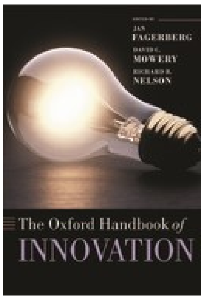

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CHAPTER

17 Innovation and Diffusion

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Abstract

In the study of innovation, the word diffusion is commonly used to describe the process by which individuals and firms in a society/economy adopt a new technology, or replace an older technology with a newer. But diffusion is not only the means by which innovations become useful by being spread throughout a population, it is also an intrinsic part of the innovation process, as learning, imitation, and feedback effects which arise during the spread of a new technology enhance the original innovation. This article provides an historical and comparative perspective on diffusion that looks at the broad determinants: economic, social, and institutional. The ways in which the different social scientific disciplines think about diffusion is discussed and a framework is presented for studying its determinants. Some of the empirical evidence on these determinants is reviewed, and a range of examples are also given.

Keywords: innovation, diffusion, technology, learning, imitation, feedback

Subject: Organizational Theory and Behaviour, Innovation, Business and Management

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17.1 Introduction[1]

IN 1953, a young female Macaque monkey in the south of Japan washed a muddy sweet potato in a stream before eating it. This obvious improvement in food preparation was imitated quickly by other monkeys and in less than 10 years it became the norm in her immediate group; by 1983, the method had diffused completely. In 1956, the same monkey innovated again, inventing a technique in which handfuls of mixed sand and wheat grains were cast upon the sea, so that the floating cereal could be skimmed from the surface. Again, by 1983, this method of gleaning wheat had diffused almost completely throughout the local populations of Macaques.[2] Besides the obvious fact that humankind does not have a monopoly on innovation, these examples illustrate a couple of things about the diffusion of innovations: first, when they are clearly better than what went before, new ideas of how to do things will usually spread via a "learning by observing" process, and second, the process can take some time; in these cases it took thirty years, and the life cycle of the Macaque monkey is somewhat shorter than ours (Kawai, Watanabe, and Mori 1992).

Turning to the world of humans, it is safe to say that without diffusion, innovation would have little social or economic impact. In the study of innovation, the word diffusion is commonly used to describe the process
p. 460 by which individuals and firms in ↳ a society/economy adopt a new technology, or replace an older technology with a newer. But diffusion is not only the means by which innovations become useful by being spread throughout a population, it is also an intrinsic part of the innovation process, as learning, imitation, and feedback effects which arise during the spread of a new technology enhance the original innovation.[3] Understanding the diffusion process is the key to understanding how conscious innovative activities conducted by firms and governmental institutions (activities such as funding research and development, transferring technology, launching new products or creating new processes) produce the improvements in economic and social welfare that are usually the end goal of these activities. For entities which are "catching up," such as developing economies, backward regions, or technologically laggard firms, diffusion can be the most important part of the innovative process.[4]

Thirty years ago, an economic historian (Rosenberg 1972) made the following observation about the diffusion of innovations:

> in the history of diffusion of many innovations, one cannot help being struck by two characteristics of the diffusion process: its apparent overall slowness on the one hand, and the wide variations in the rates of acceptance of different inventions, on the other. (Rosenberg 1972: 191)

Empirical measurement and study since then has confirmed this view. This chapter and the references included in it review the diffusion of a number of inventions and innovative processes, from the boiling of water to prevent diarrheal diseases to mobile telephony in Europe. Both these studies and the figures showing diffusion rates in various countries demonstrate the truth of Rosenberg's statement. The studies go further than simply noting the speed and variation of diffusion, in that they correlate the rates of adoption with characteristics of the technologies and their potential adopters in an attempt to explain the speed of diffusion and the ultimate acceptance of the new product. Besides the wide variation in acceptance of innovations, a second important characteristic of the diffusion process is the way in which it interacts with the innovative process. This has perhaps been a somewhat less studied aspect of diffusion, owing to the difficulty of collecting systematic data, but case studies abound. Rosenberg (1982), among others, has emphasized the fact that the diffusion of innovations is often accompanied by learning about their use in different environments, and that this in turn feeds back to improvements in the original innovation.

Why is diffusion sometimes slow? Why is it faster in some countries or regions than others, and for some innovations than for others?What factors explain thewide variation in the rate at which it occurs? This chapter provides a historical and comparative perspective on diffusion that looks at the broad determinants, economic, social, and institutional. The ways in which the different social scientific disciplines think about diffusion is discussed and a framework is presented for studying its determinants. Some of the empirical evidence on these determinants p. 461 ↳ is reviewed, and a range of examples given. The chapter concludes with a discussion of gaps in our understanding and future research questions.

17.2 Conceptual Frameworks

The diffusion of innovations has been studied from a number of different perspectives: historical, sociological, economic (including business strategy and marketing), and network theoretical. The choice of approach is often dictated by the use to which the results will be put, but there is no doubt that insights from one perspective can inform the research in another discipline. Perhaps a key example of this is the way in which historical study of the development and spread of certain major inventions has affected how economists understand the role of the diffusion process in determining the dynamics of productivity change, a topic I return to later in this chapter. First, I lay out some of the frameworks that have been used by different disciplines for the analysis of diffusion.

The sociological and organizational literature is exemplified by Rogers' wellknown book, *Diffusion of Innovations*, now in its fourth edition. In this book, he reviews the subject primarily from a sociological perspective, but one that is informed by research on organizations, the role of economic factors, and the strategies of firms and development agencies. Rogers provides a useful set of five analytic categories that classify the attributes that influence the potential adopters of an innovation:

(1) The relative advantage of the innovation.

(2) Its compatibility, with the potential adopter's current way of doing things and with social norms.

(3) The complexity of the innovation.

(4) Trialability, the ease with which the innovation can be tested by a potential adopter.

(5) Observability, the ease with which the innovation can be evaluated after trial.

Most of these attributes are recognizable in one form or another in the many analyses of specific innovations that have been undertaken by researchers in the past, albeit under different names. For example, both trialability and observability are characteristics that speak directly to the level of uncertainty faced by a potential adopter. The latter characteristic is a key feature of the real options model of technology choice which is discussed later in this chapter and which underlies some of the work on technology adoption by business firms. Complexity as a determinant is clearly related to the economist's notions of cost and complementary p. 462 ↳ investment, as is relative advantage, which an economist might consider to be determined primarily by the benefit/cost ratio of adopting the new technology.

But understanding the way in which the diffusion process unfolds, in addition to simply identifying features that determine its ultimate success or failure, requires a larger framework, one also provided by Rogers later in the same volume. In addition to the attributes listed above, which influence the adoption decision at the individual level, he points to a variety of external or social conditions that may accelerate or slow the process:

(1) Whether the decision is made collectively, by individuals, or by a central authority.

(2) The communication channels used to acquire information about an innovation, whether mass media or interpersonal.

(3) The nature of the social system in which the potential adopters are embedded, its norms, and the degree of interconnectedness.

(4) The extent of change agents' (advertisers, development agencies, etc.) promotion efforts.

Like so many students of the diffusion process, Rogers implicitly assumes that neither the new innovation nor the technology it replaces changes during the diffusion process and that the new is better than the old. These assumptions have been challenged strongly by Rosenberg (1972, 1982), who argued that not only was the new technology improved as user experience and feedback accumulated, but also that frequently the replaced technology experienced a "last gasp" improvement due to competitive pressure and that this fact could slow the diffusion of the new. A frequently given example is the rapid productivity increase in sailing ships during the nineteenth century documented by Gilfillan (1935*a*, 1935*b*).

In contrast to the focus on the external environment favored by sociologists and students of organizational behavior, many economists have tended to view the process as the cumulative or aggregate result of a series of (rational) individual calculations that weigh the incremental benefits of adopting a new technology against the costs of change, often in an environment characterized by uncertainty (as to the future path of the technology and its benefits) and by limited information (about both the benefits and costs and even about the very existence of the technology). Although the ultimate decision is made by demanders of the technology, the benefits and costs are often influenced by decisions made by suppliers of the new technology. The resulting diffusion rate is then determined by summing over these individual decisions.

The virtue of this approach to thinking about the adoption of innovations is that it is grounded in the decision making of the microeconomic unit, but this virtue comes with a cost, in that it ignores the social feedback effects (or externalities, to use the economists' term) that might result from one individual
p. 463 adopting and therefore encouraging another. Naturally, in the recent past, economists have risen to this ↳ challenge and included such concepts as network effects in their models (see the discussion in Box 17.1). Nevertheless, the factors and mechanisms considered in most of their studies typically fall short of many that other disciplines might consider important, such as social connectedness. An interesting early debate on this topic that reflected different views of the determinants of hybrid-corn adoption in the United States was conducted by a pioneering economist in the study of diffusion and a number of sociologists including Rogers in the pages of *Rural Sociology* (Babcock 1962; Griliches 1960*a* and *b*, 1962; Havens and Rogers 1961; Rogers and Havens 1962).[5] Looking back at this debate from today, a reasonable conclusion is that both economic and non-economic factors probably mattered for the diffusion of hybrid corn, although economic factors by themselves did a pretty good job explaining variation across states.

As an example of microeconomic analysis of the adoption decision in a modern technological setting, consider the decision to replace awired physical connection to the Internet with awireless one, either at home or in an office. Benefits might include the ability to work on the network throughout one's house or
p. 464 workplace rather than ↳ at a fixed location such as a desk, and the absence of wires. They might also include the fact that several members of the household can be online at the same time using a single telephone connection. The costs include the purchase of a base station and the services of a technician to install it, but they may also include the time of the user (adopter) spent reconfiguring his or her computer and ensuring that all the communication tools needed are working. Costs might also include the acquisition of new software, or the time spent training other members of the household or office in its use. Were we to enrich this story to include the adoption environment, we might focus on such factors as whether neighbors or colleagues already had undertaken such an installation, the extent to which it has been advertised by the supplier of the technology (or the extent to which it has been "sponsored" by a government agency or leading firm), and even the state of development of the new technology and the operating system necessary to use it (a complementary input). Note also that most of these factors have been changing rapidly over time.

Box 17.1 The QWERTY controversy—diffusion with network externalities

In an influential article published in 1985, Paul David proposed an answer to the question of why most keyboards have the QWERTYUIOP layout today, even though studies done in the first half of the twentieth century show that those trained on a keyboard with the Dvorak layout are able to type more quickly. He attributed this outcome to the importance of lock-in where there are network externalities. The argument is that the invention of touch typing in the late 1880s made typewriters a network good because of the interrelatedness between the keyboard layout and the typist's skills, the economies of scale in the user costs of typewriting due to training, and the quasi-irreversibility of investment in learning how to type. By the 1890s, these factors led to a significant lock-in to QWERTY layout, because it was easier to reconfigure the keyboard than to retrain the typist. The conclusion from this story of the diffusion of a new technology with network characteristics is that it is possible that the version of technology adopted (the "standard") was not the necessarily the "best" available, because of path dependence in the diffusion process induced by network externalities. That is, small accidents early in the choice of technologies can lead to the adoption of an inferior standard because the existence of an installed base makes that technology more attractive to new adopters. This point was also made by Brian Arthur (1989) using probability models of stochastic diffusion processes developed by Arthur, Ermoliev, and Kaniovski 1983).

David's view has been challenged forcefully by Liebowitz and Margolis (1990), on at least two grounds: First, they show that the historical evidence that the Dvorak keyboard was preferable may be weak. Second, they argue that if society faces large enough costs from adopting the wrong standard, it will pay individuals to change the standard via some form of collective action. One version of David's response to this critique was published by the *Economist* magazine in 1999

As alluded to earlier, the first empirical study of the diffusion of technology by an economist was Griliches' (1957) study of the diffusion of hybrid corn seed in the Midwestern United States. This study emphasized the role of economic factors such as expected profits and scale in determining the varying rates of diffusion across the Midwestern states. At the same time, it found that the variation in initial start dates for the process depended on the speed with which the seed was customized for use in particular geographic areas. That is, diffusion depended to a certain extent on the activities of the suppliers of the technology in adapting it to local conditions, again highlighting the tendency for the fundamental characteristics of the technology to change somewhat during the adoption process. This theme is repeated throughout the history of innovation. Bruland (1998, 2002) finds that the nineteenth-century development of the Norwegian textile industry was greatly facilitated by the technology transfer activities undertaken by the mostly British machinery suppliers in the form of training, increasing the supply of skilled workers in Norway.

The marketing literature on diffusion is primarily focused on two questions: how to encourage consumers and customers to purchase new products or technologies, and how to detect or forecast success in the marketplace. That is, it often looks for factors that can be influenced in order to increase the number of agents that will choose a particular product. For this reason, the literature tends to emphasize factors such as media information or the role of social networks and change agents, as well as the characteristics of the product itself, rather than individual adopter factors such as education and income levels that are less subject to manipulation by the marketing organization. The workhorse model in marketing for many years has been the Bass (1969) model, which assumes that mass media are important early on in the diffusion process but that as time passes, interpersonal communication becomes far more important. Estimation of this model on a number of consumer durables has revealed that interpersonal communication plays a much
 bigger role than the media in diffusion (Rogers 1995). For an interesting discussion of the ↳ contrast

between the economic and marketing views and a comparison of models from the two literatures, see Zettelmeyer and Stoneman (1993). Recent work on identifying and forecasting success in the marketing literature is illustrated by Golder and Tellis (1997). I defer discussion of their model to later in this chapter when I discuss some of the findings obtained by Tellis, Stremersch, and Yin (2002) using this methodology.

The activist view of diffusion taken by the marketing literature is also that pursued by specialists in technology policy, who are generally interested in encouraging the adoption of particular new technologies for welfare-enhancing reasons, either because it serves particular public policy goals (such as encouraging the boiling of water to reduce disease in less-developed countries) or because certain technologies are viewed as conferring externalities on society as a whole (such as the adoption of Internet use or vaccination against a communicable disease). In understanding the variation across countries in diffusion, variables describing their institutions and culture have proved essential in some cases (but not all, see the discussion of Tellis, Stremersch, and Yin 2002 in Section 17.5).

17.3 Modeling Diffusion

The most important thing to observe about the decision to adopt a new invention is that at any point in time the choice being made is not a choice between adopting and not adopting but a choice between adopting nowor deferring the decision until later. It is important to look at the decision in this way because of the nature of the benefits and costs. By and large, the benefits from adopting a new technology, as in the wireless communications example given above, are flow benefits that are received throughout the life of the acquired innovation. However, the costs, especially those of the non-pecuniary "learning" type, are typically incurred at the time of adoption and cannot be recovered. There may be an ongoing fee for using some types of new technology, but it is usually much less than the initial cost. Economists call costs of this type "sunk." That is, *ex ante*, a potential adopter weighs the fixed costs of adoption against the benefits he expects, but *ex post*, these fixed costs are irrelevant because a great part of them have been sunk and cannot be recovered.

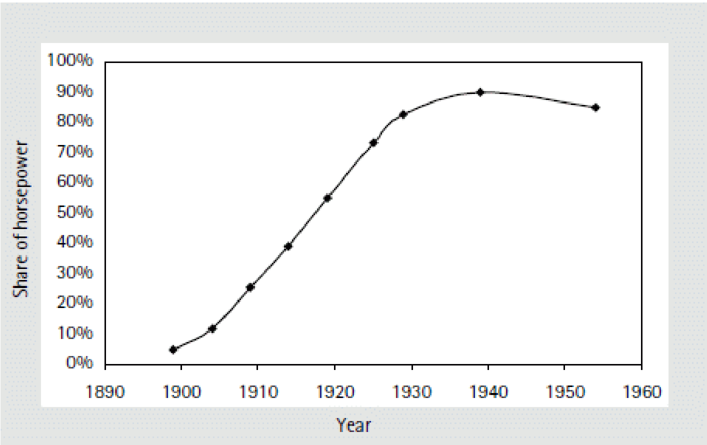
The argument that adoption is characterized by sunk costs implies two stylized facts about the adoption of new technologies: first, adoption is usually an absorbing state, in the sense that we rarely observe a new technology being abandoned in favor of an old one.[6] This is because the decision to adopt faces a large
p. 466 benefit minus cost hurdle; once this hurdle is passed, the costs are sunk and the decision to abandon ↳ requires giving up the benefit without regaining the cost, so even if the gross benefit is reduced relative to what was expected, the net benefit is still likely to be positive. Second, under uncertainty about the benefits of the new technology, there is an option value to waiting before sinking the costs of adoption, which may tend to delay adoption.[7]

An important exception to the rule that adoption is normally an absorbing state is the possibility of fads or fashions, which might be defined as things such as the "hula hoop" craze or various types of weight-loss diets, which diffuse rapidly and then disappear after a time. The experience of a wave of adoption followed by a wave of disuse seems to be somewhat more likely in the case of innovations in "practice," such as medical practice or business practice, than in the case of physical products, possibly because in the latter case the costs that are sunk are out of pocket costs paid to others, whereas in the former much of the cost (although by no means all) comes in the form of the adopter's time and effort. That is, the possibility of sunk costs may loom larger to the adopter when denominated in dollar or euro symbols. Nelson et al. (2002) discuss this phenomenon more fully and give some examples (such as the quality circle movement). These authors place considerable emphasis on the difficulty in these cases of getting feedback that the innovation truly is an improvement. Relatively low sunk costs combined with uncertain benefits will mean that the decision to adopt is more easily reversible in the case of practices. Strang and Soule (1998) also discuss the cyclicality of fashions in business practices.

It is a well-known fact that when the number of users of a new product or invention is plotted versus time, the resulting curve is typically an S-shaped or ogive distribution. The not very surprising implication is that adoption proceeds slowly at first, accelerates as it spreads throughout the potential adopting population, and then slows down as the relevant population becomes saturated. In fact, the S-shape is a natural implication of the observation that adoption is usually an absorbing state. Figure 17.1, which represents the diffusion of electric motors in US manufacturing between 1898 and 1955, shows such a curve. In 1898, the share of manufacturing horsepower produced by electric motors was about 4 per cent. It increased steadily and smoothly between 1900 and about 1940, at which point nearly all horsepower is produced by electricity. Saturation appears to be reached at around 90 per cent, presumably because for some specialized uses, other types of motors are preferred.

Looked at in terms of the benefits and costs of technology adoption, a range of simple assumptions will generate this curve. The two leading models explain the dispersion in adoption times using two different mechanisms: consumer heterogeneity, or consumer learning. The heterogeneity model assumes that different consumers expect to receive different benefits from the innovation. If the distribution of benefits over consumers is normal (or approximately normal, that is unimodal with a central tendency), the cost of
p. 467
the new product is constant or declines ↳ monotonically over time, and it is assumed that consumers adopt when the benefit they receive for the product is greater than its cost, the diffusion curve for the product will have the familiar S-shape.

Figure 17.1



Diffusion of electric motors in US manufacturing

An important alternative model is a learning or epidemic model, which is more popular in the sociological and marketing literatures (the Bass model is an exemplar), but has also been used by economists. In this model, consumers can have identical tastes and the cost of the new technology can be constant over time, but not all consumers are informed about the new technology at the same time. Because each consumer learns about the technology from his or her neighbor, as time passes, more and more people adopt the technology during any period, leading to an increasing rate of adoption. However, eventually the market becomes saturated, and the rate decreases again. This too will generate an S-shaped curve for the diffusion rate.[8] In general, combining this model with the previous model simply reinforces the S-shape of the curve. Golder and Tellis (1997) define a concept they call "take-off," which is their attempt to identify the point at which the empirical diffusion curve appears to have its greatest inflection relative to the initial growth rate.[9] For the data in Figure 17.1, this point would be in about 1910. Because for many consumer products the existence of such a point is a good predictor of eventual success, the focus of their work is to identify predictors of this point.

Regardless of the details of the mechanism generating the probability distribution of adoption times, the question which concerns both social scientists and those interested in encouraging the spread of new technologies is the question of what factors affect the rates at which these events occur. A second and no less interesting question is what are the determinants of the ceiling at which the S-curve asymptotes. That is, when would we expect this ceiling to be less than 100 per cent of the potential ↳ user base? The next section of this chapter reviews these factors and some of the empirical evidence concerning their importance.

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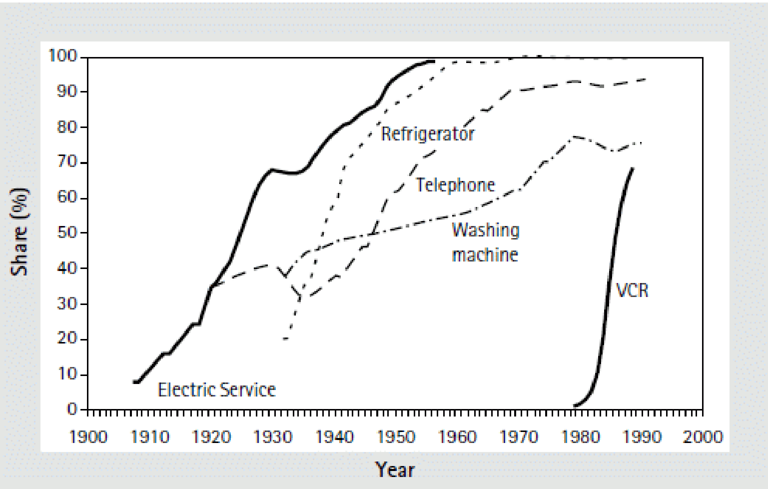
17.4 Determinants of the Diffusion Rate

Figure 17.2 shows the number of US households that have adopted particular new inventions as a function of time. Although not smooth, these curves clearly follow the S-shaped pattern noted by many observers. They also exhibit the characteristic wide variation in the elapsed time for diffusion. For example, it took over forty years for the clothes washer to go from one-quarter of all households to three-quarters, whereas it took less than ten years for the video cassette recorder or color television (not shown) to make the same leap. Table 17.1 shows the diffusion of common household electronic appliances in Japan between 1989 and 1995. It is noteworthy that there is considerable variation in the diffusion rates for different products even during the same six-year period, and this variation is not explained by the level of diffusion that was already achieved in 1989 (compare the refrigerator to the air conditioner, or the CD/cassette/radio player to the video camera).

Figure 17.2



Diffusion of major innovations in the United States

Source: Dallas Federal Reserve Bank.

p. 469 **Table 17.1** Diffusion in Japanese Households (%)

New Product	1989	1995	Change
Cordless phones	NA	43.7	NA
CD/radio/cassette player	31.5	68.2	36.7
Convection heater/cooler	34.7	57.3	22.6
Washing machine	34.7	55.4	20.7
Word processor	25.1	43.7	18.6
Microwave oven	72.9	89.5	16.6
Video camera	17.5	34.0	16.5
Air conditioner	64.8	79.3	14.5
Automobile	76.6	82.1	5.5
Personal computer	12.4	16.6	4.2
Television	98.4	99.3	0.9
Refrigerator	62.9	63.6	0.7

Source: Japan Echo, Inc. Information Bulletin No. 18.

From the considerations reviewed earlier in the chapter, one can derive a list of factors that might be expected to influence the diffusion of innovations. These can be classified into four main groups, those that affect the benefits received, those that affect the costs of adoption, those related to the industry or social environment, and those due to uncertainty and information problems. Alternatively, using the classification system of Rogers, one can identify the first and second as combining to yield relative advantage and complexity, the third as compatibility, and the fourth as being determined by trialability and observability.

17.4.1 Benefit Received from the New Technology

Clearly the most important determinant of the benefit derived from adopting a new technology is the amount of improvement which the new technology offers over any previous technology. This is to a great extent determined by the extent to which there exist substitute older technologies that are fairly close. For example, in Figure 17.2, we see that radio and the automatic clothes washer were both introduced in the United States in the early 1920s, but that diffusion of the former was much more rapid than the latter. This p. 470 may be partly because a fairly good substitute for the ↳ automatic clothes washer in the form of manual clothes washing machines existed whereas there was no very good substitute for radio. It is also consistent with the Tellis et al. (2002) finding that across European countries during the latter half of the twentieth century, the single most important factor that explains speed of diffusion is whether the good in question is “white” (household appliance) or “brown” (entertainment or information consumer durable). These authors hypothesize that the general explanation for this finding is that “brown” goods are more status-enhancing, in that they are more readily observable to non-members of the household. Unfortunately they did not control for the prices of the goods because of lack of consistent data across countries, so it is difficult to know whether this finding might also be related to differences in the full costs of adoption across goods and countries.

An important factor in explaining the slowness of technology adoption is the fact that the relative advantage of new technologies is frequently rather small when they are first introduced. As many authors have emphasized, as diffusion proceeds learning about the technology takes place, the innovation is improved and adapted to different environments, thus making it more attractive to a wider set of adopters (Rosenberg 1972; Nelson et al. 2002). The implication is that the benefits to adoption generally increase over time; if they increase faster than costs, diffusion will appear to be delayed (because the number of potential adopters will increase over time, expanding the size of the adopting population). In the Rosenberg (1982) study, the leading example was the airframe, specifically the stretching of the Boeing 747, but in fact one could argue that any technology in which learning by doing or using is an important aspect of its development will display feedback between diffusion and innovation. A good example might be applications software, most of whose development after initial launch is dictated by the experience and demands of users, or the worldwide web, where enhancements after the first web browser was created were dramatic.

17.4.2 Network Effects

Increasingly, the value of some new technology to the consumer depends partly on the extent to which it is adopted by other consumers, either because the technology is used to communicate with others (such as the Internet, or instant messaging) or because the provision of software and services for the technology depends on the existence of a large customer base. Goods of this type are usually termed network goods by economists: their chief characteristic is that they rely on standards to ensure that they can communicate either directly or indirectly. For these goods, an important determinant of the benefit of adoption is therefore the current or expected network size.

p. 471 For example, Saloner and Shepard (1995) examine the adoption of ATM machines by banks, under the assumptions that consumers prefer a larger network of ATM machines to a smaller and that banks respond to consumer preference. These authors do indeed find that banks with more branches adopt an ATM network sooner, even after controlling for overall bank size, and argue that this confirms that a higher network value leads to earlier adoption of a new technology, other things equal.[10] This example illustrates both the importance of networks and also the role of large firms as intermediates between technology and consumers in sponsoring particular standards for networks.

A famous example of the role of "network externalities" in consumer adoption of new technologies is the VHS/Beta competition, which resulted eventually in a single standard for video recorder/players in a large part of the world. Most observers attribute this outcome to the consumer desire for a large range of software in the form of pre-recorded tapes to go with this hardware, and to the fact that VHS had an initial early advantage in the length of program that could be recorded. See Park (2002) for details on the diffusion of this technology to consumers.

Although network effects (particularly those from networks that diffuse knowledge about or experience with an innovation) have always been viewed as important for the diffusion of innovations, especially in the sociological literature, recent work in economics has focused on the role played by standards in accelerating or slowing the diffusion process, as in the VHS/Beta example (David 1985; Katz and Shapiro 1985; Arthur 1989; Economides and Himmelberg 1995). The central message of the modern economic literature on standards and network externalities is that consumers and firms receive benefits from the fact that other consumers and/or firms have chosen the same technology that they have. These benefits are viewed as being of two kinds, direct and indirect. Direct network benefits are those that arise because they allow the adopter to communicate with others using the same technology. Examples are the choice of fax communication technology or the choice of word processor document format. Indirect benefits arise from the fact that adoption of a product that uses a particular technological standard by a greater number of people increases the probability that the standard will survive and that goods compatible with that standard will continue to be produced. The VHS/Beta example alluded to earlier can be viewed as an example where indirect network benefits were very important, although direct benefits presumably also play a part (the benefits from being able to loan a video made on one's own machine to a friend or neighbor).

The close connection between technological standards and network externalities comes from the fact that standards create a number of effects all of which go in the direction of making it more likely that a good will exhibit network externalities. First, a technological standard increases the probability that communication between two products such as telephones, instant messaging services, or aCD player and a CD, will be successful. Second, standards ease consumer learning and p. 472 ↳ encourage adoption when the same or similar standards are used in a range of products. The use of a particular standard, such as a Windows operating system, by others in a consumer's network, also helps learning and will encourage adoption, because of the relative ease with which a new adopter can obtain advice from those nearby. Third, a successful standard increases the size of the potential market for a good, which can be important in lowering the cost of its production and in increasing the variety and availability of complementary goods. Besides the VHS/Beta example referred to earlier, an example of this latter effect might be the wider availability of software for the Windows operating system, in comparison to Macintosh OS or Linux.

Although standards have always mattered for diffusion, the increasing importance of digital and information technologies have increased their salience and led to a variety of "standards battles" and to strategic behavior on the part of firms that hope to influence their adoption. Earlier examples of standards battles are the competition between AC and DC methods of distributing electricity (David 1990*a*), and the failure of gas-powered refrigerators to succeed in the market despite their apparent efficiency, because of the sponsorship of electric power by GE and Westinghouse (Rogers 1995). Nevertheless, it is clear that the importance of this phenomenon has increased recently, with increase in information and communication technologies. Consider for example, the battle between Netscape and Microsoft Internet Explorer for dominance in the web browser market.

The increase in the importance of standards that has accompanied the growth in importance of the information and telecommunications industries has led to a wave of economic modeling. These models incorporate the increasing returns phenomenon that results from the positive feedback from installed base to adoption by other consumers. An early effort is that by Arthur, Ermoliev, and Kaniovski (1983), which emphasizes David's insight that where there are multiple possible standards, small events early in the process that favor one of the standards can lead to an adoption process that settles on an inferior standard. By adding heterogeneity in consumers' tastes or localization in information spillovers, later researchers have produced more complex models of diffusion in the presence of network externalities that results in more than one standard surviving in the market even in the presence of increasing returns in adoption (Bassanini and Dosi 1998; Wendt and van Westarp 2000).

Industrial organization and strategy theorists have centered their modeling efforts on the implications of increasing returns in adoption for competitive strategy and market structure. Examples of this literature include Katz and Shapiro (1985, 1986, 1994), Farrell and Saloner (1992), and Shapiro and Varian (1999). In a series of papers, Katz and Shapiro have explored the implications of consumer adoption behavior in the presence of network externalities for the strategic interactions among firms offering competing products. In general, the theoretical literature of which these papers are an example identifies multiple possible equilibria among firms competing in such environments, so that it is difficult to draw firm conclusions.

p. 473 Farrell and Saloner study the speed of diffusion (relative to the socially optimal rate) when the good in question is subject to network externalities, so that early adopters ignore the consequence of their adoption on future adopters and on the users of the previous technology. They show that in this setting, diffusion can be either too fast (excess momentum) or too slow (excess inertia). Finally, the book by Shapiro and Varian draws out the implications of these various theoretical models for the production and marketing of information goods (broadly defined), many of which exhibit the properties that give rise to network externalities. They describe strategies for competing in markets where network externalities are important and where it is important to win standards battles because losing them means business failure.

17.4.3 Costs of Adopting the New Technology

The second main class of factors affecting the decision to adopt new technology are those related to its cost. This includes not only the price of acquisition, but more importantly the cost of the complementary investment and learning required to make use of the technology. Such investment may include training of workers and the purchase of necessary capital equipment (whose diffusion is therefore affected by the same factors). It is difficult to overemphasize the importance of this point about the need for complementary investment, especially for complex modern technology that requires the reorganization of the process that will use it (see Ch. 5 by Lam in this volume, for more on this topic).

For example, in a series of recent papers Eric Brynjolfsson has argued that the full cost of adopting new computer information systems based on networked personal computers is about ten times the cost of the hardware.[11] Greenan and Guellec (1998) use data on French firms and workers to make a similar point, that the effective adoption of ICT requires organizational change as well, and that this raises the cost of adoption, which slows diffusion. Caselli and Coleman (2001) compare the rates of computer investment across OECD countries between 1970 and 1990 and highlight the importance both of worker skill level and of complementary capital investments in determining the rate of purchase of new computing systems. The implication of this work is that the use of new computing technology requires both the training of workers and the installation of related equipment (for example, remodeling expenses for space to install servers, along with the necessary cooling equipment). The need for complementary investment therefore has two effects: it slows diffusion because it raises the cost, and because this type of investment usually takes time, it slows down the rate at which the benefits of the new technology are seen by the firm and the economy in the form of increased productivity.

David (1990*b*) has argued that a similar adjustment took place in manufacturing industry use of electric
p. 474 power, which took 40 years to diffuse completely in the ↳ United States (also see Figure 17.1 and Mowery and Rosenberg 1998). The installation of electric power in a factory required a complete redesign of its

layout and a change in task allocation, which meant that adopting this new technology was a rather costly process, and tended to occur slowly, or when greenfield investment was being undertaken. David argues that a similar reorganization of workflow takes place when computer technology is introduced into the workplace or when Internetbased processing replaces telephone or mail order processing. Recent productivity growth evidence in the United States appears to confirm the view that major technological-organizational change takes time for its effects to be felt (Gordon 2003; *Economist* 2003).

Shaw (2002) has documented this kind of phenomenon in the replacement of manual monitoring of production lines in continuous hot steel production lines by computerized pulpit operation. Not only does this involve a substantial investment in high technology equipment, but it also requires fewer workers with substantially higher cognitive skills. Where they used to be on the production line working physically with the machinery, they are now in small rooms ("pulpits") above the line, monitoring and adjusting the process using computer technology.

Technology producers often try to subsidize the adoption of new technologies by providing free training and other help to (potential) users and by charging reduced introductory rates for a certain period. Another symptom of the desire of innovating firms to reimburse new customers for their sunk costs in previous technologies is the widespread practice among software firms of offering competitive upgrades to owners of rival products as well as to the owners of their own products. For a more complete discussion of strategies used by technology producers to encourage diffusion and increase the installed base of their product, see Shapiro and Varian (1999).

Because most of the costs of adoption are fixed, firms' choices to change or introduce technologies may be influenced by their own scale and by the market structure of the industry within which they operate. An interesting example of this phenomenon is given by Paul David in a series of papers on the introduction of the mechanical reaper in US and British agriculture in the nineteenth century (David 1975*a* and *b*). He argues persuasively that adoption was delayed in Britain relative to the United States for two reasons: first, because the reaper was a fixed cost investment, profitability required a farm and fields of a certain size; second, because it was incompatible with the typically British pattern of small fields divided by hedgerows. In addition to the difference between countries, he also finds that diffusion was delayed in the US itself until the price of labor rose to a level that made the investment in the reaper (a labor-saving device) profitable.

In the present-day context, a similar empirical finding can be found in many studies of diffusion. Majumdar and Venkataraman (1998) looked at the replacement of mechanical switching by electronic switching in the
 US telecommunications industry and found that larger firms adopted first, presumably because the costs ↳ per customer were somewhat lower. Note that even when technology adoption involves an investment in equipment that is proportional to the existing size of the firm, the requirement that the firm have sufficient absorptive capacity, and the need for worker training or other complementary changes may create a fixed cost that is not proportional to firm size.

As in the case of investment in innovation, firm investment in new technologies is also sensitive to financial factors. As was suggested earlier, the decision to adopt new technology is fundamentally an investment decision made in an uncertain environment, and therefore we should not be surprised to find that all the arguments for a relationship between sources of finance and choice of investment strategy that have been advanced in the investment literature have a role to play here. Chapter 9 by O'Sullivan in this volume reviews these financial factors in some detail. For example, Mansfield (1968) reports that the adoption of diesel locomotives by railways depends somewhat on their liquidity, implying these firms faced a higher cost of external than internal finance.

17.4.4 Information and Uncertainty

The choice to adopt a new technology requires knowledge that it exists and some information about its suitability to the potential adopter's situation. Therefore an important determinant of diffusion is information about the new technology, which may be influenced by the actions of the supplier of the new technology. Obviously in many cases this takes the form of advertising, which influences the cost of the new technology directly. The choice to adopt may also depend on the information available about experience with the technology in the decision maker's immediate environment, either from those in geographic proximity or from those with whom he or she interacts.

Because benefits for adoption are spread over time while costs are usually incurred at the beginning, expectations about the length of life of either the technology or the adopter will matter. Uncertainty about benefits, costs, or length of life will slow the rate of adoption, and may often turn the decision problem into an options-like computation. As discussed earlier, the latter is a consequence of the fact that in most cases, once a new technology has been chosen, the costs are sunk and cannot be recovered. That is, the potential adopter has an option on new technology; if he sees the uncertain payoff reach a certain value (the strike price), he will exercise the option by adopting the technology (see Stoneman 2001*b* for a theoretical development).

Empirical work on diffusion that incorporates real options is rather scarce, although descriptive work that confirms the role of trialability and observability is widespread (for some recent examples, see Nelson et al. 2002). One notable example of an investigation of technology adoption as the exercise of an option is that of
p. 476 Luque ↳ (2002). She looks at the decision by US plants to adopt three advancedmanufacturing technologies, and finds that plants operating in industries with lower degrees of demand and technological uncertainty and a thicker resale market (higher resale prices for used machinery) are more likely to adopt these technologies. She argues that this confirms the importance of uncertainty in the decision; if adopting a new technology corresponds to the exercise of an option, we expect adoption to happen more often in industries with lower uncertainty and lower sunk costs.

17.4.5 Market Size, Industry Environment, and Market Structure

The relationship between firm size or industry concentration and the adoption of new technology by a firm is subject to many of the same considerations as the relationship of these factors to innovation. As discussed above, large dominant firms can spread the costs of adoption over more units, but also may not feel the pressure to reduce costs that leads to investment in new technologies. Empirically, in the case of technology adoption, most studies have found that large firms adopt any given technology sooner, but there are some exceptions. Oster (1982) found that small firms in the steel industry replaced the open hearth furnace with the basic oxygen furnace during the post-World War II period sooner than large firms. In a study of twelve major innovations in the coal, rail, iron and steel, and brewing industries, Mansfield (1961) found weak evidence that firms in competitive, less concentrated industries adopted new technologies sooner, as did Romeo (1977) in a study of the diffusion of numerically controlled machine tools.

In some cases the adoption of new technology is determined by firms, acting for the benefit of consumers and for their own benefit. As an example, consider airline adoption of computerized reservation systems. Consumers have little say in this decision although they ultimately benefit in the form of lower prices for air travel or better service, such as seat reservations. In other cases, the decision fundamentally rests with the consumer, for example the choice of video recording technology such as VHS, Beta, and now DVD. Although the same considerations of cost versus benefit apply broadly in both cases, the role of market structure may be more important in the former case than in the latter, because the adopting firms are likely to be few in number and therefore able to interact strategically with respect to the adoption decision itself. In the latter case, the strategic interaction occurs in choosing the technologies that are offered; in principle, firms can produce the same set of strategic outcomes as in the former case (via penetration pricing, etc.), but lack of perfect information about consumers' tastes and limits on their ability to segment the market sufficiently may prevent the firms from fully internalizing consumers' preferences.

 Market structure can affect the decision to adopt in two distinct ways: via seller behavior and via buyer behavior. Highly concentrated providers of new technology will tend to have higher prices, slowing adoption, but they also have the ability to determine a standard more easily, increasing the benefit of adoption. If two or more oligopolistic firms are competing to offer different standards, we may in fact get too rapid adoption of a new technology, because of the incentives they face to price below cost in order to build market share (Farrell and Saloner 1992). In the case of potential adopting firms, market concentration affects both their ability to pass through any costs to consumers and also the incentives they face in incurring the costs of adoption. Many of the issues raised by the tension between the fear of displacement and the exercise of market power here are familiar from the literature on monopolists' incentives to innovate (for example, see Gilbert and Newberry 1982).

Along with market size and structure, the general regulatory environment will have an influence, tending to slow the rate of adoption in some areas due to the relative sluggishness of regulatory change and increasing it in others due to the role of the regulator in mandating a particular technological standard. As an example of the former situation consider the use of plastic pipe for plumbing, which lowers construction cost, but has been slow to diffuse in many localities due to existing building codes. As an example of the latter, Mowery and Rosenberg (1982) have written about the extent to which airline regulation by the Civil Aeronautics Board in the United States was responsible for promoting the adoption of new innovation in airframes and jet engines, in its role as standard setter and coordinator for the industry.

An important example of the unintended consequences of regulation for diffusion is the difference between the United States and Europe (and Japan to some extent) in the diffusion of household Internet use. Historically, pricing in the US telecommunications industry has permitted unlimited local calling at a single monthly rate, whereas pricing for local calls in other countries has usually been proportional to usage. These policies are largely determined by regulatory bodies, but once in place, are difficult to change because consumers and firms adapt to them. In the absence of direct connection to the network such as is available in large institutions, household Internet use requires the ability to connect over local phone lines for extended periods of time. The marginal cost of the Internet for households is therefore to a great extent determined by the cost of local calling, so diffusion of the Internet along with email and instant messaging use has been far more rapid in the United States than in other countries that are just as developed. Only with the recent advent of ISDN service charged by the month in some European countries has household Internet use begun to spread there. In contrast, the diffusion of various “text-messaging” services on wireless phones, which are a form of communication popular with teenagers and similar to the Internet instant messaging widely used in the US, has been more rapid in Japan and Europe. Relative costs of the two forms of instant communication, which in turn are due to regulatory reasons, are probably the main explanation for the differences.

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17.5 Cultural and Social Determinants

Economic factors like these can go a long way toward explaining differences in rates of diffusion (Griliches 1957 and subsequent authors) but other factors may also be important. For example, many have stressed differences in cultural attitudes towards risk and simple "newness."[12] These characteristics can vary within cultures as well as between them, leading to dispersion in adoption rates that are not accounted for by the economic variables. Among others, Strang and Soule (1998) provide a useful discussion of the cultural basis of diffusion.

Rogers (1995) cites a number of situations where compatibility with existing social norms has strongly influenced the adoption of health-related innovations such as the boiling of water for consumption or various types of contraceptives in underdeveloped countries, whose relative popularity depends greatly on local religious and cultural mores. He cites as example an instance where a strong traditional distinction made between the qualities of cold and hot water discouraged the use of the very simple preventive measure of boiling water destined for human consumption in order to prevent diarrheal diseases.

On the other hand, for consumer household durables, Tellis et al. (2002) find that variables such as gender, cultural attitudes, religion, etc. have little predictive power for "take-off" on average (across European countries) in the presence of lagged market penetration. When these variables are considered separately as predictors, "industriousness" (which is measured by a climate variable) and "need for achievement" (which is measured by the ratio of Protestants to Catholics in the country) speeds diffusion, and a measure of "uncertainty avoidance" slows diffusion. This study is noteworthy in that it includes economic, cultural, and communication variables jointly in the same predictive equation.

17.6 Conclusions

Traditionally, diffusion is one of the three pillars on which the successful introduction of new products, processes, and practices into society rests, along with invention (a new idea) and commercialization/innovation (reducing the invention to practice). In some ways it is the easiest part of the process to study, because it is more predictable from observable factors than the other two. Certainly countless studies of the diffusion of individual innovations exist, and even exhibit some commonalities (see
p. 479 the references in this chapter and in Rogers 1995), such as ↳ the familiar s-shaped curve, and the importance of both economic factors and social networks.

Although many have criticized the linear model that lies behind the division of innovative activity into three parts as oversimplified, it remains true that without invention it would be difficult to have anything to diffuse, so that the model still serves us as an organizing principle, even if we need to be aware of its limitations. Nevertheless, an important insight from the many historical case studies of individual inventions has been the extent to which the diffusion process enhances an innovation via the feedback of information about its operation or utility under varying conditions and across different users, information that can be used to improve it. A second major finding from this literature has been the possible feedback from differences in the rate or scale of adoption across geographic areas to the rates of improvement in the innovation.

In the introduction to this chapter, Rosenberg's observations on the slowness and variability of the diffusion of different innovations were cited. The studies reviewed in this chapter have identified some explanations for these observations, such as the size of sunk costs (trialability), the adaptations and improvement necessary to make the invention useful after its initial conception, and the inherent slowness of interpersonal communication networks in spreading information. In the case of major innovations such as electricity or the computer, some studies have emphasized that the necessity of reorganizing the workplace to take advantage of the new innovation means that diffusion will be greatly delayed, and also that the expected gains from innovation may take time to be realized.

Several areas stand out as potentially fruitful for future research. First, most of the studies conducted to date have been methodologically rather simple; the most ambitious have used a hazard model to correlate the time until adoption with various characteristics of the innovation and the adopter (depending on the particular dataset). There is room for an approach that is more structural and grounded in the choice problem actually faced by the adopter. One promising avenue for modeling is the real options approach suggested by Stoneman (2001*b*); such a model would yield a hazard or waiting time model rather naturally, while explicitly incorporating the effects of uncertainty on the decision.[13] The cumulative distribution for adoption derived from a hazard model has the familiar S-shape.

Second, although many studies have described the process of innovation enhancement during its diffusion qualitatively, there has been relatively little systematic collection of data or modeling of the process. Investigations of this type would be very helpful in quantifying the importance of this effect, which is similar to but not the same as the well-known learning curve. One technological area where this process has been very important and might be worth study is the area of userdriven software development.

Finally, an area of research that is receiving increasing attention in a globalizing economy is that concerned p. 480 with international technology transfer.[14] This literature ↳ is generally positive (as opposed to normative) in approach and empirically based, focused on identifying the mechanisms through which technology diffuses from more developed to less developed countries rather than on the adoption choice itself. That is, this analysis is conducted at the aggregate level rather than at the level of an individual decision maker. It is probably safe to say that there is room for further research in this area, as the diffusion of technology is an important source of economic and social development. Indeed, from a welfare perspective, one of the most important areas for further study is the comparative diffusion of various health and medical practices across developing countries, especially because it is apparent that there are wide variations even among similar low income countries in rates of adoption.

Notes

1. University of California at Berkeley, Scuola Sant'anna Superiore Pisa, NBER, and the Institute of Fiscal Studies, London. I am grateful to Beethika Khan for contributing some of the literature review that lies behind the issues discussed in this paper, and other contributors to this volume, especially my discussants, Kristine Bruland, John Cantwell, and Ove Granstrand, for their very helpful comments. Finally I owe an immense debt to the editors for their careful reading of multiple drafts of this chapter.

2. I am grateful to Chris E. Hall for calling this example to my attention. It is described in McGrew (1998), where a more complete set of references to the anthropological literature is given. A third feature of this example, perhaps not directly relevant to this chapter, may be noted: the fact that once having innovated, innovators tend to innovate again.

3. As discussed in the introduction to this volume, the view that every adopter develops and adapts an invention to his own use has led some of the literature to refer to adoption itself as “innovation.” I will follow the more conventional practice of reserving the term innovation for the first “public” use of a new product, process, or practice.

4. See Godinho and Fagerberg (Ch. 19 in this volume) on the role of adoption of new technology in the catch-up process and in long run economic growth.

5. I am grateful to Paul David for calling some of these references to my attention.

6. Although see Rogers (1995) for some examples of innovations that failed to diffuse because they were rejected after trial.

7. An option is a choice between doing nothing and paying a fixed amount to purchase an uncertain return. It is real (as opposed to financial) if it involves investment in real assets. In this setting, the investment is the adoption of a new technology, which has uncertain benefits and costs that may change over time. The option value arises from the fact that waiting may reduce the chance that the wrong decision is made.

8. For a good presentation of this class of models and their extensions, see Geroski (2000). David (2003) provides an evolutionary interpretation of this mechanism.

9. For any particular parametric distribution function, this point might be defined at the point where the curvature of the
p. 481 cumulative distribution (the second derivative) is ↳ maximized. Such a point is well defined if it exists. It occurs when about 20 per cent of the population has adopted in the case of a logit and when about 15 per cent have adopted in the case of a normal. Golder and Tellis (1997) define a non-parametric discrete version of this measure by looking at the current rate of adoption as a share of adoption to date.

10. On the adoption of ATM systems, see also Hannan and McDowell (1984*a* and *b*), who emphasize the role of bank size and industry concentration, which are chiefly cost side and market structure considerations.

11. See Brynjolfsson (2000) for a summary of this work and further references.

12. For a discussion of various cultural explanations, see Mokyr (1990).

13. In the labor economics literature, Lancaster and Nickell (1980) developed a similar model for the probability of obtaining a job when unemployed (see also Lancaster 1990).

14. See Keller 2001 for a review of this literature.

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