PIERRE MOHNEN

# The Relationship between R&D and Productivity Growth in Canada and Other Major Industrialized Countries

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# Contents

# Foreword

This is one of several studies commissioned by the Economic Council of Canada as part of a larger project on Competitiveness and Trade Performance. The project was designed to explore why Canadian industry has performed so poorly over the past 20 years ant to compare Canada's performance with those of other industrial and newly industrialized nations. Studies show that Canada's position has been slipping relative to that of its trading partners, and that this jeopardizes future living standards. The project also provides valuable information about the feedback between the micro-world of management and labour and the macro-world of inflation and exchange rates. Its primary conclusion is that Canadians have not responded quickly or effectively enough to the challenges that have been taking place in international markets. The Council's findings were published in February, 1992 in a Statement titled *Pulling Together: Productivity, Innovation, and Trade*.

Research and Development improves productivity through cost reduction or through market expansion. Pierre Mohnen was asked to meet two objectives in this study: first, to survey the existing literature pertaining to the link between R&D and productivity growth, comparing the social and private rates of return on R&D; and second, to estimate the contribution of domestic and foreign R&D to Canadian manufacturing productivity growth.

The author found that the rate of return on private R&D is greater than the rate of return on physical capital. Furthermore, higher rates of return are obtained: from basic research than from applied research; from company-funded R&D than from publicly-funded R&D; and from R&D directed to generate new production processes than from new products. The benefits from R&D in one sector also spill over onto other firms. Thus, the social rate of return from R&D is substantially higher than the private rate of return.

Professor Mohnen's results suggest that Canadian manufacturing as a whole benefits from foreign R&D spillovers. They also suggest that the return on foreign R&D is lower than on domestic R&D —although there is still some controversy about this finding.

Some of the author's findings are puzzling. Further research would clarify such issues as the relative contribution of imported versus domestic R&D; and the paradoxical finding that the rates of return are higher on private than on public R&D, and that they are also higher on basic than on applied R&D — considering that most basic R&D is conducted in the public sector.

Because the Economic Council closed in June 1992, this study is being published by the Canada Communication Group.

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Judith Maxwell
Chairman
Economic Council of Canada

# Summary

This study has three parts. The first part clarifies the conceptual link between R&D and productivity growth and surveys the empirical literature on this topic. The analysis tries to answer three specific questions: What are the social and private rates of return on R&D? Are they sensitive to the way they are estimated? Do the results differ across industries and countries?

The second part presents the results of a new empirical study of R&D conducted abroad and how that R&D spills over into the Canadian manufacturing sector and affects productivity. The respective contributions of own and imported R&D are also assessed and compared.

The conclusion presents a discussion of policy recommendations in the light of the evidence gathered concerning the role of R&D in productivity growth.

# R&D and Productivity Growth: A Survey of the Literature

## Productivity Growth

By way of definition, most economists would agree that productivity growth is the measure of growth in output not explained merely by the growth in the factors of production. Thus, productivity growth measures the efficiency of the allocation of inputs within a firm or an economy. In this sense, productivity reflects total factor productivity (TFP) and not just partial productivity indices, such as the productivity of labor. For instance, it is quite normal and economically sound to substitute labor for capital if (assuming all other elements remain constant) wage rates fall compared to the user cost of capital. In so doing, the productivity of labor drops because more workers are required to produce the same level of output. However, the total factor productivity remains unchanged, because the inputs along a given isoquant are merely substituted.

The widely used Divisia index (or its Tornquist approximation in discrete time) is defined as the growth rate of output minus the weighted sum of the growth rates of the inputs, where the weights are the respective cost shares.[1] This measure captures the notion of technological change as a shift in the production function only under the restrictive hypotheses of constant returns to scale, optimal input levels and marginal cost pricing.[2]

In the growth accounting literature, total factor productivity growth, or the unexplained residual, is assimilated with technical change and ascribed to a number of explanatory factors. These include: own R&D efforts; the effects of R&D conducted by other firms, industries or countries; the so-called catch-up hypothesis; and some factors independent of research and development, such as structural change, government regulation and natural resource discoveries (see Denison, 1985, and Maddison, 1987). Denison puts the contribution of R&D to TFP growth in the U.S. nonresidential business at 20 per cent for the period 1929-1982. Maddison also estimates that, relative to the United States, the average contribution of the catch-up in France, Germany, Japan, the Netherlands and the UK is around 9 per cent of GDP growth for these five countries (collectively).

## Defining R&D

For nearly 30 years, OECD countries have been collecting data on research and development following the guidelines established in the "Frascati manual", which defines scientific research and experimental development (R&D) as: "creative work undertaken on a systematic basis in order to increase the stock of knowledge ... and the use of this stock of knowledge to devise new applications" (OECD, 1980).

The OECD data are subdivided by:

- sectors of performance - business enterprise, higher education, goverment, and private non-profit institutions (PNP)
- sources of funds - business enterprise, government, higher education, PNP, and abroad
- type of cost - labour, land and building, instruments and equipment, and other current costs
- type of R&D - basic, applied, and development and
- field of science - natural sciences and engineering, and social sciences and humanities.

According to figures for 1989 released by Statistics Canada in 1991, 54 per cent of total Canadian R&D was performed by business enterprises, 19 per cent by the federal and provincial governments and 26 per cent by higher education. As for the funding of industrial intramural R&D (i.e. R&D performed within Canada by the reporting company) 62 per cent came from business enterprises, 20 per cent from public sources and 16 per cemt from foreign sources. In terms of cost breakdown, 50 per cent of all costs were applied to wages and salaries, 37 per cent to other current costs and 13 per cent to capital expenditures. Six industries — telecommunication equipment, aircraft and parts, engineering and scientific services, business machines, computer services, and wells and petroleum products — accounted for more than half of all industrial intramural R&D.

R&D can be directed toward improvement of existing products as well as creation of new products and processes. According to a survey conducted by McGraw-Hill, New York, in 1983, manufacturing firms in the United States devoted 43 per cent of their R&D spending to new products, 19 per cent to new processes and 38 per cent to improvements of existing products. The National Science Foundation reported that an analysis of total American industrial R&D expenditure in 1989 showed that four per cent was applied to basic research, 21 per cent to applied research and 75 per cent to development.

## How R&D Contributes to Productivity Growth

In a sense, R&D is a commodity; it is a stock of accumulated knowledge derived from R&D expenditures that depreciates at a certain rate (of obsolescence) as new products and processes supersede old ones.

R&D conducted in one sector can have productivity-enhancing effects in the performing sector through cost reductions (process innovations) and/or market expansions (product innovations). Besides generating returns to the performer, benefits from R&D can also ripple out to other sectors in two notable ways (Griliches, 1979). First, externalities may occur because a downstream user derives direct benefit from the R&D without having to pay the full value of the input — as when a bank purchases personal computers that enable it to streamline its operations. In this example, the benefits to the bank measured against the cost of the computers are worth substantially more to the bank than the price paid for them. Also, qualitative improvements may not be entirely reflected in the new price of an enhanced product or service because of competition, monitoring costs and, frequently, limited or incomplete information on the part of the developer with respect to the real value of the enhanced product to the end user.

The second type of spillover relates to the inspiration a research project, technical discovery or innovation in one sector can stimulate in another sector. New ideas often trigger new avenues of research and render established methods uneconomical or inefficient. For example, the development of synthetic fibre technology by the chemical industry found wide application in the textile industry. Research undertaken by NASA focussing on space exploration, cleared the way for many innovations and new developments in the automobile and computer industries. A distinction is thus made in the literature between private and social rates of return, i.e., those that are appropriated by the developer or performer and those that cannot be appropriated. In the latter case, society at large enjoys a maximum rate of return at minimum apparent cost.

R&D can also contribute indirectly to productivity growth through its interactions with the other inputs. If capital and R&D are complementary, increasing the R&D stock will eventually induce a firm to invest in machinery and equipment which employ new technology. Cohen and Lewinthal (1989) stress the role of R&D as the capacity to learn and to absorb. Knowledge is not a public good that can be costlessly absorbed. Instead, depending on the type of knowledge and the characteristics of the firm, more or less internal R&D has to be undertaken to create the absorptive capacity.

Finally, R&D can have indirect effects on productivity growth through the interaction of supply and demand, as shown in the model developed by Nadiri and Schankerman (1981). R&D decreases cost, which in turn lowers price and increases demand. The resulting increase in output boosts productivity in the presence of returns to scale.

## Empirical Evidence on the Contribution of R&D to Productivity Growth

Other surveys on the contribution of R&D to economic and productivity growth (or to total factor productivity growth) include: Bernstein (1985), the Bureau of Labor Statistics (1989), DeBresson (1991), Griliches (1988, 1991), Hanel and Palda (1989), Lichtenberg and Siegel (1989), Mairesse and Mohnen (1990), Mairesse and Sassenou (1991), McFetridge and Corvari (1985), Mohnen (1990), Nadiri (1991) and Robidoux (1991). Each of these surveys views the literature from a different angle. The purpose of this brief survey, however, is to organize the empirical literature around three questions: Do the results differ according to the method of analysis? Does the relationship between R&D and economic growth differ from one country to another? Are there sectoral differences?

The studies on R&D and productivity growth are divided into three groups, according to whether they are based on: 1) an extended Cobb-Douglas approach; 2) a more elaborate model of factor demand based on producer's duality theory; or 3) other approaches.

### *The Extended Cobb-Douglas Approach*

The basic idea of this approach is to estimate a Cobb-Douglas production function with R&D (the own R&D, a measure of outside R&D, and sometimes R&D split into private and public R&D, and basic and applied R&D) in addition to labour, capital, and sometimes intermediate inputs as factors of production.

The production function is estimated in levels (with cross-section data) or in growth rates (with time-series or panel data). Sometimes, marginal productivities are equated to factor payments and the labour productivity or total factor productivity growth is treated as the dependent variable. Often, to avoid constructing a stock of R&D, the gross investment over sales ratio (serving as a proxy for the net investment over output ratio) is used as a regressor in lieu of the R&D growth rate. The rate of return of R&D (i.e., its marginal productivity) is then estimated instead of its output elasticity.[3] This rate of return is interpreted as net or gross, depending on whether net or gross R&D enters the intensity variable.[4] Generally, constant returns to scale are imposed and additional explanatory variables are introduced, such as the degree of unionization, the rate of capacity utilization, the quality of the workforce or sector dummies. Regarding variable measurement, the studies differ by the rates of obsolescence and lag patterns of R&D used, by whether or not conventional inputs are corrected for R&D double-counting, and by the use of annual versus long-term (i.e., over five or 10 years) growth rates. When conventional inputs are corrected for their R&D content, the rates of return are interpreted as excess or above normal rates of return.[5] Finally, evidence has been drawn from different kinds of data: firm and industry, time-series, cross-section and panel. For these reasons, the results of different studies are difficult to compare.

A number of findings seem to recur, however (see Mairesse and Sassenou (1989) for a more elaborate discussion). For example, not correcting for R&D double-counting tends to bias the output-elasticity of R&D downwards. Elasticities are lower in the time-domain than in the cross-section domain. If returns to scale are estimated, rates of return to R&D decline. The elasticity of R&D is stable with respect to different rates of obsolescence, but the net rates of return are very sensitive in this regard. The results depend more on the particular specification chosen than on the country examined. Studies based on micro-data truly capture private rates of return, whereas studies based on industry data also capture intra-industry R&D spillovers. Even with firm data, however, it is possible to interpret the disappearance of the own rates of return when industry dummies are included in the regression as a sign of interfirm spillovers: the interaction of firm effects at the industry level (the industry dummy could be a proxy for the industry-wide R&D expenditures) predominates the individual firm effect. However, this recurrent finding can also be interpreted as a sign of industry-specific opportunity effects. Therefore, in a more straightforward way, direct measures of borrowed R&D have been devised and introduced as inputs or shift factors in the regressions. The first method consists simply in summing the R&D stocks of other firms within an industry or other industries within a country.

A second approach initiated by Terleckyj (1974) makes use of the inter-industry flows of intermediate inputs or capital goods. The stock of borrowed R&D of industry i is obtained by weighting the R&D stocks of all other industries in proportion to i's purchase of intermediate inputs or capital goods from those industries. It is assumed that the more i buys from j, the more i borrows from j's knowledge.[6]

A third approach uses patent data classified by both industry of origin and industry(ies) of use to construct an inter-industry technology flows matrix. Otherwise, this approach is similar to the Terleckyj approach.

A fourth approach bases the interindustry technology flows matrix on innovations classified by industry of origin and industry of use.

A fifth approach constructs the weights from a statistical proximity measure based on the firms' positions in the technology space of patents or R&D fields.

Knowledge and its spillover effects are also sometimes measured on the output side of R&D. Deolalikar and Evenson (1988) use the number of patents granted in the United States as a proxy for the supply of international technology in India, and the number of patents granted in India as a proxy for Indian inventive activity. Adams (1990) constructs a stock of knowledge by summing the article counts in each scientific field and weighting them by the composition of scientists for each industry. The spillover variable is measured by a weighted sum of the industry stocks of knowledge, as defined above, where the weights are computed by a proximity measure of industries in the employment of scientists by field.

Table 1 presents a partial list of the empirical studies of R&D and productivity growth that belong to this group (the output side of R&D). Also, the survey is confined mainly to manufacturing firms and industries.[7] To quote Griliches (1988), "the estimated rate of return to R&D lies mainly between 20 and 50 per cent, with most of the recent estimates falling in the lower part of this range". Indeed, on a meticulously constructed dataset of manufacturing firms in the United States, Lichtenberg and Siegel (1989) estimated a gross rate of return of 13 per cent. The rates of return on indirect R&D show a much greater dispersion, partly due, perhaps, to the different choices of weighting matrices (see Wolff and Nadiri, 1987 and Sterlacchini, 1989). However, it can also be argued that the rates of return on indirect R&D are, in general, substantially higher than the own rates of return.

Inter-country differences appear to be relatively unimportant and, for the reasons mentioned earlier, difficult to identify from the data in the heterogeneous studies.[8] (The central problem is that the studies and surveys tend to use different methodologies.) For Canada, a number of studies offer little support to the existence of a strong link between R&D and productivity growth. Lithwick (1969) was unable to find a link between R&D and TFP growth rates. Globerman (1972) and Postner and Wesa (1983) estimate a direct rate of return on R&D not significantly different from zero. Hartwick and Ewen (1983) did not find any significant correlation between a sector's productivity growth and the R&D embodied in its intermediate inputs. However, Longo (1984) and Hanel (1988) obtained the traditional orders of magnitude.

A number of additional results are noteworthy:

- A higher rate of return on company-financed versus publicly-financed R&D was found by Terleckyj (1974), Griliches (1980), Mansfield (1980), Griliches and Lichtenberg (1984), Griliches (1986), Hanel (1988), and Lichtenberg and Siegel (1989). The estimated rate of return for privately-financed R&D was found to be 27.5 per cent in Mansfield (1980), 9.2 to 33.4 per cent in Griliches and Lichtenberg (1984), 35.3 per cent in Lichtenberg and Siegel (1989), 28 to 37 per cent in Terleckyj (1974), and 40 to 60 per cent in Wolff and Nadiri (1987). Griliches (1986) also estimated a 50 to 180 per cent premium on company-financed R&D. Hall and Mairesse (1992), however, found a higher effect for government R&D (than for company-financed R&D) once it rises over 20 per cent of the firm's R&D budget.

**Table 1**

**Estimated Direct and Indirect R&D Rates of Return or Elasticities Using the Extended Cobb-Douglas Approach**

| Study | Sample[a] | Direct R&D[b] | | Indirect R&D[b] | | |
|---|---|---|---|---|---|---|
| | | Elasticity (%) | Rate of return(%) | Elasticity (%) | Rate of return (%) | Support matrix |
| **Canada** | | | | | | |
| Globerman (1972) | 13 industries 1960-68 | | 0 | | | |
| Postner-Wesa (1983) | 13 manufacturing industries 1966-71 & 1971-76 | | 0 | 18<br>(-) 26 | (intramural)<br>(extramural) | intermed. inputs |
| Longo (1984) | 110 R&D-intensive firms; 1980 cross section | | 24 | | | |
| Hanel (1988) | 12 Quebec manufacturing industries 1971-77 & 1975-82 | | 50 | | 100 | intermed. inputs |
| Poole-Bernard (1992) | 4 industries with heavy defense R&D 1961-85 | | (-) 6<br>(-) 21 | | | |
| **United States** | | | | | | |
| Minasian (1969) | 17 chemical firms 1948-57 | | 54 | | | |
| Griliches (1980) | 883 firms 1963 cross-section & 1957-65 | 7 | 27[c] | | | |
| Griliches (1980b) | 39 manufacturing industries; 1959-68<br>& 1969-77 | 7<br>0 | 42<br>0 | | | |
| Mansfield (1980) | 16 firms (petroleum & chemicals); 1960-76 | | 28 | | | |

**Table 1** (Cont'd.)

| Study | Sample[a] | Direct R&D[b] Elasticity (%) | Direct R&D[b] Rate of return(%) | Indirect R&D[b] Elasticity (%) | Indirect R&D[b] Rate of return (%) | Support matrix |
|---|---|---|---|---|---|---|
| **United States** (cont'd.) | | | | | | |
| Nadiri (1980) | aggregate economy 1949-78 | 6 | | | | |
| | total private economy 1949-78 | 10 | | | | |
| Nadiri (1980b) | total manufacturing | 11 | | | | |
| | durables | 8 | | | | |
| | nondurables | 19 | | | | |
| Link (1981b) | 174 firms 1971-76 | | 0 | | | |
| Schankerman (1981) | 883 firms 1963 cross-section | | 24 - 73 | | | |
| Griliches-Mairesse (1983) | 185 French firms 343 U.S. firms 1973-78 | | 19 | | | |
| Link (1983) | 302 manufacturing firms; 1975-79 | | 0 - 5 | | | |
| Griliches-Mairesse (1984) | 133 firms 1966-77 | 6 | 30 | | | |
| Clark-Griliches (1984) | 924 business units 1970-80 | | 18 - 20 | | | |
| Griliches-Lichtenberg (1984) | 27 industries 1959-76 & sub-periods | | 3 - 5 | | | |
| Griliches (1986) | 491 firms 1972 & 1977 cross-sections | 9 - 11 | 33 - 39 | | | |

**Table 1** (Cont'd.)

| Study | Sample[a] | Direct R&D[b] Elasticity (%) | Direct R&D[b] Rate of return(%) | Indirect R&D[b] Elasticity (%) | Indirect R&D[b] Rate of return (%) | Support matrix |
|---|---|---|---|---|---|---|
| **United States** (cont'd.) | | | | | | |
| Griliches (1986) cont'd | 911 firms 1966-77 | 11 | | | | |
| Patel-Soete (1988) | total economy 1956-85 | 6 | | | | |
| Lichtenberg-Siegel (1989) | 5,240 firms 1972-85 & sub-periods | | 13 | | | |
| Griliches-Mairesse (1990) | 525 firms 1973-80 | | 25 - 41 | | | |
| Terleckyj (1974) | 20 manufacturing industries 1948-66 | | (tot.) 12<br>(pvt.) 29 | | 45<br>78 | intermed. inputs |
| | 13 non-manufacturing industries 1948-66 | | (tot.) 0 | | 187 | intermed. inputs |
| Terleckyj (1980) | 20 manufacturing industries 1948-66 | | (pvt.) 0 | | 183 | intermed. inputs |
| Sveikauskas (1981) | 144 industries 1959-69 | | 7 - 25 | | 792<br>1200 | invest. goods |
| Scherer (1982, 1984) | 36 to 87 industries 1964-78 & sub-periods | | 29 - 43 (own products) | | 64 - 104 (own process + imported products)<br>147 (imported products) | patents |

**Table 1** (Cont'd.)

| Study | Sample[a] | Direct R&D[b] Elasticity (%) | Direct R&D[b] Rate of return(%) | Indirect R&D[b] Elasticity (%) | Indirect R&D[b] Rate of return (%) | Support matrix |
|---|---|---|---|---|---|---|
| **United States** (cont'd.) | | | | | | |
| Griliches-Lichtenberg (1984b) | 193 manufacturing industries; 1959-78 & sub-periods | | 21 - 76 | | 41 - 62 own process + (imported products) 0-90 (imported products) | patents |
| Jaffe (1986) | 432 firms 1973 & 1979 | | 25 | 10 | | stat'l. prox. measure |
| Wolff-Nadiri (1987) | 19 manufacturing industries; 1947,1958, 1963, 1967, 1972 | | 11 | | 90 | intermed. inputs |
| | 50 manufacturing & non-manufacturing sectors same time periods | | 19 | | 10 | investment goods |
| | | | | | 0 | intermed. inputs |
| **Japan** | | | | | | |
| Odagiri (1983 | 370 firms 1969-81 | | 26 | | | |
| Odagiri (1985) | 15 manufacturing industries 1960-77 & sub-periods | | (-) 66 (-) 24 | | 0 | intermed. inputs |
| Odagiri-Iwata (1985) | 135 firms 1966-73 | | 17 - 20 | | | |
| | 168 firms 1974-82 | | 11 - 17 | | | |
| Griliches-Mairesse (1986) | 406 firms 1973-80 | | 20 - 56 | | | |
| Patel-Soete (1988) | total economy 1956-1985 | 37 | | | | |

**Table 1** (Cont'd.)

| Study | Sample[a] | Direct R&D[b] | | Indirect R&D[b] | | |
|---|---|---|---|---|---|---|
| | | Elasticity (%) | Rate of return(%) | Elasticity (%) | Rate of return (%) | Support matrix |
| **Japan** (cont'd) | | | | | | |
| Sassenou (1988) | 394 firms 1976 cross-section | 14 | | 10 | | simple |
| | 1973-81 | 16 | | of own effect | | sum |
| Mansfield (1988) | 17 manufacturing industries 1960-79 | 42 | | | | |
| Goto-Suzuki (1989) | 50 industries 1978-83 | | 26 | | 80 | invest. goods + intermed. inputs |
| **France** | | | | | | |
| Griliches-Mairesse (1983) | 185 French firms 343 U.S. firms 1973-78 | | 31 | | | |
| Cunéo-Mairesse (1984) | 182 firms 1972-77 panel | 22 - 33 | 55[c] | | | |
| Mairesse-Cunéo (1985) | 390 firms 1974-79 | 9 - 26 | | | | |
| Patel-Soete (1988) | total economy 1956-85 | 13 | | | | |
| Hall-Mairesse (1992) | 196 firms 1980-87 panel | 5 - 48 | 22 - 34 | | | |
| **West-Germany** | | | | | | |
| Bardy (1974) | 4 chemical firms 1951-71 | | 92 - 97 | | | |
| Patel-Soete (1988) | total economy 1956-85 | 21 | | | | |

**Table 1** (Cont'd.)

| Study | Sample[a] | Direct R&D[b] | | Indirect R&D[b] | | |
|---|---|---|---|---|---|---|
| | | Elasticity (%) | Rate of return(%) | Elasticity (%) | Rate of return (%) | Support matrix |
| **Belgium** | | | | | | |
| Fecher (1989) | 292 firms 1981-83 | | 0 | 0.5 | | intermed. inputs |
| **United Kingdom** | | | | | | |
| Patel-Soete (1988) | total economy 1956-85 | 7 | | | | |
| Sterlacchini (1989) | 15 manufacturing industries; 1954-84 & sub-periods | | 9 - 14 | | 9 - 12<br>14 - 30 | intermed. inputs<br>innov. flows |

a) Average growth rates over time period are shown, unless otherwise indicated.

b) Only significant results are reported. The absence of a significant result is indicated by 0.

c) Converted using geometric means of value-added & R&D.

- Terleckyj (1974, 1980) found no significant spillovers from government-financed R&D. The same results were obtained by Wolff and Nadiri (1987).

- Recent evidence indicates that military R&D is not conducive to total factor productivity growth. Poole and Bernard (1992) found a definite negative contribution in the Canadian aerospace and electronics industries and, with less certainty, in the shipbuilding and chemical industries. Along similar lines, Lichtenberg (1984) and (1988) obtained evidence that public R&D crowds out private R&D, at least for non-competitive R&D government contracts.

- The rate of return is higher on basic R&D than on applied or on development R&D. In Mansfield (1980) the estimated rate of return on basic R&D was found to be 178 per cent; in Link (1981) 231 per cent; and in Lichtenberg and Siegel (1989) 134 per cent. According to Link (1981b), the estimated rate of return on basic R&D in the chemical sector was 87 per cent, 586 per cent in the machinery firms and 626 per cent in the transportation equipment firms. Griliches (1986) estimated a 250 to 450 per cent premium on basic research. However, in the case of Japan, Mansfield (1988) found a higher rate of return on applied R&D (60 per cent) than on basic R&D (0 per cent). In some instances of French manufacturing firm data, Hall and Mairesse (1992) also found a lower premium on basic R&D.

- Evidence of a higher rate of return on process R&D versus product R&D has been found by Scherer (1982), Griliches and Lichtenberg (1984b), and Clark and Griliches (1984). The Griliches and Lichtenberg (1984b) studies estimate significant rates of return on process R&D that range between 58 and 76 per cent, whereas the range for product R&D is between 21 and 29 per cent.
- In the cross-section dimension, the elasticities of output with respect to R&D are higher in the scientific (i.e. research-intensive) sectors. This was also found to be the case by Griliches (1980), Griliches and Mairesse (1984), Cunéo and Mairesse (1984), Mairesse and Cunéo (1985), Sassenou (1988), Odagiri (1983), and Englander, Evenson and Hanazaki (1988). However, in the time-series dimension, where the elasticities tend to drop, there is not much difference between the two types of sectors (see Griliches and Mairesse, 1984).
- Although not specifically working with R&D measures, Adams (1990) reported a lag effect of own knowledge on total factor productivity growth ranging from 10 to 20 years and an even longer lag (30 years) for the knowledge spillover.
- The argument that the *productivity* of R&D has declined has been repudiated by Scherer (1982), Griliches and Mairesse (1984), Clark and Griliches (1984), Griliches and Lichtenberg (1984), Griliches (1986), and BLS (1989). Nonetheless, Griliches (1986), Griliches and Lichtenberg (1984), Griliches (1980b) and Odagiri (1985) found there was a decline in the *significance* of R&D. Using a more recent and better dataset, Lichtenberg and Siegel (1989) obtained significantly higher estimates for 1981-85, compared to 1977-80 or 1973-76. Griliches (1988) provides a lengthy discussion on this issue. Perhaps the decline in the productivity of R&D in the '70s followed by its rebound in the '80s is simply a reflection of the changing rates of return over the business cycle observed by Griliches and Mairesse (1990).
- There is mixed evidence concerning a decline in the externality effects of R&D. This hypothesis has been corroborated by Griliches and Lichtenberg (1984) and Sterlacchini (1989). Scherer (1982) accepts it on aggregate data but rejects it on disaggregate data. Englander, Evenson

and Hanazaki (1988) accept the hypothesis on disaggregate data, but not with great statistical significance.

- Inter-industry differences are more pronounced than inter-country differences. Englander, Evenson and Hanazaki (1988) estimated country-pooled regressions for six countries over a period of approximately 1970-83, at the level of 16 2-digit industries. They found output elasticities for used R&D, where used R&D comprised both the own and the borrowed R&D, ranging from 50 per cent in textiles to -16 per cent in social and private services. The results are often negative for non-manufacturing industries, where measurement problems are more accute. Link (1981b) estimates rates of return for large firms ranging from 25 per cent in chemicals to 160 per cent in transportation equipment.
- The percentage contribution of R&D to both TFP growth and slowdown in a growth accounting exercise vary, depending on whether private or social rates of return to R&D are considered. The Bureau of Labor Statistics (1989), using a 15 per cent elasticity of output with respect to R&D in 1948-73 followed by a 14 per cent elasticity in 1973-87, arrived at a direct contribution of R&D to TFP growth of 0.50 per cent in 1948-73 and 0.49 per cent in 1973-87 for U.S. manufacturing and a zero contribution for non-manufacturing. In contrast, Kendrick (1984) mentions a decline from 1.2 per cent in 1948-73 to 0.7 per cent in 1973-81, while Scherer (1983) attributes a 0.2 to 0.3 per cent annual contribution of R&D to the productivity slowdown. Both Kendrick and Scherer do, however, include the indirect effects of R&D in their computations.

## *Factor Demand Models Based on the Duality Theory*

This category regroups the studies based on a dual representation of the technology and a flexible functional form. Here again, caution should be exercised in comparing the results of different studies because they differ in many respects. The functional form is of the translog, generalized Cobb-Douglas or quadratic variety. The inputs are generally labor, intermediate inputs, physical capital, and R&D capital, but they are not always treated in the same way with respect to their quasi-fixity (i.e. fixity in the short- to medium-run). The models can be static or dynamic with optimal or non-optimal input levels. In the dynamic models, the hypotheses on expectations formation, the form of the adjustment costs and the length of the planning horizon can differ. Prices, especially interest rates, depreciation rates and tax parameters, are not always measured in the same fashion across different studies. R&D spillovers can also be modeled in different ways, as explained in the preceding section. Finally, the data on which the models are estimated can be firm data or industry data, time-series, cross-sections or panel data.

Compared to the extended Cobb-Douglas approach, the dual approach puts more behavioral structure on the estimation, but uses a more restrictive technological structure and exploits more of the available information on factor uses and investments, thereby increasing statistical efficiency (at the potential risk of behavioral misspecification). Given the additional number of degrees of freedom arising from the joint estimation of several equations, shorter time-series can be exploited. Typically, industry data can be estimated separately without resorting to pooling and imposing common parameters. Given the flexibility of the functional forms, the interaction of R&D with other inputs can be estimated and returns to scale and incomplete capacity utilization can be taken into account. In dynamic models additional results can be derived, such as the speed of adjustment, the cost of adjustment and the differential links of R&D with the other inputs along the adjustment path.

Although the dual approach provides more insights than the Cobb-Douglas approach, it has its own drawbacks. In total cost or variable cost functions the output is treated as exogenous, which is counterfactual and could lead to biased estimates of the model's parameters. This inference is to a large extent drawn from information contained in the factor price series, the quality of which is not always reliable. The models are generally estimated in level form with a consequent danger of collinearity between the output, stock and trend variables. In order to respect the curvature conditions imposed by duality theory, often only truncated versions of the flexible functional forms can be estimated.

Table 2 presents a reasonably complete overview of the studies that fall into this category. It can be seen that this approach has been used to estimate private and/or social rates of return for the Bell system, for various industries on the basis of firm or industry data, and for the total manufacturing sectors of various countries. It is also apparent that very few studies are based on exactly the same specifications.

Table 3 sets out the private and social rates of return that have been estimated for various industries in the United States and Canada. The results seem to depend more on the underlying model than on the country concerned (e.g. compare Bernstein and Nadiri (1989) with Bernstein (1988) or Bernstein (1989) with Bernstein and Nadiri, 1988). It also shows that industry differences are more striking than country differences.

As the results of Bernstein and Nadiri (1988), Bernstein (1989) and Mohnen and Lépine (1991) show, the estimated gross rates of return on R&D differ substantially among industries. There are specific industrial patterns related to the emission and reception of R&D spillovers. For example, non-electrical machinery and chemical products generate substantial R&D spillovers. In these areas, the social rates of return on R&D can exceed the private rates of return anywhere from 0 to 500 per cent. The margin varies noticeably between industries.

**Table 2**

**R&D Studies Based on a Dual Representation of the Technology**

| Study | Data | Specification* | Indirect R&D |
|---|---|---|---|
| Bernstein (1988) | 680 Canadian firms in 7 industries 1978-81 firms' pooling by industry | translog cost function<br>inputs = L, M, K, R<br>no quasi-fixed input<br>S = shift variable<br>no technical change**<br>static model<br>var. returns to scale | intra-industry = sum of other firms' R&D<br>inter-industry = sum of other industries' R&D |
| Bernstein (1989) | 9 Canadian industries 1963-83 | generalized Cobb-Douglas cost function<br>inputs = L, M, K, R<br>R = fixed input<br>S = shift variable<br>no technical change<br>static model<br>var. returns to scale | vectorization |
| Bernstein-Nadiri (1988) | 5 U.S. industries 1958-81 | same as Bernstein (1989) | vectorization |
| Bernstein-Nadiri (1989) | 48 U.S. firms in 4 industries 1965-78 firms' pooling by industry | generalized quadratic value function<br>inputs = L, K, R<br>K, R = quasi-fixed<br>S = shift variable<br>no technical change<br>dynamic model<br>expectation = AR process<br>constant discount rate<br>var. returns to scale | intra-industry= sum of other firms' R&D |
| Bernstein-Nadiri (1990) | 45 U.S. firms in 4 industries 1959-66 firms' pooling by industry | quadratic inverted production function; inputs = L, M, K, R<br>K, R = quasi-fixed; no R&D spillover; no technical change<br>dynamic model; rational expectations; var. returns to scale | |

**Table 2** (Cont'd.)

| Study | Data | Specification* | Indirect R&D |
|---|---|---|---|
| Cardani-Mohnen (1984) | total manufacturing France & Italy 1965-77 | quadratic cost function<br>inputs = L, M, K, R<br>K, R = quasi-fixed<br>no R&D spillover<br>T = shift variable<br>dynamic model<br>static expectations<br>constant returns to scale | |
| Mohnen-Nadiri (1985) | total manufacturing France & Italy 1965-77 | quadratic cost function<br>inputs = L, M, K, R<br>K, R = quasi-fixed<br>no R&D spillover<br>no technical change<br>dynamic model<br>static expectations<br>constant returns to scale | |
| Mohnen-Nadiri-Prucha (1986) | total manufacturing; U.S., Japan & Germany 1965-66 - 1977-78 | same as Mohnen-Nadiri (1985) | |
| Mohnen-Lépine (1991) | 12 Canadian industries 1975, 1977, 1979 1981-1983 pooled data | generalized Cobb-Douglas cost function<br>inputs = L,M,K,R,P<br>K,R = quasi-fixed<br>S = shift variable<br>no technical change<br>static model<br>constant returns to scale | inter-industry = patent matrix |
| Nadiri-Prucha (1990a) | U.S. Bell System 1951-79 | quadratic cost function<br>inputs = L,M,K,R<br>K, R = quasi-fixed<br>no R&D spillover<br>T = shift variable<br>dynamic model<br>static and rational expectations<br>homothetic technology | |

**Table 2** (Cont'd.)

| Study | Data | Specification* | Indirect R&D |
|---|---|---|---|
| Nadiri-Prucha (1990b) | U.S. & Japanese electrical machinery industries 1968-79 | quadratic cost function<br>inputs = L, M, K, R<br>K, R = quasi-fixed<br>no R&D spillover<br>T = shift variable<br>dynamic model<br>static expectations<br>homogeneous technology | |
| Schankerman-Nadiri (1986) | U.S. Bell System 1947-76 | generalized Cobb-Douglas cost function<br>inputs = L, M, K, R<br>K, R = quasi-fixed<br>no R&D spillover<br>no technical change<br>static model<br>various returns to scale | |
| This study (1992) | Canadian total manufacturing 1964-83 | generalized McFadden cost function<br>inputs = L, M, K, R, S<br>K, R, S = quasi-fixed<br>T = shift variable<br>dynamic model<br>rational expectations<br>various returns to scale | international = high-tech imports |
| Nadiri-Mamuneas (1991) | 12 U.S. manufacturing industries pooled data 1956-86 | generalized Cobb-Douglas cost function<br>inputs = L, M, K<br>no quasi-fixed inputs<br>no R&D spillover<br>I, R P, T= shift variables<br>static model<br>constant returns to scale | |

**Table 2** (Cont'd.)

| Study | Data | Specification* | Indirect R&D |
|---|---|---|---|
| Suzuki (1991) | 20 Japanese firms in the electrical machinery industry pooled data 1979-87 | translog cost function<br>inputs = L, M, K, R<br>K, R = quasi-fixed<br>no R&D spillover<br>T = shift factor<br>dynamic model<br>various returns to scale | |
| Bernstein-Nadiri (1991) | 6 U.S. industries 1957-86 | translog cost function<br>inputs = L, M, K, R<br>K, R = quasi-fixed<br>endogenous output<br>S = shift variable<br>no technical change<br>dynamic model<br>various returns to scale<br>rational expectations | vectorization |

* L = labour, M = intermediate inputs, E = energy, RP = public R&D, K = physical capital, P = payments for foreign technology, T = index of technical change, R = R&D stock, S = spillover, I = public infrastructure,

** no technical change means no disembodied technical change

In addition, the following results are especially noteworthy:

- The following average internal rates of return, net of depreciation and adjustment costs, were obtained on the total manufacturing data: 11 per cent in the United States and Italy, 12 per cent in France, 13 per cent in West-Germany, and 15 per cent in Japan. R&D growth contributed to 2 per cent of the labour productivity growth in Germany, 3 per cent in the United States, Japan and Italy, and between 4 and 8 per cent in France (depending on whether a value-added or gross output framework is used). R&D cannot be held responsible for the productivity slowdown.
- In one high-tech industry (electrical machinery), Nadiri and Prucha (1990b) concluded that the R&D contribution to labour productivity growth was substantial but declining in the United States from 27 per

Table 3

**Private and Social Rates of Return in Selected Industries and Countries: The Dual Approach (%)**

| Industry | Study | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Canada | | | | | | United States | | | | | |
| | Bernstein[b] (1988) | | Bernstein[c] (1989) | | Mohnen[c] & Lépine (1991) | | Bernstein[c] & Nadiri (1988) | | Bernstein[b] & Nadiri (1989) | | Bernstein[b] & Nadiri (1991) | |
| | private | social[a] | private | social | private | social | private | social | private | social | private | social |
| Food & Beverage | 12 | 20 | | | | | | | | | | |
| Pulp & Paper | 12 | 20 | | | | | | | | | | |
| Primary Metals | | | 26 | 42 | 17 | 51 | | | | | | |
| Metal Fabrication | 12 | 20 | 29 | 29 | 274 | 314 | | | | | 22 | 22 |
| Non-electrical Machinery | 12 | 19 | 24 | 94 | | | 27 | 58 | 7 | 9 | 22 | 39 |
| business machines | | | | | 6 | 12 | | | | | | |
| other machinery | | | | | 27 | 117 | | | | | | |
| Transportation Equipment | | | 28 | 29 | | | 10 | 11 | | | 18 | 26 |
| Aircraft & Parts | 12 | 23 | | | 8 | 11 | | | | | | |
| Electrical Products | 12 | 26 | 38 | 38 | | | 15 | 18 | | | 15 | 18 |
| communication equipment | | | | | 5 | 24 | | | | | | |
| other electrical products | | | | | 33 | 47 | | | | | | |

**Table 3** (Cont'd.)

| Industry | Study | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Canada | | | | | | United States | | | | | |
| | Bernstein[b] (1988) | | Bernstein[c] (1989) | | Mohnen[c] & Lépine (1991) | | Bernstein[c] & Nadiri (1988) | | Bernstein[b] & Nadiri (1989) | | Bernstein[b] & Nadiri (1991) | |
| | private | social[a] | private | social | private | social | private | social | private | social | private | social |
| Chemical Products | 12 | 26 | 25 | 81 | | | 13 | 21 | 7 | 12 | 21 | 40 |
| drugs & medicines | | | | | 15 | 17 | | | | | | |
| other chemical products | | | | | 51 | 132 | | | | | | |
| Petroleum Products | | | 40 | 87 | 48 | 52 | | | 7 | 16 | | |
| Scientific Instruments | | | | | 49 | 75 | 17 | 111 | 7 | 14 | 29 | 111 |
| Rubber & Plastics | | | 47 | 89 | 143 | 157 | | | | | | |
| Gas & Oil Wells | | | 33 | 37 | | | | | | | | |

a) The social rate of return is measured as the private rate plus the external cost-reducing effects on all the firms in the sample within each industry, plus the cost-reducing effects on all the industries in the sample. Mid-sample or average values are reported.
b) Net (of depreciation) rates of return.
c) Gross rates of return.

cent in 1968-73 to 3 per cent in 1974-79. In contrast, the contribution was lower in Japan but rose from 4 per cent to 10 per cent in the same time periods. Suzuki (1991) reported that the R&D contribution in Japan has doubled again between 1978-83 and 1983-88.

- In the Bell System in the United States, the R&D contribution to labour productivity growth was a mere 1 per cent. The net internal rate of return rose from 17 per cent in the '50s and '60s to 29 per cent in the late '70s.
- The marginal adjustment costs are generally higher for R&D than for physical capital, and therefore the speed of adjustment is slower and the private rate of return is higher for R&D than for capital.
- Inter-industry spillovers exert a greater downward pressure on average cost than do intra-industry spillovers. Intra-industry spillovers decrease unit costs more in industries with large R&D cost shares, whereas inter-industry spillovers are more cost-reducing in industries with small R&D cost shares. However, the intra-industry spillovers contribute more to the social rate of return than the inter-industry spillovers. The variation among industries is primarily due to the marginal intra-industry spillover effect.
- In Bernstein (1988) the inter-industry effect is a substitute to the own R&D, whereas the intra-industry effect is a substitute only in industries with a small propensity to spend on R&D. In Bernstein and Nadiri (1989) own R&D and intra-industry spillover are substitutes. In Mohnen and Lépine (1991) inter-industry R&D spillovers and own R&D are substitutes. The second part of the present study points to a complementarity between own and foreign-imported R&D.
- Physical capital and inter-industry R&D spillovers are complements in industries with heavy R&D and substitutes elsewhere. For the intra-industry spillover, the link with physical capital is less clear (see Bernstein, 1988). In Bernstein and Nadiri (1988) it depends on the industry; in Bernstein and Nadiri (1989) the two are substitutes.
- Rates of return on R&D exceed those on physical capital by 2.5 to 4 times in Bernstein (1989), by 1.5 to 2 times in Bernstein and Nadiri (1988), by 67 to 123 per cent in Bernstein and Nadiri (1989), and by 16 to 340 per cent in Bernstein and Nadiri (1990).
- R&D and physical capital are generally estimated to be complements.
- The rates of return on federally-financed R&D are lower than on private R&D, but public R&D yields higher rates of return than public infrastructure capital (Nadiri and Mamuneas, 1991).

- There appears to be a spillover network, which is relatively narrow: for each sender industry there are only a few receivers, and vice versa. The network is not symmetric (see Bernstein, 1989, and Bernstein and Nadiri, 1988 and 1991).
- The dual approach does not seem to yield drastically different results from the extended Cobb-Douglas approach, but it does bring forward the substantial inter-industry differences.

### *Other Approaches*

This group of studies does not follow either of the previous two approaches. They are based on either case studies or other theoretical models.

Mansfield *et al.* (1977) compute the private and social real internal rates of return from 17 industrial innovations. Private benefits are measured by the profits to the innovator, net of the costs of producing, marketing and carrying out the innovation, net of the profits the innovator would have earned on products displaced by the innovation, and with an adjustment for the unsuccessful R&D. Social benefits are obtained by adding the change in consumers' surplus arising from the possible price reduction, and profits made by the imitators to the private benefits, and subtracting both the R&D costs incurred by firms other than the innovator towards the same innovation, and possible environmental costs. The results indicate that the social rate of return generally exceeds the private rate by a substantial margin: the median social rate of return is about 56 per cent against a median private rate of return of about 25 per cent. Similarily, Tewksbury et al. (1980) examine the rates of return on 20 innovations. They obtain a median social rate of return of 99 per cent against a median private rate of 27 per cent.

Bresnahan (1986) tackles the measurement of the welfare gain from the reduction in the price-performance ratio of computers in the financial services sector (banking, insurance, brokerage and related business), where no real output is available. The financial services sector is supposed to act as an agent for its consumers. The value of the computer price-reducing innovation in this sector is then inferred from the firm's willingness, as well as the willingness of its downstream customers, to pay. Bresnahan estimates that between 1958 and 1972 the spillover from the adoption of mainframe computers in the financial services sector of the United States was at least five times the expenditure for it in 1972.

Nadiri and Schankerman (1981) compute a TFP growth decomposition from a structural model where all inputs are at their cost-minimizing optimum, R&D earns the normal (private) rate of return, price is equal to average cost and is market clearing, and the technology is characterized by disembodied technical change and economies of scale. Each component of TFP growth reflects both its direct and indirect impact via induced changes on output. The R&D slowdown is computed as accounting for nearly a quarter of the TFP slowdown after 1973 in total manufacturing in the United States.

Link (1978) models R&D as factor-augmenting investments with a certain probability of success. The firm maximizes the expected rate of increase in net revenue less the R&D cost to achieve that increase. Given certain hypotheses on the probability of success, Link calculates for 45 U.S. firms between 1958 and 1963 an optimal degree of factor-augmentation which, when compared to the average rate of increase in R&D investments over this period, yields an 18.8 per cent return on R&D.

Levin and Reiss (1988) specify a model where the industry pool of knowledge consists of own R&D plus a fraction of the sum of all others' R&D. The model estimates the extent of R&D opportunity and appropriability while taking the endogeneity of market structure into account. The productivity of R&D is estimated separately from the extent of the spillover. The extent of the spillover depends on the strength of appropriability in general and on the relative effectiveness of patent and non-patent means of appropriation. Proprietary and nonproprietary R&D are imperfect substitutes. The model is estimated on a cross-section of 116 lines of business in the United States. The only significant results obtained relate to the opportunity variables affecting the rates of return on R&D. The extent and the productivity of spillovers are not significant either in the process or in the product R&D equations.

# Foreign R&D Spillovers in Canadian Total Manufacturing

## Background

Knowledge spillovers have gained prominence in the new theories of economic growth (Romer, 1986) and international trade (Grossman and Helpman, 1990), while being the object of attention in productivity analysis for over two decades (see Griliches, 1991). The empirical literature on R&D spillovers is mainly confined to the examination of intra-industry inter-firm and intra-country inter-industry spillovers. This study focusses on the international aspect of the spillovers. It examines the extent to which Canadian manufacturing benefited from R&D conducted abroad between 1964 and 1983.

Although the existence of international knowledge transmission is widely accepted in theoretical studies, the empirical evidence is sparse and not very convincing. Fecher (1989) summed the sectoral R&D performed by all OECD countries in proportion to Belgium's purchase of intermediate inputs from these foreign sectors to construct a stock of foreign R&D. The estimation of an extended Cobb-Douglas production function on Belgian firm data did not yield conclusive results as to beneficial foreign R&D effects. Hartwick and Ewen (1983) computed the R&D embodied in intermediate good purchases for 29 Canadian sectors, broken down by domestic and foreign origin, as the difference between the direct and total R&D requirements. Their correlation analysis did not reveal any link between indirect R&D (domestic or foreign) and productivity growth. However, Globerman (1972) gave some credit to foreign R&D in Canada: the only significant output elasticity with respect to R&D he could obtain was attributed to invisible imported R&D.

In the four sections following, the first explains how the foreign pool of R&D is constructed, the second presents the framework and results of the extended Cobb-Douglas approach, the third specifies the econometric model based on the dual approach, and the fourth presents the results of the econometric model. Details on the data are contained in the appendices to this study.

## The Measurement of International R&D Spillovers

In the studies of inter-industry spillovers, different supporting matrices have been used to measure a pool of available R&D knowledge.[9] Likewise, in the area of international R&D spillovers (since R&D spreads across borders via foreign direct investment, the sale of patents and trademarks, international trade or the flow of scientific personnel), any of these variables could be used to aggregate foreign R&D. The more Canada buys high-tech products, acquires patents, receives foreign investment or communicates with scientists from sector i in country j, the more it benefits from that foreign sector's R&D.

In this study, I have used the imports of high-tech products not so much as a carrier of foreign R&D but rather as a proximity measure in the international technology space.[10] The foreign-available R&D stock (S) is thus constructed as follows:

$$S = \sum_i \sum_j \frac{M_{ij}}{\sum_i \sum_j M_{ij}} R_{ij}$$

where $M_{ij}$ are Canadian high-tech imports (excluding final demand destinated imports) from sector i in country j and $R_{ij}$ are their respective R&D stocks.

The spillover emitters are restricted to the five countries where most of the R&D in the OECD countries is conducted: the United States, West-Germany, Japan, France and the United Kingdom. In 1980, these five countries, taken together, accounted for over 90 per cent of the total cost of R&D in the business enterprise sector of the OECD countries.[11] The imports incorporating the foreign R&D are restricted to high-tech products.[12] Since there is no agreement on the precise definition of high-tech products, I have compiled a list of such products based on the lists adopted by OECD, the U.S. Department of Commerce and Statistics Canada (see Appendix A).[13] The list is based on the Standard International Trade Classification (SITC1 and SITC2) up to a three-digit level of disaggregation. The products were drawn essentially from five industries: electrical products (ISIC 383), transportation equipment (ISIC 384), chemical products (ISIC 351 and 352), scientific instruments (ISIC 385) and non-electrical machinery (ISIC 382).[14] In 1980, these five sectors accounted for 70 per cent of all R&D performed in total manufacturing in both Japan and the United States, 89 per cent in West-Germany, 85 per cent in the United Kingdom and 80 per cent in France.

Table 4 indicates the relative importance of the 25 sources of international R&D spillovers. According to this measure, 98 per cent of foreign R&D "flowing" into Canada originates in the United States. None of the other sources accounts for more than 1 per cent of the R&D accessible to Canadian manufacturing. This is due to the fact that 88 per cent of the Canadian high-tech imports from these 25 sources comes from the United States and, of these, the U.S. non-electrical machinery and transportation equipment industries alone account for over 70 per cent. In terms of R&D stocks, over 60 per cent of the total is in the United States, with a high concentration (23 per cent) in the U.S. transportation equipment industry.

Because of the dominance of the United States in the above spillover measurement, I have also experimented with an alternative measure of S, based only on R&D in the United States. This measure differs from the previous one in two respects: there is no weighting involved (each U.S. industry is given the same weight) and the R&D is not restricted to the industrial sector, but comprises the economy-wide R&D performances.

**Table 4**

**Components of the Weighted Sum of Foreign R&D Expenditures in 1980**

| | $M_{ij} R_{ij} / (\Sigma_i \Sigma_j M_{ij} R_{ij})$ | | | | |
|---|---|---|---|---|---|
| | NE | EP | TE | CP | SI |
| United States | 0.313 | 0.090 | 0.528 | 0.039 | 0.008 |
| Japan | 0.001 | 0.004 | 0.005 | - | - |
| France | - | - | - | - | - |
| West-Germany | 0.003 | - | 0.002 | 0.001 | - |
| United Kingdom | 0.001 | - | 0.001 | 0.001 | - |

NE = non-electrical machinery
EP = electrical products
TE = transportation equipment
CP = chemical products
SI = scientific instruments.

Note: The figures have been rounded and might not therefore total 100 per cent. Figures lower than 0.001 have been omitted.

### *The Extended Cobb-Douglas Approach*

The Canadian manufacturing sector is supposed to produce one output (Q) with five inputs: labor (L), intermediate inputs (M), the physical stock of capital (K) (henceforth "capital"), the own R&D stock of knowledge (R) (henceforth "R&D"), and the foreign R&D stock of knowledge (S). The technological frontier shifts outward under the influence of disembodied technological change.

In growth rate form, the extended Cobb-Douglas production function yields the following estimating equation:

$$\dot{Q}_t = \alpha_T + \alpha_L \dot{L}_t + \alpha_K \dot{K}_t + a_M \dot{M}_t + \alpha_R \dot{R}_t + \alpha_S \dot{S}_t + \alpha_U \dot{U}_t + \varepsilon_{1t} \qquad (1)$$

where dots denote growth rates (first differences in logarithms), U is the rate of capacity utilization, $\varepsilon_1$ is a random error term, $\alpha_T$ is the rate of disembodied technical change, and $\alpha_i$ (i = L, K, M, R, S, U) are output elasticities.

As an alternative to (1), the rates of return or the marginal productivities of R and S can be estimated directly, instead of their output elasticities, by exploiting the fact that $\alpha_R \dot{R}$ can be rewritten as $(\partial Q_t / \partial R_t)(R_t / Q_t)(R_t - R_{t-1}) / R_t$, and similarly for S, which yields:

$$\dot{Q}_t = \alpha_T + \alpha_L \dot{L}_t + \alpha_K \dot{K}_t + \alpha_M \dot{M}_t + \gamma_R (R_t - R_{t-1}) / Q_t$$
$$+ \gamma_S (S_t - S_{t-1}) / Q_t + \alpha_U \dot{U}_t + \varepsilon_{2t} \qquad (2)$$

where $\gamma_R$ and $\gamma_S$ are gross rates of return.

Another alternative specification assumes constant returns to scale with respect to L, M and K, marginal cost pricing and optimal levels for L, M and K. The corresponding output elasticities $\alpha_i$ can then be replaced by cost shares $s_i = p_i x_i / (\Sigma_i p_i x_i)$, where i = L, M, K and p and x represent the respective price (user cost) and quantity of the inputs. Equation (2) can then be transformed into:

$$\dot{TFP}_t = \alpha_T + \alpha_R \dot{R}_t + \alpha_S \dot{S}_t + \alpha_U \dot{U}_t + \varepsilon_{3t} \qquad (3)$$

or its alternative version

$$TFP_t = \alpha_T + \gamma_R (R_t - R_{t-1}) / Q_t + \gamma_S (S_t - S_{t-1}) / Q_t + \alpha_U \dot{U}_t + \varepsilon_{4t} \qquad (4)$$

where $TFP_t = \dot{Q}_t - \Sigma_i s_{it} \dot{x}_{it}$ (i = L, M, K) is the Divisia index of total factor productivity growth, measured by its Törnqvist approximation in discrete time.

First, it is seen in Table 5 that the specifications in terms of both rates of return and elasticities yield similar results. The rate of disembodied technical change hovers around one-half of one per cent per year. The own rate of return on R&D is not significant and therefore varies widely from one specification to another.[15] When converted to marginal productivities (by multiplying by 1.928, the mean of Q over the mean of S), the output elasticities of foreign R&D are concordant with the rate of return estimates. These coefficients are significant, at least at the 90 per cent level of confidence, and vary between 23 and 43 per cent. The TFP regressions yield higher elasticities than the output growth regressions, another result typical in this literature. The inclusion of a cross-effect between own and foreign R&D did not yield significant coefficients.

The fitting of cyclically volatile TFP growth figures by essentially long-term trend explanatory variables is troublesome. Therefore, the variation in capacity utilization is introduced as an additional explanatory variable, supposed to capture the cyclical movements in productivity. As a result, the S coefficients tend to decrease in value but increase in significance. The U coefficients are strongly significant and improve tremendously the adjusted $R^2$. Perhaps this is just the result of spurious correlation, since U essentially picks up the growth of output (U being the deviation of output from a fixed year of reference). However, it might also be picking up the effects of overall capacity (and not just capital) utilization, a scale effect, a learning-by-doing effect, or changes in the price/cost margin induced by growing output.

The fact that the S coefficients are significant whereas the own R&D performs very poorly raises the question whether the foreign R&D spillover variable does not contain a cyclical component through the import weighting scheme. The import weights were therefore regressed on Canadian output and a time trend. The trend was significant in seven of 25 cases.[16] The cyclical component was significant in only three cases. One of these, however, was the high-tech imports of transportation equipment from the U.S., the highest component of the spillover measure, as seen in Table 4. To further investigate the potential bias in the R&D rate of return, the regressions were rerun with only the U.S. total R&D stock as a source of spillover. Again, own R&D was not significant. Moreover, it always had the wrong sign. Foreign R&D ceased to be significant as well at the 5 per cent level and its magnitude dropped to the range of 4 to 12 per cent. Otherwise, the results were qualitatively similar to those in Table 4 and are therefore not reported here.

## *Econometric Model Based on the Dual Approach*

I will now extend the previous approach in several directions. First, I shall explicitly model short-term disequilibrium effects (as the perhaps controversial results following the introduction of the capacity utilization effect suggests), by distinguishing variable and quasi-fixed factors of production. Second, I shall resort to a more flexible functional form to investigate the interaction effect between own and foreign R&D in particular. Third, I will try to obtain more efficient estimates of the technology by exploiting the information contained in the factor demand equations (at the cost of a potential misspecification of producer behavior). Finally, I shall try to unveil a dynamic story of factor demand.

**Table 5**

**Estimates of Various Versions of a Simple Extended Cobb-Douglas Canadian Manufacturing, 1965 - 1983**

| | Equations | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Parameters* | (1) | | (2) | | (3) | | (4) | |
| $\alpha_T$ | 0.004 | 0.006 | 0.004 | 0.006 | 0.004 | 0.003 | 0.006 | 0.003 |
| | (0.722) | (1.565) | (0.784) | (1.677) | (0.501) | (0.981) | (0.787) | (1.039) |
| $\alpha_L$ | 0.126 | 0.095 | 0.130 | 0.096 | | | | |
| | (1.527) | (1.559) | (1.529) | (1.538) | | | | |
| $\alpha_K$ | -0.187 | 0.224 | -0.184 | 0.231 | | | | |
| | (-1.502) | (1.525) | (-1.551) | (1.602) | | | | |
| $\alpha_M$ | 0.948 | 0.541 | 0.948 | 0.540 | | | | |
| | (14.803) | (4.382) | (14.693) | (4.386) | | | | |
| $\alpha_U$ | | 0.415 | | 0.417 | | 0.212 | | 0.212 |
| | | (3.555) | | (3.584) | | (9.485) | | (9.454) |
| $\alpha_R$ | 0.012 | 0.003 | | | -0.115 | -0.027 | | |
| | (0.120) | (0.049) | | | (-0.654) | (-0.395) | | |
| $\alpha_S$ | 0.133 | 0.119 | | | 0.223 | 0.172 | | |
| | (1.457) | (1.785) | | | (1.313) | (2.590) | | |
| $\gamma_R$ | | | 0.036 | -0.257 | | | -3.449 | -0.509 |
| | | | (0.018) | (-0.179) | | | (-0.965) | (-0.355) |
| $\gamma_S$ | | | 0.262 | 0.238 | | | 0.431 | 0.324 |
| | | | (1.539) | (1.927) | | | (1.420) | (2.714) |
| D.W. | 2.387 | 2.292 | 2.433 | 2.365 | 2.331 | 2.134 | 2.372 | 2.198 |
| $\bar{R}^2$ | 0.984 | 0.991 | 0.984 | 0.991 | -0.015 | 0.845 | 0.007 | 0.848 |

* t - statistics are in parentheses.

The factors of production L and M are treated as variable inputs, i.e. immediately adjustable to their optimal level. K and R are modeled as quasi-fixed inputs subject to adjustment costs, such as the costs of reorganizing the production plan or breaking in new machines and the costs of giving up old techniques or introducing a new production line. Given these costs of adjustment, the firm has an incentive only to adjust gradually to the new levels of the quasi-fixed inputs. As to the stock of foreign accumulated R&D knowledge, we assume that the Canadian manufacturing sector is faced with an exogenously given level of it, over which it has no control. Hence S is considered as a completely fixed input.

The inputs are chosen so as to minimize, over an infinite horizon, the present discounted value of all future expected after-tax operating costs, investment costs and adjustment costs, subject to a sequence of expected production levels. Since the variable inputs can be easily adjusted to whatever level is optimal, the intertemporal optimization can be broken down in two stages. In the first stage, the variable inputs are chosen by minimizing the after-tax variable costs subject to a given level of output, the inherited levels and the planned investments in the two quasi-fixed inputs, a given level of technological know-how and the fixed variable input prices.[17] From the optimal solution to this problem, the technology can be represented by an after-tax variable cost function:

$$VC_t = VC(p_{Lt}, p_{Mt}, Q_t, K_{t-1}, R_{t-1}, S_{t-1}, I_{Kt}, I_{Rt}) \qquad (5)$$

where $VC_t = p_{Lt} L_t + p_{Mt} M_t$,

$p_{Lt}$ = after-tax price of labor
$p_{Mt}$ = after-tax price of materials
$I_{Kt}$ = gross investment in capital
$I_{Rt}$ = gross investment in R&D.

The input markets are assumed to be competitive. The stocks of capital, own R&D and foreign R&D spillover (measured as end-of-period stocks) are assumed to enter the technology in period t at their beginning-of-period levels.

In the second stage, the optimal quasi-fixed inputs are obtained from the following optimization problem:

$$\min_{\{K_\tau, R_\tau\}} E(t) \sum_{\tau=t}^{\infty} R_{t,\tau} \Big\{ VC(p_{L\tau}, p_{M\tau}, Q_\tau, K_{\tau-1}, R_{\tau-1}, S_{\tau-1}, I_{K\tau}, I_{R\tau}) + \sum_{x=K,R} p_{x\tau} I_{x\tau} \Big\} \qquad (6)$$

where,

$I_{x\tau}$ $= x_\tau - (1-\delta_x)\, x_{\tau-1}$, for x = K, R

E (t) = expectation conditional on all the information available at time t, i.e. expectations are formed rationally

$R_{t,\tau}$ = nominal after-tax discount rate between t and $\tau$ where

$$R_{t,t} = 1 \text{ and } R_{t,\tau} = \prod_{i=t}^{\tau-1} (1 / (1 + r_i)) \text{ for } \tau > t$$

$r_t$ = nominal after-tax rate of return between t and t + 1[18]

$p_{xt}$ = effective after-tax purchase price of x; x = K, R

$\delta_x$ = geometric depreciation rate of capital item x .

The optimal adjustment paths of the quasi-fixed inputs are described by the Euler equations derived from (6):

$$\begin{aligned} E(t) \{ \ & (1 + r_\tau) [p_{x,\tau} + \partial VC_\tau / \partial I_{x,\tau}] \\ & - (1 - \delta_x) [p_{x,\tau+1} + \partial VC_{\tau+1} / \partial I_{x,\tau+1}] + \partial VC_{\tau+1} / \partial x_\tau \} = 0 \\ & \qquad x = K, R \\ & \qquad \tau = t, \ldots, \infty \end{aligned} \tag{7}$$

Conditional on the information available at time t, each marginal addition to a quasi-fixed input has to cost as much as it yields in expected present value terms. Put another way, what it is expected to cost in terms of purchase price and marginal adjustment costs in one period has to be equal, in capitalized terms, to what it would cost one period later (in terms of purchase price and marginal adjustment costs) to purchase the non-depreciated part of the marginal investment, plus the variable cost reduction it is expected to yield.

The after-tax variable cost function is given a truncated version of the symmetric Generalized McFadden (SGM) functional form introduced by Diewert and Wales (1987)[19]

$$\begin{aligned} VC_t = \ & Q_t^{\rho} [ (0.5\, \alpha_{LL}\, p_{Lt}^2 + \alpha_{LM}\, p_{Lt}\, p_{Mt} + 0.5\, \alpha_{MM}\, p_{Mt}^2) / \tilde{p}_t \\ & + \alpha_L\, p_{Lt} + \alpha_M\, p_{Mt} ] \\ & + \beta_{LK}\, p_{Lt}\, K_{t-1} + \beta_{MK}\, p_{Mt}\, K_{t-1} + \beta_{LR}\, p_{Lt}\, R_{t-1} + \beta_{MR}\, p_{Mt}\, R_{t-1} \\ & + \beta_{LS}\, p_{Lt}\, S_{t-1} + \beta_{MS}\, p_{Mt}\, S_{t-1} \\ & + \tilde{p}_t\, Q_t^{-\rho} [ 0.5\, \beta_{KK}\, K_{t-1}^2 + \beta_{KR}\, K_{t-1}\, R_{t-1} + 0.5\, \beta_{RR}\, R_{t-1}^2 \\ & + \beta_{KS}\, K_{t-1}\, S_{t-1} + \beta_{RS}\, R_{t-1}\, S_{t-1} + 0.5\, \alpha_{KK}\, I_{Kt}^2 + 0.5\, \alpha_{RR}\, I_{Rt}^2 ] \end{aligned} \tag{8}$$

where $\tilde{p}_t = \Sigma_i\, (p_{i0}\, x_{i0} / \Sigma_i\, p_{i0}\, x_{i0})\, p_{it}$ , i = (L, M), is a Laspeyres variable input price index.

The above specification generalizes the one presented in Diewert and Wales (1987) to the introduction of quasi-fixed inputs.[20] The $\tilde{p}_t$ variable appears in the variable cost function to impose the linear homogeneity in factor prices in a symmetric way. The symmetric version of the Generalized McFadden does not suffer from the arbitrariness of normalizing the variable factor prices that would make the factor demand equations asymmetric and possibly influence the results (see Mahmud, Robb and Scarth, 1986). For reasons of identification, I have imposed the parametric restriction $\alpha_{LL} = \alpha_{MM} = -\alpha_{LM}$.[21] Because of multicollinearity, I restricted the technology to be homogeneous as in Nadiri and Prucha (1989).[22] This functional form enables the parametric imposition of the global curvature restrictions on the variable cost function by a Cholesky factorization without restricting the flexibility of the functional form.[23] The concavity of VC(.) in $(p_L, p_M)$ is imposed by replacing $\alpha_{LL}$ by $-\alpha_{11}^2$. Its convexity in $(K_{t-1}, R_{t-1})$ is imposed by reparameterizing the $[\beta_{ij}]$ matrix by $BB'$, where $B = [b_{ij}]$ is a 2 x 2 lower triangular matrix, with i, j = K,R.[24] All the regularity conditions for VC(.) to be a valid dual representation of the technology are hence imposed parametrically on the data.

The adjustment costs are modeled as being internal, but separable from each other, i.e. the adjustment costs for capital do not affect those for R&D and vice versa. For the Euler equations to be necessary and sufficient conditions of intertemporal optimality, the variable cost function has to be increasing and convex in $I_K$ and in $I_R$. The latter condition can again be imposed by a Cholesky factorization, the $[\alpha_{ij}]$ matrix being reparameterized by $CC'$, where $C = [c_{ij}]$ is a 2 x 2 lower triangular matrix, with i, j = K, R.

The system of estimating equations can now be readily derived. By Shephard's lemma, the demand equations for the two variable factors are given by:

$$\begin{aligned} L_t / Q_t = {} & Q_t^{\rho-1} \, [ \alpha_L + (\alpha_{LL} p_{Lt} + \alpha_{LM} p_{Mt}) / \tilde{p}_t \\ & - s_{L0} ( 0.5 \alpha_{LL} p_{Lt}^2 + \alpha_{LM} p_{Lt} p_{Mt} + 0.5 \alpha_{MM} p_{Mt}^2 ) / \tilde{p}_t^2 ] \\ & + Q_t^{-1} ( \beta_{LK} K_{t-1} + \beta_{LR} R_{t-1} + \beta_{LS} S_{t-1} ) \\ & + s_{L0} [ Q_t^{-p-1} ( 0.5 \beta_{KK} K_{t-1}^2 + \beta_{KR} K_{t-1} R_{t-1} \\ & + 0.5 \beta_{RR} R_{t-1}^2 + \beta_{KS} K_{t-1} S_{t-1} + \beta_{RS} R_{t-1} S_{t-1} \\ & + 0.5 \alpha_{KK} I_{Kt}^2 + 0.5 \alpha_{RR} I_{Rt}^2 ) ] + \varepsilon_{1t} \end{aligned} \tag{9}$$

$$M_t / Q_t = Q_t^{\rho-1} [\, \alpha_M + (\alpha_{MM}\, p_{MT} + \alpha_{LM}\, p_{Lt}) / \tilde{p}_t$$

$$- s_{M0} ( 0.5\, \alpha_{LL}\, p_{Lt}^2 + \alpha_{LM}\, p_{Lt}\, p_{Mt} + 0.5\, \alpha_{MM}\, p_{Mt}^2 ) / \tilde{p}_t^2 ]$$

$$+ Q_t^{-1} ( \beta_{MK} K_{t-1} + \beta_{MR} R_{t-1} + \beta_{MS} S_{t-1} )$$

$$+ s_{M0} [\, Q_t^{-\rho-1} ( 0.5\, \beta_{KK} K_{t-1}^2 + \beta_{KR} K_{t-1} R_{t-1}$$

$$+ 0.5\, \beta_{RR} R_{t-1}^2 + \beta_{KS} K_{t-1} S_{t-1} + \beta_{RS} R_{t-1} S_{t-1}$$

$$+ 0.5\, \alpha_{KK} I_{Kt}^2 + 0.5\, \alpha_{RR} I_{Rt}^2 ) ] + \varepsilon_{2t} \tag{10}$$

where $s_{i0} = p_{i0}\, x_{i0} / (\Sigma_i\, p_{i0}\, x_{i0})$, i = L, M. Equations (9) and (10) have been normalized by $Q_t$ to eliminate a possible heteroscedasticity in the error terms. The stochastic error terms appended to both equations reflect possible errors of optimization, which are assumed to be uncorrelated with the information set at time t.

The optimal demands for the two quasi-fixed inputs in period t are given by the Euler equations. Under rational expectations, the future values in the Euler equations can be replaced by the actual values, the difference between the two being random errors uncorrelated with the information available at time t. The other two equations to be estimated are therefore:

$$(1+r_t) \{ p_{Kt} + \alpha_{KK}\, \tilde{p}_t\, Q_t^{-\rho} [\, K_t - (1 - \delta_K) K_{t-1} ] \}$$

$$- (1 - \delta_K) \{ p_{K,\,t+1} + \alpha_{KK}\, \tilde{p}_{t+1}\, Q_{t+1}^{-\rho} [K_{t+1} - (1 - \delta_K) K_t ] \}$$

$$+ \beta_{LK}\, p_{L,\,t+1} + \beta_{MK}\, p_{M,\,t+1} + \tilde{p}_{t+1} ( \beta_{KK} K_t / Q_{t+1}^{\rho} + \beta_{KR} R_t / Q_{t+1}^{\rho}$$

$$+ \beta_{KS} S_t / Q_{t+1}^{\rho} ) = \varepsilon_{3t} \tag{11}$$

$$(1+r_t) \{ p_{Rt} + \alpha_{RR}\, \tilde{p}_t\, Q_t^{-\rho} [R_t - (1 - \delta_R) R_{t-1} ] \}$$

$$- (1 - \delta_R) \{ p_{R,\,t+1} + \alpha_{RR}\, \tilde{p}_{t+1}\, Q_{t+1}^{-\rho} [R_{t+1} - (1 - \delta_R) R_t ] \}$$

$$+ \beta_{LR}\, p_{L,t+1} + \beta_{MR}\, p_{M,\,t+1} + \tilde{p}_{t+1} ( \beta_{RR} R_t / Q_{t+1}^{\rho} + \beta_{KR} K_t / Q_{t+1}^{\rho}$$

$$+ \beta_{RS} S_t / Q_{t+1}^{\rho} ) = \varepsilon_{4t} \tag{12}$$

The model to be estimated consists of equations (9) to (12). The variable cost function need not be estimated since it contains no additional information. We suppose the contemporaneous variance-covariance matrix $\Sigma$ of the error vector

$$\varepsilon_t = (\varepsilon_{1t}\, \varepsilon_{2t}\, \varepsilon_{3t}\, \varepsilon_{4t})'$$

to be positive definite. We estimate the four equations jointly by the generalized method of moments (GMM). This method of estimating dynamic models does not require the derivation of closed form solutions for the adjustment paths. The GMM method is based on the idea that, given the hypotheses of our model, the error terms must be uncorrelated with any element belonging to the contemporaneous information set. The objective function is therefore to minimize the correlation between the error terms and a vector of exogenous instrumental variables belonging to the information set. Let $\theta$ be the px1 vector of parameters to be estimated, $z_t$ a kx1 vector of instrumental variables, $e_t$ the 4x1 vector of estimated residuals and n the sample size. The GMM estimator of $\theta$ is the one that minimizes the objective function S $(\theta,V)$, where:

$$S(\theta,V) = [nm_n(\theta)]'V^{-1}[nm_n(\theta)]$$

$$nm_n(\theta) = \Sigma_{t=1}^{n} e_t \otimes z_t \tag{13}$$

and V is the variance-covariance matrix of $nm_n(\theta)$, evaluated at the true value $\theta$.

Practically, since $\theta^o$ is unknown, the parameters must first be estimated $(\tilde{\theta})$ consistently. Then $\hat{V}$ is calculated using the Parzen weights:

$$\hat{V} = n\sum_{\tau=-\omega}^{\omega} w(\tau/\omega)\,\hat{S}_t$$

where,

$$\hat{S}_\tau = (1/n)\Sigma^n_{t=1+\tau}\,[e_t(\tilde{\theta}) \otimes z_t]\,[e_{t-\tau}(\tilde{\theta}) \otimes z_{t-\tau}]' \qquad \tau \geq 0$$

$$\hat{S}_\tau = (\hat{S}_{-\tau})' \quad \tau < 0$$

$$w(\tau/\omega) = 1 - 6\,|\tau/\omega|^2 + 6\,|\tau/\omega|^3 \qquad 0 \leq \tau/\omega \leq 0.5$$

$$w(\tau/\omega) = 2\,(1 - |\tau/\omega|)^3 \qquad 0.5 \leq \tau/\omega \leq 1$$

$$\omega = \text{integer.} \tag{14}$$

Gallant (1987) recommends to pick $\omega$ as close as possible to $n^{1/5}$, which in this case would be 2. Given appropriate regularity conditions, it follows from

Pötscher and Prucha (1991a and 1991b) that the estimator is consistent, asymptotically normally distributed, and that the asymptotic variance-covariance matrix can be consistently estimated by:

$$\hat{C} = [(\Sigma_{t=1}^{n} (\frac{\partial \dot{e}_t}{\partial \theta'}) \otimes z_t)' \hat{V}^{-1} (\Sigma_{t=1}^{n} (\frac{\partial \dot{e}_t}{\partial \theta'}) \otimes z_t)]^{-1} \qquad (15)$$

## Results of the Dual Approach

The GMM estimation of the dual model is based on the following instrumental variables: a constant term, the capital stock and the output lagged two periods and the relative variable factor prices lagged one period. The non-linear estimation is performed using the OPTMUM module of Gauss386 and analytical derivatives. The convergence criterion is put at .0001. To facilitate convergence, some variables are properly rescaled so that all parameter gradients in each equation have the same order of magnitude.

Given the collinearity in the data and the shortness of the time series, estimating the entire set of parameters yielded largely non-significant results. Under such circumstances, the economic magnitudes derived from my estimates would be imprecise and therefore of little use. Moreover, the imposition of the curvature restrictions often presented numerical problems of convergence to a minimum. My strategy was therefore to try and estimate the largest subset of coefficients that would be significant. I experimented with various subsets of coefficients until I found a robust one that included at least one parameter relating to foreign R&D spillovers. The need to eliminate a certain number of parameters is often encountered in econometric studies of factor demands based on duality theory and second-order approximations, whether for reasons of convergence or for violations of the curvature restrictions. Of course, the functional form underlying the estimates then ceases to belong to the family of flexible functional forms. By ensuring that at least one spillover parameter is being estimated, I consider the spillover story the most likely. The data would probably accommodate other stories, i.e. other constrained parsimonious representations. A second difficulty I encountered was the sensitivity of the adjustment coefficients to the weighting matrix in the first stage of the estimation. When estimating the parameters by 2SLS, with cross-equation parameter restrictions, at least one of the adjustment coefficients would tend to zero. I therefore estimated $\hat{V}$ from reasonable initial values, ensuring that each equation was fitting. From the obtained estimates, I recomputed the weighting matrix $\hat{V}$ and used it to re-estimate the model. Ordinarily, final estimates with non-significant or zero adjustment coefficients would be rejected. My estimation strategy has a somewhat Bayesian flavor. I believe in adjustment costs and therefore put some weight on this factor (without imposing them, however) and then let the model give the best chance to the foreign R&D spillovers, while making sure the equations are fitting well, and provide otherwise reasonable estimates of the technology.[25] As in the previous section, I estimated the model with two measures of foreign R&D: the weighted sum of foreign sectoral R&D stocks (model I) and the total U.S. R&D stock (model II).

The GMM estimates are presented in Table 6. The values of the objective function are 9.361 and 8.137. Hence, my model passes Sargan's test of over-identifying restrictions as well as a quasi-likelihood ratio test of the restricted model against the unrestricted model with 16 parameters. ($X^2_{7,\,.05} = 14.067$).[26] As a measure of the fit of the model, I compute the squared correlations between the observed and simulated factor demands: the correlations are .741 for labour, .999 for materials, .978 for capital and .989 for R&D in model I, and slightly better for model II. The estimated model thus tracks the evolution of the observed factor demands quite well.[27]

Table 7 presents some of the technological characteristics of the Canadian manufacturing sector, evaluated at the observed values of the variables in 1973.[28] The reported figures are fairly close to the average values. The returns to scale are obtained from the following formula, based on Caves, Christensen and Swanson (1981):

$$\eta_t = (1 - \partial \ln VC_t / \partial \ln K_{t-1} - \partial \ln VC_t / \partial \ln R_{t-1} - \partial \ln VC_t / \partial \ln S_{t-1} - \partial \ln VC_t / \partial \ln I_{Kt} - \partial \ln VC_t / \partial \ln I_{Rt}) / (\partial \ln VC_t / \partial \ln Q_t). \quad (16)$$

According to this measure, returns to scale are measured as the elasticity of the growth of output with respect to an equiproportional growth of all the inputs, including own R&D and R&D spillovers.[29] Model I yields constant returns to scale in Canadian manufacturing, whereas Model II points to slightly increasing returns to scale of the order of magnitude found in other Canadian studies (Robidoux and Lester, 1988, and Daly and Rao, 1986).

The marginal adjustment costs per dollar of effective spending for the respective capital items, $(\partial VC_t / \partial I_{xt}) / p_{xt}$ for x = K, R, are around 0.16 for capital and range from 0.30 to 0.60 for R&D. Those amounts must be added to every dollar spent in order to obtain the cost per dollar of investment. The shadow prices, computed as $(\partial VC_t / \partial x_{t-1}) / p_{xt}$ for x = K, R, can be interpreted as the immediate gross after-tax rates of return. The point estimates of the rates of return are slightly higher for R&D than for capital, but statistically the two rates are equal at about 12 per cent. They exceed the normal rate because they cover the adjustment costs. Over the whole planning horizon, however, both stocks earn the normal rate of return when the costs of adjustment are taken into consideration.[30] This can be seen by rewriting (7) as:

$$-\partial VC_{t+1} / \partial R_t = [r_t \bar{p}_{Rt} + \delta_R \bar{p}_{R,t+1} - (\bar{p}_{R,t+1} - \bar{p}_{Rt})] \tag{17}$$

where $\bar{p}_{Rt} = p_{Rt} + \partial VC_t / \partial I_{Rt}$. If t = today, equation (17) says that the shadow price of R&D tomorrow, when the R&D becomes effective, must equal the opportunity cost of the cost of a dollar of R&D invested today, plus the depreciation on that cost evaluated at tomorrow's price, minus the price increase of the cost between today and tomorrow. The same holds for capital.[31] My results are again consistent with previous estimates in the literature. Bernstein and Nadiri (1991) report marginal adjustment costs ranging between 25 and 87 per cent for capital and between 07 and 46 per cent for R&D in six U.S. two-digit manufacturing industries. On Quebec manufacturing data, Carmichael, Mohnen and Vigeant (1990) obtain marginal adjustment cost for physical capital of 40 cents to the dollar.

If Canadian manufacturing had to pay the same price for foreign R&D as it pays for own R&D (which is not true in our model, where foreign R&D is a public good), foreign R&D would at best yield an after-tax marginal cost decrease of one cent to the dollar.[32] The exogenous foreign R&D is complementary to the own R&D. The evidence thus suggests that Canada cannot simply free-ride on other countries' (especially the United States) stock of knowledge. Canadians must do research in order to know what is going on in the field of science and technology and to be able to assimilate what is available. By the implicit function theorem applied to the Euler equation for R&D, the elasticity of own R&D with respect to foreign R&D is found to be 0.03.[33] That there is complementarity between own and outside R&D in general has been convincingly illustrated by Levin (1988) and Foray and Mowery (1990).[34] This complementarity also confirms Mohnen and Lépine's (1991) finding of a complementarity between R&D and payments for foreign technology in Canadian industries.

Finally, these results were found to be fairly robust to the specification of adjustment costs in terms of net vs gross investments, to the use of one-period lagged prices of capital and R&D instead of two-lagged output and capital as instrumental variables, and to the use of $\omega = 1$ or 3 instead of 2 in the computation of the Parzen weights.

To come back to the central question of this study, namely the contribution of R&D, especially foreign R&D, to productivity growth, I now present a decomposition of the conventional Divisia index of TFP growth:

$$T\dot{F}P = \frac{d\ln Q}{dt} - \sum_i \tilde{s}_i \frac{d\ln x_i}{dt} - \tilde{s}_K \frac{d\ln K}{dt} \tag{18}$$

where $\tilde{s}_i$ and $\tilde{s}_K$ are total cost shares, total cost being defined as the costs of labor, capital and intermediate inputs, i = L, M, and x represents the variable inputs.

When totally differentiating the variable cost function and applying Shephard's lemma, I can write:

$$0 = \sum_i s_i \dot{x}_i - \frac{\partial \ln VC}{\partial \ln K}\dot{K} - \frac{\partial \ln VC}{\partial \ln R}\dot{R} - \frac{\partial \ln VC}{\partial \ln Q}\dot{Q} - \frac{\partial \ln VC}{\partial \ln S}\dot{S}$$

$$- \sum_j \frac{\partial \ln VC}{\partial \ln I_j}\dot{I}_j \qquad (19)$$

where $s_i$ are variable cost shares, $j = K, R$, and I stands for gross investment.

Premultiplying (19) by $A = \eta^{-1} / (\partial \ln VC / \partial \ln Q)$ and adding the resulting expression to (18) yields the following equation:

$$\dot{TFP} = (1-\eta^{-1})\dot{Q} - \sum_i (\tilde{s}_i - A s_i)\dot{x}_i - (\tilde{s}_K + A\frac{\partial \ln VC}{\partial \ln K})\dot{K}$$

$$- A\left(\frac{\partial \ln VC}{\partial \ln R}\dot{R} + \frac{\partial \ln VC}{\partial \ln S}\dot{S} + \sum_j \frac{\partial \ln VC}{\partial \ln I_j}\dot{I}_j\right). \qquad (20)$$

The first term in (20) drops out when returns to scale are constant and thus represents the scale effect on TFP growth. The second and third terms can be rewritten as follows:

$$\tilde{s}_i - A s_i = s_i \left[\frac{VC}{VC + p_K K} - \frac{VC}{VC + \sum_k p_k z_k}\right]$$

$$+ s_i \left[(1 + \sum_k p_k z_k / VC)^{-1} - (1 - \sum_k \partial \ln VC / \partial \ln z_k)^{-1}\right]$$

$$\tilde{s}_K + A\, \partial \ln VC / \partial \ln K = \left[\frac{p_K K}{VC + p_K K} - \frac{p_K K}{VC + \sum_k p_k z_k}\right]$$

$$+ \left[(p_k K / VC)(1 + \sum_k p_k z_k / VC)^{-1} + (\partial \ln VC / \partial \ln K)(1 - \sum_k \partial \ln VC / \partial \ln z_k)^{-1}\right]$$

where $k = K, R, S, I_K, I_R$, and z and p are the corresponding quantities and prices respectively. They can be given the following interpretation: the terms in the first brackets drop out when total cost is measured appropriately, i.e. with respect to all the inputs, including foreign R&D and the gross investments (assuming we could measure all prices). This is the missing inputs effect, which is always positive. The terms in the second brackets drop out when the fixed and quasi-fixed inputs are optimal, i.e. when all the envelope conditions hold. The remaining terms in the second line of (20) measure respectively the effects of own R&D growth, foreign R&D growth and the growth in the adjustment costs.

**Table 6**

**GMM Estimation, Canadian Manufacturing, 1964-82**

| | **Model I*** | | **Model II*** | |
|---|---|---|---|---|
| Parameters | Estimates | Asymptotic t-Statistics | Estimates | Asymptotic t-Statistics |
| $\alpha_L$ | 0.300 | 7.513 | 0.328 | 5.491 |
| $\alpha_M$ | 0.653 | 28.866 | 0.700 | 31.987 |
| $\alpha_{11}$ | 0.143 | 1.295 | 0.298 | 5.112 |
| $\rho$ | 0.997 | 45.155 | 0.954 | 40.910 |
| $\beta_{LK}$ | -0.219 | -2.897 | -0.267 | -2.877 |
| $\beta_{LR}$ | - | - | - | - |
| $\beta_{MK}$ | - | - | - | - |
| $\beta_{MR}$ | - | - | - | - |
| $\beta_{KS}$ | - | - | - | - |
| $\beta_{RS}$ | -0.190 | -3.875 | -0.019 | -3.631 |
| $\beta_{LS}$ | - | - | - | - |
| $\beta_{MS}$ | - | - | - | - |
| $\beta_{KK}$ | 0.506 | 3.350 | 0.581 | 4.232 |
| $\beta_{KR}$ | - | - | - | - |
| $\beta_{RR}$ | - | - | - | - |
| $c_{KK}$ | 1.818 | 2.032 | 1.768 | 2.343 |
| $c_{RR}$ | 6.311 | 2.230 | 8.239 | 3.870 |

| | **Model I** | **Model II** |
|---|---|---|
| Value of the objective function: | 9.361 | 8.137 |

| | Model I Durbin-Watson | Model I fit** | Model II Durbin-Watson | Model II fit** |
|---|---|---|---|---|
| Equation (9): | 0.064 | 0.741 | 0.067 | 0.827 |
| Equation (10): | 1.050 | 0.999 | 0.813 | 0.998 |
| Equation (11): | 0.758 | 0.978 | 0.719 | 0.980 |
| Equation (12): | 1.622 | 0.989 | 1.090 | 0.996 |

* Model I: S = weighted sum of foreign sectoral R&D stocks
Model II: S = total U.S. R&D stock

** fit = squared correlation between actual and fitted values

**Table 7**

**Estimation Results of the Adjustment Cost Model (1973 Estimates and Standard Errors)**

| | Model I* | Model II* |
|---|---|---|
| Returns to Scale | 1.003 (0.022) | 1.048 (0.026) |
| Marginal Adjustment Cost of Capital** | 0.163 (0.007) | 0.168 (0.008) |
| Marginal Adjustment Cost of R&D** | 0.300 (0.013) | 0.554 (0.025) |
| Shadow Price of Capital** | 0.111 (0.075) | 0.112 (0.089) |
| Shadow Price of Own R&D** | 0.128 (0.033) | 0.123 (0.033) |
| Shadow Price of Foreign R&D** | 0.011 (0.003) | 0.001 (0.000) |
| Elasticity of Own R&D/Foreign R&D | 0.032 (0.008) | 0.016 (0.004) |

* Model I: S = weighted sum of foreign sectoral R&D stocks
Model II: S = total U.S. R&D stock

** Divided by the respective effective purchase prices. For foreign R&D, it is divided by the effective price of domestic R&D.

Note: The standard errors are based on Taylor series linearizations around the true parameter values.

**Table 8**

**Decomposition of Total Factor Productivity Growth Canadian Manufacturing, 1965-1982**

| | 1965-82 | | 1965-73 | | 1973-82 | |
|---|---|---|---|---|---|---|
| TFP growth | 0.560 | | 1.139 | | 0.157 | |
| **Model** | **I** | **II** | **I** | **II** | **I** | **II** |
| Returns to Scale | 0.011 | 0.157 | 0.020 | 0.282 | 0.005 | 0.070 |
| Non-opt. & Missing Inputs | 0.011 | 0.005 | 0.031 | 0.038 | -0.010 | -0.024 |
| Own R&D | 0.022 | 0.021 | 0.028 | 0.028 | 0.017 | 0.014 |
| Foreign R&D | 0.014 | 0.006 | 0.020 | 0.013 | 0.008 | 0.000 |
| Adjustment Costs | -0.043 | -0.053 | -0.059 | -0.066 | -0.037 | -0.049 |

Note: These figures correspond to averages over the respective sample periods. I and II refer to Models I and II respectively (see notes to Table 3.)

In Table 8 the TFP growth decomposition reveals the following.[35] TFP growth has been relatively low in Canada over the period 1965 to 1982: it grew at an average rate of one-half of one per cent per year. The explanatory variables of my model do little, however, to explain that low figure. The main reason is the absence of a cyclical dimension of productivity in my estimates. First, there is no output effect through scale in model I and only a small effect in model II. Second, the size of the adjustment costs in capital and R&D and their effect on the evolution of the short-run disequilibrium in the quasi-fixed inputs are not sufficient to produce a good cyclical story of productivity growth. Given its small magnitude (around 10 per cent of the physical capital stock), and a shadow price that does not much exceed the normal gross rate of return, the own R&D plays a very minor role. The foreign R&D effect, despite its small rate of return, can reach half the size of the own R&D effect, because of its relative size (roughly equal to the physical capital stock in model I, and eight times larger in model II). Nevertheless, my results confirm Denison's (1985) conjectures for the United States that foreign R&D is less important than domestic R&D.

For the decomposition of the slowdown there is, again, little to say. The scale, quasi-fixity, own R&D and foreign R&D effects go in the right direction, but explain less than 10 per cent of the total slowdown.

# Conclusions and Policy Recommendations

The first part of this study presents a fairly comprehensive overview of the empirical literature on the relationship between R&D and productivity growth. From the evidence gathered in this survey, the following conclusions seem to emerge:

- R&D has been identified as an important determinant of total factor productivity.[36] Its private rate of return exceeds the rate of return on physical capital. From the evidence gathered in this survey, it appears that the private net (of depreciation) rate of return lies in the 10 to 40 per cent bracket. R&D thus deserves the attention of policy makers.

- The mix of R&D seems to be of some importance. It is by now commonly accepted that higher rates of return are obtained from basic research vs. applied research or development, from company-financed R&D vs. publicly-funded R&D and from R&D geared to new processes as opposed to new products. Hence, policy-makers should be sensitive to the type of R&D being funded or encouraged.

- R&D is to a large extent a public good that spills over onto other firms or industries. The spillover effects can be substantial. Social rates of return by 50 to 100 per cent in excess of the private rates of return are not unrealistic. The existence of spillovers should not be overlooked when making policy decisions.

- A certain picture of the main issuers and receivers of inter-industry innovation and R&D spillovers and of the relative magnitude of those inter-industry flows of technology begins to emerge. Policy makers could therefore aim their R&D support at certain key sectors of the economy where the social rates of return are the highest, such as chemicals, non-electrical machinery or scientific instruments.[37]

- How exactly to promote R&D or to provide ways of capturing outside knowledge depends on the links between R&D and market structures.[38]

- Since it has been found to be complementary to physical capital, R&D can be indirectly encouraged by the policy measures that promote investments in plant and equipment.

- The R&D opportunity factor, the intuitive possibility of finding something in a certain area, is a strong determinant of the rate of return on R&D.[39] Policy measures geared at providing the scientific knowledge base are therefore of utmost importance. In this respect, the location of research labs near certain types of academic research centers, the funding of academic research and, possibly, the locational concentration of academic facilities in order to induce private research might be wise decisions, as some of Jaffe's (1989) results tend to show.

- It has been argued by some that the productivity of R&D declined in the '70s and that this fact could explain part of the productivity slowdown. This reduction in the productivity of R&D is not a strong empirical fact and should therefore not be a reason for reducing support of R&D.

- Despite the strong evidence of a higher return on privately-funded R&D than on publicly-funded R&D, there is room for useful public support of R&D near the basic end of the continuum. Link's (1981) results suggested that government-financed basic research has a significant positive effect on total factor productivity growth while Levin, Cohen and Mowery (1985) found that the knowledge contribution from government agencies and research labs is a significant determinant of R&D intensity. Moreover, basic research is likely to have the highest social rates of return and be less privately-appropriable.

- The social benefits of R&D actually go beyond what is measured by national account conventions, because quality improvements do not show up in the data and because output is badly measured in the services sector (e.g. health, education, transportation, defense), precisely where government R&D is required.

The second part of this study presents an econometric investigation of the role of foreign R&D spillovers in Canadian manufacturing.

The results obtained do not reveal as strong an effect of foreign R&D as might have been expected, given the importance of Canadian trade with the United States, the high percentage of foreign ownership of Canadian firms and the closeness to the U.S. market. The primal approach yields marginal productivities, when significant, of the order of 25 to 40 per cent. In many cases the coefficients are not significant. The dual approach yields at best a rate of return of 1 per cent. Canadian R&D itself does not come out very strongly. In the primal approach, it is never significant, and in the dual approach, its shadow price hardly exceeds the normal gross rate of return.

The question needs to be readdressed with new data and other models and estimation procedures. A more disaggregate analysis might produce a clearer picture of what is going on. Perhaps some sectors benefit from foreign R&D spillovers, while others suffer market losses because of foreign technological competition. My model probably underestimates the contribution of own R&D, because it sweeps domestic R&D spillovers under the table by imposing the Euler equation on R&D. Finally, we know that instrumental variable estimations yield inefficient estimates.

Despite these qualifications, I put forward the following policy recommendations:

- That foreign R&D produces a cost-reducing effect on Canadian manufacturing is not rejected by the data. Some of the channels of transmission of technology from abroad are foreign investment, acquisition of foreign licenses, trade in high-tech products, joint research and exchange of information. Keeping doors open for the acquisition of technical information through these channels is therefore recommended.

- The return on foreign R&D is, however, more than 10 times lower than the rate of return on domestic R&D. Over the period 1965 to 1983, foreign R&D contributed by a modest 2.5 per cent to the total factor productivity growth in Canadian manufacturing. Therefore, Canada cannot rely solely on foreign R&D for the provision of its technological knowledge.

- Foreign R&D is found to be complementary to domestic R&D. Although it did not show up with the primal approach, it was always the case in the dual approach. This complementarity underlines the need to provide a domestic knowledge basis in order to be able to benefit from outside R&D.

# Endnotes

1. In the case of multiple outputs the growths of the various outputs must also be weighted. For a presentation of the multiple output case, see Hulten (1978) and Berndt and Fuss (1989).
2. For a decomposition of total factor productivity growth into these various elements in a multi-output framework with an application to Canadian industries, see Bernstein and Mohnen (1991).
3. See the section titled The Extended Cobb-Douglas Approach for more details.
4. See Mairesse and Sassenou (1991) for a qualification of this common interpretation.
5. See Cunéo and Mairesse (1984) for a qualification of the common interpretation of the excess rate of return.
6. The weights are either the proportion of j's sales to i or the proportion of i's purchase from j. Forward and backward linkages can be constructed; first and second round borrowings can be taken into account.
7. See, for example, Griliches (1990) for a survey of spillover results in agriculture.
8. Mansfield (1988) uncovered a striking contrast between American and Japanese R&D effectiveness. The Japanese do more process R&D, which could explain an overall rate of return on R&D as high as 42 per cent. Unlike the Americans, the Japanese are better at applied R&D because they devote more of their research efforts to improving existing products and processes.
9. The input-output transactions matrix, the capital flows matrix, the patent-based inter-industry technology flows matrix, the innovations flows matrix, or some estimated proximity matrix in the technology space of patents or of technological characteristics have been used as supporting matrices in studies on inter-firm or inter-industry R&D spillovers (see Mohnen, 1990).
10. If imports were viewed as conductors of foreign R&D into Canada, the foreign R&D spillover would be better measured as the sum of Canadian

imports weighted by the R&D/sales ratio of the i-th industry in the j-th country, as in Allard (1987). However, my view is the following: there is a foreign R&D pool available out there; the closer Canadian manufacturing is to it, the more it can borrow from it. I have worked with one proximity measure; in future, it would be interesting to compare the results based on alternative proximity measures.

11. See Levy and Terleckyj (1985).
12. In 1980, high-tech imports represented 63 per cent of total Canadian imports from the United States, 71 per cent from Japan, 36 per cent from France, 71 per cent from West Germany and 50 per cent from the United Kingdom.
13. This list is more encompassing than the one reported in Magun and Rao (1989), but more restricted than the list used by Lodh (1989).
14. See United Nations, *International Standard Industrial Classification of All Economic Activities*, Series M, No. 4, Revision 2.
15. Small and insignificant elasticities of capital and R&D when using annual growth rates have also been obtained by Griliches and Mairesse (1983), Mairesse and Cunéo (1985) and Sassenou (1988).
16. It is particularly noticeable that, over the sample period, Canadian manufacturing decreased its high-tech imports from the United Kingdom while it increased its imports from Japan.
17. To save on coefficients to be estimated, the time trend, as a proxy for technology, has been dropped. Technical change occurs through own R&D and foreign R&D spillover. It is true that other sources of technical change exist (as managerial efficiency, for example), but I doubt that a time trend would be able to capture much more than what is already picked up by S.
18. Notice that the analysis here runs entirely in nominal terms, and thus obviates the arbitrary construction of a real discount rate.
19. The asymmetric Generalized McFadden functional form with constant returns to scale is actually the form used in Mohnen, Nadiri and Prucha (1986).
20. In a similar vein, Morrison (1988) further generalized the Generalized Leontief cost function by introducing quasi-fixed inputs.
21. See Diewert and Wales (1987), equation (32).
22. Returns to scale are defined with respect to all inputs, including foreign R&D and the adjustments in capital and R&D. In other words, the scale effect refers to the whole gamut of activites, factor hirings, technology adoption, and gross investments.
23. This functional form has a number of nice properties. The quadratic approximation is amenable to aggregation (see Ramey, 1986, for a discussion). It could allow for explicit solutions for the optimal quasi-fixed

inputs under certain conditions on the expectations of the exogenous variables (see Prucha and Nadiri, 1986, for more details). Unlike the translog, it can handle negative-valued arguments.

24. See Diewert and Wales (1978), p.52.
25. The econometric difficulties encountered were not affected by the type of adjustment cost formulation (in terms of net vs. gross investment, internal vs. external, isoelastic vs. quadratic or in terms of percentage changes vs. absolute changes), nor by the discounting (in terms of nominal discounting of nominal flows vs. real discounting of real flows or in terms of constant vs. variable real discount rates).
26. The full model presented in the previous section contains 17 parameters. I therefore needed at least five instrumental variables to test my restricted version against the full unrestricted model. A GMM estimation with more than four instrumental variables was impossible, because the estimated weighting matrix would be singular.
27. For the simulation, I assume perfect foresight of the future variables.
28. Any simulation of the adjustment paths in order to compute intermediate-run or long-run elasticities of factor demands is a futile exercise in this model, where expectations are rational, but the driving processes of the exogenous variables are not estimated.
29. In a more elaborate model, R&D spillovers should be modeled as a decision variable instead of an exogenous shock: whatever new technological knowledge is available would be assimilated or not, depending on its borrowing costs.
30. In the likely presence of domestic inter-industry spillovers, R&D should earn a higher rate of return than physical capital at the aggregate level. This suggests that R&D is not optimal, and henceforth the Euler equation for R&D does not hold. Attempts to estimate the system of equations without the Euler equation for R&D yielded unrobust results for the shadow prices of own and foreign R&D. Given the collinearity in the data, sufficient structure has to be put on the econometric model to yield sensible results. Alternatively, the wedge between the market and the shadow price of R&D that we attribute to adjustments costs could also be explained by domestic R&D spillovers.
31. It is assumed that in period t + 1 another investment will take place, so that the savings in purchase price and adjustment costs can materialize.
32. This low rate of return is consistent with the idea of a public good, the consumption of which is driven to the limit of zero marginal rate of return.
33. $$dR_t / dS_t = -(\partial VC^2_{t+1} / \partial S^2_t) / (\partial VC^2_{t+1} / \partial I^2_{R,t+1} + \partial VC^2_{t+1} / \partial R^2_t)$$

34. It should be noted that my results were hardly affected by the correction for high-tech imports flowing to final demand. Anyway, the point is not to treat high-tech imports as transmitters of foreign R&D, but rather as a proximity measure between countries in the technology space.
35. The growth rates have been approximated by first differences in the logarithms, and the weights attached to each growth rate in (17) have been computed as averages over two succeeding periods as in the Törnqvist index. The decomposition is evaluated at actual values of the variables and at point estimates of the parameters.
36. The results by Globerman (1972), Odagiri (1983) and Hanel (1988) suggest that the causality runs from R&D to productivity growth rather than the opposite.
37. Hanel and Palda's (1989) regression results showing that R&D spillover-generating industries in Canada received more Industrial and Regional Development Program (IRDP) grants than spillover-receiving industries between 1983 and 1987 are very encouraging.
38. See Levin and Cohen (1989) for a survey of the empirical evidence.
39. Clark and Griliches' (1984) result that R&D has a higher effect in business units where major technological changes occurred, Jaffe's (1986) finding that only within-cluster externalities matter for TFP growth, Goto and Suzuki's (1989) result that technological knowledge diffused from electronics-related industries has a higher impact on industries with similar technological positions, our result that technical change increases the shadow price of R&D, and Levin and Reiss' (1988) evidence of the differential role of several opportunity variables on the rate of return to R&D all point in the same direction.

# Appendix A

## High-tech Industries with Corresponding Standard Industry Trade (SITC) (Rev 1 and Rev 2) Codes

### 1961 to 1977 ( SITC Rev 1 )

*Non-electrical Machinery*

| | |
|---|---|
| 711 | Power generating machinery, other than electric |
| 712 | Agricultural machinery and implements |
| 714 | Office machines |
| 715 | Metalworking machinery |
| 717 | Textile and leather machinery |
| 718 | Machines for special industries |
| 719 | Machinery and appliances (other than electrical) and parts n.e.s |

*Electrical Products*

| | |
|---|---|
| 722 | Electrical power machinery and switchgear |
| 723 | Equipment for distributing electricity |
| 724 | Telecommunications apparatus |
| 725 | Domestic electrical equipment |
| 726 | Electric apparatus for medical purposes and radiological apparatus |
| 729 | Other electrical machinery and apparatus |

*Transportation Equipment*

| | |
|---|---|
| 731 | Railway vehicles |
| 732 | Road motor vehicles |
| 733 | Road vehicles other than motor vehicles |

| | |
|---|---|
| 734 | Aircraft |
| 735 | Ships and boats |

***Professional & Scientific Instruments***

| | |
|---|---|
| 861 | Scientific, medical, optical, measuring and controlling instruments and apparatus |
| 862 | Photographic and cinematographic supplies |
| 863 | Developed cinematographic film |
| 864 | Watches and clocks |
| 891.1 | Phonographs, tape recorders and other sound recorders and reproducers |

***Chemical Products***

| | |
|---|---|
| 513 | Inorganic chemicals |
| 514 | Other inorganic chemicals |
| 515 | Radioactive and associated materials |
| 53 | Dyeing, tanning and colouring materials |
| 54 | Medicinal and pharmaceutical products |
| 56 | Fertilizers manufactured |
| 58 | Plastic materials, regenerated cellulose and artificial resins |
| 59 | Chemical materials and products n.e.s |

## 1978 to 1987 ( SITC rev 2 )

***Non-electrical Machinery***

| | |
|---|---|
| 71 | Power generating machinery and equipment |
| 72 | Machinery specialized for particular industries |
| 73 | Metalworking machinery |
| 74 | General industrial machinery and equipment, n.e.s and machinery parts n.e.s |
| 75 | Office machines and automatic data processing equipment |

***Electrical Products***

| | |
|---|---|
| 76 | Telecommunications and sound records and reproducing apparatus and equipment |
| 77 | Electrical machinery, apparatus and appliances n.e.s, and electrical parts thereof |

***Transportation Equipment***

| | |
|---|---|
| 78 | Road vehicles |
| 79 | Other transport equipment |

*Professional & Scientific Instruments*

| | |
|---|---|
| 87 | Professional, scientific and controlling instruments and apparatus n.e.s |
| 88 | Photographic apparatus, equipment and supplies and optical goods, n.e.s; watches and clocks |

*Chemical Products*

| | |
|---|---|
| 52 | Inorganic chemicals |
| 53 | Dyeing, tanning and colouring materials |
| 54 | Medicinal and pharmaceutical products |
| 56 | Fertilizers manufactured |
| 58 | Artificial resins and plastic materials |
| 59 | Chemical materials and products n.e.s |

# Appendix B

## Data Sources and Constructions

The data cover the total Canadian manufacturing sector from 1964 to 1982 and have been drawn from various sources. as indicated below.

The data on materials and gross output and their implicit deflators were taken from S.C. 61-516 *Real Domestic Product by Industry, 1961-1971* and S.C. 61-213 *System of National Accounts, Gross Domestic Product by Industry*. The source for numbers of workers was S.C. 31-203 *Manufacturing Industries of Canada: National and Provincial Areas*. Data concerning the number of hours worked per week were taken from the International Labor Office, *Yearbook of Labor Statistics*. A fifty week work-year is assumed. Data on the total compensation per hour were obtained from the U.S. Department of Labor, Bureau of Labor Statistics, *Handbook of Labor Statistics*.

The capital stock was constructed using data obtained from S.C. 13-211 *Fixed Capital Stocks and Flows* and S.C. 13-568 *Fixed Capital Stocks and Flows 1936-1983*. End-of-period capital stocks were constructed by the perpetual inventory method, using a geometric depreciation rate. The 1961 benchmark was obtained by adding one-half the total net investment for 1961 (i.e. gross investment minus replacement investment) to the published figure for mid-year net stock. The geometric depreciation rate is calculated by dividing the value of replacement investment for the current period by the value of the net stock for the previous period.[1]

The rate of capacity utilization was taken from S.C. 31-003 *Capacity utilization rates in Canadian manufacturing;* this is measured relative to the period with the lowest capital-output ratio.

The effective after-tax price of capital is constructed as follows:

$$p_K = p_I\,[(1 - k_I)\,(1 - uz)]$$

where $p_I$ is the investment deflator, $k_I$ the rate of investment tax credit, u the statutory corporate income tax rate, and z the present value of allowable depreciation deductions. The investment tax credit rates were taken from S.C. 61-208 *Corporation Taxation Statistics*. The present value of tax depreciations is computed as:

$$z = u\alpha / (.04 + \alpha)$$

for a declining balance method, and as:

$$z = [u\alpha\,(1 +.04) / .04)]\,[1\text{-}1 / (1 +.04)^{T}]$$

for a straight-line method of depreciation, where $\alpha$ is the tax-allowable depreciation rate and T is the lifetime of the asset.[2]

The nominal interest rate was computed as the monthly average annual interest rate on prime business loans and was taken from the Bank of Canada Review. To calculate the nominal after-tax discount rate (assuming the capital stock to be entirely financed by debt), multiply this rate by one minus the corporate income tax rate.[3] The statutory corporate income tax rates were taken from S.C. 61-208.

Nominal R&D data were obtained from SS 83-3 *Standard Industrial R&D Tables*. The end-of-period stock of R&D knowledge was constructed using the perpetual inventory formula with a depreciation rate of .10. The benchmark was obtained by dividing the 1963 expenditure by the sum of the depreciation rate and the growth rate of gross output over the sample period. The R&D expenditures are deflated by the GNP deflator from SC 13-201 *National Income and Expenditure Accounts*.

The after-tax effective price of R&D was constructed as:

$$p_R = f_R \, [(1\text{-}u)\,(1\text{-}k_R\,)\text{-}D]$$

where $f_R$ is the R&D deflator, $k_R$ the R&D tax credit, and D the incremental tax allowance given by:

$$D = u\gamma\,[1 - \sum_{j=i}^{n} (1\,/\,n)\,(1\,/\,(1+.04)^{j}\,)]$$

$\gamma$ being the incremental tax allowance rate and n the period of reference for the computation of the increment. The incremental tax allowance was: non-existent before 1967, during 1977 and after 1982; 25 per cent on current expenditures over a five-year period from 1967 to 1976; and 50 per cent on all R&D expenditures over a three-year period from 1978 to 1982. The R&D investment tax credit was 25 per cent from 1967 to 1976, 10 per cent in 1977, and 20 per cent thereafter.[4]

The R&D spillover variable was constructed as a weighted sum of the R&D stocks in five industries (non-electrical machinery, electrical products and electronic equipment, transportation equipment, chemical products[5] and scientific instruments) and five countries (U.S., U.K., France, West-Germany and Japan):[6]

$$S = \sum_i \sum_j \frac{M_{ij}}{\Sigma_i \Sigma_j M_{ij}} R_{ij}$$

where S = spillover variable, $M_{ij}$ = Canadian imports from sector i in country j, $R_{ij}$ = R&D stock of sector i in country j. The import data, classified by SITC (and hence available separately for the purpose of defining a list of high-tech products) were taken from the OECD, *Foreign Trade by Products, Market Summary, Imports, Series C*. In order to exclude the imports flowing to final demand, the ratios (at the commodity level) were calculated from the 1980 Canadian input-output tables. These ratios -- of intermediate input demand plus investment in construction and equipment to total disposal, (i. e., production plus imports minus exports and re-exports) -- were then applied to total imports, assuming that all imports, whatever their country of origin, were allocated to intermediate and final demand in the same proportion as the total availability of the commodities. Business enterprise R&D expenditures in natural sciences and engineering were taken from the OECD database. The foreign R&D data were borrowed from the OECD database on R&D and were, converted to Canadian dollars using the purchasing power parities (PPP) also provided in this dataset. Except for the United States, the nominal R&D figures were deflated by the national GDP deflators, taken from IMF, *Supplement on Price Statistics*, IFS no.12, 1986. For the United States, the Jaffe-Griliches R&D deflator published in U.S. Department of Labor (1989) was used. R&D expenditures were first transformed in national currencies using the PPPs, then expressed in 1971 prices using the national GDP deflators, and finally reconverted in Canadian dollars using the PPPs. Missing data at the beginning of the sample were reconstructed using: 1) the data on total R&D expenditure provided by the National Science Foundation *International Science and Technology Data Update:1988*, NSF 89-307 and 2) the first available link between the total R&D series and the sectoral R&D series. For the United Kingdom, the series taken was that set up by Soete and Patel (1985) to reconstruct mid-of-sample missing points using the growth rate of the more aggregate series applied to the data just before the missing points. The procedure used for Germany, was that used by Majer (1978) -- one-year missing values were replaced by arithmetic interpolation.

In order to avoid double-counting: the R&D labour costs, divided by the wage rate, were substracted from labour; other current costs, divided by the price of materials, were substracted from intermediate inputs; and a stock of R&D capital expenditures, constructed in the same way as the total R&D stock, was substracted from the total capital stock. The various R&D cost ratios were taken from OECD, *International Statistical Year* (1975).

The prices of labour, intermediate inputs and output were multiplied by one minus the corporate income tax rate to express them as after-tax prices. All indexes and real values are based in 1971. Data obtained from different sources or from various issues of the same publication have been linked to the most recent data by their growth rates, when the figures differed in the overlapping years.

**Table B1**

**Descriptive Statistics of the Main Data
Canadian Manufacturing 1963 - 1983**

| Symbol | Variable | Mean | Stnd. Devia- tion | Mini- mum- | Maxi- mum- | Annual Growth Rate 1965/82 |
|---|---|---|---|---|---|---|
| Q | Gross Output | 62628 | 14819 | 35613 | 82795 | 3.45% |
| L | Man Hours | 12993 | 689 | 11292 | 14110 | 0.33% |
| M | Intermediate Inputs | 42086 | 10208 | 23696 | 56112 | 3.59% |
| K | Net Capital Stock | 31535 | 7753 | 18980 | 43168 | 4.42% |
| R | Own R&D Stock | 2899 | 792 | 1626 | 4529 | 4.89% |
| $S_1$ | Foreign R&D Spillover | 32472 | 5524 | 22542 | 40668 | 2.96% |
| $S_2$ | Foreign R&D Spillover | 266641 | 20510 | 223055 | 287332 | 1.35% |
| $p_L$ | Price of Labour | 0.849 | 0.529 | 0.302 | 1.963 | 9.35% |
| $p_M$ | Price of M | 0.874 | 0.467 | 0.455 | 1.776 | 7.19% |
| r | Discount Rate | 0.092 | 0.037 | 0.058 | 0.193 | 6.72% |
| $p_K$ | Effective Price of K | 0.895 | 0.472 | 0.427 | 1.864 | 7.66% |
| $p_R$ | Effective Price of R | 0.642 | 0.324 | 0.330 | 1.346 | 5.77% |

All quantities are in millions of 1971 Canadian dollars.
$S_1$ = weighted sum of sectoral R&D stocks.
$S_2$ = total U.S. R&D stock

# Notes

1 The resulting depreciation rate is virtually invariant over time and can therefore be considered as constant.

2 Geometric depreciation rates of 5 per cent were taken for buildings and 20 per cent for machinery. Straight line depreciation schedules were in effect in 1963 - 66 (a = .2, T = 5 for buildings, a = .5, T = 2 for machinery) and in 1972 - 78 (a = .5, T = 2 for machinery only). A 15 per cent markup on the purchasing price of capital was used for capital consumption allowances in 1971.

3 See King, M. and D. Fullerton (1984).
4 See McFetridge, D. and J. Warda (1983).
5 Exclusive of petroleum products and refineries.
6 The R&D depreciation rates are assumed to be the same everywhere and the R&D spillover variable is assumed to grow proportionately to the Canadian gross output. The spillover stock can thus be constructed from the weighted sum of the R&D expenditures.

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