Technology Evolution

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Technology evolution refers to changes in production processes or institutional arrangements that make it possible with a fixed set of resources to produce either (1) a greater quantity of a given product or service or (2) to produce new or qualitatively superior products or services. Technology evolution is the primary cause of rising *living standards* in modern economies, and the divergence of technological capabilities across countries is the chief reason for international differences in living standards.

Table 1 provides a concrete illustration of the impact of technology evolution on living standards in the U.S. during the twentieth century. The first column shows the labor time required by an average worker to earn enough to purchase the specified product in 1895, while the second column shows the amount of time required in 2000. To facilitate comparison the third column shows the ratio of these two figures—the larger the ratio the greater the increase in *labor productivity* (and *purchasing power*) that has taken place.

[Table 1 about here]

The data in Table 1 suggest several important points about the effects of technology evolution. First, the quantity of goods that the average worker can consume has increased dramatically. This is reflected in column three which shows the proportionate increase in the quantity of each item that can be purchased with an hour of labor time. The median increase in productivity for this somewhat arbitrary selection of goods is between 5- and 8-fold. Second, there is considerable variation in the increase in productivity across the different items. While the number of bicycles that can be purchased with an hour of work increased by a factor of 36, it increased only 2.2 times for a Steinway piano. There is even one item in the list, the sterling silver teaspoon, which has become more expensive. These differences reflect the differential impacts of the application of modern technologies—such as mass production—and changes in the cost of raw materials on individual items.

A third point is raised by what is not in Table 1. Because we can only compare productivity for items that are similar in 1895 and 2000, we cannot directly observe the impact of the introduction of new or qualitatively different goods. A moments contemplation suggest that this list is quite long, including modern medical care, computers, MP3 players, television, and stainless steel flatware. While some of these additions serve entirely new purposes, the stainless steel flatware emphasizes the point that some new products can provide lower cost alternatives to existing items. In 1895 silver was the only rust-free flatware available; today stainless steel provides much the same service as silver at a fraction of the cost.

A more comprehensive measure of productivity improvement is provided by calculating the increase in *Gross Domestic Product* (GDP) per hour of labor input. Over the same period covered by Table 1, GDP per worker in the U.S. increased—adjusting for inflation—from \$13.7 thousand to \$65.5 thousand, while the number of hours worked per year by the typical worker fell by more than one-third. Thus the average productivity of an American worker was multiplied by a factor of nearly 7 over the last century due to technological advances. Since this calculation does not account for the many ways in which our lives are enriched by new products and services not available in 1895, the 7-fold improvement is, if anything a conservative assessment of the increase in well-being that the technology evolution has produced (DeLong 2000).

The Beginning of Sustained Economic Growth

Technology evolution is as old as human history. For most of this time, however, the pace of change remained quite gradual. Until the late eighteenth century, rising productivity supported a growing population but produced little long-run advance in living standards. In the short-run episodes of below average population growth correlated with rising living standards, and periods of more rapid population growth coincided with falling living standards. But in the long-run there was little discernable trend in living standards.

Beginning in Britain sometime between 1760 and 1800, however, the pace of technological change began to accelerate. The introduction of the steam engine, new metallurgical techniques, and advances in mechanization combined with the introduction of factory methods of production fueled a rapid increase in productivity in the manufacture of cotton textiles and other products. As a result incomes began to rise at the same time that population growth accelerated.

The technologies of the British Industrial Revolution spread relatively quickly to other countries in Western Europe, the United States and Canada. Meanwhile a stream of new innovations—railroads, electricity, synthetic dyes, better machine tools—contributed to an acceleration in the pace of economic change. By the early twentieth century sustained growth had become the norm in these economies rather than stasis. The remarkable nature of this transformation is emphasized by the divergence between the West and the rest of the world. Although Japan, South Korea, Taiwan, Singapore, and Hong Kong, have by now joined the ranks of modern, developed economies, the gulf in economic performance today is far wider than it was 250 years ago.

The Nature of Technological Creativity

The technological creativity on which the modern era's sustained economic growth is based derives from the interaction of two distinct but complementary processes that Joseph Schumpeter called: *invention* and *innovation*. Schumpeterian invention is the discovery of new knowledge about natural phenomena. It is, primarily, the consequence of a "struggle between mind and matter" to gain insight about how the world works (Mokyr 1990, p. 10). Innovation in Schumpeter's terminology is the application of the existing stock of knowledge in new combinations and new ways to meet some human need. Schumpeter placed relatively little emphasis on invention, arguing that innovation was the primary source of economic advance. "Innovation is quite possible," he wrote, "without anything we should identify as invention and invention does not necessarily induce innovation, but produces of itself no economically relevant effect at all" (Schumpeter 1939, p. 84).

The distinction Schumpeter drew between invention and innovation is conceptually important, since the factors that influence invention are likely to be somewhat different from those that affect innovation. But we should not relegate invention to secondary status. It is true that in the short run, most economic progress derives from the application of existing knowledge in new ways, but without additions to the stock of basic knowledge, opportunities for innovation would eventually run into diminishing returns, and the pace of change would slow.

How Technology Evolves

Technology appears to evolve in two distinct ways, through gradual, incremental modifications in existing products and processes, and through discontinuous leaps in technology caused by the introduction of entirely revolutionary new innovations. While it is tempting to emphasize the introduction of revolutionary technologies like the railroad, electricity, the automobile, or the computer as the primary drivers of technology evolution, closer study suggests that impact of these major new technologies would be far less dramatic without the accretion of small, almost invisible improvements to the original technologies. Indeed few if any of the innovations we would characterize today as revolutionary appeared so momentous at the time they were first introduced (Rosenberg 1996).

One important reason for this is that radically new technologies are often quite primitive when they are first introduced, and this fact substantially limits their usefulness. In the case of the steam engine, for example, the earliest variants converted only a small fraction of the heat energy they consumed into mechanical effort. As a result they were only economical when located close to a source of fuel, limiting their usefulness to raising water from deep coal mines. At the beginning of the eighteenth century no one would have predicted the uses to which the steam engine would eventually be put, and it is worth recalling that it took several generations of largely anonymous improvement in techniques of manufacture and modification in design to reach a point where steam became competitive as a power source for factories. And it took more than a century from initial introduction until steam engines could be used to power railroads or ocean-going vessels.

The computer offers another example. The earliest electronic computers were developed in the 1940s. But these devices were large, prone to frequent failure, and extremely costly to operate. Given these limitations, Thomas Watson, Sr., the president of IBM forecast that worldwide demand for their services could be met by only a handful of the devices. Neither he nor anyone else at the time could have foreseen the ubiquity of computers today.

A second factor limiting the revolutionary impact of new technologies and making it difficult to forecast their ultimate impacts arises because of the interdependence of different technologies. What we see as an integrated technology, when fully developed, is often better understood as a system of mutually interacting innovations. Fully exploiting innovation A may require the development of technology B. If technology B does not exist, or is available only in a primitive state when technology A is first developed then the potential of technology A may not be immediately obvious.

An illustration of the way in which the value of a particular innovation is affected by other innovations is provided by the laser. Today lasers are used in a wide variety of applications, including long-distance transmission of voice and data, and to record and playback music, video, and other types of data. None of these applications could have been apparent at the time lasers were first developed. The use of lasers in communication required the development of fibre-optic cables capable of transmitting their signals, while the application of lasers in data storage and playback depended on a host of innovations in microprocessors, computers, and recording media.

On the one hand, these examples indicate that technology evolution is dependent on both incremental innovations and the emergence of revolutionary new technologies. Neither could exist without the other. On the other hand, they also suggest that technology evolution is inherently uncertain.

Long Swings and the Evolution of Technology

Closely related to the question of how technology evolves is the issue of the timing of innovation. A number of economists have documented cycles in the pace of economic growth of approximately 50 to 60 years in duration consisting of alternating periods of faster and slower rates of economic growth. These fluctuations are often referred to as *Kondratiev waves* after the Russian economist who was one of the first to call attention to the evidence of long-swings in a number of key economic indicators. Joseph Schumpeter (1939) argued that these variations in the pace of economic growth reflected cycles in the pace of innovation. According to Schumpeter periods of more rapid growth were initiated by the emergence of major new technologies or the *temporal clustering* of innovations, while slower growth cycles reflected periods in which the opportunities of these innovations had been largely exhausted.

The existence of Kondratiev waves, and their relationship to the timing of innovation remain controversial topics. Given the small number of cycles that can be observed in the available data, critics have pointed out that it may be premature to conclude that variations in the pace of growth reflect any sort of recurrent phenomenon. Instead they may simply reflect the impact of exogenous shocks to the economy. Similarly they have questioned the strength of the evidence linking variations in the pace of growth to innovations. Nonetheless, there are a number of scholars who continue to argue for the importance of long waves of innovation (see, e.g., Freeman and Soete 1997, pp. 19-21; Perez 2002).

The Sources of Technology Evolution

Where do new technologies come from? Many new innovations arise through a process of gradual, incremental modification. Much of this creativity comes from processes that have been characterized as *learning-by-doing* and *learning-by-using*. Kenneth Arrow (1962) introduced the notion of learning-by-doing to describe technology evolution that takes place at the manufacturing stage and consists of increasing skill in production. Through careful observation of production processes and incremental improvement arising out of these observations substantial advances in productivity are possible. Nathan Rosenberg (1982, ch. 6) identified a parallel process of learning-by-using, in which technology evolution arises out of experience gained by users of complex products, such as modern aircraft or computers. On the one hand, knowledge thatusers of complex products gain from experience helps them to identify more clearly which features of a product are most valuable and thus lead to improvements in design that are embodied in future production. On the other hand, experience with the use and maintenance of complex products may lead to changes in how they are used or maintained that result in cost savings or increased revenue without the need for modification of the product itself.

Despite the importance of incremental improvements, however, no amount of incremental innovation can give rise to dramatic new technologies. There is, for example, no way to arrive at the automobile through incremental improvement to the horse and buggy. It might seem that such discontinuous breakthroughs would be minimally influenced by economic considerations, but there are still important feedbacks between economic activity and invention. Scientific insight begins with the perception of a problem—an area in which understanding is incomplete, and where opportunities for advance may exist. Resolution of this problem hinges on the state of existing knowledge and systematic study, which lead ultimately to a new understanding. Economic incentives influence this process through their role in helping to identify problems in need of solution. Much of the basic science of thermodynamics, for example, emerged out of efforts to better understand the factors limiting the efficiency of steam engines. Similarly much of the science of solid-state physics emerged out of the work of scientists employed at Bell Laboratories who were motivated by the problem of increasing the reliability of the telephone system (Rosenberg, 1982, pp. 141-59).

In modern, capitalist economies innovation has become an essential function for most businesses. Rather than competing with one another to produce homogeneous products at the lowest price, important sectors of modern capitalist economies are characterized small numbers of producers who are motivated to seek a degree of monopoly power through innovation. This is the dynamic of *creative destruction* that Joseph Schumpeter (1942, pp. 83-86) identified as the "essential fact about capitalism." Each innovation creates a degree of market power that rewards the innovator with supernormal profits. But the innovator knows that this advantage is temporary, lasting only until the next innovation arrives. As a result commercial survival has come to rely on the regularization of the search for new innovations, and innovation has emerged as the chief form of competition for many businesses (Baumol 2002).

The Diffusion Curve

So far this essay has focused on the forces generating new technologies. But much technological change can occur without new technologies. At any point in time, most individuals and businesses are operating behind the *technological frontier*. Consequently the diffusion of innovations into widespread use is an extremely important topic.

Typically, the diffusion of new technologies follows an S-shaped, or logistic, *diffusion curve*. Figure 1 reproduces a number of illustrative examples plotting the number of users of selected technologies over time. As these diffusion curves suggest, the rate of adoption can vary considerably from one innovation to another. Table 2 makes this point even more clearly, showing the time in years from the invention of a variety of products (which may precede commercial introduction) to the time when one-quarter of the population had adopted them.

[Figure 1 about here]

Research on diffusion has offered a variety of frameworks to understand the origins of the diffusion curve as well as the factors governing its shape. Early efforts to understand diffusion grew out of the work of sociologists and anthropologists, and focused on the role of communication and information flow between individuals and communities. The premise of much of this work is that, once developed, a new technology is superior to the existing alternatives with which it competes. Therefore any delay in adoption occurs because potential users lack information, and are uncertain about whether the new technology will actually benefit them. The rate of diffusion then depends primarily on (a) the mechanism by which information is spread from user to user and (b) variation in the willingness of individuals to adopt novel and potentially risky new technologies.

[Table 2 about here]

In contrast to this focus on information, economists have tended to attribute the diffusion curve mainly to heterogeneity in the population of potential users. In this framework, individuals adopt the new technology as soon as it becomes optimal for them to do so. Because potential adopters differ in one or more characteristics that affect the value of the innovation them, however, not all of them will find the new technology immediately superior to the existing technology. In this case the S-shaped diffusion curve arises because of shifts in the cost-benefit calculation due to incremental improvement in the technology and/or changes in the characteristics of potential adopters.

Whichever framework one adopts the central empirical question in the study of technology diffusion concerns the factors that determine the speed with which a new technology is adopted. According to Hall (2005) the determinants of the rate of diffusion can be organized into three categories. The first set of factors center around the benefits that the new technology conveys relative to the alternatives. These reflect both the intrinsic benefits of the technology and network interactions between users. Where competing *standards* exist, or the likely dominant standard is not clear, adopters may delay their choice to avoid choosing the "wrong" technology, thus slowing the rate of diffusion. The second set of factors concern the costs of adoption, including direct costs of acquisition plus investments in other complementary equipment or training. The higher the cost of adoption, the more slowly potential users are likely to adopt the new technology. The third cluster of influences affecting the rate of diffusion involve market size and structure, and the regulatory environment in which decisions are made. Highly concentrated markets may encourage speedy adoption by reducing *network effects*, or they may slow adoption if dominant firms prefer to preserve the value of existing assets. The impact of regulation is similarly ambiguous. Regulators may require firms to adopt a new technology, thus speeding diffusion; or, as in the case of the U.S. cell phone industry, regulators may impose constraints that slow the adoption of new technologies.

Path-Dependence

It is convenient to separate discussion of the emergence of new technologies from their diffusion, but in reality these phenomena are often interrelated. Recently a good deal of attention has been devoted to the way in which small "accidents" early in the development of a technology can influence the way in which the technology ultimately develops. For this type of “path-dependent” development to occur three conditions must be met. There must be: (1) some kind of technical interrelatedness between individual users of the technology, (2) increasing returns to scale in the choice of technology, and (3) costs to switching between alternative technologies (David 1986). The prototypical example of path-dependence documented by Paul David (1986) concerns the development of the QWERTY-keyboard.

According to David the arrangement of keys on typewriter and subsequently computer keyboards is sub-optimal from a purely technical perspective. Thus its persistence constitutes a puzzle for economists who are inclined to believe that technologies are chosen to maximize profits. The answer, according to David, is that while the initial selection of the QWERTY arrangement was dictated by constraints imposed by early typewriter designs. Although these technological limitations that led to the QWERTY arrangement were quickly overcome, the keyboard arrangement they had dictated became locked-in because of the interrelatedness between decisions by typewriter manufacturers about keyboard lay-outs and decisions by typists about which keyboard layout to learn, and was reinforced by the economies of standardization on a single layout. Once this standard became established the stock of typists and typewriters made the cost of switching prohibitive and perpetuated the inefficient arrangement of keys into the present.

Path-dependence is most likely to arise in “network” industries, where the benefits of adopting a particular technology depend on the choices made by other individuals. For example, the value of instant messaging (IM) technologies depends on the number of other potential users who can be reached using a particular IM system.

When competing IM technologies are incompatible with one another, potential adopters will have to consider not only the features of the particular systems, but how many of the people with whom they wish to communicate have already adopted the same system. As a result, the choices of early adopters will influence the evaluation of later adopters and may result in the emergence of a single dominant technology.

The history of technology evolution offers a number of examples that appear to fit the requirements for path-dependent diffusion to occur. In addition to the QWERTY-keyboard, other examples include the competition between Windows and Macintosh operating systems for personal computers, the choice between VHS and Beta recording formats for video cassette recorders (VCRs), and the current competition between Blu-Ray and HD-DVD formats for recording high definition video discs.

In all of the above-mentioned cases, the choice of technology has been arrived at by an essentially unregulated process of market competition between alternative technologies, each being promoted by its own developers. In some cases a single de facto standard emerges. In others the market may be able to support a small number of alternative technologies. Alternatively, where the need for coordination is paramount, a standard setting body may be established to enforce coordination on different parties.

Path-dependence may also manifest itself in the realm of product design, where complex products involve the bundling of a variety of interrelated technologies. In these circumstances during the early phases of development there may be many different design variants. But over time one particular configuration often emerges as a *dominant design* (Utterback 1996, ch. 2). This particular configuration comes in effect to define how the particular product is supposed to look and operate. Although the configuration may arise initially out of technologically imposed constraints, it may eventually become a constraint on future innovation.

Path-dependence is an interesting feature of technology evolution because it implies that the choice of technology may depend on the distant past, and that the result may be inferior to other alternatives. As such path-dependence poses a significant challenge to the conventional economic view that competition tends to move the economy toward the most efficient allocation of resources.

While accepting the theoretical possibility of path-dependent evolution, some critics have argued that it is unlikely to arise in reality. Among the most vocal critics of David's arguments are Liebowitz and Margolis (1990). They have offered empirical evidence challenging David's assertion that the QWERTY-keyboard layout is inefficient, and argued on theoretical grounds that path-dependence is unlikely because the existence of a superior technology creates opportunities to profit that will encourage firms to find ways to internalize the network externalities. For example, those who will benefit from a superior technology can subsidize early adopters or provide low cost content to build up a larger user base. This appears to have been Apple's strategy in establishing the dominance of its iPod music player. By providing content at subsidized rates it has been able to establish a music format that is incompatible with other systems and lock-in its dominance in the market for portable music players.

The strength of the Liebowitz and Margolis argument depends critically on the continued development of competing technologies, however. If the early dominance of a particular technological choice results in the abandonment of efforts to develop alternatives, it is possible that potentially more promising technologies may be abandoned without ever having the opportunity to be developed to a point where their superiority could be observed. In other cases the costs of switching may simply be too high to allow a significant change. One can, for example, view the *co-evolution* of the automobile and land-use patterns in the United States as an example of this latter type of path-dependence. The sunk costs of the current arrangements would make it very difficult to shift to a greater reliance on mass-transit and higher density settlement patterns.

Closely related to the issue of path-dependence is the establishment of standards. One way to deal with the problems of coordination that network externalities create is through the establishment of standards. In some areas, cooperative standards-setting bodies have emerged to insure a degree of order in technological choices. This is true for example in the development of Internet Protocols. In other cases, however, de facto standards emerge through competition in the marketplace. Examples of market determined standards include the VHS videocassette format and the Windows operating system for personal computers.

The Geography of Technological Progress

Historically technology evolution has been characterized by a high degree of *spatial clustering*. New inventions and innovations occur in geographically localized clusters, and diffuse into wider use only gradually. This is apparent in the international divergence of technology since the Industrial Revolution. But it also operates within countries, where certain regions—e.g., the Silicon Valley area in California—tend to specialize in producing innovations.

In part clustering appears to reflect aspects of the way in which knowledge is produced and communicated. Much technological knowledge is not subject to codification and formal communication. Instead it remains tacit, and only incompletely reflected in written and graphic explanations (Nelson and Wright 1992). In the nineteenth century, for example, the early development of the American textile industry can be traced to the migration of skilled British mechanics with first hand knowledge of the production and operation of the machinery used in spinning cotton yarn. Even today there are manifestations of this localization of knowledge transfer. Studies of the rate at which later patents cite earlier ones show that patents produced in the same state are more likely to be cited than similar patents produced elsewhere.

Learning by doing and learning by using constitute another mechanism through which technological progress tends to be localized. In the early phases of development, as an innovation is evolving rapidly, there needs to be a significant degree of two-way interaction between technology producers and technology users. As a result the two groups tend to co-locate within a relatively confined geographic region. For example, in the early nineteenth century United States textile production clustered in New England where key innovations in textile machinery were introduced rather locating near the sources of raw materials in the southern region of the country. Similarly, although early automobile manufacturing activities were spread across much of the northeastern and Midwestern United States, the industry very quickly became concentrated around Detroit where several of the key innovators in the industry happened to be located.

Scholars have noted that this clustering represents the first phase of a characteristic *technology life-cycle*. As a technology matures, it becomes increasingly standardized and the need for frequent interaction between technology producers and technology user diminishes. As a result the value of locating production close to the sources of innovation diminishes and manufacturing is likely to move to areas where labor costs are lower. Thus in the late nineteenth century the U.S. textile industry migrated from relatively high wage New England to the South. Now the industry has again relocated to even less expensive manufacturing locations overseas.

Another explanation for spatial clustering arises from *economies of agglomeration*. One important source of cost savings when economic activity is concentrated in a particular location is the benefit that workers possessing highly specialized skills and employers seeking such workers get from the size of the labor market. As the number of workers possessing specialized skills increases it becomes easier for innovating firms to find workers with the particular skills they require. By the same token, the concentration of employers at a single location increases the probability that workers will find employment that matches their skills. A second source of agglomeration economies arises from the ability of larger markets to support the development of specialized providers of inputs and services needed by innovating firms. These include legal and financial services as well as rapid prototyping and fabrication. Finally, because of the interdependent nature of production, highly skilled workers may find that working with other comparably skilled workers raises their productivity.

The existence of agglomeration economies is generally self-reinforcing. As in the case of path-dependent technology evolution positive feedbacks mean that initially small locational advantages tend to be magnified over time. Once a particular location develops an advantage vis-à-vis other locations, it will tend to grow even larger, and its advantage will increase. Only when these attractions begin to be balanced by other rising costs—such as land prices—will this effect be moderated.

Technology Transfer

The spatial clustering of innovation and the resulting geographic variation in technological evolution creates the potential for significant gains through the transfer of technology from more- to less-advanced countries or regions. Information about new products or processes of production is a *non-rival good*. That is, the use of this information by one economic actor does not diminish the ability of other economic actors to use it. Once it has been produced the knowledge does not need to be produced again. The only cost is the expense of communicating this knowledge. Yet historical experience reveals that the pace of technology transfer is highly uneven.

By the middle of the nineteenth century there already existed a highly developed international flow of information about production techniques between developed economies. Although the United States was a net importer of innovations from more advanced European countries throughout the nineteenth century, by the early 1850s it had begun to forge ahead in a number of areas, including the production of fire arms, clocks and other items requiring precision manufacturing of standardized parts. These achievements quickly captured European attention, and led to a number of delegations of skilled mechanics touring U.S. factories and working to import American ideas into

Europe. Since this time the speed and density of these information flows has increased substantially.

Manufacturing techniques developed in Europe and the United States have flowed much more slowly to countries in other parts of the world, however. The reasons for these disparities in the transfer of technology are profoundly important since the transfer of more advanced technologies holds the promise of substantially improving living standards among the world's poor. The fact that progress has been limited and the poverty of some nations remains intractable suggests the complexity of the problem. Although scholars of this topic cannot offer easily implemented policy advice they have made progress in identifying the factors that influence the international movement of technology (Nelson and Wright, 1992).

To begin, we have already noted that communicating technological knowledge at a distance is far from costless. But this cannot be the entire explanation. A second important characteristic influencing the pace of technology transfer is the ability and willingness of receiving countries to borrow technology. Countries that have been successful in importing advanced technologies are characterized by investments in human capital that have prepared their workforce to adopt new technologies; and equally important they are open to borrowing ideas from abroad. In the case of Japan, the opening to and adoption of western technologies was a very conscious decision; and one that contrasts with the Chinese effort in the nineteenth century to close themselves off from contact with the West.

A third factor affecting the pace of technology transfer is the co-evolution of technologies. The usefulness and value of many technologies is highly dependent on their interaction with other technologies. Relatedly, demand for particular types of goods is closely tied to income levels and other characteristics. Consequently it is not possible to transfer technologies piecemeal. An illustration of this phenomenon is provided by the simultaneous development of techniques of mass-production and the emergence of the modern, vertically-integrated, multi-division corporate form of business organization in the United States around the turn of the twentieth century. That these innovations emerged first in the United States reflects the fact that they were well adapted to the large, politically and economically integrated, and relatively wealthy U.S. economy. Europeans were well aware of these innovations and were not prevented from adopting them at the time. That they did not was due largely to the fact that they sold to smaller markets characterized by more unequal income distribution. After the Second World War, however, when the creation of the European Community and efforts to reduce trade barriers combined with transportation improvements to substantially expand European firms' access to markets, American manufacturing and management techniques spread quickly across Western Europe.

Conclusion

Technology evolution occurs through the expansion of the stock of useful knowledge and its application to the fulfillment of human needs. This is a process that is as old as human history. But the pace of change has accelerated dramatically over the past three centuries. Scholarship seeking to understand this phenomenon can be divided roughly into two themes. The first concerns the production of inventions and innovations. The central questions here concern the factors that determine the pace and characteristics of innovation, including the uneven distribution of innovation in space and time. The second set of concerns relates to the diffusion of innovations once they have been developed. Within this general theme studies have focused on the speed of diffusion, the role of path-dependence and factors that either encourage or inhibit the international transfer of technology.

Many scholars of the subject would argue that technology evolution is the defining characteristic of modern capitalist economies. Understanding of precisely how capitalism and technology evolution are connected remains incomplete, but given the importance of technology evolution to rising living standards and the solution of social problems continued study of these issues appears essential.

Table 1: Time Required to Earn Selected Items, 1895-2000

	Labor Time Required to Earn (in hours)		
Commodity	1895	2000	Productivity Multiple
One-speed bicycle	260	7.2	36.1
Horatio Alger (6 vols.)	21	0.6	35.0
100-piece dinner set	44	3.6	12.2
Cushioned office chair	24	2.0	12.0
Hair brush	16	2.0	8.0
Cane rocking chair	8	1.6	5.0
Solid gold locket	28	6.0	4.7
Encyclopedia Britannica	140	33.8	4.1
Steinway piano	2400	1107.6	2.2
Sterling silver teaspoon	26	34.0	0.8

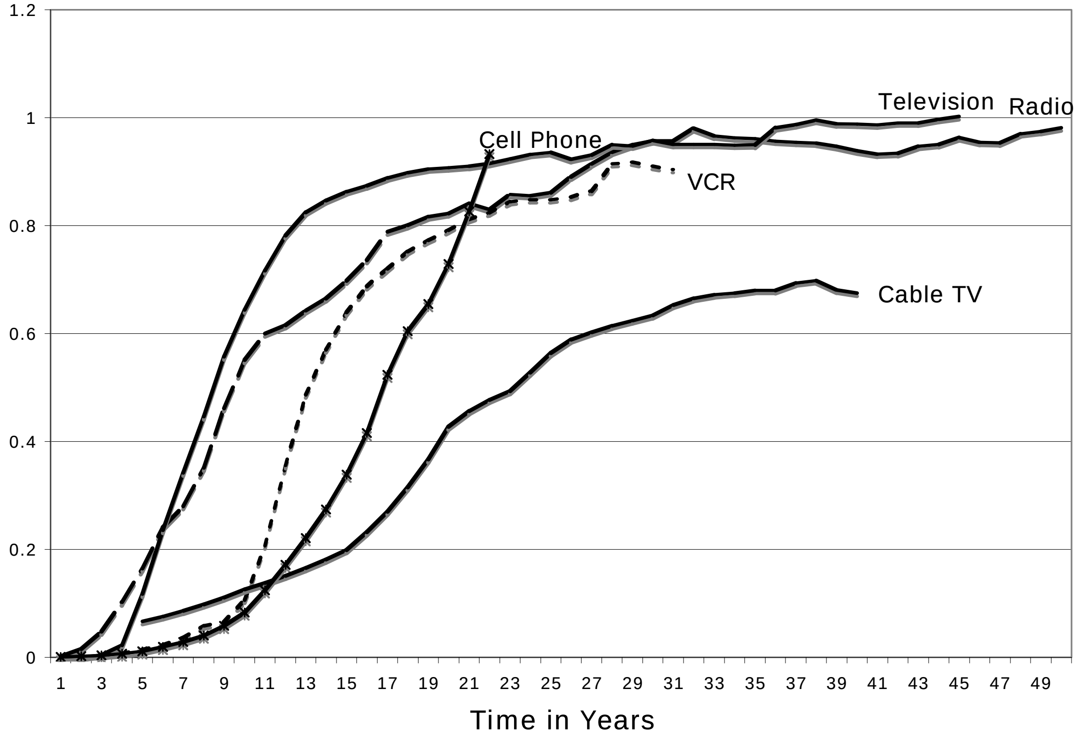
Source: DeLong (2000, p. 5).

Table 2: Years from Invention to Diffusion to One Quarter of the Population

Product	Year Invented	Years to Diffuse to One Quarter of the Population
Electricity	1873	46
Telephone	1876	35
Automobile	1896	55
Airplane	1903	64
Radio	1906	22
Television	1926	26
VCR	1952	34
Microwave oven	1953	30
Personal Computer	1975	16
Cellular phone	1983	13
Internet	1991	7

Source: Federal Reserve Bank of Dallas (1996 p. 14)

Figure 1



Source: Carter, et al (2006, series Ae 1-28, Dg 34-45, Dg 103-105, Dg 117-130); U.S. Census Bureau (2007)

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Definitions of Key Terms

Bell Laboratories: The research organization of AT&T (American Telephone & Telegraph). Formed in 1925, its principal focus was on design and support of equipment supplied to the Bell System operating companies. Bell Laboratories emerged as one of the nation's leading R&D labs during the middle decades of the twentieth century.

Co-evolution: when two technologies evolve in together in such a way that developments in one influence the course of development of the other and vice versa.

Creative destruction: the process of industrial transformation by which successive waves of innovation create value while undermining the basis of established companies.

Diffusion curve: a graph showing the percentage of a population of potential adopters who have selected a given technology as a function of time since the introduction of the technology.

Dominant design: a specific configuration of a complex product defines how the particular product is supposed to look and operate.

Economies of agglomeration: Cost savings that arise when an economic activity congregates in or close to a single location, rather than being spread out uniformly over space.

Gross Domestic Product (GDP): the monetary value of all final goods and services produced within the boundaries of a country during a set period of time such as a calendar quarter or year.

Innovation: the application of the existing stock of knowledge in new combinations and new ways to meet some human need.

Invention: the discovery of new knowledge about natural phenomena.

Kondratiev waves: recurrent cycles or wave-like fluctuations in economic aggregates with a period of approximately 50 to 60 years.

Labor productivity: the quantity of output that is produced per unit of labor input.

Learning-by-doing: improvements in productivity resulting from experience gained through producing a given product.

Learning-by-using: improvements in productivity resulting from experience gained using a technologically complex product.

Living standards: the level of well-being that can be achieved by an individual or household per unit of labor effort.

Lock-in: a situation in which a particular technology becomes dominant despite other potentially more economically efficient alternatives. Lock-in may occur other because of sunk costs or because of external economies and a lack of coordination mechanisms that prevent individuals from switching to the superior technology .

Network effects or externalities: the mechanism through which the value of a service becomes more valuable to each user as additional users are added.

Non-rival good: a product whose use by one individual does not affect its value or utility to other consumers. For example, each listener to a radio broadcast receives the same benefit regardless of the number of other listeners.

Path dependence: the idea that decisions taken in the past limit the scope of contemporary choices.

Purchasing power: the quantity of goods and services that can be purchased with a given quantity of money.

Spatial clustering: the concentration of technological innovations or other economic activities in certain geographically confined locations in greater numbers than would be expected based on the distribution of population or economic activity alone.

Standards: explicit or implicit specifications or rules regarding important aspects of a technology which facilitate interoperability, safety, reliability, or other characteristics of a technology.

Technological frontier: the most advanced instances of a particular technology.

Temporal clustering: the bunching of innovation at certain points in time and not at others.