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Industry-Science Linkage

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Industry-Science Linkage

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Preface

The social role of scientists appeared first in the 17th century Europe, and then the government-supported academy and the employment of scientists emerged in France in the later half of the 18th century. In the middle of the 19th century, the combination of teaching with research in the role of the professor and the research laboratory emerged in Germany. Then, the trained professional researchers and the department combining research and training and the more complex type of research institute emerged in the early 20th century in the US with a highly decentralized scientific system. At each of these turning points, the center of scientific activity shifted to the country where the innovation occurred, and innovations were eventually diffused to other countries, raising the general level of activity everywhere.

A high rate of complementary public and private investments in R&D is a prerequisite for sustained innovation performance, and ensuring such complementarity requires governments to be responsive to the rapid transformation of innovation processes and related business needs and strategies. Greater use of public-private partnership can increase this responsiveness and enhance the efficiency and cost-effectiveness of technology and innovation policy. The performance of an innovation system depends now more than in the past on the intensity and effectiveness of the interactions between the main actors in the generation and diffusion of knowledge. Industry-science relationship (ISR) plays an important role in the development of fast growing new industries and in training, retaining and attracting highly qualified labor. As a result, science-industry linkages have grown in importance as a central concern for policy.

The role of science during the catching-up process is two-folded: source of absorptive capability and provider of public knowledge for industry. Interactions between the technology and science, as well as the dynamics of these interactions change during the catching-up process, reaching at last a level of strong and mutual reinforcing relationships found in developed economies. As an economy develops, its growth becomes more and more dependent on its scientific and technological resources. The mutual feedback between them contributes to explain why the economic growth is fuelled by strong scientific and technological capabilities. The increase in complexity means the incorporation of more and more people, institutions, companies.

This study performed by Dr. Joon-kyung Park, KDI senior Fellow, addresses both timely and important issues. The author examines the development of relationships between industry and science from the historical perspectives, and draws policy implications of industry-science relationships for both Korea and other developing countries.

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December, 2003

Choongsoo Kim

President
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Summary

1. Evolution of Research System

The social role of scientists appeared first as a vague idea in the 17th century Europe. The role of experimental philosopher and scientific academies emerged in England. In the later half of the 18th century, the government-supported academy and the employment of scientists in various educational and consultative capacities emerged in France. In the middle of the 19th century, the combination of teaching with research in the role of the professor and the research laboratory emerged in Germany. In the early 20th century, the trained professional researchers and the department combining research and training and the more complex type of research institute emerged in the US. At each of these turning points, the center of scientific activity shifted to the country where the innovation occurred, and innovations in the organization and use of science were eventually diffused to other countries, raising the general level of activity everywhere.

- The transformation of science into a status approaching that of professional career and into an organized activity took place in Germany. Practically all scientists in Germany were either university teachers or students by the middle of the 19th century. Research became a necessary qualification for a university career and was considered as part of the function of the professor. The transmission of research skills took place in university laboratories and seminars. In the late 19th century research in experimental sciences became organized in research institutes, which were usually attached to universities and possessed their own facilities and supporting staffs. Industrial research and technological institutes became important users of university-level science by the 1870s. This did not lead to the growth of research institutes in German universities, which was curtailed by the rigidity of the university structure. The professors, as a corporate body, prevented any important modifications of the structure that separated the institute from the chair.
- The graduate training in the basic scientific subjects and the active support of problem-oriented research were developed in the US by the early 20th century. The departmental structure made it easier to assimilate the administrative arrangements for research into the university. New specialties could easily be accommodated and nurtured within existing departments until they became strong enough to operate independently. The US system had been better capable of developing within the universities (or in cooperation with the universities) a field of research that originated from practical interests.

In the US, the rise of scientific entrepreneurs and administrators, the professional research careers, and the standardized procedures for staffing, equipping, and costing different types of research made scientific research into transferable operation. Administrators would move from university administration to the administration of large industrial or governmental research laboratories and establish research units of the same kind that existed in the universities. Research workers could work in any of these settings without having to change their professional identities markedly or give up their expectations or standards.

- By the turn of the century, it was widely accepted among US industrial leaders that scientific knowledge was the basis for engineering development and it was the key to competitiveness. Accordingly, industrial research laboratories soon began to blossom as companies realized their need to foster scientific knowledge outside of the university setting. Private foundations also began to grow and to support university researchers.
- Increased pressure on the pace of scientific and technical advancements came at the beginning of World War I, when the US had been cut off from European research base. The post-war prosperity also created an atmosphere supportive of the continued support of

science and technology. A variety of modes of supporting training and research by government and industry without direct involvement also emerged from extension of the research activity beyond the limits of the university. The most common are research or training grants, contracts, and donations. These supports have advantages. They are given to persons and organizations of proven competence. They give the recipients sufficient freedom to devise their own plans and at times even change their original scheme as soon as they find out that it is not the most fruitful one. Finally, they encourage constant reevaluation, criticism, and comparison of programs and changes in policy without the necessity of abolishing or drastically changing whole organizations.

- The existence of professional research workers and standardized procedures for the organization of research has been a necessary precondition for this proliferation and flexibility of research activities. The close relationship between universities on the one hand and government, business and the community in general on the other had been initiated and managed by administrators specializing in academic and scientific affairs (university presidents, officers of foundations, governmental research directors). The emergence of the specialists in university and scientific administration with traditions in initiative and a considerable body of know-how have been a *sine qua non* of the growth of science in the US.

US academic and scientific institutions had thrived because they had learned from experience. They had to learn from experience, since their mere existence was no guarantee of their eminence. They had to compete for fame through accomplishment, and they had to compete for funds and for persons. They were helped in this competition by administrators who were not bound by the results and reputations of particular persons and whose concern for the whole institution made them more open to the lessons of experience.

- To a large extent this innovating function had been absent in Europe. Self-governing university corporations had rarely been able to exercise much initiative because of their tendency to represent the vested interests of their members. Therefore, the nationalization of the university and the scientific research system, which was supposed to lead to more objective and better coordinated planning of higher education and research, had debilitated the capacity of the system to learn from experience. The centralized systems had no constitutive feedback mechanisms such as are given by situations where universities and research institutes are free to make innovations and compete with each other. Also, there was no room in these systems for the development of executive and entrepreneurial roles.

The most obvious result of the system had been the transformation of the relationship between higher education and research on the one hand and the economy on the other. This enterprising system of universities working within a pluralistic, educational and economic system had created an unprecedented widespread demand for knowledge and research and had turned science into an important economic resource. It had been argued that making the practice of scientific research into professional career might inhibit scientists from freely following the paths opened to them by curiosity and imagination. As a matter of fact, however, the widespread uses of science had created a very wide foundation for pure research, the aim of which was to increase knowledge without consideration for its potential uses.

- It was neither industrialists nor civil servants who established the link between science on the one hand and industry and government on the other. Rather there had been a constant and subtle give and take between professional scientists and the potential users of science in the professions, industry and government. This mutually advantageous interchange was established and had been kept alive by academic and research entrepreneurs acting as organizers and interpreters between the interlocutors.

The mechanism of selection of a certain type of role and organization was competition between strong units of research operating in a decentralized common market for researchers, students, and cultural products. Decentralized systems have been more effective in the production and

selection of new types of roles and organizations than centralized ones.

- Like the perspective of science, the organization of work most appropriate for research is also constantly changing. Thus, more decentralized systems are likely to produce a greater variety of ideas and experiments than centralized ones. Due to the numerous unpredictable ways that science can be enjoyed and used, a greater variety of experiments conducted by those competing with each other is also likely to produce more widespread demand and hence greater expenditure on science than decisions made centrally by a few wise men.
- Decentralization and competition provide a built-in feedback mechanism for distinguishing between what works and what does not work satisfactorily. Centralized systems have to create artificial mechanisms of self-evaluation that have not been too successful.

The great spurts in scientific production since the middle of the 19th century took place in Germany and the US, which had highly decentralized scientific systems, and where the combination of research with education was maximal. In decentralized systems where there may be a great deal of initiative and enterprise in science, the delimitation of research from teaching will be constantly changing. It is likely that the combination of functions was not independent of decentralization. Higher education would provide the most numerous opportunities for the extension of the uses of science. Since more and more kinds of instruction were linked with research and higher education, there would be a greater likelihood for the exploitation of the opportunities that higher education created for research and vice versa.

2. Patterns of Innovation and Innovation Policies

The orientation of public research (publicly funded R&D) depends on the overall objectives of government policies and the specific role of science and technology, all of which have an important historical component in terms of national preoccupations and institutions. Large and highly developed countries offer markets with advanced customers and opportunities to reap economies of scale while maintaining diversity in R&D activities. Innovations in smaller high-income countries generally have to internationalize more rapidly and concentrate on a narrower range of fields.

- The role of the higher education sector can serve as an indication of the relationship between the science system and the rest of the innovation system. One indicator is the share of higher education research and development financed by government, which is declining in the majority of OECD countries. The enterprise sector represents a significant financial contributor for universities.
- The science bases of national innovation system are quite different among countries. Countries also differ in their pattern of technological specialization. For the majority of countries, there is a significant positive correlation between past and present patterns, indicating that technological capabilities accumulate over time and that development is strongly path-dependent.
- Innovation performance depends crucially on interactions among the main actors that make up an innovation system, which in turn depend on the incentives or barriers confronting the various individuals, companies and institutions. As a general trend, most forms of interactions and knowledge flows have intensified, contributing to an overall increase in the knowledge-intensity of economic activities. But the importance and the quality of the various linkages differ from country to country, depending on the structure and specialization pattern.
- An important interface in a national innovation system is that between the science system and the enterprise sector. Especially in countries with a large share of science-based industries and a large higher education sector, building bridges from university

research to technological innovation is an important task for policy.

- The increasing openness of national innovation systems to external knowledge flows is reflected in the share of technology acquired from abroad embodied in capital and intermediary goods; purchases of foreign patents and licenses; technological alliances between firms of different countries; and, in science, the number of internationally co-authored publications. It also shows in the innovation activities of multinational, as indicated by their patenting partners and the location of their R&D facilities.

Science, technology and innovation each represent a successively larger category of activities that are highly interdependent but distinct from each other. The relation between science and technology is better thought of in terms of two parallel streams of cumulative knowledge, which have many interdependencies and cross relations, but whose internal connections are much stronger than their cross connections.

- Science contributes to technology in at least six ways:
 - New knowledge serving as a direct sources of ideas for new technological possibilities;
 - Source of tools and techniques for more efficient engineering design and a knowledge base for evaluation of feasibility of designs;
 - Research instrumentation, laboratory techniques and analytical methods that are used in research, which eventually find their way into design or industrial practices;
 - Practice of research as a source for development and assimilation of new human skills and capabilities eventually useful for technology;
 - Creation of a knowledge base that becomes increasingly important in the assessment of technology in terms of its wider social and environmental impacts;
 - Knowledge base that enables more efficient strategies of applied research, development, and refinement of new technologies.
- The converse impact of technology on science is of at least equal importance:
 - Through providing a fertile source of novel scientific questions and thereby also helping to justify the allocation of resources needed to address these questions in an efficient and timely manner, extending the agenda of science;
 - As a source of otherwise unavailable instrumentation and techniques needed to address novel and more difficult scientific questions more efficiently.
- Germany, Switzerland, Sweden and Japan have successful diffusion-oriented technology policies that emphasize the rapid adoption and diffusion of new technology, especially production technology, as a national strategic objective. They have among the highest ratios of R&D expenditure (private and public) to GDP among industrialized countries, as well as exceptionally high levels of educational performance at all levels. A significant fraction of R&D support in these countries is for the purpose of enhancing awareness of what is going on in the world of S&T rather than necessarily for generating new knowledge for the first time in the universe.
- Scientists engaged in research actually spend a large fraction of their time and effort in communicating with others to take the fullest advantage of the progress made by others in planning their own strategy. This is the main reason for the necessity of R&D performance for the absorption and appraisal of technology. The excellence of scientists as a conduit for research knowledge to the organizations in which they work tends to be an automatic by-product of their active engagement in research.

Technological opportunities and appropriability conditions on R&D and innovative output determine R&D intensity in an industry. However, technological opportunity alone determine the rate of technical advance. Given the level of technological opportunity, a higher level of appropriability can raise only the level of technology, not the rate of technological change. In industries having new sources of technological opportunities, high R&D intensity and high rates of technical advance tend to be sustained over time.

- There are three sources of technological opportunity: advances in scientific understandings and techniques;
 - Advances in scientific understandings and techniques;
 - Technological advances originating in other industries, both inside and outside the vertical chain of production, and in other private and government institutions; and
 - Positive feedback from an industry's technological advances in one period that open up new technological opportunities for the next.
- Over the long run, the most important source of new technological opportunities has been the advance of scientific knowledge. Formal science has significantly illuminated the opportunities for technological advance and provided the basis for the other important forces that offset diminishing returns to technological opportunity.
- For some technological advances, most significant technological breakthroughs can be traced directly to advances in basic general scientific understanding that occurred just prior to the breakthrough. But direct and simple linkages are the exception, not the rule. The connections between scientific advance and technical advance are generally complex and subtle. For the most part, scientists and engineers engaged in industrial R&D employ science as a set of tools and stock of knowledge to be tapped in problem solving.

The connections with applied science tend to be more strongly associated with rapid innovation than are the ties with the basic sciences. The effects of the latter may well operate through the strengthening of the former.

- R&D intensity in an industry is strongly correlated with the strength of its connections with the fields of science. R&D intensity is positively correlated with the contributions of university research and government laboratories, suggesting that the latter two kinds of R&D stimulate and complement industrial R&D. Strong contributions from upstream suppliers were not positively correlated with industry R&D intensity. There are some indications that the work of equipment suppliers and industry R&D are partly substitutes. Two product-oriented natural trajectories were positively associated with industry R&D intensity, but no process trajectory was positively correlated with this measure.

Most of the knowledge applied by firms in innovation is not general purpose and easily transmitted and reproduced; it is appropriate for specific applications and appropriated by specific firms. Sectors vary in the relative importance of product and process innovations, in sources of process technology, and in the size and patterns of technological diversification of innovating firms. But some regularities emerge.

- Supplier dominated firms can be found mainly in traditional sectors of manufacturing – textiles, lumbers, wood and paper products, printing and publishing, and construction. They make only a minor contribution to their process or product technology. They are generally small, and their in-house R&D and engineering capabilities are weak. Most innovations come from suppliers of equipment and materials, although in some cases large customers and publicly financed research and extension services also make a contribution.
- The economic pressures and incentives to exploit scale economies are particularly strong in firms producing either standard materials or vehicles and durable consumer goods for price-sensitive users. Competitive success depends to a considerable degree on firm-specific skills reflected in continuous improvements in product design and in product reliability, and in the ability to respond sensitively and quickly to changes in users' needs. The way of appropriating technological advantage varies considerably between large-scale producers and small-scale equipment suppliers. For the large-scale producers, particular inventions are not in general of great significance. Technological leads are reflected in the capacity to design, build and operate large-scale continuous processes or to design and integrate large-scale assembly systems. Technological leads are maintained through know-how and secrecy around process innovations, and through inevitable technical lags in

imitation and through patent protection. For specialized suppliers, secrecy, process know-how and lengthy technical lags are not available to the same extent as a means of appropriating technology.

- In complex and interdependent production systems, the external cost of failure in any one part is considerable. For the purpose of trouble shooting, large-scale producers established groups of trained and specialists for production engineering. These groups develop the capacity to identify technical imbalances and bottlenecks, and eventually become able either to specify or design new equipment that will improve productivity. Consequently, engineering departments become an important source of process technology.
- Other important sources of process innovations are the specialized suppliers of equipment and instrumentation, with whom large-scale producers have close and complementary relationships. Larger users provide operating experience, testing facilities and even design and development resources for specialized equipment suppliers. Such suppliers in turn provide their large customers with specialized knowledge and experience as a result of designing and building equipment for a variety of users, often spread across a number of industries. Specialized suppliers have a different technological trajectory from their users, more strongly oriented towards performance-increasing product innovation and less towards cost-reducing process innovation.
- Science-based firms are to be found in the chemical and electric/electronic sectors. The main sources of technology are the R&D activities of firms in the sectors, based on the rapid developments of the underlying sciences. The development of successive waves of products has depended on prior developments of the relevant basic science.

The forces leading to private under-investment in innovation differ from sector to sector across the economy, and policy design should take these differences into account. The contribution of public resources can take many forms, and it is necessary for policy discussion to classify promotional measures that aim to match public action to sources of market failure in different sectors.

- In intermediate good industries, the predominant form of innovation is the development of higher quality products that will be used as inputs in vertically related industries. The software and equipment-producing industries are examples. In such sectors, opportunities for innovation are generally abundant, but are likely to be exploited through informal activities of design improvement. Idiosyncratic and cumulative skills make for relatively high appropriability of innovation.
 - The question is how to deliver public funding to provide sufficient investment funds in a risky environment without losing the monitoring ability of private venture capital firms and without trying to implement such monitoring with clumsy and costly contracts or administrative mechanisms. A contingent valuation method would establish the desired incentives for the private sector to choose the best innovation and for such innovators to carry out the appropriate amounts of investment at the least cost to the public while avoiding opportunistic behavior by either the public or the private partner.
- Dual to the category of sectors where innovation takes the form of developing higher-quality inputs that are used in vertically related downstream industries is the category of firms in the customer industries that innovate by adapting products and processes developed in upstream industries to their own commercial needs. Innovation failure can arise also in the utilization of those inputs. Public support for private innovation should be allocated so that the marginal social return to public funds is the same in both sectors. As the source of innovation failure is different in the two types of industries, the framework for providing public support should also be different.

- Small operating units can benefit from adopting state-of-the-art techniques, but ill-able to afford the expense of keeping abreast of such techniques, and able to internalize only a fraction of the overall benefits that flow from keeping the sector as a whole on the technological frontier. Public support for innovation in such sectors can take the form of extension services that serve as an open technical repository to which private firms can turn for the solution of specific problems.
- In sectors in which technological progress takes the form of application of higher-quality inputs developed elsewhere, public support for innovation must take the form of networks of public institutions, which serve as repositories of information about developments on the technological frontier and promote diffusion of innovations by transmitting such information, in usable form, to using sectors.
- Only a few sectors fall in the category of complex systems innovation. Firms in these sectors are typically large in an absolute sense, and well able to maintain their own firm-specific pools of technical competence. Innovation failure arises because the R&D projects involved carry a cost that is proportionally as large or larger than the absolute size of innovating firms, and because of the nature of risk associated with failure to stay on the technological frontier.
 - Society is concerned simply that the innovation occur; an individual firm is concerned that it be the winner of the innovation race, or more precisely, that it not be among the losers. The high set-up cost and drastic risk associated with innovation in such sector combine to limit expected private gains to such a point that the market will not undertake many socially desirable projects.
 - In selecting the themes of the research project, it became evident that it would only be possible to carry out research that was fundamental in nature and of great common interest. Thus it was necessary to find out the common interest in order to make cooperation possible. Then, there would be no introduction of company know-how.
 - Policy should also be open to the possibility of direct subsidies, at least early in the life of cooperative activity. A condition of such subsidies should be acceptance of arrangements to diffuse knowledge generated by the joint venture to all comers on reasonable terms. Learning-by-doing advantages will normally allow incumbents to profit from exploiting an innovation; the availability of the innovation to outsiders at reasonable cost will prevent first-innovators from extracting economic profits and ensure a satisfactory level of consumer benefits.
 - Innovation market failure may also arise when innovation involves the development of common standards for infrastructure technology. Such innovations involve network externalities and carry a substantial risk if a firm enters into a technological trajectory that ultimately fails to be selected as the market standard. Public bridging institutions investing in infrastructure technology would fill an essential gap in such cases.
- Where innovation relies on a technology base with a high science content, there is also a need for bridging institutions. Firms in such sectors will often be large in an absolute sense, and will typically maintain their own formal R&D laboratories. The role of bridging institutions in this case is to facilitate diffusion of advances in basic research from academic research operations to the private sector.
 - In biotechnology, recombinant DNA and genetic engineering techniques in many ways represent radical scientific breakthroughs that is transferred to industry and reduced to practice. Another is pharmaceutical. Success depended on the ability of companies to link up the clinical and chemical competence into a coherent whole by relying on basic biological and pharmaceutical knowledge. Close formal and informal connections with university researchers were important factors in making these linkages possible.
 - A common characteristic of technological progress in high-tech areas is that the firms in the private sector are able to develop and appropriate the returns from commercialization of fundamental breakthroughs. Commercial application of such advances

will typically best be carried out at private laboratories, which will be able to use information from marketing and distribution channels to direct development in the most effective direction.

- For high-tech industries, public support should promote the basic research generating the foundation for commercialization. Rather than targeting specific applications, however, public policy should attempt to broaden and enrich the R&D network and the knowledge base on which individual firms can draw in developing applications.
- Bridging institutions here could be university-industry research parks or government laboratories. Their role should be to provide a common forum for the diverse fields of knowledge that is combined to generate progress in high science-content sectors and to promote basic research and make the results of such research available to the private sector for commercial development.

A high rate of complementary public and private investments in R&D is a prerequisite for sustained innovation performance, and ensuring such complementarity requires governments to be responsive to the rapid transformation of innovation processes and related business needs and strategies. Greater use of public-private partnership (PP/P) can increase this responsiveness and enhance the efficiency and cost-effectiveness of technology and innovation policy.

- PP/Ps for innovation promote cooperation between the public sector (government agencies or laboratories, universities) and the private sector (enterprises) in undertaking joint projects. They tend to be in areas where the actors have mutual or complementary interests but deem that they lack capabilities and incentives to act as efficiently alone. They may involve joint sponsorship of R&D in government, industry and/or university laboratories with participants providing funding and/or in-kind contributions such as facilities, personnel or intellectual property. Although they have been in existence for many years in OECD countries, public-private partnerships are now playing a more prominent role in science, technology and innovation policy.
- A well-functioning of industry-science interface is necessary to reap broader economic and social benefits from investments in public research, but also contributes to the validity and quality of the science system itself. Public-private partnerships have the potential to improve the leverage of public support to business R&D, through cost and risk sharing. They can ensure higher-quality contributions by the private sector to government mission-oriented R&D and open new avenues for commercial spillovers from public research. In addition, they can be designed to achieve several goals at once (supporting pre-competitive research, building networks/linkages) that contributes to their *system efficiency*.
- The motivations to engage in public-private partnerships differ strongly depending on the actor. From the government point of view, the rationale for promoting partnerships in the context of innovation and technology policy is dual: to correct market failures resulted in under-investment in R&D by firms and to improve the efficiency of public support to R&D. For industry, motivating factors to engage in partnerships include increasing access to research infra-structure and expertise not available in corporate laboratories, expanding external contacts for industrial laboratories, increasing the level of pre-competitive research, and leveraging industrial research capabilities. Form the university point of view, partnerships can help obtain financial support for educational and research missions, broaden experience of students and faculty, and increase employment opportunities for students.
- There are various types of innovation partnerships between private and public actors. These include general research support, informal collaborations, contract research, training schemes, cluster formation, human resource development, etc. This variety in public-private partnerships in terms of size objectives and design features as well as the national specificity of their policy context has tended to hamper an assessment of critical

factors in their successful design and implementation. In addition, identification of good practices in joint creation and sharing of knowledge between public and private research sectors has been impaired by the lack of agreed definitions, methodologies and indicators to measure performance.

3. Industry-Science Relationships

Industrial research is primarily aimed at the broadening of technological knowledge rather than the development of specific products or processes that find immediate commercial applications. Therefore, the benefits of research are not apparent and the allocation of resources to research may not appear to be justified. Possible benefits of research need to be identified.

- Research projects can be seen as a first stage of a sequential process that lead to the creation of knowledge, which is then transformed in new products or new processes by means of further development. In fact, being a source of future innovations has been identified as the major function of research. Most of patents are filed during the development stage, whereas they may actually originate from research. Thus, patents reflect the final results of a long term R&D project stream, which include basic research.
 - It has been extensively argued that patent protection is rarely available for research results due to its inherent lack of immediate application, which is a core requirement for granting a patent. This argument has often been put forward to justify publicly funded research in order to compensate for insufficient private investment in research.
 - For basic research, which is defined by a hardly assessable probability of commercial success, a long time to market and the probability for very high and sustainable competitive advantages, the company obviously seeks frequent and comprehensive patent protection. Developments based on basic research are likely to lead to innovations that yield very high and sustainable advantages, which are secured by patents.
- The adoption of short planning horizons by R&D managers, the lack of full appropriation of research results, the high risk involved in research activities and the reliance on public research institutions reinforce the temptation to refrain from investment in research. The upcoming of concepts like lean management, the shortening of development times, share-holder values or business reengineering has recently led to redirection and/or downsizing of research laboratories in many companies.
 - A survey by the NSF came to the conclusion that in large companies, efforts is shifting away from central laboratories to meet the needs of customers. Since decentralized units tend to have shorter planning horizon than central unit, this will further strengthen development efforts at the expense of research.

University research has expanded considerably in the 1990s. University research enhances the stock of knowledge, generates increased technological opportunities across a wide range of industrial fields and increases the potential productivity of private industrial R&D, apart from increasing the learning ability of graduates, when performed in close interaction with university teaching.

- Strong pressures exist for the privatization of scientific knowledge and the protection of technology. This trend may not only affect scientific international cooperation, which is essential for the development of science, but also limit the access to the most modern and competitive technologies, hampering the diffusion of important innovations. The determination of the impact of intellectual property protection policies still remains controversial due to the scarcity of empirical work.
- US universities have been particularly successful at contributing to the accomplishment of commercial opportunities, whilst related actions in Europe have been erratic in quality and scarce in quantity. In the US, new innovations have benefited from a

close interaction between universities and the community. In the context of the complex web of relationships between universities and industrial firms, intellectual property by universities represent a small portion. Nonetheless, the existence of explicit strategy for intellectual property protection in the US has provided the generation of sizeable aggregate level of income, though the impact of income at the institutional level is negligible on average.

- Despite the impact of patent income at few US universities and the overall growth, we should stress that, on average, the share of royalties in the total research expenditures remains small, and below 0.2%. Although the figures do not represent the specific trends of the leading US universities, the expectation is that this share will remain small.
- Despite its outstanding scientific performance, Europe is far behind the US and Japan in terms of its technological and commercial performance. The result indicate that one of its weakness lies in its inferiority in terms of transforming the results of scientific research into innovations and competitive advantages. This has led to a shift in the European R&D policy towards seeking economic relevance in science and technology.
 - The relative weakness of European industry has been discussed since 1992: its competitive edge has been blunted; its research potential is being eroded; and finally, it has a very weak position with regard to future technology. It is clear that the EU has a relatively much lower level of R&D than the US and Japan. Especially in Europe, the supply of research personnel can hardly keep up constantly growing demand. Even more important than the absolute number of researchers are their qualifications, the ability to meet the needs of developing industries and the extent to which the capital they represent is utilized. This problem is based on European weakness in integrating R&D and innovation.

The limitations and deficiencies of traditional technology transfer mechanism are largely due to the dominance of the linear model of innovation on conventional thinking. An alternative model of technology transfer emphasizes the interactive nature of the process. A conceptual framework is developed which identifies four major components of the inward technology transfer process, awareness, association, assimilation and application. The conclusions indicate the importance of non-routine activities and effective communications between credible boundary-spanning individuals.

- Recent studies revealed that the external acquisition of technology becomes the most prominent technology management issue in multi-technology corporations, and that similarly innovative SMEs have dense networks in a variety of marketing and manufacturing relationships. However, it appears that not all firms have the capacity to forge and develop effective external linkages, formal or informal.
- The most significant factor determining SMEs' propensity for and ability to access external technology is internal to the firm: most notably the employment of qualified scientists and engineers and outward-looking managers. The lack of internal technological know-how can inhibit external know-how accumulation and the firm's receptivity to externally developed technology. R&D expenditures can be seen as an investment in a firm's *absorptive capacity*. A firm's ability to evaluate and utilize external knowledge is related its prior knowledge and expertise, which is driven by prior R&D investment.
- Accumulated technological knowledge and experience appear to outlive an individual, implying that it is the organization, rather than the individuals who pass through it, that is responsible for accumulating and retaining technical competence. Over long periods of time, organizations build up a body of knowledge and skills through experience and learning by doing. This implies the importance of practiced routines built into the organization, which is referred to as an organization's core capabilities. There is a need to uncover the processes to achieve this desirable state of *receptivity*.

- Inward technology transfer will be successful only if an organization has not only the ability to acquire but also the ability to assimilate and apply ideas, knowledge, devices and artifacts effectively. Organizations will respond to technological opportunity only in terms of their own perception of its benefits and costs and in relation to their own needs and to technical, organizational and human resources. The process view of technology transfer, therefore, is concerned with creating and raising the capability for innovation, requiring the capability to
 - Search and scan for information on technology, new to the organization (awareness);
 - Recognize the potential benefit of this information by associating it with internal organizational needs and capabilities – recognize the value of this technology (idea) for the organization (association);
 - Communicate this technology within the organization and create genuine business opportunities (assimilation); and
 - Apply them for competitive advantage.

The performance of an innovation system depends now more than in the past on the intensity and effectiveness of the interactions between the main actors in the generation and diffusion of knowledge. Industry-science relationship (ISR) plays an important role in the development of fast growing new industries and in training, retaining and attracting highly qualified labor. As a result, science-industry linkages have grown in importance as a central concern for policy.

- The intensification and diversification of industry-science relationships is most notable and well documented in the US but can also be observed in other countries, including those where informal mechanisms of interaction have traditionally played a greater role, such as Japan. This signals deeper ongoing transformation in the respective role of cooperation/competition between curiosity-driven scientific research, mission-oriented public research and profit-driven business R&D, due to the combined effect of the following factors:
 - Technological progress accelerates and market expands exponentially in areas in which innovation is directly rooted in science (BT, IT and new materials).
 - New information technology allows easier and cheaper exchange of information between researchers.
 - Industry demand for linkage with the science base increases more broadly, as innovations requires more external and multi-disciplinary knowledge. Tighter corporate governance leads to the downsizing and short-term orientation of corporate labs, and more intense competition forces firms to save on R&D costs while seeking privileged and rapid access to new knowledge.
 - Financial, regulatory and organizational changes have boosted the development of market for knowledge, by making possible the financing and management of a wider range of commercialization activities. Restrictions on public finance have encouraged universities and other publicly funded research organizations to enter this booming market, especially when they could build on already solid linkages with industry.
- In many fields, technological innovations make more intensive use of scientific knowledge. In addition, publicly funded research provides the skilled graduates that are essential to firms wishing to adopt new technologies, new instruments and methods for industrial research and an increased capacity for problem solving.

In the last decade, universities in many countries have been called to compensate for the decline of public research institutes in the commercialization of public research. In the recent period policy attention in most OECD countries has tended to focus increasingly on the role of ISR in fostering entrepreneurial activity in fast growing industries, often to neglect of other important contributions of science system.

- Leading research universities adopt now more ambitious goals, including strategic alliances with firms to consolidate their position in innovation networks and to get their share of the booming market for knowledge. Smaller universities are tempted to transform

part of their research departments into business support units and contract research organizations.

- Publicly funded research organizations value relationships with industry for different reasons depending on their main mission. Universities cultivate industry contacts to ensure good job prospects for students, keep curricula up-to-date in some disciplines and obtain financial or in-kind support to reinforce and expand their research capabilities beyond what would allow core funding.
 - Large multi-disciplinary public research institutes have always had close links with the private sector in areas where industry is an important player in the whole research spectrum, including fundamental research. The need to diversify their activities away from stagnant or declining core activities drives largely ongoing changes in their relations with industry. They now need to adapt their interface with industry to the requirements of new science-based industries where start-ups and small firms are important players. Mission-oriented public research institutes have developed almost organic linkages with the part of industry offering complementary competencies in responding to government procurement.

Innovation surveys demonstrate that improved access to better trained human resources is by far the main benefits that industry expects from linkages with publicly financed research, and this is not likely to change in the future given the risk of persistent shortages of highly qualified labor.

- Among other benefits (that include also networking and clustering opportunities or access to problem-solving capabilities), privileged access to new scientific knowledge seems to take on a new importance. Industries remain significant actors of the science system, especially in chemistry, physics and basic engineering.
- However, it relies increasingly on public research to complement its own growing R&D efforts. Industry views diverge concerning the preferred channels to access publicly funded research. For example, increased patenting by publicly funded organizations yields more benefits to small firms than larger ones that have long-established close links with public research.

The interactions between the public research sector and industry take various institutional forms and differ in nature and intensity reflecting national specificities in institutional set-ups, regulatory frameworks, research financing, intellectual property rights and in the status and mobility of researchers. Globalization and the diffusion of best practice policies reduce differences between national systems of ISR and may change their comparative advantages but cannot abolish the considerable diversity of existing models. Existing internationally comparable indicators capture some of these differences.

- The share of government in funding and performance varies considerably among the OECD countries: it is moderately high in France; close to the average of OECD countries in Germany and UK; and low in the US, Japan and Korea.
- There are also wide differences across countries regarding not only the size but also the content of research activities in universities and public research institutes, although the share of universities has been increasing in most countries in the 1990s. In the US, UK and Japan, universities conduct most of the basic research and public institutes focus more on applied research missions. In continental Europe, university research coexists with public sector labs and both perform basic research and mission-oriented activities, which raises more risks of duplicative research efforts.
- National science systems support innovation by generating new relevant knowledge and by facilitating absorption of knowledge generated in foreign countries. The balance between the two functions varies with country size and S&T specialization. Scientific specialization profiles differ substantially across countries, are more contrasted in small countries than large countries, and tend to be quite stable over time. Although their

transformation might be one of the desirable long-term outcomes of improved ISR, they must be taken as a given when considering options to trigger such improvement.

- In smaller countries, scientific output in industry-relevant disciplines is well correlated with R&D intensity, with only a few exceptions, especially Korea in which R&D performance is disconnected from scientific output. Larger countries seem to enjoy economies of scale in translating scientific efforts into R&D, except Italy and the UK, where scientific output is inflated by prolific publications by the medical sector. Under-specialization in science-intensive industries in Germany and Japan explain largely why R&D is over proportionate to scientific output. The link between science and patentable innovation is weaker in these countries than in other G7 countries. In Japan more than in Germany, an additional explanation is a relatively low productivity of the science system, as measured by citations of scientific papers.

4. Industry-Science Relations in Catch-up Economies

Economic growth has been distributed across the industrial sectors. It is by no means the case that economic growth in Europe was driven by a small number of high-tech knowledge-based sectors. There was no particular industrial structure that is conducive to growth. Certainly high-R&D sectors were high growth sectors. However, many low and medium R&D-intensity sectors (food processing, basic metals, machinery, etc.) were also among the high growth sectors. Many of these sectors were among the highest in terms of levels of employment and output. Thus, their contribution to overall growth is likely to be considerably higher than that of high R&D-intensity sectors where the shares of output and employment are much lower.

- Growth had been based on a wide spread of innovation across sectors and many of the significant sectors were those often referred to as low- or medium-tech industries. Even low-tech sectors were often highly innovative since they are knowledge-intensive from a systemic perspective. Low- and medium-tech are invariably innovative industries in the sense that they develop and market new products in a continuous fashion.
- Most of the low-tech sectors are intensive in their use of scientific knowledge. They have significant indirect science inputs. The depth and complexity of industry knowledge bases are not linked to their direct R&D performance. Science inputs in low-tech industries are supported by complex, indirect links with supplier companies, universities, and research institutes. Hence low-tech industries are frequently part of high-tech systems, and policy makers should be aware of their significance for growth.
- There was a general tendency for OECD countries to de-specialize in terms of export specialization over the period from 1965 to 1992. The OECD catching up countries (Japan, Italy, Spain, Finland, Ireland, Portugal, Greece and Turkey) on average experienced the highest degree of structural change in their specialization patterns.
 - With regard to technological specialization (measured as specialization in US patents from the late 1970s to the early 1980s), the evidence is less conclusive. About half of the countries tend to increase in terms of the level of specialization, while the other half tended to engage in de-specialization.
 - Both trade specialization and technological specialization were path-dependent in the sense that specialization patterns were correlated between seven three-year intervals. Trade specialization patterns were more stable than were technological specialization patterns. Among the OECD countries, France, Germany, the UK, Sweden and the catching up countries displayed the highest degree of turbulence in the specialization patterns.
- The determinants of trade specialization are sector-specific. But certain regularities can be identified in terms of sectors being governed by certain technological regimes, which transcend traditional sector boundary. In the technology gap approach, either cumulative character of technological change or inter-sector linkages (home market

effects) explain the trade specialization. Inter-sector linkages were important for specialized-suppliers as well as scale-intensive sectors, while the most important determinant was own sector technological efforts in the case of science-based sectors, in which linkages tend to be horizontal rather than vertical.

- As for the determinants of the direction of trade specialization, the importance of advanced users in home markets as an inducement to technological innovation is well recognized. In this context, support for upstream-downstream interaction could be more effective in influencing trade specialization towards a higher technology level than support for corporate R&D, particularly in specialized suppliers sector.
- Structural change (change in specialization patterns) is an integral part of economic development processes. The growth of market shares at the country level is related to the ability of countries to transform their specialization patterns towards fast-growing sectors, which are in general high-tech sectors.
 - The reaction speed of specialization patterns, however, might be too low to allow for an active policy. Policy makers must be prepared to aim at a high degree of interaction between their various instruments, as well as be willing to risk unsuccessful attempts, and admit these in an early enough stage. Enhancing growth by steering specialization patterns seems a quite risky *art* rather than a well-established *science* without major uncertainty. It might be too late to catch up in a fast growing sector, when the sector has started to grow rapidly, if no technological competence is present at all. From the perspective of a policy-maker, it is probably wise to support research on small scale in new areas, in order to monitor the new areas, but also in order to support/secure a minimum of technological competence, should a field take off.
 - Countries must change their level of human capital as well as their production structure as they catch up, in order to catch technology spillovers from the leading countries.

It is often argued that, over time, the high R&D-intensity sectors displace low R&D-intensity sectors. However, the rapidly growing sectors, in terms of employment growth, are not at all made up of high R&D-intensity sectors. The problem is the view that innovation is something that primarily occurs in sectors characterized by high levels of R&D input, by significant patenting activity, or by related scientific publication. The *Community Innovation Survey* shows that innovation is widely distributed across all industrial sectors; it is by no means confined to the so-called high-tech sectors of the economy.

- Because of their availability and quality, these indicators give a very limited view of the nature and extent of innovation activities and output. R&D is an input indicator, and not necessarily a good one; patenting data results from a legal process which is to do with appropriability conditions, and indicates at best an invention, not an innovation, and so on.
- The *Community Innovation Survey* (1992) for Germany, the Netherlands, Denmark and Norway provides the evidence that a sizeable proportion of firms has new products within their sales mix: Substantial proportions of sales are coming from new products, across all industries and size classes of firms. Innovation is not confined to high-tech sectors but does indeed appear to be pervasive across sectors.

The technological frontier is defined by technology-leaders; technology followers are primarily concerned with the development of new products to move up the value-chain of global market. R&D in technology-followers rarely involve research aimed at generating new technological or scientific knowledge. However, the tacit dimension and dynamic nature of technology require considerable innovation on the part of the technology-follower to keep up with the technology frontier.

- Technology-leader countries collectively define the technological frontier at any point in time, and move it forward. Successful innovations in technology-leader countries define

the new technological frontier that is commercially correct. Technology-follower countries may be far, near, or even at the technology frontier for particular industries, but are generally not involved in pushing it forward.

- Firms in technology-follower countries usually approach the frontier through the transfer of technology from technology-leader countries (avoiding reinvent the wheel). However, this requires indigenous technology learning capability. As the technology frontier is constantly moving, if a follower fails to progress technologically at more than the speed of the leader, it will not catch up.

Entry into global markets that allows for sustained income growth requires an understanding of dynamic factors in the whole value chain. Participation in global markets reflects the strategic decision of lead-firms in the value chains. Value chain analysis helps in understanding the need and scope for systemic competitiveness.

- Efficiency in production is only a necessary condition for successfully penetrating global markets. The analysis and identification of core competence will lead the firm outsource those functions where it has no distinctive competence. With the growing division of labor and the global dispersion of components manufacturing, systemic competitiveness has become increasingly important. Value chain analysis considers not just the efficiency of production link in the chain, but also factors that determine the participation of particular groups of producers in final markets. It treats the whole cycle of production, including governance of connectedness to final markets. That is, it helps in understanding the advantages and disadvantages of firms and countries specializing in production rather than services, and why the way in which producers are connected to final markets may influence their ability to gain from participating in global markets.
- Participating in global markets that allows for sustained income growth requires the capacity to learn and upgrade. The value chains is an important construct for understanding the distribution of returns arising from design, production, marketing, coordination and recycling. Essentially, the primary returns accrue to those parties who are able to protect themselves from competition. This ability to insulate activities can be encapsulated by the concept of *rent*, which arises from the possession of scarce attributes and involves *barriers to entry*. The primary rents in the chain of production are increasingly to be found in areas outside of production, such as design, branding and marketing. Yet, even within production some activities involve greater barriers to entry. The pervasive trend is towards control over disembodied activities in the value chain.
 - Economic rents take various forms in a firm, including technology rents (command over scarce technologies), organizational rents (superior forms of internal organization), human resource rents (access to better skills than competitors) and marketing rents (better marketing capabilities, valuable brand names). This cluster of attributes is often discussed in relation to dynamic capabilities and core competence in the literature. Economic rents may arise from purposeful activities taking place between groups of firms – these are referred to as relational rents.
 - Economic rents have become increasingly important since the growth of differentiated products after the 1970s. Economic rent is dynamic in nature, eroded by the forces of competition after which it is then transferred into consumer surplus in the form of lower prices and/or higher quality. The competitive process – the search for new combinations to create scarcity and the subsequent bidding away of this economic rent by competitors – fuels the innovation process, which derives capitalism forward.

Activities of a multinational corporation (MNC) are potentially mobile or contestable by other affiliates in different local settings. These activities include technology-intensive activities, such as research, development, and design. Competitive processes can be led by the parent company or initiated by affiliates. Internal competition may lead to incremental development at individual affiliate operations. The gaining of world and/or continental product mandates is not simply a

result of parent company decisions but can involve considerable affiliate initiative.

- Such affiliate initiative has been classified into attempts to defend, retain, and build local domains within global parent company organizations. Of particular interest is the entre-preneurial behavior of affiliate managers as they seek to contest their affiliates' position and status within established parent company hierarchies. Subversive strategies effectively constitute multiple alternative centers of strategic coordination.
- Intra-MNC competition can center on three different internal markets: the markets for intermediate products or services, the market for charters or mandates, and the markets for capabilities. The internal markets for inter-mediate products or services are likely to be open in something approximating a market mechanism, in which comparative costs/ prices alone determine the allocation of resources. The markets for mandates and for capabilities are likely to be managed through non-market transactions (in which a bundle of less measurable factors come into play alongside comparative costs).
- Parent company-led intra-MNC competition will tend to be managed so as to avoid the worst excesses of competition such as duplication of efforts. This of course does not preclude the possibility that some parent companies will encourage open competition among affiliates.

A key role for R&D in technology-followers is to build independent design capability for the firm. Moving up the value chain to more attractive markets depends on the capability to develop proprietary product-designs, which requires formal R&D effort. Several technology-follower firms from NICs made a transition from original equipment manufacturers (OEM) to original design manufacturers (ODM), to original brand manufacturers (OBM). Such move involved substantive learning and competence building.

- Some newly industrializing countries (NICs) spend large amounts on R&D, but the amounts is still relatively small in comparison to technology-leaders whether at national or firm level. In technology-leader countries, technological uncertainty makes R&D expensive. In technology-leader countries, the vast majority of attempts at innovation fail. Well over half of all R&D projects in technology-leading firm are simply cancelled. The degree technological uncertainty is far less for R&D in technology-followers. The key issue for R&D in technology-followers is not how much R&D, but what R&D.
- Technology-leader countries are capable of generating many alternative approaches to technical change and then have institutions in place (firms and markets) to select the best alternative. But this approach is wasteful with duplication of effort and much that turns out fruitless. This wasteful attribute of technical change makes R&D expensive in technology-leaders. In technology-followers, however, the ex-post selection of has already taken place, the new technological paradigm selected and the uncertainty of a different magnitude.
- Even in technology-leaders, over 80% of industrial R&D expenditures are devoted to development activity improving existing products. Research expands the knowledge base on which existing industries depend and generate new knowledge leading to new technologies and the birth of new industries. Research as an activity aimed at generating new knowledge is neither central to innovation, nor essential to industrial competitiveness. Research is critical to advancing the technological frontier in fields dependent on formal research such biotechnology and semiconductors. However, research tends to be much less firm-specific than product development, and proprietary innovation within the firm may well depend on knowledge added to the pool through research elsewhere.
- Technology- followers use new design within an existing technology frontier to move up the value chain. Products may range from homogenized low-cost items to high value-added items. At the high value-added end, technology-followers should be able to define the design specifications. The development of new products to meet market needs demand

design capability.

- Design tends to be market-driven rather than technology-driven; technology provides the capability to meet new market needs. The role of design changes over time in the life cycle of an industry - from the early phase primarily of designing for experimentation and technological innovation, to the phase in which designing for technical improvement, lower cost, and ease of manufacture becomes more important, and then to the mature phase where a multiplicity of design variations, fashions, styles and redesigns aimed at different market segments. Technology followers will operate mainly at the latter phases, but build capability over time to enter the early phase.
- The unity of product and process is the essence of design for manufacturability. Formal R&D effort usefully complement process innovation on the shop-floor. While shop-floor innovation arising from day-to-day operation is the major source of cost-saving, longer-term shop-floor problems require a concentration of skilled and qualified people trained in science and engineering, which can be provided by a specialized R&D laboratory. Such laboratory tends to be in-house. Only then will it be primarily responsive to the problems of the firm and develop the long-term formal and informal communication channels needed for a close relationship.

In technology-followers, in-house R&D team play a crucial role as the firm's formal learning unit of knowledge produced elsewhere; it can have intangible spin-off benefits for the rest of the organization. R&D unit can perform the role of gatekeeper to plug into external reservoir of knowledge. The knowledge is usually highly specialized, requiring advanced training to understand it. Any R&D function grouping usually contains a high concentration of more qualified people, making them suited to carry out a role of gatekeeper.

- R&D must build absorptive capacity to be able to access work done in other firms. This absorptive capacity is primarily a function of prior related knowledge that confers an ability to recognize the value of new information, assimilate it, and apply it to commercial ends.
- Understanding of research being done elsewhere may require doing some research as a ticket of admission to research done elsewhere. This learning role is of great importance in technology-leading firms. For technology-followers, R&D unit played the key role in transferring imported technology such that capability was built in house for subsequent project execution. Building learning capacity in technology-follower firms includes the information-gathering network that can survey what is available, detect new developments, and judge what is worthwhile buying and learning. Leading companies in catching-up economies have set up subsidiaries and bought firms to function as outposts that, together with in-house R&D, monitor research activities in advanced countries.
 - Organizing for learning requires that R&D engineers see themselves as technology-keepers. A technology-keeper has the responsibility for tracking useful knowledge inside and outside the firm. Useful knowledge will be overwhelmingly technological, not scientific. Recruiting new scientists and engineers from a university can keep a firm adequately up-to-date with scientific knowledge.
- R&D can also provide significant intangible benefits to the firm. These intangible benefits are vague and difficult to measure. But the role of a nucleus for new attitudes and new procedures and attracting more technical person is potentially important.
 - R&D can set the tone for a discourse on technology.
 - R&D can play a role as a change agent for the firm. R&D can play a demonstrator role of setting new standards that match the best inter-nationally. One of the most effective ways of building absorptive capacity is bench- marking against competitive products. Benchmarking should extend across all key firm activities, but R&D is a natural place to begin the process, because it directly feeds into product development - a key activity

- for the firm's future.
- R&D activity can help in attracting good technical people who are needed by the firm but who might not otherwise join.

Science played specific roles of initiating positive interactions with technological development and thus contributing for the absorptive capability, since initial stages of development and during catching up processes. Scientific institutional building must be seen as a component of modern industrial policies.

- Throughout the development process, a more interactive process between technology and science may take place. For these interactions, scientific institutions, resources and capabilities are necessary. Neither the linear model nor an inverted linear model would take place: a more interactive approach is necessary for development.
- In the catching-up process, R&D can play dual roles for firms: innovation and learning. The combination of technology acquisition and learning and the sequence that runs from imitation to creativity are two sides of the same process. Efforts to imitate depend on internal capabilities: initial stage of development and the catching-up process depend on absorptive capability. To monitor knowledge developed elsewhere, firms invest in basic research – an entry ticket for a network of technological and scientific information. Internal capabilities are prerequisite to imitate and absorb knowledge from advanced countries. Imitation and diffusion of technologies must be seen as a continuation of innovative process. A certain level of scientific capability is a key component of this absorptive capability.

The role of science during the catching-up process is two-folded: source of absorptive capability and provider of public knowledge for industry. Interactions between the technology and science, as well as the dynamics of these interactions change during the catching-up process, reaching at last a level of strong and mutual reinforcing relationships found in developed economies.

- As an economy develops, its growth becomes more and more dependent on its scientific and technological resources. The mutual feedback between them contributes to explain why the economic growth is fuelled by strong scientific and technological capabilities. The increase in complexity means the incorporation of more and more people, institutions, companies.
- The capacity of the technological sector to use scientific knowledge increases over time, becoming more efficient in the transformation of scientific information into technological products. There are more connections turned on and more interactions working. Mutual feedback and virtuous cycles become working.
- The interactions between science and technology seemed to be triggered after a certain threshold of scientific production has been attained. The attainment of a threshold of scientific production seems to be a precondition for improved technological production.
- An articulation between industrial and scientific policies may run both ways: scientific institutions would help the formulation of industrial policy as focusing devices, and industrial policy would help to transform scientific knowledge (generated abroad and locally) into new firms, new products, etc. The interaction between these two pillars of a modern developmental policy may help the establishment of the interactions.

Indigenous process of technical advance has not always been seen as the key policy problem by those most directly concerned with technology policy to support industrialization. The central technology policy issue has often been seen in terms of questions like: how to create a structure of local R&D institutions and how to ensure that those institutions are actually used after they have been created. These questions are far from being the same as the question of how to achieve and sustain indigenously driven processes of rapid technical change.

- It may be useful to adopt technology-specific focus on the radical technological advance

facing industry. However, it may be more important for many purposes to focus on a more general technological change that underlies all those revolutions. Technological change involves the associated dramatic increase in the significance of knowledge and human capital.

- In the context of industrializing economies, the central issue is not just about investment in these change-generating activities. Nor is it about reorganizing and managing more effectively the capitals for undertaking those activities. The problem at the heart of the key technology policy issue is therefore not simply about investment in R&D to create new knowledge. Instead it is about investment in creating the whole spectrum of human and institutional resources for generating and managing technical change.
 - Even in industrialized economies, R&D is only a part of the activities that contribute directly to technical change. There is a wide range of design and engineering activities through which the results of R&D must pass before they result in commercial use of technology. Without any direct inputs from R&D, design and engineering activities are frequently sufficient in their own right as sources of technical change – especially as generators of the continuous process of technology diffusion.
- Policy attention had concentrated almost exclusively on the technology supply-side (presumed to be technologically active and creative in the process of technical change), while virtually ignoring the user-side (presumed to be technologically passive selectors and adopters of technology). Over time, the focus of policy attention has shifted from supply-side to user-side. Initial ideas centered on R&D institutes as the key local sources of technology for industrial users, and on the issues of how to link the two. By the early 1970s, some studies identified local consulting and engineering organizations as a link between technology users and local machinery producers and an independent source of technical change for technology users.
- However, it became realized that the distinction between technologically active producers and technologically passive users is fundamentally misleading. The users generate a host of improvement and modification in their production systems. They make key creative contributions to technical change through interactions with suppliers of machinery and inputs, research institutes and consultants. A pre-requisite for such creativity is substantial investment in the accumulation of human resources within the technology users. In the process of industrialization, such investment has been the basis for the development of more specialized local suppliers of inputs to technical change: enterprises producing engineering services and capital goods frequently emerged out of that explicit investment in knowledge and human capital on the part of technology-using enterprises.
- More generally, economists have begun to understand two key issues. 1) Individual firms are not the source of innovation and technical change. Technical change is generated out of complex structures of interaction between firms, and sometimes between firms and supporting infrastructure. 2) Those supporting institutions can rarely generate technical change on behalf of industry without significant innovative activity on the part of industrial firms. They may play important complementary roles in relation to innovation taking place in industry, but they can rarely act as a substitute for it.
- These perspectives on the process of technical change in industry pose new problems for policy makers and new questions for policy research. It is ineffective to define industrial technology policy as industrial R&D policy and to see that policy arena as the preserve of government agencies with focus on issues about resource allocation to R&D. The problem area for policy should be much more broadly defined, with responsibility for its various dimensions spread widely across all relevant government agencies. To support this perspective, policy research needs to provide much greater understanding than is available about such questions as:

- How is the micro-level technological behavior of industrial firms influenced by key aspects of the structure of industrial production and how to those relationships differ between industrial branches and stages of industrial development?
- What aspects of government policy influence those aspects of industrial structure in ways that contribute both positively and negatively to technological change and to investment in the underlying human and institutional resources for generating and managing technical change?
- What factors influence those aspects of technological behavior within given structural conditions – not only micro-level factors concerned with management and macro-level factors stemming from overall economic policy, but also institutional factors concerned with mechanisms and incentives for investment in change-generating capacities in industry?

I. Evolution of Research System

The social role of scientists appeared first as a vague idea in the 17th century Europe. The role of experimental philosopher and scientific academies emerged in England. In the later half of the 18th century, the government-supported academy and the employment of scientists in various educational and consultative capacities emerged in France. In the middle of the 19th century, the combination of teaching with research in the role of the professor and the research laboratory emerged in Germany. In the early 20th century, the trained professional researchers and the department combining research and training and the more complex type of research institute emerged in the US. At each of these turning points, the center of scientific activity shifted to the country where the innovation occurred, and innovations in the organization and use of science were eventually diffused to other countries, raising the general level of activity everywhere.

- The Industrial Revolution and its aftermath undermined all established religious and ideological authority and created an inclination to follow the Francis Bacon's suggestion to seek true knowledge in empirical and experimental inquiry into natural phenomena. Scholars with knowledge of mathematics and natural philosophy benefited from social environments favoring to their interests at universities, studios of artists and academies.¹
- The scientific center shifted from England to France in the later half of the 18th century.² Absolutistic monarchs were apt to support science for its technological and economic implications. Natural scientists started to become a professional community.³ They took advantage of the opportunities offered to them and turned them to the benefits of scientific inquiry. Organizations became an important determinant of scientific activity around 1840. After that the jumps in scientific activity occurred as a result of the

¹ Few did research as their full-time or main occupation: at that time the role was called "natural" or "experimental" philosopher. The word scientist was substituted for these early in the 19th century, and was coined in England. The scientific role has been transformed considerably since the 17th century. Then, experimental philosopher were largely amateurs, with little or no specialized training in experimental philosophy. The large majority were highly educated, many of them having medical or mathematical training. With the partial exception of teachers at universities and college they lived on private income or income unconnected with their scientific research, and specialization among them was rudimentary.

² The shift of the scientific center from England to France did not establish a very profound French superiority. The bulk of the scientists in both countries were amateur who came from the upper bourgeoisie and the aristocracy who could afford to spend their own time and money on research. They were not designed as an attempt to transform science into a regular occupation. The function of scientists was to make discoveries. This distinguished science from scholarship, which dealt with the restoration, preservation and transmission of the literary tradition. The expected uses of science were similar in both countries. They were first and foremost technological, which made science acceptable also to the conservative groups. The supremacy of Paris was manifested in the fact that scientists and intellectuals from the other countries of the Continent treated France rather than Britain as their center and model. Their scientists and scholars went to Paris rather than to London to further study. In other political units of continental Europe such as Russia, Prussia or Austria there were no large and important social groups interested in the institutionalization of science as a social value.

³ The links of the leading scientists with the political elite were considerably extended. Scientists as a class became part of the official elite during the last years of the Revolution, and they maintained this status under Napoleon. Before 1789, the majority of scientists were wealthy men (noblemen, physicians, etc.) who financed their scientific work from their own resources. After 1796 scientists in France usually had a position either in higher education or in the educational civil service. The reason for the dissatisfaction with the educational and general intellectual monopolies of the clergy disappeared. This fact was not changed by the Napoleonic reaction against the revolutionary reforms.

discovery of new uses of science, leading to changes in the role of scientists and innovations in research organization.

- During the first three decades of the 19th century, French scientific supremacy became unequivocally established. All the fields of science were pursued at an advanced level only in Paris. This systematic coverage of all the sciences in a single center has been interpreted as the first instance of organized professional science in contrast with the amateur pattern of the 18th century.
- However, it was not the result of any new ideas or practices about scientific training and research, or about the uses of science. It was rather the result of increased support for science. This support was not done with a view to creating public facilities for the systematic training of future research workers.
- The French scientific leadership came to an end about 1830 to 1840. French system had been relatively ineffective in responding to the challenge of organized scientific research that emerged in Germany about the middle of the 19th century.
- It was difficult to adapt scientific organizations to new situations. In order not to hurt vested interests and also for reasons of bureaucratic convenience, French government preferred to create new institutions rather than to try to change existing ones.

· The transformation of science into a status approaching that of professional career and into an organized activity took place in Germany. Practically all scientists in Germany were either university teachers or students by the middle of the 19th century. Research became a necessary qualification for a university career and was considered as part of the function of the professor. The transmission of research skills took place in university laboratories and seminars. In the late 19th century research in experimental sciences became organized in research institutes, which were usually attached to universities and possessed their own facilities and supporting staffs.

- Industrial research and technological institutes became important users of university-level science by the 1870s. This did not lead to the growth of research institutes in German universities, which was curtailed by the rigidity of the university structure. The professors, as a corporate body, prevented any important modifications of the structure that separated the institute from the chair. They restricted the growth of new fields. There was no organized system for training professional research worker.
- When transferred to the US, further growth of research institutes took place, which was then partially imitated in Europe. But this imitation did not take place within the universities. It led to specialized non-university research institutes.

· The graduate training in the basic scientific subjects and the active support of problem-oriented research related to professional training were developed in the US, between 1860s and the time of World War I, which lowered the barrier against organized research in US universities.

- The departmental structure made it easier to assimilate the administrative arrangements for research into the university. New specialties could easily be accommodated and nurtured within existing departments until they became strong enough to operate independently.
- The US system had been better capable of developing within the universities (or in cooperation with the universities) a field of research that originated from practical interests.

· Germany and the US, where the two great spurts in scientific production took place, had highly decentralized scientific system. The combination of research and teaching was not independent of decentralization. Higher education provided opportunities for the extension of the uses of science. In decentralized systems with initiative and enterprise in science, the delimitation of research from teaching could be constantly changing.

1. Emergence of Organized Science in Germany

The first step towards the transformation of German university was the establishment in 1809 of a new type of university – the University of Berlin. The new university was imitated within a short time by the whole system of German language universities. Intellectuals initiated this innovation, and their needs and ideas determined the original shape of the new system.

- The initial differences between the new French and German systems were due to the differences between the composition and character of the intellectual classes, which in turn were rooted in the different class structures. German intellectuals were usually not well-to-do people with independent incomes, nor were they generously supported by rich patrons. German intellectuals came from the modest middle-class background.⁴ Therefore, the dissatisfaction with the backward state of the universities in the late 18th century led to different reactions.
- In France, the intellectuals agreed to abolish the universities and accepted the *Grands Ecoles* and the specialized faculties as a replacement for the universities. In Germany, the intellectuals resisted the attempt to follow the French example in the reform of higher education. They were interested in raising the status of philosophical faculties within the universities to the level of the academies,⁵ and tended to be much more scientific than elsewhere. Their common interests and tendency eventually led to the transformation of the university into scientific institution whose members were engaged in creative research.

The rise of empirical science starting from the late 1820s was not a result of the new university, but of the conscious revolt against its philosophy and of an important, although not deliberate and conscious, modification of its structure. The superiority of German to the French system is to be sought, therefore, in the capability of the German system to change itself according to the needs and potentialities of science inquiry in spite of the wrong ideas of the university founders. By contrast, institutions in French system were incapable of adapting themselves to changes.

- The support given to the new universities in Prussia was not the result of the acceptance of the scientific philosophy by rulers.⁶ The natural science had not been favored in the new universities. In the early 19th century, there was a tendency in the German universities to deny the distinctiveness of the role of the empirical-mathematical scientists. Many chairs in the natural sciences were filled with adherents of the romantic *Naturphilosophie* who opposed mathematics as well as experiment. By the 1830s, however, the tide had turned and there ensued a flowering of the natural sciences and of the experimental approach in general at the German universities.

⁴ By English or French standards, Prussia had been a backward country even in the early 19th century. Its middle class was small and lacked political power and many of the social classes including a majority of bourgeoisie were traditional. There were no groups at all that sufficiently wealthy and important to gain any independence from the ruler and his bureaucrats. The rulers began fostering commerce, industry and education at all levels without abandoning any of their prerogatives. As a result, groups of young people emerged who were educated according to the ideas and the ideals of the French Enlightenment.

⁵ Some German universities in the 18th century had employed up-to-date scientists and scholars among their teachers. These teachers usually taught only students studying for the lower academic degrees, and the philosophical faculty was subordinated to the faculties of law, theology and medicine. The status and income of the teachers in the philosophical faculty was much lower than those of the higher faculties.

⁶ After the defeat by Napoleon, the Germans could find comforts only in the unprecedented flowering of national philosophy and literature. For the first time, German philosophers became important public figures in their own country, and their advice was heeded, especially in matters of education. The support given to the new universities was forthcoming because of the acceptance of a new speculative philosophy that extolled an ascetic idea of nationalistic philosophical, literary, and historical culture that was believed to be superior to everything else in the world. The university representing this philosophy was granted autonomy. This support, however, was not the tantamount to the acceptance of free inquiry as an independent and socially valuable function.

- The Effectiveness of the German system depended on 1) the quality of those recruited and 2) the existence of some countervailing forces capable of neutralizing corporate defense of selfish interests by the universities.⁷ Arrangements for this purpose such as *Habilitation* and *Privatdozentur*, however, could not provide the expected checks and balances. It was the competition among universities in the large, expanding academic markets of politically decentralized German-speaking areas that counteracted the vested interests of university senates, thus enabling individual scientists to undertake and initiate innovations.
 - Great attention was paid to ensure the high quality of appointments. The requirement for academic appointment was the *Habilitation*, which was supposed to be an original contribution based on independent research. The *Habilitation* was supposed to ensure that the appointments to professorships would be competent and highly motivated researchers. There was also arrangements to create an independent countervailing force to the corporation of university professors: the institution of the *Privatdozentur* and the freedom of students to choose their lectures and to transfer credits from one university to another.⁸
 - These ingenious arrangements, however, could not provide the checks and balances for which they were intended.⁹ The condition that counteracted the oligarchic

⁷ In the absence of a wealthy and free middle class and/or strong liberal parties supporting the cause of science against governmental despotism, the only available social device for safeguarding the freedom of science was the old academic corporation. However, enlightened public opinion (the intellectuals and government circles) regarded the old university-corporation as reactionary bodies that were responsible for the decay of the university. The solution was to transfer to the state the functions of financial supervision of the universities, of responsibilities for part of the examinations qualifying for professional practice, and of the appointments to the chairs. The latter function, however, reverted in practice to the academic corporation, although the state preserved its ultimate rights. The university senate remained in charge of all the academic affairs. Thus the reformed and enlightened state was to assume responsibility for the furtherance of science and to prevent the development of guild-like rigidity, while the academic corporation was to counteract any despotic tendencies of the state and safeguard the freedom of the individual researcher. The corporate structure was not chosen for its flexibility or efficiency. Indeed it was neither flexible nor efficient. It is doubtful that academic self-government contributed positively to the adaptability of the German system.

⁸ Those who obtained a *Habilitation* had the right to lecture at the university, even if not elected to chair (they did not have salaries, and obtained only attendance fees paid by the students who choose their courses). From this community, those who excelled were to be elected as professors. Election conferred on the professor special emoluments and honors. Otherwise, a chair was not supposed to change the conditions of the professor's work, nor was it supposed to confer on him any authority over the *Privatdozenten*. All remained free and equal as scientists responsible only to their own scientific conscience, and the public opinion of the scientific community and the students. The other countervailing force was conceived as a system of checks and balances. Any shortcomings of the privileged professors were supposed to be revealed by the independent *Privatdozenten* and the students, who could show their disapproval effectively by moving elsewhere.

⁹ The university community was not identical with the scientific community of competent researchers in a field. And there was no formal structure through which such scientific communities could influence universities. The formal structure of university counteracted the effective development of such communities by the creation of an invidious power and status gap between the elite and other members of the communities. Neither *Privatdozenten* nor students shared much common competence. The university community was divided by gaps of authority and power. Each professor had in fact personal authority over the *Privatdozenten* or the candidates for the title in his own field. A *Privatdozenten* could not make possible the effective exposure of the incompetence or narrow-mindedness of a professor through competition. Neither the rest of the professors, nor the *Privatdozenten* were really competent to judge. The professors alone conferred the title, and their assembly (the senate) held the key to promotions, new appointments and the creation of new chairs. Indeed, from the very beginning, there were conflicts between professors and *Privatdozenten*. The ministers of education had to interfere in university appoint-

tendencies of university senates was the competition among a great number of universities within the large and expanding academic markets of the politically decentralized German-speaking areas of Central Europe. This freedom of scientists, which was ensured by a competitive and expanding university system, made it possible for individual scientists to undertake and initiate significant innovations.

- The universities, as a group or individually, did not develop physics or chemistry. They did not have executives whose function was to foresee and facilitate scientific development, which was done by the interactive efforts of physicists and chemists working at different universities. Their work was encouraged and facilitated by the existence of the lively demand of universities for successful researchers. As long as there was a seller's market in science, there was always a university that could be persuaded by to adopt an innovation. Academic vested interests often opposed innovations, and many an important appointment was forced on unwilling university senates by heads of the university sections of various ministries of education. The ministries used the power vested in the state to override the decisions of self-governing university bodies.

The competition among the universities and the mobility ensuing from it created an effective network of communications and an up-to-date public opinion in each field that forced the universities to initiate and maintain high standards. It was the inter-university networks of communication and public opinion in the different fields, and not the formal bodies of the university, that represented the scientific community. The pressure of this informal community (which arose and gained influence as a result of the working of the decentralized system), rather than the corporate structure of the university, ensured that the needs and potentials of creative research guided academic policies. Since the middle of the 19th century, the laboratories of some universities became the centers and sometimes virtually the seats of worldwide scientific communities in their respective fields.

- The opportunities for innovation led toward the emergence of regular training and careers in scientific research.¹⁰ Since there was a regular market for successful researchers in Germany, it paid to invest in research. It was possible for a university teacher to use his academic freedom for the purpose of concentrating much of his teaching efforts on the scientific training of the few would-be researchers. He could then use his bargaining power and that of his students (who were free to move and transfer credits to any other German-language university) to obtain laboratories and other facilities for research.
- Towards the end of the century, the laboratories of some of the professors became so famous that the ablest students from all over the world went there. The list of the students who worked in such places often included practically all the important scientists of the

ments in order to override decisions of university senates motivated by prejudice and vested interests.

¹⁰ In England during the first half of the 19th century a young man could engage in research only if he could afford it as a hobby or if he was devoted to science to an extent that he was willing to face real deprivation for its sake. In France the situation was slightly better. There, able young men, who had passed the hurdle of several more-or-less difficult and irrelevant examinations could obtain jobs where they could afford to pursue research part-time with some prospect of gradual advancement to positions permitting more and more free time for research. Both in England and in France, however, the initial opportunity to go into research was the result of means and positions attained for other reasons. Once a person could afford to do research and turned out to be successful, he could use his fame for obtaining further facilities and means of livelihood for the pursuit of his interest. In Germany, it was possible to make a realistic guess about the employment opportunities for researchers, go into research straight away at the university, and regard the four or five years spent working one's thesis and *Habilitationschrift* as an investment toward entrance into a reasonably well-paying and highly interesting position. It was this gradual transformation of research into a career that enabled the universities to realize the ideal that teachers should also be creative researchers. Those who wanted to go into research were interested in obtaining training for it.

next generation. Research started to become a regular career, and scientists in a number of fields started to develop into much more closely knit networks than ever before. Their nuclei were now university laboratories training large numbers of advanced students, thus establishing personal relationships (highly effective means of personal communication) among them, and the beginnings of deliberately concentrated and coordinated research efforts in a selected problem area.

- Unexpectedly, in empirical sciences, there emerged research organizations that required growing investment and produced new knowledge of a kind that could not be related any longer to the original purposes.¹¹ The establishment of a chair required considerable investment as well as a commitment on the part of the university to train a certain number of students on an advanced level in a new and specialized field. There was an obvious need for redefinition of the functions of university and the role of the researcher. The redefinition of the functions that became necessary was a problem that concerned not only the universities but also the place in German society in general.

The rise of organized laboratory research and the availability of trained researchers made possible a new kind of applied work. By the 1870s, science came into close relationship to technology through the scientific training of engineers and increasingly frequent recourse to scientific consultation and research by industry, hospitals and the military. Thus the science had reached the limits from which it could develop as a subsystem insulated from the rest of society. Rather than changed their structure to take full advantage of the expanding opportunities, however, the university adopted a deflationary policy of restricting the growth of new fields and the differentiation of existing fields. The professors, as a corporate body, resisted any important modifications of the structure that separated the institute from the chair. The competitive mechanism that brought experimental sciences to the forefront of the university was impaired. Therefore, the initiative in the new fields of science was addressed to the central government, leading to the establishment of non-university research institutes.

- Industrial research and technological institutes became increasingly important user and eventually also producers of university-level science. However, the professors resisted any innovation of a practical or applied character. They did not admit engineering studies to the university, and resisted the granting of academic degree-awarding powers to institutes of technology, which was nonetheless conferred by the emperor in 1899. Intellectually important innovations, such as physical chemistry and physiological chemistry, were only grudgingly granted academic recognition.
- Specialists in applied fields were very sparingly given the rank of professors. Mostly, the growth of research and specialization led only to a swelling of the ranks of assistants. There was no organized system for training professional research worker; there was no conception of career leading to professional research worker by gradual steps.
- The expansion of the university and its research activities was very rapid. Although the number of students and staff increased and the expenditure of the universities increased rapidly with the steeply growing expenses of research, no modifications were made in the organization of the university. Particularly in natural sciences, which had the greatest potential for growth, the ratio of professors to other academic ranks (*Extraordinarius* and *Privatdozenten* with some academic standing and institute assistants

¹¹ The role of the professor-researcher was deliberately created by the reformers of the German university, but the original conception had not been that of a laboratory head who directed the work of several researchers but that of a philosopher-scholar who worked on his own research. The university was to be the place where a few dozen such professors would teach a few hundred students about the intellectual foundations of the learned professions. In 1820, a single teacher could teach chemistry. He taught what was needed for the preparation of a chemistry teacher of senior high schools, and did research in his own private laboratory. By 1890, the field was too complex to be handled even by four professors, and most of their research was of interest to other active researchers.

with no formal academic standing) changed considerably. Such development was probably due to the growth of research institute that encouraged professors in experimental science to regard their respective fields as personal domains,¹² leading to a sense of frustration and hopelessness in the academic career manifested by the rise of organizations resembling trade unions in the lower ranks.¹³

- In the basic fields and established fields with direct applications, expansion continued but became selective. Among existing and well-established fields, there was a rapid growth of new university chairs only in mathematics and physics. In other established fields, there was little expansion. Intellectually important innovations, such as physical chemistry, physiological chemistry, were only grudgingly granted academic recognition.¹⁴
- The competitive mechanism that had previously ensured the prevalence of purely scientific considerations in the establishment of new fields of study was impaired. It worked as before in theoretical fields that did not require large-scale laboratory facilities (theoretical physics, mathematics). Where laboratory facilities were required, rapid growth occurred only in experimental physics and clinical medicine, which did not compete with any established disciplines. Their growth had been also stimulated by the external competition of the institutes of technology, new governmental research institutes, and public hospitals with good research facilities.¹⁵
- This new situation was a reversal of the trend that brought the experimental sciences to the forefront of the universities. The effectiveness of competition had been dependent on the opportunities for innovators of new specialties (usually young) to establish their names independently of their teachers and to obtain a separate new chair and laboratory. They used to obtain chair and laboratory first at a peripheral university, and then success would compel the other universities to allow suit. With the growth of institutes in the older experimental fields (chemistry, physiology), it became impossible for a young person to establish himself without the aid of a professor, because no one could do significant research outside the institutes any longer. This development increased the power of the heads of the institutes, who had vested interests in keeping new specialties that arose in their fields as subspecialties within their own institutes rather than allowing them to become separate chairs with claims for new institutes.

¹² Those who were to become research workers acquired specialized knowledge and skills informally as assistants working with professors in the research institutes usually attached to the chairs. It was difficult for the student to acquire an all-round training in his field, because he worked with a single teacher. Moreover, the research institute attached to the chair was like a feudal fief of the professors. It gave rise to feelings of insecurity among those who aspired to a research career. Unless they were appointed to a university chair, they remained assistants in a bureaucratic framework without independent professional standing, even if they were advanced research workers performing important tasks in research.

¹³ The difficulty experienced by the aspiring scientists was largely a result of the conservatism of the university organization and the professional oligarchy. The institute was like a feudal fief of the professors. The increase in research activity fostered a progression from the mere beginner to the most experienced and successful leader in a field. However, the organization of the university obstructed this progression as a result of the gap in power and status between the professor who had a chair and all the others who did not.

¹⁴ Specialists in these fields received titles of *Extraordinarius* (Extraordinary professors), or institute head, but they were only very sparingly given the rank of *Ordinarius* (the only real professors) and then not through the establishment of new chairs but by the appointment of individuals to existing chairs with loosely defined terms of reference. Mostly the growth of research and specialization led only to a swelling of the ranks of assistants.

¹⁵ Even here development was held back. University physics laboratories were considered inadequate by the 1880s, and clinical fields were considered as substantive specialization within the established basic medical discipline. These specializations were not given the autonomy accorded to the new clinical research units that started to emerge in the US toward the end of the century.

- There were obstinate and long, drawn-out debates about the theoretical importance of new fields to justify the establishment of any new chair. These debates, which were often conducted in terms of personal qualifications of particular candidates, often obscured the real issues and also introduced a great deal of personal bitterness into academic matters. Had the universities been organized as departments, these matters might have been treated in a quite personal fashion.
- Thus the rigidity of the corporate organization came into full play. As long as the social unit of research was the individual and the fields were few and distinct, the system of independent chairs suited the requirements of research reasonably well. Competition could compel the universities to do this. But once the basic unit of research became the group, and the boundaries of the fields became increasingly blurred, there was a need to change the organization. However, the corporate university was unwilling to change, and, in the absence of strong university administration, competition was not enough to force it. They preferred the establishment of new non-university research institutes to making changes in the structure of the universities. The initiative in the new fields of science was therefore addressed to the central government. Thus arose the *Physikalisch-Technische Reichsanstalt* in 1887, and the *Kaiser Wilhelm Gesellschaft* (now *Max Plank Gesellschaft*) in 1911.

2. Development of Professional R&D in the United States

The graduate training in the basic scientific subjects and the active support of problem-oriented research related to professional training were developed in the US, between 1860s and the time of World War I, which lowered the barrier against organized research in US universities. The departmental structure made it easier to assimilate the administrative arrangements for research into the university. New specialties could easily be accommodated and nurtured within existing departments until they became strong enough to operate independently. Furthermore, the US system had been better capable of developing within the universities (or in cooperation with the universities) a field of research that originated from practical interests.

- As welcomed visitors, US students in German universities did not have any difficulty in being admitted to institutes or in moving from one institute to another. US students were an already highly selected group who possessed a first degree and occasionally even some research experience. The problems of academic career in Germany did not disturb them, since their careers were not dependent on the German professor. Therefore, they were not acutely aware of the problems in German universities that arose from the bureaucratic subordination of the assistants to the heads of the institutes. From their point of view, the institutes were integral parts of the university where research and training for research were performed. When they returned to their country, advocating the adoption of the German pattern, they did not make any distinction between the chair and the institute. They did not see how different the departmental structure was from the combination of chair and institute that they admired, and they were establishing in their own universities.
- As the function of universities was to train people to perform and apply research of high standards, the universities had to have up-to-date research laboratories. These facilities were not only necessary to make it possible for the professors to pursue their own research, but also for the training of graduate student. By the early 1900s, the research organizations developed in some basic scientific departments became a challenge to European science, and hence served as an incentive for the establishment of new research organizations such as the *Kaiser Wilhelm Gesellschaft* (*Max Plank Gesellschaft*) in Germany and the *British Research Councils*.
- This development had started in the German universities where professors had their small research institutes: but their growth within the European universities was curtailed by the rigidity of the university structure. When transferred to the US, further growth of

research institutes took place, which was then partially imitated in Europe. But this imitation did not lead to comparable growth, nor did it take place within the universities. It led to specialized non-university research institutes.

The diffusion of innovation and eventual assumptions of its multiplicity of functions by the US universities had not occurred as a result of a preconceived plan but as a result of the system of higher education. The system of higher education was far more decentralized in the US than in Germany. As equally important conditions was the absence of important monopolies conferred on the system as a whole.

- In the formative years of the system – between 1850 and about 1920 – there was a wide range of ideas about the functions proper and improper to a university, and the arguments debated were in many years the same as those debated in Europe. But the effects of these ideas were very different because of the difference between the ecology of US academic institutions and their European counterparts.
- In Europe, the procedure for university innovation was to convey the ideas to the government, which then rendered a decision among the conflicting view points based on a more or less public debate of the issue. In the US, however, there was no central authority, or even informal establishment to lay down policy for the whole country.¹⁶ Therefore there was no concerted opinion on a national scale or organized action to press the government to put certain schemes into action or at least support them.
- The protagonists of an idea tried to realize their schemes in institutions where they worked. There were of course state-supported universities, as in Europe. But they were not the only ones, and they were far from enjoying monopolistic advantages. In the US, the state universities not only compete among themselves but also had to compete with the private universities.
- Decentralization was not, however, the only condition that made the US system more receptive to innovations. Early in the 20th century, lawyers, doctors, teachers and civil servants were often trained outside the universities. The most important middle class was business, which did not at that time require either formal or certified training. The universities had to prove that they were useful and worthy of support by initiating new courses of study and research, and by successfully marketing their services.

The US universities had constantly to adapt to innovations to maintain their standing and to compete for personnel and resources. Hence, they could not be run either in the civil service manner according to fixed personnel establishments and regulations, or in the manner of wholly autonomous corporations of teachers, scholars and scientists. The group of presidents nurtured the growth of the universities. The imitation of the German model did not involve the adoption of the German system of university governance.

- Until the 1860s, college presidents were the managers of their institutions, acting on behalf of the trustees who formed the corporation that enjoyed legal ownership of the physical assets of the college. A new type of president accompanied the rise of the new universities, who combined the qualities of autocrat, statesman, and entrepreneur. He was still very much the dominant figure, but increasing size, increasing complexity of task and increasing self-esteem on the part of academic staffs of increasing eminence required that he must be able to delegate authority and acknowledge claims to academic freedom. Group of presidents laid the foundation of governance structure by much less powerful presidents responsible to a board and assisted by full-time academic administrators, such

¹⁶ In the US, the need for a national institution related to science and technology was recognized soon after the Revolutionary War. The founders of the Constitution believed that the national government should exert its influence through indirect rather than direct means, that is, educational and scientific activities should be independent of direct national governmental control.

as vice-presidents, and deans. They had to be an entrepreneur modifying their policies and university organizations in an ever-changing situations, and trying to push his university ahead in its class through careful forward planning and rapid exploitation of new ideas.

In order to operate effectively under these conditions, the sub-units of the university had to be flexible enough to carry out all the diverse functions of the university as well as to adjust to new ones. They also had to be autonomous so as to be able to make changes in courses of study, teaching arrangements, and staff recruitment without undue delay, and of sufficient size to perform training and research functions effectively in fields requiring many kinds of specialization. The most important of the units emerged was the department in the basic arts and sciences and the larger professional schools.

- The department was the US substitute for European chair plus research institute. However, instead of having a single person fictitiously representing broad areas of research, this task was given to a group that might actually represent the subject in its entirety.
- This development had rapidly transformed the role of scientists. By the first decade of the 20th century, there emerged the conception of the professionally qualified research worker. A Ph.D. in scientific subjects assumed the same meaning as the M.D. in medicine. Those who possessed the title were considered qualified for research just as a M.D. was qualified to practice medicine. The requirement of a Ph.D. made suitable candidates scarcer, and thus raised the market value of those who possessed the degree.
- The principal effect was to create a professional role that implied a certain ethos on the part of the scientist as well as his employer. The ethos demanded that those who received Ph.D. must keep abreast of scientific development, do research, and contribute to the advancement of science. The employer, by employing a Ph.D., accepted an implicit obligation to provide him with the facilities, the time, and the freedom for continuous further study and research that were appropriate to his status. This development was a new departure from the particular status of college teachers in the 19th century.¹⁷ It also entailed an important departure from European usage.¹⁸

The new conception of the scientist's role as a professional one and the flexible structure of the university with its openness towards innovation also introduced many changes in the hitherto prevailing relationship between academic organization and science. In the US, academic freedom is not the autonomous self-government of senior professors who act as a corporate body in directing the affairs of the university as a whole. Instead, it is the scientist's guarantee of freedom from interference with the direction of his work and the expression of his views by an administration representing a lay board and from interference originating from outside the university.

¹⁷ College teachers were then employees of the president or trustees, both of whom were accustomed to treating teachers in a very authoritarian fashion, as if they were no more than the assistants of the president, helping him to do the job for which he was responsible.

¹⁸ In Germany, research was not considered a profession. The role and career of the research workers was not one of the central elements of German science organizations, which became mattered only as late as 1900. Scientific achievements were considered as being sacred, as expression of the deepest and most essential qualities of a specially gifted person, which was nothing to do with institutional provision. Research was a voluntary, non-paid activity. The professor was not in principle paid for research, but he occupied a role with a stipend that made it possible for him to do research as he wished. The *Privatdozent* could do research if he could arrange it. He received officially neither salary nor fund for research. If he worked in the laboratory, he did so on the professor's sufferance. According to this view, research that was directly paid for was not considered as research because it had none of the metaphysical pathos of the deepest expression of a creative spirit. It was simple and bureaucratic work, which could be as narrowly and specifically prescribed as the employer (such as the professor heading the institute) wished it to be. Academic freedom in this scheme was the freedom of a privileged estate.

- The professor is not legally a member of the university-corporation; from the very outset, he has been a professional, employed by an organization to perform certain loosely defined services. Although academics spend as much time on academic administration as their European counterparts, most of it concerns departmental affairs directly related to teaching, research and personal matters in the fields of most immediate interest to them. They also involve selectively in divisional or university-wide affairs. They participate in these affairs not simply in their capacity as equal members of a self-governing corporation, but as experts who advise the dean or the president.
- Academics also act as watchdogs of the autonomy of the academic staff to prevent the administration from doing anything that interferes with this autonomy. Here they appear as representatives of a professional body in a polycentric, pluralistic system of power allocation. Such institutions as the faculty assembly do not have much importance in the US. The trustees appoint the president, though staff representation and consultation play an important part in determining who is appointed.
- However, the professor has regarded it as right to insist that the university provide optimal conditions for the exercise of his scientific capacities and that it provide him with the freedom and the backing to establish those conditions for himself from funds that he seeks to obtain outside the university.

The emergence of the scientific role in US universities is intimately connected with mobility of scientists, which is the most important element that enable US universities to adapt to new possibilities in research and training. A scientist's standing in the professional community is much more important in the US than in Europe. Scientific associations play an important role.

- While mobility was strictly circumscribed in Germany by the academic career and the hierarchy of universities, it has been motivated in the US by an individual's assessment of what he wants intellectually at a particular stage of his career or what he desires in income. Scientists have become less identified with their universities than with their disciplines. There exists a professional community of scientists in each field, and one's standing in this community is a more important matter than in other countries.
- One of the tangible manifestations of the importance of the professional community is the relatively greater importance of professional-scientific associations in the US than in continental Europe. They play a more important role in publications, their conventions are more important affairs, and there is a close relationship between the scientific and professional aspects of their activities than in Europe. Only in the US has there been a general and early recognition that there is no necessary contradiction between creative accomplishment in research and the organization of research.
- Absence of prejudice against organized research and effectiveness through standardization made it much easier to devise increasingly complex and sophisticated types of organized research. Departments, research institutes, and laboratories soon outgrew their European counterparts in complexity as well as size. By the 1930s, the difference reached a stage when in some fields European scientists were no longer able to compete effectively with their US counterparts.

3. Research in Industry and Government

The rise of scientific entrepreneurs and administrators, the professional research careers, and the standardized procedures for staffing, equipping, and costing different types of research made scientific research into transferable operation. Administrators would move from university administration to the administration of large industrial or governmental research laboratories and establish research units of the same kind that existed in the universities. Research workers could work in any of these settings without having to change their professional identities markedly or give up their expectations or standards.

- The practice of scientific research in organizations that have non-scientific goals, of course, presents the possibility of conflict. The researcher may be required to engage in less interesting scientific problems. He may be limited in his freedom to communicate and cooperate with his colleagues who work elsewhere so as to safeguard industrial or military secrets. The attitudes developed in universities could not provide a ready-made answer to these problems, but they created a basis for a pragmatic approach to them.
- First of all they helped to make up a culture partly shared by industry and government that defined what could legitimately be expected of scientists. In this way, the culture of university science helped to create congenial environment in non-academic institutions for university-trained scientists. In consequence, industrial research was given considerable autonomy and a long time span to show its creativity. The industrial research worker was not considered just as any employee to be assigned at will to all kinds of trouble-shooting tasks.
- In these favorable circumstances, a type of research worker arose who was continuously and fully engaged in product development. Perhaps this role appeared first outside the university in the laboratory of Thomas Edison, where self-educated inventors performed the role. Gradually, this role was assumed by trained scientists and engineers and became more integrated with the complex activities regarded as falling within the jurisdiction of professional scientists.

By the turn of the century, it was widely accepted among US industrial leaders that scientific knowledge was the basis for engineering development and it was the key to competitiveness. Accordingly, industrial research laboratories soon began to blossom as companies realized their need to foster scientific knowledge outside of the university setting.¹⁹ Private foundations also began to grow and to support university researchers.²⁰

- Many smaller firms also realized the competitive threats that they could potentially face as a result of technological competition, but they could not afford an in-house facility due to their size. So as a market response, contract research laboratory that specialized in the area of chemicals.

Increased pressure on the pace of scientific and technical advancements came at the beginning of World War I, when the US had been cut off from European research base.²¹ The post-war prosperity also created an atmosphere supportive of the continued support of science and technology.²² A variety of modes of supporting training and research by government and

¹⁹ General Electric (GE) established the General Electric Research Laboratory in 1900 in response to competitive fears that improved gas lighting would adversely affect the electric light business, and that other electric companies would threaten GE's market share as soon as the Edison patents expired. Similarly, AT&T was the same time facing increasing competition from radio technology. In response, AT&T established Bell Laboratories to research new technology in the event that wire communications were ever challenged. As a final example, Kodak realized at the turn of the century that it must diversify from synthetic dyes. For a number of years Kodak relied on German chemical technology, but when that technology began to spill over into other areas such as photographic chemicals and film, Kodak realized that their competitive long-term health rested on their staying ahead their rivals. Kodak too formed an in-house laboratory.

²⁰ For example, the Carnegie Institution of Washington was established in 1902, the Russell Sage Foundation in 1907, and the Rockefeller Foundation in 1913.

²¹ Congress, in response, established the Council of National Defense in 1916 to identify domestic pockets of scientific and technical excellence. The National Academy of Science recommended to President Wilson the formation of the National Research Council to coordinate cooperation between the government, industry and the academic communities toward common national goals.

²² In 1920, there were about 300 industrial research laboratories, and by 1930 there were more than 1,600. Of the estimated 46,000 practicing scientists in 1930, about half were at universities and over a third were in industry.

industry without direct involvement also emerged from extension of the research activity beyond the limits of the university. The most common are research or training grants, contracts, and donations.

- These supports have advantages. They are given to persons and organizations of proven competence. They give the recipients sufficient freedom to devise their own plans and at times even change their original scheme as soon as they find out that it is not the most fruitful one. Finally, they encourage constant reevaluation, criticism, and comparison of programs and changes in policy without the necessity of abolishing or drastically changing whole organizations.

The existence of professional research workers and standardized procedures for the organization of research has been a necessary precondition for this proliferation and flexibility of research activities. The close relationship between universities on the one hand and government, business and the community in general on the other had been initiated and managed by administrators specializing in academic and scientific affairs (university presidents, officers of foundations, governmental research directors). The emergence of the specialists in university and scientific administration with traditions in initiative and a considerable body of know-how have been a *sine qua non* of the growth of science in the US.

In Western Europe, research aiming at the solution of practical problems (or more generally research taking place in fields where likelihood of practical applications was great) occurred in segregated and specialized research institutions, which were usually financed by government and directly accountable to it. European governments had stepped in industrial research since World War I and more especially since World War II. Governments either established public institutions for applied research, or encouraged trade associations with subsidies to establish and operate such institutions.

- In Europe, the new functions of science emerged in the middle of the 19th century, and were grafted onto the national systems of higher education. From the last decade of the 19th century, however, the new functions of science were increasingly supported from the budgets of publicly financed research organizations and laboratories, established from time to time in an *ad hoc* manner. In a few cases, such institutions were financed by industry. Development work was mostly done in industry, but only in a few instances was it effective and systematic. To make up for this deficiency, therefore, the governments in Western Europe had also stepped into such field.

In the US, while the trend in the US had been from specialized institutions of higher education to universities performing an increasingly greater variety of functions, there had been a parallel development from relatively small-scale specialized research institutions to large-scale multipurpose ones. Such developments occurred in industrial and governmental research institutions. In no case was this development foreseen or planned in advance. It was the result of trial and error within a pluralistic and competitive system. As far as research is concerned, the superiority of large multipurpose organization seemed to be demonstrated.

- It was generally accepted that research as a cooperative enterprise (where ideas and skills could be indefinitely shared and where the sources of stimulation were probably quite variable) was superior to small segmented institutions. In large universities, there would always be some innovating fields and changes to ensure stimulation. In small specialized and segregated institutions, the atmosphere might easily become extremely homogeneous.
- Large, multipurpose institutions were particularly important in applied or mission-oriented research. Such investigations, with goals that were not derived from the normal internal processes of scientific research, were very likely to be interdisciplinary. Not only did the mission require it, but the administrator's attitude of indifference toward the dignities of academic disciplines was also likely to favor it.

- Small, specialized research institutes are likely to be more resistant to multipurpose projects. Where the director and senior staff were of the same disciplinary background, they were unlikely to seek new problems other than those that arose within the framework of their own disciplinary tradition.
- In larger more heterogeneous organizations, the director was less likely to be committed to a particular discipline. Administrators interested in results but not in particular disciplines could greatly facilitate the process of bringing in new types of personnel and taking on new problems. Such changes would create crisis in a small, specialized research institution. Some persons might have to lose authority or even their jobs in the process. Decisions, therefore, would be delayed.
- The frontiers between basic and applied research were continually shifting. Therefore, the establishment of specialized institutions in a promising field might immobilize resources at a future date when other fields had become more interesting. The multipurpose research institution was more effective than one with specialized concerns.
- European experiences also support this view. The liveliest places scientifically had been the capital cities, such as London, Paris, Berlin and Vienna, where by virtue of the spatial proximity of many relatively small institutions provided the atmosphere that only a large organization could have provided otherwise.

4. Governance of Research System

US academic and scientific institutions had thrived because they had learned from experience. They had to learn from experience, since their mere existence was no guarantee of their eminence. They had to compete for fame through accomplishment, and they had to compete for funds and for persons.

- They were helped in this competition by administrators who were not bound by the results and reputations of particular persons and whose concern for the whole institution made them more open to the lessons of experience.

To a large extent this innovating function had been absent in Europe. Self-governing university corporations had rarely been able to exercise much initiative because of their tendency to represent the vested interests of their members. Therefore, the nationalization of the university and the scientific research system, which was supposed to lead to more objective and better coordinated planning of higher education and research, had debilitated the capacity of the system to learn from experience.

- In effect, much of university corporations' efforts had always been directed at preventing change and innovation. Thus scientific policy making usually devolved on the government. As a result, policy was made at a great distance from its execution; and since it was always made for the system as a whole, there was little opportunity to evaluate its success, except by comparisons with other countries.
- The centralized systems had no constitutive feedback mechanisms such as are given by situations where universities and research institutes are free to make innovations and compete with each other. Also, there was no room in these systems for the development of executive and entrepreneurial roles that would not be too remote from the university's day-to-day activities and yet would also not be too completely absorbed into them.

The most obvious result of the system had been the transformation of the relationship between higher education and research on the one hand and the economy on the other. This enterprising system of universities working within a pluralistic, educational and economic system had created an unprecedented widespread demand for knowledge and research and had turned science into an important economic resource.

- It had been argued that making the practice of scientific research into professional

career might inhibit scientists from freely following the paths opened to them by curiosity and imagination. As a matter of fact, however, the widespread uses of science had created a very wide foundation for pure research, the aim of which was to increase knowledge without consideration for its potential uses.

- How the practical uses support science for its own sake can be seen from a comparison of the statistics of research expenditures in different countries. While per capita expenditure on research was greater in the US than in Europe, per capita expenditure on basic research was a smaller fraction of per capita expenditure on research in the US than in Europe. Nonetheless, the absolute amount of per capita expenditure on basic research in the US exceeded by a very great margin those in other Western countries. Entrepreneurial applied science, which extended research and training to new and often risky fields, did not ultimately diminish the share of basic research relative to the society's total resources, as had been feared in Europe.
- It was neither industrialists nor civil servants who established the link between science on the one hand and industry and government on the other. Rather there had been a constant and subtle give and take between professional scientists who had a fair idea of what they wanted and could do, and the potential users of science in the professions, industry and government. This mutually advantageous interchange was established and had been kept alive by academic and research entrepreneurs acting as organizers and interpreters between the interlocutors.
 - It was learned that the best way to utilize science for non-scientific purposes was not through subjecting research and teaching to non-scientific criteria. It was to aid science in its own immanent course and then to see what uses could be made of the results for productive purposes, for education, and for the improvement of the quality of life.
 - The economy had benefited from science, but a large enough proportion of the benefits has been ploughed back into research to ensure systematically organized pure research in an increasing number of fields.
 - What began to appear in Germany around the middle of the 19th century, namely, the students of a great innovator had become the normal state of affairs in the US. Due to their secure economic base, which was never established in Europe, these activities were then pursued in the US regularly and in a constantly widening range of fields.

There were also, however, negative aspects. One of these was the delicacy of the balance between the internal structures and the traditions of scientific and scholarly creativity on the one hand and the demands of the economic and political powers on the other. This balance is more delicate in the US than elsewhere because the pluralistic entrepreneurial structure and expansive systems of science and higher education require a much greater involvement of the universities in the affairs of society.

- Until the 1940s, this involvement had typically taken two forms. Universities and colleges were at times pressed to institute degree courses in occupations that had practically no prospective scientific content and to accredit courses with little intellectual content. A similar but more legitimate external influence led to the great extension of professional training at the universities in fields that had had only potential scientific content. The early efforts of land grant colleges in agricultural and engineering belong to this category.
- These attempts had not caused serious long-term damage to the system. The groups of creative and devoted academic scientists and administrators considered them either as evils to be contained or as challenges that spurred them on to extend serious research and study to these new fields. Thus, some of the worst anomalies had either been eliminated or

contained without seriously diluting the quality of the system as a whole.²³

- Since World War II the conditions had changed due to an overwhelming extent to the rapid rise in the central governmental support of science. The share of the federal government in total research and development expenditure grew from less than one-quarter in 1940 to more than two-thirds of the total in 1965.
- The reaction of the university system to the expanding opportunities was to take full advantage of the opportunity, and the allocation of funds by grants and contracts has preserved the decentralized and competitive character of the system. As a result, the US universities have not lost ground to other types of institutions, like institutes of technology and other specialized types of higher education, but had increasingly assimilated the latter into their own structure. They also increased their share in the governmental research expenditures.
- But there were signs of crisis that perhaps can be attributed to an inflationary situation, where the scientific system, stimulated by central spending, has attempted to perform things that it is intellectually incapable of doing. One of the manifestations of this was the growth of research to an extent where serious questions are raised about its usefulness either from the point of view of its contribution to knowledge, or to the economy or to any other social purpose.
- This might only be a limited problem of waste that could be corrected. But it seemed that the inflationary situation gave rise to further problems that made the correction of the situation difficult. The most acute of these was a new type of student problem.²⁴ In many fields in which graduate education expanded rapidly, there was no specific demand, and the criteria of competence were not quite unequivocal. Hence, the sudden rise in graduate education might have created the beginning of problem of an excess supply of highly educated people, or a feeling among significant groups of students and graduates that they were not an integral part of society. This may be part of the background (in addition to the Vietnam War and the urban problem) of the alienation and radicalization among students.

The mechanism of selection of a certain type of role and organization was competition between

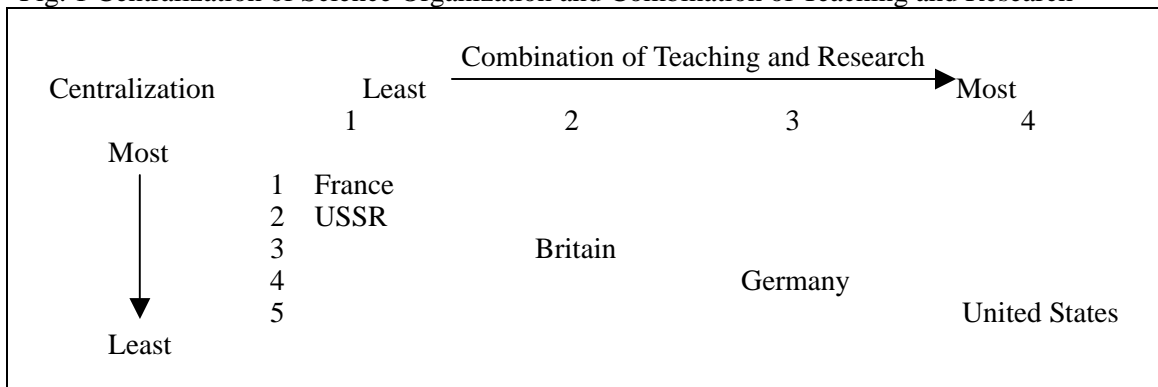
²³ The scientists in the faculties usually had little incentive or opportunity to become involved in these practical matters. Usually they regarded such involvement as a threat to science and scholarship. In this situation, university presidents had to act as mediators between the demands of the external environment and the requirements of the academic community, which demanded the greatest possible freedom for concentrating on pure science. Unenlightened state governments probably exerted the greatest pressures. They had the power, through their control of financial support, to force state universities into performing various non-academic services. In principle, boards of trustees of private universities had similar powers, but in practice at the most important private universities, they tended to share the academic rather than the non-academic outlook, at least in their capacity of trustees. Other groups, such as professional and voluntary associations, could only try to influence the universities by offering them support in exchange for the establishment of professional schools and the performance of similar services. As a result, the leading private universities that were the center of the system had to contend only with a relatively limited amount of pressure to compromise their standards. They were sustained by the prestige of their scholars and scientists, and by the fame of their institutions (not always exclusively intellectual). Despite the egalitarian deference system in the US, intellectual eminence, relative economic independence, and faithful and well-paced trustees succeeded in protecting the autonomy of intellectual activity.

²⁴ A large number of unemployed intellectuals had much to do with the alienation and radicalization of intellectual politics in Europe in the first third of the 20th century. This phenomenon had been virtually absent in the US. One of the distinctive features of the US system had been the willingness of graduates, especially of those who possessed only a first degree, to enter all kinds of occupations. This prevented the emergence of a significant group of university graduates who, either because of the specificity of their training or the level and content of their social aspirations, were unwilling to enter any but a few prestigious and well-remunerated occupations.

strong units of research operating in a decentralized common market for researchers, students, and cultural products. Decentralized systems have been more effective in the production and selection of new types of roles and organizations than centralized ones.

- Like the perspective of science, the organization of work most appropriate for research is also constantly changing. Thus, more decentralized systems are likely to produce a greater variety of ideas and experiments than centralized ones. Due to the numerous unpredictable ways that science can be enjoyed and used, a greater variety of experiments conducted by those competing with each other is also likely to produce more widespread demand and hence greater expenditure on science than decisions made centrally by a few wise men.
- Decentralization and competition provide a built-in feedback mechanism for distinguishing between what works and what does not work satisfactorily. Centralized systems have to create artificial mechanisms of self-evaluation that have not been too successful.
- The great spurts in scientific production since the middle of the 19th century took place in Germany and the US, which had highly decentralized scientific systems, and where the combination of research with education was maximal.²⁵ In decentralized systems where there may be a great deal of initiative and enterprise in science, the delimitation of research from teaching will be constantly changing. Thus it is likely that the combination of functions was not independent of decentralization. Higher education would provide the most numerous opportunities for the extension of the uses of science. Since more and more kinds of instruction were linked with research and higher education, there would be a greater likelihood for the exploitation of the opportunities that higher education created for research and vice versa.

Fig. 1 Centralization of Science Organization and Combination of Teaching and Research



- The countries that had a centrally directed science policy tried to assess the needs for science and allocated funds for it accordingly. This assessment entailed an attempt to distinguish as much as possible between the different functions of science and created a tendency to organize and support each function separately. Such policies, if executed by capable and wise people, can be very successful in creating conditions for first-rate pure

²⁵ The international diffusion of organizational and role models occurs not as a result of competition between equal units, but through the imitation of the innovations made in large countries. These latter are therefore much more likely to become scientific centers than small countries, and once they become centers they acquire monopolistic positions in science. As a result, scientists from all over the world have made these countries their spiritual home and center. They adopted the patterns of work prevailing at the center, because many of them obtained their advanced training there and because the usage of the center in training, evaluation and hierarchy of authority became the standard practice of the worldwide scientific community.

science by utilizing the experience of other countries. Such experts, however, will be in a much weaker position concerning the use of science. Foreign experience can help in this respect too, but not to the same extent as in the case of science for its own sake where the objectives are always the same.²⁶

5. Evolution of the Chemical Industry

Britain achieved an initial dominance in the chemical industry in the 19th century, because of its early entrance into textiles, but later began to flag. One important reason is that technical education and scientific research were not accorded the status in Britain. As early as the 1850s, most important chemical research and education was done on the continent. The Germans were particularly skilled in applied scientific research. Close relations were fostered between industry and universities, and industrialists sent their children to study science in universities far more frequently than did their British counterparts.

- This was particularly evident in the evolution of the synthetic organic industry based on coal tar, which revolutionized dyestuffs and eventually opened the road to synthetic fibers, plastics, and modern pharmaceuticals. German industry, in the latter part of the 19th century, established research laboratories to complement academic research, whereas no such laboratories seem to have existed in Britain until World War I.
- Another reason may be that industrialization had come about 50 years earlier in Britain, and hence more capital had been sunk in plants embodying old technology. The British investors, aided by the greatest free financial market of the time, found opportunities for lower risk and higher financial returns overseas in the rest of the British empire, as well as in the more traditional fields of iron, coal, steel and textiles. British banking system also encouraged growth in commerce and trade. German investors were latecomers on the industrial scene, forcing them to look for new opportunities, which they found in exports and in domestic industries based heavily on scientific research and newer technologies (including a drive for military self-sufficiency). Shut out of the easy opportunities for short-term profit, the Germans appear to have adopted longer time horizons than the British in their industrial undertakings.²⁷

²⁶ A good example of such research policy has been that of Britain during the last hundred years or so. Having possessed an established scientific elite with excellent political and social connections, it became alerted to the necessity of designing an official science policy earlier than any other country. Much of this policy was practically motivated as shown by the debates surrounding its formulation as well as by the priority given to the applied fields in eventual establishment of research councils. Nonetheless, the main success of these policies was in the basic fields. There are no indications of outstanding British success in applied science and development. But in basic science, British science has been quite exceptionally successful (shown by counts of publications, Nobel prizes, or any other index). The explanation of this result is as follows. The scientific advisors of the governments were eminently capable of evaluating the lessons from foreign experience. But they were not competent in making economic choices necessary for practically oriented research, and even had they been competent, the examples known to them would have been irrelevant. Therefore all that they could contribute to applied research policy was the certainty that the work done in the research establishments was of high quality. In this they succeeded, so that these establishments have indeed made important contributions to science. But whether these contributions benefited the British economy was a matter of chance. Thus contrary to its intentions, the British system became a model for a science policy designed to promote basic research. However, because the cost of basic research is also steeply rising, it is doubtful that this or any scientific policy that does not effectively promote the economic uses of science can be continued any longer.

²⁷ A thumbnail history of the first dye, mauve, illustrates many of these points. It was discovered in England by William Henry Perkin in 1856, a student of a famous German chemist, August Wilhelm von Hoffman. At the time Hoffman arrived in England (1845), English students who wanted training in

- Until the 1870s, Britain had a comparative advantage in the new chemical industry. It had the largest supplies of high quality coal in Europe, and the largest and most successful textile industry. It knew how to make dyes. It was rich. But it let its advantages slip away. By the end of the 1880s, the large German plants were producing more than 500 different dyes and pharmaceuticals at unit costs far below those of smaller competitors. Britain continued to produce dyestuffs, but it never regained its earlier prominence. The Germans came to excel in synthetic organic chemistry, based on coal tar and its derivatives.²⁸
 - Before the end of the century, it even legalized cartels (just before America's trust-busting era and legislation).
- The British government took no particular initiative to strengthen its infrastructure or its industry, whether in general or in the specific case of chemicals. It practiced more of the laissez-faire approach, letting some industries gain and some lose. In contrast, the German government became increasingly involved in the economy and concerned for national security. It imposed protective tariffs to encourage domestic industrialization, including the chemical industry. The German government also passed important patent legislation to protect intellectual property.²⁹
- Domination of dyestuffs helped to create the wealth, which propelled Germany into the position of strongest continental industrial power. Her banking system was strong, and had already assumed the major role in domestic industry that it possesses today. It worked very closely with the government to further Germany's imperial interests.

The US chemical industry was already approximately as large as German chemical industry by the time of World War I. US imports of German chemicals were cut off during the war, forcing US chemical companies to accelerate the development of their own organic chemical industry. The creation of new large-scale production techniques for new chemicals were greatly assisted by the development of a new academic discipline: chemical engineering.

- Although Germany had, in the late 19th century, established a strong tradition of chemical research at universities, the findings of the chemist were subsequently more or less handed over to mechanical engineers at individual companies. But the mechanical engineers had little understanding of chemical transformations, and were ill-equipped to evaluate the inherent trade-offs involved in designing new chemical processing equipment.

chemistry had to go to Germany. Their enthusiasm for the German methods of teaching chemistry led them, upon their return, to wish to establish educational facilities modeled on German universities. But the attempts to found the Royal College of Chemistry proved unsuccessful. Oxford and Cambridge neglected science education in favor of the classics, languages, religion, and literature. Student went into the armed forces, the foreign and civil service, law, politics, the clergy, and medicine; even sons of industrialists neglected science and shunned industry. Bernal (1939) observed that the 19th century scientists deliberately distanced himself from the industrial application of any discoveries, a self-removal which Bernal described as a 'sign of scientists aping the don and the gentleman'. By 1865, Hoffman received an attractive offer to return to Germany. He had become disappointed with the unprogressive of the dye industry, the backward state of organic chemical education, and the lack of sympathy on the part of business, the government and the conservative banks.

²⁸ By the 1913, German companies produced 140,000 tons of dyes, while 10,000 tons were produced in Switzerland, and only 4,400 tons in Britain.

²⁹ In Germany, a different atmosphere prevailed. Germany, united by Otto von Bismarck in 1871, was dominated by the landed aristocracy of Prussia, the Junkers. While the Junkers were militaristic and autocratic, learning and scholarship were nevertheless respected and received high social status. The unification of Germany resulted in the elimination of all internal tariff and customs barriers. Furthermore, victory in the Franco-Prussian War produced war reparations. An economic boom resulted, which ended in a speculative mania. Because of their continuing heavy emphasis on research and the application of the latest science, however, the young German chemical companies survived the boom and then the collapse into the great depression of 1873-1879, in contrast to their French and British competitors.

Moreover, a final boost for the US chemical industry came from a happy convergence with regard to petroleum.

- In the US, under the leadership of MIT, the separate roles of chemist and engineer were fused. Historically, success in the commercialization of new chemical technologies had turned upon the ability to make transition from small scale, batch production to large-scale plants. The emergence of the distinctly US discipline of chemical engineering, supported by a university system that was highly accommodating to the needs of a newly emerging industry, made an enormous difference to the chemical industry. By contrast, there were no departments of chemical engineering outside of the US before World War II, except for two that appeared in 1930s in Britain.
- The automobile spread throughout the US after World War I, necessitating a rise in the petroleum refining industry. At the same time, the basic feedstock for organic chemicals was in the process of shifting, on a worldwide basis, from coal to oil (although the shift was not complete until after World War II). The US had vast oil and gas resources, and the US chemical engineering discipline had matured in a direction that was distinctly well suited to developing a large-scale petrochemical manufacturing technology that was appropriate to the new feedstock.

The loss of World War II weakened the German chemical industry tremendously, although it did manage, after the war, to keep many of its technical secrets concealed from the Allied investigating teams.

- The German edge in chemical technology had been based on using coal as a feedstock, which largely involved aromatic chemicals. In the inter-war years, however, it became apparent that the cheapest feedstock would come from petroleum and natural gas. When these materials became abundantly available in the US, coal and alcohol chemistry was not economic for producing commodity organic chemicals (the building blocks of the modern chemical industry). As US oil and chemical companies recognized the value of petroleum hydrocarbons, they not only came up with a number of industrially significant processes for aliphatic chemicals, but also discovered ways to make the original chemicals derived from coal tar more inexpensively and in much larger quantities.
- The early German domination of the dyestuffs industry locked them into certain methods and approaches that were far less suited for other branches of the chemical industry. One major problem was that many dyestuffs are specialty products typically manufactured by batch processes. Thus, German manufacturers were not especially well-prepared for the shift to large-scale continuous petroleum-based manufacturing.
- The German universities continued to produce students who were very capable research chemists but could not design systems for manufacturing the products that they invented. Mechanical engineering was not taught at all in universities, but in technical high schools and trade schools, and was not held in as high esteem in the social hierarchy. The German refusal to learn this lesson until well after World War II (based upon a reluctance to make chemists less predominant, and to create space for the chemical engineer) played a large role in the decline of earlier unquestioned German leadership in the chemical industry.

The period immediately after World War II was a time of resurgence for the US chemical industry. The early phases of innovation cycle in many chemical and petroleum-based products and processes had already begun during the inter-war years. But after the war, demand for relatively homogeneous petrochemical products grew explosively, which created opportunities for scaling up chemical production processes to levels far higher than those of the prewar period. The European chemical industry had been disrupted by the war, whereas the US industry had emerged unscathed, and was well positioned to take advantage of the evolution of the chemical industry.

- The US had been a latecomer to the chemical scene. But its abundance of petroleum deposits and the experience gained in continuous processing methods in exploiting these deposits, opened up a development path that offered an excellent entry into the continuous processing technologies that became central as the industry moved to a petrochemical feedstock base. Moreover, while the German cartel arrangements had worked well for that industry in some ways,³⁰ they had also hindered innovation among its members. The US companies, operating under US law, were less inhibited. The national wartime effort had inspired crash programs involving new technologies and expanded facilities for such things as synthetic rubber, petroleum refining, chemicals, munitions, light metals, and so on. There was a tremendous burst of innovation between 1935 and 1950, which came from the loosening of the cartel bonds and the demands for the war.

Chemical firms increasingly relied upon specialized engineering firms to design, engineer and develop their manufacturing installations. By the 1960s, nearly three quarters of the major new plants were engineered, produced and constructed by specialist plant contractors. Specialized engineering firms were the channels by which US expertise in large-scale continuous process, developed in the petroleum processing and refining industry, found their way to the world chemical industry. The existence of the specialized engineering firms permitted many new entrants into the industry from petroleum, paper, food, metals, and so on. Vigorous competition ensued, both domestic and international.

- The opportunities for gaining efficiency with larger plants - and more generally, for cutting costs through more efficient production processes - induced chemical producers to focus attention on the production processes. Many set up internal departments aimed at designing and engineering new and improved manufacturing processes. However, since process development for the new high-volume products could be undertaken without simultaneously investing substantial funds in research and development for new products, there was a place for specialized contractors to design and engineer chemical production processes for the major chemical producers.

During the past 30 years, the growth rate of the chemical industry has declined substantially, and the focus of the market has shifted again. Emphasis in the modern chemical industry has shifted toward product innovation, and to the interactions between product innovation and marketing. With the help of specialized engineering firms and much licensing, a powerful European chemical industry has been reborn, providing strong competitive pressure for US companies. In many of the best companies, technology push receives as much attention as product pull. The discipline of chemical engineering has shifted as well, toward including the skills needed for producing the newer specialty products.

- After the oil shock of 1973, the rising inflation and interest rates, and extremely volatility of macroeconomic policy, the annual growth rate of the industry went from a double-digit figure to about 5%. The production of large-volume homogeneous chemicals has declined as well, as many companies have tended to place greater emphasis on the production of heterogeneous specialty chemicals.
- Firms from other industries also entered into chemical manufacturing. By grafting the strengths of the US approach on to their traditionally strong chemical research, and aided by a favorable macroeconomic climate for industry, German companies have once again become a major factor in the world chemical industry.

³⁰ With the deep recession of 1920-1921, many German chemical firms found themselves with severe over-capacity. Moreover, the government owed considerable amounts in war reparation payments. Even more significantly, the recession was followed by one of the world's greatest hyperinflation, which threatened the very existence of even the major surviving companies. Only in this environment did it become possible, and indeed urgent, for the government to encourage the major German chemical companies to merge together and form the famous I.G. Farben Industrie, and again to focus on exporting heavily. A European cartel emerged.

Global competition in the chemical industry is very tough. The top ten chemical companies account for less than 20% of the industry's worldwide sales; in comparison, the top ten auto companies command approximately 60% of the global market. The English, French, Italians, Dutch and Swiss have carved out very competitive niches of their own in the chemical industry in recent years.

- US chemical firms remain the world leaders, but the competition is not far behind. Chemical industry is the largest industry in the European market, and an important source of growth in many countries. While no country is as clearly dominant as Germany once was, everyone can be a winner in this competition.
- The Japanese chemical firms are only one third to one tenth the size of the large western companies, since Japan tended to build relatively small plants to serve individual *keiretsus*. But even though the lack of economies of scale has seriously hampered their effort to become a major force outside Japan, the Japanese chemical industry is the second largest in the world, owing to the rapid growth of the Japanese economy.

Comparative advantage is rightly seen as dynamic and ever changing. In the chemical industry, the advantage has shifted from Britain to Germany to the US, and now to a more diffuse group. Unlike many other industries, the chemical industry has fused the ideas of product and process innovation. Science and innovations are vital from beginning to end in the chemical industry, both for the relatively small number of major breakthroughs, and the relatively large number of incremental improvements. The university-industry linkage has been a profound factor in the development of chemical industry in both Germany and the US, and the decline of the industry in Britain.

- The link between new technology and the commercial capabilities of firms is critical and studies of how to facilitate this link should be a high priority. The history of the chemical industry offers a hint: German and US chemical companies have had their management and operation in the hands of scientifically trained or oriented people. These in turn have always emphasized a strong research and development activity.

II. Patterns of Innovation and Innovation Policies

1. National Innovation System

Public Research

The orientation of public research (publicly funded R&D) depends on the overall objectives of government policies and the specific role of science and technology, all of which have an important historical component in terms of national preoccupations and institutions. Large and highly developed countries offer markets with advanced customers and opportunities to reap economies of scale while maintaining diversity in R&D activities. Innovations in smaller high-income countries generally have to internationalize more rapidly and concentrate on a narrower range of fields.

- Small countries face proportionately higher costs in maintaining institutions (e.g. education and science) that cover a broad range of subjects than can be taken up by their industries. Technological change in ICT combined with globalization, however, reduces the scale advantages of large countries.
- Small high-income countries will benefit most from free flows technology across borders and thus should keep their innovation systems open and create adoption capabilities to capture the benefits of inflows of technology. Their innovation systems will be strongly shaped by the clusters in which they exhibit relative strengths, and the development of institutions will be centered around these clusters.
- In catch-up countries, government R&D expenditures accounts for a relatively higher share of total R&D than in more advanced countries, pointing to the need to build up a scientific and technological infrastructure and the relative technological weakness of the business sector. At the other end of the spectrum are countries in which the business sector provides the lion's share of R&D funding.
- Over the long-term, there has been a trend away from the traditional mission of the post-war period (defense, energy) towards other R&D objectives reflecting increasing concerns about competitiveness and changing social demands, such as the emerging problems of aging populations, and environmental issues.
- Despite these common trends, striking differences persist. Despite recent restructuring and downsizing, the defense cluster still plays an important role in France, Sweden, the UK and the US. For the majority of countries the most important civil objectives are advance-ment of research and promotion of industry.

Scientific and technological specialization

The role of the higher education sector can serve as an indication of the relationship between the science system and the rest of the innovation system. One indicator is the share of higher education research and development (HERD) financed by government, which is declining in the majority of OECD countries. The enterprise sector represents a significant financial contributor for universities.

- In countries with a strong orientation of public funding towards higher education in the form of general university funds (GUF), issues arise as to how to balance this with the growing tendency of research to become more directly oriented towards technological innovation and of development to become more short-term.

The science base of the national innovation system (NIS) are quite different among countries, even when scientific specialization is measured only by biotechnology, engineering sciences, and chemistry, which seem to have the greatest impact on technological development.

- Dissimilarities can be partly explained by country size (e.g. the broader science base of the US), standards of living (e.g. the high shares of clinical medicine and biomedical research in the richer countries spending more on their health systems) and industrial specialization (e.g. engineering sciences in Germany and Japan).
- The US is a case apart insofar as its scientific efforts are more evenly spread – hence the pronounced difference with most other countries. Despite its pronounced specialization in clinical medicine, the science base of the UK – like that of the US – appears to be fairly strong over a broader range of fields, as indicated by citation shares.
- Some countries display considerable similarities. This applies to Germany and Japan due to their specialization in mechanical engineering, chemistry and physics. Germany, France and Italy similarly resemble each other in their specialization in chemistry, physics and mathematics.

Countries also differ in their pattern of technological specialization. An examination of long-term historical developments as well as of more recent trends points out the following features. A limited number of countries show strong similarities in technological specialization; there are no overall signs of convergence. For the majority of countries, there is a significant positive correlation between past and present patterns, which indicates that technological capabilities accumulate over time and that development is strongly path-dependent.

- Clustering of countries with similar technological specialization shows strong similarities between smaller, mainly resource-based economies as well as some similarities between larger European countries. It also reveals the unique specialization patterns of Japan and the US.
- Innovation policy has to reflect these specialization patterns by fostering complementarity between science and technological specialization patterns; taking them into account in designing selective policies towards specific clusters; acknowledging that specialization patterns cannot change rapidly.

Linkages within national innovation systems

Innovation performance depends crucially on interactions among the main actors (companies, research institutes, government, etc.) that make up an innovation system, which in turn depend on the incentives or barriers confronting the various individuals, companies and institutions. As a general trend, most forms of interactions and knowledge flows have intensified, contributing to an overall increase in the knowledge-intensity of economic activities. But the importance and the quality of the various linkages differ from country to country, depending on the structure and specialization pattern of the respective NIS.

- The production of scientific knowledge increasingly cuts across disciplines, institutions, and countries. Advancement of science is no longer the sole realm of universities and specialized research bodies, but involves a widening range of other institutions (corporate R&D labs, hospitals, etc.). Further, scientific knowledge is increasingly produced with an aim to apply it.
- At the beginning of 1990s, co-authored articles amounted to over 50% of all scientific articles. Internationally co-authored articles account for more than 20%. In most countries, it has increased but by less than national. In some catching-up countries, the accelerated development of the scientific home base has led to a decline in the degree of internationalization.
- The US is still the linchpin of international scientific collaboration. A little less than one-quarter of all internationally co-authored articles involve US researchers – far more than any other country. Nevertheless, as the overall share of scientific publishing in the US is even greater (one-third of the total), its degree of internationalization is lower than that of most other countries.

- Countries differ with regard to the openness of their science systems. Japan and the former USSR show a low degree of internationalization, which cannot be explained by the size of scientific home base, but reflects less open science systems. Germany, and the UK show a much higher propensity to collaborate internationally. Some new poles of collaboration are emerging, as exemplified by increased collaboration among European countries.
- Scientific collaboration is increasing, although to a greater extent at the national/regional level than internationally. The home base and the neighborhood continue to matter in the global research village, but openness to cross-disciplinary and cross-country scientific cooperation is increasing in importance.

Links between science and technology

An important interface in a NIS is that between the science system and the enterprise sector. Especially in countries with a large share of science-based industries and/or a large higher education sector, building bridges from university research to technological innovation is an important task for policy.

- Industries and hence countries with different industrial specialization patterns differ greatly in their reliance on the science base and few have strong direct links with basic research (e.g. pharmaceuticals, organic and food chemistry, biotechnology and semiconductors). This widens the scope for policies aimed at managing the science base beyond the support of university-industry co-operations.

Scientific knowledge stemming from basic research (the production of which is the main activity of universities) is rarely a direct input into technological innovation except for science-based industries. In many industries, however, it is an essential indirect input in the process of technological innovation.

- It can be accessed and used by innovating firms in various ways and forms (published information, embedded in new instruments and methodologies, via personal contacts and participation in scientific networks, embodied in the skills and abilities of graduates, spin-off firms, joint R&D ventures and projects, etc.).
- For most of these interactions, significant localization effects can be observed – especially for those that involve informal contacts on a regular basis. Therefore, spillovers are concentrated in some clusters, facilitated by geographic proximity and the existence of a technological infra-structure comprising related business services, the existence of other innovative firms, etc.
- The importance of the science link differs from one country to another according both to industrial specialization and to the organization of the interactions (especially incentives for researchers and enterprises) between the science system and the enterprise sector.
- The US and the UK show a stronger science link. In Germany and Japan, innovation has been geared more towards engineering excellence and the rapid adoption and adaptation of technological innovation.

Although there will continue to be room for competitive advantages not based on tight linkages between scientific knowledge and technological innovation, the interplay between industry and the science base is of increasing importance for technical progress and economic performance and is thus an important target for technology and innovation policy.

Inter-firm linkages

Firms increasingly use flows from external sources to complement their internal innovation capacities built up through investments in R&D, ICT, human resources and organizational re-engineering. Networks of innovation have become the rule rather than the exception, and most

innovative activity involves interaction of multiple actors. The configuration of these interactions shows some common country characteristics and differences.

- Innovation surveys found that, as regards channels of technology transfer, the purchase of equipment, customer-supplier relations and the hiring of skilled personnel are by far the most important in many countries. Customer-supplier interactions are shaped not only by market relations but also by institutional factors and trust. The importance of other sources of technology transfer (such as consultancy) differs, perhaps reflecting both quantity and quality of existing services and government initiatives.
- Technology diffusion via embodied R&D in capital goods and intermediaries has increased in importance vis-à-vis direct R&D. If technology flows are analyzed by broadly defined technology clusters, IT accounts for a rapidly increasing share of acquired technologies, with a large proportion also accruing to material technologies. These technology clusters are generic and provide inputs to a wide range of other industries, while other clusters such as transport technologies and consumer goods technologies are of importance to a limited number of sectors.
 - Although the technology content of trade flows has generally increased, a few sectors have become the main gateways for technology flows, for example, chemicals in Denmark and the Netherlands, aerospace in the UK, motor vehicles in Germany. This reflects the differentiated patterns of technological specialization and capabilities of the respective national innovation systems and can provide guidance for setting technology and innovation policy priorities.
- The sources of information used by innovating firms are also quite diversified. Suppliers (of equipment and components) and customers are by far the most important external sources, while universities, governments labs and technical institutes rank comparatively low on average. But this average hides the fact that in many advanced countries, networks spanning beyond customer-supplier relations have evolved and a substantial number of firms participate in complete networks including suppliers, competitors, users, public research institutes and universities. Some innovation systems seem to be very conducive to co-operation among all actors of NIS, as demonstrated by the high share of complete network activities (e.g. Germany and the Netherlands).
- Analysis of the innovation strategies of Europe's largest industrial firms provides additional information on international differences with regard to the importance of the geographic location of sources of technological knowledge. In general, sources located in the home country are most important, although the difference with flows from other countries is not always very significant. Public sector research scores highest, pointing to the importance of a well-developed national research infrastructure for these large firms. Innovation systems able to provide such an infrastructure not only raise the technological competitiveness of home firms, but are also more likely to attract technology-oriented foreign direct investment.

Links between national innovation systems

The increasing openness of national innovation systems to external knowledge flows is reflected in the share of technology acquired from abroad embodied in capital and intermediary goods; purchases of foreign patents and licenses; technological alliances between firms of different countries; and, in science, the number of internationally co-authored publications. It also shows in the innovation activities of multinational, as indicated by their patenting partners and the location of their R&D facilities.

- Corporate innovation activity as measured by patents is still predominantly located to the headquarters for large countries, such as the US, Japan, Germany and France. However, there is a tendency for R&D activities to be spread. Firms establish overseas R&D mainly through the acquisition of existing firms and research facilities. Firms with

strong own-technology tend to rely on greenfield operations. In some cases R&D is shifting away from addressing local market needs to establishing competence centers carrying out R&D for the whole corporation. While the R&D intensity of domestic firms is higher than that of foreign subsidiaries, the relationship between a company and its foreign subsidiaries is influenced by the relative technological position of the country of origin and the host country, as well as by industry- and firm-specific factors.

- In most OECD countries, domestic firms are more R&D intensive than foreign affiliates. R&D intensity is roughly balanced in the US and Japan, and higher in foreign affiliates in Australia and Ireland. Foreign R&D in the US is attracted by the quality of research institutions, while locating R&D in Ireland is motivated more by the need to upgrade and adapt products and processes. From the US perspective, foreign R&D expands already intensive knowledge interactions, but is also a source of knowledge outflows. In Ireland, foreign R&D is a major driving force in the technological catching-up process.

A number of trends in the characteristics of technological innovation and in innovation systems have important policy implications:

- Innovation has become a complex activity, involving many different types of knowledge and actors. Interaction among these actors is essential for successful innovation. Inter-firm collaboration, networking and the formation of clusters of industries are examples of such interactions.
- Countries provide the environment for innovative activities through their institutions, infrastructures and policies that influence the direction and the speed of innovation and technology diffusion.
- Because of their unique history, countries' production and innovation systems have different specialization patterns, capital stock and institutions. This gives them a distinct set of strengths, but also limits their ability to manage certain kinds of change.
- Countries can be viewed as national innovation systems, with distinctive attributes (specific patterns of scientific, technological and industrial specialization, specific policy priorities) and specific structures of interactions (e.g. between the enterprise sector and the science system, collaboration between firms).
- The increasing segmentation of economic activity, as firms focus on core strengths and learn to combine and contract for complementary inputs, creates more horizontal links within and between countries. Innovation systems are increasingly inter-linked across national borders. Nevertheless, national characteristics and the strengths and weaknesses of the respective systems remain decisive for performance.

2. The Relationship between Science and Technology

Science, technology and innovation each represent a successively larger category of activities that are highly interdependent but distinct from each other. The relation between science and technology is better thought of in terms of two parallel streams of cumulative knowledge, which have many interdependencies and cross relations, but whose internal connections are much stronger than their cross connections. Science contributes to technology in at least six ways:

- New knowledge serving as a direct sources of ideas for new technological possibilities;
- Source of tools and techniques for more efficient engineering design and a knowledge base for evaluation of feasibility of designs;
- Research instrumentation, laboratory techniques and analytical methods used in research that eventually find their way into design or industrial practices, often through intermediate disciplines;
- Practice of research as a source for development and assimilation of new human skills and capabilities eventually useful for technology;
- Creation of a knowledge base that becomes increasingly important in the assessment of technology in terms of its wider social and environmental impacts;
- Knowledge base that enables more efficient strategies of applied research,

development, and refinement of new technologies.

The converse impact of technology on science is of at least equal importance:

- Through providing a fertile source of novel scientific questions and thereby also helping to justify the allocation of resources needed to address these questions in an efficient and timely manner, extending the agenda of science;
- As a source of otherwise unavailable instrumentation and techniques needed to address novel and more difficult scientific questions more efficiently.

The contribution of science to technology

The relation between science and technology is complex and varies with the particular field of technology. Electrical, chemical and nuclear technologies are deeply dependent on science, and most inventions are made by people with considerable training in science. In contrast, the contribution of science to mechanical technology is relatively weak, and it is often possible to make rather important inventions without a deep knowledge of the underlying science.

Opportunities for meeting new social needs or previously identified social needs in new ways are conceived as a direct sequel to a scientific discovery made in the course of an exploration of natural phenomena undertaken with no potential application in mind. These are the rarest, but the most dramatic cases, which may account for the persistence of the pipeline model of innovation.¹ A more common example of a direct genetic relationship between science and technology occurs when the exploration of a new field of science is deliberately undertaken with a general application that it has high likelihood of leading to useful applications, though there is no specific end-product in mind.²

- Much basic research undertaken by industry or supported by the military services has been undertaken with the latter kind of non-specific potential applicability in mind, and indeed much basic biomedical research is of this character. The selection of fields for emphasis is a strategic decision, while the actual day-to-day tactics of the research are delegated to the bench scientists. The determination of an appropriate level of effort, and the creation of an organizational environment facilitating the earliest possible identification of technological opportunities without much constraint on the research agenda is a continuing challenge to research planning in respect to this mechanism of science-technology interaction.

While the process of design is quite distinct from the process of developing new knowledge of natural phenomena, the two processes are very intimately related. This relationship has become more and more important as the cost of empirically testing and evaluating complex prototype technological systems has mounted.

- Theoretical prediction, modeling, and simulation of large systems, often accompanied by measurement and empirical testing of subsystems and components, has increasingly substituted for full scale empirical testing of complete systems, and this requires design tools and analytical methods grounded in phenomenological understanding.
- Much of the technical knowledge used in design and the comparative analytical evaluation of alternative designs is actually developed as engineering science by engineers, and is the major activity comprising engineering research in academic engineering departments. This research is very much in the style of other basic research in the pure sciences and is supported in a similar manner by the Engineering Division of the NSF, as unsolicited investigator-oriented project research. Even though it is generally labeled as engineering

¹ The discovery of uranium fission leading to the nuclear chain reaction and the atomic bomb and nuclear power, the laser and its numerous embodiments and applications, the discoveries of X-rays and of artificial radioactivity and their subsequent applications in medicine and industry, the discovery of nuclear magnetic resonance (NMR) and its subsequent manifold applications in chemical analysis, biomedical research, and ultimately medical diagnosis.

² The exploration of Group IV semiconductors was clearly motivated by the hope of finding a method of making a solid state amplifier to substitute the vacuum tubes.

rather than science, such research is really another example of basic research whose agenda happens to be motivated primarily by potential applications in design downstream though its theoretical interests and its mathematical sophistication are comparable with that of pure science.

Laboratory techniques and analytical methods used in basic research (particularly in physics) often find their way into industrial processes and process controls largely unrelated either to their original use or to the concepts and results of the research for which they were originally devised. This involves the movement of new instrumentation technologies from the status of a tool of basic research, often in universities, to the status of a production tool, or capital goods, in private industry.³

- The common denominator running through and connecting all these experiences is that instrumentation developed in the pursuit of scientific knowledge eventually had direct applications as part of a manufacturing process. In considering the potential economic benefits of science, one should not fail to examine the hardware consequences of even the most fundamental scientific research.

An important function of academic research often neglected in estimating its economic benefits is that it imparts research skills to graduate students and other advanced trainees, many of whom go on to work in applied activities and take with not just the knowledge resulting from their research but also skills, methods, and a web of professional contacts that will help them tackle the technological problems that they later face.

- This is especially important in light of the fact that basic research instrumentation so often later finds application not only in engineering but also ultimately in routine industrial processes and operations, health care delivery, and environmental monitoring.

The assessment of technology, whether for evaluating its feasibility to assess entrepreneurial risk, or for foreseeing its societal side-effects, requires a deeper and more fundamental scientific understanding of the basis of the technology than does its original creation, which can be carried out by empirical trial-and-error methods. Such understanding often requires basic scientific knowledge well outside the scope of what was clearly relevant in the development of the technology.

- As the deployment of technology becomes more extensive, and the technology itself becomes more complex, one may anticipate the need for much more basic research knowledge relative to the technical knowledge required for original development.

The planning of the most efficient of technological development is quite dependent on science from many fields. This accumulated stock of existing scientific knowledge helps to avoid blind alleys and hence wasteful development expenditures. Very creative engineers and inventors tend to read very widely and eclectically both in the history of science and technology, and about contemporary scientific developments.

The contributions of technology to science

Problems arising in industrial development are frequently a rich source of challenging basic science problems which are first picked up with a specific technological problem in mind, but then pursued by a related basic research community well beyond the immediate requirements of the original technological application that motivated them. This research went on to generate new insights and technological ideas from which new and unforeseen technology originated.⁴

³ Examples are electron diffraction, the scanning electron microscope (SEM) synchrotron radiation sources, phase-shifted lithography, high vacuum technology, industrial cryogenics, super-conducting magnets (originally developed for cloud chamber observations in particle physics, then commercialized for magnetic resonance imaging (MRI) in medicine), etc.

⁴ One of the most dramatic examples of the generation of a stimulus to a new field of basic research by a

- This process has been especially fruitful in the fields of materials science and condensed matter physics. In fact, materials science was created as a new interdisciplinary field of academic research initially as an outgrowth of an effort to understand some of the materials processes and properties that were important to improving the quality and performance of semiconductor devices.
- Many important observations made incidentally during the course of major industrial or military technological developments may never get into the general scientific literature nor get properly documented, due to the highly specialized context in which they are made. Such observations can be understood and appreciated either by other industrial researchers or basic scientists interested in and capable of pursuing their broad scientific significance.

Technological development stimulates basic research by attracting new financial resources into research areas shown to have practical implications. This has happened repeatedly for radical inventions such as the transistor, the laser, the computer, and nuclear fission power, where much of the science, even the most basic science, has followed rather than preceded the original conception of an invention. The more radical the invention, the more likely it is to stimulate wholly new areas of basic research or to rejuvenate older areas of research that were losing the interest of the most innovative scientists.⁵

- There are two areas in which the search for radical technological breakthroughs has been unusually important; defense and health care. In each case, the value of improved performance almost regardless of its cost, not only in R&D but also in ultimate social performance, has played a fundamental role in stimulating not only technological development but also related fields of basic research.
- In the defense case it has been generally believed that even a small technological edge in the performance of individual weapons systems could make all the difference between victory and defeat. In the biomedical case, where much of the focus has been on curative technology, anything that could improve the survival chances of the individual sick patient has been accorded highest priority, especially in the US. This has led to industries that are disproportionately R&D intensive with a corresponding emphasis on the science base in related fields in academia and government laboratories. The same motivation has seemed to pervade the environmental field in respect to regulation.

Technology has played an enormous role in making it possible to measure natural phenomena that were not previously accessible to research.⁶ The science of cosmology and astrophysics have been revolutionized by the opening up of the space technology. In this particular case, the new capability would probably never have been created for scientific purposes alone, but basic scientists were quick to seize the new opportunities that were made available by the space program.

discovery made in the course of a technology-motivated investigation was the discovery and quantitative measurement by a Bell Lab group in 1965 of the background microwave radiation in space left over from the original big bang. Other examples are tunneling in semiconductors, the pursuit of which as a basic science beyond practical needs led ultimately to the discovery of the Josephson effect in superconductors and the invention of the Josephson junction. The Physics Survey Committee (1972) gives numerous examples of the mutual reinforcement of theoretical and technological stimuli in the co-evolution of a new field of science and technological application, where the triggering events are difficult to entangle.

⁵ Classical optics and atomic and molecular spectroscopy in the case of the laser, and basic metallurgy and crystal growth and crystal physics in the case of transistor, as well as the burgeoning of the new science of imperfections in almost perfect crystals.

⁶ One of the most dramatic examples of this has been the role of space technology in making a much greater range of the electromagnetic spectrum accessible to measurement than was possible when observation was limited by the lack of transparency of the atmosphere to X-rays, γ rays, the far ultraviolet, and some parts of the infra-red.

- In nuclear and elementary particle physics, the physicists have developed and engineered much of the new technology. In the majority of cases, laboratory instruments have been originally developed by research scientists, but were later commercialized to be sold to a much broader research community. This later process has been very important for the rapid diffusion of new experimental techniques and is probably a prime mechanism for knowledge transfer between different disciplines, which in turn has greatly accelerated the progress of science overall.⁷
- The effectiveness of this pattern depended on close collaboration between vendors and scientific users, and between engineers and scientists, so that instruments and laboratory techniques became a mechanism by which some of the pathologies overspecialization in science are moderated.
- Closely coupled to research scientist users and enjoying the economies of scale derived from one of the largest markets of research activity in the world, the existence of entrepreneurial scientific instrument industry has been an important source of competitive advantage for the US research system in basic science. This advantage has achieved earlier than in other countries because of the enormous government investments in defense related R&D in the US compared with other countries during the first two decades following World War II.
- This instrument industry, combined with other research supply industries comprised an unexcelled infrastructure, which may have had broader general utility for commercially oriented innovation than the specific spin-offs from highly specialized defense R&D.

The positive externalities of innovative activity

The interest of economists in the economics of research, particularly in the economic rationale for investment in basic research, is of relatively recent vintage. Economists have made an important contribution by being the first to articulate the public good aspects of science and consequently its eligibility for public or collective support. But there has been considerable confusion in the public discussion between the reasonable assumption that the results of science are a public good and the unreasonable assumption that they are a free good.

- The later interpretation has led to a rapidly growing view that the generous public support for academic research in the US has been, in effect, a subsidy to foreign competitors. They have beat US firms out in the marketplace by taking advantage of the openness of US academic system to commercially exploit research results for which they have not paid.
- The assumption of pure public good about basic research neglects the fact that a substantial research capability (and indeed actual ongoing participation in research) is required to understand, interpret and appraise knowledge that has been placed on the shelf

⁷ The pattern of interaction has been described in the following terms for the case of the transfer of physics techniques to chemistry, but this pattern is similar for transfer between any two disciplines, or indeed for diffusion among researchers and sub-fields of a single discipline. When the method is first discovered, a few chemists, usually physical chemists, become aware of chemical applications of the method, construct their own homemade devices, and demonstrate the utility of the new tool. At some point, commercial models of the device are put on the market. These are sometimes superior, sometimes inferior, to the homemade machines in terms of their ultimate capabilities to provide information. However, the commercial instruments generally are easier to use and far more reliable than the homemade devices. The impact of the commercial instruments is rapidly felt, is often very far reaching, and sometimes virtually revolutionizes the field. Chemists with the new instruments need not be concerned with developing the principle of the device; they are free to devote their efforts to extracting the useful chemical information that application of the device affords. This pattern characterizes the development of optical, infra-red and radio frequency spectroscopy, mass spectrometry, and X-ray crystallography.

– whether basic or applied. The most effective way to remain plugged into the scientific network is to be a participant in the research process. Similarly, training through basic research enables more informed choices and recruitment into the technological research community.

- Germany, Switzerland, Sweden and Japan have successful diffusion-oriented technology policies that emphasize the rapid adoption and diffusion of new technology, especially production technology, as a national strategic objective. They have among the highest ratios of R&D expenditure (private and public) to GDP among industrialized countries, as well as exceptionally high levels of educational performance at all levels. A significant fraction of R&D support in these countries is for the purpose of enhancing awareness of what is going on in the world of S&T rather than necessarily for generating new knowledge for the first time in the universe.

In principle, there is a trade-off between investment in R&D and investment in information infrastructure for the efficient distribution of R&D results to their potential users. Scientists engaged in research actually spend a large fraction of their time and effort communicating with others in order to be able to take the fullest advantage of the progress made by others in planning their own strategy. This is the main reason for the necessity of R&D performance for the absorption and appraisal of technology. Thus the excellence of scientists as a conduit for research knowledge to the organizations in which they work tends to be an automatic by-product of their active engagement in research.

- But still this is no guarantee that their information retrieval habits are optimal from the point of view of fellow engineers or scientists engaged in technological development or new product design. Thus the scientists are not automatically matched in their information retrieval behavior to the information needs of the downstream phases of the innovation process.
- A significant portion of the knowledge required in technological innovation is tacit or embedded in people, not codified or written down, and not communicable except by people working side-by-side. Accordingly, personal contact and geographical proximity between the generators and users of knowledge is important in the innovation process. This is supported by the observation from patenting studies that the academic research cited in industrial patents originates to a surprising extent in universities in relatively close geographical proximity to the patenting laboratory.
- But the importance of embedded knowledge is cited in other literatures. Dependence on personal contact, tacit knowledge and serendipity to inform the application of knowledge could be gradually reduced by more systematic exploitation of IT, so that performance of research in organizations might become less essential to their capacity for the absorption of technology. More effective use of IT and better documentation for future use of organizational experience in the product development process could be of significant value in its own right.

3. Inter-industry Differences in Technological Opportunities

Technological opportunities and the ability to appropriate returns from new development determine R&D intensity in an industry. However, technological opportunity alone determine the rate of technical advance. Given the level of technological opportunity, a higher level of appropriability can raise only the level of technology, not the rate of technological change.⁸ In

⁸ The effects of appropriability conditions on R&D and innovative output are complicated. There is a conflict between the incentive and efficiency effects of appropriability. A greater ability to appropriate the returns of R&D increases R&D spending but may reduce the rate of technical change. When technology advances in discrete, independent steps, the greater incentive for innovators tends to be beneficial to society. In contrast, if technological improvements are cumulative, providing too much protection for

industries having new sources of technological opportunities, high R&D intensity and high rates of technical advance tend to be sustained over time.

- At the level of industry, R&D is subject to diminishing returns without new sources of technological opportunities: as the number of projects completed increases, technological opportunities are depleted. Technological opportunity is constantly being replenished.

Technological Opportunities

The set of technological opportunities in an industry is one of the fundamental determinants of technical advance in that line of business. There are three sources of technological opportunity: advances in scientific understandings and techniques;

- Advances in scientific understandings and techniques;
- Technological advances originating in other industries, both inside and outside the vertical chain of production, and in other private and government institutions; and
- Positive feedback from an industry's technological advances in one period that open up new technological opportunities for the next.

Over the long-run, the most important source of new technological opportunities has been the advance of scientific knowledge. Formal science has significantly illuminated the opportunities for technological advance and provided the basis for the other important forces that offset diminishing returns to technological opportunity.

- For some technological advances, most significant technological breakthroughs can be traced directly to advances in basic general scientific understanding that occurred just prior to the breakthrough. But direct and simple linkages are the exception, not the rule. The connections between scientific advance and technical advance are generally complex and subtle; the lags are long and the feedback intricate. For the most part, scientists and engineers engaged in industrial R&D employ science as a set of tools and stock of knowledge to be tapped in problem solving.
- Most applied R&D efforts start with a need or an objective and then reach back to science to enable the goal to be achieved. In general, the science employed will be in the mind of the researcher or otherwise easily accessible, as through consultation with other workers. Some industrial R&D scientists will be more up to date than others, and these often serves as *inside consultants*. It is rare that the stimulus for an applied R&D effort comes from an appreciation of new basic scientific findings, and the search for relevant science carries no presumption in favor of recent science.
- As science advances over time, the pool of potentially useful knowledge and techniques is enhanced, old understandings are sharpened or revised, and new ones are added. More generally, problem-solving power that can be tapped by industrial scientists increases. Some old problems that could not be addressed adequately before become solvable.⁹
- Newly minted graduate scientists and engineers come to their industrial jobs with up-to-date knowledge and technique. They make new resources more readily available in industrial R&D. The education of a new generation of industrial scientists may be seen as the major contribution of universities to technical advance.

Technological advances achieved in one industry can enrich technological opportunities for

innovators may inhibit technological progress.

⁹ Advances in science enhance problem-solving capabilities in applied R&D in an unsystematic, even serendipitous, way. But many contemporary sciences and related engineering disciplines are relatively closely harnessed to efforts to solve problems in applied technology. That is, research is deliberately focused on facilitating technical progress of various kinds. Work in fields like metallurgy, materials science, computer science, electrical engineering, and pathology, all of which are strongly represented in academia as well as in industry, directly facilitates technological advance and enhances the problem-solving capacity of those who endeavor to make such progress.

other industries. Advances in production process technology and equipment, which are often the result of work done by upstream suppliers, can expand opportunities for downstream industries to improve product attributes and designs. Improvements in the instruments used for measuring, testing and manipulating materials in the laboratory also affects the results of industrial R&D. The users of a product can also be the source of technological opportunities for the suppliers of the product.

- Based on their experience with the current product, customers may contribute ideas about improving the product or process. Technological advances in customer industries may also stimulate new developments in the product they buy. User feedback for product design is important in scientific instruments and semiconductor process equipment.

Innovative efforts in an industry at a given time are concentrated on a limited number of distinct, identifiable problems. When one of these bottlenecks is overcome, it generates new technical problems that must be solved if the full benefits of the initial breakthrough are to be gained. Other feedback involves the creation of new knowledge or opportunity as a result of prior advances. If the feedback mechanisms are well defined, technological developments may tend to proceed along natural trajectories.

- Technological advance along a natural trajectory proceeds fairly steadily in a relatively clear direction. Certain heuristics developed in these industries are used and strengthened to solve a particular problem. This kind of feedback from current technological advances provides a partial offset to diminishing returns to R&D. In the long run, however, they cannot totally offset that tendency.

Inter-industry Differences in Technological Opportunities

To explore inter-industry differences in the role of generic science (providing an expanding pool of theory, data, technique, and general problem-solving capability), R&D managers are asked to indicate the relevance of basic science and applied science to technical progress in their line of businesses over the preceding 10-15 years.¹⁰

- Chemistry, material science, metallurgy, and computer science were highly relevant to a large number of industries. The widespread relevance of the first three undoubtedly reflects the long standing importance of the composition and properties of materials in most industrial technologies, and the relevance of newer field of computer science surely reflects the nearly universal scope of potential applications for computers in product design and process control. Biology, geology, mathematics, applied mathematics, agricultural science, and medical science were regarded as highly relevant to only a few industries.

Table 1. Relevance of science to industrial technology

Science	# of industries with scores: > 5 > 6	Selected industries in which the relevance of science to technological progress was large
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¹⁰ The basic scientific fields were biology, chemistry, geology, mathematics, and physics. The fields of applied science were agricultural science, applied mathematics and operation research, computer science, material science, medical science and metallurgy. Respondents are asked to score relevance to the 130 lines of business on a seven-point semantic scale. Klevorick, A., R. C. Levin, R. R. Nelson and S. Winter (1995), On the sources of significance of inter-industry differences in technological opportunities, *Research Policy* 24, 185-205.

Biology	14	8	Drugs, pesticides, meat products, animal feed
Chemistry	74	43	Pesticides, fertilizers, glass, plastics
Geology	4	3	Fertilizers, pottery, nonferrous metals
Mathematics	30	9	Optical instruments, machine tools, motor vehicles
Physics	44	18	Semiconductor, computers, guided missiles
Agricultural science	16	9	Pesticides, animal feeds, fertilizers, food products
Applied math/OR	32	6	Guided missiles, aluminum smelting, motor vehicles
Computer science	79	35	Guided missiles, semiconductors, motor vehicles
Material science	99	46	Primary metals, ball bearings, aircraft engines
Medical science	8	5	Asbestos, drugs, surgical/medical instruments
Metallurgy	60	35	Primary metals, aircraft engines, ball bearings

- The high-tech sectors – semiconductors, aerospace (guided missiles, aircraft engines, ball bearings), drugs, and agricultural chemicals – heavily represented in the list of industries in which the different sciences were highly relevant to technological progress.
- Two measures of proximity of an industry to science were constructed: the mean relevance score of the science and the sum across all the fields of science of the mean relevance scores. Table 2 presents the rank ordering on these two measures of the closeness to science of the industries from which we received ten or more responses; the line of businesses closest to science appear at the top.
 - By either criterion, drugs and semiconductors appear very close to science, while motors, industrial controls, and motor vehicle parts are relatively distant from science.
 - The chemistry-based industries rank lower when proximity is based on the relevance scores than when it is judged using the highest relevance score, implying that the scientific links to these industries, though strong, are concentrated. In contrast, semiconductors and related devices tend to draw strongly on a number of fields of science, chemistry as well as physics and four of the six applied sciences.

Table 2. Proximity of lines of business to science

Ranked by highest relevance score	Ranked by sum of relevance scores
Drugs	Semiconductors and related devices
Semiconductors and related devices	Measuring and controlling devices
Plastic materials and resins	Pulp, paper and paperboard mills
Surgical and medical instruments	Drugs
Petroleum refining	Petroleum refining
Plastic products	Aircraft and parts
Steel works, rolling and finishing mills	Electronic computing equipment
Electronic computing equipment	Surgical and medical instruments
Industrial organic chemicals	Steel work, rolling and finishing mills
Aircraft and parts	Industrial inorganic chemicals
Communication equipment	Plastic products
Pulp, paper, and paperboard mills	Communication equipment
Perfumes, cosmetics, and toilet preparations	Pumps and pumping equipment
Industrial inorganic chemicals	Plastic materials and resins
Measuring and controlling devices	Industrial organic chemicals
Pumps and pumping equipment	Perfumes, cosmetics and toilet preparations
Motor vehicles parts and accessories	Motors, generators, and industrial controls
Motors, generators, and industrial controls	Motor vehicles parts and accessories

- In general, the discrepancy between the measured relevance of generic science (a pool of knowledge) and that of university science (new results) is greater for basic than applied science. Research in applied science and engineering disciplines is guided to a large extent

by perceptions of practical problems, and new findings often feed directly into their solutions.¹¹ In contrast, new research in basic science is likely to be relevant to industrial technology as an addition to the broad knowledge base rather than as directly useful results. The university research in applied sciences and engineering fields tends to have greater relevance to industry than does university research in basic sciences. (Table 3) Computer science, materials science, metallurgy, and the engineering disciplines have high relevance scores in the largest number of industries.

- Advances in fundamental scientific knowledge have their influence on industrial R&D largely through the general understandings and techniques that industrial scientists and engineers bring to their jobs; through their incorporation in the applied sciences and engineering disciplines and their influence on research in those fields.¹² Biology is an exception to the rule that university research in basic science is judged less relevant to industrial innovation than the broad stock of knowledge in that field. This reflects the fact that a very substantial fraction of agricultural and medical research is conducted in universities.

Table 3. Relevance of university science to industrial technology

Science	# of industries with scores:		Selected industries in which the relevance of University science to technological Progress was large
	> 5	> 6	
Biology	12	3	Animal feed, drugs, processed fruits/vegetables
Chemistry	19	3	Animal feed, meat products, drugs
Geology	0	0	
Mathematics	5	1	Optical instruments
Physics	4	2	Optical instruments, electron tubes
Agricultural science	17	7	Pesticides, animal feeds, fertilizers, food products
Applied math/OR	16	2	Meat products, logging/sawmills
Computer science	34	10	Optical instruments, logging/sawmills, paper mchn.
Material science	29	8	Synthetic rubber, nonferrous metals
Medical science	7	3	Surgical/medical instruments, drugs, coffee
Metallurgy	21	6	Nonferrous metals, fabricated metal products
Chemical engineering	19	6	Canned foods, fertilizers, malt beverages
Electrical engineering	22	2	Semiconductors, scientific instruments,
Mechanical engineering	28	9	Hand tools, specialized industrial machinery

The survey results for extra-industry sources of technological knowledge are reported in Table 4. Many industries valued highly the contribution made to their technological progress by firms located in the vertical chain of production. Material suppliers were especially important sources of technology in food and forest products and in electronics industries. Equipment suppliers made valuable contributions to technology in food, forest, and metal products.

- The contributions to technological progress in a line of business that were made by sources outside the vertical chain of production were seen as less important than the contribution

¹¹ There are some doubts about the ability of respondents to distinguish sharply between the general relevance of scientific field and the relevance of recent developments in that fields. When new science is important, universities are often important (dominant) sources of that new science. Thus relevance ratings that industries gave to university-based research can be used as a proxy for the relevance of new basic and applied science as well as a direct indicator of lines of business in which university research is relevant.

¹² Table 3 presents the same information concerning the relevance of university research in a field of science to industrial technology as Table 1 did for science in general. The data suggests systematic differences between the role of science as a pool of knowledge and the role of new discoveries. Overall, university-based research in a field is much less important to recent technological advance than is the overall body of science in that field.

of upstream and downstream firms in the chain. Government research labs and other government agencies seem to have played a quite minor role in generating technological progress in most of the lines of business.

- The contributions that users and customers made to technological advance were rated 5 or more by about one-quarter of the respondents. The contributions from customer industries were seen as most important in the machinery, electrical equipment and surgical and medical instruments sectors.
- Respondents in 23 of the 130 lines of business estimated that university made no contribution at all to technological progress in the industry. Respondents from 15 lines of business gave university research a relevance score of 4 or higher.¹³ The fields of research that feed into these industries tend to be applied sciences and engineering disciplines rather than more fundamental sciences. The industries have been deliberately targeted by government agencies, which have funded university research in these fields to support technological progress in these industries.

Table 4. Extra-industry sources of technological knowledge

Sources	# of industries with scores:		Selected industries in which external Contribution to knowledge is large
	> 5	> 6	
Material suppliers	55	16	Food products, Wood products, radio/TV sets
Production equipment suppliers	63	21	Food products, Wood products, metal working
Research equipment suppliers	20	4	Food products, drugs, detergent, semiconductors
Users	30	6	Machinery, electrical equipment, medical Instruments
University research	9	3	Animal feed, drugs
Government laboratories	6	2	Fertilizers, logging/sawmills, optical instruments
Other government agencies	5	2	Auto components, optical instruments
Professional/technical societies	12	3	Paper industries machinery, logging/sawmills
Independent inventors	9	5	Hand tools, metal doors / frames, etc.

Respondents are asked to rate the extent to which certain technological activities were engaged in consistently and repeatedly in their lines of business, to measure the extent to which technological opportunities feed back on themselves and are enhanced by the presence of natural trajectories. Table 5 lists a group of technological activities oriented toward production process and then a group concerned with product characteristics, together with the number of lines of business in which each activity was rated as important.

- Natural trajectories are indeed pervasive in manufacturing technology. With a couple of exceptions, each of the natural trajectories was viewed as important by at least 30% of the lines of business. Nearly two-thirds of industries rated the importance of mechanization at 5 or higher and similarly for process-yield improvements. Over two-thirds gave that high a rating to improving the product's performance characteristics, and more two-thirds rated designing products for specific market segments at that level.

Table 5. Natural trajectories of technological advance

¹³ These lines of business are fluid milk, dairy products except milk, canned specialties, logging and sawmills, semiconductors and related devices, pulp, paper and paperboard mills, farm machinery and equipment, grain mill products, pesticides and agricultural chemicals, processed fruits and vegetables, engineering and scientific instruments, millwork, veneer and plywood, synthetic rubber, animal feed, and drugs.

Sources	# of industries with scores:		Selected industries in which the indicated Technological activity is important
	> 5	> 6	
Changes in scale of production	43	13	Aluminum smelting, wet corn milling
Mechanization / automation	75	29	Radio/TV sets, logging, motor vehicles.
Improving process yield	83	41	Semiconductor, radio/TV sets, coffee
Improving input materials	53	18	Radio/TV sets, ball bearings, transformers
From batch to continuous process	40	14	Dairy products, processed vegetable/fruits
Changes in product dimensions	23	5	Semiconductor, computer
Improving physical properties	66	26	Motor vehicles, plastic materials
Improving performance characteristics	96	47	Semiconductors, computer, vehicles
Moving towards standardization	28	6	Refrigeration/heating equipment,
Designing for market segments	92	24	Paints, cosmetics, radio/TV sets
Tailoring product for customers	62	24	Mining machinery, turbines

- The presence of natural trajectories was highly inter-correlated. On the process side, mechanization and automation, improvement in process yield, and improving the properties of input materials tend to occur together. Similarly, with regard to technological activities concerned with product characteristics, the reported importance of improvements in the performance characteristics of the product, designing products for specific market segments, and customization of the product tend to be highly correlated.

Patterns of technological opportunity and industrial R&D performance

The connections with applied science tend to be more strongly associated with rapid innovation than are the ties with the basic sciences. The effects of the latter may well operate through the strengthening of the former.

R&D intensity in an industry is strongly correlated with the strength of its connections with the fields of science. R&D intensity is positively correlated with the contributions of university research and government laboratories, suggesting that the latter two kinds of R&D stimulate and complement industrial R&D. Strong contributions from upstream suppliers were not positively correlated with industry R&D intensity. There are some indications that the work of equipment suppliers and industry R&D are partly substitutes. Two product-oriented natural trajectories were positively associated with industry R&D intensity, but no process trajectory was positively correlated with this measure.

Not surprisingly, natural trajectories directed to processes tend to be correlated more strongly with the rate of process innovation than with the speed of product innovation, and the reverse is true for product-oriented trajectories. Because the standardization of products tends to occur late in an industry life-cycle when process improvement is the focus of R&D, it is not surprising that standardization measure is the single product trajectory that is more strongly correlated with the rate of process innovation. Also, the availability of improved materials from upstream sources correlates significantly with both process and product advance, while the contribution of equipment suppliers affects only process innovation.

The electronic components sector gave every source a higher score than did the three sectors with the least abundant opportunities: stone, clay and glass; metal products; and non-electrical machinery (excluding office and computing equipment). This is almost, but not quite, the case as well for comparisons between the ratings given by the aircraft and missile sector and those given by the low opportunity sector.

Within the low opportunity sectors, there are some interesting differences. The stone, clay and glass industries and metal products have relatively strong connections with at least one science. In contrast, no science is viewed as highly relevant to progress in non-electrical machinery. External sources make only a limited contribution to technology in stone, clay and glass and in the non-electrical machinery sector. On the other hand, firms in the metal products sector report that their equipment suppliers are important contributors to technological advance in their

industry.

There are also interesting differences among the high opportunity sectors. Drug and electronic components both have extremely strong links to science, but with the exception of chemistry, they are tied to entirely different sciences. The aircraft and missile is less strongly influenced by advances in the basic sciences. Upstream suppliers are very important in electronics, somewhat less so in aircraft and missile, and nor at all important in drugs. Reflecting the strong science connections, university research and government laboratories are far more important in drugs industry than in the others.

While the electronics sector has a variety of very strong natural trajectories, several of these activities, improving process yield and change in product dimensions, are much less important in aircraft and missiles. In pharmaceuticals, improving process yield and improving product performance are the only important natural trajectories; all the other feedback mechanisms are much weaker in the drugs sector than in the other two high opportunity sectors.

4. Innovation Failures and Intervention Models

*Sectoral patterns of Technological change*¹⁴

Two central characteristics of innovation emerge. 1) Most of the knowledge applied by firms in innovation is not general purpose and easily transmitted and reproduced; it is appropriate for specific applications and appropriated by specific firms.¹⁵ 2) Sectors vary in the relative importance of product and process innovations, in sources of process technology, and in the size and patterns of technological diversification of innovating firms. But some regularities emerge.

- The unit of analysis is the innovating firm. Since patterns of innovations are cumulative, its technological trajectories will be largely determined by its principal activities. Different principal activities generate different technological trajectories. These can be grouped into the three categories: supplier-dominated, production-intensive, and science-based.

Supplier dominated firms can be found mainly in traditional sectors of manufacturing – textiles, lumbers, wood and paper products, printing and publishing, and construction. They make only a minor contribution to their process or product technology. They are generally small, and their in-house R&D and engineering capabilities are weak. Most innovations come from suppliers of equipment and materials, although in some cases large customers and government-financed research and extension services also make a contribution.

- They appropriate less on the basis of a technological advantage, than of professional skills, aesthetic design, trademarks and advertising. Technological trajectories are defined in terms of cutting costs. A relatively small proportion of innovative activity is devoted to product innovation.
- A large proportion of innovative activities is directed toward process innovations, and a high proportion of process innovation in this sector is produced by other sectors. The main criteria of technical choices are the level of wages, the price and performance of capital goods. Technological diversification is mainly vertical into production technology.¹⁶

¹⁴ Pavitt, K. (1984), Sectoral patterns of technical change: Towards a taxonomy and a theory, *Research Policy* 13, 343-373

¹⁵ In making choices about which innovations to develop and produce, industrial firms cannot and do not identify and evaluate all innovation possibilities indifferently, but are constrained in their search by their existing range of knowledge and skills to closely related zones. In other words, technical change is largely a cumulative process specific to firms. What they can realistically try to do technically in the future is strongly conditioned by what they have been able to do technically in the past.

¹⁶ Vertical diversification is the percentage of innovations outside the innovating firm's principal sector of activity but used within the innovating firm's sector: it reflects the relative importance of technological diversification into the equipment, materials and components for their own production. Cocentric/

The economic pressures and incentives to exploit scale economies are particularly strong in firms producing either standard materials or vehicles and durable consumer goods for price-sensitive users. Competitive success depends to a considerable degree on firm-specific skills reflected in continuous improvements in product design and in product reliability, and in the ability to respond sensitively and quickly to changes in users' needs. The way of appropriating technological advantage varies considerably between large-scale producers and small-scale equipment suppliers.

- For the large-scale producers, particular inventions are not in general of great significance. Technological leads are reflected in the capacity to design, build and operate large-scale continuous processes or to design and integrate large-scale assembly systems. Technological leads are maintained through know-how and secrecy around process innovations, and through inevitable technical lags in imitation and through patent protection. For specialized suppliers, secrecy, process know-how and lengthy technical lags are not available to the same extent as a means of appropriating technology.
- In complex and interdependent production systems, the external cost of failure in any one part is considerable. For the purpose of trouble shooting, large-scale producers established groups of trained and specialists for production engineering. These groups develop the capacity to identify technical imbalances and bottlenecks, and eventually become able either to specify or design new equipment that will improve productivity. Consequently, engineering departments become an important source of process technology.
 - Five of the two-digit sectors (food products, metal manufacturing, motor vehicles, glass and cement) have the characteristics of scale-intensive production. In these sectors, innovative firms produce a relatively high proportion of their own process technology, to which they devoted a high proportion of their own innovative resources.
 - Innovating firms are relatively big, have a relatively high level of technological diversification into equipment related to their own process technology, and make a relatively big contribution to all the innovations produced in their principal sectors of activity.
- Other important sources of process innovations are the specialized suppliers of equipment and instrumentation, with whom large-scale producers have close and complementary relationships. Larger users provide operating experience, testing facilities and even design and development resources for specialized equipment suppliers. Such suppliers in turn provide their large customers with specialized knowledge and experience as a result of designing and building equipment for a variety of users, often spread across a number of industries. Specialized suppliers have a different technological trajectory from their users, more strongly oriented towards performance-increasing product innovation and less towards cost-reducing process innovation.
 - Mechanical and instrument engineering firms also produce a relatively high proportion of their own process technology, but the main focus of their innovative activities is product innovation for use in other sectors. Innovating firms are relatively small, diversify technologically little, either vertically or otherwise.
 - Innovating firms do not make a relatively big contribution to all the innovations produced in their principal sector of activity, where users and other firms outside the sectors make significant contributions.
 - Within mechanical engineering, firms in all the product groups have a high proportion of their innovative resources devoted to product innovation. They are technologically specialized, and are relatively small.
 - In instrument engineering, innovations are produced by firms in a wide range of user

conglomerate is the percentage of the innovations that are both used and produced outside the principal sector of innovating firm's activity.

sectors, as well as by firms principally in mechanical engineering and in electronic capital goods.

Science-based firms are to be found in the chemical and electric/electronic sectors. The main sources of technology are the R&D activities of firms in the sectors, based on the rapid developments of the underlying sciences. The development of successive waves of products has depended on prior developments of the relevant basic science.¹⁷

- The rich range of applications based on underlying science has meant that successful and innovative firms have grown rapidly, and have little incentive to look for innovative opportunities beyond their principal sector. Given the sophistication of the technologies and underlying sciences, it has been difficult for firms outside the sectors to enter them. The pervasive applications have meant a wide variance in relative emphasis on production and process technology within each of the sectors, reflecting the different performance/cost trade-off for consumer goods, standard materials, and professional applications.
- Firms appropriate their innovating leads through a mix of methods - patents, secrecy, natural technical lags, and firm-specific skills. Patent protection is particularly important in fine chemicals, with specific high-grade applications, where the predominant product innovations can be quickly and cheaply imitated. In addition, dynamic learning economies in production have been an important barrier to the entry of imitators in continuous process technology, large-scale assembly and in the production of electronic components. The particularly rapid rate and the form of technical change in electronic components involved a paradigm shift. New firms have entered the electronics industry, and to grow rapidly by aggressive product innovations coupled with the exploitation of steep dynamic economies of scale.
- Characteristics of science-based firms emerge clearly for those principally in chemicals. They produce a relatively high proportion of their own process technology, as well as a high proportion of product innovations that are used in other sectors. They are also relatively big, most of their technological diversification is concentric/conglomerate rather than vertical, and they produce a relatively high proportion of all the innovations in their principal sector of activity.
- Firms principally in electrical and electronic engineering also have most of the predicted characteristics of science-based firms: a high contribution to own process technology, relatively large innovating firms, mainly concentric/conglomerate diversification, and a relatively large contribution to all innovations in their principal sector of activity.¹⁸
- Large diversified firms make a bigger contribution to innovations by science-based firms

¹⁷ Synthetic chemistry has enabled the developments of a wide range of products, with useful structural, mechanical, electrical, chemical or biological characteristics, ranging from bulk materials replacing wood, steel, and natural textiles, to specialized and expensive chemical and biological agents for medical and other uses. Post-war advances in the fundamentals of biochemistry are enabling the extensions of these skills and techniques into biological products and processes. Advances in electromagnetism, radio waves and solid state physics have enabled products and applications related to the availability of cheap, decentralized and reliable electricity, communications and information processing, storage and retrieval. Applications in electricity varies from huge transformers to small motors within mechanical systems, in communications from expensive radar and satellite tracking systems to cheap transistor radios, in information from huge computers to electronic wristwatches.

¹⁸ However, the proportion of product innovations, although absolutely large, is relatively small; more detailed data show that this cannot be explained simply by the preponderance of process innovations in broadcasting equipment, but also reflects a high proportion of innovations in electronic components that are produced and used by firms principally producing electronic capital goods. Furthermore, the relatively big contribution to the production of innovations made by firms with less than 1000 employees reflects the increasing contribution in the 1970s by such firms in the computer product group.

than to those by specialized equipment suppliers. In chemicals, firms principally in general chemicals produced about 40 percent of the whole, and in electrical/electronic products, firms principally in electronics capital goods produced about 50 percent.

Supplier dominated firms get most of their technology from production intensive and science-based firms. Science-based firms transfer technology to production intensive firms. Science-based and production intensive firms both receive and give technology to specialized suppliers of production equipment. Technological linkages amongst sectors can go beyond transactions involving the purchase and sales of goods embodying technology. They can include flows of information and skills, as well as technological diversification into the main product areas of suppliers and customers.

- Sectors can shift from the supplier dominated to the production intensive as a result of access to larger markets and of autonomous and induced improvements in capital goods. Where process technology has matured, sectors may shift from the production intensive to the supplier-dominated pattern. For example, in bulk synthetic chemicals today, this focus has shifted from the chemical firms to their specialized suppliers of process equipment. Whatever the regularities in such change are eventually observed trends in the rate of technological change will be an important explanatory variables.

Typology of Innovation Failure and Intervention Models

The forces leading to private under-investment in innovation differ from sector to sector across the economy, and policy design should take these differences into account. The contribution of public resources can take many forms, and it is necessary for policy discussion to classify promotional measures that aim to match public action to sources of market failure in different sectors.¹⁹ Markets differ in:

- Terms of the mixture of basic and applied knowledge that contributes to their knowledge base;
- The degree of appropriability of technology;
- The extent to which commercially applicable knowledge is tacit, hence less likely to leak out; and
- The importance of complementary assets to commercialization of knowledge.

Table 1 carves what is really a continuous range of variation along these dimensions into four broad categories, based on the main mode of innovation in each group of industries. The nature of the main mode of innovation has implications for the most important sources of innovation failure in each category, and consequently, for the most effective form of public support for private innovation.

Table 6. Innovation modes, sources of innovation failures, and policy responses

Main mode of Innovation	Sources of Innovation failure	Typical sectors	Policy instruments
Development of inputs for using industries	Financial market transactions costs facing SMEs; Risk associated with standards for new technology; Limited appropriability (generic technologies)	Software, Equipment, Instruments	Support for venture capital; Bridging institution to facilitate standards adoption
Application of inputs newly developed	Small firm size, large external benefits; Limited appropriability.	Agriculture, Light industries	Low-tech bridging institution to support technology transfer
Development of	High cost, high risk, limited	Aerospace, Electronics	R&D cooperation, subsidies; Bridging institution to facilitate

¹⁹ Any such classification must be crude and approximate. The categories are not mutually exclusive, and the policy measures cited are indicative rather than exhaustive.

complex systems	appropriability (particularly for infra-technology)	Computer Semiconductors	development of infrastructure technology
Application of high-science content technology	Knowledge base originates outside commercial sector; Creators unaware of potential application or effectively communicate new development to potential users	Biotechnology Chemistry Material science Pharmaceuticals	High-tech bridging institution for the diffusion of advances in big research

In intermediate good industries, the predominant form of innovation is the development of higher quality products that will be used as inputs in vertically related industries. The software and equipment-producing industries are examples. In such sectors, opportunities for innovation are generally abundant, but are likely to be exploited through informal activities of design improvement. Idiosyncratic and cumulative skills make for relatively high appropriability of innovation.

- Innovative inputs have a generic character so that they can be used in many industries. For such technologies, complete appropriability of the returns from innovation is difficult. From a social perspective, there will be insufficient private capital for development of generically applicable innovative inputs. In these circumstances, whether appropriability is high or low, an effective mechanism for public support should make capital funding available to SMEs, including start-up firms. This will allow innovative new firms to bring socially useful products to markets. The lowering of entry barriers by such a policy would maintain competitive pressure on larger incumbent firms, inducing them to continue their own innovative activities.
 - Moreover, the idiosyncratic and cumulative nature of the skills involved means that financial market transaction costs will be high and will make the cost of capital facing new, small innovating firms differentially high. New, technologically intensive firms would not receive sufficient capital, and such capital constraints would limit R&D investment especially for SMEs.
 - Because government typically has a poor record of identifying ultimately successful lines of technological development in advance, public support for innovating SMEs should not take the form of direct grants. Nor should it take the form of government debt or direct equity financing. Rather, government should limit its role to setting up market infrastructure and creating an environment conducive to entrepreneurship.
- The question is how to deliver additional public funding to provide sufficient investment funds in a risky environment without losing the monitoring ability of private venture capital firms and without trying to implement such monitoring with clumsy and costly contracts or administrative mechanisms. A contingent valuation method would establish the desired incentives for the private sector to choose the best innovation and for such innovators to carry out the appropriate amounts of investment at the least cost to the public while avoiding opportunistic behavior by either the public or the private partner.
 - Private agents bid for the right to obtain public funds for use in financing innovation projects. Such a scheme would involve a hybrid bidding mechanism that combines an up-front bid, a periodic payments bid, and finally a royalty bid. Private venture capital companies would bid for public funds that would be used to fund innovative projects, rather than having the government accept bids directly from companies carrying out R&D.

Dual to the category of sectors where innovation takes the form of developing higher-quality inputs that are used in vertically related downstream industries is the category of firms in the customer industries that innovate by adapting products and processes developed in upstream industries to their own commercial needs. Innovation failure can arise also in the utilization of those inputs. Public support for private innovation should be allocated so that the marginal

social return to public funds is the same in both sectors. As the source of innovation failure is different in the two types of industries, the framework for providing public support should also be different.

- Small operating units can benefit from adopting state-of-the-art techniques, but ill-able to afford the expense of keeping abreast of such techniques, and able to internalize only a fraction of the overall benefits that flow from keeping the sector as a whole on the technological frontier. Public support for innovation in such sectors can take the form of extension services that serve as an open technical repository to which private firms can turn for the solution of specific problems.
- In sectors in which technological progress takes the form of application of higher-quality inputs developed elsewhere, public support for innovation must take the form of networks of public institutions, which serve as repositories of information about developments on the technological frontier and promote diffusion of innovations by transmitting such information, in usable form, to using sectors.
- The Fraunhofer Gesellschaften conduct applied research for industry on a contract basis, using the facilities and personnel of regional polytechnics or technical universities. The cooperative industrial research associations are organized by industry and identify the research needs of SMEs and actually carry out the research themselves or hire others to perform contract research. Such associations will be of greatest assistance to SMEs, and the benefits seem mostly to be related to knowledge dissemination rather than increasing the private appropriability of knowledge. They have five specific advantages:²⁰
 - Encourage industrially relevant research;
 - Promote the exchange of information between industrial and academic communities;
 - Assist commercialization and marketing;
 - Socialize university students with respect to commercial application of technology; and
 - Promote the diffusion of research.

Only a few sectors fall in the category of complex systems innovation. Firms in these sectors are typically large in an absolute sense, and well able to maintain their own firm-specific pools of technical competence. Innovation failure arises because the R&D projects involved carry a cost that is proportionally as large or larger than the absolute size of innovating firms, and because of the nature of risk associated with failure to stay on the technological frontier.

- The risk in question is the risk of extinction if a firm is not in the first round of innovators because a steep learning curve implies that second-movers fall rapidly behind. Society is concerned simply that the innovation occur; an individual firm is concerned that it be the winner of the innovation race, or more precisely, that it not be among the losers. The high set-up cost and drastic risk associated with innovation in such sectors combine to limit expected private gains to such a point that the market will not undertake many socially desirable projects.
- In selecting the themes of the research project, it became evident that it would only be possible to carry out research that was fundamental in nature and of great common interest. Thus it was necessary to find out the common interest in order to make cooperation possible. Then, there would be no introduction of company know-how.
- Policy should also be open to the possibility of direct subsidies, at least early in the life of cooperative activity. A condition of such subsidies should be acceptance of arrangements to diffuse knowledge generated by the joint venture to all comers on reasonable terms. Learning-by-doing advantages will normally allow incumbents to profit from exploiting an innovation; the availability of the innovation to outsiders at reasonable cost will

²⁰ Burton, D. and K. Hansen (1993), German technological policy: incentive for industrial innovation. *Challenge* 36, 37-47.

prevent first-innovators from extracting economic profits and ensure a satisfactory level of consumer benefits.

- Innovation market failure may also arise when innovation involves the development of common standards for infrastructure technology. Such innovations involve network externalities and carry a substantial risk if a firm enters into a technological trajectory that ultimately fails to be selected as the market standard. Public bridging institutions investing in infrastructure technology would fill an essential gap in such cases.

Where innovation relies on a technology base with a high science content, there is also a need for bridging institutions. Firms in such sectors will often be large in an absolute sense, and will typically maintain their own formal R&D laboratories. The role of bridging institutions in this case is to facilitate diffusion of advances in basic research from academic research operations to the private sector.

- In biotechnology, recombinant DNA and genetic engineering techniques in many ways represent radical scientific breakthroughs that is transferred to industry and reduced to practice. Another is pharmaceutical. Success depended on the ability of companies to link up the clinical and chemical competence into a coherent whole by relying on basic biological and pharmaceutical knowledge. Close formal and informal connections with university researchers (including the physical locations of some research operations near universities) were important factors in making these linkages possible.
- A common characteristic of technological progress in high-tech areas is that the firms in the private sector are able to develop and appropriate the returns from commercialization of fundamental breakthroughs. Commercial application of such advances will typically best be carried out at private laboratories, which will be able to use information from marketing and distribution channels to direct development in the most effective direction.
- For high-tech industries, public support should promote the basic research that generates the foundation for commercialization. Rather than targeting specific applications, however, public policy should attempt to broaden and enrich the R&D network and the knowledge base on which individual firms can draw in developing applications.
- Bridging institutions here could be university-industry research parks or government laboratories such as those operated in the US by the NIST. Their role should be to provide a common forum for the diverse fields of knowledge that is combined to generate progress in high science-content sectors and to promote basic research and make the results of such research available to the private sector for commercial development.

5. Public-Private Partnership

A high rate of complementary public and private investments in R&D is a prerequisite for sustained innovation performance,²¹ and ensuring such complementarity requires governments to be responsive to the rapid transformation of innovation processes and related business needs and strategies. Greater use of public-private partnership can increase this responsiveness and enhance the efficiency and cost-effectiveness of technology and innovation policy.²²

- PPPs for innovation promote cooperation between the public sector (government agencies or laboratories, universities) and the private sector (enterprises) in undertaking joint projects. They tend to be in areas where the actors have mutual or complementary interests but deem that they lack capabilities and incentives to act as efficiently alone. They may involve joint sponsorship of R&D in government, industry and/or university

²¹ OECD (2001), *The New Economy: Beyond the Hype – The OECD Growth Project*.

²² OECD (2002), *Policies for Public-Private partnerships: Framework for Country Notes*. DSTI/STP (2002)44

laboratories with participants providing funding and/or in-kind contributions such as facilities, personnel or intellectual property. Although they have been in existence for many years in OECD countries, public-private partnerships are now playing a more prominent role in science, technology and innovation policy.

- A well-functioning of industry-science interface is necessary to reap broader economic and social benefits from investments in public research, but also contributes to the validity and quality of the science system itself. Public-private partnerships have the potential to improve the leverage of public support to business R&D, through cost and risk sharing. They can ensure higher-quality contributions by the private sector to government mission-oriented R&D and open new avenues for commercial spillovers from public research. In addition, they can be designed to achieve several goals at once (supporting pre-competitive research, building networks/linkages) that contributes to their *system efficiency*.
- The motivations to engage in public-private partnerships differ strongly depending on the actor. From the government point of view, the rationale for promoting partnerships in the context of innovation and technology policy is dual: to correct market failures resulted in under-investment in R&D by firms and to improve the efficiency of public support to R&D. For industry, motivating factors to engage in partnerships include increasing access to research infra-structure and expertise not available in corporate laboratories, expanding external contacts for industrial laboratories, increasing the level of pre-competitive research, and leveraging industrial research capabilities. Form the university point of view, partnerships can help obtain financial support for educational and research missions, broaden experience of students and faculty, and increase employment opportunities for students.
- There are various types of innovation partnerships between private and public actors. These include general research support, informal collaborations, contract research, training schemes, cluster formation, human resource development, etc. This variety in public-private partnerships in terms of size objectives and design features as well as the national specificity of their policy context has tended to hamper an assessment of critical factors in their successful design and implementation. In addition, identification of good practices in joint creation and sharing of knowledge between public and private research sectors has been impaired by the lack of agreed definitions, methodologies and indicators to measure performance.

Public-private Partnerships in the US Innovation Policy

During the 1970s, many foreign competitors began to successfully challenge the long-standing dominance of the US in world and domestic markets. By the early 1980s, it became clear to policymakers that a change in the philosophy of federal R&D support was needed. Beginning with legislation in the 1980s, a new ear in federal technology policy began. A new paradigm for public-private technology partnerships emerged. The new paradigm viewed industry as a partner in the formation and execution of technology programs rather than a passive recipient of the output from federal research.

- Global competitors were better able to appropriate the output of US basic and mission-oriented research as their technical sophistication grew. With the advent of technology-based economies throughout the world, the increase in the number of world competitors had been greater than the increase in the size of the world market.
- What had resulted from intensifying competition was significant shortening of technology life cycles. Traditional public-sector mechanisms of technology development, transfer, and development took too long in an era of accelerating private sector development. Effective long-run competitive strategies had to be deal explicitly with technology.
- Competitive survival would depend on technology-based strategies. These strategies had

to evolve from new philosophies about interdependence. The importance of interdependence arose from the need of domestic industries to develop rapidly and efficiently complex technological elements from which specific applications (innovations) are drawn for competitive activity. However, US federal R&D represented a declining share of the world R&D as globally competitive nations increased their public funding; the marginal benefits to industry from additional public moneys declined. Thus, government must expand and adapt its role with industry for more effective joint planning in research.

- The new era in federal technology policy was based on the belief that the competitiveness of US firms can be enhanced through legislation to bolster the commercial impact of federal R&D investment. SEMATECH was one of the earliest public-private partnerships and for years was heralded as the model organizational form for other public-private partnerships to follow.²³

Table 7. Selected Public-Private Technology Partnership Legislation

Enabling Legislation	Characteristics of the Program
Stevenson-Wylder Technology Innovation Act of 1980	Act predicated on the premise that federal laboratories embody industrially useful technology. Federal laboratory mandated to establish an Office of Research and Technology Application to facilitate transfer technology to the private sector.
University and Small Business Patent Procedure Act of 1980	Known as Bayh-Dole Act. Reformed federal patent policy by providing more incentives for diffusion of federally-funded innovation results. Universities, non-profit organizations, and small businesses permitted to obtain titles to innovations developed with governmental funds; federal agencies to grant exclusive licenses to their technology to industry.
Small Business Innovation Development Act of 1982	Act required federal agencies to provide special funds to support small business R&D that complemented the agency's mission. Small Business Innovation Research (SBIR) programs. Act re-authorized in 1992.
National Cooperative Research Act of 1984	NCRA encouraged formation of joint research venture among US firms. Amended by National Cooperative Research and Production Act of 1993, thereby expanding anti-trust protection to joint production ventures.
Trademark Clarification Act of 1984	Act set forth new licensing and royalty regulations to take technology from federally-funded facilities into the private sector. Specifically permitted government-owned, contractor-operated (GOCO) laboratories to make decisions regarding which patents to license to the private sector, and contractors could receive royalties on such patents.
Federal Technology Transfer Act of 1986	Act amended by the Stevenson-Wylder Act. Made technology transfer an explicit responsibility of all federal laboratory scientists and engineers. Authorized cooperative research and development agreements (CRADAs). Amended by the National Competitiveness Technology Transfer Act of 1989 to include contractor operated laboratories.
Omnibus Trade and Competitiveness Act of 1988	Act established Advanced Technology Program (ATP) and Manufacturing Extension Partnership (MEP) within the renamed National Institute of Standards and Technology (NIST).
Defense Conversion, Reinvestment, and Transition Assistance Act of 1992	Act created infrastructure for dual use partnerships, Department of Defense given the ability to leverage the potential advantages of advanced commercial technology to meet department needs.

²³ In January 1987, President Reagan recommended \$50 million in matching federal funding for R&D related to semiconductor manufacturing, and this was to be part of the Department of Defense's 1988 budget. Soon thereafter, the Semiconductor Industry Association approved the formation of SEMATECH and the construction of a world-class research facility. In September 1987, Congress authorized \$100 million in matching funding for SEMITECH.

Funding from Government-sponsored industry-university research (GSIUR) has become an increasingly important element of US universities' research budgets over the past two decades. GSIUR funding tends to look very different from traditional research funding. They explicitly address non-scientific goals like technology transfer and commercialization. They use more complex support mechanisms like centers. They also tend to perturb university stability more than other forms of funding. All of these factors have implications for the kinds of evaluation strategies. The modified peer-review technique has most use. Center initiatives have received much evaluative scrutiny since 1980, particularly interim and outcome assessments. In addition, GSIUR have tended to be subject to a higher level of evaluative scrutiny over the past two decades, because government supported cooperative research schemes have been considered somewhat controversial.

- Federal agencies appear to differ substantially in the extent to which they take part in the GSIUR initiatives. At one extreme, the NIH, which provides the lion's share of academic research support (57%), has been relatively inactive in cooperative research – Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR).
- NSF, which provides roughly 15% of federal government's support of academic research, has been the most active agency in supporting cooperative initiatives. NSF was the first to implement the widely used SBIR program and currently support at least 6 separate initiatives that require a university and industry partnership.
- Other federal agencies (DOD, DOE, etc.) tend to fall between these two extremes. In fact, most agencies sponsor industry-targeted partnership programs which encourage but do not require university involvement, making it difficult to identify these investment.

Cooperative research centers (CRCs) are semi-autonomous research units in universities, which operate independently of academic departments and involve research teams that are typically multidisciplinary in composition, and a portfolio of research projects, often organized into a program or thrust areas. In addition, CRCs frequently possess or are associated with a facility, lab and/or specialized piece of equipment. Such complexity also presumes an organizational structure and management team.²⁴

- Baba (1988) identified 28 distinct formal university-industry linkage mechanisms evolved in the US since the 1900s.²⁵ However, only a subset of these is relevant to research-based funding (as opposed to service and/or educational partnerships). These include industrial affiliates, applied research institutes, firm-sponsored laboratories, industry-university projects, and cooperative research centers.
- Other forms such as institutes and affiliates are actually subsumed by the more general term centers, which are clearly the most widely used and significantly funded cooperative research mechanism. According to Cohen et al. (1994), over 1000 industry-university centers exist in the US and nearly 2/3 of all industry support is channeled through center funding mechanism.

²⁴ Support for US academic research is provided by a number of sources including: Federal Government, US\$14.2 billion; academic institutions, US\$4.4 billion; state and local government, US\$1.8 billion; and industry and other sources, US\$1.7 billion. Industry support of university research in the US has grown at a rate of 8% between 1981 and 1997. In fact, industrial funding is the fastest growing part of the university's portfolio and accounts for most of the growth in university research in recent years. However, industry support still only accounts for a relatively meager 7% of university research expenditures. These estimates ignore a new reality, though. A great deal of industry's support of university research is highly leveraged, sometimes two- or three-fold, by government funding. As a consequence, GSIUR represents a significant percentage of university funding. Nearly 20% of US university-research expenditures can be attributed to industry-university centers alone. (Cohen et al, 1994)

²⁵ M. L. Baba (1988), 'Innovation in university-industry linkages: university organizations and environmental change', *Human Organization*, 47(3), pp. 260-269.

Table 8. National Science Foundation Center Programs

	Industry role/ Center structure	Funding: Amount; years	Other Characteristics
Industry-university Cooperative Research Centers (50)	Very direct and formal; select research projects/ collective	US\$75,000; 10 years	Industry input and rights are collective (shared)
State IUCRC (13)	Very direct and formal; select research projects/ collective	US\$300,000; 10 years	Downstream Commercialization; Partner with states
ERC (25+)	Moderate; provide advice on strategic directions/ collective and one-on-one	US\$2 million/year; 11 years	Education Reform
STC (25+)	Indirect; provide advice with others on strategic directions/Advisory role	US\$2-3 million/year; 10 years	Educational reform; Outreach to Pre-college

- CRC tends to be very complex, multi-facet research enterprises. They typically address a broad range of research from basic to mission-driven; they serve multiple sponsors from an industry or sector (including government and non-profit organizations) as opposed to a single company or government sponsor. They serve as a training environment for graduate students and, therefore, must address educational and other goals. The very qualities that make CRC unique and promising mechanism for supporting research also present a diverse set of evaluation challenge. These challenges include:
 - Evaluating the merit of and payoff from a heterogeneous portfolio of research;
 - Deciding how and when to evaluate downstream payoffs from research within a diffused and heterogeneous industry;
 - Evaluating educational and other collateral benefits,
 - Understanding what aspects of the center's black box contributes to and/or detracts from achieving success, and
 - The diversity of the center models.

Public-private Partnerships in the French Innovation Policy

At the end of the 1990s, the French government resolved to undertake structural reforms in order to increase the economic efficiency of R&D policies and their leverage on the innovative dynamism of firms. Since then a series of initiatives have been taken that use often novel instruments, especially public-private partnership (PP/P).

For decades, the French technology policy led to a strong concentration of the research and innovation efforts in large public research bodies and groups of large firms dependent on state financing and public procurement. A significant amount of research had been performed by enterprises, especially in aeronautics, space, nuclear energy and transportation. Such features of French innovation system account for failed government initiatives in the 1980s and for difficulties in the 1990s in adapting to the emergence of a global economy founded on new mechanisms for generating and diffusing knowledge and technology. Main Problem areas identified by a number of evaluations.

- Business R&D investment is too low (1.3% of GDP) and concentrated. Reaching the R&D funding target 2% is really challenging. This cannot be achieved without broadening the basis of R&D performers. Only 25% of R&D performing firms apply for patents, with only one-fourth of them having a really global patenting strategy.
- The contribution of public research to the efficiency of private R&D investment is insufficient The French public research system is large and productive in terms of scientific output, as measured by publications. However, its organization and underlying incentive structure, as influenced by the longstanding orientation of technology policy, led

to an unbalanced development of the linkage with the business sector.

- Public research organizations lag behind their US homologues in their use of industrial property right (IPR) and licensing to commercialize research results, signal their competence, reward researchers, and generate additional revenues.
- The public sector grants the status of servants to researchers at far earlier age than in most other advanced countries. A Ph.D. in science and technology offers generally grim career prospect in industry, not only in small firms, with consequences for the governance of enterprises whose executive boards often lack a drive towards more innovation-based competitive strategies.
- Compared to public laboratories, universities are too weak actors, and lack resources and autonomy to act as strategic hubs in the system that could create stronger links between education and innovation and offer competitive platforms for multi-disciplinary research.

The French government realized the problem but tried first more to mitigate its consequences, by increasing financial incentives to private R&D, than to address its roots through deeper structural reforms. The limitation of this approach became evident at the end of the 1990s in the face of new economic and technological conditions. The challenge for the French innovation policy is to increase the efficiency of both public and private R&D through the intensification and diversification of science-industry linkages. The reorientation of policy has been pursued with the following main objectives:

- Increase business R&D, and the share performed by SMEs;
- Maintain the attractiveness of France as a location for R&D investment, and as a springboard for the internationalization of French firms' R&D strategy;
- Foster the creation of innovative firms, including spin-offs from public research;
- Modernize the governance of public research to make it more responsive to business and social needs; and
- Involve more sub-national levels of government in managing the central government's incentives.

Table 9. Public-private Partnership programs

Instruments	Description
National Centers of Technological Research (CNRT)	CNRT promote the collaboration between public research labs and corporate labs. They help structure territorial development around poles of competence and are initiators of European research projects. The Ministry of Research has certified 18 CNRT between July 2000 and February 2002
Regional Centers of Innovation and Technology Transfer	209 CRITT – 36 are certified as Center of Technological Resources (CRT) – support mainly the technological development of SMEs, and 209 Technological Platforms (PTF) promote employment creation through innovation in specific sub-regions.
Technological Research Teams (ERT)	The Ministry of Research established ERT in 1999 to stimulate industrially relevant research in universities. 41 ERT have now been established, of which 3 in economics, social sciences and humanities.
CIFRE and CORTECHS	Contracts for Training Through Research (CIFRE) and Contracts for Research Technicians (CORTECHS) are public-private partnership programs that focus on human resource aspects of research and innovation, mostly to the benefits of SMEs. In 2001, 800 enterprises benefited from CIFRE and 3223 from CORTECHS.

French government attempts to achieve high leverage from the small amount of incentive fund available by combining two instruments: regulatory reforms and competitive grants within the framework of public-private partnership program (the mobility and evaluation of researchers, a new legal framework to facilitate their entrepreneurship and cooperation with industry, and the

empowerment of regional actors). The National Networks for Research and Technological Innovation (RRITs), complemented by regionally oriented public-private partnership initiatives, play a central role in this strategy. The RRIT program was developed with the following objectives:

- Develop new forms of partnership between public research and business community;
- Contribute to the creation and/or growth of innovative technology firms;
- Encourage research that could lift the technological obstacles to joint development of products and services based on new technologies;
- Gear that research to demand, so as to satisfy medium- and long-term economic and social needs;
- Help advance knowledge in response to societal needs; and
- Position French innovation networks in European Research Area (ERA).

III. Industry-Science Relationships

1. Industrial Research and Technology Transfer

Industrial Research as a source of important patents¹

Industrial research is primarily aimed at the broadening of technological knowledge rather than the development of specific products or processes that find immediate commercial applications. Therefore, the benefits of research are not apparent and the allocation of resources to research may not appear to be justified. Possible benefits of research need to be identified.

The adoption of short planning horizons by R&D managers, the lack of full appropriation of research results, the high risk involved in research activities and the reliance on public research institutions reinforce the temptation to refrain from investment in research. The upcoming of concepts like lean management, the shortening of development times, share-holder values or business reengineering has recently led to redirection and/or downsizing of research laboratories in many companies.

- A survey by the NSF came to the conclusion that in large companies, efforts is shifting away from central laboratories with greater emphasis on risk minimization to meet the needs of customers. Since decentralized units tend to have shorter planning horizon than central unit, this will further strengthen development efforts at the expense of research.

Research projects can be seen as a first stage of a sequential process that lead to the creation of knowledge, which is then transformed in new products or new processes by means of further development. In fact, being a source of future innovations has been identified as the major function of research. Most of patents are filed during the development stage, whereas they may actually originate from research. Thus, patents reflect the final results of a long term R&D project stream, which include basic research.

- It has been extensively argued that patent protection is rarely available for research results due to its inherent lack of immediate application, which is a core requirement for granting a patent. This argument has often been put forward to justify publicly funded research in order to compensate for insufficient private investment in research.
- For basic research, which is defined by a hardly assessable probability of commercial success, a long time to market and the probability for very high and sustainable competitive advantages, the company obviously seeks frequent and comprehensive patent protection. Developments based on basic research are likely to lead to innovations that yield very high and sustainable advantages, which are secured by patents.

Table 10. Types of R&D and patent-protection terminology from a company

Types of R&D	Probability of commercial success	Time to market	Competitive Potential	Length of Competitive advantage
Incremental R&D	40%-80%	6-24 months	Restricted	Short (Competition Follows quickly)
Key R&D	20%-40%	2-7 years	High	Long (frequent Patent protection)
Basic R&D	< 20% (hard to assess)	4-10 years	Very high	Long (frequent and comprehensive patent protection)

Source: Saad, K.N. and P.A. Russel (1991), *Management der F&E-Strategie*. Gabler Verlag, Wiesbaden.

¹ Ernst, H. (1998), Industrial research as a source of important patents, *Research Policy* 27, 1-15.

From the data of 25 electronic companies, no evidence is found that companies spend more on research as a proportion of total R&D budget experience lower patents per R&D than those that spend relatively more on development. This can be attributed to two effects. (1) Research-based inventions need less development resources per se or development resources can be allocated more effectively and efficiently. (2) Research-based inventions may be of higher technological and commercial importance and are therefore more often patented. Their particular economic importance may result from the incident that these inventions serve as the base for building up long-term sustainable core technological competencies, which eventually result in various applications, e.g., product families, thus leading to a number of further patent applications.

- Research includes applied research as well as basic research, as in the definition of OECD. For practical reasons, this was identified as all R&D activities with a focus on markets five or more years from today. This time frame seems to fit the research outcome horizon of electronic firms. Interviews with R&D managers of the companies revealed that the research intensity had remained basically unchanged during the considered time period.
- Patent activity is measured by the total number of European patent applications over the period between 1990 and 1994. As an indicator of innovative activities, share of granted patent (in relation to the number of patent applications at the European Patent Office) and share of US patents (the number of patent applications at US Patent and Trademark Office) are used. Citation ratio (the average frequency by which a company's European patent application is cited in subsequent patent applications at the EPO) is also used as a quality indicator of patents. This is advocated by empirical research that has established a positive relationship between the citation frequency of patents and different measures of commercial success.
- Japanese companies show significantly higher values for each quality indicator. Comparing with the patents filed by European companies, patents of Japanese companies are granted more (77% vs. 62%), in addition they are more frequently filed at USPTO (73% vs. 52%) and they receive on average a higher number of citations (0.58 vs. 0.46). Since Japanese companies have been found to spend a larger amount of total R&D on research than European companies, this result is consistent with the result obtained from previous correlation analysis.
- Controlling for international differences with respect to the patent strategy, the positive relationships between research intensity and patent quality becomes obvious and proves to be highly significant. On the contrary, no impact of R&D intensity on patent quality is found.
 - It can be argued that the high quality of Japanese patents in comparison to patent from European companies mainly result from the incident that the former group of patents represents a highly selective group. In fact, Japanese companies file only a small fraction of their total patents at the EPO, whereas European companies regularly file a substantial share of their total patents at EPO.

Patent Quality	Yokogawa Bull Minolta Matsushita	Sanyo Fujitsu	Furukawa Sony Zeiss Sharp Mitsubisjh Sumitomo, Canon Oki Oce Toshiba Phillips
	SEL ICL	Hitachi Alcatel-	NEC Bosch Siemens Grundig
Patent efficiency (patent applications/R&D expenditures)			

University-based technology licensing²

University research has expanded considerably in the 1990s. University research enhances the stock of knowledge, generates increased technological opportunities across a wide range of industrial fields and increases the potential productivity of private industrial R&D, apart from increasing the learning ability of graduates, when performed in close interaction with university teaching.

- Nevertheless we should be aware of the intrinsic dangers that the privatization of knowledge entails. Strong pressures exist for the privatization of scientific knowledge and the protection of technology. This trend may not only affect scientific international cooperation, which is essential for the development of science, but also limit the access to the most modern and competitive technologies, hampering the diffusion of important innovations. The determination of the impact of intellectual property protection policies still remains controversial due to the scarcity of empirical work.

US universities have been particularly successful at contributing to the accomplishment of commercial opportunities, whilst related actions in Europe have been erratic in quality and scarce in quantity. In the US, new innovations have benefited from a close interaction between universities and the community.³ In the context of the complex web of relationships between universities and industrial firms, intellectual property by universities represent a small portion. Nonetheless, the existence of explicit strategy for intellectual property protection in the US has provided the generation of sizeable aggregate level of income, though the impact of income at the institutional level is negligible on average.

- Licensing of university inventions add more then \$21 billion to the US economy, including both pre-production investments (\$4 billion per year) and post-production sales of products by licensees (\$17 billion per year). More than 10,000 licenses and options were executed in 1995, which reflects the increasing success of partnerships between academic institutions and industry.⁴ There is an increasing rate of growth of royalties received in comparison with R&D expenditures, which reflects the growing importance of intellectual property rights. Some US universities have been particularly benefited from R&D income and royalty.
 - MIT has received \$38 million in license revenues. At Stanford University since 1969, when the Office of Technology Licensing was founded, royalties have surpassed \$111 million, capitalizing from inventions such as Recombinant DNA (\$53.4 million) and FM Sound (\$13.9 million). Other universities have also benefited from significant funding from license fees, normally associated with a particular invention. Other big-winners include University of Wisconsin (vitamin D and Warfarin), Michigan State (CIS Platinum), University of Rochester (Hemphilus vaccine).
- As technology transfer efforts continue to increase, new industries, businesses and jobs are being created. Since the 1980 in the US, academic licensing has helped to form 1633 new companies, which support 180,000 jobs each year (AUTM, 1997). In 1994 and 1995, a total of 464 companies were started as the result of academic licensing. More broadly, there is a strong correlation between employment and some measure of innovative activity, namely patents and R&D.

² P. Conceição, M. Heitor and P. Oliveira (1998), University-based technology licensing in the knowledge based economy, *Technovation* 18(10), 615-625

³ Rosenberg, N. and R. R. Nelson (1996), The roles of universities in the advance of industrial technology, in R. Rosenbloom and W. Spencer (eds.), *In Engines of Innovation*, Harvard University Press, Cambridge, M.A.

⁴ Gross royalties received by US universities, hospitals and research institutes increased from \$175.1 million in 1991 to \$415.8 million in 1995. Source: AUTM Licensing Survey 1991-95, 1997. (A 5-year survey on technology licensing by the Association of University Technology Managers)

- Despite the impact of patent income at few US universities and the overall growth, we should stress that, on average, the share of royalties in the total research expenditures remains small, and below 0.2%. Although the figures do not represent the specific trends of the leading US universities, the expectation is that this share will remain small.

Despite its outstanding scientific performance, Europe is far behind the US and Japan in terms of its technological and commercial performance. The result indicate that one of its weakness lies in its inferiority in terms of transforming the results of scientific research into innovations and competitive advantages. This has led to a shift in the European R&D policy towards seeking economic relevance in science and technology.

- The relative weakness of European industry has been discussed since 1992: its competitive edge has been blunted; its research potential is being eroded; and finally, it has a very weak position with regard to future technology. It is clear that the EU has a relatively much lower level of R&D than the US and Japan. Especially in Europe, the supply of research personnel can hardly keep up constantly growing demand. Even more important than the absolute number of researchers are their qualifications, the ability to meet the needs of developing industries and the extent to which the capital they represent is utilized. This problem is based on European weakness in integrating R&D and innovation.

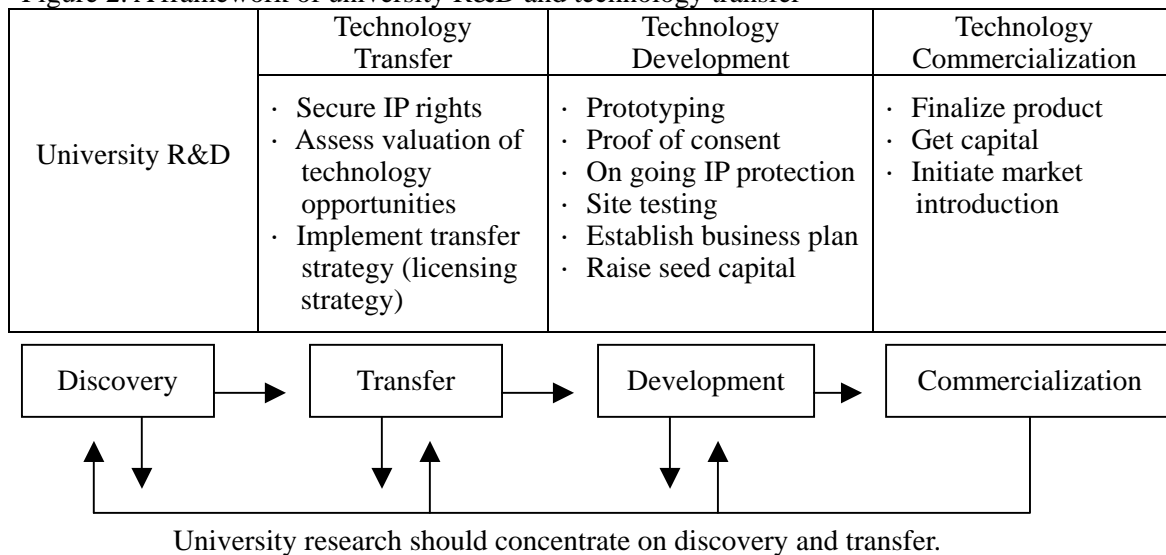
Table 11. Distribution of R&D expenditure by sector of performance (%)

	State	Enterprises	Higher Education	Non-profit Organization
US	10.0	71.1	15.4	3.5
Japan	9.0	66.1	20.2	4.7
Germany	15.0	66.1	18.9	-
France	21.1	61.6	15.9	1.4
UK	13.8	65.2	17.5	3.4
Italy	22.1	57.0	20.9	-
Netherlands	19.4	53.0	24.9	2.7
Denmark	17.8	58.3	22.8	1.0

The rationale for promoting intellectual property protection in European universities must lie on an effort to clarify the research function of the university, although it may complement the traditional type of research. Technology transfer should be explicitly acknowledged as a way to achieve the requirements of preserving the university's institutional integrity. University-based policy of intellectual property should protect the academic interest, avoiding an excessive move into commercialization concerns, which could threaten the university's institutional integrity.

- At the university level, there is both science and technology. Universities often engage in aggressive and effective programs to protect their intellectual property. The motivation is clear: to derive financial benefits from the creativity of academic scientists. In effect, this action can be visualized as a shift upward from non-excludable to excludable software.
- Europe has been copying some US practices without any effort to reflect on how to adapt them to the specificity imposed by the history and institutions of Europe. Successful technology transfer depends on a complex web of interactions, and is highly contingent on the specificity of the place where the transfer occurs. The particular institutional history, legal setting, and other factors, demand customized policies and practices. There is no single model for defining and implementing technology transfer strategies.
 - One major difference between the US and Europe is the availability of genuine risk capital, often provided by individuals rather than by investment funds, for investment in the early-stage projects with perceived and accepted high levels of risk. In Europe, such venture capital too frequently is invested in management buy-outs or buy-ins, where the risk level is low, or in company mergers or break-ups, where rapid short-term gains can be made.

Figure 2. A framework of university R&D and technology transfer



There are complex links and feedback relations between industry and the S&T system. The foundations of competitive advantage in innovation include such organizational capabilities as firm-specific knowledge, communities of practice, and technology platforms.⁵ This should be distinguished from the body of generally accessible knowledge. The issue is how research at university contributes most effectively to the profitable execution of the chains of innovation. Effective research will contribute to the base of general knowledge, but productive research requires the corporations to build organizational capabilities.

Technology transfer as an interactive process⁶

The limitations and deficiencies of traditional technology transfer mechanism are largely due to the dominance of the linear model of innovation on conventional thinking. An alternative model of technology transfer emphasizes the interactive nature of the process. A conceptual framework is developed which identifies four major components of the inward technology transfer process, awareness, association, assimilation and application. The conclusions indicate the importance of non-routine activities and effective communications between credible boundary-spanning individuals.

Recent studies revealed that the external acquisition of technology becomes the most prominent technology management issue in multi-technology corporations, and that similarly innovative SMEs have dense networks in a variety of marketing and manufacturing relationships. However, it appears that not all firms have the capacity to forge and develop effective external linkages, formal or informal.

- The most significant factor determining SMEs' propensity for and ability to access external technology is internal to the firm: most notably the employment of qualified scientists and engineers and outward-looking managers. The lack of internal technological know-how can inhibit external know-how accumulation and the firm's receptivity to

⁵ Communities of practice are ensembles of skilled technical people with expertise on working across the organization. These communities span organizational divisions and provide both a repository for the firm's expertise and a medium for communication and application of new knowledge. Technology platforms are an output of the design process, which provide a common framework on which families of specific products and services can be created over time.

⁶ Tott, P., M. Cordey-Hayes and R. Seaton (1995), Inward technology transfer as an interactive process, *Technovation*, 15(1), 25-43.

externally developed technology. R&D expenditures can be seen as an investment in a firm's *absorptive capacity*. A firm's ability to evaluate and utilize external knowledge is related to its prior knowledge and expertise, which is, in turn, driven by prior R&D investment.

- Accumulated technological knowledge and experience appear to outlive an individual, implying that it is the organization, rather than the individuals who pass through it, that is responsible for accumulating and retaining technical competence. Over long periods of time, organizations build up a body of knowledge and skills through experience and learning by doing. This implies the importance of practiced routines built into the organization, which is referred to as an organization's core capabilities. There is a need to uncover the processes to achieve this desirable state of *receptivity*.
- Inward technology transfer will be successful only if an organization has not only the ability to acquire but also the ability to assimilate and apply ideas, knowledge, devices and artifacts effectively. Organizations will respond to technological opportunity only in terms of their own perception of its benefits and costs and in relation to their own needs and to technical, organizational and human resources. The process view of technology transfer, therefore, is concerned with creating and raising the capability for innovation, requiring the capability to
 - Search and scan for information on technology, new to the organization (awareness);
 - Recognize the potential benefit of this information by associating it with internal organizational needs and capabilities – recognize the value of this technology (idea) for the organization (association);
 - Communicate this technology within the organization and create genuine business opportunities (assimilation); and
 - Apply them for competitive advantage.

Awareness is the necessary first stage in the inward technology transfer. It is defined as being informed and vigilant of technical / business environment, using various sources of information, especially the processes of scanning and networking. Scanning is a purposeful search and undirected viewing, often termed browsing. The use of networking is the process of interaction, resulting in informal trading of knowledge.

- A key characteristic of technically progressive firms is their high quality of incoming information. Organizations should ensure that their personnel are aware of technological development done elsewhere. Scanning by individuals on behalf of the organization is often regarded as informal and unassigned. Organizations do not provide support for such activity, because they are unaware of its value. *Gatekeepers* are those who possess a high degree of awareness of the external environment.

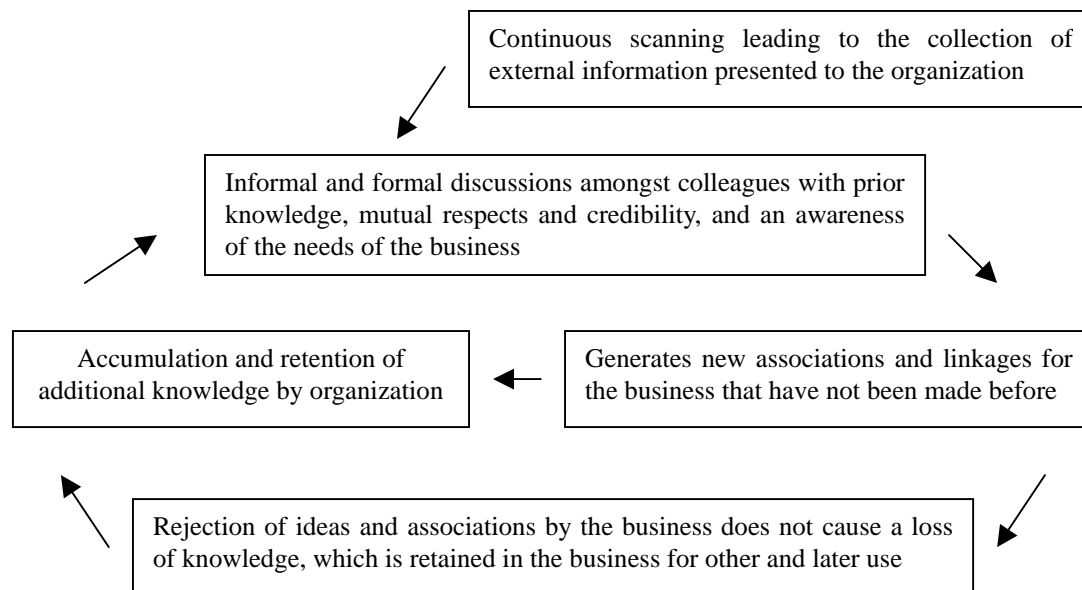
Organizations need to have thorough understanding of its internal organizational capabilities in order to search and scan effectively for technology that will match their business opportunities. This can be effectively achieved via the processes of internal scanning and networking. A thorough understanding of the business's operations, markets, capabilities and future business plans is essential for effective scanning and networking. The coupling of internal and external, technical and commercial scanning will produce business associations.

- Many internal organizational needs are not expressed explicitly as a need, but may be more appropriately described as opportunities that exist. Virtually every organization will possess a variety of opportunities; many of these may remain unfulfilled, others will be taken and changes introduced. Opportunities often exist to improve products or processes by reducing costs associated with them. These opportunities tend to be needs that are not perceived in technical terms. Small firms, particularly, do not perceive their needs in technological terms, and hence would be unlikely to be involved in scanning.

- Inward technology transfer involves more than identifying interesting technology; it is necessary to match technology with a market need. Hence the scanning process needs to incorporate commercial scanning as well as technological scanning. It is the assimilation of potential business opportunities with the organization's capabilities that will create viable business opportunities. The coordination of organizational resources is necessary for successful technology transfer.

The assimilation stage of technology transfer is a complex process, where new technology is integrating with the existing knowledge base of an organization. Related prior knowledge at the individual level provides an ability to recognize the value of new information, and facilitates the creation of linkages and associations. In order for these associations to be assimilated into genuine business opportunities, an understanding of the needs of the business is necessary. Generalized business objectives provides the participants with sufficient scope to identify potentially useful technical linkages and associations.

- The knowledge base is consists of the accumulated knowledge of all individuals together with the social knowledge embedded in relationships between these individuals, which combines individual knowledge base into a larger body of knowledge, and enables individual knowledge bases to be accessed by the organization effectively. These relationships are often recognized as organizational processes and procedures.
- Overlap of knowledge is needed for communication, cross-function interfaces between R&D, design, manufacturing and marketing (concurrent engineering). The up-down flow of communication in a traditional organization hierarchy blocks change.



2. Industry-Science Relationships in Germany and Japan

Public research and industrial innovation in Germany

In the 1990s, federal and state governments spent about DM 25 billion for R&D (30% of gross national R&D expenditure) annually, half of which went to universities and polytechnics (Fachhochschulen), and half to public research laboratories. In addition, DM 5 billion is directly given to private businesses as project-related subsidies for R&D. Germany spent more on R&D in the higher education and public research institutions as a percentage of GDP than most of the OECD countries.

- The number of researchers within natural science, engineering and medical faculties of publicly funded institutions was estimated to be 122,000 in 1993, 70% of which are at universities and polytechnics. The full-time equivalent of public researchers is 50% of the head-count. University faculties spent from 30% (clinic) to 60% (engineering) of their time on research, and faculties of polytechnics 5%.⁷
- Technical universities had been formed since the 19th century to enforce applications of scientific findings, but have subsequently focused on basic research. They received up to 40% of external research funds from industry, though it is less than 10% of all their research spending. As the public law imposes some restrictions on technology transfer, universities have established legally independent external institutes in order to gain administrative flexibility. In 1993, these institutes made up about 4% of all research at universities, but this share has been increasing rapidly in the 1990s.
- Polytechnics are specialized in the same technical fields as local businesses and are supposed to support SMEs through consultancy and the supply of graduates. They focused mainly on education, but also conduct research, though on a much smaller scale than universities. They have gained a reputation for down-to-earth research and applicable engineering know-how, compensating the shortcomings of universities that are oriented towards basic research.

Less than 9% of the firms that introduced innovations between 1993 and 1996 received the support of public research for their innovation – that is, they introduced innovations that would not have been developed without public research. These new products amount to approximately 5% of all new product sales. The figure is 15.9% in R&D-intensive industries, and 6.2% in non-R&D-intensive industries.

- Public research had a much higher impact on new products than on new processes. A larger share of private R&D expenditure is pointed at product innovation. In R&D-intensive industries, 29% of the firms introducing public-research-based innovations developed new processes. In non-R&D-intensive industries, the share was 42%, reflecting higher incentives for price-cutting process innovations relative to new products than in R&D-intensive industries.

Table 12. Share of firms with public-research-based (PRB) innovations (%)

		Manufacturing	R&D intensive	Not R&D intensive
PRB innovations to All product or process innovations	Total	8.5	15.9	6.2
	Products only	5.5	12.0	3.5
	Processes only	1.5	2.4	1.3
	Products & processes	1.5	1.5	1.4
PRB product innovations to all product innovations		7.9	14.0	5.7
PRB process innovations to all process innovations		3.4	5.2	2.9

Source: ZEW Mannheim Innovation Panel

Universities are cited as the most important source of knowledge. Publicly financed laboratories get almost as many citations. However, big science laboratories are almost invisible. Less than 1/5 mentioned the polytechnics, which, considering their low budget, turns out to be a high figure. Looking at the size distribution of firms, larger companies give priority to universities. Smaller firms receive relatively more support from polytechnics and, somehow surprisingly, from publicly financed research laboratories. It seems that universities discriminate against

⁷ Marian Beise and Herald Stahl (1999), Public research and industrial innovation in Germany, *Research Policy* 28, 397-422.

small firms in favor of large firms because the latter are more attractive in terms of funding and proximity to basic research. However, compared to polytechnics, universities still play a role in innovations for small firms.

- Firms tend to cite research institutions that are located close to the firm. Firms with high R&D intensity, however, cite remote public research institutes more frequently than less R&D-intensive firms, suggesting that high-technology does not depend on co-location of public and private research. The firm's own R&D activities support the ability to absorb the findings of public research and turn them into innovations.

The share of sales with new products introduced between 1993 and 1996 is about 1/3. The share of the public research-based products is 1/4 of all sales with new products. The sales of public-research-based product innovation were estimated to be less than 5% of total revenue for new products of manufacturing.

- Smaller firms tend to cover a higher share of sales with publicly supported innovations than larger companies. Smaller firms more often compensate a lack of basic knowledge and research capabilities with partners of the public research infrastructure than companies with large R&D laboratories, which tend to keep crucial developments in-house to prevent knowledge drains to other firms. Public-research-based innovations of smaller firms have a higher impact on their sales than their in-house innovations.
- Considering the amount of public funds, the sales of public-research-based innovations could imply that public research does not to yield social welfare in the form of spillovers to industrial innovations as much as its costs. However, the survey (2300 companies) identified only the fraction of products where public research is vital but not consciously recognized by the firm.
 - It is almost impossible to measure all additional effects of intermediate products like semiconductors that enable new functions of other products. Furthermore, the survey includes only short-term effects of public research.
- Public research, however, tend to be used for industrial innovations a fairly long time after publication. Many firms do co-operate with public research institutions on strategic long-term research projects only with no explicit agenda of product or process development in order to keep the core knowledge of their in-house innovations.
- On national level, the argument for basic research is that nations can get a head start in new technologies in such areas as IT, BT and NT, where markets are not yet developed and technological progress is pushed mainly by advances in science. These long-term effects are not only hard to measure but also disputable. It is not clear whether lead applications always occur where science is most advanced.

. Table 13. Public research institutions cited by at least two companies

	% of citation	% of R&D staffs		% of citation	% of R&D staffs
FhG	12.8	3.2	TU Clausthal-Zellerfeld	1.5	0.5
RWTH Aachen	8.2	5.8	TU Hamberg-Harberg	1.5	0.4
TU Dresden	5.1	2.6	Fachhochschulen	1.0	0.7
U Stuttgart	3.1	2.1	Aachen	1.5	2.9
Bergakademie Freiberg	2.6	0.5	TU München	1.0	3.4
U Nuernberg-Erlangen	2.6	2.8	TU Berlin	1.0	1.3
Ruhr U Bochum	2.6	2.6	U Rostock	1.0	0.1
TH Darmstadt	2.6	1.5	Fachhochschulen Aalen	1.0	1.5
F Nuernberg	2.0	0.4	U Paderborn	1.0	2.0
U Hannover	1.5	1.2	U karlsruhe	1.0	1.4

The FhG play the dominant role within the group of institutions other than universities and polytechnics. The institutes of the FhG were cited most frequently. Large technical universities with engineering faculties were cited most, leaving traditional universities that focused on natural science far behind. The most cited university was Aachen, which is the only German university cited by US companies.

- In the US, mostly privately financed elite universities such as MIT, Harvard and Stanford, which are world leaders in science and technology, attract the highest research grants from businesses, thus becoming most decisive in industrial innovation. The majority of academic institutions, however, display a rather mediocre performance when it comes to valuable research results that may be used for high-technology industrial innovation. The top four research institutions received almost 30% and the top 10 got 43% of the citations but employ 23% of the scientific staffs.

The commercialization of new technologies and firm formation in high-tech industries are influenced by regional innovation milieu, which is characterized by intensive collaboration, informal contacts and technology transfer within the business sector.

- If research outputs cannot be reduced to formal sets of codified instructions, they cannot be transferred over long distances and require face-to-face communication. The incentive to work together with public research institutes should be higher for firms that are located close to these public institutes, since the costs of collaboration increase with distance. Moreover, there should be more occasions for informal communications between scientists of private firms and public institutions who live in the same region. Informal communication leads to mutual trust, and trust raises the propensity to co-operate in R&D projects, since cooperation always increases the risk of know-how leaking-out.
- Yet there is ample criticism of the generalization of the Silicon Valley story and the dominance of regional over inter-regional effects of public research. All measured effects could still be the effects of a regional market for skilled labor and spin-offs and not of technology transfer and intensive communication between local researchers. In the case of biotechnology, 70% of 445 identified firm-university links are non-local.⁸ The influence of distance seems to depend highly on the innovation behavior of the firm. For R&D-intensive and outward-oriented innovating firms, distance to the source of know-how is irrelevant and quality of external technology to be assessed is the only important factor.
- Although regional policy and heavy public support for science parks are common in Europe, Silicon Valley seems to be US-specific phenomenon. Sternberg (1996) notes that there is no evidence yet for specialized industrial districts in Germany at all. Although there is some evidence for a positive relationship between university and firm formation in high-tech industries, the same does not hold for R&D co-operations.
- In Germany, distance did not matter much for high-tech firms.⁹ Apart from start-ups, German R&D performing companies lose their dependence on local research institutions. Polytechnics, founded mainly to support local SMEs, were named almost entirely by nearby firms as a useful knowledge source. Excluding polytechnics, the distribution of proximity to remaining research institutions turns out a lot more even.
 - A survey of technology transfer from the Aachen University found most of the companies collaborating with the machinery faculty to be located outside the region – only 15% belonged to the region and 1/3 was located in the southern states of Bavaria and Baden-Württemberg.

⁸ Audretsch, D. and P. Stephan (1996), Company-scientist locational links: the case of biotechnology, *American Economic Review* 86, 641-652.

⁹ Grotz, R. and B. Braun (1997), Territorial or trans-territorial networking: spatial aspects of technology-oriented co-operations within the German mechanical engineering industry. *Regional Studies* 31, 545-557.

*Collaborative R&D Network in Japan*¹⁰

Until the early 1980s, in addition to establishing research laboratories and conducting in-house researches, Japanese firms were willing to perform joint researches with US universities. It was widely recognized that Japanese firms have higher research capability than Japanese universities. However, the collaborative R&D activities have changed rapidly in recent years.

- Since the early 1980s, Japanese government has established various schemes to increase the role of the university in responding to increasing demand for research from industry.
- The multi-funding system, such as grant-in-aid funding systems, has adapted to Japanese universities recently. These dedicated systems have become an important and fairly successful organizational vehicle in the Japanese S&T policy framework, and generated great impacts on university-industry relations and innovation system.
- Among the 305 institutions that have Ph.D. programs, research excellence is heavily concentrated in a small number of universities. With a few exceptions, highly regarded universities are national universities, which are funded and controlled by the Department of Education. Collaboration between national universities and industry is regarded as one of the central elements, when discussing collaborative R&D networks.
- Compared with other departments, the Department of Education started to make efforts to stimulate industry-university collaboration relatively early, and launched a series of programs in the 1980s. Among them, particularly “Joint Research with the Private Sector” (JRP) program is widely accepted by both industries and universities.
- Japan Society for the Promotion of Science also plays a role in promoting industry-university collaboration. JSPS is a quasi-governmental organization that conducts various programs in line with national S&T policies to promote science. It operates a wide range of programs to promote scientific activities in Japan and abroad, including research fellowship, international exchange and university-industry collaboration.

Joint Research with the Private Sector” (JRP) program encourages researchers at national universities to conduct joint research in their laboratories on an equal footing with researchers from private companies on topics of common interests. During the 1983-1993, the number of joint research projects and the universities involved increased rapidly. The increasing trend was observed also in industry. 1740 firms and 90 universities involved in the program during 1983-1993. More than 200 firms entered for the years 1990-1993, indicating that the program widely penetrated in industry community and changed the attitude of industry toward university.

- Joint research is actively carried out in such fields as materials development, equipment development, software, civil and architectural engineering, electronics and biotechnology. In terms of number of projects, new materials and apparatus development accounted for higher percentage, 23.4% and 20.4% respectively, whereas the share software was only 10.7%. These results may reflect the industry’s viewpoint towards university’s research competence.
- Research funds are also received from the participating companies. Patents generated from the joint research are owned jointly with the participating firms, and the firms (persons designated thereby) receive patent-licensing priority for up to 7 years.

There have appeared two distinct clusters: those of top academic institutions and those of local universities. The former includes top national universities such as Tokyo University and Osaka University, which have predominantly been in collaborative R&D networks. In addition, a few universities were among the major players by collaborating with relatively large number of firms. In contrast, a group of local universities had considerable presence in the formation of the

¹⁰ Wen, J. and S. Kobayashi (2001), Exploring R&D Network: some new evidence in Japan. *Research Policy* 30, 1309-1319.

latter clusters by collaborating repeatedly with a small number of local firms. This indicates that a cluster represented by local universities already got into shape in collaborative R&D network. In terms of average number of joint project performed with universities and the number of university counterparts, firms can be broken down into three major groups; Japanese multinational corporations, large firms mainly operating in domestic markets, and the group of major local firms. The multinational corporations and top national universities have presented and have greater impacts in the whole country, while the local counterparts have emerged as important local players.

- Of the 1740 firms involved in the program, 142 firms (8%) collaborated with Tokyo University; the next highest university of origin was Osaka University at 7%, suggesting that the prestigious universities continued having significant impact on the formation of collaborative R&D network in Japan.
- Of the 90 universities participated in the program during 1983-93, 29 universities (32%) collaborated with Hitachi, and 23 universities (26%) with Toshiba. These multinationals presented significantly at nation-wide scale, reflecting the changing attitude of Japanese firms toward Japanese universities and the shift from in-house research mode to collaborative mode with universities in Japanese industry. Many of these firms have regional R&D establishments or laboratories.
- The most active representatives of the second cluster were the major local firms. This collection of firms collaborated intensively and repeatedly with limited number of local universities, reflecting lasting demands for joint researches with local universities. These universities can generate relatively satisfied research outputs to meet the needs of innovation in local firms.

Collaboration was getting more and more active across the prefecture boundaries.¹¹ It is not rare phenomena for individual researchers from different universities, firms or prefectures to conduct joint research projects temporarily, especially for more complicated projects, such as projects in priority research fields. Such kind of collaborative work extends gradually among individuals, organizations, and sectors.

- In Tokyo Metropolitan area and Osaka Metropolitan area, firms and universities performed more collaboration with counterparts in other prefecture. In contrast, joint research projects in some prefectures are performed mostly within the same prefecture. Prestigious universities with wider research fields and good faculty quality in metropolitan areas were more attractive to firms in the other prefectures. Meanwhile, major firms with subsidiaries nation-wide while locating headquarters and important facilities in metropolitan areas, were more likely to be involved in collaborative R&D with universities in respective regions.

In Japan, academics and industry became more open-minded, more favorably exposed toward collaboration in the 1990s than in the 1980s and earlier. And the collaborative R&D is shifting from in-house oriented, consortium-led mode to university-industry collaborative, cross-sector mode.

- Nevertheless, top universities and major corporations in Tokyo Metropolitan area will continue to represent nation-wide and contribute to Japanese innovation system.¹²

¹¹ Geographic dispersion is measured by numbers of joint research projects within the same prefecture and beyond the prefecture boundary.

¹² Gradual extension of collaborative R&D network observed is largely due to geographic proximity. It usually takes less than three hours to Tokyo from most local areas and more than 1/3 of university faculty concentrate in Tokyo Metropolitan area. Therefore joint research among universities and firms around Tokyo Metropolitan area contributed significantly to the increase in trans-prefecture collaborations, and the formation of collaborative R&D network.

3. The Growing and Changing Role of Industry-Science Relationships

The performance of an innovation system depends now more than in the past on the intensity and effectiveness of the interactions between the main actors in the generation and diffusion of knowledge. Industry-science relationship (ISR) plays an important role in the development of fast growing new industries and in training, retaining and attracting highly qualified labor. As a result, science-industry linkages have grown in importance as a central concern for policy.

- The intensification and diversification of industry-science relationships is most notable and well documented in the US but can also be observed in other countries, including those where informal mechanisms of interaction have traditionally played a greater role, such as Japan. This signals deeper ongoing transformation in the respective role of cooperation/competition between curiosity-driven scientific research, mission-oriented public research and profit-driven business R&D, due to the combined effect of the following factors:
 - Technological progress accelerates and market expands exponentially in areas in which innovation is directly rooted in science (BT, IT and new materials).
 - New information technology allows easier and cheaper exchange of information between researchers.
 - Industry demand for linkage with the science base increases more broadly, as innovations requires more external and multi-disciplinary knowledge. Tighter corporate governance leads to the downsizing and short-term orientation of corporate labs, and more intense competition forces firms to save on R&D costs while seeking privileged and rapid access to new knowledge.
 - Financial, regulatory and organizational changes have boosted the development of market for knowledge, by making possible the financing and management of a wider range of commercialization activities. Restrictions on public finance have encouraged universities and other publicly funded research organizations to enter this booming market, especially when they could build on already solid linkages with industry.
- In many fields, technological innovations make more intensive use of scientific knowledge. In addition, publicly funded research provides the skilled graduates that are essential to firms wishing to adopt new technologies, new instruments and methods for industrial research and an increased capacity for problem solving.
 - In the US, almost 3/4 of the references to scientific publications listed in US patents is from public science.¹³
 - The number of references to public science nearly tripled over the six-year period.
 - Between 5% and 1/3 of new products, depending on the sector, could not have been introduced without direct input from recent academic research.
 - The time delay from academic research to industrial practice has in average shortened from 7 years to 6 during the 1990s.¹⁴

Modern innovation theory stresses the complex feedback systems between basic research and industrial R&D. ISR is not simply a transaction mirroring a clear-cut division of labor in the production of knowledge. It should be evaluated not only as knowledge transfer mechanisms but also in their other capacities – building networks of innovative agents, increasing the scope of multi-disciplinary experiments. To this end industry-specific linkages must be characterized along three dimensions: nature and relative importance of the channels of interaction, their institutional arrangements and their incentive structures.¹⁵

¹³ Narin, F., K. Hamilton and D. Olivastro (1998), 'The Linkages between US Technology and Public Science', *Research Policy*, 26, pp. 317-330

¹⁴ Mansfield, E. (1998), 'Academic research and Industrial innovation: an Update of Empirical Findings', *Research Policy*, 26, pp. 773-776.

¹⁵ The channels of ISR includes contract research, consultancy and services, IP transactions, knowledge

Changing stakeholders' objective and needs

In the last decade, universities in many countries have been called to compensate for the decline of public research institutes in the commercialization of public research. In the recent period policy attention in most OECD countries has tended to focus increasingly on the role of ISR in fostering entrepreneurial activity in fast growing industries, often to neglect of other important contributions of science system.

- Leading research universities adopt now more ambitious goals, including strategic alliances with firms to consolidate their position in innovation networks and to get their share of the booming market for knowledge. Smaller universities are tempted to transform part of their research departments into business support units and contract research organizations.

Publicly funded research organizations value relationships with industry for different reasons depending on their main mission. Universities cultivate industry contacts to ensure good job prospects for students, keep curricula up-to-date in some disciplines and obtain financial or in-kind support to reinforce and expand their research capabilities beyond what would allow core funding.

- Large multi-disciplinary public research institutes have always had close links with the private sector in areas where industry is an important player in the whole research spectrum, including fundamental research. The need to diversify their activities away from stagnant or declining core activities drives largely ongoing changes in their relations with industry. They now need to adapt their interface with industry to the requirements of new science-based industries where start-ups and small firms are important players. Mission-oriented public research institutes have developed almost organic linkages with the part of industry that offers complementary competencies in responding to government procurement.

Innovation surveys demonstrate that improved access to better trained human resources is by far the main benefits that industry expects from linkages with publicly financed research, and this is not likely to change in the future given the risk of persistent shortages of highly qualified labor.

- Among other benefits (that include also networking and clustering opportunities or access to problem-solving capabilities), privileged access to new scientific knowledge seems to take on a new importance. Industries remain significant actors of the science system, especially in chemistry, physics and basic engineering.¹⁶
- However, it relies increasingly on public research to complement its own growing R&D efforts. Industry views diverge concerning the preferred channels to access publicly funded research. For example, increased patenting by publicly funded organizations yields more benefits to small firms than larger ones that have long-established close links with public research.

spillovers, cooperation with firms for teaching/training, labor mobility. Knowledge spillovers refer to a number of processes and infrastructures to facilitate informal knowledge transactions between industry and the science system (science parks, incubators, laboratory space for firms on campus, public labs as lead users of innovative equipment, informal interactions between public research staffs and industry's researchers etc). The institutional arrangements of ISR can be considered from a macro perspective (types and respective role of publicly funded research organizations, degree of intermediation) or a micro perspective (the legal and organizational framework for the management of the linkages by individual research or intermediary organizations). The incentive structures are of a financial or regulatory nature and can be also analyzed at both macro and micro levels, depending on whether they are established by government or the management of individual organizations.

¹⁶ National Science Foundation (1998), *Science and Engineering Indicators 1998*, Arlington, VA.

Informal and human resource-based linkages

Formal mechanism of ISR is only the tip of an iceberg. The bulk of ISR takes place through informal and indirect channels and also through unrecorded direct channels in countries where the regulatory framework has been for long quite restrictive.

- In the UK, innovation surveys shows that whereas almost half of manufacturing firms finds universities as an important source of innovation, only 10% have developed formal relationships with them.

The flow of skilled personnel to industry is the single most important channels of ISR. Informal networks between faculty and former graduates and between former public researchers and their lab of origin account for a large share, although difficult to measure, of the total amount of knowledge exchanged between industry and public research. New ICT can only reinforce the role of these social networks in ISR. Economists and governments generally underestimate these human resource-related linkages. They tend to overlook the fact that access to scarce human resources is always present as a key objective of industry when considering the merits of any type of linkages, formal; or not, with public science.

Increased commercialization of public research

The large increase in patents filed by the private sector, public research, or jointly by companies and public research underscores the growing transformation of knowledge into economic assets.

- In the US, university patenting has increased more rapidly than university research spending and more rapidly than national patenting rates. Universities have more than doubled their propensity to patent during the 1990s, as did also public lab, starting from a low level. The share of university in total patents is 3%.¹⁷
- In Germany, the share of patent applications listing university professors as inventors has been rising steadily since the 1980s, and represented already 4% of total applications by the mid-1990s.¹⁸
- In the first half of 1990s, licensing income of four of the main French labs (CNRS, INRA, INSERM, INRIA) was equivalent to only 0.6% of their budget, i.e. less than 1/10 the licensing revenues of US universities, but this percentage has increased rapidly since then.
- Japanese public research has distinctively weaker patenting activities than its homologues in other advanced countries. Universities represent less than 0.1% of total patent in Japan.

However, when considering the policy implications of the recent surge in patenting, using the US as a benchmark, it is important to keep in mind the following facts and emerging issues.

- Revenues from patenting do not reduce significantly the need for other sources of funding. In the US, gross revenues from licenses represent on average less than 3% of R&D funding of US universities and less than 2% of R&D spending of public labs.
- Patenting is not a reliable indicator of scientific output. The distribution of academic patents is highly skewed towards bio-medical sciences and the bulk of revenues from patenting come from a few successful inventions.
- Government played a crucial role in spurring patenting activities but was aided by other changes. Changes in the intellectual property regime (Bayh-Dole Act) was among the key factors behind the rise of US university patenting and licensing in the last two decades. But it built on a longstanding tradition of industry-university collaboration facilitated by

¹⁷ Howells, J., M. Nedeve and L. Georghiou (1998), *Industry-Academic Links in the UK*, PREST, University of Manchester.

¹⁸ BMBF (Federal Ministry of Education, Science, Research and Technology) (1997), *Germany's Technological Performance*, December.

the autonomous status of research universities.¹⁹ Other factors also played their role: institutional change (proliferation of technology and transfer offices, partly in reaction to Bayh-Dole Act), technological evolution (rise of BT and IT), financial incentives (reduced perceived government funding).

- The main contribution to innovation of increased patenting is not to make public sector research more commercially relevant but to improve information on the existence and location of commercially relevant research results.
- Buoyant patenting activities should not overshadow the parallel development of other forms of ISR. University-Industry research centers in the US – or similar mechanisms in some other countries – have become popular mechanisms to foster public-private cooperation and are successful at both leveraging government support for academic research, and orienting the latter toward more applied problems.
- Greater autonomy of publicly funded research organization increases their contribution to innovation through patenting and other means when it is paralleled by greater accountability. Centralized systems with restrictive regulatory framework but low accountability both reduce the responsiveness of public research to industrial needs and encourage the development ‘gray’ relations that would be prohibited in the name of public interest in more liberal and decentralized systems.

Increased patenting by universities and public labs has also costs and raises new issues. Concurrent with this increase, the variety of ideas and research results that are being patented has also grown. This raises the risk of erosion in the social return from public funding of research and of a possible decline in the quality of patents, and could have negative impact on innovation in the private sector.

- The expansion of patentable subject matter (e.g. from life forms, DNA fragment, business methods to software, which hitherto relied on other forms of protection) could in fact diminish the flows of ideas and the diffusion of research knowledge in some disciplines.
- Growing costs and risks of patent litigation are augmenting the uncertainty of innovation. In addition, they incite industry to impose more stringent restrictions on publications of joint research. It also contributes to lower the quality of patents since potential innovators tend to file more patent applications in order to protect themselves from litigation. Increases in damages paid to plaintiffs create situations where a patentee can gain more through litigation than exploitation of its inventions.

Globalization

The globalization of R&D strategy and access to public research together with increased mobility of scarce qualified labor now lead to much more fundamental transformations in ISR:

- The hierarchical and centralized model of ISR governance that still prevails in a majority of countries must leave way to a contractual and decentralized one. Within public/private partnerships the source of initiatives is shifting from government to firms, within government from central to regional and local authorities, within public research from public labs to universities, and within public research organizations from central management to labs and research teams. Now that mission-oriented public research can no longer play a pivotal role within ISR, new market-friendly co-ordination must be implemented, with greater involvement of the financial sector, especially venture capital.
- Foreign firms make often more intensive use of public research than domestic ones and the efficiency of national support measures enhanced when recipients are parts of dynamic

¹⁹ Mowery, D. (1998), ‘The effects of Bayh-Dole on University Research and Technology Transfer,’ Paper presented at the OECD/TIP Workshop “Commercialization of Government-funded Research,” Canberra, 25, November, 1998.

international networks. Government must rethink how to maximize national benefits from ISR that involves industrial participants taking a more global perspective. Building on globalization to increase national benefits may require easier foreign access to national programs and the relaxation of eligibility criteria regarding the location of publicly funded research activities, as well as greater international cooperation among governments to avoid opportunistic behaviors and distortions of competition.

- Globalization prompts public funded organizations to reconsider their role in the economy. Some now enters into broad alliances with homologues or private firms in order to create knowledge platforms.

4. Benchmarking Industry-Science Relationship

National patterns of industry-science linkages

The interactions between the public research sector and industry take various institutional forms and differ in nature and intensity reflecting national specificities in institutional set-ups, regulatory frameworks, research financing, intellectual property rights and in the status and mobility of researchers.

- Globalization and the diffusion of best practice policies reduce differences between national systems of ISR and may change their comparative advantages but cannot abolish the considerable diversity of existing models. Existing internationally comparable indicators capture some of these differences. Measurable national differences with implications for ISL include (1) which institutions perform and which institutions fund research development (2) trends driving the funding and performance patterns of R&D; and (3) specialization in specific scientific disciplines.
- The share of government in funding and performance varies considerably among the OECD countries: it is moderately high in France; close to the average of OECD countries in Germany and UK; and low in the US, Japan and Korea.
- There are also wide differences across countries regarding not only the size but also the content of research activities in universities and public research institutes, although the share of universities has been increasing in most countries in the 1990s. In the US, UK and Japan, universities conduct most of the basic research and public institutes focus more on applied research missions. In continental Europe, university research coexists with public sector labs and both perform basic research and mission-oriented activities, which raises more risks of duplicative research efforts.
- National science systems support innovation by generating new relevant knowledge and by facilitating absorption of knowledge generated in foreign countries. The balance between the two functions varies with country size and S&T specialization. Scientific specialization profiles differ substantially across countries, are more contrasted in small countries than large countries, and tend to be quite stable over time. Although their transformation might be one of the desirable long-term outcomes of improved ISR, they must be taken as a given when considering options to trigger such improvement.
- In smaller countries, scientific output in industry-relevant disciplines is well correlated with R&D intensity, with only a few exceptions, especially Korea in which R&D performance is disconnected from scientific output. Larger countries seem to enjoy economies of scale in translating scientific efforts into R&D, except Italy and the UK, where scientific output is inflated by prolific publications by the medical sector. Under-specialization in science-intensive industries in Germany and Japan explain largely why R&D is over proportionate to scientific output. The link between science and patentable innovation is weaker in these countries than in other G7 countries. In Japan more than in Germany, an additional explanation is a relatively low productivity of the science system, as measured by citations of scientific papers.

Channels of ISR: spin-offs and labor mobility

Spin-off is the entrepreneurial route to commercialize knowledge of public research. It attracts a lot of attention given the current “start-up fevers” in many countries. However, the growing policy interests has revealed the paucity of information that is needed to judge whether spin-offs really warrant such attention.

- Spin-off from public research are defined as: (1) firms founded by public sector employees – including staff, professors, post-docs; (2) start-ups which have licensed public sector technologies; and (3) firms in which a public institution made an equity investment or which were directly established by a public research institutions.
- The main contribution of spin-offs from publicly funded research to innovation is not direct and is more qualitative than quantitative. They probably play a different role than other new technology-based firms in the innovation system, as vital components of clusters of innovative firms formed around academia and industry, and of social networks in science-based industry. Spin-offs from public research are generally heavily concentrated in the IT and, increasingly, the BT/medical technologies sector.
 - The actual number of such spin-offs each year remains very modest compared to corporate spin-offs (few hundreds compared to thousands), which represent only between 10% and 30% of total technology-based firm start-up activity in European countries. In the US, they accounted for just over 10% of the technology licenses negotiated by universities in 1998, which is a modest share but far larger than their relative weight in the total of new technology-based firm start-ups.

Low rates of mobility of scientists and researchers remain major obstacles to improving industry-science linkages in a number of OECD countries. In some of them, public researchers find themselves in a “public employment trap” whereby low industry funding of R&D (and thus weak private demand for researchers) combined with regulatory barriers and disincentives to mobility result in a concentration of researchers in the public sector.

- Employment regulations and conditions in labor market set the overall pre-conditions for changing jobs and occupations. Flexibility in labor markets including wages can facilitate occupational and geographic mobility. General data on job mobility, based on average job tenure, suggest that overall mobility is higher in the US and UK. Mobility is lower in France, Italy and Japan.
 - In Japan it is estimated that only 20% of engineers change jobs in their career and it is likely that job changes between the public and private sector are even less, given the tradition of lifelong employment in industry and the restrictive regulations on university professors’ interaction with industry. Until recently, public researchers in Japan and France were explicitly prohibited from undertaking activities with industry due to their civil servant status.
 - In most European countries, university secondment and sabbatical provisions mainly concern research in other public research institutions, although increasingly universities such as those in the UK follow the rules in US universities which allow professors to take leave to work in industry. Even in these countries, however, temporary movement of research personnel tends to be one-way, from university to industry. Regulations regarding remunerative secondary employment for public researchers tend also to be institution-specific, except in the case of national university systems or where researchers are public employees. German university professors and public sector researchers, for example, are allowed remunerative secondary occupations (normally limited to 20% of working time) sometimes on the condition of administrative approval. Regulations affecting academic entrepreneurship mainly seek to limit the amount of time a research is involved in the day to day activities of the firm and the potential conflicts between the .
 - While such limitations may be grounded in sound considerations such as avoiding

conflict of interest and ensuring teaching missions, it is the way in which regulations are implemented in practice that has a greater impact on outcomes. In many cases, the possibility for leave, especially for longer periods, depends on finding a suitable replacement. In addition, temporary leave tends to be reserved for tenured professors or public researchers with permanent employment, whereas the propensity for mobility generally decreases with age across all occupational categories.

- Removal of regulatory barriers across OECD countries should foster greater researcher interaction with industry, but regulations are only one side of the equation. Interaction between researchers and industry depends heavily on incentives. Non-regulatory barriers such as faculty promotion and evaluation practices in universities and public research institutes that emphasize tenure and publishing over mobility and collaboration may act as disincentives for collaboration. Consequently, many OECD countries have gone further than deregulation, and have launched programs to address disincentives to human resource-based science-industry interaction. These programs can be classified according to three main functional objectives:
 - Transfer of knowledge is stimulated, especially in SMEs from traditional sectors, which lack technical and financial resources, to attract highly skilled graduates. Industry training and eventual job opportunities to students and graduates is provided. Support can take the form of tax credits or reimbursement of labor costs.
 - The training of established researchers in industry is promoted. This is the most common approach wherein established researchers in public sector work with industry on specific research projects. A main lesson from experience is that programs must be sufficiently funded in order to foster lasting relations between the producers and users of knowledge.
 - In several countries, there are new initiatives to promote the temporary movement of industry researchers into universities, often to work on longer-term projects that would not be taken up by industry alone. The experience of the US GOALI program highlights the importance of ensuring that IPR arrangements are settled from the outset to avoid conflict, and that such schemes help also to build formal and informal networks among researchers and set the stage for future collaboration.

Incentive structures: Industrial Property Rights and evaluation system

There has been much research on barriers and disincentives at the level of institutions. However, little attention has been placed on understanding the role of national regulations and practices in research funding, equity investment by publicly funded organizations, intellectual property rights, mobility of research personnel, and research evaluation in fostering or inhibiting industry-science linkage.

The ownership of industrial property rights (IPRs) creates strong incentives for universities and public research institutions to commercialize research and knowledge. In nearly all OECD countries there has been a marked trend towards transferring ownership of publicly funded research results from the state (government) to the agent (public or private) performing the research. The underlying rationale for such change is that it increases the social rate of return on public investment in research.

- Where OECD countries differ is in the allocation of ownership among performing agents (research institutions vs. individual researchers) in licensing practices, in the allocation of resulting royalties, and in provisions for ensuring national benefits flowing from patentable results of public research.
 - In the US, the Bayh-Dole Patent and Trademark Amendments Act of 1980 allowed performers of federally funded research to file patents on the results of research and to grant licenses for these patents to third parties. In addition, the 1980 Steven Wydler Innovation Act (amended in 1986 by the Federal Technology Transfer Act) authorized federal labs to conduct co-operative research and development agreements (CRADs)

- with private firms and to assign any resulting patents to those firms. While most other countries grant ownership of publicly funded research results to the performing institutions, a few countries continue to grant ownership to the inventor.
- In Germany, public research institutes receiving public grants own the resulting IPRs. However, in universities, the researcher owns the IPR arising from research funded via institutional funds. Responsibility for protection devolves to the title-holder but if the research is funded by external sources – including the BMBF – the university is responsible for patent protection.
 - In France, the ownership seems to be defined case by case, and in practice co-ownership is in many cases negotiated. In some public research institutions, title to IPRs is divided between the institution and researcher. This has been the rule in Japanese national research institutes, but from FY 1999 the inventor is allowed to retain the IPR for research results made under public funding.
 - The lack of clarity and diversity in national and institutional guidelines for IPR can be a barrier to commercialization insofar as it increases the risk and transaction costs of co-operation for industry, especially for SMEs.
 - Granting the ownership of IPR to the researcher should, in theory, increase researchers' interest in commercialization. However, by putting all the weight of disclosing and protecting ownership on a single individual, this often reduces the likelihood of patenting and subsequent licensing. In addition, the growing costs of litigation act as a more powerful disincentive for disclosing and commercializing research results when individuals own the IPRs. Firms may also be hesitant to enter into agreements due to the risk future litigation from one or more of the co-inventors. Another problem is that researcher owning the IPRs may take it abroad for commercialization, thus reducing national benefits from public investment. Given these drawbacks, a good practice might be to grant IPR ownership to the research organization but to ensure that researchers enjoy a fair share of resulting royalties.
- The main beneficiary is, in general, the owner of title but sharing of royalty revenue is common across countries and institutions and is increasingly seen as a way to provide incentives not just to individual researchers but to research teams. There are generally no standard national formula for allocating royalties from patents and licenses, but national guidelines do matter.
 - In multi-disciplinary research organizations such as universities, there is a potential for tension insofar as high yielding patents and licenses tend to be concentrated in specific technological fields (e.g. biomedical). The question arises whether the royalty should be shared not only among the main agents behind the invention but also with other departments. This could partly answer the concern that research areas that generate most of external revenues could attract also an increasing share of intramural funding to the detriment of other disciplines (e.g. physical sciences, social sciences, humanities).
 - While the decision to license on an exclusive or non-exclusive basis generally devolves to the title-holder, governments do play a role. Publicly funded research organizations may be encouraged to favor non-exclusive but royalty bearing licenses on the grounds that it both ensures a broad diffusion of knowledge and broadens the source of royalty revenues. It does not entail restrictions on the freedom of publishing, a major issue with exclusive licenses in some fields.
 - A study found that nearly 3/4 of the active licenses granted by six of the largest US research funding agencies were non-exclusive during the fiscal year 1996-1998.
 - However, the share of exclusive licenses was significantly higher in the portfolio of research performing organizations, reflecting the fact that firms, particularly in sectors where product development is very capital intensive and lengthy, often require exclusive rights.
 - In many countries, regulations governing public funding of industry-science partner-

ships or collaborative R&D programs and licensing of the resultant IPR to foreign partners are subject to restrictions to ensure national economic benefits. In the US, participants in CRADA agreements must show that benefits will accrue to the US usually by agreeing the commercial production will take place in the US.

Public research institutions are being asked to contribute to economic development but also to be more responsive to evolving societal concerns such as food safety, environmental degradation, and health issues. These pressures for accountability are in some countries the counterpart of greater autonomy, and everywhere they encounter strong resistance from the research community, which fears that under the cover of noble motives changes in evaluation criteria could reduce core funding and/or shift it away from longer-term free research. What is put into question is both the sole focus on scientific excellence and the criteria for judging this excellence when evaluating public researchers and research institutions.

- In case of applied research institutions (e.g. Fraunhofer) countries have generally chosen to stick to traditional criteria (peer review and publication) when evaluating research eligible to core funding, but made core funding increasingly dependent on the levels of industry financing, thus changing implicitly overall evaluation criteria.
 - External funding targets vary from 20% to 50% (i.e. matching funds). In addition to requirements for external industry financing, evaluations in some cases also integrate input and output measures of commercialization such as the total amount internal R&D funds invested in collaborative R&D projects, income from contract research, and the number of patents, joint publication, inventions, licensing incomes, etc.
 - Germany has instituted new rules to BMBF grant-awarding practice that require that those who obtain research result through BMBF funding must apply for IPR and commercializes the results but in exchange gain exclusive title to IPR, including the incomes from licensing.
- Different approaches are needed for balancing incentives for commercialization with support for longer-term research in universities and basic research institutes.
 - A distinction can be made in the evaluation criteria for projects in fundamental research and those in applied research.
 - Another possibility is to separate funding for commercialization activities from core intramural research funding. The ministry of Education of Japan has created a budgeting scheme whereby national universities that promote university-industry cooperation and patenting can be allocated additional funds. In France, financial incentives to research have been increased and are channeled through two distinct funds, one to support technological development, and the other to promote more fundamental research.
- Rewarding individual researchers for their contribution to commercialization goals is another means still under-exploited in majority of countries, to improve linkages between public research and industry.
- Case studies and anecdotal evidences on success factors in managing ISR are accumulating, but governments find it difficult to relate these experiences to their concerns, when assessing the situations from a nation-wide perspective, evaluating recent reforms and determining the need for further policy initiatives.²⁰

²⁰ The evaluation of industry-science linkages is generally carried out at the level of specific research institutions or public support programs, providing results that are difficult to compare from one institution to other and internationally. Identification of and learning from good practices in knowledge joint creation, transfer and sharing between the public and private research sectors are impaired by the lack of agreed-upon methodologies and indicators to measure performance.

5. Institutional Arrangements

In the last decade, a majority of OECD countries have redirected public R&D investment towards universities, to the detriment of research institutes. But this shift has not improved ISRs to the same extent everywhere. A major reason is that decentralized university systems are more responsive to ISR opportunities than centralized ones. Although the latter may be justified on other grounds, governments ought to realize that they entail increasing costs in terms of reduced commercialization potential. Governments should also accept the fact that giving more weight to commercialization objectives in allocating core funding can only accentuate the polarization of university research capabilities around existing centers of excellence.

- Changing incentive structures induces some institutional changes (e.g. the proliferation of technology transfer and licensing offices at universities following the Bayh-Dole Act in the US) but may require some others to yield their full benefits. This concerns the overall institutional profile of national systems of ISRs and the organizational framework of commercialization activities at universities and public laboratories.
- University-based systems of ISRs probably enjoy a comparative advantage, especially when ISRs increasingly require multi-disciplinary and build on people-based interactions, but with some caveats. The US and the UK demonstrate that universities can provide excellent platforms for vibrant ISRs. However, there are also counter examples, such as Japan where universities are central in poorly performing ISRs.
- The role of public research institutes declined in recent years, but their role within ISRs remains important in most OECD countries. The improvement of their relations with industry poses some common generic problems. 1) Their aging staff have lower incentives to cooperate with younger researchers in industry, and the downsizing of operations have often aggravated this generational barrier in recent years. 2) The objectives of government and of the research organizations themselves may not be consistent, especially when public institutes have a strong applied research focus and face pressure for downsizing.
 - Whereas government want to maximize economic spillovers from research that have other justifications, they run the risk of in fact encouraging diversification away from core missions, and subsidizing the development of market distorting technological services.
- In order to increase synergies between different publicly funded research organizations to the benefit of commercialization and innovation, countries follow different approaches:
 - Develop organic ties between universities and public institutes (CNRS labs within universities in France).
 - Add an institutional layer that provides a stable meeting place for collaborative research (cooperative research centers in Australia and Austria).
 - Use catalytic programs (thematic research networks or programs in the US, France, Japan, and the Netherlands).
 - Adapt existing technology transfer organizations (Fraunhofer in Germany) to changed mission or to create new types of intermediaries specialized in IPR transactions.
- Governments generally lack organized information and appropriate review mechanisms to answer these questions. They have to reinforce the coordination of commercialization activities of publicly funded research organizations, as well as their monitoring and evaluation, including through benchmarking with international best practices.

How can commercialization activities in the public research sector be organized, taking account of the need to minimize conflicts of interest while providing the efficient legal and managerial support for protecting and licensing IPR or carrying out spin-off activities? What should be the model for dedicated institutions? Should they be located on or off campus or public labs? There are various approaches in OECD but they can be summarized in 3 main institutional models:

- Technology transfer and licensing offices may be integrated as part of the research institution. On-site departments or agencies intermediaries benefits from low overhead as the fixed costs for staff and operations are absorbed by the main institutions. The physical presence also ensures closer links between commercialization and research activities. However, there is the link that on-site agencies focus mainly on existing relationships to the neglect of new opportunities. There is also an issue of scale, as smaller universities often lack the resources and technical skills to effectively staff on-site licensing agencies and may also have too small patent portfolios to justify such organizational investment.
- The advantage the arms-length subsidiary approach is that it provides a greater buffer against possible conflicts of interest between the commercialization operations and the research activities. Subsidiaries are characterized by a greater degree of financial and managerial independence that facilitates relations with venture capitalists and potential licensees. Indeed, evidence at the institutional level suggests success in licensing depends on relations to other knowledge production centers and geographic proximity to client firms and financial capital. Increasingly, following the pioneering examples of Stanford technology transfer and licensing offices are moving away from acting as purely legal support units to become entrepreneurial agents, not only marketing but also seeking out potential licensees, including overseas (e.g. MIT in the US, the Fraunhofer in Germany).
- The third approach consists in the creation of public or private intermediaries to support technology transfer and licensing. Examples of private intermediary include the Research Corporation Technologies and since recently Internet-based auction services in the US. Examples of public intermediary include the Austrian patent exploitation agency, Tecma, which provides support for the assessment of potential inventions from universities. Austrian university researchers are not however required to disclose their inventions to Tecma. In Japan, the government has supported the creation of large network of Technology Licensing Offices (TLOs) to encourage and formalize technology transfer between universities and industry. In some cases, these transfer institutions have a mandate to support SMEs, as the Intellectual Property Services Office in Canada.

While the aim of public licensing agencies is to fill the gap where there is insufficient critical mass within universities to support such activities, developing expertise and a sufficient customer base to generate revenue will require sustained levels of investment, mainly from public support. Another issue relates to their distance from research institutions, which limits their role in educating researchers about commercialization potentials. In addition, these agencies may experience difficulties in competing with private sector intermediaries, not only for clients but also for hiring the technical skills they need, especially technology examiners trained in rapidly changing fields.

IV. Industry-Science Relations in Catch-up Economies

1. Economic Growth and Structural Change

Economic growth has been distributed across the industrial sectors. It is by no means the case that economic growth in Europe was driven by a small number of high-tech knowledge-based sectors.¹ There was no particular industrial structure that is conducive to growth. Certainly high-R&D sectors were high growth sectors. However, many low and medium R&D-intensity sectors (food processing, basic metals, machinery, etc.) were also among the high growth sectors. Many of these sectors were among the highest in terms of levels of employment and output. Thus, their contribution to overall growth is likely to be considerably higher than that of high R&D-intensity sectors where the shares of output and employment are much lower.

- Growth had been based on a wide spread of innovation across sectors and many of the significant sectors were those often referred to as low- or medium-tech industries. Even low-tech sectors were often highly innovative since they are knowledge-intensive from a systemic perspective. Low- and medium-tech are invariably innovative industries in the sense that they develop and market new products in a continuous fashion.
- Most of the low-tech sectors are intensive in their use of scientific knowledge. They have significant indirect science inputs. The depth and complexity of industry knowledge bases are not linked to their direct R&D performance. Science inputs in low-tech industries are supported by complex, indirect links with supplier companies, universities, and research institutes. Hence low-tech industries are frequently part of high-tech systems, and policy makers should be aware of their significance for growth.
- There was a general tendency for OECD countries to de-specialize in terms of export specialization over the period from 1965 to 1992. The OECD catching up countries (Japan, Italy, Spain, Finland, Ireland, Portugal, Greece and Turkey) on average experienced the highest degree of structural change in their specialization patterns.²
 - With regard to technological specialization (measured as specialization in US patents from the late 1970s to the early 1980s), the evidence is less conclusive. About half of the countries tend to increase in terms of the level of specialization, while the other half tended to engage in de-specialization.
 - Both trade specialization and technological specialization were path-dependent in the sense that specialization patterns were correlated between seven three-year intervals. Trade specialization patterns were more stable than were technological specialization patterns. Among the OECD countries, France, Germany, the UK, Sweden and the catching up countries displayed the highest degree of turbulence in the specialization patterns.
- The determinants of trade specialization are sector-specific. But certain regularities can be identified in terms of sectors being governed by certain technological regimes, which transcend traditional sector boundary.³ In the technology gap approach, either

¹ For the EU-12, 2-digit NACE level manufacturing industries were examined over the period 1986-95. K. Smith (1999), Industrial structure, technology-intensity and growth; issues for policy. Paper to DRUID conference on National Innovation Systems, Industrial Dynamics and Innovation Policy, Reblid, Denmark, June 9-12, 1999.

² Laursen, K. (2000), Trade Specialization, Technology and Economic Growth. Edward Elgar.

³ K.R. Pavitt (1984), 'Sectoral patterns of technical change: towards a taxonomy and theory', *Research Policy*, 13 (6), 343-73.

cumulative character of technological change or inter-sector linkages (home market effects) explain the trade specialization. Inter-sector linkages were important for specialized-suppliers as well as scale-intensive sectors, while the most important determinant was own sector technological efforts in the case of science-based sectors, in which linkages tend to be horizontal rather than vertical.

- As for the determinants of the direction of trade specialization, the importance of advanced users in home markets as an inducement to technological innovation is well recognized. In this context, support for upstream-downstream interaction could be more effective in influencing trade specialization towards a higher technology level than support for corporate R&D, particularly in specialized suppliers sector.
- Structural change (change in specialization patterns) is an integral part of economic development processes. The growth of market shares at the country level is related to the ability of countries to transform their specialization patterns towards fast-growing sectors, which are in general high-tech sectors.
 - The reaction speed of specialization patterns, however, might be too low to allow for an active policy. Policy makers must be prepared to aim at a high degree of interaction between their various instruments, as well as be willing to risk unsuccessful attempts, and admit these in an early enough stage. Enhancing growth by steering specialization patterns seems a quite risky *art* rather than a well-established *science* without major uncertainty. It might be too late to catch up in a fast growing sector, when the sector has started to grow rapidly, if no technological competence is present at all. From the perspective of a policy-maker, it is probably wise to support research on small scale in new areas, in order to monitor the new areas, but also in order to support/secure a minimum of technological competence, should a field take off.
 - Countries must change their level of human capital as well as their production structure (and hence export structure) as they catch up, in order to catch technology spillovers from the leading countries.

It is often argued that, over time, the high R&D-intensity sectors displace low R&D-intensity sectors. However, the rapidly growing sectors, in terms of employment growth, are not at all made up of high R&D-intensity sectors. The problem is the view that innovation is something that primarily occurs in sectors characterized by high levels of R&D input, by significant patenting activity, or by related scientific publication. The *Community Innovation Survey* shows that innovation, in the sense of new product introduction, is widely distributed across all industrial sectors; it is by no means confined to the so-called high-tech sectors of the economy.

- Because of their availability and quality, these indicators give a very limited view of the nature and extent of innovation activities and output. R&D is an input indicator, and not necessarily a good one; patenting data results from a legal process which is to do with appropriability conditions, and indicates at best an invention, not an innovation, and so on.
- More general indicators are that used in the *Community Innovation Survey*, which has been carried out in the EU, Canada and other countries. This survey collects a very large volume of firm-level data on the introduction of new and technologically changed products, and on the proportion of sales derived from such products. This is an indicator of the rate at which firms change their product mixes. Unlike R&D and patent data it can be collected in a relevant way across many sectors. The *Community Innovation Survey* (1992) for Denmark, Germany, Norway, and the Netherlands provides the evidence that a sizeable proportion of firms has new products (introduced to the market within the past three years) within their sales mix: Substantial proportions of sales are coming from new products, across all industries and size classes of firms. Innovation is not confined to high-tech sectors but does indeed appear to be pervasive across sectors. These figures imply rather rapid changes in product mixes in innovating firms.

Table 14. Percentage of firms introducing new products to the market within the past 3 years.

Size classes	Norway	Netherlands	Denmark	Germany
10-19	13	20	-	35
20-49	24	30	35	35
50-99	36	52	46	39
100-199	45	59	58	49
200-499	59	61	43	57
500 and more	55	72	67	80

Source: STEP Group (Group for studies in technology, innovation and economic policy, Norway)

Table 15. Shares of new products in 1992 sales

Industry	Norway	Netherlands	Denmark	Germany
Mining, oil & gas, energy, water	25	22	-	36
Food, beverage & tobacco	45	32	48	34
Textiles & apparels	33	39	47	43
Wood products, Paper products	22	27	24	30
Petroleum refining, Chemicals	27	31	27	51
Non-metallic mineral products	24	28	23	31
Basic metals	10	15	27	33
Fabricated metals	44	28	29	42
Machine tools	40	29	32	37
General purpose machinery	44	46	31	49
Special purpose machinery	64	43	34	58
Office machinery, Telecom.	56	47	37	77
Electric machinery	52	43	29	46
Medical, precision instruments	56	42	38	51
Automobile, aircraft	31	46	38	60
Other transport equipment	46	36	40	36
Furniture, other manufacturing	46	39	41	66

Source: STEP Group

The reason why low-tech sectors play such a prominent role in the distribution of growth among sectors is not because innovation is unimportant to growth, but rather because these sectors are on the contrary highly innovative. Innovation involves learning and the creation of knowledge; it involves the creation of novelty in the various aspects of competence related to product and process development and implementation. Basic research results flow into industries in indirect ways, through capital equipment, the services of other firms, or services provided by the science and technology infrastructure.

- Industrial knowledge bases are institutionally distributed. Industries apparently low-tech can in fact be intensive users of high-grade scientific knowledge. Flows of knowledge between industries or institutions take two forms, disembodied and embodied spillovers. The latter involve knowledge that is built in to machinery and equipment, The former involve the use of knowledge, transmitted through scientific and technical literature, education systems, consultancy, movement of personnel and so on.
- Most research-intensive industries (advanced materials, information technology, etc.) develop innovative products that are used in other industries. Such products enter as capital or intermediate inputs into the production processes of other industries: that is, as components and materials or as machines and equipment. Performance improvements generated in one firm or industry thus show up as productivity or quality improvement in another.
- Competition leads directly to the inter-industry diffusion of technologies, and therefore to the inter-industry use of the knowledge embodied in these technologies. The receiving

industries must of course develop the skills and competence to use these advanced knowledge-based technologies. The disembodied flows and spillovers are also significant. Underlying these technologies is advanced research-based knowledge.⁴ A wide range of background knowledge, often developed in the university sector, flows into industries.⁵

2. Innovation in Technology Followers

The technological frontier is defined by technology-leaders; technology followers are primarily concerned with the development of new products to move up the value-chain of global market. R&D in technology-followers rarely involve research aimed at generating new technological or scientific knowledge. However, the tacit dimension and dynamic nature of technology require considerable innovation on the part of the technology-follower to keep up with the technology frontier.

- Technology-leader countries collectively define the technological frontier at any point in time, and move it forward. Successful innovations in technology-leader countries define the new technological frontier that is commercially correct. Technology-follower countries may be far, near, or even at the technology frontier for particular industries, but are generally not involved in pushing it forward.
- Firms in technology-follower countries usually approach the frontier through the transfer of technology from technology-leader countries (avoiding reinvent the wheel). However, this requires indigenous technology learning capability. As the technology frontier is constantly moving, if a follower fails to progress technologically at more than the speed of the leader, it will not catch up.

Moving up the value chain of global markets

Entry into global markets that allows for sustained income growth requires an understanding of dynamic factors in the whole value chain. Participation in global markets reflects the strategic decision of lead-firms in the value chains. Value chain analysis helps in understanding the need and scope for systemic competitiveness.

- Efficiency in production is only a necessary condition for successfully penetrating global markets. The analysis and identification of core competence will lead the firm outsource those functions where it has no distinctive competence. With the growing division of labor and the global dispersion of components manufacturing, systemic competitiveness has become increasingly important. Value chain analysis considers not just the efficiency of

⁴ For example, embodied flows in fishing industry include use of materials and design concepts in ships, satellite communications, global positioning systems, safety systems, optical technologies for sorting fish, sonar technologies (potentially linked to winch, trawl and ship management system), computer systems for real-time monitoring and weighing of catches, and so on. Fast-growing fish farming uses high-tech inputs such as pond technologies (based on incorporating complex design knowledge and advanced materials), computer imaging and pattern recognition technologies for monitoring (including 3D measurement systems), nutrition technologies (often based on biotechnology and genetic research), sonar, robotics (in feeding systems), and so on. Computer systems and the wide range of IT applications in fisheries rest on computer architectures, programming research and development, and ultimately on research in solid-state physics. Even fishing ponds rest on wave analysis, CAD/CAM design systems, etc. Within fish farming the fish themselves can be transgenic (resting ultimately on research in genetics and molecular biology), and feeding and health systems have complex bio-technology and pharmaceutical inputs.

⁵ Ship development and management relies on fluid mechanics, hydrodynamics, cybernetic systems, and so on. Sonar systems rely on complex acoustic research. It is clear that a wide range of background knowledge, often developed in the university sector, flows into fishing: e.g. mathematical algorithm for optimal control, molecular biology, and a wide range of sub-disciplines in physics.

production link in the chain, but also factors that determine the participation of particular groups of producers in final markets. It treats the whole cycle of production, including governance of connectedness to final markets. That is, it helps in understanding the advantages and disadvantages of firms and countries specializing in production rather than services, and why the way in which producers are connected to final markets may influence their ability to gain from participating in global markets.⁶

- In the past two decades, low-cost sources of supply grew for buyers procuring on a global stage. Production was increasingly undertaken by subsidiaries of TNCs in some countries. In other cases, production occurred either through foreign licenses or by firms who had managed to develop local design and technological capabilities. Many of these producers could meet global price and quality standards, and could supply in adequate volumes. The question is whose production would be utilized.
 - The lead firm may have made a strategic decision to locate its activities in a particular country or region, perhaps to balance out the consequences of exchange rate movements or ethnic and nationality ties.⁷
 - Particular forms of connectedness will affect the extent to which producers can upgrade. The large volume US buyers were vary reluctant to low-cost manufacturers developing the capacity to design and to market, which the buyers saw as their source of competitive advantage and their rents in the value chain.
- Value chain analysis helps to explain the distribution of benefits to those participating in the global economy. The key policy issue is not whether to participate in global markets, but to do so in a way that provides for sustainable income growth. If firms, sectors and countries continue to specialize in highly competitive markets, they will be increasingly subject to the erosion of their returns due to falling terms of trade, which is increasingly to be found in the export of manufactures.⁸ The decline in the terms of trade for less developed country (LDC) exports has been significant, particularly since China's entry into global markets in the mid-1980s. In many LDCs, there has been increasing economic activity (more output and more employment) but at same time falling economic returns.
- Globalization is defined as the pervasive decline in barriers to the global flow of information, ideas, factors (especially capital and skilled labor), technology and goods. Globalization in the late 20th century is increasingly in sub-components and services, while internationalization in the late 19th century tended to be in final goods.

⁶ Triangular manufacturing in the clothing chain is a good example in this regard. Initially Hong Kong clothing industry produced directly for the US market. When quotas were filled, the same entrepreneurs changed their functions in the value chain, coordinating the production of these cloths in third countries and passing these cloths to buyers in final markets. More recently, they have begun to brand these products themselves, in some cases by purchasing retail outlets in Europe and North America and in other cases by striving to establish their own brand names.

⁷ Often, ethnic links play an important role. Renault and Peugeot-Citroen have consciously located the largest part of their supply base in surrounding French-speaking regions.

⁸ A firm can insert itself inappropriately into global value chains. It can also apply to a sector or a region. Dominican Republic specialized in a narrow function (sewing) within a particular link (manufacturing denim jeans) in the value chain. It was forced systematically reduce its charge-rate; but even this was not enough and the work was eventually sourced elsewhere. Its value added was too low to allow for enhanced efficiency and most of the value anyway was appropriated in the design and branding links in this chain, which remained in the US. A cluster of leather shoe manufacturers in the Sinos Valley in Brazil built themselves into a major supplier of woman's shoes, particularly to the US. Initially, sales and exports grew rapidly during the 1970s. The connectedness into the US market was provided by the limited number of large-scale buyers who supplied very large US chain stores. These buyers moved their supply chain management capabilities to China, undercutting the Brazilian producers which they had helped to upgrade during the 1970s. The problem was that they had specialized in the particular links in the value chain (leather and shoe production), which subject to intense competition.

- Many of the world's population have experienced significant improvements in living standards in recent years. East Asia was a major beneficiary, especially after 1960s, and China and India after 1980. Yet, there have also been a large number of casualties: 1) those who have been excluded from globalization, 2) those who have suffered from globalization and 3) those who have gained but remained poor.⁹
- By focusing on all links in the chain and on all activities in each link, value chain analysis helps to identify which activities are subject to increasing returns, and which are declining returns, thus making it easier to identify policies for sustained income growth over time.

Participating in global markets that allows for sustained income growth requires the capacity to learn and upgrade. The value chains is an important construct for understanding the distribution of returns arising from design, production, marketing, coordination and recycling. Essentially, the primary returns accrue to those parties who are able to protect themselves from competition. This ability to insulate activities can be encapsulated by the concept of *rent*, which arises from the possession of scarce attributes and involves *barriers to entry*. The primary rents in the chain of production are increasingly to be found in areas outside of production, such as design, branding and marketing. Yet, even within production some activities involve greater barriers to entry. The pervasive trend is towards control over disembodied activities in the value chain.

- Economic rents take various forms in a firm, including technology rents (command over scarce technologies), organizational rents (superior forms of internal organization), human resource rents (access to better skills than competitors) and marketing rents (better marketing capabilities, valuable brand names). This cluster of attributes is often discussed in relation to dynamic capabilities and core competence in the literature. Economic rents may arise from purposeful activities taking place between groups of firms – these are referred to as relational rents.
- Economic rents have become increasingly important since the growth of differentiated products after the 1970s. Economic rent is dynamic in nature, eroded by the forces of competition after which it is then transferred into consumer surplus in the form of lower prices and/or higher quality. The competitive process – the search for new combinations to create scarcity and the subsequent bidding away of this economic rent by competitors – fuels the innovation process, which derives capitalism forward.

Value chains imply repetitiveness of linkage interactions. Governance insures that interactions between firms along a value chain exhibit some reflection of organization.¹⁰ Power asymmetry is central to value chain governance – there are key actors in the chain who take responsibility for the inter-firm division of labor, and for the capacities of particular participants to upgrade their activities.

⁹ The inter-country distribution of income has become distinctly more unequal, exhibiting a twin-peak pattern with some countries catching up with the US and others falling further behind. The intra-country income distribution (inequality between skilled and unskilled labor) worsened in much of the world.

¹⁰ Value chains are governed when parameters requiring product, process, and logistic qualification are set which have consequences up or down the value chain encompassing bundles of activities, actors, roles and functions. This is not necessarily the same thing as the coordination of activities by various actors within a value chain. Value chain is coordinated at different places in the linkages in order to ensure these consequences (intra-firm, inter-firm, regional) are managed in particular ways. Coordination usually involves managing these parameters as they are exhibited in bundles of activities undertaken by various actors performing specific roles in the chain. It also requires monitoring of the outcomes, linking the discrete activities between different actors, establishing and managing the relationships between the various actors comprising the links, and organizing the logistics to maintain networks of a national, regional or global nature. It is this role of coordination, and the complementary role of identifying dynamic rent opportunities and apportioning roles to key players which reflects an important part of the act of governance.

- The intricacy and complexity of trade in the globalization era requires sophisticated forms of coordination, not merely with respect to positioning (who is allocated what role in the value chain) and logistics (when and where intermediate inputs are shipped along the chain) but also in relation to the integration of components into the design of final products and the quality standards with which this integration is achieved.
- Coordination does not require that a dominant firm engages in these roles. Indeed, there may well be a multiplicity of nodal points of governance and coordination functions. These nodal points may change over time as the prominence accorded to different actors shift within a value chain.
- Power can be exercised in various forms. Within a value chain, this can be understood in at least two separate forms: 1) ensuring consequences along the value chain, and 2) actively managing or coordinating the operations of the links within the chain to ensure that these consequences are met.

Intra-MNC Competition and Regional Development

Activities of a multinational corporation (MNC) are potentially mobile or contestable by other affiliates in different local settings. These activities include technology-intensive activities, such as research, development, and design. Competitive processes can be led by the parent company or initiated by affiliates. Internal competition may lead to incremental development at individual affiliate operations.¹¹ The gaining of world and/or continental product mandates is not simply a result of parent company decisions but can involve considerable affiliate initiative.¹²

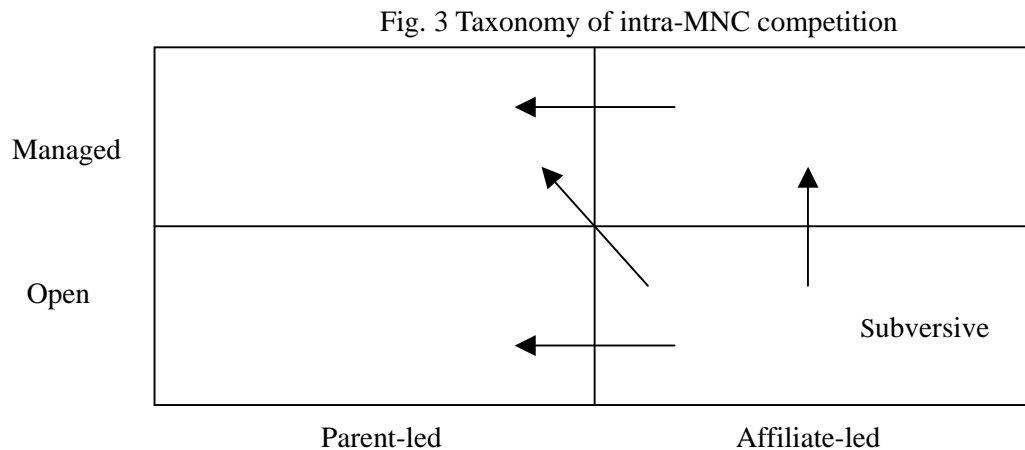
- Such affiliate initiative has been classified into attempts to defend, retain, and build local domains within global parent company organizations. Of particular interest is the entrepreneurial (or subversive) behavior of affiliate managers as they seek to contest their affiliates' position and status within established parent company hierarchies.¹³ Subversive strategies effectively constitute multiple alternative centers of strategic coordination.
- Intra-MNC competition can center on three different internal markets: the markets for intermediate products or services, the market for charters or mandates, and the markets for capabilities.¹⁴ The internal markets for inter-mediate products or services are likely to be open in something approximating a market mechanism, in which comparative costs/ prices alone determine the allocation of resources. The markets for mandates and for capabilities are likely to be managed through non-market transactions (in which a bundle of less measurable factors come into play alongside comparative costs).
- Parent company-led intra-MNC competition will tend to be managed so as to avoid the worst excesses of competition such as duplication of efforts. This of course does not preclude the possibility that some parent companies will encourage open competition among affiliates. These observations can be summarized by the four generic types of intra-MNC competition based on binary distinctions between the managed and open nature of competition on the one hand and the parent-led and affiliate-led origin of competition on the other.

¹¹ Birkinshaw, J. and N. Fry (1998), Subsidiary initiatives to develop new markets. *Sloan Management Review* 39. 51-61.

¹² Birkinshaw, J. (1997), How Multinational subsidiary mandates are gained and lost. *Journal of International Business Studies* 27: 467-496.

¹³ Birkinshaw, J. (1998), Corporate entrepreneurship in network organizations: How subsidiary initiative derives internal market efficiency. *European Management Journal* 16. 335-363.

¹⁴ Birkinshaw, J. (1999), Multinational corporate strategy and organization: An internal market perspective. In Hood, N. and S. Young (eds.) *The globalization of multinational enterprise activity and economic development*. London: Macmillan. 55-74.



- The subversive competitive strategy of affiliates appear as a transitory subset of affiliate-led open competition and also point to the likelihood of a more general transformation of competitive processes over time from affiliate-led to parent-led processes. Parent company structures and local plant-level factors will play a conditioning role in the type of intra-MNC competition observed at a given affiliate. Affiliate status, including the possession of mandate, is closely and positively related to parent company structure and the degree of integration with other parent company affiliates.¹⁵ Increased affiliate status simultaneously is associated with greater corporate integration.

In MNCs where more complex forms of integration exists, parent-managed competition is likely to be apparent, since open competition might be counter-productive to the synchronization of a group of vertically related plants.¹⁶ Intra-MNC competition is likely to center on the allocation of technology-intensive activities (since networks are highly efficient forms of industrial organization where the monetary value of activities is not easily measured).

- The status and role of affiliates are related to the life cycle of the plant and its products. Since experience can confer learning curve (first mover) advantages it often provides an important incentive for parent companies to concentrate investment and additional responsibilities at established plants. Alternatively, investment at established plants may reflect the inertia associated with the geographic spread of sunk costs. It is possible that repeat investment at given affiliate will be associated with the more negative aspects of corporate inertia when dictated by setup and exist sunk costs and associated with the more positive benefits lock-in when dictated by accumulated sunk costs (such as labor skills, technological know-how, experience).
- Aspects of life cycle theory appear to have some continuing practical bearing on the status, the capital and R&D intensity, and the functional integrity of MNC overseas operations. There are two simultaneous but contradicting trends. On the one hand, the increasing rapidity with which new products and activities such as R&D have been decentralized from core regions implies limited possibility for overseas MNC operations to contest their position within international corporate hierarchies. On the other hand, diminishing product cycle times mean that the gains made by any given affiliate are repeatedly exposed to review by parent companies and contested by other affiliates.

¹⁵ Roth, K. and A. Morrison (1992), Implementing global strategy: Characteristics of global subsidiary mandates. *Journal of International Business Studies* 23. 715-735.

¹⁶ In MNCs organized along geographic (multi-domestic) lines, there is a great scope for competition being quite open, especially where there is a large number of affiliates each producing for national markets. Processes of market integration may of course intensify competition as a mechanism for rationalization of capacity within multi-domestic structures.

National and sub-national institutions increasingly have taken an interest in intervening in the corporate processes concerning location decisions. Recently, there has been a shift from the push of parent-led competition among affiliates towards the pull of host country affiliate initiative, coupled with increased efforts by sub-national institutions to embed MNC affiliates. National policy stances toward inward investment provide the context for more specific localized efforts at aftercare and the embedding of MNCs.

- With the development and fine-tuning of aftercare policies to embed and develop local affiliates, national and local institutions have begun to play a more significant role in such intra-MNC competition. Local policy initiatives have sought to influence a wide range of local external factors that might impinge on intra-MNC competitive processes.
- Local initiatives include policies aimed at the development of specific local labor skills, local suppliers, and technology transfer opportunities between universities and industry. Support for the entrepreneurial or subversive activities of local affiliate management through fact-finding and lobbying at the parent appears to be an increasingly important aspect of the aftercare of overseas companies in host economy settings.

An important aspect of different affiliate roles is their variable indirect developmental effect through external linkages with host economies. The type of intra-MNC competitive process will have a bearing on the sort of external linkages sought by individual affiliates.

- Parent-led open competition is most closely associated with the classic "branch plant" or "enclave" scenario, where internal economy of MNCs precludes viable local external linkages.¹⁷ Except for perhaps facilitating co-located vertically integrated suppliers, these external linkages could not be bought by the best efforts of local institutions.
- At the other extreme, affiliates may seek out important local external linkages to contribute to competitive processes they themselves have initiated. The desire of parent companies to exploit competitive advantages drawn from diverse local settings means that new and repeated investment by MNCs now involves bargaining not just over direct financial incentives, but also incentives in kind.
- In the case of managed competition, selected linkages between MNC affiliates and local host economies are essentially "bought" as parts of the increasingly creative packages put together by local and regional agencies, thereby creating extended enclaves.¹⁸

The main benefits to local economies are related to different types of intra-MNC competition. It is the tangible and intangible direct and indirect benefits associated with winning new mandates or capabilities that may produce long-term economic development, and these are the most sought after by the institutions of host region economies. Mandates are relatively immobile

¹⁷ The branch plant syndrome apparent in regions at periphery of corporate hierarchies has been analyzed within the spatial divisions of labor. The spatial divisions of labor approach in the geographic literature has focused on the way the rounds of investment are produced from inter-locality competition for greenfield investment, which has prompted periodic concern over the cost-minimizing or incentive-maximizing locational strategies of MNCs. Yet the majority of MNC investment has been and continues to be composed of repeat investment. The spatial divisions of labor approach has been criticized for being imbued with a strong unidirectional logic toward deskilling, ever-increasing division of labors, and hence a stable and immutable hierarchy of regional economic development. Recent geographic literature on the subject of globalization and business studies literature on the internal markets of MNCs point in different directions regarding the possible redefinition of spatial divisions of labor through process of intra-MNC competition and repeat investment.

¹⁸ The term enclave used by Kindleberger (1969) refers to the tendency of FDI to be tightly bound to its host country but only weakly connected to its host economy. The term might be broadened to include those situations where host country suppliers and institutions (such as universities) are exclusively or largely linked to the specific requirements of a major inward investor. Kindleberger, C. (1969), *American business abroad*. New Haven: Yale University Press.

since the development of capabilities entails considerable sunk costs associated with accumulated labor skills, management practices, and the like. Not all affiliates will be suitably placed to compete for them.

- Intermediate products and services are the most mobile and contestable by a wide range of affiliates, since they can often be uncoupled from vertically related production processes, and since the location decision is one that often centers on cost reduction. Although the winning of component responsibilities can lead to jobs and even the prospect of increased skill content of work at affiliates, these benefits may be short-lived. Activities won solely on the basis of relative labor and other costs can be the subject of intense competition among affiliates, benchmarking, and deliberate strategies of location switching by parent companies.

R&D in Technology Followers

A key role for R&D in technology-followers is to build independent design capability for the firm. Moving up the value chain to more attractive markets depends on the capability to develop proprietary product-designs, which requires formal R&D effort. Several technology-follower firms from NICs made a transition from original equipment manufacturers (OEM) to original design manufacturers (ODM), to original brand manufacturers (OBM). Such move involved substantive learning and competence building.

- Major advanced countries account for more than 70% of total global R&D spending. Some newly industrializing countries (NICs) spend large amounts on R&D, but the amounts is still relatively small in comparison to technology-leaders whether at national or firm level. In technology-leader countries, however, technological uncertainty makes R&D expensive. In technology-leader countries, the vast majority of attempts at innovation fail.¹⁹ Well over half of all R&D projects in technology-leading firm are simply cancelled.²⁰ The degree technological uncertainty is far less for R&D in technology-followers. The key issue for R&D in technology-followers is not how much R&D, but what R&D.
- Technology-leader countries are capable of generating many alternative approaches to technical change and then have institutions in place (firms and markets) to select the best alternative. But this approach is wasteful with duplication of effort and much that turns out fruitless. This wasteful attribute of technical change makes R&D expensive in technology-leaders. In technology-followers, however, the ex-post selection of has already taken place, the new technological paradigm selected and the uncertainty of a different magnitude.²¹
- Even in technology-leaders, over 80% of industrial R&D expenditures are devoted to development activity improving existing products.²² Research expands the knowledge base on which existing industries depend and generate new knowledge leading to new

¹⁹ See Rosenberg, N. (1996), Uncertainty and technical change. In Landau et al. (eds.) 334-356.

²⁰ A report from 1982 indicates that for every 100 projects that enter development, 63 are cancelled, 25 become commercial successes, and 12 are commercial failures. See Leonard-Barton, D. and J. Doyle (1996), Commercializing Technology: Imaginative Understanding of User's Needs. In Rosenbloom and Spencer (eds.) 165-176.

²¹ There is a variation-generating mechanism (R&D in firms) which develops several alternatives based generally on where they have been in the past. Technical change is thus path-dependent. Having generated these alternatives, there is then a systematic mechanism (the market) which selects on these variations such that only a few survive. This selection takes place ex-post. The technical change is thus evolutionary because of both the variation and the systematic ex-post selection. See Nelson, R. (1995), Recent evolutionary theorizing about economic change. *Journal of Economic Literature* 35, 48-90.

²² See Rosenberg (1996).

technologies and the birth of new industries.²³ Research as an activity aimed at generating new knowledge is neither central to innovation, nor essential to industrial competitiveness. Research is critical to advancing the technological frontier in fields dependent on formal research such as biotechnology and semiconductors. However, research tends to be much less firm-specific than product development, and proprietary innovation within the firm may well depend on knowledge added to the pool through research elsewhere.

- Technology-followers use new design within an existing technology frontier to move up the value chain. Products may range from homogenized low-cost items to high value-added items. At the high value-added end, technology-followers should be able to define the design specifications. The development of new products to meet market needs demand design capability.
- Design tends to be market-driven rather than technology-driven; technology provides the capability to meet new market needs. The role of design changes over time in the life cycle of an industry – from the early phase primarily of designing for experimentation and technological innovation, to the phase in which designing for technical improvement, lower cost, and ease of manufacture becomes more important, and then to the mature phase where a multiplicity of design variations, fashions, styles and redesigns aimed at different market segments. Technology followers will operate mainly at the latter phases, but build capability over time to enter the early phase.
- The unity of product and process is the essence of design for manufacturability. Formal R&D effort usefully complement process innovation on the shop-floor. While shop-floor innovation arising from day-to-day operation is the major source of cost-saving, longer-term shop-floor problems require a concentration of skilled and qualified people trained in science and engineering, which can be provided by a specialized R&D laboratory. Such laboratory tends to be in-house. Only then will it be primarily responsive to the problems of the firm and develop the long-term formal and informal communication channels needed for a close relationship.

In technology-followers, in-house R&D team play a crucial role as the firm's formal learning unit of knowledge produced elsewhere; it can have intangible spin-off benefits for the rest of the organization. R&D unit can perform the role of gatekeeper to plug into external reservoir of knowledge. The knowledge is usually highly specialized, requiring advanced training to understand it. Any R&D function grouping usually contains a high concentration of more qualified people, making them suited to carry out a role of gatekeeper.

- R&D must build absorptive capacity to be able to access work done in other firms. This absorptive capacity is primarily a function of prior related knowledge that confers an ability to recognize the value of new information, assimilate it, and apply it to commercial ends.
- Understanding of research being done elsewhere may require doing some research as a ticket of admission to research done elsewhere. This learning role is of great importance in technology-leading firms. For technology-followers from NICs, R&D unit played the key role in transferring imported technology such that capability was built in house for subsequent project execution.
- Building learning capacity in technology-follower firms includes the information-gathering network that can survey what is available, detect new developments, and judge what is worthwhile buying and learning. Leading firms in catching-up economies have set up subsidiaries and bought firms to function as outposts that, together with in-house R&D, monitor research activities in advanced countries.

²³ See Rosenbloom and Spencer (1996).

- Organizing for learning requires that R&D engineers see themselves as technology-keepers. A technology-keeper has the responsibility for tracking useful knowledge inside and outside the firm. Useful knowledge will be overwhelmingly technological, not scientific. Recruiting new scientists and engineers from a university can keep a firm adequately up-to-date with scientific knowledge. The technology-keeper thus needs to be primarily concerned with what other firms are doing. The disadvantage of geographical distance between technology follower and leader can be compensated by regular access, informal and formal, to technical change at the technology leaders that originally provide the technology for the follower's current paradigm. Effective technology keeping has at least three distinct roles:
 - Boundary spanning and gatekeeping to track advances in the area whenever they may happen;
 - Codification, in that external knowledge needs to be captured in some permanent form (collecting articles, reviewing new products of other firms, and putting together to represent the state of kept technology. Codified knowledge provides a base for further since drawing on previously captured learning can dramatically shorten the learning curve); and
 - Communication and utilization, since unused knowledge is useless to an organization. Knowledge from the keeper may be useful in very different work areas. Codification permits knowledge to be communicated more easily. But knowledge may also need to be translated into a form that is understandable to those needing it. Thus the technology keeper's role is not just to codify, but to translate and then communicate knowledge.
- R&D can also provide significant intangible benefits to the firm. These intangible benefits are vague and difficult to measure. But the role of a nucleus for new attitudes and new procedures and attracting more technical person is potentially important.
 - R&D can set the tone for a discourse on technology.
 - R&D can play a role as a change agent for the firm. R&D can play a demonstrator role of setting new standards that match the best inter-nationally. One of the most effective ways of building absorptive capacity is benchmarking against competitive products. Benchmarking should extend across all key firm activities, but R&D is a natural place to begin the process, because it directly feeds into product development – a key activity for the firm's future.
 - R&D activity can help in attracting good technical people who are needed by the firm but who might not otherwise join.

Leading technology-followers from NICs have built innovative capacity, both incremental and process, and design and product. Deciding to build innovative capacity and understanding the different role for and organization of R&D is the first step in the process, and strong emphasis placed on pushing out the design frontier. They target quality attributes to move-up the value chain in global markets. They should be able to define its own design specifications, not take the given technology as given. Instead they can use their absorptive capacity to learn from the technology leaders, and then look for new designs by need finding to move up the value chain.²⁴

3. Interaction between Science and Technology in Catch-up Processes

Science played specific roles of initiating positive interactions with technological development

²⁴ Design uses the need-finding technique as a systematic exercise to articulate user needs that are unmet and usually not obvious. It is distinct from market research – asking customers what they want. Using multiple techniques ranging from market surveys, anthropological studies, partnering key customers, to building scenarios of the future, can lead to more imaginative understanding of user's needs and prediction of future frontiers.

and thus contributing for the absorptive capability, since initial stages of development and during catching up processes. Scientific institutional building must be seen as a component of modern industrial policies.²⁵

- Throughout the development process, a more interactive process between technology and science may take place. For these interactions, scientific institutions, resources and capabilities are necessary. Neither the linear model nor an inverted linear model would take place: a more interactive approach is necessary for development.²⁶
- The National Innovation System (NIS) literature defines the different role of institutions from the scientific and technological dimensions, emphasizing an institutional labor division between the production of science and the production of technology. Generally speaking, universities and research institutes produce scientific knowledge, and industry produce technology. There are firms producing basic knowledge, publishing papers and advancing science, and universities applying for patents, generating new products, etc. But the main technological labor division involves this basic labor division.²⁷
- The interaction and the mutual feedback among these institutions are key. In the former USSR, there were institutions (research labs, universities, firms, R&D resources, etc.), but there were only weak interactions among them.²⁸ The NSI represents an institutional arrangement that articulates the economic wealth with the underlying technological competence.²⁹

In the catching-up process, R&D can play dual roles for firms: innovation and learning.³⁰ The combination of technology acquisition and learning and the sequence that runs from imitation to creativity are two sides of the same process. Efforts to imitate depend on internal capabilities: initial stage of development and the catching-up process depend on absorptive capability. To monitor knowledge developed elsewhere, firms invest in basic research - an entry ticket for a network of technological and scientific information.³¹ Internal capabilities are prerequisite to imitate and absorb knowledge from advanced countries. A certain level of scientific capability is a key component of this absorptive capability.

²⁵ Bernardes, A. T. and E. M. Albuquerque (2003), Cross-over, thresholds, and interactions between science and technology: lessons for less-developed countries. *Research Policy* 32, 865-885.

²⁶ A complete inverted linear model would suggest the following schema: first economic development, then resources available for technological development, and finally the growth of scientific institutions. Without investments in science and technology what would plug them in the international network of scientific and technological information?

²⁷ Nelson (1992), for instance, shows what is public and what is private in technology, warning about the risks of privatization of knowledge that should be public. This warning points to an inadequate labor division among various spheres of NSI.

²⁸ Freeman, C. (1995) The "national system of innovation" in historical perspective. *Cambridge Journal of Economics* 19.

²⁹ Nelson (1990) summarizes this relationship presenting how the institutions of NIS constitute the engine of capitalist growth. Dosi (1997) mentions that as time goes by the weight of science increases in subsequent technological paradigms. In this regard, the constitution and evolution of NSI could be seen as the institutionalization of diverse and multifarious channels of the systematic application of science to production. Nelson, R., 1990. Capitalism as an engine of economic growth. *Research Policy* 19 (1). Dosi, G., 1997. Opportunities, incentives and collective patterns of technological change. *The Economic Journal* 107, pp. 1530-1547.

³⁰ Cohen, W. and D. Levinthal (1989) Innovation and learning: the two faces of R&D. *The Economic Journal* 99 397, pp. 569-596.

³¹ Rosenberg, N. (1990), Why do firms do basic research (with their money)? *Research Policy* 19, 165-174. Mowery, D. and N. Rosenberg (1989), *Technology and the Pursuit of Economic Growth*. Cambridge University Press, Cambridge.

- The literature on economics of technology has deeply criticized views that underplay the efforts necessary for technological imitation. Imitation and diffusion of technologies must be seen as a continuation of innovative process.³²

During the initial phases of development, scientific institutions are necessary mainly for the learning side of innovative process. The necessity of scientific institutions to support learning processes and diffusion of technologies is greater now, since the technological paradigms are more science-based than those in the past, and current technology depends more heavily on science.³³ Over time, as a country develops, the mix between the learning and innovation faces of the R&D process changes. Beyond their key role as supporting the absorptive capability, the scientific institutions have other important contributions for development.

- Scientific institutions act as a focusing device in this process. Science at periphery is important to function as an antenna for the creation of links with international sources of technology. Scientific institutions could spot avenues of technological development that are feasible backward countries, given national and international conditions. This means that scientific information is necessary even to advise in which industrial sector entry is not feasible. This is very important for LDCs: blind search could be wasteful. Therefore, the scientific institutions provide knowledge to focus search.³⁴
- The national scientific capability is a major support for industrial development, providing the knowledge necessary for the entry in key industries for the process of development. Scientific knowledge, provided by the public infrastructure, reduced the entry costs in key sectors.³⁵

The mutual feedback and the interaction between science and technology seem to be the components of catching-up process. In the catching-up process, there could be a combination between dispersion and concentration across scientific disciplines. On the one hand, a country should have capabilities to follow and monitor developments in a broad range of fields, connected to the focusing device side of the scientific capabilities (dispersion). On the other hand, a country might need to concentrate limited resources in disciplines deeply related to industrial needs, connected to the provision of public knowledge side of the scientific capabilities (concentration). Stylized facts point not only to the quantitative aspect of the interaction (the concomitant growth of papers and patents), but also the qualitative aspect (the concentration of scientific production in disciplines with deep impact on industrial technology, (engineering, computing, applied physics, materials science, chemistry, etc.). Five stylized facts about the relationship between scientific infrastructure and catching-up process can be listed:

- A high correlation between the growth of scientific and technological output;
- High opportunity taking indicators, hinting an interaction between scientific output and industrial technology;
- High concentration in few interrelated scientific disciplines;
- Increase in the concentration in scientific disciplines during the catching up;
- Decrease in concentration in patent classes during the catching up phase.

The role of science during the catching-up process is two-folded: source of absorptive capability and provider of public knowledge for industry. Interactions between the technology and science,

³² Silverberg, G. (1990), Adoption and diffusion of technology as a collective evolutionary process. In: Freeman, C. and L. Soete (Eds.), *New Explorations in the Economics of Technological Change*. Pinter Publishers, London, pp. 177–192.

³³ OECD (2002), *Benchmarking Industry–Science Relationships*. OECD, Paris.

³⁴ Nelson, R. (1982), The role of knowledge in R&D efficiency. *The Quarterly Journal of Economics*, Cambridge 97 3, pp. 453–471.

³⁵ Perez, C. and L. Soete (1988), Catching up in technology: entry barriers and windows of opportunity. In: Dosi, G., C. Freeman and R. Nelson (Eds.), *Technical Change and Economic Theory*. Pinter Publishers, London, pp. 458–479. See Perez and Soete (1988).

as well as the dynamics of these interactions change during the catching-up process, reaching at last a level of strong and mutual reinforcing relationships found in developed economies.

- As an economy develops, its growth becomes more and more dependent on its scientific and technological resources. The mutual feedback between them contributes to explain why the economic growth is fuelled by strong scientific and technological capabilities. The increase in complexity means the incorporation of more and more people, institutions, companies.
- The capacity of the technological sector to use scientific knowledge increases over time, becoming more efficient in the transformation of scientific information into technological products. There are more connections turned on and more interactions working. Mutual feedback and virtuous cycles become working.
- The interactions between science and technology seemed to be triggered after a certain threshold of scientific production has been attained.³⁶ The attainment of a threshold of scientific production seems to be a precondition for improved technological production.
- An articulation between industrial and scientific policies may run both ways: scientific institutions would help the formulation of industrial policy as focusing devices, and industrial policy would help to transform scientific knowledge (generated abroad and locally) into new firms, new products, etc. The interaction between these two pillars of a modern developmental policy may help the establishment of the interactions.

4. Key Issues of Technology Policy in Catching-up Economies

Indigenous process of technical advance has not always been seen as the key policy problem by those most directly concerned with technology policy to support industrialization. The central technology policy issue has often been seen in terms of questions like: how to create a structure of local R&D institutions and how to ensure that those institutions are actually used after they have been created. These questions are far from being the same as the question of how to achieve and sustain indigenously driven processes of rapid technical change.

- It may be useful to adopt technology-specific focus on the radical technological advance facing industry. However, it may be more important for many purposes to focus on a more general technological change that underlies all those revolutions. Technological change involves the associated dramatic increase in the significance of knowledge and human capital.
- Even in industrialized economies, R&D is only a part of the activities that contribute directly to technical change. There is a wide range of design and engineering activities through which the results of R&D must pass before they result in commercial use of technology. Without any direct inputs from R&D, design and engineering activities are frequently sufficient in their own right as sources of technical change – especially as generators of the continuous process of technology diffusion.

In the context of industrializing economies, the central issue is not just about investment in these change-generating activities. Nor is it about reorganizing and managing more effectively the capitals for undertaking those activities. The problem at the heart of the key technology policy issue is therefore not simply about investment in R&D to create new knowledge. Instead it is about investment in creating the whole spectrum of human and institutional resources for generating and managing technical change.

- Policy attention had concentrated almost exclusively on the technology supply-side

³⁶ Bernardes, A. T. and E. M. Albuquerque (2003), Cross-over, thresholds, and interactions between science and technology: lessons for less-developed countries. *Research Policy* 32, 865-885.

(presumed to be technologically active and creative in the process of technical change), while virtually ignoring the user-side (presumed to be technologically passive selectors and adopters of technology). Over time, the focus of policy attention has shifted from supply-side to user-side. Initial ideas centered on R&D institutes as the key local sources of technology for industrial users, and on the issues of how to link the two. By the early 1970s, some studies identified local consulting and engineering organizations as a link between technology users and local machinery producers and an independent source of technical change for technology users.

- However, it became realized that the distinction between technologically active producers and technologically passive users is fundamentally misleading. The users generate a host of improvement and modification in their production systems. They make key creative contributions to technical change through interactions with suppliers of machinery and inputs, research institutes and consultants. A pre-requisite for such creativity is substantial investment in the accumulation of human resources within the technology users. In the process of industrialization, such investment has been the basis for the development of more specialized local suppliers of inputs to technical change: enterprises producing engineering services and capital goods frequently emerged out of that explicit investment in knowledge and human capital on the part of technology-using enterprises.
- More generally, economists have begun to understand two key issues. 1) Individual firms are not the source of innovation and technical change. Technical change is generated out of complex structures of interaction between firms, and sometimes between firms and supporting infrastructure. 2) Those supporting institutions can rarely generate technical change on behalf of industry without significant innovative activity on the part of industrial firms. They may play important complementary roles in relation to innovation taking place in industry, but they can rarely act as a substitute for it.

These perspectives on the process of technical change in industry pose new problems for policy makers and new questions for policy research. It is ineffective to define industrial technology policy as industrial R&D policy and to see that policy arena as the preserve of government agencies with focus on issues about resource allocation to R&D. The problem area for policy should be much more broadly defined, with responsibility for its various dimensions spread widely across all relevant government agencies. To support this perspective, policy research needs to provide much greater understanding than is available about such questions as:

- How is the micro-level technological behavior of industrial firms influenced by key aspects of the structure of industrial production (the size of firms, ownership patterns, structures of specialization, etc.), and how to those relationships differ between industrial branches and stages of industrial development?
- What aspects of government policy influence those aspects of industrial structure in ways that contribute both positively and negatively to technological change and to investment in the underlying human and institutional resources for generating and managing technical change?
- What factors influence those aspects of technological behavior within given structural conditions – not only micro-level factors concerned with management and macro-level factors stemming from overall economic policy (industrial growth rates, trade regimes, etc.), but also institutional factors concerned with mechanisms and incentives for investment in change-generating capacities in industry?

The issue of human capital development is coming to receive increased attention. However, the specific aspect of that issue which is emphasized here (the development of change-generating human capital in industry) requires two fundamental changes in conventional perspectives on human resource development. The issue should not be seen simply in terms of strengthening education and training institutions like universities, technical colleges, training institutions etc.

The significance of explicit investment in these human capital assets need to be given much greater prominence.

- The role of education and training institutions are important, but just as important is the role of industrial firms. The issue is not just about human resource development for industry. It is about human resource development by industry. It is striking, for instance that, just as industrial firms in the developed countries are intensifying their investment in creating new knowledge by R&D, they also appear to be intensifying their training and learning efforts to accumulate existing knowledge and expertise embodied in their managers, engineers and operatives.
- Relatively costless forms of learning-by-doing obviously remain important; but, as the underlying knowledge-intensity of industrial production rises, more deliberate and costly forms of investment in change-generating skills and experience also become more important.
- Policy research therefore needs to generate new understandings about how investment in these kinds of industrial human capital can be massively increased and undertaken more effectively.

It is on the issue about research organization and design that the most limited degree of success can be claimed in this field of policy research. We are concerned with understanding complex evolutionary process in which the dynamic technological behavior of firms interacts with change in their economic environment. At the same time, we are concerned with the ways in which other kinds of institutions such as R&D organizations change their roles and structures over time in response to changing pressures and incentives. Moreover, concerns about policy effects necessarily require understanding about how responses to policy change over time, and about how policy itself shifts in response to changes in political structures and processes.

- With very few exceptions, research have been organized on the basis of short-period observations and cross-sectional analysis; and occasional efforts to extend the time periods of observation by reconstructing earlier history have only been very partially successful – a limitation that is inherent in the problem area addressed. At the same time, cross sectional comparisons have seldom spanned across the diversity of different systems that would be needed to yield the most fruitful insights. The comparative element in many projects has been evident more in the formalities of network organization than in the substance of data and analysis.
- Research in this field has been surprisingly non-cumulative. At the level of studies of particular firms, industries and institutions, there have been virtually no attempts to develop time-series data and understanding by building new short-period studies on top of their predecessors. At a more general level, important insights have often accumulated only very slowly between successive projects. Too frequently, insights and conclusions from earlier research have been subsumed and lost, rather than forming a basis for new research.
- This pattern of research design and organization has, in part, stemmed from the pre-occupations of researchers. The key policy problem in this field was defined in a way that requires short-period, cross-sectional research. The selection of appropriate technology may call for the analysis of technological behavior in industry. However, issues about change and dynamics were not seen as centrally important aspects of that behavior.
- The contradiction between the types of research design and organization which have been needed and those which have dominated practice has stemmed less from the researchers than from the institutional framework within which they have had to do it. There had been few established institutions where research in this area can be conducted on a sustained, cumulative basis. However, the issue is not just about creating an institutional basis for effective research in this area. More important may be the pattern of funding for research,

and the underlying interests and pre-occupations of the agencies providing that funding.

5. Major Issues in Industry-Science Relations³⁷

Universities and industrial companies interact despite many barriers and differences in their objectives, organizational structure, and policies, including orientation, philosophy, and interests of researchers. Successful interactions provide lasting benefits to both parties. Researchers and their managers, from both sides of the interaction, may evaluate the progress and the outputs of the interaction by using a combination of quantitative indicators and judgmental assessments. Although short-term, one-shot relations may prove beneficial to both parties, the longer and more lasting cooperation seems to bear the more positive and beneficial outcomes to both industry and universities because of the psychological, organizational, and social aspects of the interaction.

Inherent Differences in Mission and Objectives

Universities have chosen a role in society with the primary mission of educating future scientific and technical cadres, and of conducting research at the frontiers of science. Industry has practical problems to solve, with short-term horizon. Such inherent differences produce differences in style, behavior, and policies for inter-organizational interaction. Moreover, each organization has developed different methods for interaction with its environment. Universities prefer cooperation; industry opts for competition and confrontation. When cooperation is called for, the different approaches and their methods may prove to be incompatible and to an extent inadequate.

- Historically, the differences in the social-economic mission and the division of labor between university and industry were relatively clear and free of conflict. Universities were destined to contribute to general knowledge, and industry's mission was to use it. This clear division may have generated a perceived mismatch between university orientation toward long-term research versus industry's preoccupation with short-term product-oriented research.
- With respect to the issue of free inquiry, universities insist on the freedom to publish, without any restriction or infringement, including oral communication of the results of academic research. The right to publish was perceived by universities to constitute a major barrier to collaboration. Many universities tend to disapprove of exclusive rights to a company, although in certain circumstances, universities grant exclusive rights.
- Disputes have arisen as to who owns inventions, technical data and test results, research equipment, manufacturing know-how, drawings, unpublished reports, and new methods concepts and techniques. Many academics feel that the fruits of their research should be made available for the public good, regardless of the sponsor. However, many inventors in universities want to benefit personally from potentially commercial research results. There may be no clear solution, since both researchers and sponsors seem to have legitimate claims. Each situation requires negotiation on the merits of the relationship, within a general policy framework and the legal and ethical views of intellectual property.

Differences in Organizational Structure and Policies

There is a contrast between the structure of a university research group and that of an industrial

³⁷ Geisler, E. and A.H. Tubenstein (1989), *University-Industry Relations: A Review of Major Issues*. In Link, A.N. and G. Tasse (eds.), *Cooperative Research and Development: The Industry-University-Government Relationship*. Kluwer Academic Publishers: Boston/Dordrecht/London.

concern as perceived by both groups. There are several potential difficulties in creating a lasting interaction. The basic difficulty on the industry side seems to be relative rigidity of the decision and communication channels. On the university side, the amorphous structure generates barriers to swift and unambiguous decision processes. University researchers who try to engage in on-going relations would also confront problems relating to compensation for researchers.

- If university allows payment in stock options, such a policy may raise ethical issues and trigger problems of conflict of interests. Most universities, in their patent policies, allow for certain percentage of the proceeds from invention and discoveries to be paid directly to the inventor. However, the complexity and inadequacy of such patent, licensing and compensation policies can create biases, voids and unclear situations that tend to be perceived as barriers to the interaction.
- Universities tend to allow faculty members to conduct limited consulting activities (usually one workday per week), and perceive these activities to be beneficial to both researchers and the institution. Many firms, however, have not learned to use academic consultants effectively. Some of this because many consultants come in only occasionally, throw in some radical new idea or a bit of advice, and then leave with little or no follow-through. In addition, there are often psychological problems for industrial researchers who resent consultants who behave in a distant and superior manner.
 - Academic consultants can play a number of roles in contributing to industrial R&D, as idea generators, working team members, information sources and gatekeepers to literature or unpublished research results, linkages with the scientific community and leading universities, and reviewers of scientific work in the company, etc.
 - Universities tend to impose organizational limitations in the time expended and the scope or content of such consulting relations. Some universities assess the consulting efforts in terms of their effects on the intellectual climate and balance in the academic department, particularly when consulting requires more than the personal time of the individual researcher. Most universities formally require the faculty member to obtain permission of the dean or the chairperson, potentially adding a bureaucratic hurdle to the initiation and the maintenance of university-industry interactions.

Industrial companies tend to be reluctant to fund the total cost of joint research ventures, particularly with regard to the university's indirect costs. Rigorous time allocation of key faculty personnel to the university-industry interaction is not always possible, and there are differences between the university and the company on what constitutes the real cost of research.

- Outstanding university researchers, who have become used to large government grants, may be less than enthusiastic about industrial support, usually for applied research, at much lower levels of funding and with as many or more strings attached.

A general problem that may not be obvious to people outside the university community is that the value system of the university community is far from monolithic. The competing objectives of obtaining funds for general university purposes versus obtaining funding for very specific research projects of individual faculty members are a source of potential conflict.

- In one form, this potential conflict may be exacerbated by block grants to universities for subsequent dispersal internally. University research centers and interdisciplinary programs have been used as dispersal mechanisms in this connection. Such differences tend to create barriers in cooperation between university department or even research groups across departments.
 - Some faculty members, especially those who may not have had much experience or success in raising outside project funds themselves, may prefer this two-step procedure. Others (including perhaps the more entrepreneurial practitioner of grantsmanship) may be negatively inclined toward this system. They may see it as reducing the amount of money they can get for their own programs from a given source. This problem is

sometimes prevalent in the planning and operation of science parks and innovation centers.

- The view of the university administrator and trustees is likely to be more focused on general operating revenue with as few strings attached as possible. Research-oriented faculty members may strongly prefer funds earmarked for research. These differences also apply at the departmental level, where conflicts abound over division of available resources between general purposes and specific research projects. The industrial partner to a relationship with a university would do well to become familiar with those potential differences and be prepared to negotiate within that context. On the other hand,

Within universities, as in industry, there is hardly a unified system of values and interests. The different interests of entrepreneurial faculty and those within academic fields that are hard to sell or not as glamorous may create conflicts and barriers to the prosperity of universities and their faculty to cooperate with industry.

Differences in Orientation, Philosophy and Interests of Individual Researchers

Individual researchers, on both sides of the university-industry interaction, have formed certain attitudes that tend to foster a culture gap or lack of understanding, even in those interactions that have a reasonable level of success. Industry researchers perceive faculty as unable to effectively perform directed research. University faculty tends to perceive industrial research as oriented towards non-academic problem solving. These attitudes and perceptions can create a somewhat self-imposed division of labor, accentuating the gap between so-called exploratory and applied research agendas and thus making a smooth transition or technology transfer more difficult.

- Many university researchers encounter difficulties in adjusting their commitments to the institution (primary duties) with their desire to be involved with external research, particularly with industry. They tend to perceive the primary duties as teaching, publishing and research, whereas practical involvement with industry settings and problems (albeit scientifically challenging) seems to conflict with such duties in competing for faculty time.
- Many university faculties are essentially lone-wolf individualists, with specialized interests and insulated areas of scientific curiosity, but they develop institutional loyalties. Thus, they tend to organize their activities in the best interests and in conjunction with the objectives and the mission of their university. In some respects, working with industry represents a distraction and taxes of faculty resources.
- Industry researchers, on the other hand, find it even more difficult to allocate their time to inter-actions with university. Their commitment to company priorities tends to be collide with the more academic and exploratory aspects of university research.
- Faculties in research universities are required to conduct basic research and to publish the results. Such research outputs are used in promotion and compensation decisions. Thus, when working on industrial-type problems, faculty may feel constrained by limitations of time and by the publishability of their research. This is particularly the case with junior faculty, reluctant to join an industry-sponsored project that demands time but may not hold much promise of academic outputs and rewards.
- Many industrial scientists tend to have psychological barrier against the employment of university consultants. They may feel that their in-house capabilities are sufficient to carry out the necessary tasks. In addition, R&D units in industry undergo periodic assessments of their performance, thus having to justify cooperative effort with universities and the spending of scarce resources for the acquisition of skills and capabilities that they may feel they already do or should possess.

Effectiveness of University-Industry Arrangements

There are several general types of university-industry arrangements and a variety of specific

mechanisms designed to initiate and to maintain the interaction. In each such arrangement, many of the aforementioned issues may be relevant factors in the initiation, continuation, and success of the interaction.

- University-industry interaction may range from a one-shot transfer of information to a complex and long-term relationship, as in a research park or a cooperative research center. The more complex, long-term and binding the type of arrangement, the more complex may be the issues involved. In complex relationships such as the joint research park, issues such as commitment of researchers, and sharing of funding become crucial to the continuation and the success of the enterprise.
- Moreover, as the contracts between researchers on both sides become more frequent and more intense, differences in the culture and other misconceptions may be accentuated, or they may be diminished, due to an increased understanding on both sides. The outcome depends on the individual conditions and circumstances of each case.

Table 16. Types and Mechanisms of University-Industry Relations

Types	Modes of Interaction and Some Mechanisms
Industrial Extension Services	<ol style="list-style-type: none"> 1. Information transfer and consulting 2. Workshops, classes 3. Undirected corporate gifts to university funds 4. Capital contribution to university departments 5. Industrial fellowships
Procurement of Services	<ol style="list-style-type: none"> 1. By university from industry. Prototype development, fabrication, testing, on-the-job-training for students, theses topics and advisors, specialized training 2. By industry from university. Education and training of employees (degree programs, continuing education); contract research, consulting services. 3. Industrial associates. Industry pays fees to university to have access to total resources of the university.
Cooperative Research	<ol style="list-style-type: none"> 1. Joint research planning and execution 2. Faculty and student participation 3. Cooperative research projects: direct cooperation between university and industry scientists on projects of mutual interest; usually basic, non-proprietary research. No money changes hands; each sector pays salaries of own scientists. May involve temporary transfer of personnel for conduct of research. 4. Cooperative research programs: industry support of portion of university research project (balance paid by university, private foundation, government); results of special interest to company; variable amount of actual interaction. 5. Research consortia: one university, multiple companies, basic and applied research on generic problem of special interest to entire industry; industry receives special reports, briefings, and access to facilities.
Research park	<ol style="list-style-type: none"> 1. Research cooperation on frontiers of science and technology 2. Information interactions 3. Increased sharing of research facilities and participation in consulting, seminars and continuing education 4. Contractual arrangement - specific and detailed; both parties contribute substantially to the enterprise

The range of mechanisms and forms of relationships can provide a facilitator to cooperation in that high flexibility can help in selecting a potentially effective mechanism. It can also present a barrier in terms of delays and decision-making and extended studies of the best way of co-operating. In many instances, the search for the optimal pattern may be self-defeating, since

most mechanisms have their limitations and advantages. In order for relationships to develop and mature and for mistakes to be made and overcome, long time periods are needed, sometimes on the order of several years.

- A healthy relationship should involve multiple mechanisms and linkages between the firm and the university. One-shot deals for a specific piece of technical cooperation may be of short run benefit to a particular industrial project or a particular university financial need, yet may not build the kind of relationships that can help in the long run. Rather than search for the optimal means of cooperation, several apparently attractive linkages should be tried for a period of time to see which ones survive. This means avoiding an initial approach that leads to a rigorous test of whether a firm and a university can work together.

Benefits versus Costs

Universities appear to interact with industry primarily to acquire funding for basic research and to support the university's facilities. Industrial support is seen by universities as requiring a lesser amount of reporting requirements than government grants, and is a source for continuing opportunities for individual faculty members.

- Several academic and industry researchers and managers have written on the topic of what can be gained from university-industry interaction. In a 1984 study, the National Science Foundation (NSF) surveyed 226 university and industry principal researchers. The study found that both university and industry respondents felt that the joint effort improved their ability to cooperate with each other. University respondents showed more optimism than industry researchers with regard to likelihood of tangible benefits occurring to the firm.³⁸

Table 17. Potential Benefits from University-Industry Interactions

Benefits to Industry	<ul style="list-style-type: none"> · Window to technological state-of-the-art · Systematic review of faculty research results · Specific skills and knowledge provided by faculty consultants · Training of industrial scientific/technical personnel - part time, full time, on-site, night courses · Participation of faculty members in industrial conferences · Source of highly skilled scientific/technical employees · Increased rate of technological progress in fields of lagging technology · Solving specific problems for industrial projects · Joint effort, start-up business, economic payoffs · Access to university facilities
Benefits to University	<ul style="list-style-type: none"> · Practical updating of faculty and students · Funding for research as well as capital investment · Development of university curricula · Summer employment and other opportunities for students · Industrial membership on university advisory committees · Access to industrial facilities and equipment · Ability to utilize government funds for applied research with industry · Joint effort, start-up business, economic payoffs

- The costs associated with the interaction, on the part of the university, seem to be in terms of potential dis-equilibrium of the research agenda and the orientation of faculty away from its primary mission of teaching and publishing. For industry, a major cost is the possibility of industrial scientists becoming too involved with basic research and losing sight of practical solutions. Another cost is part of the evaluation of the cost-effectiveness

³⁸ National Science foundation (1984), *Cooperative Science. A National Study of University and Industry Researchers*. Volume I.

experienced by the company as a consequence of its monetary outlays in the interaction.

How to Evaluate University-Industry Interaction

The multi-facets and the longer-term aspect of university-industry interaction are the prime difficulties in arriving at an agreed-upon mechanism for its evaluation. There are two major approaches to the evaluation of such interactions: 1) overall evaluation of benefits and success, and 2) the use of specific indicators to evaluate levels of accomplishment of selected dimensions or aspects of the interaction.

- As in many inter-organizational interactive processes, university-industry interactions may be evaluated on the basis of the overall success and the benefits resulting from the process. Overall success may be determined by surveys of key participants and their judgment as to success or failure.
- A variant approach may include the identification of the needs and expectations that both partners have, which is followed by the subsequent comparison with actual or perceived satisfaction of these needs, once more by surveying key participants.³⁹ The problems with this approaches are:
 - Differences between industry and university key participants on the definition of the success of the interaction, including differing views of what constitutes a successful or beneficial outcome; and
 - The relatively long term usually required for an inter-organizational cooperation to be declared accomplished so that judgments may be made regarding its accomplishments. Moreover, attempts to evaluate individual stages of the process are usually opposed by key participants from both sides of the interaction with the pretext of "It's too early to tell," or "Give it more time."
- Perhaps a more useful approach is the use of selected categories of quantitative indicators to measure the level or, in some instances, the intensity of the interaction, subject to a subsequent judgmental assessment of the indicators by key participants. The main advantage of this procedure over the previously mentioned overall evaluation is the utilization of quantitative indicators of the process and outcomes of the interaction as the basis for a judgmental assessment, as well as qualifies to such an assessment, e.g., by virtue of documented factual indices. Potential indicators, from the literature, are listed in Table 16.
 - The first category of indicators focuses on dimensions of the conduct of university-industry interaction. The indicators are operational measures of selected occurrences in the life of the interaction and can be collected by periodic access to files and reports. Additionally, some indicators provide a qualitative or judgmental assessment. These can be collected through surveys of participants at given dates and occasions.
 - The second category contains indicators of short-term outcomes from the interaction, primarily those considered to be critical to any successful interaction.
 - The third category includes indicators of the longer-term outcomes, where the more lasting impacts of the interaction may be observed and measured. Although short-term, one-shot relations may prove beneficial to the parties, the longer and more lasting cooperation seems to bear the more positive and beneficial outcomes to both industry and universities, because of the psychological, organizational and social aspects of the interaction.
 - The fourth category of indicators concerning the type and pattern of interactions are related to the four modes of interaction in Table 14, in that they indicate the degree of

³⁹ Tamaribuchi, K. (1983), "Effectively Linking Industry with a University Resource: A Survey of University-Industry Liaison Programs." Paper presented at the WPI/NSF Conference on Management of Technological Innovation, May 1983.

formalization or institutionalization of the relationship, from short-term, one-shot extension or consulting service, to the longer-term establishment of research parks. Table 16 may thus be a preliminary framework for the evaluation of different types of university-industry relations, by providing indicators of outputs from the relations.

Table 18. List of Potential Indicators of University-Industry Interaction

1. Indicators of the Process of Interaction
<ul style="list-style-type: none"> · Number of contracts between parties at each stage of the interaction · Organizational level of contacts · Duration/intensity level of contacts (brief conversation, meetings, etc.) · Flavor of contacts (pleasant, stressful) · Focus of contacts (administrative, technical) · Types of participants in contact (individuals, groups, researchers/administrators) · Usefulness of information content of contacts (by survey of participants) · Perceptions of the seriousness or integrity of the other party in participating in contact · Number of decisions made in contact · Organizational level at which decisions were made · Resources initially allocated to contacts (people, facilities)
2. Immediate (Short-term) Outputs/Outcomes from Interaction
<ul style="list-style-type: none"> · Change in the probability interaction in the future · Number of commitments made: monetary information and personal exchange, access to facilities · Number of agreements drawn up (grants, licenses, joint ventures) · Number of contracts signed · Amounts of money changing hands · Number of technical problems solved · Number of reports delivered · Number of conferences, workshops, symposia, and joint seminars conducted · Number of fellowships established · Number of faculty hired as consultants to industry · Number of graduate students hired by industry · Number of joint projects established · Number of industrial researchers as guest lecturers at university · Number of patents inventions, and innovations in joint effort
3. Longer-term Outputs/Outcomes from Interaction
<ul style="list-style-type: none"> · Number of faculty accepting employment with industry · Number of spin-off enterprises · Number of consortia developed · Number of third party involvement (government, venture capital) · Level of third party involvement (amount of money) · Level of satisfaction with interaction among participants · Impacts on teaching · Level of industrial support for research centers and programs · Changes in percent or number of faculty with industrial contacts · Changes in patent and licensing rules and other procedures to accommodate needs of other party to interaction · Changes in general perception of needs, quality, and motives of other party · Developing networks: change in average number of regular contacts · Changes in production, sales, productivity, profits, and other indicators of success attributable to interaction

4. Type and pattern of Interaction
<ul style="list-style-type: none"> · Time to fruition of interactions (days, weeks, years to research agreements or research results) · Level of organization involved in a given interaction · Degree of institutionalization of contacts (multi-year agreements, permanent committees formed, etc.) · Formation of advisory boards and degree of formalizing interaction mechanisms

Table 19. Examples of Indicators to Evaluate Selected Types of University-Industry Relations

Types	Illustrative indicators
Industrial Extension Services	<ul style="list-style-type: none"> · Change in probability of interaction in the future · Number of technical problems solved · Number of fellowships established · Amounts changing hands · Number of symposia, seminars, etc.
Procurement of Services	<ul style="list-style-type: none"> · Number of patents, inventions, innovations · Number of faculty hired by industry · Number of training programs · Number of joint projects
Cooperative Research	<ul style="list-style-type: none"> · Number of research consortia developed · Size and shape of research consortia · Number of spin-off enterprises · Changes in general perceptions of needs, quality, and motives.
Research Parks	<ul style="list-style-type: none"> · Degree of institutionalization of relations · Number and level of third-party involvement · Level of continuing (multiyear) industrial support · Level of satisfaction with interaction

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Appendices

1. Commercializing New Technology¹

Products utilizing a significant new technology require technology development prior to product development. These two processes are closely linked and typically require a technology transfer step as a bridge between them.

The conceptualization, development and ultimate release of ant new technology can be viewed as following a development pathway. Along this pathway, a technology evolves from being promising to being incorporated successfully into a new product. Two important concepts bound this technology pathway: sensed technology at the start and the technology feasibility point (TFP) at the end.

- Since technical uncertainty is typically high at the start, the first step is to efficiently gain a better understanding of the underlying core technology or technologies. At the end, the objective is to decide when the technology is ready for transfer into product development.
- Technology development efforts should always have both a pre-agreed-upon performance goal and a clearly defined project duration. Targeting only a particular technology performance goal can result in a technology development program that seems to continue forever. The rate of increase of confidence in a technology is not predictable.
- A technology can be defined as being "sensed", as soon as there is a strong feeling that there is specific commercialization potential. Typically at this point, a clear definition of the ultimate product capability or new product platform is not fully known. Rather there is usually only a general understanding of the desired capabilities these future products should possess and a belief that the sensed technology can enable these capabilities. Historically, this has been defined as the point where technology moves from basic research into applied research.
- Sensed technology can take several forms. It might be a newly discovered technology with yet-undefined product application, or it might be a list of advanced technical performance criteria for future products, criteria which the selection or creation of technology must satisfy. In any case, sensed technology represents a starting point for a technology development.
- Most successful technology development programs, it is at this initial stage - prior to initiating development - that researchers, with help from marketing, construct an overall list of desired technology performance characteristics that serve as the researchers' development targets. These criteria should closely link the core technology with its ability to enable key capabilities that will differentiate the ultimate products in the market place.
- In order to know when a technology development program is completed and ready for product development, there needs to be a clear definition of the technology confidence level where the risk is acceptable. The technology feasibility point (TFP) defines this agreed-upon confidence level. It is expressed as a matrix of experimental outcomes (based on more general technical performance criteria targets), which if met would collectively provide adequate confidence that the remaining technology optimization could be completed with relative certainty during the normal course of the ensuing product development effort.

¹ Emmett W. Eldred and Michael E. McGrath, Commercializing New Technology- , *Research· Technology Management, January-February 1997*. Emmett W. Eldred and Michael E. McGrath, Commercializing New Technology- , *Research· Technology Management, March-April 1997*.

- The determination of the TFP is subjective and depends upon a number of factors, including the culture of the organization, experience with similar technologies, risk profiles of managers, external or internal pressures, and capabilities (real or perceived) of technical or developmental personnel. When the TFP is reached, other technical alternatives are typically ruled out, and the drive towards a specific product begins. It is also at this point that functional specification for the final product can be defined more accurately.
- It is also important to understand that investment during technology development is directed toward understanding the capabilities and limitations of technology. After product development begins, the investment is directly targeted at applying the technology to a specific product. Should the technology ultimately prove unsuitable, and the product development effort be cancelled, the product development investment will become a sunk cost. Management who initiate product development understood the risk they were taking by moving into product development early; however, they felt the economic opportunity offered by the faster time to market outweigh the relative investment risk in product development. In such case, their hunch was wrong, and the development effort was cancelled after several prototype applicator devices were constructed and tested.

The objective of a technology development program is to move a sensed technology to the technology feasibility point. Depending on the development program plan, progress can be made at different rates. The choice of alternative program is made at an early development stage review point. Technology development program may wander without ever reaching the TFP, if there is no formal decision-making or selection of alternatives.

- Effective management of the technology development process requires a clear understanding of the difference between technology development and product development. Understanding the difference enables better communication between scientists and management, improves management of R&D resources, increases monitoring of high-risk development components, and improves communication between technology development and product development teams. In general the key characteristics of technology development programs include:
 - Project cycle times are usually difficult to estimate.
 - Too much structure can inhibit creativity.
 - It is difficult to capture process experience and leverage it for future technology development efforts.
 - Because experimental outcomes are not known, highly detailed overall project plans are not practical.
 - Depending upon the technology, the degree of confidence or level of understanding prior to entering product development can be highly subjective and hence cause communication problems.
 - Project leaders must be able to manage uncertainty while focusing on project goals.
- In contrast, the key characteristics of product development are very different
 - Project cycle times can be accurately estimated.
 - Repeatable processes and tasks allow leverage from premier experience.
 - Creativity is less of an issue, while structure and discipline are critical.
 - Project planning and management skills and structure are required.
- Prematurely introducing an incomplete technology into the product development process often results in a series of problem caused by applying the wrong management process. Often this is compounded as technical uncertainty casts doubts relative to project deadlines for all aspects of the project dependent upon the technology. Common signs of product development projects with technology development problems include: vague predictions concerning final product release, continuing investigation of numerous possible technical alternatives, individuals reluctant to provide completion dates for certain project tasks, and substantial unpredicted schedule slippage.

Technology Realization and Commercialization (TRAC) is a structured process that evaluates and enables a given technology so that the technology can be utilized in the development of a new product or platform. The four basic elements of TRAC include a technology review process, a technology development team, a senior review committee, and a structured methodology

- Technology review process provides the overall framework for technology development. It consists of a series of pre-agreed technical reviews at the end of each development stage. At each of these technical reviews, the senior review committee decides whether the program should move to the next stage, be redirected, or be canceled.
 - Each of these technical reviews represents a significant technical milestone and a key evaluation point. Collectively, the number and sequence of the stages represent the overall technology development strategy.
 - Each technology stage provides a period for developing and evaluating a technology against the set of technical performance criteria. Because of uncertain experimental out-comes at each stage, a detailed plan outlining the experimental sequences of future stages is pointless. Detailed plans are appropriate only for the upcoming stage. However, a fairly accurate prediction of the number of stages and what each stage represents is usually possible.
 - Initiation of technology development effort begins with the definition of a technology performance criteria matrix. The matrix is market-based and derived by evaluating and selecting the technical performance criteria needed to enable key product capabilities.
 - The final stage of the technology review process is focused on technology transfer. Approval to enter this final stage means that a technology is considered ready for transfer into an upcoming product; the TFP has been attained.
- The senior review committee is a decision-making body composed of senior scientists and business managers. Typically the business managers represent the operating units and are the primary investors and supporters of the technology development efforts, while the senior scientists usually represent R&D management. Senior review committee (SRC) combines both a scientific and business perspective at stage reviews.
 - Stage reviews are usually divided into two parts: the first part being a scientific peer review, and the second part focusing on the business or investment aspects of the project.
 - During the first part, SRC senior scientists and technical advisors evaluate the program from a scientific point of view, reviewing both the conclusions reached during that stage and the experimental plans for the upcoming stage. They focus especially on the quality of science and the team's evaluation of the technology's proximity to the TFP.
 - The second part of the stage review involves attaining mutual understanding and agreement among members of the SRC as to which stage the technology has progressed to relative to being suitable for entry into product development (technology confidence level).
- The technology development team is composed of individuals responsible for specific aspects of the technology development effort. They might be responsible for the integration of several base technologies, or they might be responsible for only one aspect in the evolution of a single core technology.
 - The technology development team leader is heading the technology development effort, with overall project responsibility. This individual is empowered along the technology development team to plan, execute and evaluate the various stages of the technology development program. Advising the technology development team are various downstream functions, such as manufacturing, marketing, finance, legal, regulatory, QA, etc.
- Technology development activities need a structure. Structure provides a framework for project planning and execution that helps to make applied research more efficient. Without structure, activity can – and frequently does – wander. TRAC's structured methodology

utilizes a hierarchical approach that provides each layer of management with the correct level of detail. There are four levels of project detail.

- The technology development plan provides an overview of the entire technology development program broken down by stage and condensed onto one stage. Because the number or duration of individual stages can often only be estimated, the technology development plan provides an outline for the overall program. It is a *best guess* as to the most efficient approach to enable and evaluate the targeted underlying technology.
 - Phase plans are flowcharts of the integrated experiments within each stage. They are based upon information gained from previous stages, and collectively represent the over-all approach needed to reach the next major technical milestone. This flowchart format provides researchers with adequate structure to plan concurrent experimental activities (highlighting key dependencies or chronological linkages), while maintaining enough simplicity and flexibility that creativity is not dampened. The phase plan is created by the technology development team and reviewed by the scientific members of the SRC during the stage review.
 - Experiments and laboratory activities are planned at the laboratory level. It is the responsibility of the laboratory director to maintain a high level of scientific excellence. He or she should maintain an ongoing program of external and internal peer review. Prior to each stage review, senior SCR scientists might request that the design or results of a key experiment be included in the stage review.
- Because of the risks associated with technology development, there is no guarantee that a technology development program will ever lead to product development. As a result, the primary characteristics of a successful technology development process is not whether an actual product development effort was initiated but how efficiently it evaluates and enables the suitability of a given technology for commercialization.

Technology transfer is a consistent problem for development projects trying to incorporate or commercialize major new technologies. Incompetence or insufficient motivation is not the reasons for failure or inefficiency in technology transfer. Rather, it is absence of a process or methodology for accomplishing the transfer. Inexplicably, most companies either simply think this transfer will happen naturally or expect those involved to intuitively figure out what to do. However, companies most successful in transferring technology use a clearly defined process that functions as a bridge between technology development and product development.

- Senior technical and business managers routinely underestimate the effort and time required for accomplishing the transfer and incorporation of a new technology into a product development effort. Most often, they believe the transfer process can be accomplished relatively quickly by merely having the technology development researchers document their work and, through a series of meetings, transfer the technology to the product development team. However, numerous project mappings have demonstrated that this is rarely the case.
- Technology development and product development are often conducted at different sites and by different organizations. Technology development groups and product development groups rarely communicate. At the conclusion of technology transfer, researchers and developers are often dissatisfied with the results. The product developers often feel that the work done by the technology development team was incomplete in evaluating enabling the technology. Similarly the technology development team usually feels that the product development team was either not technically capable of receiving the incoming technology or was somehow trying to "reinvent the wheel." These feelings usually stem from the differences in viewpoints and backgrounds. Previous failures in technology transfer created much distrust between research centers and product development teams.

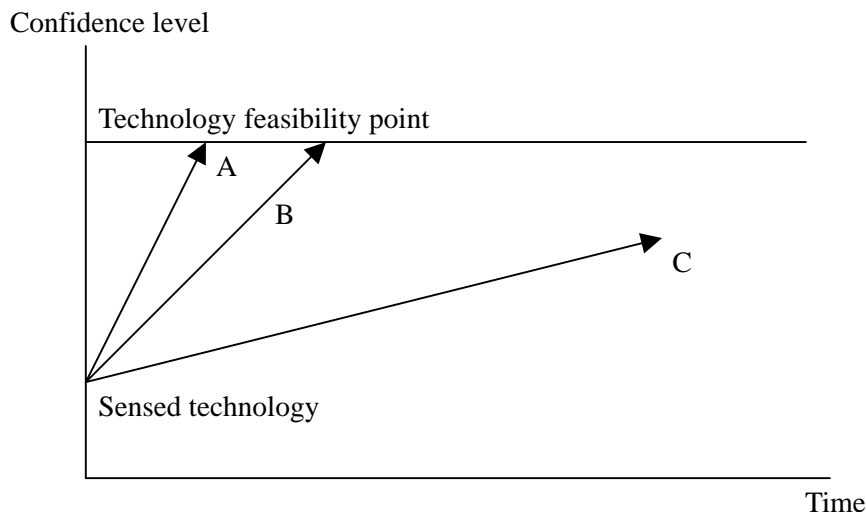
There are three basic elements in a technology transfer process: program synchronization, technology equalization and technology transfer management. Technology transfer needs to take

place at the right time. It is important to have a clear product concept prior to initiating the transfer process. Technology equalization process evaluates and enables supporting technologies that ultimately be required to develop the product. A structured management process is critical for technology transfer.

- The product development project is ready to receive the technology after the product concept is approved. At the completion of technology review process, the technology is ready to be transferred. This is synchronized with the right time in the product development process when the technology is ready to be received.
 - At the start of any product development effort, there is a requirement for a product concept, which is usually formulated by the product development champion responsible for putting together the necessary information to initiate the product development project. Occasionally, it is the responsibility of a concept development team. In both instances, technology team members should participate in the formulation of the product concept.
 - It is important to have a clear product concept prior to initiating the transfer process. Otherwise, the technical transition team members will be forced either to halt work while a concept is finalized or continue working without a clear understanding of specific customers or market needs.
- Typically, technology development focuses on evaluating and enabling a core technology for its use in product development. After the technology is deemed ready, a concept has been formulated and technology transfer begins, there is a need to broaden the project's technical scope to consider other supporting technologies. This is the role of technology equalization.
 - As a specific product concept begins to materialize, numerous other technologies often come into play. The objective of technology equalization process is to evaluate the entire anticipated product development effort relative its technology content and ascertain if there are any potential technical problem areas. This allows any identified problems to be addressed early, and greatly improves the chances for on-time product release and sale.
 - The technology equalization process initially involves surveying all technical aspects of a new product (unbundling), and then prioritizing these technical components, based on their overall importance (chronologically and relationally) and their degree of confidence. After this prioritization has been accomplished, a critical path can be derived based on the highest-risk components. From this path, specific work-plans can be used to enable and evaluate key technical components prior to key decision points. Through this process, maximum information will be available prior to key decision milestones, allowing management to better understand the tradeoffs between risks and time to market so that it can make informed decisions relative to these tradeoffs.
 - Usually, the formal technology equalization process is initiated at the beginning of the final stage of the technology development process and the earliest phase (product concept proposal phase) of product development. It continues through the planning and functional specification phase and is a critical component in the project development plan with associated key technical or design review points.
- Technology transfer is often complicated by widely differing personalities, coupled with serious logistics issues. Therefore, a structured management process with clear definition of individual and team roles and responsibilities is critical.
 - The technology transfer process requires individuals from both research and development to work effectively together. Thus, technology transfer management should facilitate effective communication and maintain parallel interests. Otherwise, the embedded cultural dichotomy can become disruptive and cause both team and program dysfunction.

- The transition team is central to the technology transfer process. It has evolving member-ships, usually starting with key representatives from the technology development team and the newly forming product development core team. Additional members from other functions are added as necessary. The product development champion or future core team leaders usually assumes the responsibility of transition team leader. The transition team may ultimately evolve into product development core team after the initial phase of product development.
- The roles and responsibilities of the various transition team members must be clearly defined. For instance, there needs to be a clear understanding of by the technology development members on the transition team that they are core members of the transition team and the product development core team only through the transition process. They are then available as advisors to the product development core team after the transition process has been completed.
- The transition team puts together a high-level transition plan, which initially concentrates on the transition of the core technology into product development and begins the process of technology equalization. Critical to this planning is the assignment of resources to evaluate the project's technical components other than the core technology.
- The technology transfer plan is reviewed and decided upon in a joint meeting of the senior management committees overseeing the technology development (SRC) and product development (Product Approval Committee) efforts as part of the (n-1)th stage review of technology development. This joint meeting serves to initialize the technology transfer program.

With the trend toward portfolio investing of R&D funds and therefore discounting the valuations for early-stage technologies, there is a critical need for efficiently enabling and evaluating new core technologies and, when deemed ready, to seamlessly transition them into product development. The implementation of improved development processes requires considerable effort on the part of the entire corporate infrastructure.



Confidence in technology builds over time, the rate of progress depends on the development program (A, B, C).

2. Technology Roadmap

The upsurge in interest in roadmap that surfaced in the 1990s was a direct consequence of the ever-shortening product development cycle times, creating a greater need for coordination (i.e. customer desires to build new technologies into products as soon as they are available). Speed (and hence time-related processes) became a premier consideration in an era where “the fast ate the slow.” In turn, this triggered the beginning of an expanding demand for roadmaps that continues and appears to be accelerating.

As a technology management tool, technology roadmapping is becoming widely used in the US and Europe. Designed to facilitate and communicate technology strategy and planning, roadmap can take a variety of forms, depending on the type (opportunities, capabilities, products, technologies, etc.) and particular company context.

- A roadmap, in its most general definition, is the view of a group of stakeholders as to how to get where they want to go – to achieve their desired objectives. The purpose of a roadmap is to help the group make sure the right capabilities are in place at the right time to achieve this objective. Experienced mappers often claim that it is roadmapping rather than the roadmap that generates the value.
- The essence of roadmapping is developing a common view within a team about their future and what they want to achieve in that future. Roadmapping is a learning process for a group – members discover gaps and new directions. The planning activity helps the group develop a common language and thereby improve communication among its members. A roadmap can also help the group communicate its vision and plan to customers, suppliers, partners and other groups.

Roadmaps have a variety of applications. Roadmap can be used to describe the future path of progress in an industry. Or, roadmap can be used to describe the past or future development of a field of science or technology in which there may be an optimal evolution path among several alternatives.

- In a corporation, an important need for roadmapping is often at the product-line level, to define the plan for the evolution of a product, linking business strategy to the evolution of the product features and costs to the technologies needed to achieve the strategic objective. The roadmap combines internal development needs with a marketplace view of technology trends.
- Several industry roadmaps have been developed under the leadership of the US Department of Energy’s Office of Industrial Technology. For example, The Semiconductor Industry Roadmap describes the next ten years of progress in semiconductors.

Frontier Experiences from Industry-Academia Consortia²

It was Motorola and Corning that first championed roadmapping approaches in the late 1970s and early 1980s. The Motorola model and experience were to become the foundation upon which the US approach and contribution has continued to evolve.

- The Motorola approach has been more visible in the US practice of technology management. Motorola initiated a corporate-wide process with the stated purpose of “encouraging our business managers to give proper attention to their technological future, as well as to provide them with a vehicle with which to organize their forecasting process”. The approach was introduced to help balance long- and short-range issues, strategic and operational matters with technology and other disciplines in the company.³

² Probert, D. and M. Radnor (2003), *Frontier Experiences from Industry-Academia Consortia*, *Research-Technology Management*, March-April 2003, pp. 27-30.

³ Willyard and McClees (1987), describing Motorola’s use and approach, was the first to appear on the

- The early Motorola approach described two types of roadmaps: an emerging technology roadmap and a product technology roadmap. The emerging technology roadmap was prepared and kept current for a single technology by a small committee of experts. More detail was to be provided on the product technology roadmap. It was not one map but a compilation of documents that provided a complete description of the product line (past, present, future) for a division or operating group.⁴

Not long after the appearance of the Motorola article, several European firms, notably BP and Phillips, adopted the concept. In Europe, EIRMA (European Industrial Research Management Association) in 1997 documented an eight-stage process based on the experiences of some 25 companies. EIRMA emphasized that the development of an effective roadmapping process within a business had to rely on significant vision and commitment for what is an iterative and initially exploratory process.

- The EIRMA working group consists of some 25 major European corporations that shared their experience of roadmapping; it quickly became apparent to them that there was no generally available guidance on how to tackle this appealing but ultimately complex activity. Some companies had invested many man-years in developing their own approach to technology roadmapping, and had experienced difficulties in embedding and maintaining the technique as part of their on-going business planning process. On the other hand, the potential value was clear and many benefits were reported from its application.

In the US, evolution of the field was even more intense, with firms such as the automobile manufacturer, Lucent, Hewlett-Packard and others taking up the baton and building beyond the original Motorola concepts.

- After a slow period of evolution following the initial impetus, Motorola launched a number of recent major advances with “Fusion Roadmaps” involving customers, suppliers and partners. Research also continues on the decision structure underlying product development, among other management processes.

The purpose of roadmapping is to support understanding of how technological and commercial knowledge combine to support strategy, innovation, and consequently, the operational processes in the firm, in the context of both the internal and external environment.

- The motivation for, and experience of, roadmapping have been investigated through surveys conducted by the MATI (Management of Accelerated Technology Innovation) consortium and CTM (the Cambridge University Center for Technology Management) in the late 1990s. Powerful attractions of the technique are the linkage of technology to business goals and the integration of diverse business functions and perspectives.
- In the MATI work, the role of a senior technical staff person in reviewing and integrating roadmaps across a business, as well as the support of senior management for the whole process, emerged as important to its success. From the CTM survey, it appeared that only a minority of firms has attempted roadmapping.

subject. The account states that roadmapping “provides a means of communicating to the design and development engineers and to the market personnel, which technologies will be requiring development and application for future products.” Willyard, C. H. and C. W. McClees (1987), “Motorola’s Technology Roadmap Process.” *Research Management* 30, pp. 13-19.

⁴ The eight sections of the roadmap were described in some detail, including tools and techniques that could be used in each case. These were: description of business, technology forecast, technology roadmap matrix, quality, allocation of resources, patent portfolio, product descriptions, status reports and summary charts as well as a minority report. (Motorola was already making use of what it termed a “Minority Report” to overcome the dangers inherent in “group-think”; this minority report concept is only recently becoming incorporated into the roadmapping process of other firms.) The technology roadmap matrix summarizes technological requirements for future products. It is this one element of the roadmapping process on which most readers later focused.

Roadmap Applications

Product planning	By far the most common type of technology roadmap, relating to the insertion of technology into manufactured products, often including more than one generation of product.
Capability planning	A type of roadmap similar to product planning but more suited to service-based enterprises, focusing on the insertion of technology into organizational capabilities.
Integration planning	Where the roadmap focuses on the integration and/or evolution of technology in terms of how different technologies combine to form new technologies.
Strategic planning	This type of roadmap includes a strategic dimension in terms of supporting the evaluation of changes in the business drivers resulting in different threats and opportunities, typically at the corporate level.
Long-range planning	Used to extend the planning time to new event horizons, often performed at sector or national level (i.e. Future Thinking)
Program planning	Focusing on the implementation of strategy and more directly relating to project planning (e.g. R&D programs)
Process planning	This new type of roadmap supports the management of knowledge, focusing on a particular process area (e.g. new product development)
Cross-roadmap analysis	Once roadmapping is successfully deployed across a number of operating units, common needs, gaps and duplicative programs can be identified by looking across the roadmaps. An issue is who can best do this. The appropriate person needs enough technical knowledge to understand potential and existing overlaps, enough clout to pull the people together, enough (slack) time to spend on this activity, and legitimacy to poke around in the technical affairs of independent business units and still be perceived as being independent. Chief Technology Officers may be assuming this role.

Industry roadmaps are generally created by bringing together firms from across the sector, research institutes, and associations, to project the pathways, rate of change, requirements, or constraints on development in the sector. The goals and processes in industry roadmapping can be quite different from corporate roadmapping. There can also be enormous variations in the industry roadmapping process.

- Industry roadmaps began to appear in the late 1980s and they can now be found for most industries (estimates are of 250 US industry roadmaps, a number of which are produced with the support of the US Department of Energy Office of Industrial Technologies).
- A key intent of industry roadmapping is to provide guidance on critical future technology areas and national and commercial research funding to enhance competitiveness.
- Translating output from industry roadmapping to the firm level (so that they may be addressed and integrated into the strategic planning of individual companies) is still at an early stage. Efforts to draw industry and corporate roadmapping close together are under discussion.

*Roadmapping in the Corporation*⁵

Deploying roadmaps across a corporation helps achieve key objectives. For each product-line, roadmaps link market strategy to product plans to technology plans. Roadmaps created at the product-line level are the base for corporate technology planning, identifying needs, gaps, strengths and weaknesses in a common language across the corporation. Roadmaps help focus attention on longer-term planning and improve communication and ownership of plans.

⁵ Albright, R. E. and T. A. Kappel (2003), Roadmapping in the Corporation, *Research·Technology Management*, March-April 2003, pp. 31-40.

- Product-Technology Roadmaps are used to define the plan for the evolution of a product, linking business strategy to the evolution of the product features and costs to the technologies needed to achieve the strategic objectives. Typically, strategies, product plans and technology plans are created independently by the people responsible for them. Roadmaps explicitly create the linkages, first linking strategic choices based on market needs and the competitive environment to product evolution and feature implementations, and then linking product plans to technology implementation plans.
- With roadmaps for several product-lines, it is possible to look across the roadmaps for common needs that may be met by a single development program or technology acquisition. This can be done by analyzing a database of roadmaps or with cross-roadmap reviews where product teams come together to identify common needs. Time-to-market improvements and other platform opportunities can result. Cross-roadmapping activity can address hidden gaps and identify key strengths that can be deployed in other areas of the business.
- The use of cross-functional team to create a product-line plan allows the members of the team to develop a shared plan. Roadmapping provides a common vocabulary that is shared across the team with diverse backgrounds such as product management, marketing, sales, R&D, manufacturing, project management and logistics. The team develops its roadmap in a step-by-step fashion, building on each member's special knowledge. The process is usually iterative, as the team realizes that the plan it has set out is not feasible or that there is a better alternative.
- A key goal of roadmapping is to identify and focus strategy and product development on the few most important elements for success. At every stage of roadmap development, the group strives to define the two or three most important drivers, elements or issues. In this way, the focus is kept on identifying the highest priorities. As the roadmap is developed and implemented, the team identifies gaps and the actions to close the gaps. Gaps may include a key technology that must be developed or acquired, or a feature that must be included in the product to meet a high-priority customer or market need.

The experience of several organizations suggests that initiating roadmapping by establishing a policy (e.g. requiring roadmaps for annual budget review) resulted in disappoint. An alternative approach is to assign responsibility to an organization for initiating roadmapping in key areas when they are needed. In a multi-business corporation, it makes sense to deploy roadmapping at the corporate level.

- The deployment task for the initiating group continues long after the first roadmaps are written, as the roadmapping life cycle moves through initiation, maintenance and, sometimes, restarts.
- During the start-up mode for roadmapping, a firm must decide which product-lines have the greatest need for multi-generation product and technology plans, and where are the greatest cross-business planning opportunities. Efforts to initiate roadmapping everywhere at once lead to failure.
- Locating a deployment function at the corporate level brings other distinct advantages. Participants in the business units often lack the slack time to investigate and absorb new roadmapping tools and techniques, available from a small community of practitioners.⁶
- The deployment task can involve several activities aimed at putting roadmaps in the right places at the right times. Chief among them is training. The product-technology roadmaps involve a style of analysis and presentation that is often new to participants. Participants

⁶ Lucent's corporate team built a unique economic trend analysis capability to prepare forecasts that were used in roadmaps across the company. "Experience Curve" cost trends are particularly important to the communications equipment industry.

are given a minimal education in industry fundamentals and used a roadmap to synthesize and articulate a strategy. In such a workshop, the act of wrestling with product, market and technical tradeoffs reinforce the essential links between these decisions.

- Roadmap training utilizes a set of common tools and templates that encourage a universal language for technology planning throughout the corporation. The roadmap template creates a common language for executive review of technology, enables cross-roadmap planning, and builds common roadmapping skills. A standard template amounted to a starting point – a minimal set of information to describe an integrated product and technology strategy.
- Corporate expertise available to facilitate made it possible to get roadmaps generated rapidly, without fumbling through process trial-and-error. Facilitators played roles in appropriately scoping the roadmap, forming the team, setting up a work plan, and assisting individuals with their tasks in the larger effort.

Product-Technology Roadmap

A product-technology roadmap presents an integrated market, product and technology plan, linking the essential elements with drivers, need and capabilities. The roadmapping process results in an action plan to develop or acquire technologies, close gaps, and monitor risks during development. A cross-functional team owns its roadmap and revisits it periodically to adapt to market, competitive or technological changes.

- The product-technology roadmap is organized into three main sections: market, product and technology. Each presents a high-level view of strategy from that perspective, but they are not merely condensed versions. A fourth section lays out the action plan and risks identified by team.
- The roadmap organized the product-technology program by showing the critical few items in priority order. It focuses attention by stating that the most vital technology areas, supporting the critical few product attributes that are most important to target markets.
- The priorities in each section are glued together with a common set of drivers, chosen by the analysis and insight of the roadmap team. The roadmap brings a view of the external landscape (competitors, competitive products and alternative technologies) over the same time horizon as internal plans.

The market section of the roadmap defines the market segments the team wishes to target in terms of size and growth and prioritized customer needs. This section lays out the competitive landscape, presenting an analysis of key competitors' strength and weaknesses.

- (Competitive assessment) Typically, this section will consider a selected few leading competitors addressing the same market space. The assessment includes such basic information as: 1) current and announced products, 2) market share, 3) core strengths and weaknesses of each firm, 4) competitive strategy for this market, and 5) competitive responses.
 - The most difficult, but most vital, of these items is understanding each competitor's strategy. Their competitive strategy suggests future competitive objectives. Firms will exploit their core strengths and focus on markets where they have strong customers and an installed base of products. Market share, manufacturing and distribution channels, in-house technology assets, and partners suggest how competitors are likely to position products into the future.⁷

⁷ Experience with roadmapping teams suggest that much of the existing competitive intelligence in an organization is not predictive. It focuses on today's competitors and current products. This view is not adequate for setting technology priorities that extend beyond the next product cycle, and is blind to attack

- (Market segmentation and trends) The story of market trends involves using several market segmentation schemes, not knowing in advance which scheme will produce the insights that drive a product strategy.
 - Needs-based segmentation starts with groups of customers who have similar needs and benefits and work backward. Geography or firm type may not contain homogeneous customers in terms of their buying priorities (drivers). Segments must be meaningfully different in terms of their drivers and product requirements.
 - Other view of market trends that should be examined are competitors' share of the market over time and product share of the market over time. Cumulative sales represent an installed base of product that carries a significant switching cost for customers, locking in future business. The product strategy must consider the current installed base, especially where customer choices are constrained by in-service product.

The product section of the roadmap includes 1) the mapping of customer drivers to product drivers and trend/target plots, 2) experience curve plots and a long-term forecasts of industry pricing and cost targets, 3) the evolution of product family over time, and 4) the product evolution plan interpreting the platform roadmap.

- (Product drivers) Product drivers are identified and plotted. The observable trends of product drivers are used to set internal development targets. In particular, the team can set the long-term targets that R&D requires and that customers are often unable to see.
 - The buying priorities of market segments suggest a set of key product metrics that customers value in their purchase decisions and that are the basis of product competition. Product drivers are the tangible measures used in the marketplace to evaluate products relative to competitors.
 - The product drivers are generally shown in priority order as a series of time trend plots. Capacity may be one such driver, and the current product might lag competitors while intention is to take the lead.
 - The hazard of this section is to ignore the possibility of attack from below. New platforms that serve smaller markets can improve at a rate that overtakes current technology and disrupts the established competitive market.
- (Experience curve price forecast) The experience curve offers the long-term forecasts of industry pricing and leads to well-founded cost targets.
 - The experience curve plots the average industry price versus the cumulative volume of industry production. On the experience curve, the vertical axis must be normalized to some industry average market price per unit. The unit should have relatively constant functionality over time.
- (Product roadmap) The product roadmap shows the evolution of the product family over time -the entire platform or relationship between products in a platform. Rationalizing the product line has significant consequences for component and other technology plans.
 - One product may have to be split into two product lines to best serve the diverging interests of target markets or regions. Products may collapse into fewer platforms. The extreme right of the product roadmap can be used to present a vision of platform, perhaps discontinuous with today's product plans.
- (Product evolution plan) The product evolution plan interprets the platform roadmap. It starts with a traditional list of key features for each product release. The next step is to interpret those features in terms of their contribution to product drivers. What value does

from below by new challengers in (currently) niche markets. The intelligence may also not be specific to the market segments under consideration. The roadmap competitive assessment represents a refinement of traditional assessment and an extension of competitive assumptions into the future.

the evolving product hold for customers when they make comparisons with competitive products? A firm may know what its product will offer and why it matters to customers today, but it should also know whether the product will remain differentiated. The firm has to make assumptions about where competitors will be in the future. This requires good competitive intelligence and knowledge of competitors' strategy and capabilities.

In technology section, the technology roadmap is organized by customer/market priority and shows the critical technology. Also, the target costs are derived from the experience curve price forecasts.

- (Technology roadmap) Technology roadmap is the centerpiece of most technology-product roadmaps, and is dense with information. Its novelty and value lie in the way that the technology program is represented. Technology changes are not merely shown as a time evolution, but are also linked with product strategy.
 - The roadmap is organized by priority and only the technologies that significantly support the product drivers are shown. Most R&D participants find it refreshing to think of technology as a strategy.
 - Technology roadmapping starts by listing the key technology areas grouped by product driver in a spreadsheet. List currently available technologies at the start of each row, and identify future technology changeovers as far as planned. Leave blank space, question marks or multiple alternatives where nothing is decided. The vision column is useful for showing potentially disruptive technologies to begin monitoring or investigating.
 - On the roadmap, start and end points typically represent when a technology or capability will be implemented in the product. It is a marketplace view. The development interval (which precedes availability) is not shown here, although it can be in a separate document. The positions must line up with capabilities shown on the platform roadmap and the product evolution plan.
 - Within each bar on the technology roadmap, the color, shape and typeface can carry special meaning. Color may be used to show funding status; shape can represent a source of technology; typeface is useful for indicating staffing or other planning status.
 - The technology roadmap contains a forward-looking assessment of each technology area. If the importance of a given technology area is changing over time relative to others, this is shown using current (C) and future (F) markers on a high-low scale. Similarly, the firm's competitive position is shown today and projected out on a scale of lead-lag. Movement along either scale suggests a changing investment level and becomes the highlight for an executive summary of technology.
 - Some firms choose to list all technology programs and also indicate the internal development interval. The technology roadmap then becomes a vehicle for making all funding decisions and an inventory for project management purposes. Its management is burdensome, if not impractical, without the use of more sophisticated tools and administrative support.
- (Forward costing) The forecasted cost can track the targets from the experience curve. This exercise can force hard decisions about performance and feature reductions to meet cost targets, treating the cost issue at the system level rather than feature by feature.

Summary/Action Plan

- (Strategic summary) The objective of strategic summary is to define the few highest-priority technologies and identify the action plans for their development. It is an executive view of the technology roadmap, telling a concise story of where development resources are creating vital market differentiation.
 - The format can include a statement of market and product strategy, followed by a set of time-lines for a few key technologies. Each timeline would indicate project start and finish, development resources, and impact on the product drivers.

- (Risk roadmap) The risk roadmap can be used to identify major “risk events” for monitoring during execution of the roadmap. Risk can be managed to minimize the risk or to limit its impact in some way.
 - Market risks include assumptions about market growth, partners or the future competitive landscape. Market risk events are placed on the timeline where one would expect to learn the validity of key assumptions. Technical risks, such as component performance, are placed where lab tests can assess technical success. Schedule, economic and resource risks are placed where a milestone completion is expected.
 - Uncertainty on a roadmap has a meaning of how sure we are about something, and is shown as a subjective probability. Risk combines that uncertainty estimate with the consequences of failure. Consequences are shown qualitatively as minor, major or “show stopper” by color.
 - To minimize the risk or to limit its impact, one can 1) separate and move high-risk items earlier in the schedule, 2) assign or share consequences (warranty, joint development), 3) test as early as possible, and 4) work multiple alternatives at once.

Linking the Content

The product-technology roadmap makes obvious the linkage between customer priorities and the key technology areas that drive progress in those areas. It begins with divining a set of market drivers – the few most important criteria used by customers in their buying decision. Because these will depend on the choice of market segments, multiple versions of this list may be necessary.

The list of market drivers carries the market view into the product realm by translating customer priorities into product priorities. Recall that product drivers are the tangible measures used in the marketplace to evaluate the product relative to competitors. They may be the same as market drivers, or may be smaller components of those drivers.

Key technology areas are the end result of sorting out priorities and setting competitive product targets. The technologies in the roadmap show how the business and product strategies are implemented in technology.

Using Roadmap in the Corporation

Roadmap enables significant improvement in planning in a multi-business corporation. In pairs or groups, reviews of roadmaps can identify common needs and opportunities for reuse. Roadmaps enable the creation of a systematic database of product features and evolution and of technologies that may be used in multiple products. Roadmaps enable specific dialogue with customers and suppliers, helping to align the corporation with both. In cases where several products are combined to form an offer or solution, roadmaps can help synchronize and align plans. Roadmaps help focus the portfolio and business planning process of the corporation on the future and provide consistent information across the portfolio to aid in decision-making.