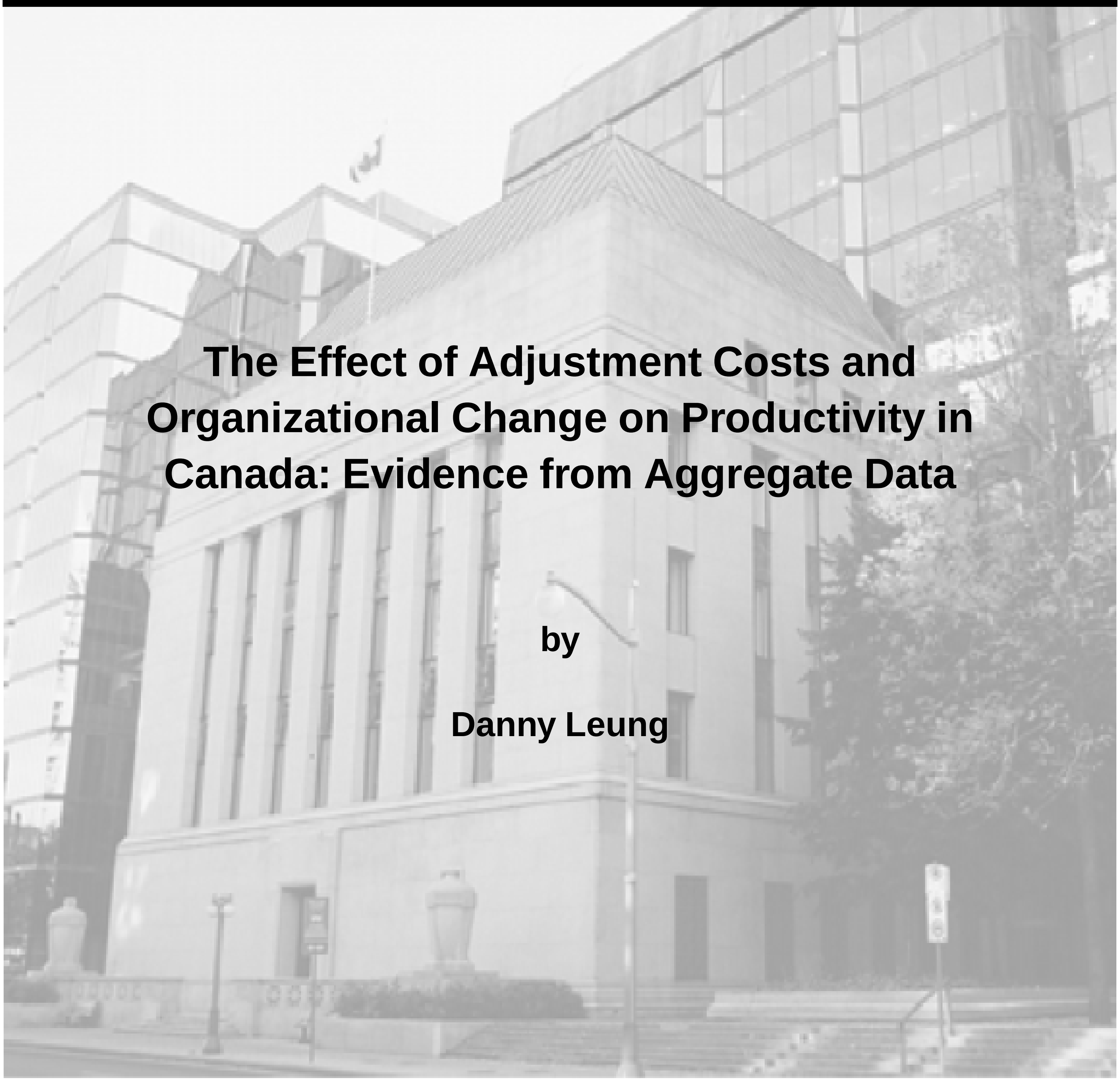
Bank of Canada Banque du Canada

Working Paper 2004-1 / Document de travail 2004-1



The Effect of Adjustment Costs and Organizational Change on Productivity in Canada: Evidence from Aggregate Data

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ISSN 1192-5434

Printed in Canada on recycled paper

Bank of Canada Working Paper 2004-1

January 2004

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The views expressed in this paper are those of the author.
No responsibility for them should be attributed to the Bank of Canada.

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Acknowledgements

I would like to thank Allan Crawford, Bob Fay, and seminar participants at the Bank of Canada, Department of Finance, and the Canadian Economics Association 2003 meetings for their suggestions and helpful comments. All errors are my own.

Abstract

A basic neoclassical model of production is often used to assess the contribution of investment to output growth. In the model, investment raises the capital stock and output growth increases in proportion to the growth in capital. It has been argued, however, that computers, as a "general purpose technology," lead to process innovations and facilitate organizational coinvestments. Since there may be a learning period before firms realize the full potential of the new technology and begin to implement new processes, there may be a lag between the growth in investment and its benefits. In fact, during periods of rapid adoption of new technologies and equipment, firms may incur adjustment costs and struggle to maintain previous levels of output.

Using aggregate annual Canadian data from 1961 to 2001, the author explores the magnitude of the effect that investment in new technology, in the form of new computer hardware, can have on output growth. He finds that such investment has a positive effect on output growth that cannot be explained by growth in inputs. This effect, however, is not instantaneous and is strongest only three years after the initial investment. Furthermore, the author's findings suggest that the effect of computer hardware investment has grown over time.

JEL classification: O31, O49
Bank classification: Productivity

Résumé

On a souvent recours à un modèle néoclassique de base de la production pour évaluer la contribution des investissements à la croissance de la production. Dans ce modèle, les investissements engendrent une hausse du stock de capital, et la croissance de la production s'accélère dans la même proportion que celle du capital. On a néanmoins fait valoir que l'informatique, en tant que « technologie d'application générale », ouvre la voie à des innovations de procédé et favorise les coinvestissements dans l'organisation de la production. Puisqu'il peut y avoir un temps d'apprentissage avant que les entreprises réalisent pleinement le potentiel des nouvelles technologies et qu'elles commencent à mettre en œuvre de nouveaux procédés, il s'ensuit, le cas échéant, un décalage entre la croissance des investissements et celle des profits. Durant les périodes d'adoption rapide de nouveaux matériels et technologies, il se peut même que les entreprises aient à subir d'importants coûts d'ajustement et qu'elles éprouvent des difficultés à maintenir leur production aux niveaux antérieurs.

En se fondant sur des données agrégées relatives à l’économie canadienne pour les années 1961 à 2001, l’auteur étudie l’incidence des investissements dans les nouvelles technologies — en l’occurrence ceux visant l’achat de nouveau matériel informatique — sur la croissance de la production. Il constate que ces investissements ont un effet positif sur la croissance de la production et que celui-ci n’est pas lié à l’augmentation des facteurs de production. Cet effet n’est toutefois pas instantané et atteint son apogée seulement trois ans après l’investissement initial. De plus, les résultats de l’étude donnent à penser que l’incidence des investissements en matériel informatique s’accroît avec le temps.

Classification JEL : O31, O49
Classification de la Banque : Productivité

1. Introduction

The contemporaneous effects of investment on output and productivity growth have been examined in many studies.[1] Fewer papers have investigated the effects of investment in new capital on productivity growth over a longer period of time. Investment raises the stock of capital and hence output, but adjustment or adoption costs may initially obscure these gains. To fully exploit the productive capacity embodied in the new capital, firms must devote resources to integrate the new technology into their production processes. These costs may be direct, in the form of installation and training costs. On the other hand, they may be more subtle, involving expenses to develop ways of using the new technology, or costs associated with implementing organizational change that complements the installation of new technologies. Lichtenberg (1988) has provided evidence of non-negligible adjustment costs at the level of the firm.[2] More recently, Basu, Fernald, and Shapiro (2001), Bessen (2002), and Kiley (1999) have found that capital adjustment costs lowered measured multifactor productivity (MFP) growth by 0.3 to 0.5 per cent per year in the U.S. manufacturing industry and the U.S. non-farm business sector.[3] The payment of these adjustment costs, however, does lead to benefits. Brynjolfsson and Hitt (2000a, b) and

1. For example, Kiley (1999) and Oliner and Sichel (2000, 2002) use the neoclassical growth accounting framework to analyze the impacts of investment in different types of capital stock on U.S. labour productivity growth and the sectoral contributions to multifactor productivity growth in the U.S. non-farm business sector. Studies that use similar techniques and Canadian data include Armstrong et al. (2002) and Khan and Santos (2002).
2. Using data on manufacturing firms from the U.S. Census Bureau's Longitudinal Establishment Data file, Lichtenberg (1988) finds that a dollar increase in expansion investment causes a 35 cent reduction in current output, while a dollar of replacement investment leads to a smaller, 21 cent reduction.
3. Concentrating on adjustment costs for computers, Kiley (1999) calibrates an aggregate adjustment cost function where adjustment costs are incurred at the time of the investment. Decomposing output growth via an accounting process into growth due to an increase in labour hours, labour quality, the stock of computers, capital excluding computers, and labour-augmenting technical progress, with and without adjustment costs, Kiley estimates the magnitude of adjustment costs on the aggregate economy. He finds that adjustment costs have lowered measured MFP growth since 1974 by 0.5 percentage points per year.

   Basu, Fernald, and Shapiro (2001) calibrate an adjustment cost function that is common to all types of capital investments, where adjustment costs are again incurred only at the time of investment. After using industry-level data to estimate the effect of factor utilization and returns to scale on labour productivity growth, they decompose the growth in the measured MFP into parts due to changes in capacity utilization, returns to scale, adjustment costs, and technology. They find that adjustment costs have lowered the average measured MFP growth rate by 0.3 percentage points during the 1987–99 period.

   Bessen (2002) directly estimates the effect of adjustment costs on measured MFP using data from U.S. manufacturing industries. Unlike Kiley (1999) and Basu, Fernald, and Shapiro (2001), Bessen allows adjustment costs to be incurred in periods after the initial investment. He finds significant adjustment costs associated with both total investment and IT investment, and finds that these adjustment costs lowered MFP by 0.4 per cent per year in the 1970s and early 1980s.

Stiroh (2002) argue that organizational coinvestments complementary to investments in information and communications technology (ICT) lead to output growth above and beyond that of growth due to the accumulation of capital in constant quality units alone. Since the restructuring process may not be immediate, the full impact of investment in new technologies may not be felt until years after the initial investment. As a result of both adjustment costs and complementary organizational change, investment in ICT equipment or any other kind of capital that embodies new technology does not necessarily have a simple one-period effect on output growth and productivity.

Empirical support for the need to consider the lagged effects of investment can be found in Brynjolfsson and Hitt (2000a), Stiroh (2002), Wolff (2002), and Basu et al. (2003). Brynjolfsson and Hitt (2000a) find that the effects of computer capital growth on MFP growth are two to five times greater over periods of five to seven years than over a one-year period, while Stiroh (2002) and Wolff (2002) cannot find any relationship between current-period MFP growth and current-period growth in any type of capital input, including ICT.[4] Furthermore, Basu et al. (2003) find that U.S. industries that had high ICT capital growth rates in the early 1990s had high MFP growth rates in the late 1990s.[5] To capture the full effect of the investment in new technologies, this paper studies the lagged impact of various types of capital investments on Canadian MFP. Using a method based on production function estimation, the net effect of capital adjustment costs and complementary coinvestments on MFP growth is estimated.

The rest of the paper is organized as follows. Section 2 discusses the relationship between adjustment costs, organizational change, and MFP. Section 3 describes the data and the empirical framework used to identify the effect of investment in new technologies. Section 4 presents the results. Using aggregate data for Canada between 1961–2001, it is found that the effects of adjustment costs on aggregate MFP growth are negligible for all types of capital investment. The effects of complementary investments or innovations, however, are significant and are found to occur most strongly three years after the initial investment in computer hardware. There is also evidence that the effects of complementary investments have grown stronger over time, and that this growth can explain approximately one-third of the average annual growth rate of MFP since 1992. Section 5 provides a summary and conclusion.

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4. Brynjolfsson and Hitt (2000a) use firm-level data from the United States between 1987–94, Stiroh (2002) uses data from U.S. manufacturing industries between 1984–99, and Wolff (2002) uses data from 44 U.S. industries between 1960 and 1990.
5. Basu et al. (2003) use the same industry-level data set that Basu, Fernald, and Shapiro (2001) use to study adjustment costs.

2. The Measurement of Improvements in Efficiency

MFP is meant to capture the part of growth that cannot be accounted for by increases in capital or labour inputs. It represents technological progress and improvements in the organization of production. The measure of MFP that is produced by statistical agencies such as Statistics Canada or the U.S. Bureau of Labor Statistics captures as well the effects of capacity utilization, returns to scale, and changing market structure. These factors must be taken into account before attempting to uncover a relationship between adjustment costs, organizational change, and MFP. This section describes the measure of productivity obtained using the traditional growth accounting framework, how the traditional measure can be adjusted to account for returns to scale and capacity utilization, and how adjustment costs and organizational change are related to the adjusted measure of productivity.

2.1 Traditional growth accounting framework

Under the assumptions of perfect competition, constant returns to scale, full utilization of inputs, and perfect adjustment to changing levels of inputs, MFP is the difference between the growth rate of value-added output and the weighted growth rates of labour and capital:

$$\Delta \ln Z_t = \Delta \ln Y_t - (1-\alpha_t)\Delta \ln K_t - \alpha_t \Delta \ln L_t,$$

where t indexes time, Δ refers to the first difference, Z is the traditional MFP, Y is value-added output, K is capital input, L is labour input, and α is the average of labour income as a fraction of nominal output for periods t and t-1. Changes in the quality of inputs do not affect Z, since outputs and inputs are measured in constant quality units. If the assumptions used to derive the above expression do not hold, however, the traditional measure of MFP will be biased.

2.2 Accounting for returns to scale, capacity utilization, and imperfect markets

The traditional growth accounting framework can be easily modified to account for returns to scale, imperfect competition in the product market, and capital capacity utilization.[6] The following expression, similar to that presented in Paquet and Robidoux (2001), shows the relationship between the measure of MFP calculated using the traditional growth accounting framework and the one that takes returns to scale, capacity utilization, and imperfect markets into account[7]:

$$\Delta \ln Z_t = \Delta \ln A_t + (\gamma_t - 1)\Delta \ln K_t + \alpha_t(\mu_t - 1)(\Delta \ln L_t - \Delta \ln K_t) + (\gamma_t - \mu_t\alpha_t)\Delta \ln U_{Kt},$$

where A indexes technology, U_k is the capacity utilization rate of capital, γ is the degree of returns to scale,[8] and μ is the markup rate, the proportional factor between price and marginal cost.[9] The second term on the right-hand side takes non-constant returns to scale into account. Since the weight on capital input growth in the traditional growth accounting framework is computed residually as one minus the labour's share of nominal output, it underestimates the true weight on capital if there are increasing returns to scale, and it overestimates the true weight on capital if there are decreasing returns. Therefore, in the case of increasing returns to scale, a one per cent increase in capital input would increase the traditional measure of MFP growth by $\gamma - 1$, the amount by which the weight on capital is underestimated.

The third term on the right-hand side is an adjustment for market power in the product market. In this case, the correct weights on labour and capital are, respectively, $\mu\alpha$ and $1 - \mu\alpha$, as opposed to α and $1 - \alpha$.[10] The traditional accounting approach uses a weight that is too small for labour

6. This paper abstracts from labour utilization. Utilization of a worker can be increased by increasing the number of hours worked or increasing effort. The former channel is taken into account because labour input is often measured in hours and not workers. Although the latter channel can be important, variation in labour effort over time is not taken explicitly into account, because it is not observed. Basu, Fernald, and Shapiro (2001) argue that average hours worked is a proxy for unobserved labour effort, because cost-minimizing firms are likely to adjust along all margins simultaneously. They also note, however, that the same argument can be used to support the idea that average hours worked is a proxy for capital capacity utilization as well. Therefore, it is likely that the effects of labour and capital utilization are difficult to disentangle in a regression framework.

7. Paquet and Robidoux (2001) use a measure of capital that is adjusted for capacity utilization when they use the traditional accounting framework to compute Z. Therefore, the expression in their paper does not include the last term on the right-hand side that accounts for capacity utilization.

8. It is the sum of the output elasticities with respect to each input. If the production function is Cobb-Douglas, it is simply the sum of the exponents on the capital and labour input.

9. In other words, the markup rate is price divided by marginal cost.

10. See Paquet and Robidoux (2001) for the derivation.

and too large for capital. An increase in the growth rate of labour would lead to an increase in the traditional measure of MFP growth by $\mu\alpha - \alpha$, and an increase in the growth rate of capital would lead to a decrease by $(1 - \mu\alpha) - (1 - \alpha)$.

The final term on the right-hand side controls for the capacity utilization of capital. If there are no economies of scale and if the product market is competitive, then a one per cent increase in capacity utilization growth would increase the traditional measure of MFP growth by $1 - \alpha$, the weight on capital input growth. If there are increasing returns to scale and no markup, a one per cent increase in capacity utilization growth would raise measured MFP growth by $\gamma - \alpha$, the correct weight on capital in the presence of increasing returns. In the case where there are no scale economies and there is a positive markup, then the correct weight on labour is $\mu\alpha$, the traditional weight on labour multiplied by the markup rate. A percentage increase in capacity utilization growth thus increases the traditional measure of MFP by the relevant weight on capital, $1 - \mu\alpha$.

Using the above framework, Paquet and Robidoux (1997) find little evidence of economies of scale and markups for both the Canadian and American business sectors.[11] Therefore, the discussion in the rest of this section and the empirical work that follows proceeds under the assumptions of constant returns to scale and perfect competition. Paquet and Robidoux (1997) do not test whether changes in the capacity utilization growth rate affect measured MFP. They instead assume that capacity utilization has an effect at the outset and adjust their measure of capital input for utilization before continuing with their analysis. This paper tests whether capacity utilization is systematically related to measured MFP.

2.3 Adjustment costs at the aggregate level

Adjustment costs can be thought of as arising from the costs related to the direct installation of new equipment, the training of individuals, devotion of resources to explore methods to fully utilize the capital, and the reorganization carried out to put those methods into effect. The magnitude of adjustment costs found in empirical studies depends on the methods and data used to obtain the estimates. As stated in the introduction, several papers (Lichtenberg 1988; Kiley 1999; Basu, Fernald, and Shapiro 2001; and Bessen 2002) have studied the magnitude of

11. Furthermore, Baldwin, Gaudreault, and Harchaoui (2000) estimate MFP growth rates for the Canadian manufacturing sector that allow for markups, scale economies, and capital fixities. They find that relaxing the assumptions of zero markups and constant returns to scale has a relatively small effect on productivity estimates.

adjustment costs at the firm, industry, and aggregate levels. They all assume that the production function of a representative firm has a form as follows[12]:

$$Y_{ord} + Y_{adj}\left(\frac{I}{K}\right) = F(A, K, L, M),$$

where *A*, *K*, and *L* are defined as before, Y_{ord} is the firm's "ordinary" gross output, Y_{adj} is the amount of the "adjustment cost" good the firm must produce, and *M* is a bundle of intermediate inputs. The amount of adjustment cost good produced is modelled as an increasing function of investment, *I*, over capital.[13] Types of capital with high ratios are relatively new types of capital or types of capital with high depreciation rates.[14] Both examples are categories of capital that embody new technology. First, it is natural to believe that wholly new categories of capital would embody the newest technologies. Second, a high depreciation rate may indicate a fast pace of quality improvement in that type of capital. Computers and other ICT equipment would fall into both of these categories, and it is commonly believed that their introduction has been associated with adjustment costs.

In empirical work, neither the technology factor, *A*, nor the amount of adjustment cost goods produced is observed. However, by moving the adjustment cost term to the right-hand side and regressing gross output on capital, labour, intermediate inputs, and investment over capital, an estimate of adjustment costs can be obtained using firm- or industry-level data.[15] Adjustment costs lower a firm/industry's measured productivity, because resources are being expended. The firm is using its own labour to produce the adjustment cost goods, or it is contracting out the work, and there is no corresponding increase in the production of ordinary output. It is important to note that adjustment costs lower measured productivity, leaving the true underlying MFP unchanged. As in the case of returns to scale, capacity utilization, and imperfect markets, adjustment costs must be taken into account.

If one were to estimate the above model using aggregate data, the magnitude of the adjustment costs should diminish.[16] The adjustment costs of one firm are now either output of another firm

12. The notion of installation costs for new investment goods is not a recent idea. It can be found as far back as Lucas (1967).
13. Adjustment costs may also be allowed to be a function of lags of the investment-to-capital ratio, or the investment-to-capital ratio of different categories of capital.
14. For Canada, the investment-to-capital stock ratio for computers was 0.42 in 2001. In contrast, the ratio for buildings and structures was 0.06.
15. Lichtenberg (1988) uses firm-level data and Bessen (2002) uses industry-level data.
16. With aggregate data, gross output would simply be replaced by value-added output and intermediate inputs would be dropped.

that produces these adjustment cost goods, or income of the former firm's workers. Either way, installation, training, and reorganization costs are now part of aggregate value added. In theory, the entire output of both ordinary and adjustment cost goods should be accounted for at the aggregate level, so adjustment costs should not cause a wedge between measured MFP and its true value.

Adjustment costs, in practice, can still bias measured MFP at the aggregate level. Both Statistics Canada and the Bureau of Labor Statistics calculate business sector MFP by aggregating industry MFP. Therefore, even though the output of adjustment cost goods may be totally accounted for by (to use one example) the business services industry, the fact that the measure of output and MFP in the manufacturing sector is downward biased implies that business sector MFP is downward biased as well. Furthermore, for the purpose of computing MFP, output is often computed using the value-added/output approach. Since value-added output is calculated by adding every firm's sales of goods and services and then subtracting every firm's intermediate input costs, it is possible that the output of adjustment cost goods that the firm produces for itself is not included.[17]

In summary, the magnitude of the effect of adjustment costs is likely to be proportionally larger at the firm level than at the aggregate level. Therefore, estimates of the effect of adjustment costs on MFP at the aggregate level inferred from adjustment costs measured at the microeconomic level should be interpreted with caution. The way in which estimates of aggregate MFP are constructed determines the extent to which true underlying movements in technology are obscured by adjustment costs. In addition, as long as growth in investment in new technology continues to be high, or as long as adjustment costs are incurred because of past investment growth, measured MFP will be lower than true MFP. As soon as investment growth stabilizes, measured MFP growth will rise to its true level, ceteris paribus. As a result of adjustment costs, growth in investment will tend to precede growth in measured MFP by a number of periods.

2.4 Investment in new technology and improvements in efficiency

The previous section described how investment in new technology led to adjustment costs and hence mismeasurement of MFP. MFP itself is not affected by investment via this channel. However, Brynjolfsson and Hitt (2000a, b) and Breshnahan, Brynjolfsson, and Hitt (2002) suggest that investment in new technology can bring efficiency gains. They argue that computers, as a general purpose technology, facilitate complementary technological and organizational innovations. In turn, these innovations bring increases in output that are above and beyond those

17. If, on the other hand, output were measured via the income approach, then the production of adjustment cost goods would be taken fully into account.

resulting from simple accumulation of computer capital. For example, ICT is thought to facilitate the flow of information between workers, and between workers and management. Arnal, Ok, and Torres (2001) argue that the strong association between ICT use and the presence of employee involvement schemes, teamwork, and decentralized decision-making is evidence of this relationship. Ichniowski, Shaw, and Gant (2002) suggest that, in contrast to a more traditional hierarchical organization structure, a flatter, involvement-oriented management structure facilitated by ICT allows each individual worker to better access the human capital of other workers, which in turn leads to higher productivity.[18] Since there is likely to be a period between the introduction of ICT and the ensuing organizational changes to exploit advantages of the new technology, the long-run effect of investment in new technology on output should be greater than that of the short run. The effect of investment in technology may even be negative in the short run, as Brynjolfsson and Hitt (2000b) suggest, with firms struggling to maintain the same level of output during the reorganization period.

Stiroh (2002) offers an alternative explanation for improvements in MFP that result from investment in ICT capital. He suggests that the improved communication between firms that results from ICT use generates network externalities that increase the productivity of all parties. Investment in ICT by one firm leads to productivity spillovers to other firms in the network. As Stiroh acknowledges, it is difficult to distinguish between increases in productivity that result from investment-led organizational change and innovation, and improvements that result from network externalities. Improved business-to-business communication due to network externalities facilitates organizational changes, such as outsourcing and just-in-time inventory control, but that does not necessarily mean that improvements in productivity should be attributed to network externalities. Increased outsourcing and better inventory-control systems may not have been possible without improved communication, but the productivity improvements may not have been realized by the development of network externalities alone. This paper attempts to find evidence of links between investment and MFP growth, but does not try to distinguish between the two differing explanations.

Not only is it difficult to distinguish the effects of improved communication links within the firm from those between firms, it is difficult to distinguish the effects of adjustment costs from those of complementary innovations. Both adjustment costs and complementary innovations are argued to

18. In Ichniowski, Shaw, and Gant (2002), the amount of human capital an individual worker can access is called the individual's connective capital. The sum of each individual's connective capital is the workplace's connective capital. Increasing the number of links between workers raises the workplace's connective capital and productivity. Ichniowski, Shaw, and Gant (2002) cite other studies that examine the positive effects of innovative human resource management systems, and present some of their own empirical evidence from U.S. steel mills.

be the result of investment in new technology. Thus, any indicator of investment in new technology, such as the investment-to-capital ratio, should lead to both adjustment costs and complementary innovations. Therefore, only the net effect of adjustment costs and complementary innovations can be identified. The only difference is in the timing of the relationships. Based on previous evidence from Bessen (2002), it is expected that the negative effects of adjustment costs should be incurred only in the first one or two years after the initial investment, whereas evidence from Brynjolfsson and Hitt (2000a) suggests that the positive effects of complementary innovations should be stronger over a longer period of time.

One possible solution to the identification problem is to find an indicator that is arguably more strongly related to one thing than the other. The capital stock-to-output ratio might be such an indicator. It is likely that productivity increases that result from improved communication linkages between and within firms cannot take place until after some threshold level of capital stock has been passed. One would not expect improvements in productivity to be noticeable if only a handful of employees had access to ICT equipment, nor expect network externalities to develop if only a small number of firms invested in ICT. On the other hand, adjustment costs should depend not so much on the existing level of capital as on the change in the capital stock. A large change in the capital stock would imply that the additional capital is less likely to be low adjustment cost replacement capital. Adjustment costs per unit of investment may even be lower after a large stock of capital has been accumulated when the installation and reorganization process has been refined. Consequently, the net effect of adjustment costs and complementary innovations is likely to be an increasing function of the capital stock-output ratio.

3. Empirical Framework and Data

This section describes the data and explains how the effect of capacity utilization, and the net effects of adjustments costs and innovations complementary to investment in new technology on MFP, are identified.

3.1 Data

The main analysis for this paper is conducted using annual data for Canada between 1961 and 2001, obtained from CANSIM. Measures of MFP, investment, hyperbolic end year net stock of capital,[19] and annual hours generally pertain to the business sector. The exceptions are the measures of investment and capital for computer hardware, telecommunications equipment and software, measures of current dollar output and labour compensation used to calculate labour's share of output, and the measure of industrial capacity utilization.[20] The measures of investment and capital for computer hardware and for telecommunications equipment and software are for the non-agricultural business sector. Since the agricultural industry likely accounts for only a small fraction of the investment and stocks of these types of capital, the results should not be affected much by this discrepancy. Also, data for software investment and capital are available only from 1981 onwards.

Labour's share of nominal output is for the total economy, because GDP in current dollars is available for the business sector only up to 1999. Since the number of data points to begin with is rather small, omitting the data for 2000 and 2001 would amount to cutting 5 per cent of the sample. Furthermore, while labour's share of nominal output is not identical for the two sectors

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19. The capital stock measure depends crucially on how depreciation is modelled. Koumanakos, Huang, and Wood (1999) show that the geometric truncated pattern of depreciation assumed by Statistics Canada yields a lower level and growth rate of capital stock than the infinite geometric pattern assumed by the United States' Bureau of Economic Analysis. Baldwin and Harchaoui (2000), however, show that the impact of different assumptions about the depreciation pattern has a small effect, one-fifth of a percentage point over a 36-year period, on average MFP growth.

    Since adjustment costs and innovations complementary to investment in new technology are hypothesized to be a function of investment over capital stock, results may still depend on the depreciation profile chosen. Statistics Canada provides capital stock numbers using hyperbolic and infinite geometric depreciation profiles in CANSIM. The truncated geometric series used to create their MFP measure is not provided in CANSIM. Coulombe (2000) states that the capital stock measures resulting from the hyperbolic and infinite geometric depreciation profiles are similar. For the sample used in this paper, the levels and the growth rates of the capital stock measure using the geometric depreciation profile are lower than the ones calculated using the hyperbolic pattern, but their correlation is very high. The correlation between the levels and the growth rates of the two series is 0.9998 and 0.9941, respectively. Although Baldwin and Harchaoui (2000) do not report the correlations, figures in their paper suggest that the growth rate of capital using geometric truncated depreciation is highly correlated to the other two measures as well. As a result, the point estimates of the parameters will depend on the measure of capital chosen because of a scale effect that is caused by differences in the magnitude of the growth rates. This should not, however, significantly affect the estimated bias of measured MFP growth due to adjustment costs and the fraction of MFP growth explained by innovation linked to investment in new technologies over a range of years.

20. The investment and capital stock numbers for computers and for telecommunications equipment and software were provided by Statistics Canada, but are not available through CANSIM.

(0.603 for the total economy and 0.576 for the business sector over the 1961–99 period), it can be shown that the impact of substituting one series for the other is minor.

The industrial capacity utilization series is for the goods-producing non-agricultural industries.[21] If this series is used to directly correct the measured MFP series by subtracting the product of the capacity utilization growth rate and capital's share of output from MFP growth, then one would be assuming that the percentage change in industrial capacity utilization is the same as in the entire business sector. Alternatively, one could estimate the effect of the change in industrial capacity utilization on business sector MFP growth, or use only the industrial sector's part of capital income in the direct adjustment, but both methods would leave a bias in MFP because of changes in capacity utilization in non-industrial sectors. Data restrictions preclude the second approach, so this paper adopts the first approach and compares it with the results that are derived by assuming that the capital utilization rates in the business and industrial sectors are the same. The measures of MFP corrected for variable capacity utilization are found to be nearly identical.[22]

3.2 Empirical framework

Value-added output is assumed to be produced by an aggregate production function like that found in Bessen (2002):

$$\frac{Y_t}{\left(1-\Phi\left(\frac{I_t}{K_t}\right)\right)} = A_t(K_t U_{Kt})^{(1-\alpha_t)}(L_t)^{\alpha_t},$$

where t indexes time, Y is value-added ordinary output, K and L are capital and labour inputs, U_k is the capacity utilization rate of capital, and $1-\Phi$ gives the factor that ordinary output must be scaled up by to obtain the output for the economy that includes adjustment cost goods. It is assumed that adjustment costs, Φ, are an increasing function of the ratio of investment, I, over capital. The variable A indexes production technology. It is hypothesized that innovations and organizational change complementary to investment in new technology are determinants of A.

21. This paper uses the terminated series based on the Standard Industrial Classification (SIC) and not the new series based on the North American Industry Classification System (NAICS), because the latter begins only in 1987. See Paquet and Robidoux (2001) for details on how both of these series are calculated by Statistics Canada.

22. Another possibility is to concentrate solely on the manufacturing sector for which a matching industrial capacity utilization rate is available. A drawback of this approach is that official Statistics Canada MFP data for the manufacturing sector are available only from 1981.

The expression for MFP growth adjusted for capacity utilization in this framework is:

$$\Delta \ln A_t = \Delta \ln Y_t - (1 - \alpha_t)\Delta \ln K_t - \alpha_t \Delta \ln L_t - (1 - \alpha_t)\Delta \ln U_{Kt} + \Delta \Phi_t,$$

where $\ln(1 - \Phi)$ has been approximated by a first-order Taylor approximation around $\Phi = 0$. In contrast, the measured MFP growth is given by:

$$\Delta \ln Z_t = \Delta \ln Y_t - (1 - \alpha_t)\Delta \ln K_t - \alpha_t \Delta \ln L_t,$$

where Z is the traditional measure of MFP. It then follows that the measure of MFP in the traditional growth accounting framework can be expressed as:

$$\Delta \ln Z_t = \Delta \ln A_t + (1 - \alpha_t)\Delta \ln U_{Kt} - \Delta \Phi_t.$$

The measured growth of MFP is composed of underlying MFP growth ($\Delta \ln A_t$), growth due to changes in capacity utilization of capital ($(1 - \alpha_t)\Delta \ln U_{Kt}$), and growth due to adjustment costs ($\Delta \Phi_t$).

Following Paquet and Robidoux (2001), this paper first adjusts measured MFP for capacity utilization before performing any further analysis. Assuming constant returns to scale and no price markups, the measure of MFP from Statistics Canada, Z_t, can be adjusted for capacity utilization in the following way:

$$\Delta \ln \tilde{Z}_t = \Delta \ln Z_t - (1 - \alpha_t)\Delta \ln U_{Kt},$$

where $\tilde{Z}$ is the measure of MFP adjusted for capacity utilization, α_t is the average of labour share of nominal output in year *t* and *t-1*, and U_K is the industrial capacity utilization rate. As pointed out in section 3.1, however, this process assumes that the capacity utilization rate in the industrial and non-industrial sectors is the same. Figure 1 shows Statistics Canada's measure of MFP growth and MFP growth adjusted for capacity utilization. It is clear that cyclically adjusted MFP growth is smoother than unadjusted MFP growth, and that, on average, the measures are approximately the same.

Substituting $\tilde{Z}$ for Z yields the following:

$$\Delta \ln \tilde{Z}_t = \Delta \ln A_t - \Delta \Phi_t.$$

The above equation can be easily estimated given functional form assumptions for the adjustment cost function and the unobserved underlying MFP. Assuming that adjustment costs are a linear function of the log of the investment-to-capital stock ratio, and that underlying MFP growth is a constant plus a linear function of the log of the investment-to-capital stock ratio plus a stochastic error term, the estimating equation becomes[23]:

$$\Delta \ln \tilde{Z}_t = \beta_0 + \beta_1 \Delta \ln\left(\frac{I_t}{K_t}\right) + \varepsilon_t,$$

where ε is an error term and β_1 captures the net effect of adjustment costs and complementary innovations on adjusted MFP. Lags of the investment-to-capital stock ratio can also be added to control for situations where the effect of adjustment costs and complementary innovations are spread out over a number of periods.

4. Results

Before proceeding with the regression of MFP growth adjusted for capacity utilization on the growth of the investment-to-capital ratio (*I/K)* and its lags, unadjusted MFP growth is used as the dependent variable instead, to highlight the importance of controlling for capacity utilization. Table 1 shows ordinary least square (OLS) regression results with various measures of investment-to-capital ratios as independent variables. Current period *I/K* growth for total investment and machinery equipment has a positive and significant effect on unadjusted MFP growth.[24] One-period lagged *I/K* growth is found to have a negative effect. These results are in

23. Adjustment costs are often postulated to be a convex function of the investment-to-capital ratio. Adding the square of the log investment-to-capital ratio to the regression does not substantially alter the results. Furthermore, since productivity shocks are thought to be persistent, it may be inappropriate to model MFP growth as simply a constant, plus a linear function of the log of the investment-to-capital stock ratio plus a random-error term. A more appropriate model would allow the error term to be autocorrelated. Since both approaches yield consistent estimates, only the results from the former approach are presented. Estimates using GLS have been calculated in most cases and are found to be similar to ones presented in this paper. Also, since trend MFP growth has changed over the sample period (Figure 2), the constant term should be allowed to vary over time. Therefore, estimates of the model for various subperiods are presented.

24. *T*-statistics that take into account serial correlation in the error term are presented throughout this paper.

opposition to the hypothesis that the negative effects of adjustment costs should initially outweigh the positive effects of complementary innovation and that the effect of complementary innovations should be stronger in the latter periods. Furthermore, *I/K* growth and its lags for ICT[25] and computer hardware—types of capital that should be more representative of embodied new technology—are insignificant.

Although capital stock is largely predetermined, investment is an endogenous variable. Therefore, simultaneity bias may be the cause of the unexpected results. Table 2 shows independent variable (IV) regression results where the various *I/K* growth rates for Canada are instrumented by their U.S. counterparts and lags of their U.S. counterparts. The point estimates are slightly different, but the results remain the same. Current *I/K* growth for total investment and machinery and equipment has a positive and then negative effect on MFP growth, and *I/K* growth for ICT and computer hardware is insignificant.[26] These unexpected findings are caused by the relationship between the *I/K* growth rates and the omitted capacity utilization growth rates. Shapiro (1986) argues that, since capital is not fully flexible, capacity utilization responds more in the short run to shocks than investment. In response to a positive shock, capacity utilization first rises and then falls in later periods when capital is moved closer to its optimal level. Thus, *I/K* growth in total investment and machinery and equipment captures the surge in capacity utilization in the first period and the decline in the second period.

Tables 3 and 4, respectively, show the OLS and IV regression results when MFP growth adjusted for capacity utilization is used as the dependent variable. The *I/K* growth and its lags are insignificant for total investment, machinery and equipment, and ICT. In fact, only the third lag of *I/K* growth for computer hardware is positive and significant. The fact that *I/K* growth and its lags for total investment and machinery and equipment are insignificant is not surprising. Total investment includes buildings and structures, and machinery and equipment includes office furniture, furnishings, automobiles, trucks, locomotives, and household equipment. Although these types of capital may embody some new technology, they are not usually associated with the creation of networks or complementary innovations that raise MFP. The finding that *I/K* growth for ICT equipment is insignificant is somewhat surprising. However, the strongest evidence of

25. ICT includes telecommunications equipment, software, and computer hardware. See the Data Appendix for more information on how the growth in *I/K* for ICT is computed.

26. The first-stage regressions indicate that, for total and machinery and equipment, the U.S. counterparts are a suitable instrument for Canadian *I/K* growth. The relationship between U.S. and Canadian *I/K* growth for ICT and computer hardware is less strong, but it is found to become stronger over time. In fact, over the 1982–2001 period, the R^2 for the regression of Canadian computer hardware *I/K* growth on U.S. computer *I/K* growth and a lag is 0.45, higher than the 0.38 R^2 for a similar regression using total capital *I/K* growth.

investment in capital affecting MFP, from Lehr and Lichtenberg (1999) and Brynjolfsson and Hitt (2000a), is for computer investment only.

It is surprising that only the third lag of *I/K* growth for computer hardware is positive and significant. This finding could be a consequence of the modelling strategy; specifically, adjusting MFP growth for capacity utilization and not estimating it, and using MFP growth as a dependent variable instead of labour productivity. To check the robustness of the finding, unadjusted MFP growth is regressed against the growth rate of the capacity utilization rate, and the *I/K* growth for computer hardware and its lags. Also, labour productivity growth is regressed against the growth rate of the capital-labour ratio, the growth rate of the capacity utilization rate, and the *I/K* growth for computer hardware and its lags.[27] Table 5 presents the results for these regressions using OLS and IV.[28] In all four regressions, only the third lag of *I/K* growth for computer hardware is significant.[29] The surprising result is therefore not due to the modelling approach of this paper. Furthermore, in all cases, the coefficient on the growth rate of capacity utilization is between 0.41 and 0.43, which is not statistically significantly different from the average of capital's share of nominal output for the business sector, 0.4241. Therefore, Paquet and Robidoux's approach of adjusting the MFP growth before performing further analysis does not bias the outcomes.[30]

It is possible that only the third lag of *I/K* growth for computer hardware is significant because the negative effects of adjustment costs cancel out the positive effects of any organizational change and complementary innovation. Before making this conclusion, however, other possible explanations are explored. It could be the case that some of the earlier lags are not identified because of a multicollinearity problem. Alternatively, the depreciation profile of computer hardware may be the cause. A computer loses much of its value through depreciation by the third year.[31] If the accounting value of computer capital drops significantly in the third year after a

27. The labour input used to compute the capital labour ratio is total annual hours. Thus, changes in labour quality have not been taken into account.

28. Again, the U.S. counterparts of the independent variables are used as instruments in the IV regressions.

29. The findings for the other types of capital are not significantly affected by different modelling strategies either.

30. Although the coefficient on the capacity utilization growth is similar to capital's share of nominal output, the two methods of adjusting for capacity utilization may still yield different results, because capital's share of nominal output is allowed to change over time in Paquet and Robidoux's (2001) approach. It is found, however, that MFP growth adjusted using Paquet and Robidoux's (2001) approach and MFP growth adjusted using the coefficient of capacity utilization growth from any of the regressions in Table 5 give almost identical series. Apparently, periods in which capital's share of nominal output is substantially different from the average of 0.42 are periods in which the growth of capacity utilization is close to zero. Thus, the difference in the amount of adjustment is extremely small.

31. Harchaoui and Tarkhani (2002) show that the median annual depreciation rate for computer and office equipment used by Statistics Canada to calculate MFP is 0.51.

large investment, but the computers themselves are still being used in production, then MFP would rise as output appears to be produced with less capital. Another possibility is that an omitted variable is biasing the results. Although the third lag of *I/K* growth for computer hardware is statistically significant, it can explain only 17 per cent of the variation in adjusted MFP growth. Finally, the period of analysis may be too long, given the question at hand. Computers did not experience widespread use until after the early 1980s. It may be the case that there is a structural break in the data, whereby the limited use of computers before 1980 did not lead to levels of adjustment costs or organizational change that can be detected using aggregate level data.

Two checks are done to determine whether multicollinearity is a problem. First, a polynomial lag model is estimated. Second, three-year moving averages of the *I/K* growth for computer hardware are taken, and then adjusted MFP is regressed against the averages centred around *t*-1 and *t*-4. The first column of Table 6 shows the results of the polynomial lag model, and the second shows the results when moving averages of the independent variables are used as regressors. The polynomial lag model gives coefficients similar to those found in Tables 3 and 4. The regression with moving averages yields an insignificant coefficient for the three-period average around *t*-1, but a significant coefficient for the average around *t*-4. Both regressions suggest that the insignificant coefficients for *I/K* growth in periods before *t*-3 are not the result of a collinearity problem.

To check whether the third lag of *I/K* growth for computer hardware is significant because of the possible rapid depreciation of computer capital in the third year of its life, investment scaled by gross capital stock is used as a regressor in place of investment scaled by capital net of depreciation. Table 7 compares the results from this regression with those shown in the last column of Table 4, where net capital is used; the results are not significantly different. Thus, the finding that the third lag of *I/K* growth for computer hardware is significant is not due to the rapid depreciation of computer hardware.

In an attempt to reduce the problem of omitted variables, three lags of the growth rate of adjusted MFP are included in the regression. Table 8 compares the results from this experiment with the results without the lagged dependent variables. It is found that only the first lag of adjusted MFP growth is significant and that the coefficients on the lags of *I/K* growth for computer hardware are unaffected. The R^2 of the regression improves to 0.38 from 0.17, but this still leaves the majority of the variation in adjusted MFP growth unexplained.[32]

32. Adding squared and cross-product terms can increase the R^2 to 0.53, but the main result—that the third lag of the *I/K* ratio for computer hardware is significant—is still unaffected.

Finally, to determine whether there is a structural break in the data, the sample is split into the pre-1982, post-1982, and post-1974 periods. Regressions are then performed on the subsamples. The break point at 1982 is arbitrary, but it does split the sample exactly in half and it roughly corresponds to the point where widespread use of computers began. The break point at 1974 is chosen because, as shown in Figure 2, trend MFP growth appears to decline after 1973. The results in Table 9 show that the effect of *I/K* growth for computer hardware on adjusted MFP growth is quite different across the subsamples.[33] Only the first subsample, 1961–81, shows evidence of adjustment costs associated with period *t I/K* growth for computer hardware. On the other hand, the positive effects of complementary innovation and organizational change are found only in the 1974–2001 and 1982–2001 periods. In the 1982–2001 regression, period *t* growth of *I/K* for computer hardware is positive and significant at the 10 per cent level, while period *t*-1 and *t*-3 *I/K* growth is positive and significant at the 5 and 1 per cent levels, respectively. The results for the 1974–2001 period are similar to the ones obtained when the entire sample is used, but the *t*-statistic on the third lag of *I/K* growth for computer hardware during the 1974–2001 period is much higher. Overall, the results in Table 9 support the idea that the negative effects of adjustment costs are cancelling out the positive effects of complementary organizational change and innovation, and that the negative effects of adjustment costs are falling and the positive effects of complementary organizational change are growing stronger over time.

The results in Table 9 also support a hypothesis that, before the early 1980s, adding computers to the mix of inputs actually decreased MFP growth, perhaps because they were not as “user-friendly” as the current vintage. Positive gains to MFP did not materialize until after the early 1980s because a critical mass of computer capital had to be accumulated before improvements in networking triggered organizational innovations. To obtain further evidence for this hypothesis, the interaction between *I/K* growth for computer hardware and the computer capital-to-output ratio, *K/Y*, is used as an explanatory variable. Since *K/Y* is a smooth series that increases over time, a time trend is also entered into the regression to prevent the interaction term from picking up the downward trend in MFP growth. The results are shown in Table 10.[34] The fact that all the interaction terms are positive and significant provides further evidence for the hypothesis that a

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33. Regressions on the subsamples using *I/K* ratios for other types of capital, total, machinery and equipment, and ICT do not reveal evidence of a change in the impact of the *I/K* growth on productivity. All the coefficient estimates, other than the constant, remain insignificantly different from zero. A regression using *I/K* growth for software as a regressor in the 1982–2001 period uncovers weak evidence of positive lagged effects. These effects disappear, however, once *I/K* growth for computer hardware is entered into the regression.

34. Table 11 uses gross computer hardware capital in the calculation of *I/K* and *K/Y.* The conclusion drawn from the results in Table 11 does not change when capital net of depreciation is used.

critical mass of computer hardware is needed to support complementary innovations and organizational change.

Finally, it would be interesting to see how much of the so-called MFP revival since 1992 can be explained by growth in *I/K* for computer capital.[35] To assess the magnitude of the effect of organizational change and complementary innovations on MFP growth over this period, the average values of the *I/K* ratio for computer hardware and its lags are taken for that period and multiplied by the corresponding coefficients from the second column of Table 9. The one exception is that the coefficient for the second lag is set to zero, because it is not statistically significant. Table 11 shows that the average annual MFP growth rate between 1992 and 2001 is 1.23 per cent. The average adjusted MFP growth rate is lower, at 1.07 per cent, because the average annual growth in capacity utilization is slightly positive. The amount of adjusted MFP growth due to *I/K* growth for computer hardware turns out to be 0.37, approximately one-third of the average annual MFP growth rate.

5. Conclusion

This paper has presented evidence that investment in computer hardware leads to growth in output and productivity above that stemming from accumulation of computer capital alone. A large portion of these gains, however, is not obtained immediately. Instead, the full impact of computer investment is not fully realized until three years after the initial investment. If one were to interpret these gains as coming from organizational change or other complementary innovations, as they are in this paper, then the findings would suggest that there may be a period of learning before firms realize the full potential of the new technology and begin implementing new processes. It is important to note that these results do not suggest that computer investment does not raise output immediately. Instead, the results imply that computer investment raises output levels more than the amount usually attributed by traditional growth accounting methods. These additional gains, however, take time to be realized.

35. Figures 1 and 2 show that MFP growth has generally been positive since 1992.

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Table 1: OLS, Unadjusted MFP

	Total	Machinery and equipment	ICT	Computer hardware
Δ $ln(I_t/K_t)$	0.1359 (2.89)	0.1260 (3.23)	0.0002 (0.01)	0.0293 (1.00)
Δ $ln(I_{t-1}/K_{t-1})$	-0.1543 (4.44)	-0.1232 (3.84)	-0.0564 (1.59)	
Δ $ln(I_{t-2}/K_{t-2})$			-0.0558 (1.34)	
Constant	1.0052 (2.72)	0.9967 (2.41)	1.341 (3.03)	0.9562 (2.37)

Notes: Dependent variable is MFP growth unadjusted for capacity utilization. Independent variables are the growth rate of the investment-to-capital ratio and its lags. Column headings indicate which type of capital the investment-to-capital ratio refers to. *T*-statistics are in parentheses. Number of lags are chosen using the Akaike information criterion.

Table 2: IV, Unadjusted MFP

	Total	Machinery and equipment	ICT	Computer hardware
Δ $ln(I_t/K_t)$	0.2521 (2.63)	0.2577 (3.06)	0.2562 (1.27)	0.1826 (1.26)
Δ $ln(I_{t-1}/K_{t-1})$	-0.1943 (3.90)	-0.1581 (2.91)	-0.0937 (1.67)	
Δ $ln(I_{t-2}/K_{t-2})$		-0.0143 (0.38)	-0.0138 (0.21)	
Δ $ln(I_{t-3}/K_{t-3})$		0.0670 (1.41)	0.0489 (0.86)	
Constant	0.8737 (2.29)	0.5395 (1.13)	-0.1318 (0.17)	0.3621 (0.78)

Notes: Dependent variable is MFP growth unadjusted for capacity utilization. Independent variables are the growth rate of the investment-to-capital ratio and its lags. Column headings indicate which type of capital the investment-to-capital ratio refers to. The U.S. counterparts of the independent variables are used as instruments. *T*-statistics are in parentheses. Number of lags are chosen using the Akaike information criterion.

Table 3: OLS, Adjusted MFP

	Total	Machinery and equipment	ICT	Computer hardware
Δ $ln(I_t/K_t)$	0.0002 (0.01)	0.0032 (0.09)	-0.0220 (0.98)	-0.0003 (0.02)
Δ $ln(I_{t-1}/K_{t-1})$				0.0040 (0.26)
Δ $ln(I_{t-2}/K_{t-2})$				0.0073 (0.32)
Δ $ln(I_{t-3}/K_{t-3})$				0.0460 (2.91)
Constant	0.9699 (3.11)	0.9622 (3.00)	1.0521 (3.13)	0.6812 (1.91)

Notes: Dependent variable is MFP growth adjusted for capacity utilization. Independent variables are the growth rate of the investment-to-capital ratio and its lags. Column headings indicate which type of capital the investment-to-capital ratio refers to. *T*-statistics are in parentheses. Number of lags are chosen using the Akaike information criterion.

Table 4: IV, Adjusted MFP

	Total	Machinery and equipment	ICT	Computer hardware
Δ *ln*(I_t/K_t)	-0.0370 (0.58)	-0.0529 (0.82)	-0.0402 (0.36)	0.0329 (0.45)
Δ *ln*(I_{t-1}/K_{t-1})				0.0104 (0.48)
Δ *ln*(I_{t-2}/K_{t-2})				0.0050 (0.26)
Δ *ln*(I_{t-3}/K_{t-3})				0.0408 (2.06)
Constant	1.0341 (3.45)	1.1068 (3.36)	1.1952 (1.61)	0.5960 (1.99)

Notes: Dependent variable is MFP growth adjusted for capacity utilization. Independent variables are the growth rate of the investment-to-capital ratio and its lags. The U.S. counterparts of the independent variables are used as instruments. Column headings indicate which type of capital the investment-to-capital ratio refers to. *T*-statistics are in parentheses. Number of lags are chosen using the Akaike information criterion.

Table 5: Robustness Check

	Δ *ln(Z)* - OLS	Δ *ln(Z)* - IV	Δ *ln(Y/L)* - OLS	Δ *ln(Y/L)* - IV
$\Delta\ ln(K_t/L_t)$			0.3735 (2.43)	0.2329 (0.92)
$\Delta\ ln(U_{Kt})$	0.4230 (5.74)	0.4086 (3.42)	0.4331 (6.14)	0.4259 (3.05)
$\Delta\ ln(I_t/K_t)$	-0.0015 (0.12)	-0.0861 (1.06)	-0.0061 (0.46)	-0.0526 (0.90)
$\Delta\ ln(I_{t-1}/K_{t-1})$	0.0067 (0.32)	-0.0087 (0.30)	-0.0002 (0.01)	-0.0033 (0.13)
$\Delta\ ln(I_{t-2}/K_{t-2})$	0.0086 (0.38)	0.0130 (0.40)	0.0068 (0.29)	0.0220 (0.85)
$\Delta\ ln(I_{t-3}/K_{t-3})$	0.0458 (2.73)	0.0565 (2.54)	0.0407 (2.03)	0.0553 (3.82)
Constant	0.6827 (1.83)	0.8497 (2.17)	1.034 (2.89)	0.9780 (2.17)

Notes: Dependent variable is indicated in the column headings. The growth rate of investment-to-capital ratio is for computer hardware. The U.S. counterparts of the independent variables are used as instruments. *T*-statistics are in parentheses. Number of lags are chosen using the Akaike information criterion.

Table 6: Multicollinearity

	1[a]	2[b]
$\Delta\ ln(I_t/K_t)$	0.0039 (0.55)	
$\Delta\ ln(I_{t-1}/K_{t-1})$	0.0050 (0.27)	
$\Delta\ ln(I_{t-2}/K_{t-2})$	0.0072 (0.38)	
$\Delta\ ln(I_{t-3}/K_{t-3})$	0.0460 (2.46)	
MA($\Delta\ ln(I_{t-1}/K_{t-1})$**)**		0.0066 (0.18)
MA($\Delta\ ln(I_{t-4}/K_{t-4})$**)**		0.0724 (2.20)
Constant	0.6805 (2.53)	0.5815 (1.62)

a. Estimates for polynomial distributed lag model with a quadratic specification. Dependent variable is MFP growth adjusted for capacity utilization. *T*-statistics are in parentheses.

b. Dependent variable is MFP growth adjusted for capacity utilization. Independent variables are three-period moving averages centred around *t*-1 and *t*-4. *T*-statistics are in parentheses.

Table 7: Depreciation of Computer Hardware

	Net capital	Gross capital
$\Delta\ ln(I_t/K_t)$	-0.0003 (0.02)	0.0006 (0.05)
$\Delta\ ln(I_{t-1}/K_{t-1})$	0.0040 (0.26)	0.0050 (0.29)
$\Delta\ ln(I_{t-2}/K_{t-2})$	0.0073 (0.32)	0.0069 (0.42)
$\Delta\ ln(I_{t-3}/K_{t-3})$	0.0460 (2.91)	0.0417 (2.97)
Constant	0.6812 (1.91)	0.6729 (1.95)

Notes: Dependent variable is MFP growth adjusted for capacity utilization. Column headings indicate whether computer investment is scaled by gross or net computer capital. *T*-statistics are in parentheses.

Table 8: Lagged Dependent Variable

	$\Delta \ln(\tilde{Z}_t)$	$\Delta \ln(\tilde{Z}_t)$
$\Delta\ ln(I_t/K_t)$	-0.0003 (0.02)	-0.0016 (0.09)
$\Delta\ ln(I_{t-1}/K_{t-1})$	0.0040 (0.26)	0.0023 (0.13)
$\Delta\ ln(I_{t-2}/K_{t-2})$	0.0073 (0.32)	0.0032 (0.41)
$\Delta\ ln(I_{t-3}/K_{t-3})$	0.0460 (2.91)	0.0439 (2.58)
$\Delta\ ln\tilde{Z}_{t-1}$		0.3312 (1.87)
$\Delta\ ln\tilde{Z}_{t-2}$		0.1451 (0.80)
$\Delta\ ln\tilde{Z}_{t-3}$		0.0760 (0.41)
Constant	0.6812 (1.91)	0.2126 (0.73)
R^2	0.17	0.38

Notes: Dependent variable is MFP growth adjusted for capacity utilization. The growth rate of investment-to-capital ratio is for computer hardware. *T*-statistics are in parentheses.

Table 9: Regressions on Subsamples

	1961–81	1982–2001	1974–2001
$\Delta\ ln(I_t/K_t)$	-0.0519 (2.51)	0.0376 (1.79)	0.0048 (0.49)
$\Delta\ ln(I_{t-1}/K_{t-1})$	-0.0514 (1.53)	0.0475 (2.32)	0.0127 (0.76)
$\Delta\ ln(I_{t-2}/K_{t-2})$		0.0294 (1.04)	0.0129 (0.069)
$\Delta\ ln(I_{t-3}/K_{t-3})$		0.0548 (3.45)	0.0484 (4.76)
Constant	2.4736 (8.53)	0.3182 (1.17)	0.2065 (0.74)

Notes: Dependent variable is MFP growth adjusted for capacity utilization. The growth rate of investment-to-capital ratio is for computer hardware. Number of lags are chosen using the Akaike information criterion. *T*-statistics are in parentheses.

Table 10: The Importance of the Size of the Accumulated Stock of Capital

	$\Delta \ln(\tilde{Z}_t)$
$\Delta\ ln(I_t/K_t)$	-0.0128 (1.22)
$\Delta\ ln(I_{t-1}/K_{t-1})$	-0.0043 (0.29)
$\Delta\ ln(I_{t-2}/K_{t-2})$	-0.0076 (0.62)
$\Delta\ ln(I_{t-3}/K_{t-3})$	0.0202 (1.56)
$\Delta\ ln(I_t/K_t)$ x K_t/Y_t	0.0418 (1.88)
$\Delta\ ln(I_{t-1}/K_{t-1})$ x K_{t-1}/Y_{t-1}	0.0536 (2.54)
$\Delta\ ln(I_{t-2}/K_{t-2})$ x K_{t-21}/Y_{t-2}	0.1096 (3.27)
$\Delta\ ln(I_{t-3}/K_{t-3})$ x K_{t-3}/Y_{t-3}	0.1420 (3.35)
t	-0.0979 (-3.45)
Constant	2.8126 (3.93)

Notes: Dependent variable is MFP growth adjusted for capacity utilization. Investment and capital stock numbers are for computer hardware. *T*-statistics are in parentheses.

Table 11: Average Annual Growth Rates (%)

	1992–2001
$\Delta\ln(Z)$	1.23
$\Delta\ln(\tilde{Z})$	1.07
$\Delta\ln(\tilde{Z})$ explained by $\Delta\ \ln(I/K)$	0.37

Figure 1: Unadjusted and Cyclically Adjusted Multifactor Productivity Growth, 1962–2001

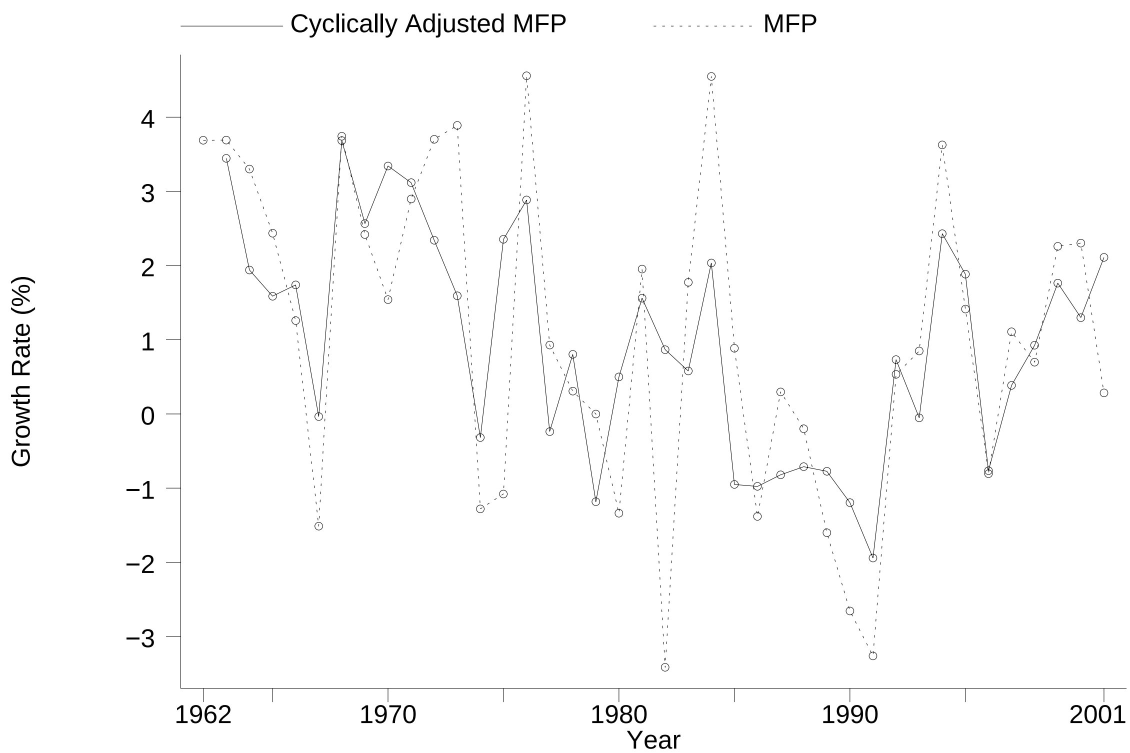
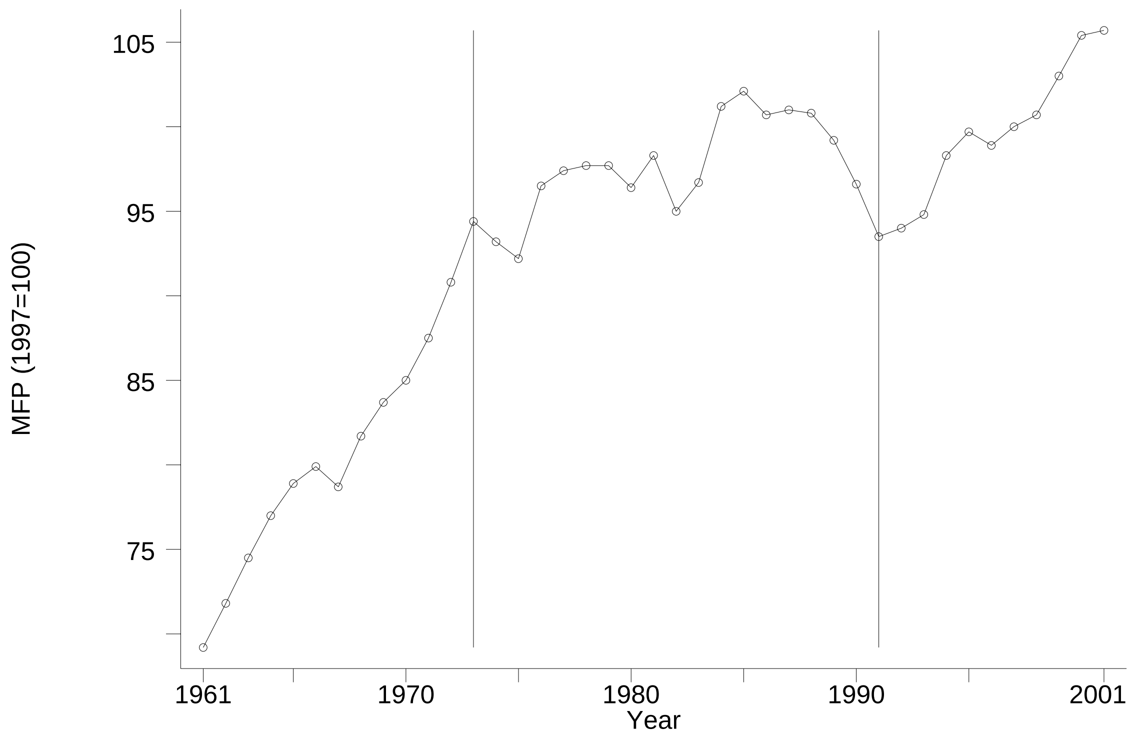


Figure 2: Multifactor Productivity, 1961–2001



Data Appendix

Data Sources and Definitions:
Canada (Data for Canada are entirely from Statistics Canada)

Multifactor productivity:	Business sector, 1961–2001 (Index 1992=100).
Investment:	Total (machinery and equipment plus non-residential buildings and structures), and machinery and equipment. Business sector, 1961–2001 (chained 1997 dollars).
	Computers and telecommunications equipment, non-agricultural business sector, 1961–2001 (current and chained 1997 dollars).
	Software, non-agricultural business sector, 1981–2001 (current and chained 1997 dollars).
Capital stock:	Total, and machinery and equipment. Business sector, hyperbolic end year net stock, 1961–2001 (chained 1997 dollars).
	Computers and telecommunications equipment, non-agricultural business sector, hyperbolic end year net stock, 1961–2001 (current and chained 1997 dollars).
	Software, non-agricultural business sector, hyperbolic end year net stock, 1981–2001 (current and chained 1997 dollars).
Capital capacity utilization rate:	Industrial capacity utilization rate, terminated quarterly series based on SIC, 1962–2001.
Labour's share of nominal output:	Total compensation for all jobs in total economy (current dollars) divided by GDP (current dollars) for the total economy, 1961–2001.
Labour input:	Hours worked for all jobs, business sector, 1961–2001.
Labour productivity:	Labour productivity, business sector, 1961–2001.

- ICT includes computer hardware, telecommunications equipment, and software. The *I/K* growth rate for ICT is computed by first calculating the investment and capital stock growth rates for each component of ICT. ICT investment growth is then obtained by taking a weighted average of computer, telecommunications, and software investment growth. The weight on each component of ICT investment growth in period t is the average of the component's share of nominal ICT investment in period t and t-1. Since data for software are available only from 1981, the weight on software investment growth is zero before then. ICT capital stock growth is calculated in the same manner. The *I/K* growth rate for ICT is calculated by taking the difference between the investment and capital growth rates.

United States

Investment:	Non-residential private fixed, and equipment and software, 1961–2001, Bureau of Economic Activity (chained 1996 dollars). Information processing equipment and software, and computers and peripheral equipment, 1961–2001, Bureau of Economic Activity (chain-type quantity index, 1996=100).
Capital stock:	Non-residential private fixed, and equipment and software, geometric infinite end year net stock, 1961–2001, Bureau of Economic Activity (chained 1996 dollars). Information processing equipment and software, and computers and peripheral equipment, geometric infinite end year net stock, 1961–2001, Bureau of Economic Activity (chain-type quantity index, 1996=100).
Capital capacity utilization rate:	Industrial capacity utilization rate, 1967–2001, Federal Reserve Board, Board of Governors.
Labour input:	Hours worked for all jobs, business sector, 1961–2001, Bureau of Labor Statistics.

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