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# The Contribution of U.S. R&D Spending to Manufacturing Productivity Growth in Canada

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## 1. Introduction*

Output expansion originates from growth in the factors of production and productivity. Moreover, the productivity component generally arises from advances in the state of knowledge transmitted through technological change. Since research and development (R&D) investment directly contributes to knowledge accumulation, R&D activities are a potentially important source of productivity gains.

A distinguishing characteristic of R&D activities is that benefits are not completely captured by R&D investors. These unappropriated benefits, referred to as R&D spillovers, provide a source of new knowledge and thereby productivity gains to spillover receivers (see the surveys by Griliches [1992], and Nadiri [1993]). Thus output growth depends, in part, on a producer's own R&D activities, as well as, on the R&D efforts of other knowledge-creators.

With international trade, foreign direct investment, and international information diffusion, R&D spillovers extend beyond national boundaries (see Coe and Helpman [1995], Bernstein [1998], Bernstein and Mohnen [1998] and Bernstein and Yan [1997]). International R&D spillovers imply that productivity growth depends, not only on domestic spillovers, but also additionally on the R&D activities undertaken in other economies. The main objective of this paper is to investigate U.S. R&D capital as a spillover source to Canada. This paper measures total factor, and labor productivity growth for the Canadian manufacturing sector, and examines the role of U.S. R&D capital as a contributor to productivity gains.

The paper is organized into a number of sections. Section 2 contains a discussion of the nature of total factor productivity growth. Because the term productivity is used in different contexts, it is useful to describe the concept of total factor productivity growth, and its relationship to technological change, R&D capital accumulation, and R&D spillovers. After delineating the concept of total factor productivity, section 3 examines the elements that contribute to its growth. Specifically, this section conducts hypothesis testing on alternative sources of productivity gains to Canadian manufacturing. Section 4 measures total factor and labor productivity growth, and calculates the contribution of the various productivity sources. Thus both the rates and decomposition of productivity are developed in this section. In addition, the concept of efficiency-based productivity is distinguished from observed productivity. Observed productivity growth is defined as output growth net of observed input growth, and efficiency-based productivity considers output growth net of the cost-minimizing set of factor requirements. Deviations between efficiency-based and observed productivity growth rates signify biases in observed rates resulting from measurement errors, such as inadequate adjustment for quality improvements. The last section is the conclusion.

## 2. Productivity Growth and R&D Capital

This section of the paper discusses the role of R&D capital as a source of productivity growth. R&D capital, like labor, plant, and equipment, is a factor of production, and thereby is an element in the determination of output supply. Moreover, a distinguishing facet of R&D from other inputs is the inability of R&D performers to completely appropriate all benefits. Benefits from R&D investment spill over throughout economic activity. Therefore, R&D capital acts as a factor of production, and a spillover source. Clarifying these two features, promotes the demonstration of the relationship between R&D capital and productivity growth.

The simplest way to understand the mechanism between R&D and productivity is to consider productivity growth in the absence of R&D capital. In most empirical research, output is produced by means of inputs such as, labor, capital, and intermediate inputs (sometimes referred to as materials), and a technology index, which is usually measured as a time trend. It is possible to add more outputs and inputs, but we are only using this framework for illustrative purposes. Thus production can be represented as

(1) $$y = F(L, M, K, t),$$

where $y$, $L$, $M$, and $K$ denote the quantities of output, labor, intermediate inputs, and capital respectively, $t$ is the disembodied technology index, and $F$ represents the production function.

In order to develop a measure of productivity growth, time differentiate the production function. In terms of growth rates we get,

(2) $$\hat{y} = \beta_l \hat{L} + \beta_m \hat{M} + \beta_k \hat{K} + \alpha_t ,$$

where the variables with a $\wedge$ above, represent growth rates in output and inputs, also $\beta_l , \beta_m , \beta_k$ , are output elasticities with respect to three factors of production, and $\alpha_t$ is the rate of disembodied technological change. With the usual definition of total factor productivity (TFP) growth, as the residual growth of output after accounting for input growth, $TFPG^1 = \hat{y} - \rho_y^{-1}(\beta_l \hat{L} + \beta_m \hat{M} + \beta_k \hat{K})$, where $\rho_y = \beta_l + \beta_m + \beta_k$ , is the degree of returns to scale, then from (2),

(3) $$TFPG^1 = (\rho_y - 1)\rho_y^{-1}(\beta_l \hat{L} + \beta_m \hat{M} + \beta_k \hat{K}) + \alpha_t .$$

The right side of equation (3) shows that TFP growth can be decomposed into a scale term, and a disembodied technological change term. If there is constant returns to scale then $\rho_y = 1$, and so TFP growth reflects technological change. If $\alpha_t = 0$, there is no disembodied technological change, then TFP growth originates from increasing returns to scale, when input growth rates are positive.

It is important to note that the variable, denoted by $t$, reflecting the index of disembodied technology is exogenous. Furthermore, although the technology index, or the "level" of technology, may not be constant, exogeneity of the technology level implies that changes in technology must also be exogenous. Consequently, disembodied technological progress, $\alpha_t > 0$ , and thereby also productivity gains, occur in the absence of any resource expenditure. There is a "free lunch", as production efficiency increases as a result of disembodied technological change, without resources allocated to efficiency improvements.[1]

Next consider the role of R&D capital. With R&D capital, the production function becomes,

(4) $y = F(L, M, K, R, t)$

where $R$ denotes R&D capital. From the viewpoint of the producer whose output is specified by (4), $R$ represents own R&D capital, and is a factor of production.

There are two ways to derive TFP growth using equation (4). In the first way, subtract from output growth the same set of inputs as for the case without R&D capital. Thus time differentiating (4), TFP growth becomes,

(5) $TFPG^2 = (\rho_y - 1)\rho_y^{-1}(\beta_l \hat{L} + \beta_m \hat{M} + \beta_k \hat{K}) + \alpha_t + \beta_r \hat{R}$ ,

where $\beta_r$ is the output elasticity with respect to R&D capital. Equation (5) shows that TFP growth is decomposed into scale and disembodied technological change terms, but the latter contains two elements. The two components are due to the time trend, and R&D capital.

Productivity growth equations, (3) without R&D capital, and (5) with R&D, appear to be consistent. However, a problem arises with respect to the actual implementation of equation (3). Although R&D capital is not explicitly recognized in equation (3), the components of R&D are, in fact, embedded within the traditional factors of production. For example, labor quantity includes scientists, and engineers, while the capital input includes structures, and machinery used in the development of new products and processes. Therefore, an alternative interpretation of equation (3), and the one that corresponds to official calculations, is that TFP growth measures output growth net of all input growth, inclusive of R&D capital.

With this alternative view of equation (3), the explicit consideration of R&D capital in the production function, implies that in order to avoid double counting, the components of R&D must be netted out of the relevant traditional (or non-R&D) inputs. This problem arises for other inputs as well. For example, in the case of energy as a distinct factor of production, all related energy components must be separated from non-energy inputs. Thus, non-R&D inputs in the production function, given by equation (4), and consequently in the TFP equation, (5), should be interpreted as net of any R&D components. With this interpretation, productivity growth reflected by (5) measures output growth net of non-own R&D capital input growth.

The second approach to the measurement of productivity growth, when R&D is an explicit factor of production, defines TFP growth as output growth net of all input growth. Thus from equation (4), we can derive,

(5’) $$TFPG^3 = (\rho_y - 1)\rho_y^{-1}(\beta_l \hat{L} + \beta_m \hat{M} + \beta_k \hat{K} + \beta_r \hat{R}) + \alpha_t$$

where now $TFPG^3 = \hat{y} - \rho_y^{-1}(\beta_l \hat{L} + \beta_m \hat{M} + \beta_k \hat{K} + \beta_r \hat{R})$, and $\rho_y = \beta_l + \beta_m + \beta_k + \beta_r$. In equation (5’), since $TFPG^3$ is defined as output growth net of input growth, inclusive of own R&D capital, consistency requires the degree of returns to scale to be defined over all inputs.

In general, the measurement of productivity growth differs according to the selection of $TFPG^1$, $TFPG^2$, or $TFPG^3$. However, since an explicit recognition of the role of R&D capital as a factor of production signifies a finer input disaggregation, then either $TFPG^2$ or $TFPG^3$ are superior to $TFPG^1$. In addition, there are important conceptual differences between $TFPG^2$, and $TFPG^3$. $TFPG^2$, derived from equation (5), assigns the role of R&D capital to technological change in the decomposition of productivity growth. Using $TFPG^3$, from equation (5’), R&D capital affects productivity growth through non-constant returns to scale. If production is characterized by constant returns to scale, $\rho_y = \beta_l + \beta_m + \beta_k + \beta_r = 1$, then R&D capital does not influence productivity growth. In this case, TFP growth represents the rate of exogenous disembodied technological change, $\alpha_t$.

The view that R&D capital generates productivity growth through deviations from constant returns to scale is consistent with conventional measures of TFP growth. As we have noted, official or conventional measures of productivity growth define it to be output growth net of all input growth, where the components of R&D capital are rooted within the traditional factors of production. A difficulty with the alternative view, own R&D capital as a source of technological change, is that it creates an artificial distinction between in house R&D, and other sources of technological change. For example, R&D activities can be "contracted out". These R&D services appear as intermediate inputs, and so, unlike own R&D, affect productivity growth through non-constant returns to scale. Like own R&D, it may be feasible to separate out purchased R&D inputs from other factors of production. However, consistency requires that we conduct the same exercise with all inputs that embody technological change. For example, plant and equipment embody technical advances, and it would be necessary to separate out those elements of capital that reflect technical progress.

*Adopting the view of "productivity as residual" is consistent with the conventional definition. Productivity growth reflects scale economies and disembodied technological change. This concept of productivity excludes other types of technological change, such as advances embodied in plant and equipment, or purchased through technology licenses.*

The disquieting aspect of the conventional interpretation of TFP growth , as we noted, is that disembodied technological change arises as "manna from heaven". To overcome this limitation, we turn to the other characteristic of R&D capital, as a source of R&D spillovers. The production function with own R&D capital input, and R&D spillovers is,

(6) $y = F(L, M, K, R, S)$ ,

where $S$ denotes the R&D spillovers.

In (6), R&D spillovers represents disembodied technological change. Spillovers arise from the R&D capital stocks of producers other than the one represented by equation (6). In other words, these stocks are endogenously determined through the production decisions of spillover sources or senders. From the vantage of spillover sources, these stocks are their own R&D capital inputs. *Spillovers are exogenous variables from the viewpoint of the spillover* *receiver, but endogenously generated by spillover senders. Spillover receivers incur costs by incorporating spillovers into their production processes. For example, inputs may have to be redirected from producing output for current revenue generation, to assimilating the new knowledge gained from R&D spillovers. In addition, it is possible that only a fraction of R&D capital generate spillovers. The extent of spillover generation and the costs of spillover incorporation are reflected through the actual specification of production processes.*

To derive productivity growth within the context of spillovers, time differentiate (6). Thus,

(7) $$TFPG^4 = (\rho_y - 1)\rho_y^{-1}(\beta_l \hat{L} + \beta_m \hat{M} + \beta_k \hat{K} + \beta_r \hat{R}) + \zeta \hat{S}\ ,$$

where $TFPG^4 = \hat{y} - \rho_y^{-1}(\beta_l \hat{L} + \beta_m \hat{M} + \beta_k \hat{K} + \beta_r \hat{R})$, and $\zeta$ is the output elasticity with respect to R&D spillovers. $TFPG^4$ and $TFPG^3$ are similar, except that the former defines output using R&D spillovers as the disembodied technology index, and the latter uses a time trend for the index.

Equation (7) shows that TFP growth is still decomposed into a scale term and a technology term. However, the technology term involves the growth of R&D spillovers. In this context, R&D capital generates output growth like other factors of production. In addition, R&D spillovers affect productivity growth. *Thus R&D capital accumulation of a producer causes its own output to grow, and through spillovers influences the productivity growth of other producers.*

*A conclusion from this analysis is that, under constant returns to scale, without costless disembodied technological change, and absent R&D spillover growth, there is no productivity growth. Non-zero measured productivity growth rates can only reflect measurement errors. For example, there may be inadequate quality adjustments for labor, or capital improvements.*

*Consequently, measured productivity gains would not signify actual improvements in technical efficiency.*

## 3. Testing for the Sources of Productivity Growth

Along with determining rates of productivity growth for the Canadian manufacturing sector, this paper seeks to investigate the sources of productivity growth. Since productivity gains emanate from positive rates of disembodied technological change and increasing returns to scale (with growing inputs), this section presents evidence on the degree of returns to scale and the rate of disembodied technological change for Canadian manufacturing.

In order to estimate the degree of returns to scale and the rate of disembodied technological change, it is necessary to specify production conditions for the manufacturing sector. In this paper, production conditions are denoted by equations characterizing the determinants of input demands per unit of output supply, or in other words factor intensities. These equations are[2],

$$(8)\quad v_{it}/y_t = \beta_i + \sum_{j=1}^{n}\beta_{ij}\omega_{jt} / \sum_{j=1}^{n} b_j\omega_{jt} - 0.5 b_i \sum_{j=1}^{n}\sum_{k=1}^{n}\beta_{jk}\omega_{jt}\omega_{kt} / (\sum_{j=1}^{n} b_j\omega_{jt})^2 + \beta_{is}S_t + \beta_{it}t + (\beta_{ss}S_t^2 + \beta_{tt}t^2 + \beta_{st}S_t t)b_i$$

$$+\alpha_i / y_t + b_i(\alpha_s S_t + \alpha_t t)/y_t + b_i\alpha_{yy}y_t + \gamma_i(1-m_i)v_{it-1}/y_t \qquad i = 1,\ldots,n.$$

where $v_{it}$ is the ith factor demand, $y_t$ is output quantity, $\omega_{it}$ is the factor price of the ith input, $S_t$ is the R&D spillover, and $t$, the time trend, is the exogenous technology index. The parameters are denoted by the $\alpha's$, $\beta's$, and $m's$.[3]

At this point both R&D spillovers and the time trend influence production cost, because hypothesis tests are conducted to discern which variable represents the technology indicator for Canadian manufacturing. Since disembodied technological change generates productivity growth, these tests enable us to determine whether R&D spillovers, or an exogenous index are sources of productivity growth.[4]

Data for output and the four inputs, labor, intermediate inputs, physical capital, and R&D capital, used to estimate equation set (8), pertain to the Canadian manufacturing sector. The R&D spillover is the R&D capital stock of the US manufacturing sector.[5] The data are presented in table A2.1 of Appendix 2. The model is estimated for two different measures of physical capital. The first measure of physical capital stock embodies a depreciation rate that annually averages 24 percent. The depreciation rate used to construct the second measure is 7 percent. The latter rate is closer to the one used to construct physical capital stock for the US manufacturing sector. Statistics Canada produced both sets of capital stock data. The estimation results are presented in table A2.2 of Appendix 2.

With respect to the disembodied technology variables, there are two tests in this context. The first one examines the case of no exogenous disembodied technological change. The parameter restrictions for zero exogenous technological change are, $\beta_{it} = \beta_{tt} = \alpha_t \quad 1 = 1,\ldots,n, \quad n = 4$. Table 1 presents the test results for both models, model 1 is the designation of the case with a 24 percent physical capital depreciation rate, and model 2 relates to the case of 7 percent depreciation. Table 1 shows that in both models, it is not possible to reject the hypothesis of no exogenous disembodied technological change. Given no exogenous technological change, we consider the hypothesis of no R&D spillovers. This test involves the following parameter restrictions, $\beta_{is} = \beta_{ss} = \alpha_s \quad 1 = 1,\ldots,n, \quad n = 4$, and is rejected in both models.[6] *Therefore, disembodied technological change occurs for Canadian manufacturing through spillovers from US R&D capital.*

Next we consider the hypothesis of constant returns to scale. Constant returns to scale (in the context of no exogenous disembodied technological change) implies the parameter restrictions, $\alpha_i = \alpha_s = \alpha_{yy} = 0, \quad i = 1,\ldots,n, \quad n = 4$. Table 1 shows the test results for both models. *Constant returns to scale cannot be rejected, and hence scale economies cannot be a source of productivity gains. Therefore, manufacturing productivity growth in Canada arises*

**Table 1. Hypothesis Tests**

| **Model 1** | **Test Statistic** | $\chi^2_{0.05}$ |
|---|---|---|
| No Exogenous Technological Change | LR(6) = 7.92 | 12.59 |
| No Exogenous Technological Change and No Spillover | LR(5) = 32.44 | 11.07 |
| Constant Returns to Scale | LR(6) = 10.80 | 12.59 |
| | | |
| **Model 2** | **Test Statistic** | $\chi^2_{0.05}$ |
| No Exogenous Technological Change | LR(6) = 9.10 | 12.59 |
| No Exogenous Technological Change and No Spillover | LR(5) = 12.48 | 11.07 |
| Constant Returns to Scale | LR(6) = 6.85 | 12.59 |

*through disembodied technological change. The source of this technological change is the spillover from US manufacturing R&D capital.*

## 4. Rates of Productivity Growth

In this section of the paper productivity growth rates for the Canadian manufacturing sector are measured. Rates of productivity growth are calculated as differences between output and input growth rates. However, measured or observed rates of productivity growth do not necessarily reflect the efficient set of factor requirements used in the production process. For example, inputs may be inadequately adjusted for quality improvements, so that observed factor quantities do not represent cost minimizing input requirements. Thus observed productivity growth rates can differ from efficiency-based productivity that reflects cost minimizing conditions.

Efficiency-based productivity growth is defined as $TFPG^{e}(s,t) = \dot{Y}/Y - \dot{Z}/Z$, where $\dot{Y}/Y$ is the output growth rate and $\dot{Z}/Z$ is the cost-minimizing input growth rate. Following Diewert [1981], Denny and Fuss [1983], Berndt and Fuss [1986], Bernstein, Mamuneas and Pashardes [1999], efficiency-based productivity growth is,

$$(9) \qquad TFPG^{e}(s,t) = 0.5\left[\left(1-\rho_{yt}^{-1}\right)(c/y)_{t} + \left(1-\rho_{ys}^{-1}\right)(c/y)_{s}\right](\dot{Y}/Y)/(c/y)_{m}$$
$$+\,0.5\left(\xi_{vt}(c/y)_{t}\,y_{t} + \xi_{vs}(c/y)_{s}\,y_{s}\right)(t-s)/(c/y)_{m}\,y_{m},$$

where $c$ is production cost, $\rho_{y}$ is the degree of returns to scale, and $\xi_{v}$ is the rate of disembodied technological change. Efficiency-based productivity growth generally consists of two elements, non-constant returns to scale and rates of disembodied technological change. In the case of Canadian manufacturing disembodied technological change arises from US R&D capital. Moreover, since there are constant returns to scale, $\rho_{yt} = \rho_{ys} = 1$, equation (9) becomes, (9') $$TFPG^{e}(s,t)= \ 0.5\left(\xi_{vt}(c/y)_{t}\,y_{t}+\xi_{vs}(c/y)_{s}\,y_{s}\right)\left(t-s\right)/(c/y)_{m}\,y_{m}.$$

Observed TFP growth between any two periods is defined as output growth net of observed input growth, or $TFPG^{o}(s,t)=\dot{Y}/Y-\dot{V}/V$, and $\dot{V}/V$ represents observed input growth, which does not necessarily correspond to the cost minimizing input quantities.

Observed rates of productivity growth can be obtained from efficiency-based growth by subtracting $\dot{V}/V$, and adding $\dot{Z}/Z$ to equation (9'). Thus,

(10) $$TFPG^{o}(s,t)= \ +0.5\left(\xi_{vt}(c/y)_{t}\,y_{t}+\xi_{vs}(c/y)_{s}\,y_{s}\right)\left(t-s\right)/(c/y)_{m}\,y_{m}+\left(\dot{Z}/Z-\dot{V}/V\right)$$

Equation (10) shows that observed TFP growth consists of two elements; a term reflecting R&D spillovers, and a factor adjustment term, $\dot{Z}/Z-\dot{V}/V$. The latter element forms part of the productivity decomposition because efficiency-based TFP growth is net of quality-adjusted input growth, while observed TFP growth is net of unadjusted, or observed, input growth.

Observed and efficiency-based productivity growth rates and their decomposition are presented in tables 2 and 3. Table 2 pertains to the first model, with a 24 percent depreciation rate for physical capital, and table 3 presents the results for the second model, with a 7 percent depreciation rate. Observed productivity growth rates over the period from 1966 to 1994, annually average 0.54 percent for model 1, and 0.49 percent for model 2. A decrease in the physical capital depreciation rate implies an increase in the growth rate of capital, and therefore a lower productivity growth rate. However, although the depreciation rate in model 1 is over three times greater than the rate in model 2, productivity growth in model 1 exceeds the rate in model 2 by only 10 percent. *Differences in depreciation rates do not dramatically affect observed average annual productivity growth in Canadian manufacturing over the period from 1966 to 1994.*

| **Table 2. TFP Growth and Decomposition: Model 1**<br>Average Annual Rates (percent) | | | |
|---|---|---|---|
| **Period** | **Observed TFP Growth** | **Spillover Effect** | **Factor Adjustment Effect** |
| 1966-1994 | 0.537 | 0.713 | -0.176 |
| 1966-1973 | 0.868 | 0.864 | 0.004 |
| 1974-1994 | 0.411 | 0.656 | -0.244 |
| 1966-1968 | 0.247 | 1.145 | -0.898 |
| 1969-1973 | 1.240 | 0.695 | 0.545 |
| 1974-1978 | 0.506 | 0.424 | 0.082 |
| 1979-1983 | -0.326 | 0.725 | -1.052 |
| 1984-1988 | 1.055 | 1.108 | -0.053 |
| 1989-1994 | 0.411 | 0.414 | -0.003 |

| **Table 3. TFP Growth and Decomposition: Model 2**<br>Average Annual Rates (percent) | | | |
|---|---|---|---|
| **Period** | **Observed TFP Growth** | **Spillover Effect** | **Factor Adjustment Effect** |
| 1966-1994 | 0.487 | 0.522 | -0.034 |
| 1966-1973 | 0.897 | 0.708 | 0.189 |
| 1974-1994 | 0.331 | 0.450 | -0.119 |
| 1966-1968 | 0.614 | 0.947 | -0.333 |
| 1969-1973 | 1.067 | 0.565 | 0.502 |
| 1974-1978 | 0.366 | 0.336 | 0.030 |
| 1979-1983 | -0.300 | 0.559 | -0.859 |
| 1984-1988 | 0.890 | 0.732 | 0.158 |
| 1989-1994 | 0.362 | 0.220 | 0.142 |

In the years prior to 1973 (the pre-slowdown period see the survey by Griliches [1994] and the references therein), annual average observed productivity growth is about 0.9 percent, for both models. In the slowdown period, observed productivity growth drops to 0.41 percent, or 0.33 percent, for models 1 and 2 respectively. The productivity slowdown represents a 53 percent (for model 1), or a 63 percent (for model 2) decline in annual productivity growth.[7] There is a substantial slowdown in manufacturing productivity growth. Moreover, we see that differences in depreciation rates tend to affect observed productivity growth rates in the slowdown period, as there is a more pronounced slowdown with longer living physical capital stocks.

Tables 2 and 3 show that in the period from 1974 to 1994, productivity growth decreased in the last half of the 1970's and through to the first half of the 1980's. Productivity growth rates rebounded in the late 80's, but not quite to the high growth rates observed in the 1969-1973 period. By the late 1980's and first half of the 1990's productivity growth rates declined again. Nevertheless, the trend since the first half of the 1980's depicts a resurgence of productivity gains for Canadian manufacturing.[8] *Therefore, although productivity performance has dramatically improved in the years following 1983, the Canadian manufacturing sector has still not attained annual growth rates that were observed in the pre 1974 period.*

Efficiency-based productivity growth rates, defined by $TFPG^e$, are in the column labeled spillover effect in tables 2 and 3. Average annual efficiency-based productivity growth was 0.71 percent in model 1 and 0.52 percent in model 2. Efficiency-based and observed TFP growth rates are quite similar in the model with relatively longer living physical capital stocks. This is not the case for model 1. Efficiency-based TFP growth exceeds observed growth rates by 32 percent. *Therefore, adequacy of observed productivity growth, as an indicator of efficiency gains, critically depends upon estimates of physical capital depreciation rates.*

The divergence between efficiency-based and observed productivity growth rates occurs mainly in the slowdown period. From 1974 to 1994, average annual efficiency-based productivity growth was 0.66 percent in model 1 and 0.45 percent in model 2. These rates represent respectively 61 percent and 36 percent higher gains than measured from observed productivity growth. *Therefore, over the last two decades measured productivity growth rates underestimate efficiency gains, and the degree of underestimation increases as depreciation rates for plant and equipment rise.*

Total factor productivity growth measures output growth net of input growth associated with all factors of production. Besides this total measure, it is possible to construct partial productivity indicators that pertain to each of the inputs. A common partial productivity indicator is labor productivity growth. Labor costs represent a large portion of revenue net of intermediate input cost (i.e. value added), and labor income represents a major source of consumer expenditure.

To derive labor productivity growth, use the definition of observed TFP growth, along with equation (10), and with the definition of labor productivity growth as $LPG^o(s,t) = \dot{Y}/Y - \dot{V}_l/V_l$, where $\dot{V}_l/V_l$ is labor growth, then,

$$(11) \qquad LPG^o(s,t) = (\dot{V}/V - \dot{V}_l/V_l) + 0.5\left(\xi_{vt}(c/y)_t y_t + \xi_{vs}(c/y)_s y_s\right)(t-s)/(c/y)_m y_m$$
$$+\left(\dot{Z}/Z - \dot{V}/V\right).$$

Equation (11) shows that observed labor productivity growth consists of physical capital, R&D capital and intermediate input growth rates net of labor growth, and observed TFP growth. The latter is composed of R&D spillover, and factor adjustment terms.

Observed labor productivity growth rates for Canadian manufacturing are presented in tables 4 and 5. Since labor productivity growth is output growth net of labor growth, different rates of physical capital depreciation do not affect the rates of labor productivity growth, but only their composition. This is seen from tables 4 and 5, as labor productivity growth rates are the same in both models.

Average, annual, labor productivity growth from 1966 to 1994 was 2.55 percent. The slowdown in labor productivity growth was not as pronounced as for TFP growth. In the period 1966-1973, labor productivity grew at an annual average rate of 3.29 percent. The annual growth rate declined to 2.27 percent over the period 1974-1994. In addition, the pattern of labor productivity growth rates was similar to the pattern observed for TFP growth, although changes in TFP growth were more severe than the turning points associated with labor productivity.

Tables 4 and 5 show that over the whole period and for all sub-periods, growth in the intermediate input to labor ratio was the main source of labor productivity growth. From 1966 to 1994 the intermediate input-labor ratio contributed 68 percent to labor productivity growth. The second principal contributor to labor productivity was R&D spillovers from US manufacturing. Spillovers contributed 28 percent in model 1, with the higher depreciation rate, and 21 percent in model 2. *Although observed labor productivity growth rates were not affected by differences in physical capital depreciation rates, the contribution of spillovers to labor productivity growth over the period 1966-1994 was markedly influenced by differences in plant and equipment depreciation rates.* The spillover contribution in the lower depreciation rate model was 33 percent smaller than in the model with shorter lives for plant and equipment. Moreover, for the preslowdown and slowdown sub-periods, spillovers accounted for 26 percent, and 22 percent between 1966-1973, in the two models, and from 1974-1994 the contributions were 29 percent in model 1, and 20 percent in model 2. *Therefore, the spillover contribution to labor productivity growth persisted throughout the preslowdown and slowdown periods.*

| Table 4. Labor Productivity Growth and Decomposition: Model 1<br>Average Annual Rates (percent) | | | | | | |
|---|---|---|---|---|---|---|
| **Period** | **Observed Labor Productivity Growth** | **Physical Capital to Labor Effect** | **R&D Capital to Labor Effect** | **Materials to Labor Effect** | **Spillover Effect** | **Factor Adjustment Effect** |
| 1966-1994 | 2.548 | 0.236 | 0.033 | 1.741 | 0.713 | -0.176 |
| 1966-1973 | 3.291 | 0.311 | 0.021 | 2.091 | 0.864 | 0.004 |
| 1974-1994 | 2.265 | 0.208 | 0.038 | 1.608 | 0.656 | -0.244 |
| 1966-1968 | 2.882 | 0.718 | 0.032 | 1.885 | 1.145 | -0.898 |
| 1969-1973 | 3.536 | 0.066 | 0.015 | 2.215 | 0.695 | 0.545 |
| 1974-1978 | 2.224 | 0.190 | 0.017 | 1.512 | 0.424 | 0.082 |
| 1979-1983 | 1.059 | 0.450 | 0.048 | 0.887 | 0.725 | -1.052 |
| 1984-1988 | 2.424 | -0.209 | 0.027 | 1.551 | 1.108 | -0.053 |
| 1989-1994 | 3.172 | 0.368 | 0.057 | 2.337 | 0.414 | -0.003 |

| Table 5. Labor Productivity Growth and Decomposition: Model 2<br>Average Annual Rates (percent) | | | | | | |
|---|---|---|---|---|---|---|
| **Period** | **Observed Labor Productivity Growth** | **Physical Capital to Labor Effect** | **R&D Capital to Labor Effect** | **Materials to Labor Effect** | **Spillover Effect** | **Factor Adjustment Effect** |
| 1966-1994 | 2.548 | 0.286 | 0.033 | 1.741 | 0.522 | -0.034 |
| 1966-1973 | 3.291 | 0.281 | 0.021 | 2.091 | 0.708 | 0.189 |
| 1974-1994 | 2.265 | 0.287 | 0.038 | 1.608 | 0.450 | -0.119 |
| 1966-1968 | 2.882 | 0.351 | 0.032 | 1.885 | 0.947 | -0.333 |
| 1969-1973 | 3.536 | 0.239 | 0.015 | 2.215 | 0.565 | 0.502 |
| 1974-1978 | 2.224 | 0.329 | 0.017 | 1.512 | 0.336 | 0.030 |
| 1979-1983 | 1.059 | 0.424 | 0.048 | 0.887 | 0.559 | -0.859 |
| 1984-1988 | 2.424 | -0.046 | 0.027 | 1.551 | 0.732 | 0.158 |
| 1989-1994 | 3.172 | 0.416 | 0.057 | 2.337 | 0.220 | 0.142 |

## 5. Conclusion

This paper measures and decomposes total factor, and labor productivity growth rates for the Canadian manufacturing sector. We find that spillovers from US R&D capital are the major contributor to total factor productivity growth, and these spillovers also provide an important source of labor productivity gains.

Productivity growth rates were measured within the context of two models. Differentiating the two models was the depreciation rate for physical capital. The first model contained a depreciation rate of 24 percent, and depreciation in the second model occurred at the rate of 7 percent. Average annual observed total factor productivity growth rates for Canadian manufacturing were 0.54 percent in model 1, with the shorter living physical capital, and 0.49 percent in model 2. Thus, differences in depreciation rates do not dramatically affect observed average annual productivity growth in Canadian manufacturing over the period from 1966 to 1994.

Prior to 1973, the pre-slowdown period, annual average observed productivity growth was about 0.9 percent, for both models. In the slowdown period, observed productivity growth dropped to 0.41 percent, and 0.33 percent, for models 1 and 2 respectively. The productivity slowdown represents a 53 percent (for model 1), or a 63 percent (for model 2) decline in annual productivity growth. We conclude that there was a substantial slowdown in manufacturing productivity growth, and differences in estimates of depreciation affect the extent of the observed productivity slowdown. There was a more pronounced slowdown with longer living physical capital stocks.

Observed and efficiency-based rates of productivity growth are distinguished. Efficiency-based rates reflect cost-minimizing factor requirements used in production, while observed rates relate to observed factors of production. Average annual efficiency-based productivity growth was 0.71 percent in model 1 and 0.52 percent in model 2. Efficiency-based and observed total factor productivity growth rates were quite similar in the model with relatively longer living physical capital stocks. However, in model 1, efficiency-based growth exceeded observed rates by 32 percent. Therefore, the adequacy of observed productivity growth as an indicator of efficiency gains, depends upon estimates of physical capital depreciation rates.

Average, annual, labor productivity growth from 1966 to 1994 was 2.55 percent. The slowdown in labor productivity growth was not as pronounced as for total factor productivity. In the period 1966-1973, labor productivity grew at an annual average rate of 3.29 percent. The annual growth rate declined to 2.27 percent over the period 1974-1994. Growth in the intermediate input to labor ratio was the main source of labor productivity growth, contributing 68 percent. The second principal source of labor productivity gains was R&D spillovers from US manufacturing. Spillovers furnished between 21 and 28 percent of labor productivity growth, and their contribution was remarkably invariable over the preslowdown and slowdown periods.

## Appendix 1

This appendix presents the model, which forms the basis for the factor intensity equations denoted by (8) in the text. To begin, consider a production function:

(A.1) $$y_t = F(z_{1t},..., z_{nt}, t),$$

where $y_t$ is output quantity in period *t*, *F* is the production function, $z_{it}$ is the *i*th utilized input quantity in period *t*, and *t* also represents the exogenous disembodied technology indicator.

The accumulation of inputs is represented by the condition:

(A.2) $$v_{it} = x_{it} + (1-\delta_i)v_{it-1} \quad i = 1,..., n,$$

where $v_{it}$ is the quantity of the *i*th input, $x_{it}$ is the addition to the quantity of the *i*th input in period *t*, and $\delta_i$ is the *i*th depreciation rate, such that $0 \leq \delta_i \leq 1$. Factor quantity ($v_{it}$) is not necessarily equal to the utilized quantity of the input ($z_{it}$) that enters the production function.

The relationship between input quantity and utilized input quantity has been specified in a number of different ways. A general relationship that encompasses the various forms is given by:

(A.3a) $$v_{it} - h_{it}(v_{it-1}) = m_i\left(z_{it} - g_{it}(v_{it-1})\right) \quad i = 1,..., n.$$

Equation (3) shows that factor accumulation depends on the difference between utilized and existing factor quantity. The functions denoted by *h* and *g* represent the possibility that measurement units can differ between current and past quantities. This can occur because of such elements as the loss of productive efficiency through depreciation, gains in productive efficiency through quality improvements (such as disembodied factor augmenting and factor embodied technological change).

Through a parameterization of the *h* and *g* functions in (3), we are able to characterize various models of quality change. A general model is

(A.3b) $z_{it} = m_i^{-1}(v_{it} - \gamma_i v_{it-1}) + \gamma_i v_{it-1}$.

From equation (3b), we can see that $z_{it}$ actually depicts the quality-adjusted utilized *i*th input in period *t*, and $z_{it}$ equals quality-adjusted input growth plus the input holdings from the previous period.

Utilized input demands are governed by minimizing the expected present value of acquisition and hiring cost. The expected present value at time *t* (defined as the current time period) is given by the following:

(A.4) $$\sum_{s=0}^{\infty}\sum_{i=1}^{n} a(t, t+s) q_{it+s}^{e} x_{it+s} ,$$

where $q_{it+s}^{e}$ is the expectation in the current period *t* of the *i*th factor acquisition (or hiring) price in period *t+s*, $a(t, t+s)$ is the discount factor with $a(t,t) = 1$, and $a(t, t+1) = (1+\rho_{t+1})^{-1}$, where $\rho_{t+1}$ is the discount rate from period *t* to period t+1. The expression in (4) is minimized subject to equation sets (1), (2) and (3b).

Replacing $z_{it}$, and $x_{it}$, by substituting equation sets (2), and (3b) into (1) and (4), the Lagrangian for the problem is:

(A.5) $$L = \sum_{s=0}^{\infty} a(t, t+s)\left(\sum_{i=1}^{n}\left(q_{it+s}^{e}\left[v_{it+s} - (1-\delta_i)v_{it+s-1}\right]\right)\right)$$

where $\lambda_{t+s}$ is the Lagrangian multiplier in period *t+s*, and $\mu_i = (1 - m_i)$. Based on (5) the first order conditions for the *i*th input quantity in period *t+s* is:

(A.6) $$\lambda_t(\partial F / \partial z_{it}) = m_i \sum_{s=0}^{\infty} w_{it+s}^{e} (a\gamma_i \mu_i)^s \qquad i = 1,...,n.$$

Equation (6) shows the shadow value of the marginal product for factor *i*, in the current period, equals the *i*th user cost, which is defined by the right side of (6). User costs are quality adjusted, and since $w^e_{it+s}$ is the period *t*, expected *i*th factor price in period *t*+*s*, the right-hand side of (6) defines user costs equal to the discounted value of quality-adjusted expected factor prices.

The optimized value of (4) defines the cost function denoted as:

(A.7) $C(\omega_{1t},...,\omega_{nt},y_t,t)$,

and by differentiating (7) with respect to the user costs, it is possible to retrieve factor utilization such that:

(A.8) $Z_i(\omega_{1t},...,\omega_{nt},y_t,t) = \partial C(\omega_{1t},...,\omega_{nt},y_t,t)/\partial\omega_{it} \quad i = 1,...,n.$

Equation set (8) shows that factor utilization depends on all user costs, output quantity, and technology indicator. In addition, through the user costs, factor requirements depend on quality parameters, and expected acquisition and hiring prices.

Equation set (8) cannot be implemented because the user costs are not observable. These variables are unobservable because quality parameters ($m_i$) are unknown, and data are usually unavailable for utilized factor quantities ($z_i$). However, since factor quantities (denoted as $v_i$) are observable, substitute (8) into (3b):

(A.9) $V_i(\omega_{1t},...,\omega_{nt},y_t,t) = \partial C(\omega_{1t},...,\omega_{nt},y_t,t)/\partial\omega_{it} + \gamma_i\mu_i v_{it-1} \quad i = 1,...,n.$

In order to estimate equation set (9), a cost function must be specified. The cost function is assumed to be,

(A.10) $$c_t = (\sum_{i=1}^n \beta_i\omega_{it} + 0.5\sum_{i=1}^n\sum_{j=1}^n \beta_{ij}\,\omega_{it}\omega_{jt} / \sum_{i=1}^n b_i\omega_{it} + \sum_{i=1}^n \omega_{it}(\beta_{is}S_t + \beta_{it}t)$$

$$+(\beta_{ss}S_t^2 + \beta_{tt}t^2)\sum_{i=1}^n b_i\omega_{it})y_t + \sum_{i=1}^n \alpha_i\omega_{it} + (\alpha_s S_t + \alpha_t t)\sum_{i=1}^n b_i\omega_{it} + \alpha_{yy}y_t^2\sum_{i=1}^n b_i\omega_{it},$$

Differentiating the cost function, equation (10), with respect to the ith factor price, and dividing the result by output quantity yields the *i*th factor demand per unit of output, or the *i*th factor intensity that is denoted by equation (8) in the text.

## Appendix 2

The data used to estimate the model are presented in this Appendix, as table A2.1. Statistics Canada is the source of all data, except for the R&D price data for Canada, and the R&D data for the U. S. manufacturing sector. U.S. R&D expenditures have been obtained from *Research and Development in Industry* (National Science Foundation various issues). Deflated U.S. R&D expenditures are accumulated for the period 1953-1996 using the perpetual inventory method with a 10 percent depreciation rate. An initial stock estimate is found by dividing the constant R&D expenditures of the year 1953 by the sum of the R&D depreciation rate and the average growth rate R&D expenditures. Canadian R&D capital stock is constructed in a similar manner, except that the period is 1963-1995. Canadian R&D price index obtained from Bernstein [1992], used to deflate R&D expenditures, and the U.S. R&D price index from Jankowski [1993] have been extrapolated using GDP deflators. The sample period is 1963-1995, and due to the lagging and leading of variables the model is estimated over the period 1965-1994.

| Table A2.1. Data | | | | |
|---|---|---|---|---|
| | Mean | Std. Dev. | Minimum | Maximum |
| Output Quantity | 223159.140 | 57740.166 | 115418.414 | 332706.500 |
| Output Price | 0.691 | 0.355 | 0.256 | 1.257 |
| Labor Quantity | 54123.781 | 3514.683 | 44438.539 | 60490.664 |
| Labor Price | 0.681 | 0.434 | 0.161 | 1.417 |
| Physical Capital Quantity (Depr. Rate, 0.24) | 27933.393 | 6712.947 | 15264.442 | 38077.336 |
| Physical Capital Price | 0.617 | 0.383 | 0.206 | 1.567 |
| Physical Capital Quantity (Depr. Rate, 0.07)l | 26327.061 | 7666.593 | 13561.104 | 37389.859 |
| Physical Capital Price | 0.642 | 0.366 | 0.243 | 1.561 |
| R&D Capital Quantity | 1403.226 | 719.633 | 497.105 | 2914.437 |
| R&D Price | 0.757 | 0.317 | 0.294 | 1.210 |
| Material Quantity | 148498.472 | 39323.692 | 76373.766 | 227518.344 |
| Material Price | 0.688 | 0.357 | 0.244 | 1.222 |
| US R&D Capital | 457636.595 | 136077.571 | 232365.391 | 671544.313 |
| Output Growth | 0.033 | 0.048 | -0.112 | 0.098 |
| Labor Growth | 0.007 | 0.037 | -0.094 | 0.059 |
| Physical Capital Growth (Depr. Rate, 0.24) | 0.028 | 0.034 | -0.029 | 0.111 |
| Physical Capital Growth (Depr. Rate, 0.07) | 0.032 | 0.020 | -0.009 | 0.078 |
| R&D Capital Growth | 0.055 | 0.021 | 0.023 | 0.105 |
| Material Growth | 0.034 | 0.045 | -0.111 | 0.090 |
| US R&D Capital Growth | 0.033 | 0.019 | 0.002 | 0.074 |

Notes

1. Period 1963-1995; except growth rates 1964-1995
2. Base Year: 1986
3. Prices are normalized to be 1 at the base year. Quantities are nominal value divided by appropriate price index. Quantities (including U.S. R&D capital) are in millions of 1986 dollars.
4. Depreciation rate of physical capital in model 1 is 0.24, and the rate in model 2 is 0.07.
5. Depreciation rate of Canadian and U.S. R&D is set to 0.10.
6. The real discount rate is 0.04

| Table A2.2. Regression Results | | | | |
|---|---|---|---|---|
| | *Model 1.* *(Depr. Rate, 0.24)* | | *Model 2.* *(Depr. Rate, 0.07))* | |
| **Parameter** | **Estimate** | **Std. Error** | **Estimate** | **Std. Error** |
| $\beta_{LL}$ | -1.28E-02 | 3.39E-03 | -8.01E-03 | 3.26E-03 |
| $\beta_{LK}$ | 1.28E-02 | 1.60E-03 | 6.78E-03 | 9.57E-04 |
| $\beta_{LR}$ | 7.79E-04 | 2.40E-04 | 3.58E-04 | 1.34E-04 |
| $\beta_{KK}$ | -1.43E-02 | 2.88E-03 | -5.91E-03 | 1.87E-03 |
| $\beta_{KR}$ | -1.97E-04 | 8.00E-05 | -1.46E-04 | 7.64E-05 |
| $\beta_{RR}$ | -2.78E-04 | 7.39E-05 | -1.53E-04 | 6.39E-05 |
| $\beta_{L}$ | 8.91E-02 | 1.67E-02 | 4.80E-02 | 1.58E-02 |
| $\beta_{K}$ | 8.78E-02 | 8.51E-03 | 5.97E-02 | 5.64E-03 |
| $\beta_{R}$ | 2.08E-03 | 3.15E-04 | 1.37E-03 | 2.66E-04 |
| $\beta_{M}$ | 3.40E-01 | 5.74E-02 | 4.05E-01 | 5.94E-02 |
| $\beta_{LS}$ | -1.23E-07 | 2.15E-08 | -8.19E-08 | 2.05E-08 |
| $\beta_{KS}$ | -6.31E-08 | 1.09E-08 | -3.60E-08 | 1.07E-08 |
| $\beta_{RS}$ | -1.57E-09 | 7.78E-10 | -2.01E-09 | 7.29E-10 |
| $\beta_{MS}$ | -1.88E-07 | 5.31E-08 | -1.61E-07 | 5.24E-08 |
| $\beta_{SS}$ | 4.86E-13 | 1.47E-13 | 4.23E-13 | 1.45E-13 |
| $m_L$ | 0.1588 | 0.0386 | 0.0709 | 0.0377 |
| $m_K$ | 0.4879 | 0.0620 | 0.3796 | 0.0455 |
| $m_R$ | 0.1917 | 0.0360 | 0.0460 | 0.0277 |
| $m_M$ | 0.4198 | 0.1046 | 0.5330 | 0.1055 |
| $\theta_L$ | 0.8787 | 0.0629 | 0.9424 | 0.0590 |
| $\theta_K$ | 0.5932 | 0.0877 | 0.6443 | 0.0880 |
| $\theta_R$ | 0.7159 | 0.0703 | 0.7537 | 0.0715 |
| $\theta_M$ | 0.5165 | 0.0898 | 0.5824 | 0.0905 |
| **Equation** | **Std. Error** | **$R^2$** | **Std. Error** | **$R^2$** |
| Labor | 5.93E-03 | 0.989 | 5.42E-03 | 0.991 |
| Capital | 6.70E-03 | 0.597 | 5.06E-03 | 0.708 |
| R&D | 2.74E-04 | 0.975 | 2.79E-04 | 0.972 |
| Material | 3.35E-03 | 0.666 | 3.36E-03 | 0.667 |
| Labor Price | 1.90E-02 | 0.998 | 1.88E-02 | 0.998 |
| Capital Price | 2.14E-02 | 0.995 | 2.08E-02 | 0.995 |
| R&D Price | 1.88E-02 | 0.998 | 1.84E-02 | 0.998 |
| Material Price | 2.93E-02 | 0.995 | 2.79E-02 | 0.995 |
| Log of L. F. | 969.92 | | 987.91 | |

## Endnotes

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[1] Analyses of TFP growth generally represent disembodied technological change by a time trend. This variable is a catchall, reflecting both productivity gains, and losses. Thus, it seems more appropriate to view changes in the trend variable as an indicator of efficiency gains or losses, as opposed to a strict measure of technological change. Intuitively, one should accept a more circumspect role for the trend variable, since under constant returns to scale (and no spillovers), productivity growth is synonymous with the effect of changes in the trend variable on output. It is difficult to imagine that productivity losses occur from a variable that is costless to change.

[2] See Appendix 1 for details of the model. The model is based on Bernstein, Mamuneas and Pashardes [1999].

[3] The coefficients $b_i$ $i=1,\ldots,n$, are set equal to input cost shares in the reference time period, 1986. The coefficient $\gamma_i$ equals one minus the depreciation rate for inputs that are not fully depreciated in a single period, and one for the other factors of production.

[4] Since the data used to estimate equation set (8) relate to the manufacturing sector as a whole, spillovers among producers within the sector are assumed to be internalized, and thereby do not affect (8).

[5] Although the spillover variable could be defined as a weighted average of R&D capital stocks pertaining to various countries, research has shown that US R&D capital stock acts as the major spillover source to Canadian industries (see Bernstein [1998], Bernstein and Yan [1998]).

[6] The same tests were conducted for both models.

[7] We also calculated Tornqvist and Fisher productivity growth rates based on observed input quantities and prices. These productivity growth rates are almost identical to the observed TFP growth rates found in tables 2 and 3. The attractiveness of observed TFP growth developed from equation (10) is that it is exact for any cost function where the second or higher order derivatives do not change over time.

[8] From tables 2 and 3, we also observe that the pattern of productivity growth rates is invariant to physical capital depreciation rates.

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