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The digital economy: Where do we stand?

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Abstract

The rapid transition towards a "digital economy" was enabled by a converging set of innovations. Computing saw the development of the semiconductor transistor, integrated circuit, personal computers (PCs), operating systems, and graphical interfaces. The physical layer of telecommunication was enabled via the emergence of optical fiber and new wireless communication technologies, while networking saw the development of the Internet (essentially packet switching) and the World Wide Web. These advances combined to realize a series of new applications of information and communications technologies (ICTs) such as business software, e-mail, and e-commerce. However, progress seriously stumbled with the collapse of the dot com bubble, which among other things revealed a huge amount of misdirected investment that could have been used more productively. The question of the day is thus how to realize new "killer apps" to stimulate a new round of growth. The use of cell phones for communicating text, pictures, and video is a rapidly expanding area, but it seems unlikely that these applications will have a macroeconomic impact. Entertainment is a key industry whose fortunes are entwined with ICTs. Indeed, the application of ICT to innovating entertainment products is an important driver for the continued growth of the industry. Distribution of music and video via the Web could significantly stimulate demand but also raises the thorny question of how to protect intellectual property rights (IPR) of content providers. Another possible killer apps are interactive video-on-demand and telecalls/teleconferencing. The latter would, among other things, stimulate adoption of telework. The current Internet is capable of handing neither one-way transmissions of high-quality video nor interactive video-on-demand. There are bottlenecks both for the "last mile" connection from Internet service provider (ISP) to the home but also the "first miles" from originating server to ISP. The effective first miles bandwidth has not increased along with

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improvements in equipment, essentially because demand increases with capacity and thus traffic jams on the net continue. Digital subscriber line (DSL) technologies over telephone wires, and possibly wireless networks, will play important roles in getting over the last mile hurdle. Upgrading the first miles will probably require new networking protocols beyond TCP/IP that support multimedia and also changes in the economic model of information transfer via the Net.

Keywords: Information technology; Computers; Internet; Broadband; Cellular phones; Economic growth; Innovation; Video-on-demand; Telecommuting

1. Introduction

Thirty years ago, electronic calculators were beginning to penetrate mass markets in rich countries. Today, around half a billion people are using machines that can store entire libraries of books, music, and video material, vastly extend their capacity to process information, and entertains with virtual realities of astonishing realism. Thirty years ago, long-distance communication was mainly via mail carrier and to a lesser extent the telephone. Today, much of the world is connected via sophisticated networks that allow volumes of text, images, sound, and video to be exchanged in an instant. The pace of innovation and adoption of information and communications technologies (ICTs) has been, to say the least, astounding. Innovation related to ICTs has continued on many levels: basic science, engineering, manufacturing, system integration, and new applications. Adoption has gone hand in hand with innovation, giving rise to a steady and growing flow of income to invest in further progress. The institutional and societal framework in many rich countries proved very able to support sustained innovation and adoption of ICTs. The important role that ICT-enabled products and services have come to play in modern economies gave birth to the idea of the "digital economy," suggesting a transition to a new set of rules for how to succeed.

Recently, something seems to have changed. While booms and busts have jiggled the industry since its inception, the dip in recent years is particularly severe. The potential of dot coms to succeed was vastly overestimated by investors leading to a collapse of ICT-related high-tech stocks. European telecoms are struggling with vast payments for cell phone technology licenses that may not realize profit for decades. The heady optimism of the late 1990s has turned into doubting voices questioning if the ICT revolution might be over.

Did something go wrong? Is the industry simply entering a new phase of slower technological progress and/or growth? Is this a natural stall due to overoptimism of investors and expansion will continue again as before? Should societies rethink how to facilitate innovation and adoption of ICTs? Given the extent that many societies have benefited economically and otherwise from ICTs, there is obvious interest in maintaining growth to the extent possible.

In this article, we attempt to shed some light on the above questions. In Section 2, we review the history of development and adoption of the different key components in

ICTs: semiconductor transistors, integrated circuits, computers, software, networking protocols, and the Internet. As growth is ultimately driven by applications, Section 3 introduces some near-term end uses with significant potential and also discusses barriers to adoption. Section 4 contains an analysis of how the industry may evolve in the coming decades, including a discussion of what societal response might contribute to enabling on-line distribution of multimedia content and videoconferencing-on-demand.

2. Development of the technology

2.1. The age of microminiaturization

In the early 1940s, senior executives at the Bell Telephone Laboratories noticed that the demand for telephone services was growing so fast that electric power requirements for switching would, within two decades or so, exceed the projected electric power production of the whole United States. Their response was to initiate a deliberate search for alternative switching devices that would consume much less power. Semiconductors, a laboratory curiosity until that time, seemed like a promising avenue for research. John Bardeen, Walter Brattain, and William Shockley were assigned to the project. The outcome of that search was the first transistor, which was announced in 1947. The three scientists shared a Nobel prize in physics in 1956. Pressure from the Anti-Trust Division of the U.S. Justice Department forced AT&T to offer licenses to all comers at the modest price of US$25,000. A number of firms jumped into the transistor manufacturing business (Texas Instruments, for one) and some new firms were created, including one founded by Shockley himself.

The first commercial application (by SONY) was for lightweight portable radios. AT&T was primarily interested in telephone switching systems. Of course Bell Laboratories continued active development work (focusing on applications in the telephone network). At about the same time, the first electronic computers were publicly unveiled by UNIVAC and then IBM. In those early machines, vacuum tube diodes were needed both for switching purposes and for memory. It was quickly realized that the complexity and hence the computational power of computers would soon be limited by the number of circuit elements because of the short operational lifetimes of the vacuum tubes. Transistors came to the rescue and replaced vacuum tubes for switching. The first transistorized computer appeared in 1956. Ferrite cores replaced the vacuum tubes in the late 1950s as memory devices. By the early 1960s, electronics had adopted solid-state technology. A new industry, computer manufacturing, was born in the early 1960s, led by the IBM 'system 360' family.

2.2. The chip

No sooner had computers proved their worth for scientific number crunching and large-scale data processing in banks and insurance companies than the infant computer industry immediately hit another roadblock. Very simply, larger computers required large numbers of individual transistors and ferrite cores that had to be connected by wires. The wiring (and soldering) requirements—together with associated testing and defect correction—quickly became an overwhelming burden to manufacturers. Complexity itself had become a barrier. Another simplifying innovation was needed.

It too came along just in time. The integrated circuit, especially for applications to high speed memory, was coinvented (but independently) by Jack Kilby of Texas Instruments and Robert Noyce of Fairchild Semiconductor in 1958–1959. This was only the first step. The 'chip' was born. Integrated circuits (IC) were quickly succeeded by large-scale integration (LSI) and very large-scale integration (VLSI). This development inspired Gordon Moore, then at Fairchild, to articulate his famous Moore's Law in 1965. Moore [1] observed that the minimum cost number of components per integrated circuit doubled every year from 1959 to 1965 and suggested a similar increase should hold in coming years. Ten years later, he suggested another formulation in which the number of transistors on the most complex chips would double every 2 years. Though some sources refer to Moore's Law as a doubling of number of transistors per microprocessor every 18 months, this is apparently a misquote, and the actual doubling rate for transistors on Intel processors ranged from 22 to 54 months from 1971 to 2001 [2]. Intel and other firms have used Moore's Law as an objective function, meaning that firms now plan investments and future prices accordingly. It has thus become not just a consequence but a driver of technological progress in electronics.

In 1968, Gordon Moore and Robert Noyce left Fairchild together and founded Intel, specializing at first in producing memory chips. The next electronics milestone was the invention of the microprocessor by Intel in 1971 and introduced a year later. Andrew Grove, the CEO of Intel, has admitted that he thought it was a distraction from the company's mission of manufacturing memory chips. He was wrong.

That first microprocessor, the Intel 4004, contained 2300 transistors. It created little stir at first, even among the computer cognoscenti. However, it was the first sign of a tectonic change. Prior to the 1970s, computer design was the fiefdom of IBM and its rivals. The trend seemed to be ever larger, ever more powerful machines, such as Seymour Cray's 'supercomputers.'

But it was Intel's microprocessors that were the real leading edge because it shifted the design function from the computer manufacturers to the chip manufacturers. Driven by Moore's law (and by Moore's firm), the microprocessor has become ever more powerful. The current versions of Intel's microprocessors (early 2002) embody more than 10 million individual circuit elements or nearly 5000 times the complexity of the first microprocessor.

2.3. From mainframes to laptops

The first nonmilitary/defense government user (in 1951) was the U.S. Census Bureau (which had also been the first customer for Herman Hollerith's punched card sorters and tabulators back in the 1880s). The first business applications (c. 1958) were in insurance and banking, where huge data bases had been transferred from punched cards and paper tapes to magnetic tapes and drums, facilitating rapid access and processing by mainframe computers. Subsequently, publishers with subscription lists and all kinds of businesses with many customers began putting their records on computers for purposes of account management and billing. This process of substitution of computers for file clerks is now far advanced. By the late 1960s, computers had already become well established in the office environment.

Most business users of computers were, and still are, companies in the service sectors. The impact of computers on the factory floor was essentially nonexistent in the age of 'hard automation' (before the 1980s), with the exception of the few computer-controlled machine tools that were needed for producing very complex shapes such as turbine blades. Hard automation was exemplified by Ford's Cleveland engine plant (1963). The impact of computers on manufacturing was still in its very early stages in the 1980s, mainly limited to so-called flexible manufacturing systems (FMSs) consisting of groups of computer-controlled machine tools linked by an automated or robotic transfer system. Such systems were just coming into use in the aircraft industry and the machine tool manufacturing industry itself, where long production runs were not appropriate [3–5].

The next stage of computer use in factories, known as computer-integrated manufacturing (CIM), brought together all of the different computer-aided operations from design (CAD), engineering (CAE), and manufacturing (CAM) operations under centralized scheduling control, ultimately linked to orders, materials purchasing, inventory management, and shipping (Ayres, op cit). Most of these software–hardware systems are still proprietary since they tend to be specialized to a particular factory. Today, there are also sophisticated management software systems, called Enterprise Resource Planning (ERP) systems, capable of integrating all the financial activities of the firm, including sales, billing, purchasing, wage payments, utilities, taxes, and other costs (the Internet is now an important element in these systems because of the need to link operations in different locations). These software systems only became reliable and widely available in the 1990s.

In the 1970s, led by Digital Equipment (DEC), computers began to shrink. The so-called 'minicomputers' were particularly suitable for engineers and scientists—especially at universities—as well as for use in small offices. The mainframes continued to dominate applications involving extremely large databases but found it increasingly difficult to compete for specialized local applications. IBM, which dominated the mainframe business, envisioned a world in which every office had a 'dumb' terminal that could download data and special-purpose programs from the central mainframe, input a few instructions, and upload for computational purposes, finally downloading the results for display or printing.

This vision was rapidly made obsolete by the rapidity of technical progress in storage and processing speed and by the fact that mainframe units were sequential processors, not well designed for efficient simultaneous processing of many different jobs at once. (On the contrary, parallel processors were a favorite topic of discussion among computer scientists). The big mainframe systems operated by stacking requests in queues. In addition, since each request entailed a time-consuming 'setup' (even though the actual time required might be mere microseconds), there was a strong incentive for the operators to maximize throughput by giving priority to big jobs involving long runs.

At any rate the central processor connected to a large number of dumb terminals could not compete with a more decentralized architecture. However, DEC also missed the trend toward desktop units. At first, very small computers, such as the Altair 8800 kit, looked like toys, at least from the perspective of the professionals. But the toy rapidly grew in computational power and capability without growing in size. Due to the invention of the microprocessor, the core technology was already embodied in a few off-the-shelf 'chips,' so constructing a small computer was merely a matter of mixing and matching off the shelf components. Many young people designed and built their own computers in those days, among them Steve Jobs and his colleagues. By 1976, the first Apple desktop computers, built around third-generation Intel microprocessors, began to create a new market for personal computers (PCs) with the power to bring many applications formerly reserved for mainframes to the individual desktop.

2.4. The rise of software

Throughout the era of mainframes, operating software was created by the major computer manufacturers, especially IBM. The earliest computers were programmed in so-called 'machine language.' Symbolic assembly languages followed soon, along with higher level languages like FORTRAN (1957), ALGOL (1958), COBOL (1960), and BASIC (1964). These were typically packaged with the hardware. BASIC has evolved into an object-oriented language (Visual BASIC) that is still in use. C appeared in the late 1970s, and being a high level language with lower level functions to control memory (pointers) could be used for a wider range of applications than its predecessors. C and its object-oriented extended successor, C++, are widely still in use. Another object-oriented language, Java, is the first platform-independent language adopted on a wide scale and is increasingly used in websites.

In the early period, specialized applications were mostly custom designed by users or specialized software firms, such as Computer Sciences (CSC) and Electronic Data Systems (EDS). The first mass-produced software applications for PC users appeared in the late 1970s. One of the first was VisiCalc, followed by the more successful Lotus 1-2-3, a spreadsheet program. Word processors soon followed (WordStar, WordPerfect).

By 1980, the Chairman of IBM, Frank Carey, was convinced that IBM had to enter and dominate the new market for PCs, despite the growing competitive threat to its mainframe business, or risk being left out. To bypass internal opposition, IBM created a completely new organization, outside the existing hierarchy and reporting directly to the Office of the Chairman, to undertake this development task. The new organization within IBM was given an extremely tight deadline. It also got authorization to subcontract for needed components and subsystems from any source, including suppliers entirely outside the IBM family. IBM itself undertook to permit other manufacturers to utilize its basic design architecture (utilizing the Intel 8086 microprocessor), so as to standardize the product and control the new market.

However, IBM wrongly saw the market in terms of hardware. A tiny firm called Microsoft got the contract to develop a disk operating system (DOS) for the IBM PC.

Microsoft took an historic gamble: It refused to sell PC/DOS outright to IBM but negotiated instead for a royalty on every machine sold (Apple, by contrast, refused to license its proprietary operating system to other hardware manufacturers). The second version was renamed MS/DOS. Later, when MS/DOS needed to be replaced, Microsoft—using its own resources—adapted the key features of Apple's highly successful operating system to create 'Windows' for IBM-type PCs.

Windows was introduced in the early 1990s. Today, there are 500 million PCs in use, worldwide, mostly (90%+) using Intel microprocessors and Microsoft Windows operating systems and other applications software. This has made Microsoft one of the world's most powerful monopolies and William Gates, founder of Microsoft, the world's wealthiest man.

2.5. Telecommunication

From the very beginning, solid state electronics was adopted instantly by the military and aerospace industry, where both weight and reliability considerations ruled out the use of vacuum tubes. Microminiaturization has revolutionized both information processing and information communications. In fact, communications is arguably the first major industrial beneficiary of the microminiaturization revolution. Satellites, in particular, would not have been possible without solid-state circuitry. Because of weight limitations, miniaturization has been the primary goal of development. Telstar, the first communications satellite, was launched by AT&T Bell Labs in the early 1960s. Transmission lines were once coaxial copper cables, but microwave "pipes" began to replace coaxial cables many decades ago and optical fibers have since taken over the heavy-duty applications, beginning in the 1980s. But whether cables or microwaves or optical fibers, all transmission lines require repeaters and amplifiers, as well as modulator–demodulators to decode and convert high frequency signals into low frequency analog signals. All of this technology began to converge in the late 1960s.

For instance, the 1970s became a landmark period for undersea cables. A new transatlantic cable in 1970 cut previous circuit costs by 80% while a transpacific cable 7 years later did the same for transpacific traffic. Demand soared as costs fell. Cable costs have continued to fall even faster than satellite costs due to the advent of optical fibers. In 1995, a transatlantic circuit cost only US$150/year, while a transpacific circuit was still about twice as expensive [6].

Meanwhile, on still another track, radiotelephone technology (originally launched by Marconi) had been commercialized in the United States since 1946. Each unit uses two frequencies, one for reception and one for transmission. The range of the individual units was limited by the density of transmitter–receiver nodes. In the 1950s and 1960s, the service had been drastically limited by the small number of frequencies allocated to it by the FCC, the relatively large power requirements of early units. By the late 1960s, transistor and integrated circuit technology had reduced the power requirements, while adding nodes along heavily traveled routes reduced the necessary transmission range. Radiotelephones for public use were installed on the Amtrak rail line between Washington and New York around that time.

But in the 1960s, there were still technical difficulties in 'handing-off' a moving subscriber from one node to the next. The key development was a technique known as 'frequency reuse,' which enabled a large number of small spatial ‘cells’ to utilize a small number of frequencies efficiently without mutual interference. The first complete cellular mobile communication system—as such—was patented in 1970 by Amos Joel of Bell Telephone Laboratories. This solved the hand-off problem, in principle, though it did not induce the FCC to allocate more frequencies to the mobile service immediately. Soon thereafter, however, the first practical hand-held mobile phone was patented in 1973 by Martin Cooper of Motorola.

These developments finally prompted the FCC to allocate more frequencies (bandwidth) in 1974, but AT&T was not allowed to conduct large-scale prototype testing until 1977. However, the FCC was concerned more with assuring competition than with encouraging innovation. Consequently, the first mobile telephone system in service was created in 1978 outside the United States (in Bahrain). The Nordic Mobile Telephone (NMT) system went into operation in 1981 and expanded rapidly beyond Scandinavia. This early start likely gave Nokia and Ericsson an edge in the emerging global market for cellular phones. The former has emerged as the world-leading producer of handsets (with Motorola a distant second), while Ericsson leads in providing systems.

As a result of continued antitrust pressure, AT&T broke itself up in 1981, spinning off the local service units (“baby Bells”) and retaining the long distance service, manufacturing, and advanced technology components. The Advanced Mobile Telephone Service (AMPS) was finally licensed by the FCC and went into operation in the United States in 1983. Comparable services were then being introduced in Canada, Europe, and Japan (the Japanese national telephone monopoly, NTT, was broken up in 1988). The hardware market in the United States was dominated by Motorola.

The first-generation cellular units were all based on analog technology; but by 1991, the second-generation units using digital technology became available. An international standard, known as IS54, was also adopted in 1991. This enabled a very rapid expansion in cellular telephony, with many new entrants. In recent years, mobile telephone usage has expanded much faster than fixed line usage, the number of cell phones in service worldwide is now equal to or greater than the number of telephones attached to fixed lines.

The number of cellular phone subscribers in 1995 was only around 50 million. By the end of 2001, it was approaching 1 billion and increasing at over 20% per year. In the United States, cell phones became a minor sideline of local phone companies (‘baby Bells’), where local telephone service was cheap, whereas the new service was provided by the same regional telephone companies, who deliberately kept it significantly more costly. This kept cellular usage in the United States relatively modest, until recently. In Europe and Japan, and elsewhere outside the United States, local phone service was typically much more expensive and the local telecom monopolies were more concerned with competition in the long-distance (international) market. This price differential created an opening for new wireless local service providers such as NTT DoCoMo in Japan, Vodafone in the UK, and many others.

2.6. The digital revolution: 1990–

Since the beginning of the computer era, visionaries had predicted a convergence of computer technologies with communications technologies. Because of its key role in the development of both, AT&T's Bell Labs was widely thought to be the likely driver of this development. After all, it was Bell Labs that originally developed the transistor, pioneered electronic telephone switching systems (essentially specialized computers), and it was at Bell Labs that Claude Shannon pioneered information theory in the 1940s [7]. However, until c. 1990, the two technological streams remained quite distinct, at least insofar as applications were concerned, for one simple reason. Communications (including radio and TV broadcasting) continued to be analog based, whereas computers were essentially digital.

The eventual convergence, in practice, was triggered partly by developments in cellular phone technology and partly by developments in TV. Since 1972, the Japanese consumer electronics giants had spent years and a great deal of money developing an improved system, of "high-definition" TV, or "hi vision." This was supposed to be the next generation TV. The Europeans jumped on the bandwagon in 1986, and the Americans, with no surviving consumer electronics industry, lagged. The usual disputes over national standards ensued, the United States adopting the Japanese standard, HDTV, and the Europeans creating their own (for protectionist reasons) called HD-MAC. Both systems were analog. However, the race changed course around 1990 when the United States began moving toward digital TV technology. The American HDTV proposals all changed from analog to digital in 1991. The pioneer was General Instrument. The Europeans followed in early 1993.

The main driver was unexpectedly rapid developments in data compression technology. The theoretical possibility of dramatic reductions in the bandwidth needed to convey a good quality TV picture on a copper wire had been known since Shannon's work at Bell Labs a generation earlier. A TV picture requires bandwidth equivalent to about 45 million Hz (cycles per second = bits/second = baud). Cable TV operations use a coaxial cable to carry many programs simultaneously using a loop configuration. However, in principle, an ordinary copper 'twisted pair' telephone wire can carry that much information and much more.

An audio compression algorithm known as MP3 cut audio tracks by a factor of 12 and created the possibility of large-scale music file sharing (Napster). Meanwhile, the minimum bandwidth needed for digital TV had dropped equally sharply due to the development of practical data-compression techniques. (This is possible because most TV consists of a sequence of pictures that change 60 times per second, although only a small fraction of the pixels actually change between any pair of successive images. Thus, there is a great deal of repetition, which can be eliminated by clever tricks.) By 1990, it was already possible to compress the information content of a standard TV program in digital form from 45 million to 1.2 million baud. This fact finally induced the TV industry to reconsider its commitment to analog technology.[1]

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[1] Data compression technology has progressed since then. The most widely used system (called MPEG-2) has a compression ratio that ranges from 8:1 to 100:1, depending on the application; 20:1 is standard. The leader is RealNetworks, whose RealPlayer-8 can compress a 2-hour movie onto 500 megabytes, which can be downloaded in an hour via a 1-Mbps cable modem [13].

2.7. The broadband transition

The limiting factor for consumers has not been the carrier, but the analog–digital 'modulator–demodulator' (better known as a modem). The first commercial telex modems had a bit rate of 300 bits/second (bps or baud). In the 1970s and 1980s, standard modems in use for telephone connections ran at only 2400 baud. In 1990, the standard was 9600 baud and 38,400-baud modems were coming into use (for fax machines and PCs). However, the rate of progress has been accelerating. As of 1998 or so, top-of-the-line PCs had 112 kilobytes/second (kbps) modems built-in. Today, 500 kbps modems are readily available at low cost. With special equipment, it is now possible to download 2 or even 20 million bits/second (Mbps). This rapid progress is a consequence of declining manufacturing costs due (in turn) to rapid progress in microelectronics: it is Moore's Law in another domain.

Digital subscriber line (DSL) technologies allow broadband level communication using existing copper telephone wires. Asymmetric digital subscriber line (ADSL) can download 1.5–12 Mbps, orders of magnitude faster than analog modems. The system is asymmetric because it accepts much less information in the reverse (upload) direction, i.e., from the subscriber. The main reason that bandwidth can be increased so dramatically is that conventional phone systems have bandwidth filters in place at the local level that, while useful in managing voice traffic, significantly limit the volume of data traffic. Replacement of these filters with modern versions allows the bandwidth of phone lines to be increased to near the physical limit. ASDL services are becoming widely available and reasonably priced around the world. Penetration was up to 25 million households worldwide in mid-2002, with 36% growth over 6 months [8], 42% of those subscribers are in Asia (mainly Korea, Taiwan, and only recently Japan) with 124% growth over 6 months. By comparison, North America had only 6.5 million DSL subscribers and 19% growth.

2.8. From ARPANET to the World Wide Web

The Internet is a development resulting from the convergence of computer and telephone technologies. It actually began with ARPANET, conceived by the Advanced Research Projects Agency of the U.S. Department of Defense in 1969. In 1970, it had 4 nodes. The system was demonstrated publicly in 1972. Its purpose was to facilitate scientific interchange among advanced computer facilities (mainly in universities). The most important of the early applications was Telnet, which allowed a researcher at one site to run a program on a computer in another site. The next application was file transfer. An accidental by-product of file transfer protocol was the first crude e-mails (c. 1972–1973). Date was transferred at 300 bps. All costs were paid by the U.S. Department of Defense.

By 1980, there were 200 nodes (host computers), and new applications appeared, including Usenet, on-line chat, and true e-mail, which took off in 1982–1983 [9]. By 1990, the number of nodes was 300,000 and nonacademic users began to get access

[9]. The World Wide Web was the crucial innovation. It was 'invented' by Tim Berners-Lee (1989), and the first website was created in 1990 at CERN, the multinational high-energy nuclear research facility in Geneva, Switzerland [10]. The Web began as a document-sharing protocol (hypertext markup text markup or HTML), but it quickly evolved into the software for creating and operating individualized 'websites' in which individuals, organizations, or firms can store information that can be read or downloaded by any user. At present, three fourths of all Internet traffic is Web traffic, to and from websites.

America Online (AOL) began in 1989 as a specialized dial-up service for Apple Macintosh users. Soon, AOL began distributing free diskettes containing the software and later, free CD-ROMS. By January 1994, AOL had a million subscribers and another million were added in 1995 alone. The success of AOL [and other Internet Service Providers (ISPs)] was synergistic with the explosive growth in the number of commercial and other websites during the second half of the 1990s. Most of that early growth was fueled by very cheap access via fixed local telephone lines (in the United States) and the fact that digital information can be reproduced at virtually zero marginal cost.

In 1994, most of the top level domains of the net were still educational (.edu or 'dot edu'). The number of .edu domains increased steadily from about 1 million in 1994 to over 5 million in 2000. However, the number of commercial (.com or dot com) domains increased from around 1 million in 1994 to nearly 25 million at the beginning of 2000, while other categories of users (.net, .mil, .org, and .gov) added another 19 million domains, of which 15 million were cable based net service providers [9]. As of the end of 1994, it was estimated that 20 to 30 million people, mostly North Americans, were Internet users [11]. Negroponte, head of MIT's media-lab, 'guessed' that a billion people would be users by the year 2000. He was overoptimistic. But by January 2000, the number of AOL subscribers worldwide had reached 20 million, while the number of Internet nodes (servers) had reached 72 million [9]. The number of PCs at that time, worldwide, had reached 400 million. The number is now (May 2002) estimated at 500 million. Although it is unclear how many of these PCs are actively connected to the Internet, virtually all of them are equipped to do so (with modems and CD-ROM drives). There is a recent market forecast from International Data (2001)[2] that 1 billion people will be using the Internet by the end of 2005.

New information services based on the World Wide Web were created in great numbers in the early 1990s, and this resulted in a need for 'browsers,' 'search engines,' and 'portals' to enable net users to find information of interest. In 1993, an Internet browser called Mosaic developed by Marc Andreessen, a young programmer at the University of Illinois, experienced a spectacular growth rate, 11% per month [11]. The phrase 'surfing the net' appeared around that time.

One of the first to appreciate the potential of the Internet, in general, and Andreessen's browser, in particular, was a Silicon Valley entrepreneur named Jim Clark. Clark was the

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[2] Cited in the *Intel Annual Report* for 2001.

inventor of a specialized chip for computer graphics (while at Stanford) and subsequent founder of Silicon Graphics. Clark had said, already in 1993, "The Internet is the future of data communications and all communications are data communications" [12]. This was a year and a half before the publication of Bill Gates' book *The Road Ahead* (1995), which scarcely mentions the Web.

At any rate, Mosaic was adopted, improved, renamed Netscape, and commercialized in 1994 by Jim Clark (founder of Silicon Graphics) and Jim Barksdale, a former AT&T executive. Netscape was spectacularly successful in its first year. In 1995, Microsoft began to feel seriously threatened. Gates demanded a piece of the Netscape browser business on favorable terms, including a seat on the board of directors. The 'or else' was a threat to put Netscape out of business [12]. Clark responded angrily by asking his lawyer to inform the U.S. Department of Justice of Microsoft's threat. Microsoft then created its competitive system, Microsoft Explorer, which was bundled into Windows 95. This brazen act triggered an antitrust lawsuit by the U.S. Department of Justice, which began in 1997 and went to trial a year later. The legal wheels grind slowly. Netscape predictably lost its dominant browser market share to Microsoft and finally merged with AOL in 1999.

Netscape included a searchable index of websites (termed a "portal"), but the most successful ones were Yahoo, Excite, and Lycos. These portals played a key role in the so-called 'dot com' boom in that they allowed connected users with the host of new services being offered via the Web. More specialized and much more powerful search engines continue to emerge, including the current leader, Google.

The rapid past growth of the Web, in the early 1990s, created a new set of demands for Web-based services, along with expectations of continued growth, all of which depended on the established telecoms or cable TV systems and their (initially) underutilized copper telephone wires [13]. The U.S. Telecommunications Act of 1996 had been intended to open up local access to competition by forcing the telephone companies with a monopoly on local service to open their networks to all comers. To take advantage of the new opportunity, a great many startup companies, called competitive local exchange companies (CLECs), were formed to offer high speed digital service to users. Examples include Northpoint, Covad, and XO Communications [14].

The CLECs in the United States went to court, seeking to enforce the rulings of the FCC, while the independent local exchange companies (ILECs) countersued on the grounds that they could not afford to share their local distribution facilities unless they were allowed to compete for long distance services as well. Besides, the 1996 law specified no deadline. The dispute was not resolved (in the CLECs favor) until May 2002, but it was too late for the majority of plaintiffs. Today, there are very few CLECs left to compete. Most of this massive investment has gone down the drain because the telecoms with a monopoly on local fixed line service—not just in the United States—did not open their networks to competition as the law supposedly required. Nor have they, or their European and Japanese counterparts, offered consumers access to digital service loops (DSL) on their own account, until very recently and in very few locations, mainly large cities. Furthermore, opening the local loop will not resolve the problem because the ILECs need to be upgraded to handle the DSL traffic and—although some are still profitable—some have crippled themselves by paying billions of dollars for third-generation (wireless) cell phone licenses, which now look grossly overpriced.

For a while, in the late 1990s, the creation of the information superhighway was a bonanza for the electronics industry. Glass fibers had begun to replace copper wires (and microwaves) for long distance service in the 1980s, and the substitution of glass for copper accelerated in the 1990s. Fiber is much the cheapest of the transmission alternatives, for high volume service, and its role has been growing in consequence. For some time, the telecoms have been replacing about 5% of their copper wire networks by glass fiber each year. The suppliers of telephone switching equipment, such as Lucent (formerly AT&T), Nortel, Ericsson, and Alcatel, and their suppliers, like Corning and JDS-Uniphase, rode the bandwagon high and suffered from its collapse. Unfortunately, the economics of fiber optics can be prohibitive for local connections (the so-called 'last mile'). In cases where new trenches must be dug for the cable, installing fiber in metro areas can run in the hundreds of thousands of dollars per mile [15]. Although installation cost can be often be reduced by creative use of existing infrastructure (e.g., sewer systems), it is difficult to justify the investment when existing phone lines can deliver adequate bandwidth via ADSL technology.

Analogous to telephone switching centers, the Internet requires specialized host computers ('servers') and so-called 'routers' (the Internet equivalent of a taxicab dispatcher). HP/Compaq and Sun MicroSystems now dominate the high end server business, while Cisco Systems and Juniper Networks dominate the router equipment category. Servers are typically clustered in so-called 'server farms' around the world, located in urban areas where most of the traffic originates. Big websites are essentially located within servers. Server farm capacity is currently increasing 50% annually, despite the demise of the dot coms. One of the biggest providers is Exodus Communications, with 9 server farms in Silicon Valley alone and 35 more in big cities around the world.[3]

Whereas the server farms are the wholesalers in the Internet, the retailers are so-called 'data caches' located around the world, near consumers of content. Technically, their function is to recombine the individual packets of data, dispatched by the routers by different routes (because of changing conditions from moment to moment), into coherent streams designated for final customers. The leader in this field is Akamai, with 11,000 caching servers in 62 countries. Akamai's customers are the content providers (including CNN and Yahoo!).

The net result of all this investment was to create an oversupply of long-distance fiber-based carrier capacity, without a matching growth in local broadband access capacity for which the established telecoms retained their monopoly (except where cable TV was also available). As of early 2002, long-distance optical fiber channel capacity is said to be only 2–5% utilized [16], whereas local access in many places outside the biggest cities, still dependent on copper wires, is badly congested.

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[3] The limiting factor is electric power consumption, especially as the farms get larger (one new server farm, being built by iXguardian near London, will have its own gas-fired power plant).

2.9. The "Net" bandwidth from Web server to ISP

Discussions of broadband almost always focus on the "last mile" from ISP to a home or office. The "last mile" connection is by no means the only important bottleneck facing the Internet: The "first miles" from originating server to ISP are arguably as—or even more—crucial, as bandwidth increases in this link are apparently relatively slow. Best-connected users with FastEthernet LAN (100 Mbps) and T1 Internet (1.5 Mbps, end-to-end symmetric) connections do not realize LAN-level speeds when communicating with hosts over the Net. File download rates of 100 kbps (0.8 Mbps) occur only in the most ideal of conditions, and rates of 20–70 kbps (.16–.56 Mbps) are far more typical. The total server-to-end user bandwidth can be divided into three parts: delays originating from processing time at the server and accessing computers, the last mile bandwidth, and the Internet (or first miles) bandwidth. A study by NetForecast suggests that, for best-connected business users, Internet bandwidth is the main bottleneck, accounting for 83% of data access time, with computer quality 17%, and the last-mile factor negligible [17]. In addition, Internet bandwidth has not shown the dramatic progress that occurred in computers and last-mile connections. A typical network delay time of 2 seconds in 1995 fell to 1.5 seconds in 2001 (ibid), an improvement that pales in comparison with the factor of around 10 gained in computing power and "last mile" speed. As computers and last mile bandwidth continue to improve, network bandwidth will become increasingly important to more and more users.

What is the origin of the limitations on network bandwidth and why has it not improved in step with other aspects? The Internet is based on packet switching technology, which means that information is broken into individually addressed packets (akin to letters in the postal system), passed through to the destination via a sequence of routers, hubs, and switches (e.g., intermediate post offices), and then reassembled to its original form. A certain degree of delay is induced simply by the physical time required to electronically/optically pass through cables and switching systems. However, traffic is also crucial: it is common place for the number of incoming packets to exceed the capacity of a networking device and thus be delayed by having to wait in a queue. To deal with this, the routing system in the Internet is dynamic and extremely complex: The system is constantly updating itself to try to find optimal paths adjusting to traffic conditions. In contrast to the postal system, however, there is no effort or cost involved with sending more data packets. Traffic thus tends to increase to approach the capacity of the system. Analysis by Barlett and Sevcik [18] indicates that the required bandwidth per user grows exponentially, doubling every 2 years. We suggest that this dynamic is responsible for the relatively slow improvement in Internet bandwidth.

For real-time applications, such as sound and video transmissions, fluctuation in Internet bandwidth is even more important that the average scale. For example, a conventional telephone call only requires 64 kbps (.064 Mbps), yet phone calls over the Internet could not attain even mediocre quality until compression–decompression techniques reduced the requirement to 6 kbps (.006 Mbps) [19]. This suggests that bandwidth can fluctuate by factors of 10–100 on a time scale of tenths of seconds. Performance for real-time applications is only as good as the lowest dip. For an Internet that performs poorly for phone service, quality video conferencing is a distant goal. For video reception only, recent improvements in computing power and streaming techniques have partially solved the short-term fluctuation problem. Computers can now buffer up to around 10 seconds of video (albeit low quality), thus allowing routine viewing of material such as movie trailers and news programs.

2.10. Rise of the cell phone

Their different histories has resulted in an interesting dichotomy between United States and other users of mobile phones. In the United States, PCs are used to connect with the Net, primarily because local telephone calls on fixed lines have been cheap or free, whereas mobile phones were quite costly. Since users are charged to receive calls, they tend to keep their units switched off. In Japan and Europe, cell phone users are much more interested in net access.

It is understandable that the cell phone firms, and the financial industry backing them, all became cheerleaders for linking cell phones directly to the Internet. The rapid growth of mobile (personal) telephones since 1995 triggered intense worldwide interest in the so-called ‘mobile Internet’ as an alternative to reliance on the ILECs or the cable companies. Moreover, the number of digital, Internet-capable mobile phones has increased even faster and is expected to overtake the number of PCs with a Web browser in the year 2002 or succeeding years. The general idea is that the cell phone (suitably upgraded) initially acts as a wireless access node, enabling some services, such as short text messages or even photos, to be delivered to the hand-held unit. Demand for this sort of service might be enough to keep the industry moving.

The primary advantage of the mobile phone over the fixed-line telephone is that the call goes to a person, not to a place. Adding color screens and cameras to hand-held mobile phones (already popular in Japan) may well increase the demand for such calls. But the service in question is not really new or revolutionary. Mobile phones compete with fixed line telephone service, but they also piggyback on the existing networks, like icing on a cake. A few years ago, it was argued that the mobile Internet would offer the same commercial shopping and other services as the fixed-line Internet, but more conveniently. This dream has mostly collapsed with the dot coms. In fact, it is not at all clear that mobile Internet can even compete with the existing Internet.

3. Possible “killer-apps” for the near-future

Telecoms around the world paid a total of US$120 billion in the year 2000 for licenses for third-generation (3G) services.[4] Unfortunately, it is now clear that the prices paid for the

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[4] First-generation (1G) mobile phones were based on analog technology. Quality is poor and calls are easily intercepted. About 70 million people, mainly in developing countries, use 1G phones. Second-generation phones are digital and encrypted. They can also send and receive data, such as texts, and are suitable for limited Net browsing using the so-called wireless access protocol (WAP). About 800 million 2G phones are in service. Enhanced second-generation (2.5G) phones became available recently. They can support more advanced data services. The third-generation 3G phones will have much high bandwidth (up to 384 kbps), with interfaces allowing transmission of multimedia content.

licenses were unrealistically high because of serious gaps in the rest of the system. The economic consequence of misdirected investment in dot coms and 'third-generation' (3G) licenses, in the absence of last mile wide-band connections, has been disastrous, at least in the short term. Internet-related activities absorbed hundreds of billions of investor dollars and briefly 'created' a lot of 'paper' wealth, which subsequently disappeared. The source of the boom and subsequent bust is likely the same that has rocked stock markets for centuries: rising stock prices attracts more investors, which in turn leads to further increases beyond real potential value. In highlight, it was probably inevitable that a rapidly advancing and widely applicable technology such as ICT would experience such a boom-bust cycle. While markets recover from such cycles over time, the bust does create a short- to medium-term shortage of capital to invest in new areas. In this section, we discuss some main areas of economic potential in the near-term.

3.1. Cell phones

The most durable service provided, so far, by the Internet is e-mail, which has spawned a boom in person-to-person text communication. The number of letters sent by household has declined from .46 to .29 per household per week from 1987 to 2002, both of these figures are dwarfed by the 120 personal e-mails sent per computer-using household per week in 2002 [20]. However, this service is usually PC-linked because of the need for large displays, keyboards, and printing. Similarly, the net has facilitated changes in more conventional activities, notably on-line banking, on-line trading of stocks and shares, and on-line shopping (e.g., Amazon.com); but in most cases, the need for receipts and confirmation also requires printers and is therefore not suitable for hand-held units. In Japan, however, most e-mail traffic goes through cell phones rather than computers, perhaps due to the combination of long-train commutes, communal offices, and late working hours.

Some fraction of these services can plausibly be offered to people riding in taxis or sitting in airport waiting rooms via Internet-linked third-generation (3G) cellular phones. Far more plausible, however, is the use of wireless connections between laptop computers and cell phones. This enables the laptop, with its full size screen and full size keyboard (among other features) to become a portable work station away from home or office, with Internet access speeds as good, or even better, than what is available at home. It is a step forward for the Internet. But it also imposes sharp limits on the market for the 'pure' 3G cell phone Internet service.

The enthusiasts for Internet-linked 3G cell phones are still searching for a 'killer app.' A few years ago, the marketers enthused about how teenagers could use the phones find each other in the mall (they can do that already with 2G cell phones), or how a sport fisherman could demonstrate the size of his latest catch triumph to a skeptical friend using a camera phone. Or it was suggested that a suburbanites driving into the city could use the Internet to find parking places (while stalled in traffic jams?). The recent use of cell phones by people without access to a TV to get on-line access to World Cup games seems to have encouraged some 3G marketers.

The most promising near-term application seems to be photomessaging, based on a link between digital cameras and cellular phones. Camera phones are now becoming a mass-market phenomenon in Japan, where 19 models of camera phones are now available, at prices between US$100 and 400. The local service in Japan was pioneered in November 2000 by J-phoneVodafone, using its 2G and 2.5G networks. Rivals in Japan are entering the market earlier than originally planned (i.e., before 3G is available) because of the high demand. Nokia, Motorola, and Sony-Ericsson are planning to introduce camera phones in Europe in 2003. The photomessaging services, in turn, evolving into multimedia messaging services (MMMS). DoCoMo in Japan already offers interactive videophone services via its FOMA network and JPhone/Vodaphone exchange of brief video messages. The Yankee Group (market consultants) recently forecast that revenues from photomessaging would reach US$44 billion in 2006, constituting a quarter of mobile phone operator revenues. The dominant infrastructure provider for the new class of service is Openwave Systems, which operates 57% of all mobile portals and 71% of active browsers (compared to 25% for Nokia).

Unfortunately, although Europe took the lead in 3G technology, it has fallen behind both the United States and Japan due to regulatory problems. In the 1990s, the European Commission imposed a common standard on 2G cell phones (called GSM), which worked well and became the standard worldwide. The EEC likewise imposed a common standard for 3G, known as W-CDMA, which was supposed to capture 80% of the world market. However, it has proved to be very difficult to meet, whereas the competing standard (CDMA2000) adopted by the United States and Japan has worked much better. In fact, the two standards are competing head-to-head in Japan, where DoCoMo has adopted W-CDMA and its rival, KDDI, has adopted the alternative standard. KDDI's 3G service, launched 6 months later than DoCoMo's, is already much more popular, especially for camera phones. The outcome of the standard wars is unclear at present.

3.2. Internet sales/distribution of multimedia content

For some years, the bandwidth of the Internet has been sufficient for distribution of music (as boosted by the MP3 format), and the recent boom in adoption of ADSL enables transmission of video content as well. These are potentially huge businesses but progress has been slow. One major obstacle is the issue of intellectual property over 'content,' which has exploded into a major controversy pitting Silicon Valley against Hollywood. Apparently, most of the influential Silicon Valley Internet equipment manufacturers, as well as 'dot coms,' were counting on free distribution of 'content' as a marketing device to keep the Internet growing. The 'affaire Napster' has converted a potentially strong ally—the entertainment industry—into a bitter opponent of free on-line content distribution.

The example of broadcast TV was an obvious model of free distribution of material paid for by advertising fees. The three major TV broadcast networks in the United States bought rights to show old Hollywood movies or BBC productions and also financed productions of their own made-for-TV materials, including classics such as Masterpiece

Theater, MASH, Hill Street Blues, West Wing, and so on. Nobody seems to worry about people making their own recordings at home with VCRs for later replay. The next generation of services was supposed to be movies-on-line. Multimedia was the watchword. Advertising on-line would pay the bills. However, digital technology seems to have changed the game. Napster, the on-line club that provided software, allowing registrants to swap music free-of-charge, was the pioneer. In the summer of 2000, Napster had 67 million registered users and the music recording industry felt the pain of lost record sales immediately.

Meanwhile, in the late 1990s, media outlets felt the urge to merge with content providers. The strategy of the day was to create a multimedia conglomerate, including content providers such as movie studios and distribution channels such as TV broadcasting networks, cable systems, and telecoms. Sony was an early entrant, with its purchase of Columbia-Tristar, which now has film, TV production, and music recording subsidiaries. Apart from Sony, six other international conglomerates have emerged, AOL-Time-Warner, Vivendi-Universal, Viacom (Paramount, MTV), Disney (ABC TV), Rupert Murdoch's News Corp (which bought 20th century Fox), and Bertelsmann. Of the six, all have publishing subsidiaries and TV production; all but Vivendi own broadcast TV outlets, all but Bertelsmann have cable TV assets and film studios, and all but Vivendi and Newscorp have radio broadcast outlets. Three (including Disney) have theme parks, and Vivendi as well as AOL has an Internet portal. Only Vivendi, among the six, owns a mobile telecom subsidiary in Italy (likely to be sold to raise cash). General Electric purchased NBC some years ago, but in late 2003 announced that it will agree to a merger with Vivendi-Universal (80% stock GE, 20% Vivendi-Universal). On the other hand, all of the once independent TV networks and most of the movie studios have been swallowed up. Virtually, all of these mergers have proven to be underperformers, necessitating enormous write-offs. Table 1 summarizes how various film, television, and music companies have agglomerated under major media firms.

The view among technology buffs in Silicon Valley seems to be that copyrights are obsolete because 'information wants to be free.' Intel and its counterparts see free distribution of information and entertainment as a spur to sales of their products. However,

Table 1
Media conglomerates ownership of major film, television, and music companies (print media excluded)

	Film	Television	Music
Sony	Columbia-Tristars	Sony Pictures Television	Columbia, Epic
AOL-Time-Warner	New Line	HBO, CNN, TBS	Atlantic Group, Elektra
Vivendi-Universal	Universal	USA Network, SciFi Channel, Canal+	Universal Music Group (many labels)
Viacom	Paramount	CBS, MTV	Famous Music
Disney	Touchstone, Miramax, Dimension	ABC	Hollywood, Mammoth
News Corporation	20th Century Fox	Fox	Festival
Bertelsmann		RTL	BMG

having lost an estimated US$4.2 billion in revenues from piracy in just the year 2000, the music recording industry sued Napster for copyright infringement. Napster reorganized and briefly tried to charge for its services, but most of its customers have gone over to rivals (Morpheus, Kazaa, Grokster, and LimeWire) that still provide free pirated music). The music industry is busy plotting new attacks on these firms, as well as their customers. Piracy of movies has not yet become a major problem, but the threat is obvious and growing. To quote Michael Eisner, Chairman and CEO of Disney, in his testimony before the Senate Commerce Committee in February 2002, "Many people in technology say the killer application is pirated content...It's very hard to negotiate with an industry that thinks its short-term growth is dependent on theft."

Hence, the music recording companies—notwithstanding the fact that many of them belong to multimedia conglomerates—are starting to introduce copy protection technology in CDs and they are actively lobbying the U.S. Congress to force electronics companies to introduce copy-protection circuitry in their products. The electronics industry lobby is resisting. This conflict cannot help but inhibit investment—which hates uncertainty—and slow down the trend toward high speed access to the Web.

3.3. Interactive video-on-demand

Apart from the vast amount of wealth that has recently been destroyed by inappropriate investment, there is simply no compelling evidence of any latent demand for radical new web-based services that can pay their way and generate a hefty profit. The much touted prospect of accessing the Web from a mobile phone in order to meet friends in the shopping mall, locate parking spaces, or trade stocks while driving a car is not going to justify the hundred billion dollars that the telecoms recently overpaid for 3G licenses.

True, a great many people use the Web, but the vast majority merely uses it for free entertainment or for shopping information (as they use the 'Yellow Pages'). Surveys indicate that the overwhelming majority of 'surfers' today are looking for pornography, games, sports news, free music, chat rooms, and opportunities for various sorts of extremists, such as neo-Nazis, to spread their message. With the minor exceptions mentioned already (e-mail, on-line banking, on-line travel reservations, stock trading, etc.), there are few, if any, 'killer apps' in the wings waiting to change our lives. We discuss one of the very few below.

The single most promising application of the Web is still probably interactive video-on-demand, including business uses such as video conferencing. For reasons discussed above, this remains a prospect for the future and its economic impact is difficult to assess. There are two major uncertainties. The first is that nobody yet knows how much the needed infrastructure investments will cost (or how they will be paid for). The second is that nobody knows extent to which this capability will increase productivity.

A possibly important Web spin-off is 'telework.' The term is used confusingly for both working at home and for working at a so-called telecenter and communicating the results via the Net. However, while a telecenter may be located in a rural area to take advantage of labor availability, a telecenter is really just a specialized kind of office. The interesting kind of telework is done from home, thus eliminating the need to commute physically to an office. According to a survey in the United States in the year 2000, there were 16.5 million regularly employed teleworkers (12.2% of the workforce) of which 13.8 million worked at home at least 1 day per month [21]. The U.S. teleworkforce was increasing at 20% per year, and the survey organization estimated that the number of teleworkers would double by 2010. Several European countries have a higher proportion of the workforce in telework. The leader is Finland (16.8% of the workforce), followed by Sweden (15.2%) and the Netherlands (14.5%) [21].

The benefits of home telework to employers include less need for office space and all the costs associated with maintaining offices in a crowded central city. It is also claimed by proponents that the flexibility of telework will pay off in terms of higher employee productivity. The (self-reported) productivity gains by home teleworkers was 15%, which corresponds to an average impact of US$9712 per full-time worker. This implies an aggregate productivity benefit of US$160 billion. A further benefit of telework to employers is the retention of valuable employees who might otherwise change jobs. While the methodology is crude, the survey authors estimated a benefit in terms of reduced turnover amounting a further US$60 billion [21].

The benefits for employees include flexible working time—especially valuable for parents of young children—and of course less commuting travel and associated use of vehicles, roads, fuel, and pollution. U.S. teleworkers travel mainly (88%) by car when they do commute, an average distance of 63 km (63 minutes) round trip [21]. The annual travel savings for a 1-day per week teleworker is 4100 km, with an energy savings of 2500 kW h, which translates into about 1 metric ton of carbon dioxide and 7 kg of other air pollutants not emitted (ibid). Auto travel avoided also translates into reduced congestion for other drivers.

There are disadvantages that must be acknowledged. For employers, the system works best for senior professionals, especially researchers and writers or artists who need no or little supervision and for people whose work can be monitored from a distance, such as telemarketers and people doing data entry or data processing. Telework is much less appropriate for people whose work requires frequent face-to-face interaction with fellow employees or customers, although such people—such as editors—can sometimes arrange to work at home part of the time and at the office part of the time (in fact, this seems to be the case for most teleworkers).

Apart from the practical difficulties slowing implementation, organizations tend to value *esprit de corps* that (in the opinion of older managers, at least) requires various symbolic expressions, ranging from group calisthenics or songs (a Japanese custom) to more or less frequent staff meetings where the ‘boss’ explains goals and strategy and demands ritual responses from suitably enthusiastic subordinates. A number of writers on the subject of telework have insisted on the need to restructure the organization as a precondition for success.

For single employees, the perceived main disadvantage is isolation, although this is only a problem for full time teleworkers. Isolation has a social dimension and a learning dimension. Social isolation is undesirable in itself for a social animal. People need the stimulation of interacting with other people, and the workplace is where this stimulation is most readily available. People deprived of social interaction soon experience psychological problems. The other disadvantage is that the potential for learning from others is restricted, and it is a natural consequence that an employee who chooses to work at home is far less likely to receive promotion or career advancement, especially if the advancement involves supervising others.

Also, for a parent with young children, the home environment may not be conducive to productive intellectual work, especially if the home is not a large one. Children can be noisy and messy and they are likely to demand priority of attention from a parent who is physically present. In fact, in some respects, it could be worse for a child to be ignored by a parent 'working' in the next room than one who is physically somewhere else.

The number of teleworkers can be increased if organizations adopt performance-based evaluation schemes and more flexible work practices. Government actions can also encourage spread of teleworking. For instance, several U.S. states have introduced incentives to employers to permit teleworking, and a bill was introduced to the U.S. Congress to require that 25% of federal government employees be allowed to telework.

Despite the fairly impressive percentages noted above, the penetration of telework in terms of man-days or man-hours is still very small, probably not above 3–4% of the total. By 2010, this may increase to 6–8%, and technological improvements coupled with changes in the organizational environment may encourage more rapid increases thereafter. However, it would be hard to describe this rather glacial process of change as a revolution.

Quality videoconferencing over the Web could, however, trigger a dramatic increase in adoption of telework. The modes of communication currently available are e-mail, file exchange, and voice (phone). This places severe limits on the capacity to do deal with tasks that are not easily subdivided into individual work. This inability of the technology to deal with "group work" explains why current telework practice is mainly limited to sales forces, researchers, and designers. As facial expression and body language are important components of human interaction, the limited modes of communication also contribute to the feelings of isolation experienced by teleworkers. If reasonable quality video and sound are added to the mix, the teleworkability of many jobs increases substantially from both management and worker perspectives.

3.4. Other (non-Web) applications of IT

Another future transportation application of IT is car sharing. Car sharing is already commercially viable in Switzerland and Germany and is now being tested in a number of other countries, especially where population densities are high. Car sharing as presently implemented is a variant of car rental, except that the clients are essentially members of a prescreened group, and there are a number of parking places where vehicles can be picked up and left. Evidently, the more members there are, the more convenient the system will be to users.

Car sharing can much more value to users as it approaches (or surpasses) the convenience of taxicabs. However, this depends upon the existence of a more sophisticated automated dispatch system, which in turn depends upon further IT development, both in hardware and software. Such systems do exist now, within shipping companies like UPS and FedEx. Net-capable mobile phones are likely to be central to an efficient, inexpensive future version of the present, rather primitive, car-sharing systems.

4. Future prospects for ICT

Looking back at the last several decades of innovation and adoption of ICTs, no single enabler stands out as dominant; rather, a combination of factors allowed the sustained rapid pace of progress. As with many other technologies, early research and use by the military acted to incubate some of the key component and networking technologies in their infancy. R&D efforts of large firms, such as Bell Labs and Fairchild, played a key role. The venture capital market contributed to incubating both technological developments and commercial applications. On the demand side, there was an overlapping and expanding series of niches for applications. Also, different technologies such as computing and networking combined smoothly and synergistically. The existing institutional/policy regime in many rich countries proved quite capable of stimulating and adopting new technologies.

What are the future prospects for ICTs as a vehicle for economic growth in the coming decades? Future developments on the technological side clearly affect the answer, though these are difficult to predict. The most optimistic case is that fundamental breakthroughs, such as artificial intelligence or essentially unlimited storage/bandwidth, are waiting in the wings. In this case, one may expect a corresponding set of applications and economic activity to spring up with new technologies. In this scenario, the most appropriate social response is facilitating these breakthroughs. This is traditionally pursued through R&D programs of governments, firms, and universities. We do not here perform an assessment of these nor ask whether they should be changed.

We focus attention on the possibility that ICTs are entering a new phase in which future technological progress is incremental. Many other general-purpose technologies, as the combustion engine and electricity, experienced a heady first few decades, but their respective industries changed as the "low-hanging" technological fruits were picked. This could also be true for ICTs. While progress will continue to be rapid in the near future, it is possible, we believe even probable, that it will slow down as the asymptotes for different components of information technology are approached. In this case, growth must be driven from new applications based on existing technology. If this is the case, what kinds of obstacles exist with regards to adopting these new uses and how might societies respond to deal with them? While there are many future applications to consider, we focus on what seems to us as two potential key ones for the near future: delivery of multimedia content (music, video) via the Web and interactive video-on-demand (especially for telework).

4.1. On-line multimedia distribution and piracy

Piracy remains a major obstacle to the business of delivering multimedia material and software over the web, a problem that will only grow worse as network connections improve to allow download of high-quality video. Entertainment and software firms have been cautious in offering products in forms that could be more easily copied. While their reluctance is understandable, it also exacerbates the problem as consumers are obliged to obtain and keep a physical copy (e.g., compact disc) of the product, an unnecessary inconvenience for a digital good.

How the row over intellectual property rights (IPR) will pan out remains an open question. If antipiracy measures such as encryption and enforcement prove infeasible, one can imagine the end of the entertainment and software industry as we have known it. One possibility is that open-source software would become dominant and entertainment content would be provided by small firms and amateurs. From a traditional economic perspective, this would prove negative: the currently profitable and large-scale entertainment and software industries would become much more diffuse and informal. The key question is what would happen to the consumer expenditures and capital currently associated with the entertainment industry? If replaced by a higher growth industry, the macroeconomic consequences are not necessarily negative. Another possibility (that we think unlikely) is that the entertainment and software industries adopt the economic model of TV and magazines and be funded purely through advertisements.

Technology and legal enforcement are key in preventing piracy. Recently, Disney announced introduction of self-destructing DVDs to be used as a pseudo-rental system. Integration among hardware, software, and service providers is clearly important in developing antipiracy systems. No antipiracy system will be infallible: the point is to make copying difficult enough to discourage most cases. The enforcement of IPR can quickly turn into a legal and social quagmire. One major issue is that prosecuting piracy by individuals requires firms to have information thought by many modern societies to be private. This tension between the right to obtain evidence and the right to privacy is highlighted in the recent series civil suits filed by the Recording Industry Association of America (RIAA) against individuals suspected of downloading MP3 files of songs. RIAA has taken legal action to compel ISPs to provide personal information on customers believed to offer copyrighted material to others for download. The U.S. courts have thus far ruled in favor of the entertainment industry: their interpretation of the Digital Millennium Copyright Act allows copyright holders to request personal information based on “good-faith belief” that bypasses traditional standards for probable cause laid down in the fourth Amendment in the U.S. Bill of Rights. Time will tell if such aggressive enforcement measures will prove effective.

While we cannot hope to suggest a silver bullet solution to piracy, we do wish to call attention to the point that the problem is exacerbated by the antiquated sales/distribution system for digital goods. Customers are not currently getting a product/service in line with available technology. For music, consumers must to go to a store, purchase a CD for US$10–20, which may contain only one to two pieces of music of interest, and then face the problem of organizing and storing large stacks of CDs. In contrast, if songs could be individually downloaded for US$1–2 each, the incentive to obtain it illegally is significantly reduced and consumers may actually spend more money on music, since they will pick songs from many more albums than before. If music companies shifted to an on-line distribution system, offering samples of music and personalized advice, as Amazon.com does for books, it is possible that revenues could increase without the need to take even stricter legal measures to control piracy.

4.2. Ensuring quality of service (QoS) for videoconferencing

How can the Internet be upgraded to support convenient and inexpensive videoconferencing? Performance depends on the combination of hardware, protocols, and organizational structure. The simplest solution would be if improvements in hardware alone would suffice, but this will probably not be so. One reason is that currently implemented networking protocols are not designed for multimedia applications. The dominant Internet protocol, TCP/IP, is unsuitable for real-time applications because it is point to point, so allows no multicasting, but has mechanisms for retransmission of lost packets (unnecessary overhead for multimedia), and has no good mechanism to deal with timing of packets. The other reason hardware upgrade will probably not be enough is that the traffic on the Net continues to increase in tandem with capacity; thus, traffic jams will continue. There are currently no "reserved express lanes" for the Net. Packets are forwarded from node to node without discrimination of where they came from or what they contain. One way to resolve this problem is to reserve capacity particularly for multimedia traffic.

There is a host of initiatives working to develop new networking protocols to guarantee QoS. The recently developed update of Internet Protocol from version 4 to version 6 does not really address the multimedia issue, its main function is to raise the ceiling of available IP addresses. There are several protocols set up to deal with multimedia, such as the resource reservation protocol (RSVP), which contains mechanisms to set up communications "sessions" over a path between machines [22]. However, there has been little initiative to adopt such protocols; they face a "chicken and egg" dilemma of being useless until adopted on a scale much larger than the individual actors concerned. The question of the appropriate business model for the Internet is relevant here. Bandwidth capacity, not actual use, is the main commodity and there is currently no way to meter and thus sell multimedia level services [23].

The Internet development community is, by and large, treating the upgrade as a pure engineering problem. For example, the Internet2 initiative, a U.S. consortium of academia, business, and government devoted to developing and testing the new Internet, does not have groups explicitly devoted to user demand issues and business models. This focus on the technology side is probably due to the past success of spontaneous development of the Net. This has led many to assume that the path for progress is to engineer the "missing link" to the next stage of development and adoption will follow naturally. However, what worked in the past is not guaranteed to do so in the future, and indeed the current slump in the industry shows that the "next thing" did not come through as expected. This could signal that a different approach is needed. Upgrading the Internet to deal with multimedia is already possible with current technology but faces a significant potential energy barrier of economic and organizational hurdles. These are central issues to tackle in upgrading the "first miles."

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