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The Process of Innovation

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by

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SUMMARY

The paper argues that innovation processes can be cognitive, organisational and/or economic. They happen in conditions of uncertainty and (in the capitalist system) of competition. Three broad, overlapping sub-processes of innovation are identified: the production of knowledge; the transformation of knowledge into products, systems, processes and services; and the continuous matching of the latter to market needs and demands. The paper identifies key trends in each of these areas: (1) increasing specialisation in knowledge production; (2) increasing complexity in physical artefacts, and in the knowledge bases underpinning them; and (3) the difficulties of matching technological opportunities with market needs and organisational practices. Despite advances in scientific theory and information and communication technologies (ICTs), innovation processes remain unpredictable and difficult to manage. They also vary widely according to the firm's sector and size. Only two innovation processes remain generic: co-ordinating and integrating specialised knowledge, and learning in conditions of uncertainty. The paper also touches on the key challenges now facing 'innovation managers' within modern industrial corporations, bearing in mind the highly contingent nature of innovation.

1. INTRODUCTION

This paper concerns the processes (or more accurately 'processes') of innovation within (mainly) large corporations with headquarters located in the advanced industrialised countries.[1] The aim is to provide an interpretation of how innovation processes have evolved historically and the key challenges now facing 'innovation managers' within modern industrial corporations.[2] In so far as it is possible, the paper draws lessons from studies of innovation processes within and between firms, bearing in mind the highly contingent nature of innovation. It examines many of the different problems facing innovation mangers within the modern corporation and shows how these have been, and are being, reacted to.

The structure of the paper explains its logic and focus. Part 1 presents a short introduction to the many theories and empirical studies of innovation. This is used in Part 2 to generate a simple framework for disaggregating the many innovation activities which take place at the firm level. Three fairly broad, overlapping sub-processes (not stages) of innovation are identified: the production of knowledge; the transformation of knowledge into products, systems, processes and services; and the

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[1] The processes of innovation in small and medium sized enterprises (SMEs) differ considerably from those of large firms. Consequently, I focus mainly on large firms within the USA, Europe and Japan, many of which are international, if not global, in scope. However, the relationship between large corporations and SMEs (increasingly important with vertical disintegration) is dealt with in several places. For processes of innovation within SMEs, see Roberts (1991) and Oakey (1995). It should also be noted that the focus of the paper is on 'leading' and to some extent 'following' firms, rather than innovation processes within firms based in the industrializing countries (or 'latecomer firms') for the latter, see Hobday (1995) and Kim (1997). The relationship between innovation in entrepreneurship is another large subject outside of the scope of this paper (see Drucker, 1985, for an examination.)

[2] As I show below, the challenges of innovation pervades the firm throughout strategic and operational functions and therefore innovation 'managers' can be found at all levels of the firm, from the corporate directors faced with generating innovative business models, to the shop floor workers tasked with continually improving ongoing production processes (and every level in between). Hamel (2000) examines 'strategic innovation' (or innovation in strategy approach) while Schonberger (1982) and

continuous matching of the latter to market needs and demands.[3] Parts 3 to 5 examine key aspects of each of the three sub-processes in turn, showing how these have evolved historically and why they pose such difficult problems for innovation directors, managers and workers.

The paper argues that the three corporate innovation sub-processes present distinctive and difficult challenges to managers and practitioners alike. The paper identifies these management difficulties and points to some of the strategies firms have deployed to meet these challenges.

2. CORPORATE INNOVATION PROCESSES

There is no easy way to organise and write a chapter on "the process of innovation". To begin with, there is more than one process. At the level of the firm innovation processes can be categorized into three broad and overlapping sub-processes: (1) cognitive (how firms generate and maintain the know-how to conduct their tasks), (2) organisational (how firms 'do things' internally or together with other organisations) or (3) economic (how firms establish internal incentives to ensure innovation proceeds quickly and in the 'right' direction). Furthermore, innovation processes differ in many dimensions according to sector, field of knowledge, size of firm, corporate strategy and prior experience, type of innovation,

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Robinson (1991) deal with *kaizen* (or continuous improvements) to current vintages of capital equipment and organisation.

[3] I avoid the use of the term 'stages' as it implies linearity. Research has consistently shown that the processes of innovation within the firm are anything but linear. The three sub-processes of innovation, although distinctive, overlap considerably and often occur concurrently. Note that the term 'artefact' is used interchangeably with 'products, systems, processes and services'.

historical period and country. In other words, innovation processes – whether cognitive, organisational or economic - are ‘contingent’.[4]

There is also no widely accepted theory of firm level processes of innovation that satisfactorily integrates its economic, cognitive and organisational dimensions. Economists tend to concentrate on the economic incentives and the effects of innovation (whilst largely ignoring what happens in between), organisational specialists on the structural and procedural correlates of innovative activities and processes, sociologists on the social determinants and consequences, and managerial specialists on the practices most likely to lead to competitive success.

Important inputs of empirical evidence and theoretical understanding have come from historians of various sorts (of economics, business, science and technology), from bibliometric and other students of the quantifiable dimensions of innovation, and from a growing number of “innovation studies” with no allegiance to any particular theory or method. In sum, then, we have a rich and varied menu of studies and insights into innovative activities and processes. Some of these are listed in Table 1 below.

[4] For a review of models of innovation and the importance of contingency, see Mahdi (2002), Chapter 2.

Table 1: <u>Empirical Studies of Innovation</u>

Study name, date	***Key focus***	***Further reference***
Project SAPPHO	Success and failure factors in matched pairs of firms, mainly in chemicals and scientific instruments	Rothwell et al (1974)
Wealth from knowledge	Case studies of successful firms – all were winners of the Queen's Award for Innovation	Langrish (1972)
Post-innovation performance	Looked at these cases ten years later to see how they had fared	Georghiou (1986)
Project Hindsight ***TRACES***	Historical reviews of US government funded work within the defence industry. Main aims were to identify sources of successful innovation and management factors influencing success	Isenson (1968)
Industry and technical progress	Survey of UK firms to identify why some were apparently more innovative than others in the same sector, size range, etc. Derived a list of managerial factors which comprised 'technical progressiveness'	Carter and Williams (1957)
Minnesota studies	Detailed case studies over an extended period of 14 innovations. Derived a 'road map' of the innovation process and the factors influencing it at various stages	Van de Ven et al (1989)
Project NEWPROD	Long-running survey of success and failure in product development	Cooper (1994) Cooper and Kleinschmidt (1990); Cooper (1999)
Stanford Innovation Project	Case studies of (mainly product) innovations, emphasis on learning	Maidique and Zirger (1985)
Lilien and Yoon	Literature review of major studies of innovation success/failure	Lilien and Yoon (1989)
Rothwell	25-year retrospective review of studies and models of innovation processes	Rothwell (1992)
MIT studies	5 major industry-level cases	Utterback (1994)
Revolutionising product development	Case studies of NPD practices	Wheelright and Clark (1992)
Winning by design	Case studies of product design and innovation	Walsh (1992)
Innovation audit framework	Review of studies to generate an innovation audit	Chiesa et al (1996)

Table 1: Empirical Studies of Innovation (Cont'd)

Radical innovation project (Rensselaer Polytechnic)	How innovation can be used to 'rejuvenate' mature businesses and the use of innovation to create advantage (US studies)	Leifer et al (2000)
Rejuvenating the mature business	As above (European Studies)	Baden-Fuller and Stopford (1994) Baden-Fuller and Pitt (1996)
Innovation and market creation	*How firms create new industries and markets through innovation*	Hamel and Prahalad (1994)
Innovation in business models	*How firms develop innovative 'business models' to change the competitive rules of an industry*	Hamel (2000)

Source: Tidd, Bessant and Pavitt (2001), Ch 2 (Amended).

The authors of the first project listed in Table 1 (Project SAPPHO) made a rather extensive survey of the previous literature in innovation. They found that the vast majority of several hundred earlier studies were in the nature of personal memoirs and anecdotes of the exploits of individual scientists, inventors or managers and contained little or no systematic comparison or analysis. It was probably for this reason that Schumpeter, who concentrated more effort on the study of innovation than any other economist in the first half of the twentieth century had so few references to earlier work. It probably also was one of the contributing factors to his bias in favour of explanations based on the character and determination of outstanding individuals, and his definition of innovations as "Acts of Will" rather than "Acts of Intellect". This chapter and this entire book may be biased in the opposite direction, over-estimating 'cognitive' aspects of innovation.

Most of the studies listed in Table 1, starting with Project SAPPHO itself were attempts to overcome the "individualist" bias of personal memoirs by examining a much wider set of organisational factors and looking at the skills and experience of a wider range of individuals participating in each innovation. SAPPHO was also one of the first studies to use systematic statistical techniques in the comparison of numerous cases of "success" and "failure", thus identifying the characteristic patterns of successful and unsuccessful attempts to innovate.

Many of the studies listed in Table 1 followed in this tradition but of course individual case studies continued to be important for many reasons, including inter-country and inter-sectoral differences, testing of hypotheses and depth of investigation.[5]

3. THE FRAMEWORK

On this rich but potentially confusing mosaic of knowledge about innovation processes, I shall impose a general pattern that I hope does not transgress any major findings about it so far.

1. Innovation processes involve the exploration and exploitation of opportunities for a new or improved product, process or service, based either on an advance in technical practice ("know-how"), or a change in market demand, or a combination of the two. It is therefore essentially a matching process. The classic paper on this subject is by Mowery and Rosenberg (1979).
2. Second, innovation is inherently uncertain, given the impossibility of predicting accurately the cost and performance of a new artefact, and the reaction of users to it. It

therefore inevitably involves processes of learning through either experimentation (trial and error) or improved understanding (theory). Some (but not all) of this learning is firm specific. In these circumstances, the processes of competition in capitalist markets can be seen as one of purposive experimentation through competition for user acceptance between alternative products, systems, processes and services and the technical and organisational processes that deliver them.

Within this general framework, this writer has been unable to find a simple or elegant theoretical framework that encompasses the richness of the findings on innovation processes.[6] However, in organising this material, it has proved useful to divide innovation into three, partially overlapping processes, consistent with the two features described above.[7] Each is more closely associated with contributions from particular academic disciplines and each derives from major historical transformations of the process of innovation.

- *The production of scientific and technological knowledge*: since the industrial revolution, the production of scientific and technological knowledge has been *increasingly specialised*, by discipline, by function and by institution. Here, history and social studies of science, technology and business have been the major academic fields contributing to our understanding.
- *The transformation of knowledge into working artefacts*: in spite of the explosive growth in scientific knowledge in recent years, theory remains an insufficient guide to

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[5] Also note that the Table is by no means exhaustive. For example, see Hobday, Rush and Tidd (2000) for a collection of papers on how the nature, value and complexity of a product shapes the processes of innovation.

[6] For critical assessments of firm level models of innovation, ranging from the linear model to chain link models and more recent interactive/contingent models, see Rothwell (1991), Forest (1991) and Mahdi (2002).

[7] As noted earlier, I explicitly avoid the term 'stages' or 'phases' as this imposes an unrealistic linearity on the various innovation processes. In fact, most innovation processes are overlapping and intertwined.

technological practice, given the *growing complexity* of technological artefacts, and of their links to various fields of knowledge. Technological and business history has made major contributions here and, more recently, so too have the cognitive sciences.

- *Responding to and creating market demand:* this involves a continual process of matching working artefacts with users' requirements. The nature and extent of the opportunities to transform technological knowledge into useful artefacts vary amongst fields and over time, and determine in part the nature of products, users and methods of production. In the competitive capitalist system, corporate technological and organisational practices therefore *co-evolve with markets*. These processes are central concerns of scholars in management, economics and marketing studies.

We shall now discuss the implications of how each of these features of innovation processes has evolved through time presenting considerable challenges to the modern innovation manager and the corporation as a whole.

4. THE PRODUCTION OF SCIENTIFIC AND TECHNOLOGICAL KNOWLEDGE

Adam Smith's identification of the benefits of specialisation in the production of knowledge has been amply confirmed by experience[8]. Today, co-ordinating increasing specialisation remains a fundamental task of the large corporation. Professional education, the establishment of laboratories, and improvements in techniques of

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[8] "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*

measurement and experimentation have increased the efficiency of discovery, invention and innovation. Increasingly difficult problems can be tackled and solved[9]. New and useful fields of knowledge have been developed, punctuated by the periodic emergence of fields with rapid rates of technological advance and rich opportunities for commercial exploitation: metal cutting and forming, power sources, physics, chemistry and biology, and a variety of related engineering disciplines.

Three further forms of corporate specialisation have happened in parallel: first, the development in large manufacturing firms of R&D laboratories specialised in the production of knowledge for commercial exploitation; second, the development of a myriad of small firms providing continuous improvements in specialised producers' goods; third, specialisation between private knowledge developed and applied in business firms, and public knowledge developed and disseminated by universities and similar institutions. Taken together, all these forms of specialisation have combined to make a heterogeneous and path-dependent pattern of technical change, and to require complex processes of co-ordination. As I show below, these processes of change have intensified and broadened the challenges facing managers, 'intrapreneurs', and entire corporations.[10]

4.1 Functional Specialisation & Integration: Industrial R&D Laboratories

One major source of innovation in the twentieth century was – and still is – the industrial R&D laboratory. It emerged first in Germany in the chemical industry and in the USA in

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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, 1937, p.8, my italics; original 1776)).

9 The classic texts on this are Rosenberg (1974), Price (1984) and Mowery and Rosenberg (1989).

10 See Pinchot III (1997) for a discussion of the intrapreneur, that is, an innovator operating within a large corporations.

the electrical industry for two reasons: first, as part of the more general process of functional specialisation of the large manufacturing firm (Mowery, 1995), which itself emerged from the exploitation of economies of scale and speed made possible by radical innovations in materials processing and forming, and in power sources (Chandler, 1977); second, as a means of exploiting effectively the rich veins of useful knowledge emerging from fundamental advance in chemistry and physics.

Mowery (1995) has shown for the USA that a growing proportion of industrial R&D in the twentieth century was integrated within large manufacturing firms, rather than in independent companies. Until about 10 years ago, business-funded R&D in all OECD countries was almost exclusively performed within manufacturing firms. Mowery explained this lack of vertical disintegration by the difficulties of writing contracts for an activity whose output is uncertain and idiosyncratic. Today, this writer would place greater emphasis on the advantages of integration. Thus competitive advantage can be gained by the effective combination of specialised and often tacit knowledge across functional boundaries, within the individual firm, stressing the importance of accumulated firm-specific experience.

In any event, a very robust conclusion emerging from research on innovation processes is that one of the most important factors differentiating successful from unsuccessful innovation has been the degree of collaboration and feedback between product design and other corporate functions, especially manufacturing and marketing (Rothwell, 1991). In addition, there are many stories of product designs that turned out to be technically difficult (even impossible) to manufacture, and/or do take into account often elementary users' requirements (Forrest, 1991)

From a corporate strategy perspective, this trend highlights the importance of cross functional integration spanning departmental boundaries. The 'heavyweight' project manager has emerged, empowered to control resources across the firm, reporting directly to the senior management team at the same level as the departmental manager (Clark and Fujimoto, 1992). These project managers can link directly into innovation processes within customers and key suppliers, enabling fast, project-based innovation. This tendency has sometimes led to tensions with functional bosses, some of whom are unwilling to 'give up' control over their resources and object to project-led management. The professional project manager now receives formal training, sponsored by various project management associations, on how to manage fast moving project teams tasked with integrating research outputs, conceptual and detailed design, and various engineering functions, while at the same time and responding to changing or emerging customer requirements during the production process.

Many writers stress the importance of personal contacts and exchanges across functions to deal with tacit elements of both product design and its successful transfer to manufacture and market. Some point to different practice amongst countries. Others stress the importance of largely informal processes that ensure effective feedback. However, there is no perfect or foolproof process for ensuring effective co-ordination. Indeed, so-called "best practice" can be positively harmful when its application is taken too far. As Leonard-Barton (1995) has pointed out, the excessive use of heavyweight project managers with considerable power and autonomy to develop a product can lead to the loss of benefits from integration, including economies of scale and reduced costs in using common components in automobile development. And what to do with a heavyweight product manager (and the associated staff) when a product development is failing? The experience of many countries that established agencies to develop nuclear power suggests that they are often difficult to stop, leading to the problem of 'escalation' (or the never-ending project failure)[11]. Managing the trade-offs between project and functional management and overcoming the inherent difficulties in project-based management is a major difficulty for senior technology managers.

4.2 Technological Convergence & Vertical Disintegration in Production Techniques

However, even in industries with heavy investments in product innovation, some 'vertical disintegration' (defined as the outsourcing of specific activities to supplier firms) in manufacturing process innovation has been happening since the nineteenth century, stimulated at each stage by technological advances. Thus, Rosenberg (1976) has shown how specialised machine tool firms emerged in the nineteenth century, because advances in metal cutting and metal forming techniques led to technological 'convergence' (i.e. in operations that were common to a number of manufacturing processes). For example, boring accurate circular holes in metal was common to the making of both small arms and sewing machines. Although the skills associated with such machining operations were often craft-based and tacit, their output could be

[11] For a discussion of escalation using examples from the UK stock exchange and other major ICT project failures, see Flowers (1996).

codified and standardised. The size of the market for such common operations therefore often became large enough to sustain the growth of small and specialised firms designing and making the machines to perform them. Large manufacturing customers could therefore buy machines incorporating the latest improvements fed back from many users, and therefore superior to what they could do by themselves. In contemporary terms, designing and making such machines no longer gave large manufacturing firms a distinctive competitive advantage.

Table 2 Examples of Technological Convergence & Vertical Disintegration

UNDERLYING TECHNOLOGICAL ADVANCE	TECHNOLOGICAL CONVERGENCE	VERTICAL DISINTEGRATION
Metal cutting & forming	Production operations	Machine Tool Makers
Chemistry & metallurgy	Materials analysis & testing	Contract Research
Chemical engineering	Process control	Instruments Makers Plant Contractors
Computing	Design Repeat operations	CAD Makers Robot Makers
New Materials	Building Prototypes	Rapid Prototyping Firms
ICT	Application software Production systems	KIBS* Contract manufacture

* = Knowledge-Intensive Business Services

As Table 2 above shows, similar processes involving technological convergence and vertical disintegration have been frequent since then. New opportunities for technological convergence and vertical disintegration have emerged from breakthroughs that have created potentially pervasive applications across product groups: material shaping and forming, properties of materials, common stages of continuous processes, storage and manipulation of information for controlling various business functions such as manufacturing operations and design.

As Lundvall (1988) and other writers have shown, the links between the often small firms providing these specialised production inputs and their mainly large customers are often “relational” rather than arms-length, with exchanges between them of information and personnel related to the development, operation and improvement of the specialised inputs. Managing the outsourcing of these critical inputs has become a major challenge to managers of large firms (Quinn, 2000). At a relatively simple technical level, logistics and IT systems often differ between component suppliers and integrator companies. More fundamentally, the choice of which activities to outsource and which to retain in-house goes to the heart of the ‘core competence’ of the modern corporation, defining and redefining the boundaries of the firm (Hamel and Prahalad, 1994; Davies et al, 2001).

4.3 Industrial Linkages with Universities

As innovative activities in business firms have become more professionalised, and university research more specialised, universities have in some sectors come increasingly to provide the trained researchers for firms to perform their innovative activities. At the same time, firms have found it important to have effective processes in order to benefit from progress in the longer-term research programmes in universities in fields with possible impacts of their current and future activities. The range of interactions between firms and universities is considerable. At one extreme, there is the so-called (but relatively rare) “linear model”, where fundamental research by a university scientist leads to a discovery, the practical importance of which is recognised by a business firm, which collaborates with the university scientist in order to exploit it. This happens most often in science-based industries including the chemical, bio-technology and pharmaceutical sectors, where the focus is on the discovery of interesting and useful synthetic molecules. One famous example involves, Nylon, Carrothers and the Dupont Company (Hounshell and Smith, 1988).

At the other extreme, the provision of trained researchers, familiar with the latest research techniques and integrated in international research networks, is ranked by many industrialists as the greatest benefit to them provided by universities (Martin and Salter, 1996). Thus, even if university research in mechanical engineering has fewer direct applications than in chemistry, it still provides some of the mechanical engineers trained (for example) in the simulation and modelling techniques that are increasingly important in the design and development of automobiles and aero-engines.

In between, there are a variety of other – often complementary – processes which have to be managed in order to link university research with industrial innovation, including direct industrial funding of university research, university-based consultants, and exchanges of research personnel. Three common features of university-firm links emerge from studies so far:

1. The importance of personal and often informal contacts – thus industrial publications in the scientific literature can be seen as signals to the wider academic community of fields and problems of industrial interest that would benefit from more intense personal exchanges (Hicks, 1995).
2. US-based studies by Mansfield (1995) and Narin et al (1997) suggest that useful (to industrialists) university research is also good (to academics) research. A high

proportion is publicly funded, performed in the academically prestigious research universities and published in high quality academic journals.

3. The practical benefits of most university research emerges from processes that are roundabout and indirect, involving combinations including new theoretical insights, new techniques and observations, and new skills of a kind that industrial firms find difficult to provide themselves.

However, the past 20 years have seen changes in the practical benefits that are expected from universities, and also in what they actually provide. Governments have begun to expect greater direct usefulness, often without a full understanding of the indirect benefits appreciated by industrialists, but with the support of some empirically questionable theories[12]. For entirely different reasons, certain fields of university research – principally biotechnology and software - have begun to provide an increasing stream of potentially useful inventions, reflected in increases in university licensing income, and in university-founded spin-off firms. For the first time, private financial capital has become involved on a large scale in the funding and exploitation of university research. In chapter 8, Mowery unravels the nature and implications of these recent developments.

These university-industry relationships can be extremely difficult to manage at the level of the firm. Managers often complain that universities operate on extended 'time lines' and have little regard for the urgent deadlines of business. Therefore, they argue, universities should not be placed on the critical path of any important

[12] Specifically, (1) the output of university research is a free good available to everybody (orthodox economics); (2) the locus of useful scientific discovery is moving from universities to "contexts of application" (Gibbons et al, 1994); (3) publicly funded university research is a form of conspicuous intellectual consumption reflecting technological and economic achievements, but not contributing to them (Kealey, 1996).

projects. Universities, in turn, sometimes find themselves in the invidious positions of being viewed as a low cost resource for firms to exploit, a position encouraged by some governments and some research council programmes of "technology transfer" which focus on the short term S&T needs of industry, rather than the long term quality of university basic research, the supply of graduates and the experimentation and critical questioning which should go on in universities (Salter et al, 2000). It is worth pointing out that underlying these technology transfer programmes is often the much discredited linear model of innovation, which begins with science/basic research, which is then followed by engineering, manufacturing and marketing. Worse still, the underlying model is a "public sector", linear model, where universities (and other public sector organisations) are seen as generating innovations "for" industry[13].

4.4 Heterogeneity in Innovation Processes

We can now begin to discern the major features that make innovation processes heterogeneous. The dominant sources of technical change in the twentieth century were – and still are - large manufacturing firms with in-house R&D laboratories, based on the exploitation of different fields of specialised knowledge, combined with a myriad of small firms providing specialised producer goods. The mix of firms and technologies has changed over the period reflecting the differential rates of growth of innovative opportunities generated by the different rates of growth of specialised knowledge.

[13] For critiques of the linear model based on evidence and for alternative more realistic models which place private enterprise at the heart of the innovation process, see Mahdi (2002) and Forrest (1991).

Nonetheless, the broad pattern has remained, and has major implications for what we can say about innovation processes.

- Given the increasingly specialised and professionalised nature of the knowledge on which they are based, manufacturing firms are *path-dependent*. Where they search for the future is heavily conditioned by what they have learned to do in the past. As we shall see in section 6.3, part of this path-dependence reflects the conservatism of professional and functional groups. But a large part results from cognitive limits. For example, it is difficult, if not impossible, to convert a traditional textile firm into one making and selling semiconductors. More realistically, the recent experience of *Vivendi* suggests it may also be difficult to transform a national water company into an international ICT and media giant.
- Firms with specialisations in different products and related technological fields are likely to stress *different features* of innovation processes, given the nature of the fields on which they depend. Thus, for automobile firms, effective feedback between product design and manufacture is more important than feedback between product design and university research. For a pharmaceutical firm, the reverse is likely to be the case, given the greater direct usefulness of university research and the lesser complexity of manufacture. Similarly, users are likely to be an important source of innovations for small innovating firms, who are primarily producing producers' goods. For large firms who are selling to users without strong technological capabilities, this will not be the case.
- Innovation processes will *differ greatly between large and small firms*. Innovations in large firms involve a larger number of people in more specialised functions, with shifting responsibilities over time. They are also more likely to involve recognisable

procedures, whether formal or informal. In small firms, by contrast, decisions related to the recognition of opportunities, the allocation of resources, and the co-ordination of functional activities are more likely to reflect the competencies and behaviour of senior managers.

5. TRANSFORMATION OF KNOWLEDGE INTO WORKING ARTEFACTS

In spite of the spectacular increases in scientific knowledge over the past 200 years, theory remains an insufficient guide to technological practice partly because of the increasing complexity of physical artefacts and the knowledge bases that underpin them. This is reflected in the continuing dominance in industrial R&D laboratories of *development* activities - the design, building and testing of specific artefacts – compared to *research* in fields on which they are based. According to Constant (2000), technology advances through the recursive practices of scientists and engineers, involving "alternate phases of selection and of corroboration by use. … The result is strongly corroborated foundational knowledge: knowledge that is implicated in an immense number and variety of designs embodied in an even larger population of devices, artefacts, and practices, that is used recursively to produce new knowledge." (p. 221)

For corporate managers, the heterogeneity and contingent nature of innovation means that there can be no simple ‘best practice’ innovation model for firms or managers to follow. Each firm must proceed on the basis of its prior experience and the technological trajectories evident in the specific industry or product group. However, this is not to suggest that innovation strategy does not matter or that good management cannot make a difference to the performance of firms in terms of productivity, market share or profitability. On the contrary, while prescribed best practice models of innovation may be misleading, by consciously reflecting upon and questioning the firm's innovation approach, it may be possible to improve the efficiency of current operations, to generate new products and service markets more quickly, and ultimately to build a distinctive 'business model' capable of changing the rules of the competitive game (Hamel, 2000).

Scientific advances enable artefacts of increasing complexity, embodying both an increasing number of subsystems and components, and a broadening range of fields of specialised knowledge. This increasing system complexity is one consequence of the growing specialisation in knowledge production and has resulted in both better understanding of cause-effects relations, and better and cheaper methods of experimentation. This has reduced the costs of technological search, and thereby enabled greater complexity in terms of the number of components, parts or molecules that can be successfully embodied in a new product or service. Developments within ICT itself are accelerating this trend: digitalisation opens options for more complex systems, and simulation techniques reduce the costs of experimentation (Pavitt & Steinmueller, 2001).

Managers involved in transforming S&T knowledge into products, systems and services need, in particular, to be aware of specific trends in their industries in: (a) technology trajectories and scientific theories; (b) (in some cases) government-funded R&D programmes; (c) systems integration: and (d) techniques and approaches to managing uncertainty. I deal with each of these issues, in turn, below.

5.1 Keeping Technological Practice (not too far) Ahead of Scientific Theory

Continuous innovation requires constant improvements in methods of technological search. Technical complexity cannot run too far ahead of scientific understanding[14]. The feedback loops in both directions between improvements in scientific understanding and improvements in technical performance have been well documented by historians and others in areas such as aerodynamics and thermodynamics[15].

Advances in the technologies of measurement and manipulation of the increasingly small are a major source of improvements in technological search. This has been the case in the past few decades in molecular biology and materials, both of which have opened major new opportunities for technical change[16]. A second factor reducing the costs of search and selection has emerged from ICT. Major advances in large-scale computing and simulation technology are reducing considerably the costs of exploring alternative technical configurations, as well as opening challenging opportunities for increasingly complex systems made possible through digitalisation (Pavitt and Steinmueller, 2001). Innovation managers and engineers at the coal face of transforming knowledge into working artefacts today need to be acutely aware of specialised ICT trends in their own industries, as well as new measurement and manipulation techniques, where are themselves frequently underpinned by the application of advanced ICTs. Nightingale (2000) has shown that experimental techniques in the pharmaceutical industry have in the past ten years seen major

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[14] For example, without any theory and any cheap methods for constructing and testing prototypes, the costs of search and selection become prohibitively high. See Martin (2000) on why Japanese swords did not improve over a period of more than 500 years.

[15] See, for example, Rosenberg and Nelson (1994) on the origins of the engineering disciplines in US universities.

changes resulting from the mechanisms described above: first, a shift towards more fundamental science, for example, linking biochemical mechanisms to the expression of genes; second, using simulations and data banks to conduct virtual experiments complementary to real ones; third, using high throughput screening techniques[17]. Mahdi (2002) has recently developed a taxonomy of eight methods of technological search, which depend on three factors: (1) the degree to which technological problems can be decomposed into simpler sub-tasks; (2) the degree of understanding of cause-effect relations; and (3) the costs of experimentation with possible solutions.

5.2 Government-Funded Programmes

Since the 1980s, with the proliferation of government programmes for 'pre-competitive' R&D in Europe (e.g. ESPRIT and Eureka), the USA (e.g. Sematech) and Japan (e.g. the 5G ICOT Programme), most major firms are presented with opportunities for participation in collaborative government-sponsored programmes for R&D. Firms need to treat these programmes with caution and they require methods for evaluating their potential contribution to corporate goals, the financial and organisational costs of participating, the risks involved in not participating, and the ways in which government programmes can complement or fit into the overall corporate strategy. A wide array of management tools are now available to assist managers in assessing (or at least systematically 'thinking about') pre-project assessment, 'strategic fit' of the programmes, high and low priorities, and post project

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[16] A similar conclusion has been reached by Becker and Murphy (1992). They argue that the degree of specialisation in tasks is limited not by the extent of the market, but by the costs of co-ordinating specialised activities. These co-ordination costs are reduced by increases in general knowledge.

[17] In addition, some prestigious academic institutions, such as Stanford University in the USA, and the *Ecole des Mines* in Paris, are developing research programmes in "bio-informatics", responding to the challenges of the complex results of the Human Genome project.

evaluation. Most large consulting firms provide service lines to support companies unsure as to the costs, benefits, and risks of these programmes (Floyd, 1997).

It is worth mentioning that technological activities directly financed by governments have sometimes been of major importance in opening and exploiting innovative opportunities, but there are also many disappointments. Successes include ICT in the USA, where military-related programmes played a major role in the early development of computers, semiconductors , software and the Internet. Military programmes have also had important technological spin-offs into civil aviation in the USA, while governments in Japan and France have successfully supported the development of high-speed trains. On the other hand, policies to support the development of civilian nuclear power have on the whole not been successful. Nor have those for the support of high-rise industrial building. More recently, policies to encourage the development of renewable energy technologies have met with mixed success.

It is difficult to generalise from these experiences. All have involved technical lobbies successfully putting pressure on governments for financial support, often in fields related closely to military applications, or (often large-scale) infrastructure, such as transport, energy, housing and communications. This process can lead to neglect of commercial constraints and to premature commitments to particular designs. Economists more generally would point to the opportunity costs of these programmes. But government support can also speed up critical technological learning at a time when purely private markets are not ready to take the risks. The early development of ICT in the USA suggests the importance of diversity and experimentation in government support for technological progress. But would this have worked for the development of high-speed trains, where the costs of experiments are much higher and technical change is more incremental? And, as we shall see in the next section, everyone makes mistaken assumptions about future developments in a complex and fast-changing world.

5.3 Multi-Technology Firms, Modularization and Systems Integration

In addition to increasingly complex artefacts, specialisation in knowledge production has increased the range of fields of knowledge that contribute to the design of each product. Compare what originally was the largely mechanical loom, with the many fields of specialised knowledge – electrical, aerodynamic, software, materials – that are now embodied in the contemporary design; or observe the contemporary automobile that must increasingly integrate plastic and other new materials, as well as electronic and software control systems.

Firms designing these increasingly complex products have found it more difficult to master advances all the fields embodied in them. Hence the growing importance of modular product architectures, where component interfaces are standardised, and interdependencies amongst components are decoupled. This enables the outsourcing of design and production of components and subsystems, within the constraints of overall product (or system) architecture.

Opportunities have also emerged for further vertical disintegration between product design and manufacture, based on further technological convergence. Sturgeon (1999), for example, has documented the rise of contract manufacturing in electronics. He shows that specialised firms take over product design from other firms, and then do the detailed engineering and manufacture. This technological convergence is based on increasing automation of routine operations (e.g. component insertion), and on the increasing use of standard software tools. He reports that contract manufacturing is also growing in other industries[18], and stresses the importance of the development of the modular production network, where distinct breaks in the value chain tend to form at points where information regarding product specifications can be highly formal. This occurs within functionally specialized value chain nodes, where activities tend to be highly integrated and based on tacit linkages. Between these nodes, linkages are achieved by the transfer of codified information.

At first sight, these recent changes might appear to point to a neatly specialised system for the production of innovations, with product and systems designers, their sub-contractors for components and subsystems, and their manufacturers, working together through arm's-length market relations, as foreseen by Sturgeon (1999). However, such a conclusion neglects the consequences of important distinctions that need to be made between the properties of artefacts, the knowledge on which they are based, and the degree to which such knowledge can be transformed into codified information (Granstrand et al, 1997).

Briefly stated, the development and production of increasingly complex artefacts are based on the integration of an increasing number of fields of specialised knowledge, that cannot be reduced completely to codified information, and that advance at different speeds. As I have argued elsewhere with Brusoni and Prencipe (Brusoni et al, 2001), this

[18] He lists apparel and footwear, toys, data processing, offshore oil drilling, home furnishings and lighting, semiconductor fabrication, food processing, automotive parts, brewing, enterprise networking

means that the division of labour between companies in production is not mirrored by an equivalent division of labour in knowledge. Some overlap between companies in knowledge competencies is necessary to deal with the transfer of tacit knowledge, with unforeseen consequences of systemic complexity, and with imbalances between components resulting from uneven rates of technical change between them. Similarly, arms-length relations between firms will not be as effective as forms of "loose coupling" with periodic bouts of integration, when systems architectures and the tasks of component suppliers are redefined by firms specialising increasingly in systems design and integration.

5.4 "Managing" Innovation Uncertainty?

Specialised R&D and related activities in business firms have certainly become an institutionalised and predictable source of discoveries, inventions, innovations and improvements. However, the process of innovation is complex, since it involves many variables, the technical properties and interactions (and economic usefulness) of which are understood only very imperfectly. As a consequence, firms are not able to explain fully and predict accurately either the technical performance of major innovations, or their acceptability to potential users (or in some cases even who the potential users are). Business firms remain incapable of predicting accurately the technical and commercial outcomes of their own (and others') innovative activities: on average, research scientists and engineers tend to be over-optimistic about the costs, benefits and time periods of their proposed projects, but the variance of the ratio of *ex post* outcomes to *ex ante* estimates in any specific corporate portfolio of projects tends to be large (Freeman, 1982; Mansfield, 1995). As a

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and pharmaceuticals. In addition, Prencipe (1997) has shown increases in the outsourcing of production of aircraft engine components.

consequence, high proportions of corporate R&D and corporate patenting activity are associated with commercially failed projects (Griliches, 1990).

In addition, business firms (and others) are incapable of defining fully the possible futures that might emerge as a consequence of innovations, especially radical ones. Examples of inaccurate predictions about what turned out later to be spectacularly successful technologies and innovations are legion. Rosenberg (1994) has pointed out that, in the nineteenth century, the Western Union turned down Bell's patent for the telephone, which it perceived as an inferior product to the telegraph. In the early twentieth century, the pioneers of radio communication conceived it as a system of point-to-point communications, particularly between naval vessels; it was only much later that the much larger market for mass radio communications was recognised. After World War II, the owner of IBM foresaw a world market for computers in single figures. For the more recent period between the 1960s and the 1980s, Schnaars and Berenson (1986) concluded that only about half the major new product families announced in the USA turned out to be commercially successful. And we have the recent experience of inaccurate forecasts of the potential markets for various generations of the mobile phone.

Corporate management therefore continues to have difficulties in deciding how to deal with innovative activities, which have some of the elements of conventional investments activities, but which are also uncertain and therefore require continuous feed-back from the market, past experience and experimentation. In practice, top-down corporate visions can be a poor guide to innovation strategies. In the academic and business literatures, the failures of such visions are easily forgotten and the successes oversimplified. For example, as told by Prahalad and Hamel (1990), the story of Canon's successful diversification from optics and precision mechanics into electronics technology, and from cameras into photocopying and computer peripheral products, do not touch on Canon's failed diversification into recording products and electronic calculators (Sandoz, 1997). And Ericsson's success in opening up mobile telephony began with initiatives from middle-level technical management, rather than from the top.

The broad differences between search and selection activities have been recognised for a long time in practice with the distinction between corporate and divisional R&D activities, and in theory with the distinction between "knowledge building" and "strategic positioning" on the one hand, and "business investment " on the other (Mitchell and Hamilton, 1988). However, as the recent history of corporate R&D shows, maintaining balance and linkages between the two is not an easy task. Briefly stated, there is no one best way of evaluating the costs and benefits of corporate R&D expenditures *ex ante*. Rule-based systems fail because they inevitably simplify, and may therefore neglect what turn out to be important factors in a complex system. Judgement-based systems fail because of the impossibility of quickly distinguishing good judgement from good luck. As a consequence, there are periodic swings in fashions and management practices, very often reflecting struggles for influence between financially trained managers who tend to prefer rule-based systems, and those who are technically trained and prefer to rely on technical judgements.

6. MATCHING OF ARTEFACTS, ORGANISATIONAL PRACTICES AND MARKET DEMAND

The matching of products, processes, systems and services (and organisational practices) with market demand and potential demand is a major and continuous innovation function of the successful corporation. In carrying out this function, the corporation builds on its accumulated knowledge of product and process technologies, of organisational practices, and of users' needs. The most important processes that have to be managed are those of responding to and creating market needs and demands, and matching organisational practices with technological opportunities. This involves dealing with disruptive change, and with one of the negative consequences of specialisation, namely the potential for tribal warfare over the old and the new between specialised functions and disciplines within the firm.

6.1 Matching Technology and Organisational Practices with Market Needs

It is commonplace today to argue that technologies and organisational practices co-evolve with market demands (or should). It is less common to expose oneself to accusations of "technological determinism" by arguing that, on the whole, corporate organisational practices adapt, in order to exploit emerging market needs and technological opportunities. On historical grounds, Chandler (1977) has shown that the rise in the USA at the end of the nineteenth century of the large, multi-unit firm, and of the co-ordinating function of professional middle managers, depended critically on the development of the railroads, coal, the telegraph and continuous flow production. Similarly, the later development of the multi-divisional firm in part reflected the major opportunities for product diversification in the chemical industry opened up by breakthroughs in synthetic organic chemistry.

Technical advances normally precede organisational and market advances, because of their firmer knowledge base and the lower costs of experimentation. This does not mean that technology imposes one organisational "best way" or even a clear strategy towards the marketplace. Variety in the characteristics of technologies, their continuous change and uncertain applications lead also to variety and experimentation in organisational and marketing practices. But it also does not mean that "anything goes" in either organisational or marketing terms. For example, a firm practising conventional cost-benefit analysis and strict cost controls with all its investment decisions will not prosper in the long term in a competitive market governed by the exploitation of a rich, varied and rapidly advancing body of technological knowledge[19].

Based on the empirical literature, the first two columns in Table 3 below identify the key features of technologies that must be matched with corporate organisational and marketing practices.

- External linkages with potential customers, and with the important sources of knowledge and skills.
- Internal linkages in the key functional interfaces for experimentation and learning.
- Degree of centralisation of resource allocation and monitoring consonant with the costs of technological and market experimentation.
- Criteria for resource allocation consonant with levels of technological and market opportunity.
- Alignment of professional groups with power and control with fields of future opportunity.

The richness of the technological and market opportunities and the scale of technical experiments will determine the appropriate share of resources allocated to technological search, as well as the degree of centralisation and fluidity in organisation structures. Supporting skills and networks will define the specific competencies to be accumulated,

[19] See, for example, the history of the UK General Electric Company under Arnold Weinstock (Aris, 1998).

professional networks to be joined and key functions and functional interfaces within and across which learning must take place within the firm.

TABLE 3 MATCHING CORPORATE TECHNOLOGY AND ORGANISATIONAL PRACTICES WITH MARKET NEEDS AND DEMANDS

CORPORATE TECHNOLOGY ➔	MATCHING ORGANISATIONAL AND MARKETING PRACTICES➔	DANGERS IN RADICAL TECHNOLOGICAL CHANGE
INHERENT CHARACTERISTICS 1. Richness of opportunities	1a. Allocating resources for exploring options 1b. Matching technologies with product markets	1a. Greater opportunities not matched by resources for exploring options 1b. Matching opportunities missed in the market place
2. Costs of specific experiments	2. Degree of centralisation in decision-making	2. Reduced cost of experiments not matched by decentralisation or market testing
SUPPORTING SKILLS AND NETWORKS 1. Specific sources of external knowledge	1. Participation in specific professional knowledge networks	1. Difficulties in recognising & joining new knowledge networks
2. Accumulated knowledge of specific customers' demands, distribution channels, production methods, supply chains. - Anticipating and organising for the necessary communication and gatekeeper skills	2. Learning and improving in key functions and across key functional interfaces	2a. Difficulties in recognising & responding to new customers' demands, distribution channels, production methods, supply chains 2b. Difficulties in recognising new key functional interfaces 2c. Scepticism and resistance from established or potentially obsolescent professional and functional groups

The particular circumstances of the individual firm and project will obviously define the basic skills required but the discussion in this chapter leads to a clear-cut conclusion: in addition to specialist skills, “gatekeeper” skills and general communication skills are becoming more important almost everywhere. People who are capable of communicating across organisational barriers, disciplinary barriers and professional barriers may be invaluable. In very small firms one or two individuals may possess the unique combination of skills required and this can be a very satisfactory solution but in larger firms, it may be possible to anticipate the requirements. There is no single managerial planning prescription.

Differences amongst technologies are reflected in differences in organisational and marketing practices. Thus, given rich technological and market opportunities, both pharmaceutical and consumer electronics firms devote substantial resources to technological search; but given the much higher costs of experimentation, the former tends to have centralised and formal procedures for launching new products, whilst the latter is more likely to be decentralised and informal. Similarly, both pharmaceutical and automobile companies have centralised decision structures, but the former will stress interfaces between corporate R&D and public research in bio-medical fields, whilst the latter will stress links between R&D and production.

6.2 Coping with Radical Change

The past 200 years have seen periodic step-jumps in technological understanding and performance in specific fields, based increasingly often on major scientific breakthroughs. These have reduced considerably the costs of key economic inputs, and have therefore been widely adopted and become the catalysts for major structural changes in the economy. They include steam power, electricity, motorization, synthetic materials and radio communications (Freeman and Louçã, 2001). The contemporary example is of course the massive and continuing reductions in the costs of storing, manipulating and transmitting information brought about by improvements in ICT.

Each wave of radically new technologies has been associated with the growth of firms that have mastered the new technologies, and that have led in the development and commercialisation of related products, processes and services. In the current jargon of corporate strategy, these firms have developed *core competencies* in the new technologies, which have become a distinctive and sustainable competitive advantage.

Ever since Schumpeter associated the advent of revolutionary technologies with "waves of creative destruction", there has been debate about the relative role of incumbent large firms and new entrants in exploiting them. Over the past 20 years, most of the analytical writing has been stacked against incumbents, although recent empirical studies can point to evidence in favour of both (Methe et al, 1996). Over time, the weight of the arguments against has shifted. Earlier studies emphasised the difficulties facing incumbents in mastering new fields of technological knowledge (Cooper and Schendel, 1976; Tushman and Anderson, 1986; Utterback, 1994). More recently, there has been a shift towards emphasising the difficulties in changing and matching established organisational practices to the opportunities opened by revolutionary technological changes: examples include the organisational consequences of changes in product architectures (Henderson and Clark, 1990), resistances from groups with established competencies (Leonard-Barton, 1995; Tripsas and Gavetti, 2000), and of the unexpected emergence of new markets (Christensen, 1997; Levinthal, 1998).

Contrary to a widely used assumption, the nature and directions of radical new technological opportunities are easily recognised by the technically qualified: for example, miniaturisation, compression and digitalisation today in ICT. The technological consequences of these trends can be explored in corporate R&D laboratories: thus, a growing number of large firms in a growing number of industries are now technically active in ICT (Granstrand et al, 1997; Mendonçã, 2000). However, the difficult, costly and uncertain task is that of combining radically new technical competencies with existing technical competencies and organisational practices, many of which may be threatened or need to be changed in order to exploit potential market opportunities. Experimentation and diversity is therefore necessary, not only in exploring the directions of radical technological changes, but also their implications for products, markets and organisational practices.

The third column of Table 3 tries to identify some of the reasons why such experiments may fail in incumbent firms. Some are a consequence of the need to modify competencies or organisational practices, and some of the inevitable uncertainties in the early stages of radically new technologies. The likelihood that established firms will fail increases with the number of practices and competencies that need to be changed. Here a comparison between the conclusions of two recent industry studies is instructive. Klepper and Simons (2000) have shown that firms already established in making radios were subsequently the most successful in the newly developing colour TV market. On the other hand, Holbrook and his colleagues (2000) have shown that none of the firms established in designing and making thermionic valves were subsequently successful in establishing themselves in semiconductors. With the benefit of hindsight, we can see that success in semiconductors required more changes in technological competencies, organisational practices and market experimentation amongst incumbents than success in colour TV. The valve firms required the new competencies and networks in quantum physics, a much stronger interface between product design and very demanding manufacturing technology, and the ability to deal with new sorts of customers (computer makers and the military, in addition to consumer electronics firms). For the radio firms, the shift to colour TV required basically the same technological competencies, augmented by well-known screen-technologies. Otherwise, the customers and distribution channels remained unchanged, as did the key networks and linkages both inside and outside the firm.

At a more aggregate level of structural change in the economy with major waves of new technology, Chandler (1997: 76) developed the so-called 'continuity' thesis. According to this idea, the population of incumbent large firms has tended to remain rather stable in recent times because of their accumulated skills and resources in adopting new technologies and adapting to them. However, this thesis was challenged by Louçã and Mendonçã (1999) and by Freeman and Louçã (2001: 340-55). These authors argued that, contrary to the continuity thesis, a cohort of new large firms continued to join the population of incumbent large firms with each new wave of technical change. Only a minority of the largest firms were able to remain at the top through several waves. These arguments suggest that the evidence at the micro level considered in this Section has considerable significance and that the factors listed in the third (right-hand) column of Table 3 must have had some weight.

However, the first point in the Table (1a) relates also to the attitude and behaviour of the financial system. Some recent work on financial capital has returned to the original Schumpeterian emphasis on 'credit creation' for the finance of innovation at various stages of the successive technological revolutions. These factors which affect the growth, composition and fluctuation of demand and hence the influence of demand upon innovation at the firm level are further considered in Chapter 19 (Verspagen and Louçã) and Chapter 9 (O'Sullivan).

Firms in the vanguard of developing and exploiting radically new technologies must be distinguished from the far more numerous firms who adopt and integrate the new technologies with their current activities. For these firms, in-house competencies in the new technologies are *background*: in other words, necessary for the effective adoption of advances made outside the firm. Paradoxically, the very fact that radically new technologies allow step-jump reductions in the costs of a key input simultaneously makes their adoption both a competitive imperative, and an unlikely source for the adopting firms of their own distinctive and sustainable competitive advantage. For example, in the past many factories had no choice but to adopt coal and steam - and later electricity - as a source of power, given their cost and other advantages. The same is true today for many ICT-based management practices. In neither case were - or are - these revolutionary advances by themselves a source of sustainable competitive advantage for the adopting firms. This means that much of the emphasis by writers on corporate strategy - like Barney (1991) and Porter (1996) - on the importance of establishing a distinctive and sustainable advantage does not, and cannot, apply to the major transformations now inevitably happening in many companies through the adoption of ICT. Their framework helps understand *CISCO* (a major US supplier of equipment for the Internet), but does not help much with *TESCO* (a major UK supermarket chain, increasingly using the Internet).

6.3 Tribal Warfare

In his enumeration of the potential advantages of increasing specialisation in knowledge production, Adam Smith describes the various scientific disciplines as "tribes". This descriptor carries with it an important element in contemporary processes of innovation, namely, the potential for "tribal" conflicts between different professional groups with specialised knowledge. Some of these have been touched upon above: financial versus technological competencies in the evaluation of R&D programmes; technical versus marketing in product development. But perhaps the most important is the potential resistance in a company of today's top managers and technical staff, reflecting the successes of the past, to the introduction of new specialised competencies and methods, reflecting potential opportunities for tomorrow.

The difficulties in introducing the untried new, in the face of the tried and tested old, were spelled out long ago:

> "It must be considered that there is nothing more difficult to carry out, nor more doubtful of success, nor more dangerous to handle, than to initiate a new order of things. For the reformer has enemies in all those who profit from the old order of things, and only lukewarm defenders in all those who would profit by the new order, this lukewarmness arising partly from fear of their adversaries … and partly from the incredulity of mankind, who do not truly believe in anything new until they have had actual experience of it. Thus it arises that on every opportunity for attacking the reformer, his opponents do so with the zeal of partisans, the others only defend him half-heartedly "
> (Machiavelli (1950) pp. 21-22).

Well documented contemporary examples of this process include IBM's early reluctance to enter the personal computer market and Polaroid's early commitment but subsequent failure to develop a business based on digital imaging (Tripsas and Gavetti, 2000). In both cases, the company had the technical resources to develop the new technology, but failed to do so in the light of resistance and scepticism from the established power structures. In these cases, it can be plausibly be argued that yesterday's "core competencies", became today's "core rigidities" (Leonard-Barton, 1995).

But the new does not always turn out to be better than the old. Conservative resistances in oil companies to investments in nuclear power in the 1970s turn out to have been largely justified, and more recently so was scepticism about the dot.com boom. And in the light of IBM's subsequent success in systems integration and software, resistance to heavy commitment to the PC could yet be seen as positive, rather than negative. This is what makes decision-making about radical innovations so difficult. The successes and failures only become clear well after the smoke of battle has cleared. And the political battle for influence often involves one-sided and distorted analyses, reflecting the interests of specific disciplines and functions, where crucial factors and key uncertainties may be ignored, consciously or otherwise.

For today's corporate manager there can be no simple tools or model to neutralise the uneasy, politicised task of dealing with radical innovations. Good judgement, experience, trial and error learning remain the only feasible 'toolkit' available to today's innovative corporations.

7. CONCLUSIONS

Despite spectacular improvements in the scientific knowledge base, and slower but steady improvements in organisational know-how, innovation processes are neither tidy, nor easy to delineate or manage. Increasing specialisation in the production of artefacts and in knowledge has also increased levels of complexity – in artefacts themselves, in the knowledge on which they are based, and in the organisational forms and practices for their development and commercial exploitation. As a consequence, and contrary to the predictions of Schumpeter (1962) and Penrose (1959):

- innovations – especially radical innovations – remain unpredictable in their technical and commercial outcomes;
- technical entrepreneurship is not a general-purpose management skill but specific to a particular technological field at a time of radical breakthroughs and new opportunities, and often to a particular place;
- major innovation decisions are a largely political process often involving professional groups advocating self-interested outcomes under conditions of uncertainty (i.e. ignorance), rather than balanced and careful estimates of costs, benefits and measurable risk.

As a consequence, established large firms have sometimes (not always) found it difficult to deal with the radically new. In the future, there will be new challenges for them. Increasing complexities in products, systems and the underlying knowledge base are leading firms to experiment with modular product architectures and greater use of ICTs and the outsourcing of component design and production. Large innovating firms are therefore likely to become less self-sufficient in their processes, not more so.

Finally, increasing specialisation in the production of artefacts and their underlying knowledge base has made innovative processes increasingly path-dependent. As a consequence, the following aspects of innovation processes are contingent on sector, firm and technology field: the knowledge base underlying innovative opportunities; the links between scientific theory and technological practice; possibilities for knowledge-based diversification; methods of research budget allocation; degree of centralisation; and critical skills, interfaces and networks. Only two innovation processes remain generic: co-ordinating and integrating specialised knowledge, and learning under conditions of uncertainty.

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