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LINKAGES BETWEEN TECHNOLOGICAL CHANGE AND PRODUCTIVITY GROWTH

Occasional Paper Number 23
May 2000

Industry Canada Research Publications Program

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Occasional Paper Number 23
May 2000

Aussi disponible en français

Canadian Cataloguing in Publication Data

Globerman, Steven

Linkages between technological change and productivity growth

(Occasional paper; 23)
Text in English and French on inverted pages.
Title on added t.p.: Liens entre changement technologique et croissance de la productivité.
Includes bibliographical references.
ISBN 0-662-64787-4
Cat. no. C21-23/23-2000

1. Technological innovations Canada.
2. Industrial productivity Canada.
I. Canada. Industry Canada.
II. Title.
III. Series: Occasional paper (Canada. Industry Canada).
IV. Title: Liens entre changement technologique et croissance de la productivité.

HC79.T4G56 2000 338.'064'0971 C00-980118-9E

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ACKNOWLEDGEMENTS

The author would like to thank an unidentified reviewer for helpful comments on an earlier draft.

TABLE OF CONTENTS

1. INTRODUCTION

The purpose of this study is to review and synthesize the relevant literature dealing with the linkages between technological change and productivity change. The two concepts, although theoretically distinct, are often linked in policy discussions, and both are the focus of a wide range of public policies.

Recent commentaries in the popular press have highlighted Canada's stagnating productivity performance relative to that of the United States.[1] Various possible explanations have been suggested including a long-standing concern in Canada about the relatively small amount of research and development (R&D) carried out by firms in this country.[2] Indeed, a number of other possible explanations including government regulations and the decline in the value of the Canadian dollar, which raises the cost for Canadian companies to import productivity-enhancing technology, are also linked to technological change.[3]

A slowdown in the rate of technological change has also been widely bruited as a possible cause of the post-1973 productivity growth slowdown among developed countries. While the evidence (reviewed below) on this issue is inconclusive, there is now a growing perception that major technological developments in computing and telecommunications, including the emergence and growth of the Internet as a major new mode of mass communications, will induce a new and dramatic improvement in productivity growth, as well as in the growth of real incomes.[4]

The propensity of policymakers to look to the promotion of technological activities as an important component of industrial growth strategies is certainly not new, especially in Canada where a debate about the causes and consequences of technological change has taken place over at least three decades.[5] Having implemented one of the most generous R&D tax regimes among OECD countries, the apparent failure of Canadian productivity growth rates to track those of other countries is disappointing. It is also a cause for questioning the faith being reinvested by the Canadian government in offering yet more financial assistance for technological activities.

The linkages between technological activities and productivity changes are complex and difficult to measure. Thus, notwithstanding the relatively large literature on the topic, there is no "conventional wisdom" on either the nature or the magnitude of these linkages. The purposes of this report are to review and synthesize the relevant literature, as well as to highlight important areas for future research and suggest specific research projects.

The report proceeds in the following way. Section 2 sets out the simple theoretical linkages between productivity growth and technological change. It also identifies and evaluates the conceptual and empirical problems associated with specifying and estimating those linkages. Section 3 summarizes and synthesizes empirical studies of the relationships between R&D, innovation and productivity at the levels of both the aggregate economy and individual industries and firms, or groups of industries and firms. Section 4 discusses factors that have been identified as "conditioning" the empirical relationship between technological change and productivity change, including the educational level of the workforce, industrial competition and so forth. Section 5 looks at whether there is any temporal pattern in the observed linkages between technological change and productivity change and what factors might account for any observed pattern. Section 6 focuses on the relationship between computerization and related technological changes in telecommunications and productivity change. The main issue of interest here is whether the "Digital Revolution" is sparking an accelerated growth in productivity and, if not, why. Section 7 identifies the important remaining gaps in our knowledge about the relationship between technological change and productivity change. Section 8 suggests a number of research projects designed to address the gaps identified in the preceding section.

2. TECHNOLOGICAL CHANGE AND PRODUCTIVITY CHANGE

While technological change is sometimes identified synonymously with productivity change, the two are distinct, albeit related concepts. Specifically, technological change is a contributor (of greater or lesser importance) to productivity change. Identification of the contribution of technological change to productivity change, in turn, requires some precision in the measurement of the latter.

Productivity Measures

Productivity measures encompass indexes for individual factors of production, e.g. labour or capital, and indexes for a weighted average of individual factors of production. Productivity measures for individual factor inputs are known as partial factor productivity indices. Productivity measures encompassing all input factors are known as total factor productivity indices. Hence, labour productivity is an index of a series of real output divided by a series of real labour input. The most common index of labour productivity is real output per hour worked. Similarly, capital productivity is an index of a real output series divided by a real capital input series. In fact, output per labour hour is the most widely available productivity measure for international comparisons, as well as inter-industry comparisons.[6]

Multi-factor or total factor productivity (TFP) is constructed as the ratio of real output (or real value added) to a weighted average of inputs, where the weights are the relative importance of each factor in the cost of production. TFP indices are constructed for both gross and net output (value added), where gross output includes intermediate material inputs and net output excludes such inputs.[7] International comparisons most frequently report the ratio of real output to a weighted average of labour and capital inputs.

The growth in the calculated partial or total factor productivity over time is, therefore, a measure of the growth of productivity. When the index is expressed as a rate of change, one obtains an estimated productivity growth rate. Table 1 reports labour productivity growth estimates for a sample of Canadian industries. The main observation worth highlighting is the relatively sharp decline in the rate of productivity growth, post-1973, in all of the sample industries. In most cases, productivity growth continued to decrease throughout the 1980s and 1990s, albeit at a slower pace than in the immediate post-1973 period. This pattern is essentially mirrored in other developed economies. Explanations of productivity performance must therefore be consistent with this striking and ubiquitous observation.

Table 1
Labour Productivity

Industry	Annual Rate of Growth	
	1963–73	**1973–92**
Agriculture, forestry and fishery	4.96	2.85
Mining and quarrying	5.37	0.91
Food, beverage and tobacco	3.23	1.58
Textile, apparel and leather	4.46	2.40
Wood products and furniture	3.29	2.51
Paper, paper products and printing	3.10	1.22
Chemicals	4.26	0.75
Non-metallic mineral products	3.88	0.68
Basic metal products	2.88	2.33
Metal products	3.44	0.93
Agricultural and industrial machinery	3.95	3.41
Electrical goods	4.09	3.83
Transportation equipment	5.95	1.99
Other manufacturing equipment	4.01	0.46
Electricity, gas and water	5.16	1.41
Construction	2.48	1.23
Wholesale and retail trade	2.17	1.29
Restaurants and hotels	1.26	–0.55
Transport and storage	5.47	1.89
Communications	6.03	5.69
FIRE and business services	1.70	1.21
Community and personal services	1.03	0.52

Labour productivity is measured by gross output per hour worked.
Source: Gera, Gu and Lee (1998b).

The causes of observed changes in productivity performance will be conditioned, in part, by the way in which productivity is measured. For example, in the case of partial productivity measures, productivity growth rates or levels can be higher in one country (or one industry) than another either because the two use different combinations of factor inputs, or because one uses a factor input more efficiently than the other. An obvious illustration is provided in the case of the labour productivity measure. Labour productivity will ordinarily increase as capital is substituted for labour due to the diminishing marginal productivity of variable inputs. Hence, labour productivity will ordinarily be higher in more capital-intensive economies, industries and firms, all other things constant. At the same time, labour productivity might be higher in specific economies or organizations because labour is used more efficiently holding the input of capital constant.

The use of TFP measures mitigates the impact of factor substitution on measured productivity performance and, hence, isolates the consequences of “pure” efficiency gains more precisely. Nevertheless, there are complications shared by both partial and multi-factor productivity measures that can potentially give rise to misleading or inappropriate conclusions about the behaviour of productivity. For example, productivity measures should, in principle, account for both the quantity and quality of output(s) and input(s); however, incorporating quality changes meaningfully into output and input series presents a very difficult challenge.[8]

Another complication is the emergence of new outputs over time. To the extent that price indices used to deflate monetary measures of outputs and inputs to their real values are based upon baskets of outputs that are not perfectly representative of the actual mix of outputs purchased, price indices (and real output measures) will be biased. This implies biases in the calculated productivity indices.

Divergences between the output weights used to develop price indices and actual output weights are virtually certain to occur as statistical agencies such as Statistics Canada and the Bureau of Labor Statistics use a defined basket of goods as output weights for a discrete period of time. An implication is that measured productivity is unlikely to be an accurate measure of “true” productivity at any point in time. Moreover, if factors contributing to measurement errors vary in importance over time, even the temporal performance of measured productivity can be an inaccurate guide to true productivity trends.[9]

Technological Change

In its broadest sense, technological change can be thought of as the rate at which new production processes and products are introduced and adopted in the economy. The former is traditionally identified as the innovation stage, while the latter is identified as the diffusion stage. Most observers contend that any distinction between the innovation and diffusion stages of technological change is arbitrary, since diffusion involves continuous adaptation and improvement of the initial innovation. The introduction and adoption of new production processes and products presumably enable society to enjoy higher levels of real output holding constant the services of traditional inputs such as labour and capital. Hence, it should lead to increased productivity. Similarly, a faster rate of growth of technological change should lead to a faster rates of productivity growth, all other things constant. In this context, technological change is not necessarily a “free lunch.” That is, real resources must be expended to encourage technological change. However, the presumed net result is still increased real output given any initial endowment of factor inputs.[10]

New production processes often require the introduction and adoption of new products, e.g. new capital equipment, in order to be used. Hence, there is often no clear dividing line between a new process and a new product. Nevertheless, economists tend to think of new processes as primarily leading to reductions in conventional costs of production, whereas new products primarily lead to direct increases in the welfare of consumers by offering either new attributes or greater “conventional” attributes for the same price as older products (or a lower price).[11] While there is no implication that one form of technological change is more desirable, cost-reducing innovations are often more readily identifiable than “quality” improvements to existing products.

As noted above, technological change leads to increased productivity by increasing the real output (or, equivalently, the real income) of society that is attainable with the available productive resources. It might be noted that meaningful increases in real income also arise from reductions in “undesirable” outputs in the economy, such as pollution, crime and disease. Hence, technological change does not have to be associated with increases in material wealth in order to improve productivity.

The conceptual and practical problems associated with measuring technological change are, if anything, even more severe than those associated with measuring productivity change. Indeed, it is difficult to conceive of a single measure that would accurately reflect the complex and heterogeneous nature of technological change. As a result, various proxy measures are used by economists.

R&D as a Proxy for Technological Change

Perhaps the most widely used proxy for technological change is research and development (R&D) expenditures.[12] The straightforward presumption is that R&D is a necessary, albeit not sufficient, prerequisite for technological change. While there is much direct and indirect support for this presumption, it is much less clear that there is a precise and consistent relationship between R&D and technological change. For example, it is sometimes argued that the linkage between R&D and technological change is stronger during specific historical periods than others. Thus, it has been argued that the basic science “available” to be exploited by commercially oriented R&D was more abundant at various times prior to the mid-1900s, which is partially why rates of technological change (and productivity change) slowed during the post-1973 period.

It has also been argued that the nature of the R&D activities undertaken will condition the latter's linkage to technological change. For example, while it is conventionally assumed that R&D carried out in the private sector has a larger direct impact on productivity than R&D carried out in government or university laboratories, the indirect impact of non-profit R&D, especially basic research, can be quite large. Specifically, research carried out by non-profit organizations can be complementary to the R&D carried out by for-profit concerns. This leads to the possibility that both the "mix" and the quantity of R&D carried out in society influence subsequent rates of productivity change.[13] The evidence relating the composition of R&D to productivity and real economic growth will be reviewed in a later section.

The measurement of the stock of R&D capital, as an approximation of the stock of technical knowledge, is also subject to some of the problems that plague the accurate measurement of productivity growth. Two particular challenges complicate the construction of R&D capital stock measures: 1) deciding upon the appropriate depreciation rate for historical R&D expenditures,[14] and 2) determining the "correct" weight for R&D conducted outside the firm (or industry, or nation) to combine this potential source of borrowed or acquired technical knowledge with "own" R&D expenditures.[15]

Notwithstanding these measurement problems, R&D measures continue to be the most widely used proxies for technological change.

Patents and Other Proxies

Patents are prominent among other proxy measures of technological change. Whereas R&D expenditures are input-based proxies, patents are presumably output-based proxies. All other things constant, output-based proxies should be more meaningful than input-based proxies. Nevertheless, there are a number of well-known shortcomings associated with using patent intensities as measures of technological change. One is that patents may not be needed for technological activities where trade secrecy is a robust means of protecting intellectual property. A second is that simple patent counts are not necessarily indicative of the commercial significance of the underlying technology, or of the productivity impact of the underlying technology, all else constant. Indeed, patenting in some circumstances may be motivated primarily by a desire to increase the costs of entry facing potential rivals, in which case the major direct outcome of patenting activity is to generate monopoly profits rather than real productivity improvements. These caveats suggest caution in linking productivity change to patenting activity in order to assess the linkages between technological change and productivity change.[16]

In other cases, statistical or case studies focus on specific innovations and link the introduction and adoption of those innovations to the productivity performance of an industry.[17] The focus on specific innovations and their utilization allows a more detailed evaluation of the rich set of background factors that ordinarily condition managerial decisions to implement new technology, as well as the consequences of creating and implementing new technology. On the other hand, such focus limits the extent to which the findings can be generalized. Also, many innovations cannot be easily identified or segmented for purposes of specific study. For example, it is often difficult to identify organizational changes that may, in turn, affect productivity, or else specific changes are linked to other ongoing changes so that one is trying to attribute individual effects to what is really a set of joint "technological" inputs.

Technological Spillovers

Any measure of technological change needs to acknowledge that technological change going on outside the unit of analysis, whether that unit is an individual firm, an industry or a country, will affect the linkages between technological change and productivity change within the unit. Indeed, technological change occurring outside the unit can affect technological activities within the unit by altering the relevant marginal products and marginal costs of those activities.

The relevant concept here is technology spillover, which may be thought of as new technology created by specific organizations that is appropriated by other organizations without compensating (fully or at all) the creators for the value of the technology appropriated. An implication is that the productivity impacts of technological change may extend over a much broader range of organizations than those performing the bulk of the R&D, patenting and related activities associated with the technology in question. A related implication is that observing individual (or groups of) organizations performing relatively small amounts of R&D or patenting activity does not necessarily suggest that technological change is unimportant to ongoing productivity change in those organizations. Rather, it might suggest that conventional measures of technological activity are poor proxies for the actual stock of technological knowledge available to these organizations.

There is a substantial literature examining the technology spillover process, as well as the factors conditioning the magnitude of those spillovers.

This literature will be briefly reviewed in a later section. At this point, it is worth noting that the spillover phenomenon is of special potential relevance to Canada. In particular, the presence of relatively high degrees of foreign ownership has been linked to relatively low R&D intensity levels in Canadian manufacturing industries. The latter, in turn, has been linked to Canada's "poor" record in industrial innovation and productivity growth by those who believe that tighter controls on foreign ownership are in Canada's economic interest. On the other hand, proponents of a liberal foreign ownership regime argue that foreign-owned companies are a robust source for importing technology into Canada and therefore reduce the need for Canadian companies to undertake costly indigenous R&D.[18] Evaluation of these two competing positions requires evidence on the magnitude of the returns to indigenous versus "spillover" technology, as well as an assessment of the impacts of foreign ownership on each.

Technology Embodied in Labour and Capital

> "The introduction of new methods of production is so completely intertwined with capital investment that a monumental estimation problem presents itself to those who wish to measure the various influences of capital investment on productivity."
> (Boucher 1981, p. 94)

To the extent that new technology is embodied in labour and capital inputs, a potential identification problem arises. Specifically, it becomes difficult to identify empirically the contribution of "conventional" factor inputs to productivity growth separately from the contribution of new technical knowledge. Some economists have argued that the greatest portion of technological change takes the form of improved inputs, especially capital inputs. To the extent that this is true, increased usage rates of newer inputs will contribute to productivity growth, and it may be difficult to separate the impact of using improved inputs from that of an increased use of inputs, *per se*. A similar consideration applies to situations in which technological change is accompanied by increases in the scale of organizations and industries. That is, it can be difficult to empirically separate the productivity effects of increases in the scale and scope of economic organizations from the effects of implementing and exploiting new technologies, holding scale and scope constant.

Exogenous and Endogenous Technological Change

Complexities in modelling and estimating the linkages between productivity growth and technological change are exacerbated by the potential for direct and indirect simultaneity between the two processes. For example, a disembodied technological change, such as mathematical research that facilitates the implementation of high-speed digital communications networks, may ultimately spur investment in new computers and communications equipment that, in turn, introduces new technology into a wide range of manufacturing and service-sector activities. Productivity improvements resulting from the investment in new computer and communications equipment therefore reflect both the underlying mathematical research, as well as new capital investment. Separating the contributions of each to productivity growth is obviously a difficult empirical task.

3. EMPIRICAL STUDIES OF R&D, INNOVATION AND PRODUCTIVITY GROWTH

> "Inventions and innovations have been a major source of technological improvements and productivity gains."
> (Fortin and Helpman 1995, p. 17)

Notwithstanding the widely acknowledged difficulties in identifying the linkages between technological change and productivity growth, there is a vast empirical literature on the subject. Indeed, the size and scope of the relevant literature are far too extensive to summarize thoroughly in this report. Rather, reliance is placed upon reviewing other, fairly comprehensive, summary reviews of the literature along with relatively recent studies that significantly reinforce or amend earlier findings.[19]

There have been two broad approaches to identifying the contribution of technological change to productivity growth. One involves econometric and non-econometric identification of residual TFP growth after all factors potentially contributing to TFP growth (other than technological change) have been identified. This approach is associated with economists such as Edward Denison and Dale Jorgenson.[20] While these studies tend to document the statistical importance of the "unexplained" productivity residual (presumed to be technological change), there is substantial controversy surrounding the interpretation of the residual. In particular, there has been substantial debate surrounding the degree to which the residual reflects biases in the measurement of "conventional" physical capital and other inputs, as well as the contribution of economies of scale related to new production techniques.

A second approach, which is more representative of recent research seeking to identify linkages between technological change and productivity change, incorporates measures of technological change as explicit variables in models of productivity growth. The bulk of these studies focus on R&D performance as the proxy measure of technology; however, some case studies look at specific innovations and their economic effects. Our review of the relevant literature focuses on this second set of studies.

The literature review in this section will give separate consideration to econometric and non-econometric evidence. The primary focus of the review will be to identify and synthesize reported findings with respect to the following issues: 1) the private and social rates of return to R&D and other measures of innovation and technological change; 2) the private and social rates of return to different types of R&D and innovation, e.g. basic versus applied; government-funded versus privately funded; undertaken by for-profit or not-for-profit (including academic) organizations; and 3) the sources of technology spillovers, e.g. foreign R&D versus domestic R&D.

A second focus of the review is to summarize the specific available findings on these issues for Canada and to identify and explain, if possible, any distinctive differences between the Canadian and non-Canadian experiences.

Econometric Studies

These studies encompass statistical analyses of the linkages between real output (or productivity) measures and factors determining output (or productivity) changes including measures of technological change. The typical "setup" in these studies is to express the real growth of (or differences in) output as a function of the real growth of (or differences in) "conventional" factor inputs including labour and capital, and non-conventional inputs such as the services of R&D capital. Within a Cobb-Douglas (or a more flexible) production function framework, we can get direct estimates of output elasticities. In related models, the real output equation is transformed into a productivity specification. For example, labour productivity may be expressed as the difference in the growth rates of real output and real labour input. In models where the dependent variable is a measure of productivity, the estimated coefficients of the "technological change" variables are rates of return to technology inputs such as R&D.[21] The constant term is interpreted as a measure of the rate of "disembodied" technological change — that is, productivity growth unrelated to the growth in explicit technology input variables.

Canadian Evidence

Bernstein (1988) provides econometric evidence on private and social returns to R&D in Canada for a set of industries. He identifies the relative and absolute importance of spillovers through the fact that social rates of return to R&D investment are substantially higher than private rates of return. In fact, inter-industry spillovers are relatively small for all of the sample industries. Conversely, intra-industry spillovers are relatively large, particularly in industries that have a relatively large R&D spending propensity.[22]

The orders of magnitude are as follows: the social rates of return to R&D capital (net of depreciation) in industries with a larger R&D spending propensity are slightly more than double the 11.5 percent net private rate of return. Social rates of return to R&D capital in other industries are somewhat less than double the net private rate of return.

Bernstein also provides some evidence on the relationship between R&D spillovers and R&D performance in his sample. Specifically, inter-industry spillovers act as a substitute for the R&D capital input of the firm itself in every sample industry. The effect is quite pronounced, especially in industries with a relatively low propensity to spend on R&D capital. The intra-industry spillover effect on the performance of "own" R&D is smaller in absolute value than the inter-industry spillover effect. In industries with a relatively low R&D propensity, R&D spillovers discourage the performance of own R&D. In industries with a relatively high R&D propensity, there is a complementary relationship between intra-industry spillovers and own R&D performance.

Bernstein does not identify the specific channels through which spillovers occur, and he mentions this as an important focus for extending his work. It is perhaps suggestive that in the five industries where there is a significant difference between Canadian and foreign-owned firms' response to intra-industry spillovers, the unit costs of foreign-owned firms decrease relatively more than those of their Canadian counterparts. This result suggests that foreign direct investment may be an especially robust channel for intra-industry technology spillovers.

In a related study, Bernstein (1989) identifies the R&D spillovers from one Canadian industry to another. Nine separate manufacturing industries are examined for the period 1963–83. He finds substantial variation across receiving countries with respect to the number of industries generating spillovers. As well, spillover elasticities for the receiving countries were significantly different from each other. All nine industries had consistently high private returns to R&D. This latter result is not supported by a number of other Canadian studies. However, Bernstein's finding that social rates of return substantially exceed private rates of return is consistent with other studies. Industries with a relatively high R&D intensity did not necessarily have a higher rate of return on R&D capital. Nor were they consistently the major sources of R&D spillovers.

In a more recent study, Bernstein (1996) focuses on technological spillovers associated with R&D activity in the communications equipment industry. He finds substantial spillovers from this industry to the entire Canadian manufacturing sector. In terms of relative importance, however, the R&D spillovers from the U.S. manufacturing sector have a greater impact on Canadian manufacturing factor intensities than spillovers from the domestic communications equipment industry. At the same time, there are spillovers from both the Canadian manufacturing sector and the U.S. electrical products industry to the Canadian communications equipment industry. The R&D capital from the U.S. electrical products industry has a greater impact on the production structure of the Canadian communications equipment industry than R&D capital from the Canadian manufacturing sector.

Bernstein's study of the communications equipment industry further underscores the importance of international technology spillovers to Canadian industries. Specifically, he finds that spillovers from the U.S. manufacturing sector accounted for around three-quarters of the average annual rate of productivity growth in all Canadian manufacturing industries. The important spillovers from the Canadian communications equipment industry are underscored by the differences between the private and social rates of return to R&D in that industry. Specifically, the social rate of return to Canadian communications equipment R&D capital is estimated at 55 percent, or 225 percent higher than the private rate of return. By contrast, the social rate of return associated with Canadian manufacturing R&D capital is estimated at 21, or 24 percent higher than the private rate of return. The implied negative private rate of return to manufacturing R&D capital is consistent with a number of other studies that fail to identify any within-industry productivity effects of private R&D expenditures in Canadian manufacturing industries. This latter result is a curiosity that remains to be explained satisfactorily.

Mohnen (1992) reviews a number of Canadian and non-Canadian studies of the returns to R&D and presents some original econometric evidence. He notes in his review that there is mixed evidence for Canada. Specifically, a number of studies offer little support to the existence of a strong link between R&D and TFP growth; however, others obtain estimates that are consistent with those found for other countries. His own econometric results suggest a weak linkage between Canadian R&D and TFP growth in Canadian industries.[23] Indeed, in some specifications of the model, there is no statistically significant relationship. He suggests that the issue be re-addressed with new data and new models. In particular, a more disaggregated analysis might provide a clearer picture of why the impact of R&D performed in Canada differs from that of R&D performed elsewhere.

With respect to other characteristics of R&D, Mohnen tends to confirm "conventional wisdom". In particular, social returns to R&D are substantially higher than private returns, and returns are higher on company-financed R&D than on publicly financed R&D. The latter result underscores the indirect contribution of publicly financed R&D, i.e. it is a complement to privately financed R&D.

The previously cited findings of relatively low private rates of return to R&D expenditures by Canadian manufacturing firms seemingly belie the wisdom of frequent calls for increased government encouragement of private R&D expenditures. Indeed, they may suggest that Canada's relatively generous framework of support for private sector R&D encourages a substantial number of marginally profitable innovation activities. Alternatively, they may suggest that the environment for exploiting industrial scientific "breakthroughs" in Canada is unfavourable, and that the breakthroughs, such as occur, are exploited by the user companies in ways that do not directly improve the productivity of Canadian manufacturing establishments. For example, new industrial knowledge might be used primarily by the foreign affiliates of Canadian multinational companies.[24] Given the paucity of evidence bearing upon this issue, it is impossible to do more than speculate on the plausibility of both the reported findings on private returns to Canadian industrial R&D, and the explanations of those findings.

Other Studies

Griliches (1998) summarizes the results of extensive econometric studies of rates of return to privately and publicly funded R&D in the United States. These returns tend to cluster in the range of 18 to 20 percent. He highlights the fact that there is no differential impact of federal versus private company R&D dollars on the levels and rates of growth of total factor productivity at the firm level, although differences are evident at the industry level. It is suggested that the latter result reflects the differential rates of government R&D funding across industries. To the extent that government funding is concentrated in areas where private funding would otherwise be "excessively low" from the perspective of social efficiency, perhaps because the returns to R&D are particularly difficult to appropriate in those areas, differences between returns to privately and publicly funded R&D should be expected. The studies almost uniformly show substantial and significant returns to own R&D.[25] Significant spillovers from R&D conducted outside the firm are also documented.[26]

The difficulty with identifying returns to own R&D and R&D conducted outside the organization is that own R&D may enable the organization to better exploit available R&D spillovers. Studies tend to show that the interaction between a firm's R&D stock and foreign R&D spillovers is generally positive and significant.[27] This result is consistent with findings that foreign technology spillovers are a complement to the firm's own R&D. This complementarity was noted earlier in Canadian studies referenced. What is less well established in the literature is how the nature of internally performed R&D affects the ability of an organization to benefit from technology spillovers. For example, is applied research more complementary to technology spillovers than expenditures on process and product development? The issue seems especially relevant for Canada, given the prominent contribution that foreign technology spillovers make to productivity growth in this country.

Available evidence suggests that returns to R&D vary with the nature of the R&D undertaken. For example, the rate of return to basic research is higher than the rate of return to R&D expenditures, on average (Griliches 1998).

Case Studies

Case studies of specific innovations provide another approach to examining the social and private returns to innovation. Such case studies are subject to the familiar criticism that their results cannot necessarily be generalized. However, they tend to be consistent with the outcomes of econometric studies. Hence, in combination with econometric studies, case studies tend to paint a fairly consistent picture of the impacts of innovative activities.

Mansfield (1996) summarizes a number of major case studies of industrial innovations including some of his own work. The innovations identified primarily took place in manufacturing industries, albeit covering a wide range of manufacturing activities. Many of the innovations studied were of "average" importance, so as to avoid the obvious bias of focusing on particularly successful innovations. While social rates of return vary across innovations, they are typically quite high, i.e. generally in the range of 30 to 50 percent, and sometimes much higher. Typically, these estimated social rates of return are substantially higher than the corresponding private rates of return, and the gap is especially pronounced for major innovations.

Baily and Chakrabarti (1988) examine four industries (chemicals, machine tools, electrical power and textiles) quite intensively. Based upon case studies, they argue that the evolution of technology has been a vital part of the productivity performance of these industries.

Griliches (1998) summarizes several other case studies, particularly those focused on government-supported innovative activities. These studies also confirm the existence of very high rates of return to innovation. For example, the rate of return to R&D expenditures by NASA is about 40 percent per year in perpetuity. This is more than double the rate of return to all other types of R&D undertaken in the United States. However, Griliches offers a number of strong methodological criticisms of these studies.

Existing research tends to conclude that publicly financed R&D has a lower rate of return that privately financed R&D. In part, this reflects the "non-commercial" nature of much of the R&D financed and undertaken by governments. However, government-financed R&D, on average, generates spillovers for private R&D endeavours. Specifically, it reduces the cost to industries and thus enhances their productivity growth. However, it also seems that publicly financed R&D "crowds-out" company-financed R&D in many industries (Mamuneas and Nadiri 1996).

Patent data indirectly support the conclusion that technological activity undertaken in government and university laboratories leads to significant scientific benefits. For example, Henderson, Jaffe and Trajtenberg (1998) examine a comprehensive database consisting of all U.S. patents granted to universities or related institutions from 1965 until mid-1992. They show that, averaged over the whole period, university patents are both more important and more general than the average patent, but that this difference has been declining over time. Their measure of importance is the number of "citations received". Given the government's funding priorities, it is not surprising that university patenting is particularly intensive in the areas of pharmaceuticals and medical technologies.

To be sure, scientific significance does not equate to "commercial" significance. Especially in the health care area, there has been substantial controversy surrounding the issue of whether technological innovation has improved efficiency, on balance, or whether the costs have exceeded the relevant benefits. The critical notion here is that hospitals compete against each other, in part, by investing in new technology. Since the expected private returns to investment in new diagnostic and treatment procedures include the net revenues competed away from other hospitals, the average social rate of return to introducing new technology in individual hospitals might well be lower than the average expected private rate of return. This controversial issue is difficult to resolve empirically. Indeed, case studies highlight the difficulties associated with quantifying the net benefits of new technology and, by extension, publicly funded technological activities in this area.

Perhaps the most careful attempt to quantify the net benefits of new health care technology is Baily and Garber's (1997) comparison of the relative productivity of the U.S., British and German health care systems in treating a set of illnesses, including diabetes, breast cancer, lung cancer and gallstones. In their comparison, the authors try to incorporate morbidity and mortality among patients into their productivity estimates. For our purposes here, their main finding is that technology adoption was an important factor affecting productivity. Specifically, faster adoption of new techniques such as CT scans generally improved productivity.

Critics of the Baily and Garber study highlight the crucial importance of their assumptions about morbidity and the controversial nature of these assumptions. In effect, output measurement problems cast some doubt on the reliability of their conclusions.[28] In a similar vein, biases in the measurement of "quality-adjusted" output in the pharmaceuticals industry render estimates of the net benefits of new drugs highly uncertain.[29]

The health care sector is of major importance to technology policy. For one thing, it is a relatively large sector in developed economies, and productivity growth in that sector is extremely important to the successful containment of spending growth without the sacrifice of accessibility and service quality. For another, it is the focus of a substantial amount of innovation activity in developed countries, particularly government-funded innovation activity. The serious lack of knowledge about the net social benefits of this activity therefore constitutes a substantial and worrisome gap in our understanding of the technological change process and the factors conditioning this process. This may be a particularly relevant criticism for Canada. Although Canada spends absolutely and relatively less than the United States on promoting health care technology, the presumption has been that Canada benefits from technology spillovers in this sector, as it does in the manufacturing sector. However, the previously cited studies of technology spillovers in Canadian industries shed little light on whether the spillover phenomenon extends to "public sector" activities such as health care. For example, it can be conjectured that Canadian health care suppliers, under the direction of government policy makers, may be relatively slow to adopt new technology developed outside the country.

4. FACTORS CONDITIONING THE INNOVATION-PRODUCTIVITY GROWTH LINKAGE

This section of the report reviews and synthesizes evidence about the factors that increase or diminish the contribution of technological change to productivity growth. In effect, it focuses on factors that promote closer and stronger linkages between technological change and productivity change. These factors can operate on at least two levels: 1) they can encourage a faster rate of technological change by accelerating and/or deepening the introduction and diffusion of new “best practices”; 2) They can promote the more effective commercialization and use of new best practices.

Factors that have been identified as relevant in this regard include: 1) the education and skill level of the workforce; 2) the extent of competition in domestic industries; 3) the openness of the domestic economy to foreign trade and foreign direct investment; 4) the strength and nature of intellectual property protection; 5) the social “infrastructure”; and 6) government policies of various types.[30]

The linkages between government and private sector research organizations, as well as those among innovating organizations, have been the focus of what has been described in the literature as “systems of innovation.” A set of potentially relevant linkages is provided in Table 2. In effect, the concept of a national or international system of innovation codifies the main specific sources of innovation spillovers among and between public and private sector organizations. While some evidence exists about most of the linkages identified in Table 2, the bulk of reliable statistical evidence concerns international linkages.

Table 2 **Factors Underlying a National System of Innovation**
Linkages with foreign research institutions
National tradition of scientific education
National funding of basic research
Commercial orientation of research institutions
Labour mobility
Venture capital market
Government role in technology diffusion
Collaboration with research institutions
Inter-firm R&D cooperation
Utilization of foreign technology

Source: Bartholomew 1997, p. 247.

International Integration

The available evidence tends to provide overwhelming support for the arguments that international trade and foreign direct investment are important channels for the global distribution of new technologies, and that smaller countries such as Canada are disproportionate beneficiaries of international technology flows. There is less agreement on the relative importance of specific alternative modes of international business with regard to linking technological changes to domestic productivity growth.

Potential channels for the international transmission of technical knowledge include: 1) imports of capital goods and intermediate inputs; 2) foreign direct investment; 3) joint ventures and strategic alliances; 4) technology licenses; and 5) migration of skilled labour. Some studies have attempted to evaluate the robustness of these various channels of international technology transfer, although most do not address the issue in any comprehensive manner.

Gollop and Roberts (1981) provide a relatively early contribution to this literature in their study of a sample of approximately 20 U.S. industries. They conclude that foreign-supplied intermediate inputs have important direct and indirect effects on the sectoral productivity growth of their sample of U.S. manufacturing industries. Gera, Gu and Lee (1998b) confirm this broad finding with respect to imported information technology (IT) products. In particular, they conclude that international R&D spillovers from the IT sector played a dominant role in Canada over the period 1971–93. They estimate the rate of return on R&D embodied in IT imports at about 37 percent per year over the period, while it is only around 9 percent per year on R&D embodied in non-IT imports. They also find that international R&D spillovers are insignificant for the United States, although when they distinguish between international R&D embodied in IT and non-IT imports, they find a strong and significant effect of international R&D spillovers embodied in IT imports on productivity growth.

Conversely, Mohnen (1992) focuses on the role of foreign R&D spillovers in Canadian manufacturing. His results do not suggest an effect of foreign R&D as strong as might have been anticipated. Indeed, over the period 1965–83, Mohnen estimates that foreign R&D contributed a modest 2.5 percent to total factor productivity growth in Canadian manufacturing industries. However, this contribution was relatively more significant than the contribution of domestic R&D.

Globerman, Kokko and Sjoholm (forthcoming) provide some additional insight into the nature of international channels of technology spillovers in their study of patent citations by Swedish firms. The authors examine patent citations of Swedish multinational companies (MNCs), as well as small and medium-sized enterprises (SMEs) in Sweden in order to assess whether the sources of the patents cited differ across the two samples. Their results show that Swedish firms use more references to countries with large patent stocks, as well as to countries located close to Sweden. Trade contacts and outward Foreign Direct Investment (FDI) also seem to facilitate technology diffusion. However, there seems to be some differences between MNCs and SMEs regarding the importance of the various technology transfer channels. Most notably, trade contacts appear to be more important for SMEs than for MNCs. A plausible explanation is that the latter enjoy access to information through their network of foreign affiliates, while SMEs must rely more on "arms-length" sources of technological information including foreign trading partners.[31]

Industry-specific studies further support the notion that the importance of specific international channels of technology transfers is "context-specific." For example, international cooperative alliances are a particularly important means for firms to enhance their innovative capability in biotechnology (Bartholomew 1997). Whether this will remain true as major multinational companies emerge as important suppliers of biotechnology products is a matter for speculation.

The preceding results unveil a promising line of inquiry for Canadian research. Specifically, while the available research summarized above strongly suggests the existence of international spillovers to Canada, we are aware of no research that attempts to identify whether firms of different sizes and degrees of international exposure emphasize different international technology transfer channels. In particular, while there is an abundant literature on the nature of the technology transfer mechanism within multinational companies in Canada, the ways in which small and medium-sized enterprises assimilate and use new foreign technology have not been studied extensively.

Management

The intuitive notion is that the "quality" of management affects the creation and utilization of technology. In principle, "effective" managers should exploit available technology to promote productivity growth within their organizations. While there is some broad support for this intuitive notion in specific industry case studies (Baily and Chakrabarti 1988), there is no consensus on the characteristics that make for "good technology management." Thus, Globerman

(1975) found no systematic evidence that the educational background of managers was a significant factor affecting the adoption of new technology in the Canadian tool and die industry. However, more educated managers seemed more inclined to adopt new computer technology in several service sector industries (Globerman 1984).

In other cases, the influence of management might be indirect. For example, the organizational structure can influence the willingness and capability of firms to adopt and exploit new technologies. Management, in turn, presumably influences the organizational structure. An interesting study in this regard is that of Adams and Jaffe (1996) who find that the productivity-enhancing effects of parent-firm R&D diminish with the geographical distance separating production facilities from the research laboratory, as well as with the "technological distance" between the product field focus of the company's R&D facilities and the company's plants. Another suggestive plant-level study concludes that plants with integrated fabrication and assembly operations appear to use technology more effectively than plants engaged only in fabrication or assembly (Beede and Young 1998).

Education

It also tends to be "conventional wisdom" that universities and technical colleges can promote the productivity-enhancing effects of new technology by, among other things, encouraging the dissemination of "laboratory" results to industrial practice. In principle, government research institutions can play the same role, although the absence of a teaching function these organizations deprives one mode of faster commercialization of new technology, i.e. the migration of students into industry as researchers and administrators.

Bartholomew (1997) argues that the "academic" environment is an important conditioning factor of national performance in the biotechnology industry. In particular, closer ties between the academic research system and industry, which can take the form of more industrial consulting by academics and more funding of academic research by industry, promote the accumulation and diffusion of technical knowledge. However, the importance of such ties may vary across countries. For example, "small" nations such as Canada may be able to capitalize on the research activities of foreign universities. However, in some industrial activities, the characteristics of Canadian industries may be sufficiently unique that basic and applied research conducted in foreign research institutions would be largely inapplicable in Canada.[32]

Engelbrecht (1997), among others, shows that general human capital is a vehicle of international knowledge transfer associated with productivity catch-up amongst OECD countries. That is, general human capital better equips organizations to exploit potential technological spillovers from abroad.[33] At the same time, scientific expertise in production facilities can promote faster and more effective diffusion of technology from a company's research facilities to its production facilities.

Intellectual Property Protection

There is a fairly substantial literature assessing the importance of intellectual property protection for the generation and utilization of new technology. The findings of this literature can be summarized as indicating that formal intellectual property protection is of importance only in a few industries, most notably pharmaceuticals and industrial chemicals.[34] For a small country like Canada, stronger intellectual property protection does not seem to be a promising policy to promote more robust linkages between technological change and productivity growth in most domestic industries.

Venture Capital

Yet another element of conventional wisdom is that venture capital financing must be available to help entrepreneurial firms commercialize new technology and ultimately enable that technology to be used to increase productivity. The available evidence offers no reason to gainsay this piece of conventional wisdom. What is much less clear in the literature is whether venture capital markets are geographically segmented and, if so, what accounts for any such segmentation. Moreover, one should not necessarily presume that concentration of both venture capital sources and high-technology activities implies that government policies encouraging the former will lead to the latter. That is, venture capital sources may "follow" the emergence of technological "centres of excellence" rather than substantially contributing to the creation of such centres.

5. TEMPORAL PATTERNS IN THE LINKAGES

This section will address the speculation that the relationship between technological change and productivity change has undergone profound alterations over the post-war period by considering the available evidence on the issue. One hypothesis is that the productivity payoff to science and technology declined in the 1970s and 1980s because the major scientific "breakthroughs" of earlier periods had been largely exploited commercially by the early to mid-1970s. A second hypothesis is that the emergence of new computer and communications technologies and related developments, such as the Internet and the World Wide Web have dramatically increased the productivity returns to investments in technological activities. A third hypothesis is that developments in international trade and investment, as well as increases in the education and skill levels of the workforce, have led to increased intra-national and international spillovers of technology, thereby increasing social rates of return to R&D and innovation but reducing comparable private rates of return.

Griliches (1988) argues against the existence of a secular decline in R&D productivity based upon the observation that manufacturing and agricultural productivity in the United States has exhibited no secular declining trend. He argues that the linkage between R&D and productivity growth is probably more stable and more readily identified in those sectors than in other sectors of the economy. Hence, if R&D productivity were declining, it should be most readily apparent in a declining productivity performance of the manufacturing and agriculture sectors.

Mohnen (1992) provides a comprehensive assessment of the literature relating productivity growth to R&D performance. The studies reviewed are primarily econometric in nature. He interprets the evidence as rejecting the notion that the productivity of "own" R&D has declined over time, but he considers the evidence more equivocal with respect to whether there has been a decline in the productivity of "imported" R&D.

As Fortin and Helpman (1995) note, the decline in labour productivity during the post-1973 period does not seem associated with a decline in the capital-to-labor ratio, at least in Canada. This suggests that technological change may be the culprit. The decline in R&D intensity in many developed countries in the 1970s is potentially consistent with a future decline in productivity, although the decrease in R&D intensity does not seem sufficiently substantial to be a major part of the post-1973 productivity growth slowdown story. The more general view is that "exogenous" events such as the energy crisis, increased government regulation and a stronger emphasis on "non-commercial" objectives such as environmental remediation are more important explanatory factors.

6. COMPUTERIZATION AND PRODUCTIVITY GROWTH

> "Information technology-broadly defined to include computers, software and communications is the most important technology today."
> (Bresnahan and Greenstein 1996, p. 2)

A number of studies focus explicitly on the impact of computerization on productivity change, as well as on the factors conditioning that impact. Siegel (1997) summarizes and evaluates a number of relevant studies. His main point is that earlier studies are potentially unreliable because of biases in the measurement of computer prices and utilization, and because of a failure to explicitly acknowledge that improved labour quality usually accompanies increased computerization.[35] Previous studies also generally ignore the potential for productivity change to influence computerization as well as the reverse. These shortcomings make it likely that earlier studies have produced biased and inconsistent estimates of the linkage between productivity change and computerization.

Siegel attempts to rectify for these shortcomings by estimating a model linking total factor productivity differences across a set of four-digit (SIC) U.S. industries to differences in computer usage, as well as to other independent variables. His results imply that the marginal productivity of investment is higher for computers than for other types of capital. Moreover, he finds a positive and statistically significant relationship between productivity growth and investment in computers, with an excess estimated rate of return on computers of about 6 percent.

Conversely, Stiroh (1998) argues that sectoral differences are crucial in understanding the impact of computers. He examines data on 35 manufacturing and service sectors for the period 1947–91. He finds that the computer-producing sector enjoyed rapid TFP growth over the sample period. For other sectors of the economy, the decline in the price of real computing power encouraged a substitution away from relatively expensive labour and non-computer capital towards relatively cheap computers. However, there is no evidence that this accumulated investment in computing capacity increased TFP in using industries, on average. In a similar vein, Lehr and Lichtenberg (1996) examine trends in computer usage and the effect on productivity growth for a sample of U.S. federal government agencies over the period 1987–92. They find that computer usage contributed to productivity growth, although the impact was not dramatic.

Other studies focus more broadly on "Information Technology" (IT) and its linkages to productivity growth. One notable study in this regard for Canada is Gera, Gu and Lee (1998a). The authors study the extent to which investments in IT contribute to labour productivity growth in Canada and the United States, and whether domestic and international R&D spillovers from the IT sector are important for labour productivity growth. Their main conclusions are: 1) IT investments are an important source of labour productivity growth across Canadian industries; 2) R&D spillovers in Canada are primarily international in scope; and 3) IT investments and international R&D spillovers embodied in IT imports also have positive and significant impacts on labour productivity growth across U.S. industries, but the results are less robust than for Canada.

The OECD also considered the linkage between investment in information technology and productivity growth in an international context. Its examination underscores the difficulties in reliably identifying the precise linkage, especially in the presence of measurement errors in the relevant variables and an uncertain lag structure among the variables. Hence, while it finds a positive impact of IT capital on productivity in the service sectors of OECD countries, its statistical significance was not confirmed.

Part of the explanation of the somewhat ambivalent findings with respect to the strength of the measured linkages between computerization, investments in IT capital more generally, and productivity growth may reflect a heterogeneous experience across organizations. For example, Antonelli and Marchionatti (1998), among others, argue that only large, vertically integrated firms can “bear” the delays between the adoption of new information technologies and their positive effects on productivity growth.

7. AGREEMENTS, DISAGREEMENTS AND UNCERTAINTIES

> "As progress was made, it became clearer how much we still don't know and how thin are our data."
> (Griliches 1998, p. 270)

This section attempts to summarize the major areas of agreement, disagreement and uncertainty surrounding the linkages between R&D and innovation, technological change and productivity growth.

At a relatively broad level, there is a fair degree of consensus on several issues. One is that technological change is, indeed, a major contributor to productivity growth. As a related point, there is also agreement on the fact that this contribution is not uniform across firms, industries and countries, and that the contribution of technological change to productivity growth probably has not changed substantially over the post-war period.

A second point of broad consensus is that social rates of return to R&D (and innovation, more generally) exceed private rates of return by a substantial margin. International technology spillovers are especially important for smaller countries such as Canada. International spillovers take place through a number of different channels including foreign direct investment, trade and strategic alliances. The robustness of these channels varies with the nature of the economic activity; however, it is difficult to generalize about these differences with any precision.

A third point of broad agreement is that attributes of the domestic environment influence the linkages between technological change and productivity growth. For example, the adoption of new technology, as well as the benefits derived from new technology adoption, will be functions of domestic economy attributes such as the exposure of domestic industries to competition, the general educational level of the work force, and the availability of venture capital, among other things. There is much less agreement on the relative importance of these various factors, or on whether and how the importance of individual factors varies across industries or economic activities.

A fourth broad point of agreement is that government-funded R&D has significant private sector spillover benefits, although most of the evidence pertains to U.S. government activity, and the results may be idiosyncratic to an individual government experience. It is also agreed that basic research provides important spillover benefits and is a strong complement to private sector R&D activities. The factors that condition the spillover benefits from public sector R&D funding and performance are less clear. Obviously, the closer the "integration" between government and private sector research laboratories, the more complementary private and public sector R&D are likely to be. However, it is unclear how to best structure this integration. As well, the literature tends to ignore the "public choice" aspects of any such integration, i.e. will it lead to increased funding of projects with relatively high private rates of return and relatively low social rates of return?

A fifth point of agreement is that formal intellectual property protection is an important determinant of technological behaviour only in some industries.

Finally, virtually all economists agree that the measurement of both productivity change and technological change is highly problematic and that it is likely that "official" estimates are seriously biased. They also agree that the estimation of the relevant linkage between technological change and productivity change is extremely difficult. In particular, it is subject to daunting statistical difficulties, while case study approaches to their issue suffer the potential weakness of being case-specific.

Most of these points of agreement are relevant in the Canadian context. However, there are attributes of the Canadian experience that are arguably less well established than for other countries, especially the United States. In particular, there is a significant body of evidence suggesting that rates of return to R&D are lower in Canada than in other developed countries and, indeed, may be statistically insignificant across broad samples of firms and industries. The reasons for such differences remain unclear, notwithstanding claims that they reflect Canada's industrial structure including relatively high levels of foreign ownership and a relatively large primary manufacturing sector.

From both a Canadian and an international perspective, it seems fair to conclude that we know relatively little about the linkage between technological change and productivity change in major "public sector" activities such as health care and education. Indeed, while it is suggested that the advance in IT technology is, perhaps, the major future source of productivity growth in service industries, most available studies of the linkages between technological change and productivity growth have focused on manufacturing industries and even agriculture. We know comparatively so little about the welfare impacts of technological change in the health care sector, for example, that whether technological change in this sector is welfare improving or welfare decreasing, from a social perspective, is a matter of strong debate.

Correspondingly, most of our understanding of international technology spillovers is associated with the experience of manufacturing industries. Given the size and policy importance of service sectors such as health care and education, the relative paucity of information about international technology spillovers for these sectors is a major shortcoming. In particular, given the very limited “trade” and cross-border investment taking place in these sectors, there are grounds for real concern that Canadian suppliers are not benefiting from the strong spillover benefits realized by Canadian manufacturers.

8. FUTURE RESEARCH AGENDA

Identification and prioritization of a research agenda will ultimately reflect the biases of the researcher. For example, Griliches (1998) sets out a research agenda that emphasizes dealing with econometric and variable measurement problems that have plagued earlier statistical studies of the linkage between R&D and productivity growth. Others underscore the merits of a broader focus on the innovation structure of a country including the role that educational and government research institutions play in the innovation and diffusion process.

While it is certainly important to refine our understanding of measurement and econometric problems plaguing statistical identification of the linkage between technological change and productivity change, my view is that Canadian policymakers would benefit more from examinations of more basic issue :

1. Perhaps first and foremost, we know very little about the role of technological change in the delivery of health care services in Canada beyond the obvious fact that new technology has been adopted by Canadian health care providers and that health care practices have changed accordingly. For example, we are far from a consensus about whether technological change is proceeding “too rapidly” or “too slowly” from a productivity perspective. We also know relatively little about the channels through which international technology spillovers occur in this sector, or about the robustness of the channels, or, indeed, whether the institutional arrangements of the Canadian health care sector strongly condition the international technology spillover process. While similar statements can be made about other public sector activities such as education, the relative size and policy prominence of the health care sector would seem to dictate that priority be give to addressing the relevant gaps in our knowledge about this sector.

It would seem that alternative approaches to filling this knowledge gap are potentially viable, although, as noted above, measuring productivity in this sector is extremely difficult. Nevertheless, the emergence of studies identifying the adoption of new procedures and techniques in different countries, as well as the consequences of those innovations, offers the basis for a comparison between Canada and other countries. For example, would econometric or more qualitative studies show that productivity-enhancing medical innovations are being adopted at a slower rate in Canada than elsewhere? If so, what factors are contributing to this phenomenon? Is international technology transfer to Canada proceeding more slowly in the health care sector than in manufacturing? And so forth.

Obviously, similar questions can be raised about the educational sector. Budgets permitting, a similar research focus on the educational sector could be justified for reasons similar to those relevant to the health care sector. The fact that there is a fairly substantial private educational system offers the basis for an additional perspective on the main issue of interest. Specifically, it enables a direct examination of differences that ownership incentives make in adopting and exploiting new technology to promote productivity growth.

2. As noted above, available evidence suggests that rates of return to privately funded R&D in Canada are generally lower than in the United States and perhaps in other developed countries. The reasons for any such gap are unclear, although numerous hypotheses have been posited. The majority of Canadian studies have focused on the determinants of R&D intensity in Canada, rather than on the determinants of the "marginal productivity" of technology inputs. Yet the latter issue is clearly important, since promoting a higher R&D intensity may be an inferior policy measure if public resources "spent" on improving the "yield" of innovation activities in Canada have larger net social benefits.

There are various approaches to studying this issue. However, it would seem that the most promising approach would involve a number of careful case studies in which relatively homogeneous samples of Canadian firms would be compared to similar samples of foreign firms. The samples could be constructed to represent various manufacturing and service industries. It is unlikely that published data would be sufficiently detailed to permit an adequate examination of the relevant issues. Indeed, it seems more likely that an original data set would need to be constructed.

It is not possible to consider here all the difficulties associated with this task. However, it would seem possible to gather sufficient original data, perhaps through surveys, to produce estimates of productivity growth and of rates of adoption of new production techniques. With data on other firm- and plant-level attributes of the sample organizations, it would seem possible to undertake a statistical examination of the factors conditioning the linkage between productivity growth and new technology adoption. Thus, one might "estimate" productivity growth equations in which the "technology-adoption" variable is "interacted" with variables such as the educational background of managers and workers, the size and scope of the organization and so forth, to see which factors, if any, significantly enhance or diminish the strength of the linkage between productivity growth and innovation adoption. The values of the significant variables could be compared between the Canadian and non-Canadian samples to shed some light on the specific factors that might account for a lower (or higher) productivity payoff to new technology adoption in Canadian organizations.

3. A third broad focus of the Canadian research agenda might be to contrast and compare the role of Canadian universities to U.S. universities in promoting and enhancing the linkages between technological change and productivity change in Canada. Most of the focus of policy-oriented research in Canada has been on the nature of university-industry collaboration in domestic innovation activities. Virtually no attention (of which we are aware) has been paid to the issue of how Canadian universities bring foreign-developed technology into the Canadian economy, and whether and how Canadian universities are promoting international technology spillovers in Canada. Given the documented importance of international technology spillovers to Canadian productivity growth, this would seem to be of importance to Canadian policy makers.

Various possible approaches might be taken to address this issue. For example, patents issued to Canadian university-based researchers might be examined to identify citations to other patents. Whose patents are being cited? Compared to a comparable sample of, say, Swedish university-based researchers, are Canadian researchers more likely to cite foreign sources in their patent applications, all other things constant? Are Canadian university-based researchers as likely to file patents jointly with foreign researchers as, say, Swedish university-based researchers, or their counterparts in U.S. universities, all other things constant. If patent data did not permit an adequate examination of this issue, it might be feasible to construct an original data set through interviews with Canadian university technology liaison offices.

NOTES

1 See, for example, Chipello and Ricklefs (1999). There is a good deal of controversy surrounding recent estimates by Statistics Canada of Canadian productivity performance. See, for example, McCarthy (1999).

2 In his February 1999 budget, Finance Minister Paul Martin highlighted the government's view that more R&D and innovation is critical to improving productivity growth in Canada and promised financial incentives to encourage increased technological activity in Canada.

3 *Ibid.*

4 For a temperate perspective on this issue, see Bresnahan and Greenstein (1996).

5 An early seminal review of the technological performance of Canada, as well as its causes and consequences, is provided in the Report of the Senate Special Committee on Science Policy (1970).

6 A non-technical discussion of the various productivity indices is provided in Baily and Chakrabarti (1988). A more technical discussion is found in Wagner and van Ark (1996). It has been shown that for U.S. calculations, productivity measures tend to be in agreement as to which industries have high versus low productivity growth rates; however, this is not necessarily the case for other countries. See Mann (1997).

7 Estimation results can be sensitive to the precise output measure selected, although it is beyond the scope of this report to consider the differences. The interested reader might consult Basu and Fernald (1995).

8 The consequences of failing to adjust accurately for input and output quality changes are discussed in a later section.

9 Englander (1988) reports some evidence suggesting that measurement problems may make it difficult to derive any useful inferences on short-term and medium-term evaluation of total factor productivity.

10 The endogenous growth literature describes the potential for essentially increasing returns to investment in technological change. In effect, the

marginal product of "technology" as an input to production can be expected to increase as expenditures on technology increase. This view cuts against the traditional notion of diminishing returns to any factor input. For an overview of the endogenous growth literature, see Howitt (1996).

11 See, for example, Bernard and Jones (1996).

12 It should be explicitly acknowledged that R&D expenditures are inputs to the technological change process. The usual presumption is that productivity change is directly related to R&D expenditures; however, the nature and magnitude of the linkage between the two quantities is ultimately an empirical question.

13 We shall review the evidence on this and related points in a later section. For a perspective on these issues, see Henderson, Jaffe and Trajtenberg (1998).

14 Lev and Sougiannis (1998) demonstrate empirically that the identification of the (private) economic benefits of R&D expenditures is sensitive to the assumed pattern for amortizing past R&D expenditures.

15 These issues are discussed in Griliches (1998).

16 Issues associated with the use of patents as an indicator of technological change are comprehensively discussed in Griliches (1990).

17 For an example of this approach, see the industry case studies in Baily and Chakrabarti (1988). In the Canadian context, see Baldwin, Diverty and Sabourin (1996).

18 This debate and the surrounding literature is reviewed in Globerman (1985a).

19 Major reviews of the literature can be found in Griliches (1998) and Mairesse and Sassenou (1991).

20 For a review of this literature, see Baily and Chakrabarti (1988).

21 Estimates of the rate of return to investment in R&D can be indirectly derived by multiplying the relevant output elasticities by the appropriate ratios of R&D to capital stocks. See Coe and Helpman (1995).

22 The inter-industry spillover variable is defined as the sum of the R&D capital stocks for all other industries lagged one period. The intra-industry variable for any corporation in the sample industry is defined as the sum of the R&D capital stocks of all rival firms in the same industry, lagged one period.

23 Several industry-specific studies also fail to identify a statistically significant relationship between R&D and productivity growth. For example, Mohnen, Jacques and Gallant (1996) find that R&D in Canada's pulp and paper and wood industries had a minimal impact on TFP growth over the period 1963 to 1988. However, the estimated rate of return, while lower than for some countries such as the United States and Finland, was higher than for others such as Sweden.

24 The large presence of Northern Telecom's manufacturing facilities in the United States suggests the plausibility of this inference in the case of this large R&D performer.

25 Estimated rates of return are in the 30–40 percent range, which is consistent with the results cited by Mohnen (1992).

26 Exceptions to this statement have been identified. For example, Bernstein and Mohnen (1998) find that there are international spillovers from the United States to Japan but not in the reverse direction. As well, the own-R&D variable has been found insignificantly related to productivity growth in other countries beside Canada, for example Korea. See Kim and Nadiri (1996).

27 See, for example, Basant and Fikkert (1996). This is also apparently true for spillovers that occur at the plant level. That is, spillovers affecting plant-level productivity are a function of firm-level R&D intensity. See Adams and Jaffe (1996).

28 See Cutler (1997).

29 For a discussion of this point, see Berndt, Cockburn and Griliches (1996).

30 The relevant body of literature is broadly concerned with national and international systems of innovation. For a seminal contribution to this literature, see Nelson (1993).

31 Henderson, Jaffe and Trajtenberg (1993) examine geographical patterns of patent citations. They find that citations to domestic patents are more likely to be domestic and more likely to come from the same State and Standard Metropolitan Statistical Area compared with a "control frequency" reflecting the pre-existing concentration of related research activity.

32 For a discussion of this issue in the context of the Canadian forest products industry, see Globerman, Nakamura, Ruckman and Vertinsky (1998).

33 More generally, an educated work force presumably enables new technology to be introduced sooner and adopted more quickly in national economies. More literate and numerate workers are easier to train in the use of new technology and, arguably, less likely to resist the introduction of new technology. For a review of the theory and evidence on this issue, see Globerman (1985b).

34 The convergence between pharmaceutical and biotechnology R&D suggests that intellectual property protection is also likely to be of importance to biotechnology companies.

35 A similar point is made in Griliches (1994).

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