4 The nature of innovation and the evolution of the productive system*

I. Introduction and summary

This chapter discusses the relationship between productivity changes and technical innovation. Whilst economists have always accepted that technical change is a fundamental driving-force of productivity growth, they have differed in their assumptions and theories about its sources and its impact. Some have stressed its 'exogenous' aspects, describing it as 'manna from heaven'. Others have argued, following Schmookler (1961), that inventions and innovations are endogenous activities within the economy, responding to demand pressures or changes in factor costs. These economists have tended to stress the smooth and continuous nature of technical change, whereas others, following Schumpeter (1912), have depicted it as a series of shocks or explosions, uneven in their incidence over time and space. They have stressed the unpredictable and largely autonomous developments in fundamental science in their interactions with technology and the creative pioneering role of innovative entrepreneurs, with characteristics differing from the ordinary routine managers and businessmen. Schumpeter's view is discussed in Section II.

The evidence from much recent research on technical change, as well as the evidence from the history of technology indicates that there is substance in both views and that a satisfactory theory of technical change must be based on a taxonomy of innovations, which includes both 'radical' and 'incremental' innovations. Although both are essential to the growth of productivity, their effects are quite different over a long period. This distinction is discussed in Section III.

When they are first introduced, just because they mark a break with past production practice and experience, by definition both management and work-force are unfamiliar with radical new products and processes and sometimes resist their introduction. Moreover, even with the best-

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organised research and development, it is seldom possible to eliminate all 'bugs' in the R&D stage. There are almost always teething problems with radical innovations, which may last for many years. Case studies of radical inventions and innovations (e.g. Jewkes, Sawers and Stillerman, (1958) provide abundant evidence for this proposition. Consequently, even though imaginative entrepreneurs, scientists and engineers may be quite confident about the ultimate technical and economic benefits, early productivity and profitability are often disappointing. For this reason, 'me-too' or 'fast-second' strategies are often preferred to the tribulations of first innovators. For this reason too, as well as market acceptance problems, most diffusion studies and models start with the flatter part of the familiar 'S'-shaped curve.

Incremental innovations are usually needed to overcome the early teething problems with radical innovations, so that user and producer experiences are taken into account in the redesign of product and process. These improvements continue throughout the product life so that once fast diffusion commences, a combination of learning by doing, learning by using and economies of scale can yield strong productivity gains for a considerable period, even for several decades. Ultimately, however, further incremental improvements begin to bump up against both scale and technical limits (Wolf's Law). Although slower productivity gains may continue for a long time and even receive further stimulus from the competition of new radical innovations, in the end the focus shifts to radically new types of production which offer once more the *potential* scope for more substantial gains.

DR to incremental innovations

However, the analysis of productivity growth cannot be confined to the level of the single innovation. All the empirical evidence points to the interdependence of many radical and incremental innovations. Both historians of technology (e.g. Gille, 1978) and studies of diffusion (e.g. Gold, 1981) point to the importance of 'systems' of innovation and 'networks' of interdependent elements. Obvious examples are electric power, railways and telecommunications systems. Here, the success of any innovation is often dependent on modifications elsewhere in the system and imbalances are a powerful inducement to complementary innovations (Rosenberg, 1976, 1982). These system aspects of innovation are more widespread than is commonly realised for many radical innovations require new combinations of inputs, such as materials, instruments and machinery as well as new skills. New technology systems are discussed in Section IV.

System gains in productivity depend therefore on a combination of related innovations, so that the time required for the realisation of the potential major incremental productivity gains is even longer, normally extending over decades rather than years. If new infrastructural investment is also needed and the new technology system is so extensive and influential that it affects the performance of the entire economy, this

amounts to a change of 'techno-economic paradigm' (Perez, 1983). The final section of this chapter (Section V) argues that such a shift to a new 'information and communication technology' paradigm underlies some of the paradoxical movements in productivity in the 1970s and the 1980s.

II. Schumpeter

Any attempt to discuss the role of technical change in economic theory must go back to Schumpeter. Almost alone among leading twentieth-century economists, he attempted to place technical innovation at the heart of his system. However, with Schumpeter, as with other economists, we find some dualism in his work. On the one hand in his *Theory of Economic Development* (1912), science and technology are treated, at least implicitly, as exogenous to the system. On the other hand, in his famous paper on the 'Instability of capitalism' (1928) and even more in his later work (e.g. 1943), he emphasised the role of 'bureaucratised R&D' which had become an internalised function of the large enterprises and the source of their supposed competitive superiority. So strong was this contrast that Almarin Phillips (1971) even spoke of 'two Schumpeters'—the young and the old. No doubt there is some validity in this distinction, but it is also possible to view the contrast as reflecting Schumpeter's own historical sense of the changes which were taking place in the process of technical innovation during his own lifetime (Freeman, Clark and Soete, 1982). Be this as it may, it is evident that any attempt to deal with the issues of exogeneity and endogeneity must start with a critique of Schumpeter's approach.

Ruttan (1959) has maintained that Schumpeter did not even have a theory of innovation. This is putting the matter too strongly. Schumpeter had a theory of innovation, although it was a one-sided theory subordinated to his theory of entrepreneurship. This led him on the one hand to neglect incremental innovation, and on the other hand to neglect the interdependencies between major radical innovations. His theory of innovation was based on his definition of the 'entrepreneur' as that individual (or combination of individuals) responsible for the business decisions which lead to the introduction of new products, processes and systems or the opening up of new markets and new sources of supply. In his view, such innovative entrepreneurship was an act 'not of intellect but of will', and this creative leadership was the source of the enormous dynamism in capitalist society. This led him to concentrate attention on the more spectacular, 'heroic' types of innovation, which were identified with outstanding individuals, reflecting the business climate of the years before the First World War. He recognised corporate and even state entrepreneurship (Schumpeter, 1939, p. 346) but they fitted less easily into his framework. ?

The *source* of the scientific and technical ideas, which were ultimately embodied in new products and processes by an act of entrepreneurship was never of very much concern to him. Although he consistently stressed the importance of history in the social sciences, he was in no sense a historian of science or technology and there is remarkably little about the technical aspect of inventions or innovations in the whole of Schumpeter's work. In this respect his approach was similar to that of the 'manna from heaven' economists. However, in no way did he regard the flow of technical and organisational innovations as a smooth, continuous process fed by a steady stream of exogenous developments in science and technology. On the contrary, no one emphasised more than Schumpeter the uneven, discontinuous, unpredictable aspects of technical change which is 'more like a series of explosions than a gentle though incessant transformation' (Fels, 1964, p. 75). Innovations are 'lop-sided, discontinuous, disharmonious by nature' and are not evenly distributed over time or space, but tend to cluster 'because first some, and then most firms, follow in the wake of successful innovation'.

His well-known distinction between 'invention', 'innovation' and 'diffusion', which has since been adopted in most economic analyses of technical change, served to highlight the role of the entrepreneur in the entire process and to put the main emphasis on the more radical innovations. Both invention and diffusion were relegated to a somewhat inferior status. The role of the inventor, although of course acknowledged, was not comparable to that of *innovator*, even though the roles might sometimes be combined in the person of the inventor-entrepreneur. Many inventions would never go any further than the laboratory or the proverbial attic or would gather dust in the patent office. Only an act of innovative entrepreneurship would bring an invention from the status of scientific curiosity to that of commercial artefact; for Schumpeter this was the true and only source of profit and growth in capitalist society, and its most characteristic feature.

Similarly, Schumpeter's sharp distinction between innovation and diffusion, was linked to a clear division between the creative entrepreneurs and 'mere' routine managers (normal businessmen) who simply followed in the wake of the business leaders. Rosenberg (1976) in particular has consistently emphasised the dangers of this Schumpeterian dichotomy (or trichotomy if inventors are included). He has repeatedly pointed out that the product or process which is diffusing through a population of adopters is subject to a continual process of improvement and modification, so that diffusion is seldom if ever a simple process of replication by unimaginative imitators.

To be fair to Schumpeter, he occasionally emphasised this point himself, as in relation to the history of the automobile. He pointed out that 'those who follow the pioneers are still entrepreneurs, though to a degree that continually decreases to zero' (Schumpeter, 1939, p. 414). Nevertheless, the main thrust of his argument undoubtedly tends to put the spotlight on

the innovator-entrepreneur and to detract attention somewhat from the diffusion–improvement–learning-by-doing-and-using complex of events, as well as the science–technology–invention nexus leading up to innovations. Yet, it is precisely the interdependence of invention, innovation and diffusion which emerges from most of the empirical work on technical change which has been carried out in the forty years or so since Schumpeter's death. Most of the productivity gains associated with the diffusion of new technology do *not* come as an immediate consequence of the first radical innovation. On the contrary, they are usually achieved only as a result of a fairly prolonged process of learning, improving, scaling up and altering the new products and processes. This entails many follow-through inventions and innovations throughout the commercial life of the product or system. The steam-engine, the generation of electricity, the automobile and the computer are all obvious examples.

At this point, one might protest that these examples are a-typical. They are all extremely important innovations, which were systemic in nature and each put their stamp on an entire historical era in the development of technology. But this is precisely the point. It is *not* possible to treat all innovations as though they were isolated and equal separate events. A satisfactory theory of technical change must embrace a taxonomy of innovation which recognises the qualitative differences between different types of innovation and their systemic interdependencies. Although there are glimpses of this in Schumpeter, his basic approach prohibited its full development. Although he recognised the importance of Gilfillan's work, he deliberately chose to emphasise other features of the process

III. Incremental and radical innovations

Schumpeter's work on the sociology of *innovations*, (and he was as much a sociologist as an economist) (Shionoya, 1986), differed from Gilfillan's (1934) work on the sociology of *invention*, despite his attempt (1939, p. 226) to reconcile the two. Gilfillan emphasised the continuous and often anonymous stream of discoveries, inventions and improvements and discounted the individual leaps of invention and entrepreneurship which were Schumpeter's main concern. Much recent empirical work on technical change has vindicated Gilfillan's emphasis on a fairly steady process of incremental innovations over long periods and on the great importance of learning by doing and using. These expressions, introduced by Arrow (1962), von Hippel (1976) and other post-Schumpeterian economists, have now become part of the accepted jargon of the analysis of technical change. More recently, learning by 'inter-acting' (Lundvall, 1988) has also become part of the common currency, serving to emphasise the mutual interdependence of 'suppliers' and 'users' of innovations within a national or international system. Although Gilfillan used none of these expressions himself, they are a logical development and refinement from the spirit of his work. Indeed they are essentially an elaboration of one aspect of the treatment of technical change already developed by Adam Smith and Karl Marx.

Although Smith stressed the combined role both of producers and of users of machines as the joint source of technical improvements, he also pointed to the scientists ('philosophers') whose role is to speculate and to combine the understanding of dissimilar objects. Marx, too, stressed the way in which users of tools and machines modified them to meet the innumerable and changing needs of specific applications, as in the example (Clark and Juma, 1988) of the large variety of hammers in use in British engineering workshops during the Industrial Revolution. However, Marx also recognised the ways in which science was increasingly pressed into the direct service of production.

Smith and Marx were interested in the detail of technical change and recognised the role of science as well as incremental modifications in changing the production system. But most of the neo-classical economists preferred to abstract from this nitty-gritty concern with innovation. Rogers (1962) could find only one case study of the industrial diffusion of innovations by an economist. However, since the 1950s there has been a resurgence of empirical research so that we now have far more evidence on which to base generalisations on the role of producers and users of innovation during diffusion.

Among many studies of technical change in specific industries, two in particular amply demonstrate the role of learning by doing and using in incremental innovation. These are Hollander's (1965) study of Du Pont's rayon plants and Townsend's (1976) study of the Anderton shearer-loader in the underground mechanisation of the British coal industry. Hollander's detailed longitudinal study showed that 90 per cent of the steady productivity gains achieved in Du Pont rayon plants over the 1950s could be ascribed to incremental improvements in the operation of the plant introduced by production engineers, systems engineers, and operators and could not be ascribed to the central R&D department of the firm. Townsend showed that after the original development and manufacture of the shearer-loader machine by Anderton-Boyes (itself based on prototype experiments at the coal-face initiated by a production engineer), hundreds of incremental improvements to the design were made during the 1950s and 1960s. These flowed from suggestions made at the coal-face and introduced by the manufacturers, just as Adam Smith had indicated. Here too, the process of incremental innovation led to very substantial productivity gains, particularly as the machine was modified to meet the wide variety of geological conditions and the exacting safety requirements of the Coal Board's tests.

These two studies are typical of many which have amply confirmed that the incremental improvements associated with learning by doing and using

are indeed a major source of productivity gains in many industries. Such incremental improvement is not of course simply a process of *technical* change, it also involves *organisational* innovation and skill improvements based on experience. It is difficult to discern the role of Schumpeter's heroic entrepreneurs in this rather hum-drum process, except perhaps in creating an environment receptive to the innovative ideas of engineers, workers and users. As Pavitt (1984) has shown, it is a long process of accumulation of tacit as well as formal knowledge within enterprises. - no!

Does all this mean then that Schumpeter's emphasis on major creative leaps was entirely misplaced and that Gilfillan-style incrementalism combined with Arrow's learning by doing gives us a sufficient account of innovation in capitalist society? By no means. Instructive though the Hollander, Townsend and similar studies are, they reflect only one part of the complex set of innovative activities which transform the production system. Studies of incremental improvement must be complemented by studies of more radical discontinuities in the economy. No matter how much the underground operation of the shearer-loader users improved, it could never lead to an automated moving coal-face system based on electronic sensing and electronic controls. Such changes cannot arise from the purely incremental improvements associated with doing and using. Or, as Schumpeter himself put it: no matter how many stage coaches you put together you will not get a steam locomotive or a railway system. A satisfactory theory of innovation must embrace both Gilfillan incrementalism and Schumpeterian entrepreneurship with its more radical discontinuities in both products and processes, on the lines which Enos (1962), Mensch (1975) and others have proposed. 071

Incremental improvement has its limitations. There are technical limits to the use of candles in illumination, the use of horses in traction, the uses of iron and steel as engineering materials, the use of the abacus in statistical processing or of the valve (tube) in electronic computers. No amount of experience, learning, organisational and technical improvements can ultimately overcome their limitations, even though the arrival of a radical (and discontinuous) innovation may sometimes stimulate a last surge of incremental innovations—the so-called 'sailing-ship effect' which should more properly be called the 'steam-ship effect', for it was the arrival of the radical innovation which led to the final wave of improvements in the design of sailing-ships. Both economists and technologists have demonstrated the tendency for any incremental improvements to asymptote towards limits which may be either economic or technical or both.

The scaling up of plant and equipment is a process which has yielded enormous productivity gains in such industries as steel, petrochemicals, oil refining (Enos, 1962), road, sea and air transport, in the post-war period. However, as technical limits are approached (Wolf's Law), there is an increasing cost for additional minor improvements. Similar limitations may affect both the management of very large units and the marketing of output in relation to transport and distribution. Thus, oil tankers and ethylene plants have probably reached the limits of their efficient scaling up. In many industries, such as steel, the trend towards larger capacity plants has even been reversed since the productivity gains from radically new technology, from electronic instrumentation and control systems and from computer-controlled marketing and distribution are greater than further gains from scaling up giant plants

Schumpeter was not mistaken in stressing the importance of 'successive industrial revolutions' and of radical discontinuities in the productive system, or in recognising the enormous difficulties and risks confronting the innovative entrepreneurs in their attempts at radical innovation The classic study by Jewkes, Sawers and Stillerman (1958) not only demonstrates the extraordinary persistence of inventors despite all kinds of discouragement, but also shows that the final development and commercialisation of major inventions does indeed depend on acts of entrepreneurship whether in large or small firms, and whether or not the inventor is also the entrepreneur.

A satisfactory theory of innovation therefore must embrace *both* the innumerable incremental improvements *and* the radical discontinuities. Even though the borderline is sometimes difficult to draw, as with all such distinctions, there really is an important difference between the introduction of nylon or electricity and the incremental improvement of rayon manufacturing or steam engines. In the case of incremental innovations the changes which take place can be expressed as change in the coefficients of the input–output matrix of the *existing* array of products and services. In the case of radical innovation, logically, new rows and columns would be needed as they change the array of products and services and not just the efficiency in use of existing commodities. In practice, of course, there are always long delays before the introduction of entirely new products, such as electronic computers, is recognised in established statistical systems, such as input-output tables. They appear first in rag-bag categories such as products 'not elsewhere classified', but this does not invalidate the basic point.

Radical innovations cause structural change in the economy and lead ultimately to entirely new branches of industry. They are indeed, as Schumpeter insisted, the main source of dynamic development, distinguishing capitalism from earlier production systems. Today they require different types of research and development, different relationships with basic science, different types of marketing and financing, different types of input and lead to a different pattern of productivity gain. By definition they need quite new skills and management organisation and different types of production equipment. Mensch (1975) defined radical innovations ('basic innovations') as those requiring a new type of facility for their production and/or a new market.

For productivity movements, the distinction between radical and

incremental innovations is clearly of decisive importance. Major and prolonged productivity increases are likely to be achieved during the main incremental *improvement* phase or a radical innovation, but not in the early *introduction* phase, when the scale of production is too small to achieve scale economies, when standardisation of supply of new materials and components has not yet taken place and when designs of both product and process are still in flux. These considerations assume far greater importance when we take into account the *systems* aspect of most important radical innovations. The *potential* leap to much higher levels of productivity from a radical innovation may become a reality only when it is complemented by a wide range of other innovations, including especially organisational, managerial and social innovations. Keirstead (1948) was one of the first economists to recognise explicitly the great economic significance of these clusters, which he described as 'constellations' of innovations

IV. Radical innovations and new technology systems

As Spike Milligan pointed out, one telephone was not much use without a switchboard to connect it to others. Innovations are not a set of isolated events but are inevitably linked together, both in their underlying technical and scientific foundations and in their physical connections to other parts of the economic system. They may often induce other innovations both directly and indirectly. Historians of technology such as Gille (1978), Hughes (1982) and Rosenberg (1976, 1982) have pointed to numerous examples Hughes (1982) has shown that in complex supply networks, such as electric power, innovation in one part of the network can lead to intense engineering efforts to solve related problems or restore balance in its other parts. Rosenberg (1976) rightly insists that what is involved is not simply the inducement mechanism of relative factor costs, but also a complex interplay between new technological possibilities and 'trajectories', various cost pressures and bugs or imbalances in the system

The expression generic technology has been used to express the ways in which some new technologies open up a wide range of possibilities for further innovations in many sectors of the economy. Nelson and Winter (1977 and 1982) used the expression 'generalised natural trajectories of technology', to convey an essentially similar idea: that some developments in science and technology are so powerful that they set in train a number of chains of technologically related innovations.

For example, in the first Industrial Revolution, both Rosenberg (1976) and Rolt (1970) have demonstrated the critical role of machine tool technology for all kinds of other eighteenth and nineteenth-century capital goods innovations. Rolt (1970, p. 128) points out that Watt's steam-engine remained a good idea in the mind of its inventor until John Wilkinson had evolved a machine which could bore the cylinder accurately enough.

'From that time onwards it became plainly apparent that engineering progress would be governed by the ability of the machine shop to translate new ideas into hardware.' Rolt attributes to Henry Maudslay a number of the key innovations which facilitated this type of technical advance in other industries:

> He was the first to realise that workshop precision depended upon four things: accurate screw threads; true plane surfaces; absolute rigidity in all machine tools and precise methods of measurement. The origins of the lathe, man's basic machine tool, may be traced back into prehistory, yet Maudslay's first screw-cutting lathe was the undoubted parent of the modern lathe because it was built on these principles.

Rolt shows that the accuracy of these early machine tools was largely self-propagating, once the necessary accuracy had been built into them. His innovation of the bench micrometer enabled detection of differences up to 1/10,000th of an inch and clearly these advances in machine tools technology affected productivity gains in every other part of the system.

In their turn, advances in machine tools technology were dependent upon and stimulated related advances in metallurgy, especially in steel technology. Towards the end of the nineteenth century, a new cluster of innovations in steel, heat treatment, electric motors, electric furnaces and cutting-tool speeds made possible enormous further improvements in the productivity of machining systems throughout the engineering industries (Ayres, 1988). However, as in the first Industrial Revolution, the realisation of these new potential productivity gains was a prolonged process, requiring as it did not merely the diffusion of discrete individual innovations, but also the reorganisation of production systems to accommodate unit drive or batch drive, new factory layouts based on electric power, new skills and maintenance systems.

It was a similar story for synthetic materials, including synthetic fibres and synthetic rubbers. Most of these materials were first innovated in the German chemical industry in the 1920s and 1930s and they shared a common underlying scientific base in macromolecular chemistry. In the early days they were rarely competitive with natural materials, such as rubber, wool, leather and metals. The driving motivation was often autarkic—to overcome German dependence on imported materials. As learning progressed, however, many related and induced innovations were made in extrusion machinery, injection-moulding machines and in new applications. During and after the war the scaling up of production and numerous process innovations made the new materials increasingly competitive, and in the 1950s and 1960s they were the fastest growing sector of the world chemical industry, with very high annual gains in both labour and capital productivity. The universal availability and falling cost of oil-based 'building block' chemicals also greatly facilitated the growth of productivity as the industry switched to petrochemical technology. Thus, once again it can be seen that the productivity gains in this industry were certainly associated with a cluster of radical innovations but these bore their full fruit only when a new technological system was established after a complex social learning process lasting several decades (Freeman, Clark and Soete, 1982).

Among a number of economists who have developed similar ideas about interrelated innovations in 'systems', 'trajectories' and 'paradigms' (Dosi, 1982), the ideas of Sahal (1985) and of Perez (1983, 1985, 1987) are of particular interest in relation to long-term changes in productivity.

In line with the argument advanced so far in this paper, Sahal rejects either exclusive demand-pull or technology-push theories, maintaining that 'technology both shapes its socio-economic environment and is in turn shaped by it. Neither is a sole determinant of the other, the two codetermine each other.' He stresses in particular the influence of scale and size on the evolution of technology; ultimately he argues that the process of scaling up (or of miniaturisation) reaches limits and that at this time new radical innovations are needed to open up broad 'avenues of innovation' affording new opportunities in many sectors.

Perez similarly stresses the interplay between institutional change and technological change in developing her concept of 'techno-economic paradigms'. The realm of the technically feasible is far wider than the realm of the economically profitable. The selective mechanisms of the economy and of the natural and social environment interact with new technological trajectories to shape successive 'techno-economic paradigms'. Her theory has several important distinguishing features which are particularly helpful in considering long-term trends in productivity.

In the first place her concept of a change in techno-economic paradigm is one of a change in the basic approach of designers, engineers and managers which is so pervasive that it affects almost all industries and sectors of the economy. It is a 'meta-paradigm' theory. Secondly, she argues that the *economic* motivation for such a change of paradigm lies not only in the availability of a cluster of radical innovations including organisational innovations offering numerous new potential applications; but also in the *universal* and *low cost* availability of a key factor or combination of factor inputs. She suggests that this key factor was cheap *steel* from the 1880s to the 1930s, cheap *oil* from the 1930s to the 1980s, and cheap micro-electronics (chips) at the present time. Finally, she argues that before a new techno-economic paradigm can generate a new wave of expansion, there is a crisis of 'structural adjustment' corresponding to the recession and depression phases of Schumpeter's 'long waves' of economic development. The old institutions were adapted to a now increasingly obsolete technological style. They tend to 'lock out' alternative systems. There is therefore a period of mismatch between the new technology and the old institutional framework. The need for new institutions is perhaps

cf. Marx

most obvious in education and training, although it affects almost all institutions, including the capital market, standards, proprietary aspects of technology, government regulation of various sectors of the economy, industrial relations, trade union structure and so forth.

Perez therefore offers a link between the cyclical theories of technological evolution advanced by Abernathy and Utterback (1975), Sahal (1985) and others and the theories of path-dependency, structural change and 'lock-out' of alternatives put forward by Arthur (1988), David (1985) and Dosi and Orsenigo (1988).

The link to long-term productivity trends is evident. The productivity potential of a new techno-economic paradigm is at first realised only in one or a few leading sectors. Not until these effects have been clearly demonstrated does the diffusion begin to affect the entire economy. However, since what is needed is now a new infrastructure, many institutional and organisational changes, universal availability of new skills, as well as new types of equipment and materials, there is inevitably a prolonged period of structural adaptation.

So far this chapter has drawn upon the evidence of empirical and historical studies of innovation to develop a taxonomy of innovations and to relate the characteristics of their various types to their effects on productivity. This exposition was designed to explain some of the paradoxes in the present debate on long-term productivity trends. In the final section of the chapter we consider the specific use of information and communication technology and advance the hypothesis that the paradoxical slow-down in the 1970s and 1980s may be explained in part by the change of techno-economic paradigm. The final section is based on an analysis originally put forward in a paper for the OECD 25th Anniversary Symposium (Freeman, 1986).

V. Productivity effects of innovations in information and communication technology

The new 'information technology' (IT) paradigm, based on a constellation of industries, which are among the fastest growing in all the leading industrial countries, such as computers, electronic components and telecommunications, has already resulted in a drastic fall in *costs* and a counter-inflationary trend in prices in these sectors as well as vastly improved technical performance. This technological revolution is now affecting, although very unevenly, all other sectors (Freeman and Soete, 1987), because of its actual or potential economic and technical advantages. In considering this technological revolution, we must take into account not only particular products, processes or services but also the changes in organisation and structure of both firms and industries, which accompany the introduction of IT.

In addition to fundamental changes in management structure of large firms, and in their procedures and attitudes, there are many other parallel effects of the spread of IT through the economy: the capability which it confers for more rapid changes in product and process design; the much closer integration of design, production and procurement functions within the firm; the reduced significance of economies of scale based on dedicated capital-intensive mass production techniques; the reduction in numbers and weight of mechanical components in many products; the much more integrated networks of component suppliers and assemblers of final products and the related capital-saving potential; the growth of new 'product services' to supply manufacturing firms with the new software, design, technical information and consultancy which they increasingly require; and the extremely rapid growth of many small new innovative enterprises to supply these services and new types of hardware and components. According to some estimates, if software is included with R&D expenditures in electronics and telecommunications, then this accounts for nearly half of all contemporary R&D activity.

The skill profile associated with the new techno-economic paradigm appears to change from the concentration on middle-range craft and supervisory skills to increasingly high and low-range qualifications, and from narrow specialisation to broader multipurpose basic skills for information handling. Diversity and flexibility at all levels substitute for homogeneity and dedicated systems. Software design and maintenance become key skills everywhere.

The transformation of the profile of capital equipment is no less radical. Computers are increasingly associated with all types of productive equipment as in computer numeric control (CNC) machine tools, robotics and process control instruments as well as with design through computer-aided design (CAD), and with administrative functions through data processing systems, all linked by data transmission equipment. According to some estimates, computer-based capital equipment already accounts for between a quarter and a half of all new fixed investment in plant and equipment in the United States and other leading industrial countries.

The deep structural problems generated by this change of paradigm are now evident in all parts of the world. Among the manifestations are the acute and persistent shortage of the high-level skills associated with the new paradigm, even in countries with high levels of general unemployment. In the early 1980s studies in many different OECD countries unanimously reported persistent skill shortages in software design and development, systems analysis and computer engineering. If anything these problems have become more acute with manufacturing firms in both Japan and Britain complaining of 'poaching' by the service industries.

As a result there is a growing search for new social and political solutions in such areas as flexible working time, re-education and retraining systems, regional policies based on creating conditions for information technology (rather than tax incentives to capital-intensive mass production industries), new financial systems, possible decentralisation of management and government, and access to data banks at all levels. So far, however, there still seem to be partial and relatively minor changes. If the Keynesian revolution and the profound transformation of social institutions in the Second World War and its aftermath were required to unleash the post-war wave of growth, then social innovations on a much more significant scale are likely to be needed now. This applies especially to the international dimension of world economic development and the telecommunications network.

In describing the advantages of a new techno-economic paradigm, we have stressed the ability to bring about a 'quantum jump' in productivity. However, the *actual* rates of productivity increase have declined since the 1960s in most industrial countries. How is this apparent paradox to be explained? There are of course many factors to be taken into account, such as macro-economic policies, the exhaustion of 'catching up gains' in the 1960s and 1970s, demographic changes and so forth. Varying levels of capacity utilisation are particularly important for short and medium-term changes, although for *long-term* trends in the entire world economy, technical change is clearly a major factor. Why then the *slowdown* of the 1970s and 1980s?

First of all, it is essential to keep in mind that the new paradigm has been diffusing in a world still dominated by the older energy-intensive mass production paradigm. The symptoms of diminishing returns to the massive investment in this older paradigm were evident in declining capital productivity in most industrial sectors in almost all OECD countries since the late 1960s. However, they have also become apparent in the declining rate of increase in labour productivity

Secondly, in assessing the growing impact of the new techno-economic paradigm, it is necessary to take into account all that has been said above about the problems of structural adjustment, before a 'good match' is achieved between the new paradign and the institutional framework. This process is very uneven between different countries and different industrial sectors. Therefore in examining these phenomena it is essential to move to a disaggregated level of analysis, since what we are discussing is the extremely uneven diffusion of a new technological paradigm from a few leading sectors to the economy as a whole.

The TEMPO project at SPRU attempted to study the long-term changes in labour and capital productivity in the principal sectors of the British economy (the forty industries distinguished in the Cambridge growth model) from 1948 to 1984. The account which follows is based on the five volumes of that analysis and the full summary (Freeman and Soete, 1987). In our view, although there are important national variations, the broad picture which is described below is characteristic of all the major OECD industrial economies.

When we analyse changes in labour productivity and in capital productivity over the past twenty years at a sufficiently disaggregated level, then we find the following picture:

1. The sectors with the highest rates of growth in labour productivity are the electronic industries, and especially the computer industry and the electronic component industry. These are the industries which make the greatest use of their own technology for design, production, stock control, marketing and management. They are also the only industrial sectors which show a substantial rise in *capital* productivity. They are the sectors which demonstrated the advantages of the new technologies for everyone else and may be described as the 'carrier' and 'motive' branches of the new paradigm. Baily and Chakrabarty (1988) have estimated that no less than half of the total growth of US manufacturing productivity in the 1980s is due to the computer industry alone.
2. In those sectors which have been heavily penetrated by microelectronics, both in their product and process technology, there is also evidence of a considerable rise in labour productivity and even some advance in capital productivity in the most recent period. This applies, for example, to the scientific instruments, the telecommunications and the watch industries. These sectors have now virtually become a part of the electronics industry
3. In sectors where microelectronics has been used on an increasing scale over the past ten years, although older technologies still predominate in product and process technology, there is a very uneven picture. Some firms have achieved very high productivity increases, some have stagnated, and others actually show a decline in productivity. This is the case, for example, in the printing, machine-building and clothing industries This uneven picture is completely consistent with Solter's (1960) vision of the spread of new technologies within established industries through new capital investment. In many cases information technology is introduced in a piecemeal fashion in one department or for one activity and not as part of an integrated system For example, one or a few CNC machine tools are introduced or a few robots or word processors. These are small 'islands' of automation. This is not yet computer-integrated manufacturing or office systems and does not yet achieve anything approaching the full *potential* productivity gains There may even be a temporary fall in productity because of the lack of the necessary skills in design, software, production engineering, maintenance, and management generally. Problems of institutional and social adaptation are extremely important, and flexibility in this social response is very varied between countries, as well as between enterprises.
4. Sectors producing standardised homogeneous commodities on a flow production basis in rather large plants have made considerable use of

mechtronics

information technology in their process control systems and in various management applications. They were indeed among the earliest users of computers for these purposes. This applies for example to the petrochemical, oil, steel and cement industries. This has helped them to achieve considerable improvements in their use of energy and materials, although gains in labour productivity have often been less than in the 1950s and 1960s, and capital productivity usually shows a marked decline. To understand this phenomenon it is essential to recognise that these industries are amongst those most heavily affected by the shift from an energy and materials-intensive mass production technological paradigm to an information-intensive paradigm. At the height of the consumer durables and vehicles consumption boom of the 1950s and 1960s, they were achieving strong labour productivity gains based on big plant economies of scale. However, with the change in technological paradigm, the slowdown in the world economy and the rise in energy prices in the 1970s, they often faced problems of surplus capacity and high unit costs based on below-capacity production levels. Nevertheless, see (8) below for those cases in which surplus capacity has been eliminated.

5 Service sectors which are completely based on information technology —software services, data banks, computerised information services, design services, etc.—are among the fastest growing and (for individual firms) the most profitable activities in the leading industrial countries. However, although their growth potential is enormous, they so far account for only a small proportion of total service output and employment and they suffer from acute skill shortages.

6 Some other service sectors have been considerably affected by information technology, such as banking, insurance and distribution. In these sectors, although the diffusion of new technology is extremely uneven, both by firm and by country, there is evidence of significant gains in labour productivity although measurement problems are acute. This phenomenon is rather important because hitherto it has often been observed that the service sector of the economy was not capable of achieving the type of labour productivity gains achieved in manufacturing. Information technology now offers the *potential* (and in some cases already the reality) of achieving such gains outside manufacturing. However, the progress of technology depends heavily on organisational, institutional and structural changes. The institutional factors, for example, are extremely important in explaining the very slow rate of change in Japanese retail distribution.

7 In most service sectors, information technology has diffused to only a small extent, and these are still characterised by very low labour productivity gains, or none at all. The capacity to design, use and maintain software systems is largely lacking and although the stagnation in labour productivity in these sectors may be attributed to the *lack* of information technology, it certainly cannot be attributed to the impact of information technology. These account by far for the larger part of the tertiary sector.

8. Finally, in many industrialised economies there are sectors which have shown labour productivity gains over the past ten years, which are owing far more to structural rationalisation than to the direct impact of new technology. Examples are in the textile industries and also some of those sectors discussed in (4) above, where plant closures and rationalisation have been implemented as in the UK steel industry and European petrochemicals. Since in any industry there is always a 'tail' of low productivity plants, a significant rise in *average* labour productivity can always be achieved simply as a result of scrapping the older generation of plant, even without any further technical improvements in the more recent plants, which can now work closer to full capacity. This may be described as the *Verdun* effect in contrast to the *Verdoorn* effect of the high boom period.

Summing up this discussion, it is not difficult to see that the slowdown in *average* labour productivity gains over the 1970s and 1980s, which has been a world-wide phenomenon by comparison with the 1950s and 1960s, is precisely the aggregate outcome of a structural crisis of adaptation or change of techno-economic paradigm, which has accentuated the uneven development in different sectors of the economy.

On the one hand, the previously dominant energy-intensive mass production paradigm or 'technical regime' was reaching limits of productivity and profitability gains, due to a combination of exhaustion of economies of scale, erosion of profit margins through 'swarming', market saturation in some sectors, diminishing returns to technical activities (Wolf's Law) and cost pressures on input prices. On the other hand, the new paradigm, which offers the *possibility* of renewal of productivity gains and increased profitability, has so far deeply affected only a few leading edge industries and services.

The full realisation of the productivity gains which can be achieved as a result of information technology depends on the diffusion of the new paradigm throughout the economy. This in turn will be possible only as a result of many social and institutional changes, which will involve interrelated organisational and technical innovations, as well as a large increase in new skills and a transformation of the existing capital stock. The recent book of the MIT Commission on Industrial Productivity (Dertouzos, Lester and Solow, 1989) provides rather strong confirmation of this view in relation to the US economy in the 1980s.

VI. Conclusion

The hypothesis which has been advanced in this chapter to explain part of the productivity paradox of the 1970s and 1980s would require a large amount of long-term statistical analysis in many countries to verify thoroughly. However, the work of historians as well as the analysis of contemporary trends lends it some plausibility. For example, Landes (1970) commenting on the slowdown in British productivity growth in the 1870s and 1880s says:

> We may note simply that such calculations as we have of her rates of industrial growth and increase in productivity—and they are confirmed by the major industrial time series—show a distinct falling-off after the mid-century decades of high prosperity. They do not turn up again until after 1900. From 1870 on, with the exception of a branch like steel, which was transformed by a series of fundamental advances in technique, British industry had exhausted the gains implicit in the original cluster of innovations that had constituted the Industrial Revolution. More precisely, it had exhausted the big gains. The established industries did not stand still. Change was built into the system, and innovation was if anything more frequent than ever. But the marginal product of improvement diminished as the cost of equipment went up and the physical advantage over existing techniques fell. (p. 235)

The recognition of diminishing returns in the old steam-powered factory systems was also apparent in the debates of the 1880s about the subcontracting arrangements, which were characteristic of both American and British Industry. There was a search going on for managerial and organisational innovations simultaneously with the efforts to improve technology by process innovations, and by the introduction of electricity. However, as in the 1970s, the realisation of these potential gains depended on a paradigm change with a new infrastructure. Abramowitz (1986) has pointed in the same direction in his analysis of 'catching up'. Technological leadership and even catching up depend on being able to run in new directions (Perez and Soete, 1988).

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5 Networks of innovators: a synthesis of research issues*

This chapter will first of all summarise some of the key findings of earlier empirical research in the 1960s on the role of external sources of scientific, technical and market information in successful innovation by business firms. This already demonstrated unambiguously the vital importance of external information networks and collaboration both with them and with users during the development of new products and processes. Moreover, the dilemmas of co-operative research in competitive industries were recognised and studied long ago (e.g. Solo, 1954; Woodward, 1965; Johnson, 1973). What then is new about the present wave of interest in 'networks of innovators'? Are there new forms of organisation or new technologies or new policies which justify renewed research efforts since they go beyond those developments already analysed in earlier empirical and theoretical work?

Section 2 reviews the evidence of new developments in the 1980s in industrial networks, regional networks and government-sponsored innovative activities. It shows that there has indeed been a major upsurge of formal and semi-formal flexible networks in the 1980s including some new types. It also shows that some older forms of research co-operation have been modified and transformed. The papers at Montreal largely concentrated on the role of regional supplier networks, which are a good example of such 'new wine in old bottles'. This chapter attempts to locate the regional network discussion within a wider context of new developments in networking.

Section 3 discusses the causes of these new developments and whether they are likely to remain a characteristic of national and international innovation systems for a long time to come, or prove to be a temporary upsurge to be overtaken later by a wave of take-overs and vertical integration.

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