Is the Internet a U.S. Invention? – An Economic and Technological History of Computer Networking

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1. Introduction

The Internet is the world's largest computer network—a steadily growing collection of more than 70 million computers that communicate with one another using a shared set of standards and protocols. Together with the World Wide Web, a complementary software innovation that dramatically increased the accessibility of the network for many users, the Internet helped stimulate a communications revolution that has changed the way that individuals and institutions use computers in a wide variety of activities. The Internet and World Wide Web jointly comprise a "general purpose technology," an invention with the potential to transform the dissemination of information in a global economy that relies ever more heavily on knowledge.[1]

The Internet was created through a series of inventions and innovations in fields ranging from computing and communications to utility regulation, business and finance. Although its development and deployment occurred largely within the United States, the inventions embodied in the Internet originated in a more diverse set of industrial economies. Nonetheless, the United States consistently was among the first nations to improve and transform these inventions into components of a national and global network or networks, and was an early adopter of new applications. This paper addresses the question of why other nations, including several that made important inventive contributions to the Internet, failed to play a larger role in its development, especially in the creation of new business organizations, governance institutions, and applications. Our explanation relies on a comparison of the US "national innovation system" with those of other developed countries.

The origins and evolution of the Internet highlight several nationally unique characteristics of the U.S. innovation system that have endured in the face of economic globalization and domestic institutional change. At the same time, several characteristics of the U.S. economy that contributed to its early 20th-century technological development,

[1] Lipsey, Bekar and Carlaw (1998) use four criteria to define a technology as a GPT—the ability to make dramatic technical improvements, the existence of a variety of technological complementarities, and the breadth and scope of applications for the technology. Although they argue that Information Technology represents a single GPT, we feel that these criteria apply equally well to the Internet.

characteristics portrayed by some scholars as no longer consequential for U.S. economic competitiveness, appear to have facilitated the development and diffusion of the Internet within the United States.

To understand the role of the various components of the U.S. national innovation system in the development of the Internet, we examine three distinct phases in this history. In the early stages of technology development, federal R&D funding with roots in cold-war defense spending played a key role in the creation of an "infrastructure" of trained researchers and related institutions, including universities. Although several countries participated in the basic research efforts that supplied critical communications technologies, the scale of this research (both in dollars and geographic scope), the development of close relationships among universities, defense researchers and small firms, and the creation of complementarities between research in computer networking and the emergence of large domestic hardware and software industries occurred most extensively in the United States.

As the technology underlying the Internet matured and the diffusion of the network entered its second phase, a different set of U.S. institutions became influential. Widespread adoption of the Internet was encouraged by antitrust and telecommunications policies that weakened any nascent market power held by established telecommunications firms and created the conditions for the emergence of a domestic ISP (Internet Service Provider) industry based on reselling local Internet access at flat rates. Differences between the United States and other industrial in telecommunications regulation and the associated rate structures for telecommunications services influenced the slower pace of Internet adoption outside of the United States. Of equal importance during this stage of the Internet's development, however, was a long-established characteristic of the U.S. economy, the large size of its domestic market. The scale of the U.S. domestic market was made even more economically significant by the widespread and rapid diffusion of desktop computers and computer networks, which accelerated Internet adoption.

During the 1990s, the Internet entered a third phase of growth characterized by the rapid development of commercial content and business applications. These activities were fueled by the availability of capital, much of which was supplied by the U.S. venture capital industry, as well as the strong performance of the U.S. economy. And the "dotbomb" phase that followed this boom illustrates some of the risks associated with the Schumpeterian "swarming" supported by the U.S. venture capital industry.

At least some of the characteristics of this history, including the importance of the large, monoglot U.S. domestic market for the diffusion of the Internet and the rapid growth of industries supplying its components, revive central themes of U.S. technological development before 1940 (See Mowery and Rosenberg, 1998; Nelson and Wright, 1990). A number of scholars have argued that the economic significance of this large internal market, especially in scale-intensive manufacturing industries declined during the postwar period, as a result of the reduction in trade barriers and the revival of international flows of trade and capital (see Nelson and Wright, 1990). In the development of the Internet and other postwar information technology industries, however, the large U.S. domestic market appears to have played a strategic role. Another characteristic of early-20th century U.S. economic development was its reliance on foreign sources of invention for the innovations that were widely adopted within the U.S. economy. The Internet also contains important examples of foreign invention and U.S. development, most notably the cases of HTML and HTPP.

Our analysis of the factors underlying the unique US role in the development of the Internet is organized as follows. Section 2 provides an overview of the economic and technological history of the Internet, focusing on the source of critical innovations. Section 3 explores the relationship between the development of the Internet and the institutions within the U.S. national innovation system, offering a series of international comparisons. Section 4 compares the development and diffusion of the Internet in the United States and other industrial economies, and Section 5 offers concluding remarks.

2. A Brief History of the Internet

The evolution of the Internet from an experimental network connecting three U.S. research facilities at top speeds of 56 thousand bits per second to a global network with over 72 million hosts and a backbone capacity in excess of 2 billion bits per second has relied on innovations in many technologies that have dramatically improved the performance of the Internet's components.[2] Innovations in semiconductor technology, software engineering, signal processing, and communications technology have contributed to declines in the costs of computing technology for more than thirty years, and have made feasible the operation of networks linking computers of unprecedented power. In addition to expanding markets for computer and communications hardware and software, these advances have placed increasingly complex applications, especially those associated with computer networking, within reach of the mass market. These improvements in the performance of semiconductors, software and networking technologies propelled the growth of the Internet.

But the history of the Internet involves more than purely technological developments. As a collection of independent but interconnected computer networks built and managed by a variety of institutions, the Internet's growth also benefited from organizational innovations. As the network evolved from its origins within a U.S. Department of Defense research project into a novel tool for educational and research organizations and subsequently, to a vast collaboration among public and private sector institutions, it drew on a number of formal and informal governance mechanisms to coordinate its standards and infrastructure. Partly because of its development and early application in an academic and "quasi-academic" environment, the Internet retained many of the characteristics of an informal collaboration, even as it grew exponentially and made the transition from a public to a privately managed and financed infrastructure.

Our history of the Internet is divided into three phases. From 1960 to 1985, computer scientists and engineers made a number of fundamental theoretical and technical

[2] A bit represents a single one or zero—the fundamental unit of digital information. The term "backbone" refers to the fiber-optic cables and high-speed switches at the center of a network that carry large quantities of data aggregated from many thousands of simultaneous users. For a simplified guide to the networking terminology of bandwidth and capacity, see Appendix B.

contributions to its development. During this period, the Internet remained a loosely organized communications technology used largely by the research community. As the number of users and applications grew, the technical and organizational challenges shifted from inventing the network to expanding its core infrastructure and establishing a framework for connectivity that could accommodate the growing demand for service.

During the 1985-1995 period, the Internet shifted from public to private management and experienced a number of critical organizational changes, beginning with the introduction of NSFNET, the National Science Foundation's national Internet "backbone." In the United States, the growth and gradual privatization of NSFNET coincided with the emergence of a market for private access built on top of the public telecommunications infrastructure. A third phase in the evolution of the Internet began in 1995 with the privatization of NSFNET and the initial stock offering of Netscape, a company founded to take advantage of the recently invented HTML and HTTP software protocols that are commonly referred to as the World Wide Web. With the introduction and incredibly fast diffusion of the Web, a large number of companies began to develop commercial content and applications for the growing network. This section provides a historical overview of the economic and technological history of the Internet, focusing on the critical institutions and innovations within each of these three phases and emphasizing the international origins of several key inventions in the Internet's technological development.

Evolution of the Internet

Time Period	Critical Developments
1960-1985	Invention of digital packet-switching and associated standards/protocols Birth of Internet self-governance institutions
1985-1995	Growth of NSFNET and parallel private infrastructure Growth in installed base of PC's and LAN's
1995-Present	Diffusion of the World Wide Web Commercialization of Internet content Emergence of eCommerce applications

1960-1985: Early Computer Networks

Packet Switching

Research on computer networking began in the 1960s, roughly 15 years after the advent of the computer itself. This early research was motivated primarily by the desire to promote sharing of the scarce computing resources located at a few research centers. Like many of the early academic and industrial efforts in computing technology, much of this networking research was funded by the U.S. Department of Defense. Although the Department of Defense sought to exploit a number of these new technologies in defense applications, the DoD supported "generic" research and the development of a substantial infrastructure in academia and industry for such research, on the assumption that a viable industry capable of supplying defense needs in computer technology would also require civilian markets (Langlois and Mowery, 1996).

During the early 1960s several researchers, including Leonard Kleinrock at MIT, Paul Baran of RAND, and Donald Davies at the National Physical Laboratories in the United Kingdom, developed various aspects of the theory of packet switching.[3] Digital packet switching offered performance and reliability advantages over analog networks for data communications and was attractive to DoD-funded researchers hoping to construct a communications network that was less vulnerable to attack than the relatively centralized telephone network.[4] In order to realize these advantages, however, computer science researchers needed to develop a set of communication protocols and devices that did not rely on the circuit-switched infrastructure operated by incumbent telecommunications companies.[5] From its inception, therefore, the fundamental design advance that

[3] Packet switching is fundamentally different from circuit switching, the technology that connects ordinary telephone calls. On a packet-switched network, information is broken up into a series of discrete "packets" that are sent individually, and reassembled into a complete message on the receiving end. A single circuit may carry packets from multiple connections, and the packets for a single communication may take different routes from source to destination.

[4] DARPA's support for this networking research, as well as the agency's eventual commitment to deploy a packet-switched computer network, was also motivated by the agency's interest in linking the mainframe computer systems of the academic, government, and industrial computer science research teams that it was supporting.

[5] The researchers did, however, lease the long-distance phone lines used to carry their data from AT&T.

underpinned the Internet thus tended to weaken the market power of the dominant provider of telecommunications services in the United States.

By the late 1960s, the theoretical work and early experiments of Baran, Kleinrock and others led the U.S. Department of Defense Advanced Research Projects Agency (DARPA) to fund the construction of a prototype network.[6] In December 1968, DARPA granted a contract to the Cambridge Massachusetts-based engineering firm of Bolt, Beranek and Newman[7] to build the first packet switch. The switch was called an Interface Message Processor (IMP), and linked computers at several major computing facilities over what is now called a wide-area network. A computer with a dedicated connection to this network was referred to as a "host." The resulting ARPANET is widely recognized as the earliest forerunner of the Internet. (NRC, 1999a Ch. 7).

The entire collection of computers attached via an IMP to the DARPA network backbone grew quickly throughout the 1970's.[8] By 1975, as universities and other major defense research sites were linked to the network, ARPANET had grown to more than 100 nodes. DARPA's contract with BBN, and its support for ARPANET applications and extensions reflected a broad shift in the R&D programs overseen by the agency during the 1970s towards near-term research and the development of stronger links with industry (NRC, 1999a, Chapter 4).

ARPANET was not the only prototype network constructed during the late 1960's and early 1970's. Donald Davies completed the construction of a data network at the National Physical Laboratories in the UK before the development of ARPANET, and a French

[6] In contrast, Davies's efforts to enlist the support of the NPL and Britain's public telecommuncations agency, the General Post Office, for the construction of a similar network in the U.K. met with limited success and the prototype network that was eventually developed was far smaller than the early ARPANET (Abbate, 2000).

[7] Bolt, Beranek and Newman, an MIT "spinoff" founded in 1948, was an early example of the new firms that played an important role in the Internet's development. The firm was started by MIT Professors Bruce Bolt and Leo Beranek in partnership with a graduate student, Robert Newman. Populated as it was in its early years by a mixture of recent graduates, professorial consultants, and other technical employees with close links to MIT research, BBN is a good example of the "quasi-academic" environment within which many Internet-related innovations were developed. (Wildes, 1985)

network called CYCLADES was built in 1972. Though motivated by civilian rather than military applications, Davies's original proposal suggested a national network along the lines of ARPANET. However, funding difficulties restricted the "Mark I" project to a single node located at NPL. The project was also hampered by British efforts to rationalize the national computer industry. These efforts led to the cancellation of a minicomputer that the NPL team planned to use as their network interface.[9] (Abbate, 2000) Cyclades, a French networking experiment led by Louis Pouzin, was first demonstrated in 1972. The motivation behind Cyclades was to link together a number of databases in disparate parts of the French government. Cyclades introduced som significant technical advances, including datagram networking, but also had funding difficulties, and was shut down in 1978.[10]

U.S. dominance thus did not result from a first-mover advantage in the invention or even the early development of a packet-switched network. The factor that does seem to separate ARPANET from these simultaneous projects was its sizeable public financing and flexibility in its deployment, which resulted in a prototype computer network of large scale that included a diverse array of institutions. The initial DARPA network spanned the continent and connected three universities (UCLA, UCSB and Utah), a consulting firm (BBN), and a research institute (Stanford Research Institute). Its size and inclusion of a diverse array of institutions as members, even in its earliest development, both appear to distinguish the ARPANET from its British and French counterparts.

TCP/IP

In 1973, two DARPA-funded engineers, Robert Kahn and Vinton Cerf, developed an improved data-networking communications protocol that simplified routing, eliminated the need for an IMP, and allowed physically distinct networks to interconnect with one another as "peers" in order to exchange data. Special hardware, called a gateway, handled the task of passing packets between one type of physical network architecture and

[9] Mark I ultimately used hardware supplied by U.S. vendors Honeywell and Digital Equipment.
[10] Datagrams are a more "pure" implementation of the packet-switching idea than the implementation used by the original ARPANET, which relied in "virtual connections" to transport messages. Pouzin's technology thus anticipated the development of TCP/IP.

another. The idea of an open architecture that allowed for network-to-network connectivity was a key intellectual advance in computer network design. Kahn and Cerf called the new protocol Transmission Control Protocol (TCP), and published the specification in the IEEE Transactions on Communication in 1974. TCP/IP was thus important and influential both because of its technical characteristics and because of its widespread dissemination through publication in the open literature.

The TCP protocol eventually was split into two pieces and renamed TCP/IP (Transmission Control Protocol/Internet Protocol). TCP/IP was rapidly adopted for several reasons. First, it was highly reliable and fixed many of the problems associated with first-generation network protocols like Network Communications Protocol (NCP). Second, it was implemented as an open standard—a complete description of TCP/IP was freely available to the networking community along with several different implementations.[11] Finally, TCP/IP arrived just as the computing research community began to standardize on a common platform, IBM or DEC hardware running the Unix operating system. The TCP/IP protocols became an integral part of this standard platform (see below).

During the fifteen years following the introduction of TCP/IP, a number of other protocols were introduced, including proprietary standards like IBM's SNA or Digital equipment's DECNET and open alternatives such as the Unix to Unix Copy Protocol (UUCP) and Datagram (UDP) networking. But the free, reliable, and open characteristics of TCP/IP supported its emergence as an ideal "glue" for integrating networks built on a variety of different platforms and protocols. TCP/IP emerged in the early 1990's as the dominant protocol for most networking applications, and is now virtually synonymous with the technical definition of the Internet.

[11] In software development, standards refer primarily to the specification of an interface—a set of commands that can be used by other programmers to write new software. These interfaces simplify the complex task of writing a program from scratch. With open standards, the developer of an interface places the set of commands—and generally the source code used to create them—into the public domain. This allows other developers to improve and extend the interface, and encourages programmers to adopt the commands contained in it as a true industry standard.

Although TCP/IP now dominates Internet applications, its emergence as a dominant, open standard was uncertain during the 1980s, a period during which computer networks utilized a number of different, often proprietary, networking protocols. The eventual dominance of the TCP/IP protocol owes much to the decision by the National Science Foundation (NSF) to adopt TCP/IP as the standard on its national university network (discussed below). The NSF decision helped create a large installed base and the resulting network externalities influenced future adopters of TCP/IP. NSF's decision to use TCP/IP was based in part on the networking protocol's inclusion within the 4.2 BSD version of Unix, which was available at a nominal cost and was widely used in the academic research computing community.[12]

Early Coordination Efforts

In addition to technological innovations, development of the Internet relied on the creation of a set of flexible and responsive governance institutions. Most of these institutions trace their origins to an informal correspondence process called Request for Comments (RFC), which was started in 1969 by Steve Crocker, a UCLA graduate student in computer science.[13] The use of RFCs grew quickly, and another UCLA student named Jon Postel became the editor of the series documents, an informal yet influential post that he held for many years. RFCs were distributed over the nascent computer network and quickly became the standard forum for ARPANET's growing technical community to communicate new ideas, comments and refinements to existing proposals. RFCs combined open dissemination and peer review, features characteristic of academic journals, with the speed and informality characteristic of an e-mail discussion list.[14] The

[12] The Unix operating system was invented by Kenneth Thompson and Dennis Ritchie at Bell Labs in 1969, and is another example of the power of an open standard. AT&T originally licensed the Unix source code to universities for a nominal fee because of a 1956 consent decree that restrained them from competing in the computer industry mandated the licensing of patented technology. The licensing policy had several offsetting effects. Research users, including computer scientists at UC Berkeley, developed modifications that significantly improved the operating system (including the bundling of TCP/IP), but developed several incompatible versions of the program. AT&T's subsequent efforts to commercially exploit Unix failed in the presence of free and arguably superior, albeit incompatible, competing versions of the operating system. [http://www.datametrics.com/tech/unix/uxhistry/brf-hist.htm]

[13] *Host Software*, RFC 001, April, 1969

[14] Indeed, the RFC process of widely distributed problem-solving individuals and teams that discovered and fixed technical flaws in the network technology anticipates some of the key features of "open source"

documents were used to propose specifications for important new applications such as Telnet (used to control networked computers from a remote terminal) and FTP (File Transfer Protocol, used to transfer files between networked machines), as well as to refine networking protocols such as TCP/IP (Request for Comments #318, 1972).

The Internet's first formal governance organizations appeared in the United States during the late 1970s, a period of consolidation and rapid expansion. Efforts to rationalize the resources and infrastructure of several U.S. networking initiatives operated by NASA, the Department of Energy, and the National Science Foundation led to the creation of a set of organizations, funded by NSF and DARPA, to oversee the standardization of the backbone on TCP/IP. The Internet Configuration Control Board (ICCB) was established in 1979 by Vinton Cerf, who was director of the DARPA network at the time. The ICCB and its successors drew their leadership from the ranks of computer scientists and engineers who did much of the early government-funded networking research, but membership in the organization was also open to the community of Internet users.

In 1983, when ARPANET switched over to TCP/IP, the ICCB was reorganized and renamed the Internet Activities Board (IAB). The IAB had two primary sub-groups, the Internet Engineering Task Force (IETF), which managed the Internet's architecture and standard-setting processes including editing and publishing the RFCs, and the Internet Research Task Force (IRTF), which focused on longer-term research. The IAB and its progeny coordinated the infrastructure and connectivity boom that took place in the next decade. By the early 1990s, the costs of managing the Internet infrastructure began to exceed the available federal funding, and in 1992 the Internet Society (ISOC) was founded with funding from a variety of private and public sector sources. ISOC helped coordinate the activities of a number of loosely affiliated institutions including the IAB, IETF, IRTF, and IANA.

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software development, an activity that depends on the communications and interactions made possible by the Internet (see Lee and Cole, 2000, and Kuan, 2000).

The informal organizations governing the growth of the Internet made a number of architectural and standards decisions that contributed to the remarkable growth in scale and technical performance of the overall network. Their track record owes much to their informal "quasi-academic" style of organization and their ability to develop open standards in an environment free of the pressures of standard setting for proprietary technologies. These Internet governance organizations also formed an effective source of alternatives to the data-networking protocols promoted by established global telecommunications operators, such as X.25 (Abbate, 2000). Partly from sheer luck in the timing of various advances in its development, and partly because of the academic venue within which much of its development occurred, the Internet benefited from a standard-setting process that produced open standards and did so in a relatively timely fashion.

1985-1995: Infrastructure Development and Growth

Although the Internet grew during its early years, through at least 1985 its use was limited to researchers, computer scientists, and networking engineers. During the next 15 years, however, the Internet infrastructure was tested by a dramatic expansion in the number of new networks and users (Figure 1.1 depicts growth in the total number of Internet hosts during the 1981-2000 period).

In 1985, the NSF, by then one of several federal government agencies managing the "backbone" of the U.S. national network, made the first in a series of policy decisions that encouraged the standardization of Internet infrastructure and promoted expansion and utilization of the network. Beginning in 1985, any university receiving NSF funding for an Internet connection was required to provide access to all "qualified users" and use TCP/IP on its network. Standardization around TCP/IP encouraged interoperability and supported the creation of a large pool of university-trained computer scientists and engineers skilled in use of the protocol. In the same year, all of the federal agencies operating networks—DARPA, NSF, DOE and NASA—established the Federal Internet

Exchange (FIX), a common connection point that allowed them to share their backbone infrastructure.

The "peer to peer" model for exchanging traffic represented by FIX became a fundamental feature of the core Internet infrastructure. The process of infrastructure rationalization concluded with the decommissioning of the original ARPANET in 1990 and the transfer of its users and hosts to the new NSFNET. As had been the case with federal support for the early development of other computer technologies, DoD policymakers were willing to turn over the Internet infrastructure created under their sponsorship to a broader academic research community.[15]

In spite of growing private-sector participation in the management of the Internet, the NSF maintained an Acceptable Use Policy (AUP) throughout this period that prohibited use of NSFNET for "commercial purposes." In practice, the AUP meant that commercial users could access the NSFNET as a research tool but were prohibited from using it to conduct business. As more commercial users attached to the network, on their own or in partnership with academic institutions, they lobbied the NSF to abandon the AUP. Private-sector demand for commercial-use inter-networking was stimulated by the growth in local-area networking, which had been developing since the late 70's. As Unix workstations and microcomputers (PC's) began to overtake the minicomputer and as demand for these machines was fueled by the creation of "killer applications" such as document processing and spreadsheets, the number, size and scope of corporate networks began to grow. Growth in the demand for networking services also was spurred by the spread of the client/server computer architecture for distributed computing.

Although the NSF's Acceptable Use Policy was formally terminated in 1991, it served as an important catalyst for the creation of a private Internet backbone. Between 1987 and 1989 the major "backbone ISPs" CERFnet (California Education and Research

[15] In the case of early technological advances in computing technology, DoD research sponsors sought the broadest possible dissemination of the underlying technical developments, in the expectation that the long-term national security benefits from such broad diffusion would exceed those associated with the exploitation of the technologies by defense-related researchers and firms (Langlois and Mowery, 1996).

Federation Network—named in honor of Vint Cerf), PSINET, and Alternet/UUNET emerged as major providers of high-speed capacity for commercial users. (Zakon, 2000) By this time the US domestic telecommunications system was well into its lengthy transition from regulated monopoly to competitive service provision, and the ability of these new companies to enter a growing telecommunications market is evidence of the progress of U.S. antitrust and deregulatory measures aimed at opening markets to new competitors. In 1995, the transition of the core network infrastructure into private hands was completed when the NSF transferred control of its four major Network Access Points to Sprint, Ameritech, MFS, and Pacific Bell.

During this period, a substantial data networking communications infrastructure developed in Western Europe. An important catalyst for European networking was the founding of RIPE (Reseaux IP European) in late 1989. RIPE provided technical and administrative coordination for a fledgling European IP network. Other experiments, such as EUNet (European Unix network running UUCP), were also underway at this point. Nevertheless, the large scale of the NSFNET infrastructure as well as its open standards made it an attractive alternative to the European networks and many networks from industrial economies outside the United States linked themselves to the NSFNET infrastructure. In 1988, Canada, Denmark, Finland, France, Iceland, Norway, and Sweden connected to the NSFNET. They were followed in 1989 by Australia, Germany, Israel, Italy, Japan, Mexico, Netherlands, New Zealand, and the United Kingdom.

Technical Advances

Growth in regional networks and the NSFNET backbone during the late 1980's inspired a number of technical innovations. Increasing demand for capacity on the network backbone led to a continual stream of more efficient routers and bridges, specialized switches that control the flow of data at branching points in the network. The speed of the NSFNET backbone was upgraded from 56K (57,600 bits/sec.) in 1985 to T1 (1.5 million bits/sec.) in 1988 and to T3 (46.1 million bits/sec.) in 1991. Another technology made necessary by the growth in Internet infrastructure was the Domain Name Server (DNS), introduced in 1984. A DNS is a file maintained on particular computers with known

physical addresses that contains a map from Internet domain names (e.g. haas.berkeley.edu) to the numerical network address scheme utilized by TCP/IP. The DNS provides a real-time concordance between machine-readable and humanly recognizable Internet addresses, a feature that was indispensable to the growth of a public network such as the Internet. A third important technological contribution was the creation of a hierarchical classification scheme for sub-networks. The creation of this classification system prevented saturation of the IP address space, a critical constraint to the growth of the Internet.[16]

The advances in domain name servers and classification schemes were the work of computer scientists in U.S. universities. The advances in Internet capacity and speed were the result of innovations in the networking hardware and software products whose markets grew exponentially throughout the 1990s. The firms that came to dominate this market were not large systems vendors such as IBM, DEC or Sun. Instead, a group of smaller firms, most of which were founded in the late eighties, rose to prominence by selling multi-protocol products that were tailored towards the open platform represented by TCP/IP and Ethernet. Cisco, Bay Networks and 3Com, all new entrants into the industry, built large businesses selling products based on this open network architecture.[17] U.S. firms achieved a dominant position in the global networking equipment market because of their "headstart" in serving the large U.S. domestic market, just as U.S. packaged computer software firms had benefited from the burgeoning U.S. domestic personal-computer market during the 1980s.

Origins of the Consumer Internet

As the commercial and academic networking infrastructures experienced rapid growth and consolidation, another type of networking, centered on individual rather than institutional users, began to emerge in the late 1970s and early 1980s with the introduction of the "personal computer." Hobbyists quickly began to connect personal

[16] Class A IP addresses were reserved for large national networks, Class B for regional networks, and Class C for the growing number of smaller LANs.

computers to the telephone network through modems that enabled communication with other PCs. Compuserve launched the first commercial "bulletin board" or BBN service in 1979, the same year that Hayes Incorporated introduced a $400 modem for microcomputers that transmitted data at 300 bits per second.[18] Although Compuserve quickly gained thousands of subscribers, most bulletin boards remained local affairs run by hobbyists. Initially, online service providers could not offer their customers access to the broad portfolio of applications already available on the Internet.

Several companies followed Compuserve into the market, and the entire group became known as online service providers. The three largest online service providers—Prodigy, Compuserve and America Online—became household names. Prodigy was a joint venture between IBM, Sears and CBS Television (which exited the venture after two years) that was launched in 1984, and AOL was founded in 1985. These companies built their own networks that initially were independent of the NSFNET infrastructure.[19]

During the early 1990s, many small regional ISPs began to offer dial-up Internet connections that linked subscribers to the NSFNET. These small businesses copied many of the technical features of academic computer networks and quickly discovered that no more than a few hundred customers were needed to provide sufficient revenues to fund a modem pool and high-speed Internet connection (Greenstein, 2000a). The distance-sensitive pricing of long distance telecommunications in the U.S. created opportunities for these small ISPs to enter local markets (local dialup access was not metered) while the larger ISPs and online service providers focused on high-density urban locations. Although many of the larger online services initially hesitated to provide unrestricted Internet access, which they saw as diluting the value of their proprietary applications, the

[17] However, many of these companies early products reflect the multi-protocol environment prevalent at the time and were capable of running a number of different standards. This remains true of much of the network infrastructure today.
[18] Compuserve was a small Ohio computer company founded in 1969 that happened to be among the first enterprises to spot the potential of micro-computer networking.
[19] The proprietary online services and the broader Internet utilized different technologies to link users' personal computers to the network. Since most PC's were not capable of running TCP/IP using a dial-up connection, they communicated with online service providers using modem protocols such as v.22 and v.32.

rising number of Internet hosts and users compelled the major online service providers to offer e-mail connectivity and later, browsing, in order to keep their customers.

It is difficult to document the emergence of European online service providers, with the notable exception of France's Minitel. It seems clear that no consumer access provider comparable to Compuserve or AOL emerged in a major European market during the 1980s. And although RIPE was founded shortly after the major U.S. backbone service providers created CIX, Europe lacked many of the important complementary factors that propelled rapid growth of hosts and users in the United States during the early 1990s. These complements included an extensive academic network operating on a common platform, a large regional LAN infrastructure, a commercial online services industry, a strong domestic base of network equipment manufacturers, and a huge private investment in computing infrastructure.

World Wide Web

In May 1991, Tim Berners-Lee and Robert Cailliau, two physicists working at the CERN laboratory in Switzerland, released a new document format called Hyper-Text Markup Language (HTML) and an accompanying document retrieval protocol called Hyper-Text Transfer Protocol (HTTP).[20] HTML added two key innovations to the well-known document formatting language known as Standard Generalized Markup Language (SGML). First, HTML incorporated a basic set of multimedia capabilities that allowed authors to incorporate pictures and graphics into the text of their documents. Second, HTML was an implementation of hypertext, enabling authors to specify particular words, phrases or images as HTTP "links" that direct a reader to other HTML documents. Together, HTML and HTTP turned the Internet into a vast cross-referenced collection of multimedia documents. The collaborators named their invention the "World Wide Web" (WWW). The Web proved to be another "killer application" and accelerated the emergence of the Internet as a global social and economic phenomenon.

[20] The development of these important technical advances was motivated by Berners-Lee and Caillau's interest in facilitating the ability of physicists to archive and search the large volumes of technical papers being transmitted over the Internet as it then existed.

In order to use the World Wide Web, a computer needed a connection to the Internet and the application software that could retrieve and display HTML documents. Although it was not the first functional Internet "browser," Mosaic, a free program written by a graduate student at the University of Illinois' National Center for Supercomputing Applications named Marc Andreesen, was widely adopted and accelerated the growth of the Web. During 1993, the first year that Mosaic was available, HTTP traffic on the Internet grew by a factor of 3,416. By 1996, HTTP traffic was generating more packets than any other Internet application.

Following its introduction, the HTML standard rapidly incorporated extensions that allowed programmers to add multimedia capabilities, searching, purchasing and other complex interactions between the Internet user and a web site. An informal Internet-based standard setting body, the World Wide Web Consortium (W3C), maintained a common standard for HTML in the face of the competitive battle between Microsoft and Netscape over their respective browsers (See Cusumano and Yoffie, 1999, for an account of the "browser wars"). The W3C was founded in 1994 by Tim Berners-Lee, who by then had moved to MIT, in collaboration with CERN. The organization was also supported by DARPA and the European Commission, and developed a set of technical specifications for the Web's software infrastructure that promoted openness, interoperability and a smooth evolution for the HTML standard.

Although HTML and HTTP were not invented in the United States, nearly forty years of federal and private-sector investments in R&D and infrastructure supported their rapid domestic adoption and development. By the early 1990s, the basic protocols governing the operation of the Internet had been in use for nearly 20 years, and their stability and robustness had improved considerably. As Greenstein (2000a) has pointed out, the explosive growth of the Web during the 1990s benefited from the lengthy period of gestation and refinement experienced by network infrastructure. The fact that U.S. researchers and entrepreneurs were among the pioneers in developing commercial applications of the Web, despite the fact that their efforts relied on the non-U.S. inventions of HTML and HTTP, partly reflects the U.S. origins of much of the

infrastructure that supported the Web. But the successful inward transfer and exploitation of these key foreign inventions echoes a key feature of U.S. technological development during the late 19th and early 20th centuries (Mowery and Rosenberg, 1998).

1995-Present: Diffusion, Application and Commercialization

Although the commercialization of network infrastructure occurred gradually in response to the ponderous forces of regulatory reform and public investment, use of the Internet infrastructure to deliver commercial content and applications grew explosively during the late 1990's. The magnitude of this shift is suggested by changes in the distribution of top-level domain name suffixes. In 1996, the commercial ".com" and ".net" domains contained roughly 1.8 times as many hosts as the educational .edu domain. But by 2000, the term "dot com" had become a popular expression for fledgling Internet businesses, and the .com and .net domains accounted for more than 6 times as many hosts as the .edu domain.

The invention of the World Wide Web catalyzed the development of commercial content and applications by simplifying the Internet and providing a set of standard protocols for delivering a wide variety of content to almost any desktop. At the same time, a booming U.S. economy, an overheated stock market, and the spectacular financial success of several early technology entrepreneurs created a receptive environment for new Internet-related ventures. As a result, even though Internet access diffused internationally with remarkable speed, U.S. firms retained a dominant position in its early commercial exploitation. One indicator of this trend is the geographic distribution of Secure-Sockets Layer web servers, which are used to conduct most commercial Internet transactions (Figure 3.10). As the Figure shows, the United States remains the most intensive user of secure web servers on a per-capita basis, nearly 50% greater than Iceland, the next most intensive user of secure servers.

Financing New Applications

Perhaps the defining moment that initiated the manic commercialization of Internet content was the initial public offering of Netscape in August of 1995. Netscape hoped to

commercialize a version of the Mosaic browser, but at the time of its IPO, had few assets other than Mr. Andreesen and a rapidly growing installed base of users. Nevertheless, the success of the offering sparked a surge in Internet-related entrepreneurial activity, much of which focused on implementing various forms of e-commerce. The level of enthusiasm for almost any business opportunity related to the Internet can be judged by the growth in the late 1990s in the stock-market valuations of Internet start-ups, the number of IPOs, or the amount of venture capital made available to Internet entrepreneurs throughout the late nineties. In 1995, there were a total of 657 information technology-related venture capital financings worth $3.3 billion. In 1999, four years later, there were more than 1,600 deals with a combined valuation in excess of $20 billion.[21] European venture capital figures for 1999 indicate a total valuation of 4 billion ECU, about half of which originated in the UK. Although in retrospect the U.S. venture capital industry was unrealistically optimistic in promoting many of these Internet investments (the abundance of venture capital also drove up the price of equity stakes in even young U.S. startups, further inflating the reported value of financings) during the late 1990s, venture funding played an important role in a number of significant commercial innovations during this period.

Changes in Access

The Internet access industry consolidated somewhat during the late 1990s as a number of new technologies promising faster connection speeds for the home user began to compete with the traditional dial-up ISP, a competitive process that was aided by the regulatory reforms enacted during the previous decade.[22] In particular, competition emerged between a technology known as Digital Subscriber Line (DSL), which utilizes an upgraded public telecommunications infrastructure, and proprietary services that operate over cable television wires. As of 2001, the DSL industry bears some resemblance to the ISP industry of the late 1980s--a large number of small independent resellers lease infrastructure to compete with major telecommunications providers.

[21] www.ventureone.com

[22] According to the FCC's web site, the Telecommunications Act of 1996, the major regulatory reform during the 1990s in U.S. telecommunications, sought "…to let anyone enter any communications

Meanwhile, the European ISP industry appears to be in the midst of a phase of rapid and fragmented growth similar to that experienced by U.S. ISP's during the first half of the 1990's. While access penetration rates range from 4 percent in Greece to 47 percent in Sweden, in 1999 subscriptions on the continent increased by nearly 20 percent. By 1999, Europe had more than 4,000 ISP's. By comparison, U.S. ISP's numbered around 3,800 as of 1996, and more than 6,000 by 1998.[23] Like their U.S. predecessors the many small European access providers have pursued a wide variety of different business models, and the ultimate shape of the industry remains unclear.

Perhaps the most significant development affecting the access industry, however, is the convergence of the Internet and the public telecommunications infrastructure. During the late 1990s a number of private firms made massive investments in building a global broadband communications infrastructure. The speed and reliability of the data network now allow traditional applications such as telephony to be routed over the packet-switched infrastructure, and the large investments in capacity have made long-distance communication a commodity good, characterized by fierce price competition and falling average prices. (See Figures 3.2 and 3.8) These developments are being further assisted by deregulation in the telecommunications service industries of most industrial economies.

This section has discussed on the history of the Internet and computer networking, focusing in particular on the reasons for the rapid development and adoption of the Internet and the WorldWide Web in the United States. In the next section, we describe the ways in which the U.S. national innovation system influenced these developments, by way of explaining how the unique features of the U.S. innovation system contributed to American leadership in computer networking.

3. The Internet and the U.S. Innovation System

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business—to let any communications business compete in any market against any other." (www.fcc.gov/telecom.html).

[23] European figures are from a report by the consulting firm Analysys, presented on www.isp-planet.com U.S. figures are taken from Greenstein (2000a), who obtained data from thelist.com

The Internet resembles many postwar innovations in information technology in that it was invented and commercialized primarily in the United States. The invention, diffusion and commercialization of computer networking technology illustrate the operation of the unusual mix of institutions and policies that characterize the post-1945 U.S. "national innovation system" (Mowery and Rosenberg, 1993, 1998). Federal agencies such as the Department of Defense and National Science Foundation played a critical role in funding the development and diffusion of early versions of the technology. Federal spending on R&D and procurement was complemented by the R&D investments of large corporations and the many start-ups that quickly came to populate Internet-related industries. These small firms often drew on expertise developed in U.S. research universities or in large corporations and benefited from the regulatory and antitrust policies of federal agencies such as the Federal Communications Commission and the Justice Department.

The Role of Government-Sponsored Research

Public funds were used to develop many of the early inventions that fueled the development of the Internet in the United States. Although it is tempting to attribute U.S. leadership in computer networking to a "first-mover advantage" in government-funded basic research, the development of critical technologies such as HTTP/HTML outside the United States, and the early work of non-U.S. networking pioneers such as Donald Davies and Louis Pouzin cast some suspicion on this hypothesis. On the other hand, U.S. government agencies, such as the Department of Defense, appear to have been unique in their willingness to commit to funding a national network infrastructure and in their support of strong links between industry and academia. The lack of data on Internet-related public spending in the United States and elsewhere makes explicit cross-national comparisons difficult. Nonetheless, inasmuch as the United States government was by no means the only national government supporting domestic R&D in computer architectures and networking, the benefits of government-sponsored R&D in the United States appear to have flowed as much from scale and structure as from first-mover advantages.

Federal R&D spending, much of which was defense-related, played an important role in the creation of an entire complex of "new" postwar information technology industries

(including semiconductors, computers, and computer software) in the United States. The origins of the Internet can be traced back to these efforts. Internet-related projects funded through the Department of Defense include Paul Baran's early work on packet switching, the ARPANET, and research on a variety of protocols, including TCP/IP. These public R&D investments in networking technology were preceded by a fifteen-year DoD investment in hardware and software technology that began with the earliest work on numerical computing. Federal R&D investments strengthened U.S. universities' research capabilities in computer science, bankrolled the early deployment of the ARPANET, facilitated the formation of university "spinoffs" like BBN and Sun, and trained a large cohort of technical experts who aided in the development, adoption, and commercialization of the Internet.

We lack the necessary data to estimate the total federal investment in Internet-related R&D. Even were such data available, the complex origins of the Internet's various components would make construction of such an estimate very difficult. Nevertheless, federal investments in the academic computer science research and training infrastructure that contributed to the Internet's development were substantial. According to a recent report from the National Research Council's Computer Science and Telecommunications Board, federal investments in computer science research increased fivefold during the 1976-95 period, from $180 million in 1976 to $960 million in 1995 in constant (1995) dollars. Federally funded basic research in computer science, roughly 70% of which wsa performed in U.S. universities, grew from $65 million in 1976 to $265 million in 1995 (National Research Council, 1999a, p. 53).

Langlois and Mowery (1996) compiled data from a variety of sources that indicate that between 1956 and 1980 the cumulative NSF funding for research in "software and related areas" amounted to more than $250 million (1987 dollars). Most of this funding went to U.S. universities. DARPA R&D funding from its Information Processing Techniques Office (IPTO), which went to both universities and industry, averaged roughly $70 million annually (1987 dollars) between 1964 and 1980, before growing sharply to more than $160 million in 1984-85. Between 1986 and 1995, the NSF spent roughly $200

million to expand the NSFNET (Cerf, 2000). The investments of NSF and DARPA in almost certainly constituted a majority of Internet-related R&D funding, especially in academia. These federal R&D expenditures were sizeable and importantly, contributed to both research and training of skilled engineers and scientists. Nevertheless, the scale of these investments pales in comparison with the investments by private firms in information technology during the 1990s (see below).

In addition to their size, the structure of these substantial federal R&D investments enhanced their effectiveness. DARPA's research agenda and managerial style gave researchers considerable autonomy and the agency spread its investments among a group of academic "centers of excellence" (MIT, U.C. Berkeley. Stanford, Carnegie-Mellon, the University of Utah, and UCLA).[24] In its efforts to encourage exploration of a variety of technical approaches to research priorities, DARPA frequently funded similar projects in several different universities and private R&D laboratories. Moreover, the Department of Defense's procurement policy complemented DARPA's broad-based approach to R&D funding.[25] Contracts were often awarded to small firms such as BBN, which received the contract to build the first IMP. This policy helped foster entry by new firms into the emerging Internet industry, supporting intense competition and rapid innovation.

The large scale of the U.S. defense-related programs in computer science research and networking distinguished them from those in the United Kingdom and France; but the contrasts extend beyond the scale of these R&D programs. Unlike their counterparts in the Soviet Union or the United Kingdom,[26] DoD program managers in information

[24] DARPA's early strategy in information technology R&D, beginning in the late 1950s, focused on the development of strong academic research institutions, rather than on peer-reviewed awards to individual investigators. Although DARPA research grants typically were made to individual researchers, this remarkably successful program did not adhere strictly to the norms of peer review that now are widely viewed as indispensable to research excellence (Langlois and Mowery, 1996).

[25] DARPA was strictly a defense R&D agency, and did not engage in large-scale procurement.

[26] Goldstine, one of the leaders of the wartime project sponsored by the Army's Ballistics Research Laboratory at the University of Pennsylvania that resulted in the Eckert-Mauchly computer, notes that "A meeting was held in the fall of 1945 at the Ballistic Research Laboratory to consider the computing needs of that laboratory 'in the light of its post-war research program.' The minutes indicate a very great desire at this time on the part of the leaders there to make their work widely available. 'It was accordingly proposed that as soon as the ENIAC was successfully working, its logical and operational characteristics be

technologies, even before the establishment of DARPA, sought to establish a broad national research infrastructure in computer science that would be accessible to both civilian and defense-related firms and applications, and disseminated technical information to academic, industrial, and defense audiences.[27] Classified R&D was important, but a great deal of U.S. defense-related R&D consisted of long-term research that was conducted in universities, which by their nature are relatively open institutions.

Hendry (1992) argues that a lack of interchange between military and civilian researchers and engineers weakened the early postwar British computer industry;[28] the very different situation in the U.S. enhanced the competitiveness of this nation's hardware and software industry complex. The experiences of Donald Davies, a pioneering British researcher in packet-switching technologies, are consistent with this characterization. As early as 1965, Davies proposed building a national data network. The British Defense Ministry was already aware of the work of Paul Baran and others in the United States, and Davies sought funding from British public ministries or state-owned industries in the defense, computing and telecommunications sectors, but his Mark I project at NPL remained limited in scope. Paradoxically, much of the reluctance of British government sources to finance Davies's prototype network stemmed from his inability to demonstrate near-term commercial applications in the midst of the Wilson government's search for civilian "new industries" based on advanced technologies (Abbate 1999 p. 34). Davies's Mark I

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completely declassified and sufficient be given to the machine...that those who are interested...will be allowed to know all details.'" (1972, p. 217). Goldstine is quoting the "Minutes, Meeting on Computing Methods and Devices at Ballistic research Laboratory, 15 October 1945 (note 14). Flamm (1988), pp. 224-226, makes a similar point with respect to military attitudes toward classification of computer technology.

[27] The Office of Naval Research organized seminars on automatic programming in 1951, 1954 and 1956 (Rees 1982, p. 120). Along with similar conferences sponsored by computer firms, universities, and the meetings of the fledgling Association for Computing Machinery (ACM), the ONR conferences circulated ideas within a developing community of practitioners who did not yet have journals or other formal channels of communication (Hopper 1981). The ONR also established an Institute for Numerical Analysis at UCLA (Rees 1982, p. 110-111), which made important contributions to the overall field of computer science.

[28] "Indeed, despite what was in many respects a first-rate network of contacts, the NRDC [Britain's National Research and Development Corporation] was not even aware of some of the military computer developments taking place in the 1950s and early 1960s. Nor were the people carrying out these developments in many cases aware of work on the commercial front. In America, in contrast, communications between different firms and laboratories appear to have been very good, even where classified work was involved." (Hendry, 1992, p. 162).

prototype was eventually deployed, but it remained much smaller than the U.S. prototype and used equipment purchased from U.S. vendors such as Honeywell and Digital Equipment (Abbate, 2000).

In France, Louis Pouzin's Cyclades/Cigale packet network research program, though financed by the French government through the Institute Recherche d'Informatique et d'Automatique (INRIA), experienced quite similar difficulties. Eventually, the scale of U.S. networking initiatives served as an effective deterrent to the creation of smaller regional alternatives, as the "network effect" created by a growing network that already linked the extremely active American computer science community led international researchers to join the U.S. effort.

Another factor in the success of federal R&D programs was their "technology-neutral" character. U.S. research programs avoided the early promotion of specific product architectures, technologies, or suppliers, in contrast to efforts in other industrial economies, such as the French "Minitel" program, or celebrated postwar U.S. technology policy failures, such as the supersonic transport or the fast-breeder nuclear reactor (Nelson, 1984). The NSF, for example, focused on funding a variety of academic reesarch projects, largely through grants to university-based computer scientists. NSF support, dating back to the late 1950s, literally laid the foundation for the formation and growth of many U.S. universities' computer science departments, a key component of the research and training infrastructure that supported the development and diffusion of the Internet. In addition to their research contributions, university computer science departments and CSNET formed the core of the early Internet.

The diversity of the federal Internet R&D portfolio reflected the fact that these federal R&D investments were not coordinated by any central agency (even within the Defense Department), but were distributed among several agencies with distinct yet overlapping agendas. NASA and the DoE, for example, pursued their own networking initiatives in parallel with ARPANET during the 1970's, and DoD spending paralleled and occasionally duplicated NSF grants. In fact, the NSF's greatest single contribution to the

diffusion of the Internet was the NSFNET program, which was initiated and carried out during a period of declining defense-related R&D investments in information technology. In an environment of technological uncertainty, this diversified and pluralistic program structure, however inefficient, appears to have been beneficial.

Despite considerable publicity, the Clinton Administration's initiatives in the "National Information Infrastructure" area involved modest new funding and consisted primarily of loose coordination among federal agencies of their programs in the computing and information technology areas (Kahin, 1997). The NII initiatives' most significant contributions may lie in their support for the pro-competition provisions of the 1996 Telecommunications Act, rather than in any R&D or investment funding. In some respects, the various advisory and interagency groups that comprised the Clinton Administration's NII may represent an interesting innovation in "post-Cold War" technology policy. Rather than allocating federal R&D investment funds or committing these funds to a particular technological architecture, these groups provided a forum for consultation and limited coordination among federal agencies and between the public and private sectors. These efforts primarily focused on promoting the development of the Internet infrastructure that by the mid-1990s was already expanding rapidly due to private investments.

Other federal policies

The role of the federal government in the development and diffusion of the Internet was not limited to its financial support for R&D, but also worked through federal regulatory, antitrust, and intellectual property rights policies. The overall effect of these (largely uncoordinated) policies was to encourage rapid commercialization of Internet infrastructure, services and content by new, frequently small firms.

AT&T's failure to capture a large share of the computer networking market is a good illustration of the important role played by federal regulatory and antitrust policy. The Department of Justice's 1949 antitrust lawsuit against AT&T was settled by a 1956 consent decree that was modified in the 1982 conclusion to the federal antitrust suit

against AT&T that was filed in 1974. The FCC hearings, "Computer I and II," (decided in 1971 and 1976 respectively) declared that computing lay outside the boundary of AT&T's regulated monopoly (Weinhaus, 1988). The 1956 consent decree and the FCC hearings imposed significant restrictions on AT&T's activities outside of telecommunications services. As a result, several of Bell Laboratories' major information technology innovations, including both Unix and the C programming language, were licensed on liberal terms and diffused extensively. Unix in particular was widely adopted within the academic community and played a major role in the diffusion of TCP/IP.

Federal telecommunications policy, particularly the introduction of competition in local markets following the 1984 break-up of AT&T, also affected the evolution of the Internet in the United States. The 1984 Modified Final Judgment stipulated that Regional Bell Operating Companies (RBOCs) would not be allowed into long distance until they established competitive local markets. This meant allowing Competitive Local Exchange Carriers (CLEC's) to connect to the network infrastructure on reasonable terms that would allow them to compete in various retail markets. The spread of local competition promoted the widespread availability of affordable leased lines that allowed commercial ISPs to connect their networks to IX points, long-haul carriers, and one another.[29] The Telecommunications Act of 1996 reinforced competition in markets for broadband data communication.

State and federal regulations in the pricing of telecommunications services also aided the domestic diffusion of the Internet. State regulators have long enforced low, time-insensitive rates for local telecommunications service, in order to encourage the broadest possible access to local phone service. Regulators extended this time-insensitive pricing policy to ISPs. Most ISPs established their modem-banks within the local loop and were classified by the FCC as "enhanced service providers." This classification was reaffirmed in the FCC's May 1997 "Access Reform Order," and ensured that ISPs did not have to pay the same per-minute access charges that long-distance companies pay to local

telephone companies for use of the network. Unmetered local access for residential telephone services encouraged the growth of the ISP industry in local markets and the widespread diffusion of the network among residential customers, who are less sensitive to the amount of time spent online than their counterparts in countries with metered pricing for local telephone service.[30] By comparison with the United States, most countries were slower to institute deregulatory and other structural changes in telecommunications (see Figure 3.1) that appear to have promoted the diffusion of the Internet by encouraging competition in infrastructure markets and by lowering the price of Internet access.

U.S. intellectual property rights (IPR) policy also affected the evolution of the Internet, although the influence of IPR policy is less obvious and direct than that of antitrust policy or telecommunications deregulation. Many of the key technical advances embodied in the Internet (such as TCP/IP) were placed in the public domain from their inception. This relatively weak intellectual property rights regime reflected the network's academic origins, the Defense Department's support for placing research into the public domain, and the inability of proprietary standards to compete with the open TCP/IP standard. The resulting widespread diffusion of the Internet's core technological innovations lowered barriers to the entry by networking firms in hardware, software and services. Although patent rights in the United States have been strengthened significantly since 1980, this policy shift did not initially affect the software-based architecture and protocols at the heart of the Internet.[31] Intellectual property rights for Internet-related software and services recently have been strengthened by federal judicial decisions and other developments, and they are likely to exercise a greater influence over the future evolution of the Internet.

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[29] The absence of a single dominant telecommunications service provider in Finland, where several dozen firms have provided telecommunications services for much of the 20th century, also appears to have contributed to the rapid diffusion of the Internet in that nation.

[30] As we note below, metered pricing of local telephone service is associated with lower penetration rates for the Internet in other industrial economies.

[31] The Internet helped to spawn the Free or Open Source software movement, which has taken an extremely strong stance against the use of patents and copyright in the software industry.

The Role of the Private Sector

Our emphasis thus far on the numerous examples of successful publicly funded R&D in Internet-related technologies should not be construed as suggesting that private R&D and related investments were unimportant to the development and diffusion of the Internet. Private-sector institutions played important roles in inventing, diffusing and commercializing the Internet. Privately financed research led to the development of several basic networking technologies, including networking hardware, Unix and the Ethernet protocol.[32] Start-up firms were crucial to the commercialization of Internet-related innovations. And perhaps most importantly, U.S. industry invested heavily in information technology during the 1980s, supporting the eventual rapid diffusion of the TCP/IP network during the 1990s.

Although we lack data on the size of corporate R&D investments in the development of Internet-related technologies, several firms made major contributions to networking research. Two of the standards contributed by the corporate research community, Unix and Ethernet, arguably were as influential as TCP/IP in supporting the diffusion of the Internet.[33] The proprietary network architectures and protocols developed during the 1980s by a number of large firms, such as IBM's SNA architecture, remain significant. Interestingly, very few of the corporate developers of these advances, most of whom were large firms, reaped significant profits from their innovations. The growth and stock market performance of open-architecture entrants such as 3Com rapidly outstripped those of larger incumbents that focused on proprietary solutions.

Small firms and startups, many of which had close links to U.S. university researchers, also played an important role in commercializing networking technology. Beginning

[32] Ethernet was developed by Robert Metcalfe at the Xerox Palo Alto Research Center (Xerox PARC) in 1972. It is the most widely used protocol in the many corporate, academic and institutional Local Area Networks (LANs) that comprise the Internet. Unlike TCP/IP, which operates through gateways to connect different networks, Ethernet governs the operation of computers on a single network that share a physical connection.

[33] Both Unix and Ethernet were developed within the private sector, but quickly became part of the public domain. Critics who note that Xerox failed to capture most of the surplus generated by the invention of Ethernet tend to overlook the link between openness and the success of the standard, as well as the complementary relationships between Ethernet and other Xerox-owned technologies in fields such as laser printing.

with BBN's contract to build the first IMP, small private firms commercialized a number of important Internet-related innovations. Start-ups contributed to the development of the basic Internet infrastructure (BBN, Novell, 3Com) and expanded the market for Internet service (AOL, Prodigy, Compuserve). The importance of new firms in networking and Internet services echoes their importance in other postwar U.S. information technology industries, such as semiconductors and software.

A third major contribution of private sector institutions was their sustained level of investment in the information technology that provided the foundation for the domestic adoption of the Internet. Data from the U.S. Department of Commerce indicate that expenditures on software and information technology accounted for 24 percent of total U.S. private fixed investment in 1970, $8.31 billion in constant 1996 dollars. IT's share of annual private sector investment flows grew during the next thirty years, exceeding 30 percent throughout the 1980s and remaining above 40 percent during the 1990s, reaching $542.2 billion in constant 1996 dollars by 1999. This investment in computing power created a huge installed base of hardware that could be attached to the network, an attribute shared by few other industrial nations. Moreover, much of this hardware was already attached to some type of network, whether an office LAN running Ethernet or the Wide Area Network of an online service provider. Adoption of the Internet involved little more than connecting these various networks and installing TCP/IP on each of the computers.

Internet Commercialization and the Changing U.S. Innovation System

The commercial exploitation of the Internet that began in the 1990s drew on federal investments in network infrastructure that originated in the Cold War era. Many of the institutions that contributed to the development of the Internet also played a role in its explosive commercial growth, but the role of others declined in importance during the post-Cold War period of the 1990s. This shift reflected both the maturation of the technology and underlying changes in the structure of the U.S. innovation system. Although antitrust and deregulatory telecommunications policies remained influential, defense spending on basic R&D came to be overshadowed by private sector R&D

investment. Commercialization was fueled by the availability of capital in a healthy macroeconomic environment and the unique opportunities associated with a large and technologically sophisticated domestic market.

As the population of Internet users continued to grow throughout the 1990s, many businesses quickly moved online, producing a dramatic surge in the number of .com hosts and in the visibility of the 30 year-old network. U.S. financial markets played a key role in the commercialization of the Internet by ensuring a robust supply of equity and venture-capital financing for new firms (Gompers and Lerner, 1999). Figure 2.1 shows the growth in U.S. venture capital funding of technology start-ups between 1995 and 2000. The important role of venture capitalists in supporting the creation of new firms for commercial exploitation of the Internet parallels their roles in the development of the semiconductor, computer, and biotechnology industries in the postwar U.S. economy (Mowery and Rosenberg, 1993, 1998).

The large size of the U.S. domestic market and its heavy investments in information technology also accelerated Internet commercialization. The diffusion of personal computers in the home and workplace established a large domestic market that was standardized around two desktop computing platforms (Apple and the IBM-PC). This large, uniform "installed base" created private fortunes in packaged software as well as the creation of a large domestic market for the commercialization of consumer Internet applications, including e-commerce. As a result, U.S. firms were first-movers in many hardware, software and networking applications and products. Many of these firms took advantage of the scale economies characteristic of both hardware and software products to gain large leads in supplying the global market for Internet-related products and services.

The Internet explosion of the 1990s in the United States relied on close university-industry links, an abundant supply of venture capital, an increasingly active antitrust policy, and a deregulatory posture in telecommunications. Most if not all of these policy elements have been important factors within the U.S. innovation system since 1945,

although the type of intra-governmental and public-private coordination exemplified by the NII contains some novel elements within civilian technology policy. Defense-related procurement, which played a prominent role during earlier stages of the Internet's development, was not an important factor during the 1990s. Defense-related R&D investment in Internet-related fields, such as computer science, also declined modestly throughout the decade, although cutbacks in DoD R&D investments in computer science were more than offset by increased investments from other federal agencies such as NSF and the Department of Energy (National Research Council, 1999b, pp. 83-84). The relatively open intellectual property rights regime that typified the development of Internet infrastructure also appears to have shifted towards a "pro-patent" posture. Finally, the shift in U.S. macroeconomic policy from its destabilizing posture during the 1970s and 1980s toward a much more stable posture during the 1990s assuredly contributed to the capital investment boom that underpinned the domestic diffusion of the Internet.

4. The Internet in Other Industrial Economies

Although the United States was consistently among the leaders in networking research, computer scientists from around the world made significant contributions to the development of the Internet. European academic accomplishments often rivaled those of U.S.-based computer scientists, but the lack of a common public platform as large as ARPANET or NSFNET meant that many European countries lagged the United States in the early stages of Internet development and adoption. The persistence of state telecommunications monopolies, the scarcity of technical talent, and the dominance of English language content on the Internet (which arguably was as much an effect as a cause of Continental lags in Internet adoption) also slowed European adoption. Nevertheless, current measures of Internet adoption indicate that parts of Europe have caught up to or surpassed the United States. This section reviews the historical and statistical evidence on the international diffusion of the Internet.

History

From its beginning, computer networking research was an international endeavor, and a number of European countries established experimental networks during the early years of ARPANET. In 1967, the British networking pioneer Donald Davies (who invented the term packet) developed the National Physical Laboratory Data Network in Middlesex, England. In 1972, Louis Pouzin led a French effort to build an ARPANET replica called CYCLADES. Experimental packet-switched networks were developed and tested throughout Europe during the next decade, but the research community on the continent never developed a unified networking platform comparable to the ARPANET.

During the early 1980's the first links between U.S. and European networks were established and experiments in intra-European and U.S.-European collaboration began. In 1982, the first international ARPANET nodes were established at University College in London and at NORSAR, a research laboratory in Norway, and two new European research networks, EUNet (European Unix Network) and EARN (European Academic and Research Network), were launched. EUNet ran the UUCP protocol (Unix to Unix Copy Protocol) and EARN ran a protocol called NJE (Network Job Entry). These networks offered basic services similar to those of ARPANET, such as e-mail and file transfer, to the European academic and research community. NJE was developed by IBM, while UUCP utilized a store-and-forward protocol commonly bundled with the Unix operating system. Ultimately, neither standard achieved the widespread success of the TCP/IP protocol suite, and the European networks grew more slowly than the TCP/IP-based ARPANET.[34]

Perhaps the best-known European networking experiment of the 1980s was the French Minitel service, launched in 1981. In many ways, Minitel was a precursor of the World Wide Web, offering users a variety of services ranging from computer dating to government services, travel reservations, banking and telephone directories. Despite its qualified success within France, however, Minitel did not achieve the success of its eventual successor, the World Wide Web. While some of Minitel's limitations were

[34] Ironically, the decision to use TCP/IP as the standard for the rapidly growing NSFNET was made in 1985 with the help of Dennis Jennings, who came to the NSF from Ireland to help coordinate the transition from ARPANET to NSFNET.

technological, the system was based on a proprietary architecture, rather than the open architecture characteristic of the Internet. Partly because of its closed architecture, the development of new applications for Minitel was more difficult than was true of the Internet, and the smaller commercial opportunities provided by the Minitel further discouraged such development activity. Nevertheless, Minitel was a farsighted, early attempt to bring the benefits of data networking to a large group of users. (OECD, 1998)

Computer users from industrial economies outside the United States began to attach to the NSFNET infrastructure in large numbers towards the end of the 1980s. In 1988, Canada, Denmark, Finland, France, Iceland, Norway, and Sweden connected to the NSFNET. They were followed in 1989 by Australia, Germany, Israel, Italy, Japan, Mexico, Netherlands, New Zealand, and the United Kingdom. Around this time, Reseaux IP Europeens (RIPE) was created by the fledgling European ISP industry to provide the administrative and technical coordination needed to establish a European IP Network. Although RIPE was founded shortly after the major U.S. backbone service providers PSI, UUNET and CERFnet had created CIX, Europe lacked the important complementary factors that propelled rapid growth of hosts and users in the United States during the early 1990s. These complements included an extensive academic network operating on a common platform, a large regional LAN infrastructure, a commercial online services industry, a strong domestic base of network equipment manufacturers, and a huge private investment in computing infrastructure.

The structure of regional telecommunications markets also slowed the development of an ISP industry and the growth of Internet-based commercial business models throughout much of Europe and Japan. The widespread persistence of local telecommunications monopolies and the use of metered access charges for local telephony limited Internet usage and restricted entry by ISPs. Figure 3.1 illustrates the lag in telecommunications deregulation of many OECD countries relative to the United States. As late as 1997, fewer than half of the OECD member economies had significant domestic competition in telecommunications services. Figure 3.2 shows the relationship between Internet access charges and adoption rates for the OECD countries. Not surprisingly, the figure depicts a

downward sloping “demand” for Internet services (i.e. higher access charges are associated with slower diffusion rates for the technology). Additional evidence on the relationship between telecommunications pricing and network diffusion is provided by the high penetration of both Internet hosts and secure servers in Australia, Canada, New Zealand and the United States, the four OECD countries with unmetered pricing of local telecommunications services. (OECD, 2000 p. 30)

Despite the apparently slower pace of Internet adoption in some European economies, by the late 1980s the Internet had been widely adopted throughout the industrial economies. Slight lags in infrastructure development or the adoption of new services can easily be overcome in an environment characterized by double-digit compound growth rates in both investment and use. Indeed, international statistics on Internet adoption suggest that several European countries had surpassed the United States in various measures of Internet penetration by the late 1990s. Nonetheless, even these economies appear to lag the United States in the adoption of e-commerce (see below).

International Adoption and Diffusion Patterns

The data on Internet hosts used to construct Figure 1.1 and several of the other statistics presented below are from a census of Internet hosts originally run by Network Wizards and now maintained by the Internet Software Consortium. This project tracks Internet hosts dating back to the first computers on the original ARPANET, and is one of the best-known sources of data on network growth and diffusion. Although these data provide measures of aggregate adoption that extend back to the formative days of the Internet, meaningful international comparisons are not available until the 1990’s, when the network had been widely adopted in the largest and wealthiest economies. Even as the Internet penetrated more nations, however its growth remained very rapid in the regions that originally had dominated its adoption. This section discusses the diffusion of the Internet during the 1990s, supplementing direct measures of network adoption with a variety of telecommunications infrastructure indicators collected by national regulatory authorities and the OECD.

One measure of the international diffusion of the Internet is the number of countries with Internet access, proxied by the number of country-specific top-level domains, such as .uk (United Kingdom) or .de (Germany). Figure 3.3 shows the rapid growth in country-specific top-level domains between 1991 and 1997. All of the OECD countries were connected to NSFNET prior to 1991, and much of the developed world was connected to the network by 1993. The rapid growth after 1994 corresponds to late-adopting African and Asian countries as well as a number of smaller nations. By 1997, with a few small exceptions, the Internet had reached every corner of the globe.

Host counts provide another indication of the relative intensity of Internet use within different regions.[35] Figure 3.4 depicts growth in the total number of Internet hosts for five major geographic regions during the 1986-2000 period on a logarithmic scale. Within each of these regions, the number of Internet hosts grew exponentially during this period. The roughly parallel growth trends for each region depicted in the figure suggest that the United States and Canada are about one year ahead of Europe and as much as four years ahead of Asia in overall Internet adoption, with the rest of the world lagging considerably behind. The continuing rapid growth of the network in North America makes it difficult to predict when or whether this international "adoption gap" will begin to close. Infrastructure indicators, such as the global distribution of Internet Exchange points (IX's) shown in Figure 3.5, provide a similar picture of the size of regional networks.[36]

Host counts and IX counts indicate the absolute size of regional networks but do not provide a useful metric for international comparisons of the intensity of utilization in different regions; nor do they provide a basis on which to predict future growth. Per

[35] The top-level domain of each host computer provides a good indication of that hosts country of origin. While many top-level domain names indicate the country of origin directly (e.g. .de for Germany or .uk for England) this is problematic for a few countries—notably the United State—where the majority of hosts have a "generic" top-level domain, such as .com or .edu. There is, however, a limited amount of information on the domain name registration system that allows allocation of these generic top-level domains (gTLDs) among countries. We have chosen to allocate gTLDs based on the gTLD registration data for 1998 published by Imperative, Inc. and published in the OECD Communications Outlook 1999.
[36] The number of IX's around the world—and particularly in the US—is now growing so rapidly that there is a reasonable level of uncertainty about the figures, but across various counts, the relative size of regional networks appears fairly consistent.

capita measures of computer and Internet penetration and statistics on infrastructure investment are needed to address these questions. The per capita host counts in Figure 3.6 were constructed by the OECD using data from Network Wizards. This comparison indicates that several Nordic countries have achieved higher rates of penetration of the Internet than the United States and Canada, which lead the rest of the industrial economies. The relatively high levels of Internet penetration in countries like Finland may be associated with that nation's historically competitive telecommunications industry structure, in addition to high levels of domestic adoption of personal computers, currently the most common method of Internet access, within these nations.[37] One measure of the potential for future Internet growth in various national economies is the extent of network penetration relative to PC ownership (Figure 3.7). The United States and several Nordic countries have achieved relatively high levels of per-PC connectivity, indicating that short-run network growth opportunities may be greater in other large European countries that currently have lower shares of their large domestic PC installed base connected to the Internet.

Another indicator of the potential for future Internet growth is the worldwide investment in data networking capacity. Investments in bandwidth are necessary for the growth of Internet infrastructure, and promote Internet adoption through the downward pressure they exert on prices for telecommunications services. Investments in bandwidth also reflect investors' expectations of growth in the demand for capacity required to link new devices, applications, and users to the global network. Figure 3.8, which shows FCC projections of the total available trans-Atlantic and trans-Pacific bandwidth originating in the United States, illustrates the dramatic surge in bandwidth that will accompany the arrival of several new fiber-optic lines during 1999 and 2000. OECD forecasts of capacity and pricing trends around the world also suggest that declining prices for leased lines will continue to encourage expansion of the Internet and electronic commerce (OECD, 1999b p. 5).

[37] With the rapid adoption of Internet-capable cell telephones and other handheld electronic devices, PC connectivity is likely to become a less reliable indicator of Internet penetration. Adoption of some of these devices, such as Internet-capable cell phones, is occurring more rapidly outside of the United States.

In addition to evidence on the growth and regional penetration of the Internet, more limited data illustrate global trends in Internet use, especially the commercialization of Internet content during the late 1990s. The share of different top-level Internet host domains (".edu," ".com," ".gov," etc.) is one indicator of change over time in Internet content within the global network. Figure 3.9 shows the total number of Internet hosts within the six major generic top-level Internet domains between 1996 and 2000. Hosts within the .edu and .org domains correspond to the academic institutions and quasi-academic governance organizations that were the earliest adopters of the Internet, and the majority of .com and .net hosts are owned by commercial organizations and private network service providers. The rapid growth of .com and .net hosts and domain name registrations illustrate the explosion of commercial Internet content discussed above.[38]

A clearer picture of contrasts in national adoption of e-commerce applications is provided by data from a census of Secure-Sockets Layer (SSL) servers conducted by Netcraft and published by the OECD (OECD, 1999). SSL is a protocol used by commercial websites to encrypt sensitive information, such as credit card numbers, before transmitting it over a network. The number of Internet hosts using SSL therefore is a reasonable proxy for the number of e-commerce sites within a given domain. Figure 3.10 shows the number of SSL servers per capita as calculated by the OECD, and suggests that the United States appears to be the world leader in adopting e-commerce, based on the per capita level of encryption-enabled Internet servers.[39] Surprisingly, this measure suggests that the Nordic states with high Internet penetration rates have been slower to adopt e-commerce than other nations, such as New Zealand and Australia.

[38] This figure understates the actual growth in commercial Internet content because it fails to account for the many non-US commercial sites registered under country-specific top-level domains (e.g. www.amazon.de).

[39] This indicator of e-commerce adoption is not without problems. In particular, U.S. statistical leadership may simply reflect the much larger number of U.S. websites—the United States almost certainly leads among industrial nations in the number of ".com," ".edu," and ".gov" sites per capita. But the available alternative measure of e-commerce adoption, the ratio of "SSL Hosts / Total Internet Hosts" on a per-country basis, is difficult to interpret. SSL servers constitute an extremely large share of total hosts in small countries (e.g. Poland) with relatively few overall Internet hosts. Pornographic sites also exercise a disproportionate influence within simple counts of e-commerce hosts. We believe that the per-capita SSL host count is the best available measure of e-commerce adoption within individual nations.

As a whole, these statistics on Internet adoption underscore the importance of the relationships among domestic telecommunications regulation, telecommunications infrastructure, and Internet adoption. Although the United States arguably is no longer the indisputable leader in Internet utilization, the United States appears to be a leader in e-commerce applications. These statistics also reinforce the central statistical fact about the Internet as a general purpose technology—its remarkable rate of growth. In spite of the significant national and regional differences in the adoption of network infrastructure and applications, the Internet has grown and continues to grow at an exponential pace within the global economy.

5. Conclusion

In a recent review of the "New Economy" debate, the OECD pointed out that the 1990s were characterized by a pattern of growing divergence in GDP per capita among OECD member economies (OECD, 2000), and argued that information technologies, including the Internet, have played a key role in facilitating these developments.[40] Moreover, the report argues that divergence among member economies in their performance during the late 1990s could prove to be enduring. In this view, the first-mover advantages enjoyed by U.S. firms in exploiting the Internet rely in part on demand-side scale economies within a global information-technology marketplace. The ultimate effects of U.S. leadership in commercial application development, however, remain unclear. As the American economy and equity markets slowed during 2001, the level of investment in Internet businesses has declined. Moreover, the rapid growth of the Internet outside the United States may allow other industrial economies to "catch up" in the development of commercial applications. The United States also lags much of the developed world in the adoption of wireless technologies (cell phones), and other nations, especially in Europe, are poised to leapfrog the U.S. in developing commercial applications for a wireless Internet.

[40] The OECD report also acknowledges that the economic effects of the large-scale adoption of the Internet cannot yet be observed in aggregate economic data (OECD, 2000, pp. 56-57).

The Internet's development began nearly 40 years ago, and its diffusion is still unfolding. It is impossible to forecast the ultimate effects of this "general purpose technology" on incomes, economic growth, and the conduct of our daily lives. The rapid diffusion of the Internet during a period of strong U.S. economic performance has fueled speculation about the role of the network in creating a new economy. But the full economic impact of the Internet will not be felt for some time, and its effects may never admit of easy measurement. Nevertheless, preliminary indications are that the Internet's effects on all of these areas are likely to be profound. The network of networks that is the Internet began as a small publicly funded experiment run largely by academics, but it has grown into a global enterprise requiring major private investments in infrastructure and applications, spurring a host of technological and commercial innovations.

Among the important "nontechnological" innovations spawned by the Internet was an unusually informal, yet responsive, set of institutions to manage its evolution and, in particular, to establish technical standards. The ability of these institutions of governance to develop open standards and to adapt these standards rapidly to meet new technical and economic challenges was remarkable, and contributed powerfully to the rapid diffusion of the Internet. The success of these standard-setting institutions may have implications for the governance of related innovations, because of the central importance of technical standards for technological development and market structure in the information technology sector.

Although it drew on important technical advances from foreign sources, the development of the Internet was primarily a U.S-based phenomenon, and drew on many of the same institutions and policies of the postwar U.S. "national innovation system" that were influential in other postwar high-technology industries. The prominent role of Defense Department funding and procurement in the development of the Internet and related technologies is in many respects an artifact of the Cold War era, and DoD funding is likely to play a smaller role in the future evolution of these technologies. The strength and breadth of formal intellectual property rights, whose relative weakness in Internet-related technologies arguably supported the Internet's rapid development, also have been

extended considerably since the early 1980s, with uncertain effects on the future development of the Internet and related technologies. Other elements of the postwar U.S. "national innovation system," however, such as the vibrant equity-finance system and the historically close relationships between U.S. industry and universities, have undergone little if any change. Although many other industrial economies now seek to emulate the remarkable success of U.S. firms in commercializing the Internet, the "transferability" of the web of U.S. policies and institutions, not least the scale of the U.S. domestic market, may limit the diffusion of these business models. In a global economy that is more and more tightly integrated, many of the institutions and policies characteristic of the U.S. national innovation system remain unusual, if not unique, by comparison with those of other industrial economies.

For all its novelty, the development and diffusion of the Internet closely resemble those of other "general purpose technologies," such as the much broader area of information technology or electric power, or such important yet more limited technologies as the airplane. Like all of these major innovations, the Internet underwent a prolonged period of "gestation" that dates back more than 30 years (the first "node" was inaugurated in 1969). Although the current Internet relies on the same basic protocols and principles as its predecessor of more than 30 years ago, the ease of use and performance of the current Internet have dramatically improved, due in no small part to the remarkable advances in the complementary technologies on which the Internet relies. We confidently predict that this period of incremental refinement and improvement will continue for some years to come. Another hallmark of the Internet, like radio, is the profound uncertainty over its economic applications and effects. The "dot.com depression" of 2000 should give pause to anyone claiming to understand "best practice" for commercial applications of the Internet. Both this uncertainty over applications and the prolonged period of incremental improvement and refinement are hallmarks of virtually all major innovations, and means that the economic effects of the Internet, like those of these other major technical advances, are likely to be realized gradually and through a process of trial and error.

Like other major innovations, the Internet also raises profound challenges to policy in a number of areas. These policy issues will challenge governments in the industrial and industrializing nations alike. For example, further commercialization of the Internet by U.S. firms is likely to require the resolution of policy conflicts among the United States and other industrial economies in areas such as intellectual property and personal privacy. The ability of the Internet to overcome the "tyranny of distance" means that its global diffusion is likely to add to the growing pressure for harmonization of the many policies that affect various national innovation systems. This process will be slow, conflict-ridden, and uneven, not least because of the enduring national uniqueness of many such policies in the United States and other industrial economies. Ultimately, however, the computer network's impact in the policy arena, as in business and technology, will reflect the tremendous breadth and scope of application inherent in this important general purpose technology.

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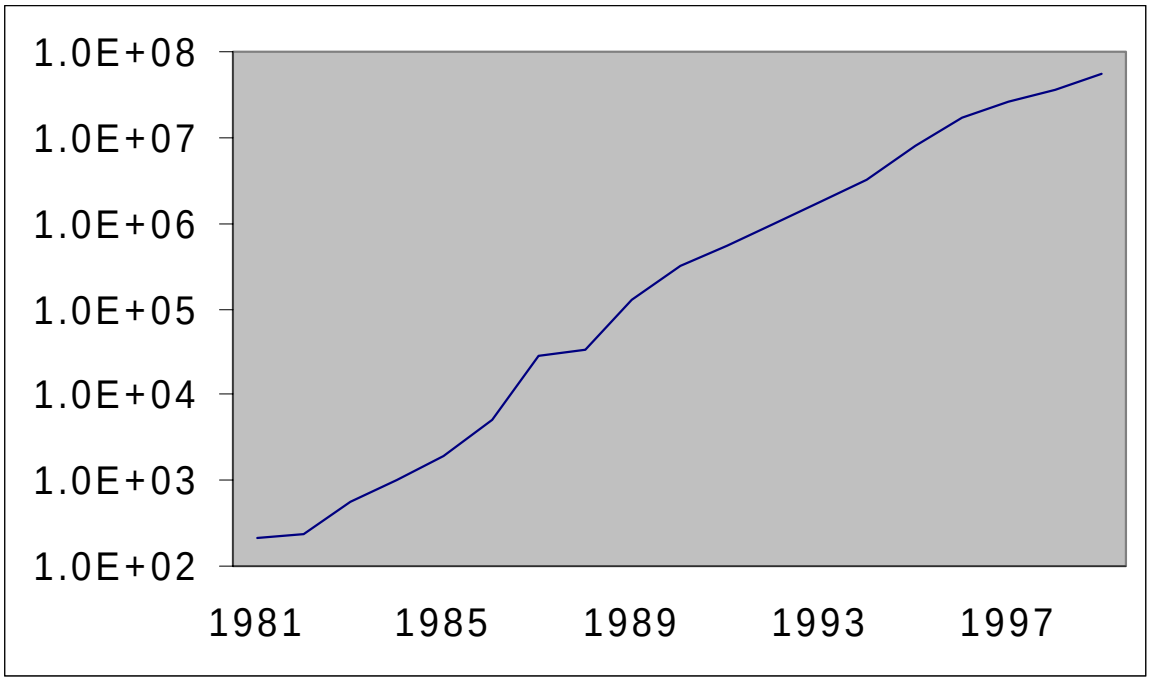
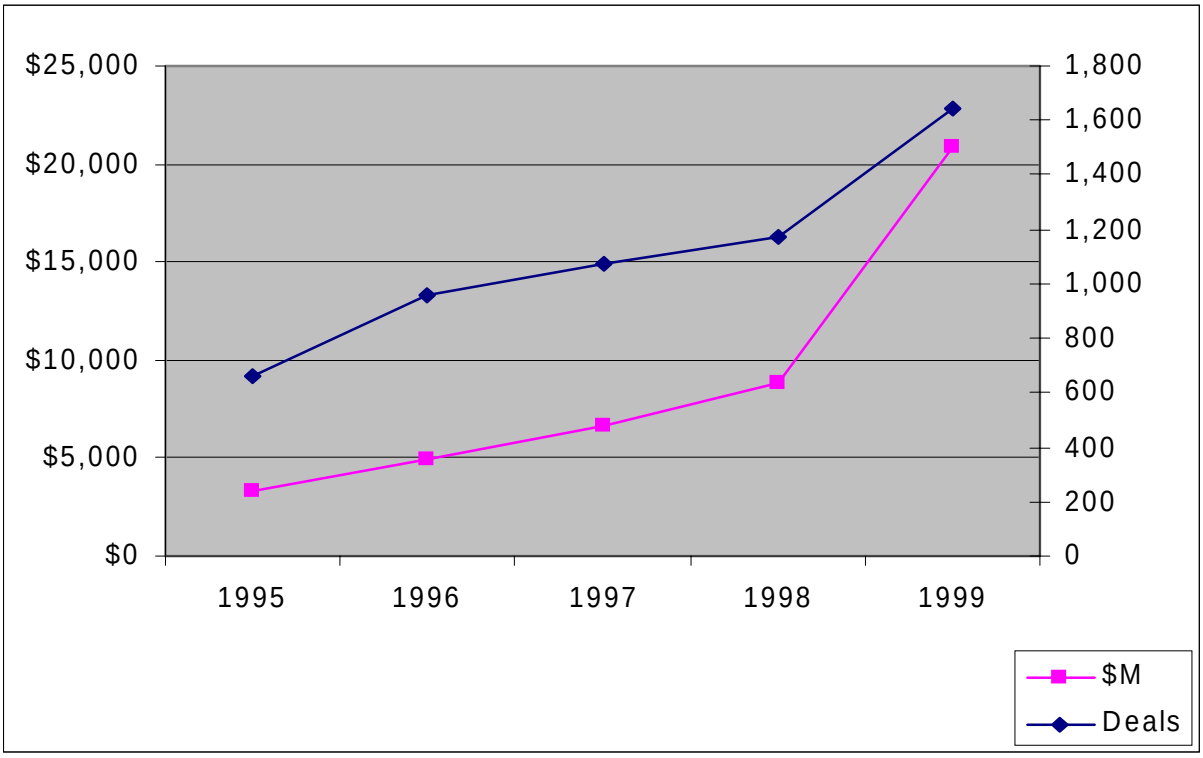
Figure 1.1: Total Internet Hosts



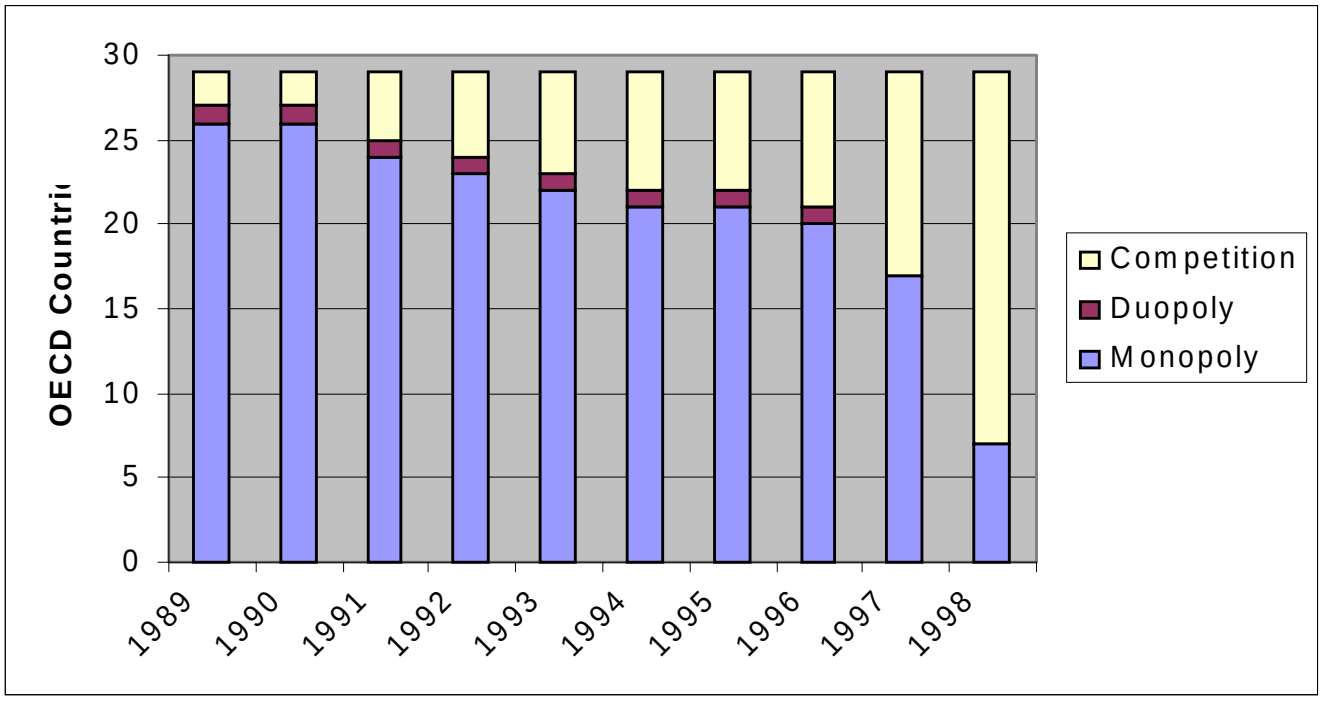
Source: Internet Software Consortium

Figure 2.1: VC Investments



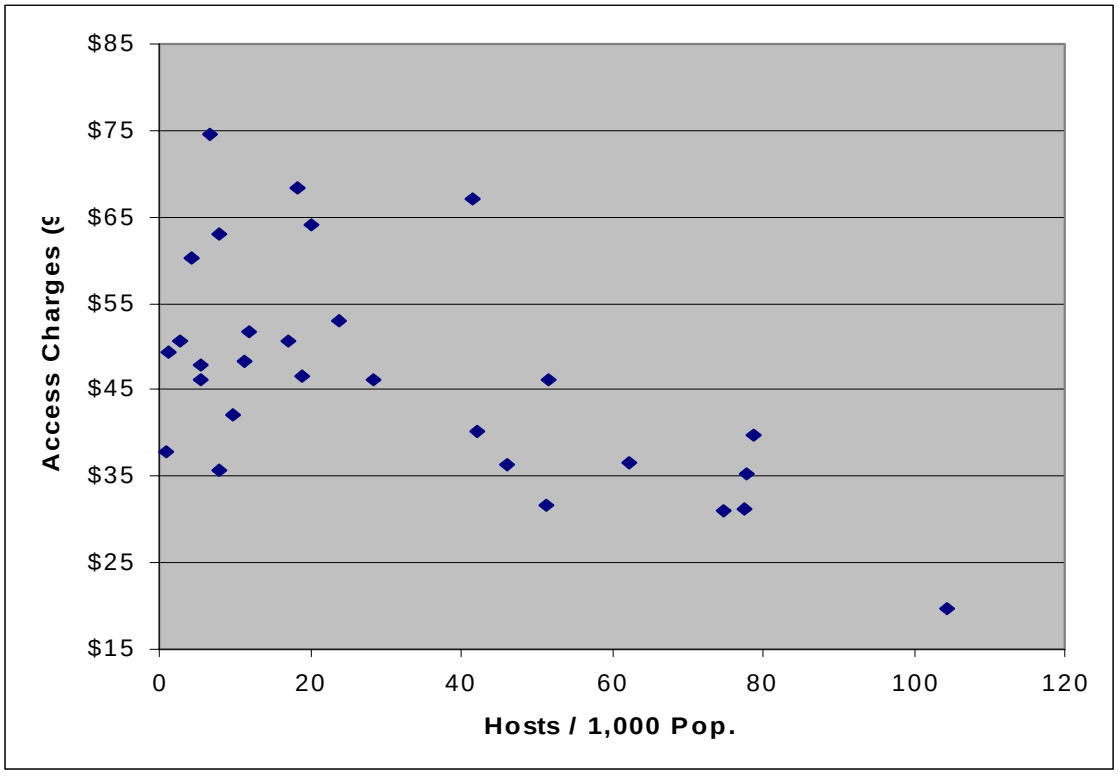
Source: Venture One

Figure 3.1: OECD Telecom Regulation



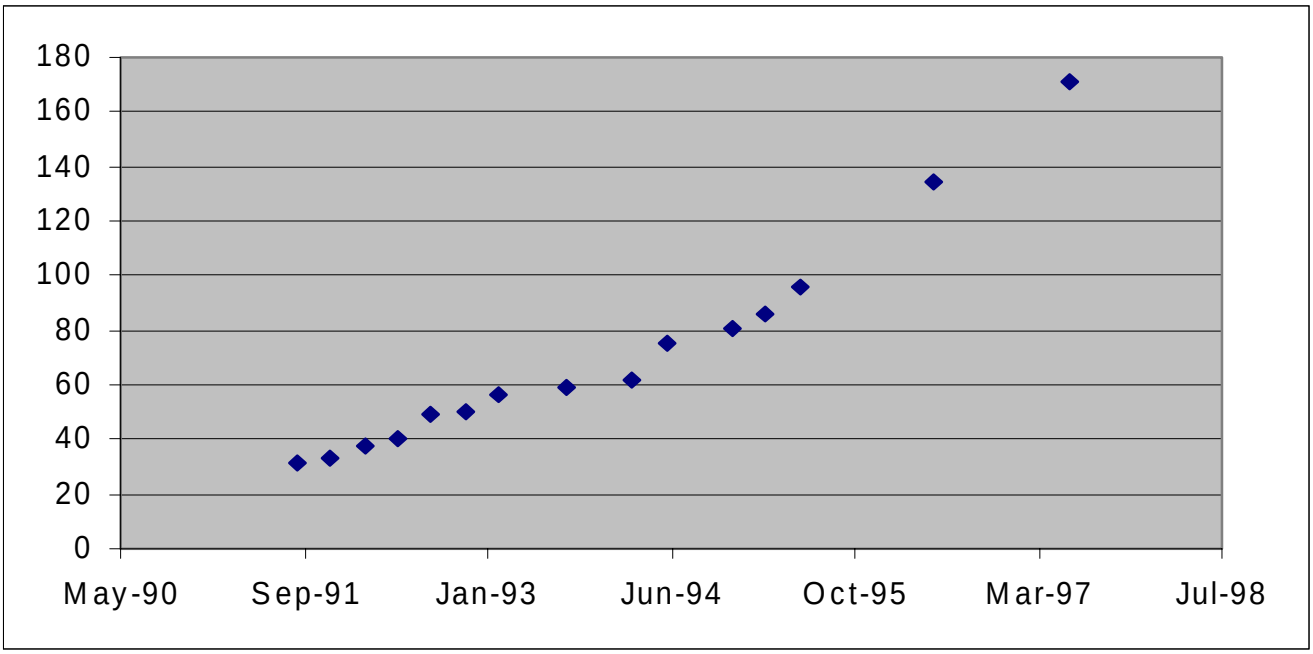
Source: OECD

Figure 3.2: Pricing and Internet Hosts



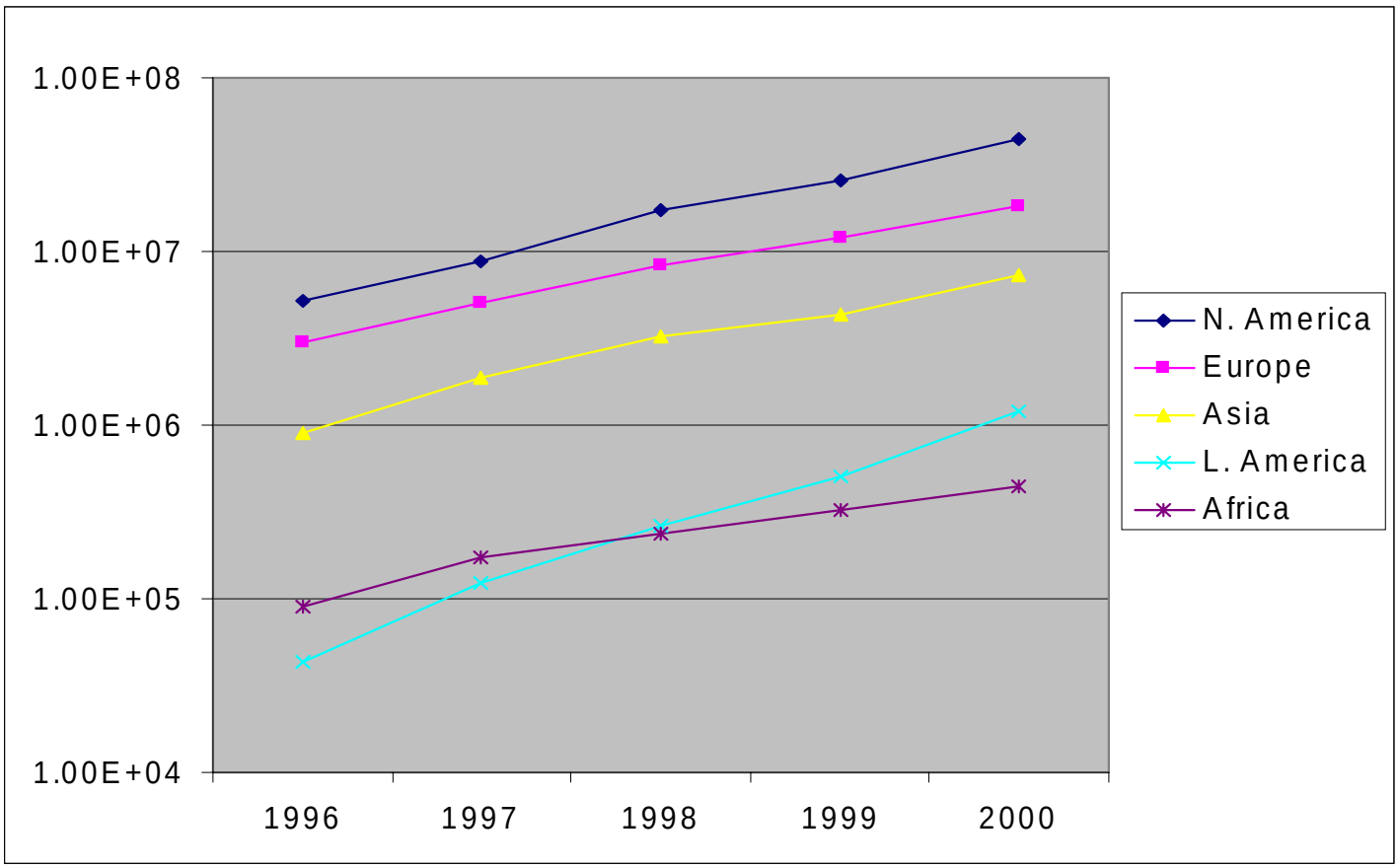
Source: OECD

Figure 3.3: Country-Specific Top-Level Domains



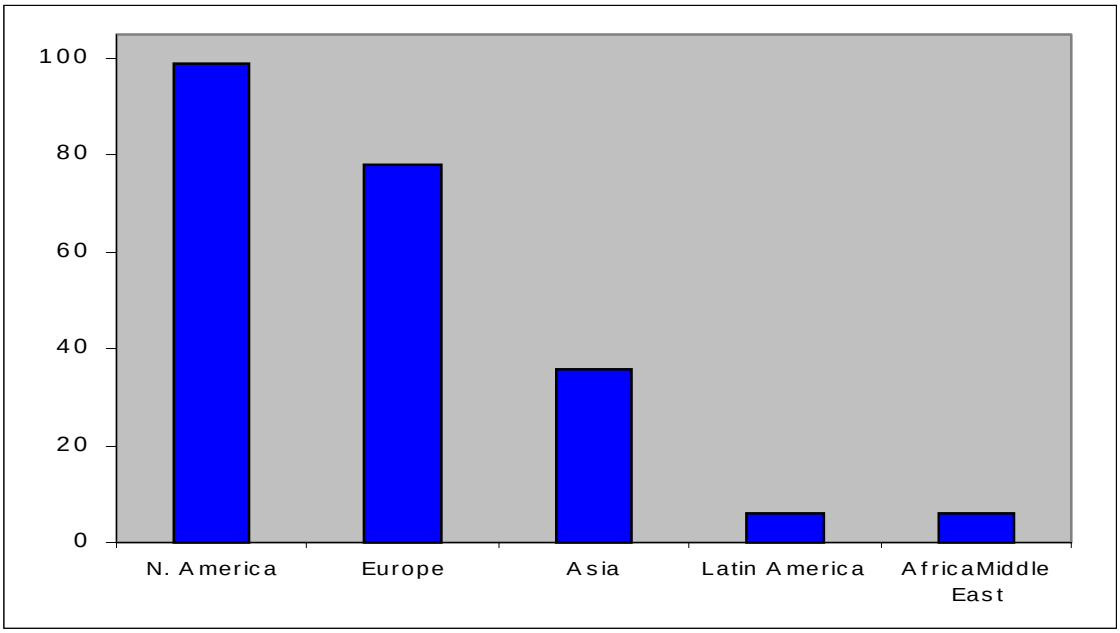
Source: Internet Software Consortium

Figure 3.4: Regional Internet Diffusion



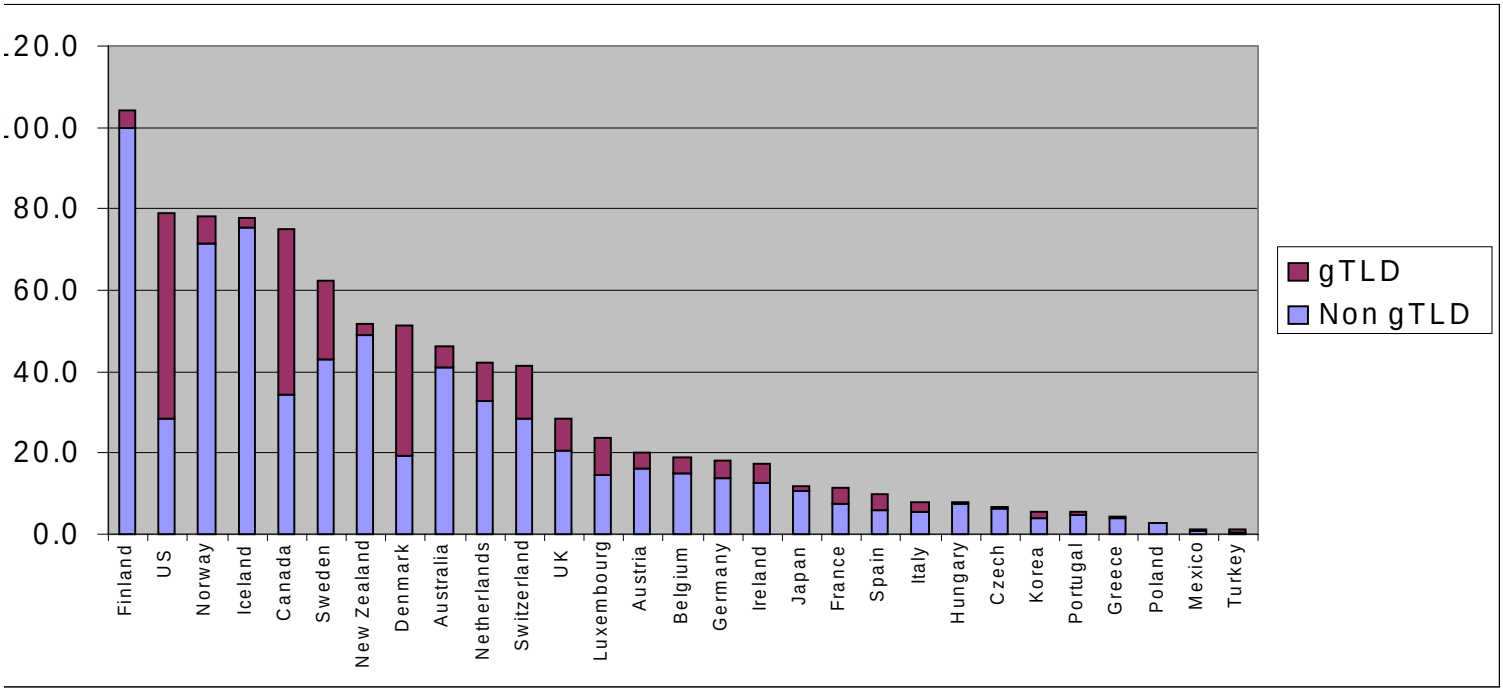
Source: Internet Software Consortium

Figure 3.5: Regional Internet Exchanges



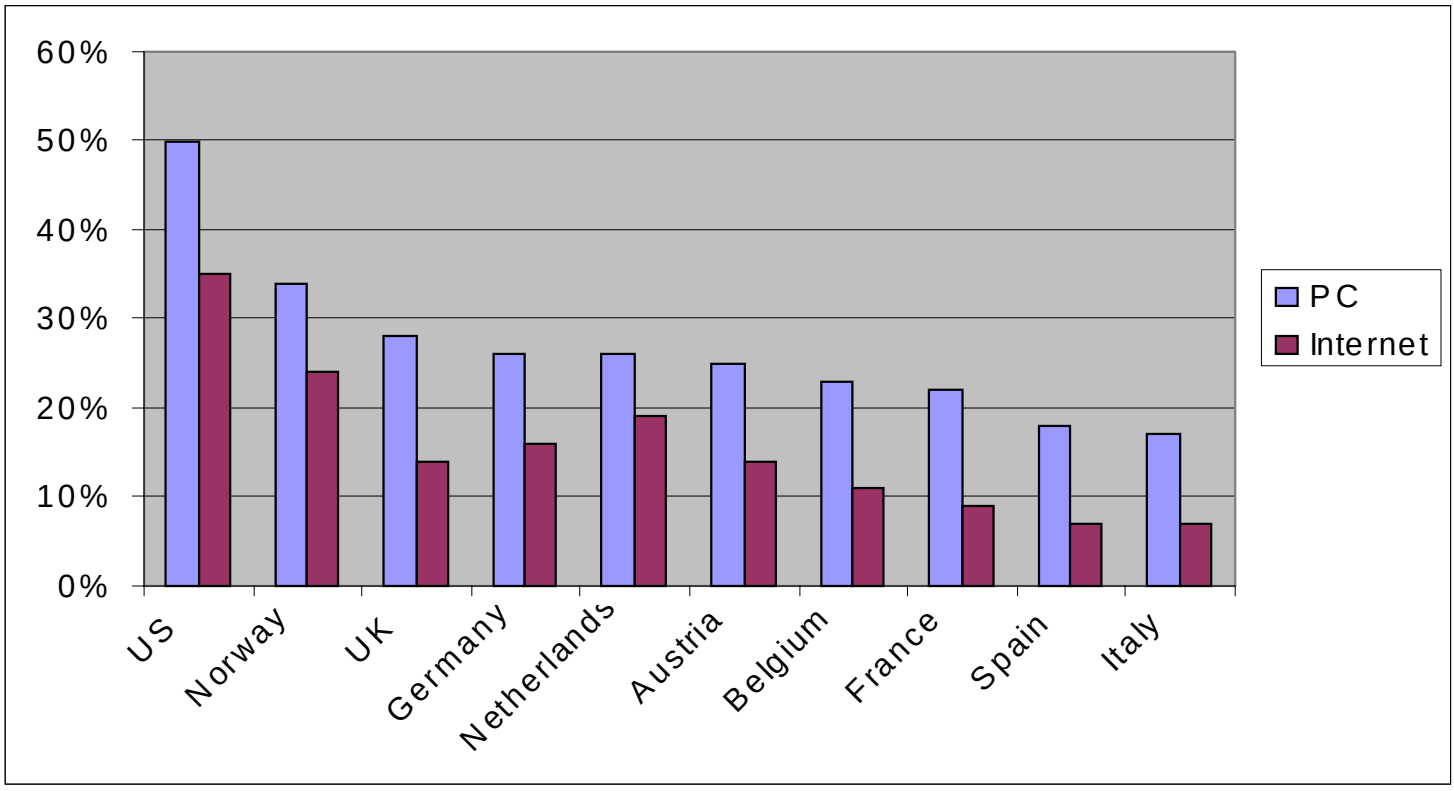
Source: Telegeography

Figure 3.6: Hosts per Capita



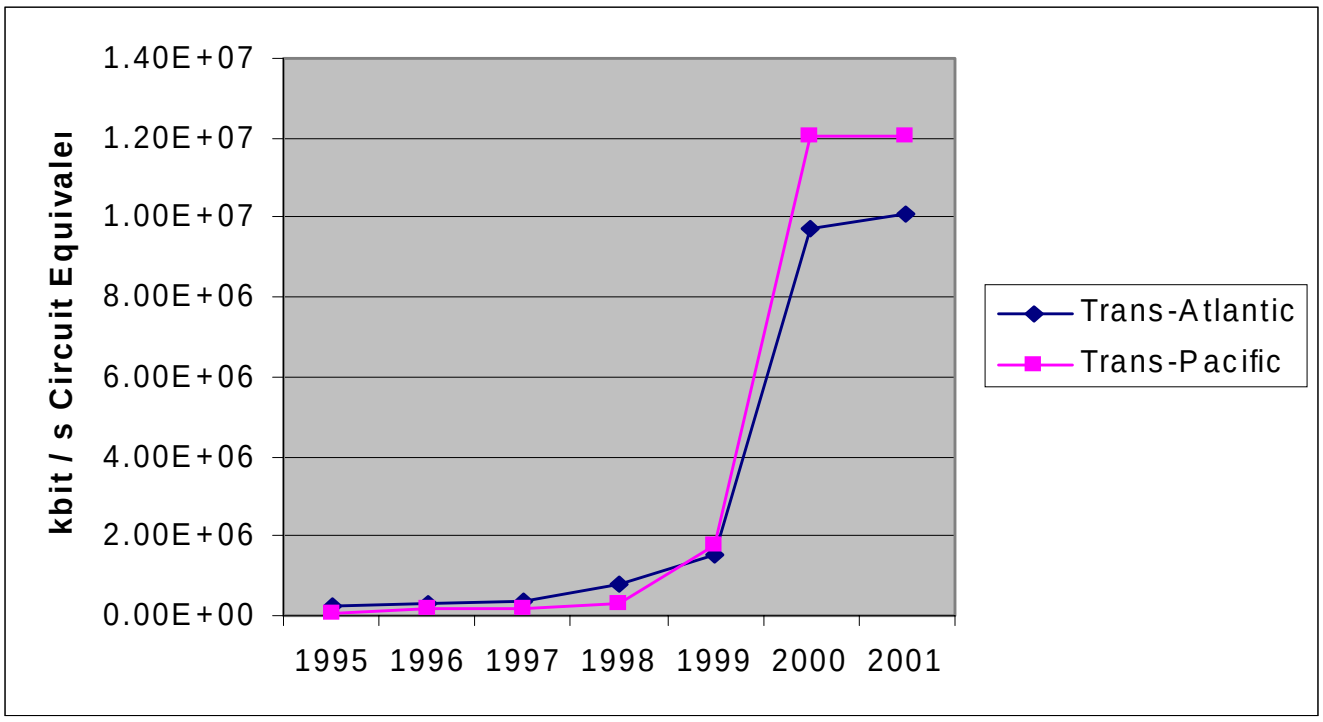
Source: OECD

Figure 3.7: PC & Internet Penetration



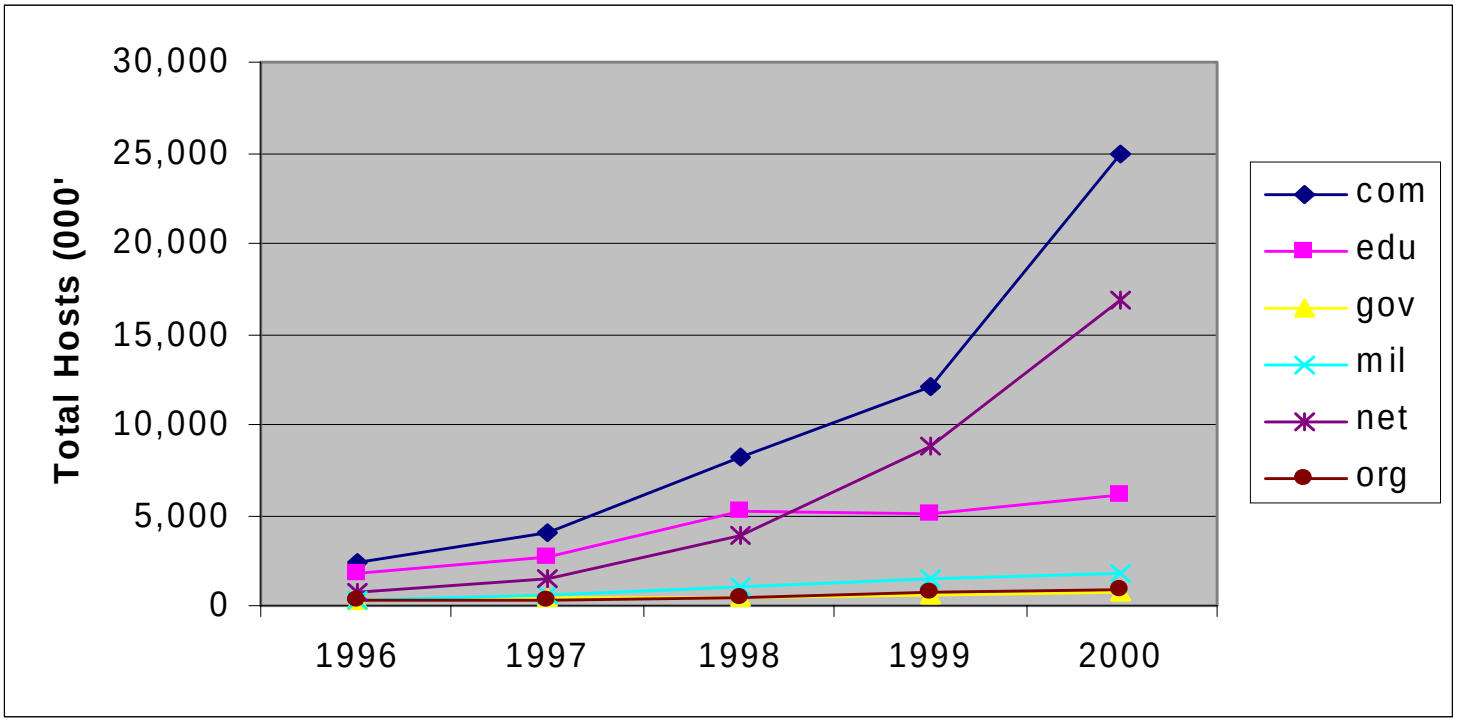
Source: IDC/Goldman Sachs

Figure 3.8: US Network Capacity Expansion



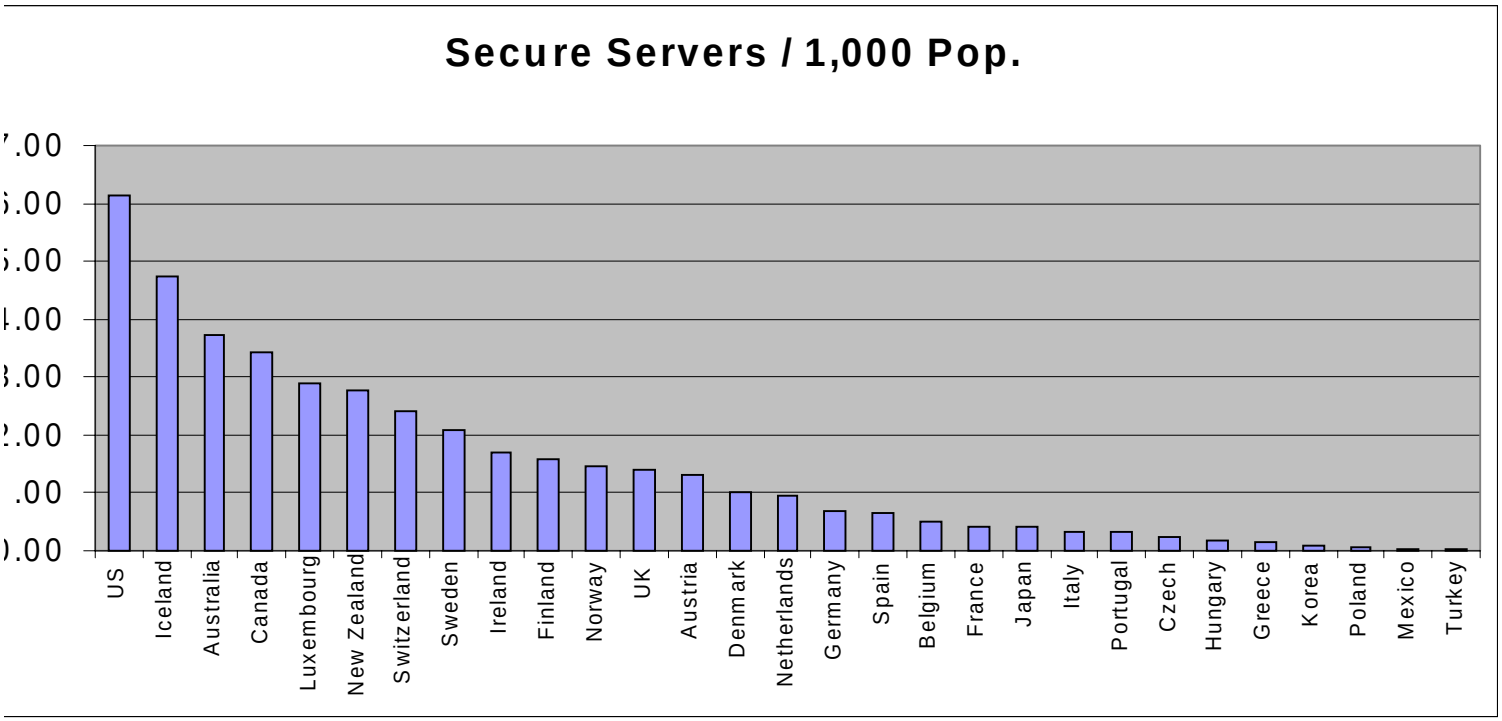
Source: FCC

Figure 3.9: Hosts by Top-Level Domain



Source: Internet Software Consortium

Figure 3.10: Secure Servers per Capita



Source: OECD

Appendix A – An Internet Timeline*

1957

USSR launches Sputnik, first artificial earth satellite. In response, US forms the Advanced Research Projects Agency.

1961

Leonard Kleinrock, MIT: "Information Flow in Large Communication Nets", first paper on packet-switching theory

1964

Paul Baran, RAND: "On Distributed Communications Networks" p acket-switching networks; no single outage point

1965

ARPA sponsors study on "cooperative network of time-sharing computers" -- MIT Lincoln Lab and System Development Corporation (Santa Monica, CA) are directly linked (without packet switches) via a dedicated 1200 bps phone line. Digital Equipment Corporation (DEC) computer at ARPA later added to form "The Experimental Network"

1966

Lawrence G. Roberts, MIT: "Towards a Cooperative Network of Time-Shared Computers" -- First ARPANET plan

1967

ARPANET design discussions held by Larry Roberts at ARPA IPTO PI meeting in Ann Arbor, Michigan
First design paper on ARPANET published by Larry Roberts: "Multiple Computer Networks and Intercomputer Communications
National Physical Laboratory (NPL) in Middlesex, England develops NPL Data Network using 768 kbps lines

1968

Request for proposals for ARPANET sent out in August; responses received in September
University of California Los Angeles (UCLA) awarded Network Measurement Center contract in October
Bolt Beranek and Newman, Inc. (BBN) awarded Packet Switch contract to build Interface Message Processors (IMPs)
US Senator Edward Kennedy sends a congratulatory telegram to BBN for its million-dollar ARPA contract to build the "Interfaith" Message Processor, and thanking them for their ecumenical efforts

1969

ARPANET commissioned by DoD for research into networking
Nodes are stood up as BBN builds each IMP [Honeywell DDP-516 mini computer with 12K of memory]; AT&T provides 50kbps lines
Node 1: UCLA (30 August, hooked up 2 September)
Node 2: Stanford Research Institute (SRI) (1 October)
Node 3: University of California Santa Barbara (UCSB) (1 November)
Node 4: University of Utah (December)
First Request for Comment (RFC): "Host Software" by Steve Crocker (7 April)
First packets sent by Charley Kline at UCLA as he tried logging into SRI. The first attempt resulted in the system crashing as the letter G of LOGIN was entered. (October 29)

1970

First publication of the original ARPANET Host-Host protocol: C.S. Carr, S. Crocker, V.G. Cerf, "HOST-HOST Communication Protocol in the ARPA Network," in AFIPS Proceedings of SJCC
ARPANET hosts start using Network Control Protocol (NCP), first host-to-host protocol
First cross-country link installed by AT&T between UCLA and BBN at 56kbps.

1971

Ray Tomlinson of BBN invents email program to send messages across a distributed network.

1972

Ray Tomlinson (BBN) modifies email program for ARPANET

Larry Roberts writes first email management program (RD) to list, selectively read, file, forward, and respond to messages
International Conference on Computer Communications (ICCC) demonstration of ARPANET between 40 machines organized by Bob Kahn.
International Network Working Group (INWG) formed in October as a result of a meeting at ICCC identifying the need for a combined effort in advancing networking technologies.
Louis Pouzin leads the French effort to build its own ARPANET - CYCLADES

1973

First international connections to the ARPANET: University College of London (England) via NORSAR (Norway)
Bob Metcalfe's Harvard PhD Thesis outlines idea for Ethernet.
Bob Kahn poses Internet problem, starts internetting research program at ARPA. Vinton Cerf sketches gateway architecture in March on back of envelope in a San Francisco hotel lobby
Cerf and Kahn present basic Internet ideas at INWG in September at Univ of Sussex, Brighton, UK
ARPA study shows email composing 75% of all ARPANET traffic

1974

Cerf and Kahn publish "A Protocol for Packet Network Interconnection" which specified in detail the design of a Transmission Control Program (TCP). [IEEE Trans Comm]
BBN opens Telenet, the first public packet data service (a commercial version of ARPANET)

1976

UUCP (Unix-to-Unix CoPy) developed at AT&T Bell Labs and distributed with UNIX one year later.

1978

TCP split into TCP and IP (March)

1979

Meeting between Univ of Wisconsin, DARPA, National Science Foundation (NSF), and computer scientists from many universities to establish a Computer Science Department research computer network (organized by Larry Landweber).
ARPA establishes the Internet Configuration Control Board (ICCB)

1981

CSNET (Computer Science NETwork) built by a collaboration of computer scientists and Univ of Delaware, Purdue Univ, Univ of Wisconsin, RAND Corporation and BBN through seed money granted by NSF to provide networking services (especially email) to university scientists with no access to ARPANET. CSNET later becomes known as the Computer and Science Network.
Minitel (Teletel) is deployed across France by France Telecom.
RFC 801: NCP/TCP Transition Plan

1982

Norway leaves network to become an Internet connection via TCP/IP over SATNET; University College London does the same
DCA and ARPA establish the Transmission Control Protocol (TCP) and Internet Protocol (IP), as the protocol suite, commonly known as TCP/IP, for ARPANET
EUnet (European UNIX Network) is created by EUUG to provide email and USENET services. Original connections between the Netherlands, Denmark, Sweden, and UK
Exterior Gateway Protocol (RFC 827) specification. EGP is used for gateways between networks.

1983

Name server developed at Univ of Wisconsin, no longer requiring users to know the exact path to other systems
Cutover from NCP to TCP/IP (1 January)
CSNET / ARPANET gateway put in place
Desktop workstations come into being, many with Berkeley UNIX (4.2 BSD) which includes IP networking software
EARN (European Academic and Research Network) established. Very similar to the way BITNET works with a gateway funded by IBM

1984

Domain Name System (DNS) introduced

Number of hosts breaks 1,000

1986

NSFNET created (backbone speed of 56Kbps)
Internet Engineering Task Force (IETF) and Internet Research Task Force (IRTF) comes into existence under the IAB.
The first Freenet (Cleveland) comes on-line

1987

NSF signs a cooperative agreement to manage the NSFNET backbone with Merit Network, Inc.
UUNET is founded with Usenix funds to provide commercial UUCP and Usenet access.
First TCP/IP Interoperability Conference
Number of hosts breaks 10,000

1988

DoD chooses to adopt OSI and sees use of TCP/IP as an interim. US Government OSI Profile (GOSIP) defines the set of protocols to be supported by Government purchased products
NSFNET backbone upgraded to T1 (1.544Mbps)
CERFnet (California Education and Research Federation network) founded by Susan Estrada.
Internet Assigned Numbers Authority (IANA) established in December with Jon Postel as its Director.

Countries connecting to NSFNET: Canada (CA), Denmark (DK), Finland (FI), France (FR), Iceland (IS), Norway (NO), Sweden (SE)

1989

Number of hosts breaks 100,000
RIPE (Reseaux IP Europeens) formed by European service providers
First relays between a commercial electronic mail carrier and the Internet: MCI Mail and Compuserve

Countries connecting to NSFNET: Australia (AU), Germany (DE), Israel (IL), Italy (IT), Japan (JP), Mexico (MX), Netherlands (NL), New Zealand (NZ), Puerto Rico (PR), United Kingdom (UK)

1990

ARPANET ceases to exist
Electronic Frontier Foundation (EFF) is founded by Mitch Kapor
The World comes on-line (world.std.com), becoming the first commercial provider of Internet dial-up access

Countries connecting to NSFNET: Argentina (AR), Austria (AT), Belgium (BE), Brazil (BR), Chile (CL), Greece (GR), India (IN), Ireland (IE), Korea (KR), Spain (ES), Switzerland (CH)

1991

Commercial Internet eXchange (CIX) Association, Inc. formed by General Atomics (CERFnet), Performance Systems International, Inc. (PSInet), and UUNET Technologies, Inc. (AlterNet), after NSF lifts restrictions on the commercial use of the Net
World-Wide Web (WWW) released by CERN; Tim Berners-Lee developer
PGP (Pretty Good Privacy) released by Philip Zimmerman
NSFNET backbone upgraded to T3 (44.736Mbps)
NSFNET traffic passes 1 trillion bytes/month and 10 billion packets/month

Countries connecting to NSFNET: Croatia (HR), Czech Republic (CZ), Hong Kong (HK), Hungary (HU), Poland (PL), Portugal (PT), Singapore (SG), South Africa (ZA), Taiwan (TW), Tunisia (TN)

1992

Internet Society (ISOC) is chartered
Number of hosts breaks 1,000,000

Countries connecting to NSFNET: Antarctica (AQ), Cameroon (CM), Cyprus (CY), Ecuador (EC), Estonia (EE), Kuwait (KW), Latvia (LV), Luxembourg (LU), Malaysia (MY), Slovakia (SK), Slovenia (SI), Thailand (TH), Venezuela (VE)

1993

US National Information Infrastructure Act
Mosaic takes the Internet by storm; WWW proliferates at a 341,634% annual growth rate of service traffic.

Countries connecting to NSFNET: Bulgaria (BG), Costa Rica (CR), Egypt (EG), Fiji (FJ), Ghana (GH), Guam (GU), Indonesia (ID), Kazakhstan (KZ), Kenya (KE), Liechtenstein (LI), Peru (PE), Romania (RO), Russian Federation (RU), Turkey (TR), Ukraine (UA), UAE (AE), US Virgin Islands (VI)

1994

NSFNET traffic passes 10 trillion bytes/month

Countries connecting to NSFNET: Algeria (DZ), Armenia (AM), Bermuda (BM), Burkina Faso (BF), China (CN), Colombia (CO), Jamaica (JM), Jordan (JO), Lebanon (LB), Lithuania (LT), Macao (MO), Morocco (MA), New Caledonia (NC), Nicaragua (NI), Niger (NE), Panama (PA), Philippines (PH), Senegal (SN), Sri Lanka (LK), Swaziland (SZ), Uruguay (UY), Uzbekistan (UZ)

1995

NSFNET reverts back to a research network. Main US backbone traffic now routed through interconnected network providers
The new NSFNET is born as NSF establishes the very high speed Backbone Network Service (vBNS) linking super-computing centers: NCAR, NCSA, SDSC, CTC, PSC
WWW surpasses ftp-data in March as the service with greatest traffic on NSFNet based on packet count
Traditional online dial-up systems (Compuserve, America Online, Prodigy) begin to provide Internet access
Net related companies go public, with Netscape leading the pack
Registration of domain names is no longer free (NSF continues to pay for .edu registration, and on an interim basis for .gov)

1996

Internet phones catch the attention of US telecommunication companies who ask the US Congress to ban the technology (which has been around for years)
MCI upgrades Internet backbone adding ~13,000 ports, bringing the effective speed from 155Mbps to 622Mbps.
WWW browser war fought between Netscape and Microsoft

1998

Web size estimates range between 275 (Digital) and 320 (NEC) million pages for 1Q
Network Solutions registers its 2 millionth domain on 4 May

* Adapted From: Hobbes' Internet Timeline by Robert H Zakon.

Appendix B – Bandwidth Terms

Network Capacity Terminology

	Bits/Sec	Mbit/Sec	Dowload Time for 5M File
14.4 Modem	14,400	0.01	52 Min.
56k Line	57,600	0.06	12 Min.
128K ISDN	131,072	0.13	5 Min.
T1	1,536,000	1.54	43s
T2	6,144,000	6.3	7s
T3	46,080,000	45	1s
OC-3	155,000,000	150	0.5s
OC-12	600,000,000	600	0.15s
OC-48	2,400,000,000	2400	Na
OC-192	9,600,000,000	9600	Na