International Congress on Environmental Modelling and Software

4th International Congress on Environmental Modelling and Software - Barcelona, Catalonia, Spain - July 2008

Jul 1st, 12:00 AM

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iEMSs 2008: International Congress on Environmental Modelling and Software
Integrating Sciences and Information Technology for Environmental Assessment and Decision Making
4th Biennial Meeting of iEMSs, http://www.iemss.org/iemss2008/index.php?n=Main.Proceedings
M. Sànchez-Marrè, J. Béjar, J. Comas, A. Rizzoli and G. Guariso (Eds.)
International Environmental Modelling and Software Society (iEMSs), 2008

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Abstract: We assess the contention that the force of the ICT revolution was spent when the dotcom bubble burst. We identify the fundamental principle of *flexible machine logic*, the use of which distinguishes the group of modern ICTs — the electronic computer, the Internet and some related technologies — that make up the GPT of *programmable computing networks* (PCNs) and that have driven the ICT revolution. We seek to place PCN on two logistic trajectories that describe its evolving efficiency and applications. We argue that PCN still has significant scope for increasing its efficiency, that it is still creating an undiminished (potentially accelerating) flow of new applications, and conclude that the force of the ICT revolution will continue for some decades.

Keywords: ICT revolution, Technological change, Sustainable economic development**)**

1. INTRODUCTION

For some decades most of the world has been living through a period of revolutionary change induced by what is commonly called the information and communication (ICT) revolution — the economic, social and political transformations currently being driven by a cluster of technologies centered on the electronic computer and the Internet. Elsewhere (Lipsey 2002 and Lipsey Carlaw and Bekar 2005: 108-119, hereafter LCB), we have made the case for the existence of this revolution and replied to critics, such as Robert Gordon (2000 and 2003) and Triplett (1999) who deny its importance. We say no more about these issues here except to note that the profound transformation of the social, political, and economic aspects of our society wrought by the computer, the internet, and a few other related electronic technologies began in the late 1970s and continued through the year 2000.

When the dotcom bubble burst early in the 21st century, many observers argued that the ICT revolution had run it course and so ceased to be a source of economic change and new commercial opportunities. In this paper, we 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 trajectories of efficiency and applications. We argue that the evidence shows that PCN still has significant scope for 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 near future.

1.1 Some Definitions

In this paper we follow LCB in the use of three concepts defined as follows

- 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 *spillover effects* of a GPT are effects that spread through the economy well beyond the sector that produces the GPT itself.
- The *facilitating structure*, is the set of actual physical objects, people, structures and institutions in which technological knowledge is embodied, including plant and equipment — what it is, how it works, how it is organized, and where it is located — the internal organisation and industrial concentration of firms, all infrastructure, and all financial institutions.[1]

1.2 The Evolution of a Typical GPT

A new GPT typically begins in a crude form that is only slowly improved and adapted; later in its evolution, as it becomes well developed, its efficiency rises quickly; eventually, however, physical limits are approached, causing gains in efficiency to slow, finally coming to a halt if the GPT remains in use long enough.

As it is with efficiency, so it is with applications. A mature GPT is widely used for multiple purposes. There are, for example, few products and manufacturing processes that do not now use electronic computing power in one way or another. 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. The second source of new applications arises because the new GPT makes possible goods, processes and forms of organisation that were technically impossible with the technology that it replaces. Indeed, most of their really transforming effects come because of the new technological possibilities that are created. 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.

A technology that eventually becomes a GPT typically is initially incorporated into a facilitating structure that has been designed for the incumbent technology that the new GPT is challenging. Slowly, this structure is redesigned to suit the new emerging GPT. When the changes required are deep and long lasting, it is common to refer to a ‘revolution’ being brought about by the GPT in question. 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. And a similar order of events was observed on the shop floor. However, some unforeseen and revolutionary changes wrought by the introduction of computers were things such as the changes to economic, social and cultural interaction, with whole communities and even new cultures emerging and existing strictly online unconstrained by geographic location.

1.3 The Evolution of Efficiency and Applications

LCB stylize the evolving increases in the efficiency, defined as the cost at which the GPT delivers a unit of its service, and the evolving increase in the GPT’s range of applications, defined as products, processes, forms of organization that include the GPT in one form or

[1] The full list is given by LCB.

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

Phase 1: A new limited-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 conflict since the adjustments create many winners and losers. The growth rates of applications and efficiency tend to accelerate.
Phase 3: The principles of the new GPT are applied to produce many new applications — new products, new processes and new organizational forms — *within a newly evolved facilitating structure that is by now fairly well adapted to it*. The number of new applications grows rapidly and eventually reaches a maximum rate. Efficiency growth is also reaches its maximum rate of growth 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 part of the curve is then horizontal.[2]
Each of these phases varies from one GPT to another, depending on the productivity potential of each and how it is exploited. For example, Phases 1 and 2 may be very short if efficiency increases rapidly quite early in the GPT's evolution. It may enter its Phase 4, or even Phase 5, while applications are still in their Phase 3.

1.4 The Co-evolution of Applications and Diffusion

The evolving set of applications of a GPT covers both the development of new applications and the spreading use of existing applications, i.e., diffusion.

1.4.1 New applications

In some cases, new applications may depend solely on the GPT in question and a number of other lesser technologies, not themselves GPTs. In other cases, the GPT may cooperate with other GPTs. To consider such cooperation further we need to define two new terms.

- *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 a new GPT is evolving, its changing characteristics influence the nature of the innovations that depend on it — it is contributing primary applications. Eventually, however, it gives way to even newer GPTs which become the prime movers in the application generating process and while it becomes a background enabler.

1.4.2 Diffusion

When a new application is developed, its diffusion 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

[2] In LCB, 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.

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.

As we will see in a later section, 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.

1.5 The Co-evolution of Efficiency and Applications

Next, we enquire into the co-evolution of the efficiency and the applications of any new GPT, which we illustrate with 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 application curve may still be logistic but Phase 3 will be prolonged because efficiency is continually increasing. If efficiency finally stabilizes at some given level, the applications will continue to evolve for some time, but will eventually enter Phase 4 as the pool of potential applications begins to be exhausted.

In most real cases, both of these developments are occurring simultaneously: the efficiency with which the GPT delivers its services and its range of applications are increasing together in a positive feedback loop where increases in one encourages increases in the other.

2. INFORMATION AND COMMUNICATION TECHNOLOGIES (ICTs)

We define ICTs as all technologies that communicate, analyse, transform and store information, including 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 one person’s use of a piece of information, does not preclude someone else from using it simultaneously. We refer to the physical, or objective form of information as a *signal*. These are of little use unless they can be transmitted from one user to another and interpreted by the receiver. Thus, an essential part of useable information is the process by which information is transmitted, analyzed, organized, and received. Communicating information requires a transmission medium such as the electromagnetic spectrum, or air for sound waves. Throughout history, humans have developed technologies to improve their ability to communicate, to a great extent by improving the transmission process. The 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 enabled 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.

2.2 Machine Logic

By the 19th century, knowledge of electricity had advanced to a stage where an electrical current could serve as a long-distance transmission medium. Although 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 monitor an electrical current to receive signals. This requires an application of 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, such as encoding/decoding, tabulating, organizing or filtering, and/or converting it from one transmission medium to another. The ability to impose a logical structure on a transmission medium allows a transmitted signal to be analysed without direct human intervention.

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 early electronic calculating machines that were developed during World War II had their logic built into their physical design. In contrast, the important property of modern computers is that the logic of the system is alterable through the use of software without a physical re-arrangement of its circuits, which are hard wired according to the principles of machine logic.

2.3 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 itself a network since it is comprised of a set of logical components, each designed for specific tasks and communicating with each other via a system bus. 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. At an even higher level of aggregation, distributed computing networks 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 among 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 of *programmable computing networks (PCN)*, which is composed of all logical processors of information that use flexible machine logic. This 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. We use the term programmable computing networks to distinguish this grouping from both the narrower class of computers as they are usually defined, and the wider class of ICTs as defined earlier.

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

3. PLACING PCN IN ITS EFFICIENCY CURVE

In Section 3.1, we use some indexes of efficiency to argue that PCN is still in Phase 3 of its efficiency curve. We then disaggregate to study the major sources of this increasing efficiency. The efficiency of any 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 3.2, 3.3 and 3.4. In section 3.5 we use these discussions to look into the future.

3.1 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. As a result, the indices for personal computers, microprocessors, software, and telecommunications equipment serve as a proxy for changes in the efficiency of each of these technologies that utilise PCN.

In their Figure 3.1 Carlaw, Lipsey and Webb (2007) (here after referred to as CLW)[3], show a hedonic real price index for computers purchased by business and government. The figure shows a constant rate of price decrease, which is about an order of magnitude every decade for at least four decades.

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.

A matched-model price index for integrated circuits, both microprocessors and memory modules, is given in Figure 3.2 of CLW. The decrease in price over the period 1975 – 2001 has been roughly 5 orders of magnitude. 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 3.3 and 3.4 in CLW 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 for micro processors and memory chips.

All of these indices show that the quality-adjusted prices of devices that embody and implement the GPT have been falling continuously. We 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.

3.2 Advancements in Engineering Processes

Early in the lifetime of the modern electronic computer, transistors and integrated circuits produced large efficiency gains. Later Moore’s Law, first stated in 1965, predicted that the number of transistors per integrated circuit would increase steadily while the cost per transistor would fall, resulting in about a doubling of the performance/cost ratio every two years (see also Stokes, 2003). Indeed the past 40 years have seen great technological advances in all of the areas which 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.

Recently, the cost of further increasing the computational capacity of CMOS has risen significantly. An upper bound in wafer size may be reached before long due to inherent

[3] All figures referred to in the text are found in Carlaw, Lipsey and Webb (2007).

material limitations, such as crystal strength (Chaterjee and Doering, 1998). Serious technical problems 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 the chip) impede further attempts to reduce etching size. (Chaterjee and Doering, 1998). 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 major 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 (ITRS, 2005). But note that a decade or two is not tomorrow! The second track is research into post-CMOS devices that we discuss in Section 3.5.

3.3 Advancements in Logic: optimisation and functionality[4]

Programmable computers have a hierarchy of software and hardware logic[5] One key to the device’s efficiency is that more complex functions can be created from simpler ones by designing a higher level instruction that is composed of other instructions (including more basic ones from lower levels in the hierarchy). 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, efficiency can be reduced by having too many instructions either at lower levels where they increase the complexity of the hardware logic, or at higher levels where they increase the complexity of the software logic layers. A process called ‘optimization’ is used to maximise the overall efficiency of the device by balancing these factors. A subset of this process, software optimization, repeats this task within the software layers.[6] Although the feed back between adding functional complexity and optimizing the placement of instructions in the logic hierarchy tends to be positive on average, bottlenecks or salients can be created, causing efficiency improvements generated by logic advances to evolve irregularly.

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 itself encounters physical limitations. The development of multi-core processors and “grid” computing have potential to side-step this issue, however to be scaleable, they must be accompanied by advances in parallel programming. Software developers schooled in serial programming must first be re-trained to take advantage of the extra cores.

3.4 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. These scale effects come from at least three sources.

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[4] Although we simplify our discussion in this sub-section by focusing on the logical design of the electronic computer, 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).

[5] 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.

[6] 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 (Stokes, 2005).

First, the physical delivery grid of the network is a source of increasing returns. Over the latter half of the 20^{th} century, by 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 for gains in network bandwidth capacity, only some of which has been realised so far. 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 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, creating a positive externality. 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.

3.5 Looking into the Future

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 3.4 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 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." (ITRS, 2005) An example of such a possibility is the quantum computer.

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. So even if the GPT of PCN moves into its phase 4, the ICT revolution may continue, driven by some non-CMOS-based GPT.

4. PLACING PCN IN ITS APPLICATIONS CURVE

In Section 4.1, we measure the diffusion of some of the major technologies spun off from PCN. In Section 4.2 we deal with current and perspective new applications.

4.1 Diffusion

The quantitative data available to us 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.[7]

Figure 4.1 of CLW shows that the number of personal computers, one of the most prolific embodiments of PCN, sold each year 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 economic slowdown during this period. International data for this aggregate category reflects a similar temporary slowdown, followed by a quick resurgence.

Figure 4.2 of CLW 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 4.3 of CLW 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 4.4 of CLW shows that the growth in the number of unique domains hosted on the Internet over the past two decades has been close to exponential. Figure 4.5 of CLW 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. Web usage appears to have grown in spite of the economic slump in the early 2000's.

Figure 4.6 of CLW gives data for digital mobile (cellular) phones, which undertake a growing number 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 4.7 of CLW.

For yet another example of diffusion, 45 percent of multi-channel TV households 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.

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[7] In measuring the diffusion of various applications of PCN, we must rely on the evidence collected by various statistical agencies. 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 unsuited for enumerating applications in the absence of category specific price data. 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.

We have reported on those generic products for which we have been able to obtain 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.[8] However, on the basis of what we have shown above, it seems 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.

4.2 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) fills several pages with an illustrative list of new products, processes and organisational forms that were computer driven during the last three decades of the 20th century.

We enumerate illustrative cases to show that the pace of new applications is still rapid and that many of these suggest further applications that build on them.[9] In contrast, when any GPT is entering Phase 4 of its 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. The following cases represent only a sampling, 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 posted on the website sfu.ca/~rlipsey.

- 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.
- 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.
- 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.

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8 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.

9 Our case data have come 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.

- 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.
- 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.
- 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.
- 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.
- 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.

The illustrations repeatedly show 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 Lipsey (1999). 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.

4.3 CONCLUSION

The data presented in this section strongly suggest that PCN is still well within Phase 3 of its applications 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 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, or a dramatic scaling of multi-core processors, 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.

- Even if PCN evolves well into Phase 4 of its efficiency curve, new non-CMOS based technologies may take over as the drivers of an on-going ICT revolution.
- We have seen from the sample of applications for which we could get reliable data that the diffusion of PNC applications 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 anticipated 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 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 the world's technologically driven economic and social change for at least several decades to come, offering countless opportunities for the development and exploitation of new applications throughout much of the economy.

We also conducted a comparison with the GPT of electricity the results of which are also posted on the website sfu.ca/~rlipsey This led us to two further 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, then 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.

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