

Communications and economic growth

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Abstract

Over the past millennium, each of the three centuries of most rapid demographic growth in the West coincided with the diffusion of a new communications technology. This paper examines the hypothesis of Harold Innis (1894–1952) that there is two-way feedback between such innovations and economic growth. First, detailed historical evidence is studied. Second, Innis's ideas are translated into a formal growth model. Finally, the model is simulated and its predictions compared with historical data. The results suggest a technological explanation for the long cycles of the period 1000–1975 and for the puzzling productivity growth slowdown in industrialized countries after 1975. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Visitors to Paris are generally taken to see Notre Dame Cathedral, the Louvre, and the Eiffel Tower; those who go to London usually do not miss Westminster Abbey, Hampton Court, and Big Ben. These buildings belong to Western Europe's legacy from three centuries of exceptionally rapid growth

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compared to the rest of the past millennium.¹ Yet neoclassical growth theory has no satisfactory explanation for the very long cycles that such evidence implies.

Some fifty years ago, the Canadian economic historian Harold Innis argued that two-way interaction between a society's production system and its communications technology generates very long growth cycles. Innis's writings on possible links between communications and economic growth have lain dormant since his death in 1952.² Why might they be worth dusting off for a contemporary audience? Unlike neoclassical growth theory, Innis's ideas offer a possible explanation for prolonged periods of decelerating growth, such as the puzzling slowdown in productivity growth that occurred in industrialized countries during the 1970s and 1980s. The object of this paper is to reexamine Innis's theory in the light of recent historical and theoretical research.

The neoclassical theory of economic growth developed in the 1950s and 1960s predicted the gradual convergence of an economy to a steady-state rate of growth determined by exogenous technological change. Beginning in the early 1970s, however, all of the major industrialized economies experienced a sudden sharp slowdown in rates of total factor productivity growth compared to the immediately preceding decades. In the case of the United States, for example, average annual GDP growth declined from 3.72% between 1950 and 1973 to 2.32% between 1973 and 1984.³ Well over half of this decline remains unexplained by neoclassical growth accounting, even when structural changes, crime rates, energy prices and factor-augmenting technical progress are taken into account (Maddison, 1987, p. 679). Nor do recent models of endogenous growth offer much help in explaining the slowdown. They predict a *rise* in the growth rate over time due to the accumulation of knowledge and the widening of the market (Lucas, 1988; Romer, 1990).

A paradoxical feature of the productivity-growth slowdown of the 1970s and 1980s is that it coincided with very rapid innovation in information technology. Throughout this period, the integrated circuit, first developed in 1959, was reducing the cost of information storage by about 30% annually (Forester, 1987, p. 27). Was it simply a coincidence that a high rate of innovation in a communications technology was accompanied by a fall in productivity growth rates?

A look at other long periods of decelerating growth might provide a clue to a possible relationship between communications and growth. For the years

¹ The exceptional centuries are the years 1150–1250, 1500–1600, and 1800–1900.

² Dudley (1995) offers an introduction to Innis's writings on communications.

³ As is evident in Fig. 1, the postwar growth rate was exceptionally high compared to the nineteenth century. Thus, the slowdown after 1975 might be seen simply as a return to the previous long-run growth path. This paper will offer an alternative explanation in which the underlying rate of technological change itself rises over time.

prior to 1750, there are no reliable estimates of aggregate production for most Western countries. However, more recent data from the nineteenth and twentieth centuries shown in Fig. 1 indicate that growth of output tends to follow approximately the same cycle as population. A possible explanation for the observed correlation is that a society will develop a long-term rule for dividing increased output between higher per-capita income and the support of additional population.⁴

Accordingly, the data for demographic growth in Western Europe over the last 1000 years shown in Fig. 2 may be considered an approximate indicator of swings in the rate of output expansion. From this very long-term perspective, a number of features stand out. First, it is evident that there have been three cycles, one from the beginning of the millennium to the mid-fifteenth century, another running from the renaissance until the mid-eighteenth century, and yet another from then until the third quarter of the present century. Moreover, each cycle appears to have had three phases; namely, an initial period of relatively slow growth, a second of acceleration and deceleration, and a final phase of relatively slow growth if not actual decline. Finally, the cycles differ from one another. Not only does their length decrease over time, from about 450 years to 300 years to about 225 years; but also the underlying rate of growth accelerates, from a barely perceptible annual rate of one-twentieth of 1% to three-tenths of 1% to about six-tenths of 1%.

Economic historians have tended to interpret these cycles as the result of innovation clusters in production and transportation technology. In the high Middle Ages, it is argued, the iron plow, the horse collar and the three-field system permitted a steady rise in agricultural productivity. In the fifteenth century, the compass, the sternpost rudder, and the lateen sail reduced the cost of long-distance maritime transport. And finally, in the nineteenth century, the steam engine and new techniques for producing steel, textiles and chemicals generated a long rise in industrial output (Mokyr, 1990; Cameron, 1993, pp. 51–54, 99–103, 197–210). The principal difficulty with this explanation is that for almost a millennium this growth was confined to Western Europe and regions settled by Europeans (Jones, 1987). Indeed, two centuries after the beginning of the industrial revolution, modern economic growth remained limited to a fifth of the world's population (Kuznets, 1966, p. 469). This simple fact suggests that there must be some other conditions that are necessary, and perhaps also sufficient, to generate accelerated growth.

Some idea of what these conditions might be is offered in the theory of historical change developed by Harold Innis during the last years of his career.

⁴ Jones (1987, p. 226) has suggested that because the frequency of natural disasters is lower in Europe than in Asia, European societies have tended to devote a smaller share of output gains to producing more children than their Asian counterparts.

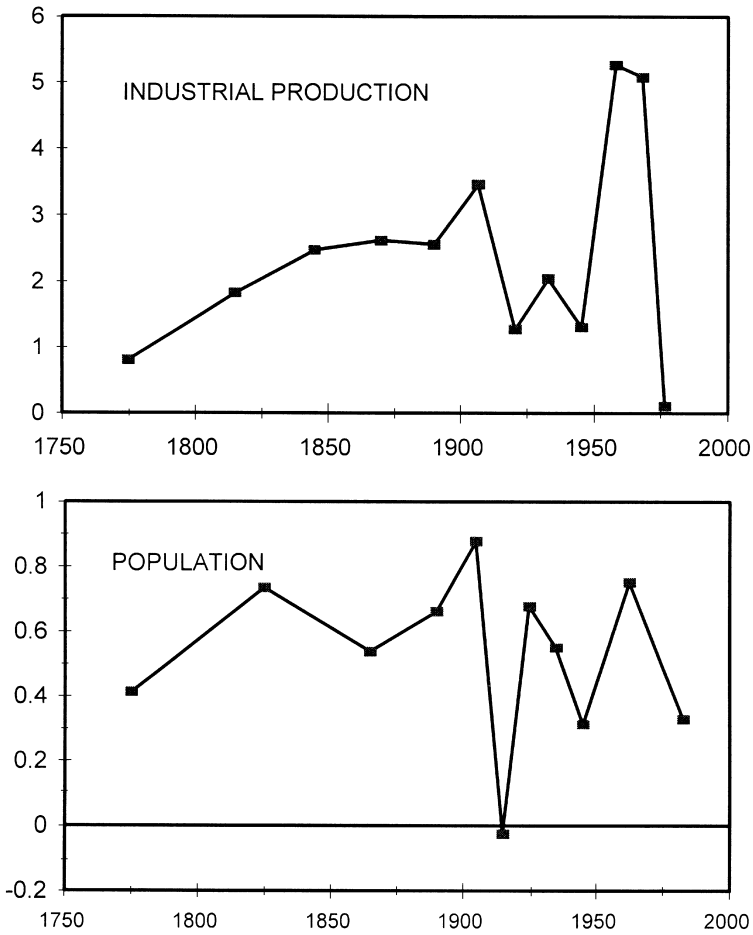


Fig. 1. Growth of industrial production and population, Western Europe, 1750–1990, annual rates in present. Sources: P. Bairoch, 1982. International industrialization levels from 1750 to 1980. *Journal of European Economic History* 11, 292, 299; W.S. Woytinsky and E.S. Woytinsky, 1953. *World Population and Production: Trends and Outlook*. Twentieth Century Fund, New York, p. 44; United Nations Demographic Yearbook, 1991, New York, p. 103.

In *Empire and Communications* and the initial essays of *The Bias of Communication*, he proposed a three-phase theory of the impact of a new communications technology on economic activity.⁵ To understand Innis’s hypothesis, consider a moment at which a single technology has come to dominate the

⁵ Neill (1972) assessed Innis’s writings on communications, evaluating them with respect to Innis’s earlier historical research on the staple theory.

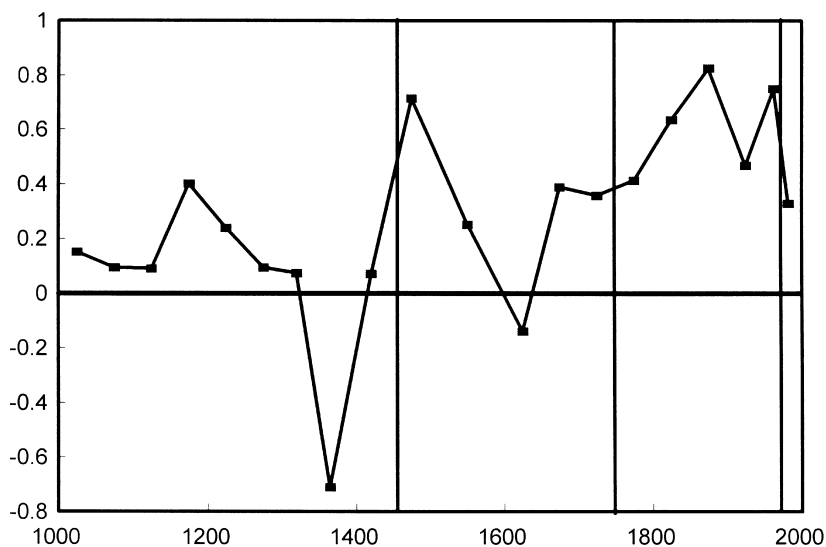


Fig. 2. Growth of population, Western Europe, 1000–1990, annual rates in percent. Sources: 1000–1800, H. Ott and H. Schäfer, 1984. *Wirtschafts-Ploetz*. Verlag Ploetz, Freiburg, p. 292, 299; 1800–1990, see Fig. 1 above.

communications system of a society. Innis argued that since the group that controls this medium will tend to charge a monopoly price for access to it, the high cost of information will encourage innovative activity. For example, he wrote, from the first century BC, the Romans monopolized the use of papyrus through their control of its production sites in Egypt. They used this mastery to build up a centralized bureaucratic administration that dominated the Mediterranean basin. However, in the early centuries AD, improvements in the technique for producing parchment, which could be made from animal skins virtually anywhere, broke this monopoly (Innis, 1950, pp. 140–141).

Second, Innis proposed, if these attempts to innovate are successful, there will be a subsequent phase during which the new technology is diffused widely. Initial success will occur in marginal areas where the power of the controlling group is weak. In the early middle ages, for example, parchment production established itself in the British Isles. Subsequently, the new technique will challenge the previously dominant medium. With the fall of Egypt to Islam, he argued, papyrus supplies to Europe were cut off. Accordingly, the use of parchment spread to the northern parts of the continent (Innis, 1950, pp. 48–49). It is during the phase of balance where two or more media coexist, that welfare

will be highest.⁶ Innis noted the beneficial effects of coexistence of papyrus and parchment under the Byzantine Empire and the later impact of competition between parchment and paper on trade and urban growth in Western Europe (Innis, 1951, p. 53, 64).

In the third and final phase of the cycle, the successful new medium attains a monopoly position. Innis suggested that each medium will have its own characteristics or 'bias' (Innis, 1951, p. 33). Papyrus being light, easily transportable, and perishable was suited to the needs of a centralized administration concerned with expansion through space. Parchment, with its weight and durability, produced a bias in terms of conserving information over time (Innis, 1950, p. 7). Once the new medium has displaced the old, a new monopoly will be created and economic progress will again be stifled (Innis, 1951, p. 34).

In studying these arguments today, one quickly discovers that Innis's historical information is not always accurate. For example, papyrus was not the brittle, fragile material that he portrayed it to be (Roberts and Skeat, 1983, pp. 6–7). Moreover, the replacement of papyrus by parchment in Western Europe was gradual, beginning well before the seventh century. And papyrus continued to reach Europe for centuries after the Arab conquest of Egypt in 641 (Roberts and Skeat, 1983, p. 8).

In addition, there seems no strong evidence to support Innis's argument that innovative activity is triggered by monopoly pricing for access to existing media. For example, Innis wrote that at the end of the middle ages, 'monopolies of knowledge controlled by monasteries were followed by monopolies of knowledge controlled by copyist guilds in the larger cities. The high price for large books led to attempts to develop a system of reproduction by machine and to the invention of printing' (Innis, 1951, p. 53). While there might well have been some monopoly rents in the price of manuscripts in certain towns in the late middle ages, the high price of such documents would seem to be attributable primarily to the scarcity of skilled labor for reproduction by hand (Cardwell, 1972, p. 20).

Finally, one must ask whether Innis's ideas constitute a theory; i.e., a set of consistent statements that lead to falsifiable predictions. Previous attempts to assess his final works have concluded that they contain no consistent causal structure (Neill, 1972, p. 96; Christian, 1977, p. 29). Nathan Rosenberg has set out the conditions that a theory of long cycles must satisfy. 'A technological theory of long cycles needs to demonstrate that [inventions, innovations, diffusion paths and investment activity] interact in a manner that is compatible with the peculiar timing requirements of such cycles' (Rosenberg, 1994, p. 68). Does Innis' theory fulfil these conditions?

⁶ Recently, De Long and Shleifer (1993) have found a positive correlation between the degree of political competition and the rate of population growth in European cities over the period prior to 1800. Innis's theory of communications offers an explanation for this phenomenon: both rapid growth and institutional competition are characteristic features of the second or diffusion phase of Innis's hypothesis.

The remainder of this paper examines these issues. The following section studies the historical evidence for a possible causal link running from communications technology to economic growth with the help of a simple framework based on Innis's writings. Section 3 then examines the possibility of feedback in the opposite direction, from the price system to innovation in communications techniques. It attempts to model Innis's hypothesis that from the beginning of each growth cycle a small number of induced technological breakthroughs channel subsequent technological change in a specific direction. Finally, Section 4 simulates this model over the past millennium and compares its results with observed population growth rates for Western Europe.

It should be emphasized at the outset that this paper is not seeking a unique source for all fluctuations in output in the West over the past millennium. Rather, communications technology is examined as one of the fundamental structures around which the European economy has been organized.

2. The economic impact of new media

In any society, the communications structure must accomplish several different tasks. One of Harold Innis's important contributions to communications theory was to note that each medium is capable of doing some of these tasks well and others less adequately. This section examines the effects of major transformations in the characteristics of Europe's communications system on its rate of economic growth.

2.1. *Time, space and number*

When Innis argued that certain media were appropriate for the dissemination of information over *time*, he was in effect saying that with such media the cost of *storing* information is low. As a result, information can be transferred accurately from any moment to a later one. Other communications techniques are clearly more appropriate for dissemination over *space*. Here the key feature is low *transmission* costs from the center of the administrative unit to its periphery. Although Innis devoted most of his attention to these two dimensions of communications technology, he was well aware that a simple time–space dichotomy could not capture all of the essential features of a communications medium. In the introduction to one of his last essays, 'The problem of space', he briefly mentioned an additional concept that he placed on the same level as time and space; namely, *number*.⁷ When a complex system of communication is

⁷ At issue, Innis realized, is the complexity of the communication system. "A complex system of writing becomes the possession of a special class and tends to support aristocracies. A simple flexible system of writing admits of adaptation to the vernacular but slowness of adaptation facilitates monopolies of knowledge and hierarchies" (Innis, 1951, p. 4).

replaced by a simpler one, he argued, there is deeper penetration into the society. What was formerly reserved for an elite becomes accessible to a much wider segment of the population. Translating this notion into more familiar terms, we realize that Innis was concerned with the cost of *decoding* information. For given storage and transmission costs, the ease of translating coded messages into understandable form will determine the probability that any two individuals in a society can communicate effectively with each other.

Consider how these ideas might be expressed more formally. Assume an economy in which individual workers may use their acquired skills to produce a homogeneous good using a Cobb–Douglas production function. In any period τ , total output, q_τ , is an increasing function of the total population, n_τ . Because of the impact of knowledge on productivity, output also increases with the amount of information stored. Under competitive factor markets, this amount is inversely proportional to the cost, s , of storing a unit of information over a unit of time.

$$q_\tau = \left(\frac{n_\tau}{s_\tau}\right)^\alpha \left(\frac{1}{t_\tau}\right)^\beta \left(\frac{n_\tau - 1}{d_\tau}\right)^\gamma. \quad (1)$$

If there are scale economies to joint production, output is also decreasing in the cost, t , of coordinating workers by transmitting a unit of information across a unit of distance. Finally, because, as North (1981) has explained, the efficiency of markets depends on people's ability to negotiate and enforce contracts, output is decreasing in the cost, d , of decoding a unit of information. Owing to network effects, this transaction cost is offset by increases in the number of other people, $n_\tau - 1$, with whom each individual can communicate.⁸

2.2. Three network structures

How do the costs of these three dimensions of communication affect a society's production structure? Consider three polar examples. Assume first that transmission costs are low relative to storage and decoding costs. Neoclassical production theory predicts that transmission will be substituted for decoding and storage. The latter two functions will tend to be concentrated in a central node, with information being transmitted from this node to stations on the periphery. In other words, the society will have a centralized communications network such as that illustrated in Fig. 3a.

Suppose that storage costs now fall relative to decoding and transmission costs. Then it will be economical to decentralize storage, with multiple local nodes replacing the single central node and a reduction in distances over which

⁸ In Katz and Shapiro (1985), network externalities reduce the hedonic price of a consumer good. Here they increase the productivity of a factor of production.

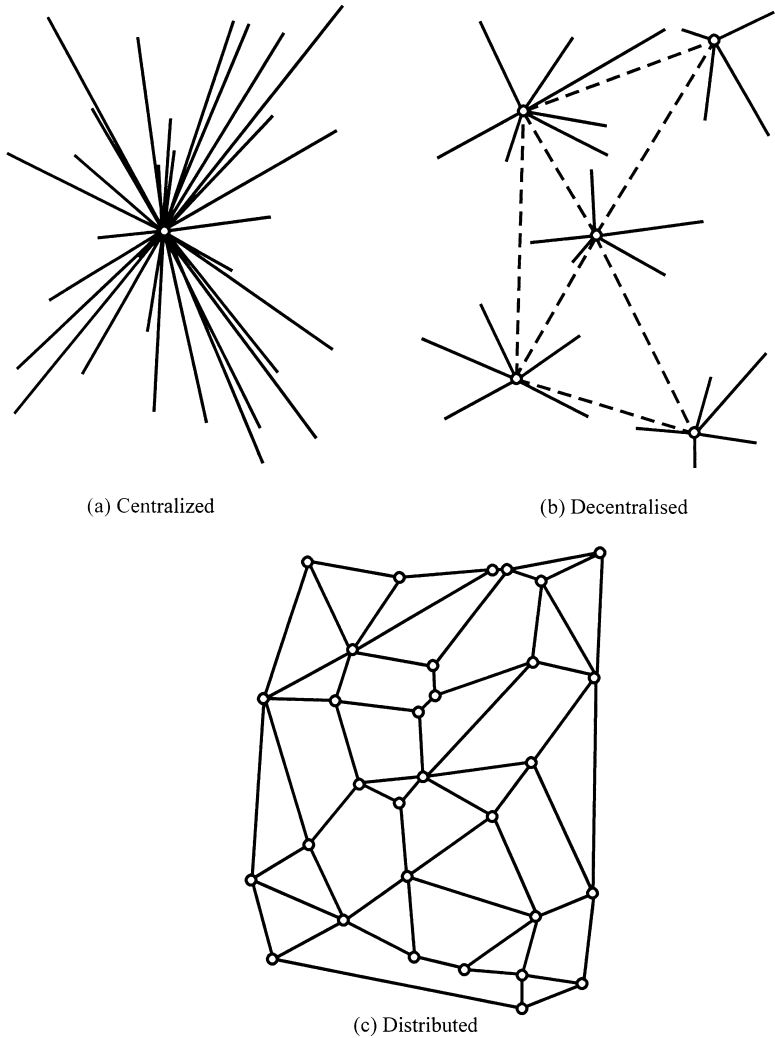


Fig. 3. Three network structures.

information is transmitted. Because of the continued high cost of decoding, however, there will still be intermediation at the nodes between the producers and users of knowledge. The result is the decentralized structure shown in Fig. 3b.

Finally, let decoding costs fall relative to transmission and storage costs. Any station on the network may then produce information that may be used directly

by any other station. In the distributed network shown in Fig. 3c, each station is a node connected to several other nearby stations.⁹

2.3. *Communications technology and long-term growth*

What has been the relationship, if any, between Europe's communications technology and its rate of economic growth over the past millennium? In the early eighth century, vigorous mayors of the palace from the eastern part of the Frankish lands (Austrasia) managed to obtain control over much of Northern Europe. At that time, literacy levels were very low; consequently, it was expensive not only to store information accurately over time but also to decode it at a later date.¹⁰ However, information could be transmitted orally at relatively low cost to a group of assembled individuals. Until the eleventh century, the oral command of the ruler took precedence, with written notes serving primarily as a reminder for later recall of the content of the spoken language (Stock, 1983, p. 13). As a rough measure of economic output, one should note that Western Europe's population in the eighth century was lower than it had been under the early Roman Empire (Russell, 1985, p. 36).

With information transmission costs low relative to storage and decoding costs, the model set out above predicts the use of a centralized information network. Under the Frankish ruler Charles Martel (688–741) and the first three generations of his descendants, decision-making was in fact centralized in an itinerant court. Since the essential contacts were oral, the king spent much of his time on a circuit that brought him periodically into personal contact with his principal subordinates in each region of his realm (Ganshof, 1971, pp. 257–258; Reuter, 1991, p. 86). For general policy, Charles Martel's grandson, Charlemagne, convened his some 250 counts annually; for more urgent administrative matters, he used a system of *missi dominici* (royal messengers) (Heer, 1975, p. 39).

A fundamental change that lowered information *storage* costs in Western Europe appears to have begun around 800. Clerics associated with the court of Charlemagne developed a standardized form of spoken and written Latin (Wright, 1982; McKittrick, 1994). From the year 1000 onward, as this new medium began to be generally adopted, there occurred in European society what Brian Stock (1983, p. 3) has described as the 'rebirth of literacy' Society passed from a mode of interaction in which oral communication took precedence to one in which written texts structured social behavior. Between the

⁹ Hafner and Lyon (1996, pp. 58, 59) cite a seminal 1960 paper by Paul Baran of the RAND Corporation comparing these three structures of information networks.

¹⁰ The number of charters and diplomas had sunk to 'an alarming level' (Brown, 1994, p. 8). Lay education had become increasingly rare: in northern Europe, urban schools had completely disappeared (Graff, 1991, pp. 40–46).

eleventh and thirteenth centuries, written forms of the vernacular languages began to be used with increasing frequency (Stock, 1983, p. 25).

Innis's theory predicts that a reduction in storage costs will lead to a decentralization of economic activity. From the ninth to the mid-tenth centuries, there was indeed a disintegration of centralized power, as the initial diffusion of the new medium disrupted the previous oral structure of authority. When new institutions emerged, in the early eleventh century, they did so at the level of the county or duchy. Under the contractual ties of feudalism, exclusive rights to large properties were recognized for individuals and their descendants in exchange for military service. The custom of liege lordship, by which one of the lords from which each noble held property took precedence over the others began to crystallize in the 1040s in Western France (Poly and Bournazel, 1991, pp. 138–143).

With property rights secure, landowners had an incentive to increase productivity. The famous innovations of medieval agriculture – the horse collar, the wheeled plow and the three-field system – were all known at the time of Charlemagne (Mokyr, 1990, Chapter 3). However, as Georges Duby has shown, their use remained limited in Northern Europe until the twelfth century.¹¹ Although it was in the interest of all landholders to adopt the new technologies, because of the difficulty of changing established practices, diffusion of the new techniques was easiest on newly cleared land.¹² Many secular lords made large grants of land for the opening of new monasteries. As the principal centers of literacy, they had the administrative techniques required for efficient agricultural administration. In the Romance-speaking regions, it was the Benedictine monasteries associated with the house of Cluny, that took the lead in the new colonization movement.¹³

Another change, the substitution of written for oral contracts, facilitated the growth of trade. In eleventh-century Italy, the appearance of a new official, the *iudex* or literate lay notary, made possible a shift from oral to written law (Stock, 1983, p. 41). Not only did written documents permit the systematic prosecution of individual merchants who failed to respect contracts, but also they allowed collective sanctions against rulers who reneged on their commitments, as modeled by Greif et al. (1994).

¹¹ See Duby (1974, pp. 189–194). In Britain, too, diffusion was delayed: there is no unambiguous evidence of the use of plows with a moldboard until the twelfth century (Wailles, 1972, pp. 163–167).

¹² With the Mediterranean scratch plow, fields tended to be square, since it was necessary to plow in both directions; but with the heavy plow, rectangular fields were preferred because they reduced the number of times the plow had to be turned (White, 1962, pp. 42–43).

¹³ Duby (1974, p. 214) writes that from the late eleventh century, the great Benedictine monasteries “meticulously drafted manorial surveys: *censiers* (*censarii*) recording burdens on land, and ‘customaries’ (*consuetudinarii*) establishing lists of banal exactions”.

The fall in information storage costs clearly preceded the great population upswing of the high Middle Ages. Between 1000 and 1340, the population of Western Europe more than doubled. At the same time, there was a widespread movement from the countryside to the towns. At the time of Charlemagne, there had been only two large cities (Rome and Naples) in Latin Christendom. Even in 1000, there were only four cities (Rome, Venice, Regensburg and Salerno) with populations of 35 000 or greater. Yet by 1300, there were 18 cities on this territory with populations of 35 000 or more (Bairoch et al., 1988).

By the early fifteenth century, after the introduction of paper into Europe, the cost of storing information in easily retrievable standardized code was remarkably low by the standards of earlier eras; however, only a small portion of the population was able to *decode* that information. In England, for example, fewer than 10% of men and 1% of women were able to read (Cressy, 1980, p. 176). A first step in solving this problem was taken in 1455, when Gutenberg and his associates used movable metal characters to produce a 42-line Bible. In a stroke, the marginal cost of reproducing information fell to one three-hundredth of its former level (Eisenstein, 1980, p. 46).¹⁴

Yet the availability of low-cost printed material was not sufficient to relieve the decoding bottleneck. For the first 50 years, the diffusion of the new technology remained limited largely to the few who could read and write in Latin.¹⁵ The second step was to adapt the printing press to the vernacular languages. By 1515, the appearance of texts in standardized printed versions of the spoken word had become sufficiently important for the papacy to impose censorship on all works translated from Latin into the vernacular (Hirsch, 1974, p. 90). As a final step, people had to be taught to read. In 1522, Luther began to translate the Bible from Latin into the high-German dialect spoken in the Saxon court. His insistence that his followers learn to read the scriptures printed in their native tongue served as a model for other Protestant leaders.¹⁶ The effect of making available inexpensive material printed in a language close to that which people spoke in their everyday lives was to reduce the cost of decoding stored information. By the early seventeenth century, about 10% of women and 30% of men in England were able to read and write (Cressy, 1980, p. 177).

The theoretical model predicts that a fall in decoding costs will reduce the need for intermediation, allowing each station in a network to become a node. This process seems to have occurred in Northern Europe as literacy rates rose.

¹⁴ In the place of parchment, the new printing industry used paper, production of which had been introduced into Europe from China in the fourteenth century.

¹⁵ It has been estimated that three-quarters of all texts printed in Europe before 1500 were written in Latin (Steinberg, 1955, p. 81).

¹⁶ By the end of the sixteenth century, a majority of works were being published in languages other than Latin (Hirsch, 1974, p. 132).

With the fall in decoding costs, a rising portion of the population was drawn into the distributed network of the market economy. Owing to the gains from specialization, it was possible to feed a larger population with the same resources. Shortly before 1500, Western Europe's population had been at the level of the early fourteenth century. By 1600 it had surpassed that level by one-third.

With these improvements in the decoding of information, the cost of *transmitting* multiple copies of a message in a short time became the principal bottleneck to the flow of information. In 1700, owing mainly to the high cost of gathering and distributing information, neither London nor Paris had a daily newspaper. The impact of the few periodicals that were published was probably not much greater than that of the hand-written newsletters which had circulated among the Romans. Similarly, the postal services of European states would have been hard pressed to match the claim of the Roman *cursus publicus* to be able to cover 270 km in 24 hours (Encyclopaedia Britannica CD97). Since it was virtually impossible to reach large numbers of people rapidly with a common message, information tended to circulate slowly and within sharply circumscribed circles.

Then over the following decades, changes in transmission costs began to come rapidly. In England, turnpikes built using new construction and drainage techniques cut the time for intercity travel (Ashton, 1962, p. 85). With the resulting increased supply of information, intermediation between producers and consumers became more profitable. By 1760, London had four daily and six tri-weekly newspapers; 37 other newspapers existed in the provinces (Encyclopaedia Britannica CD97). Yet these sheets were printed on presses whose technology differed little from that developed by Gutenberg three centuries earlier. In 1771, the French printer, François-Ambrose Didot discovered that by modifying Gutenberg's pressure screw he could double the number of pages produced per hour, from 150 to 300. Paris obtained its first daily in 1777; in London, the predecessor of *The Times* began publication in 1785. In 1794, Claude Chappe invented the semaphore visual telegraph, which allowed messages to be sent over hundreds of kilometers in a few hours. The following year, the metal press developed by Lord Stanhope doubled the number of pages that a single printer could prepare per hour, from 300 to 600 (Bellanger et al., 1969, Vol. 1, p. 18). In 1814 *The Times* installed a steam-operated press developed by Friedrich Koenig that tripled the rate of production to 2000 pages an hour (Bellanger et al., 1969, Vol. 2, p. 15). Another important development came with the invention of the electric telegraph in 1837. Then, in the following decade, the rotary press and typesetting further increased the efficiency of printing, while the introduction of paper made from wood pulp reduced materials costs. By 1851, with the completion of a cable under the English Channel, information could be sent virtually instantly across Europe and made available to large numbers of people at low cost within hours (Cameron, 1993, p. 209).

One effect of the new transmission technologies was to accelerate the rate at which existing ideas were combined to generate new ones. In the early eighteenth century, Thomas Newcomen had designed his atmospheric engine with only a plumber for an associate. He was unaware that Thomas Savery had already patented a similar pumping device. More than half a century then elapsed between the construction of the first Newcomen steam engine in 1712 and the first significant improvements to it.¹⁷ James Watt had not only a model of Newcomen's device to work from in designing his improvements but also the benefit of scientific input from university researchers, financial backing from English industrialists, and technological assistance from the related armaments industry. Watt's own discovery was quickly subjected to important improvements, both by himself and by other inventors such as Richard Trevithick, who within 25 years had built a locomotive powered by a high-pressure steam engine.

Despite the numerous inventions of the last half of the eighteenth century, it was only with the gradual spread of the new information transmission techniques in the first half of the following century that the use of mechanized production technology became generalized. In 1801, the share of Britain's national product from manufacturing, was at virtually the same level – 23% – as it had been at the moment of the Glorious Revolution over a century earlier. By 1841, however, manufacturing accounted for 34% of Britain's national product (Kuznets, 1966, p. 88). Similarly, outside Britain, industrialization had barely begun in Europe by 1800, but after 1820 – subsequent to improvements in inland communications and publishing – continental manufacturing output began to grow rapidly.¹⁸

By reducing information asymmetries, the new transmission technologies made it possible for the first time for large numbers of investors to participate effectively in common projects. In Britain, the repeal of the Bubble Act in 1825 allowed parliament to grant charters for joint-stock companies with limited liability. By 1862, this privilege had been made available by simple registration (Cameron, 1993, p. 213). This and similar nineteenth-century legislation in France and Germany allowed the capital required for railroads and large industrial projects to be mobilized. More generally, the new transmission technologies made it possible to coordinate the activities of large numbers of people from a central point. As the theoretical model predicts, their diffusion was accompanied by a massive centralization of economic activity. During the eighteenth century, London's annual rate of population growth, at 0.5%, was little more than that of the British population as a whole. However, in the first

¹⁷ The separate condenser, discovered by James Watt, was first applied in 1776.

¹⁸ As an indication, French coal production grew from under 1 000 000 tons before 1820 to over 5 000 000 tons in 1847 (Cameron, 1993, p. 238).

half of the nineteenth century, London's population grew at 1.7 percent per year – a rate almost twice that of the rest of the country (Bairoch et al., 1988, p. 33).

It may be seen, then, that over the millennium prior to 1975 Western Europe's economic institutions underwent fundamental restructuring three times. In each case, innovations in a particular dimension of information processing appear to have accelerated both the generation of new ideas and the diffusion of existing ones.

3. The dynamics of innovation

As soon as one attempts to model feedback from the economy to communications technology formally, several gaps in the writings of Harold Innis become apparent. First, he did not detail clearly the process by which innovations are generated from an existing body of knowledge. Second, although the changes Innis described do appear to follow the introduction of new communications techniques, he failed to explain why innovations in this sector should be given any more attention than those in other areas such as agriculture, transport, or energy production. Finally, Innis's theory of monopoly does not provide a convincing explanation for the burst of innovation that characterizes the initial phase of the life cycle of a communications medium. Each of these issues must be addressed carefully.

3.1. *Innovation as a directed search process*

Turn first to the details of the innovation process. Although it is evident that for Innis innovation is triggered by a signal from the price system, the process by which innovations regularly emerge is not clear. Innis of course understood that new ideas generally require inputs from existing knowledge.¹⁹ To understand the process by which the existing concepts to be combined are identified, however, we must look elsewhere. Perhaps the most convincing account of how inventions arise was proposed over a decade after Innis's death by the Hungarian writer Arthur Koestler. In *The Act of Creation*, Koestler (1964) argued that innovations arise when existing ideas are combined in hitherto untried ways. Recently, Weitzman (1995) has formalized this process as a model of 'recombinant' growth. Economic growth occurs when the techniques resulting from successful crosses of old ideas replace existing ways of doing things.

Since all crosses are equally probable in Weitzman's formulation, there is no direction to technological change in his model. In reality, however, some crosses

¹⁹ For example, he described how the development of printing required the combination of four different techniques: the metal punch, an alloy with a low melting point, oil-based paint, and the screw press (Innis, 1950, pp. 173–174).

are more likely to be tried than others. People may have explicit objectives in mind when they combine ideas, choosing those combinations that their experience suggests may be most fruitful. Equally, they may use search routines or habits that arbitrarily exclude certain combinations. In the model below we will follow Innis, assuming that research resources tend to be directed toward products or processes whose relative cost is high.

3.2. *On the importance of communications*

This hypothesis of *directed search* provides a possible answer to the second question that has long troubled readers of Innis. Why should technological change in a particular sector, communications, be singled out for special attention? In criticism of Innis's approach, it might be argued that other types of innovations, for example, in food production, in transportation, or in energy production, have been at least as important as those in communications. But if technical progress comes from the combination of old ideas in new ways, then the nature of technological change will depend in part upon the direction fixed by the dominant communications medium. For example in antiquity, the discovery of writing may have led to the record-keeping necessary for hydraulic agriculture, the alphabet to the network of correspondents necessary for the profitability of long-distance navigation technologies, and the efficient transmission of information over land to the mobilization of the resources to harness inanimate (i.e., water) power at a remote site.

Communications technology may also influence the degree to which previous ideas are synthesized. For example, the medieval inventor who adapted the waterwheel to reciprocating motion was probably a craftsman with limited education who by trial and error managed to improve upon existing technology. Thomas Savery, the military engineer who in 1698 patented the first steam engine, had no formal post-secondary education but was able to understand principles advanced by the French physicist Denis Papin. In the 1880s, Nikola Tesla, a Serbian electrical engineer with a university scientific training, could call upon his knowledge of the physical properties of electricity in conceiving the alternating-current generator.²⁰ It is perhaps this application of a new communications technology to an existing set of ideas that explains the clusters of innovations noted by Rosenberg (1982, Chapter 3).

A final way in which communications media may affect other types of technology is through their impact on the speed of technological diffusion. Each major improvement in communications technology seems to have been followed by an acceleration in the general pace of technological dispersion. Thus, the

²⁰ Edison, who favored direct current and opposed the introduction of alternating current, had a very limited formal education.

period of diffusion of the waterwheel must be measured in centuries, while that of the steam engine may be counted in decades, and that of the alternating-current generator in years. In short, communications media are arguably the most fundamental of ‘enabling’ technologies in that they help determine the direction in which research resources are applied, the degree of synthesis of existing ideas, and the speed of diffusion of the resulting discoveries.²¹

3.3. *A model of biased growth*

As mentioned in the introduction, there seems to be no strong evidence to support Innis’s argument that innovative activity is triggered by high prices due to monopoly of existing media. However, the directed-search hypothesis described above provides an alternative and more plausible explanation for such price signals. As mentioned above, a society’s communications structure must perform three essential tasks; namely, the storage, transmission, and decoding of information. If the costs of any single dimension get seriously out of line with those of the other two, bottlenecks will occur. Resources will therefore be devoted to the development of a new medium capable of relieving the bottlenecks.

The result is the technological counterpart of a mutation in biology: something fundamentally new is added to the existing set of ideas. Assume that there are three possible avenues of research in information processing; namely, to reduce storage costs, s , to lower decoding costs, d , or to cut the costs of information transmission, t . Suppose further that because of the externalities generated by multiple related projects, research into only one of these processes is feasible in any period. For each process, i , let there be a switch, δ_i , that can take the values zero or one, $i = s, d, t$. In Fig. 4, the ratio of the cost of decoding a unit of information to the cost of transmitting it over a fixed distance, d/t , is indicated on the horizontal axis; the ratio of the unit storage to transmission costs, s/t , is presented on the vertical axis.²² Approached from below, the line AB represents the threshold at which research is switched from transmission to storage. Similarly, BC represents the decoding threshold and AC the transmission threshold.

To use terminology proposed by Mokyr (1990), the key ‘macroinventions’ at the beginning of each cycle will tend to channel subsequent ‘microinventions’. For example, the development of clear, detached minuscule characters around

²¹ Lipsey and Bekar (1995) define innovations in ‘enabling’ technologies as those having economy-wide applications that lead to the development of other technologies.

²² Note that the choice of variables for each axis determines the subsequent sequence of innovation. The presentation of Fig. 4 is intended to yield the sequence of innovations observed in the West over the past millennium.

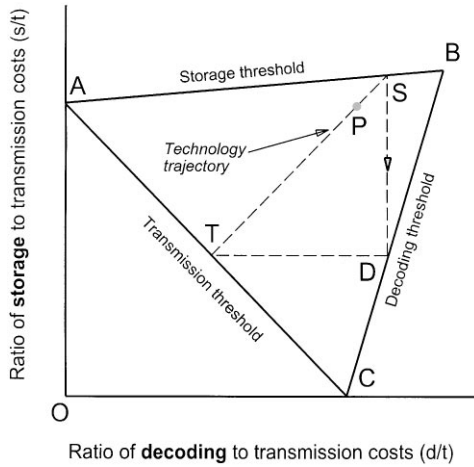


Fig. 4. Induced innovation in communications technology.

780 created a need for rules of punctuation, spacing, and the choice of script. Suppose that initially innovative resources are being used to lower transmission costs, with the society moving from a point such as *P* toward the upper right in Fig. 4. When the technology point strikes the storage threshold *AB* at *S*, resources are switched into generating inventions that reduce storage costs. A burst of macroinvention then initiates a downward movement that continues under further microinventions, until at *D* the decoding threshold is reached. With resources now switched into improving the decoding of information, movement is to the left. Finally, at *T*, when the society reaches the final threshold, innovative resources are shifted into the reduction of transmission costs. The technology point then moves toward the upper right once again.

Although the direction of technological change is endogenous, the number of macroinventions at the beginning of each cycle, ε will be assumed to be determined exogenously. However, the effect of crossing these new macroinventions with existing ideas may be modeled directly with the help of Weitzman’s hypothesis of recombinant growth. Let m_τ be the number of ideas that exist at the beginning of period τ . The number of possible binary combinations of these ideas is $m_\tau(m_\tau - 1)/2$. Some of these combinations will already have been tried previously. If m'_τ represents the number of ideas at the beginning of the *preceding* period, the number of new combinations, τ , that may be tried is

$$c_\tau = [m_\tau(m_\tau - 1) - m'_\tau(m'_\tau - 1)]/2. \tag{2}$$

Let π_i be the success rate of these crosses. Assume then that with δ_i as the innovation switch defined above, the level of the cost parameters in Eq. (1)

under the best technology in period τ is inversely proportional to the number of ideas. Then,

$$i_{\tau}^* = i_{\tau-1}^*(1 - \delta_i \pi_i c_i / m_i), \quad i = s, d, t. \tag{3}$$

In any given period, τ , only a small percentage of the population will use the best technology, i_{τ}^* . The fraction of people $\theta_{\tau-k}^i$ that use technology $i_{\tau-k}^i$ is assumed to follow a logistic distribution,

$$\theta_{\tau-k}^i = \frac{1}{b^{\tau-k} + 1} - \frac{1}{b^{\tau-k-1} + 1}, \tag{4}$$

where $0 < b < 1$. The overall level of information-cost parameter i is then

$$\bar{i}_{\tau} = \sum_{k=0}^{\tau-\tau_0} \theta_{\tau-k}^i i_{\tau-k}^*, \quad i = s, d, t. \tag{5}$$

Inspection of Eq. (5) indicates a growth cycle with three phases. Initially, the overall growth rate of productivity is low and possibly declining, since in the information-processing activity where innovation is occurring, diffusion remains limited, while in the other two activities no new innovation is occurring. Paradoxically, it is in this *innovation* phase, characterized by what Schumpeter (1950, p. 87) described as “creative destruction”, that the rate of technological change is most rapid. Then once the new vintages of technology come to be more widely adopted, productivity growth accelerates. In this *diffusion* phase of the cycle, although the rate of productivity improvement in the latest vintages is falling, the effect is more than offset by the increase in the proportion of the population that is adopting the improvements from the preceding periods. Growth subsequently decelerates, however, as the number of new ideas to be crossed with old ones falls. In the final, *dominance* phase of the cycle, the new technologies developed in preceding periods have become widely diffused. At the same time, the number of new combinations yielded by the initial set of macroinventions has declined sharply. Therefore, the growth rate is low.

As mentioned in the introduction, to proceed from output growth to population growth, it is necessary to specify how additional units of output are divided between raising per-capita income levels and increasing population. In any culture, there will be some mechanism for adjusting family size to economic conditions. A simple rule is to assume that there is a fixed portion, σ , of increases in output in a period which is devoted to raising the size of population in the subsequent period:

$$\frac{\Delta n_t}{n^t} = \sigma \frac{\Delta q_{t-1}}{q_{t-1}}. \tag{6}$$

Eqs. (1)–(6) define a dynamic system by which technology, production and population interact over time.

4. A numerical simulation of very long-term growth

A numerical example will illustrate the nature of economic growth in the theory proposed by Harold Innis. Table 1 sets out the assumptions made to carry out the simulation.²³ As far as possible, the number of parameters was kept to a minimum. Thus, the elasticities of output with respect to storage, transmission and decoding costs were fixed at a uniform 0.625. Similarly, the success rate of new combinations was set at 0.07, while the approach-rate parameter for the diffusion process, b , was fixed at 0.175 and the symmetry parameter, a , at 1.0.

Three parameters were allowed to change over time so as to capture observed historical trends. To generate relatively slow growth of per-capita income over the first two logistics, the portion of output growth dedicated to increasing the population, σ , was set at the high level of 0.75. For more rapid per-capita income growth over the third logistic, this parameter was then reduced to 0.6.²⁴ In addition, the length of the lag, l , from the beginning of each cycle to the mid-point of the diffusion process was reduced across the cycles.

Finally, the remaining parameter, the number of new ideas – ‘macroinventions’ – at the beginning of each cycle was set at the level required to yield the observed rate of population growth. The resulting figures were not implausible: roughly one macroinvention in the medieval period, two in the early modern period, and three to set off the most recent cycle. One may think perhaps of the Carolingian minuscule as the seed idea in the high Middle Ages, of paper and the printing press as triggering the developments of the sixteenth century, and of the all-weather road, the single-stroke press, and the semaphore telegraph as the new ideas in the late eighteenth century.

Fig. 5 portrays the overall rate of population growth over time for the three successive cycles of Table 1. To compare this graph with the demographic data of Fig. 2, note that each period corresponds to 15 years. The resemblance of the simulated to the historical series is quite evident. First, there are three cycles. Second, each cycle may be divided into three phases. There is an initial *innovation* phase of slow growth followed by a *diffusion* phase of above-average growth and a *dominance* phase of slow and declining growth. Finally, over time the cycles decrease in length, since as the stock of previous ideas accumulates, the number of potential crosses for each *new* idea rises. It therefore takes less and less time to reach the threshold at which innovation resources are redirected. In addition, the underlying growth rate rises from one cycle to the next.

²³ Within each cycle, the combinatorial process was assumed to be continuous, applying not only to integers but also to fractions, fractions of ideas being interpreted in probabilistic terms.

²⁴ Historically, the fall in the proportion of income devoted to population growth over the third logistic was much more gradual than is assumed in the simulation.

Table 1
Parameter values for three cycles of innovation

Parameter	Cycle 1	Cycle 2	Cycle 3
Process undergoing innovation	Storage	Decoding	Transmission
Fraction of additional income devoted to population growth σ	0.75	0.75	0.60
Number of ideas at end of last cycle	1	2.2	5.6
Number of new ideas at beginning of cycle (ε)	1.1	2.6	3.6
Success rate of new combinations (π)	0.07	0.07	0.07
Production function parameters			
Storage elasticity (α)	0.625	0.625	0.625
Decoding elasticity (γ)	0.625	0.625	0.625
Transmission elasticity (β)	0.625	0.625	0.625
Logistic function parameters			
Symmetry (a)	1.0	1.0	1.0
Approach rate (b)	0.175	0.175	0.175
No. of periods in lag (l)	6	3	2
Number of 15-year periods in cycle	30	20	15
Average annual population growth rate (%)	0.056	0.304	0.605

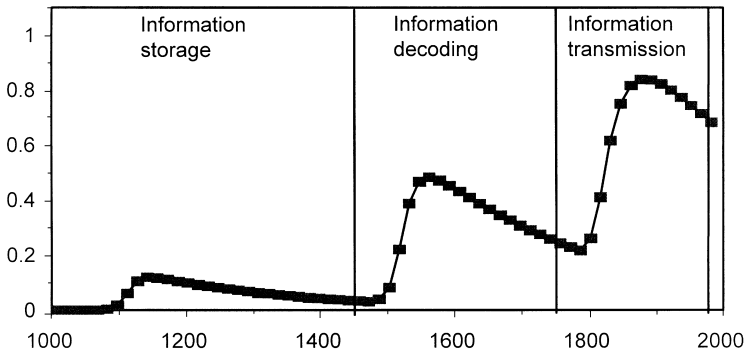


Fig. 5. Simulation of three innovation cycles, average annual growth rates in percent.

The principal discrepancy between the Figs. 2 and 5 occurs at the end of the first and second cycles. Historically, the fourteenth and seventeenth centuries were not merely periods of stagnation; as Fig. 2 shows, they were times of actual population *decline*. These setbacks are sometimes explained by intervals of cooling of Europe's climate. However, generalized warfare and a decline in population growth also appeared in the corresponding phase of the third logistic in the first-half of the twentieth century, when no such climactic change occurred. A possible explanation is that as the payoffs to innovative efforts that

increase the pie decline, individuals become increasingly willing to invest in activities to redistribute the existing pie. If so, following Hirshleifer (1994), we would have to expand the model of production presented above to include the technology of destruction.

5. Conclusions

Freeman (1994) has proposed a taxonomy of theories of technical change that distinguishes between sources of technology that are internal and external to the firm, between radical and incremental innovations, and between demand-pull and technology-push processes of innovation. In terms of this framework, Harold Innis argued that the essential components of technical change are largely external to the producing unit, that they involve radical changes to information and communication technology, and that they are generated by interaction between the price system and the innovative process. This paper has presented historical evidence, a theoretical model, and a computer simulation to help assess Innis's hypothesis.

Let us review the evidence. In the early Middle Ages, the high cost of *storing* information provided an incentive to standardize the coding of a vehicular language – medieval Latin. Introduction of this new medium was followed by an acceleration in the diffusion of agricultural technologies, increased use of written contracts, and a doubling of Western Europe's population. Later, in the late Middle Ages, the difficulty of *decoding* information led to the development of low-cost material printed in the vernacular. As this medium was diffused in Northern Europe, there occurred a sharp rise in literacy rates, a generalized conversion to the market economy, and a substantial rise in population. Finally, in the mid-eighteenth century, the high cost of *transmitting* rapidly led to the development of techniques for building smooth, well-drained roads, for doubling the rate of printing, and for transmitting coded information by aerial signal. The introduction of these technologies ushered in a century of unprecedented growth. A theoretical model in which three types of information processing are combined with labor yielded network structures that correspond closely to those observed in Europe over the past millennium. Moreover, a simulation of this model proved to be surprisingly successful at replicating the main characteristics of Western Europe's long-run demographic growth.

It is worth speculating about why accelerated growth over the last millennium was confined to the West. Because of its many homonyms, the written form of the Chinese language was logographic rather than phonetic. With thousands of characters, storage was costly relative to transmission. The resulting centralized network proved vulnerable to exploitation by a group that captured its central node. As for the Arabic language, it could be codified cheaply with 28 consonantal characters. However, as scripts proliferated, with no standardized way of

indicating vowels, and no separation between letters and groups of words, subsequent decoding of that information was often difficult (Diringer, 1968, Vol. 1, pp. 212–215). The resulting set of local networks with tenuous connections could be seized piecemeal by a well-organized foe.

Between these two extremes lies a third possible form of partially literate society. The Latin language could be expressed by a small number of fully phonetic characters. Once a standardized means of storing information had been developed, there emerged a set of linked, decentralized networks. Such a structure could not easily be captured, since even if one node was taken, the system would not fall (Fig. 3b). Despite the absence of a central government, Latin Christendom successfully resisted the invasions of the Vikings and Magyars in the ninth and tenth centuries, and then began the reconquest of Spain. No group from either inside or outside the continent was ever able to repeat Charlemagne's exploit of monopolizing political power.

How relevant are Innis's ideas for understanding contemporary economic growth? Consider how he might have explained the puzzling slowdown in productivity growth that characterized the industrialized world during the 1970s and 1980s despite very rapid innovation in the electronics sector. If he had lived to see this period, Innis would likely have recognized the characteristics of the first or *innovation* phase of his technological cycle. In this phase, despite rapid generation of new ideas, the new micro-electronics technologies were not yet sufficiently cost-effective to challenge the mass-transmission techniques that were left from the *dominance* phase of the preceding wave. It is only in the second or *diffusion* phase when the rate of innovation has slowed but the new technologies have become cost-effective that growth accelerates. If so, the true test of Innis's theory of communications lies ahead.

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