving force behind a giant component that harbors widespread infection is the overall average degree in a network. The tendency for most individuals to have a degree above one in many human networks is what makes contagions and the diffusion of information so ubiquitous.

Nonetheless, high-degree individuals are more susceptible to infections, can accelerate transmission, and in networks that are right at the phase transition, can make a difference. More important, if one wants to target nodes that might have the biggest impact, the most central nodes are the place to start. As such, the idea that higher-degree individuals are at higher risk of infection has helped guide new analyses of the spread of diseases in the wild.

As an example, Stephanie Godfrey and her colleagues in Australia and New Zealand studied how prevalent ticks and mites are in populations of tuatara—a lizardlike reptile that lives in New Zealand.[35] The tuatara were named by the Maori for the ridges on their back. Tuatara are actually a fascinating species—not truly lizards, but instead the last remnant of the Rhynchocephalia, of which the other species became extinct more than sixty million years ago at the end of the Cretaceous period, along with many dinosaurs. The tuatara have a third "eye" on the top of their heads that is not used for vision, but is hypothesized to absorb ultraviolet rays and regulate the tuatara's metabolism. Tuatara live a fairly lonely life, spending most of their time alone within their own territory eating bugs as well as an occasional bird egg or frog, and basking in the sun. Not a bad life, at least on some dimensions.

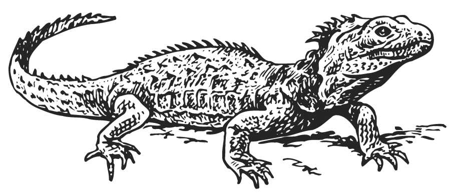


Figure 3.3: A tuatara[36]

Despite their solitary nature, their territories overlap and thus tuatara come into occasional contact with each other—and, of course, their reproduction requires it. The tuatara are hosts to a form of tick that carries a blood parasite, harmful to the tuatara, and the tuatara also are often infected with a type of mite. The interesting aspect from a network perspective is that the ticks don't live off of the hosts for long. Thus, moving from one tuatara to another requires the tuatara to come in close contact and so the network of interactions is important for the spread of ticks. In contrast, the mites can live off of the tuatara, and so are less dependent on tuatara interactions to spread.

Godfrey and her colleagues followed many of tuatara on Stephens Island and charted their movements and territories. Their territories had very different patterns, so that some tuatara only overlapped with one other tuatara, while some were much more central and overlapped territories with ten or more others. This is their degree centrality: how many other individuals they had a chance to interact with. Then by counting ticks on the tuatara (how did you spend your summer?), Godfrey and her colleagues found that there was a substantial and significant correlation between the degree centrality of a tuatara and how many ticks, and associated blood parasites, it had. Since ticks depended on the network to go from one tuatara to another, having a high degree put a tuatara at greater risk. Interestingly, they did not find the same relationship for the mites that can survive off of the tuatara. Here, the network was not essential to transmission, and the degree did not matter in the infection rate.[37]

Such analyses have been conducted for a variety of species,[38] including humans. Nicholas Christakis and James Fowler[39] examined which students at Harvard University came down with the flu the earliest. They monitored two groups: one group of a few hundred students who were picked at random from the population, and another group of a few hundred students who were named by others as a friend. As we know from the friendship paradox, the students named as friends should have higher degree than those picked randomly from the population. Indeed, as Christakis and Fowler found, those named as a friend by others had the flu on average two weeks earlier than the random group of students. Popularity has its downside.[40]

Network Dynamics and Conductance

In 2009 an unusually deadly and dangerous flu strain, a variety of H1N1 virus, spread around the world—a close relative of the virus responsible for the Spanish flu that devastated the world's population in 1918.

Along with all of the other people flying into Beijing that summer, I walked by a device that took my temperature. China was not the only country to screen travelers. Dozens of countries screened travelers and asked them to fill out forms reporting any symptoms.

People who were thought to be infected were denied entry or quarantined. The network was changing in response to the disease.

In some cases, the travel restrictions and alerts turned out to be extremely costly. As Mexico had some of the first H1N1 flu cases in 2009, many of the travel alerts that were issued that spring mentioned Mexico. That led travel to and from Mexico to drop by around 40 percent in the late spring of 2009. For a country in which tourism is a major industry, such an abrupt and huge drop in travel was deeply felt.

In hindsight, by carefully analyzing networks of travel, as well as the timing and location of cases of flu around the world, we can see that the change in travel did little to stem the spread of the flu. Travel changes delayed the spread by a few days.[41] Even the countries that did the strongest travel screening look to have only delayed the flu from spreading widely within their border by seven to twelve days, and did not avoid the inevitable contagion.[42]

World travel is so extensive these days that even cutting a large portion of it, and catching as many infected individuals as possible, makes a small difference in the spread of a flu. We can think of such strategies as cutting some, but not all, of the many connections that move long distances in the world network. It does not come close to really undercutting the reproduction number of such a flu. Of course, this does not mean that an individual could not remain healthy by avoiding travel during a flu pandemic. If you want to spend the flu season in a cabin in the remote mountains, you can all but eliminate your personal chances of catching the flu. But cutting the travel of large populations is economically infeasible.

Attempts at quarantining have on occasion even been disastrous, especially before contagion was well-understood. Reactions to early polio epidemics illustrate this point. Polio had been around from at least the days of ancient Egypt, and its infected included many famous people, from Emperor Claudius to Sir Walter Scott, but it often popped up fairly randomly. It began to appear in larger epidemics around 1910 in Europe, and the polio epidemic that hit New York in the summer of 1916 was large and dramatic. Polio was ill-understood at the time: children would go to bed one night and wake up in the morning unable to walk.

The epidemics were terrifying and not surprisingly led to panic.

Polio is transmitted from human feces to other humans orally: so, having open sewers near children is a deadly mix. But the variety of hypotheses surrounding polio led to the killing of eighty thousand cats and dogs, and in addition people blamed mosquitoes, mercury, bedbugs, and many other things. The majority of the first cases in New York happened to be Italian and so some Italian neighborhoods were quarantined. The quarantining led sanitation to deteriorate and more children to become exposed; and children who developed fevers for other reasons were shut in with others who had polio, with deadly consequences.[43]

This does not mean that changing the contact patterns in a network is never an effective strategy. With a disease like Ebola, with a much lower basic reproduction number, identifying outbreaks at an early point and restricting travel in and out appears to have been effective. This is also aided by the fact that the outbreaks have often been in places with lower rates of travel. Restricting travel around a village in Sierra Leone is different from trying to cut travel in and out of Beijing, London, New York, or Mexico City. A variety of studies[44] suggest that the only ways to effectively manage large flu pandemics are by vaccinating, quarantining infected individuals (making sure they stay at home or in a clinic until no longer contagious), and in some cases using antivirals that shorten infection and lower the chance that it is transmitted. These methods can all significantly lower the reproduction numbers of a flu and have a substantial impact.

The point here is that networks change and react to what passes along their connections. With the spread of dangerous contagions, such as diseases or financial distress, people react with fear, cutting ties, isolating nodes, and turtling up. In the other direction, the arrival of some important news can lead people to actively contact each other and increase a network's density—accelerating the spread of good news and salacious rumors. Fully understanding the contagion properties of a network depends on understanding that networks are dynamic entities and they often react to a contagion. We will return to some of these ideas in Chapters 7 and 8, where we will discuss things like technology adoption, decisions to invest in education, and social learning. Those are processes in which the way people act is dependent on what others are doing and the state of the network.

Summary of Comments on Jack_9781101871430_2p_all_r1.j.indd

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Number: 1 Author: matthewjackson Subject: Sticky Note Date: 3/29/2020 12:44:43 PM

And an update here: extreme travel restrictions and lock downs - by lowering a reproduction number, at least locally - can spread the contagion over a longer period. When the disease can otherwise overwhelm available medical resources, this can outweigh the enormous economic costs such policies incur.

Collecting Thoughts

In the modern world, many of our networks are connected and, for better and worse, you sit in the giant component, along with most of the rest of us. We are constantly exposed to flus and other diseases, but also privy to the spread of the latest news and rumors. Some news is almost impossible to avoid hearing.

As part of a fun diversion, a group of people challenge themselves to have low numbers of interactions and to be the last to hear a piece of news. The challenge is known more formally as the "Last Man in America to Know Who Won the Super Bowl," and its participants call themselves "knowledge runners," as they attempt to escape being informed about who won that year's Super Bowl. It is played on an honor system, and the goal is to go as long as possible without becoming informed of the Super Bowl champion.[45] This is a contagion process that is difficult to evade. First, it begins with a third of the U.S. population being "infected" with the knowledge of who won the Super Bowl, as they watch the game directly. Next, it is very hot news—not only is it a central topic of conversation for several days afterward, but it is also a top story in many news outlets.

Trying to avoid hearing hot news is actually quite a challenge—it requires carefully altering one's habits to avoid a lot of media, conversations, and people. A fascinating aspect of the challenge is that it is nearly impossible for the contestants to last very long. The many ways in which they quickly "die" (learn who won the Super Bowl) are amusing. Contestants last only hours or at most a few days, with only occasional contestants surviving for more than a week. The record reported on the challenge's Web site for shortest time is eight seconds and the longest being an outlier of several years. When a contestant inevitably succumbs, they are supposed to let others know of their cause of "death." The list includes numerous forms of social interaction. A partial list of what they report is "Death by airline stewardess, Death by professor, Death by roommate, Death by college friend, Death by wife's whooping and hollering (just 8 seconds in!), Death by friend at a rest stop, Death by idle conversation, Death by sabotage in AP Biology class, Death by CNBC news meeting, Death by

Black History Month conversation (seriously). The causes of death also include long lists of emails and texts, broadcast, social and other media, and apps.

These lists make it clear how many different types of interactions people have that can convey information, and that people may exchange information that is completely unrelated to the primary purpose of their interaction. This can lead people to have enormous degrees when it comes to learning about very topical information, which means that the network for such diffusion is highly expansive with large basic reproduction numbers and very short distances between people.

Basic reproduction numbers, phase transitions, giant components, and externalities all play prominent roles in many forms of diffusion and contagion, well beyond the spread of disease and news. Some fascinating twists appear when what is spreading is more than a germ, as we will now see with financial contagions.

ACKNOWLEDGMENTS

As we have seen in these pages, people are embedded in many different networks that combine to shape our views and actions. This is never truer than when writing a book. Stress also reveals much about your true friendships, and writing a book shines a bright light on relationships.

The seed for this book came from my wife's line-by-line proofreading of a text I wrote called *Social and Economic Networks*. Sara loved the descriptions of the concepts and ideas that came at the beginning of each chapter, before the technical presentation. Compiling those descriptions would have made for a short and dry book, but it made it clear that the many wonders of how networks influence human behavior could be made accessible to a wide readership, and there was at least one person interested in learning more.

A special thanks to Asher Wolinsky, for a lunch conversation in 1992 that sparked my interest in networks, and for his collaboration that launched me on the journey that eventually led to this book. I have a long list of coauthors on social interactions whose deep influences on my views are explicit or implicit in the pages here. In chronological order: Asher Wolinsky, Alison Watts, Bhaskar Dutta, Ehud Kalai, Anna Bogomolnaia, Anne van den Nouweland, Toni Calvó-Armengol, Roland Fryer, Francis Bloch, Gary Charness, Alan Kirman, Jernej Čopič, Brian Rogers, Massimo Morelli, Dunia López Pintado, Leeat Yariv, Andrea Galeotti, Sanjeev Goyal, Fernando Vega-Redondo, Ben Golub, Sergio Currarini, Paolo Pin, Daron Acemoglu, Tomas Rodriguez Barraquer, Xu Tan, Abhijit Banerjee, Arun Chandrasekhar, Esther Duflo, Yiqing Xing, Yves Zenou, Matt Elliott, Stephen Nei, Matt Leduc, Ramesh Johari, Sylvia Morelli, Desmond Ong, Rucha Makati, Jamil Zaki, Pietro Tebaldi, Mohammad Akbarpour, Evan Storms, Nathan Canen, Francesco Trebbi, Zafer Kanik, and Sharon Shiao.

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I have drawn on a lot of social capital in the writing of this book. My family—my wife, Sara; my daughters, Lisa and Emilie; my parents, Sally and Hal; and my brother and sister, Mark and Kim—commented on many drafts, kept my morale high, and put up with outlandish hours. My academic "parents," Hugo Sonnenschein, Salvador Barberà, and Darrell Duffie, have shaped me over the years, and their decades of friendship and mentoring are greatly appreciated. Salvador also provided very helpful comments on a draft, as did several of my academic "children," Yiqing Xing, Eduardo Laguna Műggenburg, Isa Chaves, Sharon Shiao, and Evan Storms. My literary family—Tim Sullivan, Max Brockman, Erroll McDonald, and Nicholas Thomson—guided me and kept me moving through the long process of writing such a book. Erroll McDonald is a remarkable editor and his surgical cuts and suggestions are deeply appreciated.

patented with in the past) leads to more successful patents than co-patenting with less connected individuals.

42. Jackson and Rogers (2007a). Another possibility is that people copy others' links or mix random and preferential attachment (Kleinberg, Kumar, Raghavan, Rajagopalan, and Tomkins (1999); Kumar, Raghavan, Rajagopalan, Sivakumar, Tomkins, and Upfal (2000); Pennock, Flake, Lawrence, Glover, and Giles (2002); Vázquez, (2003), which also leads to a similar distribution, with some differences in other network features.
43. For instance, see Fafchamps, van der Leij, and Goyal (2010), Chaney (2014), Jackson and Rogers (2007a).
44. Jackson and Rogers (2007a).
45. There are many more measures of centrality than those mentioned here. Some are conceptually similar, but involve slightly different calculations, while others involve other concepts. The mathematically inclined and endeavoring reader can find more background and references in Borgatti (2005); Jackson (2008a, 2017); Bloch, Jackson, and Tebaldi (2016); Jackson (2017).
46. This also relates to a measure called "closeness centrality," which keeps track of how close an individual is to others.

3. DIFFUSION AND CONTAGION

1. A study by Katharine Dean et al. (2010) suggests that the medieval spread of the Black Plague may have been primarily due to fleas and lice that live mostly on humans, and not so dependent upon rats and other animals. The hygiene of the day meant that such fleas and lice were abundant and could easily make their way from one host to another. The rarer modern cases of the plague are more dependent upon flea-bearing animals or close human-to-human contact, given that fewer people now live with lice and fleas regularly upon them so that it is now harder for, say, a flea to make its way directly from one human to another.
2. See Marvel, Martin, Doering, Lusseau, and Newman (2013).
3. This figure is based on data from a study by Peter Bearman, James Moody, and Katherine Stovel (2004), involving the Add Health data set (the National Longitudinal Adolescent Health data set, as referenced in Chapter 1). The figure differs slightly from their figure 2.
4. More precisely, a component is a part of a network in which every node can reach every other node via a path in the network, and is maximal in the sense that every link that involves any node in the component (and hence any neighbor of a node in the component) is included in the component.

5. Networks tend to have at most one giant component. Having two of them requires having many people in each of the two components. However, for those two components to be separate, it has to be that nobody in either component has any connections to the other component, which becomes very unlikely as the numbers of people in each of the two components increase. It only takes one connection across the two components to combine them into one.
6. I am glossing over an issue of timing here. Some of the relationships ended before others began, and so there are certain restrictions on which directions a disease might move in this network. That can slow contagion down, but would not necessarily eliminate it from still infecting large numbers of those in the giant component. See Johansen (2004); Wu et al. (2010); Barabási (2011); Pfitzner, Scholtes, Tessone, Garras, and Schweitzer (2013); and Akbarpour and Jackson (2018) for discussion and details.
7. The estimates of its prevalence vary widely depending on the sample of the population and the techniques used to measure and define infection, and are complicated by the fact that many people have no idea that they are infected. Estimates of the fraction of sexually active people who have been infected at one point in their lives are well above 50 percent (see Revzina and DiClemente [2005] for a meta-study).
8. For background, see Stanley (1971).
9. The Big Fifty rifle earned notoriety in a battle in 1874 between roughly thirty buffalo hunters and several hundred Comanche, Cheyenne, and Kiowa warriors at a trading post known as Adobe Walls in the Texas Panhandle. On the third day, one of the hunters, Billy Dixon, in what he acknowledged as a lucky shot, killed an Indian chief at an estimated 1,538 yards, helping to convince the Indians to end the battle.
10. Althaus (2014).
11. These sorts of high-level calculations are abstracting from a great amount of heterogeneity in populations—it may be that reproduction numbers within schools are much higher than in the general population. These sorts of broad estimates are made from observing the number of cases over time in large populations, and much more detailed information can be used in designing policies for stemming contagions. However, for our discussion, these high-level numbers provide the essential insights.
12. The reproduction number of a disease can be greater than one in part of a population or in some locations and not in others, and this can still lead it to reach large portions of the population and cross boundaries. A detailed analysis of this phenomenon appears in Jackson and López Pintado (2013).

13. Sidgwick found externalities inescapable when trying to devise measures of a society's well-being. Earlier philosophers, such as John Stuart Mill and Jeremy Bentham, grappled with externalities as they developed ways of measuring a society's well-being, but failed to articulate them as clearly. Economists such as Adam Smith (1776) and Alfred Marshall (1890) mentioned the issue in their writings on the efficiency of markets, but largely sidestepped externalities, even though Marshall was familiar with Sidgwick and his writings. Marshall seems to have been distrustful of a government's ability to do much of anything, and so it is perhaps not surprising that he avoided the topic of externalities, since overcoming externalities often involves regulations, taxes, or other government interventions. Arthur Cecil Pigou is the name that many economists associate with externalities, as he mentioned them directly in a 1920 essay. Interestingly, this may be in part responding to a critique by Allyn Young, who in 1913 pointed out that such effects were glossed over in earlier work by Pigou (*Wealth and Welfare,* by A. C. Pigou, M.A., London: Macmillan, 1912) and suggested that it deserves a fuller treatment (see Young's p. 676—and thanks to Ken Arrow for pointing me to Young's paper). Yet it would not actually be until the 1960s, with a pair of papers by Ronald Coase and James Buchanan and Craig Stubblebine, that externalities would really be completely laid out in their modern form (Coase [1960]; Buchanan and Stubblebine [1962]). One can also find intermediate works that wrestle with these concepts such as that of Frank Knight (1924) and Tibor Scitovsky (1954). An excellent discussion is given by Kenneth Arrow (1969).
14. This definition of externalities is a broadly encompassing and modern version. It does not require that the consequences of one's behaviors on others be intended, and it applies to all sorts of behaviors from a single person smoking to a tire factory polluting. It includes both positive externalities, such as someone coming up with the idea for public-key encryption for Web security, and negative externalities, such as someone cheating in a sports competition. Often externalities are incidental and not the reason for the original behavior: as in the case of a person smoking. But there are cases in which externalities are intended, as for instance when someone writes software and makes it freely available. This makes the definition a bit slippery, since one person punching another is not really what we mean to capture with the concept of externality, but it is admitted under the definition here. I will stick with the definition that may be over-inclusive for the sake of simplicity and to cover the wide variety of ways that externalities appear in networks.
15. There are many forms of externalities in network settings. They should not be confused with the special class that are termed "network exter-

nalities." Those refer to situations in which a person's consumption value of, say, a new technology depends on how many others also use the same technology. Network externalities certainly matter in networks, but there are many other forms of externality that are of interest to us.

16. Pew Research Center Internet Project Survey, August 7–September 16, 2013, http://www.pewresearch.org/fact-tank/2014/02/03/what-people-like-dislike-about-facebook/.
17. Ugander, Karrer, Backstrom, and Marlow (2011).
18. Backstrom, Boldi, Rosa, Ugander, and Vigna (2012).
19. It was first studied mathematically by Ray Solomonoff and Anatol Rapoport (1951), and then studied more extensively in the late 1950s and early 1960s by the mathematicians Paul Erdős and Alfréd Rényi (1959; 1960), when they built the foundations of random graph theory. It is less well known that it was independently studied by Edgar Gilbert (1959).
20. More detailed numbers appear in a follow-up study by Travers and Milgram (1969).
21. See Dodds, Muhamad, and Watts (2003).
22. The answer to this question is important to cover here, but given its extensive treatment elsewhere I will stick to the basic insights. See Watts (1999) for more discussion and illustrations, and Jackson (2008) for mathematical detail.
23. More generally, beyond Facebook, estimates of the number of people known by a given individual (where known means having some contact in the last two years and reciprocally being able to contact each other) vary but are in the range of upper hundreds to thousands depending on the technique and populations used for estimation. See McCarty, Killworth, Bernard, and Johnsen (2001) and McCormick, Salganik, and Zheng (2010).
24. This is roughly right when accounting for the friendship paradox, which leads to more friends, and the rate at which Diana's friends might be friends with each other, which lowers the number of new people reached. For those of you interested in the mathematical details, there are two problems with this quick calculation. This first is that we overestimated the rate at which the neighborhoods expand, since not every friend at every step is "new": some have already been reached. For instance, some of a user's friends' friends are that user's friends. For instance, if Diana is friends with Emilie and Lisa, then when going out on paths of length 2, if they are friends with each other, then we have already counted them among the 200 friends, and so they should not be counted at the next step. Thus, the 200 new friends at each step for each person generally involves some double counting. However, even if we do a conservative approximation and

cut the number of new friends reached at each step after the first in half, to 100, we would end up with 200 × 100 × 100 × 100 = 200 million after four steps. (A better approximation has the number of new friends be higher at early steps and lower at later steps. But it generally has mostly new friends until the very last step, since most of the population is reached at the last step.) By the fifth step we would have reached 720 million users, and this tells us almost exactly why Ugander Karrer, Backstrom, and Marlow (2011) found an average distance between any two active users of 4.7. The other problem with our calculation is to assume that every friend brings in the same number of additional friends on the next step. There is substantial heterogeneity in the population and one friend might reach 500 new friends and another almost none. However, with this large a network and average degree, this variation essentially washes out. This is a fact that traces back to the work of Erdős and Rényi mentioned above (1959; 1960) for networks in which links are formed uniformly at random, and has now been established in much richer random network models (e.g., see Jackson [2008b]). Variations of laws of large numbers apply and working with approximations that ignore individual to individual variations are very accurate in many settings, even in networks as rich and global as Facebook.

25. "A Few Things You (Probably) Don't Know About Thanksgiving," Becky Little, *National Geographic,* November 21, 2016.
26. See Marvel, Martin, Doering, Lusseau, and Newman (2013) for more comparison.
27. As Cesaretti Lobo, Bettencourt, Ortman, Smith (2016) point out, medieval cities involved social and spatial structures that share many features in common with modern cities. The medieval population, however, was much more rural than a modern population, and traveled much less. For more discussion see Ferguson (2018).
28. See Valentine (2006).
29. See Altizer et al. (2006) for more detailed discussion.
30. For instance, see Jared Diamond's (1997) illuminating description.
31. See Shulman, Shulman, and Sims (2009).
32. See Schmitt and Nordyke (2001).
33. For instance, see Randy Shilts's book *And the Band Played On* (1987).
34. Lau et al. (2017).
35. Godfrey, Moore, Nelson, and Bull (2010).
36. Image from Barbulat/Shutterstock.com (Vectorstock), under an expanded license.
37. There are many other things that might also correlate with degree here, for instance, how large a territory a tuatara has, which might also relate to the animal's chance of having ticks. One cannot rule out all such alternative explanations without a controlled experiment, but

the fact that the mite infections do not exhibit the correlation with degree but are correlated with territory and body size is reassuring.

38. See Godfrey (2013).
39. Christakis and Fowler (2010).
40. Having high degree does not always mean bad news in terms of infection. Japanese macaques (monkeys) with more social contact have been found to have fewer lice than other macaques who had less social contact. This is a seasonal effect, as found in Duboscq, Romano, Sueur, and MacIntosh (2016). A key form of contact between macaques is to groom each other, with one removing lice eggs from the other—a form of true friendship. Thus, contact not only leads to the spread of lice, but also to their removal. Higher degree translates into more grooming by others and ultimately to having fewer lice.
41. Bajardi et al. (2011).
42. Cowling et al. (2010).
43. See Donald G. McNeil Jr., "In Reaction to Zika Outbreak, Echoes of Polio Global Health," *New York Times,* August 29, 2016.
44. E.g., see Ferguson et al. (2006).
45. The Super Bowl is usually the most viewed event in the U.S. each year: more than one third of the U.S. population watched its television broadcast in 2016. Although it has some international viewership, it is small in comparison to FIFA's World Cup Final or the opening of the Olympics (Beijing's opening holds the record), which can be orders of magnitude higher in viewers. Thus, it is really a U.S.-based game.

4. TOO CONNECTED TO FAIL: FINANCIAL NETWORKS

1. More than thirty countries are major producers of coffee (producing more than thirty million pounds per year). Global chains such as Starbucks and Costa Coffee ride out a political crisis or weather disaster that causes temporary shortages in one region by sourcing from somewhere else. World commodity prices can still be volatile (and coffee prices are certainly no exception), but a company trying to consistently deliver coffee to consumers is better off if it can buy from many countries than if it is locked into just one region and exposed to the idiosyncratic production gyrations in that one region.
2. This is just part of Sheila Ramos's story, as reported by Paul Kiel. The fuller story is fascinatingly told by Kiel in "The Great American Foreclosure Story: The Struggle for Justice and a Place to Call Home," ProPublica, 2012.
3. Fannie Mae is the common nickname for FNMA, which is the Federal National Mortgage Association; and Freddie Mac stands for FHLMC—which is the Federal Home Loan Mortgage Corporation.