# ICT and Productivity:

## A synthesis of Canadian, American, and European Research

By
Avi Goldfarb
Rotman School of Management
University of Toronto

Report for Industry Canada, Electronic Commerce Branch
March 2011

## Executive Summary

In this report, I summarize the existing literature on how the rise of computers and other information and communication technologies (ICTs) has affected productivity in companies around the world. It is important to understand this impact because, in the long run, it is productivity growth that determines changes in the standard of living.

There are two main ways in which productivity has been studied in the literature: growth accounting and firm-level analysis. Growth accounting is useful for identifying general trends but it cannot determine causality. Firm-level analysis is therefore needed to understand policy implications. The recent productivity literature strongly emphasizes that the future of productivity research is in firm-level methods.

The growth accounting literature showed a sharp increase in US productivity in the late 1990s, and this surge was largely sustained into the 2000s. This literature shows that this increase is largest in industries with substantial IT capital, suggesting a link between IT capital and productivity.

The firm-level productivity literature has generally documented a causal link from ICT adoption to firm-level productivity growth, but only under certain conditions. While there is little evidence that ICT investments by one firm generate productivity spillovers to other firms, this literature does show that the following all play important roles in determining whether ICT investment leads to productivity:

- Organizational capital: ICT investments are most effective when accompanied by incentive systems, decentralized decision-making, and/or increased (internal and external) information flow.
- Co-invention: ICT investments are most effective when accompanied by small innovations that adapt a particular ICT to the context of the investing firm.
- Human capital: ICT investments are typically skill-biased. Therefore, they are most effective in firms with an educated labour force.
- Type of ICT: The specific type of organizational capital, co-invention, and human capital needed depends on the type of ICT.
- Location: The benefits and costs of ICT investments vary across locations.
- Regulation: The impact of ICT investment on overall productivity depends on the ability of efficient firms to grow, to change prices and strategies, and to replace inefficient firms.

For Canada, there is little firm-level analysis on ICT and performance, perhaps because of past difficulties (hopefully soon to be resolved) in enabling academics to use the firm level data. Growth accounting data shows Canada generally in the middle of pack: firmly behind the United States in total factor productivity but in the middle of, if not leading, the rest of the G7. Firm-level analysis of European and American data suggests that this positioning might be due to low levels of post-secondary education relative to the United States and high levels relative to elsewhere, higher labour and product market regulation relative to the United States but lower levels than elsewhere, and high levels of foreign direct investment from the United States. However, in order to understand the best policies for Canada in particular, it is important to have high quality micro analysis of Canadian firm- and establishment-level data. The new Survey of Business and Innovation Strategy is an important step in that direction, at least for manufacturing. The next task is to dig into this data, particularly once a panel of several years has been established and, ideally, to have a comparable data set for services as well as manufacturing.

Table of contents

## 1. Introduction

Since their commercial invention in the 1940s, computers have been gradually diffusing into businesses in Canada, the United States, and around the world. This diffusion accelerated in the 1980s and computing investment increased particularly sharply in the late 1990s. In this report, I summarize the existing literature on how the rise of computers and other information and communication technologies (ICTs) has affected productivity in companies around the world. It is important to understand this impact because, in the long run, it is productivity growth that determines changes in the standard of living.

Computers do three things: they compute, they remember, and they communicate. In the information systems literature, these are referred to as the information processing, storage, and input/output functions respectively. Electronic computation, memory, and communication have the potential to reduce the labour and capital intensity of many tasks, thereby increasing productivity. Indeed, the existing literature documents that the sharp rise in ICT investment in the late 1990s is strongly associated with a coincident increase in productivity.

There are two main ways in which productivity has been studied in the literature: growth accounting and firm-level analysis. Growth accounting is useful for identifying general trends but it cannot determine causality. Firm-level analysis is therefore needed to understand policy implications.

The growth accounting literature showed a sharp increase in US productivity in the late 1990s, and this surge was largely sustained into the 2000s. This literature shows that this increase is largest in industries with substantial IT capital, suggesting a link between IT capital and productivity. Growth accounting methods examine correlations at a macro level and provide a sense of how national productivity changes over time, across countries, and sometimes across industries. Growth accounting therefore is the best tool for describing productivity patterns.

The growth accounting literature, however, cannot determine causality and therefore it cannot provide policy recommendations. As understanding of this limitation grows (in response to the "identification revolution" in economics led by Charles Manski, Joshua Angrist, and others), statistical agencies and economists around the world have built and analyzed firm-level panels to understand how information and communication technologies affect productivity.

The recent productivity literature strongly emphasizes that the future of productivity research is in micro-level methods rather than national growth accounting, though growth accounting will continue to play a supporting role in establishing patterns and setting up puzzles to be analyzed with micro data. This is a main point of emphasis in Van Reenen et al's (2010) recent review and in Brynjolfsson and Saunders' (2010) book. Draca, Sadun, and Van Reenen (2006) show that firm level data is required to understand the roles of organizational capital, spillovers, and network effects for productivity and ICTs. Even Jorgenson, Ho, and Stiroh (2005) say (in their growth accounting research) "It is only at the micro level that production analysts can seek to understand the specific changes in technology, business practices, and input choices that firms make in response to changing economic incentive and opportunities" (p. 415), though by "micro level" they mean industry rather than country.

This firm-level ("micro-to-macro" in the language of Van Reenen et al 2010) productivity literature has generally documented a causal link from ICT adoption to firm-level productivity growth, but only under certain conditions. This literature shows that organizational practices, skills, geography, and regulation all play important roles in determining whether ICT leads to productivity. Spillovers do not appear to play an important role, likely because ICTs are an embodied technology.

Growth accounting can underestimate the potential benefits of ICT adoption because it does not take into account heterogeneity across firms. By focusing on nationwide averages, it underestimates the potential impact by mixing firms with good ICT practices with firms that invest in the technology but not in the skills and structure required to take advantage of it.

For Canada, there is very little firm-level analysis on ICT and performance, perhaps because of past difficulties (hopefully soon to be resolved) in enabling non-government economists to use the firm level data. Growth accounting data shows Canada generally in the middle of pack: firmly behind the United States in MFP but in the middle of, if not leading, the rest of the G7.

The remainder of this review summarizes the key points in the literature and provides comprehensive references to the ideas discussed. It is not the first review of the ICT and productivity literature. Therefore, there is some overlap with the studies by Draca, Sadun, and Van Reenen (2006), Brynjolfsson and Saunders (2010), and especially Van Reenen et al (2010). Overall, the views discussed here on the strengths and weaknesses of the growth accounting approach relative to the use of micro data are largely consistent with these recent reviews, though perhaps the strengths and limitations of growth accounting are stated more forcefully here.

## 2. Growth accounting

### 2.1 Growth accounting methodology

Growth accounting enables the measurement of productivity and productivity growth at the national and industry level. Most commonly, growth accounting takes national measures of labour, capital, output, and perhaps materials and ICT capital, to generate measures of labour productivity and multifactor productivity. More recently, the growth accounting literature has also used industry-level data in order to better understand the drivers of productivity at the national level.

As discussed in Van Reenen et al's (2010) review, growth accounting builds from a standard national production function. In the literature on ICT and productivity, the production function typically looks like this:

$$Y=AF(L,K,C,M) \qquad (1)$$

Where L is labour input (employment), K is non-ICT capital, C is ICT capital, and M is materials. If the production function is Cobb-Douglas, and taking logs, this can be rewritten as

$$y=a+\alpha_l l+\alpha_k k+\alpha_c c+\alpha_m m \qquad (2)$$

where lower case letters denote the log of the corresponding upper case letters. A similar equation can be derived for other production functions such as translog or constant elasticity of substitution. Given that data on inputs and output tend to come in discrete time periods (years, quarters, or months), output growth can be rewritten as

$$\Delta y=\Delta a+\alpha_l\Delta l+\alpha_k\Delta k+\alpha_c\Delta c+\alpha_m\Delta m \tag{3}$$

Assuming factor and product markets are perfectly competitive, the revenue shares of the inputs can replace the coefficients.

$$\alpha_x=s_x=\rho_x X/pY \tag{4}$$

$$\Delta y=\Delta a+s_l\Delta l+s_k\Delta k+s_c\Delta c+s_m\Delta m \tag{5}$$

Where $s_x$ is the revenue share, $\rho_x$ is the price of factor X per unit, and p is the price of output (Y). For example, $\rho_l$ is the wage rate. Equation (5) is an identity that can be calculated from data because all parts of it are known except $\Delta a$, which can then be calculated as the only unknown in a single equation. Specifically, in every year, output growth, labour force growth, capital growth, computing growth, materials growth, wages, the price of capital, the price of ICT capital, and the price of materials are known. Given these, the change in multi factor productivity can be trivially derived—no regressions needed.

Sometimes, the growth accounting literature rewrites equation (5) in terms of labour productivity growth by assuming constant returns to scale ($\alpha_l+\alpha_k+\alpha_c+\alpha_m=1$):

$$\Delta(y\text{-}l)=\Delta a+ s_k\Delta(k\text{-}l)+s_c\Delta(c\text{-}1)+s_m\Delta(m\text{-}1) \tag{6}$$

Materials are sometimes dropped by assuming Leontief production in materials, and y in equation (6) becomes value added rather than output.

For further details on basic growth accounting methods, see Van Reenen et al (2010, p. 27-31) and Jorgenson, Ho, and Stiroh (2005). Using these methods, Jorgenson, Ho, and Stiroh (2008) allocate a 0.59 share of TFP growth from 1995 to 2000 to ICTs (as well as some share of capital deepening). In contrast, in the 1973 to 1995 and 2000 to 2005 periods, the share is between 0.38 and 0.42. In this way, these methods are important for establishing the basic relationships in the aggregate data. However, they cannot convincingly establish causality because of the inherent endogeneity of the inputs. Two types of endogeneity are relevant here and firm level analysis is necessary to address either of them.

Specifically, there is the potential for omitted variables bias and simultaneity. Omitted variables bias means that something else is driving the change in ICT investment and productivity that is not contained in the equation (such as changes in management practices). Simultaneity (sometimes called reverse causality) means that anticipation of improvements in productivity generates extra revenue that is used for investments in ICTs, rather than ICTs causing investments.

A handful of papers in the literature have tried to address these concerns. The most promising route is to estimate the equations at the industry level rather than at the country level (e.g. Jorgenson, Ho, and Stiroh 2005). This helps researchers determine whether the industries that gained were the ones with the most intensive use of ICT. Still, it suffers from the same general endogeneity problems, just at a lower level. And in the absence of a natural experiment or reliable instruments (both of which are much more likely at the firm level), the results from industry-level analysis also has to be viewed as suggestive and should not be used to determine specific policy initiatives.

Some researchers have tried to use instruments at the aggregate level. For example, Roller and Waverman (2001) extend this basic framework in their analysis of the impact of telecommunications investments on productivity to try to account for the endogeneity of telecom investments. By modeling the decision to invest in telecommunications, their estimation strategy implicitly uses the price of telecommunications investment as an instrument. Therefore, instead of taking telecommunications investment as exogenous, they take the price of telecommunications as exogenous and use it to estimate how telecommunications investment affects productivity. This method does try to determine a causal relationship, but it relies on strong assumptions about the drivers of telecommunications prices across countries and over time. As will be discussed below, while it is reasonable to assume firms take ICT prices as given, it is harder to justify that assumption in an economy-wide equilibrium. Therefore, this method just pushes the endogeneity problem a step back rather than eliminating it. The state of the art in identification of causal relationships has moved substantially since 2001.

Another commonly used set of instruments is lagged inputs. By using a Blundell-Bond (2000) type approach with GMM estimation, a handful of recent papers claim to find a causal link between ICT investment and productivity. Furthermore, some of these papers also claim to be able to identify the drivers of this link. For example, Meijers (2007) claims to identify positive externalities in IT software and in telecommunications equipment.

However, these claims should be interpreted cautiously. In the case of Meijers (2007), the results show that total factor productivity lags software investments by seven years and telecom equipment investments by three years. If ICT investments have a lagged impact, the use of lagged ICT measures as instruments for current ICT is necessarily imperfect. Furthermore, the finding of a seven year lagged effect using fifteen years of data in just fifteen countries highlights the potential for spurious correlation to drive the results as interpreted.

Broadly, this inability to say much about causality is the most important limitation of growth accounting. Draca, Sadun, and Van Reenen (2006) summarize this literature by noting (p. 36) that "None of the literature has produced convincing evidence of a causal impact of ICT on productivity...the attempt to find alternative credible instrumental variables should be a priority of future research." I would argue that such attempts are likely to be futile because country-level instruments for ICT investments that are exogenous to (perhaps anticipated) productivity changes will be hard to find.

Instead, the growth accounting literature should be seen as a tool for understanding general trends but without causal inference, growth accounting results alone should not drive policy. Importantly, many of the other limitations of growth accounting do affect its usefulness if growth accounting is primarily used to identify broad trends and interesting correlations.

Specifically, Van Reenen et al (2010) discuss three additional limitations of growth accounting: (1) the strong assumptions of perfect competition in factor and output markets, especially in light of possible market power in ICT industries, (2) externalities, such as knowledge spillovers, are only captured in the residual, and (3) the assumption of no adjustment costs is strong, especially in the presence of rapid technical change.

To the extent that growth accounting results are interpreted as suggestive of interesting trends that require further analysis, these additional limitations are not a problem. For example, the assumption of perfect competition only matters if within-country changes in market power are correlated with productivity in a systematic way. In terms of knowledge spillovers and adjustment costs, growth accounting might reveal changes in the residual over time in some countries. While researchers cannot therefore declare that these changes are due to knowledge spillovers, lagged adjustment costs, or something else, the results are informative to researchers by telling them where such effects might be found using micro data.

Growth accounting is the best tool for describing productivity patterns. Therefore growth accounting estimates are essential for motivating and identifying interesting questions for micro-level causal analysis. In the absence of growth accounting, there would be no motivation or understanding of which kinds of micro analysis might matter and why. It provides a necessary big picture understanding of productivity trends and ICT investments.

### 2.2 What have we learned from growth accounting?

The strengths of the growth accounting method discussed above imply that it is particularly useful for identifying broad trends in productivity and ICT. Here I discuss four key findings of the growth accounting literature: (1) how productivity has changed over time in the United States, Europe, and elsewhere, (2) the correlation of these productivity changes with investments in ICT, (3) differences in this correlation across industries, and (4) differences in this correlation across types of ICT. Draca, Sadun, and Van Reenen (2006) provide a comprehensive paper-by-paper list of the contributions in this literature in their Tables 2 and 3. Many of these papers are discussed below but the tables in Draca, Sadun, and Van Reenen (2006) provide an itemized list that complements the structured argument I provide in this section.

Most studies show similar patterns in overall productivity over time (Oliner and Sichel 2002; Stiroh 2002; Jorgenson 2007; Van Ark, O'Mahony, and Timmer 2008). Until 1995, productivity in the United States and in the rest of the OECD grew at a steady pace. Productivity growth was slightly higher in the European Union than the United States, leading to some convergence in incomes across regions. Between 1995 and 2000 the United States experienced a productivity surge. After (perhaps) a slight dip, this surge continued through 2003 and perhaps even later. European countries experienced no such surge in productivity. Therefore, a substantial productivity gap between the United States and Europe appeared between 1995 and 2005. Other developed economies, including Canada and Japan, either had a similar experience to Europe, or were somewhere in the middle, depending on the source and the analysis.

Increasingly, the consensus in the literature is that effective investment in ICTs caused this divergence between the United States and other countries (Van Reenen et al 2010; Jorgenson, Ho, and Stiroh 2006; Brynjolfsson and Saunders 2010; Van Ark, O'Mahoney, and Timmer 2008; etc.). Up until the late 1990s, the productivity literature frequently referred to the "Solow paradox" that investment in computing is ubiquitous but the productivity benefits were not seen by economists. Over time, this view has faded based on the evidence described below. But, as late as 2003, the data and methods available with growth accounting made this a reasonable position—best articulated by Gordon (2000, 2003).

Country-level data showed a sharp increase in ICT capital in the late 1990s, particularly in the United States. This increase was coincident with the productivity surge. For example, Lehr and Lichtenberg (1999) show that investments in personal computers appear to have yielded excess returns in the United States from 1977 to 1993 (though they argue that this metric will become less informative as computers become ubiquitous). Roller and Waverman (2001) argue that telecommunications infrastructure is correlated with economic growth across 21 OECD countries from 1970 to 1990, particularly as a country approaches universal telephone service. They find that a 1% increase in telecommunications adoption increases growth by 0.15%. Oliner and Sichel (2002) also argue that the productivity surge from 1995 to 2000 was due to ICT investment. They also highlight the puzzle that IT investment fell sharply from 2000 to 2001 though productivity continued to rise. They argue that IT usage explains this puzzle because IT usage continued to rise even as investment fell.

As the papers typically acknowledge, these correlations are clearly insufficient to drive the claim that ICT capital and usage drove the productivity surge. Some other unobserved factor might drive both. The growth accounting literature has therefore increasingly examined productivity growth at the industry level. O'Mahony and Vecchi (2003) argue that industry-specific data show an even stronger correlation between ICT investment and TFP growth than country-level data. More directly addressing causality, Jorgenson, Ho, and Stiroh (2005) summarize their work (Stiroh 2002, 2004; Jorgenson and Stiroh 1999) and provide new analysis that divided industries into three groups: ICT-producing, ICT-using, and others.[1] They then look at patterns of ICT investment and productivity changes across these groups of industries. They find substantial productivity growth in ICT-producing and ICT-using industries, and much less growth in other industries. Furthermore, they find the rate of productivity growth in

[1] They use the label "IT" not "ICT" but do include communications. They define "IT producing" as computer services (SIC 737), computers and office equipment (357), Communications Equipment (366), and Electronic Components (367).

They define "IT using" as Communications (SIC 48), Business Services excluding computer services (73), Wholesale Trade (50-51), Finance (60-62, 67), Printing and Publishing (27), Legal Services (81), Instruments and Miscellaneous Manufacturing (38-39), Insurance (63-64), Industrial Machinery excluding computers (35), Gas Utilities (492, 496, and parts of 493), Professional and Social Services (832-839), Other Transportation Equipment (372-379), Other Electrical Machinery (36, except 366-267).

these industries is connected to ICT investments. ICT-producing industries in particular experienced rapid productivity growth from 1995 to 2000 and they argue that the importance of the ICT-producing sector in the United States relative to elsewhere explains a substantial fraction of the productivity gap over this time period. Looking at Greece, Antonopoulos and Sakellaris (2009) also find that a substantial portion of Greek TFP growth was due to the ICT-using sector.

Van Ark, O'Mahony, and Timmer (2008) document that the productivity difference between the United States and the European Union from 1995 to 2005 is largely related to the ICT-producing and ICT-using sectors. For ICT-using, they emphasize US investment in ICT by market services firms as particularly important. In Dion and Fay's (2008) review, in discussing the growth accounting literature they also argue that ICT production and use were key drivers of the US productivity surge in the late 1990s. In addition, they say that while the effect in the labelled ICT-producing and -using industries fell from 2000 to 2005, this was made up by an increase in ICT-intensity for industries that were not traditionally labelled "ICT-using".

Jorgenson and Stiroh (1999) link ICT-producing and ICT-using industries by arguing that the productivity increases in the ICT-producing sector led to a rapid price decline in ICT capital. This in turn increased investment in ICT capital relative to other production inputs. Timmer and Van Ark (2005) similarly argue that TFP growth in ICT-producing industries and related ICT capital deepening in ICT-using industries explain the US lead in labour productivity growth from 1995 to 2001, though they argue that within the European Union, non-ICT sources of growth explain variation across countries.

In rare cases, it is possible to generate causal inferences from industry-country-level data due to the presence of plausibly exogenous instruments. For example, Aghion et al (2005) use Thatcher era privatization, EU single market reforms, and Monopoly and Merger Commission outcomes as instruments for competition that vary across industries and countries. However, many papers that have attempted to go beyond identifying patterns to claim to understand the drivers of the correlation between ICT investments and productivity lack appropriate controls and nuance. As discussed above, the finding of spillovers in Meijers (2007) is subject to several alternative interpretations, including over-interpretation of noise in the data. Meijers (2010) shows a correlation between ICT adoption and trade and argues that ICT adoption increases productivity primarily through trade but cannot rule out the possibility that some omitted variable is driving both or that reverse causality is at play in the form of an anticipated trend in trade, productivity, or ICT investment that drives the other effects.

This literature has focused on the differences between IT-using sectors, IT-producing sectors, and other sectors. There has been much less attention to the differences between investing in software and hardware, or between information technology and communication technology. As discussed in the firm-level analysis below, these distinctions are important. For example, with UK data Chesson and Chamberlain (2005) separate hardware, software developed in-house, and purchased software. Corrado et al (2006) conduct a similar exercise with US data. They find some differences but generally conclude with no clear pattern on the impact of different types of ICTs on productivity. As discussed below, the firm-level analysis leads to differences, particularly in the types of complementary organization capital required to convert ICT investment into productivity.

The growth accounting literature can be summarized as arguing that ICT is responsible, directly or indirectly, for most of the resurgence in US productivity since 1995 (Brynjolfsson and Saunders 2010). Draca, Sadun, and Van Reenen (2006), Van Reenen et al (2010), and Dion and Fay (2008) also summarize this literature as arguing that the productivity surge in the United States is due to ICT investment and usage. Draca, Sadun, and Van Reenen (2006) emphasize that this connection is largely because of TFP improvements in the IT-producing sector combined with ICT capital deepening in the IT-using sectors. This ICT capital deepening was likely driven by lower quality-adjusted prices for ICT.

### 2.3 Where does Canada stand?

Canadian performance is rarely considered in the academic literature. Even when Canada is included in the analysis, research papers rarely report Canada-specific results. There are a few exceptions (often by researchers working for the Canadian government), and I review these below.

Baldwin and Gu (2008) show that Canadian labour productivity kept pace with US labour productivity through the 1990s, but then fell in relative terms between 2000 and 2006. Despite this, Canadian GDP per capita grew steadily over the same time period (perhaps due to changes in resource prices).

Dion and Fay (2008) and Fuss and Waverman (2005) assess to what extent these differences relate to investments in ICT. Dion and Fay review the broader literature and conclude that the Canada-US productivity gap is not due to differences to industry mix. Instead the gap is due to intensity differences within industries in ICT investment, educational attainment, and capital investment, and note that Canadian retail trade is particularly unproductive in a relative sense.[2] Fuss and Waverman argue that half of the gap between Canadian and US labour productivity is explained by telecom and personal computer penetration. More generally, Gera, Gu, and Lee (1999) show that ICT investments increased labour productivity in both Canada and the United States from 1973 to 1993.

Jorgenson (2007) compares the G7 economies from 1980 to 2001. Canada lags the United States in ICT capital in all periods. Relative to the rest of the G7, Canada is comparable but relatively low for ICT capital. Interestingly, despite these relatively low investments, Canada leads Italy, France, Germany, the UK, and Japan in generating output growth from ICT capital (though it lags the United States). Similarly, Canada leads all four European G7 members in the correlation between ICT capital deepening and labour productivity growth though this is likely a simple result of relatively higher ICT capital intensity in Canada over the 1995 to 2001 period. Canada lags all other G7 members in productivity in the IT-producing sector. It is important to note that the data in this study are puzzling in some ways. For example, Canada has higher total factor productivity than the United States, which seems unlikely given that most other research puts the United States as the productivity leader (and even this study puts the

[2] In terms of specific numbers, nominal ICT investment growth in Canada was 6.1% from 1987 to 1995, 13% from 1995 to 2000, and -1.5% from 2000 to 2004. Software grew in all three periods (11.8%, 10.6%, 4.9% respectively). This contrasts with hardware/computers and communications equipment which both experienced rapid growth from 1995 to 2000 but a decline from 2000 to 2004 (they cite Sharpe 2005 as the source of these numbers).

United States as the technology leader). Furthermore, Italy and France also have higher TFP than the United States. This is not consistent with widely held views of productivity measures.

Similarly, Pilat (2005) notes that Canada has had a mediocre performance in the contribution of ICT production to labour productivity. Still, he notes that Canada was one of the strongest performers in the OECD from 1995 to 2003 primarily because of MFP growth in the ICT-using retail sector (perhaps overcoming the gap mentioned above and identified by Dion and Fay). Other factors correlated with Canada's strong growth are human capital investments and capital deepening in both ICT and non-ICT capital.

Growth accounting therefore shows that Canada lags the United States in productivity growth since 1995 and is, at best, in the middle of the G7. Part of the reason for this lag relative to the United States likely has to do with IT capital. Another part relates to particularly low productivity growth in Canada's ICT-producing industries relative to the United States and even elsewhere.

Broadly, the growth accounting literature suggests that Canadian productivity growth has lagged others due to low ICT capital deepening and the relative unimportance of the ICT-producing sector. At the same time, one interpretation of Pilat (2005) and Jorgenson (2007) is that Canada is relatively strong in converting ICT investments into productivity (particularly in retail); however, an alternative interpretation is that Canada simply increased ICT capital over the 1995 to 2001 period and therefore this investment has a high contribution to output growth in a growth accounting framework. In other words, while the correlations are consistent with the interpretation given by Pilat (2005), there is no way to determine causality and simple arithmetic does suggest the possibility of spurious correlation: ICT investment rises and therefore it, by construction, contributes more to GDP in a growth accounting sense. If Pilat and Jorgenson's interpretation is correct, the growth accounting literature does not provide an explanation for why. The micro-level literature discussed below suggests several likely explanations that have not yet been compared in the literature: (1) Canada has many US multinationals operating and these firms are particularly effective at converting ICT into productivity growth (Van Reenen et al (2010) showed this to be true in Europe), (2) Canada's retail productivity lagged sufficiently much that minor investments led to major improvements, and (3) Canada's urban population facilitates coinvention when ICTs are adopted (Forman, Goldfarb, and Greenstein (2008) show this to be true in the United States). My opinion is that the effect of US multinationals is a particularly likely strength for Canada because the relationship is strongest in retail and co-incident with the arrival of Wal-Mart; however, more research needs to be done before a definitive conclusion can be established (on even the basic finding that Canada leads the EU in converting ICT investment into productivity).

## 3. Firm-level analysis

### 3.1 Methods for firm-level analysis

The growth accounting literature has suggested a compelling link between ICT investments and productivity growth. As discussed above, in order to identify causal effects and the drivers of the relationship between productivity and ICT investment, it is necessary to use micro-level data at the firm or establishment level. Van Reenen et al (2010, p. 12) note "to tackle the complexities we must use, gather and analyse data at the level where decisions are actually made, the firm level." This section reviews the main methods used in the literature to estimate production functions at the firm level. It shows that, while necessary, micro data is by no means sufficient for identifying causal relationships between ICT, productivity, and other factors. The literature contains three main strategies: (1) a basic model that controls for various potential omitted variables through, for example, firm fixed effects (or ideally, some natural experiment), (2) the Olley-Pakes model that uses a "control function" approach to endogeneity, leveraging a transformation of lagged inputs as controls, and (3) GMM models that use lagged inputs as direct instruments for current inputs. Each of these methods has strengths and weaknesses, though natural experiments, when present, are always best. As in the review of the growth accounting method, this section draws on Van Reenen et al (2010). Their Appendix C section I provides further detail.

The same productivity equation that was estimated at the national or industry level above in equations (2) and (3) can also be applied to the firm level, so that output for firm *i* in industry *j* in country *k* at time *t* can be written as:

$$y_{ijkt}=\beta^c c_{ijkt} + \beta^k k_{ijkt} + \beta^l l_{ijkt} + \gamma x_{ijkt} + u_{ijkt} \qquad (7)$$

Besides the micro level of the data, there are four main differences between this equation and the growth equations described above. First, materials are not included in this equation. This is typically for data reasons: firm-level data on inputs in general and materials in particular are rare though easy to add in when available. Second, there is a stochastic error term to take into account the fact that these models pool coefficients across observations, in contrast to growth accounting models where all coefficients are observed. Third, there is no "total factor productivity" estimate because micro analysis is primarily for finding causal relationships between variables rather than backing out and interpreting residuals. Fourth, a vector of controls $x_{ijkt}$ is included. These controls enable the researcher to take advantage of potentially rich firm-level data on geography, business practices, organization, and other characteristics. As such, they reduce the potential for omitted variables bias (often called unobserved heterogeneity in the context of micro data) by including such variables. Of course, these controls are necessarily imperfect. It is likely that some further unobserved factors might drive both productivity and ICT adoption at the firm level. Furthermore, it is likely that *L*, *K*, and especially *C* are measured with error at the firm level and this might bias coefficient estimates downwards.

The literature addresses these issues in a variety of ways. First, and perhaps most commonly, researchers add firm-level (or establishment-level) fixed effects to the error term. This controls for firm-level time invariant effects (including measurement error). Because this is relatively straightforward to implement, even studies that use more sophisticated methods almost always include a fixed effects specification. Using European data from 1996 to 2008, Van Reenen et al (2010) estimate the coefficient on ICT/worker as 0.091 suggesting a 10% increase in ICT capital is associated with a 0.9% increase in ouput (p. 31). In contrast, the fixed effects ("within-groups") estimation yields a coefficient estimate of 0.023. This lower estimate is much more credible because it controls for potential confounds, but still higher than the share of ICT capital in output.

Second, if plausible exogeneity is present in the form of a natural experiment, such variation is used as an instrument. Such natural experiments (or real experiments) are best in identifying causal relationships, however they are extremely rare and often require analysis of specific parts of the economy such as Agrawal and Goldfarb's (2008) analysis of the impact of online communication on academic productivity and collaboration, Athey and Stern's (2002) analysis of IT adoption by 911 operations and emergency health outcomes, and Mukhopadhyay et al's (1997) analysis of IT adoption and productivity of road toll collectors. While these studies are informative about the relationship between IT and productivity in specific settings, the relatively narrow scope of the natural experiment makes it difficult to come to broader conclusions about the economy as a whole. Economy-wide natural experiments are rare, though Forman, Goldfarb, and Greenstein (2011) interpret the rapid diffusion of the internet from 1995 to 2000 as a natural experiment for looking at the impact of the internet on wage growth across all US counties. Broadly, as noted by Van Reenen et al (2010), a key part of this approach is access to excellent micro-level data.

Third, Olley and Pakes (1996) suggested a solution to omitted variables bias in the form of a control function (similar Heckman's (1979) correction) that effectively debiases the error term under certain assumptions. The intuition is that this method adds a new covariate to the regression that controls for the biases in the error due to omitted variables. Specifically, Olley-Pakes takes the basic production function above and splits the error term into an unobserved productivity state, $\omega_{ijkt}$ and an i.i.d. error $\eta_{ijkt}$:

$$y_{ijkt}=\beta^c c_{ijkt} + \beta^k k_{ijkt} + \beta^l l_{ijkt} + \gamma x_{ijkt} + \omega_{ijkt} + \eta_{ijkt} \qquad (9)$$

If we assume capital takes one period to become productive and labour is productivity immediately such that current investment stock of capital (and computing capital) is the sum of lagged capital investment flow and depreciated lagged capital stock, then with some algebra $\omega$ can be expressed as a function of investment and capital, $\phi(i_{ijkt}^K, k_{ijkt}, c_{ijkt})$. This leads to a two stage specification where the first stage estimates the equation

$$y_{ijkt}=\beta^l l_{ijkt} + \gamma x_{ijkt} + \phi(i_{ijkt}^K, k_{ijkt}, c_{ijkt}) + \eta_{ijkt} \qquad (10)$$

where $\phi()$ is estimated with a non-parametric approximation such as a polynomial expansion and is often called the "control function". This gives consistent estimates for $\beta^l$, $\gamma$, and $\phi$. Then, these results are used as a control function in the second stage to estimate:

$$E(y_{ijkt} | \Omega_{t-1})=\beta^c c_{ijkt} + \beta^k k_{ijkt} + g[\phi(i_{ijkt-1}^K, k_{ijkt-1}, c_{ijkt-1}) - \beta^l l_{ijkt-1} - \gamma x_{ijkt-1}] \qquad (11)$$

The intuition for this method is that TFP, proxied by $\omega$ here, determines investment in K and C. This method instruments for K and C using information about the nature of $\omega$, specifically that capital takes longer to become productive than labour (by assumption). This method is most suspect in situations where we expect lags in the impact of the covariates on productivity. Given that a growing consensus in the ICT and productivity literature emphasizes the importance of co-invention (Bresnahan and Greenstein 1996) and gradual organizational change (e.g. Brynjolfsson and Hitt 2003), Olley-Pakes methods should not be overinterpreted. Levinsohn and Petrin (2003) partially address this issue by using intermediate inputs as instruments in the control function term $\phi$. Ackerberg, Caves, and Frazer (2005) argue that Levinsohn-Petrin can suffer from collinearity issues and therefore adjust the above method so that all coefficients are estimated in the second stage, and the first stage is only used to generate the control function (still using intermediate inputs as instruments). Van Reenen et al (2010) estimate the coefficient on ICT/worker to be 0.06 using the Olley-Pakes method which is higher than the fixed effects results but lower than the OLS estimate. Given that the Olley-Pakes estimate is within the range of the other two estimates, they do not emphasize it. Instead they argue that OLS and fixed effects provide meaningful bounds on the size of the effect.

A fourth method to address omitted variables bias is the GMM estimation strategy of Arellano and Bond (1991), Blundell and Bond (2000), and others. These papers show that it is possible to use lagged covariates as instruments for current values under certain conditions. In particular, in a panel model that assumes serially uncorrelated errors, by definition the lagged independent variables are valid instruments. This means that lags of first differences can be used as instruments for the levels. Typically, these methods combine lagged first differences with the second difference as instruments to generate the underlying parameters. The growth equation is rewritten to have the lagged dependent variable on the right hand side (here z encompasses all inputs and controls):

$$y_{it}=\pi_1 y_{it-1}+ \pi_1 z_{it} + \pi_3 z_{it-1} + \eta_i+ \tau_t + \nu_{it} \quad (10)$$

where instruments are: $E(z_{it-2}\Delta\nu_{it})=0$ and $E(\Delta z_{it-1}(\eta_i+\nu_{it}))=0$ (11)

Clearly, as with Olley-Pakes instruments, this method is also most suspect in situations where we expect lags in the impact of the covariates on productivity and GMM methods should be taken to data cautiously, even relative to Olley-Pakes results that also rely on functional form identification. Despite their weaknesses, GMM methods are more commonly used than Olley-Pakes in the productivity literature, perhaps because they are relatively easy to implement using Stata and other common statistical programs. Van Reenen et al (2010) estimate the coefficient on ICT/worker to be 0.089 using GMM. Again, they do not emphasize this estimate arguing that OLS and fixed effects provide meaningful bounds on the size of the effect.

Given that none of the methods commonly available to productivity researchers addresses the endogeneity concerns inherent in estimating the causal impact of ICT and other covariates on productivity, researchers have looked for consistency across methods. Therefore, increasingly, micro productivity papers show some results with OLS, Fixed Effects, Olley-Pakes, *and* Blundell-Bond-type GMM estimators (e.g. Van Reenen et al 2010); and perhaps adding a natural experiment on some subset of the data. Given that the various methods have distinct biases, showing results are generally robust to specification increases confidence in the causal interpretation. Van Reenen et al's (2010) strategy of using many estimation strategies to determine the upper and lower bounds of the coefficient is the current best practice.

### 3.2 What have we learned from firm-level analysis

There is a large and growing literature that documents a direct link from ICT adoption and usage to productivity growth at the firm level. By using micro data and various econometric techniques to address selection, omitted variables bias, and simultaneity, this literature has found that ICT adoption and usage does enhance productivity. However, the story is not as simple as it seems at first. Only some types of firms benefit and many fail to get any productivity gain. The literature has shown that as the more successful firms grow, the reallocation of economic output plays a substantial role in overall productivity growth (Bartelsman et al 2002, 2004; Davis, Faberman, and Haltiwanger 2006; Davis, Haltiwanger and Schuh 1998). In this section, I first review the literature confirming the main effect of ICT adoption on productivity and performance. I then discuss the various factors that enhance or mitigate this relationship including organizational change, skills, geography, regulation, and the potential for spillovers and/or network externalities. Draca, Sadun, and Van Reenen (2006) provide a paper-by-paper list of the various contributions in this literature in their Table 4. Many of these papers are discussed below but their tables provide an itemized list that complements the structured argument I provide in this section.

#### 3.2.1 ICT and productivity

Reviews by Brynjolfsson and Saunders (2010) and Van Reenen et al (2010) conclude that ICT adoption and usage appears to increase firm-level performance. This conclusion is driven by a large number of papers and a variety of settings. Brynjolfsson and Hitt (1997, 2003) look at large US firms between 1987 and 1994. The 1997 paper documents a correlation between ICT investment and productivity. The 2003 paper documents that this effect is even stronger when the impact of ICT investment is modeled with a lag. Several studies have documented the impact of ICT adoption on firm productivity and performance in specific industry settings. As examples:

- Baker and Hubbard (2004) show ICT improves productivity in trucking.
- Athey and Stern (2002) show ICT improves productivity in emergency medical response.
- Miller and Tucker (2011) show ICT improves productivity in health care.
- Mukhopadhyay et al (1997) show ICT improves productivity in toll collection.
- Agrawal and Goldfarb (2008) show ICT improves productivity in academic research

Recently, and perhaps most comprehensively, Van Reenen et al (2010) use a large-scale multi-country (though without Canada) firm-level panel database on ICT and productivity. Their database contains 19000 firms in 13 EU countries over 11 years, plus a smaller panel of US firms over the same time period. This database is constructed by combining government data with private sector data and their own surveys of plant managers. They estimate production functions using OLS, fixed effects (i.e. within groups), Olley-Pakes, and GMM methods.[3] They find that ICT capital is characterized by above

[3] They focus on the fixed effects results, arguing that they are relatively conservative due to the potential for measurement error. The OLS results are also presented prominently. They do not emphasize their Olley-Pakes and GMM results because they lie between OLS and fixed effects and therefore they argue that they provide little additional insight.

normal returns: a 10% increase in ICT capital is associated with a 0.23% increase in firm productivity (using the fixed effects estimates, 0.9% using OLS), whereas their calculations suggest that normal returns should be 0.16%. The finding of above normal returns is highly subject to the assumptions used in depreciating ICT capital relative to other capital. If the depreciation of ICT is actually faster than assumed, then the finding of above normal returns may go away. They conclude that ICT does increase productivity, though they find considerable heterogeneity in this effect across countries and type of firm. Understanding this heterogeneity is the subject of the next subsection.

### 3.2.2 Factors that affect the relationship between ICT and productivity

*Organizational capital*

Using similar data and methods to Van Reenen et al (2010), Bloom, Sadun, and Van Reenen (2011) show that US multinationals operating in the UK experienced the same "productivity miracle" as US-based establishments. In contrast, other multinationals (and other firms) in the UK did not. This appears to be due to US multinationals higher productivity from use of IT. Further, when US multinationals take over UK companies, they increase the productivity of those companies IT. Simply, as the paper is titled, "Americans do I.T. better". Bloom, Sadun, and Van Reenen argue that a likely explanation for this is that US firms are organized in way that allows them to use IT more efficiently.

Therefore, they suggest that organizational capital complements ICT capital. Van Reenen et al (2010) argue that this evidence on multinationals suggests that approximately half of the US-EU productivity gap over the 1995 to 2005 period can be accounted for by organizational capital (with the rest of the gap accounted for by higher US investment in ICT capital and other firm characteristics).

This essential role of organizational capital and organizational structure in making productive use of ICT investments is a recurring theme elsewhere in the literature. Brynjolfsson and Saunders (2010) point to incentive systems, training, and decentralized decision-making as some of the practices most complementary to ICTs. Bresnahan, Brynjolfsson, and Hitt (2002) show complementarity between ICT adoption and workplace reorganization. Zand, van Beers, and van Leeuwan (2010) use firm-level data from Holland to document complementarity between organizational change and ICT investments, particularly in services. In contrast, they find that non-ICT investments appear to be substitutes for organizational change. Garicano (2010) summarizes his prior work to emphasize that ICT has a larger impact on productivity when accompanied by complementary organizational changes. The list goes on. There is one important exception: Black and Lynch find no connection between ICT adoption, productivity, and workplace information flow.

Overall, however, the literature overwhelmingly documents that ICT investments are most effective when accompanied by organizational changes such as incentive systems, training, decentralized decision-making, and/or increased information flow. A related literature emphasizes the importance of organizational change for productivity growth, unrelated to ICT adoption (Bertschek and Kaiser 2004, Black and Lynch 2001). A portion of this organizational change and structure has sometimes been labelled "management practices" in the literature, and the role of managers is emphasized in many of the papers listed above as well as several others (Bertschek and Kaiser 2004; Bresnahan, Brynjolfsson, and Hitt 1999, 2002; Draca, Sadun, and Van Reenen 2006; Bloom, Sadun, and Van Reenen Forthcoming; Bloom and Van Reenen 2007; etc).

In a recent working paper, Tambe, Hitt, and Brynjolfsson (2011) add external focus to the list of organizational capital required for ICT investments to drive productivity. They show that external information awareness, decentralization, and ICT investments are complementary (in the sense of a positive three-way interaction in a regression of productivity on these covariates). They document this using a 2001 survey on the organizational practices of 253 medium-to-large sized firms. They define external focus as the use of external information, including competitive benchmarking, inclusion of suppliers, partners, and customers in project teams, adoption of new technologies, and time executives spend recruiting. While they note that finding complementarities is challenging due to the endogeneity of organizational practices (Athey and Stern 1998), they argue that such practices are fixed in the short term in their case, using a variant of the basic estimation strategy described above in equation (9)—a simple linear model of productivity growth on organizational practices, ICT employment, their interactions, and controls. They also show robustness to an instrumental variable specification.

Measuring the payoff to organizational changes and organizational capital is challenging for several reasons. First, as Brynjolfsson and Saunders (2010) point out, accounting rules identify organizational capital as an expense rather than an investment. This makes the payoff difficult to measure and the size of the investment difficult to identify separately. Van Reenen et al (2010) try to address this issue by directly questioning plant managers, for example by asking how much capital investment the plant manager could undertake without prior authorization from headquarters.

*Co-invention*

Furthermore, in order for ICT investments to be successful, the organizational change needs to be accompanied by several smaller innovations that adapt the particular ICT used to the context of the investing firm. This idea, labelled "co-invention" by Bresnahan and Greenstein (1996), emphasizes that ICTs are a general purpose technology and that the firm-specific application requires subtle changes to the hardware and software. Forman, Goldfarb, and Greenstein (2008) found evidence in favour of co-invention as a partial explanation for differences in advanced internet adoption by firm size and location in the United States. Hempell (2002) provided some evidence consistent with co-invention: past experience with ICT increases the productivity benefit of future ICT adoption among German services firms.

*Human capital*

In addition to organization changes and co-invention that adjusts the technology to firm-specific needs, it is important for workers to have the necessary skills to use the technology. Using micro-level data on firms and workers, much of the research in labour economics has emphasized the importance of human capital and the skill-bias of ICTs (Autor 2001; Autor, Murmane, and Levy 2002; Levy and Murmane 2004; Lemieux 2006; Juhn, Murphy, and Pierce 1993; etc.). Bresnahan, Brynjolfsson, and Hitt (2002) and Forman, Goldfarb, and Greenstein (2011) also emphasize the importance of skills in generating a benefit from ICT adoption. Lucchetti and Sterlacchini (2004) examine ICT adoption by

Italian small and medium size enterprises. They also emphasize the importance of skills in successful use of three kinds of ICTs (general use ICTs, production integrating ICTs, and market-oriented ICTs). Also examining different types of ICTs, Arvantis and Loukis (2009) show that employee skills, combined with some organizational changes, increase productivity using Swiss and Greek data, particularly for intranet related ICTs.

*Type of ICT*

The difference between types of ICTs is another important theme in the literature. In particular, the ways in which ICTs impact productivity are clearly related to the type of ICT in question. Broadly, ICTs can be classified as related to computation, communication, and memory. Furthermore, each group can be split into "advanced" or "basic" applications. The roles of skills, co-invention, and organizational change depend on the specific types and applications of the ICTs.

For example, Mukhopadhyay et al (1997) look at toll collection on the PA turnpike. In this case, the ICT used was to calculate the payment and change required. This ICT was therefore purely for computation (or information processing). They found that computation generated a large efficiency gain for complex transactions but little or no gain for simple transactions.

Similarly, Forman, Goldfarb, and Greenstein (2011) find that advanced internet technologies are correlated with an increase in wages while basic technologies do not appear to be correlated with local wage growth. Forman, Goldfarb, and Greenstein (2005) find the co-invention is much more important for advanced technologies. Broadly, these results can be interpreted as suggesting that generating a benefit from advanced technology adoption might be more challenging than from a basic technology; however, the payoffs to a successful implementation may also be higher.

Bloom et al (2009) emphasize the difference between information technologies and communication technologies. They argue that information technology empowers lower level agents to do complicated tasks (consistent with the results of Mukhopadhyay et al 1997) while communication technology leads to centralization due to improved monitoring. They provide a formal model and some evidence consistent with this hypothesis.

Van Reenen et al (2010) divide ICT into several different types and components. In broad terms, they discuss the relative benefits of human resources management software, application development software, enterprise resource planning, workflow software, networking hardware, and collaborative and non-collaborative ICT. For example, they argue that among the various collaborative technologies, networking hardware increases productivity more than enterprise resource planning software. They also conduct a rigorous empirical analysis of hardware, purchased software, and own-account software, following Corrado et al (2006). They find that own-account software and network hardware are particularly associated with productivity growth. In contrast, they find little relationship between purchased software and productivity and argue that it is likely due to co-invention costs.

*Location*

The benefit of various types of ICT depends crucially on the location of the investing firm. Forman, Goldfarb, and Greenstein (2005) contrast four different internet technologies: basic within-establishment internet, advanced within-establishment internet, basic cross-establishment internet, and advanced cross-establishment internet. Within-establishment internet includes the set of internet technologies that facilitate communication within a single establishment, such as enterprise resource planning. Cross-establishment internet includes the set of internet technologies that facilitate communication across establishments, such as supply chain management.

Forman, Goldfarb, and Greenstein (2005) find that non-urban firms get a particularly large benefit out of adopting cross-establishment internet, probably because it allows them to overcome isolation. This is particularly true of basic cross-establishment internet. In contrast, urban firms are more likely to use within-establishment internet, likely because the costs of adopting advanced technologies are lower, perhaps due to thicker labour markets for IT workers, lower costs of equipment and service, or Marshallian spillovers of another kind.

Forman, Goldfarb, and Greenstein (2008) explore this further and show suggestive evidence that part of the benefit of urban locations for within-establishment internet relates to reduced co-invention costs due to access to skilled IT workers. Specifically, they show that large firms with many IT workers do not get an extra benefit to being in a city in terms of the likelihood of adopting within-establishment internet technology.

Therefore, these papers argue that non-urban areas have the potential to benefit from adopting communications technologies in order to overcome some of the costs of geographic isolation; however, urban firms have access to more skilled workers and can therefore implement the necessary co-invention more easily. In Forman, Goldfarb, and Greenstein (2011), we estimate the net effect on wages of advanced internet adoption. We find that it is only urban areas that yield a wage increase from adoption of the technology. Even when rural areas were leading adopters, they did not experience a measurable wage increase as a consequence of the investment in advanced internet ICTs. These issues related to overcoming isolation and co-invention help explain Van Reenen et al's (2010) finding that higher levels of ICT are associated with less spatial concentration in manufacturing but more spatial concentration in services.

Location matters in ICT adoption and usage for other reasons besides issues related to overcoming isolation and facilitating co-invention. Glaeser and Ponzetto (2007) argue that linking urban and rural areas might benefit urban firms more than rural firms partly because it allows the urban firms to enter rural markets more easily. Blum and Goldfarb (2006) show that location matters for online behaviour because tastes are spatially correlated. Agrawal, Catalini, and Goldfarb (2011) show that location matters for online investment decisions because social networks are spatially correlated.

*Regulation*

Another important influence on the ability of firms to generate productivity advances due to ICT investments is the regulatory environment. Several aspects of regulation directly impact the relationship between ICT and productivity including product market regulation, labour market regulation, antitrust enforcement, intellectual property policy, privacy policy, and net neutrality policy.

Of these, product and labour market regulation have received the most attention. These regulations comprise one of the key themes of Van Reenen et al's (2010) review and analysis. They show that firm-level estimates for Europe suggest labour and product market regulation may explain cross-country differences in the productivity benefits of ICT. More regulation means a lower productivity impact of ICT. They conclude that strict labour market regulation decreases the impact of ICT on productivity by 45%. Strict product market regulation decreases the impact of ICT on productivity by 16%.

They argue that labour market regulation matters because reallocation is hardest in countries with more regulated labour and product markets. Because prior research emphasized the importance of reallocation to productivity (e.g. Davis, Faberman, and Haltiwanger 2006), challenges to reallocation will slow the productivity benefits of ICTs. Furthermore, they argue that regulations increase the cost of developing organizational capital. Van Reenen et al (2010, p. 19) argue that the stronger labour market regulation in Europe relative to the United States "hampers the ability of European firms to rapidly adapt their organizational structures to most effectively use new ICT".

Other aspects of the regulatory environment matter for innovation more generally. Goldfarb and Tucker (2011) show that strict European privacy regulation reduced the productivity of online advertising in the EU relative to the United States. Miller and Tucker (2011) show that US states with stricter privacy regulation on healthcare IT have higher neonatal mortality due to reduced ICT investments. Copyright and fair use policies can impact innovation in creative and media industries (Lichtman 2008). Branstetter, Fisman, Foley, and Saggi (2011) show that intellectual property rights reforms appear to increase industrial activity and exports, suggesting an increase in productivity due to these regulations. Net neutrality and wireless competition also have the potential to impact innovation in ICTs and therefore productivity from using these technologies.

*Spillovers and network externalities*

In addition to the above discussion, there is potential to generate especially large productivity returns to ICT investments if such investments generate positive spillovers or network externalities. Spillovers mean that the investment in, and benefit from, ICT use by one firm causally increases the likelihood that other (perhaps nearby) firms invest and benefit from ICT. Direct network externalities are a type of spillover in which the benefit of using the technology increases with the number of users. For communications technologies, such direct network externalities are common. For example, the first telephone is useless. It is only beneficial when people can use it to communicate with others. Indirect network externalities are also a type of spillover in which the markets for complementary inputs to a technology become increasingly thick as the technology is adopted. For example, we see more computer programmers looking for work in places with ICT-using firms. We also see more software programs available for more successful hardware.

Empirically identifying such causal relationships is challenging. This difficulty is largely due to the reflection problem, identified by Manski (1993). The reflection problem is a name for the challenges in identifying whether the distribution of a group's behaviour causes a change in the behaviour of an individual. There are three aspects to this challenge: (1) reverse causality (or simultaneity) in which the direction of causality is unclear, (2) omitted variables bias in which some other factor is causing both the individual and the group to behave in a particular way, and (3) selection in which the individual and the group behave in a similar way because they exist in the data for similar reasons.

In the face of the reflection problem, identification of spillovers (and network externalities) relies on four distinct strategies. In order of robustness in identifying causal effects, these are:

1) Researchers can rely on some real or natural experiment that increases the propensity of a group of firms to invest in (or benefit from) a technology. They then see how these approximately random investments affect other nearby firms' behaviour.
2) Instead of a natural experiment, researchers can rely on instrumental variables that shift the benefit of investing by a subgroup of the population, for example input prices of a particular technology.
3) Researchers can try to make the unit of observation sufficiently narrow so that they can rely on individual-to-individual transmission and the timing of effects (Granger causality) to identify effects.
4) Researchers can simply ignore the problem, apologize, and suggest something interesting is happening even if the direction of causality is undetermined.

Unfortunately, natural experiments and reliable instruments are hard to find. Therefore, much of the existing literature has relied on Granger causality or on identifying interesting correlations. These methods are most reliable when they find no evidence of spillovers as the reflection problem typically leads to a bias in favour of identifying spillovers.

Using US industry-level data, Stiroh (2004) finds no evidence of ICT productivity spillovers. Using micro data, Van Reenen et al (2010) rely on narrowly defined units of observation and also find no evidence of spillovers from ICT adoption. Specifically, Van Reenen et al add a term *spillover* to the basic ICT production function estimation shown above in equation (7):

$$y_{ijkt}=\beta^{c}c_{ijkt} + \beta^{k}k_{ijkt} + \beta^{l}l_{ijkt} + \gamma x_{ijkt} + \mu ln(spillover)_{ijkt} + u_{ijkt} \tag{12}$$

*Spillover* is the weighted sum of other related firms' investment in ICT. "Related" could be through same industry, through input-output tables, through geographic proximity, and through technology class. They emphasize the same-industry and same-region-industry results. They show that when firms adopt ICTs, neighbouring firms do not experience a productivity increase.

Their result on no spillovers is surprising in light of the reflection problem and in light of prior research that finds substantial spillovers in R&D investments (though subject to the reflection problem critiques to varying degrees): Lychagin et al (2010); Griliches (1992); Jaffe, Trajtenberg, and Henderson (1993); Bloom, Schankerman, and Van Reenen (2009); etc. In light of their result, Van Reenen et al (2010) argue that ICT is embodied and therefore knowledge spillovers are less likely than in R&D.

In particular, Van Reenen et al (2010) argue that firms are investing in a technology that provides direct benefit when they invest in ICTs. This contrasts with disembodied technologies whose value depends partly on its ability to create knowledge and innovation in the future. For disembodied technologies, other firms may benefit through imitation or learning without necessarily paying the cost to the firm. For ICT investment, firms pay the cost of the investment and receive the benefits directly. Therefore, "there are fewer channels for such spillover mechanisms to operate" (p. 34).

In contrast to these results that group all ICT together, studies that focus on communication technologies do find some evidence of spillovers (through network externalities) in particular situations. In this case, the spillover is not through learning or imitation but due to the idea that a communication network increases in value as more people connect. Agrawal and Goldfarb (2008) show that, for some groups of researchers, there do appear to be spillovers from BITNET (a 1980s academic computing network) due to the ability to connect to a broader research network. Similarly, Forman and Van Zeebroeck (2010) show that the diffusion of the internet increased research collaborations within firms. Internet adoption increased innovation and team size across geographic locations, though they see little impact on productivity for research teams that are not geographically dispersed. The communications technology increased productivity by connecting dispersed groups. The network externality exists because the benefit of one group adopting is increasing in the number of other groups within the firm that adopt. For individual internet users, one interpretation of Goldfarb (2005) is that adoption is much more likely for people whose communication networks are likely to have already adopted.

In summary, there is little evidence of direct spillovers from ICT investment, likely because such investment is embodied. This "non-result" is quite strong given that the econometric biases inherent in the reflection problem should lead to a finding of spillovers, even when none exist. Interestingly, for specific communications technologies there is some evidence of productivity spillovers through the network externalities inherent in an expanding communication network. The current empirical evidence suggests that the only productivity spillovers from ICT investments happen through the network externalities generated by a handful of communications technologies.

*Trade and Foreign Direct Investment*

Meijers (2010) argues that there are spillovers from ICT adoption, but that these are all related to international trade. Specifically, he argues that ICT adoption causes trade and this is the driver of all excess productivity growth from ICTs. Unfortunately, the use of macro-level data makes it particularly difficult to assess the degree to which omitted variables and simultaneity drive the underlying correlations. Still, the importance of trade to productivity and ICTs is worth highlighting

Van Reenen et al (2010) directly address questions related to productivity, ICT investment, trade, and FDI. They find that openness to trade is an important driver of ICT investments. Specifically, greater trade with China from 2000 to 2007 accounted for 15% of the ICT upgrading in Europe. Openness to trade has been shown in several other settings to lead to productivity gains more generally (e.g. Lileeva and Trefler 2010).

Van Reenen et al also document that subsidiaries of US multinationals are particularly ICT-intensive and they are relatively effective at undertaking the organizational change required to generate productivity gains from the ICT investments. Specifically, they argue (p. 9) that "having developed this organisational capital, US firms can then export it to their subsidiaries in other countries."

### 3.3. So, overall, why are micro estimates higher than macro estimates?

Comparing the micro (firm-level) analysis and the macro (country- or industry-level) analysis shows that the micro analysis tends to estimate a higher impact of ICTs on productivity. Pilat (2004) argues that ICT investment has three effects in the country-level data: (1) capital deepening, (2) multifactor productivity due to technological progress, and (3) multifactor productivity through efficiency. US-based firms have generally been able to convert the investments into multifactor productivity and therefore macro-level analysis that focuses on the United States *has* found positive and significant productivity benefits to ICTs (e.g. Jorgenson, Ho, and Stiroh 2005). Outside of the United States, effective use of ICTs is more varied.

Therefore, Pilat argues that Solow's paradox may not be solved for all countries using macro data. Firm-level data allows researchers to identify those firms (both outside and inside the United States) with requisite levels of organizational capital, human capital, and co-invention. Furthermore, firm level analysis allows more careful accommodation of competitive effects when product and labour markets are highly regulated.

In light of this, Pilat discusses five main reasons why micro level estimates of the effect of ICT investment on productivity are higher than macro level estimates. First, aggregation across firms and industries may disguise impact because it does not enable disentangling development, diffusion, lags, and coinvention. Second, firm-level benefits may not be large enough to aggregate (especially in light of lagged impact). Third, successful firms gain share and grow in competitive markets like the United States but not in less competitive markets. This means that lack of competition outside the United States implies that aggregate effects are seen in the United States but not elsewhere. Fourth, services output is poorly measured, particularly outside the United States. Fifth, potential spillovers already occurred in the United States but not yet elsewhere.

Given the discussion above, and the research that has been conducted since Pilat's (2004) article, the role of competitive markets and the difficulty in identifying lagged effects in aggregate data seem like particularly plausible explanations for the difference. Furthermore, I would add that many adopting firms do not have good practices related to organizational capital, human capital, and coinvention and these failures are averaged with the successes in aggregate data, particularly in markets without robust competition. In contrast, differences in potential spillovers seems unlikely given the lack of evidence for spillovers from most ICT investments even within the United States.

### 3.4 Where does Canada stand?

I could find very little Canadian firm-level research, either published or in working paper form. The above results on organizational change, geography, skills, and regulation are likely to apply in Canada. Therefore, the broader literature suggests several likely reasons why Canada lags the United States in terms of productivity and particularly productivity from ICT capital.

Canadians lag the United States in post-secondary education. In Goldfarb (2009), I documented how the relatively low level of post-secondary education in Canada explains much of the difference between Canadian and American internet use by consumers in terms of internet adoption, ecommerce use, information search, and e-government. Given that managers of Canadian firms are relatively less likely to have post-graduate degrees than American managers (and are especially less likely to have MBAs), it seems likely that Canadian firms may not have the skills necessary to adopt the organizational changes required to make ICT investments pay off to the extent that they do in the United States. At the same time, relative to the European Union, Canada performs well in these dimensions.

In terms of regulation, there are several reasons to believe that Canadian regulations might affect how Canadian firms invest in, and benefit from, ICT. First, Canada has relatively little competition in the product market in many sectors that are ICT-intensive users including telecommunications and ICT-using retail (especially in areas where online competes with offline like books but also grocery). Second, Canadian regulations on data privacy are stricter than current US regulations (though less strict than EU regulation). Third, Canadian labour market regulations some somewhat stricter than US regulations, though they are unlikely to have nearly the impact on ICT adoption, human capital investments, and organizational change that the strict continental European regulations have.

In terms of spillovers due to agglomeration or due to foreign investment, Canada is relatively well positioned. As noted in Goldfarb (2009), Canada has a relatively urban population (which led to early adoption of broadband by consumers). Canada has high levels of foreign direct investment, particularly from US firms (and recently some ICT-leading retailers like Wal-Mart). At the same time, the evidence for spillovers of any kind is limited outside of foreign direct investment.

Of course, the above is all speculation. In the absence of actually analyzing data on Canadian firms, it is not possible to understand whether the differences in productivity and ICT performance between Canada, the United States, and Europe are due to human capital differences, regulations, positive externalities from spillovers, or some other factor. Specifically, the data requirements include firm- (or establishment-)level measures of organizational capital and organizational change (internal and external), geographic information, ICT investments, regulatory environment and constraints, types of ICT used, human capital, and foreign ownership. This data needs to cover services as well as manufacturing. With new Canadian data coming online from the Survey of Innovation and Business Strategies, our ability to answer these questions for manufacturing should improve substantially in the near future. Eventually, hopefully we will see a similar data set available for services.

## 4. Conclusions and recommendations

This review described the two main methods for assessing the contribution of ICT to productivity: growth accounting and firm-level data ("micro-to-macro"). I have argued that growth accounting should be seen as a tool for understanding general trends. Growth accounting cannot be used to determine causal relationships and therefore growth accounting alone should not be used to drive policy. Instead, careful firm- (or establishment-) level analysis should be used to determine the causal effects of ICT on productivity, as well as the drivers of this relationship.

Drawing on this firm-based literature, I have assessed the evidence on a number of drivers of ICT-based total factor productivity growth. The first and clearest conclusion of the firm-based literature is that ICT improves productivity at the firm level in a variety of industries from trucking (Baker and Hubbard 2004) to health care (Miller and Tucker 2011). Second, the literature emphasizes that this positive relationship between ICT and productivity is only true when firms make investments in organizational capital that is complementary to ICT. Such investments include incentive systems, decentralized decision making, specific types of training, and perhaps external information gathering. This leads to the third conclusion in the literature: the essential role of human capital in converting ICT into productivity. Essentially, workers need to have the necessary skills to efficiently use ICTs and to adapt them to a particular organization's needs. Otherwise, the investment had little benefit. Fourth, the literature emphasizes the role of location in determining whether there is a pool of workers with the required skills to use and adapt the technology. Fifth, the literature mentions that the conclusions vary by type of ICT. The impact of specific organizational changes, human capital investments and locations depend on whether the ICT is primarily about communication, information processing, memory, or some combination. Sixth, ICT investments by one firm generally do not appear to spill over to other firms in the same industry or region, likely because ICTs are an embodied technology. Finally, at the aggregate level, any changes in behaviour will only have an impact on overall productivity if the regulatory regime enables the most successful firms to grow (and the least successful firms to shrink or disappear). Highly regulated labour and product markets mean it is difficult for economies to reallocate resources to the most productive firms.

In addition to these main conclusions, the literature also examines other issues such as differences across types of ICTs, the roles of privacy and intellectual property regulation, and the role of trade and foreign direct investment in generating productivity spillovers. On this last point, while productivity spillovers and network externalities have not been found to be particularly important to the ICT and productivity relationship, foreign direct investment is an important exception. US multinationals are associated with an increased ability of collocated non-US establishments to convert ICT investments to productivity.

The firm-based literature therefore provides a more complete picture than the growth accounting literature and provides several broad policy recommendations:

1. Do not simply subsidize ICT investment. Such investment needs to be accompanied by other investments such as organizational capital, co-invention, and human capital.
2. Invest in training. Training includes human capital training in the use of ICTs (i.e. engineers) as well as management training in the effective organizational changes that accompany productive ICT deployments (i.e. MBAs).
3. Perhaps most importantly, consider the role of the regulatory environment on the productive use of ICT. Will the most efficient firms be able to grow? Will they be able to offer new products at different prices? Will the least efficient firms become less important and perhaps disappear? Are there any specific regulations on digital markets (such as privacy or intellectual property) that unduly limit the potential of firms to convert ICT investment into productive activity?

More broadly, Van Reenen et al (2010) argue that instead of subsidies and tax incentives that focus on correcting market failures in ICT investment, policies should focus on assisting the accumulation of the complementary factors of organizational capital and skills as well as ensuring that the regulatory environment does not prevent successful ICT investments from growing.

The growth accounting literature helps us understand the potential importance of effective investment in ICT. Specifically, this literature has shown that ICTs are a main source of growth in productivity since 1990. While the overall impact of ICTs on productivity are lower from growth accounting estimates than from firm-level estimates this is likely because the aggregated data mixes effective and ineffective ICT investments. Still, even with this mixing, ICTs have still been shown to be key elements of growth.

The growth accounting literature has placed Canada as a middle-of-the-pack country in ICT-driven productivity growth. In many ways, Canada lags the United States but leads the European Union. Canada is a relative laggard in ICT investment levels, partly due to industry mix and partly due the relatively low ICT investment levels in the retail sector. Thus far, there has been little micro-level analysis of Canadian data to understand if, when, and how Canadian firms have effectively turned ICT investments into productivity growth.

The growth accounting literature suggests one area that gives reason for optimism is the relatively high Canadian dollar. Over the past 20 years, Canadian firms have lagged firms in many other countries in terms of ICT spending. Because Canadian firms are not generally ICT-producing, the strong Canadian dollar should mean that such investments are less expensive for Canadian firms. As ICT investments become less expensive relative to other inputs, we should see more of them. And these investments, if combined with investments in organizational capital, co-invention, and human capital should lead to increasing total factor productivity if the effects observed in Europe and the United States apply here.

The micro literature also suggests several explanations for Canada's relative position: low levels of post-secondary education relative to the United States and high levels relative to elsewhere, higher labour and product market regulation relative to the United States but lower levels than elsewhere, and high levels of foreign direct investment from the United States.

Going forward, however, these explanations are only suggestive of the optimal policies. In order to understand the best policies for Canada in particular, it is important to have high quality micro analysis of Canadian firm- and establishment-level data. As Brynjolfsson and Saunders (2010) note, in the absence of high quality broadly representative data, productivity analysis risks appearing like a "drunk looking for his keys under a lamppost": he looks only where it is easy to see rather than where the keys are most likely to be. The temptation is to focus on easily measured aspects of the economy like manufacturing and tangible inputs and outputs; ignoring services and intangibles such as organizational capital. However, to effectively understand how ICT impacts productivity in Canada (or anywhere), it is essential to have micro data on services and intangible inputs and outputs. This makes the data challenges harder but without this data, there is no way to develop effective policy recommendations. Ideally, the data would be firm- or establishment-level and contain measures of organizational capital and organizational change (including decentralization, external information focus, and incentive systems), geographic information, specific types of ICT investments, regulatory environment, human capital investments, and foreign ownership. The new Survey of Business and Innovation Strategy is an important step in the direction of having the ideal data to conduct such analysis, at least for the manufacturing sector. The next task is to dig into this data, particularly once a panel of several years has been established. Eventually, a data set for services will improve our understanding even more.

This analysis will allow Canadians to understand whether and how the conclusions of prior research on Europe and the United States apply here. For example, both Van Reenen et al (2010) and Brynjolfsson and Saunders (2010) emphasize a variety of complementary factors that drive effective ICT investment. It is important to analysis Canadian data to understand which of these are most important in Canadian industry, which of these Canadian industry has widely adopted, and which of these Canadian industry has not implemented.

## References


Ackerberg, D., Caves, K. and Frazer, G. 2005. Structural identification of production functions. *Working paper UCLA*, Los Angeles

Aghion, P., Bloom, N., Blundell, R., Griffith, R. and Howitt, P. 2005.Competition and Innovation: An Inverted U Relationship. *Quarterly Journal of Economics*, 120(2):701-728, May.

Agrawal, Ajay, Christian Catalini, and Avi Goldfarb. 2011. Offline Relationships, Distance, and the Internet: The Geography of Crowdfunding. NBER Working Paper #16820.

Agrawal, Ajay, and Avi Goldfarb. 2008. Restructuring Research: Communication Costs and the Democratization of University Innovation. *American Economic Review* 98(4), 1578-1590.

Antonelli, Cristiano. 2003. The digital divide: understanding the economics of new information and communication technology in the global economy. *Information Economics and Policy*. 15, 173-199.

Antonopoulos, Christos, Plutarchos Sakellaris. 2009. The contribution of Information and Communication Technology investments to Greek economic growth: An analytical growth accounting framework Information Economics and Policy 21, 171-191.

Arvanitis, S. 2004. Information Technology, Workplace Organisation, Human Capital and Firm Productivity: Evidence for the Swiss Economy, in OECD (2004), *The Economic Impact of ICT – Measurement, Evidence and Implications*, OECD, Paris.

Arvanitis, S. 2005. Computerization, Workplace Organization, Skilled Labor and Firm Productivity: Evidence for the Swiss Business Sector. *Economics of Innovation and New Technology* 14(4) 225-249.

Arvantis, Spyros and Europidis N. Loukis. 2009. Information and communication technologies, human capital, workplace organization and labour productivity: A comparative study based on firm-level data for Greece and Switzerland. Information Economics and Policy 21, 43-61

Athey S. and Stern, S. 1998. An Empirical Framework for Testing Theories About Complimentarity in Organisational Design. *NBER Working Papers* 6600.

Atrostic, B.K., P. Boegh-Nielsen, K. Motohashi and S. Nguyen. 2004. IT, Productivity and Growth in Enterprises: Evidence from New International Micro Data, in OECD, *The Economic Impact of ICT – Measurement, Evidence and Implications*, OECD, Paris.

Atrostic, B.K. and S. Nguyen. 2002. Computer Networks and US Manufacturing Plant Productivity: New Evidence from the CNUS Data, *CES Working Paper 02-01*, Center for Economic Studies, Washington DC

Autor, David, Lawrence F. Katz, and Melissa S. Kearney. 2006. The Polarization of the U.S. Labor Market. *American Economic Review*, 96(2): 189-194.

Autor, David, Frank Levy, and Richard J. Murnane. 2003. The Skill Content of Recent Technological Change: An Empirical Exploration. *Quarterly Journal of Economics*, 118(4): 1279–334.

Baldwin, John R. and Wulong Gu. 2008. Productivity: What is it? How is it measured? What has Canada's Performance been? *The Canadian Productivity Review* 15-206-X, no 017.

Baldwin, J.R. and D. Sabourin. 2002. Impact of the Adoption of Advanced Information and Communication Technologies on Firm Performance in the Canadian Manufacturing Sector, *STI Working Paper 2002/1*, OECD, Paris.

Baldwin, J.R., D. Sabourin and D. Smith. 2004. Firm Performance in the Canadian Food Processing Sector: the Interaction between ICT Advanced Technology Use and Human Resource Competencies, in OECD (2004), *The Economic Impact of ICT – Measurement, Evidence and Implications*, OECD, Paris, pp. 153-181.

Barro, Robert J. and Xavier Sala-i-Martin. 1991. Convergence across States and Regions. *Brookings Papers on Economic Activity*, (1991)1: 107-158.

Bartel, A., C. Ichniowski, K. Shaw. 2007. How Does Information Technology Affect Productivity? Plant-Level Comparisons of Product Innovation, Process Improvement, and Worker Skills. *Quarterly Journal of Economics* 122(4) 1721-1758.

Bartelsman, E., Bassanini A., Haltiwanger J., Jarmin, R., Scarpetta,S. and Schank,T. 2002. The Spread of ICT and Productivity Growth: Is Europe Really Lagging Behind in the New Economy?. *Working Papers halshs-00289168v1*, HAL.

Bartelsman, E.J. and M. Doms. 2000. Understanding Productivity: Lessons from Longitudinal Micro Datasets, *Journal of Economic Literature*, Vol. 38, September.

Bartelsman, E.J., S. Scarpetta and F. Schivardi. 2003. Comparative Analysis of Firm Demographics and Survival: Micro-Level Evidence for the OECD Countries, *OECD Economics Department Working Paper No. 348*, OECD, Paris.

Bertschek, I. and H. Fryges. 2002. The Adoption of Business-to-Business E-Commerce: Empirical Evidence for German Companies, *ZEW Discussion Paper No. 02-05*, ZEW, Mannheim.

Bertschek, I., U. Kaiser. 2004. Productivity Effects of Organizational Change: Microeconometric Evidence. *Management Science* 50(3) 394-404.

Black, S. E., L. M. Lynch. 2001. How to compete: The impact of workplace practices and information technology on productivity. *Review of Economics and Statistics* 83(3), 434-445.

Black, S. and Lynch, L. 2004. 'What's Driving the New Economy? The Benefits of Workplace Innovation'. *The Economic Journal*, 114: F97-F116.

Bloom, N. and Van Reenen, J. 2007. Measuring and explaining management practices across firms and countries. *Quarterly Journal of Economics* 122 (4): 1351-1408.

Bloom, Nicholas, Luis Garicano, Raffaella Sadun, and John Van Reenen. 2009. The Distinct Effects of Information Technology and Communication Technology on Firm Organization. NBER Working Paper #14975.

Bloom, Nicholas, Raffaella Sadun, and John Van Reenen. 2011. Americans Do IT Better: US Multinationals and the Productivity Miracle. Forthcoming, *American Economic Review*.

Blum, Bernardo, and Avi Goldfarb. 2006. Does the internet defy the law of gravity? *Journal of International Economics* 70(2), 384-405.

Blundell, R. and Bond, S. 2000. GMM estimation with Persistent Panel Data: An Application to Production Functions. *Econometric Review* 19(3): 321-40.

Bond, S. and Soderbom, M. 2005. Adjustment Costs and the Identification of Cobb Douglas. Production Functions. *IFS Working Paper* 05/04.

Branstetter, Lee, Ray Fisman, Fritz Foley, and Kamal Saggi. 2011. Does intellectual property rights reform spur industrial development? *Journal of International Economics* 83(1), 27-36.

Bresnahan, T. F., Brynjolfsson, E., and Hitt, L. M. 2002. Information Technology, workplace organisation, and the demand for skilled labor: Firm-level evidence, *Quarterly Journal of Economics*: Vol. 117 Issue 1: 339-376.

Bresnahan, T.F. and S. Greenstein. 1996. Technical Progress and Co-Invention in Computing and the Use of Computers, *Brookings Papers on Economic Activity: Microeconomics*, pp. 1-77.

Brynjolfsson, E., L. M. Hitt. 1996. Paradox Lost? Firm-level Evidence on the Returns to Information Systems Spending. *Management Science* 42(4) 541-558.

Brynjolfsson, E., L. M. Hitt. 2000. Beyond computation: Information technology, organizational transformation and business performance. *Journal of Economic Perspectives* 4 23-48.

Brynjolfsson, Erik and Lorin Hitt. 2003. Computing Productivity: Firm-Level Evidence. *Review of Economics and Statistics*, 85(4): 793-808.

Brynjolfsson, E., and A. Saunders. 2010. *Wired for Innovation: How Information Technology is Reshaping the Economy*. MIT Press, Cambridge, MA.

Cairncross, F. 1997. *The Death of Distance*, Boston: Harvard Business School Press.

Chwelos, Paul, Ronald Ramirez, Kenneth L. Kraemer, and Nigel P. Melville. 2010. Does Technological Progress Alter the Nature of Information Technology as a Production Input? New Evidence and New Results. *Information Systems Research* 21(2), 392-408.

Davis, S. J., Faberman, R. J. and Haltiwanger, J. 2006. The Flow Approach to Labor Markets: New Data Sources and Micro-Macro Links. *NBER Working Papers* 12167.

Davis, S. J., Haltiwanger J.C. and Schuh, S. 1998. *Job Creation and Destruction*. Cambridge: MIT Press

Devaraj, S., R. Kohli. 2003. Performance Impacts of Information Technology: Is Actual Usage the Missing Link? *Management Science* 49(3) 273-289.

Dion, Richard, and Robert Fay. 2008. Understanding Productivity: A Review of Recent Technical Research. Bank of Canada Discussion Paper 2008-3.

Doms, M., R. Jarmin and S. Klimek. 2002. IT Investment and Firm Performance in US Retail Trade, *CES Working Paper 02-14*, Center for Economic Studies, Washington DC.

Draca, Mirko, Raffaella Sadun, and John Van Reenen. 2006. Productivity and ICT: A Review of the Evidence. CEP Discussion Paper # 749.

Falk, M. 2001. Organizational Change, New Information and Communication Technologies and the Demand for Labor in Services, *ZEW Discussion Paper No. 01-25*, ZEW, Mannheim.

Forman, Chris and Avi Goldfarb. 2006. Diffusion of Information and Communication Technologies to Businesses. In *Handbook of Information Systems, Volume 1: Economics and Information Systems*, ed. Terrence Hendershott, 1–52. Amsterdam: Elsevier.

Forman, Chris, Avi Goldfarb, and Shane Greenstein. 2005. How Did Location Affect the Adoption of the Commercial Internet? Global Village vs Urban Density. *Journal of Urban Economics*, 58(3): 389–420.

Forman, Chris, Avi Goldfarb, and Shane Greenstein. 2008. Understanding the Inputs into Innovation: Do Cities Substitute for Internal Firm Resources? *Journal of Economics and Management Strategy*, 17(2): 295–316.

Forman, Chris, Avi Goldfarb, and Shane Greenstein. 2011. The Internet and Local Wages: A Puzzle. Forthcoming, *American Economic Review.*

Forman, Chris, and Nicolas van Zeebroeck. 2010. From wires to partners: How the Internet has fostered R&D collaborations within firms. Working paper, Georgia Tech.

Friedman, Thomas L. 2005. *The World is Flat: A Brief History of the Twenty-First Century.* New York, NY: Farrar, Straus, and Giroux.

Fukao, K and Miyagawa, T. 2007. Productivity in Japan, the US and the Major EU Economies: Is Japan Falling Behind? *EU KLEMS Working Paper.*

Fuss, M. and L. Waverman. 2005. Canada's Productivity Dilemma: The Role of Computers and Telecom. Appendix E-1 to Bell Canada's Submission to the Telecommunications Policy Review Panel, Ottawa.

Garicano, Luis. 2010. Policemen, managers, lawyers: New results on complementarities between organization and information and communication technology. *International Journal of Industrial Organization*. 28, 355-358.

Garicano, Luis and Esteban Rossi-Hansberg. 2006. Organization and Inequality in a Knowledge Economy. *Quarterly Journal of Economics*, 121(4): 1383-1485.

Garicano, L., and Heaton, P. 2009. Information Technology, Organisation and Productivity in the Public Sector: Evidence from police departments, forthcoming *Journal of Labor Economics.*

Gaspar, J. and E.L. Glaeser. 1998. Information technologies and the future of cities, *Journal of Urban Economics*, 43(1): 136–156.

Gera, Surendra, Wulong Gu, and Frank C. Lee. 1999. Information Technology and Labour Productivity Growth: An Empirical Analysis for Canada and the United States. *Canadian Journal of Economics* 32(2), 384-407.

Glaeser, Edward L. and Giacomo A. M. Ponzetto. 2007. Did the Death of Distance Hurt Detroit and Help New York? NBER Working Paper #13710.

Goldfarb, Avi. 2006. The (Teaching) Role of Universities in the Diffusion of the Internet. *International Journal of Industrial Organization* 24(2), 203-225.

Goldfarb, Avi. 2009. Understanding differences between Canadian and American Internet Use: Geography and education. Working paper written for Industry Canada.

Goldfarb, Avi and Catherine Tucker. 2011. Privacy Regulation and Online Advertising. *Management Science* 57(1), 57-71

Gordon, R. 2000. Does the New Economy Measure up to the Great Inventions of the Past? *Journal of Economic Perspectives.* 14(4): 49-74.

Gordon, R. 2003. High-Tech Innovation and Productivity Growth: Does Supply Create its Own Demand? *NBER Working Paper.* No 9437.

Griliches, Z. and Mairesse, J. 1997. Production functions: The search for Identification in Scott Storm (ed.), *Essays in honour of Ragnar Frisch,* Econometric Society Monograph Series, Cambridge University Press, Cambridge

Hall, Bronwyn H., Francesca Lotti, and Jacques Mairesse. 2010. Evidence on the Impact of R&D and ICT Investment on Innovation and Productivity in Italian Firms. Working paper, US Berkeley.

Haltiwanger, J., R. Jarmin and T. Schank. 2003. Productivity, Investment in ICT and Market Experimentation: Micro Evidence from Germany and the United States, *Center for Economic Studies Working Paper CES-03-06,* US Bureau of the Census, Washington, DC.

Hempell, T. 2002. Does Experience Matter? Productivity Effects of ICT in the German Service Sector, *Discussion Paper No. 02-43,* Centre for European Economic Research, Mannheim.

Henderson, Vernon. 2003. Marshall's Scale Economies. *Journal of Urban Economics* 53(1): 1-28.

Higgins, Matthew J., Daniel Levy, and Andrew T. Young. 2006. Growth and Convergence across the United States: Evidence from County-Level Data. *Review of Economics and Statistics*, 88(4): 671–81.

Hitt, L.M. 1998. Information Technology and Firm Boundaries: Evidence from Panel Data, University of Pennsylvania, *mimeo.*

Jorgenson, Dale. 2007. Information Technology and the G7 Economies. *Managing in the Information Economy* v 1 part 1, p. 29-57.

Jorgenson, D. W. and Stiroh, K. J. 2000. 'Raising the Speed Limit: US Economic Growth in the Information Age'. *Brookings Papers on Economic Activity.* 1: 125-211.

Jorgenson, Dale W., Mun S. Ho, and Kevin J. Stiroh. 2005. *Productivity, Volume 3: Information Technology and the American Growth Resurgence.* Cambridge, MA: MIT Press.

Jorgenson, D.W., Ho, M.S and Stiroh, K. J. 2008. A Retrospective Look at the US Productivity Resurgence. *Journal of Economic Perspectives* 22(1): 3-24.

Lehr, Bill, and Frank Lichtenberg. 1999. Information technology and its impact on productivity: firm-level evidence from government and private data sources, 1977-1993. *Canadian Journal of Economics* 32(2), 335-362.

Levinsohn J. and Petrin, A. 2003. Estimating Production Functions Using Inputs to Control for Unobservables. *Review of Economic Studies* 70(2): 317-341.

Lichtman, Douglas. 2008. Copyright as Innovation Policy: Google Book Search from a Law and Economics Perspective. In Josh Lerner and Scott Stern eds. *Innovation Policy and the Economy* v. 9. P. 55-78.

Lileeva, Alla, and Daniel Trefler. 2010. Improved access to foreign markets raises plant-level productivity...for some plants. *Quarterly Journal of Economics* 125(3), 1051-1099.

Lucchetti, Riccardo & Alessandro Sterlacchini. 2004. The Adoption of ICT among SMEs: Evidence from an Italian Survey. *Small Business Economics*, 23(2), 151-168.

Lychagin, Sergey, Joris Pinkse, Margaret Slade, and John Van Reenen. 2010. Spillovers in Space: Does Geography Matter? Working paper, UBC.

Majumdar, S.K., O. Carare, and H. Chang. 2009. Broadband adoption and firm productivity: evaluating the benefits of general purpose technology. Industrial and Corporate Change 19(3), 641-674.

Maliranta, M. and P. Rouvinen. 2004. ICT and Business Productivity: Finnish Microlevel Evidence, in OECD, *The Economic Impact of ICT – Measurement, Evidence and Implications*, OECD, Paris, pp. 213-239.

Marshall, Alfred. 1920. *Principles of Economics.* 8th ed. New York: Porcupine Press.

Meijers, Huub. 2007. ICT Externalities: Evidence from cross country data. UNU-MERIT Working paper.

Meijers, Huub. 2010. Trade, Internet and economic growth: a cross country panel analysis. UNU-MERIT Working paper.

Miller, Amalia, and Catherine Tucker. 2011. Can healthcare IT save babies? Forthcoming, *Journal of Political Economy.*

Morrison, Catherine J. 1997. Assessing the productivity of information technology equipment in U.S. manufacturing industries. *Review of Economics and Statistics* 471-481

Mukhopadhyay, Tridas, F. Javier Lerch, and Vandana Mangal. 1997. Assessing the impact of information technology on labor productivity: A field study. *Decision Support Systems.* 19, 109-122.

Oliner, S. D. and D. E. Sichel. 2002. Information Technology and Productivity: Where Are We Now and Where Are We Going? FRB Atlanta *Economic Review* 87 (3): 15–44.

Olley, G. S., A. Pakes. 1996. The dynamics of productivity in the telecommunications equipment industry. *Econometrica* 64(6) 1263-1297.

O'Mahony, Mary, and Marcel Timmer. 2009. Output, Input, and Productivity Measures at the Industry Level: The EU KLEMS Database. *Economic Journal* 119(538): F374-F403.

O'Mahony, Mary, and Michela Vecchi. 2003. Is there an ICT impact on TFP? A heterogeneous dynamic panel approach. NIESR working paper.

Peri, Giovanni. 2005. Determinants of Knowledge Flows and their Effect on Innovation, *Review of Economics and Statistics,* 87(2): 308-322

Pilat, Dirk. 2004. The ICT Productivity Paradox: Insights from micro data. *OECD Economic Studies*, 38(1), 37-65.

Pilat, Dirk. 2005. Canada's Productivity Performance in International Perspective. *International Productivity Monitor* 10, 24-44.

Pilat, D., F. Lee and B. Van Ark. 2002. Production and use of ICT: A sectoral perspective on productivity growth in the OECD area, *OECD Economic Studies*, No. 35, Paris, pp. 47-78.

Sharpe, A. 2005. What Explains the Canada-US ICT Investment Intensity Gap? CSLS Research Report No. 2005–06.

Stiroh, Kevin J. 2002. Information Technology and the U.S. Productivity Revival: What Do the Industry Data Say? *American Economic Review*, 92(5): 1559-76.

Tambe, Prasanna, Lorin M. Hitt, and Erik Brynjolfsson. 2011. The Extroverted Firm: How External Information Practices Affect Innovation and Productivity. Working paper, MIT-Sloan.

Timmer, Marcel and Bart van Ark. 2005. Does information and communication technology drive EU-US productivity growth differentials? *Oxford Economic Papers* 57, 693-716.

Triplett J. E. 1999. The Solow's productivity paradox: what do computers do to productivity? *Canadian Journal of Economics* 32(2) 309-334.

Van Ark, B., J. Melka, N. Mulder, M. Timmer and G. Ypma. 2003. ICT Investments and Growth Accounts for the European Union, 1980-2000, *Research Memorandum GD*-56, Groningen Growth and Development Centre, Groningen, *www.eco.rug.nl/ggdc/homeggdc.html.*

Van Ark, B; O'Mahoney, M and Timmer, M. 2008. The Productivity Gap Between Europe and the United States: Trends and Causes. *Journal of Economic Perspectives* 22(1): 25-44.

Zand, Fardad, Cees van Beers, and George van Leeuwen. 2010. Information Technology, Organizational Change and Firm Productivity: A Panel Study of Complementarity Effects and Clustering Patterns in Manufacturing and Services. OECD working paper.