Science and Public Policy, volume 14, number 4, August 1987, pages 182–188. Beach Tree Publishing, 10 Watford Close, Guildford, Surrey GU1 2EP, England.

Overview

The objectives of technology policy

Keith Pavitt

It is not useful, either in theory or in practice, to equate technology with science or with information. Many empirical studies show that most technology is specific, complex, partly tacit, and cumulative in its development. As a consequence, key questions for analysis and policy are, first, the nature and the extent of the interactions between science and technology; and, second, the accumulation in firms of technological knowledge, necessary not only for new and original inventions and applications, but also for effective assimilation of science and technology developed elsewhere.

This is an edited version of Professor Keith Pavitt's inaugural professorial lecture, delivered at the University of Sussex on 23 June 1987. Professor Pavitt is Deputy Director of the Science Policy Research Unit, Mantell Building, University of Sussex, Falmer, Brighton, Sussex BN1 9RF, England.

He would like to thank Richard Nelson and Geoffrey Oldham for comments and suggestions which helped greatly in preparation.

I SHALL BE USING the term 'technology' to encompass both physical artefacts themselves, and the person-embodied knowledge to develop, operate and improve them.

The continuous development and diffusion of technology is widely recognised to be one of the key distinguishing features of modern and modernising societies. It has become central to major political and moral debates: about war and peace, about life and death, and about the future survival of the species and the planet.

I shall address an issue which is central to most of these debates: namely, the development and diffusion of often rather prosaic technologies in industry, agriculture and services; technologies associated with economic and social change, with international competition, and with increases in measured Gross National product per head. Such a focus inevitably reflects my values which, for what it is worth, are that continuous improvements in the quality of life depend — amongst other important things — on keeping up with, or getting closer to, world best practice in these technologies; and that the experience of the UK over the past 25 years is an ample justification for this position.

Fortunately, the relevance of what I shall have to say does not require agreement with this view. But I suspect that we nearly all would agree that effective action to guide technology towards whatever objectives we consider desirable requires an accurate understanding of its nature, sources and determinants.

There are perhaps two groups who might argue that such understanding is not necessary. The first consists of the so-called technological determinists, who often argue or assume that technology develops and diffuses strictly according to its own logic, and that society can (and does) simply adapt to its requirements. In places like Sussex University, technological determinists are generally in bad odour, and considered to be intectually and morally suspect. I would simply add that their arguments fail the empirical test, since

- a high proportion of developed technology does not get diffused but is rejected on economic and social grounds,
- much technology is continually being adapted in the light of economic and social constraints, and
- any given technology allows some variation in organisational forms in exploiting it.

There is also a second group that might not see much point in understanding the nature and determinants of technology. Its members would tend to argue that both the rate and the direction of technological change are very sensitive and responsive to economic and social signals, be they market prices or planning targets. Provided that markets, or plans, or social and political relations more broadly, are got right, the appropriate technologies will inevitably follow. I suspect that these (what might be called) "socio-economic" determinists are in fact more important in the UK in influencing action and attitudes than their technological counterparts. In their reasoning, the development and diffusion of technology are assumed to be cheap, whereas they are not.

In any event, since technology is not strictly determined by either its own dynamic, or by economic and social forces, wise action to influence it depends, amongst other things, on the degree of understanding of how these and other factors interact. Results emerging from empirical research are adding to this understanding, and are influencing policy. I believe that they should also influence underlying theory, models and their assumptions. Keynes' comforting dictum that practical men are influenced by academic scribblers is one persuasive reason why academics should get it right. Another is that academics might ultimately be ignored if they get it wrong; being ignored is not a healthy state for an academic community.

In this context, I shall argue that assumptions equating technology with either science or information are misleading, and can result in unbalanced or inaccurate policy prescriptions. My concerns are not particularly original. They were expressed in the 1960s by Derek de Solla Price (1965), in the 1970s by Nathan Rosenberg (1976), and in the 1980s by David Mowery (1983).

Science and technology

Analysis of the links between science and technology goes back a long time. In chapter 1 of *The Wealth of Nations*, Adam Smith identifies "philosophers or men of speculation" as one of the three major sources of technology, together with both producers and users of machinery — a categorisation that still has its relevance today.

In the 1830s, Alexis de Tocqueville predicted a rosy and growing future for science in the modernising society that he observed in the USA. Its application would create considerable opportunities for profit, so that business demand would grow for applied scientists and for the institutions that trained them. Basic research, unconstrained by preoccupations of immediate application, would be necessary if profitable opportunities for application were not to dry up.

Events since then have on the whole confirmed de Tocqueville's prediction: the relative contribution of science to technology has been increasing. For example, Christopher Freeman and his colleagues (1982) have shown the pervasive influence across all sectors of the economy of the diffusion of technologies growing out of basic research in chemistry and physics. Rosenberg (1985) has described the economically important economic contributions made by the application of rather elementary chemistry and other sciences in sectors like steel and food processing. Numerous writers have also shown the major contributions made by technology to science, mainly through improved or radically new instrumentation.

When scientists working in US General Electric, Dupont, Bell or EMI win Nobel prizes, the separation of science from technology ceases to be clear-cut

With the growth of industrial research and development (R & D) departments in the 20th century, and the large-scale recruitment of university trained scientists by them, the debate has become more complicated. When scientists working in US General Electric, in Dupont, in the Bell laboratories or in EMI, win Nobel Prizes, is the distinction between science and technology useful any more?

Such events help explain why some social scientists have recently questioned the analytical usefulness of distinguishing between the content of science and of technology. Thus, it has been suggested that the analytical tools of the sociology of science can readily be transferred to technology (Pinch and Bijker, 1984, 1986). Two distinguished economists, Partha Dasgupta and Paul David (1986), have argued that the essential difference between science and technology is that the former produces public and published knowledge, whilst the latter produces private and often unpublished knowledge. They thereby implicitly define science as what goes on in universities and related institutions, and technology as what goes on in business firms.

Similar definitions underlie most of the studies to which I shall refer later, as well as the recent UK policy report, entitled *The Science Base and Industry*, published jointly by The Advisory Council for Applied Research and Development (ACARD) and The Advisory Board for the Research Councils (ABRC). Dasgupta and David's is a useful definition, although it leaves academic engineering in an ambiguous position (that I return to later).

However, Dasgupta and David also assert that much of the content of science and of technology has become indistinguishable, and they cite molecular biology, biochemistry and solid state physics as examples. By doing so, I think that they have fallen into a trap, common in studies of science and technology policy, of generalising from the particular, in what are in fact very heterogeneous activities. This was understandable when science and technology policy studies were mainly of particular cases, but has become less so with the accumulation of this case material, and (perhaps more important) with the development of a variety of statistical data banks on various aspects of scientific and technological activity.

These show that the content of science is in general different from that of technology, that the nature and extent of interaction between the two varies considerably across industrial sector, and that these interactions are important subjects for analysis and policy.

To begin with, aggregate statistics for countries in Western Europe and North America all show very different types of activities being carried out in universities and in business firms. In universities 90% of research activity is defined as basic and applied research: in other words, knowledge aiming at general applicability. In the firms, up to a quarter is also basic and applied research, but three quarters or more is the development and testing of prototypes and related production systems: in other words, knowledge related to the specific products and the specific production processes that firms eventually hope to commercialise.

Clearly, the significant proportion of basic and applied research undertaken in industrial firms can and does sometimes lead to very fundamental results, and in some sectors the contents of science and of technology may well be very similar. Whether and where they are similar can now be assessed relatively systematically through the examination of citations in patent documents, which are the most extensive public record of codified technology. Patents citing other patents reflect technology building on technology; patents citing journals reflect technology building on science.

This field of analysis has been pioneered largely by Francis Narin and his colleagues in the USA (Carpenter, 1983; Carpenter *et al*, 1981; Narin, 1982; Narin and Noma, 1986). The main conclusions emerging from their analysis is that technology builds largely on technology, but that the rate of interaction with science varies considerably amongst scientific fields and amongst technologies.

Between biotechnology patents and biomedical research, the links between the two are at present very strong, with the former using scientific results just as up to date as the latter — and a recent case study of a development in monoclonal antibodies comes to a very similar conclusion (Mackenzie *et al*, 1987). In this type of sector, at least, the assumption that science and technology are very close may well be correct, and concern about the private encroaching on the public, to the long-term detriment of both, entirely justified.

However, biotechnology may well be the limiting case, since a comprehensive survey of citation patterns shows enormous variations amongst technologies in 'science dependence', as measured by the frequency of patent citations to journal papers: on average, a pharmaceutical patent cited journals 36 times more frequently than a patent in transportation. Chemical and biochemical patents are the most frequent in their citations of journals, the majority of which relate to basic research. Electronics and electrical patents are the next most frequent, but with a higher proportion of citations in journals reporting the results of applied research and engineering. Machinery patents have most of their citations to applied engineering, whilst instrumentation patents cite over the whole range of journals.

As might be expected, chemical patents refer mainly to journals in chemistry, biology and medicine; electrical and electronics patents to journals in physics and engineering; and mechanical patents to those in engineering.

Similar differences amongst industrial sectors and

In biotechnology, it may often be hard to distinguish science from technology. Generalising from this to, say, mechanical engineering, is not helpful

scientific fields emerge from a recent survey of 650 directors of industrial R&D in the USA (Nelson, 1986; Levin *et al*, 1984). They expected a higher proportion of biochemical and chemical knowledge emerging from academic research to find direct applications, than of knowledge from other disclines.

However, the survey also found that, across a wide range of industries, the perceived value of universities was less for the content of their research, than for the training that it gave to future industrial researchers. This pattern is reflected in a Science Policy Research Unit (SPRU) study of British radio-astronomy. It concluded that the main economic benefit of such research has been the skills that it has given to Doctoral and Masters students who eventually work in industry: in particular, skills in computing and electronics, and in the ability to define complex problems, to communicate effectively and to work in a team (Irvine and Martin, 1980).

Another important benefit of such postgraduate training emerges from other studies of the information sources used by technical problem-solvers in firms (Gibbons and Johnson, 1974; Rothwell *et al*, 1974; Allen, 1977). In nearly all cases, the sources of such information are varied (a point that I shall return to later). What the university-trained scientist or engineer brings to technical problem-solving is not just substantive and methodological skills, but also the rich and informal network of professional contacts which can be called upon to help to solve problems: science and engineering graduates involved in application are part of a larger intelligence system, involving their former teachers and colleagues.

Given these characteristics, the relations between the differentiated and interrelated systems of science and technology are bound to be of concern to policy-makers at a number of levels. In the British context, they point to the following conclusions.

First, the arguments that Britain could usefully carry a smaller "burden" of the world's freely available scientific knowledge begins to look as thread-bare and wrong-headed as those earlier arguments about the white man's imperial burden (which Britain was sometimes said to be carrying for the benefit of the world). As we have seen, the world's basic research cannot be applied by users without costs, comprising the costs to firms of employing graduate scientists and engineers, and the costs to governments of providing the academic infrasctructure, including postgraduate training and research. If a government decides to run down the infrastructure, industrial firms will have to provide it themselves or, as hinted by the recently retired chairman of ICI (*The Economist*, 18 April 1987), they will move their core activities to places where an adequate infrastructure is provided.

Second, any policy must recognise that the nature of the complementarities between science and technology varies considerably amongst sectors of application, in terms of the direct usefulness of academic research results, and of the relative importance attached to such results and to training. In addition to direct transfers of knowledge, any evaluation of the science base for industry should include academic engineering, research training, and an assessment of the effectiveness of informal networks between academic research and places of application.

These networks can probably best be traced and assessed through the employment patterns of scientists and engineers outside academia. In the short term, this will be difficult to do, given the poor state into which British statistics on scientists and engineers have fallen since the late 1960s. In the meantime, we should be asking ourselves whether research funded by the Research Councils is sufficiently linked to postgraduate training, since such links are essential for the formation of these informal networks, (Hague, 1986).

Third, we should be aware that the complementarities of the science and technology systems mean that the efficiency of the whole does not necessarily result from making the science system more like the technology system. There has been considerable pressure in the past few years to make the British science system more applied in its objectives. This should not be allowed to be taken too far. As we have seen, de Tocqueville rightly predicted a growing division of labour and interdependence between basic research and training, on the one hand, and technological activities on the other. He also predicted that neglect of the former would eventually destroy the latter.

Finally, we should be aware that some British science has been very relevant to application. In a paper recently presented at the British Government's Department of Industry, Narin and a colleague (1987) identify the most frequently cited US patents of British origin in the period from 1975 to 1982. Since frequency of citation in other patents turns out to be a pretty good indicator of an invention's usefulness, it is relevant to note that the top patent by far, with nearly 100 citations, was not granted to a British firm, but to the National Research Development Corporation (now called The British Technology Group), and resulted from publicly-funded research by the Agricultural Research Council into synthetic pyrethrin insecticides (Barclay and Fottit, 1987; Davies, 1980).

It is also relevant that the second most frequently cited British patent was for work on liquid crystal materials and devices carried out at Hull University.

British-based firms have been active in converting these examples of relevant science into commercial technology. Unfortunately, there is more general evidence that the relevance of British science is often better perceived by foreign firms. There are at least two cases on the Sussex campus — my home ground — where foreign firms have been more active in the commercial exploitation of the University's academic research than British firms. The Medical Research Council has gone on record to regret the lack of prominence of British firms, compared to their foreign counterparts, in exploiting the results of the Council's research in scientific instrumentation and specialised patient care (Select Committee on Science and Technology, 1983).

In other words, the British problem should be seen not as "too much science" but as "too little technology", a point to which I shall return later.

Experience and doing

Given the central importance of technology in firms for the use of outputs from the science base, it is necessary to delve more deeply into the nature of technology.

One influential tradition of analysis assumes that technology has the properties of information, in being

The British problem is not too much science, but too little technology

much more costly to produce than to transmit and to use. Often related to this has been the assumption that technological knowledge can be more or less completely codified in the form of patents, blueprints, operating manuals, and the like.

Empirical analysis suggests that neither of these assumptions are true: most technology is specific, complex, often tacit, and cumulative in its development. These characteristics have important implications for the ways in which national and international systems for the development, the evaluation and the diffusion of technology can and do work.

In market economies, technology is specific in two senses: it is specific to firms, where most technological activity is carried out; and it is specific to products and processes, since most expenditure is not on research, but on development and production engineering, after which knowledge is also accumulated through experience in production and use — or what has come to be known as "learning by doing" and "learning by using".

This combination of activities reflects the essentially pragmatic nature of most technological knowledge. Although a useful input, theory is rarely sufficiently robust to predict the performance of a technological artefact under operating conditions, and with a high enough degree of certainty, to eliminate the costly and time consuming construction and testing of prototypes and pilot plant.

One of the oldest technologies — civil engineering — still has difficulties in foreseeing all important contingencies on the basis of past experience, design studies and computer simulations. And even the most science-based and science-dependent of all technologies — pharmaceuticals and pesticides — was described recently in *The Economist* as "a highly empirical business" (1 February 1987), involving the development and screening of a vast range of synthetic compounds, the full range of biological effects of which cannot be completely predicted from knowledge of their molecular structure.

The problem is even more severe in the design and development of complex machinery and production systems, involving multiple objectives and multiple constraints, and the combination of a variety of technologies and materials. In this context, the essence of engineering skill and the engineering profession is the ability to make things work, by drawing upon and combining technology from a variety of sources, which is presumably why academic engineering teaches the range of subjects that it does.

This inherent complexity of technology has implications for both its development and its diffusion. The first is uncertainty and the inability to make an early and accurate assessment of either the performance or the utility of an innovation. Predictions made before development turn out to be unerringly inaccurate; and after initial development, there are often considerable possibilities for improvement, as a result of learning from production and use. Amongst competing innovations, it is therefore often difficult to know precisely when a technological race has ended, and (without much hindsight) who has won or lost it.

The second implication is that the assimilation of technologies developed in other organisations (or countries) is rarely costless, because the specificity of technology means that assimilating organisations have to undertake technological modifications and obtain additional knowledge, if they are to make it work. This is well illustrated in the detailed analysis by the Economic Council of Canada (de Melto *et al*, 1980) of the characteristics and costs of more than 200 innovations commercialised in Canada, and about a quarter of which involved agreements to assimilate technology from other firms, often in other countries. The magnitude of licence payments by users to firms supplying technology were in fact much smaller than the sums spent by the user firms themselves on technological activities.

The study concludes as follows: ". . . the importation of technology by agreement or arrangement with other firms . . . acts as a strong substitute for research spending but has little effect on the relative proportion of development spending required to launch the . . . innovations . . ." (page 35).

The relatively high cost and long time, necessary in most sectors for imitators to imitate, is reflected in innovating firms' assessment and use of the patent system as a barrier to imitation. Although patents are sought by firms in most industries, they are considered as the most important barrier against imitation only in very few, particularly in fine chemicals, where product innovations are expensive to develop, but often cheap to replicate. In most other industries, the costs of imitation are in themselves a sufficient barrier against imitation to justify the costs and risks incurred by the innovating firms themselves (Bertin and Wyatt, 1986; Levin *et al*, 1984; Mansfield *et al*, 1981; Wyatt, 1985).

In other words, there are very few free technological lunches. Even borrowers of technology must have their own skills, and make their own expenditures on development and production engineering; they cannot treat technology developed elsewhere as a free, or even a very cheap, good. The lessons for both developed and developing countries are obvious. And like his predecessors, Mr Gorbachev is no doubt pondering the effects of the continuing separation in the USSR of most development and production engineering competence from operating firms, on the Soviet Union's lack of technological dynamism (Hanson and Pavitt, 1987).

The second consequence of the complexity of technology is paradoxical: although (as we have seen) imitation rarely is cheap, it can only equally rarely be prevented completely. Of course, innovating firms are always trying to protect their lead, through patent protection, through secrecy, and/or through a variety of other means.

However, a number of empirical studies show that they hardly ever succeed. Precisely because technology is complex, and therefore difficult to define completely and precisely, it is possible to invent round existing patent protection, and firms that want to generally succeed in doing so pretty quickly: according to an American study, about 60% of them within four years (Mansfield *et al*, 1981). Furthermore, since most new technology is embodied in products, one major method of imitation — much neglected in the academic literature — is what is called reverse engineering: taking other firms' product innovations to pieces to understand how they work and how they are made (De Melto *et al*, 1980; Levin *et al*, 1984; Nelson, 1986).

If technology were like information, then innovation would be expensive (as it is), whereas copying and imitation would be cheap (and it is not)

As with the assimilation of outside technology, neither inventing round other people's patents, nor reverse engineering, are cheap. They require considerable in-house investments in development, production engineering, and even research, and they sometimes result in imitations that are better than the original.

As we can see, this is a world very different from that where, technology having the properties of information, innovation is expensive but imitation virtually costless. We find instead that innovation and imitation are often indistinguishable, both in their inputs and their outputs, and that it is difficult to decide which is the "best" of a number of competing innovations. Under such circumstances, some pluralism and variety in technological activities is likely to be beneficial.

Another justification for in-house or indigenous technological activity emerges from the second key characteristic of technology, namely, its cumulative nature. Partly as a result of its specificity and complexity, technological activity in firms tends to build out incrementally from what they know already, even when they are seeking major changes or breakthroughs — a characteristic already remarked upon in the 19th century by Marx. Technological search and choice in firms are therefore constrained by what they (or firms they purchase or join with) have already learned, and their technological activities tend to follow a "trajectory".

There is at present much research at the Science Policy Research Unit (SPRU) on these so-called trajectories, at the level of firms, of countries, and of major technologies. There are also links with other research groups to explore their theoretical implications: in particular, the development of evolutionary theories, that have as their central characteristics the diversity and adaptation of business firms in a dynamic and uncertain environment (Nelson and Winter, 1982).

I want to spell out briefly one of the implications of the existence of such trajectories that has recently been explored by the economist, Joseph Stiglitz (1986). He had already been joint author of a paper in 1969 that began to explore the consequences of what he called localised technological change, and I am only sorry that it has been 17 years before he has returned to the subject.

He argues in his recent paper that, if technical change is specific and cumulative, choices about technology should reflect not only what is available at present, but also expected developments in future. A decision to choose the cheapest alternative now will be short-sighted if an immediately more expensive technology offers greater opportunities for improvement in future, in terms of both cost and the development of more new products.

In his paper, Stiglitz is concerned mainly with the problems of developing countries, but what he says is of potentially wider applicability. For example, many technological decisions in British firms might be myopic, because of short-term financial pressures, or of an inability to assess seriously the future rate and direction of technological change. More generally, consider the typical choice facing either a firm or a country on how best to assimilate some successful technology first developed elsewhere. Whilst the immediate lowest cost alternative may be the purchase of a licence, it may be that reverse engineering and independent redevelopment will offer greater benefits in future, in terms of accumulated knowledge, and the generation of a stream of competitive innovations.

The reality of such choices is supported in the study of Canadian innovations, mentioned above, and in a study of the Brazilian software industry recently completed at SPRU by Fatima Gaio.

The final key characteristic of technology that I want to mention briefly is its partial tacitness: in other words, it cannot be completely codified. Learning through experience, example and training is therefore an essential feature of technological accumulation, and this is reflected in the greater volume of technology trade amongst companies and countries in know-how than in patent rights. Neglect of the tacit element in technology can lead to policies and practices that turn out to be unproductive. For example, in the 1960s and 1970s, government policies in some third world countries set out to reduce the costs and the time periods of licensing agreements for technology purchases from the advanced countries. This sometimes led to the neglect of the personal contacts, the training and the experience, essential for effective technology transfer, and to disappointing results in recipient firms (Bell and Scott-Kemmis, 1985).

Technological capacity in firms

There is, I suggest, one major policy conclusion that emerges from this discussion, namely, the central importance of technological knowledge and activities embedded within firms, and necessary not just for new ideas and innovations, but also to enable effective assimilation of knowledge — technological and scientific — from outside. R&D expenditures, and other indicators of technological activity in business enterprises, therefore reflect not just the ability to get ahead, but also the capacity to keep up.

In this context, I am obliged to draw attention to the low level and rate of growth of British industrial R&D compared to other OECD countries, a subject that received considerable coverage and debate earlier this year. In a paper that Pari Patel and I are preparing for the 1987 meeting of the British Association for the Advancement of Science, we show the considerable changes that have taken place over the past 20 years in the sectors of British technological strength and weakness; in particular, the relative improvement compared to the rest of the world in the chemical-based sectors, with spectacular growth in pharmaceutical products; and at the same time, the relative decline in engineering — mechanical, electrical and (above all) electronic.

In major sectors like chemicals, electronics and aerospace, British growth and decline can be attributed to the technological policies and commitments of not much more than a handful of companies, the comparative study of which will be rich in future lessons for both business strategy and national policy.

References

Advisory Council for Applied Research and Development, and the Advisory Board for the Research Councils (1986), *The Science Base and Industry* (London, HMSO).

T Allen (1977), *Managing the Flow of Technology* (MIT Press).

G Barclay and M Fottit (1987), British Technology Group, personal communication.

M Bell and D Scott-Kemmis (1985), "Technology import policy: have the problems changed?", and "Technological dynamism and technological content of collaboration", *Economic and Policy Weekly*, vol XX, nos 45, 46, 47, pages 1975–2004.

G Bertin and S Wyatt (1986), *Multinationales et Propriété Industrielle* (Paris, Presses Universitaires de France).

I Byatt and A Cohen (1969), *An Attempt to Quantify the Economic Benefits of Scientific Research* (London, HMSO).

M Carpenter (1983), "Patent citations as indicators of scientific and technological linkages", Annual Meeting of the American Association for the Advancement of Science.

M Carpenter, F Narin and P Woolf (1981), "Citation rates to technologically important patents", *World Patent Information*, volume 3, Detroit, 30 May.

N Clark (1987), "Similarities and differences between scientific and technological paradigms", *Futures*,

P Dasgupta (1986), *The Economic Theory of Technology Policy* (London, Centre for Economic Policy Research).

P Dasgupta and P David (1986), "Information disclosure and the economics of science and technology", in G Feiwel (editor), *Essays in Honour of K Arrow* (Macmillan).

D Davies (1980), personal communication.

G Dosi (1982), "Technological paradigms and technological trajectories", *Research Policy*, **11**(3), pages 147–162.

The Econimist (1987), In search of a cure", 7 February.

The Economist (1987), "Britain's university challenge", 18 April.

G Eliasson (1986), "Innovative change, dynamic market allocation and long-term stability of economic growth", Working Paper No 156, The Industrial Institute for Economic and Social Research, Stockholm.

J Fagerberg (1987), "A technology gap approach to why growth rates differ", *Research Policy*, volume 16, numbers 2, 3 and 4.

C Freeman (1977), "Economics of research and development", in I Spiegel-Fosing and D de Solla Price, *Science, Technology and Society* (Sage).

C Freeman (1986), "The case for technological determinism" (mimeo), Brighton, Science Policy Research Unit.

C Freeman, J Clark and L Soete (1982), *Unemployment and Technical Innovation: A Study of Long Waves and Economic Development* (London, Frances Pinter).

M Gibbons and R Johnston (1974), "The roles of science in technological innovation", *Research Policy*, **3**(3), pages 220–243.

P Hanson and K Pavitt (1987), *The Comparative Economics of Research, Development and Innovation in East and West* (mimeo), Brighton, science Policy Research Unit).

D Hague (1986), Evidence submitted to the House of Lords Select Committee of Science and Technology, on behalf of the Economic and Social Research Council. *Civil Research and Development*, Vol II (HMSO, London).

J Irvine and B Martin (1980), "The economic effects of big science: the case of radio-astronomy" in Proceedings of the International Colloquium on Economic Effects of Space and Other Advanced Technologies, Strasborg, 28–30 April (Ref ESA SP 151, September 1980).

J Kay and C Llewellyn Smith (1985), "Science policy and public spending", *Fiscal Studies*, volume 6.

J Keynes (1935), *The General Theory of Employment, Interest and Money* (Harcourt Brace and Company).

R Levin, A Klevorick, R Nelson and S Winter (1984), "Survey research on R&D appropriability and technological opportunity. Part 1: Appropriability", (mimeo, Yale University).

D MacKenzie and J Wajcman (1985), "Introductory Essay", in *The Social Shaping of Technology* (UK, Open University Press).

M Mackenzie, A Cambrosia and P Keating (1987), "The Commercial Application of a Scientific Discovery; The Case of the Hydridoma Technique" (mimeo) (Crest, University of Quebec at Montreal).

B Madeuf (1984), "International technology transfers and international technology payments: definitions, measurements and firm's behaviour", *Research Policy*, **13** (3), pages 125–140.

E Mansfield, M Schartz and S Wagner (1981), "Imitation costs and patents: an empirical study", *Economic Journal*, 91, pages 907–918.

B Martin and J Irvine (1983), "Assessing basic research: some partial indicators of scientific research in astronomy", *Research Policy*, **12**,

D de Melto, K McMullen and R Wills (1980), *Innovation and Technological Change in Five Canadian Industries*, Discussion Paper No. 176, Ottawa, Economic Council of Canada.

D Mowery (1983), "Economic theory and government technology policy", *Policy Sciences*, volume 16, pages 27–43.

R Nelson (1959), "The simple economics of basic scientific research", *Journal of Political Economy*.

R Nelson (1986), "Institutions supporting technical advance in industry", *American Economic Review*, volume 76. See also "The Generation and Utilisation of Technology: A Cross Industry Analysis", (mimeo).

R Nelson and S Winter (1982), *An Evolutionary Theory of Economic Change* (Belknap).

F Narin (1982), Assessment of the Linkages between Patents and Fundamental Research, Workshop on Patents and Innovation Statistics, OECD (DSTI/SPR) 82, 36).

F Narin and E Noma (1985), "Is technology becoming science?", *Scientometrics*, volume 7.

F Narin and D Olivastro (1987), *Identifying Areas of Strength and Excellence in UK Technology* (CHI Research, 1050 King's Highway North, Cherry Hill, NJ 08034, USA).

P Patel and K Pavitt (1987), "The Technological Activities of the UK: A Fresh Look", (ESRC DRC Discussion Paper no 49, Brighton, Science Policy Research Unit).

K Pavitt (1980), (editor), *Technical Innovation and British Economic Performance* (Macmillan).

K Pavitt (1981), "Technology in British Industry: A Suitable Case for Improvement", in C Carter (editor), *Industrial Policy and Innovation* (London, Heinemann).

T Pinch and W Bijker (1984), "The social construction of facts and artefacts: or how the sociology of science and the sociology of technology might benefit each other", *Social Studies of Science*, volume 14, pages 399–441. See also (1986), "Science, relativism and the new sociology of technology: reply to Russell", *Social Studies of Science*, volume 16, pages 347–360.

D de Solla Price (1965), "Is technology historically independent of science? A study in statistical historiography", *Technology and Culture*, volume 6.

N Rosenberg (1976), "Problems in the Economist's Conceptualization of Technological Innovation", *Perspectives on Technology*, Cambridge University Press.

N Rosenberg (1982), *Inside the Black Box: Technology and Economics* (Cambridge University Press).

N Rosenberg (1985), "The Commercial Exploitation of Science by American Industry", in K Clark, R Hayes and C Lorenz (editor), *The Uneasy Alliance: Managing the Productivity/Technology Dilemma* (Harvard Business School).

N Rosenberg and C Frischtak (1985), *International Technology Transfer: Concepts, Measures and Comparisons* (Praeger).

R Rothwell *et al* (1974), "SAPPHO updated — Project SAPPHO, Phase 2", *Research Policy*, **3**(3), pages 258–291.

Select Committee on Science and Technology (1983), *Engineering Research and Development* (London, House of Lords), volumes I, II and III, HMSO).

Select Committee on Science and Technology (1986), *Civil Research and Development* (London, House of Lords, volumes I, II and III, HMSO).

Adam Smith (1985 edition), *The Wealth of Nations* (G Routledge and Sons).

L Soete (1981), "A general test of technological gap trade theory", *Weltwirtschaftliches Archiv*, **117**(4), pages 638–660.

J Stiglitz (1986), "Learning to learn, technological change, and economic and social structure", (mimeo, Princeton University).

A de Tocqueville (1963 edition), *De La Democratie en Amerique* (abridged edition, Paris, Union Generale d'Editions).

S Wyatt (1985), "Patents and multinational corporations: results from questionnaires", *World Patent Information*, volume 7.