Chapter 13

Geography and Technological Change

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As global production becomes increasingly integrated, workers and firms in different regions are forced more directly into competition with one another. How do these firms, and the regions in which they are embedded, compete for the capital and labor required to sustain competitiveness? The dominant strategies of competitive advantage, in one form or another, hinge on technology. More specifically, technological change is the primary determinant of profitability and growth. This much was clear in the 1950s (Abramowitz, 1956; Solow, 1956, 1957) and it remains so today (Grossman and Helpman, 1991; Lucas, 1988; Romer, 1986, 1990).

The role of technical change in fueling economic growth has been the subject of much recent discussion as growth rates have declined in many of the advanced industrialized nations and as certain newly industrializing countries (NICs) are reducing the technological gap (Baumol, 1986; Fagerberg, 1994; Maddison, 1982). Explanations of national differences in innovative performance have turned to focus on industrial organization, on the sectoral and spatial linkages between firms, and on the institutional systems within which they operate (Archibugi and Michie, 1995; Freeman, 1991; Lundvall, 1992; Nelson, 1993; von Hippel, 1988).

Increasingly it is recognized that the motors of national economic performance are sub-national technology districts (Amin and Thrift, 1994; Scott, 1996; Storper, 1992). These innovative regions are characterized by strong ties between regional actors, embedded in institutional structures that reinforce common sets of rules, norms, business cultures, and decision routines (Benko and Dunford, 1991; Brusco, 1982; Grabher, 1993; Granovetter, 1985; Harrison, 1992; Stöhr, 1986; Maillat, 1995; Storper, 1995). With boundaries to the spatial flow of information (Jaffe et al., 1993), region-specific knowledge bases and localized processes of search and learning (David, 1975) are hypothesized to channel technological change along relatively distinct regional trajectories (Aydalot, 1988; Rigby and Essletzbichler, 1997; Rigby and Haydamack, 1998). This gives rise to regional systems of innovation and technological advance.

This chapter examines the geography of technological change. The following section summarizes the importance of technological change, showing how technology shapes broad patterns of growth and income. Attention then shifts to definitions of technology, and the key processes by which technology is altered – namely invention, innovation, imitation, learning, differential firm growth, and turnover. Geographical differences in technology, and the influence of space on the processes of technological change, are analyzed in turn.

Economic Growth and Technological Change

Between 1820 and 1982, the real value of output in the world's largest industrialized economies increased by a factor of seventy. The population of these economies also grew, nevertheless the average worker produced fourteen times more real output at the end of this period than at the beginning (Maddison, 1982). Rates of growth of output and productivity in member nations of the Organization for Economic Cooperation and Development (OECD) generally accelerated over the last 150 years, peaking in the two decades after World War II. From 1950 to 1970, OECD output grew at an annual average rate of about 5 percent. Growth rates decelerated sharply from the late 1960s, popularly since the first oil shock in 1973, but subsequently rebounded after the deep recession of the early 1980s (Maddison, 1987). The growth experience of different groups of countries has varied (Webber and Rigby, 1996). While the advanced, industrialized economies have become richer, and more alike in terms of productivity (Barro, 1991; Baumol, 1986), underdeveloped countries have fallen further behind (Landes, 1998). Newly industrialized countries (NICs) enjoyed unprecedented expansion and productivity growth over the last thirty or so years (Dicken, 1998), though the fragility of this growth has recently been exposed. Some attribute the success of these economies to technological "catch-up" (Barro, 1991; Fagerberg, 1994), though others advance different arguments (Young, 1995).

Since the pioneering work of Solow (1956, 1957), it has become conventional to account for these "stylized facts of growth" using some variant of the following relationship:

$$Y = a \cdot K + (1 - a)L + T \tag{13.1}$$

This equation argues that the rate of growth of output (Y) is equal to the growth rates of capital (K) and labor (L), each weighted by their respective share of net output (a), plus the rate of growth of aggregate productivity (T). This last term, typically represented by time and thus exogenous to the economy, measures the contribution of technological change to output growth. Using this equation, Solow (1957) demonstrated that technological change was the principal determinant of US output growth over the first half of the twentieth century. Over the last forty years numerous economists have augmented Solow's model, notably Denison (1962, 1967), by adding terms measuring changes in the quality of capital and labor inputs, thus reducing the contribution of technology to growth. These challenges notwithstanding, technological change remains the key to long-run economic growth, to rising productivity and income levels.

The Solow model also explains international differences in long-run growth rates (Jones, 1998). In the Solow tradition technology is viewed as a free or public good, and thus growth rate variations between rich and poor countries are linked to national differences in savings and investment rates, in population growth, and (after Mankiw et al., 1992) in rates of accumulation of human capital.

Although technological change was regarded as the primary motor of economic growth it remained exogenous in Solow's model, where it appeared, as Joan Robinson (1953/54) commented, rather "like manna from heaven." In large part this ignorance of the processes driving technological change reflected a theoretical myopia as well as analytical convenience: the neoclassical economic model was simply unsuited to analyze a disequilibrating process like technological change, which is characterized by uncertainty, by asymmetries of information within a heterogenous population of firms, and by markets that are at best imperfect.

After a hiatus of some twenty or so years, interest in growth theory and technology was rekindled in the late 1980s by Romer (1986, 1990), Lucas (1988), and Grossman and Helpman (1991). In their "endogenous growth models," technological change – although largely still a "black box" – was at least conceptualized as an integral part of the economy. Technology is no longer viewed as a public good: firms are able to capture some of the returns from their own research and development efforts. Thus, increasing returns to technology development and adoption emerge as a basis for agglomeration and the maintenance of growth rate disparities. Once more, questions about the meaning of technology and the processes of technological change have moved to the forefront as we try to understand the nature of competition and economic growth.

Technology and Technological Change

In the capitalist economy, production is controlled largely by individual firms. While these firms may adopt a variety of short-term strategies, their fundamental aim is to make a profit. No firm is guaranteed profit, for the market is a chaotic arena where prices for inputs and outputs cannot be determined a priori (Alchian, 1950; Farjoun and Machover, 1983; Nelson and Winter, 1982). Some firms attempt to manage this uncertainty by controlling the market. However, the majority of firms can only control the manner in which they transform inputs into output, seeking to achieve a competitive advantage by increasing the efficiency of their production. For most, efficiency is unknown until they enter the market and are evaluated by their rivals. In this competitive environment firms are compelled to search for new technology, sure only in the knowledge that others are doing the same.

Schmookler defines technology as the "social pool of knowledge of the industrial arts" (1966, p. 1). In this sense, technology represents the set of known ideas or information about the range of products that can be made and the variety of processes that may be employed in their production, including the specific combinations of capital and labor inputs used to produce output, the division of labor (the separation of tasks within and between firms), and the broader, institutional structures within which economic activity is embedded. Technological progress represents the expansion of this pool of information, and technological change occurs when an economic agent uses a new part of this knowledge pool.

The history of technological change is governed by the production of knowledge, by the application of that knowledge, and by how it diffuses throughout the economy. Since Schumpeter (1939), it has become commonplace to distinguish between the processes of knowledge production (invention and learning), of the introduction of that knowledge to the economy (innovation), and the spread of that knowledge through the economy (diffusion). While this conceptual division may be useful for purposes of explication, it is important to remember that these processes are often indistinguishable.

Invention

The production of knowledge and its application have changed considerably over time. Although a division of labor might be considered a prerequisite for the inventive process, advances in science were not closely linked to technology and economic activity much before the nineteenth century (Usher, 1954; though see Musson and Robinson, 1969, for a dissenting opinion). Consistent with this separation of science and economy, invention was initially regarded as a discontinuous process resulting from the inspiration of the occasional genius. Sociologists of invention such as Gilfillan (1935) rejected this view, claiming that invention is more often the result of incremental problem-solving within a relatively familiar framework of ideas and economic relations. Usher (1954) integrated these two approaches, arguing that while invention depends on critical acts of insight, such acts can be encouraged by the creation of appropriate economic and knowledge environments.

"The great invention of the nineteenth century was the invention of the method of invention" (Whitehead, 1925, p. 96). The production of knowledge, or invention, was slowly institutionalized in the research and development (R&D) laboratories of large firms throughout the late nineteenth century. Freeman (1982) traces the emergence of R&D labs in the German chemicals and dyestuffs industries and links the "professionalization" of in-house R&D to the growing costs of technological development. Growth in the system of technology production was also encouraged by consolidation of patent systems throughout North America and Western Europe. Through protection of intellectual property rights and through the system of assignment, by which individual inventors sold the rights to their inventions, the patent system hastened the emergence of a market and trade in technology, leading to a more specialized division of labor in technology production (Lamoreaux and Sokoloff, 1996).

It was not until World War II, and the success of science-based military technology, that a new orthodoxy emerged. This characterized modern technology as applied science (Bush, 1945; Thirtle and Ruttan, 1987). The result was a rapid expansion in private and public support for R&D, and an explosion of economic growth fueled by rising productivity and incomes, by the establishment of new technology-intensive industries, and by the associated growing range of new products. Consistent with this "science-led" picture of technological change, a simple, linear model of the process of invention and technological change became widely accepted (Malecki, 1991). According to this model, basic science, performed in the research labs of universities and government research centers, produced knowledge that was then commercially applied in the research and development labs of modern corporations. From such applications, engineers developed blueprints and prototype commodities that were passed to marketing departments to assess the likelihood of commercial viability. Although this simple model has been roundly criticized for ignoring various feedbacks between the different stages of technology development (Kline and Rosenberg, 1986), and for assuming that science leads industry in the production of ideas for new technologies (Mowery and Rosenberg, 1979), its focus on science–industry links appears increasingly prescient. Scientific activity has become more expensive and therefore more frequently financed by private business, and university–industry linkages have proliferated (Henderson et al., 1998; Malecki, 1991; Saxenian, 1994; Trajtenberg et al., 1997).

This linear model of technology development fails to embrace the variety of means by which individual manufacturing firms and groups of interlinked firms and related institutions generate new technologies. New techniques do not emerge only through the deliberate process of R&D but also are generated by various learning processes, and sometimes are the unintended consequences of problem-solving in production (Arrow, 1962; Lundvall, 1988, 1992). As long ago as 1962, Arrow noted that the experience learned by firms through production was not always appropriated by the firm, but sometimes passed as a public good to society overall. Indeed, these technological spillovers form the basis for the so-called new endogenous growth models of Romer (1986, 1990). Regardless of their origin, whether or not new techniques are adopted in the economy depends upon the process of innovation.

Innovation

Innovation is the application of new ideas to the economy. While innovation depends on invention, the introduction of new technologies is a complex process that also depends on the cost of change and the potential demand for new technology. The rate of introduction of new technology and the characteristics of that technology exert critical controls on economic growth and on the demand for inputs to production such as labor. As growth has slowed and unemployment increased in many parts of the world, there has been intense economic debate about not only the pace of innovation, but also the direction of innovation (i.e. whether new techniques economize on the use of particular inputs to production).

Research on the pace of innovation regards the introduction of a new technology to the economy as a discrete event that can be dated and located. Mensch (1979) and Freeman et al. (1982), following Schumpeter (1939), examine the timing of major innovations. Mensch (1979) argues that major or radical innovations tend to cluster in time, giving rise to periods of intense technological activity akin to Schumpeter's "gales of creative destruction," while other times are characterized by technological stagnation. The periodic clustering of innovations is sometimes used to explain long waves of economic growth (Berry, 1991; van Duijn, 1983). Figure 13.1, taken from Dicken (1998), summarizes these claims.

These arguments have repeatedly been criticized. Freeman et al. (1982) and Kleinknecht (1987) claim that Mensch's (1979) identification of radical or major innovations was *ad hoc*, and dispute his evidence of technological clustering. Kleinknecht also argues that innovation should not be considered a discrete event, because it is merely the prelude to a long series of incremental improvements that may have a far greater economic impact than the introduction of a new technology. Fishlow (1966) has provided support for this claim, documenting the productivity gains associated with a long succession of minor improvements in railroad and

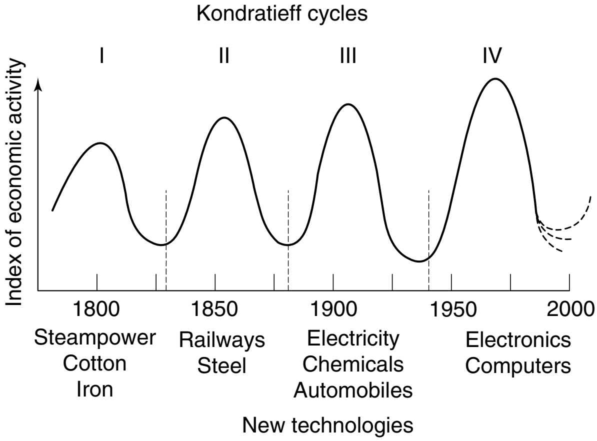

Figure 13.1 Long waves of economic activity
Source: Adapted from Dicken (1998, p. 148)

related technologies, as has Hollander (1965) in studies of Du Pont. In addition to these concerns, proponents of a long-wave, technology-driven model of economic growth do not provide convincing explanations of why technologies cluster, whether or not innovation leads or follows the upswing in economic activity, and why the long cycles of growth have a periodicity of around 50 years.

The impacts of innovation on the nature of technological change, on economic growth, and on the structure of competition are examined further using the concept of the product cycle (Vernon, 1966). In Vernon's (1966) model, as a product ages the factor intensity and skill requirements of production alter. Utterback and Abernathy (1975) explore how the focus of innovation switches from products to new production processes as a commodity matures, as its market expands, and as firms increasingly adopt competitive strategies based upon controlling costs rather than shaping demand. The product-cycle model (figure 13.2) is not without its detractors, however. Taylor (1986) notes that few commodities actually pass through the different stages of the cycle, while Storper (1985) condemns the deterministic nature of the

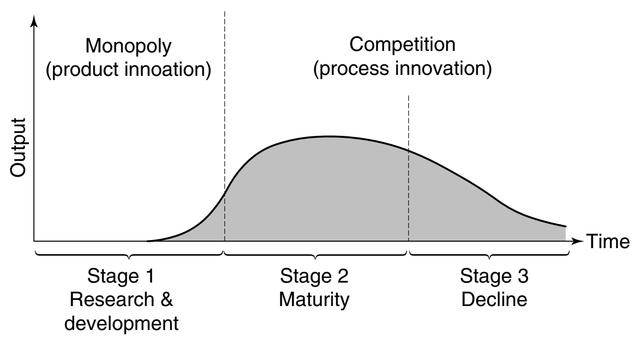

Figure 13.2 The product cycle
Source: Author

whole concept. Debate over the direction of innovation is often traced to Hicks' (1932) claim that firms will tend to adopt techniques that save on relatively more expensive inputs to production. Fellner (1961) disputed this claim, arguing that in competitive markets all inputs are equally costly. Salter (1960) continued the criticism, noting that firms are interested only in reducing costs, and not in the manner of such reduction. Extensive attempts in the late 1960s and early 1970s to link the direction of technological change to the relative prices of inputs in models of induced innovation (see Ahmad, 1966; Kennedy, 1964; and Thirtle and Ruttan, 1987 for a detailed review) were unsuccessful. In large part this is because of a failure to recognize that the processes of searching for and adopting new technologies are expensive. In models where the costs of innovation are considered explicitly, differential returns from reducing inputs with varying costs will encourage firms to economize on more expensive inputs (Binswanger and Ruttan, 1978). A large number of empirical studies of individual industries and economies have examined the induced innovation hypothesis (see Thirtle and Ruttan, 1987). In some of the more well-known, David and van de Klundert (1965) found a labor-saving bias to innovation in the first half of the twentieth century in the US economy, when labor was scarce and thus relatively expensive. Habakkuk (1962) finds consistent results for the nineteenth century, lending general support to the induced innovation hypothesis.

More recently, David (1975) has reformulated the induced innovation model, arguing that the search for new techniques is localized, and that the choice of technique is path dependent. For David, firms accumulate knowledge about technology through experimentation with existing techniques. The local nature of search is conditioned by sharply declining returns to investment in research and development efforts that are relatively dissimilar to existing technology, and by costs of knowledge acquisition that rise steeply beyond the boundaries of existing knowledge bases (Arrow, 1994; Webber et al., 1992). Thus, technological change is increasingly understood as an evolutionary process moving gradually along relatively distinct pathways, subject to interruption by the infrequent development of radically different technological knowledge.

Accordingly, the general history of innovation is perhaps best described as a sequence of radical breaks with past scientific knowledge, and incremental changes along relatively well-defined technological trajectories. Technological trajectories are broadly shaped by a knowledge base that imposes a certain logic of problem-solving, often involving a core technology and an agenda for subsequent improvement. This idea is incorporated in Sahal's (1981) technological guideposts, Dosi's (1982) technological paradigms, Nelson and Winter's (1982) natural trajectories, and Clark's (1985) design hierarchies. Technological trajectories are further shaped by regulatory constraints, common standards, requirements for systems compatibility (railroad gauge and computer operating systems provide simple examples), and other institutional limitations (David, 1985, 1992; Henderson and Clark, 1990; Katz and Shapiro, 1985; Nelson, 1994).

Diffusion

Diffusion, or imitation, is the process by which new technology or knowledge spreads throughout the economy. If the impact of technological change is measured

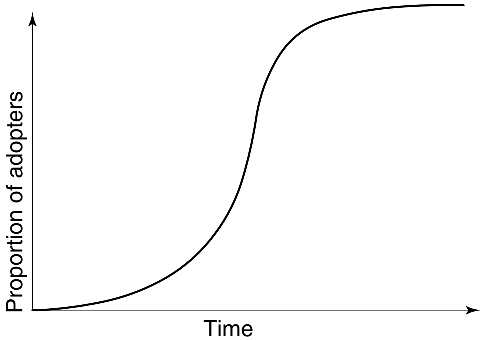

Figure 13.3 The logistic diffusion curve
Source: Author

by aggregate productivity improvements and economic growth, then diffusion is probably the most significant influence on such change (Baldwin and Scott, 1987; Rosenberg, 1982). Perhaps the most well-known studies of diffusion examine determinants of the adoption process. From the pioneering empirical work of Griliches (1957) and Mansfield (1961) came the discovery of the S-shaped, logistic adoption curve, rationalized as a result of the progressive dissemination of information about the technical and economic characteristics of the innovation (see figure 13.3). In this case, new technology is adopted once information about it becomes available, as in Hägerstrand's (1953) study of the adoption of costless techniques in Swedish agriculture. The speed of diffusion in most of these accounts is shown to depend on the anticipated profitability of adoption. This in turn depends upon the distribution of techniques employed within an industry, on the costs of purchasing new technology and learning how to use it, and on the cost of abandoning old techniques (Webber et al., 1992).

The classic, logistic model of epidemic diffusion has two main failings. First, it assumes a constant adoption environment in which new technologies and the characteristics of potential adopters do not change. Second, it focuses on the demand side of the diffusion process, largely ignoring how information about technology is disseminated. "Threshold models," in which changes in economic conditions over time tip the balance in favor of adoption, have been developed in response to the former criticism. For instance, David (1966) accounts for the twenty-year time lag between the development of the mechanical reaper and its widespread adoption in the US Mid-west by a growth in average farm size and increasing labor costs which eventually made mechanization imperative. Olmstead (1975) disagrees, noting that adoption of the mechanical reaper was encouraged by continuous small design improvements. Davies (1979) also discusses the importance of post-innovation improvements in technology that stimulate diffusion, along with differences in the complexity of technology, firm size, and other economic characteristics. Learning by using, which reduces uncertainty about particular technologies, and the emergence of industry standards and growing networks of complementary technologies, have also been viewed as critical in understanding diffusion from a threshold perspective (David, 1992; Nelson, 1994). In addition, Gertler (1993 and 1995) has recently demonstrated how "cultural" differences between firms retard processes of technology adoption and learning.

Focusing on the demand side of the diffusion process, the logistic model ignores the different mechanisms by which technological information is transferred (see also Brown, 1981). First, through the nineteenth century, in the USA at least, trade in technology became institutionalized as the patent system was consolidated. This system spurred the transmission of codified knowledge through the practice of assignment and by public advertisement of new patents (Lamoreaux and Sokoloff, 1996). Second, both codified and tacit knowledge is spread when workers move between firms (Landes, 1969; Saxenian, 1994). Third, growing specialization and the division of labor also speed technology diffusion by increasing inter-firm trade. Product innovations (new products) in capital goods industries become process innovations (new production processes) for the firms that purchase them (Kuznets, 1930). The purchase of rival firms' goods, and reverse engineering (the disassembly of commodities and direct imitation of component technologies), allow less efficient firms to rapidly catch up with "best practice" techniques. Finally, technology can transfer through firm mergers, acquisitions, and joint ventures which have accelerated in recent years (Dicken, 1998; Malecki, 1991).

Learning

Learning, though often neglected, is another mechanism of technological change. Learning is simply the acquisition of knowledge. Knowledge about technology and its use is not generated solely through formal processes of search and adoption, but frequently originates as a byproduct of other activities. Arrow (1962) notes how experience accumulated through production results in productivity gains. Rosenberg (1982) distinguishes a somewhat more general form of learning that occurs through use of specialized capital equipment. Malecki (1991) identifies a series of other forms of learning, and Stiglitz (1987) focuses on the importance of learning how to learn. David (1975) stresses that the localized nature of the learning process imparts a significant degree of inertia in the process of technology development. Recent attention given to industrial districts as fonts of knowledge creation (Amin, this volume) stems from the importance of networks as a means for sharing knowledge, and of the creation of network-based institutions of knowledge governance that help markets function (Lundvall, 1988; Storper, 1997).

Plant heterogeneity and aggregate technological change

The processes of technological change reviewed above operate at the firm level, although firms are influenced by broader industrial and geographical influences. At the aggregate level of the industry or region, technological change is also produced through selection, or the differential growth of firms, by the entrance of new firms into the economy, and by the exit of established firms (Nelson and Winter, 1982; Webber et al., 1992). These aggregate processes of technological change are shaped by various forces. Selection is governed largely by variations in efficiency, as market competition rewards more productive firms with increased market share at the expense of less productive firms. This, in turn, raises aggregate productivity. The effect of selection on technological change depends upon the degree to which productivity varies between firms, on the size distribution of firms, and on the intensity of competition (Baily et al., 1992; Baldwin, 1998). Firm entry and exit influence technological change if entering and exiting firms have technologies that differ from the average. Entrants often bring new technologies to the market, reshuffling the relative efficiency of existing firms. Evidence is mixed as to whether new firms are typically more or less efficient than average. Exiting firms are typically less efficient than average and so their departure improves aggregate productivity. Entry and exit are influenced by similar factors to selection, although economies of scale, industry concentration, and the costs of advertising and research and development reduce the rate of entry and/or exit (Bain, 1956; Baldwin, 1998; Caves and Porter, 1977).

The Geography of Technology

At any moment in time, a regional economy crudely may be conceived as a collection of economic agents, firms, and workers, embedded within a set of organizational and institutional structures that guide behavior to a greater or lesser extent. As such, regions are also repositories of accumulated knowledge, both codified and tacit. Region-specific knowledge bases consist of familiarity with the production of particular commodities and of specific techniques used in their production. They also include experience with organizational forms, of different ways of separating production through the division of labor, of different ways of managing intra- and inter-firm relations, and experience with institutional structures that regulate the environment within which economic agents operate. Most importantly, these knowledge bases also incorporate behavioral conventions that shape the way in which knowledge is produced or somehow obtained within the region. Because these pools of knowledge differ over space, technology may be differentiated geographically, along with the characteristics and determinants of technological change. This part of the chapter considers geographic differences in technology, and how location affects processes of technological change.

Geographic differences in technology

International differences in technology and the pace of technological change are relatively clear (Dicken, 1998; Webber and Rigby, 1996). Industrial specialization and the overall growth of trade indicate that technological (sectoral) capabilities are nation-specific (Soete, 1987). Cantwell (1991) shows that these capabilities are cumulative, that is, they persist over time. Significant international variations in productivity and in the skill composition of the workforce are reported by the OECD (1996), and Amendola et al. (1992) and Fagerberg (1987) demonstrate the impacts of technology, narrowly conceived, on international competitiveness. Differences in the pace of technological change between countries are usually reported as variations in rates of total factor productivity growth (Denison, 1967; Maddison, 1987; Mankiw et al., 1992). These variations are typically accounted for by rates of R&D spending, by trade in technology, by industry mix and the nature of firm and industry linkages, and by the more general characteristics of national systems of innovation (Archibugi and Michie, 1995; Freeman, 1995; Lundvall, 1992; Porter, 1990).

Industrial specialization and concentration at the sub-national level is also clear (Ellison and Glaeser, 1997). However, the existence of sub-national, regional differences in production techniques remains an open question. A number of studies have documented marked regional variations in labor productivity across a series of industries and at a variety of spatial scales (Casetti, 1984; Hulten and Schwab, 1984; Moomaw, 1983; Rigby, 1992). Others, who view technological change as embodied in capital, and investment as the medium through which new techniques are introduced to the economy, employ differences in the age of capital as a surrogate for geographical differences in technology (Anderson and Rigby, 1989; Rigby, 1995; Varaiya and Wiseman, 1981). Persky and Klein (1975) and Gleed and Rees (1979) provide evidence of regional differences in capital productivity between regions, and Beeson (1987) and Beeson and Husted (1989) reveal differences in total factor productivity across US states, attributing the differences to labor-force characteristics, industry structure, and levels of urbanization. In related work, regional differences in production functions are noted in Lande (1978) and Luger and Evans (1988). Such studies provide useful information about technological variety over space but they remain partial, focused largely on a single input to production, on a few relatively aggregate economic sectors or regions, or on limited time periods. In fact we know surprisingly little about geographical variations in production techniques, and even less about the evolution of technologies over space.

Recent research by Rigby and Essletzbichler (1997) and Rigby and Haydamack (1998) examines regional differences in production techniques within a number of industrial sectors over much of the post-war period. Their analysis suggests that regions tend to occupy broadly similar positions in "technology-space" from one industry to the next. For example, regions with production techniques in one industry that are more capital-intensive than average, or more labor-intensive than average, tend to have production techniques in other industries that exhibit the same characteristics. This is a remarkable finding, indicating that there may be strong geographic tendencies shaping the choice of technique regardless of the manufacturing sector. In related work, Essletzbichler et al. (1998) find significant regional differences in production techniques that persist over time.

Choice of technique at the plant or firm level is closely related to product type, to the characteristics of the market in which a product is traded, and to industrial organization. Industrial organization, another dimension of technology, refers to the social and technical division of labor, to how the processes of production are separated into discrete tasks, and how those tasks are allocated across firms (Williamson, 1975). Since the early work of Coase (1937), that allocation was typically explained by transaction costs and by economies of scale and scope (Scott, 1988). However, by the end of the 1980s it was clear that a simple transactions cost approach was insufficient to account for the varied relationships that bind individual firms and workers to one another and to particular industrial districts. Relations among firms increasingly were seen as governed by various forms of what Storper (1995) calls untraded interdependencies (see also Amin and Thrift, 1994; Camagni, 1991; Camerer and Vepsalainen, 1988; Grabher, 1993). In large part these interdependencies were understood, after Granovetter (1985), as broader sets of social relations that over time coalesce to form regional "cultures," or tacitly understood conventions/institutions that encourage trust, reduce uncertainty, and guide behavior. Thus, the individual firm became less significant as the locus of competitive advantage and technology creation. Case studies of "regional worlds of production" revealed the varied institutional foundations of industrial and regional performance (Saxenian, 1994; Storper, 1993; Tödtling, 1992). The geographical dimensions of industrial organization are explored by Scott and Storper (1987, 1992).

The geographical evolution of technology

Different theoretical visions of the spatial dynamics of production technology exist. Product life-cycle studies suggest that as industries and products mature, technology becomes increasingly standardized and thus more geographically mobile. Models of technology diffusion are also frequently invoked to explain the narrowing of technological variation over space (Brown, 1981; Griliches, 1957; Hägerstrand, 1967), and competition and factor mobility within the neoclassical regional growth model are similarly seen as eroding geographical differences in techniques of production (Borts and Stein, 1964). Technological "catch-up" is commonly thought to underpin convergence in international productivity levels (Fagerberg, 1994).

More recent analysis of technological change in space focuses on the dynamic capabilities of economic agents in different places to generate and sustain a creative milieu that undergirds competitive advantage (Maillat, 1991, 1995; Malmberg, 1996; Marshall, 1920; Myrdal, 1957; Storper, 1997). In this work regional technological change does not take place solely within the boundaries of the firm, but is also generated through interaction with other institutions (Freeman, 1995; Lundvall, 1992; Lundvall and Johnson, 1994; Nelson, 1993). Firms are seen as embedded in overlapping sets of socio-spatial relations including buyer–seller linkages, subcontracting ventures, local business cultures, conventions, and institutions, as well as various types of competitive capital and labor transactions (Granovetter, 1985; Harrison, 1992; Johnson and Lundvall, 1992; Saxenian, 1994; Storper, 1995, 1997; Teece, 1992). Attention has thus shifted toward the shared "technological capital" of industrial districts as the motor of agglomeration, and to the development of a regional variant of the national system of innovation (DeBresson and Amesse, 1991; Freeman, 1991, 1995; Lundvall, 1992; Nelson, 1993).

Accordingly, the evolution of technology is closely tied to the economic and institutional character of particular places. Jaffe et al. (1993) confirm the localized nature of technological progress. The tacit knowledge that often dominates early stages of the innovation process is person- and place-specific, and exhibits strong distance-decay effects (Scott and Storper, 1992). Minimizing the uncertainty of the innovation process demands frequent exchange of information (Teece, 1980, 1986) and this, coupled with the fixed costs of technical choice, encourages spatial, institutional, and technological "lock-in," or inertia (Clark and Wrigley, 1995; Grabher, 1993; Herrigel, 1993; Storper, 1995). The advantages of agglomeration result from a shared knowledge base, enhanced local information exchange and learning (Lundvall and Johnson, 1994; Malmberg and Maskell, 1997; Scott, 1995), multiple sources of innovation (von Hippel, 1988), and the collective sharing of knowledge spillovers (Anselin et al., 1997; Jaffe et al., 1993). As technological and institutional regimes are produced and reproduced in space they are seen as imbued with distinctive geographical and historical characteristics, and this imparts a strong path dependence on future trajectories of regional development (Arthur, 1989; David, 1975, 1985).

These theoretical claims suggest that marked variation exists in the innovative capacity of different regions. Unfortunately, empirical investigation of this claim is difficult as data on the components of technological change are rarely available at the national, let alone the subnational, level. This has prompted the use of a number of proxy measures of regional technological change. Malecki (1979, 1980) explores the geography of R&D spending, considered as an input to the process of technology creation. He reports that R&D activities in the USA are spatially concentrated: putative evidence of the geographic unevenness of technological change. This concentration is explained on the basis of corporate organization, specifically headquarter activities, the existence of large, skilled pools of labor in urban areas, and by industrial agglomeration. Similar findings for the UK are reported by Howells (1984), for Austria by Tödtling (1992), and for industry-specific R&D concentrations by Scott and Angel (1987). Feldman and Florida (1994) provide more recent evidence of the spatial clustering of R&D in research universities and in private industry. In related fashion, Florida and Kenney (1988) and Leinbach and Amrhein (1987), show that the availability of venture capital is limited to relatively few "high tech" regions in the USA.

Measures of technology output in the form of patents are also receiving considerable attention as indicators of technological change. As well as providing detailed information on the nature of new technology, patents indicate the location of the inventor, and whether or not rights to the patent were assigned (transferred) to another individual or organization. They also list citations to existing knowledge in the form of other patents or publications (see Jaffe, 1986). This information has been employed primarily to answer questions regarding the geography of invention by examining the location of inventors, and the existence of knowledge spillovers, although Scherer (1983) and Pavitt (1985) question the reliability of patent data as an index of innovation.

In their examination of the institutionalization of the US patent system, Lamoreaux and Sokoloff (1996) discuss the concentration of patenting in New England and the Mid-Atlantic region through much of the nineteenth century, and its later diffusion as a market for technology developed in the United States. Feldman and Florida (1994) show that US patent activity in 1982 was dominated by the old manufacturing belt, along with California. Jaffe (1989) reports similar inter-state variations in patenting in the early 1980s. O'hUallachain (1998) shows the bias of invention toward large metropolitan areas for much of the 1990s, attributing this to the spatial concentration there of technology-intensive manufacturing industries, well-educated people, and universities and research institutions. Fischer et al. (1994) report significant regional variations in patent activity in Austria.

Motivation for research on knowledge spillovers stems from the new endogenous growth theory (Lucas, 1988; Romer, 1986, 1990; Sunley, this volume). In this literature, spillovers occur when R&D activities undertaken by one firm or industry are used as inputs into the R&D activities of other firms or industries. It is claimed that such externalities bring about continued productivity growth. Griliches (1992) provides an overview, focusing on different methods of measuring spillovers. In aggregate there is considerable evidence of spillovers, though their magnitude varies considerably across studies. Examination of knowledge spillovers embodied in R&D investments weighted by patent data can be traced to the work of Scherer (1982). Analysis of disembodied knowledge spillovers is more frequently associated with Jaffe (1986). Jaffe et al. (1993) examine whether patent citations link geographically proximate inventors. They find that citations are significantly concentrated at a variety of spatial scales, and use this evidence to support their claim of localized knowledge spillovers. Zucker et al. (1998) contest these claims. Anselin et al. (1997) use innovation data for 1982 to examine the geographical boundaries of knowledge spillovers from university research to private sector R&D.

While regional variations in the production of new knowledge are not easily measured, the application of that knowledge in the form of product and process innovations has received attention, limited by the availability of data. In surveys of UK manufacturing establishments, Oakey et al. (1982) distinguish between product and process innovations, arguing that the former provide a reliable indicator of a region's indigenous innovation potential. They show that the incidence of product innovation is considerably higher in core regions than in peripheral regions, and account for this on the basis of R&D costs, the availability of skilled workers, access to information, and manufacturing plant characteristics. These results are echoed by Edwards and Gibbs (1982), Harris (1988), and Tödtling (1992). In the USA, Feldman and Florida (1994) show that innovation is spatially concentrated and attribute this to the usual list of factors for explanation – university and private R&D expenditures, the presence of firms in related industries, and access to producer services.

One problem with the above accounts is that the production of regional competitive advantage through technological change is too narrowly conceived, as dependent upon innovation. We have abandoned the neoclassical model of the representative firm to recognize the heterogeneity of firm characteristics and behaviors, but appear to have too readily adopted a model of the representative region, an innovative territory whose technological dynamism and growth rests upon a rather narrow set of processes and supporting characteristics. Rigby and Essletzbichler (1999) go beyond innovation to examine the relative strength of different sources of aggregate regional technological change: innovation and imitation; changes in plant market share; and plant entry and exit. They show that the geography of aggregate technological change is complex: the absolute and relative sizes of the sources of change vary considerably between regions, and that in many US states innovation and imitation are not the principal determinants of productivity improvements.

Conclusion

At the level of the nation-state, competitiveness is linked to technology and the ability of the elements that define a "system of innovation" to generate and sustain growth (Best, 1990; Nelson, 1993; Porter, 1990). There is increasing recognition, however, that the spatial scale of such systems is local or regional, and that the dynamism of sub-national technology districts is responsible for a considerable proportion of aggregate growth (Amin and Thrift, 1994; Scott, 1996; Storper, 1997). A good deal of academic capital has been invested in searching for the conditions that underpin technological dynamism and the wealth of regions and nations. Not very long ago, the developmental status of a region was linked to the presence or absence of "high-tech" workers, "high-tech" capital, "high-tech" firms, and related research institutions (see the review in Malecki, 1991), and attempts to clone "high tech" spaces such as Silicon Valley and Route 128 in the USA became a widespread foundation of regional policy throughout the world (Castells and Hall, 1994). Walker (1985) and Scott and Storper (1987) outline the weaknesses of these arguments, and Sternberg (1996) suggests that distilling the lessons from successful technology districts produces few generalities.

Current debate on technology and regional growth focuses on social relations. The production and exchange of knowledge that powers technological progress is regarded as a social activity, enhanced by personal interaction, by a common language, and by a common understanding of problems and strategies (Gertler, 1995; Lundvall, 1992; Malmberg and Maskell, 1997). With the "right" infrastructural support, or the "right" mix of tangible elements, the regional problem is now seen as one of generating the appropriate social capital to make those elements operate cohesively. Whether or not "high tech" social capital is the critical ingredient for regional competitive advantage remains to be seen.

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