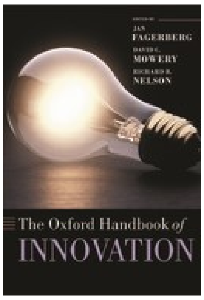

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CHAPTER

4 Innovation Processes

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Abstract

This article is concerned with innovation processes within firms, focusing mainly on innovation within large corporations in advanced countries. It draws on empirical studies of innovation processes, bearing in mind the difficulties for generalization posed by the highly contingent nature of innovation. It presents a short introduction to the many theories and empirical studies of innovation and suggests a simple framework for disaggregating the many innovation activities which take place at the firm level. Three broad, overlapping subprocesses of innovation are identified: the production of knowledge; the transformation of knowledge into artifacts—which mean products, systems, processes, and service; and the continuous matching of the latter to market needs and demands. This article examines key aspects of each of these three subprocesses, showing how each has evolved historically and why they pose such difficult problems for innovation-related managers, entrepreneurs, researchers, and workers.

Keywords: innovation processes, empirical studies, products, systems, processes, service

Subject: Organizational Theory and Behaviour, Innovation, Business and Management

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4.1 Introduction[1]

THIS chapter concerns innovation processes within firms, focusing mainly on innovation within large corporations in advanced countries.[2] What do we know about the historical evolution of these innovation processes and about the key challenges facing "innovation managers" within modern industrial corporations?[3] The chapter draws on empirical studies of innovation processes, bearing in mind the difficulties for generalization posed by the highly contingent nature of innovation. Section 4.2 presents a short introduction to the many theories and empirical studies of innovation[4] and suggests a simple framework for disaggregating the many innovation activities which take place at the firm level. Three broad, overlapping subprocesses (not stages) of innovation are identified: the production of knowledge; the transformation of knowledge into artifacts—by which we mean products, systems, processes, and services; and the continuous matching of the latter to market needs and demands.[5] Sections 4.3 through 4.5 examine key aspects of each of these three subprocesses, showing how each has evolved historically and why they pose such difficult problems for innovation-related managers, entrepreneurs, researchers, and workers. The chapter identifies these management difficulties and points to some of the strategies firms have deployed to meet these challenges.

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4.2 Corporate Innovation Processes

Since there is more than one process of innovation, there is no easy way to organize this chapter. Innovation processes differ in many respects according to the economic sector, field of knowledge, type of innovation, historical period and country concerned. They also vary with the size of the firm, its corporate strategy or strategies, and its prior experience with innovation. In other words, innovation processes are "contingent."[6] These difficulties are compounded by the fact that there is no widely accepted theory of firm-level processes of innovation that satisfactorily integrates the cognitive, organizational, and economic dimensions of innovation processes in firms. Economists tend to concentrate on the economic incentives for, and the effects of, innovation (largely ignoring what happens in between). Organizational specialists focus on the structural and procedural correlates of innovative activities and processes, sociologists on their social determinants and consequences. Managerial specialists address the practices most likely to lead to competitive success, psychologists may examine the phenomenon of creativity or the ways in which people's vision is restricted to one or other set of opportunities. Rich accounts and data resources have come from these and other lines of work over the past decades. Empirical evidence and theoretical understanding have been amassed by historians, from survey researchers and those concerned with bibliometrics, patenting, and other quantifiable dimensions of innovation. A growing number of "innovation studies" shows little allegiance to any particular discipline, and widely disparate theories and methods coexist in relevant journals and handbooks.

Joseph Schumpeter is considered a pioneer in the economic analysis of innovation, having concentrated more effort on this topic than any other economist in the first half of the twentieth century. His insights have guided the subsequent development of the field, and helped to explicate the vital role of innovation in growth and competitiveness. But Schumpeter's early work in particular (see Fagerberg 2003; Fagerberg, Ch. 1 in this volume), stressed the role of individuals, rather than organizations, in the innovation process, highlighting the character and determination of outstanding individuals, and defining innovations as "Acts of Will" rather than "Acts of Intellect." His interpretation reflected the nature of the evidence available to him at the time. As the authors of the SAPPHO study (Rothwell et al. 1974) found, the vast majority of earlier studies of successful and unsuccessful innovation were personal memoirs and anecdotes of the exploits of individual scientists, inventors or managers and contained little or no systematic comparison or analysis. Project SAPPHO and many similar, subsequent studies were in part attempts to overcome the "individualist" bias of personal memoirs. They set out to examine a wider set of organizational factors, as well as the skills and experience of a wider range of individuals participating in each innovation.

p. 88 In order to understand this rich but potentially confusing mosaic of knowledge about innovation processes, I suggest the following general framework:

(1) Innovation processes involve the exploration and exploitation of opportunities for new or improved products, processes or services, based either on an advance in technical practice ("know-how"), or a change in market demand, or a combination of the two. Innovation is therefore essentially a matching process. The classic paper on this subject is Mowery and Rosenberg (1979).

(2) Innovation is inherently uncertain, given the impossibility of predicting accurately the cost and performance of a new artifact, 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. The processes of competition in capitalist markets thus involve purposive experimentation through competition among alternative products, systems, processes, and services and the technical and organizational processes that deliver them.

In organizing the evidence, it is useful to divide innovation into three, partially overlapping processes, consistent with the two features described above.[7] Each process is closely associated with contributions from particular academic disciplines. Each process also has undergone major historical transformations as the process of innovation has evolved.

- *The production of scientific and technological knowledge*: a major trend, since the industrial revolution, has been for the production of scientific and technological knowledge to have become increasingly specialized, by discipline, by function and by institution. History and social studies of science, technology and business have contributed significantly to our understanding of this transformation.
- *The translation of knowledge into working artifacts*: in spite of the explosive growth in scientific knowledge in recent years, theory remains an insufficient guide to technological practice. This reflects an underlying trend for growing complexity of technological artifacts,[8] and in the knowledge bases underpinning them. Technological and business history have made major contributions here as have the cognitive sciences more recently.
- *Responding to and influencing market demand:* this involves a continual process of matching working artifacts with users' requirements. The nature and extent of the opportunities to transform technological knowledge into useful artifacts 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 organizational practices co-evolve with markets. Social change and innovations in marketing and market research have contributed to complex problems and equally complex solutions to the challenge of matching technological opportunities with market needs and organizational practices. These ↳ processes are central concerns of scholars in management, economics and marketing studies.

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I now discuss the implications of change over time in the structure and nature of each of these features of innovation processes. Such change presents considerable challenges to the modern innovation manager and to the corporation as a whole.

4.3 The Production of Scientific and Technological Knowledge

> 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 1937 (orig. 1776): 8, my italics)

Adam 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.[9] New and useful fields of knowledge have been developed, punctuated by the periodic emergence of fields with rapid rates of technological advance and offering rich opportunities for commercial exploitation. For example, progress in such activities as metal cutting and forming, or the use of new power sources, has been informed by and has drawn upon physics, chemistry, and biology, as well as a variety of related engineering disciplines. Today, the coordination of increasing specialization remains a fundamental task of the large corporation.

Three forms of corporate specialization have developed in parallel. First is the development in large manufacturing firms of R&D laboratories specialized in the production of knowledge for commercial exploitation. Second is the development of a myriad of small firms providing continuous improvements in specialized producers' goods. A third trend of specialization is the changing "division of labor" between
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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 specialization have combined to make a heterogeneous and path-dependent pattern of technical change that places great demands on corporations for coordination of processes within their boundaries and between these organizations and others external to the firm. These processes of change, examined below in more detail, have intensified and broadened the challenges facing managers, "intrapreneurs," and entire corporations.[10]

4.3.1 Functional Specialization and Integration: Industrial R&D Laboratories

A major source of innovation in the twentieth century was the industrial R&D laboratory, which remains important in the twenty-first century. It emerged first in Germany in the chemical industry and in the USA in the electrical industry, for two reasons. It was part of the more general process of functional specialization of the large manufacturing firm (Mowery 1995; see also the chapter by Bruland and Mowery in this volume), 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). But the industrial research laboratory also provided these firms with a means for exploiting the rich veins of useful knowledge emerging from fundamental advances in chemistry and physics. In addition, these new in-house laboratories served as a "monitoring post" for established firms seeking to acquire new technologies from other firms.

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 innovating firms (not only manufacturing firms, since telecommunications and some other services have long undertaken R&D). Mowery explained this lack of vertical disintegration by the difficulties of writing contracts for an activity whose output is uncertain and idiosyncratic, and pointed out that integration of R&D within the firm reflected important operating advantages as well. Thus competitive advantage can be gained by the effective combination of specialized and often tacit knowledge across functional boundaries, within the individual firm. Accumulated firm-specific experience is very important.[11]

A 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
p. 91 within the firm (Rothwell 1992). Many product designs turn out to be technically difficult (even ↳ impossible) to manufacture, and/or fail to take into account often elementary user requirements (Forrest 1991).

From a corporate strategy perspective, the importance of such intrafirm collaboration has increased the importance of cross-functional integration spanning departmental boundaries. Japanese automobile firms pioneered the use of "heavyweight" project managers, 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 were in turn linked to innovation processes within customers and key suppliers, enabling fast, project-based innovation. These "heavyweight" project managers occasionally clash with functional bosses, some of whom are unwilling to "give up" control over their resources and object to project-led management. Many large firms now provide formal training in project management to their professional project manager, covering such issues as management of fast-moving project teams responsible for integrating research outputs, conceptual and detailed design, and various engineering functions, while at the same time responding to changing or emerging customer requirements during the production process.

Many writers stress the importance of personal contacts and exchanges across functions within the firm to deal with tacit elements of both product design and its successful transfer to manufacture and market. There is no perfect or foolproof process for ensuring effective coordination. Indeed, so called "best practice" can be positively harmful when its application is taken too far. Excessive use of "heavyweight" project managers can lead to the loss of such benefits from integration as economies of scale, and cost reductions from the use of common components (e.g. in automobile development; see Leonard-Barton 1995). Firms can find it hard to decide what to do with a heavyweight product manager (and the associated staff) when a product development is failing. Failure to grasp this difficult nettle can lead to the problem of "escalation" or an inability to terminate a failing project.[12] Managing the trade-offs between project and functional management, and overcoming the inherent difficulties in project-based management, present major difficulties to senior technology managers.

4.3.2 Technological Convergence and Vertical Disintegration in Production Techniques

Even in industries with heavy investments in product innovation, however, some "vertical disintegration" (outsourcing of specific activities to supplier firms) in manufacturing process innovation has occurred since the nineteenth century, often stimulated by technological advances. Rosenberg (1976) highlighted the
p. 92 emergence of specialized machine tool firms in the nineteenth-century US economy as a ↳ result of advances in metal cutting and metal-forming techniques that produced technological "convergence" in operations that were common to a number of manufacturing processes. For example, boring accurate circular holes in metal was an operation common to the making both of small arms and of sewing machines. Although the skills associated with such machining operations were often craft-based and tacit, their outputs could be codified and standardized. The demand for such common operations grew sufficiently that markets for machines to perform them became large enough to sustain the growth of specialized firms who designed and made such machines. Large manufacturing customers could therefore buy machines that incorporated the latest improvements (drawing on the feedback from many users) and were far superior to what they could do by themselves.

Similar processes of technological convergence and vertical disintegration have been common features of twentieth-century capitalist development (see Table 4.1). New opportunities have emerged from breakthroughs that have created applications spanning multiple product groups. Examples include: materials 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.

Lundvall (1988) and other writers show that the links between the (often small) firms providing these specialized production inputs and their (mainly large) customers are often "relational" rather than arm's-length, and include considerable exchange of information and personnel related to the development, operation and improvement of the specialized inputs. Managing the outsourcing of these critical inputs has
p. 93 become a major challenge to managers of large firms (Quinn 2000). For ↳ example, logistics and ICT systems often differ between component suppliers and integrator companies, creating serious (albeit often technically simple) problems for communication and transactions among these firms. More fundamentally, the choice of which activities to outsource and which to retain in-house defines the "core competence" of the modern corporation, molding the boundaries of the firm (Hamel and Prahalad 1994; Davies et al. 2001).

Table 4.1 Examples of technological convergence and 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	Instrument Makers *Plant Contractors*
Computing	Design Repeat operations	CAD Producers Robots Makers
New Materials	Building Prototypes	Rapid Prototyping Firms
ICT	Application software	Knowledge-Intensive
	Production systems	Business Services Contract manufacture

4.3.3 Industrial Linkages with Universities

As innovative activities in business firms have become more professionalized, and university research more specialized, universities now play an important role in providing the trained researchers for firms in some sectors 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 those longer-term research programs in universities in fields that have possible impacts on their current and future activities.

The range of interactions between firms and universities is considerable. At one extreme, there is something close to the so-called (but relatively rare) "linear model." Here, fundamental research by a university scientist leads to a discovery, its practical importance is recognized by a business firm, which may collaborate with the university scientist in order to exploit it. This happens most often in science-based industries including the chemical, biotechnology, and pharmaceutical sectors, where the focus is on the discovery of interesting and useful synthetic molecules.

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

In between 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 the literature.

(1) The importance of personal and often informal contacts. Informal relationships give practitioners entry points into the academic world, people who they can ask about where the important developments lie and who the relevant people are. Such relationships give researchers insight into the ↳ problems that are confronting industry, how the leading edge of corporate practice is developing, and so on. The informal relationships can result in formal outputs that can in turn trigger more informal contacts. For instance, 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).

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(2) Much university research that is useful to industrialists also is valued by academics. Some academics erect a demarcation between industrially relevant applied work and more fundamental research, and such a demarcation may apply to the work of some university groups playing a role in technology transfer to local businesses. But it does not apply to a good deal of more advanced research activities. US-based studies by Mansfield (1995) and Narin et al. (1997) suggest that a high proportion of industrially significant research 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 emerge from processes that are roundabout and indirect. Probably the most frequent contribution is the provision of graduates trained by leading researchers, and often conversant with emergent research methods and approaches. Such individuals can be “carriers” of new theoretical insights, new techniques and observations, and new skills, all of which industrial firms find difficult to provide themselves. Over time, they will turn these capabilities to solving the problems that their employers face—or provide support by means of forming spin-offs or joining consultancies that provide innovation-supporting services to industrial clients.

Over the past twenty years, governments have begun to expect greater direct usefulness from university research. Often this has been supported by empirically questionable assumptions and theories,[13] or an incomplete understanding of the indirect benefits actually valued by industrialists. For entirely different reasons, certain fields of university research—many fields of biotechnology and some of software and related activities—now provide an increasing stream of inventions with potential industrial application. These are reflected in increases in university licensing activity, in university-founded spin-off firms, and increases in private funding of university research. In Chapter 8, Mowery and Sampat discuss the nature and implications of these recent developments.

These university–industry relationships can be extremely difficult for firms to manage.[14] Managers often complain that universities operate on extended “time lines” with little regard for the urgent deadlines of business. Therefore, they argue, universities should not be placed on the critical path of any important projects. Universities, in turn, sometimes find themselves in the invidious position of being viewed as a low-cost performer of industrial projects, often with the encouragement of government and research council programs of “technology transfer.” At worst, ↳ these programs may focus on the short-term needs of industry at the expense of the long term quality of universities' basic research, graduate training, and support for experimentation and critical questioning (Salter et al. 2000). Such technology transfer programs often are based, implicitly or explicitly, on a version of the linear model of innovation in which universities (and other public sector organizations) perform the science/basic research, which generates innovations “for” industry to take up in its engineering, manufacturing, and marketing.

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4.3.4 Heterogeneity in Innovation Processes

These characteristics of industrial innovation contribute to inter-industry heterogeneity in the structure and management of the processes of innovation, as well as change over time in the identities of the major actors in these processes. The dominant sources of technical change in the twentieth century were—and still are—largemanufacturing firms exploiting different fields of specialized knowledge, with in-house R&D laboratories, together with a myriad of small firms providing specialized producer goods. Over time, the mix of firms and technologies has changed, reflecting the appearance of innovative opportunities generated by the different rates of growth of knowledge in various specialized fields. These characteristics and heterogeneity have major implications for the study of innovation processes.

- Given the increasingly specialized and professionalized 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.[15] As we shall see below, path-dependency reflects the conservatism of professional and functional groups. It also results from cognitive limits in individuals' knowledge about technologies, markets, and the opportunities presented by developments in each. Thus, for example, it is difficult if not impossible to convert a traditional textile firm into one making and selling semiconductors. The recent experience of Vivendi suggests it may also be difficult to transform a national water company into an international ICT and media giant, however enthusiastic some managers and financiers were about this.

- Firms that specialize in different products and related technological fields are likely to stress different features of innovation processes, reflecting the nature of the fields of knowledge on which they depend. Thus, for contemporary 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. These patterns reflect the direct usefulness of university research in the field, and other factors, such as the complexity of manufacturing processes. Users are likely to be an important source of innovations for small innovating firms providing producer p. 96 goods; but users' ↳ role in innovation is likely to be low where large firms are selling to a mass market of users who lack strong technological capabilities (e.g. many consumer products).

- Innovation processes will differ greatly between large and small firms in other respects. Innovations in large firms involve a larger number of people in specialized functions, with shifting responsibilities over time. Innovation processes in large firms are also more likely to involve recognizable procedures, whether formal or informal. In small firms, there are fewer resources to apply to such issues. Decisions related to the recognition of opportunities, the allocation of resources, and the coordination of functional activities, are more likely to reflect the competencies and behavior of senior managers.[16]

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 proceeds on the basis of its prior experience and the technological trajectories evident in the specific industry or product group. But the lack of global "best practices" should not be taken to mean that innovation strategy does not matter, nor that good management cannot make a difference to firms' productivity, market share, or profitability.

4.4 Transformation of Knowledge into Working Artifacts

Scientific advances enable the creation of artifacts of increasing complexity, embodying an increasing number of subsystems and components, and drawing on a broadening range of fields of specialized knowledge. This increasing system complexity is one consequence of the growing specialization in knowledge production. It has resulted in both better understanding of cause–effect relationships, and better and cheaper methods of experimentation. These advances have reduced the costs of technological search, enabling 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 are accelerating this trend: digitalization opens options for more complex systems, and simulation techniques reduce the costs of experimentation (Pavitt and Steinmueller 2001).

Managers involved in transforming S&T knowledge into products, systems, and services need to be aware of four sets of specific trends in their industries. These are: (*a*) technology trajectories and scientific theories; (*b*) where relevant, governmentfunded R&D programs; (*c*) systems integration; and (*d*) techniques and approaches to managing uncertainty. I deal with each of these issues below.

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4.4.1 Keeping Technological Practice (not too far) ahead of Scientific Theory

In spite of the spectacular increases in scientific knowledge over the past 200 years, theory remains an insufficient guide to technological practice. This is partly because of the increasing complexity of physical artifacts and the knowledge bases that underpin them. The importance of practice is reflected in the continuing dominance in industrial R&D laboratories of development activities—the design, building and testing of specific artifacts—compared to research in fields on which they are based. Constant (2000) describes this as technology advancing 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, artifacts, and practices, that is used recursively to produce new knowledge” (p. 221).

Continuous innovation requires constant improvement in methods of technological search, but technical complexity cannot run too far ahead of scientific understanding.[17] The feedbacks 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.[18] Mahdi (2002) has recently developed a taxonomy of technological search that depends on three factors: (1) the degree to which technological problems can be decomposed into simpler sub-tasks; (2) the level of understanding of cause–effect relations; and (3) the costs of experimentation with possible solutions.

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.[19] ICT can also reduce the costs of search and selection. Major advances in large-scale computing and simulation technology have reduced the costs of exploring alternative technical configurations, and have created opportunities for increasingly complex systems made possible through the digitalization of data of all sorts (Pavitt and Steinmueller 2001). Innovation managers and engineers involved in transforming knowledge into working artifacts today need to be aware of specialized ICT trends in their own industries, as well as new measurement and manipulation techniques elsewhere that themselves frequently involve the application of advanced ICTs.

Nightingale (2000) has shown that these mechanisms have radically changed experimental techniques in the pharmaceutical industry during the past ten years. There has been a shift towards more fundamental science, for example, linking biochemical mechanisms to the expression of genes; and there has been a much greater use of simulations (involving models, extensive data banks, etc.) to conduct p. 98 ↳ virtual experiments complementary to real ones. A third related development has been the use of high throughput screening techniques.[20]

4.4.2 Government-Funded Programs

Technological activities directly financed by governments have sometimes been of major importance in opening and exploiting innovative opportunities. Successes include ICT in the USA, where military-related programs played a major role in the early development of computers, semiconductors, software, and the Internet. Military programs 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. But there have also been many disappointments. Policies to support the development of civilian nuclear power have on the whole not been successful, nor have those for the support of high-volume, low-cost residential construction (See Eads and Nelson 1971, as well as the case studies in Nelson 1982). More recently, policies to encourage the development of renewable energy technologies have met with mixed success. And controversy surrounds the achievements of a whole series of EU programs.

Since the 1980s government programs for "pre-competitive" collaborative R&D in Europe (e.g. ESPRIT and Eureka), the USA (e.g. Sematech) and Japan (e.g. the 5G ICOT Program) have proliferated. Thus, most major firms are presented with opportunities for participation in such programs. Firms require methods for evaluating their potential contribution to corporate goals, the financial and organizational costs of participating, the risks involved in not participating, and the ways in which government programs can complement or fit into the overall corporate strategy (Floyd 1997).

It is difficult to generalize from the recent history of government support for industrial innovation. All such programs involve 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 highlight the opportunity costs of these programs; 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.

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4.4.3 Multi-Technology Firms, Modularization and Systems Integration

In addition to increasingly complex artifacts, specialization in knowledge production has increased the range of fields of knowledge that contribute to the design of each product. Compare the original mechanical loom with the many fields of specialized knowledge—electrical, aerodynamic, software, materials—that are now embodied in the contemporary design. Or observe the way in which modern automobiles increasingly integrate plastic and other new materials, as well as electronic and software control systems.

Firms designing these increasingly complex products find it difficult to master advances in all the fields that they embody. Hence the growing importance of modular product architectures, where component interfaces are standardized, 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.

Technological convergence has also provided opportunities for further vertical disintegration between product design and manufacture. Sturgeon (1999), for example, describes recent growth in contract manufacturing in electronics, in which specialized firms take over product design from other firms, and assume responsibility for detailed engineering and manufacture. The technological convergence here is based on increasing automation of routine operations (e.g. component insertion), and on growing use of standard software tools.

Contract manufacturing is growing in other industries as well,[21] giving rise to "modular production networks." These modules are defined by distinct breaks in the value chain at points where information regarding product specifications can be highly formalized. This occurs within functionally specialized value chain nodes, where activities tend to be highly integrated and based on tacit linkages. Between these nodes linkages depend on the transfer of codified information.

At first sight, these recent changes might appear to point to a neatly specialized system for the production of innovations, with product and systems designers, their subcontractors for components and subsystems, and their manufacturers, working together through arm's-length market relations—a trend foreseen by Sturgeon (1999). But this neglects the consequences of important distinctions that need to be made between the properties of artifacts, 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 artifacts are, as we have seen, based on the integration of an increasing number of fields of specialized knowledge. These fields advance at different speeds and their progress cannot be tracked solely by monitoring codified information. The division of labour between companies in production thus cannot be mirrored by an equivalent p. 100 ↳ division of labour in knowledge (Brusoni et al. 2001). Some overlap between companies in knowledge competencies is necessary to deal with the transfer of tacit knowledge, to manage unforeseen consequences of systemic complexity, and to resolve imbalances between components that are liable to result from their uneven rates of technical change. Similarly arm's-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 specializing increasingly in systems design and integration.

4.4.4 "Managing" Uncertainty?

Specialized R&D and related activities in business firms have become institutionalized and predictable sources of discoveries, inventions, innovations, and improvements. However, the process of innovation is complex, involving many variables whose properties and interactions (and economic usefulness) are understood 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). They cannot accurately predict the technical and commercial outcomes of their own innovative activities, nor those of other firms.[22] On average, research scientists and engineers tend to be over-optimistic about the costs, benefits, and time periods of their proposed projects, and about market demand for the products resulting from them. But there is typically great variation in the ratio of *ex post* outcomes to *ex ante* estimates of investment or profit within any corporate portfolio of projects (Freeman 1982; Mansfield 1995). Indeed, commercially unsuccessful projects often account for a disproportionate share of corporate R&D spending (Griliches 1990).

Business firms (and others) rarely are capable of defining the full array of possible uses that may emerge for their innovations, especially radical ones. Examples of inaccurate predictions about what turned out later to be spectacularly successful technologies and innovations are legion. Early twentieth-century 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 recognized. After World War II, the founder 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. The recent experience of inaccurate forecasts of the potential markets for various generations of the mobile phone, and various functions associated with these (the unexpected success of text messaging, for instance) is equally instructive.

p. 101 Corporate managers therefore face severe difficulties in deciding how to deal with innovative activities, which have some of the elements of conventional investment activities, but for which severe uncertainty means that continuous feedback from the market, past experience and experimentation are essential. In practice, top-down corporate visions can be a poor guide to innovation strategies. Ericsson's success in opening up mobile telephony began with initiatives from middle-level technical management, rather than from the top. In the academic and business literatures, the failures of top-down visions are easily forgotten and the successes oversimplified. For example, Prahalad and Hamel (1990) tell the story of Canon's successful diversification from optics and precision mechanics into electronics technology, and from cameras into photocopying and computer peripheral products; but they ignore the firm's failed diversification into recording products and electronic calculators (Sandoz 1997).

The broad differences between search and selection activities have been recognized 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. One consequence is periodic swings in fashions and management practices. These often reflect 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.

4.5 Matching of Artifacts, Organizational Practices and Market Demand

The matching of products, processes, systems, and services (and organizational practices) with actual and potential market demand is a major responsibility for managers overseeing innovation in the successful
p. 102 corporation. The corporation ↳ builds on its accumulated knowledge of product and process technologies, of organizational practices, and of users' needs to carry out this function. Responding to (and creating) market needs and demands, as well as matching organizational practices with technological opportunities, involves dealing with disruptive change. This disruptive change interacts with one of the negative consequences of specialization: namely, the potential for tribal warfare over the old and the new between specialized functions and disciplines within the firm.

4.5.1 Matching Technology and Organizational Practices with Market Needs

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 coordinating 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 multidivisional firm reflected in part the major opportunities for product diversification in the chemical industry opened up by breakthroughs in synthetic organic chemistry. Although it is commonplace today to argue that technologies and organizational practices do, or should, co-evolve with market demands, there is some risk of "technological determinism" in Chandler's argument that this process largely involves the adaptation of corporate organizational practices to emerging market needs and technological opportunities.

Technical advances often precede organizational and market advances, among other reasons because of the firmer knowledge base and lower costs of experimentation associated with technical, as opposed to market or organizational, innovation. This does not mean that technology imposes one organizational "best way" or even a clear strategy towards the marketplace. Variety in the characteristics of technologies, their continuous change and uncertain applications also produces variety and experimentation in organizational and marketing practices. But this variety and change does not mean that "anything goes" in either organizational or marketing terms. It may be practically impossible for a firm that wishes to remain competitive to resist making use of new technologies and knowledge in its own future product and process development—unless it wishes to become a niche producer like the manufacturers of clockwork watches and analogue record players. But moving into new technologies without appropriate changes in terms of skills and training, divisions of labour and interrelations between parts of the organization, can be even more costly. Or consider the firm's investment decisions. A firm applying conventional cost–benefit analysis and strict cost controls to all of these decisions will not prosper in the long term in a competitive
p. 103 market governed by ↳ the exploitation of a rich, varied and rapidly advancing body of technological knowledge.[23]

The empirical literature summarized in the first two columns in Table 4.2 highlights the organizational and marketing practices that must be made consistent with key features of technologies:

- 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.
- The centralization of resource allocation and monitoring activities needs to be consonant with the costs of technological and market experimentation.
- p. 104 ↳ Criteria for resource allocation need to be consonant with levels of technological and market opportunity.
- Alignment of professional groups, who possess power and control, with fields of future opportunity.

Table 4.2 Matching corporate technology and organizational practices with market needs and demands

Corporate technology →	Matching organizational 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 marketplace
2. Costs of specific experiments	2. Degree of centralization in decision making	2. Reduced cost of experiments not matched by decentralization or market testing
Supporting skills and networks		
1. Specific sources of external knowledge	1. Participation in specific professional knowledge networks	1. Difficulties in recognizing & joining new knowledge networks
2. Accumulated knowledge of specific customers' demands, distribution channels, production methods, supply chains.	2. Learning and improving in key functions and across key functional interfaces	2a. Difficulties in recognizing & responding to new customers' demands, distribution channels, production methods, supply chains 2b. Difficulties in recognizing new key functional interfaces
3. Skill and Expertise Base	3. Anticipating and organizing for the necessary communication and gatekeeper skills	3. Scepticism and resistance from established or potentially obsolescent professional and functional groups

The richness of the technological and market opportunities and the scale of technical experiments should determine the appropriate share of resources allocated to technological search, as well as the degree of centralization and fluidity in organization structures. Supporting skills and networks will define the specific competencies to be accumulated, professional networks to be joined and key functions and functional interfaces within and across which learning must take place within the firm.

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

Differences amongst technologies are reflected in differences in organizational and marketing practices. For example, both pharmaceutical and consumer electronics firms see rich technological and market opportunities, and thus devote substantial resources to technological search. The much higher costs of experimentation in pharmaceuticals mean that drug firms tend to have centralized and formal procedures for launching new products, whilst in consumer electronics the situation is more likely to be decentralized and informal. Similarly, as already mentioned, both pharmaceutical and automobile companies have centralized decision structures, but the former stress interfaces between corporate R&D and public research in biomedical fields, whilst the latter concentrate on links between R&D and production.

4.5.2 Coping with Radical Change

The past 200 years have seen periodic step-jumps in technological understanding and performance in specific fields. During the past several decades, these discontinuous advances have been more often than not based on major scientific breakthroughs. "Radical" innovations 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 most celebrated contemporary example, of course, is 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 have pioneered in the development and commercialization 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 twenty years, most of the analytical writing has been stacked against incumbents, although recent empirical studies point to evidence in favour of both (Methe et al. 1996). Over time, the weight of the argument has shifted somewhat away from emphasis on the difficulties facing incumbents in mastering new fields of technological knowledge (Cooper and Schendel 1976; Tushman and Anderson 1986; Utterback 1994).

More recent work has emphasized the difficulties faced by incumbent firms that must adapt established organizational practices to seize the opportunities opened by revolutionary technological changes. Examples include the organizational consequences of changes in product architectures (Henderson and Clark 1990), resistance from groups with established competencies (Leonard-Barton 1995; Tripsas and Gavetti 2000), and the unexpected emergence of new markets (Christensen 1997; Levinthal 1998).

Contrary to a widespread assumption, the nature and directions of radical new technological opportunities are easily recognized by the technically qualified: for example, miniaturization, compression, and digitalization are key trajectories in ICT. The result in this case is that 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 organizational practices, many of which may be threatened or must be changed in order to exploit potential market opportunities. Experimentation and diversity therefore are necessary for exploration of the directions and implications of radical technological changes, but also for assessing the implications of these changes for products, markets and organizational practices.

The third column of Table 4.2 identifies some reasons why such experiments may fail in incumbent firms. Some are a consequence of the need to modify competencies or organizational practices; and some of the inevitable uncertainties in the early stages of radically new technologies. The likelihood that established

p. 106 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 was subsequently successful in semiconductors.

With the benefit of hindsight, we can see that success in semiconductors required more changes in technological competencies, organizational practices, and market experimentation amongst incumbents, than did success in colour TV. The valve firms required 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 color 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.

According to Chandler's (1997: 76) so-called “continuity” thesis, the population of incumbent large firms has remained stable in recent times, because of their accumulated skills and resources in adopting new technologies and adapting to them. This thesis has been challenged by Louçã and Mendonçã (1999) and by Freeman and Louçã (2001: 340–55), who argue that, on the contrary, a cohort of new large firms continues to join the population of incumbent large firms with each new wave of technical change. Only a minority of the largest firms was able to remain at the top through several waves. This suggests that the micro-level evidence considered in this Section, especially the factors listed in the third (right-hand) column of Table 4.2, have had significant consequences for the evolution of industry structure.[24] Radical technological change, and the success or failure of incumbent firms in adapting to it, thus may have important consequences for structural change in the economy as a whole.

Firms in the vanguard of developing and exploiting radically new technologies must be distinguished from the 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 a competitive imperative and an unlikely source for sustained competitive advantage among adopting firms. 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. But in neither case were these revolutionary advances by themselves a source of
p. 107 sustainable competitive ↳ advantage for the adopting firms. 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 accordingly does not, and cannot, apply to the major transformations now inevitably happening in many companies through the adoption of ICT. Their framework can help 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).

4.5.3 Tribal Warfare

In his enumeration of the potential advantages of increasing specialization in knowledge production, Adam Smith describes the various scientific disciplines as "tribes." Certainly an important element in contemporary processes of innovation is "tribal" conflict between different professional groups with specialized knowledge. Some such conflicts have been touched upon above: financial versus technological competencies in the evaluation of R&D programs; technical versus marketing competencies in product development. But perhaps the most important is the potential resistance of a company's current top managers and technical staff (rooted in the successes of the past), to the introduction of new specialized competencies and methods, reflecting potential opportunities for tomorrow.

The difficulties in introducing the 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: 21–2)

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, a company with the technical resources to develop the new technology, failed to do so, due to resistance and scepticism from the established power structures. In these cases, it can 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. So, more recently, was p. 108 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 beneficial in the longer run. This is what makes decision making about radical innovations so difficult. The political battle for influence often involves one-sided and distorted analyses, reflecting the interests of specific disciplines and functions. Crucial factors and key uncertainties may be ignored, consciously or otherwise. The successes and failures only become clear well after the smoke of battle has cleared.

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

4.6 Conclusions

Despite spectacular improvements in the scientific knowledge base, and slower but steady improvements in organizational know-how, innovation processes are neither tidy, nor easy to delineate or manage. Increasing specialization in the production of artifacts and in knowledge has also increased levels of complexity—in artifacts themselves, in the knowledge on which they are based, and in the organizational forms and practices for their development and commercial exploitation. As a consequence—and contrary to some of 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; at a time of radical breakthroughs and new opportunities it is in large part specific to a particular technological field 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 found it difficult to deal with the radically new. In the future, they will confront new challenges. 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 specialization in the production of artifacts, and their underlying knowledge bases, has made innovative processes increasingly path-dependent. As a consequence, several aspects of innovation processes are contingent on sector, firm, and technology field. These include: 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 centralization; and the critical skills, interfaces and networks that need to be developed. Only two innovation processes remain generic: coordinating and integrating specialized knowledge, and learning under conditions of uncertainty.

Notes

1. Keith Pavitt had prepared several drafts of this chapter, but passed away before completing it. Amendments to the original have been made by Christopher Freeman, Mike Hobday, Ian Miles, and the editors.
2. This chapter focuses mainly on large firms within the USA, Europe, and Japan. It does not consider issues arising in connection with entrepreneurial attitudes and motivations, such as their willingness to take risks (Drucker (1985) examines some of the links between entrepreneurship and innovation, and Roberts (1991) and Oakey (1995) examine the process of innovation within SMEs). For studies of innovation processes within firms based in the industrializing countries (or “latecomer firms”) see Hobday (1995), Kim (1997), and Fagerberg and Godinho in this volume.
3. Arguably, “innovation managers” (in practice, if not formally identified by job title) can be found at all levels of the firm (for an overview of innovation management in firms see Tidd et al. 2001). Hamel (2000) examines “strategic innovation” (or innovation in strategy approach) while Schonberger (1982) and Robinson (1991) deal with *kaizen* (or continuous improvements) to current vintages of capital equipment and organization.
4. 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 (1992), Forrest (1991) and Mahdi (2002).
5. The term “stages” is avoided here, as it implies linearity. Research has consistently shown that the process of innovation within the firm is anything but linear (Kline and Rosenberg 1986; Tidd et al. 2001; Van der Ven et al. 1999). The three sub-processes of innovation, although distinctive, overlap considerably and often occur concurrently.
6. For a review of models of innovation and the importance of contingency, see Mahdi (2002: ch. 2).
7. As noted earlier, most innovation processes are overlapping and intertwined, terms like “stages” or “phases” impose an unrealistic linearity on the various innovation processes.
8. Recall that by artifacts we mean services and systems as well as more tangible material artifacts such as items of

equipment.

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

p. 110 10. See Pinchot (1997) for a discussion of the intrapreneur, that is, an innovator operating within a large corporation.

11. See Georghiou et al. (1986).

12. For a discussion of escalation using examples from the UK stock exchange and other major ICT project failures, see Flowers (1996). In the public sector, or state-dependent industries, the problem can be acute. The experience of many countries that established agencies to develop nuclear power, for instance, suggests that these are often extremely difficult to restrain.

13. Three very different lines of argument have been mobilized over recent years. First is the view that the output of university research is a free good available to everybody—as assumed by orthodox economics. In contrast, a second view argues that publicly funded university research is a form of conspicuous intellectual consumption reflecting technological and economic achievements, but not contributing to them (as suggested by Kealey 1996). A more nuanced argument is the "mode 2" claim that the locus of useful scientific discovery is moving from universities to "contexts of application" (as persuasively argued, if somewhat overstated, by Gibbons et al. 1994).

14. Universities also face management challenges here, of course—not least in reconciling the established structures of academic recognition with the contexts of industrially relevant research.

15. Georghiou et al. (1986).

16. Community Innovation Survey data (see the chapter by Smith in this volume for further discussion) are now beginning to provide us with systematic data on many aspects of the innovative effort and sources of innovative ideas for firms of different types and in different sectors.

17. For example, in the absence of theory and/or 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.

18. See e.g. Rosenberg and Nelson (1994) on the origins of the engineering disciplines in US universities.

19. A similar conclusion has been reached by Becker and Murphy (1992). They argue that the degree of specialization in tasks is limited not by the extent of the market, as in Smith's famous formulation, but by the costs of coordinating specialized activities. These coordination costs are reduced by increases in general knowledge.

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

21. Sturgeon lists apparel and footwear, toys, data processing, offshore oil drilling, home furnishings and lighting, semiconductor fabrication, food processing, automotive parts, brewing, enterprise networking, and pharmaceuticals. In addition, Prencipe (1997) demonstrates that outsourcing has increased in the production of aircraft engine components.

22. Rosenberg (1994) has pointed out that in the nineteenth century, the Western Union turned down an opportunity to purchase Bell's patent for the telephone, which it regarded as an inferior product to the telegraph.

23. See e.g. the history of the UK General Electric Company under Arnold Weinstock (Aris 1998).

p. 111 24. Note also, the first point in this column (1a). This relates also to the attitude and behavior 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 the chapters by Verspagen and O'Sullivan in this volume.

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