The Learning Curves Underlying Convergence

Brian R. Gaines
Knowledge Science Institute
University of Calgary
Alberta, Canada T2N 1N4
gaines@cpsc.ucalgary.ca, http://ksi.cpsc.ucalgary.ca/KSI

Abstract

The convergence of telecommunications and computing technologies and services into a new medium offering integrated services through digital networks was predicted in the 1970s and is beginning to have major social and commercial impacts in the 1990s. This article analyzes the technological infrastructure of convergence to an information highway, tracing the origins of the concept, the false starts, the growth and origins of the Internet and World Wide Web, convergence as a substitution process, and the learning curves of the technologies involved. A number of substitution processes underlying convergence are identified: electronic for mechanical devices; digital for analog devices; and general-purpose programmable devices for special-purpose devices. A model of convergence in terms of a tiered infrastructure of learning curves in information technology is proposed and used to explain the past and forecast the future.

1 Introduction

Future historians may see the millennium as ushering in an era of *convergence*: of the diversity of human cultures amalgamating into some multinational norm (Featherstone, 1990); of separate national economies coalescing into a global economy (Didsbury, 1985); of education combining with entertainment to become edutainment (Brown, 1995); of telephone and cable television industries merging to provide a unified telecommunications industry (Intven and Ménard, 1992); of papers, magazines and books becoming subsumed into digital information distribution (Lancaster, 1978; Hills, 1980; Greenberger, 1985); of computer and communications technologies combining to become information technology (Arnold and Guy, 1986) capable of providing an *information superhighway* (Baran, 1995; Goldsborough, 1995) supporting all these media, cultural, economic, industrial, and technological phenomena.

The first editorial of the new journal, *Convergence: The Journal of Research into New Media Technologies*, summarized the current situation:

> *"One word describes the current developments in broadcasting, multimedia, programme-making, virtual reality, entertainment and telecommunications: 'convergence'. The term is most frequently used to signal the convergence of once-discrete technologies such as the arcade game and the personal computer. But, of course, the range of developments is much greater and other factors are involved: social, cultural and economic as well as technological. For instance, the traditional boundaries between visual and typographical cultures are being eroded as innovators explore the potential of new media forms. Established industrial and social hierarchies are also being challenged by promises of greater access. And within the communications industry new alliances and strategies are*

emerging, blurring the boundaries of public and privately consumed media." (Knight and Weedon, 1995)

Convergence is a critical factor in the emerging role of telecommunication and in the innovative applications and industries that are arising out of new combinations of technologies. However, the phenomena of convergence have been present and their impact predicted from the earliest days of computing. Why are the *mega-mergers* resulting from the repositioning of long-established media and communications institutions occurring now (Burstein and Kline, 1995; Maney, 1995)? What is it about the current period that has captured the imaginations of governments, companies and individuals in the *information highway* (Baran, 1995; Goldsborough, 1995)? Can the underlying phenomenon be seen as one of *being digital* (Negroponte, 1995)? Is convergence the culmination of a *control revolution* that results from the growing complexity of modern civilization and whose origins predate both telecommunications and computers (Beninger, 1986)?

This article addresses these questions by analyzing the learning curves of the information technologies underlying convergence.

2 The Path to the Information Highway

USA Vice President Gore has been a major proponent of the information highway as an open access network making content available to all at low cost (Gore, 1995). However, the basic concept was in place in 1937, just prior to the advent of computer technology, when Wells was promoting the concept of a "world brain" based on a "permanent world encyclopaedia" as a social good through giving universal access to all of human knowledge. He remarks:

"our contemporary encyclopaedias are still in the coach-and-horses phase of development, rather than in the phase of the automobile and the aeroplane. Encyclopaedic enterprise has not kept pace with material progress. These observers realize that the modern facilities of transport, radio, photographic reproduction and so forth are rendering practicable a much more fully succinct and accessible assembly of facts and ideas than was ever possible before." (Wells, 1938)

Bush, a technical advisor to Roosevelt, published in 1945 an article in *Atlantic Monthly* which highlighted problems in the growth of knowledge, and proposed a technological solution based on his concept of *memex*, a multimedia personal computer:

"Science has provided the swiftest communication between individuals; it has provided a record of ideas and enabled man to manipulate and to make extracts from that record so that knowledge evolves and endures throughout the life of a race rather than that of an individual. There is a growing mountain of research. But there is increased evidence that we are being bogged down today as specialization extends. The investigator is staggered by the findings and conclusions of thousands of other workers—conclusions which he cannot find time to grasp, much less to remember, as they appear. Yet specialization becomes increasingly necessary for progress, and the effort to bridge between disciplines is correspondingly superficial. Professionally, our methods of transmitting and reviewing the results of research are generations old and by now are totally inadequate for their purpose...The difficulty seems to be not so much that we publish unduly in view of the

extent and variety of present-day interests, but rather that publication has been extended far beyond our present ability to make real use of the record." (Bush, 1945)

Wells' world brain concepts have continued for over fifty years to provide an active objective for the information systems community (Goodman, 1987), and Bush's memex concept is often quoted as having been realized fifty years later through the World Wide Web (Berners-Lee, Cailliau, Luotonen, Nielsen and Secret, 1994).

The advent of time-shared *conversational computing* (Gruenberger, 1967; Orr, 1968) in the early 1960s allowed computers to be used to begin to address these early visions in providing a *national information system* (Rubinoff, 1965) or a *computer utility* (Parkhill, 1966). Martin's model of a "wired society" in 1978 comes closest to forecasting many aspects and impacts of the information highway as it is envisioned today:

"In the past, communications networks have been built for telephony, telegraphy, and broadcasting. Now the technology of communications is changing in ways which will have impact on the entire fabric of society in both developed and developing nations. In the USA the technology revolution coincides with a change in the political and legal structure of the telecommunications industry; the combination is explosive. Some countries will take advantage of the new technology; some will not. Some businessmen will make fortunes. Some companies will be bankrupted." (Martin, 1978)

However, attempts to make available the wired society at the time of Martin's seminal work were presented in terms of greatly exaggerated expectations. For example, in 1979 Fedida and Malik, in presenting the UK Viewdata system quote McLuhan's analysis of the impact of a new medium:

"A new medium is never an addition to an old one, nor does it leave the old one in peace. It never ceases to oppress the older media until it finds new shapes and positions for them." (McLuhan, 1964)

and present Viewdata as having the potential to have major social and economic impacts:

"We believe that Viewdata is a major new medium according to the McLuhan definition; one comparable with print, radio, and television, and which could have as significant effects on society and our lives as those did and still do. Like them, it may well lead to major changes in social habits and styles of life, and have long-lasting as well as complex economic effects." (Fedida and Malik, 1979)

Other books of the same period describe the commercial, social and educational potential of Viewdata and interactive Videotex in similar glowing terms (Sigel, 1980; Woolfe, 1980; Chorafas, 1981; Winsbury, 1981), but the potential never materialized although systems such as Minitel in France may be seen as primitive ancestors of the information highway. In the 1970s there were also experiments into wide-ranging applications of other technologies such as two-way cable television (Kaiser, Marko and Witte, 1977), but again these did not develop into commercial technologies having significant social impact. This period also saw the advent of a literature warning about the potential negative social consequences of the transition to wired society (Wicklein, 1979; Mowshowitz, 1985).

It was not until the 1990s and the advent of the World Wide Web that a system with many of the attributes of Well's permanent world encyclopaedia and Bush's memex came into being. The web makes available linked and indexed interactive multimedia documents so that it emulates the printed publication medium but also goes beyond it in offering sound, video and interactivity. Its founders describe it in terms reminiscent of Wells' vision:

> *"The World Wide Web (W3) was developed to be a pool of human knowledge, which would allow collaborators in remote sites to share their ideas and all aspects of a common project" (Berners-Lee et al., 1994)*

However, even an active and interactive encyclopaedia is an inadequate model of existing Internet activities because it neglects the integration of human-to-human discourse. Newsgroups and list servers provide technological support for mutual support communities where questions are answered not be consulting an encyclopaedia but by consulting other people. This corresponds to another prophesy from the early days of timeshared computing:

> *"No company offering time-shared computer services has yet taken advantage of the communion possible between all users of the machine...If fifty percent of the world's population are connected through terminals, then questions from one location may be answered not by access to an internal data-base but by routing them to users elsewhere—who better to answer a question on abstruse Chinese history than an abstruse Chinese historian." (Gaines, 1971)*

Research in computational *artificial intelligence* has not been very successful in developing computer-based *expert systems* (Dreyfus and Dreyfus, 1986). However, news groups and list servers are providing access to human-based 'expert systems' that truly deserve the appellation.

Wells and Bush described the implementation of their visions in terms of the media technologies of their time and did not foresee the advent of television and its impact as a source of knowledge (Bianculli, 1992). They also neglect human discourse as another significant source of knowledge, human society as a *living encyclopaedia*. The envisioned information highway may be seen as an extended "world brain" accessed though the personal computer as a "memex" that integrates all available media and means of discourse to give active presentations of, and interactive access to, all of human knowledge. The current facilities of the Internet and World Wide Web provide a primitive implementation of the highway.

3 The Growth of the Internet and World-Wide Web

The Internet standards document, the *Request for Comments* (RFC) that answers the question "What is the Internet?", offers three different definitions (Krol, 1993):

1. a network of networks based on the TCP/IP protocols,
2. a community of people who use and develop those networks,
3. a collection of resources that can be reached from those networks.

These are complementary perspectives on the net in terms of its technological infrastructure, its communities of users, and their access to resources, respectively. The network perspective emphasizes the telecommunications infrastructure. The community perspective emphasizes the human discourse through that infrastructure. The resource perspective emphasizes the multimedia and computational resources available to the community through the telecommunications infrastructure.

The Internet and the World Wide Web both typify technologies that come into being through serendipity rather than design in that the intentions and aspirations of their originators had little relation to what they have become. As the development of the electronic digital computer can be attributed to needs and funding in the 1940s arising out of the second world war, so can that of the Internet be attributed to needs and funding in the 1960s arising out of the cold war. The Eisenhower administration reacted to the USSR launch of Sputnik, the first artificial earth satellite, in 1957 with the formation of the Advanced Research Projects Agency (ARPA) within the Department of Defense to regain a lead in advanced technology. In 1969 ARPANET (Salus, 1995) was commissioned for research into networking with nodes at UCLA, UCSB and the University of Utah. By 1971 ARPANET had 15 nodes connecting 23 computers and by 1973 international connections to the UK and Norway had been created.

Use of ARPANET by the scientific and engineering communities grew through the 1970s and in 1984 the National Science Foundation in the USA funded a program to create a national academic infrastructure connecting university computers in a network, NSFNET. In 1987 the net had grown to such an extent that NSF subcontracted its operation to Merit and other commercial providers, and in 1993/1994 the network was privatized and its operation taken over by a group of commercial service providers. Email on the Internet commenced in 1972, news distribution in 1979, gopher in 1991, and web browsers with multimedia capabilities in 1993. The growth to over one million nodes, the growing commercial usage of Internet services, and the multimedia capabilities of the web in the 1993/1994 period combined to persuade government and industry that the Internet was a new commercial force comparable to the telephone and television industries, and the concept of an information highway came into widespread use.

In recent years the number of computers connected through the Internet has grown from some 213 in August 1981, to over 16 million in January 1997. Figure 1 shows data plotted from the Internet Domain Surveys undertaken by Network Wizards using a sampling methodology involving checking 1% of machines (NW, 1996). The January 1997 data may be put into perspective by comparing it with the world population of 5.8 billion and noting that it constitutes one machine on the net for every 360 people on the planet. The growth rate has been consistently some 100% a year so that, if this was sustained, within nine years there would be one Internet computer for each person. The demographics are such that Internet access is heavily biased to the developed world, and there are substantial barriers to access elsewhere (Matta and Boutros, 1989), but the size and growth rate of the net have already made it a substantial medium for communication. Universities and other research organizations were the primary source of the initial growth, net access became routinely available to scholars in the late 1980s, and to the general public in North America and parts of Europe in the mid 1990s.

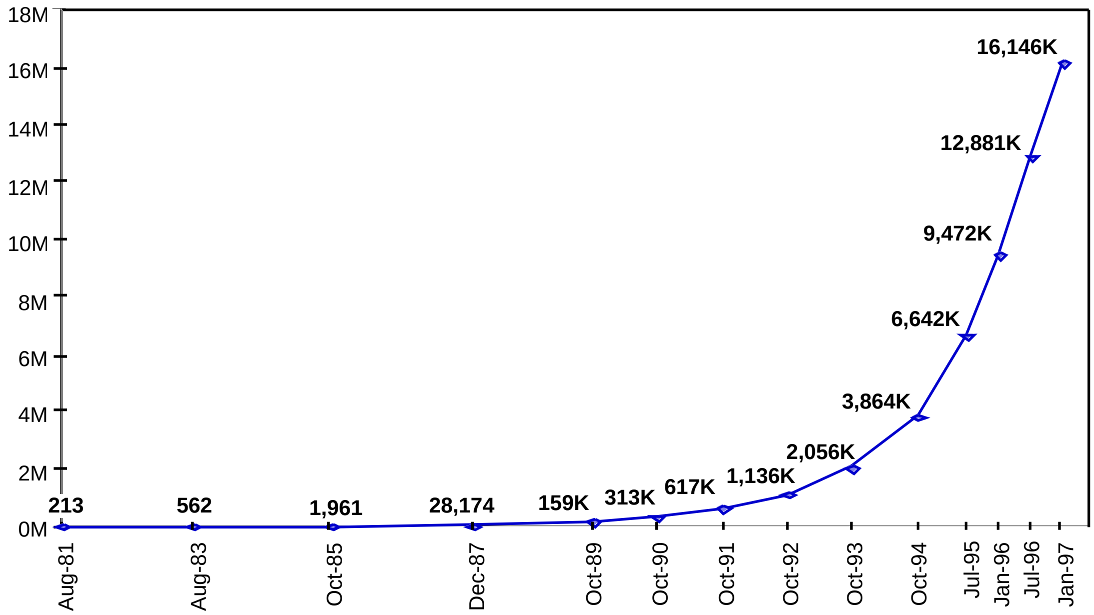


Figure 1 Growth in number of hosts on the Internet

It is difficult to estimate the number of users of the net. Multipliers of 10 to 100 were applicable to the number of machines in the early stages of growth, but no longer apply as the computers on the net becoming increasingly workstations and personal computers rather than timeshared mainframes. The number of email users was estimated at some 27 million in October 1994 (IBC, 1995), most of whom would have at least Internet email gateways so that the multiplier then was about 7 to 1 between users and machines. An October 1995 survey (CommerceNet, 1995) estimated that 17% (37M) people aged 16 or above in North America have access to the Internet indicating that the multiplier is remaining at the same level. Some 11% (24M) had used the Internet in the previous 3 months, and the average usage of these users was over 5 hours a week.

Until 1994 the "acceptable use" policy of NSF restricted the use of the net backbone operated by Merit to academic and industrial research stating "NSFNET Backbone services are provided to support open research plus research arms of for-profit firms when engaged in open scholarly communication and research. Use for other purposes is not acceptable." (Aiken, Braun, Ford and Claffy, 1992). Hence, the substantial usage of the net up to the 2 million host level was for scholarly purposes, and such usage continues to grow as part of the much more general growth of the current information highway.

The primary net protocols supporting such usage have been: FTP for transfer of files; HTTP for access to the World Wide Web; Gopher for searching and reading of text archives; NNTP for news group distribution; SMTP for electronic mail and list servers; Telnet for remote console interaction; IRC for group conferencing through Internet Relay Chat; and DNS for domain name lookup. Figure 2 shows the amount of data transported through each of these protocols along the Merit backbone during 1993 and 1994 (from November 1994 traffic began to migrate to the new NREN architecture and the Merit traffic levels out).

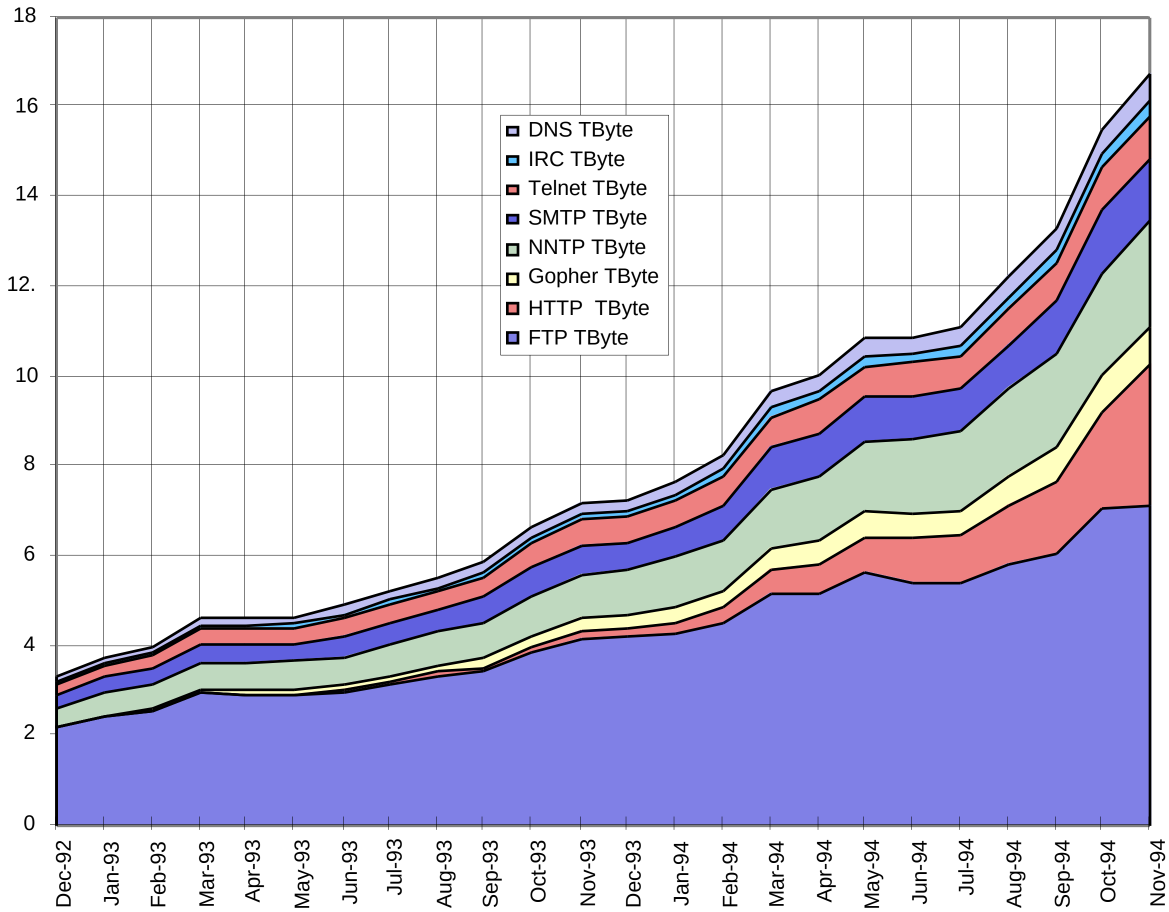


Figure 2 FTP, web, Gopher, News, Mail, Telnet, IRC and DNS data on NSFNET backbone, Terabytes/month

The World Wide Web has become recognized as a potential basis for an information highway. It was conceived by Berners-Lee in March 1989 (CERN, 1994) as a "hypertext project" to organize documents at CERN in an information retrieval system (Berners-Lee and Cailliau, 1990). The design involved: a simple hypertext markup language that authors could enter through a word processor; distributed servers running on machines anywhere on the network; and access through any terminal, even line mode browsers. The web today still conforms to this basic model. A poster and demonstration at the ACM Hypertext conference in December 1991 announced the web to the computing community. However, major usage only began to grow with the February 1993 release of Andreessen's Mosaic for X-Windows (Andreessen, 1993). Whereas the original web proposal specifically states it will not aim to "do research into fancy multimedia facilities such as sound and video" (Berners-Lee and Cailliau, 1990), the HTTP protocol for document transmission was designed to be content neutral and as well-suited to multimedia material as to text. The availability of the rich X-Windows graphic user interface on workstations supporting color graphics and sound led naturally to multimedia support, although the initial objective of meaningful access through any terminal was retained. Most web material can still be browsed effectively through a line mode browser.

In March 1993 the web was still being presented (Berners-Lee, 1993) as primarily a hypermedia retrieval system, but in November that year a development took place that so changed the nature of the web as to constitute a major new invention in its own right. Andreessen (Andreessen, 1993) issued NCSA Mosaic version 2 using Standard Generalized Markup Language (SGML) tags (Goldfarb, 1990) to encode definitions of Motif widgets embedded within a hypermedia document, and allowed the state of those widgets within the client to be transmitted to the server. Suddenly the web protocols transcended their original conception to become the basis of general interactive, distributed, client-server information systems. This change was again serendipitous since the original objective of the design had been to enable the user to specify retrieval information in a dialog box that was embedded in a document rather than in a separate window. However, the solution generalized from an embedded dialog box to any Motif widget including buttons, check boxes and popup menus. The capability of the user to use a web document to communicate with the server is the basis of commercial transaction processing on the web.

The growth rate of overall Internet traffic shown in Figure 2 is some 100% a year. However, web traffic was growing when last accurately measured at some 1,000% a year as shown in Figure 3. The proportion of hosts on the Internet that are web servers has risen from 1 in 13,000 in June 1993 to 1 in 94 in January 1996 and 50% of the ".com" sites at that date were web servers (Gray, 1996). An October 1995 survey (CommerceNet, 1995) estimates that 8% (18M) people aged 16 or above in North America had used World Wide Web in the previous 3 months. The growth of web traffic is widely recognized as a major impediment to its effective application, and a number of commercial services developed to operate through the web have been discontinued because the current infrastructure cannot sustain the traffic (Bayers, 1996).

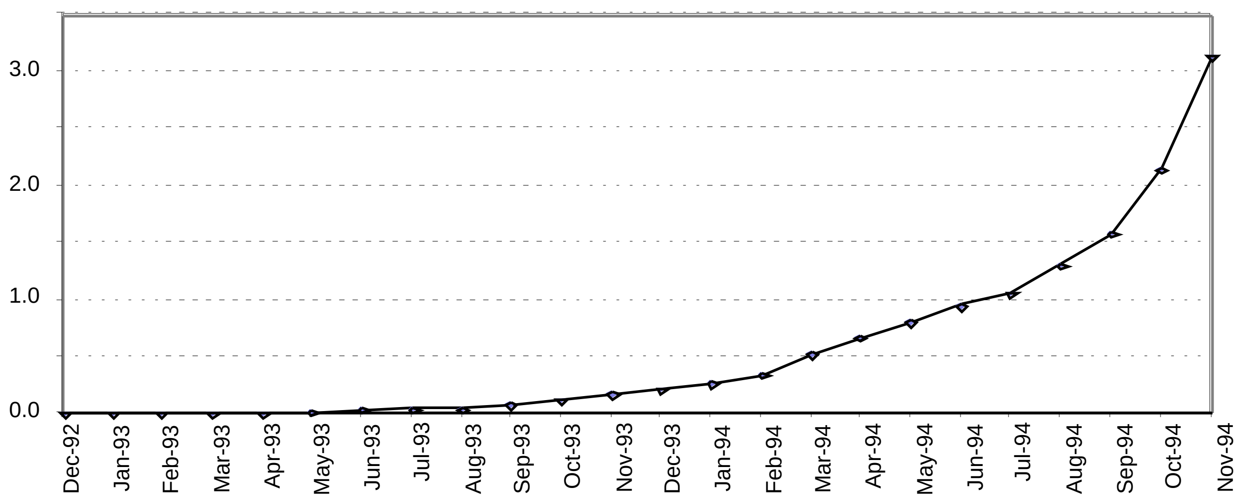


Figure 3 World Wide Web data on NSFNET backbone, Terabytes/month

The corpus of materials on the web is also growing very rapidly. The Lycos search robot (Lycos, 1995) had indexed 10.75M documents in October 1995 which was estimated to be 91% of the total web corpus, and the catalog was growing at 300,000 documents a week. The AltaVista (AltaVista, 1995) search robot in December 1996 had indexed some 31M documents. The growth rate since the web was first established is some 1,000% a year.

The growth of the web relative to all the other services is even more apparent if one plots the proportion of the data accounted for by each service. The Merit statistics can then be used through to their termination in April 1995 on the assumption that the relative traffic on the original backbone is representative of that on the whole Internet after November 1994. Figure 4 shows the proportion of FTP, web, Gopher, News, Mail, Telnet, IRC and DNS data on the NSFNET backbone from December 1992 through April 1995.

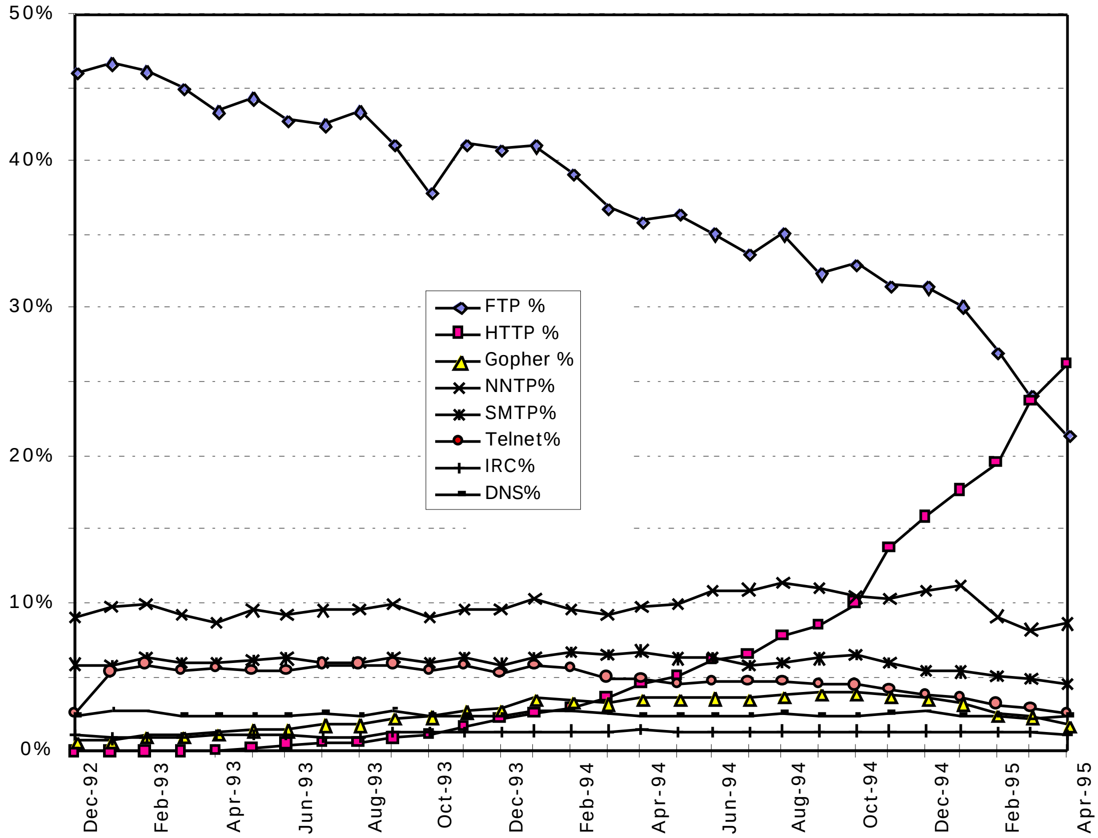


Figure 4 Proportion of FTP, web, Gopher, News, Mail, Telnet, IRC and DNS data on NSFNET backbone

The Internet Relay Chat traffic is lowest because, even though hundreds of conferences are occurring on IRC on a continuous basis, the discourse consists of single lines sent as they are typed in. The Domain Name Service traffic is low but significant—the conversion of names to TCP/IP addresses is a significant overhead in terms of network traffic. Gopher traffic grew until late 1994 but declined relative to web traffic thereafter. Mail traffic constitutes about 6% of net usage and news traffic about 10%. The greater traffic in news than mail does not indicate a greater flow of news items but rather reflects that news items are sent to all major sites whereas mail items are typically sent to one recipient.

It can be seen that the proportion of all services except FTP and HTTP remain relatively constant throughout the period, declining slightly towards the end. However, the proportion attributable to FTP decreases while that due to the web HTTP protocol increases and becomes greater than that through: IRC in October 1993; Gopher in March 1994; mail in July 1994; news in November 1994; and FTP in March 1995. This corresponds to the basic web protocol becoming the primary carrier of net data traffic with a 25% and growing share when last measurable.

It should be noted that one factor in the growth relative to other services is that the web traffic consists of large documents with embedded graphics. These statistics do *not* indicate that the number of web transactions exceeds the number of email transactions. It should also be noted that web browsers typically support many of the protocols shown including FTP, Gopher and News, but their usage of these protocols will show up under those protocols in the statistics. The crossover of web and FTP curves in Figure 4 shows a transition in the *servers* being primarily accessed, from FTP servers to web HTTP servers.

We may see the massive growth of usage of the Internet and World Wide Web as a *natural phenomenon* in which an unidentified social need became satisfied by a series of technical advances none of which were targeted on that need, and where the socio-economic potential became recognized very late in the diffusion of the technology. Visionaries such as Wells saw a societal need for universal access to knowledge. Visionaries such as Martin saw the convergence of computers and telecommunications to provide a wired society as satisfying a wide range of social needs and having massive economic impact. However, experiments with what appeared to be relevant technologies such as two-way cable television, videotex, and so on, never generated the market demand that was expected. The Internet and World Wide Web coming out of academia and largely used for scientific and engineering research until 1993 were not designed to be, or envisioned to be, the universal new medium that they have become.

Experience to date also makes it problematic to characterize the commercial potential of the information highway, its actual social impact, and whether the protocols, technologies, carriers and equipment on which the present implementation is based are an adequate basis for future development. The information systems industry is well-known for over-ambitious expectations of technologies and their impact—a decade ago ‘expert systems’ were going to revolutionize industry and create a new five billion dollar industry—they did neither. The ‘video phone’ and ‘voice typewriter’ have been on the horizon for over thirty years but have found no market and no adequate technology, respectively. It is eminently reasonable to be suspicious of claims that the information highway will be the driver of the next economy, and that the technology to implement it is practically in place.

The remaining sections present the substitution and learning processes of the information technologies underlying the information highway in order to provide a basis for forecasting the time scales of convergence and its socio-economic impact.

4 Convergence as a Technology Substitution Process

Telecommunications and computing technologies have common roots in electronics device technology, exploiting it to provide systems and services in similar ways. The early histories of the typewriter, the phonograph, the telephone, the movie, the computer and radio and television broadcasting share much the same timelines from the late nineteenth through twentieth century. This common background is based on a technological progression from mechanical devices through vacuum tubes to the transistor and the integrated circuit containing a number of transistors (Eames and Eames, 1973; Braun and Macdonald, 1978; Freed, 1995).

The transition from mechanical to electronic motion leads to increased reliability and greatly increased speed of operation. However, all of the applications above have also been involved in three other transitions of equal significance. The first is the transition from analog electronic signals directly representing the continuous variables involved to a digital electronic signal *encoding* those variables. The second is the transition from special-purpose computing architectures where the circuits are designed for a particular task, to general-purpose computing architectures which can be *programmed* for a particular task. The third is the transition from programs as fixed circuits to programs as themselves variable digital data allowing general-purpose machines to be simply *reprogrammed* for different tasks.

This sequence of transitions can be illustrated with respect to the solution of differential equations. In 1931 Bush built a machine for the solution of differential equations using an assembly of mechanical wheel and disk integrators and mechanical torque amplifiers (Bush, 1931). With the advent of vacuum tube amplifiers Bush's design was implemented in two forms, in *analog computers* (Korn and Korn, 1964) where a resistor and capacitor were used together as an integrator, and in *digital differential analyzers* (Mayorov and Chu, 1964; Sizer, 1968) where a digital counter was used as an integrator. Such systems enjoyed commercial success in parallel with the stored-program general-purpose computer until the mid-1970s when technology limitations (the propagation delay across an electrical patch board became greater than that of the transistors being patched) and improved speeds of general-purpose computers made the substitution of general-purpose computers more cost-effective. Similar sequences of substitutions have occurred for watches, calculators, typewriters, and so on—for example, the transition from mechanical typewriters to special-purpose word processors to word processing programs running on general-purpose personal computers..

The transition from analog to digital representation is often taken as that having greatest impact because a digital encoding can emulate any other form of representation. It is this which has enabled computers to be applied beyond the realm of numeric calculation to arbitrary symbolic transformation of any form of representable information, text, images, symbolic logic, and so on. Negroponte (Negroponte, 1995) ascribes to *being digital*, and the universal representational power that this gives, the growing social impact of computers, the information highway, and beyond. However, other transitions, to programmability and programs as data, have been equally significant.

Whereas the transition from mechanical to electronic devices may be seen as a simple substitution of a faster more reliable technology, and that from analog to digital may be seen as a simple substitution of a more precise and reliable technology, the profound impact of transition to programming was serendipitous because the basic reason for doing it was to improve reliability by using fewer electronic components. In the early 1940s the concept emerged that the use of unreliable electronic components could be minimized by using a sequence of instructions to carry out a complex operation:-

> *"simplicity of construction and operation in the electronic computor is achieved by utilizing only the simplest step by step methods" (Mauchly, 1942)*

From its earliest days the stored program digital computer has been characterized by:-

> "*(1) an extensive internal memory;*
> *(2) elementary instructions, few in number, to which the machine will respond;*
> *(3) ability to store instructions as well as numerical quantities in the internal memory, and modify instructions so stored in accordance with other instructions." (Mauchly, 1947)*

Programming gives to computers a fundamental property of being, in some sense, universal machines, since they can be programmed to emulate the calculation performed by any other machine. This means that, in principle, any special-purpose electronic circuit can be substituted by a general-purpose computer together with a program to emulate the operation of the special purpose circuit. For the electronics industry this makes possible economies of scale through very high-volume mass production of computer chips that can be functionally specialized to a wide range of applications as required. For customers it makes it possible to purchase one general-purpose system that can be used for a variety of functions, some of which may be unknown at the time of purchase.

The economic logic for substituting special-purpose systems with general-purpose programmed systems is straightforward. At a given state of the art in circuit technology the counter-balancing considerations are:-

1 Negatively, the programmed system is generally slower (by a factor of between 10 and 100) than the special-purpose system— a potential decrease in performance.
2 Negatively, the programmed system generally uses more storage than the special-purpose system— a potential increase in cost.
3 Positively, the programmed system is more widely applicable and subject to mass production— a potential decrease in cost.
4 Positively, the programmed system is multi-functional— a potential decrease in cost and improvement in capabilities.

Consideration 1 is fundamental. If the application requires processing speeds not feasible with existing computer technology then substitution cannot occur. This is why digital television is a late arrival since the data rates required for television signal processing have been too high for mass market computer products until the mid-1990s. Consideration 2 is also a limitation in television applications such as digital editors where the cost of random-access digital storage is still high compared with analog tape. However, once the technology has improved to the point where 1 and 2 are no longer barriers then the economies in scale of consideration 3 become dominant and, in the case of digital computers, are accelerated by the general-purpose nature of the technology as noted in consideration 4.

Improvements in general-purpose computer technologies have been apparently inexorable since the 1940s. For example, the number of transistors on an integrated circuit chip has increased exponentially with time since the first planar transistor in 1959 (a growth curve commonly termed Moore’s law after a joking prediction made by Gordon Moore, a cofounder of Fairchild Semiconductor, in 1964 when there were only about 60 transistors on a chip). The early growth may be ascribed to a normal technological “learning curve” in which increasing knowledge is gained of the underlying manufacturing processes. However, such learning curves are typically sustained over two orders of magnitude improvement whereas that for integrated circuit technology has been sustained over nine orders of magnitude. Figure 5 shows the number of devices on an integrated circuit chip:

- 20 in 1964 allowed the first flip-flop to be integrated.
- 5,000 in 1972 allowed the first 1 Kilobit memory (Intel 1103) and microcomputer (Intel 4004) to be integrated.
- 500,000 in 1980 allowed major central processing units such as the HP-9000 to be integrated.
- 16,000,000 in 1987 providing 16 Megabit memories.

The current projected limit is some 1,000,000,000 million devices on a chip in the late 1990s when quantum mechanical effects will become a barrier to further packing density on silicon planar chips. However, three-dimensional packing, semiconducting peptides, optical devices, or, most likely, new materials and fabrication processes not yet considered, are expected to extend the growth shown in Figure 5 (Turton, 1995).

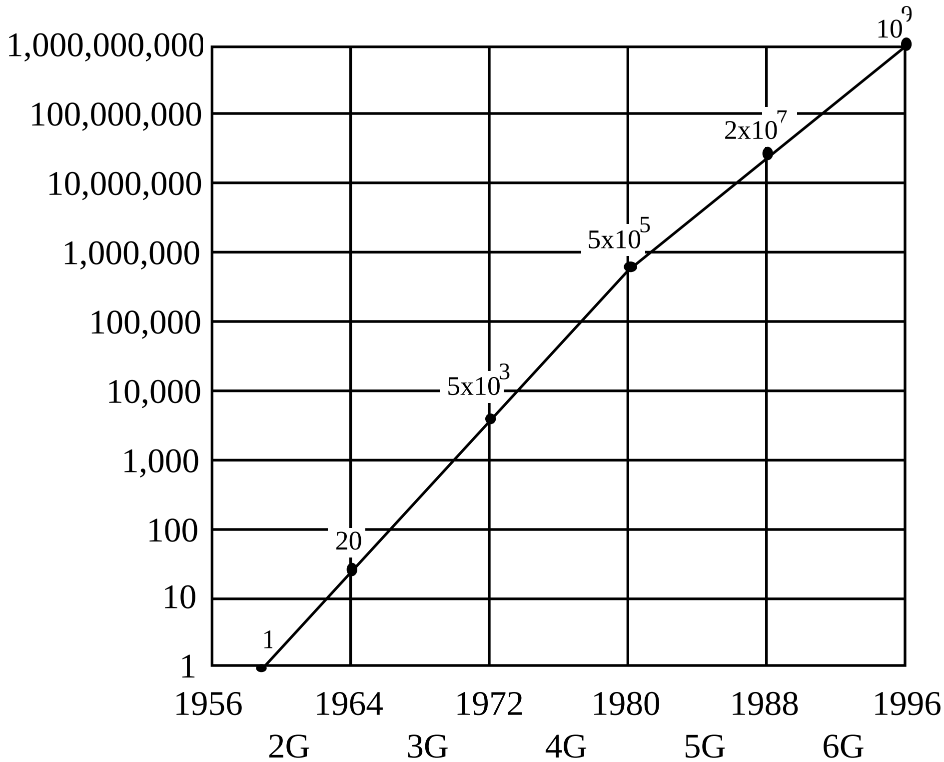


Figure 5 The number of devices on a chip

The diffusion of computer applications may be seen as a process of substitution of electronics for mechanics, followed by a process of substitution of general-purpose programmed electronics for special-purpose electronics. Special-purpose circuits remain essential for applications where the rate of information processing exceeds that possible in a low-cost general-purpose computer, or where the cost of transforming the signals involved to and from digital form exceeds the cost savings of using a general-purpose computer. However, the information processing performance of computers has improved, in major part as a side-effect of increasing miniaturization—clock speeds of computers have increased from a kilohertz in the 1950s to approaching a gigaherz in the late 1990s. Once the necessary performance can be achieved, then the economies of scale of mass production of general purpose computer chips, and the product advantages of multi-purpose programmable systems make substitution inevitable. Convergence may be seen as a phenomenon of such substitution taking place in the consumer telecommunication markets with telephones, radio, television, VCR's, cameras, and so on, becoming an integral function of the multi-media personal computer.

This analysis may suggest that convergence is a simple process of technological substitution. However, analysis of convergence as substitution must also take into account two “emergent phenomena”:-

- Computer technology is itself being changed profoundly by the new interfaces required by telecommunications applications. The transition from keyboard/printer interaction to the new forms of voice and video input and output appropriate to telecommunications applications changes the nature of computing technology.

- The integration of so many human communications media into a single coherent system in itself creates a new technology with opportunities for the development of new products and services.

The next section presents a model of how such new phenomena arise through the learning infrastructure of information technology.

5 The Learning Infrastructure of Information Technology

The number of transistors on a chip has seen a 1,000,000,000 increase in less than 40 years, whereas other high-technology industries have typically seen less than 100 performance increase in 100 years. This improvement depends on the capacity of silicon to support minute semiconductor logic circuits, but this capacity could not have been fully exploited over 9 orders of magnitude performance improvement without the use of the computer to support the design and fabrication of such circuits. This is one example of a positive feedback loop within the evolution of computers, that the computer industry has achieved a learning curve that is unique in its sustained exponential growth because each advance in computer technology has been able to support further advances in computer technology. Such positive feedback is known to give rise to emergent phenomena in biology (Ulanowicz, 1991) whereby systems exhibit major new phenomena in their behavior. The history of computing shows the emergence of major new industries concerned with activities that depend upon, and support, the basic circuit development but which are qualitatively different in their conceptual frameworks and applications impacts from that development; for example, programming has led to a software industry, human-computer interaction has led to an interactive applications industry, document representation has led to a desktop publishing industry, and so on.

Each of these emergent areas of computing has had its own learning curve (Linstone and Sahal, 1976), and the growth of information systems technology overall may be seen as the cumulative impact of a tiered succession of learning curves, each triggered by advances at lower levels and each supporting further advances at lower levels and the eventual triggering of new advances at higher levels (Gaines, 1991). It has also been noted in many disciplines that the qualitative phenomena during the growth of the learning curve vary from stage to stage (Crane, 1972; De Mey, 1982; Gaines and Shaw, 1986). The era before the learning curve takes off, when too little is known for planned progress, is that of the inventor having very little chance of success but continuing a search based on intuition and faith. Sooner or later some inventor makes a *breakthrough* and very rapidly his or her work is *replicated* at research institutions world-wide. The experience gained in this way leads to *empirical* design rules with very little foundation except previous successes and failures. However, as enough empirical experience is gained it becomes possible to inductively model the basis of success and failure and develop *theories*. This transition from empiricism to theory corresponds to the maximum slope of the logistic learning curve. The theoretical models make it possible to *automate* the scientific data gathering and analysis and associated manufacturing processes. Once automaton has been put in place effort can focus on cost reduction and quality improvements in what has become a *mature* technology.

Figure 6 shows this BRETAM sequence plotted along the underlying logistic learning curve. As noted previously, in most industries the learning curve takes some tens of years and the major effects are substitution ones. Substitution occurs an old technology has reached maturity and a new, more effective technology, reaches a point on its learning curve where it economically replaces the old one. There is also a secondary phenomenon that when a technology reaches a point on the learning curve where it is cost-effective and reliable new technologies develop dependent on the first one. For example, the electric lighting and appliance industries developed as the power generation industry came to offer cost-effective and reliable electricity supply.

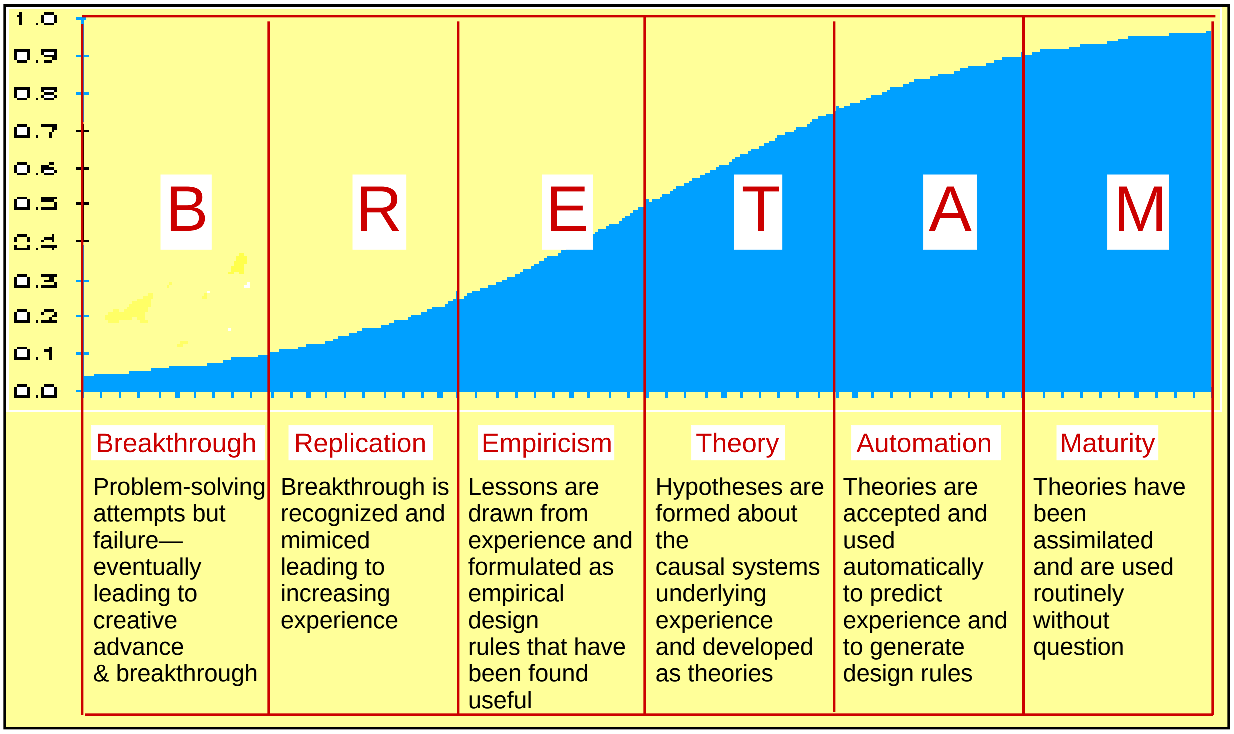


Figure 6 Qualitative changes along a technological learning curve

The dependent technologies themselves develop along their own learning curves and may come to support their own dependents. Figure 7 shows a tiered succession of learning curves for dependent technologies in which a breakthrough in one technology is triggered by a supporting technology as it moves from its research to its empirical stage. Also shown are trajectories shown the eras of *invention*, *research*, *product innovation*, *long-life product lines*, *low-cost products*, and *throw-away products*. One phenomenon not shown on this diagram is that the new industries can sometimes themselves be supportive of further development in the industries on which they depend. Thus, in the later stages of the development of an industrial sector there will be a tiered structure of interdependent industries at different stages along their learning curves.

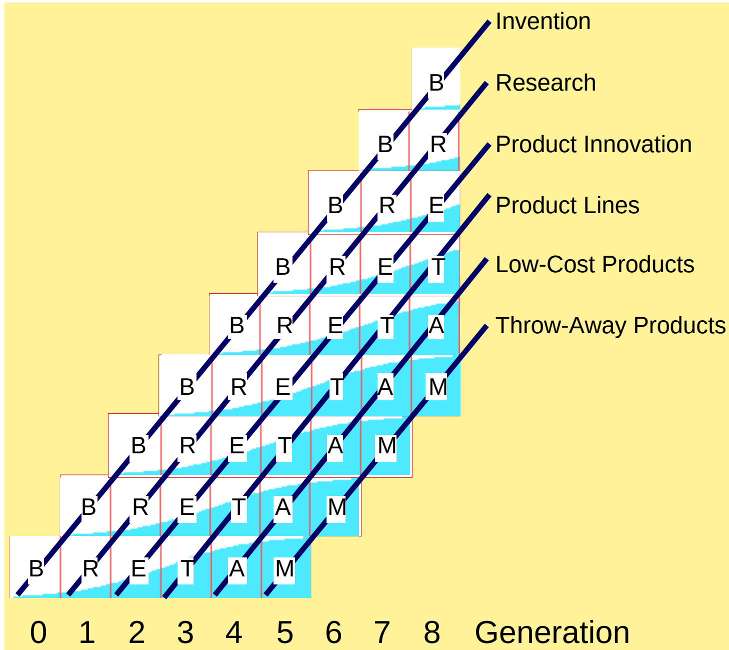
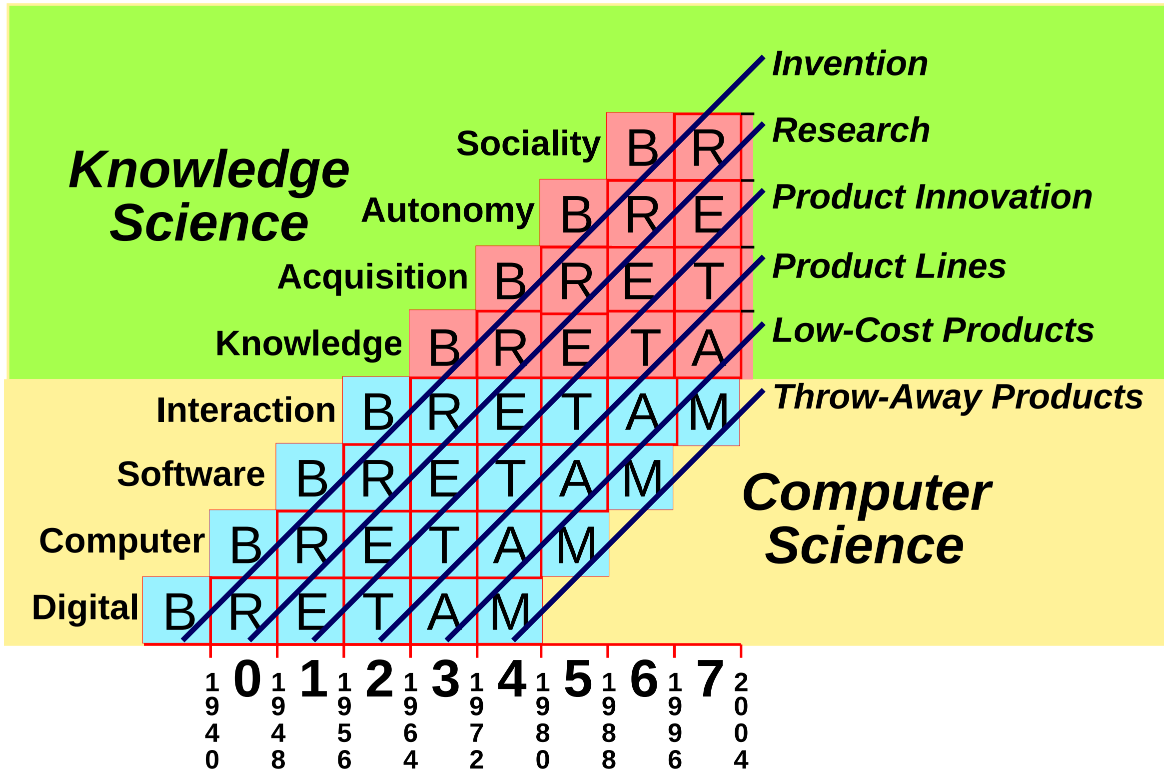


Figure 7 The tiered infrastructure of learning curves in the growth of a technology

Few industry sectors develop the elaborate infrastructure shown in Figure 7. However, the fast, sustained, learning curve for electronic devices, and the scope for positive feedback in the development of information technologies, together result in a tiered infrastructure for information technologies which is extremely well-defined and fundamental to their nature. This is shown in Figure 8.



- Breakthrough: creative advance made
- Replication period: experience gained by mimicing breakthrough
- Empirical period: design rules formulated from experience
- Theoretical period: underlying theories formulated and tested
- Automation period: theories predict experience & generate rules
- Maturity: theories become assimilated and used routinely

Figure 8 The infrastructure of information technology

The breakthrough in *digital electronics* leading to the zeroth generation is placed at 1940 about the time of the Atanasoff and Berry experiments with tube-based digital calculations. Experience was gained with COLOSSUS and ENIAC during the next eight years leading to a spate of empirical designs in the 1956-63 period, theoretical foundations for logic minimization and automata theory, automation with computer-aided design tools, and culminating into maturity with the 4004/8008 microprocessor chips in 1971/1972. Automation has reached the extreme level where silicon compilers allow a designer to implement ideas directly in devices with little further human intervention (Fields, 1983).

The first breakthrough generating a computing infrastructure was the introduction of the *general-purpose stored program computer architecture* which led to the transition from the ENIAC to the EDVAC designs. The key concepts were discussed by Mauchly in his paper of 1947 and the first implementations were the BINAC and EDSAC machines in 1949. Mauchly (Mauchly, 1947) recognized the significance of stored programs in enabling the machine instruction set to be extended, noting that subroutines create “a new set of operations which might be said to form a calculus of instructions.” This was the key conceptual breakthrough in computer architecture, that the limited functionality provided directly by the hardware could be increased by stored programs called as subroutines or procedures, and that the hardware and these routines together may be regarded as a new virtual machine. This is the foundation of the development of a variety of forms of virtual machine architectures (Weegenaar, 1978) that separates out computing science as a distinct discipline from other areas of electronic applications. The use of subroutines to give access to arithmetic and operating system capabilities was followed by the development of machine architectures dependent on traps to procedures emulating missing hardware and led to theories such as those of semaphores, Petrinets and the logic of databases underlying diverse architectural concepts.

The next level of breakthrough was in *software* to bridge the gap between machine and task through the development of problem-orientated languages. Their foundations in the first generation were subroutine libraries providing virtual machines closer to the problem requirements, notably floating point arithmetic and mathematical functions. Work on the design of FORTRAN in 1954 and its issue in 1957 marks the beginning of the second generation era with languages targeted to specific problem areas of business data processing, text processing, database access, machine tool control, and so on. A 1968 paper on the coming fourth generation notes that “programming today has no theoretical basis” and calls for a scientific basis in the next generation (Walter, Bohl and Walter, 1968). Sure enough the theory linking languages to the underlying virtual machines developed during the fourth generation era, for example, that of abstract data types and initial algebras (Goguen, Thatcher and Wagner, 1978). In the fifth generation era the application of experience, design rules and theory to the automation of software production became the top priority (Balzer, Cheatham and Green, 1983).

The next level of breakthrough was in continuous *interaction* becoming a significant possibility as the mean time between failures of computers began to be hours rather than minutes in the early 1960s. The move from batch-processing to direct human-computer interaction was made in 1963/1964 with the implementation of MIT MAC, RAND JOSS and Dartmouth BASIC systems (Gaines and Shaw, 1983). The study of such systems led to design rules for human-computer interaction in the 1970s (Hansen, 1971) and theoretical foundations have started to emerge in the 1980s (Gaines, 1984). The improvement of human-computer interaction is a major stated priority in the Japanese fifth generation development program (Karatsu, 1982). Other forms of interaction also became feasible as a result of improved reliability such as direct digital control, and various forms of digital communications systems. The ISO open systems interconnection (OSI) layered protocol is an example of a theoretical model developed to unify and automate digital communications (Day and Zimmerman, 1983).

The next level of breakthrough was one of *knowledge-processing*, the human capability to store information through its inter-relations and make inferences about its consequences. The breakthrough in knowledge-based systems dates from the development of DENDRAL (Buchanan, Duffield and Robertson, 1971) for inferring chemical structures from mass-spectrometry data and MYCIN (Shortliffe, 1976) for the diagnosis of microbial infections in the early 1970s. It led to a spate of expert system development in the fourth generation era of the 1970s (Gevarter, 1983), and pragmatic design rules for knowledge engineering in the fifth generation era (Hayes-Roth, 1984). The utilization of their massive VLSI production capability (Galinski, 1983) for the support of knowledge-based systems through PROLOG machines (Clark and Tarnlund, 1982) has been the other major priority in the Japanese fifth generation development program (Moto-oka, 1982).

Defining the upper levels of the infrastructure becomes more and more speculative as we move into the immediate past of our own era and look for evidence of learning curves that are at their early stages. It is reasonable to suppose that the level above the representation and processing of knowledge in the computer is that of its *acquisition*, breakthroughs in machine learning and inductive systems. Two breakthroughs in this area have been Lenat's AM learning mathematics by discovery (Davis and Lenat, 1982) and Michalski's inductive inference of expert rules for plant disease diagnosis (Michalski and Chilausky, 1980). In the fifth generation era machine learning became a highly active research area in its replication phase (Michalski and Carbonell, 1983; Michalski, Carbonell and Mitchell, 1986).

One may speculate that the growth of robotics will provide the next breakthroughs in which goal-directed, mobile computational systems will act *autonomously* to achieve their objectives. It is possible to see the nascent concepts for this breakthrough in the adoption of the goal-directed programming paradigms of logic programming languages such as PROLOG. When, in a robot, a goal specification is expanded by such a programming system into a sequence of actions upon the world dependent on conditions being satisfied in that world, then the behavior of such a system will deviate sufficiently from its top-level specification, yet be so clearly goal-directed, as to appear autonomous. One may speculate further that interaction between these systems will become increasingly important in enabling them to cooperate to achieve goals and that the seventh generation era commencing in 1996 will be one of *socially organized systems*.

However, it is also reasonable to suppose in the light of past forecasting failures in computing technology that these speculations may be in error. The projected breakthroughs may not occur or may occur much earlier. The recognized breakthroughs may be in completely different areas. The Japanese "Sixth Generation" research program proposals emphasize emulation of creativity and intuition and the development of inter-disciplinary *knowledge sciences* (STA, 1985; Gaines, 1986), and there is a conceptual separation between the lower four learning curves in Figure 8 which may be seen as those underlying "computer science" and the upper four curves which may be seen as a basis for "knowledge science." It is even possible that building an adequate forecasting model based on the premises of this section may undermine the very processes that we model. If we come to understand the dynamics of our progress into the future then we may be able to modify the underlying process—to make the next steps more rapidly when the territory is better mapped.

6 Convergence and the Learning Infrastructure of Information Technology

The BRETAM tiered learning curves infrastructure of Figure 8 brings together the various phenomena of convergence in an integrated model which has the potential both to explain the past and forecast the future.

Well's vision of a *world brain* immediately predates the initial breakthrough that triggered the learning curves of information technology. The invention of the digital computer was triggered by the type of problem in the processes of civilization that he hoped to prevent. He foresaw a technological solution but not the technologies that actually provided it. Bush, as inventor of the differential analyzer and with his war time knowledge of computing as Roosevelt's advisor, described Memex in the context of the relevant technology. However, it was not until the 1960s that the mean time between failures of computers became long enough to make interactive use routinely possible, and it was not until the 1970s that the costs became low enough for "personal computers" to be developed and these did not come into widespread use until the 1980s.

The learning curves in Figure 8 on which information highway technology depends are the lower four supporting *computer science*: digital electronics; computer architecture; software; and interaction. The *product innovation* trajectory passes through the last of these in the fourth generation, 1972-1980, and led to the premature development of Viewdata and Videotex products and Martin's detailed forecasts of the potential for a wired society. The *low-cost products* trajectory passes through the last of these in the sixth generation, 1988-1996, and led to the explosive growth of the World Wide Web. In the current seventh generation this trajectory passes through the *knowledge* level in Figure 8 corresponding to the growth of knowledge available through the web and the current focus on indexing and retrieval technologies and the transition to electronic publishing of journals and newspapers. Figure 9 summarizes the technologies underlying the World Wide Web.

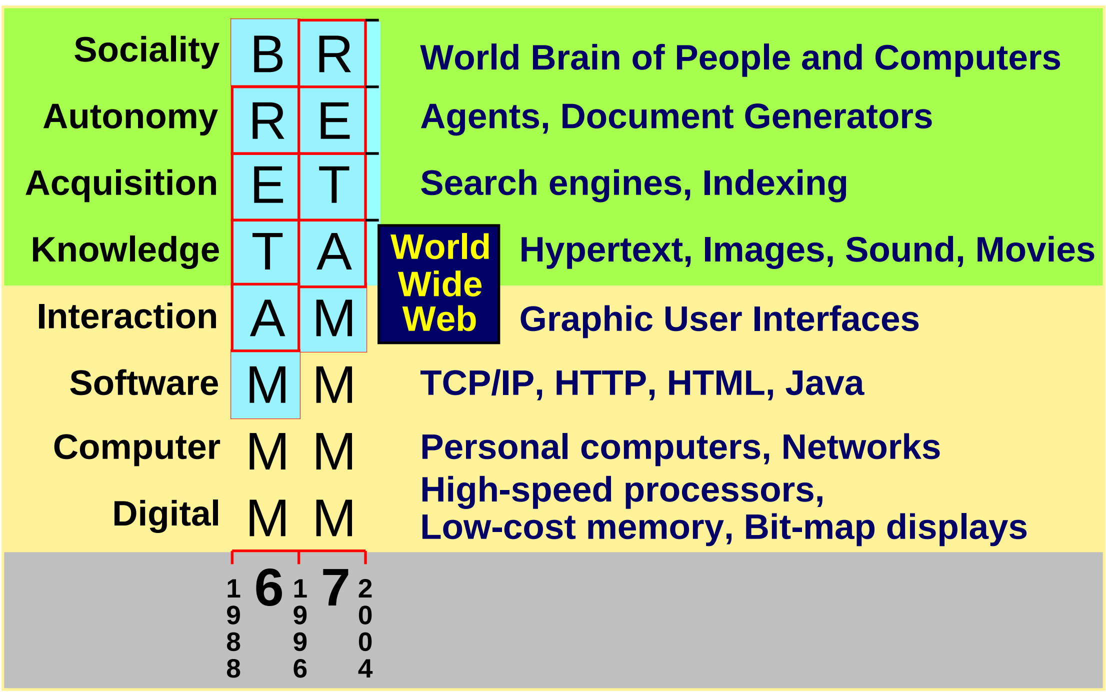


Figure 9 Technologies underlying the World Wide Web

The mass market potential for wired society technology at costs comparable to other mass media such as the telephone and television is dependent on the cost reductions possible in the post-maturity phase of the learning curves leading to *throw-away products*. This trajectory passes through the interaction learning curve in the current seventh generation era, 1996-2004, and it is this that has made the information highway economically feasible. It is not until the eighth generation era, 2004-2012, that this trajectory passes through the *knowledge* level and we can expect the universal access to knowledge at low-cost that corresponds to Wells' *world brain*.

In projecting the BRETAM model into the future, one critical analysis is whether the learning curves in the lower level technologies can be sustained. The learning curve for the number of devices on a chip shown in Figure 5 has been maintained as a continuing exponential growth even though our knowledge of the underlying silicon device technology is mature because it has been possible to continue to miniaturize the individual transistors using increasingly refined and automated production processes. Such miniaturization is now coming up against fundamental physical limits and against commercial considerations that there are declining economies of scale in fabricating devices with greater numbers of transistors (Ross, 1995). A Forbes survey of eleven leading industry figures in 1996 gave predictions that Moore's law would fail by the year 2005 (Forbes, 1996). However, current digital circuit technology seems sufficient to support the information highway through one or two generations, particularly given the simplicity of the computer architectures currently in use. The learning curve for the single processor general-purpose Von Neumann computer architecture is mature, but much more processing could be achieved with the same number of devices on a chip by adopting multi-processor architectures. For example, in applications such as computer vision where the human eye comprises some 100M processing elements operating in parallel, Mead (Mead, 1989) has suggested architectures for image processing chips with similar numbers of computer processing elements operating in parallel on a single chip.

The weak link in the chain of technologies underpinning the information highway is that at the third level. The theoretical foundations for software engineering developed in the 1970s have resulted in powerful tools in the 1990s such as C++ (Stroustrup, 1994) and its Standard Template Library (Musser and Saini, 1996) supporting generic programming. These have been supported by commercial compilers that provide excellent tools for code visualization, design and debugging. However, major problems continue in software development, costs, budgets and quality assurance. The reason is that expectations of computers have risen so rapidly that the learning curve of software development has not kept pace with that of aspirations for information systems. Another is that the intrinsic human element, of expressing a requirement to be satisfied by a computer system, is not subject to theoretical modeling and automation.

If one returns to the software engineering conferences of the 1960s the issues expressed and the solutions proposed look timely and appropriate today. In 1968 Naur suggested an approach to software design based on a tree of decisions about components:

> *"In the design of automobiles, the knowledge that you can design the motor more or less independently of the wheels is an important insight, an important part of an automobile designer's trade. In our field, if there are a few specific things to be produced, such as compilers, assemblers, monitors, and a few more, then it would be very important to decide what are their parts and what is the proper sequence of deciding on their parts. That is really the essential thing, what should you decide first. The approach suggested by Christopher Alexander in his book: 'Notes on the Synthesis of Form', is to make a tree structure of the decisions, so that you start by considering together those decisions that hang most closely together, and develop components that are subsystems of your final design. Then you move up one step and combine them into larger units, always based on insight, of some kind, as to which design decisions are related to one another and which ones are not strongly related. I would consider this a very promising approach." (Naur, 1969)*

In 1969 Dijkstra posed the problems of software engineering as:

> *"What is actually happening, I am afraid, is that we all tell each other and ourselves that software engineering techniques should be improved considerably, because there is a*

crisis. But there are a few boundary conditions which apparently have to be satisfied. I will list them for you:
1 We may not change our thinking habits.
2 We may not change our programming tools.
3 We may not change our hardware.
4 We may not change our tasks.
5 We may not change the organizational set-up in which the work has to be done.
Now under these five immutable boundary conditions, we have to try to improve matters. This is utterly ridiculous." (Dijkstra, 1970)

Some twenty five years later in the 1990s, Alexander's *design patterns* are beginning to be applied to object-oriented software development (Gamma, Helm, Johnson and Vlissides, 1995) and the Department of Defense Software Engineering Institute (SEI) at Carnegie-Mellon University has addressed some of the conceptual and organizational problems Dijkstra describes through its *capability maturity model* (Humphrey, 1989). However, software development capabilities are lagging expectations and represent the major risk factor in predictions about the future of information technology.

The analysis of product opportunities arising from the existence of the information highway involves the upper learning curves of the BRETAM model—knowledge representation and acquisition, autonomy and sociality. Knowledge representation and processing encompasses all the media that can be passed across the web, not just the symbolic logic considered in artificial intelligence studies but also typographic text, pictures, sounds, movies, and the massive diversity of representations of specific material to be communicated. The significance of discourse in the human communities collaborating through the Internet has been underestimated in the stress on 'artificial' intelligence in computer research. Knowledge need not be machine-interpretable to be useful, and it can often be machine-processed, indexed and enhanced without a depth of interpretation one might associate with artificial intelligence. The World Wide Web is already a "pool of human knowledge" (Berners-Lee et al., 1994) and the extension of that pool to encompass more and more knowledge is the most significant way of adding value to the web. The problems with this are socio-economic in that much represented knowledge is owned by copyright holders who seek some financial reward before they will offer it to others. Technologically it is important to develop ways of charging for access to knowledge at a low enough rate to encourage widespread use at a high enough volume to compensate the knowledge provider. The knowledge-level problem for the information highway is not so much representation and processing but rather effective trading.

The growth of available material on the web is already causing problems of information overload. The 30M documents currently available are not readily searched by an individual and the web was not designed for central indexing. The acquisition learning curve is at a level where it has been possible to solve the problem using software programs, spiders, that crawl the web gathering information and indexing it by content so that documents can be retrieved through a key word search. In 1995 indexing spiders solved the problem of acquiring a dynamic model of the rapidly expanding web. However, the simple key word searches offered for retrieval have already become inadequate in that they usually result in a large corpus of documents most of which are irrelevant to the searcher. Information retrieval techniques have to be improved, probably to allow queries to be expressed in natural language and refined through a natural language dialog. Ultimately a user should not be able to determine whether a query is being answered by another person or by a computer program. On the web as a pool of human knowledge the way in which the knowledge is generated will become irrelevant.

The autonomy learning curve in Figure 8 is at an early stage. There is much research on *intelligent agents* that can be requested to perform tasks and do so on a fairly autonomous basis, and there is the beginning of product innovation with systems such as General Magic's Magic Cap (Knaster, 1994). However, the primary growth potential for the information highway over the next decade is through representation of massive amounts of knowledge and the development of more effective tools for its acquisition both originally and selectively through the web.

7 Conclusions

The convergence of telecommunications and computing technologies and services into a new medium offering integrated services through digital networks was predicted in the 1970s and is beginning to have major social and commercial impacts in the 1990s. This article has analyzed the technological infrastructure of convergence to an information highway, tracing the origins of the concept, the false starts, the growth and origins of the Internet and World Wide Web, convergence as a substitution process, and the learning curves of the technologies involved. A number of substitution processes underlying convergence have been identified: electronic for mechanical devices; digital for analog devices; and general-purpose programmable devices for special-purpose devices. A model of convergence in terms of a tiered infrastructure of learning curves in information technology has been proposed and used to explain the past and forecast the future.

Information technology is characterized by high rates of growth in performance parameters sustained over long periods. The number of devices on a chip is growing at 60% a year and has grown by 9 orders of magnitude in 37 years. Clock speeds of computers have grown by some 6 orders of magnitude over the same period. The number of computers connected through the Internet is growing at 100% a year and has grown by 7 orders of magnitude in 27 years. The volume of traffic on the Internet is growing at over 100% a year, and that component attributable to the World Wide Web was growing at 1,000% a year when last accurately measurable in 1994.

It is suggested that these high sustained growth rates have been possible because computer technologies are mutually supportive providing positive feedback such that advances in existing technologies trigger breakthroughs in new technologies which themselves help to sustain the advance of the existing technologies. Much of the socio-economic impact of information technology has arisen not through research, development and product planning targeted on that impact but rather from the serendipitous application of technologies developed for very specific technical purposes to much more widely based social needs. Programmability was itself invented as a technique to overcome technical problems of hardware reliability. Email and news were invented to coordinate computer research. The World Wide Web was targeted on the documentary needs of a specific scientific community.

Serendipitous developments are to be expected when a technology that is essential to the operation of complex modern societies undergoes massive and sustained growth. Government funding of computing research for purposes of defense and administration provided the initial impetus for computer development, and commercial applications to accounting and business administration have supported the growth of an industry. However, the major innovations ascribed to convergence have arisen primarily from a technological push targeted on the internal needs of research communities, rather than on those of major markets. Governments and the computer and communications industries have only come to recognize the socio-economic importance of convergence as consumers have come to make technology substitutions that cross traditional market sectors; for example, the substitution of electronic mail for postal and telephone services, the substitution of electronic journals and magazines for paper-based equivalents, the substitution of digital telephony through the Internet for conventional telephone services.

The main problem in forecasting the future of convergence and information technology in general is that the learning curves of most of the major performance parameters still appear to be in their initial exponential growth phase. This makes it impossible to predict the later parts of the curves from past data. For some parameters there are basic physical limitations to existing technologies that indicate that current growth rates cannot be sustained beyond some 10 years. However, there are possibilities for new materials and new architectures that could maintain effective growth rates for the foreseeable future.

Tracking the individual learning curves of the major technologies that comprise the infrastructure of information technology provides a more detailed account of the present and future state-of-the art of the technologies underlying convergence. The base technologies of digital electronics, general-purpose computer architectures, software and interaction are mature and provide solid foundations for *computer science*. The upper technologies of knowledge representation and acquisition, autonomy and sociality, support product innovation and provide the beginnings of foundations for *knowledge science*. Well’s dream of a world brain making available all of human knowledge is well on its way to realization and it is in the representation, acquisition, and access and effective application of that knowledge that the commercial potential and socio-economic impact of convergence lies.

Acknowledgments

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