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Digitalization: Productivity

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Overview

This paper, which is part of the Digitalization Overview series, provides an overview of the relationship between digitalization and productivity, the factors that influence this relationship and the potential that digitalization has to change the economic landscape. Over recent decades, the production of goods and services has increasingly relied on digital technologies. We start this paper, in section 1, by discussing digitalization's productivity impact at both the industrial and country level. Section 2 then highlights the most promising channels through which digitalization affects productivity. At the firm level, this comes in the form of automation, improved data and information availability, and increased capital efficiency. To categorize the relationship at a higher level, we use the traditional Solow growth accounting framework and showcase literature-based linkages. In section 3, we leverage the insight that much of the quantified impact of productivity is capital-embodied and discuss digital capital and its effect on productivity. In section 4, we turn to digitalization's role in enhancing the efficiency of the inputs to production. Of particular importance is the investment in necessary intangible capital and innovation, since many productivity gains from digitalization require alignments of capital, labour and organizational inputs. Section 5 concludes by highlighting key trends and open questions.

Key messages

- **Digitalization has the potential to shape an era of economic growth, with research generally indicating that digitalization has a positive impact on productivity.** Despite this, since the early 2000s, accelerated digitalization has coincided with a relatively weak productivity performance in advanced economies. Differences in digital investment across industries explain a portion of the differences in productivity performance. When compared with other developed countries, Canada's information and communication technologies (ICT) investment is slightly above average, suggesting there is still room to catch up to the frontier.

- **At the firm level, digitalization affects productivity through automation, data and information availability, and more efficient capital.** In Canada, on aggregate, the growth accounting approach implies that measured digital capital makes a small contribution to productivity growth—about 0.2–0.3 percentage points (pps) per year since the early 2000s. Productivity growth in the ICT-producing sector has been weak and has slowed over time in Canada. Regulatory environments, the availability of skills and firm size are major determinants of digital investment.

- **The impact of digitalization on productivity is magnified when accompanied by other complementary assets.** Since it takes time to coordinate and integrate effective complementarities, productivity gains may materialize with a delay. Skilled human capital and effective management practices improve the impact of digitalization on productivity.

- **Evidence suggests significant spillovers from digitalization (e.g., automation, artificial intelligence [AI], use of big data) to total factor productivity (TFP).** Digitalization can increase productivity by promoting business dynamism through the creation of new firms and sectors, but the existing empirical evidence is inconclusive. Recent waves of digitalization partly imply rising market power, which is reflected in higher markups and greater benefits for large firms than small and medium-sized firms.
- **Digitalization has played an important role in the economic adjustment to the pandemic shock.** However, the long-term effects will depend on firms' use of organizational capital as well as digital assets.

1. Impact of digitalization on productivity

The global economy has gone through three industrial revolutions. The first was the result of steam power and mechanization, the second was a result of electricity and fossil fuel energy and the third happened due to the adoption of ICT. More controversial is the arrival of a fourth revolution, which is ongoing and builds on its predecessor. At its core lies the acceleration of digitalization (see Faucher and Houle [forthcoming] for more details). The question of whether digitalization is a new element in the ICT revolution, or a new ICT in its own right, is secondary to its undisputed potential.

1.1. Digitalization and its impact on productivity so far

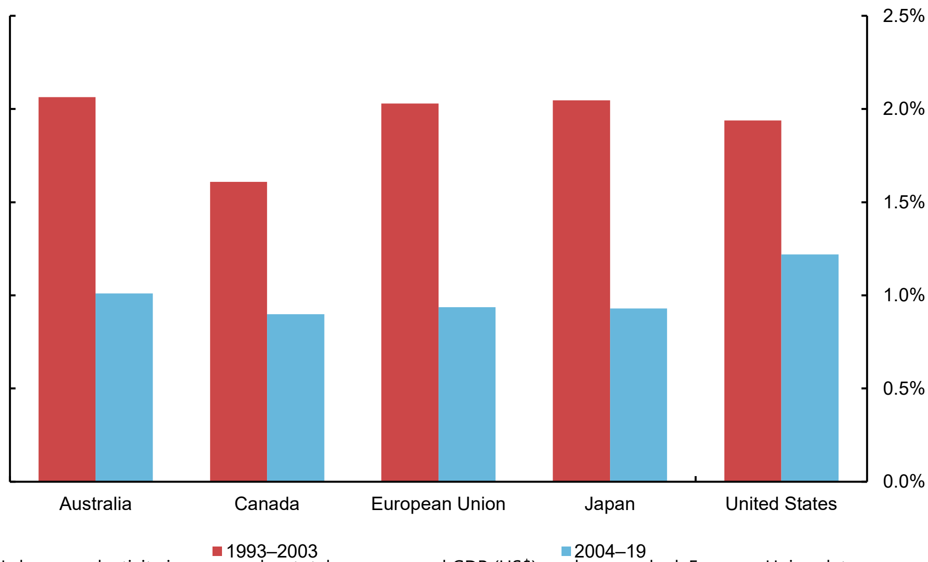
The third industrial revolution in North America began in the 1990s. In Canada and the United States, strong growth in labour productivity coincided with a high degree of ICT investment. Software, personal computers and telecommunications were at the heart of this revolution and economic progress (Cette, Clerc and Bresson 2015). The acquisition of this technological infrastructure laid the groundwork for the digital economy.

The speed at which digital technologies have advanced has at times felt dizzying in terms of scope and implications for economic growth. From Fintech to smartphones to AI and robotics, digitalization has affected most aspects of how we live and work. However, despite the seemingly rapid technological progress since the early 2000s, recent decades have been characterized by relatively poor growth in productivity (**Chart 1**).[1, 2]

[1] It should be noted, though, that breakpoint tests on quarterly Canadian labour productivity growth do not indicate any structural breaks in the data over the past 40 years.

[2] While many scholars show that the productivity slowdown started around 2004–05 in the United States (Fernald, Inklar and Ruzic 2023), others argue that it began one to three years earlier in Canada (Sharpe and Tsang 2018; Conesa and Pujolas 2019).

Chart 1: Average labour productivity growth



Note: Labour productivity is measured as total economy real GDP (US$) per hour worked. Euopean Union data begins in 1996.
Sources: Organisation for Economic Co-operation and Development and Bank of Canada calculations
Last observation: 2019

Various explanations for this productivity slowdown have been proposed. Some suggest reduced business dynamism causes less productive firms to remain in the market, dragging down productivity statistics (Decker et al. 2017; St-Amant and Tessier 2018). Gu and Willox (2018) find that in Canada, the productivity slowdown can be partly explained by increased difficulty in extracting natural resources and by a decline in capacity utilization in the manufacturing sector. Tang and Wang (2020) suggest that the slowdown in Canada was caused by less innovation from large, high-productivity firms.

According to Gordon (2016), the broad-based slowdown in productivity growth across advanced economies can be understood through the lens of declining innovation rates. He argues that growth in productivity has weakened because the technological advancements of digitalization have not had as much impact as those in previous eras. Similarly, Fernald (2015) makes the case that productivity has not slowed at all but rather has returned to normal following the exceptional growth of the mid-1990s to early 21st century. In contrast, van Ark (2016) defines the new digital economy as one that increasingly relies on ICT services and a rise in knowledge-based assets. The author argues that the structural shift is ongoing and that productivity gains might be observed once the new technologies mature and enter the broader "deployment phase."

Despite the coincidence of the productivity slowdown with the new digital era, **research generally indicates that digital technology adoption contributes positively to productivity growth** (Liu 2021; Borowiecki et al. 2021; Cette, Nevoux and Py 2021). However, the positive relationship is nuanced, and the gains are not shared equally. Evidence indicates that digitalization creates a "winner-takes-all" market environment that increases disparities in productivity performance across firms, ultimately lowering aggregate productivity growth (Andrews, Criscuolo and Gal 2016).[3] Moreover, contributions to growth from ICTs and the spillovers to TFP have declined over recent decades (DeStefano, De Backer and Moussiegt 2017; Gordon and Sayed 2020).

Another branch of research has investigated whether mismeasurement of the digital economy could explain the productivity slowdown. It asks whether the decreasing cost of digital goods and services is only partially captured by the national accounts (such that a decline in the value of production is attributed to lower real output rather than lower prices), and if part of the slowdown is consequently "missing output."

However, as Ahmad, Ribarsky and Reinsdorf (2017) explain, this source of mismeasurement is unlikely to account for why productivity growth has declined compared with previous decades. Statistical agencies have been grappling with this issue for many decades as they improve the measurement of computer and service deflators. Faucher and Houle (forthcoming) note that the "missing" expenditure of free digital goods and services may also be a source of reduced output or understatement of the digital contribution to growth.[4] Ultimately, this line of research points to a relatively small role, if any at all, for mismeasurement in explaining the productivity slowdown (Byrne and Corrado 2017; Ahmad, Ribarsky and Reinsdorf 2017; Bellatin and Houle 2021; Syverson 2017).

1.2. Sectoral comparison

The amount of digital adoption and its effect on productivity depends on the industry in which it occurs. In Canada, Liu and McDonald-Guimond (2021) group industries into two broad categories: digitally intensive and non-digitally intensive. Liu (2021) finds that the productivity

[3] For further discussion on the implications of digitalization for competition, refer to Chu et al. (forthcoming).

[4] As Faucher and Houle (forthcoming) discuss, GDP is ultimately a measure of output, not welfare. Productivity statistics often do not, and are not meant to, fully capture the benefits we receive. For example, the ability to conveniently access interactive maps online to navigate instead of paper copies presents clear gains for our welfare but not necessarily for productivity statistics. Additionally, the increased time for leisure caused by reduced commute time is not necessarily captured by conventional productivity measures.

growth in digitally intensive sectors has been higher than in non-digitally intensive ones, despite a higher starting point in labour productivity (**Table 1**).

Table 1: Digitally intensive sectors' productivity outperformed post-1997

	1997		2018	
	Digitally intensive sectors	Non-digitally intensive sectors	Digitally intensive sectors	Non-digitally intensive sectors
Labour productivity	51	40	76 (48%)	52 (28%)
Labour share	56%	62%	58% (2 pp)	57% (-4 pp)
Share of total hours worked	22%	78%	22% (0 pp)	78% (0 pp)
Compensation per hour	25	17	47 (88%)	31 (87%)
Average hours per job	1,895	1,825	1,824 (-4%)	1,718 (-6%)
Share of output (approx.)	26%	73%	29% (3 pp)	71% (-3 pp)

Note: Labour productivity is measured as chained (2012) dollars per hour. Compensation is dollars per hour and includes wages, salaries and imputed labour income for self-employed people. Output is also measured in chained (2012) dollars and is approximate because a simple division is used. Numbers in brackets represent cumulative growth from 1997 to 2018 and may not add up due to rounding. "pp" is percentage points.

Sources: Statistics Canada Table: 36-10-0480-01 and authors' calculations

Table 1 also shows that although wages are higher in digitally intensive sectors, they have increased by the same percentage as in non-digitally intensive sectors despite a much faster increase in productivity in digitally intensive sectors. While total hours worked have increased at the same rate for both sectors, average hours per job per year have increased by 6% in non-digitally intensive sectors but only by 4% in digitally intensive ones. However, this likely does not account for informal "gig" employment, which may not be fully reflected in official statistics (Kostyshyna and Luu 2019).

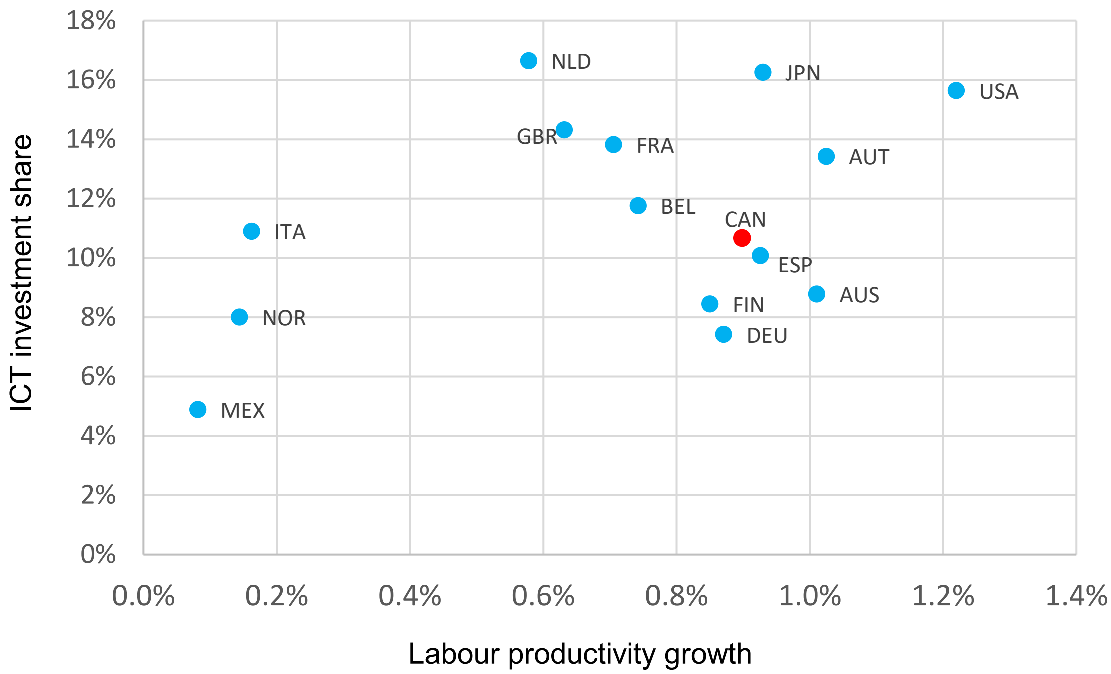
These results seem to indicate that digital intensity has a positive impact on productivity. Indeed, Tambe et al. (2020) find that digital capital accumulation can predict firm-level productivity performance, although the type of industry matters. For example, manufacturing industries and those with high degrees of routine tasks benefit the most from digital and ICT technologies because automation is easier in these sectors (Gal et al. 2019). Nonetheless, due to the importance of complementarities for digital capital, being in an industry with existing information technology intensity also contributes to the impact on productivity growth from within-industry knowledge spillovers (Müller, Fay and Brocke 2018).

1.3. Advanced economy comparison

Because advanced economies increasingly rely on and produce output with digital infrastructure, the countries that can effectively deploy the new technologies may gain an edge in productivity performance. While digital adoption is only partially responsible for similar dynamics seen globally, it may indeed help explain cross-country heterogeneity in productivity growth.

When investigating the impact of digitalization on productivity internationally, scholars typically use ICT as a convenient barometer for digital investment. As Faucher and Houle (forthcoming) discuss, **across several measures of digitalization, Canada typically ranks slightly above average compared with other developed nations**. **Chart 2** maps ICT investment as a share of total investment against productivity growth. Canada’s roughly average position on both axes indicates that neither its ICT investment nor its labour productivity performance is globally exceptional, but it also shows that Canada has likely benefited from digitalization and has room to catch up to the technological frontier.

Chart 2: ICT investment intensity and labour productivity growth (2004–19 average)



Note: ICT is information and communication technologies.
Sources: Organisation for Economic Co-operation and Development (OECD), "GDP per hour worked" (indicator), (accessed 16 October 2022); OECD, "Investment by asset" (indicator), (accessed 26 October 2022).

Last observation: 2019

Many countries have experienced sustained investment in digital capital but simultaneously slowing productivity. Dabla-Norris et al. (2015) highlight that a slowdown has occurred in both the advancement of the global technology frontier and the pace of catch-up.[5] Specifically, the frontier was advancing rapidly in the United States in the late 1990s to early 2000s, but as this progress slowed, the pace of catch-up by other countries also stalled.[6]

While the role of digitalization in the global productivity slowdown is likely small (Cette, Devillard and Spiezia 2022), the adoption of digital technologies may help explain cross-country heterogeneity. For example, Adarov et al. (2020) regress ICT capital (both tangible and intangible) on productivity to show that increasing ICT investment to US levels could

[5] For Canada, Tang and Wang (2020) argue that the productivity slowdown was driven by a *retreat* of the aggregate technological frontier.

[6] Dabla-Norris et al. (2015) also highlight the need for policy and structural reforms for countries lagging behind the frontier, and innovation in products and processes for those at the frontier (for more on the determinants of digital investment, see section 3.3).

significantly impact EU productivity growth. For Canada, Gu and Willox (2018) find that **lower contribution to productivity growth from sectors that use and produce ICT was one of the main causes of lower productivity in Canada relative to the United States between 1987 and 2010**. They also find that these industries are responsible for some convergence of productivity growth from 2010 to 2014.

Similarities in industrial composition and existing ICT capital across countries will affect international spillovers of technological progress. Particularly for Canada, a small open economy, any discussion of the determinants of productivity growth must consider international innovation spillover effects. Gu and Yan (2017) decompose TFP by sector providing intermediate inputs, including imported inputs, to show that **a substantial share of the gains in TFP growth in Canada is a result of innovation on upstream intermediate goods in other economies.**[7] As innovation and digitalization occur, they may take time to reach other countries.

2. Channels of digitalization's effect on productivity

Given that the size and nature of the impact of digitalization on productivity are not obvious, it is helpful to conceptually categorize key relationships. This categorization can be done at the firm level: the channels through which productivity is affected as firms adopt digital technologies. It can also be done at the macro level using the growth accounting framework to separate contributions from different inputs.

2.1. Digitalization's productivity effects at the firm level

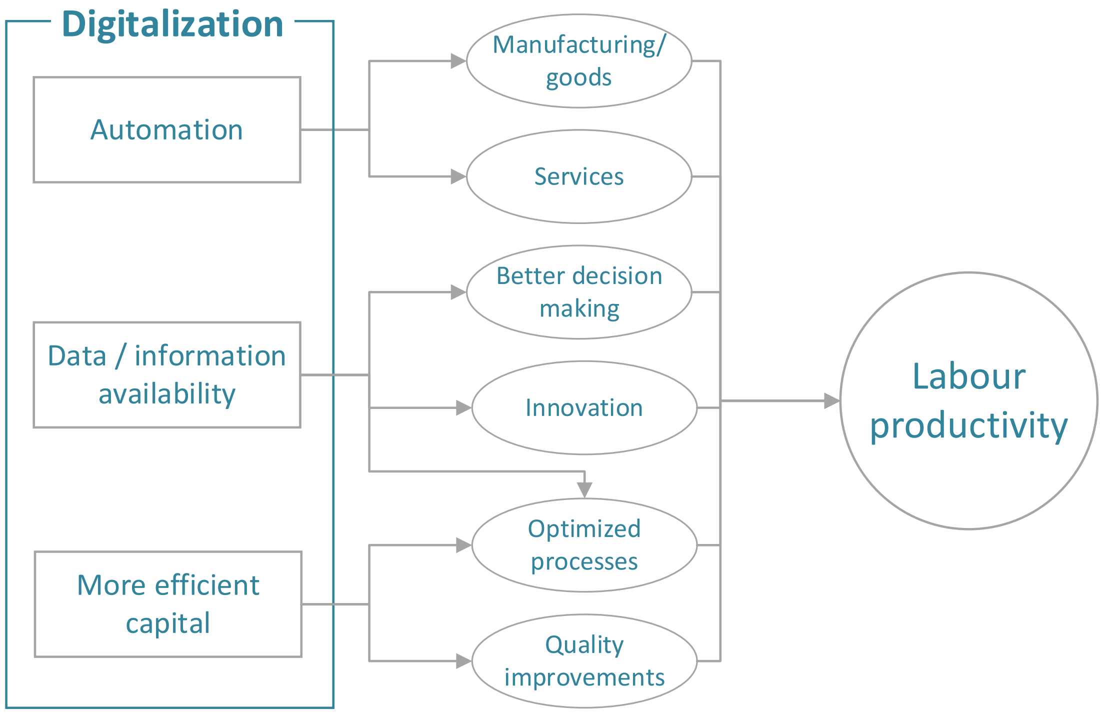
Conceptually, digitalization affects productivity through three firm-level channels: automation, increased availability of information and data, and more efficient capital (**Figure 1**). Each of these channels interacts with capital deepening, labour skills and other complementarities, and results in TFP spillovers.

At the firm-level, these channels are difficult to isolate empirically and conceptually, since most digital technologies relate to more than one channel. For example, cloud computing increases availability of data and information, but it can also represent more efficient capital and allow for substitution away from labour. Another challenge is the absence of a coherent

[7] Gu and Yan (2017) use the concept of effective multi-factor productivity, which is defined as the weighted sum of multi-factor productivity growth of the intermediate sectors. They use data from the World Input-Output Database and from the EU KLEMS productivity database.

understanding of how the triggered channels work and what their relative importance will be. What we know is based largely on studies focusing on concrete examples.

Figure 1: Firm-level channels for digitalization and productivity



Automation

The largest use of digital and ICT automating technologies has taken place in industries with repeatable and predictable tasks. Manufacturing is the best example, with robots able to directly substitute in assembly lines.[8] Jungmittag and Pesole (2019) show that **robot use has a positive impact on productivity above other forms of capital,** but they also highlight that some of the intensified use of modern robots has the effect of augmenting capital. These investments therefore primarily represent ongoing improvements to a long-run process of industrial automation rather than a breakthrough innovation.

The type of automation that has been occurring through the use of computerized information and ICT capital is distinct from the automation that newer digital technologies promise. The

[8] This is not exclusive, though. Computer software has already automated processes such as data entry, translation and logistics.

ability to automate tasks that have a higher degree of complexity, such as those in the services industries, would rely more heavily on unsupervised robots and software that operate in unstructured environments. Recent advancements in AI represent clear progress toward that outcome but also highlight that more time is needed before these technologies can transform productivity dynamics.[9] Some researchers have pushed the idea that digitalization is still in its investment phase, during which its advent reduces productivity. In the next phase, productivity will increase once technologies such as machine learning and AI mature (Brynjolfsson, Jin and McElheran 2021).

Another important distinction, as Acemoglu and Restrepo (2018a) articulate, is the false dichotomy between AI automation causing labour displacement effects versus creating new tasks for labour (see also Chernoff and Galassi 2023). While both effects ultimately increase labour productivity, they are often presented as opposing forces. Acemoglu and Restrepo (2018a) argue that although displacement is likely the first to occur, countervailing economic forces, such as the creation of new tasks where labour has a comparative advantage, will likely lead to balanced long-run growth.

Data and information availability

When economic agents more frequently interact on digital platforms, these activities create large and accessible datasets. E-commerce and mobile phone usage, for instance, create opportunities for firms to use consumer data to optimize their business processes and make more informed decisions. In this way, data and information have an inherent function that encourages firms to efficiently coordinate their inputs to production.[10] This effectively reduces the cost of producing a given output and augments the returns to labour and capital.

Of course, these outcomes are possible only when access to data is combined with the necessary analytical skills to extract relevant inferences. For example, Tambe (2014) highlights that **the returns to firms' investments in big data software are positive only in industries with the relevant skilled labour**. We further discuss such complementarities in section 4.

Some digital technologies, notably AI and machine learning, not only automate the extraction of and inferences from data but also enhance the insights derived from a given dataset. In this space, innovation can occur at a more rapid pace as learning on data and information compounds. For example, Cockburn, Henderson and Stern (2019) mention a bio-pharma firm

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[9] For example, autonomous vehicles have made incredible progress in their functionality, but multiple obstacles remain. These include the need for sufficient infrastructure (like 5G cellular networks), sensors that work well in all weather conditions and decision-making programming (Adams 2020).
[10] Corrado et al. (2022) also point to the role of data in "informative activities" such as marketing and brand-building that affect market concentration.

that has developed technology that predicts bioactivity using AI tools to identify drug candidates. This technology has the potential not only to automate much of the labour required to research new drugs, but also to enhance the discovery process to retrieve previously inaccessible insights as the AI continues to learn and improve.

An increase in access to data and information does, however, lend itself to some negative impacts on productivity in the aggregate. Specifically, data collection and processing require large initial fixed investments as well as ongoing investments such as database maintenance and management and the legal/administrative costs associated with property rights adherence. The barriers to entry for digital capital deepening have resulted in a lack of digital diffusion to laggard firms and winner-takes-all outcomes.

More efficient capital

Digitalization occurs as information and processes are transferred to digital mediums. Although some of these transfers have already occurred, particularly during the ICT boom that began in the 1990s, improvements in their performance can still impact productivity. For example, consider the video game industry which, according to the Entertainment Software Association of Canada, contributed roughly $5.5 billion to Canadian gross domestic product (GDP) in 2021.[11] In previous decades, video games were very expensive and labour-intensive to make. As better supporting software has been developed, the speed at which output can be delivered has improved. This is not necessarily automation, but rather a means to increase the quality of output for a given labour input. As Faucher and Houle (forthcoming) note, however, some of the increase in quality is most likely not captured by GDP and instead attributed to consumer surplus.

Improvements in existing technology often present themselves as changes in the relative price of investment. Decreases in the price of investments for a product of a given quality represent efficiency gains that are passed on to productivity. For example, the hardware required for a computer with 8 gigabytes of RAM was much more affordable and accessible in 2022 than it was in 1992. According to Mollins and St-Amant (2018), the decrease in ICT prices relative to other goods and services in Canada is an important factor in the contribution of ICT to productivity growth.

The level of ease of making these improvements and price adjustments is a major promise of the digital economy. Whether through AI deep learning or simply the cost trade-off of training

[11] See the Canadian Video Game Industry Report, 2021 for more details.

an entire workforce versus implementing several lines of code, digital technologies offer the potential to lower input prices and increase returns to scale.[12]

2.2. Digitalization through the lens of Solow growth accounting

A commonly used tool to understand economic growth is Solow growth accounting, whereby productivity growth ($\dot{y}$) is decomposed into three main factors: growth in labour skills ($\dot{E}$), capital deepening ($\dot{k}$) and TFP growth ($\dot{A}$). Assuming a very basic Cobb-Douglas technology, we have the following simple relationship:

$$\dot{y}_t = \dot{A}_t + \alpha \dot{k}_t + (1 - \alpha) \dot{E}_t.$$

Next, we discuss each term in the above equation in detail.

Total factor productivity

TFP is sometimes considered a proxy for technological progress, as changes in TFP indicate how much additional output can be produced using a given quantity of capital and labour inputs. **TFP has historically been the largest contributor to labour productivity growth, accounting for about half the observed growth in the late 1990s and early 2000s for both the United States and Canada** (see Appendix A).

The role that digitalization has played in the vicissitudes of TFP is difficult to measure. TFP captures many aspects of digital and non-digital technological progress, along with many other factors. Comparing digital capital formation with TFP growth can still give useful insights, and researchers have often found that the technologies provide a source of innovation or gains in efficiency (Cette, Nevoux and Py 2021; Dinlersoz and Wolf 2018). The spillovers of digitalization to TFP may become larger over time as firms invest in AI and machine learning, which could produce sizable intangible output.

Capital deepening

Capital deepening is the most-studied channel for the effect of digitalization on productivity. A number of studies have linked investment in digital capital to productivity growth (Cette, Clerc and Bresson 2015; Tambe et al. 2020). **Digital capital assists firms in a variety of ways,**

[12] Since the beginning of 2010, Statistics Canada tables 18-10-0061-01 and 18-10-0207-01 indicate that the prices of commercial software and computers and peripherals have increased by 10% and decreased by 36%, respectively. However, as Faucher and Houle (forthcoming) show, these indices may be subject to mismeasurement, particularly with the former, because quality is difficult to capture.

such as automating tasks, reducing the operational costs of interacting with market agents and improving business process organization.

Investments in digital capital are the lynchpin for the growth and maintenance of a digital economy. ICT capital is often used as a barometer for digitalization because it is the infrastructure upon which digital platforms and digital economic activity occur. While ICT investment does not appear to have contributed to the initial slowdown of productivity in the early 2000s, the Great Recession represents a breakpoint after which ICT became a factor in continued lackluster productivity growth (Bergeaud, Cette and Lecat 2014; Mollins and St-Amant 2018). The reduced positive contribution came from declining ICT capital growth as well as a convergence in the growth of ICT prices to the GDP deflator. However, digital capital, such as software and AI, is not captured well in the national accounts (see section 3 for more details).

Labour composition and skills

The labour composition necessary to optimize the gains of digital technologies relies on highly skilled workers interacting directly with the detailed mechanisms of the underlying systems. However, it also relies on the generic digital literacy of any worker that uses the platforms. For example, a systems architect may be required to customize and maintain the capabilities of a firm's logistics software, but the warehouse workers interacting with the system also need to be trained on how to use the front-end features.

Empirically, **strong evidence suggests the importance of complementary skills for technological optimization and therefore productivity growth**. For example, Tambe (2014) shows that certain labour skills are essential to optimize big data investments, and this is particularly important in newer and less mature technologies.

Limitations of growth accounting

Some advancements affect all three channels at the same time or might even change the production technology itself. In these cases, growth-accounting equations must be used with care. Digitalization seems to frequently give rise to such multi-impact forces. For instance, when a firm invests in advanced software and better process-monitoring technology, this is directly measured through the capital deepening channel. However, the increase in the firm's productivity is not solely due to the addition of more capital to its existing stock. **TFP could also increase because the technology inherent in the capital purchased is more advanced, and therefore more productive compared with previous investments**. In addition, employees may need to acquire new skills over time to fully utilize the new equipment, contributing to an increase in labour efficiency. This is an example where a capital expenditure affects all three channels.

At the aggregate level, an additional contribution to overall productivity comes from the production of ICT goods and services. For example, the services of an information technology consulting firm would not be fully recorded as capital by the purchasing firm but are nonetheless part of the digital economy. Therefore, the contribution is not necessarily captured by the growth accounting terms and is often called the production effect (see **Box 1**).

3. Investment in ICT, digital, and intangible capital

ICT investment either lays the foundation on which digital technologies are built (e.g., computer hardware) or represents digitalization directly (e.g., software development services). Therefore, the contribution of ICT investment to productivity growth can be a very good approximation for the impact of digitalization. However, **some digital investments, such as ICT services or databases, add extra value that contribution estimates often do not capture**. Furthermore, **the value of digital intangibles, such as own-account software and in-house AI, is likely not fully embedded in national accounts**. This section provides an overview of these issues and concludes with a discussion of why firms decide to make digital investments.

3.1. Contributions of ICT adoption to productivity

Direct contribution of ICT capital to productivity growth is small

The measurable, direct contribution of ICT investments to productivity growth in Canada appears to be small and declining; but this contribution tells only part of the story. In Canada during the ICT boom of the late 1990s and early 2000s, **the contribution of ICT capital deepening to labour productivity growth has been estimated at around 0.4–0.5 pps per year**. Since then, however, the contribution has fallen to approximately 0.2–0.3 pps per year (Cette, Clerc and Bresson 2015; Mollins and St-Amant 2018). While this decline is roughly in line with other countries, the contribution as a share of total labour productivity growth for Canada remains similar for both periods, indicating that the ICT contribution does not fully explain the slowdown.

Shift to ICT services implies additional contribution to growth

The calculations of the capital deepening contribution in Canada do not fully account for the transition from ICT infrastructure to ICT services.[13] The productivity gains of the previous ICT boom occurred mostly through automation, while productivity gains from recent digitalization are more likely to be caused by improved efficiency of existing capital and increased information and data. Van Ark (2016) highlights this shift toward ICT services and knowledge-

[13] As a share of output, ICT services climbed from 17% of total ICT sector output in 1997 to 40% in 2018.

based assets and away from ICT assets for advanced economies.[14] The author argues that these purchased services encourage optimization in business processes by providing flexibility while the adoption of "internal" cloud computing improves the efficiency of existing capital.

Box 1 details a decomposition analysis, illustrating that the recent contribution to labour productivity growth of ICT-producing industries in Canada is still weak. However, these estimates are unlikely to fully capture the effect that ICT services have on growth, for two main reasons.

First, ICT services are particularly difficult to measure. This is because the quality adjustments use sum-of-costs instead of hedonic methods like those used for computers, which likely results in mismeasurement.[15]

Second, **services are not included as a capital input**. This is important because even though the production of ICT services is captured in national accounts, these services, once rendered, may affect the efficiency of existing capital stock. Byrne and Corrado (2017) give the example of an ICT services firm designing "private" cloud computing platforms within the purchasing firm. The service builds upon the existing stock of computing power within the purchasing firm, and once complete, increases the contribution of existing capital through more efficient utilization. The increased utilization acts as a persistent stock with ICT capital depreciation, not as a one-time service production as typically measured in national accounts. In the previous industrial revolution, automation occurred as businesses adopted computing technologies that replaced labour. In the previous example, capital is augmented by ICT services to produce more output for a given cost rather than to automate existing tasks.

In their examination of ICT adoption and productivity in the United States, Byrne and Corrado (2017) correct for the services issue by including ICT services as production inputs. They show that, with the appropriate price adjustments, their revised estimate of ICT contribution to productivity growth is significantly higher.[16] However, the additional calculated channels for ICT have not dramatically changed over the 2000s for the United States, indicating that ICT investment does not explain the slowdown in productivity.

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[14] In Canada, according to Statistics Canada Table 36-10-0401-01, ICT services represents 96% of ICT sector GDP in 2019, up from 78% in 1997.

[15] In other words, for a product like computers, you can point to features such as better processors or more memory as indications of quality, whereas services do not have as many tangible elements that display scalable improvements.

[16] Over 2004–14, Byrne and Corrado (2017) estimate contributions to be 0.4 pps higher due to the "diffusion effect" of ICT services as an input, and 0.2 pps higher due to the inclusion of some digital platform capital (entertainment originals). Mismeasurement of prices adds an additional 0.22 pps to output per hour growth and 0.44 pps to ICT contribution estimates.

While ICT services production is smaller in Canada than in the United States, including it in contribution calculations is particularly relevant for Canada as a small open economy.[17] **Imports of digital services are often overlooked in calculations of digital contribution** because they do not typically appear in capital formation or production effects. International payments for ICT services in Canada have increased between 1997 and 2022 as a share of total transactions.[18] Rostami (2018) shows that imports of ICT services were about $8 billion in 2016 in Canada, which is roughly 2.6% of total investment. For context, investment in software, computers and peripheral equipment combine for about $47 billion in 2016, which implies that ICT services imports are non-trivial for contribution measurements.[19, 20]

The benefits of data and information capital are likely ill-measured

A main mechanism through which digitalization affects productivity is improved accessibility of data and information (see also section 1.2). Specifically, the value of digital platforms is based on their use and collection of data. Assessing the impact of the digital economy on productivity requires properly measuring the output and capital of these platforms. However, these are not currently captured in ICT data.

Rassier, Kornfeld and Strassner (2019) present an approach to measuring the value of data embedded in databases. Focusing on the United States, they estimate that own-account data products and purchases of data are worth roughly US$150 billion in 2017.[21] This is undoubtedly a missing component in the estimation of the effect of the digital economy on productivity and output.

A small but growing literature relying on firm-level data has shown that a sizable contribution of digital capital is often ill-measured by statistical agencies. For example, Tambe (2014) and Müller, Fay and Brocke (2018) show that investment in big data, combined with relevant skills, can increase firm productivity by 3% or more. **More research is needed to broaden the scope**

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[17] Using the special aggregation for ICT producing sectors provided by the Bureau of Economic Analysis (consisting of NAICS 334, 5112, 513, 518 and 519130) minus 334 (computer manufacturing), we find that the US ICT services industry accounts for approximately 6.2% of GDP. Using Statistics Canada's special ICT services aggregation from Table 36-10-0401-01 (consisting of NAICS 4173, 5112, 517, 518, 5415 and 8112), we find that Canada's ICT services production accounts for approximately 4.4% of GDP.

[18] The source for this is Statistics Canada Table 36-10-0021-01. Quantification is difficult with publicly available data because many of these services are likely to be consumed by the ICT-producing sector in Canada, and no industry breakdown is available.

[19] Investment data reflect nominal prices.

[20] Typical ICT capital also includes telecommunication equipment, although this is usually much smaller than software and computer investment.

[21] While Kornfeld and Strassner (2019) make it clear that this cannot be reconciled with GDP or investment data, it would add roughly 0.3% to net private fixed assets (according to Bureau of Economic Analysis data, Fixed Assets Accounts Tables, Table 2.1).

of digital capital to properly capture output such as databases and to understand the impact of digital capital that is difficult to measure.

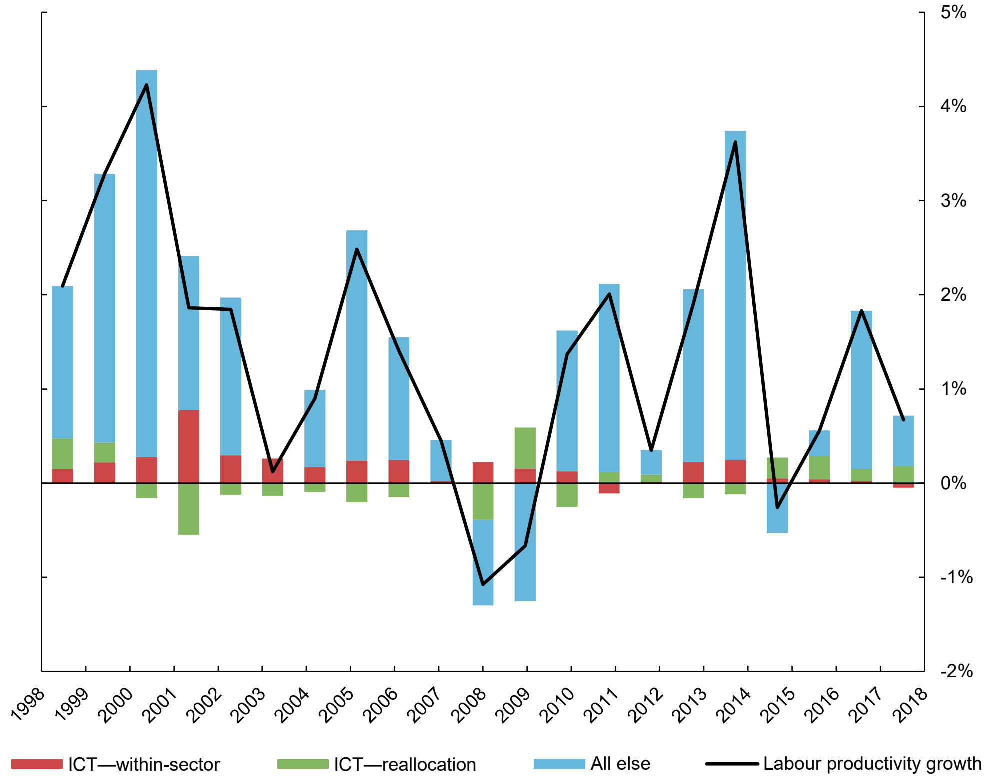
Box 1

Production of information communications technology capital and its effect on productivity

Digitalization can also affect productivity through the channel of its impact on domestic production. In Canada, the production of digital capital is relatively small as proxied by ICT sector value added. However, the contribution of digital capital to labour productivity might be disproportionately large due to different utilization rates across sectors and within sectors. To quantify this channel, we conduct an analysis of the contribution of ICT capital to labour productivity using methodology from Tang and Wang (2004) and present the results in **Chart 1-A**.

The analysis decomposes growth whereby "ICT—reallocation" is an aggregation of the effect of workers moving to and from industries with different productivity levels and growth rates. These effects were negative throughout the early 2000s largely because of a drop in the share of hours worked by the ICT-producing sector from its peak in 2000. Since 2015, this trend has reversed, and because of the high level of labour productivity in the sector compared with the total economy, this has resulted in positive reallocation effects. The "within-sector" effect, measured as the output share multiplied by productivity growth, has remained low since the recession due to the below-average productivity growth rates in the ICT sector, despite accounting for a rising share of output. Pre-recession production contributed 0.2 pps to overall productivity growth in Canada and 0.1 pps from 2010 to 2018.

Chart 1-A: Shift-share decomposition of labour productivity growth



Note: ICT is information and communication technologies. ICT—reallocation is an aggregation of the effect of workers moving to and from industries with different productivity levels and growth rates. ICT—within-sector is measured as the output share multiplied by productivity growth. Labour productivity is measured as business sector real GDP (Can$) per hour worked.
Sources: Statistics Canada Table 36-10-0480-01 and Bank of Canada calculations

Last observation: 2019

These findings are in line with the empirical literature. Mollins and St-Amant (2018) find that ICT production effects have contributed about 0.1 pps to Canada's growth slowdown since the recession. Similarly, the ICT production industry has contributed to the slowdown in the United States and the United Kingdom, although only slightly (van Ark 2016).

3.2. Contribution of digital intangible assets

The direct contribution of intangible assets is small in Canada

Researchers have identified intangible assets as both direct additions to the stock of digital capital and complementary investments to digital capital. The latter relates to, for example, managerial or organizational capital that helps foster digital innovation and adoption. An example of direct digital intangible investment is when a firm engages in the development of its own software. As Faucher and Houle (forthcoming) discuss, statistical agencies capture some of this in ICT expenditures.

Intangible capital appears to have a very small direct impact on productivity growth through the capital deepening channel in Canada. For example, Gu and Macdonald (2020) create estimates for computerized information, one of the most discussed segments of the digital economy. This category refers to new or improved software and is captured directly through capital deepening, but it also likely shows up in TFP due to measurement difficulties. **They show that this type of capital likely contributes only 0.05 pps per year to labour productivity growth after 2000** through direct capital deepening. Other intangible capital that may fall loosely under the umbrella of digital capital—such as own-account research and design, advertising, human capital and organizational capital—together add only an additional 0.09 pps to productivity growth.[22] Including all forms of intangible capital, the contribution is on average about 0.4 pps per year since 2000, or about one-quarter of total productivity growth.

Estimates for other countries suggest a larger role for intangibles. For example, Corrado et al. (2016) show that intangible capital deepening was a major contributor to productivity growth for the United States and several other countries from 2000 to 2013, contributing more than even tangible capital. However, these estimates do not differentiate between "digital" intangibles and other forms. The explanation for the lower intangible investment in Canada is an area for future research.

The contribution of digital intangible assets to growth is difficult to measure but has significant promise

Much like ICT services, the quality adjustments of other types of digital capital are difficult to measure. This is particularly true for technologies like AI and machine learning, where much of the outputs are intangible and depreciation rates are imprecisely measured. This most likely results in an underestimation of productivity and output, as well as of the role that the technologies have in producing tangible output. Corrado, Haskel and Jona-Lasinio (2021) model AI investment as a combination of measured and unmeasured intangibles and ICT tangibles. They find little evidence of an underestimation of TFP growth thus far, due largely to the high depreciation rate of the new technology. Brynjolfsson, Rock and Syverson (2021) show theoretically how productivity can become increasingly underestimated before intangible investments in technologies like AI mature. **Once fully realized as general-purpose**

[22] Gu and Macdonald (2020) estimate human capital using employer-provided workplace training costs. They measure organizational capital as a percentage of compensation of managers and spending on management consulting services. These could be important for digitalization given that, for example, firms provide training on IT infrastructure or organize resources to take advantage of digital technologies.

technologies (GPT), these will likely become meaningful inputs into the production of measured and unmeasured output.

The direct output of digital intangibles also overlooks the potential for changing the production function by use of complementary intangible investments. It can take time for these complementarities to have an impact on productivity. Nonetheless, empirical evidence already supports the claim that the combination of ICT and intangible assets positively impacts output elasticity as business processes improve and capital is used more efficiently (Corrado, Haskel and Jona-Lasinio 2017). How complementarities between digital capital and intangible assets affect productivity growth in Canada is an important area for future work and is discussed more in section 4 of this paper.

3.3. Determinants of digital investment and adoption

The relatively small contribution of digital investment to productivity growth in Canada and a lack of catch-up by many countries and firms to the technology frontier highlight the need for a closer look at the determinants of digital adoption. While many potential factors can influence a firm's decision to invest in digital capital, three stand out: policy environment, existing human capital and firm size.

First, **targeted policy measures have been shown to play a large role in the adoption and use of digital technology**. However, policy measures need to be tailored for specific ICTs; no one-size-fits-all policy exists (DeStefano, De Backer and Moussiegt 2017). The policy environment can greatly impact most of the factors that feed into a firm's decision to invest in digital technology, although certain focuses appear most effective. For example, studies find that policy measures to facilitate access to high-quality broadband internet are essential when firms access online platforms to support digital economic activities (Sorbe et al. 2019; Andrews, Nicoletti and Timiliotis 2018). DeStefano, De Backer and Moussiegt (2017) indicate that Canada ranks roughly average across measures of policy environments such as product market regulation in the telecommunication sector or government promotion of ICT.

Second, **adoption of digital technologies relies on the availability of relevant skills**.[23] The complementarity of skills and digital technology is well-evidenced. The causality is sometimes blurred; on the one hand, workers with existing digital skills are better able to adopt new ICT when investments are made so the assets are more effectively utilized (DeStefano, De Backer and Moussiegt 2017). On the other hand, a lag in productivity gains following investment indicates that even when skills are present, learning-by-doing effects are important and human capital is developed after the investment (Cette, Nevoux and Py 2021).

[23] For more details on digital skills, see Chernoff and Galassi (2023).

Third, firm size affects productivity and digital adoption rates. Related to the previous point on human capital, Berlingieri et al. (2020) suggest that laggard productivity firms, which are most often younger and smaller, face financial constraints that limit their ability to train and attract labour with ICT skills.[24]

Generally, **large firms are better equipped to invest in digital technologies**.[25] In Canada in 2016, for example, 53.7% of large firms (250 or more employees) used cloud computing software, compared with only 27.6% of small firms (10 to 49 employees) (OECD 2017). Barriers to entry in the form of intellectual property protections of market leaders may also induce higher adoption rates for large firms (Akcigit and Ates 2019). Evidence suggests that multinational firms have an extra incentive to invest in ICTs since digital technologies can help coordinate across regions (OECD and World Bank 2017). Canadian firms are typically smaller than those in the United States (**Chart 3**), which may explain some of the differences in ICT adoption between the two countries.[26]

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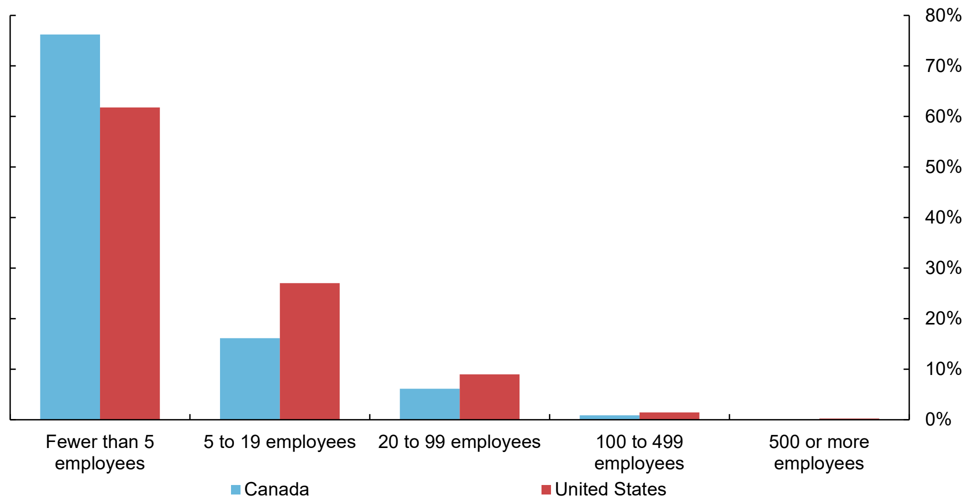
[24] Berlingieri et al. (2020) make use of the Organisation for Economic Co-operation and Development's MultiProd firm-level database, with data spanning 24 countries including Canada. They also point out that while laggard firms are characteristically young and small, policies aimed at improving digital diffusion should not focus on firm size. Rather, policy-makers should identify firms with potential for growth and customize policy efforts based on their needs.

[25] Despite higher adoption rates among large firms, the relative benefits depend on the type of technology. For example, Gal et al. (2019) suggest that enterprise resource planning has a greater impact on large firms, while smaller firms benefit more from cloud computing as a means of avoiding complex information technology infrastructure.

[26] Firm size has also been shown to explain a sizable portion of the Canada–US productivity gap (Leung, Meh and Terajima 2008).

Chart 3: Share of firms by employment size



Sources: Statistics Canada Table 33-10-0164-01, US Census Bureau SUSB Data Tables, and Bank of Canada calculations Last observation: 2019

Researchers have proposed other determinants of ICT investment. For example, economic uncertainty can reduce ICT investment because it is often less liquid than other forms of capital (Choi et al. 2018). Firm age may have mixed impacts: older firms may be less flexible due to their reliance on sizable legacy infrastructure, but they may also be better positioned because of their accumulated knowledge and organization (DeStefano, De Backer and Moussiegt 2017). Declining business dynamism could also have an impact, as large firms have fewer pressures and incentives to innovate (Andrews, Nicoletti, and Timiliotis, 2018).

4. Complementarities, spillovers and total factor productivity

TFP captures a significant portion of the impact of digitalization on labour productivity. First, the interaction of complementary investments in human skills and organizational capital interact with the existing or future digital capital stock, making their use more efficient and improving productivity. Second, the effect of digital investments can spill over to TFP growth as firms re-organize and optimize production processes or create space for more innovation. Moreover, because digitalization creates new business and industries, it affects productivity through business dynamism and competition (**Box 2**).

4.1. Complementarities between digital capital and other assets

Understanding complementarities between digitalization and other input factors is key when assessing digitalization's impact on productivity. The literature suggests that productivity gains from digitalization rely heavily on the interaction of multiple firm-level adjustments at the same time (e.g., data collection, relevant human capital and managerial practices).

The role of complementarities between ICT adoption and other investments is usually investigated using the theory of the firm that highlights synergies within the organizational structure (Milgrom and Roberts 1990; Holmstrom and Milgrom 1994). Building on the theory of organizational complementarities, studies find that investment in different assets can mutually enhance their impact on a firm's performance. This applies to both tangible and intangible investments such as ICT, digitalization, human capital, organizational structure and managerial quality (Athey and Stern 1998; Brynjolfsson and Milgrom 2013; Brynjolfsson, Rock and Syverson 2021). In general, ICT adoption, human capital investment and organizational structure are all critical factors for a firm's productivity. New technologies such as ICT and automation may reduce expenditures on specific labour skills (e.g., Acemoglu and Restrepo 2018b), improve product variety and quality, increase the flexibility of production processes and enhance economies of scale (e.g., Barua, Kriebel and Mukhopadhyay 1995; Milgrom and Roberts 1995).

Human capital investment improves efficiency of digital capital

Skills such as proficiency with computers and software programs are critical for the effective adoption of digital technologies. Such skills usually require training workers to ensure the necessary complementarity between human capital and the adopted technology (e.g., Bresnahan, Brynjolfsson and Hitt (2002). In the context of Canadian firm-level data, Turcotte and Whewell Rennison (2004) examine complementarities between various inputs in increasing labour productivity. They show that the impact of ICT adoption on labour productivity is magnified if augmented with related training programs as well as the right skill level of the workforce. This finding points to the importance of on-the-job training programs in enhancing workforce performance with ICT adoption.

Over recent decades, manufacturing industries have embraced ICT-based automation of information sharing within inventory and production management, an important component of digitalization. Jacobsen, Skaksen and ASørensen (2013) analyze this practice using a Danish firm-level dataset to explore the interaction between human capital and digitalization in improving firm performance. They show that automation in inventory and production management increases firm productivity only if the labour skill level is sufficiently high, confirming the complementarity between skills and digitalization. Additionally, Andrews, Nicoletti and Timiliotis (2018) conduct a cross-country industry-level study and show that matching existing skilled labour with the appropriate technology increases productivity growth.

The combination of organizational and digital capital leads to more informed decision making

Managerial and organizational structures can amplify the impact of ICT investments on firm productivity through, for example, management practices and decision-making processes (Bloom, Sadun and Van Reenen 2012; Arvanitis and Loukis 2009; Brynjolfsson and McElhan 2019). Using an employee–employer matched survey, Gu and Gera (2004) and Cozzarin and Percival (2010) present evidence on complementarities between ICT and workplace practices in some sectors in Canada.

The recent advancements in computing power and computational methods have popularized the use of digital information. This could improve firm performance when complemented with appropriate assets and practices. Brynjolfsson, Jin and McElheran (2021) examine this channel in the data by conducting a large firm-level survey in the United States. They show that some major components of digitalization—such as data mining, statistical modelling and machine learning—improve firm-level productivity when they are accompanied by appropriate ICT capital, management practices and organizational structure. Similarly, Chen Liu and Song (2019) show that high-speed internet significantly increases firm-level productivity, especially if it is augmented with improvements in management practices and workers with the right skill composition.

Understanding and implementing these complementarities take time. Improvement in productivity through digitalization may therefore be achieved but only after a delay, resulting in a J-curve relationship between ICT adoption and productivity (Brynjolfsson, Rock and Syverson 2021; Brynjolfsson and Hitt 2003; Calza and Rovira 2011; Marsh et al. 2017). In this context, skilled labour might become a limiting factor to faster progress. Van Ark (2016) has also suggested that a lack of relevant labour skills relative to the state of technology is one reason digital technologies have not yet offset the productivity slowdown.

4.2. Spillovers from digital capital to total factor productivity

The Solow growth accounting framework attributes the contribution of digital capital solely to its direct effect through capital deepening. This does not mean that no further benefits exist, especially through TFP. To understand these spillover effects, the literature has pursued different strategies.

Gordon and Sayed (2020) propose a method to capture the broader contribution of ICT adoption to productivity growth using aggregate industry-level data. Their findings suggest that the main impact of ICT adoption on labour productivity growth may be through TFP rather than the channel of direct capital deepening. Much of what is captured in ICT, though, is enabling the digital economy and thus is a decent approximation for firms engaging in digital activities. Therefore, the link between traditional ICT expenditure and TFP growth could be the impact of firms operating in a more digital environment, working through channels such as optimized production processes and innovation spillovers. We explore these channels in turn.

Digitalization assists in optimizing business processes

Digital technologies are shown to improve TFP through optimized business processes. The use of digital capital can impact TFP through shorter production and inspection times, improved inventory management practices and better coordination across production factors. For example, US firm-level data reveal that automation positively and indirectly affects TFP by enhancing some unmeasured input factors, such as factory floor coordination (Dinlersoz and Wolf 2018).

Using 2018 cross-sectional data, Cette, Nevoux and Py (2021) show how the use of digital technologies and the relevant ICT specialists in French manufacturing firms could improve their labour productivity by 23% and TFP by 17%. Using survey responses indicating the duration of ICT employment, they also find that it takes time for firms to fully optimize ICT skills in the workplace. This apparent impact delay reflects learning-by-doing and second mover advantage mechanisms—that is, the benefits are realized with a lag and the late adopters build on the experience of early adopters without incurring the high appropriation costs. DeStefano, Kneller and Timmis (2016) find no such evidence among UK firms. They use an alternative proxy for digitalization, namely the adoption of broadband infrastructure. They show that the use of faster internet is highly correlated with the size of the firm, resulting in an insignificant impact of faster internet on firm-level productivity.

Using US and UK firm-level datasets, Bartel, Ichniowski and Shaw (2007) and Bartel et al. (2009) show that implementing advanced computerized machines in the manufacturing industry improves productivity by shortening setup, production and inspection times. Similarly, Edquist, Goodridge and Haskel (2021) refer to recently available cross-country data on the use of AI and document a statistically significant correlation between digitalization and TFP growth. Others use cross-country industry-level data to investigate the spillovers between ICT investment and adoption on TFP and present mixed results (Inklaar, Timmer and van Ark 2008; Stiroh 2002; Strobel 2016; Acharya 2016).

Knowledge accumulation through digital technologies and automation improve total factor productivity

The spillover of knowledge and the invention of new products are two significant ways digitalization may impact TFP. Using patent data on the adoption of intelligent technologies such as AI, flexible automation, additive manufacturing and big data, Venturini (2022) and Benassi et al. (2022) document a statistically significant correlation between knowledge accumulation in digital technologies and the level of TFP across firms.

Evidence across countries and industries points to a significant impact of automation on TFP. Kromann et al. (2020) investigate the effects of automation on TFP using industry-level panel data for nine countries and find that a more intensive use of industrial robots has a significantly positive effect on TFP. Similarly, Kromann and Sørensen (2019) show that automation has a significant impact on productivity, especially for firms that face international competitors. They find this in the context of Danish administrative firm-level data combined with a survey on automation.

Box 2

How does digitalization affect market structure and competition?

Digitalization has far-reaching and impressive scope to change how firms conduct business and markets are structured. From a growth-accounting standpoint, these effects will largely show up in TFP but may also represent changes to the production function through returns to scale. We discuss two key examples featured in the literature.

Digitalization can foster business dynamism

The level of competition and market concentration has implications for the incentives of new entrants and incumbents. Digitalization plays a key role in this regard, with effects for business dynamism and productivity in the economy.[27] A lack of competitive pressure reduces investments in research and development, which in turn reduces innovations by market leaders. If the situation persists, technological progress and productivity in the affected sector will slow, with consequences for aggregate productivity (Akcigit and Ates 2019).[28] Digitalization can act as an antidote to this situation since **the production and use of digital technologies naturally results in the creation of new firms as new markets and opportunities arise.**

Only a limited number of studies have examined the implications of digitalization for business dynamism and productivity simultaneously. Calvino and Criscuolo (2019) investigate a cross-country dataset on

[27] Business dynamism is defined as the reallocation of resources from unproductive firms to more productive ones through business creation and closures. It is usually proxied by entry and exit rates of businesses in an economy.
[28] Chu et al. (forthcoming) provide a detailed discussion on the link between digitalization and competition in the context of the pricing behaviour of firms and markups.

digital adoption and business dynamism. They define digitalization through four main components: share of ICT specialists in the workforce, ICT investments, online sales and robots per employee. Their findings suggest that digitally intensive sectors are, on average, more dynamic than other sectors of the economy. However, they also find that business dynamism has been declining globally across economies, and more so in digital intensive sectors, especially since the 2000s.

Digital investments increase markups and productivity dispersion

Related to market concentration and competition, Calligaris et al. (2018) examine the distribution of markups across firms and how these relate to digitalization. They find that **markups are higher in digitally intensive sectors than in less digitally intensive sectors.** Moreover, markup differentials between digitally intensive and less digitally intensive sectors have increased significantly over time. Berry et al. (2019) argue that this divergence could be driven by the relatively larger sunk costs and lower marginal costs in digital sectors. Yet, Weche and Wagner (2021) find no empirical evidence supporting this hypothesis using German industry-level data.

Polder de Bondt and van Leeuwen (2018) examine Dutch industry-level data and show that the heterogeneity in ICT adoption increases differences in firm productivity and leads to a higher market concentration. This is also in line with the strong network effects among consumers that use goods and services such as restaurants, hotels and news provided by digital platforms (Berry et al. 2019; US Bureau of Economic Analysis 2018). The availability of big data and advanced computing technologies enables firms to reach out to a large number of consumers at low cost. Chiavari (2021) finds that digitally intensive sectors benefit from these increasing returns to scale in the form of rising market power. Iacovone, Pereira-López and Schiffbauer (2017) further investigate the relationship among ICT, competition and productivity. Using a novel dataset of Mexican firms, they show that the impact of ICT usage on TFP is amplified by the level of competition in which firms operate.

Laggard productivity firms, which are typically young and small, may also face financial constraints that limit their ability to train and attract ICT skilled labour (Berlingieri et al. 2020). **The fact that smaller firms are more constrained in their capacity to upgrade their digital capital limits their ability to catch up to the frontier and share equally in the gains from digitalization**. This is consistent with the growing evidence that digitalization is contributing to productivity dispersion at the firm level (Andrews, Criscuolo and Gal 2016; Corrado, Haskel and Jona-Lasinio 2021).

5. Future trends and open questions

5.1. Digitalization and future productivity growth

Digital technologies are potentially the next GPT in waiting (see Brynjolfsson and Mcafee 2011). AI and automating technologies, in particular, have the potential for wide-ranging impacts on the economy.

The full extent to which this structural shift has, and will continue to, impact productivity remains unclear. Though strong economic arguments have been made supporting its realization, the evidence of a large, positive impact from digital technologies on productivity has been scarce thus far. While continuing automation will certainly improve productivity levels, Gordon (2016) argues that the growth rates of the third industrial revolution represent the peak impact from digital technologies. According to Gordon, not only are these technologies constrained to a limited portion of economic activity, but we are also now confronted with "headwinds" such as rising inequality and debt. These limitations present major barriers to the emergence of digital technologies as GPTs and for future productivity growth.

Some researchers, however, point to signs of an AI-led productivity resurgence (Brynjolfsson, Rock and Syverson 2019). The argument for AI as a GPT often focuses not just on the automation of tasks, but more importantly on the improvement of the method of invention (Crafts 2021). This shift toward using digital technology such as large datasets and AI as research enhancers is already occurring and could improve the efficiency of research and development. This may, in turn, eventually feed into not just the pace of innovation but also its growth (Babina et al. 2022; Cockburn, Henderson and Stern 2019). Investments in digital technologies that occurred during the COVID-19 pandemic may contribute to these shifts (**Box 3**).

Box 3

Digitalization and productivity during the COVID-19 pandemic

During the pandemic, the sources of productivity growth have become more difficult to analyze given the volatility in the data resulting from health-related restrictions, adjustments to new ways of working and supply-chain disruptions. Nevertheless, recent studies attempt to measure how the pandemic has affected productivity. On the one hand, long-run productivity may have decreased as work from home creates less innovative and collaborative environments. On the other hand, the increased use of digital tools to facilitate collaboration may have resulted in more diffusion of digital technologies and the development of new skills (see Chernoff and Galassi 2023).

Unsurprisingly, amidst the forced isolation of the pandemic, firms and industries with pre-existing digital capital fared better than those without, as workers were able to use communication technology and other digital capital during the quarantines (Liu 2021; Cariolle and Leon 2021).[29] This is offset by non-

[29] See section 5.1 of Chernoff and Galassi (2023) for more details.

digitally intensive industries and those unable to adjust due to the nature of the work, such that aggregate patterns of productivity are unchanged (de Vries, Erumban and van Ark 2021).

In Canada, survey data indicate **that firms' investment intentions in automation and digital capital have remained consistently high since the onset of the pandemic**.[30] The extent to which productivity will benefit from the increased focus on digitalization will depend on proper organizational change management and the efficiency of technology deployment moving forward. Working from home represents a powerful example of these opposing channels for productivity growth. Overall, working from home is associated with relatively strong productivity growth for industries able to take advantage of it during the pandemic (de Vries et al. 2021).[31] Barrero, Bloom and Davis (2021a) show that better digital services and infrastructure can help firms and their employees optimize performance (see section 5.2 of Chernoff and Galassi 2023). However, the providers of the corresponding IT services have struggled with coordination costs associated with the new work arrangements (Gibbs, Mengel and Siemroth 2021). In other words, long-term benefits from new ways of working inspired by the pandemic require not only digital capital but also organizational capital to facilitate them.[32]

5.2. Some key questions

- **What is the contribution of digitalization to TFP growth?** Research on digitalization and productivity has focused on a few key areas as described in this paper. We can conveniently examine the channels through the lens of growth accounting. However, each of the channels has its own weaknesses. It is difficult to explicitly include spillovers and complementary investments in contribution estimates. Research shows that human and intangible capital greatly impact the effectiveness of digital technologies, but little has been done to quantify digital complements and their intersection with tangible capital for Canada.[33] Additionally, TFP is arguably an important channel of digitalization's impact on productivity. The very nature of TFP (defined as a residual) makes it difficult to assess, given that it includes not just technological change but also capacity utilization, input mismeasurement and any other missing inputs. More

[30] The Bank of Canada's Business Outlook Survey has cited firms prioritizing digital investments since the Summer 2020 report. For example, see *Business Outlook Survey—Second Quarter of 2022* (July).

[31] Using a survey from the Netherlands, Huls et al. (2022) suggest that while productivity may have decreased in the short-term due to the distractions inherent with working from home, more time was allocated to leisure. On the other hand, Barrero, Bloom and Davis. (2021b) find that higher levels of working from home will boost productivity, but much of the gains will not be accounted for in traditional measures because they do not account for reduced commute time.

[32] As discussed in section 3.3 of Chernoff and Galassi (2023), Canada has remained resilient in terms of post-secondary education enrolment over the pandemic, indicating that Canada may be in a relatively good position to adapt to accelerating digitalization.

[33] Corrado, Haskel and Jona-Lasinio (2021), for example, use a multi-country database that includes Canada to find that digital technologies can cause more productivity dispersion in industries with higher intangible capital. This is because larger firms are more able to invest in intangibles, suggesting complementarity between digitalization and intangible investment. This type of analysis with a Canada-specific focus would be informative.

research is needed to isolate the portion of TFP growth in Canada that has been driven by digital advancements.

- **Do we properly account for the impact of ICT services on productivity?** We can accurately measure capital deepening through direct ICT investment, but some components of capital—such as databases or AI, ICT services and intermediate imports—are likely missing in estimates. Traditional methods therefore likely understate the use of digital technologies as an input to production. Properly measuring digital capital inputs and enriching growth accounting for Canada is a promising area for future research.
- **What are the next stages of the interaction between productivity and digitalization, especially in the context of the Canadian economy?** While no consensus exists on whether the digital economy will spur future large productivity gains, a few indicators could signal imminent growth. Researchers suggest that the returns to investments, particularly for GPTs, likely come with a lag. Brynjolfsson, Rock and Syverson (2019) argue that past productivity performance (i.e., the disappointing growth of the last two decades) holds no predictive power over future gains. Gathering the capital stock and labour skills to convert a technology into a GPT that spurs large productivity gains takes a long time. The dispersion of productivity performance at the firm level could be a sign that the technology is able to boost productivity for those at the technology frontier but simply has not yet been diffused broadly. The catch-up of laggard firms to sector-leading firms could be a sign that digital diffusion and subsequent productivity growth is occurring.
- **What key assets should accompany digital capital to promote productivity?** A lack of skills in the economy may be restricting the use of digital technologies and limiting their effect on productivity (van Ark 2016; Berlingieri et al. 2020). Jacobs and Nahuis (2002) suggest that the introduction of GPTs can initially result in slower productivity growth as skilled workers focus on learning rather than on actual production. Increased complementary skills and investment in business and managerial processes could be signs of future productivity gains from new technologies. More research is needed to investigate these complementarities in the Canadian economy.

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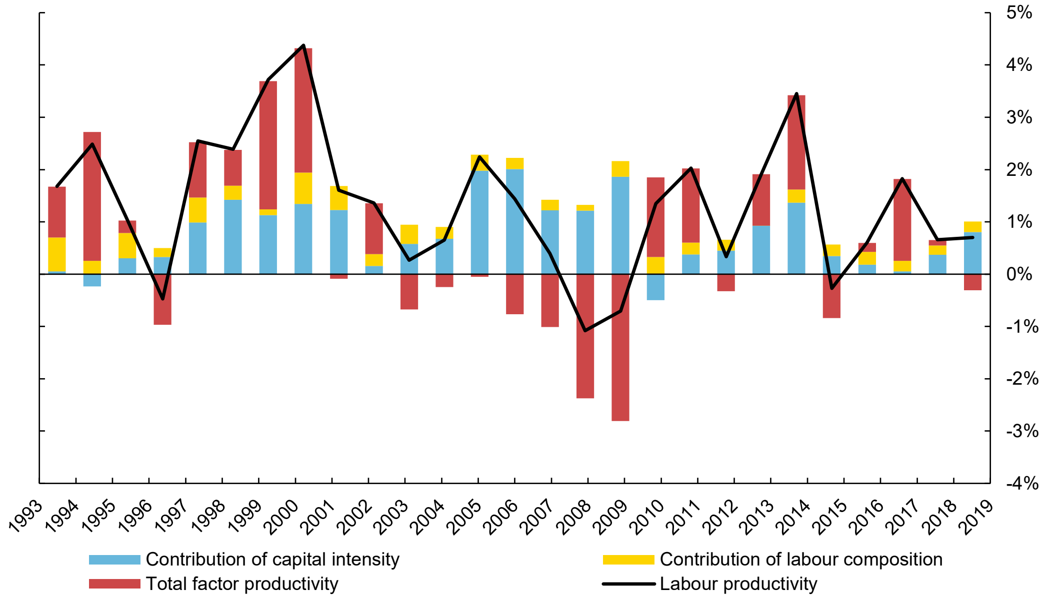
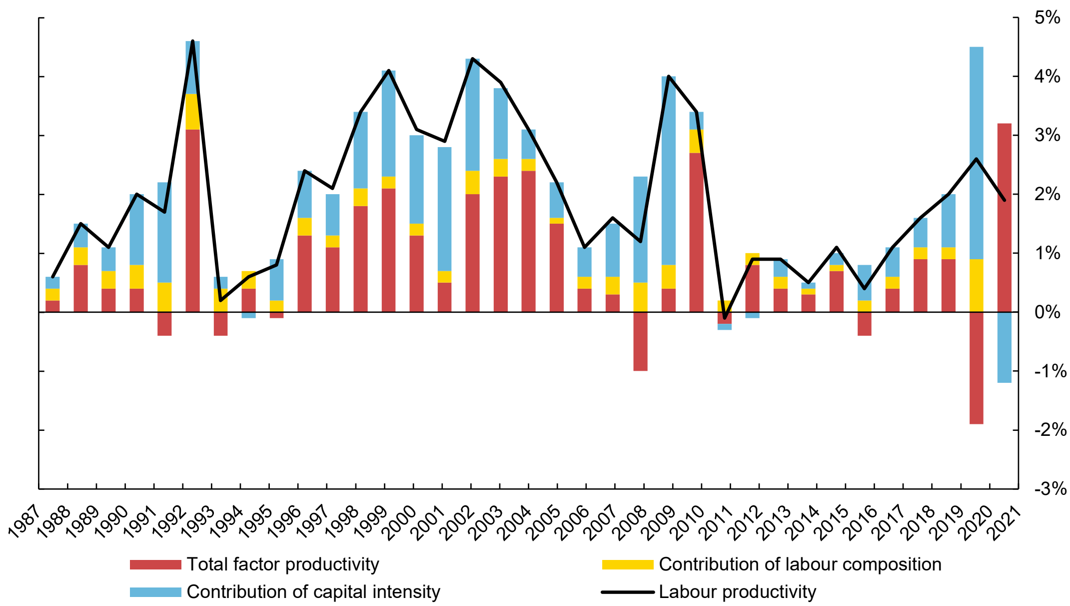
Appendix A: Growth accounting details

Chart A-1: Decomposition of labour productivity growth—Canada



Source: Statistics Canada Table 36-10-0208-01

Chart A-2: Decomposition of labour productivity growth—United States



Source: US Bureau of Labor Statistics total factor productivity and related measures tables

Table A-1: Decomposition of labour productivity growth—Canada

	Labour productivity	Contribution of capital intensity	Contribution of labour composition	Total factor productivity
1993–2002	2.1%	0.7%	0.4%	1.0%
2003–09	0.5%	1.4%	0.2%	-1.1%
2010–19	1.3%	0.4%	0.2%	0.6%

Table A-2: Decomposition of labour productivity growth—United States

	Labour productivity	Contribution of capital intensity	Contribution of labour composition	Total factor productivity
1993–2004	2.5%	1.2%	0.3%	1.1%
2005–09	2.0%	0.3%	0.3%	1.4%
2010–19	1.3%	0.6%	0.2%	0.5%

Note: Tables A-1 and A-2 use different time periods to highlight differences in phases of productivity growth.

Appendix B: Shift-share decomposition

We adapt the decomposition proposed by Tang and Wang (2004) to our application and derive the used relationship.

Aggregate labour productivity can be expressed as:

$$X = \frac{Y}{L} = \frac{\boldsymbol{\Sigma}_i Q^i}{PL}, \qquad (\mathrm{B}-1)$$

Where Y is real output, L is labour input and Q^i is nominal output for industry i. Define p^i = P^i/P, or the relative output price; l^i = L^i/L, or the labour input share; and s^i = $p^i l^i$, or the labour input share adjusted for its relative output price. The growth of labour productivity can be written as:

$$g(X_t) = \frac{X_t - X_{t-1}}{X_t}. \qquad (\mathrm{B}-2)$$

Expanding and rearranging, we get the following:

$$g(X_t) = \boldsymbol{\Sigma}_i \frac{Q^i_{t-1}}{Q_{t-1}} g\left(X^i_{t-1}\right) + \boldsymbol{\Sigma}_i \frac{X^i_{t-1}}{X_{t-1}} \Delta s^i_t + \boldsymbol{\Sigma}_i \frac{X^i_{t-1}}{X_{t-1}} \Delta s^i_t \, g\left(X^i_t\right). \qquad (\mathrm{B}-3)$$

The three components of equation (B-3) are the shift-share decomposition. The first component, the within-sector effect, is simply labour productivity growth in industry, *I*, weighted by nominal GDP. The second component, the reallocation-level effect, states that as labour shifts across industries, moving to an industry with a higher level of productivity provides a one-time growth effect. The third component states that as labour shifts to an industry with higher growth at time t, it will also impact aggregate labour productivity.