The Economics of
Industrial Innovation
3rd Ed.

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CHAPTER 1

INTRODUCTION

> All the improvements in machinery, however, have by no means been the inventions of those who had occasion to use the machines. Many improvements have been made by the ingenuity of the makers of the machines, when to make them became the business of a peculiar trade; and some by that of those who are called philosophers or men of speculation, whose trade is not to do anything but to observe everything; and who, upon that account, are often capable of combining together the powers of the most distant and dissimilar objects. In the progress of society, philosophy or speculation becomes like every other employment, the principal or sole trade and occupation of a particular class of citizens. Like every other employment too, it is subdivided into a great number of different branches, each of which affords occupation to a peculiar tribe or class of philosophers; and this subdivision of employment in philosophy, as well as in every other business, improves dexterity and saves time. Each individual becomes more expert in his own peculiar branch, more work is done upon the whole, and the quantity of science is considerably increased by it.
>
> (Smith, 1776, p. 8)

> It is a scientifically based analysis, together with the application of mechanical and chemical laws, that enables the machine to carry out the work formerly done by the worker himself. The development of machinery, however, only follows this path once heavy industry has reached an advanced stage, and the various sciences have been pressed into the service of capital. . . . Invention then becomes a branch of business, and the application of science to immediate production aims at determining the inventions at the same time as it solicits them.
>
> (Marx, 1858, p. 592)

> When you adopt a new systematic model of economic principles you comprehend reality in a new and different way.
>
> (Samuelson, 1967, p. 10)

1.1 INTRODUCTION

In the world of microelectronics and genetic engineering, it is unnecessary to belabour the importance of science and technology for the economy. Whether like the sociologist, Marcuse, or the novelist, Simone de Beauvoir, we see technology primarily as a means of human enslavement and destruction, or whether, like Adam Smith and Marx, we see it primarily as a liberating force, we are all involved in its advance. However much we might wish to, we cannot escape its impact on our daily lives, nor the moral, social and economic dilemmas with which it confronts us. We may curse it or bless it, but we cannot ignore it.

Least of all can economists afford to ignore innovation, an essential condition of economic progress and a critical element in the competitive struggle of enterprises and of nation-states. In rejecting modern technology, Simone de Beauvoir was consistent in her deliberate preference for poverty. But most economists have tended to accept with Marshall that poverty is one of the principal causes of the degradation of a large part of mankind. Their preoccupation with problems of economic growth arose from the belief that the mass poverty of Asia, Africa and Latin America and the less severe poverty remaining in Europe and North America, was a preventable evil which could and should be diminished, and perhaps eventually eliminated.

Recently both the desirability and the feasibility of such an objective have been increasingly questioned. However, innovation is of importance not only for increasing the wealth of nations in the narrow sense of increased prosperity, but also in the more fundamental sense of enabling people to do things which have never been done before. It enables the whole quality of life to be changed for better or for worse. It can mean not merely more of the same goods but a pattern of goods and services which has not previously existed, except in the imagination.

Innovation is critical, therefore, not only for those who wish to accelerate or sustain the rate of economic growth in their own and other countries, but also for those who are appalled by narrow preoccupation with the quantity of goods and wish to change the direction of economic advance, or concentrate on improving the quality of life. It is critical for the long-term conservation of resources and improvement of the environment. The prevention of most forms of pollution and the economic recycling of waste products are alike dependent on technological advance, as well as on social innovations.

In the most general sense economists have always recognized the central importance of technological innovation for economic progress. The famous first chapter of Adam Smith's *Wealth of Nations* plunges immediately into discussion of 'improvements in machinery' and the way in which division of labour promotes specialized inventions. Marx's model of the capitalist economy ascribes a central role to technical innovation in capital goods – 'the bourgeoisie cannot exist without constantly revolutionizing the means of production'. Marshall had no hesitation in describing 'knowledge' as the chief engine of progress in the economy. A standard pre-war textbook states in the chapter on economic progress that 'Our brief survey of economic expansion during the last 150 years or so seems to show that the main force was the progress of technique' (Benham, 1938, p. 319). The standard post-war textbook by Samuelson (1967) comes to much the same conclusion.

Yet although most economists have made a deferential nod in the direction of technological change, until recently few have stopped to examine it. Jewkes and his colleagues explained this paradox in terms of three factors: their ignorance of natural science and technology on the part of economists; their preoccupation with trade cycle and employment problems; and the lack of usable statistics (Jewkes *et al.*, 1958).

These factors may partly explain the relative neglect of innovation but they cannot be held to justify it, as all of them can be overcome at least to some extent. Jewkes and his colleagues demonstrated this in their study of *The Sources of Invention*, and it has been confirmed by other empirical studies before and since. Indeed, whereas earlier literature reviews (e.g. Kennedy and Thirlwall, 1971) complained of the dearth of studies of innovations and their diffusion, more recent reviews (e.g. Dosi, 1988; Freeman, 1994) pointed to the explosion of interest in the 1980s and 1990s.

The earlier neglect of invention and innovation was not only due to other preoccupations of economists nor to their ignorance of technology; they were also the victims of their own assumptions and commitment to accepted systems of thought. These tended to treat the flow of new knowledge, of inventions and innovations as outside the framework of economic models, or more strictly, as 'exogenous variables'. A large body of economic theory was concerned with short-term analysis of fluctuations in supply and demand for goods and services. Although very useful for many purposes, these models usually excluded changes in the technological and social framework from consideration, under the traditional *ceteris paribus* assumption (other things being equal). Even when, in the 1950s, economists increasingly turned their attention to problems of economic growth, the screening off of 'other things' was largely maintained, and attention was concentrated on the traditional factor inputs of labour and capital, with 'technical change' as a residual factor embracing all other contributions to growth, such as education, management and technological innovation.

It was, of course, always recognized in principle that 'other things' were extremely important, but it was only recently that they began to be the subject of systematic economic analysis. For what they are worth, most of the early econometric studies of growth in industrialized countries attributed the greater part of measured growth to technical progress, rather than to increases in the volume of the traditional inputs of capital and labour. However, technical change remained on the fringe and not at the centre of economic analysis. Yet it would not be unreasonable to regard education, research and experimental development as the basic factors in the process of growth, relegating capital investment to the role of an intermediate factor. This is indeed the tendency of the so-called new growth theory (Romer, 1986; Verspagen, 1992b). It is of course new only in the sense of the belated recognition by modellers of some of the long-held ideas of economic historians and of those economists, such as Schumpeter, who always gave a central place to technical and institutional change. The World Bank (1991) review of development theory also reflected this major shift in thinking about growth mainly in terms of 'intangible investment' (see Chapter 13).

Looked at in this way, the investment process is as much one of the production and distribution of knowledge as the production and use of capital goods, which embody the advance of science and technology.[1] 'Intangible' investment in new knowledge and its dissemination are the critical elements, rather than 'tangible' investment in bricks and machines. Yet our whole apparatus of economic thought, as well as our whole system of statistical indicators, are still largely geared to the 'tangible' goods and services approach.

This will surely change in the coming decades, if only for the reason that the specialized industries concerned with generating and distributing knowledge will employ a large part of the working population. Bernal's model (1958) of the probable patterns of future employment (Figure 1.1)

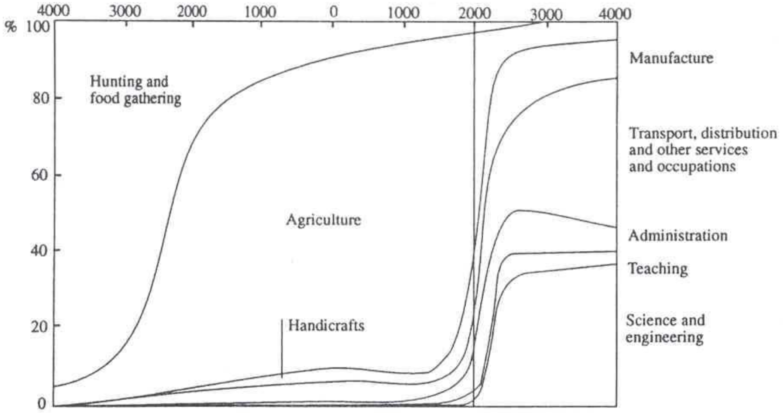

Fig. 1.1 Changes in occupation in the past and future

Source: Bernal (1958).

was speculative. It probably exaggerates the future share of science and engineering and underestimates the future share of 'teaching' but it illustrates the kind of fundamental change which is occurring. Agriculture, which once occupied almost the whole population, now employs less than 10 per cent in the most advanced economies (although still more than 50 per cent in many less developed countries). Not only is the share of manufacturing declining, as services expand their share, but within manufacturing and services an increasing number of people are concerned primarily with generating and disseminating information rather than goods.

Indeed, if a very wide definition of knowledge industries is adopted, then Machlup demonstrated that they already employed a quarter of the United States labour force in 1959. In his book, *The Production and Distribution of Knowledge* (1962), he estimated that over 30 per cent of the US labour force were engaged in occupations essentially concerned with producing and handling information rather than goods. In his definitions he included not only research, development, design and education of all kinds, but also the larger numbers of people employed in printing, publishing, scientific libraries, testing laboratories, design and drawing offices, general statistical services, resource survey organizations, radio, television and other communication industries, as well as computers and information machines of all types, and professional services concerned with analysing and displaying information. All of these activities are important in generating, disseminating and applying advances in technology, although some of them are more important in a broader sense as entertainment. More recently, Porat (1977) estimated that the share of 'information occupations' in the United States economy was already half the total, hence the increasing use of the expression 'information society'. As we shall see in

Chapter 7, when we come to discuss Information and Communication Technology (ICT), the distinction between information and knowledge is an important one. Raw data have to be converted into useful knowledge. The information society can be regarded as the culmination of a long process of the growth of intangible investment in information-based activities.

1.2 THE RESEARCH AND DEVELOPMENT SYSTEM

Research and inventive activities are only a small proportion of this very wide complex of 'information' industries. The professional labour force engaged in research and experimental development is less than 2 per cent of the total working population in the United States, and less than 1 per cent in most other countries. But this Research and Development system is at the heart of the whole complex, for in contemporary society it originates a large proportion of the new and improved materials, products, processes and systems, which are the ultimate source of economic advance. This is not to underestimate the importance of dissemination of knowledge through the education system, industrial training, the mass media, information services and other means. Nor is it to deny the obvious fact that in the short run rapid progress may be made simply by the application of the existing stock of knowledge. Nor yet is it to deny the importance of feedback from production and from markets to R&D and other technical and scientific activities. It is only to assert the fundamental point that for any given technique of production, transport or distribution, there are long-run limitations on the growth of productivity, which are technologically determined. In the most fundamental sense the winning of new knowledge is the basis of human civilization.

Consequently there is ample justification for concentrating attention on the flow of new scientific ideas, inventions and innovations. Efforts to generate discoveries and inventions have been increasingly centred in specialized institutions – the Research and Experimental Development network. This professionalized system is generally known by the abbreviated initials R&D. Its growth was perhaps the most important social and economic change in twentieth-century industry. This book is primarily concerned with the innovations arising from the professional R&D system, and with the allocation of resources to this system. Its interaction with other knowledge industries and with industrial production and marketing are of critical importance for any economy, but it is only recently that it has become the subject of systematic study. The policy adopted for R&D in any country, whether it is implicit in the sense of *'laissez-faire, laissez-innover'*, or explicit in the sense of national goals and strategies, constitutes the main element of policy for science and technology, or, more briefly, national science policy. A wider spectrum of scientific and technological services (STS) link the R&D system with production and routine technical activities. STS includes such activities as design, quality control, information services, survey and feasibility studies. They are also essential for efficient innovation, and may predominate in the diffusion of technical change in many branches of industry.

Although government and university laboratories had existed earlier, it was only in the 1870s that the first specialized R&D laboratories were established in industry. The professional R&D system was barely recognized at all by economists in the nineteenth century and even in the early part of this century the young Schumpeter (1912), who gave innovation pride of place in his theory of economic development, treated the source of inventions as exogenous to the economy. We owe to Schumpeter the extremely important distinction between inventions and innovations, which has since been generally incorporated into economic theory. An invention is an idea, a sketch or model for a new or improved device, product, process or system. Such inventions may often (not always) be patented but they do not necessarily lead to technical innovations. In fact the majority do not. An innovation in the economic sense is accomplished only with the first commercial transaction involving the new product, process system or device, although the word is used also to describe the whole process. Of course, further inventions often take place during the innovation process and still more inventions and innovations may be made during the diffusion process. Nevertheless, Schumpeter's conceptual distinction is a valuable one.

The chain of events from invention or specification to social application is often long and hazardous. Schumpeter (1912, 1928, 1942) always stressed the crucial role of the entrepreneur in this complex innovative process. But as Almarin Phillips (1971) has pointed out, it was only in his later work that he recognized the 'internalization' of much scientific and inventive activity within the firm. In his 1928 article he pointed out that the 'bureaucratic' management of innovation was replacing individualistic flair and that the large corporation was becoming the main vehicle for technical innovation in the economy. This shift of emphasis from the early Schumpeter ('Mark' 1) to the late Schumpeter ('Mark' 2) will be discussed further in later chapters. It reflected the real change which had taken place in the American economy between the two world wars and the rapid growth of industrial R&D in large corporations during that period.

By the outbreak of the Second World War there was already in existence an extensive network of organized research laboratories and related institutions in government, universities and industry, employing a full-time professional staff. This R&D industry can be subjected to economic analysis like any other although it has some unique characteristics. Its 'output' is a flow of new knowledge, both of a general character (the result of 'fundamental' or 'basic' research) and relating to specific applications ('applied' research). It is also a flow of models, sketches, designs, manuals and prototypes for new products, or of pilot plants and experimental rigs for new processes ('experimental development'). The inputs and outputs of this system are summarized in Table 1.1. But, of course, long before the twentieth century, experimental development work on new or improved products and processes was carried out in ordinary workshops. When Boulton brought Watt's steam engine from the stage of laboratory invention to commercial production model, he most certainly carried out extensive 'research and development' at his Soho works, even if there was no department with that name.

The classical economists were well aware of the critical role of R&D in economic progress even though they used a different terminology. Adam Smith (1776) observed that improvements in machinery came both from

Table 1.1 Inputs and outputs in research, invention, development and innovation

Stage	*Input*			*Output*	
	(i) *Intangible*	*(ii)* *Tangible and human*	*(iii)* *Measurable*	*(iv)* *Intangible*	*(v)* *Measurable*
1 'Basic research' (intended output: 'formulas')	Scientific knowledge (old stock and output from 1a) Scientific problems and hunches (old stock and output from 1b, 2b and 3b)	Scientists Technical aides Clerical aides Laboratories Materials, fuel, power	People, hours Payrolls, current and deflated Outlays, current and deflated Outlays per person	a. New scientific knowledge: hypotheses and theories b. New scientific problems and hunches c. New practical problems and ideas	Research papers and memoranda
2 'inventive work' (including minor improvements but excluding further development of inventions) (intended output: 'sketches')	Scientific knowledge (old stock and output from 1a) Technology (old stock and output from 2a and 3a) Practical problems and ideas (old stock and output from 1c, 2c, 3c and 4a)	Scientists Non-scientists Inventors Engineers Technical aides Clerical aides Laboratories Materials, fuel, power	People, hours Payrolls, current and deflated Outlays, current and deflated Outlay per person	a. 'Raw inventions' technological recipes patented inventions patentable inventions, not patented but published patentable inventions, neither patented nor published non-patentable inventions, published non-patentable inventions, not published minor improvements b. New scientific problems and hunches c. New practical problems and ideas, 'bugs'	Patent applications and patents Technological papers and memoranda Papers and memoranda

continued overleaf

Table 1.1 *(continued)*

Stage	*Input*			*Output*	
	(i) *Intangible*	*(ii)* *Tangible and human*	*(iii)* *Measurable*	*(iv)* *Intangible*	*(v)* *Measurable*
3 'Development work' (intended output: 'blueprints and specifications')	Scientific knowledge (old stock and output from 1a) Technology (old stock and output from 3a) Practical problems and ideas (old stock and output from 1c, 2c, 3c and 4a) Raw inventions and improvements (old stock and output from 2a)	Scientists Engineers Technical aides Clerical aides Laboratories Materials, fuel, power Pilot plants Prototypes	People, hours Payrolls, current and deflated Outlays, current and deflated Outlay per person Investment	a. Developed inventions, blueprints, specifications, samples b. New scientific problems and hunches c. New practical problems and ideas, 'bugs'	Blueprints and specification for new and improved products and processes
4 'New-type plant construction' (intended output: 'new-type plant' and new products)	Developed inventions (output from 3a) Business acumen and market forecasts Financial resources Enterprise (venturing)	Entrepreneurs Managers Financiers and bankers Builders and contractors Engineers Building materials Machines and tools	$ investment in new-type plant and products $ investment in new-type plant	a. New practical problems and ideas, 'bugs'	New-type plant or production lines producing novel products, better products, cheaper products, i.e. products and process innovations

Note: Ames (1961) has pointed out that 'bugs' (persistent irritating obstacles to the completion of scientific and technical work) are an important part of the output, since they may lead to novel results at later stages, including new scientific theories.

Source: Modified slightly from Machlup (1962).

the manufacturers and users of machines and from 'philosophers or men of speculation, whose trade is not to do anything but to observe everything'. Although he had already noted the importance of 'natural philosophers' (the expression 'scientist' only came into use in the nineteenth century), in his day the advance of technology was largely due to the inventiveness of people working directly in the production process or immediately associated with it: 'a great part of the machines made use of in those manufactures in which labour is most subdivided, were originally the inventions of common workmen' (Smith, 1776, p. 8). Technical progress was rapid but the techniques were such that experience and mechanical ingenuity enabled many improvements to be made as a result of direct observation and small-scale experiment. Most of the patents in this period were taken out by 'mechanics' or 'engineers', who did their own 'development' work alongside production or privately.

1.3 THE PROFESSIONALIZATION OF INDUSTRIAL R&D AND ITS GROWTH

What is distinctive about modern industrial R&D is its scale, its scientific content and the extent of its professional specialization. A much greater part of technological progress is now attributable to research and development work performed in specialized laboratories or pilot plants by full-time qualified staff. It is this work which is recorded in R&D statistics. It was not practicable to measure the part-time and amateur inventive work of the eighteenth or nineteenth century. Thus our R&D statistics are really a measure of professionalization of this activity. This professionalization is associated with three main changes:

1. The increasingly scientific character of technology.[2] This applies not only to biological, chemical and electronic processes but often to mechanical processes as well. Even eighteenth-century mechanics actually depended on the formal science of Newton but the combination of mechanical with electronic engineering strengthens this dependence. The Japanese, who are one of the most advanced nations in the applications of electronics to mechanical engineering, have coined the word 'mechatronics', which aptly expresses this transition. A formal body of 'book learning' is usually necessary now for those who wish to advance the state of the art, as well as practical experience.
2. The growing complexity of technology and the partial replacement of 'batch' and 'one-off' systems of production by 'flow' and 'mass' production lines. It is expensive and sometimes almost impossible to use the normal production line for experiments in large-scale plants. The physical separation of experimental development work into specialized institutions was often a necessity in such cases. The sheer number of components in some processes and products has similar effects in prototype and pilot plant work. These are now designated as 'complex systems'.
3. The general trend towards division of labour, noted by Adam Smith, which gave some advantages to the specialized research laboratories,

> with their own highly trained people, information services and scientific apparatus. R&D activities are characterized by a very high concentration of engineers and scientists with a relatively small proportion of supporting staff – often only one or two per engineer or scientist.

Starting in the chemical and electrical industries, these laboratories have become increasingly characteristic institutions. Like all changes in the division of labour, the specialization of the R&D function and other STS has given rise to serious social problems, as well as to the benefits, which Adam Smith observed. As we shall see, the departmental separation of R&D from the production line and the marketing function in the firm gives rise to major management co-ordination problems. The rise of a professional 'R&D establishment' as a distinct social group may also lead to even more serious divisions and tensions in society, between those who generate new knowledge and others who may not understand it or may not want to see it applied. The R&D 'establishment' itself becomes a vested interest and political lobby, both in the industrial and in the military field. Some of these problems are discussed in the final section of this book.

The extent of specialization should not be exaggerated. Important inventions are still made by production engineers or private inventors, and with every new process many improvements are made by those who actually operate it. In some firms there are technical or engineering departments or Operations Research (OR) sections, whose function is often intermediate between R&D and production and who may often contribute far more to the technical improvement of an existing process than the formal R&D department, more narrowly defined. But the balance has undoubtedly changed, and it is this specialization of the R&D function which justifies some such expression as the 'research revolution' to describe what has been happening in twentieth-century industry. During this time most large firms in the industrialized countries have set up their own full-time specialized R&D sections or departments. Until the late 1960s, R&D activities were expanding very rapidly in many countries, but during the 1970s and 1980s growth slowed down somewhat, especially in the United Kingdom and the United States. In the 1990s there was a more general slow-down and even some decline, except in some Asian countries where very rapid growth continued. In the former communist countries of Eastern Europe there was a steep decline of formal R&D in the 1990s (Table 1.2 and Figures 1.2 and 1.3).

These contrasting trends are discussed in Part Three. Regular survey publications of the European Union (European Science and Technology Indicators, 1994 onwards) of the US National Science Foundation and of the OECD now provide detailed statistics for many countries of R&D expenditures and of personnel employed. Most of the early surveys confined themselves to these 'input' statistics but the more recent publications make increasing use of 'output' statistics, such as patents, publications and citations (Table 1.1). Some of the problems of measuring output are discussed in Chapter 5.

For the economist, it is obviously desirable to examine the operations of this R&D system from the standpoint of its efficiency in employing scarce resources. How can the flow of new information, knowledge, inventions and innovations be improved? Could the scientists, engineers and technicians employed in an industrial laboratory or a government research station be more effectively deployed elsewhere? Could the information required be obtained free or at a lower cost from abroad? Are part-time or amateur inventors or scientists sometimes more productive than full-time professionals? What kind of economies of scale are there in research or in development? Can the gestation period for innovations be shortened?

Table 1.2 Trends in gross domestic expenditures on R&D (GERD)

	GERD million current PPP $	*Average annual growth rate*		*Percentage change from preceding year(s)*				*GERD as a percentage of GDP*		
	1993	*1981–85*	*1985–89*	*1990*	*1991*	*1992*	*1993*	*1981*	*1991*	*1993*
USA	169,964	7.3	2.0	3.2	—[9]	1.4	−0.5	2.4	2.8[9]	2.7
Canada	8,320	6.7	2.4	6.0	1.9	0.8	1.3	1.2	1.5	1.5
Mexico	1,964	—	—	—	—	—	—	—	—	0.3
Japan[1]	69,535	8.9	6.5	8.4	3.2	−1.0	−3.0	2.1	2.9	2.7
Australia[2]	3,713	8.2	4.6	5.0	—	—	—	1.0	1.4	—
New Zealand[3]	410	—	—	0.3	−0.8	—	—	—	0.9	—
Austria	2.416	4.0	4.6	8.0	8.8	3.2	3.7	1.2	1.5	1.6
Belgium[3]	2,853	—[9]	—[9]	—	1.6	—	—	—	1.7	—
Denmark	1,786	6.9	7.0	6.4	5.8	3.6	3.6	1.1	1.7	1.8
Finland	1,755	10.5	8.1	4.2	—[9]	1.4	0.3	1.2[9]	2.1[9]	2.2
France	25,984	5.0	4.0	6.1	0.5	0.9	−0.8	2.0[9]	2.4	2.4
Germany[4]	37,265	4.3	—[9]	1.5	—[9]	—[9]	−1.1	2.4	2.6[9]	2.5
Greece	560	—[9]	—[9]	—	1.1	—	15.3	0.2[9]	0.5	0.6
Iceland[5]	65	5.4	12.2	−1.8	18.8	10.8	—	0.6	1.2	1.3
Ireland[5]	504	5.6	5.3	13.4	18.6	10.7	—	0.7	1.0	1.1
Italy	13,220	8.3	5.8	6.7	3.2	−0.3	−1.3	0.9	1.3	1.3
Luxembourg	—	—	—	—	—	—	—	—	—	—
Netherlands[5]	4,965	—[9]	3.6	−0.6	−3.3	−1.3	—	1.9	1.9	1.9
Norway	1,632	—[9]	2.4	—	1.1	—	4.2	1.3	1.8	1.9
Portugal[5,6]	709	5.6	9.8	16.1	—	9.8	—	0.4	0.6	0.7
Spain	4,567	8.7	13.2	16.9	5.1	—[9]	−5.3	0.4	0.9	0.9
Sweden	4,578	8.2	3.0	—	−1.4	—	2.4	2.3[9]	2.9	3.1
Switzerland[5,7]	4,243	—[9]	—[9]	—	—	−1.4	—	2.3	2.9[9]	2.7
Turkey	1,436	—	—	—	64.3	−1.7	—	—	0.5	0.5
United Kingdom	21,584	1.8	3.2	1.9	−4.8	0.3	2.5	2.4[9]	2.2	2.2
North America[8]	180,248	7.3	2.0	3.3	—[9]	1.3	−0.6	2.3	2.6[9]	2.4
EU-15[4]	123,056	4.6	4.4	3.7	—[9]	0.3	−0.3	1.7	2.0[9]	2.0
Total OECD[4,8]	**385,495**	**6.6**	**3.6**	**4.3**	**1.6**	**0.7**	**−0.8**	**2.0**	**2.3**	**2.2**

1. Adjusted by the Secretariat to improve international comparability.
2. Latest year available 1990. Growth 1981–6 and 1986–90. 1990 for 1991.
3. Latest year available 1991.
4. German totals from 1991 onwards include former East Germany.
5. Latest year available 1992.
6. Growth 1980–84 and 1984–8. 1982 for 1981.
7. 1990 for 1991.
8. Including Mexico from 1991 onwards.
9. Break in series.

Source: OECD, MSTI database, July 1995.

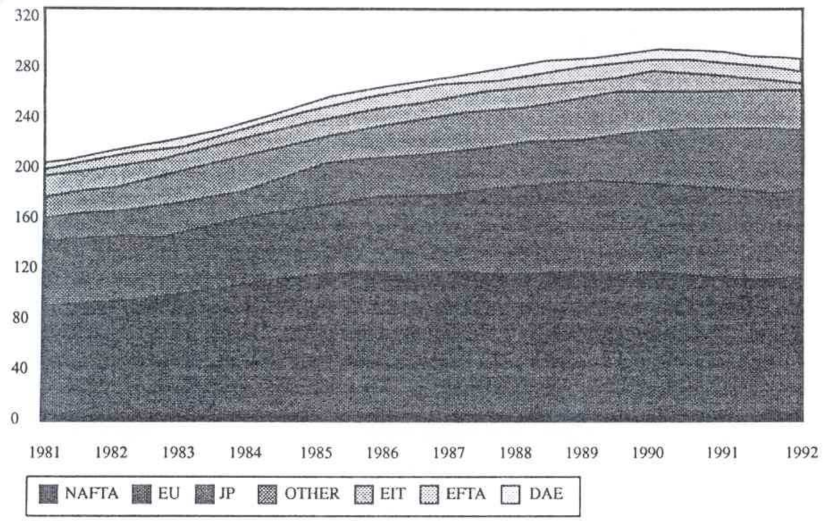

Fig. 1.2 Trends in R&D expenditures in 50 leading countries (1987 US prices Bn. ECU)
NAFTA: USA, Canada, Mexico
EIT: East and Central Europe (Economies in Transition)
DAE: East Asia (Dynamic Asian Economies)
JP: Japan

Source: European report on Science and Technology indicators (1995).

What kind of firms are most likely to innovate and under what market conditions? What type of incentives stimulate invention and innovation most effectively? How are innovations diffused through the economy? In what ways do universities contribute to industrial innovation and how could this contribution be improved? These are the kind of questions which economists ask about the R&D system. They should also ask some more fundamental questions about the relationship of innovations to wider human values. Are the main goals of science and technology the most desirable way of using these resources?

There is a considerable resistance to looking at invention and research in this way. One result has been that many studies of invention and innovation have been written by biographers who tended to concentrate on the personal peculiarities of famous inventors and innovators and memorable anecdotes of their exploits. A mythology has grown up, stressing mainly the random accidental factors in the inventive and innovative process. Sometimes these myths depart altogether from reality as in the case of Watt and the steam from the kettle; in other cases they simply exaggerate the role of chance events as in the case of penicillin.

The treatment of R&D as an exogenous and largely uncontrollable force, operating independently of any policy, has been promoted in the past by

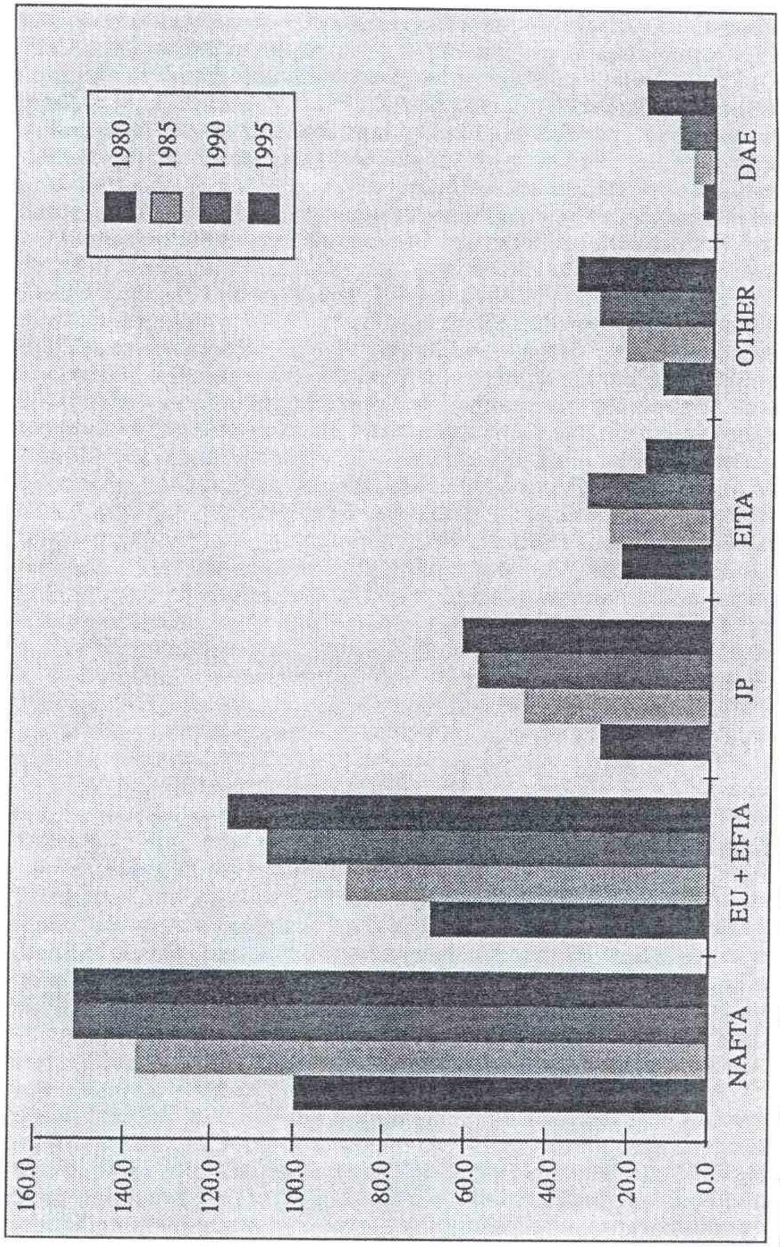

Fig. 1.3 Gross domestic expenditure on R&D (GERD), 1980–1995 (NAFTA 1980 = 100)
Source: MERIT.

both economists and scientists, though for different reasons. In either case it encouraged the 'black box' and 'magic wand' approach to science and technology, which not only discouraged attempts to understand the social process of innovation, but even endangered the whole future relationship between science, technology and society. What is not understood may often be feared, or become the object of hostility.

Polanyi (1962) made an interesting analogy between a free market economy and the basic research system, arguing that in both cases decisions must be completely decentralized to get optimal results. In the one case only firms have the necessary information on which to base good decisions and in the other case only scientists. Like most economists, Polanyi accepted the need for a central government subsidy to basic research because the private market would not finance such an uncertain long-term investment, but he maintained that the scientists should be completely free to pursue whatever projects they thought best. Friedmann took the argument one stage further in maintaining that there was no need for government to finance basic research at all. Kealey (1996) elaborated this position at book length in attempting to establish 'laws' of the economics of science. Like all such arguments, they can be carried to the point of absurdity by over-zealous logic. The market mechanism can be a useful technique for allocating resources in certain rather specific circumstances, but it has its limitations, so that the definition and implementation of social priorities for science and technology cannot be left simply to the free play of market forces (Nelson, 1959, 1977; Pavitt, 1996). The political system is inevitably involved and the full implications of this situation are taken up in Part Four.

1.4 MODERN TECHNOLOGY

The 'research revolution' was not just a question of change in scale, it also involved a fundamental change in the relationship between society and technology. The very use of the word technology usually carries the implication of a change in the way in which we organize our knowledge about productive techniques. If by technology we mean simply that body of knowledge which relates to the production or acquisition of food, clothing, shelter and other human needs, then of course all human societies have used technology. It is perhaps the main characteristic which distinguishes humanity from other forms of animal life. But until recently knowledge of these 'arts and crafts', as they used to be called, was largely based on skills of hand and eye, and on practical experience which was transmitted from generation to generation by some sort of apprenticeship or 'learning by doing'.

The expression technology, with its connotation of a more formal and systematic body of learning, only came into general use when the techniques of production reached a stage of complexity where these traditional methods no longer sufficed.[3] The older arts and crafts (or more primitive technologies) continue to exist side by side with the new 'technology', and it would be ridiculous to suggest that modern industry is now entirely a matter of science rather than craft. The 'heating and ventilating engineer' may still be a plumber, the 'tribologist' may still be a greaser and the 'food technologist' has not yet superseded the cook. They may never do so.

Nevertheless, there has been an extremely important change in the way in which we order our knowledge of the techniques used in producing, distributing and transporting goods. Some people call this change simply 'technology'; others prefer to talk about 'advanced technology', or 'high technology', to distinguish those branches of industry which depend on more formal scientific techniques than the older crafts. Because in a sense human societies have always had technology, some people see little new in modern technology. It will be argued here that this is a profound mistake and that the newer technologies are revolutionizing the relationships between science and society.

Some historians have argued that 'science' and 'technology' are two subsystems which developed autonomously and with a considerable degree of independence from each other. Derek Price (1965) maintained that the two bodies of knowledge were generated by distinct professions in quite different ways and with largely independent traditions. The scientific community was concerned with discovery and with the publication of new knowledge in a form which would meet the professional criteria of their fellow scientists. Application was of secondary importance or not even considered. For the engineers or technologists on the other hand, publication was of secondary or negligible importance. Their first concern was with the practical application and the professional recognition which came from the demonstration of a working device or design. Derek Price did not of course deny that 'science' and 'technology' have interacted very powerfully. He used the simile of two dancing partners who each have their own steps although dancing to the same music. The development of the steam engine obviously influenced thermodynamics (to put it mildly), whereas scientific knowledge of electricity and magnetism was the basis for the electrical engineering industry. But each partner in the dance has his or her own interpretation and moves in a different way.

This simile can be a useful one, but if it is used to argue that nothing has changed since the nineteenth century in the relationship between science and technology, then it can be dangerously misleading. At the very least there are some new 'dances' and some of them are 'cheek to cheek'. The relationship has become very much more intimate, and the professional industrial R&D department is both cause and consequence of this new intimacy. Two very important empirical studies, one British (Gibbons and Johnston, 1972) and the other American (National Science Foundation, 1973) demonstrated in some depth the importance of science and communication with the scientific community for contemporary technical innovation. Since the relationship is one of interaction, the expression 'science-related' technology is usually preferable to the expression 'science-based' technology with its implication of an oversimplified one-way movement of ideas. Marx spoke of the machine as the 'point of entry' of science into the industrial system, but today this expression might be used with more justification about the R&D department.

Walsh *et al.* (1979), in their study of science and invention in the chemical industry, showed that there was a very close similarity in the patterns of growth of patenting activity by firms and the publication of scientific papers. Liebermann (1978) demonstrated that scientists in the electronics industry actually cited more recent papers from the fundamental physics journals than their colleagues in universities (see also Chapter 7).

Other historians and economists, notably Hessen (1931), Musson and Robinson (1969) and Jewkes *et al.* (1958) have insisted that already in the seventeenth, eighteenth and nineteenth centuries, there was a great deal of interaction between science and industry technology. There is much truth in this contention, but it does not alter the fact that professionalized R&D, carried out within industry itself, has put the relationship on a regular, systematic basis and on a far larger scale.

This change has affected especially the design of new products, but the new science-related technologies also affect the way in which improvements and changes are made in production. As has already been suggested, in the older industries these could be made predominantly 'at the bench' by direct participants in the production process. The subdivision of mechanical process did not remove this possibility. Indeed, as both Adam Smith and Marx noted, the workers themselves were often responsible for inventions leading to further subdivision. But the introduction of flow processes in the chemical industry and of electronic control and automation in other branches of industry mean that improvements and changes now depend increasingly on an understanding of the process as a whole, which usually involves some grasp of theoretical scientific principles. It also means that experiments often have to be made 'off-line' in a separate workshop or pilot plant, rather than 'on-line' by production engineers or operatives. 'Systems analysis' becomes important in its own right. All this has accentuated the relative importance of the specialized R&D group or engineering or technical service department and diminished the relative importance of the 'ingenious mechanic'. In the newer industries R&D personnel, as well as other technical departments and OR sections, often have to spend a good deal of time 'troubleshooting', that is resolving difficulties which arise in the normal production process and are referred back to them for solutions. This is not strictly R&D but it illustrates the changed position of production staff. The use of R&D personnel to start and control new production lines in the semiconductor industry is another indication of this change, as is the trial operation of new instruments and machines first of all by R&D personnel.

This can also be seen from the patent statistics for the various branches of industry. In mechanical engineering, applications from private individuals are still important by comparison with corporate patents, but in electronics and chemicals they are very few. The overall share has been declining since 1900 (OECD, 1982).

The increasingly scientific content of technology and the increased subdivision and specialization within science itself have led to major problems of communication between specialist and non-specialist. These have been accentuated by the divisions within the educational system between the different disciplines and between the arts and the sciences. For many people these tendencies, together with some of the unpleasant features of modern industrialization, have increased the sense of alienation from modern technology to the point where they question the desirability of any further innovation. They feel that the whole system is like an uncontrollable and unpredictable juggernaut which is sweeping human society along in its wake. Instead of technology serving human beings it sometimes seems to be the other way about. The constant reiteration of the stock reply, 'You can't stop technical progress anyway', serves to reinforce rather than to diminish these fears.[4]

As a result, the social mechanisms by which we monitor and control the direction and pace of technical change are one of the most critical problems of contemporary politics. In Part Four of this book it is argued that a more explicit policy for science and technical innovation is increasingly necessary. It is also argued that the market demand mechanism for innovation in consumer goods and services has serious deficiencies. But it is by no means easy to understand or to control this complex system and the high degree of autonomy which it enjoys is partly the result of this difficulty. Socialist societies were not particularly successful either.

This is not to deny that a pure *'laissez-innover'* system is unacceptable. Nor is it to deny the paramount importance of human values in deciding whether to promote or to halt particular new technical developments. Technical innovation need not be a purely random or arbitrary process, but control depends upon understanding. An important part of this understanding relates to economic aspects of the process, such as costs, return on investment, market structure, rate of growth and distribution of possible benefits. We still know far too little about these economic aspects of innovation, but slowly we are beginning to build up a body of systematic observations and generalizations, together with explanatory hypotheses which are supported to a varying extent by the empirical data. No doubt some of these hypotheses will be wholly or partly refuted or modified by future observations and experiments. As our knowledge extends so does the possibility of using innovations more satisfactorily.

1.5 SCHUMPETER'S THEORY OF SUCCESSIVE INDUSTRIAL REVOLUTIONS

This book reflects the relatively elementary state of our present knowledge. The generalizations are tentative because they have been insufficiently tested and corroborated by applied research. Although the book describes the results of some of the empirical studies by economists, it also poses some of the principal unsolved problems, in the hope that this will help to stimulate new thinking and research. Finally, the last part of the book raises some of the difficult policy issues which arise from the analysis.

The choice of a historical method of approach in the first part of the book is deliberate. The abstract 'representative firm' is a fictional device which is of little value in understanding the role of industrial R&D. In order to make useful generalizations about R&D in relation to firm behaviour it is essential to place the growth of this phenomenon firmly in a historical context and also in the context of specific industrial sectors. Robinson Crusoe is of little help, and a pure hypothetico-deductive approach is impotent without a preliminary process of observation and description. This is the purpose of Part One. It is designed to illustrate the three basic aspects of the rise of the professionalized industrial R&D system discussed above – growing complexity of technology, increased scale of processes and specialization of scientific work. Such historical description is of course intended to lead to the generation and examination of hypotheses in a systematic manner.

The whole of Part Two is devoted to an examination of the empirical evidence which might be held to support or refute various contemporary theories of innovation, particularly in relation to firm behaviour. The evidence which is used includes both the historical material cited in Part One and additional studies which have a bearing on the problems. The main concern of Part One is with description and historical context, Part Two with micro-level analysis and Part Three with macro-economic aspects of technical change and innovation, i.e. 'national systems of innovation' and international trade and technology flows. Finally, Part Four deals with some issues of public policy. Some readers may wish to skip the historical detail contained in Part One, but they will find that Parts Two and Three sometimes revert to cases cited in Part One for illustration and support.

Part One (Chapters 2–7) deals in a historical–descriptive manner with research, invention and innovation in the waves of technical change which Schumpeter described as 'successive industrial revolutions' (Table 1.3). He followed the Russian economist Kondratieff (1925) in describing these long, roughly half-century phases of development as 'cycles' but most economists have preferred to call them 'waves' or 'phases' of growth. The expression cycle carries too much of a deterministic flavour for what is a rather variable and imprecise phenomenon. Many economists, including Jevons, Pareto and Dupriez had discussed these long-term fluctuations in the economy in terms of price trends or variations in interest rates or trade flows. Schumpeter (1939) and Van Gelderen (1913) were the first to suggest that these long waves were due to the introduction of major new technologies into the economic system.

Table 1.3 illustrates this Schumpeterian conception of long waves based on successive technological transformations but it does not strictly follow Schumpeter's own work. He urged his successors not to follow his scheme precisely but to build on the results of new research and we have followed his advice.

In his major work on *Business Cycles*, Schumpeter (1939) accepted the reality of the phenomenon of 'Kondratieff'[5] long cycles, lasting half a century or so, and offered a novel explanation of them, differing from that of Kondratieff (1925) himself. According to Schumpeter (1939, Chapter 2), each business cycle was unique because of the variety of technical innovations as well as the variety of other historical events such as wars, gold discoveries or harvest failures. But despite his insistence on the specific features of each fluctuation and perturbation, he believed that the task of economic theory was to go beyond a mere catalogue of accidental events, and analyse those features of the system's behaviour which could generate fluctuations irrespective of their specific and variable form. The most important of such features in his view was innovation, which, despite its great specific variety, he saw as the main engine of capitalist growth and the source of entrepreneurial profit.

The ability and initiative of entrepreneurs (who might or might not themselves be inventors but more usually would not be) created new opportunities for profits, which in turn attracted a 'swarm' of imitators and

Table 1.3 Successive waves of technical change

Long waves or cycles		Key features of dominant infrastructure			
Approx. timing	*Kondratieff waves*	*Science technology education and training*	*Transport communication*	*Energy systems*	*Universal and cheap key factors*
First 1780s–1840s	Industrial revolution: factory production for textiles	Apprenticeship, learning by doing, dissenting academies, scientific societies	Canals, carriage roads	Water power	Cotton
Second 1840s–1890s	Age of steam power and railways	Professional mechanical and civil engineers, institutes of technology, mass primary education	Railways (iron), telegraph	Steam power	Coal, iron
Third 1890s–1940s	Age of electricity and steel	Industrial RD labs, chemicals and electrical, national laboratories, Standards laboratories	Railways (steel), telephone	Electricity	Steel
Fourth 1940s–1990s	Age of mass production ('Fordism') of automobiles and synthetic materials	Large-scale industrial and government RD, mass higher education	Motor highways, radio and TV, airlines	Oil	Oil, plastics
Fifth 1990s–?	Age of microelectronics and computer networks	Data networks, RD global networks, lifetime education and training	Information highways, digital networks	Gas/oil	Microelectronics

improvers to exploit the new opening with a wave of new investment, generating boom conditions. The British industrial revolution was a clear example of this process and was viewed by Schumpeter as the first Kondratieff wave. It is analysed in some detail in Chapter 2 since it was the starting-point of the entire historical process with which we are concerned.

However, in this first period, mechanization was largely based on water power and confined mainly to the textile industries. It was in the second Kondratieff wave that the widespread diffusion of steam power made possible the mechanization of many other industries and the development of the new railway infrastructure. Although these changes required many more engineers and new craft workers and the spread of literacy in the population, it was not until the rise of the electrical industry (Chapter 3) and the technical transformation of the chemical industry (Chapters 4 and 5) that the professional industrial R&D department became a key institution in the development of new products and processes (Table 1.3). Its importance grew still further with the worldwide diffusion of automobiles and petrochemical based products described in Chapters 5 and 6. Finally, the last few decades of the twentieth century have been characterized by the computerization of the economy based on cheap microelectronics (Chapter 7).

In Schumpeter's theory therefore the 'successive industrial revolutions' were based on the qualitative transformation of the economy by new technologies, rather than the simple quantitative growth of individual industries.

Whether or not such a theory offers a plausible explanation of 'long' waves in economic development depends crucially – as Kuznets (1940) pointed out in his review of Business Cycles at the time – on whether some innovations are so large and so discontinuous in their impact as to cause prolonged perturbations or whether they are bunched together in some way. The construction of a national railway network might be the type of innovative investment which would qualify as a 'wave generator' in its own right, but obviously there are thousands of minor inventions and technical changes which are occurring every year in many industries whose effect is far more gradual and which might well adapt to some sort of smooth equilibrium growth path. If these smaller innovations were to be associated with economic fluctuations, then this could only be if they were linked to the growth cycles of new industries and technologies.

Our account differs from Schumpeter's own account in his book on *Business Cycles* in several important respects. First, of course, Schumpeter himself died soon after the Second World War so that he only analysed the first three waves. The notes on the fifth and sixth waves in Table 1.3 are partly speculative although the speculation on the fifth is fairly well grounded. Second, this table is based on the large-scale *diffusion* of new technology systems, not on their first introduction. Schumpeter himself discussed the steam engine mainly in relation to the first Kondratieff wave and steel in relation to the second. In both cases of course the very first innovations came even earlier. However, the standpoint adopted in this book is that what matters for a major upswing and transformation of the economy in terms of new investment and employment is the widespread diffusion of numerous innovations based on a new infrastructure. The previous gestation period for this new infrastructure and a corresponding cluster of innovations can be several decades. Thus, whereas Schumpeter (quite correctly) spoke of the innovations in automobile production and especially the internal combustion engine in the period from the 1880s to the 1940s, we take the age of mass production and universal use of the automobile as the 'fourth Kondratieff'.

Table 1.4 Boulton and Watt engines by horsepower, c.1800

Horsepower	*cost per HP* £
2	89
10	40
20	30

Source: von Tunzelmann (1978, p. 51).

The first steam engines (especially the Newcomen engine) were in use in European coal mines quite early in the eighteenth century but they were confined to pumping applications in the mines. Even with Watt's greatly improved engine towards the end of the century, the number of applications was still very limited as von Tunzelmann (1978) showed in his book on *Steam Power and British Industrialisation*. The mills and factories of the first British industrial revolution mainly used water power not steam. The widespread diffusion of the steam engine in the second Kondratieff wave (Table 1.3) depended on three trajectories:

1. The fall in cost per horsepower with increasing size of steam engine (Table 1.4).
2. The reduction in coal consumption per HP in the new high pressure engines mainly developed in the Cornish mining industry (Table 1.5).
3. The improvements in design of railway locomotives and the rapid increase in their use for the transport of people and goods from 1825 onwards.

This example has been chosen because all of these trends were mutually reinforcing. The huge improvements in transport greatly reduced the price of coal in the key industrial areas where the new industries were growing most rapidly (Table 1.6). The falling costs of steam power facilitated its application in many other industries in addition to cotton (although cotton still accounted for one-third of total UK manufacturing horsepower as late as 1870). An attempt has been made in each of the historical chapters to illustrate this sort of interdependence of technical and economic change and the interdependence of many innovations themselves. Innovations are systemic in nature (Gille, 1978; Hughes, 1982), not isolated events. It is this systematic economic and technological interdependence which gives rise to the 'lock-in' effects of each dominant style in technology.

Each of these technological revolutions was based on clusters of innovations, some of them involving big changes and discontinuities ('radical' innovations) and others involving many small improvements ('incremental'

Table 1.5 Coal consumption in various types of steam engine in manufacturing applications (lbs of coal per hour per HP)

Savery engine (18th century)	30
Newcomen engine (mines) (1700–1750)	20–30
Newcomen engine (1790)	17
Watt low pressure engines (1800–1840)	10–15
High pressure engines (1850)	5

Source: von Tunzelmann (1978, pp. 68–70).

Table 1.6 Coal prices in Britain by region, 1800–1850 (shillings per ton)

	London	*Birmingham*	*Manchester*
1800	46	9	16
1810	38	12	13 (1813)
1820	31	13	10 (1823)
1830	26	6 (1832)	10 (1833)
1840	22	8	7 (1841)
1850	16	5	6

Source: von Tunzelmann (1978).

innovations). The selection of innovations which are discussed are not of course more than a small fraction of the total; they have been selected to illustrate some of the main features of each phase of historical development.

1.6 STRUCTURE OF THE BOOK

It is not possible in Part One to describe any of the innovations fully, as each one would merit a book in its own right. Some of the books which have been written are cited in the references. The intention here is to select only some of the most important characteristics of the innovations for discussion, from the standpoint of the economist. The treatment of technical aspects of the innovations is minimal, and so is the treatment of the personal characteristics of the inventors and innovators. Attention is concentrated on such questions as scale of effort, patents, size of firm, marketing and time lags. What kind of firms made the principal innovations? At what stage and in which industries were they made? Were they the result of professionalized R&D? How long did it take to develop and launch the new products and processes? How much did it cost? What were the expectations of management and the pressures which led to the decision to innovate? What are the implications for the theory of the firm?

Although the approach concentrates on the economic aspects, this does not mean that technical, psychological and social aspects of innovation are unimportant. Such an attitude would obviously be absurd. It would be a fair criticism that a more integrated theory of innovation is desirable, but it is beyond the scope of this book. However, some of the wider social issues involved in policy for technical innovation are discussed in the concluding chapters.

The largely descriptive historical treatment of technical innovation in Part One is followed by an analytical treatment of some of the general implications for innovation theory in Parts Two and Three. Chapters 7 to 11 are concerned with problems of the firm in relation to innovation.

In the analytical section it is argued that the professionalization of R&D described in Part One had far-reaching consequences on the nature of the competitive struggle between firms, both on the national and the world market. The factors which lead to success or failure in this new type of competitive struggle are discussed in Chapter 8, and the implications for size of firm in Chapter 9. In general the growth of industrial R&D has favoured the large firm and has contributed to the process of industrial concentration, but small new firms retain an advantage in some types of innovation. The giant international corporation has the great advantage of being able to spread the very high development costs of some kinds of innovation and the associated technical services over a very large sales volume. This is an enormous asset in industries such as telecommunications, turbine generators, refineries, aircraft and drugs. But a high degree of uncertainty remains characteristic of technical innovation whether in large or small firms. The problems for the firm in coping with this high degree of uncertainty in managing innovation are discussed in Chapter 10.

The type of groping and experimental decision-making characteristic of the innovation process is not compatible with theories of the firm which postulate a high degree of accuracy in investment calculations or extensive foreknowledge of the consequences of the firm's behaviour. The uncertainty associated with innovation is such that differences of opinion about the desirability of alternative projects and strategies are the norm rather than the exception. This means that the firm is typically the arena of political debate between the advocates of alternative courses of action, and that power struggles will take place around these issues.

This leads to some reconsideration of the theory of the firm in Chapter 11. The firm attempts to use R&D and other scientific and technical services to reduce the uncertainty which confronts it. But the nature of R&D is such that technical and market uncertainties remain despite its best efforts. Some types of R&D may indeed increase the uncertainty. Consequently, a high degree of instability will remain and decision-making in the firm will continue to resemble a process of 'muddling through' rather than the ordered, rational calculation beloved of neoclassical theory.

The analysis in Part Three moves from the micro to the macro level. The historical analysis in Part One and the theoretical analysis in Part Two show that the performance of firms in their innovative efforts is strongly related to the institutional environment in which they operate. Countries have varied greatly in their rates of economic growth over the last two centuries. The leading countries which forged ahead in the nineteenth and twentieth centuries opened up a huge gap in living standards with the less developed countries of Africa, Asia and Latin America. Many European countries closed this gap in the twentieth century and more recently some East Asian countries have begun to do so. These efforts to catch up and close the gaps in living standards depend heavily on closing the gaps in *technology*. The chapters in Part Three analyse the process of forging ahead, falling behind and catching up in economic growth and the ways in which national performance relates to the transfer of technology, international investment flows and the 'national system of innovation' within each country.

Finally, Part Four discusses the responsibilities of government for science, technology and innovation. During the last half-century governments have increasingly accepted some responsibility, not only for some aspects of R&D and other STS but also for some forms of technology assessment, that is for comprehensive social cost benefit analysis of the probable consequences of technical change. The socialization of some of the risks and uncertainties of technical innovation is difficult to avoid because of the pressures of world competition, externalities and scale factors in R&D, and some of the adverse consequences of '*laissez-innover*'. Such socialization, however, carries with it the responsibility for the development of an explicit rather than an implicit national policy for science and technical innovation. Some problems associated with this major government responsibility are discussed in Part Four.

It is argued there that in the USA, the USSR, France and Britain the priorities of the 1945–89 period were largely determined by the Cold War. Government support for aircraft, nuclear and electronics R&D was both massive and effective. Firms in these industries became part of a special military–industrial complex, in which state-supported innovation was normal. Quite different priorities should be established in the next century and national policy should be concerned to promote other kinds of innovation. A great deal of R&D will be needed to cope with environmental problems, to secure long-term supplies of renewable cheap energy, to deal with natural resource limitations, to promote full employment, to develop much better transport and construction systems and generally to improve the quality of life in industrialized countries. Even more critical is R&D to deal with problems of underdevelopment. This redeployment of scarce R&D resources to meet the most urgent priorities is unlikely to occur solely as the result of short-term market factors. It must therefore be the main concern of national policy for science and technology, and increasingly of international policy.

NOTES

1. Strictly speaking, as the word itself implies, technology is simply a body of knowledge about techniques. But it is frequently used to encompass both the knowledge itself and the tangible embodiment of that knowledge in an operating system using physical production equipment. In this book the expression 'technical innovation' or simply 'innovation' is used to describe the introduction and spread of new and improved products and processes in the economy and technological innovation to describe advances in knowledge.

2. For the changing connotation of the word 'technology' see Ezrahi *et al.* (1995, p. 17).
3. The establishment of the Massachusetts Institute of Technology in 1861 was a landmark in the use of the word.
4. See Ezrahi *et al.* (1995) *Technology, Pessimism and Postmodernism.*
5. As has often been pointed out, Kondratieff was by no means the originator of the long cycle theory and it is in some respects a misnomer that the phenomenon bears his name. The Dutch Marxist van Gelderen could be much more fairly credited with the idea, which he articulated clearly in 1913. At about the same time a variety of economists, including Pareto (1913), had drawn attention to the apparent tendency for long-term price movements, interest rates and trade fluctuations to follow a cyclical movement lasting about half a century. However, during the 1920s while heading the Institute of Economic Research in Moscow, Kondratieff did more to propagate and elaborate the idea than any other economist. For a selection of papers illustrating the controversies surrounding Schumpeterian theories of long waves see Freeman (1996).

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