BELL CANADA'S SUBMISSION TO THE
Telecommunications Policy Review Panel

Appendix E-1

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Canada's Productivity Dilemma: The Role of Computers and Telecom

Bell

Executive Summary

"In 2004, Canadian businesses recorded their worst performance in labour productivity growth in eight years as both economic activity, hit by the rising Canadian dollar, and the number of hours worked increased in tandem for a second year in a row … Productivity is measured as the ratio of output for every hour worked. For example, it improves when GDP increases more rapidly than the number of hours worked. Productivity growth is a key factor determining the living standard of Canadians."

-- Statistics Canada, *The Daily*, March 10, 2005

According to most research, Canada has lagged its major trading partner, the United States, in productivity growth since the middle of the 1990s. That is when U.S. productivity growth began to accelerate, fuelled by what Alan Greenspan, the Chairman of the U.S. Federal Reserve Board, has labelled the New Economy. This phenomenon was triggered by the combination of high economic growth and low inflation which, in turn, was enabled by the rapid penetration of new information and communications technologies (ICT) across the U.S. business landscape.

Table E-1: ICT contribution to productivity growth, Canada vs. U.S., 1995 -2000[2]

	Canada	United States
Labour Productivity Growth	1.76%	2.49%
ICT Contribution to Labour Productivity	1.25%	2.14%

As Table E-1 shows, research indicates that Canada fell behind the U.S. in the adoption of ICT in the last five years of the 20th century. Labour productivity growth and the contribution of ICT to labour productivity have been lower in Canada than in the U.S. Further, the years since 2000 have not seen a catch-up in Canadian performance. Since productivity drives income and living standards, any gap with the U.S. – especially if that gap is widening – signals problems for Canada. Falling productivity makes our exports more expensive or puts downward pressure on the Canadian dollar. Lower income growth makes it more difficult to retain and attract workers.

It is important, then, to determine the reasons for differential productivity performance in Canada in relation to the U.S. and relative to other countries as well.

A number of researchers have examined productivity growth (the changes in output per hour) and accounted for its sources. This research on "growth accounting" breaks into constituent parts the changes in productivity to key drivers, principally the amount of capital (both ICT and non-ICT) that labour has to work with – called "capital deepening." Studies generally show that

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[2] Van Ark, et al (2003)

Canada uses less ICT capital per hour worked than the U.S. and that this difference is significant in explaining lower productivity growth. This is a crucial finding: ICT's importance to the economy is far greater than its share of GDP (about 5% in Canada in 2002[3]) would seem to indicate.

This report goes farther than the growth-accounting literature, which cannot explain the majority of labour productivity changes. The models in that literature cannot explain technological progress also drives labour productivity.[4] Using data for 16 countries over the 1980-2000 period and data for five of these countries (Canada, U.S., the United Kingdom, France, and Finland) to 2003, the econometric model we employ here adds key characteristics to explain why ICT may be so important. Our model captures different levels of technology among countries by adding three characteristics of ICT: The number of personal computers (PCs) per capita, the number of telephones (mainline and mobile) per capita, and the spread of the digitalization of telephone exchanges.

In this model, it is not just the accumulation of ICT capital per hour that drives labour productivity differences, but the diffusion of technological change represented by three proxies – the diffusion of PCs and of telephones, as well as the digitalization of telephone exchanges. All three of these technological advances are vital to the New Economy. Telephones per capita measures the reach of communications in the country. Digital telephone exchanges enable the digital information revolution.

Of course, the New Economy is more than a PC and a telephone in every home. And modern telephony now includes broadband and fibre-optic transmission. However, there are limits to available data on more complicated proxies, and using these three measures adds an important element to the literature and to the understanding of what drives productivity. The "spillover" impact of these three measures accounts for the diffusion of technology across economies.

Table E-2 provides a summary of the basic results indicating Canadian output per hour worked fell behind that of the U.S. by 18% in 2000 and by 21% in 2003. These values are similar to findings by other researchers, but are higher than the recent estimates of the labour productivity gap made by John Baldwin and colleagues at Statistics Canada.[5] Collectively, these studies show a worrisome trend: a widening gap between Canada and the U.S. in labour productivity since 2000.

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[3] See http://strategis.ic.gc.ca/epic/internet/inict-tic.nsf/en/it07183e.html.

[4] Factors such as new management techniques and better organisation of work also drive labour productivity.

[5] Baldwin et al estimate that the labour productivity gap in 2002 was 7%. See Baldwin, Maynard and Wong (2005)

Table E-2: Sources of Labour Productivity Differences: Canada vs. U.S., 2003[6]

	Percentage	Proportion of Percentage Difference	95% Confidence Interval
Difference	21%		
Contributions			
Non-ICT Capital Deepening		5%	
Hours/ Scale		15%	
ICT		56%	(51%, 61%)
ICT Capital Deepening		12%	
ICT Spillovers		44%	(40%, 48%)
Telecom Penetration		2%	
IT Penetration		42%	(38%, 46%)
PC Penetration		31%	
Digital/PC Interaction		11%	
Unexplained by Above Factors		25%	

Sources of Labour Productivity Differences: Canada vs. U.S., 2000

	Percentage	Proportion of Percentage Difference
Difference	18%	
Contributions		
Non-ICT Capital Deepening		2%
Hours/ Scale		18%
ICT		60%
ICT Capital Deepening		17%
ICT Spillovers		43%
Telecom Penetration		3%
IT Penetration		40%
PC Penetration		30%
Digital/PC Interaction		10%
Unexplained by Above Factors		20%

[6] Explanation of Variables:

- Difference refers to labour productivity per hour in the U.S. divided by labour productivity per hour in Canada
- Non- ICT Capital Deepening refers to the percentage of the Difference which is due to higher non-ICT capital per worker in the U.S. than in Canada
- Hours/scale refers to the percentage of the Difference which is due to the advantage of being larger – economies of scale where we measure size by hours worked
- ICT refers to the percentage of the Difference due to all ICT factors
- ICT capital refers to the amount of ICT capital stock per hour
- ICT spillovers refers to the combination of Telecom and IT penetration per hour
- Telecom Penetration is measured by total telecoms – mainlines and mobile refers to the amount of ICT capital stock per hour
- IT Penetration is the sum of PC penetration and the interaction of PC and digitalization of exchanges
- PC penetration is PCs per capita
- Digital/PC interaction is the interaction of PC penetration and the percentage of exchange digitally enabled

ICT (telecom and computer capital and their spillovers – telephone penetration, PC penetration and the digitalization of telecom networks) accounted for 60% of the Canada-U.S. labour productivity gap in 2000 and 56%[7,8] in 2003. These important results indicate how the contribution of ICT is more than the amount invested in computers and telecom equipment (which by itself directly raises GDP). ICT also increases productivity; as it becomes more widespread across society there are spillovers from ICT investment. Modern production techniques rely on the ability to transport vast amounts of data between computers in multiple locations at factories, stores, homes, government, and in academia. Well-known business cases — Zara in clothing, Cemex in cement, and Dell in the production of computers – demonstrate the importance of linking computers and telecommunications networks for instant high-speed communication. It should come as no surprise, then, that the gaps in ICT between the U.S. and Canada figure prominently in the productivity gap.

Of the factors listed in Table E-2, PC penetration explains a large percentage of the gap. As stated, PCs are a proxy for ICT diffusion, so the spread of PCs indicates their wide use and acceptance in the home and in businesses. Note that productivity increases are not linked merely to PC penetration. It is also the connectivity of these computers – enabled by telecommunications' networks and measured by the interaction of PCs and the digitialization of telecom networks – that also impacts productivity performance. In essence, the spread of PCs and of telecoms have network effects – the more there is of both, the higher generally is their value.

There are a number of reasons why it is important to account for this networking aspect of telecommunications in analyzing productivity gaps. Advances in transmission capabilities – through digitalization and fibre optics – have allowed for the *economical* transfer of enormous amounts of data at high speed, supporting the computer-to-computer communication that has become vital to business. This "network effect" must be considered when examining productivity. Technological advances in transmission capabilities, provided at reduced costs, aided the widespread adoption of the Internet that, in turn, helped businesses reduce expenses through better communication. The essential role of telecommunications in providing the network through which computers connect must be accounted for in understanding Canada's lag in productivity in relation to the U.S.

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[7] This figure is quite tightly estimated. A 95% confidence interval for 2003 is 51% to 61%.

[8] While the percentage ICT contribution fell from 60% in 2000 to 56% in 2003, the 2003 proportional contribution was applied to a larger labour productivity gap. Hence the absolute gap attributed to Canada's lower level of ICT capital and lower diffusion of ICT technology remained essentially unchanged between 2000 and 2003 in these data. As explained in the text, there is a possibility that Canada's position vis a vis the U.S. may have deteriorated somewhat between 2000 and 2003.

Table E-3, presents the ratio of the estimated number of PC's installed in the U.S. relative to Canada, based on research from IDC Canada.

Table E-3: U.S./Canadian Intensity Ratio*

	2003	2004	2005
Home	0.88	0.91	0.93
Small Business (1-99 employees)	1.21	1.23	1.30
Medium / Large Business (100+)	1.64	1.67	1.72
Government	1.66	1.71	1.75
Education	1.56	1.57	1.59
Total	**1.14**	**1.16**	**1.19**

* Calculated as the number of PCs in use in the U.S. relative to Canada. A ratio less than one shows that PCs per capita are greater in Canada than in the U.S. Conversely, a number greater than one indicates the reverse.

The number of PCs in homes in Canada is approximately one-ninth the number of PCs in American homes, a slightly higher ratio than the ratio in population. Clearly, then, the large gap in the diffusion of PCs between Canada and the U.S. lies not in the residential sector – per capita, there are more PCs in Canadian homes than in American ones – nor in small firms, but in medium and large businesses, education and government.

This sheds a light on Canada's relatively poor productivity performance**:** *There is a significantly lower accumulation of ICT by medium and large firms, education and government in Canada.*

Policy conclusions are beyond the scope of this paper. It is, however, important to note the lower adoption of PCs across Canadian industry, government and education. Several studies have examined the ICT investment behaviour of firms and the impact of ICT on firm performance and profitability.[9] The ability of ICT to transform production requires more than an addition to the ICT stock. It is not only an issue of "a PC on every desk." The transformational ability of ICT requires deep changes to a firm's organization, the types of processes, and the nature of what is produced – what Brynjolfson and Hitt called "The Digital Organization."

The major difference in the stock of PCs in Canada used by medium and large corporations compared to U.S. firms may signal reluctance in Canada by managers to embrace completely the New Economy and the significant changes it requires. But further analysis is needed before policy conclusions can be made. The mix of industry is different in the U.S. and Canada, and this may explain part of the gap. If U.S. industry has been quick to adopt ICT, this may reflect the intense competitive nature and flexibility of the U.S. generally.

What can government do? Two possibilities emerge. The first is to eliminate barriers to ICT adoption and ensure that general policy is consistent with expanding the ICT base to maximize spillovers to productivity. Many other countries have implemented changes to tax codes to allow faster write-offs of ICT. This also could be beneficial in Canada. The second

[9] Brynjolfson and Hitt (2002)

possible response depends on gaining a deeper understanding of why ICT is not as diffused in Canada as it is in the U.S.

Importantly, governments in Canada do not appear to be leaders in the New Economy, at least as measured by PCs in use. Leadership by example is important. Governments themselves can become leaders in the New Economy.

The gap between the U.S. and Canada in ICT in the education sector also is deeply troubling. Here the issue is not so much about how education could be more productive if ICT were spread more widely within the sector, but how the educational sector is using ICT and the attitudes being developed in students as to the ICT revolution.

Canada's Productivity Dilemma: The Role of Computers and Telecom

1 Introduction

1.1 The Gap

Interest in productivity performance is in no way an esoteric pursuit. It is of critical importance to all of us. Productivity is the long-term driver of income growth and well being in economies. It drives prosperity. Productivity depends on the quantity and quality of the factors of production available to a country and the social framework in which they operate. That framework includes basic property rights, rule of law, openness, and sector-specific issues such as regulation. According to the Conference Board of Canada's recent publication *How Can Canada Prosper in Tomorrow's World? "*Productivity alone can provide us with the resources required to build the future Canada that we want."

Productivity is generally measured in two ways: Output per hour worked, or labour productivity, and output per total input (i.e., labour and capital), called total factor productivity (TFP). Most Western economies began to experience a productivity slowdown after 1973. In the U.S., measured economy-wide productivity – both labour productivity and TFP – averaged just 1.7 % annually in the 1973—1993 period, well below the averages of the proceeding decades.[10] Since productivity growth is the underlying source of growth in income per capita, reversing the productivity slowdown was crucial.

In the late 1980s and early 1990s, this slowdown in productivity growth in the U.S. was of particular concern given the large capital investments in Information Technology (IT) and the increases in labour skills accompanying the spread of the new computer technology. Robert Solow, Nobel Prize Laureate in Economics, lamented in 1987 that one saw "computers everywhere but in the productivity statistics."[11] However, beginning about 1995, both labour productivity and TFP began to surge in the U.S. However, it was not until the landmark study of Jorgenson and Stiroh in 1999 that economists recognized that something unusual actually had occurred in U.S. economy-wide productivity in the mid 1990s. This unexpected surge caught most people off stride.

It is now widely agreed that the technical advances in the information and communications technologies (ICT) led to large direct and indirect benefits to economic growth and productivity.

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[10] Federal Reserve Bank of San Francisco, Economic Letter, 2002-34, November 15, 2002.

[11] New York Review of Books, July 12, 1987.

Jorgenson (2000) summarizes the ICT productivity growth literature for the U.S. as follows:

> *"The vaulting contribution of capital input since 1995 has boosted growth by close to a percentage point (in the U.S.). The contribution of investment in IT accounts for more than half of this increase. Computers have been the predominant impetus to faster growth, but communications equipment and software have made important contributions as well."*

Studies show that the New Economy effects of ICT investment have so far spread less throughout Europe and in Canada than in the U.S. [12] Table 1.1 highlights the differences in growth in value added per worker over the 1995-2000 period between the U.S. and Canada, as well as the European Union (EU). The New Economy appears to be largely a U.S. phenomenon, with significantly higher growth rates in the ICT-producing and ICT-using sectors. Note that Canada has the highest annual growth rate in value added per worker in the non-ICT-using sector, but lags the U.S. in growth rates in both the ICT-producing and ICT-using sector and trails Europe in the ICT-producing sector.

Table 1.1: Average Annual Growth Rate in Value Added per Person Employed (In Canada, the U.S. and European Union 1995-2000)*

	Canada	U.S.	E.U.
ICT-producing sector	7.1% (24%)	10.1% (30%)	8.7% (33%)
ICT-using sector	3.2% (47%)	4.7% (56%)	1.6% (29%)
Non-ICT sector	0.8% (30%)	0.5% (14%)	0.7% (34%)
Average for entire economy	1.8% (100%)	2.5% (100)	1.4% (100%)

***Contribution to the overall growth rate given in brackets.

Table 1.2 provides data for 1995–2000 for Canada and the U.S. showing labour productivity growth and the portion of labour productivity growth attributable to ICT. As demonstrated in the table, productivity is accelerating in the U.S. While acceleration is occurring in Canada, it is not happening as fast. Other studies report similar findings. Harchaoui and Tarkhani (2004) estimate that labour productivity grew in Canada at about half the U.S. rate in the 1995–2000 period (1.31% in Canada, 2.46% in the U.S.).

It is critical to understand why these differences in national productivity performance exist and whether policies can be devised to enhance Canadian performance.

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[12] See Van Ark, Inklaar and McGuckin (2002).

Table 1.2: ICT contribution to productivity growth, Canada vs. U.S., 1995 -2000[13]

	Canada	United States
Labour Productivity Growth	1.76%	2.49%
ICT Contribution to Labour Productivity	1.25%	2.14%

1.2 Labour Productivity to 2003

It is perhaps surprising that there are significant differences among research findings in measured labour productivity in Canada relative to the U.S. Sulzenko and Kalwarowsky (2000) claim a 15% gap in favour of the U.S. Sharpe (2001) and Card and Freeman (2002) claim Canadian productivity was 20% below U.S. levels in the mid to late 1990s. Rao, Tang and Wang (Industry Canada, 2005) studied Canada – U.S. labour productivity gaps (real GDP per hour) for the 1987–2003 period for the business sector and manufacturing. Their analysis shows a sharp deterioration in Canada since 1995, especially in manufacturing, where Canadian productivity was above 90% of U.S. levels in 1995 but fell to below 70% in 2003.

A study by Baldwin, Maynard and Wong (2005) for the 1994–2002 period suggests that the labour productivity gap between the U.S. and Canada over that period averaged only 5.8%, far less than all other researchers report (including our reports below).[14] The differences in these estimates relate to whether labour productivity is measured per employee or per hour and the ways in which employees or hours are measured. In this report, we use output per hour as the appropriate measure of labour productivity to estimate a 21% gap between Canadian and U.S. labour productivity in 2003 (see Section 4 below[15]).

What is clear from all studies are several facts:

- Canadian labour productivity and TFP followed closely the U.S. experience over the 1973-to-1995 period, but with Canadian productivity somewhat ahead of the U.S. until the early 1980s

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[13] Van Ark, et al (2003).

[14] Baldwin et al's work is important to the extent that they are correct that the U.S. and Canada report hours worked on different bases, and that this difference is significant for measured labour productivity. They adjust U.S. hours upward and, in so doing, lower the relative gap between Canada and the U.S. We cannot study the implications of Baldwin et al's work for several reasons. Their adjustments to hours worked begin only in 1994 and our required data begin in 1980. The adjustments are made for only for one country- the U.S.- and we have no way of knowing whether similar adjustments should be made for the European countries in our sample.

[15] Baldwin, Maynard, Tanguay, Wong and Yan (2005), (hereafter Baldwin et al) provide the detailed analysis of how they alter the standard data to arrive at their estimates. One percentage point of the difference between our measures of per hour productivity differences relative to the U.S. is due to the fact that Baldwin et al measure relative productivity as Canadian values divided by U.S. values whereas other researchers, including us, have the U.S. values divided by Canadian values. Two percentage points of the

and then somewhat behind until the early 1990s. In neither country was productivity growth strong.

- Canadian labour productivity growth did not match that of the U.S. in the 1995-2000 period -- all research except Baldwin, Maynard and Wong (2005).
- Canadian productivity performance has not matched the U.S. performance over the most recent 2000-2003 period. While Baldwin et al give the lowest estimate of the labour productivity gap between the U.S. and Canada, even this research shows a deterioration post- 2000.[16]

1.3 The Contribution of ICT to Labour Productivity Growth

Table 1.3, assembled by Michael Tretheway, shows the contribution of ICT to economic growth as measured by a number of economists for nine countries, including Canada. Of the nine countries, Canada had among the highest GDP growth rates in the 1995–2000 period – near 5%. However, the percentage contribution of ICT to this growth was the lowest of the nine countries summarized, a performance tied with France. The U.S., Japan and Australia had the largest contributions from ICT to economic growth – 27% to 33%. For Canada, the contribution of ICT to growth is estimated at between 11% and 14%, roughly one-third of the impact of ICT on growth for the top three countries. Imagine what Canadian prosperity would have been like if Canada raised its ICT performance.[17]

Some observers suggest there is no problem – Canada's GDP growth rates were high; they were above the growth rates of many countries. However, when we observe Canada lagging behind many countries in productivity performance and unable to match world leaders in ICT contribution to the economy, there are, indeed, profound reasons to be deeply concerned. Canada's strong GDP growth performance may turn out to be an unusual blip and may not be sustainable long term if the underlying ways we produce goods and services do not keep pace with our neighbours and competitors.

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difference is explained by Baldwin et al's adjustments to purchasing power parity values. The bulk of the difference – ten percentage points - emanates from Baldwin et al's adjustments to U.S. hours worked.

[16] They estimate a 4.2 % gap in 2000 increased to 6.2% in 2002. This deterioration of 1% a year, if sustained, would, of course, amount to an additional 10% gap over 10 years.

[17] We do not here account for important differences such as industry mix between countries that may explain part of ICT contribution.

Table 1.3: The Link between ICT and Economic Growth

Country/Study	Overall Economic Growth Rate	Percentage Point Contribution of ICT	ICT Contribution to Economic Growth	Period
Canada				
Armstrong et. al. (2002)	4.9%	0.7	14%	1995-2000
Khan and Santos (2002)	4.75	0.5	11%	1995-2000
United States				
Jorgenson et. al (2002)	4.6%	1.3	28%	1995-2000
Pakko (2002)	4.3%	0.8	19%	1995-2000
Japan				
Motohashi (2002)	1.5%	0.5	33%	1995-2000
Germany				
RWI and Gordon (2002)	2.5%	0.5	20%	1995-2000
France				
Cette, et. al. (2002)	2.2%	0.3	14%	1995-2000
United Kingdom				
Oulton (2001)	3.1%	0.6	19%	1995-2000
London Economics	3.2%	0.8	25%	1992-2000
Australia				
Simon and Wardrop (2001)	4.9%	1.3	27%	1995-2000
Belgium				
Kegels, et. al. (2002)	2.8%	0.5	18%	1995-2000
Korea				
Kim (2002)	5.0%	1.2	24%	1995-2000

1.4 The Varying Impact of ICT

But how do we explain these significant differences in economic performance across countries and, in particular, between Canada and the U.S.?

First, there is a lower level of ICT diffusion across much of the world when compared to the U.S.

We estimate that in Canada in 2003 this gap in PC diffusion per capita relative to the U.S. was approximately 33%. The amount and the diffusion of ICT varies widely across countries studied, with the U.S., Canada, New Zealand, Australia, the Nordic countries and the Netherlands having the highest rates of diffusion of ICT while Italy, Spain, Portugal, and Greece have lower rates. A lower level of ICT adoption in a country compared to the U.S. means less ICT capital per worker. Since ICT capital is an important source of overall productivity enhancement, these lower diffusion levels will, by themselves, lead to lower productivity performance in the economy relative to the U.S. This may not represent permanent bad news: If the lower ICT investment in Economy X relative to the U.S. is because of adoption lags, productivity could rise toward U.S. levels when adoption of ICT catches up to the U.S.

However, it appears the level of ICT investment in the U.S. is not slowing down – and may even be accelerating. Also, the amount of ICT capital in a country masks the ICT diffusion pattern – how it is spread across sectors and this diffusion pattern may be important.

Furthermore, countries may not catch up for a number of reasons. Several important papers have demonstrated that for ICT to be truly valuable in raising productivity, a set of complementary capital and skills are required (Brynjolfsson and Hitt, 2002). Finally, an inability to capture fully all the productivity enhancement improvements flowing from ICT may signal managerial failure.

Second, while in the U.S. the impact of ICT capital on productivity growth initially occurred in the ICT-producing sectors – see Gordon (2000), Jorgenson and Stiroh (2000) – these beneficial impacts moved quickly to ICT-using sectors, namely wholesale and retail trade and finance.

In Canada and in Europe, in contrast, little acceleration in productivity growth in ICT-using sectors is evident – indeed several studies show a *fall* since 1995 in productivity growth in the main ICT-using sectors outside the U.S.

For example, the UK has Europe's most flexible labour market and the largest finance sector outside the U.S.[18] Yet, recent analyses by Basu et al (2004) show that labour productivity in UK retail trade *fell* relatively by 1.9% per year in the 1995–2000 period (compared to 1990–1995), while it *rose* relatively by 4.5% per year in the U.S. In wholesale trade, productivity in the U.S. rose relatively by 3.7% in this latter period, but only by 0.3 percent in the UK. Other studies of the U.S. – McKinsey, (2001), Triplett and Bosworth (2002) – also show the acceleration in productivity in these three main ICT-using sectors. Several studies, including Parham (2002) and Gretton et al (2002), have shown strong productivity growth from ICT in Australia in both ICT-producing and ICT-using sectors. The Canadian picture noted above is mixed.

Few researchers attempt to distinguish the two components of ICT – computers and telecom networks. That is, are there differences in the investment, usage profiles of telecom, and IT between the U.S. and Canada and other countries?

1.5 The Telecommunications Part of ICT

"Until the mid 1990s, the billions of dollars that businesses had poured into information technology seemed to leave little imprint on the overall economy. The investment in the new technology arguably had not yet cumulated to a sizeable part of the U.S. capital stock, and computers were still being used largely on a stand-alone basis. ***The full value of computing power could be realized only after ways had been devised to link computers into large-scale networks…****"*

-- Alan Greenspan[19]

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[18] A study of OECD countries shows a correlation between stricter product market regulation and lower ICT diffusion as well as a correlation between stricter employment regulations and lower ICT diffusion.

[19] Remarks of Alan Greenspan, 'Technology Innovation and its Economic Impact' before the National Technology Forum, St. Louis MO April 7, 2000, emphasis added.

The quote above underlines the importance of telecommunications as part of ICT. It is not simply the spread of computers that generates productivity increases but the ability to interconnect computers via modern telecommunication systems. The New Economy is, indeed, a product of technical advances and the spread of computing but it is also the result of the equally rapid advances in telecommunications. In essence, the "productivity miracle" [20] is a result of not just the computer itself but of "The Networked Computer." [21]

There are a number of reasons why the networking aspect is important. First, productivity in the U.S. did not slowly increase from year to year but seemed to explode in 1995. What caused this explosion? Could there have been "network effects" in computer growth and in IT's impact on growth and productivity? Second, we know of significant advances in telecommunications networks – digitalization of exchanges and the spread of fibre-optic transmission – that made it possible and economical to transmit huge data flows between firms, offices and locations. But these advances in telecom networks must be modelled for what they are – network effects – and not summarized in a static framework. Few studies examine the telecommunications role in ICT and those that do ignore the networking aspect. That is, telecom is treated as either an information-communications-using sector or an information-communications-producing sector and its contribution to growth and productivity measured directly. Those studies that do analyse telecoms in this productivity and growth literature do not address telecom's essential nature – it is the network medium on which computers ride. Hence, it is not just the fall in prices of telecom equipment and computer prices that is important but also the spread of telecom and computing technology, and the interaction between computing and telecom developments

The studies we have summarized above are growth-accounting exercises. That is, they are basically accounting identities with output (GDP) changes being accounted for by the changes in the underlying variables that make up GDP – essentially labour and capital. These calculations are also basically static and thus it is difficult to attempt to relate unexpected breaks in behaviour to their underlying causes. The econometric model we use in this report estimates statistically the relationships that drive GDP and productivity.

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[20] Jorgenson (2004) states "Communication technology is crucial for the rapid deployment and diffusion of the Internet, perhaps the most striking manifestation of information technology in the American economy." We attempt to determine whether the spread of modern telecom in conjunction with computers helps explain the productivity puzzle. We do this by including three kinds of capital in the economy- wide production function- computer and software capital, telecom capital, and other non-ICT capital. Both the computer and telecom capital stocks have associated characteristics such as memory (computers) and digitalization (telecom) which are (potentially) determined endogenously.

[21] This is the proposed title of a book we are working on.

1.6 Data and the Undervalued Role of Telecom

There is some literature, now 20 years old, examining the contribution of telecommunications to growth and productivity. Leff (1984) was one of the first to analyze whether the spread of communications systems lead to spillovers for the economy. Leff analyzed both one–way (radio) and two-way (telecommunications) developments in countries over the 1960–1980 timeframe. Leff and other studies identified spillovers to economic growth from the spread of mainlines. Roeller and Waverman (2001) provide a more articulated model that incorporates the demand and supply of mainlines in order to control for endogenity. That is, they identify separately the contribution of increases in mainline telecom penetration on GDP and the increased demand for mainlines that results from income growth. They find a high spillover from the spread of mainlines as networks approach universal service. In this report, we use an extension of the Roeller-Waverman framework to model the impacts of both computer and telecom capital, as well as several characteristics of these capital stocks in order to re-examine the ICT/growth/productivity issues.

Since 1985, the U.S. has adjusted the capital stock and prices of computers in its National Accounts to account for quality changes – a dollar spent on a computer in 2005 buys much more computing power than a dollar spent 20 years ago. Many countries, including Canada, follow U.S. procedures. Changes in the quality and price of communications equipment are not as comprehensively accounted for. The prices of switching and terminal equipment, where technical advances essentially have been the incorporation of semiconductors, are adjusted for quality changes in the U.S. and several other OECD countries.[22] The enormous changes in transmission capabilities of telecom networks are not accounted for in any national statistics for the 1980–2003 period.[23] That is, national statistical agencies treat a dollar spent on investing in a microwave system in 1985 as similar to investing in a fibre optic cable in 2005, with average changes in producer costs considered. However the huge advance in the carrying capacity of transmission equipment is not accounted for. Thus, national statistics generally under-report the productivity embodied in telecom networks.

In addition, digitalization of exchanges enabled the spread of computer-to-computer communications. This technical advance changed the basic nature of the way firms operate and

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[22] Australia, Canada and France use hedonic output price indexes. Denmark, Sweden and the UK use U.S. deflators along with currency adjustments (see Van Ark et al. 2002)

[23] In brief, in the 1950s and 1960s transmission of telephony – essentially voice calls, between cities and countries- utilized cables. In the 1970s and 1980s, microwave radio became the new dominant transmission technology across land. In the 1990s, extraordinary advances in fiber-optic technology led to their use for most transmission, including sub-oceanic. In 1956, the first trans–oceanic cable TAT-1 that joined North America and the UK had a capacity of 83 simultaneous voice calls. In 2002, one single cable- the FLAG fiber optic cable- had a capacity of millions of voice calls.

communicate. Hence, digitalization of telecom networks across countries is an important characteristic of modern telecom networks and is a characteristic included in our analyses

It is these advances in transmission technology and the fall in costs per voice channel that have helped spur the Internet explosion and the concomitant ability of firms to use communications as a tool to cut costs. For example, just-in-time production requires the ability to transfer vast amounts of data speedily between plants, offices, suppliers and stores – often across several continents.

The nature of the extent of the data issue in accounting for telecoms properly can be documented simply. Harchaoui, Tarkhani & Khanam (2004) estimate significant price declines for computer equipment for Canada and the U.S. from 1981–2000 as follows: for computer investment, minus 15.3% per year for Canada and minus 15.5% for the United States; for software, minus 2.11% per year for Canada and 0.7% for the U.S. They estimate, however, that the price of telecommunication equipment grew at 0.6% per year in Canada, while it fell only 0.1% per year in the U.S. It is not credible for prices of constant quality telecommunications equipment not to have followed somewhat the same path as computer prices [24].

Table 1.4 is taken directly from Doms (2004). Note the remarkably similar growth in nominal levels of investment in computers and communications equipment in the U.S., but the surprising differences in "real" growth rates based on official price deflators. That is because the "quality" of computers is carefully tracked, while the "quality" of telecom equipment is not carefully modeled. The growth rates of "real'" computing are estimated to have grown at rates three times as great as real telecom equipment. This difference in real growth rates is likely a statistical artifact.

Table 1.4: Business Investment in Computers and Communications Equipment[25]

	Computers	**Communications Equipment**
Average nominal growth in investment (%)		
1990- 1995	5.6	5.0
1995- 2000	10.6	10.5
1990- 2000	8.0	7.6
Level of investment, 2000 ($ billions)	**109.3**	**116.3**
Average annual price change (%)		
1990- 1995	-12.6	-1.1
1995- 2000	-21.6	-2.9
1990- 2000	-17.6	-2.1
Average real growth rates (%)		
1990- 1995	20.9	6.2
1995- 2000	41.0	13.8
1990- 2000	31.1	9.9

Note: price changes and corresponding real growth rates use official BEA values.

[24] Jorgenson (2004) suggests that the pace of advance in transmission is indeed faster than in computing.

[25] From Doms, 2004

Doms uses a variety of sources to make back-of-the-envelope adjustments to the prices of imported components of machine (not mobile) systems. As a result of his adjustments, he suggests an average price fall for communications equipment of between 6.4% and 10.6% per year, two to three times as great as the official Bureau of Economic Analysis annual price decreases of 3% per year (but 21.2% per year for computers).

In this report we have suggested that technical advances in digitalization of switching and transmission play key roles in aiding the spread of networked ICT and hence productivity. Optical fibre is a key invention that began to replace cable and microwave systems in the late 1980s and provided vast increases in scale. Fibre-optic equipment, in nominal terms, accounts for 45% of all spending on telecom equipment over the 1997–2001 period in the U.S. No adjustments are made in national accounts for the technical advance in providing vast carrying capacity for transmission.

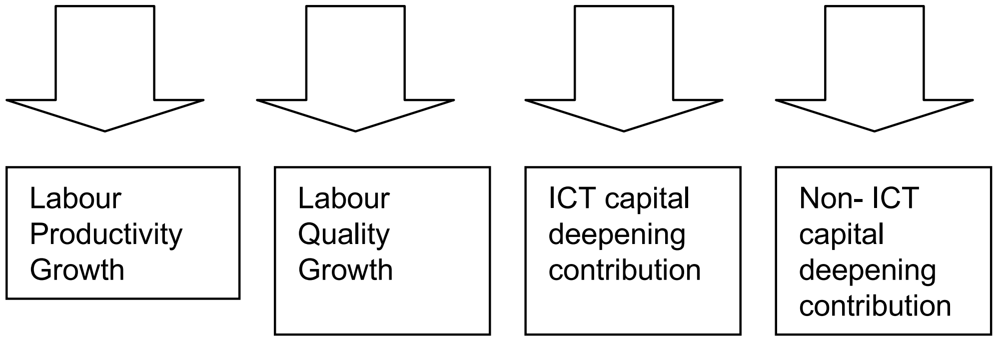
We model the impact of at least some of these characteristics, notably digitalization and its interaction with the spread of computers. We cannot model the change in transmission technologies nor account for the vast changes in carrying capacity across transmission. We do, however, model the spread of both computing and telecom by changes in their penetration levels. We also capture (to some extent) the increasing demand for computers and telecom services. Our model allows us to capture the substitution of ICT capital for other capital, and for labour. In addition, our modeling of the intensity or penetration levels of telephone and computer technologies allows us to capture the impact of externalities and spillovers from ICT diffusion. Even with these efforts, the inherent limitations of national accounts data and the frequently inconsistent nature of data on fibre-optics ensure that the contribution of telecom continues to be understated.

1.7 Our Contributions and the Growth Accounting Framework

- We use an econometric framework so as to analyze the sources of productivity advance and to isolate contributions from a series of factors, as well as their interaction as compared to the growth accounting frameworks largely used by others.
- We examine the contributions of both computers and telecom advances.
- We incorporate network effects and non-linearities.

If we follow the standard growth accounting framework of Jorgenson and Griliches (1967) then the decomposition of labour productivity growth is as follows:

$$\overset{o}{y} = v_l \overset{o}{q} + v_{ICT} \overset{o}{k}_{ICT} + v_N \overset{o}{k}_N + \overset{o}{tfp}$$



That is the growth in annual labour productivity consists of four factors: changes in labour quality, increases in non-ICT capital, increases in ICT capital and the residual after accounting for changes in capital and labour - TFP

In contrast our econometric approach can generally be written as:

$Y=AH^{al}KAP_{NI}{}^{aNI}[G(KAP_{ICT},PEN,PCI,DIG)]^{aIT}e^{at*t}$

Y, or output, is estimated as a Cobb-Douglas function of three inputs- labour (H) and two capital stocks KAP_{NI} (non-ICT capital) and [G(.)] (ICT capital). The function G(.) is the “effective” real ICT capital stock. Our contribution is to measure this effective capital stock as a function of the actual measure of the stock and the stock’s characteristics: the penetration rate of telephones (fixed line plus mobiles) (PEN), personal computers (PCI), and the degree of digitalization of the country’s telecommunications infrastructure (DIG). Thus we are able to ascertain conceptually the drivers of productivity changes – capital deepening as the growth accounting methodology does, but in addition, to determine the impact on productivity of the diffusion of PC’s, the spread of the telecom network and the interaction between the digitalization of telephone exchanges and the spread of PC’s. Growth accounting methodologies while extraordinarily valuable cannot determine how the diffusion of new technologies through the economy contributes to productivity growth.

The differences between our approach and the growth accounting literature are as follows:

(1) Growth accounting is a static accounting/explanation of the past. Econometric production function analyses such as ours provide explanations of past changes.

(2) Econometric analyses, but not growth accounting, has the ability to provide future views, depending on predictions of variables.

(3) In the standard growth accounting framework, ICT equipment enters as input and output sources of growth. For example, the role of telecom equipment is determined by its weight in the economy as a source of output growth, and its weight as a source of capital input into services, manufacturing, and other sectors. In our model, telecom equipment also affects output through the spread of mainlines and cell phones, the digitalization of networks, and the interaction between telecom and computing equipment[26]

(4) We examine non-linearities - characteristics of networks unable to be considered in growth accounting models.

2 The Model

The model developed and estimated in this paper is an extension of the one found in Roeller and Waverman (2001). That model is extended in a number of dimensions. First, we include information technology (e.g. computers) as well as communications technology as a source of economic growth. Second, we develop a hedonic version of the aggregate production function so that the impact of investment in ICT capital, as well as the characteristics of that capital, can be estimated. Third, we interact personal computer penetration with the degree of digitalization. This third extension permits us to analyze the impact of the networked computer on economic activity.

The model consists of a production function (output equation) and four additional equations. A system of equations approach is used to account for the fact that ICT capital and the characteristics of this capital can be expected to be endogenously determined.

We now outline the five equations that will be estimated.

2.1 Output/Labour Productivity Equation

The output equation is based on the aggregate Cobb-Douglas production function

[26] We had hoped to include the spread of fibre optics, but to this point have not accumulated sufficient data to do so.

$$Y=AH^{al}KAP_{NI}^{aNI}[G(KAP_{ITC},PEN,PCI,DIG)]^{aIT}e^{at*t} \quad (1)$$

Where Y is aggregate output (measured by real GDP), H is the labour input (measured by the total hours worked), and KAP_{NI} is the country's real capital stock net of the ICT capital stock.

The function G[.] is the "effective" ICT real capital stock. This effective stock is a function of the actual measure of the stock and the stock's characteristics: the penetration rate of telephones (fixed line plus mobiles), personal computers (PCI), and the degree of digitalization of the country's telecommunications infrastructure (DIG). These characteristics should be viewed as proxy variables for the diffusion of ICT technology throughout an economy.

We assume that the hedonic function G can be written (in terms of logarithms) in the form:

$$\log G = \log KAP_{ITC} + B_{PEN}\,PEN + B_{PCI}\,PCI + B_{MED}\,(DIG\_MED*PCI) + B_{HIGH}\,(DIG\_HIGH*PCI) \quad (2)$$

The degree of digitalization was divided into three categories: low (less than 20 percent of mainlines digital), medium (20 percent - 80 percent of mainlines digitalized) and high (over 80 percent of mainlines digitalized). DIG_MED is a dummy variable which equals unity if the degree of digitalization is medium, and zero otherwise. The dummy variable DIG_HIGH is similarly defined. The variables DIG_MED*PCI and DIG_HIGH*PCI are interaction variables. If B_{MED} and B_{HIGH} are positive, then the impact of computer penetration is enhanced by digitalization when the degree of digitalization is in the medium and high ranges respectively. Since digitalization is a requirement for computers to be networked, we associate the impact of these coefficients with the effects of networking.

If we take logarithms of (1), substitute (2) into (1), and subtract log H_{it} from both sides of the equation, we obtain the labour productivity equation estimated:

$$\begin{aligned}\log(GDP_{it}) - \log(H_{it}) = a_0 + a_t t &+ a_k[\log(KAP_{it} - KAP_{ICT,it}) - \log(H_{it})] \\ &+ a_{ICT}[\log(KAP_{ICT,it}) - \log(H_{it})] \\ &+ (a_k + a_l + a_{ICT} - 1)\log(H_{it}) \\ &+ a_{PEN}(PEN_{it}) + a_{PCI}(PCI_{it}) + a_{MED}(DIGMED*PCI) \\ &+ a_{HIGH}(DIGHIGH*PCI) + u_{GDP,it} \quad (3)\end{aligned}$$

where:

$a_{PEN} = a_{IT}B_{PEN}$

$a_{PCI} = a_{IT}B_{PCI}$

$a_{MED} = a_{IT}B_{MED}$

$a_{HIGH} = a_{IT}B_{HIGH}$

and $u_{GDP,it}$ is the error term in the output equation, where i indexes the country and t indexes the year. The variable t is a time trend that represents trended influences on labour productivity through time that are not captured by the other variables in the model. An example of such an influence is autonomous technical change or smoothly changing skill levels of workers.

The dependent variable is the logarithm of output per hour worked, or labour productivity. The input variables are non-IT and IT capital per hour worked respectively. The coefficient on $\log(H_{it})$ measures the extent of non-constant returns to scale. If this coefficient is positive, labour productivity is higher when size (measured by number of hours worked) is greater.

The coefficients a_{PEN}, a_{PCI}, a_{MED} and a_{HIGH} measure the impact of changes in the ICT characteristics on the level of labour productivity. If these coefficients are positive, then increases in the characteristics will increase labour productivity, in addition to the increasing effects of the accumulation of the ICT capital stock per hour worked. This impact is often referred to as the externality or spillover effect of enhanced technology.

Equation (3) can also be written in difference form:

$$\begin{aligned}\Delta[\log(GDP_{it}) - \log(H_{it})] = {} & a_t \Delta t + a_k \Delta[\log(KAP_{it} - KAP_{ICT,it}) - \log(H_{it})] \\ & + a_{ICT} \Delta[\log(KAP_{ICT,it}) - \log(H_{it})] \\ & + (a_k + a_l + a_{ICT} - 1) \Delta\log(H_{it}) + a_{PEN} \Delta(PEN_{it}) \\ & + a_{PCI} \Delta(PCI_{it}) + a_{MED} \Delta(DIGMED{*}PCI) \\ & + a_{HIGH} \Delta(DIGHIGH{*}PCI) + \Delta u_{GDP,it} \qquad (4)\end{aligned}$$

If the difference is taken over time for a fixed country index i, $\Delta[\log(GDP_{it}) - \log(H_{it})]$ is a measure of the growth of labour productivity in that country. If instead, the difference is taken between countries i and j at a particular time t, $\Delta[\log(GDP_{it}) - \log(H_{it})]$ is a measure of the difference in labour productivity between the two countries. In either case, the a_{PEN}, a_{PCI}, etc. coefficients indicate the effects of changes in the characteristics of the ICT capital on labour productivity.

These coefficients are also indicators of the impact of increases in these characteristics on a country's total factor productivity level (TFP). From equation (3), the total factor productivity level is defined as

$$TFP_{it} = [\log(GDP_{it}) - \log(H_{it})] - a_k [\log(KAP_{it} - KAP_{ICT,it}) - \log(H_{it})] - a_{ICT} [\log(KAP_{ICT,it}) - \log(H_{it})] \quad (5)$$

$$TFP_{it} = a_0 + a_t t + (a_k + a_l + a_{ICT} - 1) \log(H_{it}) + a_{PEN} (PEN_{it}) + a_{PCI} (PCI_{it}) + a_{MED} (DIGMED*PCI) + a_{HIGH} (DIGHIGH*PCI) \quad (6)$$

The level of total factor productivity depends on the level of non-IT related production characteristics $[a_0 + a_t t]$, the interaction of returns to scale and the size of the economy $[(a_k + a_l + a_{ICT} - 1) \log(H_{it})]$, and the level of the characteristics of IT capital $[a_{PEN} (PEN_{it}) + a_{PCI} (PCI_{it}) + a_{MED} (DIGMED*PCI) + a_{HIGH} (DIGHIGH*PCI)]$.

Differencing equation (6) leads to the expression

$$\Delta TFP_{it} = a_t \Delta t + (a_k + a_l + a_{ICT} - 1) \Delta\log(H_{it}) + a_{PEN} \Delta(PEN_{it}) + a_{PCI} \Delta(PCI_{it}) + a_{MED} \Delta (DIGMED*PCI) + a_{HIGH} \Delta(DIGHIGH*PCI) \quad (7)$$

If the difference is taken over time for a fixed country index i, ΔTFP_{it} is a measure of the growth of total factor productivity in that country. If instead, the difference is taken between countries i and j at a particular time t, ΔTFP_{ij} is a measure of the difference in total factor productivity between the two countries.

In our model, Total Factor Productivity growth depends on the non-IT related production characteristics, growth in hours worked in the presence of non- constant returns to scale, and the growth in the characteristics of the IT capital stock (the spillover effect). Similarly, the difference in Total Factor Productivity between two countries at a point in time depends on differences in the non-IT related production characteristics, differences in hours worked in the presence of non-constant returns to scale, and the differences in the characteristics of the IT capital stock.

2.2 Telephone Penetration Demand Equation

As in Roeller-Waverman, we specify a demand equation for the penetration of telephones. We begin by specifying separate demand equations for mainline telephone and mobile telephone penetrations. Following Roeller-Waverman, we specify the demand for mainline telephone penetration (MLPEN) as

$$MLPEN_{it} + WL_{it} = b_{0p} + b_{gdp} \log(gdp_{it}/population_{it}) + b_{price} \log(telp_{it}) + u_{pit} \quad (8)$$

where WL_{it} is the waiting list (per hundred population), gdp_{it} is real output, $telp_{it}$ is the real price of mainline telephone service, and u_{pit} is the random error term in the mainlines demand equation.

The demand for mobile telephone penetration (MOB) is given by

$$MOB_{it} = b_{0m} + b_{gdpm} \log(gdp_{it}/population_{it}) + b_{pricem} \log(price_{mobile,it}) + u_{mit} \quad (9)$$

where $price_{mobile,it}$ is the price of mobile telephone services (measured as real revenue per mobile subscriber) and u_{mit} is the random error term in the mobiles demand equation.

Significant mobile telephone penetration did not begin until the mid 1990s. In order to retain a balanced time series, cross section data set, it is necessary to aggregate equations (8) and (9) into a single equation. We define D_{MOB} equal to unity if telecommunications revenue from mobiles is positive, and equal to zero otherwise. Multiplying both sides of equation (9) by D_{MOB} and adding the result to equation (8) yields the telephone penetration equation used for estimation:

$$(PEN_{it} + WL_{it}) = b_{0p} + b_{gdp} \log(gdp_{it}/population_{it}) + b_{price} \log(telp_{it}) + D_{MOB} [b_{0m} + b_{gdpm} \log(gdp_{it}/population_{it}) + b_{pricem} \log(price_{mobile,it})] + u_{demand,it} \quad (10)$$

where

$$PEN_{it} = MLPEN_{it} + D_{MOB}MOB_{it}$$

$u_{demand,it} = u_{pit} + D_{MOB}\, u_{mit}$

2.3 PC Intensity Demand Equation

The third equation in our system is an equation specifying the demand for personal computer penetration. This equation is assumed to have the same form as the telephone penetration demand equations.

$$PCI_{it} = c_0 + c_{gdp} \log(gdp_{it}/population_{it}) + c_{price\_it} . \log(ITPRICE_{it}) + u_{demand\_pc,it} \quad (11)$$

where $ITPRICE_{it}$ is the price of personal computers and $u_{demand\_pc,it}$ is the random error term in the personal computers demand equation.

2.4 Supply Equation for ICT Investment

In our dataset we observe the total annual investment in ICT infrastructure. It consists of the sum of investments in mainline telephone, mobile telephone and personal computer infrastructure[27]. For investment in mainline telephone infrastructure, we essentially adopt Roeller and Waverman's equation (in terms of per hour worked):

$$TELINV_{it}/H_{it} = d_{T0} + d_{TGA} \log(GA_i) + d_{TGD}\, GD_{i,t-1} + d_{T,wait}\, WL_{i,t-1} + d_{telp}\, (1- USCAN) \log(telp_{it}) + d_{T,USCAN}\, USCAN \log(telp_{it}) + d_{TT}\, t + u_{T,it} \quad (12)$$

where $TELINV_{it}$ is the investment in mainline telephone infrastructure, GA_i is the geographic area of the ith country, $GD_{i,t-1}$ is the real government deficit (lagged one period), and USCAN is a dummy variable which equals unity if country i is Canada or the United States, and equals zero otherwise. This latter variable is included to allow for the possibility that the supply price elasticity is different in Canada and the United States than elsewhere. The difference between equation (12) and Roeller-Waverman's equation is that we specify the government deficit variable and the waiting time variable to be lagged rather than contemporaneous variables.

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[27] When we use the normally available data on ICT investment, the communications portion also includes investment in broadcasting equipment.

We assume a similar supply structure for mobile telephone infrastructure (excluding the separate supply elasticities for the US and Canada and the wait times variable.):

$$MOBINV_{it}/H_{it} = d_{M0} + d_{MGA}\log(GA_i) + d_{MGD}\,GD_{i,t-1} + d_{mob}.\log(price_{mobile,it}) + d_{MT}\,t + u_{M,it} \qquad (13)$$

where $MOBINV_{it}$ is the investment in mobile infrastructure.

The supply structure for personal computer infrastructure is assumed to be

$$PCINV_{it}/H_{it} = d_{P0} + d_{PGA}\log(GA_i) + d_{PGD}\log GD_{i,t-1} + d_{IT}\log(ITprice_{it}) + d_{PT}\,t + u_{P,it} \qquad (14)$$

We obtain the supply of infrastructure estimation equation by multiplying both sides of equation (13) by D_{MOB} and adding the result to equations (12) plus (14):

$$\begin{aligned} ICTINV_{it}/H_{it} &= d_0 + d_{GA}\log(GA_i) + d_{GD}\,GD_{it} + d_{T,wait}\,WL_{it} \\ &+ d_{telp}.(1- USCAN)\log(telp_{it}) + d_{T,USCAN}.USCAN.\log(telp_{it}) \\ &+ d_{IT}\log(ITprice_{it}) + D_{MOB}.[d_{M0} + d_{MGA}\log(GA_i) + d_{MGD}\,GD_{i,t-1} \\ &+ d_{mob}\log(price\_s_{it}) + d_{MT}\,t] \\ &+ d_T\,t + u_{sup,it} \end{aligned} \qquad (15)$$

where $ICTINV_{it}$ is total investment in ICT infrastructure, and

$d_0 = d_{T0} + d_{P0}$

$d_{GA} = d_{TGA} + d_{PGA}$

$d_{GD} = d_{TGD} + d_{PGD}$

$d_T = d_{TT} + d_{PT}$

$u_{sup,it} = u_{T,it} + u_{P,it} + D_{MOB}\,u_{M,it}$

2.5 Demand Equation for ICT Investment

The investment demand equation is an adaptation of Roeller and Waverman's investment equation, adapted so that multiple characteristics can be included in the specification. We begin by inverting Roeller and Waverman's equation (4') so that the dependent variable is TTI (real investment in telecommunications infrastructure). This investment is now a function of the increase in the mainline telephone penetration rate, and can be interpreted as an investment requirements function. In our case, the investment requirements are a function of changes in the number of mainline plus the number of mobile telephone subscribers, the number of personal computers, and the number of digital lines. The investment equation can be specified as:

$$ICTINV_{it} = e_i + e_{DIG}.(digital_{it} - digital_{i,t-1}) + e_{SUB}.(Subscribers_{it} - Subscribers_{i,t-1})$$
$$+ e_{pc}.(PC_{it} - PC_{i,t-1}) + u_{invst,it}$$

(16)[28]

where

$digital_{it}$ = the number mainlines which are digitalized

$Subscribers_{it}$ = the number of mainline + mobile telephone subscribers

PC_{it} = the number of personal computers

3 Data

In order to estimate the model described above, we gathered data from a range of public sources. These included the OECD, the International Telecommunication Union (ITU) and the datasets constructed by the Groningen Growth and Development Centre (GGDC). The latter data are based upon national accounts as compiled by individual national statistical agencies and the OECD. For purchasing power parities and relative price levels across countries, we relied on the Penn World Tables Mark 6.1 for data until 2000. For the period after 2000, we relied upon the OECD's published estimates of Purchasing Power Parity exchange rates.[29]

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[28] Unlike equation (15), which has the geographic area (GA) as a right hand side variable to control explicitly for the size of the country, equation (16) has no such control variable. Therefore, in this equation we have included country-specific dummy variables.

[29] The Penn World Tables has information on the relative price levels of investment goods, and so for the data up to and including 2000, we were able to construct purchasing power parities for the capital stock series that we use. The OECD data, post-2000, only provide estimates at an economy-wide level.

3.1 Sample Selection

Availability of relevant data drove the choice of countries in our sample. While sources such as the Penn World Tables 6.1 certainly cover major macroeconomic series for virtually all nations, there is far less detailed information available for capital stocks estimated at the sectoral level. Since the model described in the previous section requires estimates of ICT capital stock as well as overall capital stock, we needed either to construct these capital stocks ourselves or rely upon existing efforts at estimating ICT capital stock. Construction of capital stock estimates is, in theory, possible if one has an initial starting value for the capital stock and also has estimates of gross fixed capital formation (for which annual series are more widely available than are estimates of stocks), and can make some reasonable assumptions about depreciation. However, in practice, it is not easy to find data on initial capital stocks, or indeed to make reasonable conjectures about what these starting values should be.

Our sample mostly covers the 15 nations for which the Groningen Growth and Development Centre's "Total Economy Growth Accounting Database" of Timmer, Van Ark and Ypma (2003) provides the relevant data. This contains (among other variables) estimates of capital stocks in the following areas: (1) IT equipment, (2) Software, (3) Communications Equipment, (4) Non-ICT Equipment, and (5) Non-Residential Structures. The GGDC has collected these data for 14 EU nations (excluding Luxembourg) and the United States spanning the period from 1980 to 2001.[30] The GGDC provides detail about how these estimates were constructed – primarily from national accounts data – on their Internet site at www.ggdc.net. We supplemented these data with data for Canada, based upon Statistics Canada.

We updated the above data set to the year 2003 for five countries: Finland, France, Canada, the United Kingdom and the United States using national statistical agencies sources. The major difficulty we encountered was updating the ICT capital stocks. This updating was accomplished by applying the perpetual inventory method, utilizing the various ICT investment series that were available.

The data up to 2000 were converted to a common currency using the purchasing power parity data from the Penn World Tables. We use these data to translate all our capital stock and investment estimates from constant local currency terms or constant U.S. dollar terms into purchasing power parity U.S. dollars, based to the year 1996. (After 2000, we used the OECD PPPs for our conversions).

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[30] In July, after we had virtually completed our empirical analysis, the GGDC posted on the Internet an updated database for the U.S and 15 European countries (adding Luxembourg) to 2004.

We will be presenting two sets of estimation results. The difference in the two sets is due to alternative data construction for the ICT investment and capital stock variables. In the first set, communications is defined to include radio and TV broadcasting. This is the way communications is usually defined because most countries' statistical agencies do not separate out telecommunications from broadcasting. This is true of all the countries in our sample, with the exception of Canada. The second set of results is based on our attempt to separate out telecommunications data and thus to define ICT to exclude broadcasting.

3.2 Data Description and Construction

3.2.1 Capital Stocks and Price Indices

Differences in national accounting practices in measuring ICT capital, especially differences in the capitalization of software in the national accounts and construction of constant-quality price indices for computers, software and communications equipment pose a major problem for studies such as ours. The GGDC capital stock measures make use of the OECD's "price index harmonization" proposed by Schreyer (2002). This harmonization method uses the U.S. "constant-quality" price indices for IT and Communications equipment as the starting point and then accounts for country-specific inflationary factors – for example, the authors apply the ratio of the U.S. IT price index to the U.S. GDP deflator to control for IT inflation relative to general inflation, and then apply this ratio to the particular country's GDP deflator index to obtain the country-specific IT goods deflator. In other cases, they apply the U.S. ratio of IT to non-IT capital good price deflators to the country-specific non-IT capital goods price index (where available). Such an approach seems intuitively appealing, since IT goods are widely traded with most countries being net importers of IT equipment. Therefore, the rapid declines in constant-quality prices of computers, semiconductors and the like reported by the U.S. are also being experienced in the EU, Canada and Japan. (Figures 3.1 and 3.2 show price deflation for the U.S.).

Figure 3.1: Relative Price of IT Outputs and Inputs, United States

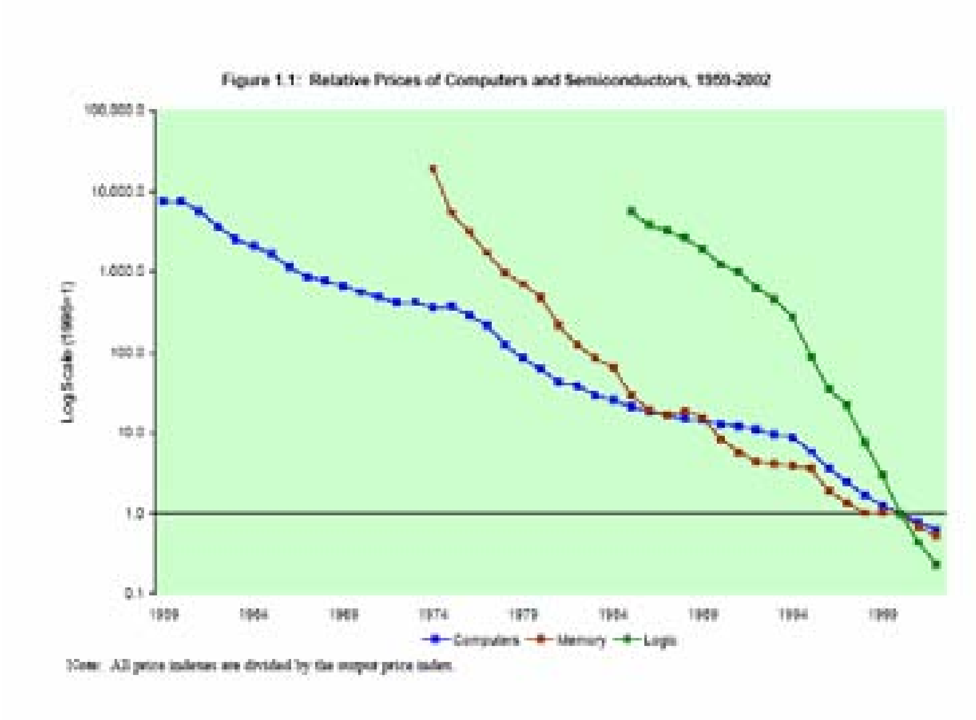
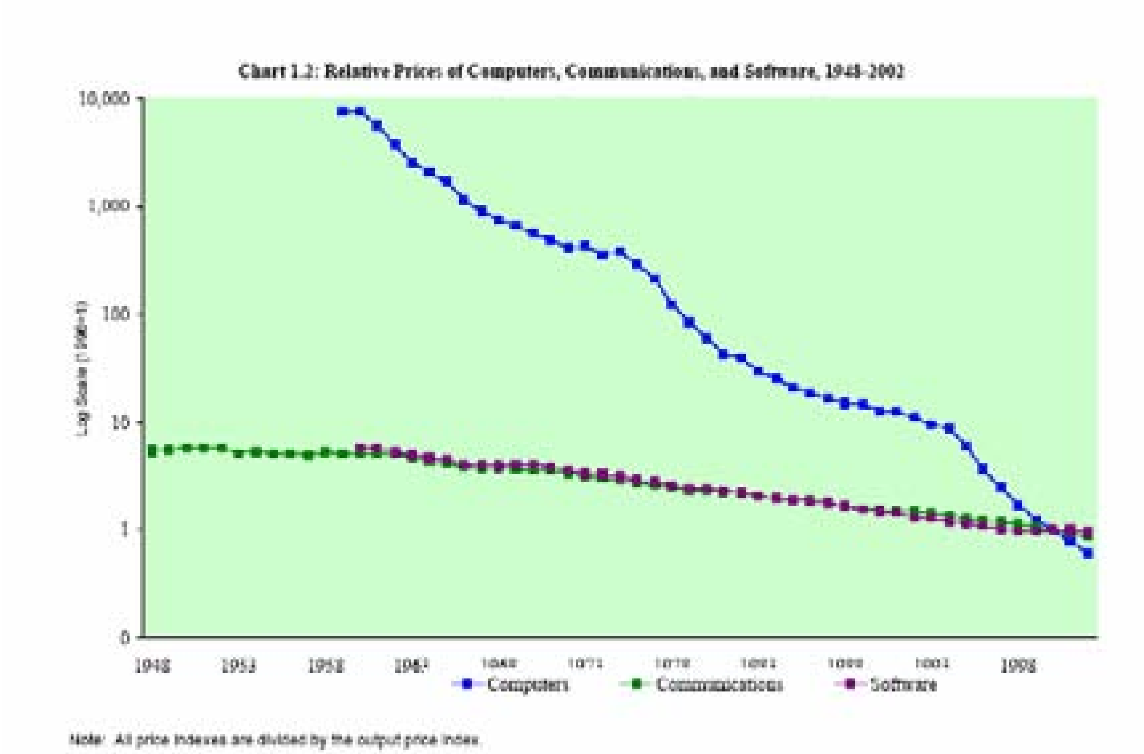


Figure 3.2: Computers, Communications and Software, U.S.



One objection to applying the U.S. adjustments to the capital stocks of other nations is that there may be wide cross-national variations in the composition of ICT capital stocks. Considering IT equipment, it could be that between 1990 and 2000, the computers typically in service in Greece or France could have improved (in terms of their operational characteristics such as clock speed and memory) less rapidly than those in the U.S. and therefore the constant-quality price deflation that should be applied to the entire stock of IT equipment should be much lower than in the U.S.

Waverman and Fuss (2005) explored this issue. Using data on PC shipments from IDC Corporation, they were able to analyze new PC sales arranged according to processor speed characteristics, for the countries in our sample between 1990 and 2000. They concluded that there was little need to worry about cross-sectional variations in the quality of computers being sold and used; the difference between countries is in volume and intensity terms, not quality terms.

The evidence thus suggests that the construction of harmonized IT price deflators using the U.S. hedonic adjustments as their basis has considerable empirical validity. For Canada we had to make the necessary adjustments ourselves. For the Canadian case, we relied upon data obtained from Statistics Canada, inferring the necessary deflators by comparing the constant dollar investment series for the relevant assets with the current dollar series.[31]

The hedonically adjusted capital stocks for each country were initially obtained in constant local currency terms. We then constructed purchasing power parity conversion factors for non-ICT and ICT capital goods, thus providing us with a basis to convert the capital stocks from local currency terms to 1996 U.S. dollar purchasing power equivalents.

For the overall capital stock, with the exception of Canada, we can infer the appropriate deflators from the Timmer et al dataset (up to and including 2001). For the years 2002 and 2003 we constructed the appropriate deflators for each country by applying the same “price harmonization” method suggested by the Groningen researchers. For our other macroeconomic series, such as GDP, we had PPP estimates available from the Penn World Tables through the year 2000. For the years 2001-2003, these PPP conversion factors were obtained from the OECD’s Statistics Portal.

Table 3.1 shows the average share of (real) ICT annual investment in real GDP in our sample over the 1980-2001.

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[31] Specifically, we relied upon data from CANSIM, Statistics Canada’s online data retrieval services, for investment series. Statistics Canada Catalogue No. 15-204 provided us with initial capital stock estimates for selected sectors and depreciation rates.

Table 3.1: ICT Investment as a Share of Real GDP[32]

Year	ICT Share of GDP
1980	0.56%
1981	0.61%
1982	0.65%
1983	0.75%
1984	0.87%
1985	0.98%
1986	1.11%
1987	1.14%
1988	1.29%
1989	1.43%
1990	1.49%
1991	1.54%
1992	1.64%
1993	1.75%
1994	1.90%
1995	2.15%
1996	2.49%
1997	2.96%
1998	3.73%
1999	4.39%
2000	5.11%
2001	5.3%

The next table shows the share of ICT capital in real GDP for 2001-2003, based on the five-country sample for which we have extended data. Finland and the U.S. are especially ICT intensive economies in this smaller sample.

Table 3.2: ICT Investment as a Share of Real GDP (Five-Country Sample)

Year	ICT Share of GDP
2001	5.64%
2002	5.20%
2003	5.13%

3.2.2 Other Macroeconomic Variables

We obtained data on GDP, the GDP deflator, exchange rates, and relative prices of GDP and capital goods from the Penn World Table up to 2000. For data from 2001 to 2003, we used the OECD's Statistics Portal, and the ITU's World Telecommunications Indicators (which also has

[32] These calculations are for the 16 countries included in our sample.

macroeconomic data). Our measure of labour input is the total number of hours worked. For this, we relied on the GGDC's Total Economy Database, details of which are available from their website at http://www.ggdc.net/dseries/totecon.html. Data on the government budget balance were obtained from the OECD's *Economic Outlook No. 74*.

3.2.3 Telecom and PC Variables

Data on the ITC characteristics (telecom penetration, PC penetration, and digitalization) were gathered from the ITU's World Telecommunications Indicators database. We obtained information on mainline and mobile penetration, mainline and mobile revenues, percentage of main lines converted to digital lines, mainline and mobile telecom investment, personal computers used and waiting lists from the ITU.

3.3 Variables Used in the Estimation

The mapping between the variables used in the regression analysis and the raw data is as follows:

Table 3.3: Variables Used in the Regression

Variable	Description
GDP/hour	Real GDP per hour in 1996 U.S.$ at PPP
Hours	Annual hours
Capital net of ICT/ITT per Hour	Total capital less ICT (or ITT) capital per hour worked, 1996 U.S.$ at
ICT/ITT Capital per Hour	ICT (or ITT) capital per hour worked, 1996 U.S.$ at PPP
Telecom Penetration	Main lines plus mobiles per 100 population
PC Intensity	PCs per 100 population
D_{MOB}	Dummy that equals 1 when revenues for mobile are available
GDP/Population	Real GDP per capita in 1996 U.S.$ at PPP
Mobile Retail Price	Revenue per mobile subscriber
Fixed Telecom Retail Price	Revenues per main line subscriber
IT Price	Deflator for IT services (software and hardware)
U.S.CAN	Dummy that equals 1 for U.S. and Canada if year>1983
Wait	Waiting list for mainlines divided by population
Real ICT Investment	Gross Fixed Capital Formation in Communications, IT Equipment and Software, 1996 U.S.$ at PPP
Government Deficit	Government receipts minus outgoings, 1996 U.S.$ at PPP
Mobile Supply Price	Revenues per mobile subscriber
Fixed Telecom Supply Price, non U.S.-CAN	Revenues per fixed line subscriber if U.S.CAN=0
Fixed Telecom Supply Price, U.S.-CAN	Revenues per fixed line subscriber if U.S.CAN=1
Subscriber Growth	Annual change in total telecom subscribers
PC Subscriber Growth	Annual change in number of PCs
Digitalization Growth	Annual change in number of digital main lines

Sample statistics for the main regression variables are provided below:

Table 3.4: Sample Statistics for Major Regression Variables (1980-2003)

	N	Mean	STDEV	Min	Max
GDP/HOUR ($)	361	26.53	6.25	10.83	40.24
GDP/CAPITA ($)[33]	361	18805	4671	8967	33701
ICTKAP/HOUR ($)	361	1.78	1.50	0.194	9.35
NONICTKAP/HOUR ($)	361	38.47	12.81	8.62	79.05
ITTKAP/HOUR ($)	361	1.73	1.45	0.191	9.16
NONITTKAP/HOUR ($)	361	38.52	12.83	8.62	79.16
HOURS (Millions)	361	31,295	53,268	2,084	257,000
PCI (PC per 100)	361	12.93	14.55	0.00	73.00
PEN (Telephones[34] per 100)	361	58.55	31.59	10.67	155.94
Fixed Line Revenue per subscriber ($)	362	772.32	220.80	235.96	1451.12
Mobile Revenue/Subscriber ($)	194	822.69	539.24	200.80	2663.80
IT AND SOFTWARE PRICE INDEX	361	1.08	0.43	0.47	3.88
Government Balance ($ Millions)	361	-32303	67908	-473941	133022
REAL ICT INV ($ Millions)	361	28361	90226	128	706144
ICTINVEST/HOUR ($)	361	0.62	0.60	0.06	3.43

It should be noted that in the dataset all variables expressed in dollar terms refer to constant 1996 U.S. dollars in purchasing power parity terms.

4 Estimation Results

We estimated a system of equations consisting of equations (3), (10), (11), (15) and (16). Estimation was carried out using the SAS subroutine for Generalized Method of Moments (GMM) system estimation. The endogenous variables were GDP, KAP_{ICT}, PCI, PEN, telp, $price_{mobile}$, and ICTINV. All other variables in the model are assumed to be exogenous and are used to form instruments. The estimation results are presented in Table 4.1, for the case where broadcasting is included in the definition of communications. Table 4.2 contains the estimation results when broadcasting is excluded from the definition of communications. The results are virtually identical. This occurs because television cable transmission facilities remain in the communications data, so broadcasting (net of cable) is a small proportion of the communications investment and capital stock[35]. Since the two sets of estimates contained in Tables 4.1 and 4.2 are virtually identical, we will confine most of our comments to one of them. We have chosen to discuss in detail the version in which communications capital is defined to include broadcasting.

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[33] This is an explanatory variable in the demand equations for telecoms and PCs.

[34] This includes both main lines and mobile phones. The mean value of main lines for the entire sample was approximately 45 (per 100 population), whereas the mean value of mobiles over the period for which mobile data were available was roughly 24 per 100 population.

Our main focus is on the parameters contained in the labour productivity equation (3). However, before considering this equation in detail, we will review the results in the other four equations. The majority of the estimated coefficients are statistically significant, and are of the expected sign. We will discuss the equations in turn.

Table 4.1: Nonlinear GMM Parameter Estimates (Communications includes broadcasting)

Parameter	Estimate	Std Err	t Value	Pr > |t|
e_1	-3022.57	575.4	-5.25	<.0001
e_2	742.7968	446.4	1.66	0.0971
e_3	-17941.1	1888.3	-9.50	<.0001
e_4	-12891.4	2188.1	-5.89	<.0001
e_5	-52616.1	5201.8	-10.12	<.0001
e_6	-2214.95	533.5	-4.15	<.0001
e_7	-4272.22	1697.8	-2.52	0.0123
e_8	-2050.67	392.4	-5.23	<.0001
e_9	-12086.5	3865.2	5.46	<.0001
e_{10}	-232.92	249.4	-0.93	0.3511
e_{11}	-2039.41	202.6	-10.06	<.0001
e_{12}	-6167.83	1304.8	-4.73	<.0001
e_{13}	-8888.4	1610.1	-5.52	<.0001
e_{14}	-1155.82	278.4	-4.15	<.0001
e_{15}	-4004.28	730.9	-5.48	<.0001
e_{16}	-21455	3597.8	-5.96	<.0001
e_{17}	-86004.9	17881.1	-4.81	<.0001
a_0	-8.98122	0.0845	-106.28	<.0001
a_k	0.455334	0.00850	53.54	<.0001
$a_k+a_l+a_{ICT}-1$	0.013999	0.00187	7.49	<.0001
a_{ICT}	0.036764	0.0101	3.66	0.0003
a_{MED}	0.004968	0.00176	2.82	0.0051
a_{HIGH}	0.001194	0.00180	0.66	0.5078
a_{PEN}	0.000412	0.000192	2.14	0.0327
a_{PCI}	0.003499	0.00191	1.84	0.0673
a_T	-0.00404	0.000648	-6.24	<.0001
b_{0p}	197.8546	4.7572	41.59	<.0001
b_1	-327.267	16.9534	-19.30	<.0001

[35] Our definition of telecommunications corresponds to the North American Industrial Classification System (NAICS) Industry 517, “Telecommunications”, which includes “Cable and Other Program Distribution).

b_{gdp}	46.79914	1.1169	41.90	<.0001
b_{price}	-4.60576	0.6460	-7.13	<.0001
b_{gdpm}	-9.39105	3.1690	-2.96	0.0033
b_{pricem}	-43.5937	1.1838	-36.82	<.0001
c_0	183.6425	2.0671	88.84	<.0001
c_{gdp}	42.34665	0.5290	80.05	<.0001
c_{price_it}	-20.7063	0.3465	-59.76	<.0001
d_0	0.003513	0.000320	10.99	<.0001
d_{GA}	6.379E-6	0.000013	0.48	0.6289
d_{GD}	2.62E-10	2.71E-10	0.97	0.3342
$d_{T,wait}$	0.000458	0.000350	1.31	0.1921
d_{telp}	0.000453	0.000036	12.68	<.0001
$d_{T,USCAN}$	0.000402	0.000035	11.49	<.0001
d_{IT}	-0.00029	0.000055	-5.24	<.0001
d_T	-6.94E-7	3.529E-6	-0.20	0.8442
d_{M0}	-0.00083	0.000328	-2.52	0.0123
d_{MGA}	-0.00007	0.000019	-3.61	0.0004
d_{MGD}	-78E-11	3.33E-10	-2.35	0.0196
d_{MOB}	-0.00005	0.000049	-1.09	0.2752
d_{MT}	0.000105	0.000010	10.40	<.0001
e_{DIG}	-0.00107	0.000808	-1.32	0.1862
e_{SUB}	0.002008	0.000513	3.91	0.0001
e_{PC}	0.039668	0.00169	23.41	<.0001

Table 4.2: Nonlinear GMM Parameter Estimates (Communications excludes broadcasting)

Parameter	Estimate	Std Err	t Value	Pr > |t|
e_1	-2987.24	568.3	-5.26	<.0001
e_2	748.8163	443.4	1.69	0.0922
e_3	-17445.3	1586.8	-10.99	<.0001
e_4	-12611.2	2132.3	-5.91	<.0001
e_5	-51446.6	5323.3	-9.66	<.0001
e_6	-2141.61	528.7	-4.05	<.0001
e_7	-4230.3	1669.6	-2.53	0.0118
e_8	-2048.66	384.5	-5.33	<.0001
e_9	-20456.3	3895.6	-5.25	<.0001
e_{10}	-234.521	252.9	-0.93	0.3544

e_{11}	-2008.24	200.7	-10.01	<.0001
e_{12}	-6200.22	1312.3	-4.72	<.0001
e_{13}	-8704.06	1585.6	-5.49	<.0001
e_{14}	-1160.86	276.8	-4.19	<.0001
e_{15}	-3902.66	711.9	-5.48	<.0001
e_{16}	-20889.7	3517.4	-5.94	<.0001
e_{17}	-83955.7	17291.6	-4.86	<.0001
a_0	-8.97941	0.0845	-106.24	<.0001
a_k	0.455212	0.00862	52.82	<.0001
$a_k+a_l+a_{ITT}-1$	0.013948	0.00190	7.36	<.0001
a_{ITT}	0.036942	0.0105	3.52	0.0005
a_{MED}	0.005002	0.00177	2.83	0.0050
a_{HIGH}	0.001225	0.00181	0.67	0.5004
a_{PEN}	0.000418	0.000195	2.14	0.0329
a_{PCI}	0.003458	0.00192	1.80	0.0732
a_T	-0.0041	0.000647	-6.34	<.0001
b_{0p}	198.155	4.8161	41.14	<.0001
b_1	-328.826	17.0696	-19.26	<.0001
b_{gdp}	46.89389	1.1131	42.13	<.0001
b_{price}	-4.61774	0.6464	-7.14	<.0001
b_{gdpm}	-9.62535	3.1768	-3.03	0.0026
b_{pricem}	-43.6763	1.1916	-36.65	<.0001
c_0	183.5999	2.0686	88.75	<.0001
c_{gdp}	42.3366	0.5292	79.99	<.0001
c_{price_it}	-20.7135	0.3453	-59.98	<.0001
d_0	0.003447	0.000312	11.05	<.0001
d_{GA}	6.258E-6	0.000013	0.48	0.6290
d_{GD}	2.79E-10	2.67E-10	1.05	0.2964
$d_{T,wait}$	0.000397	0.000344	1.15	0.2490
d_{telp}	0.000444	0.000035	12.73	<.0001
$d_{T,USCAN}$	0.000394	0.000034	11.54	<.0001
d_{IT}	-0.00029	0.000054	-5.32	<.0001
d_T	-3.14E-7	3.486E-6	-0.09	0.9282
d_{M0}	-0.00082	0.000324	-2.53	0.0120
d_{MGA}	-0.00007	0.000018	-3.61	0.0004

d_{MGD}	-78.7E-11	3.25E-10	-2.42	0.0161
d_{MOB}	-0.00005	0.000048	-1.11	0.2692
d_{MT}	0.000103	0.000010	10.30	<.0001
e_{DIG}	-0.00119	0.000778	-1.52	0.1283
e_{SUB}	0.002025	0.000470	4.30	0.0001
e_{PC}	0.03907	0.00166	23.47	<.0001

4.1 Telephone Penetration Demand Equation

The estimated coefficients are consistent with a negative price elasticity and positive income elasticity for fixed line telephones. For mobile telephones, both the price elasticity and income elasticity are negative. The negative income elasticity of mobiles is counterintuitive, but may be due to the fact that low-income countries have tended to bypass extensions of fixed line infrastructure in favour of more rapid deployment of mobile telephone infrastructure. The implied price elasticities of demand at the mean penetration levels are -0.10 for fixed lines and -1.79 for mobiles. Mobiles are considerably more price-elastic. The income elasticity for fixed lines at the mean penetration level is estimated to be 1.03.

4.2 PC Penetration Demand Equation

The estimated coefficients are consistent with a negative price elasticity and positive income elasticity for personal computers. At the mean PC intensity level, the price and income elasticities are estimated to be –1.61 and +3.29 respectively. Demand for PCs is estimated to be highly elastic.

4.3 Supply Equation for ICT Penetration

The supply of ICT equation allows us to distinguish between the supply of mobiles infrastructure and other ICT infrastructure, but not fully between fixed lines infrastructure and PC infrastructure, due to data limitations.[36] The only parameter of the PC supply equation that is separately identified is d_{IT}, the PC price coefficient. Unfortunately, it has a counterintuitive negative sign and is statistically significant. This result is not surprising since the price of computers fell rapidly over the sample period as the penetration rate was increasing substantially. The supply equation that we have estimated does not account for the equally rapid decline in the

[36] Recall that the data we have available does not permit us to disaggregate investment in ICT infrastructure by type. The reason we can identify the parameters of the mobiles infrastructure supply is because mobile supply was zero through much of the 1980-2000 period.

cost of producing personal computers over this period. At the present time there does not appear to be available the cost data that could be used to rectify this situation.

We now turn to the other results of the supply equation estimation. ICT investment is positively related to the size of the country for mainlines but not for mobiles (coefficients d_{GA} and d_{MGA}). ICT investment in fixed lines plus PCs is positively related to the amount of (lagged one period) country debt (coefficient d_{GD}), whereas the investment in mobiles is negatively related to this variable (coefficient d_{MGD}). It is not clear which sign one would expect, but one would probably expect the same sign for both types of ICT supply. The impact of wait lists on ICT supply is positive (coefficient $d_{T,wait}$), This is the sign we would expect since investment in fixed lines should increase, the more pressing is the wait list problem.

The price elasticity for fixed line supply is positive and similar in Canada and the U.S. as in the rest of the sample since d_{telp} and $d_{T,USCAN}$ are positive and of similar magnitude. The supply elasticity for mobiles is estimated to be negative ($d_{mob}<0$), although it is insignificant. This counterintuitive result is probably due to our difficulty in finding a satisfactory price series for mobiles. Finally, the trend in mainlines and PCs supply for reasons unaccounted for in this equation is negative ($d_T<0$), and the trend in mobiles supply for reasons unaccounted for by this equation is positive. ($d_{MT}>0$).

4.4 Investment Demand Equation

The ICT investment equation is specified as an input requirements function, so we would expect that the amount of ICT investment would increase when the ICT outputs (digital lines, subscribers, and PCs) increase. This is indeed the case for two of the three input-output parameters (e_{SUB} and e_{PC}), which are positive and significant. The third parameter (e_{DIG}) is negative, but insignificant[37].

4.5 Labour Productivity Equation

The primary focus of this paper is the labour productivity equation (equation (3)), and in particular, the impact of ICT infrastructure on labour productivity. We begin by noting that our estimate of economies of scale implies slightly increasing returns to scale ($a_k + a_l + a_{ICT} = 1.01$). The coefficient associated with technical change and other trended influences on labour productivity unrelated to ICT activity is estimated to be negative. The rate of change is quite low (less than one-half of one percent).

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[37] If we include data only to the year 2000, the digital lines parameter estimate is positive. However, in the last few years of the sample, in a number of countries the number of digital mainlines declined as mobiles/mainlines substitution occurred, while telecom investment continued to increase.

We begin our analysis of the impact of ICT by comparing the relative marginal product of ICT capital (MP_{ICT}) with that of non-ICT capital (MP_{NICT}). The relative marginal products can be expressed as

$$MP_{ICT}/MP_{NICT} = (a_{ICT}/a_k)^* (K_{NICT}/K_{ICT}) \qquad (17)$$

where K_{NICT} is the non-ICT capital stock and K_{ICT} is the ICT capital stock. When we evaluate equation (17) at the mean value of the capital stock variables, MP_{ICT}/MP_{NICT} = 1.74. Hence we estimate that the marginal product of ICT capital is almost twice that of non-ICT capital. Allocation of capital accumulation resources towards ICT capital accumulation will raise labour productivity through more productive capital deepening. Of course it must be kept in mind that ICT capital is more expensive than non-ICT capital in terms of user costs, since depreciation rates are higher and capital losses are higher (due to falling asset prices).

We now turn to the impact of the characteristics of the ICT capital. Since we have already accounted for the capital deepening effects of ICT capital accumulation, the additional labour productivity enhancement effects of increased penetration of telephones and personal computers and through digitalization of the telecom infrastructure is in the form of productivity spillovers from technological change. Alternatively, the impacts can be interpreted as increases in effective ICT capital. The changes in characteristics described above lead to increases in labour productivity. This can be seen from the positive coefficients a_{PEN}, a_{PCI}, a_{MED}, and a_{HIGH}[38]. The impact of PC penetration appears to be greater than that of telephone penetration. At the mean penetration rates, the PC penetration labour productivity elasticity is approximately 1.9 times as great as the telephone penetration elasticity. However, that calculation does not take into account the impact of digitalization, an impact we have associated with the networking of the personal computer. According to our point estimates, the coefficient for PC penetration increases from .0035 for low digitalization to .008 for medium digitalization, and to .005 for high digitalization Digitalization of the telecom infrastructure appears to improve the labour productivity impact of increases in the penetration of personal computers. This statement must be tempered by the realization that the impact of high digitalization is poorly estimated, since the t statistic on the estimate of a_{HIGH} is very low[39]. However, for the analysis of the impact of penetration of computers on labour productivity differences post 2000 between Canada and the United States (and Europe), what needs to be estimated precisely is the sum of coefficients $a_{PCI} + a_{HIGH}$. This fact can be seen

[38] Not all of these coefficients are statistically significant. The problem is probably the degree of collinearity among the characteristics of the ICT capital. Countries with high penetration rates for telephones also tend to have high penetration rates for PCs and advanced digitalization.

from equation (4), the labour productivity decomposition equation. Since digitalization is above 80% post 2000, DIGMED=0 and DIGHIGH=1. Then equation (4) becomes:

$$\Delta[\log(GDP_{it}) - \log(H_{it})] = a_t \Delta t + a_k \Delta[\log(KAP_{it} - KAP_{ICT,it}) - \log(H_{it})] +$$

$$a_{ICT} \Delta[\log(KAP_{ICT,it}) - \log(H_{it})]$$

$$+ (a_k + a_l + a_{ICT} - 1) \Delta\log(H_{it})$$

$$+ a_{PEN} \Delta(PEN_{it}) + [a_{PCI} + a_{HIGH}] \Delta(PCI_{it})$$

$$+ u_{GDP,it} \qquad (18)$$

The combined term $a_{PCI} + a_{HIGH}$ is estimated very precisely. It has a value of 0.0047 with a standard error of 0.00023, so the t value is approximately 20.

4.6 The Impact of ICT on Labour Productivity

We applied the estimation results to equation (4) to analyze the sources of labour productivity differences. Table 4.3 contains two comparisons. First, for the last year in our sample (2003), we compare labour productivity in Canada with labour productivity in the United States. Second, we conduct a similar comparison for the year 2000. In Table 4.4 we compare Canada with the European countries in our updated sample. “Europe” in this comparison is a population weighted average of Finland, France and the United Kingdom. All comparisons utilize the version of communications capital that includes broadcasting. The results when broadcasting were excluded are virtually identical.

Table 4.3: Sources of Labour Productivity Differences: Canada vs. the U.S., 2003*

	Percentage	Proportion of Percentage Difference	95% Confidence Interval
Difference	21%		
Contributions			
Non-ICT Capital Deepening		5%	
Hours/ Scale		15%	
ICT		56%	(51%, 61%)

[39] This low t value and the marginal significance of a_{PCI} are due to multicollinearity problems in the data. This is indicated by the fact, as noted in the text, that the sum of coefficients $a_{PCI} + a_{HIGH}$ is estimated precisely.

ICT Capital Deepening		12%	
ICT Spillovers		44%	(40%, 48%)
Telecom Penetration		2%	
IT Penetration		42%	(38%, 46%)
PC Penetration		31%	
Digital/PC Interaction		11%	
Unexplained by Above Factors		25%	

Sources of Labour Productivity Differences: Canada versus the U.S. , 2000

	Percentage	Proportion of Percentage Difference
Difference	18%	
Contributions		
Non-ICT Capital Deepening		2%
Hours/ Scale		18%
ICT		60%
ICT Capital Deepening		17%
ICT Spillovers		43%
Telecom Penetration		3%
IT Penetration		40%
PC Penetration		30%
Digital/PC Interaction		10%
Unexplained by Above Factors		20%

* Communications Capital includes Broadcasting

We turn first to the Canada-U.S. comparison for 2003. From Table 4.3, it can be seen that labour productivity (GDP per hour worked) was calculated to be 21% higher in the U.S. than in Canada.[40,41] The third column of Table 4 contains the contributions of the various factors that we have estimated contribute to the productivity differential. The numbers in this column are interpreted as follows. Consider non-ICT capital deepening. The number "5%" means that 5% of the 21 percentage points U.S. advantage in labour productivity in 2003 was attributed to the fact that the U.S. used more non-ICT capital per hour in production than did Canada. An alternative way of presenting this information is to say that a 1% (5%of 21%) labour productivity gap is attributed to non-ICT capital deepening.

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[40] This number was calculated as log $(GDP/hr)_{US}$ - log $(GDP/hr)_{Canada}$.

[41] The 20% differential is consistent with most estimates of the labour productivity gap. An exception is the recent paper by Baldwin, Maynard and Wong (2005). They estimate the productivity differential to be 7% as of 2002. The discrepancy is due primarily to a difference in the U.S. hours-worked data. Baldwin, Maynard and Wong make a number of adjustments to the series used by most other researchers.

Because we estimate that there exist increasing returns to scale in production, the larger size of the U.S. economy provides it with a labour productivity advantage. In 2003, we estimate that 15% of the 21-percentage points gap is attributed to the size advantage of the U.S. economy.

We now come to the contribution of ICT. The combination of ICT capital deepening and ICT spillovers account for 56% of the U.S. labour productivity advantage. Production in the U.S. in 2003 was more ICT capital intensive than production in Canada (capital deepening). In addition telephone and personal computer penetration, our indicators of the spread of ICT technology, was greater in the U.S. than in Canada (ICT spillovers). For this important result we have computed a 95% confidence interval (see column 4 of Table 4.3). From the calculated confidence interval we conclude that with 95% probability, the true proportion of the 21 percentage points labour productivity gap due to Canada's ICT disadvantage lies between 51% and 61%.

We now turn to the components of ICT. ICT capital deepening accounted for 12% of the 21 percentage points labour productivity difference, whereas ICT spillovers accounted for 44 percent of the difference. We estimate that the Canada-U.S. difference in the spread of ICT technology throughout the economy was a more important source of the labour productivity gap than the difference in ICT capital accumulation per se, although both were important. The 95% confidence interval for the contribution of ICT spillovers is the interval (40%, 48%).

Most of the impact of ICT spillovers is due to what we are calling IT penetration. Recall that this phenomenon is modeled as the penetration of personal computers plus the interaction of this spread with the digitalization of the telecom network. As discussed in the last section, we cannot estimate with any reasonable accurately the separate parameters a_{PCI} and $a_{HIGH,}$ but we can estimate accurately their sum. This implies that we have an accurate estimate of the contribution of IT penetration, but not the separate personal computer and digital/PC interaction effects. We attribute 42% of the 21 percentage points Canadian labour productivity disadvantage in 2003 to the fact that the U.S. had a greater IT penetration than Canada. With 95% probability, the true proportion lies between 38% and 46%. Based on our point estimates of the parameters a_{PCI} and a_{HIGH}, of the 42% contribution, 31% is attributed to PC penetration, and 11% to the digital/PC interaction. However, as noted earlier, not much confidence can be placed in this split.

The impact of ICT investment on the Canada-U.S. labour productivity gap as of the year 2003 is readily apparent from these results. More than 50% of the differential is due the fact that ICT capital was more pervasive in the U.S. economy than in the Canadian economy. The most important component was the differential spread of IT technology. Over 40% of the Canada's labour productivity gap is attributed to the fact that IT technology has exhibited greater penetration into the U.S. economy than it has into the Canadian economy.

We now turn to a comparison of the U.S. and Canada in the year 2000. The results can be found in the bottom half of Table 4.3. The gap in labour productivity was 18 percentage points, less pronounced than in 2003, so that there was a deterioration in Canada's relative position over the 2000-2003 position. Of the 18 percentage points labour productivity difference, 2% was due to more non-ICT capital-intensive production in the U.S. and 18% to the U.S. scale advantage.

ICT accounted for 60% of the productivity disadvantage in 2000, which is a higher proportion than we estimated in 2003. The reduction in the percentage ICT contribution from 2000-2003 is primarily due to the capital deepening effect (17% in 2000, 12% in 2003). It appears that there was a higher growth in real ICT capital per hour in Canada than in the U.S. over the 2000-2003 period[42].

While the percentage ICT contribution fell from 60% in 2000 to 56% in 2003, the 2003 proportional contribution was applied to a larger labour productivity gap. Hence the absolute gap attributed to Canada's lower level of ICT capital and lower diffusion of ICT technology remained essentially unchanged between 2000 and 2003 in these data. As discussed in footnote 37, there is a possibility that the Canadian accumulation of real ICT capital between 2000 and 2003 is overstated. If this is the case, Canada's position vis a vis the U.S. with regard to the absolute contribution of ICT to the labour productivity gap could have deteriorated somewhat between 2000 and 2003.

ICT spillovers accounted for 43% of the labour productivity difference in 2000 (44% in 2003). IT penetration was also the dominant source of ICT spillovers in 2000, accounting for 40% of the 43%. Between the years 2000 and 2003, ICT remained the most important component of the Canada-U.S. labour productivity differential.

We now turn to a comparison of labour productivity between Canada and Europe[43] for the year 2003. The results are contained in Table 4.4.

Table 4.4: Sources of Labour Productivity Differences: Canada versus Europe, 2003*

	Percentage	Proportion of Percentage Difference
Difference	12%	
Contributions		
Non-ICT Capital Deepening		90%

[42] These different rates of growth may be an artefact of price deflation. Canada's price deflators for IT equipment fell more quickly in Canada over the 2000-2003 period than in the U.S., probably due to more aggressive hedonic adjustments.
[43] Recall that Europe is defined as a population weighted average of Finland, France and the United Kingdom.

Hours/ Scale		4%
ICT		-36%
ICT Capital Deepening		1%
ICT Spillovers		-37%
Telecom Penetration		11%
IT Penetration		-48%
PC Penetration		-36%
Digital/PC Interaction		-12%
Unexplained by Above Factors		42%

*Communications Capital includes Broadcasting

In 2003 Canada had a labour productivity disadvantage of 12 percentage points compared with Europe. However, the sources of that gap were very different than what we saw when comparing Canada and the United States. The primary reason for the Canada-Europe productivity disadvantage in 2003 was the existence of a much greater non-ICT capital stock per hour worked in Europe than in Canada. This factor accounted for 90% of the differential.

The negative numbers in the third column of Table 4.4 indicate a factor where Canada has an advantage. Hence, the ICT factor provides a labour productivity advantage to the Canadian economy that partially offsets the disadvantage associated with a lower level of non-ICT capital deepening. The contrast with the U.S. couldn't be more stark. IT penetration is a major source of Canadian advantage over Europe. Compared with the U.S., Canada has suffered from a lower level of investment in ICT and a less extensive diffusion of ICT technology. By contrast, it is Europe that has suffered, compared with Canada.

In summary, the spread of ICT investment into the U.S. economy is a very important component of the U.S. labour productivity advantage over Canada. The same cannot be said with respect to Europe. As of 2003, Canada actually had an ICT advantage over the European countries that we have included in our updated data set. Canada had a labour productivity disadvantage with respect to these countries, but it was attributable mainly to a lower non-ICT capital per hour worked.

5 Policy Conclusions

We have shown the importance of ICT capital in fostering productivity growth, as have many other researchers. Our analysis highlights the importance of the diffusion of ICT technology throughout the economy. Our indicators of this diffusion are the spread of PCs, the spread of telephones including mobile phones, and the spread of digitalization of telecom networks. The econometric results show that the greater ICT capital in the U.S. and its diffusion '"explain" some 50% to 60% of the Canada-U.S. productivity gap.

The policy implications of this gap are not simple to develop. One can begin with basic issues – eliminating impediments to ICT adoption. A number of countries, for example, recognizing the importance to the economy of ICT, provide incentives for ICT purchases by firms. Such policies would be welcome in Canada.

Table 5.1 presents date provided by IDC Corporation on the diffusion of PCs across five segments of Canadian society – households, small enterprises, medium and large enterprises, government, and education. Each entry in the table shows for the year (1993 to 1995) the per capita ratio for the U.S. relative to Canada in that segment. If PC ownership were identical on a per capita basis between Canada and the U.S., then the entry would be 1.0. Where a ratio is above 1.0; per capita PC penetration is behind in Canada; where the ratio is below 1.0, Canada leads.

Table 5.1: U.S./Canadian PC Intensity Ratio

	2003	2004	2005
Home	0.88	0.91	0.93
Small Business (1-99 employees)	1.21	1.23	1.30
Medium / Large Business (100+)	1.64	1.67	1.72
Government	1.66	1.71	1.75
Education	1.56	1.57	1.59
Total	**1.14**	**1.16**	**1.19**

As can be seen, the residential sector in Canada uses more PCs (per capita) than does the U.S. This may be surprising to some, but is consistent with other data, namely the greater use of broadband in Canadian households than American households.

Where Canada lags the U.S. especially is in the sectors of medium and large business, government and education. We turn to each of these.

5.1 Medium and large enterprise

PCs are a proxy for the diffusion of ICT generally. The far lower diffusion of PCs, or ICT capital in general, in medium and large Canadian enterprises is a significant concern. Here we must begin by benchmarking Canadian incentives for ICT adoption against the U.S. and other leading countries. Many of these countries provide certain tax incentives to enterprises to invest in ICT. This lowers the cost of ICT and speeds adoption. Given the fact that ICT – here PCs and telephony – and the nature of the telephony infrastructure have important spillovers to productivity, it means that the social return for investing in this capital is high.

While providing the proper incentives for ICT accumulation is important, it’s not the whole story. Research shows that the true productivity-enhancing ability of ICT at the enterprise level involves much more than a firm raising its IT budget. MIT’s Eric Brynjolfson and his co-authors have coined a term -- the Digital Organization -- referring to the firm that invests in ICT, its complementary skills and assets, and reorganizes itself by changing business processes to accommodate the full potential of ICT. These complementary skills and assets involve labour skills as well as a managerial environment where transformations are made easy.

Thus the numbers in Table 5-1 indicate not only a gap in ICT capital but may signal a deeper issue - the inability of enterprises in Canada to adapt to the New Economy, to alter the ways in which the firm operates. We need to begin by investigating how much other factors account for perceived gaps in PC penetration. First is the obvious difference in industry mix: Does Canada have an industry mix in which PC use is not as prevalent at best practice levels as it is in other industries? Second, is greater ICT adoption in the U.S. another feature of the general competitive and flexible U.S. economy?

What is required is a better understanding of the reasons for the ICT gap between Canada and the U.S. for large enterprises. That analysis is beyond the scope of this paper and requires an analysis of how ICT is used in similar industries across the two countries.

5.2 Government

The data in Table 5-1 show a very large difference in the use of PCs by governments in the two countries. Many surveys indicate that the Canadian federal government rates high in e-government, that is, citizen’s use of ICT infrastructure for communication and interaction. What Table 5-1 indicates is that at some or all levels of government, PCs (ICT generally) are not utilized nearly to the extent that they are in the U.S.

Again, more analysis is required to understand the nature of the problem before solutions can be addressed. Adding large-scale IT projects to government services is not the answer.

A policy here would be for government in Canada to be leaders, not laggards, in their adoption of ICT as transformational technologies. This transformation would also serve as an important indicator to Canadian business of the value using ICT to enable change. This policy could be called the evolution towards “Digital Government.”

5.3 Education

Finally, the gap in PC use in education between Canada and the U.S. is surprising, as the use of PCs in primary and secondary schools in Canada is thought to be high. The gap with the U.S. shows in this table is of real concern. It may signal gaps at the university level, and if so it would be critical to understand where these gaps are and if the U.S. is quickly moving to a PC based higher education system.

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