# *Technologies, Products and Organization in the Innovating Firm: What Adam Smith Tells Us and Joseph Schumpeter Doesn't*

KEITH PAVITT
(Science Policy Research Unit, Mantell Building, University of Sussex, Brighton BN1 9RF, UK)

*Adam Smith's insights into the increasingly specialized nature of knowledge production are crucially important in understanding the contemporary problems of managing innovating firms. Products and firms are based on an increasing range of fields of specialized technological understanding. Competition is not based on technological diversity, but on diversity and experimentation in products, etc. Firms rarely fail because of an inability to master a new field of technology, but because they do not succeed in matching the firm's systems of coordination and control to the nature of the available technological opportunities.*

> All the improvements in machinery, however, have by no means been the inventions of those who had occasion to use the machines. Many . . . have been made by the makers of the machines, when to make them became the business of a peculiar trade: and some by . . . 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. . . . *Like every other employment . . . it is subdivided into a 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.* (Smith, 1776, p. 8, my italics)

Industrial and Corporate Change Volume 7 Number 3 1998

## 1. *Setting the Scene*

### Evolutionary Theory and the Innovating Firm

Attempts over the past twenty years to build an evolutionary theory of the firm have grown in part out of a dissatisfaction with the inability of mainstream theory to deal satisfactorily with two important, interrelated and empirically observable characteristics of contemporary society: continuous technical change, and the central role of the business firm in generating learning, improvement and innovation, through deliberate and purposive action. At the beginning, concepts like 'technological trajectories' and 'routines' were introduced by Nelson and Winter (1977, 1982) to reflect the cumulative and path-dependent nature of technical change, the often tacit nature of the knowledge underlying it, and the trial-and-error behaviour of business practitioners trying to cope with a complex and ever-changing world.[1]

Since then, two influential streams of analysis have helped deepen our knowledge of the innovating firm. First, numerous attempts have been made to apply the tools and techniques of evolutionary theory (and particularly biological evolution) directly to modelling and understanding technical change (e.g. Dosi and Marengo, 1993; Metcalfe and de Liso, 1995). Second, numerous empirical studies have attempted to formulate generally applicable laws that explain when and why established firms succeed in innovation, and when and why they fail (e.g. Iansiti and Clark, 1994; Teece, 1996). This paper will argue that, whilst both schools have made notable contributions to understanding of both the nature of the innovating firm and the conditions for successful innovation, much remains to be done.

### Multi-technology Products and Firms

In particular, greater care and attention needs to be devoted to the distinctions between the *artefacts* (products, etc.) that the firm develops and produces, the firm-specific technological *knowledge* that underlies its ability to do so, and the *organizational* forms and procedures that it uses to transform one into the other. We shall argue that, in the late twentieth century, lack of technological knowledge is rarely the cause of innovation failure in large firms

[1] This paper concentrates on these aspects of firm behaviour, and not on the wider implications of evolutionary theory for the theory of the firm. For a concise evaluation of the latter, together with that of other recent theoretical developments, see Coriat and Weinstein (1995).

based in OECD countries. The main problems arise in organization and, more specifically, in coordination and control.

This can best be understood if more attention is paid to what Adam Smith said about the division of labour, and less to what Schumpeter said about creative destruction. Smith's identification of the benefits of specialization in the production of knowledge has been amply confirmed by experience. Professional education, the establishment of laboratories, and improvements in techniques of measurement and experimentation have increased the efficiency of discovery, invention and innovation. Increasingly difficult problems can be tackled and solved.[2] Two complementary forms of specialization have happened in parallel.

First, new disciplines have emerged, with all the benefits of the division of labour highlighted by Smith himself at the beginning of this paper. These specialized bodies of knowledge have become useful over a growing range of applications, so that products incorporate a growing number of technologies: compare the eighteenth-century loom with today's equivalent, with its fluid flow, electrical, electronic and software elements improving the efficiency of its mechanical functions. In other words, products are becoming increasingly 'multi-technology', and so are the firms that produce them. Each specific body of technical knowledge cannot be associated uniquely with a single, specific class of product.[3] Products and related technologies co-evolve within firms, but their dynamics are different. For example, Gambardella and Torrisi (1998) found that the most successful electronics firms over the past ten years have been those that have simultaneously broadened their technological focus and narrowed their product focus. In other cases, firms have used their range of technological skills to create or enter new product markets (see Granstrand, 1982; Granstrand and Sjolander, 1990; Oskarsson, 1993; Granstrand and Oskarsson, 1994).

Second, in addition to the benefits of the cognitive division of labour into more specialized fields, the rate of technical change has been augmented by the functional division of labour within business firms, with the establishment of corporate R&D laboratories and similar groups devoted full-time to inventive and innovative activities. In addition to the Smithean benefits of specialization, professionalization and improved equipment, these laboratories enabled firms to monitor and benefit more systematically and effectively from

[2] The classic texts on this are Rosenberg (1974), de Solla Price (1984) and Mowery and Rosenberg (1989). See, for example, the reasons why problems in mechanics were solved more easily than those in medicine.

[3] Amongst other things, this is a source of frustration for economists who would like to match statistics on inventions from technology-based patent classes with product based trade and production statistics. See, for example, Scherer (1982).

the outside advances in specialized academic disciplines. And with growing experience in the development and testing of prototypes, they have allowed systematic experimentation with a wider range of products and processes than had previously been possible through incremental improvements constrained by established products and production lines. In fields of rich technological opportunity, firms have in consequence become multi-product as well as multi-technology.

## Two Bodies of Knowledge

Hence the importance, in analysing the innovating firm, of distinguishing clearly artefacts (products) from the knowledge sources on which they are based.[4] Nelson (1998) identifies two, complementary elements in firm-specific knowledge. First, there is a 'body of understanding', based on competencies in specific technological fields, and reflected in the qualifications of corporate technical personnel, and in the fields in which they patent and publish.[5] The second element is what Nelson (1998) calls a 'body of practice', related to the design, development, production, sale and use of a specific product model or a specific production line. This firm-specific practical technical knowledge is often obtained through the combination of experimentation, experience, and information and other exchanges amongst different parts of the organisation.[6] As such, it is an organizational task, so that 'a body of practice' consists largely of organizational knowledge that links 'a body of understanding' with commercially successful (or, more broadly, useful) artefacts.

[4] For an earlier discussion of this distinction, see Archibugi (1988).

[5] For measurement of corporate technological competencies through the fields of qualifications of technical personnel, see Jacobsson and Oskarsson (1995); through patenting, see Patel and Pavitt (1997); and through scientific papers, see Narin and Olivastro (1992), Godin (1996) and Hicks and Katz (1997).

[6] The difference between the two forms of knowledge is nicely illustrated in the following passage from Iansiti and Clark (1994), in relation to the firm-specific capabilities for the design and development of dies used in the production of body panels for automobiles: 'The knowledge that underlies that capability includes an understanding of metallurgy, the flow of metal under pressure and the relationship between the characteristics of the material, the forces and pressures applied to the material and the surface properties that result. These kinds of knowledge pertain to the fundamental properties of the die and its production system. But the firm must also have knowledge about how the fundamental concepts can be operationalised into effective actions. These include knowledge of techniques of die design, die modelling, die testing and finishing, for example. Additionally, knowledge can take the form of the skill of die designers in anticipating processing problems, customised software that allows for rapid and effective testing, patterns of communication and informal interaction between die designers and manufacturing engineers that allow for early identification of potential problems, and an attitude of co-operation that facilitates coordinated action between the die designers and the tool makers that will build the dies. These elements (and many others) define an organisational capability for die design and development' (p. 560).

## Method

The starting point for our analysis is the large, multi-divisional manufacturing firm, with established R&D activities and a product range that has grown out of a common, but evolving, technological competence. In part, this reflects the focus of this author's recent research (Patel and Pavitt, 1997; Tidd *et al.*, 1997). More important for the purpose of this paper, large multi-divisional firms are the largest single source of the new technological knowledge on which innovation depends. They perform most of the R&D activities, employ most of the qualified research scientists and engineers, perform and publish most of the corporate basic research, and maintain the closest links with academic research (Hicks, 1995). They also contribute to the development of knowledge and products for their suppliers of production equipment, components and software (Rosenberg, 1963; Patel and Pavitt, 1994). Finally, even when they fail in innovation themselves, they remain the major source of the technological and other competencies which enable new firms with different organizational approaches to succeed. Understanding the reasons for their success and failure therefore has the widest implications, not only for their managers, but also for the distribution of innovative activities amongst companies of different sizes and ages. It is not the main concern of this paper to argue in general for or against the large firm's ability to sustain radical innovation, but to understand better the reasons for its success and failure in trying to do so.[7]

We divide our analysis into four parts, reflecting four mechanisms identified by earlier analysts of the innovating firms: competition, cognition, coordination and control.[8] Table 1 sets out schematically how the division of labour, both in knowledge production and in corporate innovative activities, has influenced these four mechanisms. We argue in Section 2 that failure to distinguish between technologies and products has led to confusion in evolutionary

[7] Many analysts in the evolutionary tradition are pessimistic about the ability of large firms to sustain radical innovations, pointing to recent spectacular failures and to the emergence of new organization forms: Teece (1996) recently identified four types of firm: conglomerate, multi-product integrated hierarchy, virtual corporation and 'high flex' Silicon Valley type. Others argue that the obituary of the large innovative firm may well be premature, since there remain many examples of their success in developing and exploiting major innovations: for example, according to Methe *et al.* (1996): 'established firms, including industry incumbents and diversifying entrants, play vital and underemphasized roles as sources of major innovations in many industries" (p. 1181). And now even the oldest and best established of capitalists—grocers (supermarkets) and moneylenders (financial services)—have become major players in the development and exploitation of information technology.

[8] These dimensions of the innovating firm emerge from the original work of Nelson and Winter (1982), and from later work by Cohendet *et al.* (1994). In the language of Teece and Pisano (1994), in their analysis of the 'dynamic capabilities' of the firm, our competitive mechanisms relate their notions of corporate *position*, cognitive mechanisms to corporate *paths*, and coordination and control mechanisms to corporate *processes*.

TABLE 1. Some Consequences of the Division of Labour in the Production of Technological Knowledge

| Analytical implications | | | Technology ≠ products | Technological discontinuities ≠ product discontinuities | Technological diversity within firms, and within countries, but *not* within industries |
|---|---|---|---|---|---|
| Division of labour in knowledge production → | Laboratories<br>Disciplines<br>Trained scientists and engineers → | Increasing output, range and usefulness of knowledge → | Multi-technology products → | Multi-technology firms → | Multi-product firms |
| Division of labour in business functions → | Specialized technical functions, inc. R&D labs → | Increasing competence to understand and improve artefacts → | | | |
| Management implications | | Co-ordination<br>Organizational competence to experiment and learn across organizational boundaries | | Competencies<br>Technological competence enhancement > competence destruction | Control<br>Organizational competence to reconfigure divisions and evaluate options in the light of technology characteristics |

writings about what kind of 'diversity' is desirable in competitive processes. In Section 3, we further argue that, although there are clear cognitive limits on the range of technologies that a specific firm is capable of mastering, failure in innovation in established firms is not the result of the destruction of their technological competencies, but of their inability to match the technological opportunities with organizational forms and procedures appropriate for their development and exploitation. In Sections 4 and 5, we analyse in greater depth how the appropriate forms of two organizational elements that are central to corporate innovative activities—mechanisms of coordination and control—depend in part on the nature of the technology itself.

## 2. *Competitive Mechanisms and Technological Diversity*

It is around the notion of diversity[9] that the distinction between technologies (bodies of understanding) and products (bodies of practice) is most confused —and potentially most misleading, given the central importance accorded to diversity in the evolutionary theory of technical change.[10] In recent research undertaken at SPRU on the technological competencies of the world's largest firms, we have used the level and distribution of corporate patenting by technical field as a measure of the corporate body of technological understanding (Patel and Pavitt, 1997; O. Marsili, in preparation). This showed that technological diversity is prominent in some dimensions, but virtually absent in others.

- Large firms are active in a range of technologies *broader* than the products that they make. This reflects the multi-technology nature of their products, and the knowledge required to coordinate in-house product innovation with innovation in related production systems and supply chains. What is more, the range of technological competencies mastered by large firms is increasing over time, as new technological opportunities emerge.
- There is *high* diversity amongst large firms in the level and mix of their technological competencies, depending on the products that they produce. These largely sector-specific mixes of technological competence change only slowly over time, again in response to changing technological opportunities.

[9] A reading of the *Oxford Concise English Dictionary* suggests that the term 'diversity' is interchangeable with 'variety' and 'heterogeneity'.

[10] 'It is a basic proposition of evolutionary theory that a system's diversity affects its development' (Cohendet and Llerena, 1997, p. 227).

- There is *low* diversity in the level and mix of technological competencies amongst large firms producing similar products. What is more, the degree of technological diversity is lowest in the product fields with the highest rate of technical change: computers and pharmaceuticals.

In other words, for the *individual firm*, technological diversity gives it the basis to make and improve its products. For the *economy as a whole*, more diversity amongst firms in their mixes of specialized technological knowledge enables them to explore and exploit a fuller range of product markets. But at the level of the *product market or industry*, there is similarity rather than diversity in the level and mix of technological activities in competing firms, and especially in those with high rates of technical change. Technological diversity is certainly not a characteristic of competition amongst innovating firms.[11] The diversity exists downstream in the body of practice, namely the product and process configurations that can be generated from the same or very similar base of technological knowledge. We know that some of these configurations do not work out technically, and many more do not work out commercially (Freeman and Soete, 1997). What emerges is a world where firms with broad and stable bundles of technological competencies have the capacity to generate and experiment with a range of product (and process and service) configurations, some of which succeed, but many of which fail.

At any given time, advances in some fields of technology open major opportunities for major performance improvements in materials, components and subsystems (e.g. economies of scale in continuous processes, economies of miniaturization in information processing). The directions of these improvements are easily recognized, even if they require the commitment of substantial resources for their achievement, e.g. Moore's Law in semiconductors.[12] Thus, experimentation and diversity do not take place between different technologies. On the contrary, rich and well-known directions of

[11] A (frivolous) translation of these results into biological evolutionary terms might be (i) species need a range of genetic attributes for survival; (ii) since they live in different parts of the forest, the elephant and the mouse have different genetic mixes, which change only slowly; (iii) there is little room (or need) for genetic deviance when things are changing fast (and in predictable directions—see below).

[12] Recent comments by an IT expert make the point nicely: 'Precious little has happened in digital technology over the past five years. . . . Steady increases in processor speed and storage size have become as predictable as a child's growth. . . . Just as the computer industry is predicated on Moore's Law—that chips will double in speed every 18 months, which companies can literally plan on—the telecom industry can be predicated on the transparent network. . . . Change is routine and uneventful. . . . The fiber-optic backbone has joined the microprocessor on a steady predictable climb. Processing speeds will double every 18 months. Bandwidth will quadruple every two years. Corporate planners can rest easy' (Steinberg, 1998, pp. 80–84). In our framework, the conclusion of the last sentence does not follow from the preceding analysis. Such rapid if predictable change in underlying technology is bound to create a plethora of difficult-to-predict products and services.

improvement in underlying technologies[13] create opportunities for diversity and experimentation in product configurations. Technological opportunities create product diversity. There is no convincing evidence that technological diversity creates product opportunities.[14]

## 3. *Cognitive Mechanisms and Creative Destruction*

Large firms may have competencies in a number of fields of technology but, in the contemporary world of highly specialized knowledge, the costs of mastering all of them clearly appear to outweigh the benefits. Firms develop their technological competencies incrementally, and constrain their search activities close to what that they already know. Thus, over the past 20 years, electronics firms have moved heavily into semiconductor technology (but not biotechnology), and drug firms into biotechnology (but not semiconductor technology). The firm's knowledge base both determines what it makes, and the directions in which it searches (Patel and Pavitt, 1997). In this sense, there are clear cognitive limits on what firms can and cannot do.

The central importance of firm-specific technological competencies has led some analysts to place technological discontinuities (i.e. major technological improvements) at the heart of the theory of the innovating firm. In particular, they argue that such discontinuities may either enhance established competencies and strengthen incumbent firms, or destroy established competencies and undermine them. Again, it must be stressed that technological discontinuities are not the same as product discontinuities, even if they are often treated as such. For example, perhaps the most influential paper on discontinuities by Tushman and Anderson (1986) talks of *technological* discontinuities in its title, whilst the basis for its empirical analysis are new products and processes (e.g. jet engines, oxygen steel-making).

Although they may have revolutionary effects, technological discontinuities rarely encompass all—or even most of—the fields of knowledge that feed into a product. Typically they may affect the performance of a key component (e.g. transistors vs. valves) or provide a major new technique (e.g. gene splicing). But they do not destroy the whole range of related and complementary

[13] Nelson and Winter (1977) originally called these 'natural trajectories' and were roundly criticized by those arguing that technologies are socially constructed. But perhaps Nelson and Winter were right. The range of opportunities in different technological fields depends heavily on what nature allows us to do. Compare rates of increase of information storage capacity over the last 20 years with rates of increase in energy storage capacity. In the former, newsprint, punch cards and analogue recording have been overwhelmed by digital methods. In the latter, petroleum remains supreme, in spite of considerable technological efforts to develop better alternatives.

[14] In this context, a recent paper, Stankiewicz (1998) proposes the notion of interrelated 'design space' for artefacts, and 'operands' for the underlying knowledge base, techniques, etc.

technologies (e.g. sound reproduction in radios, memories in computers, molecular design in pharmaceuticals) that are necessary for a complete product.[15] Indeed, they create opportunities for product 'discontinuities' that often can be achieved only through improvements in complementary but long-established technologies (e.g. metal tolerances and reliability for robots).

Furthermore, as Gambardella and Torrisi (1998) have shown, corporate technological dynamics can have different dynamics from corporate product dynamics, with technological diversification going hand in hand with increasing product focus: for example (i) when a technological discontinuity is incorporated in a product family at the mature stage of its product cycle; or (ii) when a technological discontinuity provokes the emergence of radically new but technology-related product markets with different—but as yet ill-defined—characteristics; this is probably the case in the electronics industry studied by Gambardella and Torrisi (1998).

Finally, it should be noted that the predominance given to revolutionary technologies in the destruction of corporate competence has often been associated with the notion of paradigm shifts in technology (Dosi, 1982), similar to those in science (Kuhn, 1962). But this is a misinterpretation of the notion of paradigm. A new paradigm does not discredit and displace all the knowledge generated in the earlier paradigms, but instead adds to them. Newtonian physics still has major theoretical and practical uses, and at least a quarter of all the new technology created today is still in mechanical engineering. The development and commercial exploitation of technological discontinuities turns out to be a more cumulative process than is often supposed.

Certainly, there are many historical examples of firms that have failed because they did not master major emerging fields of technology (Cooper and Schendel, 1976). But competence-destroying technologies are the exception rather than the rule today, especially amongst large firms, who have demonstrated a strong capacity through their R&D departments to acquire and develop competencies in 'discontinuity-creating' technologies like computing and biotechnology (Patel and Pavitt, 1997). The key factors behind the success and failure of innovating firms must be sought elsewhere, in the organizational processes linking technologies, products, their production and their markets.

Cognitive mechanisms also underlie the taxonomy of innovation proposed by Abernathy and Clark (1985), which distinguishes four types: incremental, component, architectural and revolutionary. Based on an analysis of innova-

[15] On biotechnology, see McKelvey (1996).

tion in photolithographic aligners, Henderson and Clark (1990) argued that innovations in product architecture[16] destroy the usefulness of the architectural knowledge in established firms, and this is difficult to recognize and remedy. More recently, and based on analysis of innovations in computer disk drives, Christensen and Rosenbloom (1995) concluded that architectural innovations do not necessarily destroy established competencies. What does is a change in the 'value network' (i.e. user market) of the innovation.[17]

Whilst these studies throw interesting and important light on innovation processes within firms, they must be interpreted with care. An alternative reading of the Henderson and Clark story is that failure has less to do with cognitive failure by design engineers to recognize the value of alternative product architectures, than with organizational factors such as the inability of design engineers to recognize signals from users or the marketing department, or the unwillingness or inability of corporate management to establish a new design team or product division. Furthermore, it may be a mistake to generalize from the experience of US firms specialized in the IT sector to firms in other sectors and countries. In contrast, for example, to Christensen and Rosenbloom's emphasis on the difficulties of US firms making computer disk drives in switching end-user markets, most of the world's leading chemical firms have been very successful in the twentieth century in deploying their techniques and products deriving from organic synthesis in markets as diverse as textiles, building, health and agriculture (Hounshell and Smith, 1988; Plumpe, 1995).

## 4. *Co-ordination Mechanisms and Learning across Organisational Boundaries*

One of the most robust conclusions emerging from empirical research on the factors affecting success in innovation is the importance of coordinating learning and other change-related activities across functional boundaries (Burns and Stalker, 1961; Rothwell, 1977; Cooper, 1988; Wang, 1997).[18] Here we see the second major feature of the division of labour that is central to contemporary corporate innovative activities, namely coping with functional specialization, with the emergence of specialized departments for

[16] '. . . reconfiguration of an established system to link together existing components in a new way' (Henderson and Clark, 1990, p.12)

[17] The authors liken a change in the 'value network' (i.e. disk configuration and user market) to a paradigm shift, which implies a much broader definition of the notion of paradigm than that probably envisaged by Dosi (1982).

[18] Problems of such coordination have also figured largely in the works of Coase (1937), Penrose (1959), Aoki (1986) and Loasby (1998).

R&D, production, marketing, logistics, strategy, finance, etc. Such coordination cannot realistically be reduced to designing flows of codified information across functional boundaries. It also involves coordinated experimentation (e.g. new product launches), and the interpretation of ambiguous or incomplete data, where tacit knowledge is essential. As the observations of Iansiti and Clark in footnote 6 (p. 436) show, personal contacts, mobility and interfunctional teams are therefore of more central importance than pure information flows.

In our present state of knowledge, effective coordination belongs in the field of practice rather than the field of understanding. Unlike purely technological processes, organizational processes are difficult to measure and evaluate, and do not lend themselves readily to rigorous modelling and controlled experiments. In addition, the coordination processes in which we are interested are complex. Experimentation and learning across critical organizational interfaces are particularly difficult when combining knowledge from different functions, professions and disciplines, each with their distinct and different analytical frameworks and decision rules—which is another reason why firms may try to compensate for greater technological complexity by greater market focus.[19]

In addition, the identification of the location of critical interfaces is not easy, for three reasons. First, there are potentially several such interfaces, involving a multitude of possible linkages between R&D, production, marketing and logistics within the firm, and a variety of sources of outside knowledge in universities, other firms (suppliers, customers, competitors, etc.) and other countries. Second, the interfaces that merit analysis and managerial attention vary considerably amongst technologies and products. Compare firms in pharmaceuticals and automobiles. In the former, strong interfaces between in-house R&D and the direct output of academic research (in medicine, biology and chemistry) are essential. In the latter, they are not, but strong interfaces between in-house R&D and production are of central importance. These differing characteristics have important implications for both the appropriate organizational forms, and geographical location of corporate innovative activities.

Finally, the key interfaces for organizational learning change over time, very often as a result of changes in technology-related factors themselves. Witness the growing importance for the pharmaceutical industry of the interface with

[19] Models of intra-corporate coordination have not got very far in grappling with these essential features of innovative activities. For example, in Aoki's models (1986), problems of coordination are in production and dealt with through information flows, rather than in learning and innovation mediated through tacit knowledge. Furthermore, sources of instability and change are in an exogenous environment, rather than created by the firms themselves.

research in academic biology, the consumer market interface for producers of telephones and computers, and of interfaces with software and materials technologies for firms in virtually all sectors. One major source of failure in innovation is likely to be inadequate recognition of the importance of these new interfaces, or the inability of management to take effective action to establish them. We should look for what Leonard-Barton (1995) calls 'core rigidities', when individuals and groups with the established competencies for today's products are either ignorant of, or feel threatened by, the growing importance of new competencies.

## 5. *Control Mechanisms: Matching Strategic Styles with Technologies*

The lack of a one-to-one link between each product and each technology has at least two major implications for organizational practice in business firms.[20] The first is that firms which master fields of rich technological opportunity are often able to develop and produce several products based on the same body of knowledge. In other words, they compete and grow through technology-related diversification.[21] Second, the very existence of this broadly useful knowledge means that the classic M-form organization is unable to match tidily each field of its technology to one product or to one division.

As a consequence, systems of corporate control in the multi-product firm have a major influence on the rate and direction of its innovative activities. Chandler (1991) distinguishes two essential functions of corporate control: the *entrepreneurial* function of planning for the future health and growth of the enterprise, and the *administrative* function of controlling the operation of its many divisions.[22] The administrative function is normally exercised through systems of financial reporting and controls. The entrepreneurial function for technology is the capacity to recognize and exploit technology-based opportunities. This requires an ability to evaluate projects and programmes where the normal financial accounting techniques are often inoperable and inappropriate, since exploratory research programmes should be treated as options, rather than full-scale investments (Myers, 1984; Hamilton, 1986; Mitchell, 1986; Mitchell and Hamilton, 1988). It may also require the establishment of a central corporate research programme or laboratory, funded in part independently from the established product divisions

[20] For more extended discussions, see Kay (1979), Prahalad and Hamel (1990), von Tunzelmann (1995) and Marengo (1995)

[21] See Rumelt (1974). Numerous examples can be found in the electrical and chemical industries.

[22] See also the earlier pioneering work of Goold and Campbell (1987).

(Graham, 1986). And it will certainly require the capacity to reconfigure the composition and objectives of established divisions in the light of changing opportunities (Prahaled and Hamel, 1990).

Different balances between the administrative and the entrepreneurial functions are likely to be appropriate to different levels of technological opportunity. In addition, the appropriate degree of decentralization of the entrepreneurial function within the corporation will depend in part on the nature of the firm's core technology.[23] The higher the costs of product development, the greater the need for central control of the entrepreneurial function. In other words, the appropriate system of corporate control will depend in part on the nature of the technology.

Thus, Table 2 suggests that firms with low technological opportunity are likely to be compatible with an emphasis on the administrative rather than the entrepreneurial function, and with more centralization with increasing capital intensity. Firms with high technological opportunities and high costs of product and process development—such as those in drugs and automobiles—are likely to be best suited to a strong entrepreneurial function at the corporate level. Those with high technological opportunities, but low costs of product development—like those in consumer electronics and the 3M Corporation—will be best served by more decentralized entrepreneurial initiative.

Table 2 also shows that there can be mismatches between strategic style and the nature of technological opportunities. For example, tight financial control and emphasis on short-term profitability do not allow investments in exploring longer-term options emerging from new technological opportunities: this is one reason why GEC in the UK and ITT in the USA have progressively excluded themselves from many high-technology markets (*Economist*, 1995, 1996). Similarly, the characteristics of technology, and the corresponding organizational requirements, change over time. Thus, one reason for the recent deliberate demerger of ICI was the reduced technological opportunities in the previously fast-moving field of bulk chemicals (Owen and Harrison, 1995). Similarly, the high costs of mainframe computers in the 1960s and 1970s, and their specificity to the corporate office market, imposed centralized entrepreneurship. With the advent of the microprocessor and packaged software, the costs of experimentation tumbled and new markets emerged. Mainframe firms had great difficulty in adjusting in time to the requirements of greater decentralization.

[23] Marengo (1995) models learning, and comes to some intuitively appealing conclusions about the balance between organizational centralization and decentralization. But his learning is also about changes in the environment, rather than about internally generated changes.

TABLE 2. Technology and Corporate Control

| | | Strategic style | |
|---|---|---|---|
| | | Entrepreneurial | Administrative |
| Levels of decision-making | HQ | *High-tech opportunity + high costs of product development*<br>• drugs<br>• automobiles<br>• bulk chemicals in 1960s →<br>• mainframes in 1970s<br>↓ | *Low-tech opportunity + high cost of investments*<br>→ GEC (UK)<br>→ ITT (USA)<br>• aluminium<br>• steel |
| | Division | *High-tech opportunity + low costs of product development*<br>• consumer electronics<br>• 3M | *Low-tech opportunity + low cost of investments*<br>• conglomerates |

## 6. *Conclusions*

The main argument of this paper is that—as foreseen by Adam Smith—specialization in knowledge production is a central feature of the innovating firm. It is therefore of great importance to distinguish products (and other artefacts) from the underlying bodies of technological understanding on which they are based. Although the two evolve together, they do not have the same dynamics. Inadequate care in distinguishing the two can result in mistaken policy prescriptions (e.g. Granstrand *et al.*, 1997). And it can lead to too much emphasis in evolutionary theorizing on the economic benefits of technological diversity, on the frequency and causes of creative destruction, and on the nature and implications of changes in technological paradigms.

The main challenge is to improve understanding of the organizational processes of coordination and control that make for a successful matching between the development and deployment of bodies of technological knowledge, on the one hand, and commercially successful (or useful) working artefacts, on the other. We have stressed that our practical and theoretical knowledge of these organizational processes are less well grounded than our knowledge of the processes of technological advance *per se*. This why companies with outstanding technological competencies—Xerox and IBM in the early days of personal computers, for example—failed to develop organizational forms to exploit them. Nonetheless, large firms are capable of restructuring their activities to benefit from the new technological opportunities that they have mastered. 'Routines' can and do change. 'Creative destruction' is not inevitable.

The appropriate organizational processes will depend on the characteristics of the technologies, such as their sources, the rate and direction of their change, and the costs of developing and building artefacts based on them. And since technologies vary greatly in these characteristics, and they change over time, any improved knowledge that we acquire will be highly contingent. Nonetheless, the research of Woodward (1965) and Chandler (1977) on the organizational dimensions of changes in process technologies shows that such research can make a major difference to our understanding of innovation in firms. The following avenues of research appear to be particularly fruitful:

1. Bibliometric studies and surveys that map linkages between knowledge, products and organization in business firms over a range of sectors. This is essential given intersectoral variety. The great challenge is to develop measures of organization that are conceptually clear and empirically robust.
2. Detailed studies by historians and sociologists of the interactions between the development of the technological knowledge base, and the associated artefacts that emerge from them (e.g. Constant, 1998; Stankiewicz, 1998).
3. Case studies of the effects on firms, their organization and their products of the introduction of technological discontinuities, whether in the form of new sources of useful knowledge, or of order-of-magnitude improvements in the performance in one field. If then our analysis is correct, large firms in advanced countries will have few difficulties in mastering the new technology, resultant product discontinuities will happen only after a extended period of learning,[24] and failure is likely to result from 'core rigidities', namely resistance from established groups within the organization.

Finally, our analysis suggests that truths about the real innovating firm will never be elegant, simple or easy to replicate. It is nonetheless to be hoped that formal theorizing will try to incorporate more real-world features of the innovating firm. In particular, evolutionary economics grew out of dissatis-

[24] See Miyazaki (1995) for an account of the extended period that Japanese firms spent learning about opto-electronics. It might be argued that the personal computer began with a component innovation (the microprocessor) which, after a number of complementary component innovations (e.g. memories), and architectural innovations (internalizing the disk drive) and incremental improvements, created the conditions for the emergence of the revolutionary innovation that was the PC.

faction with mainstream formalizations of technical change. It would be a pity if it ended up going down the same path.

## Acknowledgements

The author has benefited greatly in the preparation of this paper from the comments of Stefano Brusoni, Mike Hobday, Patrick Llerena, Richard Nelson, Ed Steinmueller and two anonymous referees. The usual disclaimers apply.

## References

Abernathy, W. and K. Clark (1985), 'Innovation: Mapping the Winds of Creative Destruction,' *Research Policy*, 14, 3–22.

Aoki, M. (1986), 'Horizontal vs. Vertical Information Structure of the Firm,' *American Economic Review*, 76, 971–983.

Archibugi, D. (1988), 'In Search of a Useful Measure of Technological Innovation,' *Technological Forecasting and Social Change*, 34, 253–277.

Burns, T. and G. Stalker (1961), *The Management of Innovation*. Tavistock: London.

Chandler, A. D. (1977), *The Visible Hand: The Managerial Revolution in American Business*. Belknap Press: Cambridge, MA.

Chandler, A. (1991), 'The Functions of the HQ Unit in the Multibusiness Firm,' *Strategic Management Journal*, 12, 31–50.

Christensen, C. and R. Rosenbloom (1995), 'Explaining the Attacker's Advantage: Technological Paradigms, Organisational Dynamics, and the Value Network,' *Research Policy*, 24, 233–257.

Coase, R. (1937), 'The Nature of the Firm,' *Economica*, 4, 386–405.

Cohendet, P. and P. Llerena (1997), 'Learning, Technical Change and Public Policy: How to Create and Exploit Diversity,' in C. Edquist (ed.), *Systems of Innovation: Technologies, Institutions and Organisations*. Pinter: London.

Cohendet, P., P. Llerena and L. Marengo (1994),: 'Learning and Organizational Structure in Evolutionary Models of the Firm', EUNETIC Conference 'Evolutionary Economics of Technological Change: Assessment of Results and New Frontiers', Strasbourg.

Constant, E. (1998), 'Recursive Practice and the Evolution of Technological Knowledge,' in J. Ziman (ed.), *Technological Innovation as an Evolutionary Process*. Cambridge University Press: Cambridge (in press).

Cooper, A. and D. Schendel (1976), 'Strategic Responses to Technological Threats,' *Business Horizons*, February, 61–69.

Cooper, R. (1988),'The New Product Process: A Decision Guide for Management,' *Journal of Marketing Management*, 3, 238–255.

Coriat, B. and O. Weinstein (1995), *Les Nouvelles Theories de l'Entreprise*. Livre de Poche, Librarie Generale Française: Paris.

de Solla Price, D. (1984), 'The Science/Technology Relationship, the Craft of Experimental Science, and Policy for the Improvement of High Technology Innovation,' *Research Policy*, 13, 3–20.

Dosi, G. (1982), 'Technological Paradigms and Technological Trajectories: A Suggested Interpretation of the Determinants and Directions of Technical Change,' *Research Policy*, 11, 147–162.

Dosi, G. and L. Marengo (1993), 'Some Elements of and Evolutionary Theory of Organisational

Competencies', in R. W. England (ed.), *Evolutionary Concepts in Contemporary Economics*. University of Michigan Press: Ann Arbor, MI.

*Economist* (1995), 'The Death of the Geneen Machine', June 17, 86–92.

*Economist* (1996), 'Changing of the Guard', September 7, 72.

Freeman, C. and L. Soete (1997), *The Economics of Industrial Innovation*. Cassel-Pinter: London.

Gambardella, A. and S. Torrisi (1998), 'Does Technological Convergence Imply Convergence in Markets? Evidence from the Electronics Industry,' *Research Policy* (in press).

Godin, B. (1996), 'Research and the Practice of Publication in Industry,' *Research Policy*, 25, 587–606.

Goold, M. and A. Campbell (1987), *Strategies and Styles: The Role of the Centre in Managing Diversified Corporations*. Blackwell: Oxford.

Graham, M. (1986), 'Corporate Research and Development: The Latest Transformation,' in M. Horwitch (ed.), *Technology in the Modern Corporation: a Strategic Perspective*. Pergamon Press: New York.

Granstrand, O. (1982), *Technology, Management and Markets*. Pinter: London.

Granstrand, O. and C. Oskarsson (1994), 'Technology Diversification in "Multi-tech" Corporations,' *IEEE Transactions on Engineering Management*, 41, 355–364.

Granstrand, O. and S. Sjolander (1990), 'Managing Innovation in Multi-technology Corporations,' *Research Policy*, 19, 35–60.

Granstrand, O., P. Patel and K. Pavitt (1997), 'Multi-technology Corporations: Why they Have 'Distributed' rather than 'Distinctive Core' Competencies', *California Management Review*, 39, 8–25

Hamilton, W. (1986), 'Corporate Strategies for Managing Emerging Technologies', in M. Horwitch (ed.), *Technology in the Modern Corporation: A Strategic Perspective*. Pergamon Press: New York.

Henderson, R. and K. Clark (1990), 'Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms,' *Administrative Sciences Quarterly*, 35, 9–30.

Hicks, D. (1995), 'Published Papers (1995) Tacit Competencies and Corporate Management of the Public/Private Character of Knowledge,' *Industrial and Corporate Change*, 4, 401–424.

Hicks, D. and S. Katz (1997), *The Changing Shape of British Industrial Research*, STEEP Special Report no. 6, Science Policy Research Unit, University of Sussex.

Horwitch, M. (ed.) (1986) *Technology in the Modern Corporation: A Strategic Perspective*. Pergamon Press: New York.

Hounshell, D. and J. Smith (1988), *Science and Corporate Strategy: Du Pont R&D, 1902–1980*. Cambridge University Press: New York.

Iansiti, M. and K. Clark (1994), 'Integration and Dynamic Capability: Evidence from Product Development in Automobiles and Mainframe Computers,' *Industrial and Corporate Change*, 4, 557–605.

Jacobsson, S. and C. Oskarsson (1995), 'Educational Statistics as an Indicator of Technological Activity,' *Research Policy*, 24, 127–136.

Kay, N. (1979), *The Innovating Firm*. Macmillan: London.

Kuhn, T. (1962), *The Structure of Scientific Revolutions*. Chicago: University of Chicago Press.

Leonard-Barton, D. (1995), *Wellsprings of Knowledge*. Harvard Business School Press: Boston, MA.

Loasby, B. (1998), 'The Organisation of Capabilities,' *Journal of Economic Behaviour and Organisation* (in press).

Marengo, L. (1995), 'Structure, Competence and Learning in Organisations,' *Wirtschaftspolische Blatter*, 42, 454–464.

McKelvey, M. (1996), *Evolutionary Innovations: The Business of Biotechnology*. Oxford: Oxford University Press.

Metcalfe, S. and N. de Liso (1995), 'Innovation, Capabilities and Knowledge: The Epistemic Connection', in

J. de la Mottre and G. Paquet (eds), *Evolutionary Economics and the New International Political Economy*. Pinter: London.

Methe, D., A. Swaminathan and W. Mitchell (1996), 'The Underemphasized Role of Established Firms as Sources of Major Innovations,' *Industrial and Corporate Change*, 5, 1181–1203.

Mitchell, G. (1986), 'New Approaches for the Strategic Management of Technology,' in M. Horwitch (ed.), *Technology in the Modern Corporation: a Strategic Perspective*. Pergamon Press: New York.

Mitchell, G. and W. Hamilton (1988), 'Managing R&D as a Strategic Option,' *Research- Technology Management*, 31, 15–22.

Miyazaki, K. (1995), *Building Competencies in the Firm: Lessons from Japanese and European Optoelectronics*. Macmillan/St Martin's Press: New York.

Mowery, D. and N. Rosenberg (1989), *Technology and the Pursuit of Economic Growth*. Cambridge: Cambridge University Press.

Myers, S. (1984), 'Finance Theory and Financial Strategy,' *Interfaces*, 14, 126–137.

Narin, F. and D. Olivastro (1992), 'Status Report: Linkage between Technology and Science,' *Research Policy*, 21, 237–249.

Nelson, R. (1998), 'Different Perspectives on Technological Evolution,' in J. Ziman (ed.), *Technological Innovation as an Evolutionary Process*. Cambridge: Cambridge University Press (in press).

Nelson, R. R. and S. G. Winter (1977), 'In Search of a Useful Theory of Innovation,' *Research Policy*, 6, 36–76

Nelson, R. R. and S. G. Winter (1982), *An Evolutionary Theory of Economic Change*. Belknap Press: Cambridge, MA.

Oskarsson, C. (1993), *Technology Diversification—The Phenomenon, its Causes and Effects*. Department of Industrial Management and Economics, Chalmers University of Technology, Gothenburg.

Owen, G. and T. Harrison (1995), 'Why ICI Chose to Demerge,' *Harvard Business Review*, March–April, 133–142.

Patel, P. and K. Pavitt (1994), 'The Continuing, Widespread (and Neglected) Importance of Improvements in Mechanical Technologies,' *Research Policy*, 23, 533–546.

Patel, P. and K. Pavitt, (1997), 'The Technological Competencies of the World's Largest Firms: Complex and Path-dependent, but not Much Variety,' *Research Policy*, 26, 141–156

Penrose, E. (1959), *The Theory of the Growth of the Firm*. Blackwell: Oxford.

Plumpe, G. (1995), 'Innovation and the Structure of the IG Farben,' in F. Caron, P. Erker and W. Fischer (eds), *Innovations in the European Economy between the Wars*. De Gruyter, Berlin.

Prahalad, C. K. and G. Hamel (1990), 'The Core Competencies of the Corporation,' *Harvard Business Review*, May–June, 79–91.

Rosenberg, N. (1963), 'Technological Change in the Machine Tool Industry, 1840–1910,' *Journal of Economic History*, 23, 414–446.

Rosenberg, N. (1974), 'Science, Invention and Economic Growth,' *Economic Journal*, 84, 333.

Rothwell, R. (1977), 'The Characteristics of Successful Innovators and Technically Progressive Firms,' *R&D Management*, 7, 191–206.

Rumelt, R. (1974), *Strategy, Structure and Economic Performance*. Graduate School of Business Administration, Harvard University.

Scherer. F. (1982), 'Inter-industry Technology Flows in the US,' *Research Policy*, 11, 227–45

Smith, A. (1776), *The Wealth of Nations*. Dent (1910): London.

Stankiewicz, R. (1998), 'Technological Change as an Evolution of Design Spaces', in J. Ziman (ed.), *Technological Innovation as an Evolutionary Process*. Cambridge: Cambridge University Press (in press).

Steinberg, S. (1998), 'Schumpeter's Lesson: What Really Happened in Digital Technology in the Past Five Years,' *Wired*, January.

Teece, D. (1996), 'Firm Organisation, Industrial Structure and Technological Innovation,' *Journal of Economic Behaviour and Organisation*, 31, 193–224.

Teece, D. and G. Pisano (1994), 'The Dynamic Capabilities of Firms: An Introduction,' *Industrial and Corporate Change*, 3, 537–556.

Tidd, J., J. Bessant and K. Pavitt (1997), *Managing Innovation: Integrating Technological, Market and Organisational Change*. Wiley: Chichester.

von Tunzelmann, N. (1995), *Technology and Industrial Progress*. Elgar: Aldershot.

Tushman, M. and P. Anderson (1986), 'Technological Discontinuities and Organisational Environments,' *Administrative Science Quarterly*, 31, 439–465.

Wang, Q. (1997), 'R&D/Marketing Interface in a Firm's Capability-building Process: Evidence from Pharmaceutical Firms,' *International Journal of Innovation Management*, 1, 23–52.

Woodward, J. (1965), *Industrial Organisation: Theory and Practice*. Oxford: Oxford University Press.

Ziman, J. (1998), *Technological Innovation as an Evolutionary Process*. Cambridge: Cambridge University Press (in press).