Knowledge and Innovation:
A Discussion Paper

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Introduction

In the mid–1990s the OECD identified the shift towards the knowledge–based economy as a defining feature of the contemporary period. The innovation system in a knowledge–based economy encompasses the key functions of: knowledge production – developing and providing new knowledge; knowledge transmission – educating and developing human resources; and knowledge transfer – disseminating knowledge and problem solving. The distinguishing feature of the knowledge–based economy is the extent to which the production, use, and distribution of knowledge and information are critical to the process of economic growth and development. Central to both the production and use of knowledge in this economy is the science system, "A country's science system takes on increased importance in a knowledge–based economy. Public research laboratories and institutions of higher education are at the core of the science system, which more broadly includes government science ministries and research councils, certain enterprises and other private bodies, and supporting infrastructure." The science system performs three key functions: 1) the development and provision of new knowledge; 2) the transmission of knowledge through the education and development of human resources; 3) the dissemination of knowledge and provision of inputs to problem-solving (OECD 1996).

In a modern industrial economy, the science system is essential for ensuring that there is adequate support for basic and long–term research. Economic theory and empirical research demonstrate that, if left to its own devices, the market will tend to underinvest in the socially optimal level of research. The reason for this is that firms expect that they will not be able to capture or appropriate the full economic benefits generated by their investment or that the technical risks associated with the new investment are greater than the firm is willing to assume (Nelson 1959; Audretsch, Bozeman, et al. 2002, 173–75).

The increased dependence of the business sector on public research institutions results from a number of critical changes in the nature of the innovation process. Under competitive pressure to introduce new products, processes and services more quickly, many large corporations have restructured their R&D operations to link research programs more tightly with product development processes. Broader–based inquiries into fundamental science have consequently been scaled back in many firms (Rosenbloom and Spencer 1996). It also corresponds with a shift to what has been labeled the 'open innovation' paradigm in which firms adopt external ideas as well as internal ideas and follow different paths for taking these ideas to market. According to Henry Chesbrough under this new paradigm, firms combine both internal and external ideas into the architectures for new products based upon their definition of a business model that will ensure the firm effectively claims some portion of the value created by the resulting product (2003).

According to the OECD, business expenditures on R&D grew rapidly between 1985 and 1999 to more than 60 per cent of total R&D expenditures, while the government share fell correspondingly. Yet industry funds relatively little basic research itself. At the same time, universities are the primary performer of basic research, but the share of university research financed directly by industry remains small. Over 70 per cent of university R&D funding in the OECD area comes from governments. Business relies increasingly on universities and public sector research as the source of innovative ideas in high technology industries as the knowledge–intensity of these industries increases. Furthermore, public sector research institutions are a critical source of the highly qualified labour that industry depends upon to undertake its own research and development activities. This trend has not been diminished by the increasing globalization of R&D and the more widespread sharing of knowledge among researchers and business in different countries. The ability to understand and use the results of basic research performed in other countries requires a strong domestic R&D capability. Countries must develop their internal scientific capabilities in order to participate in, and make use of, new knowledge developed elsewhere (OECD 2001, 62).

The recent experience in Canada stands in sharp contrast to that of most of the rest of the OECD. Canada is a relatively low performer of R&D overall, spending just 1.9 per cent of GDP on R&D, below the OECD average of 2.2 per cent and well below that of some of the top R&D spenders, such as Sweden at 4.0 per cent and Finland at 3.5 per cent. Canada's weakness in R&D spending is particularly marked in the business sector with business expenditure on R&D at 1.0 per cent, in comparison with the OECD average of 1.5 per cent and the 1.8 per cent spent in the U.S. Overall R&D spending by the private sector in Canada accounts for just 55 per cent of total R&D spending in contrast to the average of 68 per cent for all the OECD countries. Where Canada ranks higher than the OECD average is in R&D spending by the higher education sector which accounts for 0.7 per cent of the total, in contrast to the OECD average of 0.4 per cent (Expert Panel on Commercialization 2006, 26–28; OECD 2006, 86–89).

These recent shifts in the relative importance of the science system within the knowledge–based economy, and the corresponding changes that have occurred in the respective roles of the public and private sectors in performing research and development activities, underline the importance of understanding the relationship between knowledge creation and innovation. This paper surveys the current literature and summarizes the key issues and debates with respect to knowledge creation and innovation. It explores some of the key themes in the literature on the relationship between knowledge generation and its dissemination and application. It examines the relative contribution of both public and private sector research institutions and the changing relation between the respective roles played by each of these over the past two decades. It also discusses the distinctions between different typologies of research and how these relate to the process of knowledge creation. The oft referred to distinction between basic and applied research tends to gloss over a number of other important distinctions in both the nature of the research process and the process of knowledge creation.

The paper examines a number of leading empirical studies in the field on the process of knowledge creation and explores key findings about the link between knowledge creation and dissemination with respect to its implications for the innovation process. Of particular significance is the relation between different types of knowledge creation and the capacity of firms to take up and use the knowledge created in research institutions. It surveys the mechanisms by which knowledge is diffused or transferred from research institutions to firms. Of particular interest here are the research findings on the nature of knowledge flows – in particular, how knowledge flows across the institutional boundaries between knowledge generators and the adopters and users of that knowledge. It notes the important distinction between technological knowledge, or research findings, and management knowledge, or the capacity to exploit technological knowledge in a commercial setting.

Definitions of Knowledge

The concern with the nature and importance of the knowledge–based economy has given rise to a number of efforts to distinguish between different conceptions of knowledge. Drawing upon a concept originally introduced by Simon Kuznets, Joel Mokyr argues that from the perspective of technological innovation, the fundamental interest lies with 'useful' knowledge, which is primarily concerned with knowledge of natural phenomena that are relevant to the manipulation of nature for human gain, which he views as the essence of technology. Building on this relationship, he suggests that the central distinction within conceptions of useful knowledge is that between *episteme* and *techne*. The first concerns knowledge of what, or *propositional* knowledge about natural phenomena and regularities, which can then be used to create knowledge of how, or *prescriptive* knowledge which involves the creation and application of techniques. Propositional knowledge takes two forms: the first is the observation, classification, measurement and cataloging of natural phenomena, while the second concerns the establishment of regularities and principles that allow for the interpretation of observed phenomena. While science is central to this conception of propositional knowledge, it also includes a great deal of practical information about the fundamentals of nature. The expansion of propositional knowledge serves as the underlying basis for the application of techniques in the process of economic production. However, he emphasizes that,

> Progress in exploiting the existing stock of knowledge will depend first and foremost on the efficiency and cost of access to knowledge. Although knowledge is a public good in the sense that the consumption of one does not reduce that of others, the private costs of acquiring it are not negligible, in terms of time, effort and often other real resources as well (Mokyr 2002, 7).

The shift to a more knowledge–based economy embodies a number of changes in both the production and application of new scientific knowledge that have critical implications for the processes of knowledge transfer. One of the most significant of these changes involves the relation between the codified and tacit dimensions of knowledge. The dramatic expansion of the higher education sector and the increased funding for research associated with the postwar contract for science has generated substantial increases in scientific and research output which largely take the form of codified knowledge, transmitted relatively easily between researchers through published scientific papers and formal presentations. But as the stock of scientific knowledge has grown and become more widely accessible through electronic and other means, the relative economic value of that knowledge is diminished by its sheer abundance. Often access to the key elements of the knowledge base depends upon the second or tacit dimension.

Following the work of Michael Polanyi, tacit knowledge refers to knowledge or insights which individuals acquire in the course of their scientific work that is ill–defined or uncodified and that they themselves cannot articulate fully. It is highly subjective and often varies from person to person (Polanyi 1967). Often this knowledge is deeply embedded in the social and institutional procedures of the context in which it is created. As Senker points out, scientific culture has tended to minimize the importance of skills and tacit knowledge for the research enterprise, yet "while tacit knowledge can be possessed by itself, explicit knowledge must rely on being tacitly understood and applied. Hence all knowledge is either tacit or rooted in tacit knowledge," (Senker 1995, 426). The context of a university laboratory is strongly shaped by the background knowledge and skills of its researchers, as well as their goals, the instruments, materials, other physical infrastructure, and laboratory procedures that they use. Firms interested in accessing this knowledge base must be concerned with both its tacit and explicit dimensions.

Data, Information, Knowledge

Another important distinction in the literature draws its inspiration from a classical discussion in information theory. According to David and Foray, data refers to the elementary units in communication and message transmission that provide clear bits of information (transmitted as 0's and 1's in digital technologies); information then consists of the same data in a structured format that is ready for transmission and processing in the more sophisticated programs that analyze and use the data. Knowledge, however, involves a higher order of conceptual and factual interpretation that depends on the ability of human agents to interpret and understand the data and information generated and transmitted through the enhanced power of information and communication technologies (1995, 26). Knowledge, in contrast to data and information, involves a critical degree of discernment, or rather the ability to distinguish those pieces which may be technologically or economically valuable. Knowledge is also cumulative; the ability to understand and appreciate certain pieces of knowledge may depend fundamentally on prior learning, "If we have no previous knowledge of a particular subject, it is usually difficult if not impossible to make sense of data related to that subject. Conversely, the more we know about a subject, the better able we are to evaluate and use new data about it" (Burton–Jones 1999, 5).

A great deal of confusion arises in the literature over exactly what it is that firms draw from public research – information or knowledge (Salter and Martin 2001). In many innovation surveys, these terms are used interchangeably and, for many firms, the distinction between information and knowledge is an academic one. However, the difference between information and knowledge is important for understanding the role played by publicly–funded basic research. The traditional justification for government–funded basic research relied on the public good qualities of information (Nelson 1959; Arrow 1962). However, the evidence deduced from the relevant studies indicates that what firms draw upon is not information per se, but knowledge. Understanding information almost always requires knowledge. Conventional economic approaches to the issue of knowledge flows frequently treat knowledge itself as a universally available commodity, virtually as a free public good, and knowledge transfer as a commercial and legal transaction between clearly defined agents.

But as Mokyr observed above, this perspective flies in the face of evidence from a growing number of sources that successful knowledge transfer depends on the type of knowledge involved, and how it is employed. Individuals and organizations require a complex set of skills and must expend considerable resources both to absorb and understand information. The tacit component of scientific knowledge, especially new scientific discoveries in cutting edge fields such as biotechnology, makes direct access to the scientists who made the discovery critical. The combination of potential commercial value to the discovery combined with its unique and tacit components gives the discovery a *natural excludability*. "Tacit knowledge can be view as at least partially rivalrous and excludable information and thus 'appropriable' as long as it remains difficult . . . to learn it (Zucker, Darby, et al., 2002, 141). Information only becomes accessible knowledge (and therefore valuable and useful) when potential users have access to its underlying tacit dimension, as well as the skills and capabilities to make sense of it.

This emphasis on the skills and capabilities required to absorb knowledge underscores the centrality of learning for the innovative process. The potential flow of information to the firm has become so rich that the key challenge it faces is how and where to draw upon that information flow. Lundvall and Johnson, among others, argue that the knowledge frontier is moving so rapidly that access to, or control over, specific knowledge assets affords merely a fleeting competitive advantage. It may be more appropriate to describe the emerging paradigm as that of a *learning economy*, rather than a *knowledge–based* one. The emphasis on learning processes arises from a combination of factors: the need to draw upon a diversity of knowledge sources, steep increases in the cost of new product development, and shorter product life cycles.

Learning in this sense refers to the building of new competencies and the acquisition of new skills, not just gaining access to information or codified scientific knowledge. In tandem with this development, forms of knowledge that cannot be codified and transmitted electronically (tacit knowledge) increase in value, along with the ability to acquire and assess both codified and tacit forms of knowledge, in other words, the capacity for learning (Lundvall and Johnson 1994).

Differential Knowledge Bases

A further distinction has recently been introduced in the literature between different types of knowledge bases that underlie the innovation process in different industrial sectors. Recent analyses of this question have adopted the distinction between 'analytical' and 'synthetic' knowledge bases (Laestadius 1998; Asheim and Gertler 2005). A *synthetic* knowledge base dominates industrial settings where innovation takes place mainly through the application or novel combinations of existing knowledge. Innovation in such industries tends to be driven by the need to solve specific problems arising in the interaction with clients and suppliers. Classic industry examples come from sectors within advanced industrial engineering (such as the development of specialized machinery). Tacit knowledge sharing among firms along the supply chain or between engineers in different firms can constitute an important source of innovation. In such sectors, research is less important than development. University–industry linkages play an important role, but they tend to take the form of applied problem solving rather than basic research. The most prevalent form of innovative activity might be described as incremental product or process development to solve technological or production problems presented by customers. Knowledge tends to be created inductively rather than deductively, through a process of testing, experimentation, and simulation. While the knowledge embodied in technical solutions is at least partially codified, tacit knowledge tends to be more important, since shop floor or office experience, on–the–job training, and learning by doing, using and interacting are crucial to knowledge generation. Much of this knowledge resides in concrete know–how, craft and practical skill.

In contrast, an *analytical* knowledge base refers to industrial settings which rely upon scientific knowledge and where the production process draws upon sources of knowledge that make extensive use of cognitive and rational models. Prime examples of industrial sectors that rely upon this type of knowledge base are found in information technology and biotechnology. Both basic and applied research, as well as more formal development of products and processes, constitutes the central activities of this type of knowledge production. While firms in these sectors need their own R&D departments to interpret and select from the vast sources of codified knowledge available to them, they tend to draw upon research results from the higher education system or national laboratories as a source for potential innovations or product modifications.

University–industry linkages are an essential part of the knowledge transfer for sectors that rely upon this type of knowledge base. It follows that formal or codified sources of knowledge play a greater role in these settings. This does not, however, mean that tacit knowledge is irrelevant, as detailed studies of the geography of innovation confirm that analytical knowledge flows are highly ‘sticky’ and the outputs of research institutes and universities are often applied by firms in close geographic proximity to the research centre.

Just as all innovation processes make use of both tacit and codified forms of knowledge, so too do many industries draw upon *both* synthetic and analytical knowledge bases. One example is the medical devices and technologies sector, in which product development draws upon knowledge from a wide range of fields including bioscience, ICT, software, advanced materials, nanotechnology, and mechanical engineering (Gertler and Wolfe 2006). Thus it is appropriate to locate individual industries along a spectrum between purely analytical and synthetic knowledge bases, with many occupying an intermediate position along the continuum.

Innovation

Both traditional neo–classical models and more recent evolutionary, or neo–Schumpeterian, models in economics appreciate the link between technological innovation and long–term economic growth. Innovation is understood here simply as the process of creating something new. Innovations may include new products or processes, as well as the introduction of new organizational methods that increase the value of economic activity (Audretsch, Bozeman, et al. 2002, 156–57). In the neoclassical perspective, innovation is viewed largely as an exogenous variable, operating outside of the properties of their general equilibrium models (Nelson 1994). Recent studies of the innovation process highlight a number of facts that do not fit comfortably into the neo–classical framework. The focus in neo–classical economics is the static efficiency of an economy in allocating scarce resources at a single point in time, rather than its dynamic efficiency in generating increasing resources over time. Its assumptions about the presumed rationality of economic agents, the easily codified and undifferentiated nature of technical knowledge, the relatively free access to knowledge by firms, and the largely symmetrical behaviour of identical firms in the innovation process, are challenged in the body of literature associated with evolutionary economics (Boyer 1993; Metcalfe 1997).

The evolutionary approach to innovation and economic growth emphasizes the complex, uncertain and interdependent nature of technological change. Central to this conception of the process of innovation is the role of firms and entrepreneurs. These individual economic agents and organizations are endowed with access to different knowledge bases, different sets of organization and technological capabilities and even different risk profiles. They are confronted with a high degree of market uncertainty in which the potential for success or failure of a new innovation is unpredictable at best. In this context, the process of innovation emerges out of the interactions between the cumulative increase in the knowledge base and the technological capabilities of firms in the development and diffusion of new technologies. “The process of scientific and technological advance, in this view, is seen . . . to be a phenomenon of ‘organized complexity that results in cumulative and irreversibly long–run change, in which successive events are uncertain, highly contingent and difficult to forecast (David and Foray 1995, 17).

Different Dimensions of Innovation

Analyses of the innovation process identify several different typologies of innovation. The recently revised *Oslo Manual* of the OECD differentiates between four different types of innovations that are now studied in innovation surveys: *product* innovation involves the introduction of a good or service that is entirely new or has significantly improved characteristics or uses; *process* innovation refers to the adoption of a new or significantly improved method of production of method of delivering a service; *organizational* innovations include a new method of organizing the firm's business practices, the organization of its workplace, or its relations with other firms or outside organizations; and finally *marketing* innovations include new developments in the design or packaging of the firm's products, the channels for distributing products to the marketplace, their promotion and their pricing. All four types of innovation involve a degree of novelty, whether the innovation being introduced is the first in the world or merely new to the firm itself (OECD 2005).

The distinction between analytic and synthetic knowledge bases introduced in the previous section has an interesting parallel in the typology recently introduced by Jensen et al. between two different modes of innovation. They argue that the mode of innovation varies significantly depending on both the industries in which the innovation occurs and the knowledge bases from which it draws. They distinguish between a science, technology and innovation mode (STI) that draws primarily on the basis of formal research and codified knowledge and a mode that involves doing, using and interacting (DUI) that draws primarily upon experience–based learning (Jensen, Johnson, et al. 2004).

Innovation in the STI mode draws substantially upon existing bodies of codified knowledge, both those involved in previous research undertaken by the firm, as well as research drawn from external sources. Increasingly, this mode of innovation is team–based and draws upon discrete pieces of research whose results are combined into an overall product. The end result requires the transfer of results in a codified form both within the organization and across the boundaries of cooperating organizations that contributed to the innovation. In contrast, the DUI mode depends upon an innovation process where the knowledge required is much more tacit, involves a process of learning–by–interacting and is much more local in nature. The DUI mode of innovation frequently builds upon the skills and knowledge of employees throughout the firm, not just in its research department. The increasingly complex nature of innovation within the DUI mode requires close cooperation between teams within the organization and its success frequently depends upon the effectiveness with which it is embedded in organizational routines. Both the diversity of knowledge bases that firms draw upon and the different modes by which they innovate reinforce the point that the 'knowledge–based economy' consists of many 'pool's of knowledge accessible to different knowledge 'communities' within the broader economy (Lundvall 2006).

Another typology distinguishes between innovations according to the disruptive nature of the new technology, or the degree of dislocation created in the marketplace. Most students of technology adopt a simple two–fold classification scheme that distinguishes between incremental (or minor) innovations and radical or (major) innovations (Freeman 1991, 305; Freeman 1994, 474). Incremental innovations happen as a regular part of economic activity throughout the various branches of industry. This type of change frequently occurs in the process of 'learning by doing' or 'learning by using' rather than as a result of consciously directed research and development efforts in the firm. They emerge out of the interaction of engineers and production designers involved in the manufacture of a product or the provision of a service, or may arise from suggestions made by the end users of the firms' products. Incremental innovations have a limited, but significant impact on overall economic growth and productivity. They may result in significant improvements in the quality or market appeal of specific products, but their net economic effects are limited to the existing mix of products, services or processes. Although such innovations are important for continuous improvements in productivity, they are not of a sufficient magnitude in themselves to occasion significant adjustment problems for the economy as a whole (Freeman 1991: 305–07).

The second order of change consists of radical innovations. These represent irregular developments in the process of innovation and result from the introduction of unique products and processes. They are increasingly the outcome of consciously directed research and development efforts in university or government laboratories and in the firm. The development of a radical innovation may result in the opening of new markets for the original product or may contribute to radically altering the cost and competitive structure of an industry through the introduction of radical process innovations. Innovations of this magnitude exert a much broader effect on overall levels of economic activity, although the extent of the effect depends upon the speed at which the new innovation is diffused throughout the economy. Radical innovations may lead to a significant degree of structural change in the economy arising from the emergence of entirely new branches of industry. They may also cause significant structural dislocation because of the new types of capital equipment or the new type of skills required to supply the product or service (Freeman 1991, 305-07).

Significant improvements in productivity are more likely to be associated with the phase of incremental improvements in a radical innovation than with the early introduction phase of the innovation itself. In the early startup phase of a radical innovation, both the extent of adoption and the scale of production are too small to realize the full scale economies that may eventually arise. In this early phase, the supply of materials and components for the new product is not yet standardized, the design, or architecture, of the product or process is still variable and the network externalities discussed above have yet to be achieved. The more dramatic productivity gains and economic benefits of a radical innovation begin to be realized as it diffuses more widely in the context of a cluster of related innovations. These clusters are described as 'constellations' of innovations that are systematically linked to each other in both technological and economic terms (Freeman, 1991: 307).

Historians of technological change note that the introduction of these constellations of innovations takes place in a highly uneven fashion. In his study of the diffusion of electrical generation and transmission systems in the early twentieth century, Thomas Hughes highlights the importance of salients and reverse salients. Salients are those parts of an emerging technological system that develop faster and are out in front of the system because they are more efficient or more economical than other parts. Reverse salients are those components that lag behind the pace of development because they do not work effectively or efficiently with the more advanced components of the system. The presence of salients and reverse salients stimulates innovative activity within the overall technology system as their uneven pace of development highlights critical problems for engineers to solve (Hughes 1992). The impact of these constellations of innovations tends to be far-reaching, affecting several branches of the economy at once and possibly generating entirely new branches of economic activity; but as Paul David also notes, realization of the full benefits of the new technology system can stretch out over several decades, as complementary components of the system are put in place the corresponding organizational innovations are adopted and diffused throughout the economy (David 1991). This also helps explain the so–called productivity paradox of the early 1990s where leading economists, such as Simon Kuznets, puzzled over why “we see computers everywhere except in the productivity statistics”. It was the widespread diffusion of a ‘constellation’ of interrelated innovations and the gradual diffusion of those innovations from the producing sectors of the economy to the adopting and using sectors that generated the substantive increases in productivity that Kuznets was expecting (Oliner and Sichel 2000; Jorgenson 2001; Sharpe 2005).

Firm–Based Innovation

The innovation process within the firm is characterized by uncertainty and develops through a variety of heuristic search techniques. Firms or organizations do not know what their research efforts will produce at the outset. Different organizations and different people usually disagree over how to conduct the search. This is the source of the organizational complexity and diversity that characterizes the innovation process. Given the uncertain nature of technological innovation, firms or organizations rely upon their existing knowledge base in their efforts to solve new technological problems. The firm–specific knowledge base is the set of information inputs, knowledge and capabilities that they use to support their production activities. It is highly structured and forms part of the cumulative memory of the organization. It is both codified, as in the case of scientific knowledge, and tacit (Nelson and Winter 1982, 76–82; Dosi 1988, 1126; Saviotti and Metcalfe 1991, 9–10).

According to Polanyi, the tacit component of knowledge is highly subjective and often varies from person to person. However, individuals or groups working together for the same firm or organization often develop a common base of tacit knowledge in the course of their research and production activities. This common knowledge base knowledge arises from the internal procedures and the heuristic techniques developed by firms in the process of applying new scientific knowledge to improve existing products and processes or develop new ones. Thus, it resides in organizational routines developed by the firm and is operationalized in the process of exercising that routine, much the way an individual remembers the tacit dimension of their skills by exercising them. “Information is actually stored primarily in the memories of the members of the organization, in which reside all the knowledge, articulable and tacit, that constitutes their individual skills and routines . . . ” (Nelson and Winter 1982, 104).

Effective innovation is tied to every phase of activity within the firm and involves all four categories identified by the OECD – product, process, organizational and marketing. Different innovations can emerge as easily from the production process as from the research laboratory. Especially in the DUI mode, but often in the STI mode as well, technical knowledge does not exist not just in the designs and blueprints of scientists and engineers, it includes a complex set of skills, knowledge and techniques shared by many members of the enterprise. Innovation arising from using and interacting frequently draws upon knowledge and insights gained from marketing and sales staff. Furthermore, this source of technological knowledge and insight is cumulative and dynamic. Insights gained by scientists, engineers and production workers in the design and manufacture of one product may transfer into significant new insights and comparative advantages useful in the production of others as well.

Starting from their existing base of knowledge, firms or organizations employ a variety of search activities, routines and decision rules to guide their innovation efforts. The particular knowledge base of the firm, and the specific organizational practices associated with that knowledge base, contribute to what is termed the 'core competence' of the firm, in other words, the things that it is good at. In the evolutionary perspective, the varied nature of this 'core competence' establishes the degree of variety, or asymmetry, which exists among competing firms. "Core competencies are the collective learning in the organization, especially how to coordinate diverse production skills and integrate multiple streams of technologies" (Prahalad and Hamel 1990, 82). The extent to which firms rely on established routines and decision rules in their research efforts depends, in part, on the overall results of their past search activities and their capacity to learn from that experience. In periods of relative economic stability the incentives to modify their established practices may be minimal. However, in periods of major economic change and emerging new technologies, the very survival of the firm depends upon its dynamic capability to alter these routines in response to the increased uncertainty caused by the changes (Dosi, 1988: 1131–33).

Despite the dynamic and unpredictable nature of the innovation process, it invariably develops along ordered paths defined by the economic and technical properties of past discoveries. This is one of its central paradoxes. The early stages in the development and diffusion of new technologies are marked by an increase in diversity, in terms of the range of products, processes and services associated with the technology. In this early stage of the technology, the design is still variable and there is no certainty about which products will dominate the market. The degree of diversity is further compounded by differences that may exist across national markets. However, the cumulative and irreversible character of technological change results from the tendency for markets to lock into particular technologies as their use becomes more widespread. In other words, history matters; additions to technological knowledge are by nature cumulative and the ability to exploit new knowledge depends on the technological capabilities that already exist (Rosenberg 1994, 15).

Technologies become more useful and more attractive to end users as this occurs. This phenomenon is referred to in the literature as that of increasing returns. It refers to the self–reinforcing aspect of the process of technological change. According to Brian Arthur, the phenomenon of 'increasing returns to adoption' arises from five different sources: the more widely a technology is used, the more is learned about how to improve it (learning by using); the greater the number of users of a particular technology, the more widely available it becomes and the greater the advantage of going along with the existing network of users (network externalities); the greater the number of units produced, the more likely that the cost of the technology will fall (scale economies); the more widely used a technology, the better known it becomes and the less risky to adopt for new users (informational returns); the more widely a technology is adopted, the greater the number of sub–technologies, or add–ons that are developed for use with it (technological interrelatedness) (Arthur 1988, 591; David 1997).

In many areas of economic activity, the impact of positive feedback amplifies the effects of small economic shifts. The presence of positive feedbacks and the phenomenon of increasing returns make possible many equilibrium points, rather than the single equilibrium point posited by the neoclassical model based on the notion of diminishing marginal returns. There is no guarantee that the particular economic outcome selected from among many competing alternatives will necessarily be the best one. Once a set of chance economic events or a series of small historical accidents push the trajectory of technological development onto a certain path, it gains a clear economic lead, regardless of the purely technical advantages of the competing alternatives. The initial advantage may be acquired through small, seemingly insignificant events and its dominance may be based purely on the fact that it was the first to gain wider acceptance in the marketplace, that many supplying businesses, distribution networks, supporting technologies and users, plus a large community of users and developers, all converged on its design. However, once it clearly establishes a lead, further technological development is 'locked into' the trajectory or path established by the dominant products. Competing technologies that were available at the outset quickly fade from view and become little more than historical footnotes (Arthur 1988).

Research and Innovation

As we have seen above, the innovation process is intimately related to the knowledge bases from which it draws, but the relationship is far more complex and varied than frequently depicted. As noted at the outset, there is a widespread conviction that the accelerating rate of innovation which characterizes the knowledge–based economy is closely linked to increases in the amount of basic scientific research and the consequent growth in the stock of knowledge. However, failure to appreciate the complexity of the relationship can lead to an overly simplistic understanding of the connection and naive policy conclusions. Early work on the economics of knowledge provided a theoretical justification for public support for basic research. The traditional view premised this support on the potential for market failure and for external economies to be generated by higher levels of research spending. Richard Nelson's work (1959) suggested that the rationale for government support of basic research was the existence of external economies in the form of multiple potential applications and new combinations of knowledge, which given the conditions of uncertainty, would not be fully explored or exploited, if the business firms undertaking the basic research tried to capture all the benefits for themselves, either through the maintenance of secrecy or the enforcement of property rights. The subsequent and complementary paper by Kenneth Arrow (1962) underlined the informational properties of scientific knowledge, suggesting that this knowledge is non–rival and non–excludable. Non–rival means that others can use the knowledge without detracting from the knowledge of the producers and non–excludable means that other firms cannot be stopped from using the information. In this sense, the main product arising from publicly supported scientific research is seen to be economically useful information, freely available to all firms in a non–exclusionary fashion.

By increasing public support for basic research, it was deemed possible to expand the pool of economically useful information available for industrial firms to draw upon. This information is seen to be durable, freely available, and costless to use. Government funding overcomes the reluctance of firms to finance their own research (to a socially optimal extent) due to its non-appropriability; new packets of economically useful information are created; and the distribution of this information is enhanced through the tradition of public disclosure in science. In contrast, the evolutionary perspective suggests that an approach based purely on the notion of market failure provides insufficient justification for public intervention in this sphere. Stan Metcalfe suggests that in reality future markets for prospective benefits derived from potential innovations do not exist in a substantial enough sense for individuals to trade risks and determine appropriate prices. This inability to establish an appropriate price structure creates numerous distortions in the market for future benefits from scientific research. Instead he argues that in the evolutionary approach the focus of attention ceases to be "market failure per se and instead becomes the enhancement of competitive performance and the promotion of structural change" (Metcalfe 1995).

A critical difference between the two perspectives is their conception of the origins, nature and accessibility of technical knowledge. In the traditional approach, technology is seen as information that is generally applicable, easy to reproduce and reuse, and is not always distinguished from the general base of scientific knowledge. Firms can produce and use innovations by drawing upon a freely available pool of technological knowledge (Dosi, 1988: 1130). In the evolutionary view, firms have no direct and costless access to this kind of knowledge, other than to that which they are currently using,

> . . . technology is not a free good, but involves specific, often idiosyncratic, partly appropriable knowledge which is accumulated over time through specific learning processes, whose directions partly depend on firm–specific knowledge and on the technologies already in use (Dosi and Orsenigo 1988, 16).

One issue underlying this tension between the traditional and evolutionary perspectives concerns the distinction between basic and applied research – and which sector of society should assume primary responsibility for the performance of each. In its annual report in 1952, the National Science Foundation defined the relationship between the two as a linear model involving the progression through a technological sequence leading eventually to product development, the final stage involving the systematic adoption of research findings into useful materials, devices, systems, methods and processes (Stokes 1997). Theoretical support for this model, and an underlying justification for government funding, was drawn from the work of Nelson and Arrow discussed above. This economic rationale provided strong support for the postwar social contract for science which underlay the so–called linear model of innovation: knowledge transfer became a two–step process in which the science system first produced and disseminated potentially useful knowledge and then firms put that knowledge to work (Pavitt 2001; Martin 2003).

An alternative perspective, more closely aligned with the evolutionary approach, argues that positing an absolute dichotomy between basic and applied research misapprehends the fundamental aspects of scientific research. Much scientific investigation, in the biomedical and other areas of science, is driven by concerns for both the expansion of knowledge and its potential use (Rosenberg and Nelson 1996). Donald Stokes argues that research needs to be conceived as consisting of more than a one dimensional plane. The research enterprise consists of two dimensions: the first classifies it by the degree to which research seeks to expand the frontiers of fundamental understanding; the second classifies it according to the degree to which it is inspired by considerations of use. The relationship between basic and applied research moves along parallel trajectories that interact with each other, but maintain their autonomy. Science often proceeds to a higher level of understanding with little regard to the implications for technological improvement, while much technological innovation involves narrowly targeted engineering or design changes, based on existing or well–understood science. "But each of these trajectories is at times strongly influenced by the other, and this influence can move in either direction, with *use–inspired basic research* often cast in the linking role" (emphasis added) (1997: 87).

Lewis Branscomb argues in a similar fashion that much of what is classified as applied research in official statistics is really need–driven creative research into new kinds of materials, new processes or ways of exploring or measuring and new ways of doing and making things. He calls this ***basic technological research*** that involves work that creates new capabilities, as well as new understanding that goes beyond narrow problem-solving or product development (Branscomb 1998). Both use–inspired basic research and basic technology research may potentially lead to commercializable products, but the path to this end is fraught with difficulty. Only a small portion of the research conducted within universities has immediately commercializable potential. The effective exploitation of that knowledge depends on the capacity of firms to absorb and apply research results, not all of which is transmitted in a codified form.

Over the years, a number of studies have attempted to estimate the social returns to investments in basic research, relying on the relationship between science and innovation implicit in the linear model. Econometricians have made several attempts to calculate the portion of economic growth that can be accounted for by technological innovation, in general, and government–funded scientific research, in particular. Econometric attempts to account for the role of technology adopt the technique of 'growth accounting', which focuses on the contributions of various factors of production, such as labour and capital, to economic development.

Most studies of the social and private rate of return to publicly funded research stress the positive rates of return. The difference between the two rates of return stems from the fact that the results of a specific research project, or even a firm–based innovation, do not accrue entirely to one firm. The scientific benefit of a piece of basic research may be appropriated by more than one firm, or imitators may flood the market and replicate the new product or technology developed by a specific firm, without having to shoulder the substantial cost of the original research. However, by lowering the costs incurred in developing new technologies or products through investing in the inputs, publicly funded projects generate a broader social benefit. Because of this difference, estimates of the private rate of return to research and development tend to be lower than those for the social rate of return (Mansfield 1995). This difference underscores the necessity of estimating the social rates of return for investments in scientific research, despite the methodological problems involved. Estimates of social and private rates of return to privately funded R&D vary between 20 and 50 per cent (Griliches 1995, 56).[1] One line of research into the benefits of publicly–funded research has investigated the spillovers from government funding to other types of activities, such as industrial R&D. The existence of these spillovers augments the productivity of one firm or industry by expanding the general pool of knowledge available to it. "[I]t is assumed that the level of productivity achieved by one firm or industry depends not only on its own research efforts but also on the general pool of knowledge accessible to it" (Griliches 1995, p. 63).

Mansfield has also made an interesting contribution to the attempts to measure the benefits of basic research. His studies focus on recent academic research, i.e. research occurring within fifteen years of the commercialization of whatever innovation is being considered (Mansfield 1991). Based on a sample of 75 major American firms in seven manufacturing industries (information processing, electrical equipment, chemicals, instruments, pharmaceuticals, and metals and oils), he obtained estimates from R&D managers about what proportion of the firm's

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[1]A more detailed discussion of the various methods used to estimate the social and private rates of return to investments in R&D and the specific results of individual studies can be found in (Wolfe and Salter 1997).

products and processes over a ten year period could not have occurred without the results of the academic research. The survey results suggest that about 11 per cent of these firms' new products and 9 per cent of their new processes could not have been developed, in the absence of the academic research, without substantial delay. These percentages of products and processes accounted for 3 per cent and 1 per cent of sales respectively for the firms concerned.

Mansfield also measured those firms' products and processes that were developed with 'substantial aid' from recent research (last fifteen years). He suggests that 2.1 per cent of sales for new products and 1.6 per cent of new processes would have been lost in the absence of the academic research. Mansfield concluded that the economic benefits of academic research are spread over seven years. By the eighth year, the firms themselves would have realized such research. These benefits accrue only to American firms and they provide benefits to only the innovating firm. Using these figures, Mansfield estimates the benefit from academic research to be 28 per cent. The figure represents "the present value of the stream of benefits associated with the research equal to costs. (In other words, it is the annual profit rate on society's investment in academic research)" (Mansfield, 1991, 10; cf. also 1995).

In a more recent study conducted in Germany, Beise and Stahl replicated Mansfield's methodology using a larger sample of firms to assess the effects of publicly funded research at universities, polytechnics and federal research laboratories on industry innovations. In surveying 2300 companies, they found that less than one tenth of product– or process–innovating firms introduced innovations between 1993 and 1995 that would not have been developed without the benefit of public research. These new products amount to approximately five per cent of all new product sales. Firms cited universities with publicly supported innovations as the most important source, although publicly financed laboratories received almost as many citations, while large federal research centres lagged behind. The primary variable determining the success of technology transfer was the degree of movement of qualified academics between the research centres and industry. Firms also tended to cite research institutions located close to the firm and the firm's own R&D activities as support in the ability to absorb the findings of public research and turn them into innovations (two points discussed in more detail below). Additionally, firms with high R&D intensities cited remote public research institutes more frequently than less R&D–intensive firms (Beise and Stahl 1999).

Another approach to evaluating the benefits of publicly–funded scientific research is found in the work of Narin et al. using a citation analysis of the US patent data base. They measured the academic citations in US patents to conclude that over a seven year period, there was a tripling in the knowledge flow from US science to US industry. Based on an analysis of the front pages of over 400,000 US patents issued between 1987 and 1994, they traced the 430,000 non–patent citations contained in these patents. Of these 430,000 non–patent citations, 175,000 were references to papers published in the 4000 journals covered by the Science Citation Index (SCI). A library search of 42,000 matched papers with at least one US author. They located these papers and were able to determine the sources of US and foreign research support acknowledged in the papers. They demonstrated a secular increase across countries (UK, France, German, and Japan) in citations of science in patent records. Patents also tend to cite their own country's papers two or three times more often than expected, when adjusted for the number of a country's scientific publications. Large US funding agencies were also highly listed as sources of funding for the citations included in the patents. Narin et al. suggest that this indicates a strong reliance by US industry on the scientific results of research funded by the public sector (Narin, Hamilton, et al. 1997).

Subsequent research found that this phenomenon was even more notable for biotechnology than for other areas of scientific research. The research examined the patents that a group of 119 US biotechnology companies had acquired between 1993 and 1997. They again identified the non-patent references as they appeared on the front pages of the patents and isolated those that could be matched to papers cited in the journals covered by the Science Citation Index. Of the 11,961 citations for which they could identify at least one US author, at least 71.6 per cent were to papers originating solely at public science institutions (universities, medical schools, research institutes) and another 11.9 per cent cited joint efforts by public and private institutions. They conclude, "the biotechnology industry is even more public science linked than other industries". They also explored the country of origin of the cited papers and found that 64 per cent of the total citations (including those without a US author) were of US origin, with the next highest country of origin being the UK. "The results suggest that the national bias is stronger in biotechnology than in the overall US industrial base" (McMillan, Narin, et al. 2000).

Another substantial body of research on the impact of government investments in research has been undertaken by the US National Institute of Standards and Technology. NIST has been conducting economic impact studies on a regular basis since 1992, as a means to: 1) provide management with information on the nature and magnitude of NIST research projects; 2) inform the policy and budget communities of the economic returns to society from NIST projects; and 3) fulfill the reporting requirements of the US Government Performance and Results Act (GPRA) for performance evaluation data. In general, economic impact measures such as the benefit–cost ratio (BCR) and social rate of return (SRR) provide useful and informative outcome data for the agency. However, NIST regards it as impossible to measure *all* of the downstream effects of their research and services. Most of NIST's impact analyses have focused on firms and/or industries in the supply chain that benefit most directly from their output. Collectively, the entire set of economic impact studies conducted demonstrates that the rates of return on NIST infratechnologies consistently match or exceed rates of return to private investment in technology. In addition, these studies and other economic analyses suggest that public investment in infratechnologies complements private investment in proprietary technologies, which in turn generates higher rates of economic growth (Tassey 1999).

The difficulties and challenges in effectively determining the economic benefits derived from public and private investments in basic research are strongly underlined in the most recent review of the literature by the staff of the Science Policy Research Unit (SPRU) at the University of Sussex in their report to the UK Office of Science and Technology. Their review identified a number of limitations that arise from using primarily econometric techniques based on the linear model of innovation and suggested that patterns of interaction between basic research and the innovation process are often too complex to be captured by these techniques:

- They do not allow for the fact that technology often leads science: basic science is frequently not the source for new ideas, but is used to understand new technologies and complete new projects;
- They overlook the spillovers and benefits from the scientific research conducted by industry, as well as the capabilities and capacities at the industry end of the relationship;

- They underestimate the significant differences between industrial sectors and the body of academic research that highlights the different ways in which, and differing degrees to which, industry makes use of scientific knowledge;
- They ignore the many 'non-linear' channels through which knowledge flows in the university-industry relationship (SPRU 2001).

Thus, while the econometric studies and evaluation methodologies reviewed above demonstrate a clear link between the economic benefits of investments in basic research, including public support for basic research, the limitations of the methodologies themselves fail to capture the full dynamics and interplay of the way in which these investments in research impact upon industrial innovation. To do so requires a better understanding of the institutional context within which the research is performed and the way in which that context has changed in recent decades.

The Role of Universities

By all accounts universities occupy a central place in the science system of the knowledge–based economy. Among the key contributions that research universities make to economic growth are the performance of research and the training of highly qualified personnel, both of which are sustained by networks and social interaction. Universities act as a primary source of 'knowledge workers', as well as a primary source of the key factor of production – knowledge itself. These points were strongly emphasized in a recent report prepared for the Ontario government,

> Basic university research advances fundamental understanding and provides a substantial rate of economic return through the preparation of a highly skilled workforce, contributing to the foundation of many new technologies, attracting long-term foreign (and domestic) investment, supporting new company development and entrepreneurial companies and participating in global networks. Government funding is the primary support for virtually all investment in truly frontier university research (Munroe–Blum 1999, 14).

While the main research role of universities has traditionally been seen as the conduct of basic research, they have come under increasing pressure in recent years to expand this role. A more comparative and historical perspective suggests that the role of the universities has never been limited to the performance of basic research. This view is very much the result of the postwar 'social contract' for science which Ben Martin suggests was forged in the aftermath of World War II. Based on the success of the wartime research efforts in mobilizing national scientific research capabilities in aid of the war effort (Audretsch, Bozeman, et al. 2002, 162–64), the social contract saw society willing to fund massive investments in basic research in the expectation of long–term economic benefits, while leaving the principal research institutions, the universities, autonomous in the conduct of that research. The social contract for science implied a high degree of autonomy for the realm of science, vigorously reinforced by the 'boundary work' of the scientific community itself; it afforded 'expert' status to the role of scientists in the exercise of judgment about most matters relating to the conduct of scientific investigations and the application of the resulting knowledge; and it privileged the role of the universities and other public research organizations as the principal site for the conduct of scientific research (although these arrangements exhibited considerable national variation) (Martin 2003; Brooks 1996).

However, if one adopts a longer–term historical perspective, this shift appears less like a new phenomenon than a return to the conditions that prevailed prior to World War II. As Stokes suggests (1997), and Martin acknowledges, the university has been the locus of both basic and applied research over most of its history, and even at the height of the postwar period, much government funding was also directed at applied research. In the late 19th century the expectation that universities would contribute to broader social and economic goals was widespread among some of the European universities, particularly those in Germany which were based on the Humboldt model, as well as in Japan. Even in the U.S., the land grant universities established by the Morrill Act in 1862 were allocated many of these functions (Martin 2003).

Although the postwar social contract, with its strong affinity to the linear model of innovation, set out the guiding principles for federal funding of university research, the research system in the U.S. was characterized by a high degree of decentralization in terms of the multiple sources of institutional control and sources of funding, both for ongoing operations, as well as the conduct of scientific research. Closely related to this was the highly competitive nature of the university system, especially in terms of research funding. Competition for research funding placed continuing pressure on the universities to adjust their research priorities, policies, and cost structures to the prevailing demand in the market for academic research both. The highly regional nature of the university system in the U.S. ensured that the research activities of the universities were linked to the economic base of their regions (a legacy of the land grant tradition), but also provided an important source of new knowledge and ideas for the stimulus of local industry. Finally, the linking of research activities and graduate teaching contributed to the process of knowledge transfer from the universities to industry embedded in the tacit know–how of their graduates (Rosenberg and Nelson 1996; Feller 1999; Pavitt 2001).

In contrast to the experience in the U.S., the constitutional allocation of responsibility for education to the provinces meant that there was almost no effort in Canada to emulate either the Humboldt model or the U.S. land grant system. The federal government developed little national capability for applied science and assumed almost no responsibility for providing financial support to the nation's research infrastructure prior to the establishment of the forerunner to the NRC in 1916 and the first national laboratories in 1929. While the NRC assumed responsibility for the federal provision of research funding until the separate establishment of the granting councils in 1978, it was never assigned the broad mandate to support research funding in the universities enjoyed by the National Science Foundation (Kenney–Wallace and Mustard 1989). The institutional supports for university–based research in Canada began to change significantly in the 1980s as it did in the U.S. Four provinces – Alberta, British Columbia, Quebec and Ontario – all established their own programs to promote research excellence and increased networking between university researchers and industrial partners. This was followed by the establishment of the federal Networks of Centres of Excellence program in 1988 (Friedman and Friedman 1990) and subsequently the Canada Foundation for Innovation and the Canada Research Chairs program, as well as the transformation of the Medical Research Council into the Canadian Institutes for Health Research and increased funding for the three federal granting councils after 1997. The contribution of this new round of federal initiatives, combined with the introduction of a number of new provincial programs, has greatly strengthened the research capacity of post-secondary institutions, including the research and teaching hospitals, within the province (Wolfe 2005).

The changes that have impacted on the university system in recent decades are part of the broader trends in the shifting locations for the performance of basic and applied R&D. At issue is the changing nature of the relationship between the universities and the broader innovation system in which they are embedded, as well as the process of scientific investigation and discovery that underlies the knowledge production function (Gibbons, Limoges, et al. 1994). Since the early 1980s, private firms have expanded their research linkages with universities, partly in response to the rising cost of conducting R&D. This trend has been marked by the proliferation of a new range of university–industry technology transfer mechanisms, including: industry liaison offices (ILOs) in universities, research parks affiliated with universities, university–industry consortia, research institutes and centres of excellence, regional development organizations and spinoff firms. These mechanisms perform a wide range of functions, including the negotiation of industrial research contracts, the identification of opportunities for university research in the marketplace and the facilitation of licensing or patenting of research results or the spinoff of new firms. However, the mere proliferation of these activities should not be equated with an increase in their effectiveness or efficiency (Doutriaux and Barker, 1995, Etkowitz, 1999).

Expectations about the new role for universities were affected by three intersecting trends: 1) the linking of government funding for academic research and economic policy; 2) the development of more long term relationships between firms and academic researchers; and 3) the increasing direct participation of universities in commercializing research (Etkowitz and Webster 1998; Geiger 2004). The resulting pressure on universities to collaborate with private firms created an internal tension between their role in the development and transmission of knowledge (research and teaching) and that of transferring knowledge to other actors in the innovation system (OECD 1999, 7–8). Universities are now expected to generate more applied knowledge of greater relevance to industry, to diffuse knowledge, and provide technical support to industry. In part, this shift reflects the change in the nature of business R&D described above, but it is also the result of a parallel expectation on the part of government that their investments in basic research will produce an increased economic return.

However, this new view is also based to a great extent on a substantial misreading of the way in which universities contributed to economic growth during the prosperous years of the postwar boom and even during the sharp economic upswing of the 1990s, especially the U.S (Pavitt 2001). Consistent with the view of universities as potential ‘knowledge factories’ for the new economy, many policy makers, both in Canada and elsewhere, reverted to the view of universities as largely untapped reservoirs of new knowledge waiting to be taken up by firms and applied. Their hope was that once this knowledge was harnessed, it would fuel innovation within the firm, thereby increasing the firm’s productivity and national economic growth. This was clearly the view expressed in the report of the expert panel on the commercialization of university research to the Advisory Committee on Science and Technology which recommended that,

> in order for researchers to qualify for federal research funding and universities to qualify for commercialization support . . . universities (and their affiliated organizations) must recognize the importance of research–based innovations as a mainstream activity by identifying “innovation” as their fourth mission, in addition to teaching research and community service (Advisory Council on Science and Technology 1999).

Yet the task of transferring knowledge from universities to industries has proven to be more complex and the role of universities in economic development is much more varied than the linear conception of the innovation process allows. As noted above, conventional approaches to the issue of knowledge flows between universities and industry frequently treat knowledge itself as a universally available commodity, virtually as a free public good, and knowledge transfer as a commercial and legal transaction between clearly defined agents. This view simplifies the complex nature of scientific knowledge and the linkages and processes that facilitate knowledge flows across institutional boundaries and enable a firm to absorb and employ that knowledge. Successful knowledge transfer depends on the type of knowledge involved, and how it is employed. A careful examination of the existing research on university–industry knowledge transfer is essential for a more balanced perspective on this relationship. As Mowery et al. have recently argued, "Any assessment of the economic role of universities must recognize the numerous, diverse channels through which university research influences industrial innovation and vice versa" (2004, 179).

Universities are not just providers of commercializable knowledge or even highly qualified research scientists; they perform a variety of additional roles that are crucial for the development of the local economy. In addition to generating new knowledge through the conduct of basic research, universities provide both formal and informal technical support, as well as specialized expertise and facilities for on–going, firm–based R&D activities. A recent examination by the National Academy of Engineering documents the multiple ways in which universities contribute to the development and expansion of local industry: through the provision of skilled graduates who become key players in local industry; through the conduct of long–term fundamental research that contributes to the science base and understanding available to private firms; through the promotion of an atmosphere of intellectual diversity that tolerates different approaches to the solution of technical problems; through direct collaboration with industry both on specific projects and in longer term relationships; by serving as test beds for new technologies and research instrumentation that are ultimately transferred to industry and finally as the nuclei for start–up companies that spin–off from universities to become the seeds of new business (National Academy of Engineering 2003, 46–48; Grossman, Reid, et al. 2001; Mowery, Nelson, et al. 2004). As national science systems become more interconnected and as the knowledge base required to support the production of 'complex technologies', university research becomes increasingly important to local firms not just for the transfer of knowledge generated through its own research activities, but also as a conduit enabling firms to access knowledge from the 'global pipelines' of international academic research networks (Bathelt, Malmberg, et al. 2004; OECD 1999).

Adoption and Diffusion of Research

Part of the challenge in understanding how firms adopt and diffuse the results of basic research lies in appreciating how the different dimensions of knowledge affect their capacity to do so. The transfer of research results for purposes of innovation is influenced by the two dimensions of knowledge – the tacit and the codified; the different knowledge bases that firms draw upon to innovate – analytic, synthetic and more hybrid forms of knowledge; and the differing modes of innovation – such as the STI mode and the DUI. As was pointed out above, this will occasion considerable variation by industry sector. It will also depend on whether firms are targeting their development efforts toward the introduction of a radical new product or process, or whether they are focused on making incremental changes to existing products or processes in response to the needs of customers, to stay ahead of current and potential market competition or to meet an unarticulated, but perceived niche in the marketplace.

A key part of the difficulty in managing the process of knowledge transfer arises from the fact that much of the knowledge resulting from basic research is either tacit in nature, or relies on tacit knowledge to be fully understood and applied – as Keith Pavitt argues, it is person–embodied. Pavitt maintains that the most effective mechanism for knowledge transfers between research institutions and commercial firms is through the flow of researchers. Policies that attempt to direct basic research towards specific goals or targets ignore the considerable indirect benefits across a broad range of scientific fields that result from the training of highly qualified personnel in institutions of higher education and the kind of unplanned discoveries that invariably result from the conduct of basic research (Pavitt 1991; Rosenberg 1990).

This view reinforces the idea of knowledge as the capacity to acquire and apply research results, rather than as an end in itself. In this perspective, knowledge is the ability to put information to productive use. It provides the basis for understanding new ideas and discoveries and places them in a context that enables more rapid application. The development of such internalized or 'personal knowledge' requires an extensive learning process. It is based on skills accumulated through experience and expertise. It also emphasizes the learning properties of individuals and organizations. Knowledge is therefore not a freely available good, but involves a large tacit component of skill and capabilities embodied in people, products, and procedures. To deploy this knowledge in a commercial setting, firms need to capture both its tacit, as well as its more explicit, or codified, component. A recent study by Faulkner and Senker analyzed the nature of both dimensions of knowledge transfer in greater detail. The study examined the relationship from the perspective of the innovating organization, focusing on its knowledge requirements and trying to develop a better understanding of the knowledge flows from academia to industry. The researchers conducted a series of interviews with a number of researchers and managers in each firm across three science–related industries, biotechnology, engineering ceramics, and parallel computing. They probed for both the links that exist between firms and universities and the types of knowledge flowing to the firms. They also attempted to determine the degree of formality of these links and the relative importance of tacit versus codified knowledge (Faulkner and Senker 1995).

While their findings differ slightly by industry they concluded that partnering with universities contributes most to firm innovation through an exchange of tacit knowledge and that the channels for communicating this knowledge are often informal. Such informal linkages, they argue, are both a precursor and a successor to formal linkages and many useful exchanges of research materials or access to equipment take place through "non-contractual barter arrangements." Faulkner and Senker argue that the flexibility inherent in such arrangements promotes the goodwill between partners that supports more formal linkages. Their evaluation of the types of knowledge firms find most useful shows that codified and tacit knowledge are often used in tandem. "While publications are generally a vital first source of information. . . personal contacts provide the tacit knowledge which is essential if researchers wish to implement or adapt experiential practices and procedures" (Senker 1995, 183; Faulkner and Senker 1995).

Despite the fact, that it has less investigated, and much less appreciated, than the tacit dimension of firm–based innovation, the context of a university laboratory is equally shaped by background knowledge and skills of its researchers, as well as their goals, the instruments, materials, other physical infrastructure, laboratory procedures, financial resources that they use. This notion is derived from the insight that scientists acquire a wide range of skills and tacit knowledge during their apprenticeship, including how they assess data and information, and the methods for manipulating and using tools, including both physical instruments and statistical techniques. Together these elements involve a major degree of tacit knowledge. Gaining access to cutting edge research results from the laboratory frequently requires direct involvement with the scientists conducting the research as they are often willing to transfer that knowledge in the context of their laboratory work. When their is a high degree of tacit knowledge involved in the research results, it is the direct collaborators on the research team who are most likely to be recipients of the knowledge, thus raising the initial cost of entry to the new knowledge and providing a strong motivation for firms to partner with cutting edge or 'star' scientists (Zucker, Darby, et al. 2002, 142).

Firms interested in accessing this tacit knowledge base have to build common ground that overlaps the context of the university laboratory with that of their own R&D laboratories, design shops, and manufacturing plants. Understanding how this common ground is created and how it facilitates the reciprocal exchange of material and knowledge, tacitly embodied in people and technologies or codified in publications is key to understanding how university–industry knowledge occurs. A key aspect of the process of knowledge transfer from universities and research institutes is through personal connections given that the knowledge being transferred is 'tacit' and 'embodied'. To deploy university–generated knowledge in a commercial setting, firms must capture both its tacit, as well as its codified, component (Wolfe and Lucas 2001).

Another study on a smaller scale also casts considerable light on the way in which firms draw upon the university knowledge base to support their innovation efforts. Ajay Agrawal and Rebecca Henderson employed a combination of quantitative and qualitative methods to survey the extent to which patents provided a key means for transferring knowledge from MIT's Departments of Mechanical and Electrical Engineering to industry. They found that both firms and university faculty view patenting as a relatively unimportant mechanism for transferring research results out of the university to industry. They found instead that faculty members rely upon a broad cross–section of dissemination methods to communicate their research results to private firms, including publications, participating in conferences, conducting collaborative research, co–supervising graduate students with industry partners or collaborators, the recruitment of graduate students to work in industry and individual conversations. Somewhat surprisingly, the dissemination method that ranked highest was private consulting to industry, a finding that is consistent with the results of the Faulkner and Senker study. Consulting frequently serves as a low cost method for firms and researchers to test out their compatibility and potential for longer–term collaboration. They argue that, "Our results suggest that a focus on patenting or licensing statistics, in isolation, may significantly misrepresent the nature of the university's impact on the economy and that any comprehensive study of the issue must include a focus on the other channels through which university knowledge is transferred to private firms" (Agrawal and Henderson 2002, 46).

The nature of knowledge transfer, and the actual substance of what firms draw from basic research, varies significantly across industrial sectors. Several large–scale surveys of industrial R&D managers have probed for the extent and implications of intersectoral differences in the way that firms in different industry sectors deploy scientific knowledge in the innovation process. One study that cast considerable light on this question was the Yale survey conducted by Richard Nelson and several colleagues in the early 1980s. It queried 650 R&D managers in U.S. firms, representing 130 lines of business. The goal was to understand inter–industry differences in sources of technological opportunity. It distinguished between two roles that science plays in supporting innovation: one as an expanding pool of theory and problem–solving techniques deployed in industrial R&D, but not necessarily new science; the other as a direct source of new technological possibilities pointing the way towards new solutions to old problems. Overall, university–based research in a field is reported as being much less important to recent technical advance in industry than is the overall body of scientific knowledge in the field. 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. The disciplines with the highest relevance scores of university research for the largest number of industries were computer science, materials science, metallurgy and the engineering disciplines (Klevorick, Levin, et al. 1995, 197).

In most fields, what academic research provides are not pilot inventions, but the broad understandings and techniques that industry can later employ for a variety of different purposes. Industrial R&D managers value the scientific background and training of their R&D staff more highly than the current research activities of university–based researchers. The Yale researchers also noted that advances in fundamental scientific knowledge influence the pattern of innovation in industry through a second, more indirect route – through their incorporation in the applied sciences and engineering disciplines and their impact on research in those fields. Biology is the exception to this rule in that R&D managers in an equal number of industries rated university research in the field as relevant to industrial innovation as the broad stock of scientific knowledge in the field. Nelson expands on the reason why the direct impact of university research activity on industrial innovation is limited in research organizations that specialize in the conduct of R&D, such as university research laboratories,

> "To do effective industrial R&D generally requires knowledge about the technology of an industry that is not taught in school. It also often requires a certain amount of close and not preprogrammable interaction between the lab and client firm or firms, and complementary work and investment on their part. . . . Thus effective lab work requires not only industry-specific, but firm specific, knowledge and sensitivity of the lab to the needs of its client firm" (1996, 62).

The Pace Report, based on a survey of 615 of the largest firms in Europe conducted in 1993, provides further confirmation for the conclusions of the Yale Study. In the Pace Report, respondents were asked to rate different fields of science in terms of their importance to their firms' technological base. Applied areas of research received fairly high scores. Chemistry also scored high, while physics, biology and mathematics did not (Arundel, Van de Paal, et al. 1995). These findings indicate that firms draw from the public–funded science and technology base in a heterogeneous fashion. In some sectors, the link is rather tight, with high citations for scientific papers in patents and a great interest in scientific research. In other sectors, such as automobiles, firms draw from the public base indirectly, mostly through the flow of students. Only in pharmaceuticals – where the links are tight and often visible – might some measurement of the benefit be possible.

Both the research methodology and the findings of the original Yale survey were replicated by a more recent survey of industrial R&D managers conducted at Carnegie Mellon University in 1994. The results of the Carnegie Mellon Survey (CMS) reinforce the notion that industrial firms draw upon feedback from their own customers and manufacturing operations as the primary source of ideas for new product and process innovations. Public research is significant in addressing previously identified needs or problems, rather than suggesting new lines of innovative activities, with the exception of a select few industries, such as pharmaceuticals, that draw directly upon the public research base. However a significant proportion, almost a third, of industrial R&D projects do make use of public research findings and the authors of the study argue that knowledge from public research findings beyond this stated level is transmitted to industrial researchers through a wide range of supplementary channels, such as consulting and informal communications. This insight is supported by an additional finding that the most important mechanisms for communicating research results from public research institutes to industry are the traditional ones of publication and conferences, strongly complemented by informal exchanges and private consulting arrangements between firms and researchers (Cohen, Nelson, et al. 2003, 139–41).

What is striking is that these findings hold true in direct forms of university–industry cooperation specifically targeted at improving industrial competitiveness. The role played by collaborative research networks in the process of knowledge transfer has been the focus of a great deal of research which suggests that firms and industries link with the publicly–funded scientific research for a variety of reasons. Some researchers stress the positive role that collaborative networks and institutes play in generating new forms of social interaction among actors in the innovation system (Corey 1997). Bridging institutions, such as provincial and national Centres of Excellence in Canada or Engineering Research Centers in the US, provide institutional mechanisms to embed and support interaction and facilitate knowledge flows between universities and industry (National Academy of Engineering 2003, 59–60); but whereas the motivation for the establishment of these networks and centres has often been to transfer university research results directly to industry, what industry values most in these collaboration is surprisingly consistent with the findings of the surveys reported above.

The Engineering Research Centres (ERCs) were a major policy initiative in the 1980s to foster greater university–industry collaboration in the U.S. Individual centres are co–sponsored by the National Science Foundation, universities and industry. The ERCs were designed to develop basic knowledge in areas critical to the competitiveness of U.S. firms in world markets by concentrating on research areas of major industrial importance that cut across disciplinary boundaries. A recent study of 355 firms participating in 18 different ERCs using both surveys and interviews found that firms participating in the centres were more interested in gaining access to upstream forms of knowledge, rather than developing specific products and processes. Close to 80 per cent of the firms participating reported that their primary reason for joining the ERC was to gain access to 'new ideas' generated by the centre; in contrast, only 15 per cent reported that the ability to license inventions and/or software was a motivating factor in their decision to participate. Consistent with their original motivation, the most commonly reported benefits included access to new ideas, know–how and technologies through interaction with the ERC (Feller, Ailes, et al. 2002, 462–64).

Many studies of the mechanisms by which knowledge is transferred from research universities to industry point to the critical role played by the flow of students. New graduates, who have had the opportunity to participate in the conduct of basic research, enter industry equipped with training, knowledge, networks and expertise. They bring to the firm knowledge of recent scientific research, as well as an ability to solve complex problems, perform research, and develop ideas. The skills developed through their educational experience with advanced instrumentation, techniques and scientific methods are extremely valuable. Students also bring with them a set of qualifications, helping set standards for knowledge in an industry. Senker suggests that graduates bring to industry an 'attitude of the mind' and a 'tacit ability' to acquire and use knowledge in a new and powerful way (Senker 1995). Nelson also notes that academics may teach what new industrial actors need to know, without actually doing relevant research for industry. Basic techniques in scientific research are often essential for a young scientist or technologist to learn to participate in the industrial activities within the firm (Nelson 1987).

Gibbons and Johnston's research in the 1970s demonstrated that students provide a form of benefit that flows from research funding (Gibbons and Johnston 1974). Studies by Martin and Irvine in the 1980s also showed that students trained in basic research fields, such as radio astronomy, move into industry over time and make substantial contributions (Martin and Irvine 1984). Research on the experience with Ontario government programs to promote international collaborative research, as well as university–industry partnering, also suggests that the movement of doctoral and post–doctoral students into industry frequently provides the most effective method for transferring research results from the laboratory directly to industry. These benefits are often difficult to anticipate or measure, yet the evidence indicates that students bring a wide range of skills and techniques to industry. They enable firms to increase their base of tacit knowledge and expand into new activities (Wolfe 2000; Wolfe and Lucas 2001; Lucas 2005).

Firms also indicate that students fresh from their educational experience bring to the firm an enthusiasm and critical approach to research and development that stimulates other members of the research team. Over the entire career of the new hire, the skills acquired in their education and research experience are valuable and often serve as a precursor to the development of more industry–related skills and knowledge that appear over time. This point was strongly underscored by Mike Lazaridis, the founder, President and co–CEO of Waterloo–based Research in Motion in his presentation to the fourth annual Re$earch Money Conference in Ottawa,

> The number one reason to fund basic research well and with vision is to attract the very best researchers from around the world. Once here, they can prepare Canada's next generations of graduates, masters, PhD's and post-doctorates, including the finest foreign students. All else flows from this. . . . If you really want to understand commercialization, all you have to do is attend convocation at your local university. At mine, the University of Waterloo, we celebrate – yes celebrate – the passage of the next generation of students into the economy and society twice each year. Armed with cutting edge technology from around the world, the latest tools, the latest techniques and processes learned from their work under the very best researchers, they graduate with much fanfare and go on to build the industry, institutions and society of our country (Lazaridis 2004).

Students provide a key transfer mechanism for the benefits of public sector research to be channeled into industry and the broader society. The critical role played by students underlines the earlier points that the most effective mechanism of knowledge transfer is person–embodied and what industry often values most is access to where the knowledge base is expanding at the frontier in disciplines of interest and relevant to them.

Proximity and Innovation

The preceding analysis emphasizes the fact that knowledge transfer between universities and their partners are highly personalized and, as a consequence, often highly localized. This underscores the significance of geographical proximity for the process of knowledge transfer.

Proximity to the source of the research is important in influencing the success with which knowledge generated in the research laboratory is transferred to firms for commercial exploitation, or process innovations are adopted and diffused across developers and users. The growing interest in the significance of proximity for knowledge transfer underlines the fact that there are particular geographical patterns of local and global knowledge transfer and coordination. Given the increasing importance of knowledge creation and dissemination for economic development, these geographical concentrations of knowledge transfer and coordination reinforce distinctive regional and national patterns of industrial specialization and economic growth (Lorenzen 2005, 401).

A growing body of empirical research reinforces the finding that the linkages and benefits that flow from public investments in basic research are localized in this manner. The most frequently cited explanation for this proximity effect is the need to gain access to tacit knowledge, or at least knowledge that is not yet codified. Conversely, the role of proximity declines when useful knowledge is readily available in more codified forms that can easily be transmitted and accessed across broad distances. Proximity may also be more important for the transfer of relatively new research results in science-based fields, where personal access to those conducting the research is critical for the effective transfer of its insights (Feldman 2000; Adams 2002; Arundel and Geuna 2004).

One prominent line of research has investigated the geographic spillovers from government funding of scientific research to other types of activities, such as industrial R&D. Access to the U.S. patent office data base enabled researchers to assemble large volumes of patent data with geographic precision. These data provide a rich geographic time series which has been further broken down into patent families, patents that reference or cite each other and are used to indicate the flows of knowledge from one intervention to another. Using patents as a proxy for innovative output, Jaffe related the incidence of patents assigned to various corporations in different states with industrial R&D and university research. He found an important indirect or induced effect. There is also an association between industrial R&D and university research at the state level (1989). In a subsequent study, Acs et al (1991) replaced the number of patents with the number of announcements of new or improved products found in newspapers and trade journals. Their analysis indicated that spillovers from university research to industrial innovation were greater than Jaffe described.

Using the same data as Acs, Feldman and Florida's model showed that the process of innovation is highly dependent on the underlying technological infrastructure of an area, consisting of both university and industrial R&D, agglomerations of related firms and business services. Furthermore, these innovative capabilities tend to be highly specialized in regional concentrations of distributed across the U.S. "In the modern economy, locational advantage in the capacity to innovate is ever more dependent on the agglomerations of specialized skills, knowledge, institutions, and resources that make up the underlying technological infrastructure" (Feldman and Florida 1994, 226).

Jaffe et al (1993) also used patent citations (in a manner similar to Narin's studies discussed above) to analyze the spillover effects of academic research. The results indicated that knowledge flows from universities to firms are highly localized at the regional or state level. They found evidence that patents cite other patents originating in the same city more frequently. Citations are five to ten times as likely to come from the same city as the control patents. This research highlights some of the factors that condition localization. Citations are more likely to be localized in the first year following the patent. This effect fades with time: citations show fewer geographic effects as knowledge diffuses. In a subsequent study, Jaffe (1996) found that electronics, optics, and nuclear technology enjoyed high immediate citations, but due to the rapid obsolescence of new knowledge in these fields, experienced a rapid fading of citations over time.

In a slightly different approach, Audretsch and Feldman (1996) used innovation citations that represent the market introduction of new commercial products. These data consist of new product announcements compiled from technology, engineering, and trade journals. They found a direct relationship between the propensity for industries to concentrate geographically and the knowledge intensity of the industries' activity. They also used survey data to discern the disciplines that form a common science base that contribute to cross-industry increasing returns. This work found that industries relying on the same science base also tend to cluster geographically.

This strand of research is also confirmed in the work of Edwin Mansfield, referred to above. In a survey of 70 major US companies, Mansfield and Lee found that distance helps to determine which firms reap the economic benefits from an innovation based on academic research. Firms located in the nation and area where academic research occurs are significantly more likely than distant firms to be among the first to apply the findings of the research. Firms located close to major centres of academic research are deemed to have a 'major advantage' over those located at a distance from the academic source of research.

> "… distance also helps to determine which firms reap the economic benefits from an innovation based on academic research. While economists and others sometimes assume that new knowledge is a public good that quickly and cheaply becomes available to all, this is far from true. According to executives from our sample, firms located in the nation and area where academic research occurs are significantly more likely than distant firms to have an opportunity to be among the first to apply the findings of this research" (Mansfield and Lee 1996, 1057).

The study by Beise and Stahl (1999) discussed above also includes some significant results about the extent of geographic spillovers in Germany. Their main results differ from most of the findings of the US based studies above. They found that firms located near universities or polytechnics do not have a higher probability of using the results of publicly funded research. However, they also recognize that their analysis involved much larger spatial scales than most of the US studies. A recent study by Adams (2002) analyzed the results of a survey of 208 private R&D laboratories to investigate the relative importance of knowledge acquired from public research organizations. The results of his survey offer solid evidence of the localization effects of academic knowledge spillovers. The spillovers are more localized than firm spillovers and more localized than the general distribution of university R&D. Adams attributes this effect to the strong traditions of university-industry cooperation in the US which dates back to the establishment of the land grant colleges in 1862, "This evidence can be viewed as consistent with policies that have coupled scientific training and research with state agricultural and industrial interests (the industry-university cooperative movement), strongly complementing the results of open science (2002, 24).

A recent study by Arundel and Geuna (2004) uses the data from the PACE Survey described above and compares it with previous analyses of the European Union's Community Innovation Survey to examine the significance of proximity effects across the continent. They examined the relative importance of domestic public research organizations compared to foreign ones for industrial innovation. The results obtained by their model show that proximity effects decline with an increase in the firm's R&D expenditures, the importance attached by the firm to basic research results in publications and it's activity in the North American market, but increase with the quality and availability of outputs from public research organizations in the firm's own country.

A number of other studies confirm the overall results of the studies cited above. Anselin et al. demonstrate that university research has a positive impact on innovative activity within a fifty mile range of the university as the source of new knowledge, while Varga estimates the knowledge spillovers exert a positive impact on innovative activity in neighbouring metropolitan areas up to 75 miles away (Anselin, Varga, et al. 1997; Varga 2000). Social networks and direct interaction between the university–based researchers and the firms that benefit from the knowledge spillovers are often a critical transmission mechanism (Zucker and Darby 1996). This reinforces the point made earlier about the necessity of direct involvement with university researchers to gain access to the knowledge developed at the laboratory workbench (Zucker, Darby, et al. 2002).

Factors Affecting Firm-based Innovation

The preceding analysis of what industry values most in public–sector conducted basic research presumes that firms have the capacity to differentiate and absorb the knowledge that is potentially most valuable to them. But as Lundvall and others argued above, in an era when the knowledge base is expanding at an unprecedented rate, this capacity to learn is most critical. Analyzing this process from the perspective of the firm, Cohen and Levinthal argue that the process of knowledge transfer is strongly conditioned by the capabilities of firms. Firms need to build an internal knowledge base and research capacity to effectively capture and deploy knowledge acquired from external sources. The ability to evaluate and utilize outside knowledge is largely a function of the level of prior, related knowledge within the firm, including basic skills or even a shared language, but may also include knowledge of the most recent scientific or technological developments in a given field. These abilities collectively constitute a firm's '*absorptive capacity*' (Cohen and Levinthal 1990).

The overlap between the firm's knowledge base and external research allows the firm to recognize potentially useful outside knowledge and use it to reconfigure and augment its existing knowledge base. Research shows that firms which conduct their own R&D are better able to use externally available information. This implies that the firm's absorptive capacity is created in the process of developing its own R&D capability. A key implication of this argument is that firms require a strong contingent of highly qualified research scientists and engineers as a precondition of their ability to absorb and assess scientific results, most frequently recruited from institutions of higher education. The members of this scientific and engineering labour force bring with them not only the knowledge base and research skills acquired in their university training, but often, more importantly, a network of academic contacts acquired during their university training.

Recent empirical research has provided confirmation for the broader conceptual argument presented above. Drawing upon a sample of 2655 manufacturing firms in the U.K., Laursen and Salter analyze the role that search strategies employed by the firms affect their innovative capabilities and how structural variables, such as the size and age of the firm and the level of R&D investment influence their propensity to draw upon knowledge from universities. Overall, the research demonstrates that firms which employ a more ‘open’ search strategy, i.e. draw upon many external sources of knowledge, tend to make more extensive use of university research. However, only 27 per cent of the firms in the sample draw upon university research and, of these, only 2 per cent indicate that the knowledge they derive from this source is highly important. They also confirm the findings of Klevorick et al. (discussed above) that there is a considerable cross–industry variation in the propensity of firms to draw upon university research in their innovation strategies. The examination of structural variables strongly reinforces this point, confirming “that firms in sectors characterized by high levels of investment in R&D and other scientific and technological activities have a higher propensity to draw from universities, indicating that the average level of absorptive capacity within the sector can influence the propensity of firms to draw from university sources . . .” (Laursen and Salter 2004, 1208).

Another recent empirical study uses the results of the 2000 KNOW survey covering seven E.U. countries to analyze the determinants of firms’ participation in R&D projects with public research organizations (PROs), including both universities and other public research centres. The results of this study confirm that the propensity of firms to become involved with PROs in collaborative R&D projects is influenced by their absolute size, their own level of R&D activity and by their degree of openness. In general, larger firms with a greater absorptive capacity tend to cooperate more with academic researchers. Firms which are more open to their external environment in terms of drawing upon external knowledge sources demonstrate a higher level of collaboration with PROs. The authors conclude that policies which focus primarily on creating incentives for PROs to interact with firms to a greater extent overlook the fact that their success in this respect is strongly conditioned by the level of ‘demand’ evinced by firms in terms of their own openness to the external environment (Fontana, Geuna, et al. 2006, 321).

The preceding analysis has major implications for the relative capacity and success of Canadian industry in adopting and using university generated research. As noted at the outset of this paper, Canada’s relative weakness in in national R&D spending is particularly marked in the business sector, where R&D spending by the private sector accounts for just 55 per cent of total R&D spending in contrast to the average of 68 per cent for all the OECD countries. In contrast, Canada ranks higher than the OECD average in R&D spending by the higher education sector which accounts for 0.7 per cent of the total. This suggests that government policies designed to promote greater uptake and commercialization of university–based research may encounter a significant obstacle in terms of the absorptive capacity of Canadian industry to adopt and utilize those research results.

This factor has long been recognized as relevant to any attempt to evaluate Canada’s R&D performance and considerable effort has been expended in analyzing the Canada’s lower level of business expenditures on R&D (BERD). Among the factors that have been identified as possible explanations of this phenomenon are relative firm size, the degree of foreign ownership and the industrial structure of the Canadian economy. Comparative studies suggest that national differences in terms of areas of industrial specialization, inputs to the innovation process, trade patterns, technological specialization and the institutional infrastructures that support innovation all affect the capacity to perform R&D. A background paper prepared for the consultations on the S&T Review argued that size rather than foreign ownership was a major determinant of the propensity to perform R&D among Canadian firms (Holbrook and Squires 1996), while an earlier report to the Science Council of Canada concluded that roughly 40 per cent of Canada's underperformance of R&D in the business sector was accounted for by the industrial structure of the economy (Canada Consulting Group 1991). Jorge Niosi's analysis of Canada's national innovation system also provides a clear picture of its distinctive industrial and sectoral patterns. Telecommunications, aerospace, engineering and scientific services, finance, insurance and real estate, electronic equipment and pharmaceuticals together account for more than half of all business expenditures on R&D in Canada. Canada's R&D system also displays strong regional patterns of variation (Niosi 2000, 57–73).

A recent working paper for the federal Department of Finance confirms the underlying significance of industrial composition and technological intensity for Canada's overall R&D performance. The paper finds that the low aggregate R&D intensity of private sector firms conceals significant disparities in R&D performance across industrial sectors. The more research–intensive, high technology industries in Canada are very research–intensive by world standards and research intensity has been increasing in some of these. The problem lies in the fact that these industries constitute a smaller proportion of GDP in Canada than in other leading industrial countries, such as the U.S. In addition, there may not be enough firms in these industries or the firms may not have grown large enough. However, two sectors stand out in particular as key sources of low research intensity – motor vehicles and the service sector – where Canadian research intensity lags relative to the U.S. The motor vehicle industry is particularly significant as the industry is relatively larger in Canada than the U.S. This may be one case where the high degree of foreign ownership of the industry does explain Canada's poor relative R&D performance.[2] Overall, the paper concludes that it may not be possible to increase the level of BERD (and the absorptive capacity of Canadian industrial firms) without increasing the relative size of the BERD performing sectors in the Canadian economy, or the size and number of firms in those sectors (Iorwerth 2005).

Canada's private sector R&D performance is also linked to the innovative behaviour of Canadian firms. Overall, innovation density, the share of firms undertaking innovation is reasonably high, but Canadian firms have a lower share of their sales coming from innovative products than in four leading European countries. Large firms in Canada tend to be more innovative than smaller ones and they are also likely to have dedicated R&D teams that are both capable of generating new ideas internal to the firm and absorbing ideas from external sources. However, Canada has significantly fewer large firms than the U.S., which has important implications both for its R&D and its innovative performance. Once again, the sectoral composition of manufacturing industry plays a significant role in innovative behaviour; the occurrence and intensity of innovation is significantly lower in Canada which has a higher proportion of low tech sectors than the European countries it was compared with. In those sectors in which the Canadian economy is strong, however, innovative intensity is greater than in the European countries it was compared with (Mohnen and Therrien 2003, 327–35; OECD 2006, 77).

The critical challenge in ensuring that the knowledge outputs of Canada's research sector are taken up and applied by Canadian firms lies in growing the number and scale of firms in

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[2] It should be noted that the University of Windsor/Daimler Chrysler Automotive Research and Development Centre and General Motors' new Beacon Project in conjunction with the University of Ontario Institute of Technology in Oshawa may represent a significant new trend in the opposite direction.

Canada's research–intensive sectors, thereby increasing the relative proportion of those sectors in the Canadian economy. Studies conducted in Canada over the past three decades demonstrate that a key impediment in this regard is the lack of managerial and marketing skills, rather than a low or inadequate level of R&D. A recurring theme in a variety of studies is the link between the innovation process and the marketing activities of the firm. Earlier studies indicated that the greatest constraint on Canadian threshold firms – those with sales under the $25 million mark – was not the lack of R&D support, but a lack of entrepreneurial talent and marketing skills on the part of the firm's managers Also identified as a critical factor of success was the ability of indigenous firms to make the transition from competing in domestic markets to competing in global ones. One study found that strong marketing expertise in the founding teams of young high–tech firms helped achieve good results at start–up and facilitated entry of the firm into foreign export markets. Other studies indicated that Canadian hi–tech companies frequently had difficulty assessing their market or getting skilled marketing managers. The marketing mix was considered less important than other activities and there were marketing lags, especially with respect to forecasting markets and analyzing competitors' strategies. These studies concluded there was a definite need to upgrade the skills of Canadian managers in this area (Wolfe 1990).

Depressingly, it seems that these same problems still represent a major obstacle for the successful growth of Canadian research–intensive firms. The recent OECD review of Canada noted that Canadian firms have a lower share of highly–educated managers than U.S. firms and that less than 10 per cent of Canadian managers have degrees in commerce, management or business administration. It cites a recent survey of CEO's of startup and early–stage firms spending specified amounts of total revenue on R&D. Overall the survey found that there was a dearth of sales, marketing and management skills and insufficient MBAs to fill the gap. Because of this, CEOs of these startup and early stage companies frequently lack in significant areas of knowledge and experience related to critical marketing and management skills. While government programs exist to support R&D and technology adoption, there are relatively fewer to support the marketing and business development activities of the firms. Overall, these represent significant challenges for both the survival and growth of these firms (Barber and Crelinsten 2005; OECD 2006, 79). While there is a growing recognition of the problem of emphasizing R&D at the expense of a broader range of management skills, there is little consensus as to how the public policy mix should be changed to foster the necessary set of skills within Canadian management (Institute for Competitiveness and Prosperity 2004).

Conclusion

This paper provides an overview of conceptual approaches to, and empirical research on, the relation between knowledge, research and innovation. It warns against relying upon a model which is linear in its outline and information–based in its depiction of how knowledge is transferred from the research community to those who apply that knowledge for commercial innovations. It views the process of knowledge transfer as intensely personal, experience–based (tacit) and proximate. It suggests that the process of knowledge transfer must be viewed in the context of the institutional structures and firm capabilities which determine the ability of a region or nation to develop and market new commercial products – in other words, its innovation system (Wolfe 2002). Applying the insights derived from this review of the literature to the evaluation of policy rationales for public support of research and innovation requires that they be grounded in the institutional specificities of both the national and regional innovation systems.

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