THE PAST, PRESENT AND FUTURE OF THE ICT REVOLUTION
Industry Canada sponsored research final report
RED (SHORTER) REPORT

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EXECUTIVE SUMMARY

For some decades now we have been living through a period of revolutionary change induced by what is commonly called the information and communication (ICT) revolution. This term refers to the economic, social and political transformations currently being driven by a cluster of technologies centered on the electronic computer and the Internet. When the dotcom bubble burst early in the 21st century, many observers argued that the ICT revolution had run it course so that we could no longer look to it as a source of further economic and social change in general and of new economic opportunities in particular. Our main objective in this paper, called the Red Report, and its longer companion, called the Blue Report, is to examine this contention. We identify what we call *programmable computing networks* (PCN) as the fundamental general purpose technology that is driving the modern ICT revolution and seek to determine how far along PCN is in its evolving, economic trajectories of efficiency and applications.

In Section 1, we first discuss the power of technology in general and to change society, giving some illustrative historical examples to put the current changes into perspective. We then define a general purpose technologies (GPTs) as a major transforming technology that is widely used for multiple purposes and that has many "spillovers," particularly in enabling the development of new products, new process and new forms of organisation in places well beyond the industry that produces the GPT itself. We identify the principle that lies behind modern ICTs as *flexible machine logic,* which is the process of applying an inanimate logical system to a transmission medium in order to analyze a signal for some purpose; the logic being flexible because it can be altered without altering the physical structure of the device that uses it. For example, early computers used machine logic that was inflexible because their logical processes were hard wired into their circuits, while later computers used flexible logic in which the logical structure could be altered without altering the machine's internal physical circuits. We identify the GPT that uses this type of logic and that is driving the modern ICT revolution as *programmable computing networks* (PCN), which includes computers, the Internet and many other networks that use flexible machine logic. These are all grouped together as one GPT rather than their more common treatment as separate technologies because they are all electronic networks identified as a system of electronic, flexible machine logic dispersed across multiple nodes.

The evolution of emergent technologies from crude single-purpose technologies into fully fledged GPTs, can be charted in terms of an efficiency and an application time series, each of which tend to be logistic in shape. Efficiency is measured by the cost per unit of output of the good or service that the GPT provides. Applications refer to the number of new products, new processes and new organisational forms that are enabled by the GPT. These tend to co-evolve with increased efficiency enabling new applications and new applications tending to encourage increases in efficiency.

Section 2 deals with some basic concepts related to ICTs. Information is transmitted through signals that need to be received and processed for meaning. Information is not subject to deprecation nor is it rivalrous: one person using it does not necessarily reduce or increase its value for other persons nor does it preclude others from using it simultaneously. The development of modern computers as users of flexible machine logic is studied and it is argued that all networks that use such logic are similar enough to be grouped into one GPT.

Section 3 deals with the modern ICT revolution. Its scope is established by listing a small sampling of the vast number of changes that it has produced in terms of new products, new production processes and new organizational forms. These leave us in no doubt that most of the world's peoples have been living over the last few decades through a profound transformation of their economic, social, and political structures. We say no more about that and concentrate instead on the future course of the ICT revolution. Has the force gone out of it, or does it still have great potential to create further economic opportunities?

Section 4 places PCN in its efficiency curve. To do this, we first separate engineering process advancements, such as the ability to etch ever more circuits on given sized silicon chips, from logical advancements, such as the invention of multiple core processors. Process advancements are covered by Moore's law. While this empirical generalisation has held good for several decades, the end dictated by physical limits to increasing the engineering efficiency of semiconductors (at least as we now understand them) may be reached in a decade or two from now. Many advances have been made in logical processes, such as the ability to optimise the allocation of functions to various levels in the hierarchy of the computer's structure. We also note the sources of scale effects, from networks and bandwidth improvements, the exploitation of which increases efficiency at an increasing rate over some interval of time or space. The combined effects of these major forces acting on efficiency are measured by quality adjusted price indexes for various components of PCN, such as microprocessors and memory chips. In all cases, efficiency is shown to have been growing exponentially over many decades. How long this can continue before physical limits prevent further major increases in efficiency is a matter of debate. But it is now accepted that these limits exist, at least with the present types of networks, and are no more than a decade or two away — rather than being a century or two away.

Section 5 places PCN on its applications curve. This is the critical part of the study because it is as the as-yet unexploited applications that create new opportunities for profitable enterprises and the creation of high value jobs. Applications of the GPT on its own are looked at in two ways. First, the diffusion of existing applications is shown to have gone a long way but to still have potential for further diffusion. Second, wholly new applications are shown by a series of case studies to be coming at a rapid rate and in many different parts of the economy. There is as yet no evidence of a slowing of new applications that would indicate a transition to a flatter portion of the applications time series curve. Furthermore, almost none of these applications suggest a local trajectory that has gone its full course. Instead, virtually all of them indicate further developments of products and processes that are enabled by them, the diffusion of which, through the entire economy will take years, offering in the meantime massive opportunities for local adaptations and improvements. Opportunities that are created by a union of the GPTs of PCN, biotechnology and nanotechnology offer an almost unlimited range of potential new applications stretching for decades into the future. Eventually, as it is with electricity today, PCN will become nothing more than a background input that is used everywhere in bio- and nano-technology but in the development of applications that owe their entire form to biology and physics and not to the evolving structure of the computer. But that is still some way off because further efficiency developments of PCN are needed before some of the foreseeable applications can be realized.

Section 6 compares the evolution of PCN with that of electricity. Two conclusions are suggested. First, PCN seems to be about where electricity was on its efficiency curve in the early 1920s, with a decade or two more of efficiency gains in store. Second, if primary applications follow the same path as charted by electricity, then there are also at least two decades of new primary applications with large implications for productivity in store for PCN and another decade or two of high demand based on the diffusion of already innovated applications.

THE PAST, PRESENT AND FUTURE OF THE ICT REVOLUTION

RED (SHORTER) REPORT

For some decades now we have been living through a period of revolutionary change induced by what is commonly called the information and communication (ICT) revolution. This term refers to the economic, social and political transformations currently being driven by a cluster of technologies centered on the electronic computer and the Internet. When the dotcom bubble burst early in the 21st century, many observers argued that the ICT revolution had run it course so that we could no longer look to it as a source of further economic and social change in general and of new economic opportunities in particular. Our main objective in this short version, called hereafter the red version, and in its longer companion main report, called hereafter the blue version, is to examine this contention.[1]

In Section 1, we first set the stage with a discussion of the importance of technical change as a driver of economic growth. We then introduce the key concept of *general purpose technologies (GPTs)*. After noting their importance in the history of economic growth, we outline the complex evolution of a typical GPT. Here we stress the increasing efficiency with which the typical GPT delivers its services and the continuing growth in the new applications that it enables — applications that present opportunities for profitable exploitation. In Section 2, we look in some detail at the nature of information and communication technologies. Here we stress the importance of *machine logic,* which is used by all ICTs, and of *flexible machine logic,* the use of which distinguishes the group of modern ICTs that make up the GPT that we call *programmable computing networks (PCNs)*. PCNs include the electronic computer, the Internet and some related technologies that also use flexible machine logic. In Section 3, we look in a little more detail at the nature of the ICT revolution. We trace its evolution up to the present time and end with the key question of it future prospects: is it spent as a force for new economic opportunities, or does it still have large, as-yet unexploited, potential? In the next two sections, we answer that PCN still has significant scope of increasing the efficiency with which it delivers its services and that it is still creating a vast array of new applications that provide opportunities for profitable economic exploitation, a process that shows no signs of slowing in the foreseeable future. We conclude, therefore, that the ICT revolution will continue for some time to come, being driven by efficiency gains and new applications of PCN devices — reports of its demise have been greatly exaggerated. In the postscript, Section 6, we compare the evolution of electricity with that of PCN to gain some outside perspective on the latter's future potential.

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[1] The sources of the data that appear in this report and a full bibliography are given in the main Blue report.

I. THE TRANSFORMING POWER OF ECONOMIC GROWTH AND TECHNOLOGICAL CHANGE[2]

Over the last 10 millennia, economic growth has helped to turn us ever so slowly but quite decisively from hunter gatherers, consuming only what nature directly provided, into people who consciously produce what we consume, often using materials that we ourselves have created. Importantly, economic growth has occurred not because we have produced more of the same, using static techniques, but because we have created new products, new ways of making them, and new ways of organizing our productive activities. We call these product, process and organizational technologies. Changes in these technologies, 'technological change' for short, drives economic growth.

People living at the beginning of the 21st century experience measured real consumption that is over ten times as much as the consumption of those living at the beginning of the 20th century. But they consume this enormous increment largely in terms of *new commodities* made with *new techniques* and *new forms of organization*. Those who lived 100 years ago did not know modern dental and medical equipment, penicillin, bypass operations, safe births, control of genetically transmitted diseases, personal computers, compact discs, television sets, automobiles, opportunities for fast and cheap world-wide travel, affordable universities, central heating, air conditioning, and food of great variety free from ptomaine and botulism, much less the elimination of endless kitchen drudgery through the use of detergents, washing machines, electric stoves, vacuum cleaners, refrigerators, dish washers, and a host of other labour-saving household products that their great grandchildren take for granted. Nor could they have imagined the robot-operated, computer-controlled, modern factories that have largely replaced their noisy, dangerous, factories that spewed coal smoke over the surrounding countryside. Technological change has transformed the quality of our lives. It has removed terrible diseases that maimed, crippled, and killed — plague, tuberculosis, cholera, dysentery, smallpox, and leprosy, to mention only the most common. In 1900, death from botulism and ptomaine poisoning from contaminated food was common. Chemical additives virtually eliminated these killers and allowed us to live long enough to worry about the long run cancer-causing effects of some of these additives. Now they are being replaced by safer preservatives. In summary, technological advance not only increases our incomes; it transforms our lives through the invention of new, hitherto undreamed of products that are made in new, hitherto undreamed of ways.

The basic source of the changes just referred to is that we know more than the Victorians did. We have vastly more scientific and technological knowledge than they, just as they had more than those who lived a century before them. To be clear in our further discussions, we need to define *technological knowledge*, or technology for short. It is the set of ideas specifying all activities that create economic value. It comprises: (1) knowledge about product technologies, the specifications of everything that is produced; (2) knowledge about process technologies, the specifications of all processes by which goods and services are produced; (3) knowledge about

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[2] The material in the first three paragraphs is drawn from Lipsey, Carlaw and Bekar, *Economic Transformations: General Purpose Technologies and Long Term Economic Growth* (Oxford: Oxford University Press, 2005).

organizational technologies, the specification of how productive activity is organized in productive and administrative units for producing present and future goods and services.

1.1 General Purpose Technologies

Technological change proceeds in many ways. Much of it takes the form of small incremental improvements that individually go almost unnoticed but cumulatively have big effects on productivity over long periods. There are also many larger changes in both products and processes that occur quite frequently, some of which come more or less out of the blue but most of which can be seen as movements along the development trajectory of some broadly defined technology, such as factory robots or cell phones. Every once in a while a new technology comes onto the scene that impacts on more or less everything in our lives: what we produce and how we produce it, how we organize and manage production, the location of productive activity, the infrastructure we need, as well as the laws we require concerning such things as property rights and permitted forms of business organisation. Such technologies are called *general purpose technologies (GPTs.)*

1.1.1 GPTs in history

To gain some insight into the transforming effects of GPT's, we look briefly at the past. We can identify perhaps a couple of dozen such GPT-driven shocks in all of human history. The economic, social and political impacts of each were so profound that it takes a book-length treatment to deal with them. So all we can do here is to mention of some of the most important.

About 10,000 years ago, the *Neolithic agricultural revolution* turned us from hunter gatherers into settled farmers, planting crops and using animals, both of which we genetically altered by selective breeding. Around 3500 BC, the invention of *writing* in what is now southern Iraq allowed a massive leap in our power to organize complex economic and social activities, compared with what could be done when all records had to be preserved in human memory. A little less than a thousand year later, the invention of *bronze* allowed great improvements in utensils, tools and weapons, enabled organised warfare and the resulting multi-city empires to enter human experience for the first time. Late in the second century BC, the invention of techniques for *smelting iron* reliably allowed the creation of both low-cost tools, such as the iron plough that permitted the colonisation of vast areas that could not be cultivated by wooden ploughs, and low cost weapons that allowed 'barbarians' to overwhelm and destroy the great city states of the Eastern Mediterranean. Shortly after the dissolution of the Western Roman Empire *water wheels* came into widespread use in Western Europe, allowing the mechanization of many European manufacturing industries and setting Europe on a trajectory of the use of mechanical power. In the mid 15th century, the invention of *printing with moveable type* had enormous repercussions, including the spread of literacy, the breaking of monopolies of knowledge, the spread of science, commerce and learning and, not the least, the Protestant Reformation whose appeal to the masses to interpret the holy scriptures for themselves could not have happened without cheap printed pamphlets and a literate population to read them. Also developed in the 15th century, *the three masted sailing ship* allowed Europeans to travel overseas in relative safety for the first time in history, discovering (from their point of view) the rest of the world and conquering much of it. In the early 18th century *the steam engine* started as a specialized technology to pump water out of mines and developed over a century and a half into the efficient machine that produced the Victorian age of steam where it powered factories, and propelled ships, railway trains, coaches and tractors. Also the 18th century, *automated textile machinery,* reached a stage in its multi-century evolution when it became efficient to take production out of homes where it had been located for centuries and move it into water-wheel driven factories. Then in the early 19th century, the steam engine entered textile production creating the *modern factory system*, which moved the population out of the country side where water-wheel-driven factories had to be located near fast running water and into the new great industrial cities. This created the urban proletariat and the mass produced goods that eventually raised the living standards of ordinary worker to levels undreamed of by their counterparts in any past time (but causing much misery along the way). In 1867 the centuries long series of discoveries concerning the nature of electricity and magnetism culminated in the invention of the *dynamo.* By allowing the practical generation of electricity for mass consumption, it transformed society in the many ways that can be dramatically seen today when the electricity supply is interrupted (and would be even more dramatically obvious were it not for back-up generators in critical places such as hospitals). Late in the 19th century *the internal combustion engine* altered the ratio of weight to power in such a way as to enable the automobile and the airplane, both of which helped to transform 20th century society. Today we are living through another great transformation in our economic, social and political behaviour brought on by the new technologies of the *computer, the internet and a few other related electronic technologies*, which together make up another GPT which is the subject of this paper.

1.1.2 The evolution of a typical GPT

A technology that eventually becomes a GPT typically starts being used for a small number of purposes, often just one. It is both crude and inefficient as judged by the standards it later achieves. It is initially incorporated into an economic and institutional structure (what we define below as the ‘facilitating structure’) that has been designed for the incumbent technology that the new GPT is challenging. Slowly, these structures are redesigned to suit the new emerging GPT. For example, computers were first introduced into management organisations designed for handling information on hard copies. Later, as all levels of the structures of management and administration were redesigned to accommodate electronic means of communicating, analysing, and storing information, the organisation of the typical business was redesigned and only then did administrative efficiency rise. A similar order of events was observed on the shop floor.

As the GPT evolves, it increases in efficiency[3] and in its range of applications[4] until it spreads through most of the economy, being widely used for multiple purposes. There are, for example, few products and manufacturing processes today that do not use computing power in one way or another. It is important to note that although new GPTs typically have an impact by reducing the direct cost of the commodity or service that they provide, most of the really transforming effects come because they enable goods,

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[3] A GPT’s *efficiency* is the cost at which it delivers a unit of its service.

[4] An *application* of the GPT is a product, process, form of organization, or some combination of the three, which includes some part, or all, of the GPT, either as a component or as instructions (explicit or implicit) on how to use the GPT.

processes and forms of organisation that were technically impossible with the technologies that they supplanted. The iron steam ship, equipped with refrigeration, could do things that transformed agriculture world-wide but that could never have been done with sailing ships even if the price of transport by sail had fallen to zero. Similarly, no steam engine could have been attached to the carpet sweeper to turn it into a vacuum cleaner, to the ice box to turn it into a refrigerator, or a washing tub to turn it into a clothes washing machine.

This discussion serves to introduce three key definitions.

- The *spillover effects* of a GPT (or any new technology) are effects that spread through the economy beyond the sector that produces GPT itself. This is to some extent because the GPT reduces the cost of the service that it provides but more so because it makes possible new goods, new production processes, and new forms of organisation that were technically impossible with the old GPT.
- A *general purpose technology (GPT)* is a single generic technology, recognizable as such over its whole lifetime, that initially has much scope for improvement and eventually comes to be widely used, to have many uses, and to have many spillover effects.
- The *facilitating structure,* is the set of actual physical objects, people, and structures, in which technological knowledge is embodied, including plant and equipment — what it is, how it works, how it is organised, and where it is located — the internal organisation and industrial concentration of firms, all infrastructure, and all financial institutions.[5]

Any new technological knowledge requires some change in the facilitating structure before it can have an effect on production—at very least, it must be embodied in new or revised physical and/or human capital. GPTs typically cause major changes in virtually all of the elements of this structure. When these changes are deep and long lasting, it is common to refer to a ‘revolution’ being brought about by the GPT in question.

It is necessary to distinguish between the evolution of a GPT itself and the accompanying economic, social and political changes that it induces. The evolution of the GPT is indicated by the increasing efficiency with which it delivers its services and the increasing range of its applications. For example, as electricity generation and distribution became increasingly efficient, so that the cost of a kilowatt hour delivered to a user fell dramatically from the time the dynamo was invented until sometime between

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[5] The full list given by Lipsey, Carlaw and Bekar (2005) is as follows: (1) consumers’ durables and residential housing; (2) people, who they are, where they live, and all human capital that resides in them and that is related to productive activities, including tacit knowledge of how to undertake existing value-creating activities; (3) actual physical organization of production facilities, including labour practices; (4) managerial and financial organization of firms; (5) geographical location of productive activities; (6) industrial concentration; (7) all infrastructure; (8) all private-sector financial institutions, and financial instruments; (9) government-owned industries; (10) educational institutions; and (11) all research units whether in the public or the private sector.

the two world wars. After that time, although the price of electricity fluctuated, there was no further downward trend. All through that time, the range of applications of electricity expanded, including lighting in streets, homes and factories, street railways, powering factories, enabling a host of new consumers' durables such as washing washings and vacuum cleaners, powering many tools, propelling transport vehicles (to great extent through diesel electric motors), and a host of other applications that continue to be developed even today. Also all through that time, there were induced changes in the facilitating structure, such the growth of suburbs, the introduction of mass production techniques in assembly factories, changes in the skill requirements of labour, changes in the location of industry, to name but a small sub-set of the alterations in the facilitating structure made possible and /or necessary by electricity.

New GPTs also induce changes in public policies, such as anti-monopoly legislation, and in the policy structure, defined as the human and physical capital that gives effect to public policies, such as regulatory bodies. In this paper, we say little about the policy effects of new GPTs. But when the wider impacts of a GPT's evolution are considered, induced changes in policy and in the policy structure need to be considered.

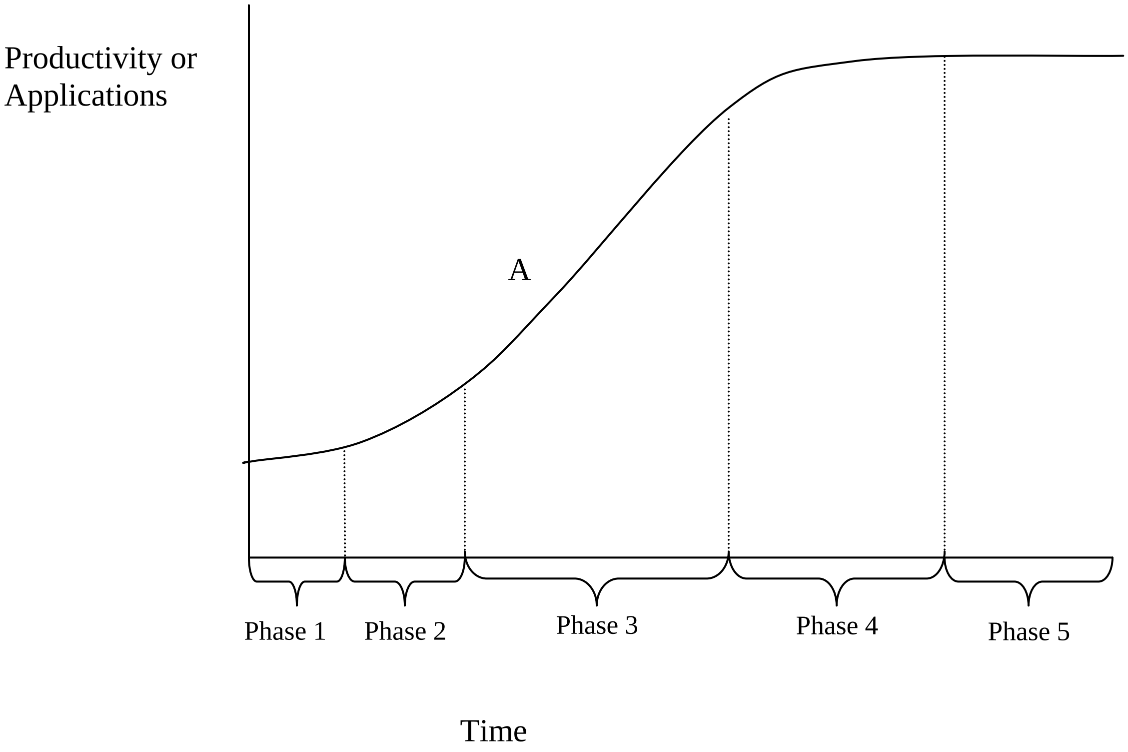
1.2 The Evolution of Efficiency, Applications and Diffusion

We have stated that as a GPT evolves the efficiency with which it delivers its services, its range of applications, and the extent of its use across the economy all increase. These evolutions of efficiency, applications and diffusion can each be stylized by a time pattern that is logistic in form. Although there are differences from one GPT to another, this logistic form is a reasonable stylization of the typical developments in almost all cases.

The basic reasoning behind the logistic nature of the evolution of a GPT's efficiency is that when the GPT begins life, it is in a crude form that is only slowly improved and adapted; later in its evolution, when it is becoming well developed, its efficiency rises quickly; eventually, however, physical limits are approached, causing gains in efficiency to slow, and finally coming to a halt if the GP remains in use long enough. This pattern is shown in Figure 1.1, where efficiency is measured on the *Y* axis — in units such as cost per horsepower produced by a steam engine or cost per kilowatt hour produced by an electric generator. Plotting these variables produces what we call an efficiency curve.

As it is with efficiency, so it is with applications. However, the evolution of the applications of a new GPT is driven by two distinct sources. First, as the GPT delivers its services with ever-increasing efficiency, many tasks that were prohibitively expensive with the displaced GPT now became economically viable. For example, some of the less complex calculations done in fractions of a second by a modern computer could have been done by armies of workers using mechanical calculators over weeks, months or even years. The second source of new applications arises because the new GPT makes possible applications that were technically impossible with the technology that it replaces. For example, even if the price of energy generated by a steam engine had fallen to zero, it would have remained impossible to transmit the energy produced by such an engine to distant users. Because these developments occur slowly at first, when the GPT is in fairly crude single-purpose form, then accelerate as its efficiency and number of uses increases, and finally slow as the potential of the GPT is more fully exploited and physical limits begin to be approached, the cumulative applications of each GPT also tend to follow a logistic time path. This can also be shown in Figure 1.1 where the *Y* axis now measures the number of applications. When this is done, we call it the 'applications curve'.

Figure 1.1: An Efficiency and an Applications Curve.



The curve A is standing for two quite distinct curves with different scales on the Y axis. It is *either* an efficiency curve *or* an applications curve.

Although we show just one curve with *either* efficiency *or* applications on the *Y* axis, they are distinct curves. Although both will typically be logistic, one may be steeper or more long drawn out than the other. Also the trajectories of efficiency and applications for any one GPT may be at different points on its two curves at any one time. For example, as we will see later, electricity reached Phase 4 of its efficiency curve while it was still well within Phase 3 of its applications curve.

Whether it is efficiency or applications that are being measured, the tendency for a logistic time path can be divided into phases as shown on the figure.

Phase 1: A new single-purpose technology that eventually evolves into a GPT is introduced into the facilitating structure that is designed for a pre-existing set of GPTs. Both its efficiency and the number of applications that it spins off increase only slowly.

Phase 2: The facilitating structure, is slowly being redesigned to fit the new technology that is evolving into a GPT. This stage is often long drawn out, full of uncertainty, and prone to conflict since the adjustments create many winners and losers. The growth of new applications and of the GPT's efficiency tend to accelerate.

Phase 3: The principles of the new GPT are applied to produce many new applications in terms of new products, new processes and new organizational forms *within a newly evolved facilitating structure that is by now fairly well adapted to it*. This is the time when the number of new applications grows rapidly and eventually reaches a maximum rate. Efficiency growth is also reaches its maximum during Phase 3 of the efficiency trajectory.

Phase 4: The opportunities for applications of the GPT to create new product, processes and organizational technologies (and to improve existing ones) diminish as does the rate at which its efficiency is rising.

Phase 5: If the GPT remains in use long enough, the scope for further increases in efficiency and applications may be exhausted. often because physical limits of one sort of another are reached. The relevant curve is then horizontal.[6]

To repeat for emphasis: each of these phases varies greatly from GPT to GPT, depending on the productivity potential of each and how it is exploited; efficiency may have very short Phases 1 and 2 if efficiency increases rapidly quite early in the GPT's evolution; efficiency may enter its Phase 4, or even Phase 5, while applications are still in the middle of their Phase 3.

1.3 The Co-evolution of Applications and Diffusion

When we discuss the growing number of applications of any GPT there are two distinct aspects: the development of new applications and the spreading use of existing applications, i.e., diffusion.

1.3.1 New applications

First, consider new applications. In some cases, they may depend solely on the GPT in question and a number of other lesser technologies, not themselves GPTs. For example, the computer was used to create robots, which were used, among other things, to conduct many surgical procedures with more accuracy than was possible with human hands. This in turn gave rise to the invention of new surgical tools to be used in robotized operations. These new tools turned out to have other uses that spread to non-surgical applications, and so on in a concatenation of linked inventions and innovations.

In other cases, the GPT may cooperate with other GPTs. To consider such cooperation further we need to define two new terms.

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[6] In Lipsey, Carlaw and Bekar Phase 5 refers to the time at which a new GPT arrives to challenge the incumbent. For our purposes, it is more useful to use the term for the time at which either new applications cease to be developed or efficiency ceases to increase.

- *A primary application of a GPT* is an application whose nature is mainly influenced by the characteristics of the GPT itself.
- *A background, enabling application of a GPT* is an application for which the GPT is a necessary condition but whose nature is not mainly determined by the characteristics of that GPT.

When two GPTs initially cooperate with each other, the nature of the GPTs tend both to be more or less equally important in setting the path of development. Eventually, however, one becomes the prime mover in the application-generating process and the other becomes a background enabler. Consider an example. Although computers are just starting to be used in testing drugs, routine computer assisted drug design (CADD) is still some way off. Indeed, many protein molecules are too complex to be simulated on an existing electronic computer in such a way that the results of altering them can be predicted just as we now can predict the results of altering an airplane's wing. But a more powerful generation of computers, when and if they come, will probably make CADD as common as CAD is now. So currently results are determined both by the biological characteristics of the materials and the physical characteristics of the computers. Eventually, however, computers will become like electricity is in most developments today: it is a necessary input but the shapes of the developments are determined by the GPT that it enables. Computers will then be nothing more than a background enabling force that does not directly influence the trajectory of the new developments in the technologies that it enables. This is the sense in which electricity is an enabling force behind any product or process that uses electronics today, but is not directly moulding the direction of most of these applications. For example, electricity is used to power a computer that is used in genetically engineering many grains. But the nature of such agricultural innovations depends basically on biology, while the computer is just a tool and electricity just a power source for that tool. The basic innovations are thus correctly seen as being driven by bio-technology and neither by the nature of the computer that is used nor of the electricity which powers the computer. Further advances are primary applications of biotechnology while computers and electricity are the background enabling technologies.

1.3.2 Diffusion

Now consider the spreading use of existing applications. On the one hand, if a new application is a superior way of doing something already being done by some existing product, as was the digital camera compared to the conventional camera, then its market diffusion is through an increasing share of an existing market — as well, possibly, of an expanding market if new users are attracted into the market by unique features of the new product. On the other hand, if the new application does something that is wholly new, as with the two-week overseas holiday made possible by jet aircraft, then its diffusion depends on a growing new market.

When a new application is developed, its diffusion through the economy is often slow, costly and uncertain. Just to discover what is currently in use throughout the world is a daunting task, particularly for small firms. Even if a firm can identify best practice techniques, this (at best) provides it with a blueprint; learning how to produce successfully what is described in a blueprint implies acquiring all the tacit knowledge that goes with adopting something new. It follows that the existing set of technologies does not provide a freely available pool of immediately useful knowledge. Furthermore, adapting technologies in use elsewhere to one's own purpose often requires innovation. As a result, innovation of new applications and the diffusion of existing ones interact in a system of mutual causation; they shade into each other rather than being clearly distinct activities.

We will see in Section 5 that this blurring of the creation of new applications with the diffusion of existing applications creates a challenge when we seek to identify the applications curve for computer related technologies. The data we present does not permit a clear distinction between the creation of new applications and their diffusion although they do give us important information.

1.4 The Co-evolution of Efficiency and Applications

Next, we enquire into the co-evolution of the efficiency and the applications of any new GPT. If we hold the efficiency with which the GPT delivers its services constant, the potential for new applications, and spillovers, takes time to be exhausted — often decades, sometimes centuries. This is because the development of economically valuable applications of any GPT requires inventive activity, money and time. Often new applications build on each other. For example, the replacement of wood by metal in machine tool manufacture allowed much more elaborate factory procedures, which enabled the invention of tools that could cut pre-hardened steel, which allowed parts having identical blueprints to be identical when produced, which allowed Henry Ford to mass-produce automobiles, which induced him to invent the assembly line (which came last not first in the evolution of mass production), which process spread to many other lines of production reducing their costs, which allowed them to find new uses, which sparked other inventions and innovations. Also, when new applications involve large leaps into the unknown, new developments involve coping, not just with risk, but with genuine uncertainty. In some states of the economy, these uncertainties may not seem worth taking on. Even when they are taken on, much time and money will go into any new sought-after invention and even determined efforts will sometimes fail. The upshot of all this is that, even when the GPT’s efficiency becomes static, its effects will continue to ripple through the economy for a very long time in terms of new applications.

Nonetheless, there are frontiers beyond which the applications cannot be economically pushed for a given level of the GPT’s efficiency and hence a given cost its services. For example, if the price of electricity had stayed where it was during its first decade of consumer use, many of the now-common household gadgets could not have commanded a mass market. Thus, when the costs of delivering the new GPT’s services do fall, the frontier of economically feasible applications is extended.

We illustrate this co-evolution in a stylized example. At one extreme, we can imagine a GPT that arrives with an initial level of efficiency (a fixed blue print) that cannot be improved. At this extreme, one initial set of potential applications has been enabled, with no possibility for it to be widened. Of course, many of these will not be known or even guessed at when the GPT first arrives. The set of applications will be developed over time after the arrival of the GPT, typically following a logistic pattern. At the other extreme, we can think of a GPT whose efficiency goes on increasing, and hence the cost of its services declining, indefinitely. As this happens, the set of potential applications that it enables increases. The application curve may still be represented as logistic but Phase 3 will be prolonged because more efficiency gains are being made. If we then stabilise the efficiency of the GPT at some given level, the applications will evolve for an extended period of time, but will eventually enter Phase 4 as the pool of potential applications begins to be exhausted. Thus, a GPT that undergoes continued efficiency gains has a much greater potential to impact economic growth than the GPT that does not.

2. INFORMATION AND COMMUNICATION TECHNOLOGIES (ICTs)

Information and communication technologies (ICTs) are all technologies that deal with information, doing such things as communicating, analysing, transforming and storing it. These technologies include speech, writing, the printing press, and many more modern technologies, such as telegraph, telephone, radio and computer.

2.1 The Nature of Information

Because information is neither matter nor energy, the physical laws of conservation do not apply to it. It can be copied and used without loss or depletion and its use is *non-rivalrous* in the sense that if you use a piece of information, I am not precluded from using is as well.. Although information is non-rivalrous in its use, communication is necessary for information to be useful and *human created* communication technologies require scarce resources such as time and energy.

Consider for example, the blueprint for building a bicycle. The blue print can be used an indefinite number of times and still be unchanged from the first time it was used (no depreciation). Also, as many people as have blue prints can build a bicycle at the same time (the knowledge of how to build the bicycle is non-rivalrous in use). In practice, however, the fact that the blueprint is located on a piece of paper in someone’s garage does present physical and temporal limitations to the use of that particular piece of *embodied* knowledge. Time and effort are needed to create the blueprint if anyone is to use it, and to duplicate it if many are to use it simultaneously. This is an example of the resource cost of communication and it is this that ICTs play an important role in lowering.

2.2 Information as Transmitted Signals

We refer to the physical, or objective form of information as a *signal*. Signals, however, are of no use unless they can be interpreted by the receiver, and only of limited use unless the information can be transmitted from one user to another. But information does not transmit itself. Some form of "meaning" or processing must be associated with the use and transfer of information. Thus an essential part of useable information is the process of communication by which information gets transmitted, analyzed, organized, and received. Communication processors can be animate (e.g., humans and other animals) or inanimate (e.g., computers).

The communication of information must use a transmission medium such as the electromagnetic spectrum or air (in the case of sound waves). Throughout history, we humans have developed technologies to improve our ability to communicate, and the transmission process has proved to be an ideal candidate for improvement. The obvious physical limitations of speech led to the development of the principle of *inanimate transmission,* the use of inanimate objects to transmit information. The invention of writing enabling information to be encoded, stored and transported over long distances in an accessible form, bypassing the need for direct human-to-human speech. The printing press further improved transmission by enabling this encoded information to be duplicated and mass-produced efficiently, but with the important limitation that the information still needed to be physically moved from place to place.

2.3 Machine Logic

By the 19th century, knowledge of electricity had advanced to a stage where it was recognized that an electrical current could serve as a transmission medium over long distances. However, an important issue remained unresolved. Whereas humans have senses for detecting and analyzing signals sent through many types of transmission media, such as sound waves and the visible light spectrum, they cannot regularly monitor an electrical current to receive signals. For this what was needed was the principle of *machine logic*, which is the process of applying an inanimate logical system to a transmission medium in order to analyze a signal for some purpose. That purpose may involve encoding/decoding, tabulating, organizing or filtering, and may also involve converting it from one transmission medium to another. Importantly, a logical system must be designed to serve some specific function. Moreover, the ability to impose any logical structure on any transmission medium that can transmit a signal allows that signal to be analysed without direct human interaction. A mechanical and an electronic calculator use machine logic, as does a mechanical sorting machine. The first important modern use of machine logic to transmit messages over distances was the telegraph in the 1830's, which used electricity as its transmission mechanism. Combined with Morse code, this technology revolutionised communications worldwide.

The radio, the first device to use electro-magnetic radiation as a transmission medium, provides a good example of an electronic machine logic technology. For the sender, a microphone captures the audio pulse, which is first blended with the carrier pulse into a modulated carrier wave, then amplified and fed into the antenna. Both the processes of modulation, blending the audio and carrier waves, and amplification, performed in modern designs by a transistor, are applications of machine logic. For reception, the receiving antenna and tuner catch the weak signal, amplify it, sort the audio pulse from the carrier, and play a now re-amplified audio pulse through the speaker, again by means of a transistor. While a human listener is still responsible for receiving and decoding the resulting audio signals, the burden of receiving and decoding the radio transmission signal is eliminated by the principle of machine logic. The result is a technology for communicating verbally over long distances by analyzing and codifying electro-magnetic signals.

2.4 Flexible Machine Logic

The modern electronic computer makes use of the important principle of *flexible machine logic,* which is machine logic with the added characteristic that it can be altered without altering the internal physical structure of the device that uses it. For example, the initial physical design determined the logic of the early electronic calculating machines that were developed during World War II to break German codes and calculate the trajectories of missiles. In contrast, the important property of modern computers is that the logic of the system is alterable without a physical re-arrangement of its circuits.

Mechanical calculating machines have a long history going back into the 19th century. By the beginning of the Second World War, numerous electromechanical computers had been developed. These used mechanical relays as their switching mechanisms so that the computational speed was limited by the physical inertia of the mechanical switches. The first truly electronic digital computer the ENIAC, was completed in 1946. It used vacuum tubes as switches, greatly reducing the time required to open and close them. The second major innovation on the road to the modern computer was the Delay Line memory device, which resulted in a hundredfold reduction in vacuum tube requirements for a comparable amount of memory. To take advantage of this, the storage capacity was increased by a factor of 100. This in turn paved the way for the concept of the stored program computer. Then came the discovery of a new electronic switching device, the transistor. It was far more efficient than the vacuum tube in terms of switching speed, power usage and failure rates, and provided much potential for further improvement. In 1951, the newly invented software compiler provided a layer of abstraction over binary machine language. It allowed operators to use mnemonics to issue instructions to the computer thus eliminating time-consuming translations. It was the combination of the programmable computer, the transistor-based integrated circuit, and the software compiler that made up the components of the first electronic computer that could genuinely be called a GPT, the EDVAC introduced in 1952.[7] While the logic of earlier technologies that involved some calculation and computing, such as the telegraph and telephone, was determined by their initial designs, the important property of these new computers was that the logic of their systems was alterable without a physical re-arrangement of circuitry, creating what we defined above as *flexible machine logic*.

2.4 Programmable Computing Networks (PNC)

A *network* is a system of flexible machine logic dispersed across multiple nodes. In much of the literature, a distinction is made between computers and the best known network, the Internet. However, a computer is comprised of a set of logical components, each designed for specific tasks and communicating with each other via a system bus; this is a network. To repeat: a computer itself *is* a network. Going to a lower level of aggregation, one of the computer's components is a pre-designed set of logical gates that communicate in series (or even in parallel). This is also a network. At higher levels of aggregation, modern supercomputers are comprised of a networked set of personal computers communicating in parallel. On at an even larger level of aggregation, consider distributed computing networks that span the entire Internet. All of these examples perform one fundamental function: they use a logical electronic system to communicate and to manipulate information.

This understanding of the interrelationship between computers and other networks based on flexible machine logic leads us to regard them not as two or more distinct GPTs, but as a single GPT, which we call programmable computing networks (PCN). Although this GPT is part of a larger class of ICTs that use the principle of machine logic, it is distinguished by its use of *flexible* machine logic, using electricity (and more recently a hybrid of electricity and lasers) as a transmission medium to accomplish specific logical functions.

- The GPT of *programmable computing networks (PCN)* is composed of all logical processors of information that use flexible machine logic. This non-standard definition includes the computer plus all electronic information networks that use flexible machine logic, including the Internet, local area networks (LANs), wide area networks (WANs), and wireless networks.[8] We use the term programmable computing networks to distinguish this

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[7] The time sequence is a bit complicated. The EDVAC's conceptual design was completed in 1946 but the machine was not constructed and marketed until 1952. It was beaten to the market in 1951 by a machine that was actually based on its original design, the UNIVAC. In between those dates, the Delay Line memory, the transistor, and the software compiler had been invented. The software compiler was incorporated into EDVAC's design but it still used vacuum tubes instead of transistors.

[8] Other electronic networks do not make use of flexible machine logic. For example, the logic used by telegraphs and telephones is physically hard-wired and, thus, unalterable.

grouping from both the narrower class of computers as they are usually defined, and the wider class of ICTs as defined earlier.

Of course, definitions are not to be judged as being correct or incorrect but as being useful or not useful. Anyone who is uncomfortable with this combination can merely read what follows as referring to two related GPTs, the computer and the Internet.

As with all GPTs, PCN fulfills myriad functions and has myriad applications. They are the active logical components of communications networks, acting as servers, routers or fibre-optic relays. They are used in imaging devices. They are used to solve complex mathematical equations and to conduct auctions on EBay. In each case, there is a system of logic programmed into the device and executed according to the principle of machine logic. Perhaps the most obvious multiple use aspect of PCN is the ubiquitous uses of the personal computer to accomplish both the common and highly specialized tasks that used to be delegated to numerous individual devices. Many people consider their computer to be their office. It can serve the function of typewriter, filing system, answering machine, calendar/scheduler, phonebook, mail room, telephone, telex, transcriber and with the aid of a peripheral, a printshop. Before the advent of computers and their associated networks, each of these tasks would have been delegated to individual devices and/or persons, but the GPT has made these separate devices and positions obsolete for the most part. Furthermore, as well as replacing devices used for functions that existed prior to its introduction, PCN has enabled a new, continuously expanding, set of functions such as computer animation, CAD, and robot exploration.

That a single GPT is capable of implementing all of the functions described above should come as no surprise once we understand the scalable and flexible properties of this GPT. In the popular press and in some academic literature, this development is termed *convergence*. We will see in later sections that the concept of convergence is useful in determining the further transformative potential of this GPT.

Two other GPTs, namely electricity and lasers, are important technologies used by PCN. The resulting PCN applications, however, are mostly background enabling applications of electricity and lasers and primary applications of PCN. They are generated by the evolution of PCN not by those of electricity or lasers. Of course, both electricity and lasers have a variety of primary applications that extend well beyond PCN.

3. THE ICT REVOLUTION

In this section, we argue that the ICT revolution has already induced major transformations in the economic social and political structures sufficient to rank it as one of the most profound technological revolutions of all time. It is futile to try to develop a scalar measure such that different revolutions caused by different GPTs can be quantitatively compared with any precision. All we argue here is that, although it differs in the specifics of its impacts compared with electricity, the current transformation is more or less on a par with the revolution accomplished by electricity. In later sections, we argue that this ICT revolution has by no means run its course so that further major developments can be anticipated, even though their details cannot be predicated.

To get a sense of the importance of PCN as a key driver of the modern ICT revolution, we provide a by-no-means exhaustive sample of the pervasive economic, social and political changes that the evolution of PCN had already wrought by the beginning of the 21st century.[9]

Large numbers of products, both goods and services, have either been created or radically changed through the applications of PCN. Blackberries, ipods and cellular telephones are now common place. The ability to download music into computers that burn CDs is welcomed by many users while threatening the music recording industry. Many goods now contain chips that allow them to do new things or old things more efficiently. Computer and satellite linked ATMs have transformed personal banking, allowing, among other things, customers to access their bank account and obtain funds in any currency in almost any part of the world. Email has largely replaced conventional mail with a large increase in volume and speed of transmission. Distant education is growing by leaps and bounds and many are enrolled in education courses where they never (or only rarely) set foot inside the institution that they are ‘attending’. Smart buildings and factories already exist and are growing rapidly in number.

Process technologies have been truly revolutionised in many ways. Computerized robots and related technologies have transformed the modern factory and eliminated most of the high-paying, low-skilled jobs that existed in the old Fordist assembly line factories. Computer assisted design is revolutionizing the design process for manufactured products. The millennia-old link between physical presence and the provision of a service has been broken in many lines with profound social and political effects on such things as place of residence and the ability to regulate and tax many activities. Many types of surgery are being done more accurately than human doctors, and distant surgery will soon permit specialists working in major urban hospitals to operate on patients in remote parts of the world. Research in everything from economics to astronomy has been changed dramatically by the ability to do complex calculations that were either impossible or prohibitively time consuming without electronic computers. Crime detection aided by computers is much more sophisticated than it was in the past. Here the biological and the ICT revolutions complement each other as is so often the case with co-existing GPTs. Traffic control in the air and on the ground has been revolutionized while satellite and computer based sea navigation is now so accurate that many lighthouses, the sailor’s friend for several millennia, are being phased out.

The revolution in organisational technologies has been if anything even more dramatic. Just as the First Industrial Revolution took work out of the home, the ICT revolution is putting much of it back, as more and more people find it increasingly convenient to do all sorts of jobs at home rather than “in the office.” The ability of PCN to coordinate activities worldwide and ensure that parts manufactured anywhere in the world arrive when and where they are wanted has been central to the globalisation of trade in manufactured goods, shifting the location of much manufacturing and allowing poorer countries to industrialize. Firms are increasingly disintegrating their operations as a result of the ability to coordinate dispersed activities using modern communications and computing power. The management of firms has been dramatically reorganized as direct

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[9] A fuller list is provided in the Blue Report.

lines of communication opened up by computers eliminated the need for the old pyramidal structure in which middle managers processed and communicated information.

Political and social effects are too numerous even too sample satisfactorily. The computer-enabled Internet is revolutionizing everything from interpersonal relations to political activity. Non-governmental organizations (NGOs) are able to organize activities to protest such things as clear-cut logging, WTO efforts to reduce trade barriers, and the push for a Free Trade Area of the Americas (FTAA). Bloggers create a level and scope of political participation never before seen. Children do the reserach for their homework on the Internet as well as having access to pornography in quantity and explicitness ("quality'?) unknown in all previous times. Dictators find it much harder to cut their subjects off from knowledge of what is going on in the outside world. Driven by the Internet, English is becoming a lingua franca for the world.

Surely there can be no doubt, even with so short a sampling of the fundamental technological changes that are being driven by PCN, that the world's peoples have been living over the last few decades through a profound transformation of their economic, social, and political structures. We say no more about that and instead concentrate for the rest of this paper on the future course of the ICT revolution. Has the force gone out of it, or does it still have great potential to create further economic opportunities and to bring about further important structural changes?

4. PLACING PCN IN ITS EFFICIENCY CURVE

In section 4.1, we inspect some indices of the increasing efficiency of various devices that embody PCN. This establishes that this GPT is still in Phase 3 of its efficiency curve. To look into the future, we then need to disaggregate to study three major sources of this increasing efficiency. The efficiency of any computing device depends on the speed with which instructions can be carried out and on the nature of the instruction set that is used. Traditionally, this separation between the capability of a device and its instruction set is referred to as the separation between hardware and software. However, for purposes of measuring efficiency, it is more convenient to use another separation. The efficiency of a computing device can be improved in two basic ways: *electrical engineering process advancements*, such as the ever-shrinking etching size of a transistor, and *logical advancements*, such as the stored program computer, multi-core processors, and software optimization — the latter including both the evolution of the software instruction set *and* the logical arrangement of electronics on any piece of computer hardware. Engineering process advancements bring greater speed, miniaturization, and capability to the electronics, while logical advancements optimize the organization of the electronics. The effects of advancements in both of these ways are enhanced by the exploitation of scale effects. We study each of these sources of efficiency changes in sections 4.2 - 4.4. In section 4.5 we draw these discussions together to look into the future in order to suggest where PCN is in its Phase 3.

4.1 Increasing Efficiency of PCN

Since there is no way to look at the overall efficiency of so complex a general purpose technology as PCN, we do this piecemeal by examining a selection of the many existing quality-adjusted price indexes for various devices that incorporate PCN. For example, a price index for personal computers uses such characteristics as processor speed, memory capacity, and disk storage capacity. For a semiconductor price index for microprocessors, characteristics include clock speed, cache size, addressable memory and number of transistors. As a result, the indices for personal computers, microprocessors, software, and telecommunications equipment can serve as a proxy for changes in the efficiency of each of these technologies that utilise PCN.

Figure 4.1, shows an hedonic real price index for computers purchased by business and government. Note that because of the logarithmic scale the straight line indicates a constant rate of price decrease, which is about an order of magnitude every decade. (All figures for sections 4 and 5 are given at the end of the paper. Note that all figures for Section 4 are plotted on a logarithmic scale, while several of those in Section 5 are on a natural scale.)

Similar trends are observable in U.S. real price data, compiled by the Bureau of Economic Analysis (BEA) for computer related prices, those of mainframes, PCs, disk storage devices, tape storage devices, terminals, printers and other peripherals. The price in indices for each of these products declines by several orders of magnitude from 1958 to 1994.[10]

A matched-model price index for integrated circuits, both microprocessors and memory modules, is given in Figure 4.2.[11] The decrease in price over the period 1975 – 2001, presented on a logistic scale, has been roughly 5 orders of magnitude.[12] Since uncorrected market prices did not change anything like as much, it follows that most of the marked decline in the price index is explained by quality increases.

Figures 4.3 and 4.4 show hedonic indices using U.S. Bureau of Economic Analysis data for both microprocessors and memory chips, albeit for a shorter time period. Here we can observe a price decrease close to two orders of magnitude per decade.

These indices show that the quality-adjusted prices of devices that embody and implement the GPT have been falling continuously. While the estimates vary slightly depending on which index is used, they suggest a decrease of at least an order of magnitude every 10 years. We can conclude that PCN has had an efficiency increase of at least five orders of magnitude since its introduction. Since these increases as yet show no sign of slowing, it seems clear that PCN is still in Phase 3 of its efficiency curve with ongoing rapid increases. To look ahead we need to disaggregate to inspect the sources of these efficiency increases, which we identified at the outset of Section 4 as advances in engineering, improvements in logical processes, and the exploitation of scale effects.

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[10] See Table 4.1 in the Blue Report for the details of these data. The indices were calculated from BEA data by Triplett and reported by him in Triplett, J.E. (1996), "High-Tech Industry Productivity and Hedonic Price Indices," in Organization for Economic Cooperation and Development, *Industry Productivty,* Paris, 119-42. Unfortunately, they are not available for subsequent years.

[11] Matched-model indexes use panel data to measure quality changes by assuming that price differences at a point in time reflect the market's valuation of differences in quality. Product models are to remain assumed homogeneous over time so that quality change occurs only when new models are introduced. Conceptually, the gap between the introductory price and existing price is the method's estimate of the value of quality improvement in any new chip. The results of matched-model indexes are numerically similar to hedonic indexes for semiconductor price data because old models are rarely discontinued immediately, thus there is a matching period of appropriate length (Aizcorbe, Corrado and Doms, 2003).

[12] The second panel of the figure shows a stronger downward trend on MPU (microprocessor) prices in the late 1990's relative to DRAM (memory modules). Aizcorbe (2004) attributes this drop to an increase in competition in the microprocessor market, primarily AMD's competition with Intel, as "the increase in competition that Intel faced over the 1990s might have distorted the measure of quality change implicit in matched-model indices."

4.2 Advancements in Engineering Processes

The replacement of the vacuum tube by the transistor in 1947 offered immediate efficiency improvements in many important aspects of the performance of electronic computers such as size, heat dissipation, failure rate, and speed, as well as much potential for further efficiency gains as the transistor itself was improved over time. Integrated circuits, developed in 1959, combined active electronic devices, such as transistors, and diodes, and passive components, such as resistors, and capacitors on a single semiconductor crystal. The following statistics illustrate the potential efficiency benefits enabled by the transistor and the integrated circuits (more precisely silicon based integrated circuits or CMOS).[13]

(1) Over the last 40 years revenue in the semiconductor industry has grown exponentially, averaging about 16% per year.

(2) There are more bits of memory on a single 300 mm wafer produced today than were produced by the *entire* industry in 1984.

(3) There are more transistors produced per year (about 1 quintillion) than grains of rice, and each rice grain their users as much as 100s of transistors.

In 1965, Gordon Moore, stated what has become known as Moore's Law. He predicted that the cost of manufacturing would decrease each year and that the minimum average cost would occur at an ever larger number of components per integrated circuit. As a result, the number of transistors per integrated circuit would increase steadily while the cost per transistor fell. Figure 4.5 shows the exponential increase in the number of transistors per integrated circuit as predicted by Moore. Since the number of transistors roughly determines the computing power of an integrated circuit, Moore proposed that the performance of integrated circuits would increase while per unit average cost of manufacturing them would decrease, resulting in about a doubling of the performance/cost ratio every two years.

The past 40 years have seen great technological advances in all of the things that determine the minimum average cost of producing integrated circuits—the maximum number of transistors per square inch, the size of the wafer, the average number of wafer defects per square inch, and the costs associated with producing and connecting many small integrated circuits to perform the function of a larger one. The result has been a massive increase in the computational power of an integrated circuit, as well as comparable decreases in cost per transistor (currently referred to as cost per function in the semiconductor literature). This reinforces the conclusion reached in Section 4.1 that PCN is still in Phase 3 of its efficiency development.

However, because Moore's Law is only an empirical extrapolation, it gives little help in predicting the future course of productivity gains in CMOS production. In fact, the cost of further increasing the computational capacity of CMOS has already risen dramatically. It is becoming increasingly costly to increase wafer size and reduce etching size. An upper bound in wafer size may be reached before too long due to inherent material limitations (e.g., crystal strength). Serious technical problems are encountered with attempts to further reduce etching size. These are related to transistor leakage (small amounts of current flowing through an "off" transistor), power density (the amount of heat generated in each area of the chip) and power usage (energy required to power

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[13] CMOS stands for "Complementary metal-oxide-semiconductor" which is a class of silicon based integrated circuits. However, "Silicon based integrated circuits" or just CMOS is a sufficient descriptor for our purposes.

the chip). These issues are primarily responsible for what has been popularly termed the "megahertz wall," referring to the recent difficulty chip manufacturers have had in increasing processor clock speeds. While a continued increase in the number of instructions that can be executed per second is still theoretically possible, this requires a massive shift in how software developers handle the instruction flow sent to the processors to take advantage of multiple cores.

The semiconductor industry is moving on two tracks to combat these problems. One attempts to deal with the issues directly by engineering smaller transistors, new materials, and integrating new technological breakthroughs such as nanotechnology with CMOS-based devices. It appears, however, that we are nearing the final decades of efficiency gains realizable with such devices. But note that a decade or two is not tomorrow! The second track is research into post-CMOS devices that we discuss in section 4.5.

4.3 Advancements in Logic: optimisation and functionality

Here we simplify our discussion by focusing on the logical design of the electronic computer. However we emphasize that the same analysis applies to the logical design of other networks that we include in PCN, or any other inanimate communications structure.

Programmable computers have a hierarchy of software and hardware logic as illustrated in Figure 4.6.[14] One key to the device's efficiency is that it is unnecessary for the processor to have a basic logic capability for performing every possible function. Instead, more complex functions can be created from simpler ones, in effect, designing a higher level instruction that is composed of other instructions (including more basic ones from lower levels in the hierarchy). However, as the instruction sets increase in complexity and are adapted to new uses, serious performance issues arise. As one level in the instruction set hierarchy grows in functional complexity, further potential for efficiency gains arise by shifting some of those functions to lower levels of the hierarchy. However, too many instructions at the lower levels increase the complexity of the hardware logic, reducing efficiency; too many instructions at the higher levels increase the complexity of the software logic layers, reducing efficiency. A process called 'optimization' is used to delicately balance these factors so as to maximise the overall efficiency of the device. A subset of this process, software optimization, repeats this task within the software layers.[15]

For the reasons just discussed, alterations in a device's logic can have unforeseeable positive or negative impacts on its ultimate efficiency. The feed back between adding functional complexity and optimizing the placement of instructions in the logic hierarchy tends to be positive on average but at any given moment in time, bottlenecks or salients can be created. As a result the process of efficiency improvement generated by logic advances evolves in fits and starts.

Logical advances offer myriad ways of improving efficiency but are ultimately constrained by the physical engineering structures of PCN. Thus they will encounter limitations as CMOS

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[14] As the Figure shows, this is really a "reverse hierarchy" because it is an upside down pyramid, with the basic instructions at the bottom rather than at the top.

[15] One reason why the instruction set may become overly complex is the demand for a device to perform a wider variety of functions. There are many examples of software designers adding instructions for functional reasons to the detriment of the device's performance, often described as "bloat." Adding functions usually alters the optimal distribution of instructions. Thus the design of a device's logic needs to create an effective balance between the allocation of functions (optimization) on one hand and functionality on the other.

itself encounters physical limitations. As discussed in Section 4.2, multiple core or other alternatives to CMOS are on the horizon and logical advances such as parallel or “grid” computing might overcome foreseeable limitations arising from CMOS. But these forms of logical advance require a complete change in the way that developers design flexible logic to exploit the foreseeable alternatives to CMOS.

4.4 Exploitation of Scale Effects

A significant portion of the efficiency gains from PCN have resulted from dealing with information networks. Because these networks are just scale increases in the size and effectiveness of computing devices, they amplify the efficiency gains for computers by exploiting the latent scale effects of electronic information networks.[16] These scale effects come from at least three sources.

First, the physical delivery grid of the network is a source of increasing returns. Over the latter half of the 20th century, by the far the largest proportion of our network traffic used electrical current as a transmission medium, usually via the telephone or cable distribution networks. Recently, however, fibre-optic technology, based on the GPT of the laser, has provided vast potential, both realized and as yet untapped, for gains in network bandwidth capacity. While the control components of network infrastructure of PCN is still implemented by means of electronic components, efficiency improvements in fibre-optic cabling are driving a replacement of electricity as the transmission medium, resulting in scale effects from bandwidth increases.

Second, the information that is transmitted in a network is non-rivalrous in consumption. This allows for a positive externality[17] in the sense that the cost of transmission does not rise with the number who receive it. When exploited, this is another source of increasing returns.

Third, there is a classic network externality. As new users join a network, all existing network members gain a benefit. This creates a positive externality that is larger the larger the number of existing network members, all of whom benefit when new members join. This is a source of increasing returns since the larger the network the more is the total benefit from the externality.

The continuing exploitation of these scale effects is one of the major causes of the geometric progression that we observe in our indexes of PCN’s efficiency and performance and there is no reason to believe that the potential for such exploitation has been fully exploited.

4.5 Looking into the Future: putting it all together

We argued in Section 4.2 that although the efficiency curve for engineering process advancements is still in its Phase 3, it may be approaching Phase 4 due to the physical barriers that exist in developing CMOS further. We also argued in Section 4.3 that while logical advancements do offer ways of improving efficiency, they are

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[16] These are what Lipsey Carlaw and Bekar (2005: 397) call ‘historical increasing returns.’ They occur, according to these authors, “…because the scale effects are permanently embedded in the geometry and physical nature of the world in which we live but our ability to exploit them is dependent on the existing state of technology.”

[17] A typical economic transaction has two parties, a seller and a buyer. An externality is a benefit or a cost that is imposed on a third party who is not a participant in the transaction.

eventually constrained by the state of the physical engineering processes. While logical advances that are related to parallel programming and “grid” computing may occur in the near future, these will require a massive shift in how developers design instruction sets and the potential efficiency gains are still unrealized and difficult to forecast. So logical advances may also enter their Phase 4 in a decade or so — unless there is some breakthrough, possibly in the ability to make logical advancements without the engineering advance of an increase in the number of transistors available.

So the overall judgment for PCN is that it is still well within Phase 3 of its efficiency curve, but in the absence of unexpected breakthroughs in engineering and logical processing, it will in a decade or two enter Phase 4 with steadily falling rates of efficiently growth. In contrast, we argued in Section 4.4 that there are unlimited potential scale effects that can be exploited by advancemans in either engineering or logical processes.

Note also that when efficiency gains do slow this need not herald an imminent slowing of new applications and a consequent slowing of the social and economic gains from PCN. First, as discussed in Section 1, new applications typically continue to be developed, often for decades, after a stabilisation in the efficiency with which the main GPT delivers its services. Second, new technologies may replace CMOS based devices with the same as well as newly enabled applications. For example, the International Technology Report on Semiconductors has laid out a roadmap for moving beyond an “ultimately scaled” CMOS, “accomplished by … extending the CMOS platform via heterogeneous integration of new technologies and, later, via developing new technological and nano-architectural concepts.” Some of these new technologies such as multi core processors already exist, while others, such as quantum computing, have not progressed far beyond theoretical possibilities. Although estimates vary, the engineering consensus is that a move to post-CMOS devices will be made by about 2020. It is impossible to say at this stage whether the replacements will fall under our definition of PCN or be better regarded as a wholly new GPT. For instance, quantum computing may present a completely new technical architecture with its own tremendous potential for efficiency advancements and wide range of uses. So although CMOS-based devices may reach their efficiency limits in a decade or two, new engineering technologies that integrate well with existing and future logical structures of PCN are on the horizon with promises of further engineering gains and new applications.

5. PLACING PCN IN ITS APPLICATIONS CURVE

Section, 5.1, is devoted to measuring the diffusion of some of the major technologies spun off from PCN. Then in Section 5.2 we deal with current and perspective new applications. We conclude that the evidence strongly suggests that PCN is well within Phase 3 of its applications curve. Since new application are still being developed rapidly, there is as yet no evidence that it may be nearing its Phase 4 when such developments slow and eventually peter out.

5.1 Diffusion

We first look at the degree of diffusion of some existing applications and in the next we look at new applications.

5.1.1 Practical measurement problems

In measuring the diffusion of various applications of PCN, we must rely on the evidence collected by various statistical agencies.[18] Much of the useful sector-specific data is collected by industry groups or commercial organizations for commercial purposes and is not available for unfunded academic research. A significant proportion of what is available is given in terms of dollar values, a metric that is relatively useless for enumerating applications in the absence of category specific price data.[19] Also, the quantitative data mainly show market diffusion of specific aggregate categories, such as "personal computers" and it is impossible to get sufficient sectoral data to aggregate up to a measure of PCN's overall diffusion.

5.1.2 Diffusion data for specific categories

We begin with one of the most prolific embodiments of PCN, the personal computer. Figure 5.1 shows that the number of personal computers sold in Canada began to climb in the early 1980's with an accelerating growth rate through the 1990's and mid 2000's. There was a temporary slowdown in diffusion in the early 2000's, which paralleled the international economic slowdown during this period. International data for this aggregate category reflects a similar temporary slowdown, followed by a quick resurgence. (All figures for Section 5 are given at the end of the section.)

While Figure 5.1 shows the flow of current sales of personal computers, Figure 5.2 shows the stock of PCs held. Fully 30% of Canadian households did not have a personal computer at the terminal observation and the absolute growth in household adoption remained relatively constant over the time period. Although the majority of Canadian households have PCs, the rising sales suggest a mixture of faster replacement due to faster obsolesce and a rising number of multi-computer households.

Figure 5.3 shows a pronounced growth in Internet users comparable to the growth in personal computer ownership. Since 2000, the gap between PC ownership and Internet use has closed because a larger number of people are using the same personal computer as more members of a household go online and because more devices with Internet access are becoming available, the mobile phone being a primary example.

Figure 5.4 shows that the growth in the number of unique domains hosted on the Internet over the past two decades has been close to exponential.

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[18] We have used Canadian evidence wherever possible. Much of our data comes from the International Telecommunications Union, which is responsible for coordinating the operations of telecommunications networks and services. Where possible, ITU data was corroborated by other international sources including the CIA World Factbook, the OECD, and national statistical agencies including Statistics Canada.

[19] For example, the Worldwide Semiconductor Trade Statistics (WSTS) gives a sectoral breakdown of semiconductors sold in terms of value, however the types of semiconductors sold to various categories have a large variance in price. Without a specific breakdown of the types of semiconductors sold to each industry, and related price data (which is available from WSTS but at considerable cost), we cannot break the sectors down in terms of units sold.

Figure 5.5 shows the same data for worldwide hostnames, adding data for active names. These data are useful for examining the collapse of the "Internet bubble" on Internet hosts. While the number of registered hostnames dropped substantially in 2001-2002, the number of active hostnames deemed to have unique content remained relatively constant. This suggests that most of the hostnames that went offline during this period were hostnames that were not actually being used by the Internet community. Thus web usage appears to have grown in spite of the economic slump in the early 2000's.

Figure 5.6 gives data for digital mobile (cellular) phones. While analogue mobile phone technology allowed an individual to connect to the telephone network wirelessly, the technology itself did not use PCN. However, the digital mobile network that followed used *embedded* microprocessors, a catch-all category of microprocessors designed for devices other than personal computers. These allowed the phones to undertake many of the same tasks as a standard personal computer. Digital phones were introduced in 1996 and ten years later they accounted for 85% of the total mobile phone market and rising. International data shows similar exponential growth and a larger percentage of the total mobile phone market in many European and Asian countries.

Another generic product that embodies PCN technology is the digital camera. The growth of the market for such cameras highlights the role of PCN in replacing earlier technologies, in this case the film-based camera, as shown in Figure 5.7.

For yet another example of diffusion, 45 percent of multi-channel TV households now had either digital cable or satellite TV service, according to the 2004 edition of an annual report from media researcher Horowitz Associates. This presents many opportunities for new products and services that utilise this medium.

Finally, according to the "2004 Ownership and Trend Report from The Home Technology Monitor", 4% of homes with TV report owning a DVR (such as TiVO) – a figure that had doubled in the previous 6 months; 6% had an HDTV set, up 50% six months previously; 18% a VCR/DVD dual deck; and 5% a PC with a TV tuner. These applications are obviously in their infancy in terms of diffusion. It seems most likely that they will diffuse rapidly over the next few years as more networks convert to HD broadcasts. This diffusion will in turn require more sophisticated home theatre setups and such things as DVRs to fully exploit the new, higher audio and signal and signal quality.

We have reported on those generic products for which we have been able to find useful data. Although we are sure that similar patterns exist in many other home electronics industries such as video cameras, home theatre and audio, as well as household appliances, such industry data are not available for academic purposes without a fee.[20] However, on the basis of what we have shown above, it is probably safe to assume that although many major applications of PCN have already deeply penetrated many markets, they have yet further to go in most of these.

While market penetration data is useful for studying the diffusion of PCN applications, they tell us nothing about the proliferation of new applications of PCN—new applications that are

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[20] The most noteworthy of these are data collected by organisations in the semiconductor industry that detail semiconductor usage, and OECD data for diffusion statistics covering such health applications as MRI and CT scanners. Indeed, most diffusion data are controlled by industry groups, including those covering the majority of home electronics applications.

enabling even more new applications in a trajectory of linked inventions and innovations. We discuss these in the next section.

5.2 New Applications

PCN began to be applied to the creation of new products, processes and organisational forms soon after the first electronic computers were developed in the 1940s. While computers became more powerful but remained large cumbersome machines, the number of application grew slowly. The number of potential applications then increased greatly with miniaturisation. Computing power began to be added to many existing products and processes, as well as enabling the development of wholly new ones. Dramatic ICT-driven changes began to be felt throughout the economy in a major way in the late 1970s, with impacts that grew exponentially in the 1980s and 1990s. Lipsey (2002) lists several pages of new products, processes and organisational forms that were computer driven during the last half of the 20th century.

There is little to gain by just adding up all applications in each decade and comparing rates of development. The numbers would depend too much on the level of aggregation that was used. What we can hope to show by an enumeration of illustrative cases is that the pace of new applications is still rapid and that many of these suggest further applications that build on them. In contrast, when any GPT is entering Phase 4 of it applications curve, the pace of new applications slows appreciably and many of those that are developed are dead ends in the sense that they do not suggest further applications that build on them — more and more specific technological trajectories that stem originally from the main GPT reach the end of their road, rather than turning a corner to reveal a road continuing onwards into further as-yet uncharted fields of applications.

The case data we report here have been collected from various sources, including traditional media outlets (both online and print), relevant mailing lists, press releases, technology websites and the quarterly technology review section of the *Economist* Magazine. The following cases represent only a sampling of new applications but they should sufficient to show that new applications are still being invented and innovated at a rapid rate and are of the type that in their turn enable yet further applications. Here we briefly mention those on our list. The details are given in an Appendix of the Blue Report.

- Computing power is still in the process or being added to just about every imaginable kind of consumers' good, from washing machines to children's' toys. Sensors and controls are being built into clothing in a first step towards a new realm of "smart fabrics." Carmakers are putting artificial neural networks into engines to increase fuel-efficiency and reduce pollution. Smart houses and smart office building are being built with of all kinds of newly developed automatic controls that add to comfort, safety, and efficiency.
- Video games, often denounced for their supposed ill effects, are being shown to have a surprising range of therapeutic uses, opening opportunities to develop games specifically designed for such purposes.
- Objects are being sprayed with thousands of tiny microdots that, when read by a computer, give them a unique identity just as finger prints do for humans.
- Protection against Internet fraud and identity theft is forthcoming in terms of a tiny security chip called the Trusted Platform Module that permanently assigns a unique, permanent and unalterable identifier to every computer before it leaves the factory.

- A small computer that can take in just about any spoken language and turn it efficiently into speech in just about any other language is now moving beyond the realms of science fiction.
- Researchers have developed a revolutionary new way to control computers by thought alone, opening myriad possible applications including the control of artificial limbs by a computer that intercepts brain impulses and converts them into movement commands for artificial muscles.
- The increasingly common practice of passengers booking their own flights on line demonstrates the as yet only limited, but ever expanding, utilization of online goods and service provision to replace more antiquated systems.
- Home buyers with internet access who are looking for finance are no longer at the mercy of their own bank or agent, the thoroughness of whose advice is hard to monitor.
- Many opportunities now exist for new small manufacturers to sell new goods with limited appeal in virtual markets with low transactions costs.
- Authors can publish books and articles and post them on the net for downloading, with free access or as a credit-card purchase, thus opening markets for limited edition publications that were unavailable to authors when all publications had to be in hard copy.
- A nationwide vehicle-tracking service is allowing fleet operators to monitor the performance and location of their vehicles, making it easier to manage the performance of their fleets, reduce fuel costs, analyze driving behaviour and improve delivery time.
- Silicon chips embedded in people are just beginning to be used and the number of potential applications is great. (In an interesting illustration of spillovers, the implants were originally designed for medical purposes.)
- Dairy framers can remain in their living rooms while controlling the movements of their herds, including milking and monitoring health. Diagnostic practices have been greatly aided by computers; more such developments are in the pipeline; others are still in researchers' imaginations.
- Many hospitals are acquiring their own fibre networks and deploying their optical equipment allowing improved interconnection among hospital groups that not only results in improved care but reduces malpractice risk for hospitals, insurance carriers, and physicians and lowers costs for insurance providers.
- A group of national weather centres across Europe is creating a global weather forecasting system that allows meteorologists to make more accurate and more timely predictions. Indeed, virtually anything that has sufficient regularities to allow prediction can be better predicted by high powered computers than methods that were state-of-the-art 10 or 15 years ago.
- Originally the term mashup was used to describe the mixing together of musical tracks, but it now refers to the increasingly common websites that weave data from different sources into a new service.

- Distance learning is now reality allowing any person with qualifications and access to a computer to enrol in countless programs worldwide.
- Computers are increasingly invading traditional forms of learning from universities to primary schools.
- User-generated content, best known for fuelling the popularity of Web sites such as You Tube and MySpace, is rapidly taking hold in advertising representing a fundamental shift in the democratization of content.
- Software programs that monitor all sorts of behaviour and infers tastes are widely used by stores, hotels and service organisations.
- MacDonald's has pioneered the centralized handling of orders where an operator located in a central clearing house hears instructions given by drive-in clients from around the continental United States and Hawaii and routes them back to the local kitchen for handling.
- Blackberries and Ipods that were things of science fiction only a few years ago illustrate how hard it is to envisage new products that will be enabled by PCN but have not yet been developed.
- Cell phones continue to adopt new functions, the latest at the time of writing being banking and international transfers of funds.

Additional illustrations and more elaborated versions of the one listed above are given in the Blue Report. All of the illustrations repeatedly illustrate several key features. First, most of these developments are new and have much scope for direct improvements and further applications. Second, most of them suggest many spinoffs in terms of other new technologies that can exploit those on the list to create different new products and different new processes. Third, many of the items would have seemed like science fiction a mere few years before they were developed, illustrating how difficult it is to predict what new applications of PCN are around the corner. What is clear is that the pace of new developments and applications has not slackened and there is nothing in the nature of these to suggest that it will slacken in the near future.

Yet this is not the end of the story. So far, we have concentrated on developments that are mainly enabled by PCN on its own. Also in sight are many present and myriad foreseeable future applications based on a union of PCN with biotechnology and nanotechnology. A sampling of these is given in the Blue report and they make it clear that the union of PCN with biological and nano science has already become highly fruitful and is spawning a mass of new applications in fields that span most of the economy.

Eventually, as it is with electricity today, PCN will become a mere background, enabling input that is used everywhere in bio- and nano-technology applications that owe their form to biology and physics and not to the evolving structure of PCN. But that is still some way off because further efficiency developments of the PCN are needed before some of these applications can be realised.

5.3 Conclusion

The data presented in this section strongly suggest that PCN is still well within Phase 3 of its development trajectory. Diffusion of existing applications is continuing apace and new applications are being developed almost daily. Inspection of our sample of these strongly suggests that many of them are will spawn (or have already spawned) further new applications. We elaborate briefly on each of the sources of future potential for PCN.

- The efficiency of PCN has increased rapidly over an extended period of time (beginning in the middle of last century), and has extended over a large number of dimensions, enabling a succession of wider and wider possibilities for applications. Although it is possible that, absent a major breakthrough such as the perfection of quantum computing, PCN may be approaching Phase 4 of its efficiency trajectory, further increases in efficiency can still be expected for years, possibly a decade or two to come. These efficiency gains will, if past experience is any guide, enable a host of new applications that are either too costly or technically infeasible with today's ICT technology.
- We have seen from the sample of applications for which we could get reliable data that their diffusion is far from complete. Since diffusion often goes along with the discovery of new opportunities for innovations, applications that come from this source have yet to be fully exploited.
- Given the logistic behaviour of new applications, even if efficiency stopped increasing today (PCN reached late Phase 4 or Phase 5 on its efficiency curve), many applications would remain to be exploited — a list that no one can enumerate in full since it is in the nature of new knowledge that it cannot be fully described until it is discovered.
- Finally the union of PCN with biotechnology and nanotechnology will spawn an almost unlimited set of new opportunities for inventions and innovations over at least the next half century. Gradually, these applications will become more and more background enabling applications from the point of view of PCN, and primary applications only from the points of view of biotechnology and nanotechnology. But this will be a slow evolution and for some time to come many developments in these two fields will arise from, and will create opportunities for, new developments in PCN.

Given all this evidence, it seems clear that PCN will continue to have a profound and formative influence on technologically driven economic and social change in Canada and the world for at least several decades to come, offering countless opportunities for the development and exploitation of new applications throughout much of the economy.

6. POST SCRIPT: A COMPARISON BETWEEN PCN AND ELECTRICITY

In this section, we compare and contrast the experience of PCN and electricity with respect to their efficiency and applications experience.

6.1 Efficiency

Price data for electricity can be used as a measure of efficiency improvements in electric power generation. In the US, Schurr et al. (1990) find a real price drop upwards of 700% over the time period 1913-1970.[21] Figure 6.1, plotted on a log scale, shows a continued decline in its real price of electricity in Canada through the first half of the 20th century, even in the face of rising demand.

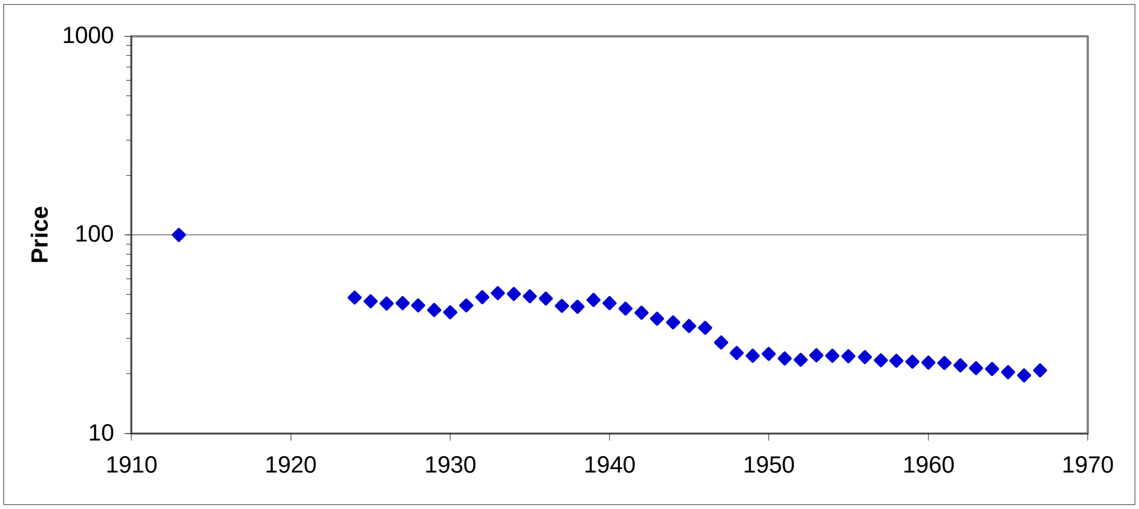

Figure 6.1: Real Price Index of Electricity for Domestic Use in Canada
Source: Statistics Canada, Dominion Bureau of Statistics

Since price data on electricity were not collected prior to 1913, we are forced to estimate past experience. We do this by first taking the reciprocal of the price index shown in Figure 6.1 to obtain an index of the amount of kwh obtained per dollar of expenditure. We assume the price index followed a standard logistic curve, bounded by the date of the first electric power plant in Canada, 1883, and the relative price stabilization about 1965, and fit a logistic curve to the data as shown in Figure 6.2.[22] From it, we draw two tentative conclusions. First, the total efficiency improvement over the technology's lifetime has been roughly 700%, or somewhat less than one order of magnitude. Second, electricity entered Phase 4 of its efficiency evolution somewhere toward the end of the 1940s.

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[21] They attribute this drop to economies of scale, efficiency gains in production, and declining cost of input fuels the first two of which relate to efficiency while the third does not. The effect of fuel costs is of much less significance in Canada due to considerable hydro-electric production capacity..

[22] This crude methodology relies heavily on the initial 1913 observation.

Data for the period 1949 to 2005 given in the main report, confirm that electricity entered Phase 4 of its efficiency curve around the late 1940s and came close to its Phase 5, with static around the 1960s.[23]

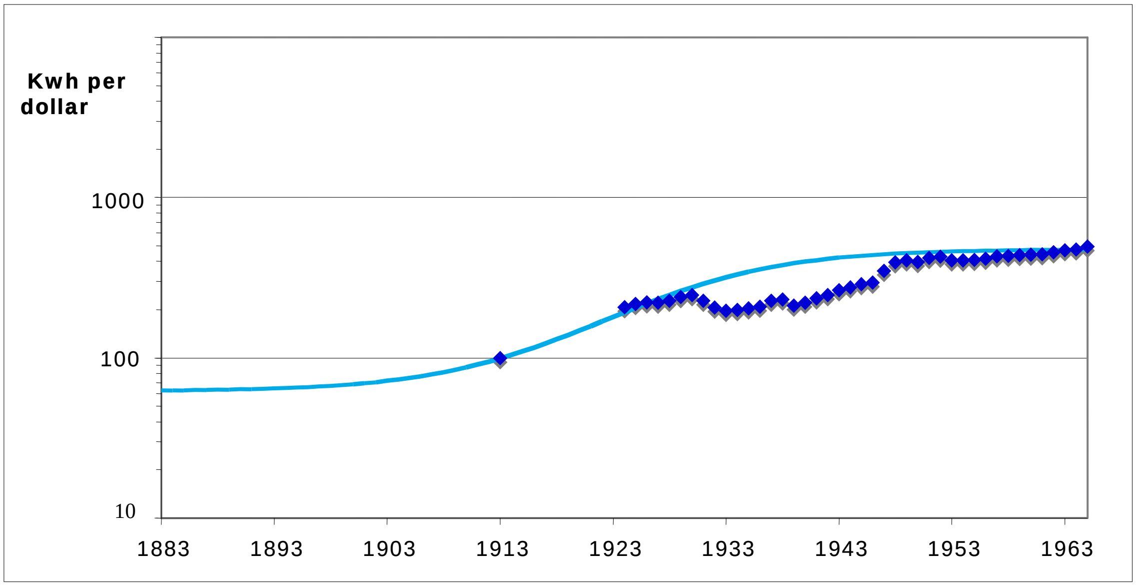

Figure 6.2: Extrapolation of Real Price Index of Electricity for Canadian Domestic Use
Source: Dominion Bureau of Statistics.

So electricity's transition to Phase 4 occurred about 80 years after the invention of the dynamo. If we take the beginning of PCN as the late 1940s, that GPT has been evolving in efficiency for about 60 years. Given what we have said about the future outlook for its efficiency, there seems to be a good possibility that the time spans in which both of these GPTs evolve though Phases 1 to 4 on their efficiency curves may be about the same. But the big difference is in the height of the two curves. While electricity‘s efficiency increased by something just less than one order of magnitude over its first 70 years, computing efficiency has increased many, many more times, closer to an order or magnitude every decade.

6.2 Applications

On the applications side, electricity began with such major primary applications as street lighting and electric railways (often called street cars), then went on to light homes and factories, power factory machines with the resulting revolution in factory layout, and diesel-electric motors, that came to play a large part in rail and steamship transportation. In also spawned a whole host of communication goods over its first several decades, including wireless transmission via Morse code, radio, recorded sound of speech and music, and telephones. In the early 20th century, it also entered the household in a big way with new gadgets that took much of the then-existing drudgery

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[23] There is some evidence of a reduction in efficiency in the latter part of the period but this was largely caused by non-technical forces.

out of household work, vacuum cleaners, dish washers, clothes washing machines, electric irons, electric stoves, deep freezers, and many other similar products. All of these applications had been invented before electricity entered its Phase 4 of its efficiency curve in the late 1940s.

During the nearly 30 years of secular boom that followed the end of The Second World War in 1945 there were several main developments.

- Already invented technologies that were enabled by electricity (and the internal combustion engine) diffused throughout the western world. Because of the world-wide Great Depression and because of the generally lower incomes in Europe compared to North America, many of the important technologies invented in the inter-war period had not diffused far though the various economies of Western Europe by the end of the Second World War. For example, only a small minority of households in Britain and continental Europe owned refrigerators, washing machines or cars by the end of the 1940s. Most French workers commuted to their jobs by bicycle while their wives remained at home to wash clothes and dishes by hand, and to shop every day because of lack of refrigeration.
- There were relatively few primary new applications of electricity, most of which had already been invented and innovated even if they had not diffused fully. Television, and air conditioning were two of the main exceptions. The spread of TV in the 1950s and 1960s transformed the entertainment industry, as well as news reporting, among many other things. Important also was the replacement of steam engines on railways by electric and diesel electric trains. A few new less important gadgets, such as power tools, electric tooth brushes, and electric can openers were innovated, but these were minor compared with the great primary applications of electricity in the late 19th and early 20th centuries.
- The stream of new primary electronic applications did not peter out because electricity ceased to fall in cost but merely because most possible primary applications had already been exploited by that time. Whenever new applications did come along, such as TV and air-conditioning, the non-decreasing cost of electricity did not prevent them from being adopted.
- The great postwar boom from 1945 to the early 1970s was thus based not so much on new technologies as on the diffusion of technologies that had been invented and proven in the earlier period (and that were mainly enabled by electricity and/or the internal combustion engine, and later the jet). There was also a steady stream of marginal improvements to these technologies leading to a fairly rapid rate of obsolesce that held consumer demand high. This all took place within the context of a facilitating structure that had been adopted in the first decades of the 20th century to the new product and process technologies.
- As a background enabling technology, electricity is still vastly important. We still live in an electronic age in which the applications of electricity permeate the entire economy and in which many, possibly the majority, of new technologies, both important and unimportant, could not have come into existence without electricity.

In contrast, PCN began to penetrate the economy seriously in the 1970s when there was no great backlog of demand created by a decade and a half of depression and war. Also, the steady efficiency increases in PCN allowed things to be done that could not have been done at lower levels of efficiency. This also contrasts with electricity: if TV or air conditioners had been invented in the 1920s, there was nothing in the nature of electricity generation, distribution, or cost that would have prevented them from being developed and marketed then. In contrast, miniaturization enabled a vast number of new applications of PCN that were not technically feasible with the older generation of computers. The PC did the same. Many of the uses of PCN in biotechnology and nanotechnology, as well as crime prevention and detection, and many other 'hi-tech' uses were not feasible, either technically or economically, with the older generations of computers.

6.3 Conclusions

First, PCN seems to be about where electricity was on its efficiency curve in the early 1920s, with a decade or two more of efficiency gains in store. Second, if primary applications follow the same path as charted by electricity, there are also at least two decades of new primary applications in store for PCN and another decade or two of high demand based on the diffusion of already innovated applications.

But we must not make too much of this second point. Electricity is primarily a power GPT while PCN is primarily an ICT. Many of the main primary applications of electricity were to revolutionize the shop floor and to introduce a vast array of consumers' durables. In contrast, although PCN did revolutionize the shop floor with such things as computer operated robots, it also revolutionized the organization and administration of firms by altering the flows of information within it. Also, by allowing distant activities to be coordinated, it allowed many production processes to be disintegrated, with parts production spreading around the world rather than being close to the assembly plant as they had to be when transportation and communications were based on mid 20th century technologies. Furthermore, many of its biggest effects of PCN were on services rather than goods. Many service operations were altered, and in particular decentralized, while many new ones were innovated. It is an open question how much potential for primary applications each GPT created. Given that services are by far the largest part of any advanced economy and contain many more separate activities than there are consumers 'goods, it does not seem unreasonable to conjecture that the stream of primary applications of PCN will be larger and will extend over a longer period of time than did those of electricity. This may be mistaken, but it would seem rash to conjecture the opposite, that PCN would be much less rich in primary applications than was electricity.

END OF TEXT

FIGURES FOR SECTIONS 4 AND 5

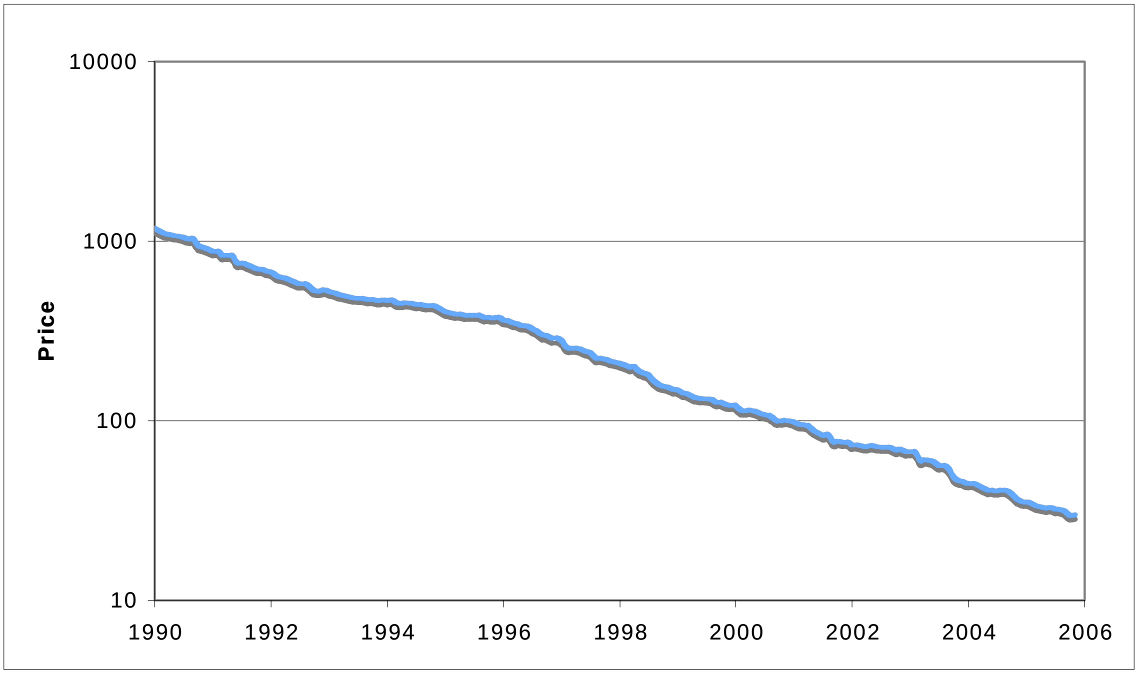


Figure 4.1: Computer Real Price Index - Business and Government Purchasers
Source: Statistics Canada, Consumer Price Index, V21570979

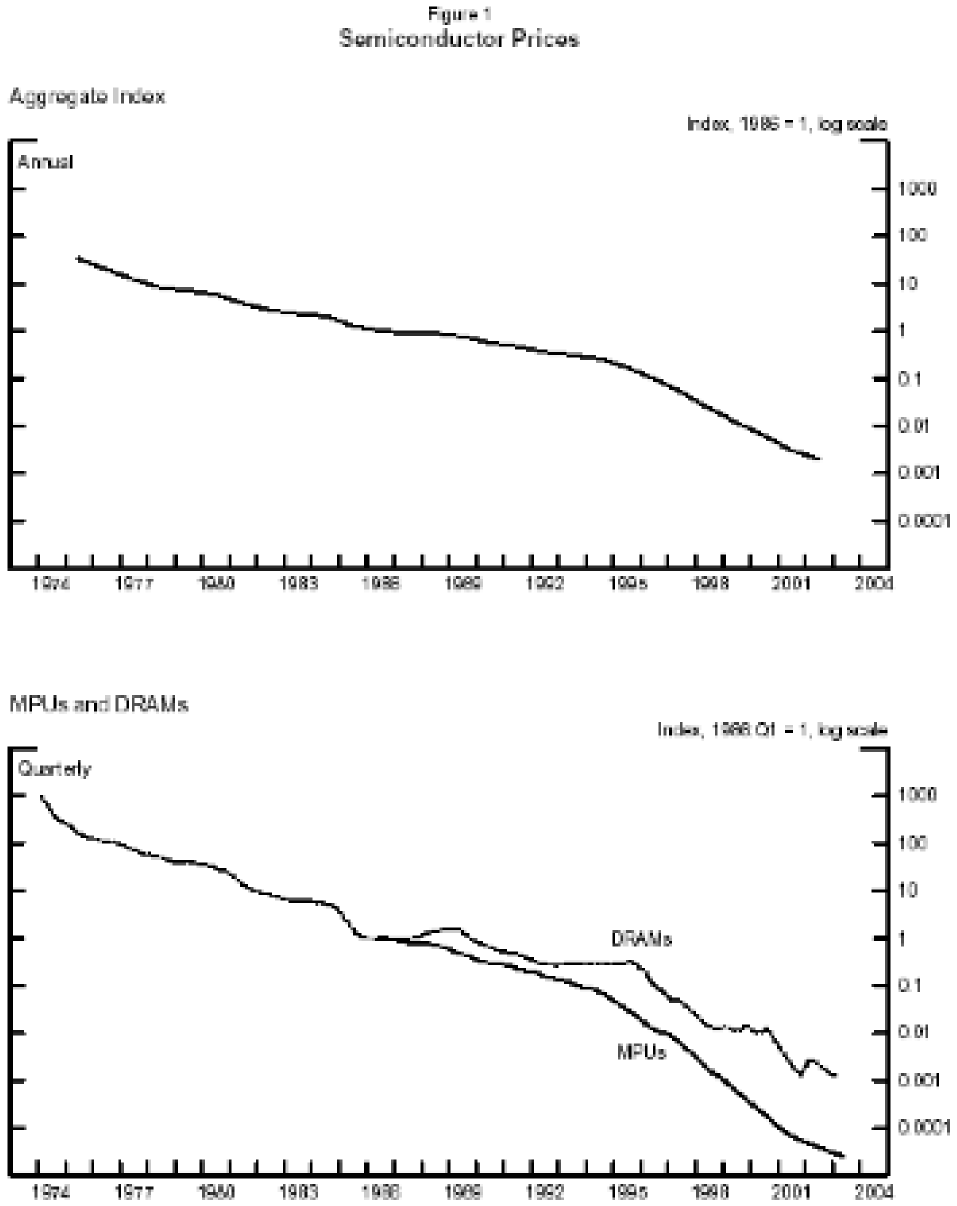


Figure 4.2: Matched-Model Price Indexes for Integrated Circuits
Source: Aizcorbe, Oliner, and Sichel (2003) Aizcorbe, Corrado and Doms (2003), “Why Do Matched-model and Hedonic Techniques Yield Similar Price Measures?” *Federal Reserve Board Working Paper 2003-14*.

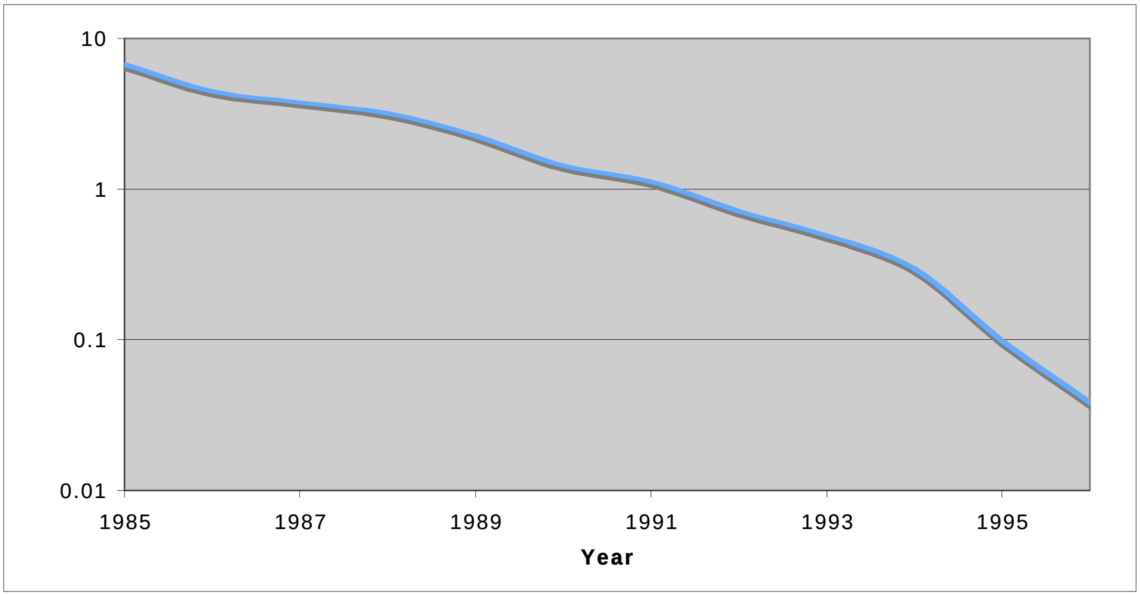


Figure 4.3: Summary of Real Price Index for Microprocessors, 1985-1996
Source: Grimm (1998), “Price Indexes for Selected Semiconductors, 1974-1996,” *Survey of Current Business*, February.

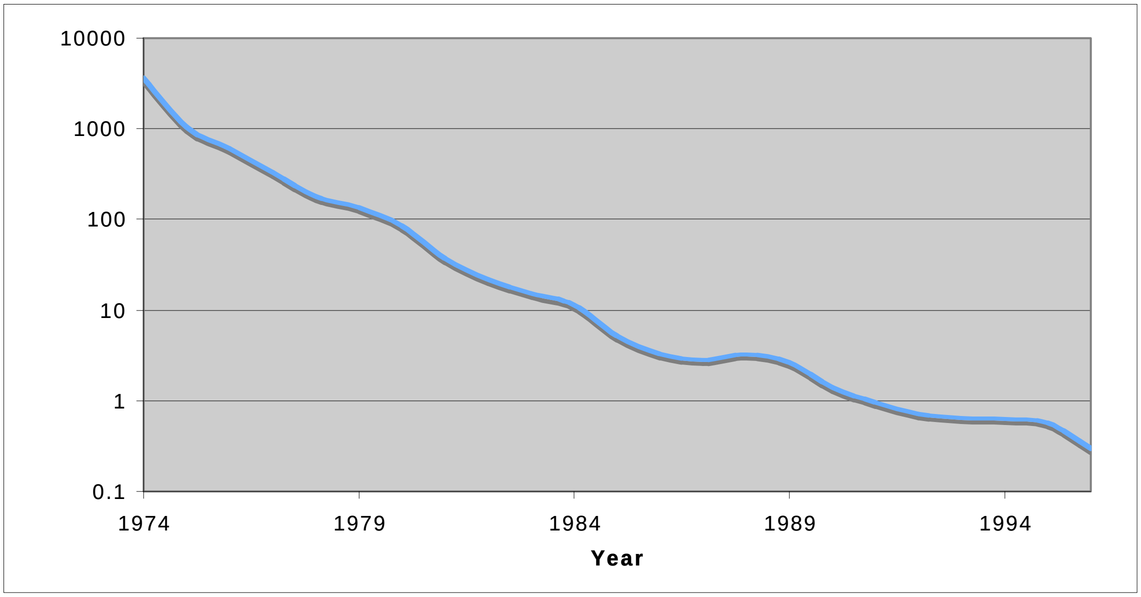
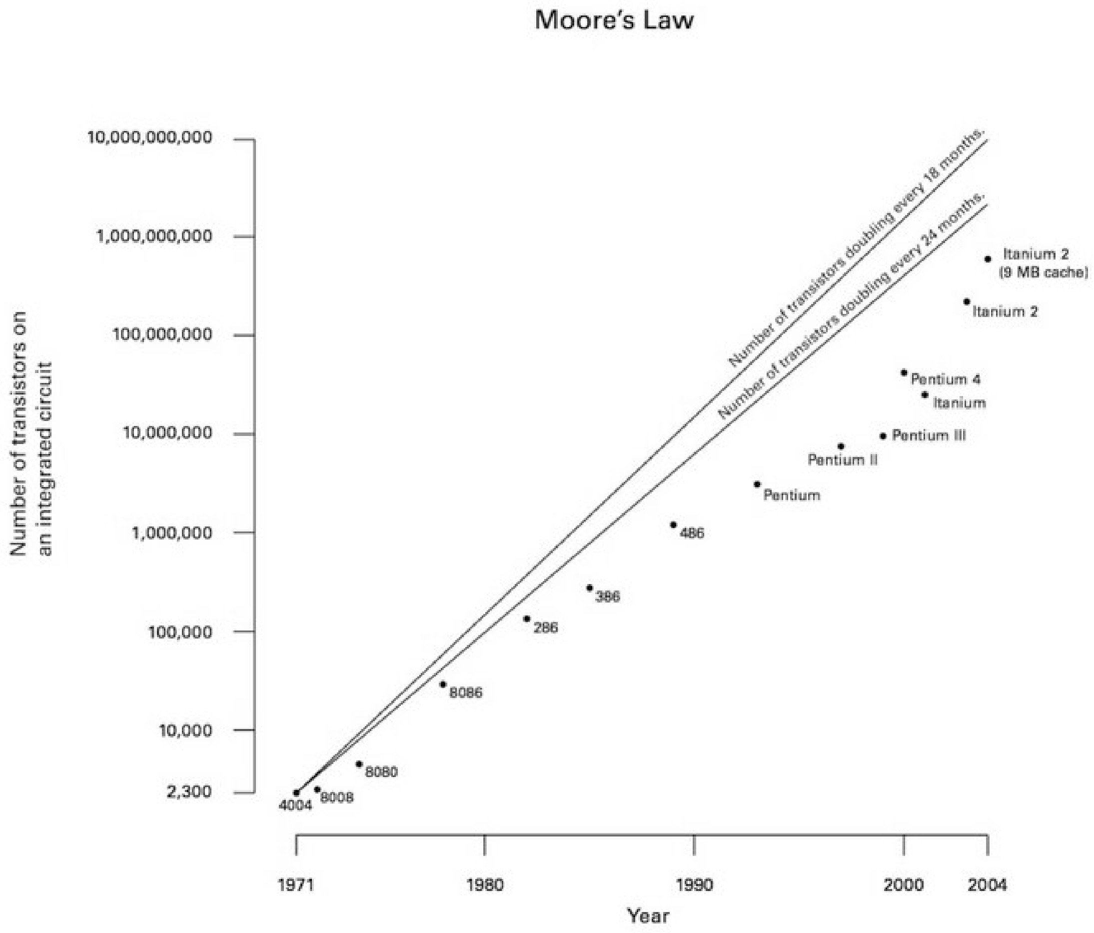


Figure 4.4: Summary of Real Price Index for Memory Chips, 1974-1996
Source: Grimm (1998), “Price Indexes for Selected Semiconductors, 1974-1996,” *Survey of Current Business*, February.



Figure

Figure 4.5: Transistor Count, 1971 – 2004
Source: www.intel.com

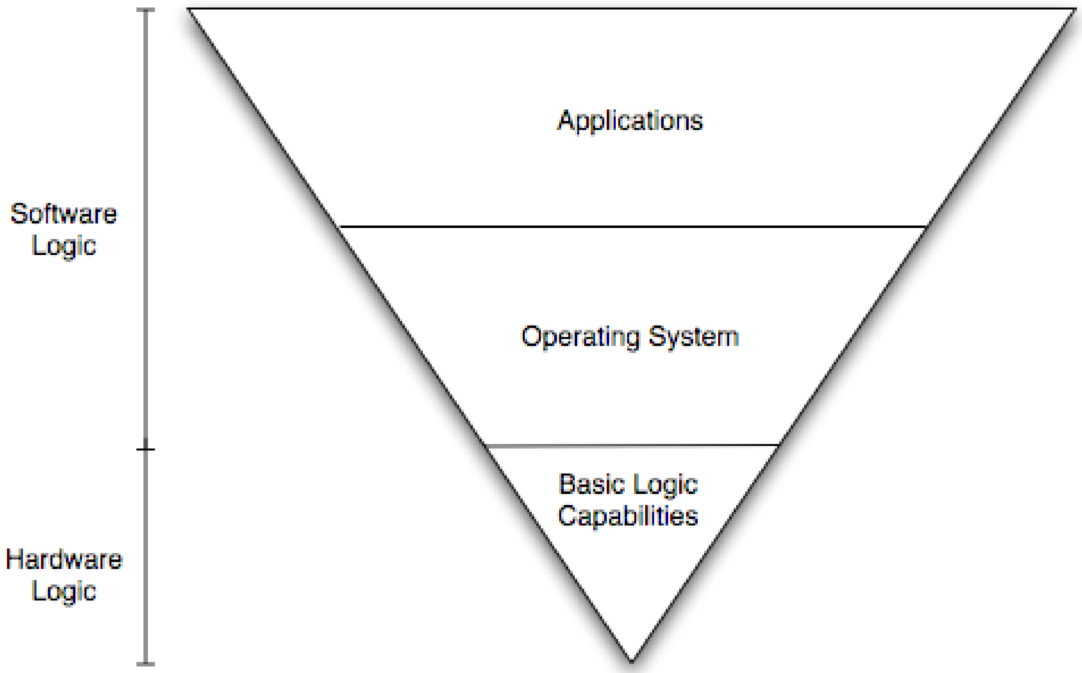


Figure 4.6: The Logical Hierarchy of a Personal Computer

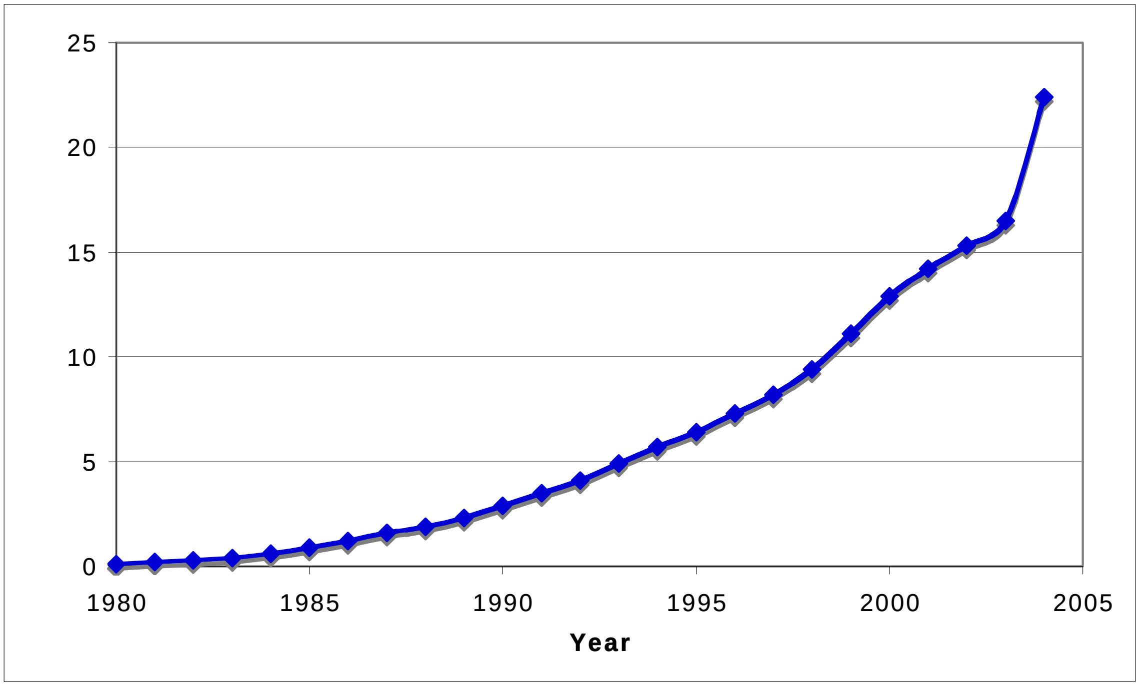


Figure 5.1: Annual Sales of Personal Computers in Canada (in millions)
Source: International Telecommunications Union (2005), International Telecommunications Union, World Telecommunications Indicators Database (2005). Series I422
http://www.itu.int/ITU-D/ict/statistics/ <http://www.itu.int/ITU-D/ict/statistics/>

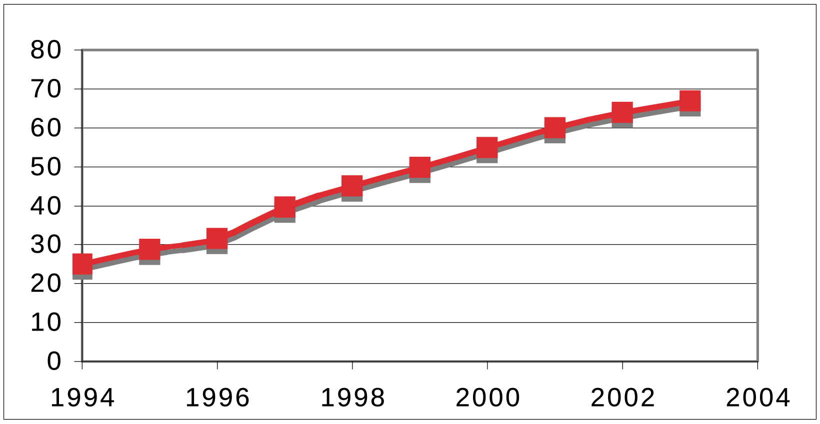


Figure 5.2: Percentage of Homes with a Personal Computer in Canada
Source: International Telecommunications Union (2005), Series I422HP

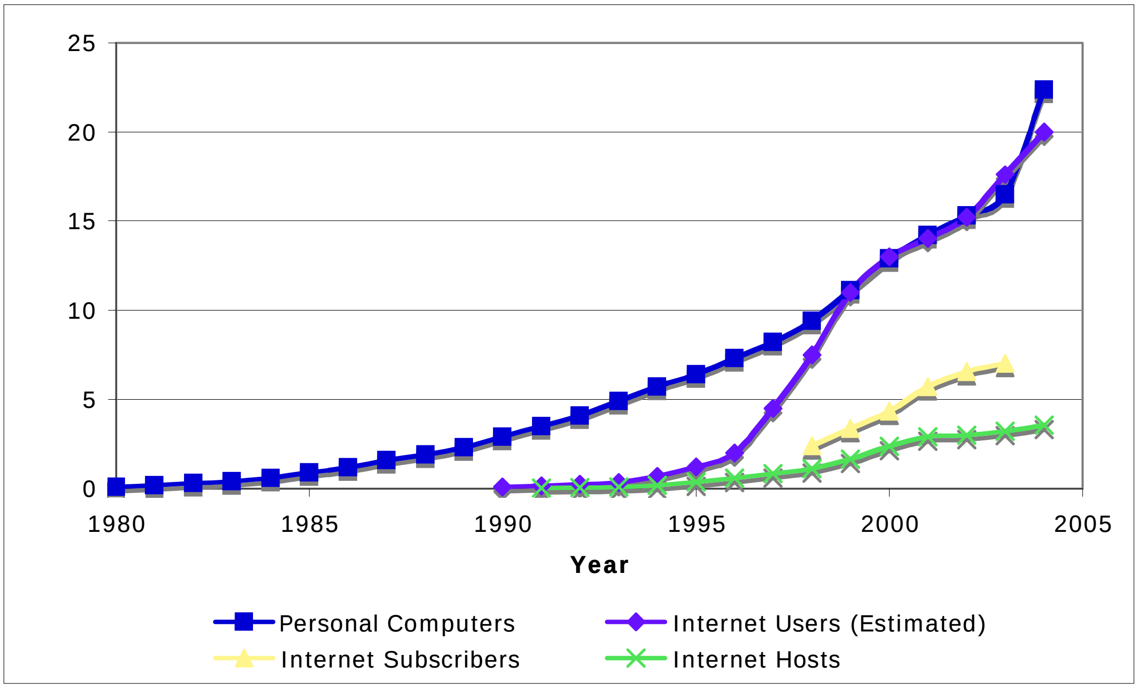


Figure 5.3: Comparisons of PC and Internet Diffusion in Canada (in millions)
Source: International Telecommunications Union (2005), Series I422, I4213 and I4212

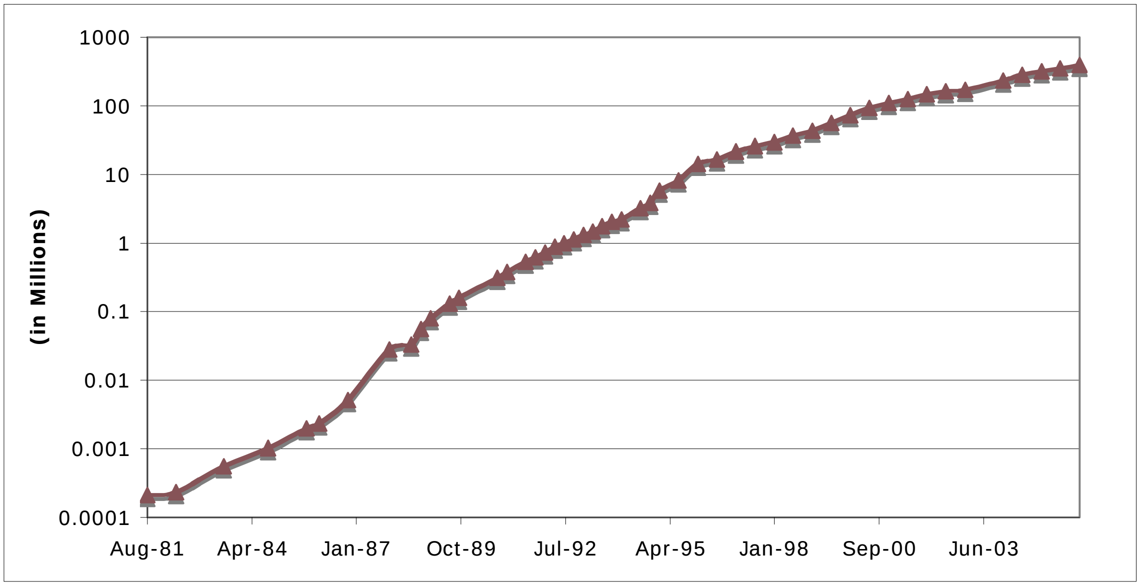


Figure 5.4: Internet Hosts Worldwide (in millions)
Source: Internet Systems Consortium (2006), "ISC Internet Domain Survey,"
http://www.isc.org/index.pl.

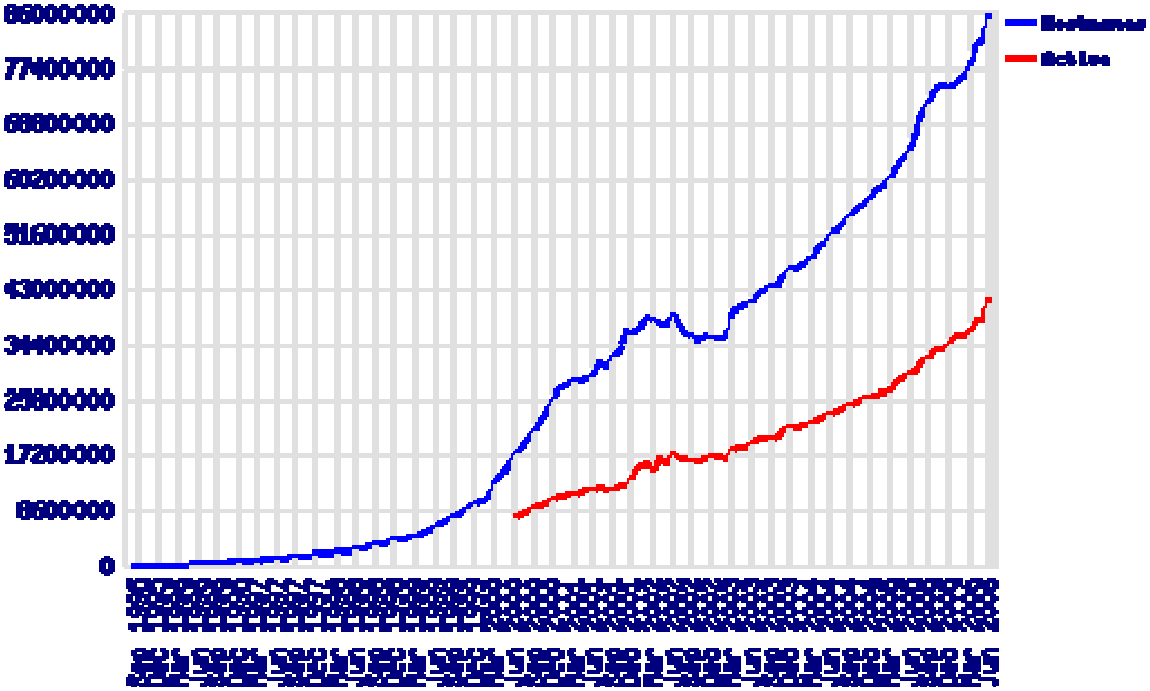


Figure 5.5: Internet Hosts Worldwide
Source: Netcraft (2006), "Netcraft Websurver Survey,"
http://news.netcraft.com/archives/web_server_survey.html

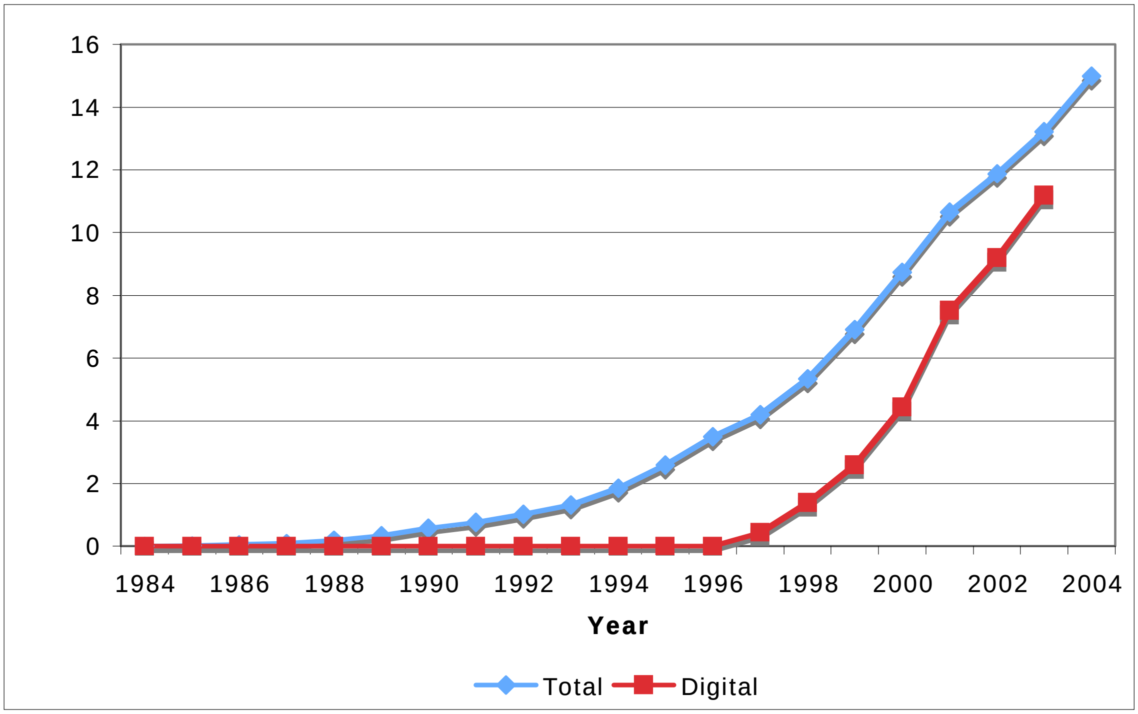


Figure 5.6: Number of Mobile Phone Subscribers in Canada (in millions)
Source: International Telecommunications Union (2005), Series I271, Series I2712

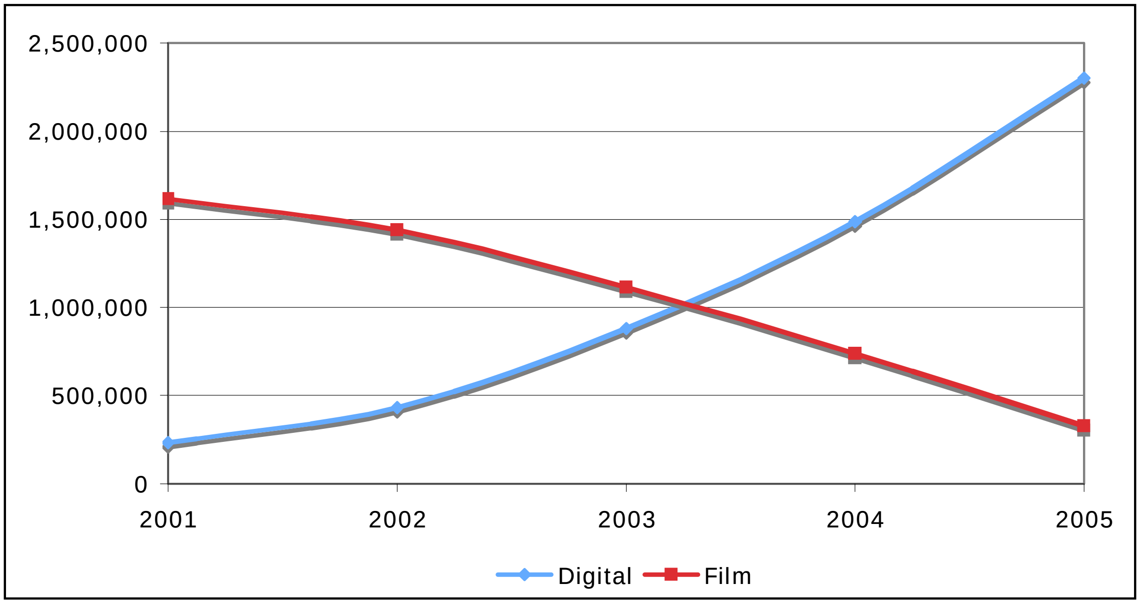


Figure 5.7: Number of cameras sold in Canada
Source: Canadian Imaging Trade Association (2006). “Industry Data,” http://www.citacanada.ca/News/industry.htm.

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