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Is the Internet a US invention?—an economic and technological history of computer networking

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Abstract

Although the inventions embodied in the Internet originated in a diverse set of industrial economies, the US was consistently the source of critical innovations and an early adopter of new applications. Why did other nations, including several that made important inventive contributions to the Internet, not play a larger role in its development, particularly in the creation of new business organizations, governance institutions, and applications? We argue that the role of the US "national innovation system" in the creation of the Internet echoes several key themes of US technological development before 1940. The presence of a large domestic market, a set of antitrust and regulatory policies that weakened the power of incumbent telecommunications firms, and a diverse private/public research community that was willing to work with both domestic and foreign inventions were important preconditions for US leadership in computer networking innovation.

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1. Introduction

The Internet is the world's largest computer network—a steadily growing collection of more than 100 million computers that communicate with one another using a shared set of standards and protocols. Together with the World Wide Web (WWW), a complementary software innovation that has increased the accessibility and utility of the network, the Internet stimulated a communications revolution that has changed the way individuals and institutions use computers in a wide variety of activities. The Internet and WWW jointly comprise a "general purpose technology," an innovation 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 regulatory policy, business and finance. Although its development and deployment

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[1] Lipsey et al. (1998) use four criteria to define a technology as a GPT (Bresnahan and Trajtenberg, 1995). Their criteria are the ability to make dramatic technical improvements, the existence and creation of complementary technologies, the breadth of potential applications throughout the economy, and the scope of applications within many particular fields. Although they suggest that the revolution in information and communication technologies based on digital computing is a single GPT, their criteria apply equally well to the Internet in particular.

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occurred largely within the US, the inventions embodied in the Internet originated in a more diverse set of industrial economies. Nonetheless, the US has consistently been a source of critical innovations and 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, did not 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 industrial economies.

The origins and evolution of the Internet highlight several unique characteristics of the postwar US innovation system that have endured in the face of economic globalization and domestic institutional change. At the same time, the development and diffusion of this networking technology within the US draw on several characteristics of the US economy that contributed to its early 20th-century technological development, characteristics portrayed by some scholars as no longer consequential for US economic competitiveness in an age of economic globalization.

In the first stages of the Internet's development, federal defense-related R&D funding played a key role in the creation of an R&D infrastructure of trained researchers and related institutions, including universities. Although scientists and engineers from several countries made significant contributions to the basic research efforts that supplied critical communications technologies, the scale of the publicly funded US R&D programs and of the data networks deployed by these programs exceeded contemporaneous efforts in the UK and France. In addition, the close relationships among academic, defense, and industrial researchers in the US, the large US domestic market, and the strong US computer hardware and software industries aided the development of the Internet.

As the technology underlying the Internet matured, different components of the US national innovation system played a greater role. Adoption of the Internet in the US was encouraged by antitrust and regulatory policies that weakened the market power of established telecommunications firms and aided the emergence of a domestic ISP (Internet Service Provider) industry. The large size of the US domestic market, as well as American firms' large investments in desktop computing and computer networks, created the conditions for rapid diffusion of the Internet following the introduction of the WWW. "Network effects" created by the scale of the US market and the predominance of English language content also contributed to rapid US standardization and diffusion.

During the late 1990s, the Internet entered a third phase of growth characterized by the development of commercial content and business applications. This phase followed the completion of a long process of infrastructure privatization and a dramatic surge in Internet use associated with the introduction of the WWW. Commercial interest and activity were fueled by the availability of capital from the US venture capital (VC) industry, as well as the strong performance of the US economy. The subsequent "dotbomb" collapse in Internet companies' share prices during 2000–2001 illustrates some of the risks associated with the Schumpeterian "swarming" of US investors and entrepreneurs to the Internet. Indeed, the investment-led economic decline of late 2000 and 2001 in the US resembles the business cycles of the 19th century that inspired Schumpeter's original 1912 conceptualization of the entrepreneur and the swarming phenomenon (Economist, 2001).

At least some of the characteristics of this history, including the importance of the large, monoglot US domestic market for the diffusion of the Internet and the rapid growth of industries supplying its components, recall central themes of US 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 declined after 1945, 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 fact, however, the large US domestic market appears to have played an important role in the development of the Internet and other information technology industries during the postwar period. Another characteristic of early-20th century US economic development was its reliance on foreign sources of invention for the innovations that were widely adopted within the US economy. The Internet's development contains several examples of foreign invention and US development, most notably the cases of hyper-text markup language (HTML) and hyper-text transfer protocol (HTTP).

Our analysis of the factors underlying the 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 US national innovation system, offering a series of international comparisons. Section 4 offers concluding remarks.

2. A brief history of the Internet

The evolution of the Internet from an experimental network connecting three US research facilities at top speeds of 56,000 bits per second to a global network with over 100 million hosts and a backbone capacity in excess of 2 billion bits per second has relied on innovations in many technologies that have improved the performance of the network's components.[2] Dramatic improvements in the performance of semiconductors, computer hardware, software, and networking technologies have propelled the growth of the Internet, particularly by making powerful computing technologies available to a mass market at low prices.

But the Internet's growth also benefited from organizational innovations. The evolution of this network from a US 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, drew on a number of formal and informal governance mechanisms to coordinate standards and infrastructure investment. 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 (see Fig. 1). From 1960 to 1985, computer scientists and engineers made a number of fundamental theoretical and technical contributions. During this period, the Internet remained a loosely organized communications technology used largely by the research community. But as the number of users and applications grew, the technical and organizational challenges shifted from developing and deploying 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 that include the introduction of NSFNET, the National Science Foundation's national Internet "backbone," and the emergence of a market for private access that utilized the public telecommunications infrastructure. A third phase in the evolution of the Internet began in 1995 with the completion of the privatization of NSFNET and the initial stock offering of Netscape, a company founded to take advantage of the HTML and HTTP software protocols that are the core technology of the WWW. With the introduction and rapid diffusion of the Web, a large number of companies began to develop commercial content and applications for the growing network.

2.1. 1960–1985: early computer networks

2.1.1. Packet switching

Research on computer networking began in the early 1960s, roughly 15 years after the invention of the modern computer. Most of the US research in this field during the 1960s was funded by the Department of Defense (DoD) in order to develop technologies to support shared use of the scarce computing resources located at a few research centers. Although the Department of Defense sought to exploit a variety of new computer-related technologies in defense applications, the agency supported "generic" research and the development of a substantial infrastructure in academia and industry for this research, in the expectation that a viable computer industry capable of supplying defense needs would 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 UK developed various aspects of the

[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.

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 Privatization of Internet infrastructure and commercialization of Internet content

Fig. 1. Evolution of the Internet.

theory of packet switching.[3] Digital packet switching offered performance and reliability advantages over analog networks for data communications and was attractive to researchers hoping to construct a communications network less vulnerable to a targeted attack than the centrally-switched telephone network (Brand, 2001). In order to realize these advantages, however, computer science researchers had to develop communication protocols and devices that did not utilize the circuit-switched infrastructure operated by established telecommunications companies.[4] From its inception, the fundamental design advance that underpinned the Internet thus tended to weaken the market power of incumbent telecommunications monopolists in the US and abroad.

By the late 1960s, the theoretical work and early experiments of Baran, Kleinrock, Davies and others led the Defense Advanced Research Projects Agency (DARPA) of the US Department of Defense to fund the construction of a prototype network. In December 1968, DARPA granted a contract to the Cambridge Massachusetts-based engineering firm of Bolt, Beranek and Newman[5] 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 ARPANET network is widely recognized as the earliest forerunner of the Internet.

The first "killer application" developed for ARPANET was electronic mail (e-mail), released in 1972. A 1973 ARPA study showed that within 1 year of its introduction, email generated 73% of all ARPANET traffic (Zakon, 2001). Email was the first example of an unanticipated application rapidly gaining popularity on the network, a pattern repeated several times in the history of the Internet. By 1975, as universities and other major defense research sites were linked to the network, ARPANET had grown to more than 100 nodes.

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

[5] 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 and Lindgren, 1985).

ARPANET was not the only prototype packet-switched network deployed during the late 1960s and early 1970s. Donald Davies completed the construction of a data network at the National Physical Laboratories (NPL) in the UK before the deployment of ARPANET, and a French network, CYCLADES, was built in 1972. Although it was focused on civilian rather than military applications, Davies's original proposal sought to deploy a national network similar to ARPANET. Funding difficulties restricted the "Mark I" project to a single node located at NPL, and the British computer hardware for which the Mark I system was originally designed was withdrawn from the market, forcing the NPL team to use computing equipment from Honeywell and DEC (Abbate, 1999). CYCLADES was first demonstrated in 1972 as a network linking a number of databases in disparate parts of the French government. The French network, developed largely by Louis Pouzin, introduced several significant technical advances, including datagram networking,[6] but ran out of funding in 1978.

The ARPANET, by contrast, benefited from sustained and substantial development funding and from its large-scale deployment. The US network spanned a continent and connected three universities (UCLA, UCSB and Utah), a consulting firm (BBN), and a research institute (Stanford Research Institute). The size and organizational diversity of the US prototype network distinguished it from British and French counterparts.

2.1.2. 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 packets through special hardware, called a gateway. Kahn and Cerf published their specification for the "transmission control protocol (TCP)" in the IEEE Transactions on Communication in 1974. By effectively placing this technical advance in the public domain, these researchers made a critical contribution to the future structure of the Internet. The TCP protocol subsequently was split into two pieces and renamed TCP/IP (Transmission Control Protocol/Internet Protocol).

Although TCP/IP is now the de facto communications standard for Internet applications, its emergence as a dominant standard was uncertain for more than a decade following its introduction. During the 1980s, a number of protocols were introduced, including proprietary standards such as IBM's SNA and Digital equipments DECNET, open alternatives such as the Unix to Unix Copy protocol (UUCP), Datagram (UDP) networking, and standards supported by established telecommunications firms, such as X.25. The TCP/IP protocol ultimately won out for several reasons. TCP/IP ran on a variety of network hardware configurations and was more reliable than first-generation network protocols such as the network communications protocol (NCP). Another important factor was that TCP/IP is an open standard—a complete description of TCP/IP and the rights to use it were freely available to the networking community along with several different implementations.[7]

TCP/IP also benefited from good timing, since it was developed 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 implicit standard, since the networking protocol was included in the 4.2 BSD version of Unix that was available at a nominal cost and was widely used in the academic research computing community.[8]

[6] Datagrams are a more "pure" implementation of packet-switching than the network communications protocol (NCP) initially used by ARPANET, which relied on "virtual connections." Pouzin's technology thus anticipated the development of TCP/IP (see below).

[7] 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.

[8] The Unix operating system was invented by Kenneth Thompson and Dennis Ritchie of Bell Labs in 1969. Its evolution illustrates the power of an open standard as well as the difficulties in maintaining technical compatibility within an "unsponsored," open standard. AT&T originally licensed the Unix source code to universities for a nominal fee because of a 1956 consent

Finally, a 1985 decision by the National Science Foundation (NSF) to adopt TCP/IP as the standard on its university research computing network helped create a large installed base. The resulting network externalities influenced future adopters of TCP/IP.

2.1.3. Early coordination efforts

In addition to technological innovations, diffusion 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. The use of RFCs grew quickly and another UCLA student named Jon Postel became the editor of the series of documents, an influential post that he would hold for many years. RFCs were distributed over the nascent computer network and quickly became the standard forum where ARPANET's growing technical user community gathered to propose and debate new ideas. RFCs combined open dissemination and peer review, features characteristic of academic journals, with the speed and informality characteristic of an e-mail discussion list.[9] The documents were used to propose specifications for important new applications such as Telnet (used to control networked computers from a remote terminal) and FTP (used to transfer files between machines), as well as to refine networking protocols such as TCP/IP (RFC #318, 1972).

The Internet's first formal governance organizations began to appear in the US during the early 1980s, a period of consolidation and rapid expansion. Efforts to rationalize the resources of several US networking initiatives operated by NASA, the Department of Energy, and the NSF 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, then serving as the director of the DARPA network. 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 open to the community of Internet users. In 1983, when ARPANET switched over to TCP/IP, the ICCB was reorganized as the Internet Activities Board (IAB), incorporating the influential Internet Engineering Task Force (IETF), which managed the Internet's architecture and technical standard-setting processes, along with several other sub-committees.

The IAB and its progeny coordinated the infrastructure and connectivity boom that took place in the next decade, but by the early 1990s, the costs of managing the Internet infrastructure began to exceed the available federal funding. In 1992 the Internet Society (2002, 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, and the Internet Assigned Numbers Authority (IANA).

These informal organizations 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 ability to develop open standards in an environment free of the pressures of standard setting for proprietary technologies. These Internet self-governance organizations were also a credible alternative to the standard-setting committees of the global telecommunications industry, which advocated the X.25 standard (Abbate, 1999). 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 in a relatively timely fashion.

2.1.4. European efforts

Although early research efforts in Europe, including Mark I and Cyclades, failed to develop a

decree that restrained them from competing in the computer industry and 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.

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

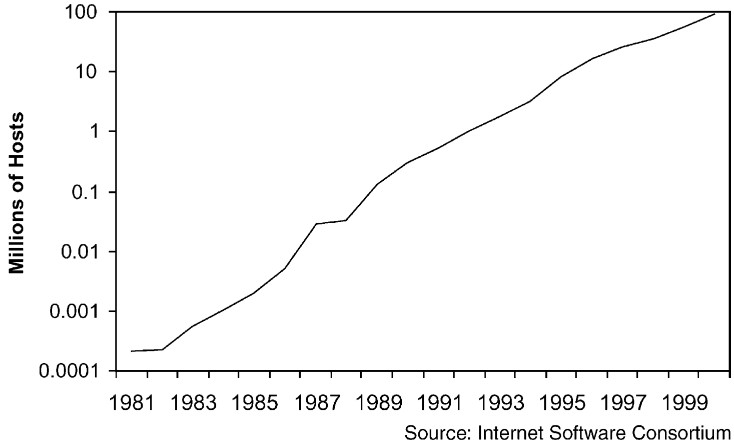

Fig. 2. Total Internet hosts.

network comparable in scale to the ARPANET, the early 1980s saw a number of efforts at intra-European and US-European collaboration. In 1982, the first international ARPANET nodes were established at University College in London and at NORSAR, a research laboratory in Norway. In the same year, two European research networks, European Unix Network (EUNet) and European Academic and Research Network (EARN), were launched. EUNet ran the Unix to Unix Copy Protocol (UUCP protocol) and EARN ran a protocol called Network Job Entry (NJE). Although these networks offered the European research community the same basic services as ARPANET, such as e-mail and file transfer, the alternative standards did not achieve the widespread success of the TCP/IP protocol suite, and the European networks grew more slowly than the ARPANET.

2.2. 1985–1995: infrastructure development and growth

Use of the Internet was primarily limited to researchers, computer scientists, and networking engineers through at least 1985. During the next 15 years, however, the Internet infrastructure was tested by a dramatic expansion in the number of new networks and users (Fig. 2 depicts the exponential growth in Internet hosts between 1981 and 2000). Growth was accompanied by consolidation and privatization of the network infrastructure, as well as by expanded commercial use.

2.2.1. Infrastructure evolution

The first steps toward privatization of the US network infrastructure were taken in 1983, when DARPA split the ARPANET into two parallel networks—ARPANET and MILNET. The latter network was used exclusively for military applications, while ARPANET remained a network primarily linking research computers in industry, academia, and government research facilities. Following the DARPA-MILNET split, several different federal government agencies continued to manage the "backbone" of the non-military network. In 1985, the NSF mandated that any university receiving NSF funding for an Internet connection must use TCP/IP on its network, NSFNET, and must provide access to all "qualified users."

The NSF requirement strengthened the position of TCP/IP as the dominant network protocol, and its extensive deployment in academic computing supported the creation of a large pool of university-trained computer scientists and engineers skilled in its use.[10] In the same year, all of the federal agencies then 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

[10] Given the fragemented state of European networking at the time, it is ironic that 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.

exchanging traffic pioneered 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.

Prior to 1991, the NSF maintained an acceptable use policy (AUP) that prohibited the use of NSFNET for "commercial purposes." The growing population of commercial Internet users was allowed to access NSFNET as a research tool, but commercial users were prohibited from using it to conduct business.[11] Commercial users continued to attach to the network, however, often in partnership with academic institutions, and their lobbying led the NSF to abandon the AUP in 1991. The transition of the core network infrastructure into private hands was completed in 1995, when the NSF transferred control of its four major Network Access Points to Sprint, Ameritech, MFS, and Pacific Bell.

Meanwhile, a growing demand for commercial networking services was fueled by expansion in corporate local-area networking, which began as early as the late 1970s. The installed base of Unix workstations and microcomputers (PCs) overtook that of minicomputers, fueled by the creation of "killer applications" such as document processing and spreadsheets. Growth in the number, size and scope of corporate networks was also spurred by the spread of the client/server architecture, in which a series of smaller "client" computers (often, desktop computers) were linked by a local network to one or more large "servers." The demand for corporate networks encouraged public and private research into networking technology, led to the creation of firms such as Novell and expanded the installed base of users that could benefit from a connection to the NSF's "network of networks."

Data from the US Department of Commerce (2002) indicate that expenditures on software and information technology accounted for 24% of total US private fixed investment in 1970, US$ 8.31 billion (in 1996 dollars). ITs share of annual private sector investment flows grew during the next thirty years, reaching US$ 542.2 billion (1996 dollars) by 1999. The creation of a large installed base of computing and networking hardware, much of it based on the "Wintel" architecture, made it easy for many US companies to connect to the Internet. In many cases, adoption of the Internet involved little more than establishing a connection to an existing network, and "turning on" TCP/IP for the host computers. This large privately financed IT investment created a huge domestic "platform" in the US for the rapid adoption of the Internet and for user-led innovation in Internet services and technologies.

Western Europe also developed a data-networking infrastructure during the late 1980s, but its scale and standardization lagged US efforts. A significant milestone in European networking was the creation of Reseaux IP European (RIPE) in late 1989 to provide technical and administrative coordination for the fledgling European IP network. RIPE's initial funding came from the academic networks EUNet and EARN, which were apparently migrating towards the US TCP/IP standard. Nevertheless, the large scale and open standards of the NSFNET made it an attractive alternative to the European networks, and many networks from industrial economies outside the US chose to connect with the NSFNET infrastructure. In 1988, networks from Canada, Denmark, Finland, France, Iceland, Norway, and Sweden connected to the NSFNET. Australia, Germany, Israel, Italy, Japan, Mexico, Netherlands, New Zealand, and the UK followed 1 year later. By the time RIPE was formed, 6 years after the reorganization of the ICCB, the US network had started to consolidate its lead.

2.2.2. Technical advances

Growth in regional networks and the NSFNET backbone in the late 1980s induced a series of incremental improvements and innovations that cumulatively improved the performance of the Internet by orders of magnitude. The speed of the NSFNET backbone was upgraded from 56 K (57,600 bits per second) in 1985 to T1 (1.5 million bits per second) in 1988 and to T3 (46.1 million bits per second) in 1991. Another technology made necessary by the growth in Internet infrastructure was the domain name server (DNS), introduced in 1984. A DNS maps Internet domain names (e.g. haas.berkeley.edu) to the numerical network address scheme utilized by TCP/IP, providing

[11] Ironically, the AUP proved to be an important catalyst for the creation of a private Internet backbone. Between 1987 and 1989 three major "backbone ISPs" CERFnet (California Education and Research Federation Network), PSINET, and Alternet/UUNET were created, in part to provide high-speed capacity for commercial users (Zakon, 2001).

a real-time concordance between machine-readable and humanly recognizable Internet addresses. This feature was indispensable to the eventual growth of the WWW. 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.

The advances in domain name servers and classification schemes were the work of computer scientists in US universities. The advances in Internet capacity and speed resulted from innovations in the networking hardware and software products whose markets grew exponentially throughout the 1990s. The firms that eventually came to dominate this market were not large incumbents such as IBM, DEC, or Sun. Instead, a group of smaller firms, most of which were founded in the late 1980s, rose to prominence by selling multi-protocol products that were tailored towards the open platform represented by TCP/IP and Ethernet.[12] Cisco, Bay Networks and 3Com, all new entrants into the industry, built large businesses selling products based on this open network architecture. The rapid growth of the US network created a large domestic market for these firms and aided their dominance of the global networking equipment market, just as US packaged computer software firms had benefited from the burgeoning US domestic personal-computer market during the 1980s.

2.2.3. Origins of the consumer Internet

Simultaneously with the rapid growth and consolidation of the NSFNET infrastructure, another type of networking appeared. The introduction of the "personal computer" in the late 1970s and early 1980s made networking available to individual as well as institutional users. Compuserve launched the first commercial "bulletin board" or BBN service in 1979 and rapidly gained thousands of subscribers. 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, a joint venture between IBM, Sears and CBS Television, was launched in 1984 while AOL was founded in 1985.

The online service providers' networks initially were independent of the NSFNET infrastructure, but by the early 1990s they were competing with a host of regional ISPs that offered dial-up connections to the larger Internet.[13] These regional ISPs often adopted technologies developed by academic "modem pools," and their operators 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).

With the notable exception of France's Minitel, there is little evidence of the contemporaneous emergence of a European online service provider industry.[14] Although RIPE was founded shortly after the major US backbone service providers created CIX, Europe lacked many of the important complementary factors that propelled rapid growth of hosts and users in the US during the early 1990s. These factors 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 large private investments in computing infrastructure.

2.2.4. World Wide Web

The final major event in the second phase of Internet development was the invention and diffusion

[12] Ethernet was developed in 1972 by Robert Metcalfe at the Xerox Palo Alto Research Center (Xerox PARC). Unlike TCP/IP, which operates through gateways to connect different networks, it governs a set of computers attached to a single network. As the most widely used local area networks (LAN) protocol on the Internet, Ethernet represents another "open standards" success story.

[13] The first true ISP was world.std.com, which began offering dial-up Internet access to customers in the greater Boston metropolitan area in 1990.

[14] Launched in 1981, Minitel was a precursor of the WWW, offering users a variety of services ranging from computer dating to government services, travel reservations, banking and telephone directories. Despite its success within France, Minitel did not diffuse globally or spawn a commercial boom comparable in size to that created by the Internet. Some of Minitel's limitations stemmed from its use of older technologies, but the system's potential was also limited by its use of a proprietary architecture. This made the development of new applications for Minitel more difficult, and the resulting smaller scale of the network reduced its attractiveness to commercial developers, particularly after the larger Internet provided such opportunities in the 1990s (OECD, 1998).

of the WWW. In May 1991, Tim Berners-Lee and Robert Cailliau, two physicists working at the CERN laboratory in Switzerland, released a new document format called HTML and an accompanying document retrieval protocol called HTTP.[15] HTML incorporated multimedia capabilities that allowed authors to include pictures and graphics into the text of their documents. The HTML protocol was an implementation of hypertext, which allowed authors to specify particular words, phrases or images as "links" that direct readers to other documents. Together, HTML and HTTP turned the Internet into a vast cross-referenced collection of multimedia documents. The collaborators named their invention the "WWW". The Web proved to be another "killer application" and accelerated growth in Internet usage.

In order to use the WWW, a computer user needs a connection to the Internet and application software, known as a "browser," to retrieve and display HTML documents. Though it was not the first Internet browser, the program that launched the WWW was a free browser named Mosaic, and written by Marc Andreesen, a graduate student working at the University of Illinois' National Center for Supercomputing Applications (NCSA).[16] During 1993, the first year that Mosaic was available, HTTP traffic on the Internet grew by a factor of 3416. By 1996, HTTP traffic was generating more Internet traffic than any other application.

The proliferation of browsers and extensions to the HTML standard during the 1990s posed significant challenges to a standards body established in 1994, the WWW Consortium (W3C). The W3C, which was funded by CERN, DARPA, and the EU Commission, was headed by Berners-Lee and maintained a common standard for HTML in the face of the competitive battle between Microsoft and Netscape over their respective browser technologies (see Cusumano and Yoffie, 1998, for an account of the "browser wars"). The Consortium also 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 US, 20 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 network infrastructure's lengthy period of gestation and refinement. The pioneering role of US researchers and entrepreneurs in developing commercial applications of the Web (discussed in the following section), reflects the US origins of much of the infrastructure that supported the Web. This inward transfer and exploitation of foreign inventions echoes a central theme of US technological development during the late 19th and early 20th centuries (Mowery and Rosenberg, 1998).

2.3. 1995–present: creating commercial content and applications

2.3.1. Commercialization of the Internet

The invention of the WWW 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. The manic commercialization of Internet content arguably began with the initial public offering of Netscape in August 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, generally defined as any use of the Internet that facilitates commercial transactions. Commercialization was fueled by a booming US economy and overheated equities market, in

[15] The development of these important technical advances was motivated by Berners-Lee and Caillau's interest in helping physicists archive and search the large volume of technical material being transmitted over the Internet.

[16] NCSA was an NSF-funded facility devoted to research on supercomputing architecture and applications. By the early 1990s, networking technologies and powerful desktop computers had reduced the need of academic researchers for access to supercomputers. As a result, Andreesen and co-workers at the NCSA focused on developing new technologies to support expanded use of computer networking (Abbate, 1999, p. 216). Federally funded "excess capacity" in the research computing infrastructure thus contributed to an important innovation in networking.

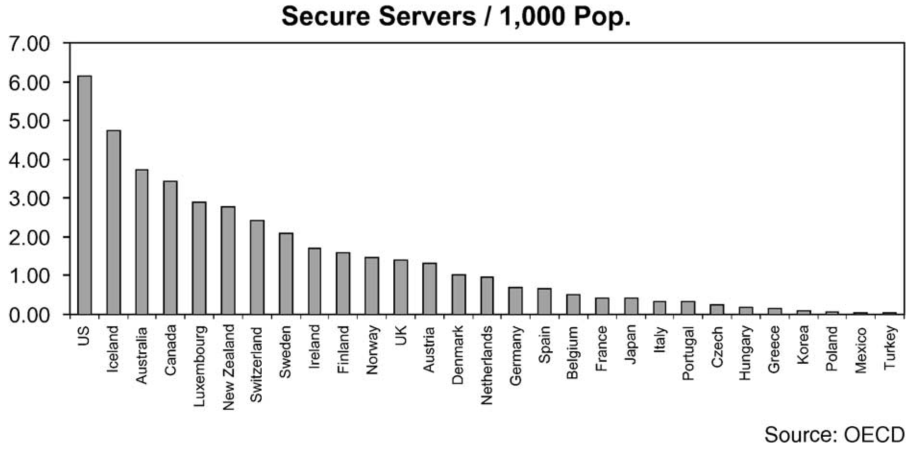

Fig. 3. Secure servers per capita (July 1998).

addition to the growing recognition of the potential long-run benefits of Internet technology.

The speed and magnitude of the shift in the Internet from a research network to a commercial opportunity is suggested by changes in the distribution of top-level domain names during the second half of the 1990s. In 1996, the commercial ".com" and ".net" top-level domains contained roughly 1.8 times as many hosts as the educational ".edu" domain. 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 six times as many hosts as the .edu domain. While international comparisons of growth in commercial applications of the Internet are difficult, a few indicators suggest that commercial exploitation of the Internet was concentrated in the US. One such indicator is the geographic distribution of secure-sockets layer web servers, which are used to conduct most commercial Internet transactions (see Fig. 3). The figure shows that in 1998 the US was the most intensive user of secure web servers on a per-capita basis, with a usage level that is nearly 50% greater than Iceland, the next most intensive user of secure servers.

A wide variety of hardware and software businesses related to Internet commercialization flourished during the late 1990s. Among the most visible were Cisco, the maker of routing and switching equipment for the network infrastructure and Dell, the computer manufacturer that pioneered extensive use of the Internet for order-tracking and inventory management. Consumer-oriented e-commerce markets, such as on-line retailing, content delivery and auctions generated high-visibility and a number of recognizable "Internet brands" such as Yahoo!, Amazon.com and eBay, but the use of the Internet for intermediary or business-to-business transactions appears to have grown even faster.[17]

US financial markets played a role in the commercialization of the Internet during the 1990s by ensuring a robust supply of equity and VC financing for new firms (Gompers and Lerner, 1999). US venture capitalists historically have been major sources of financing in both information technology and biomedical ventures, but their role in the commercialization of the Internet during the 1990s appears to have outstripped their importance in biotechnology during the 1980s and in other information technology sectors during earlier periods (see Fig. 4). Fig. 5 highlights the divergence between VC investments in information technology and healthcare (including biotechnology) during the 1995–2000 period, underscoring the rapid growth in both the number

[17] The US Census estimates that the total volume of shipments for wholesale e-commerce transactions in 2000 was US$ 777 billion. However, close to 90% of these transactions utilized a pre-Internet e-commerce technology called EDI, while only 8% of these transactions used the Internet. Census estimates that in 2000, Internet-based e-commerce accounted for nearly 1% of US retail sales (US$ 28.8 billion) with a growth rate of 92% (Census, 2002).

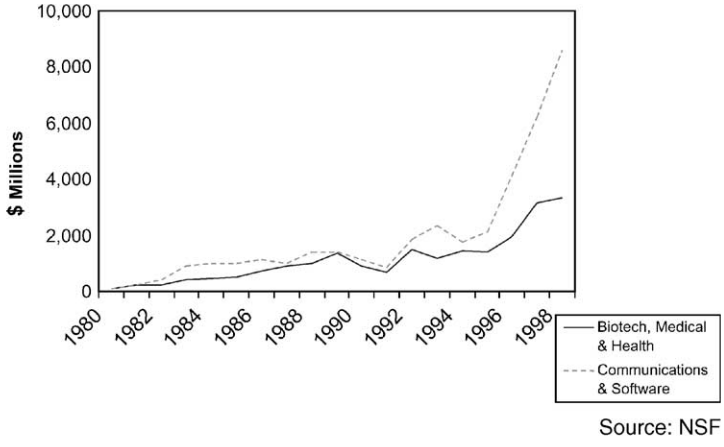

Fig. 4. IT vs. bio-medical VC disbursements.

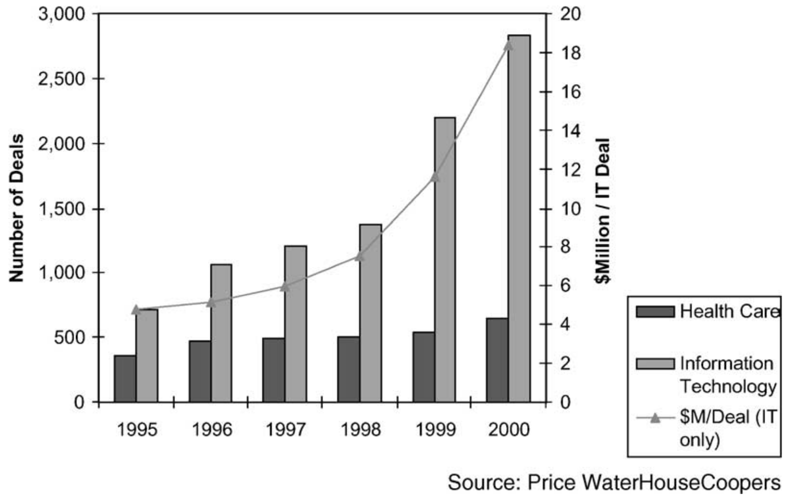

Fig. 5. IT VC boom (1995–2000).

of investments and the size of overall VC funding for information technology ventures, many of which were focused on the Internet and related applications. Venture capital funding for Internet ventures was not entirely lacking in Europe, but it was much less abundant, consistent with the more modest level of overall development of VC in Europe and other industrial economies (European Venture Capital Association, 2002).[18] Although the sharp decline in Internet related stock-prices that occurred in 2000 signaled the end of the investment euphoria, the large investments in commercial applications of the Internet are likely to have pervasive and significant economic effects.

3. The US national innovation system and the Internet

The Internet resembles many postwar innovations in information technology in that it was invented

[18] Berners-Lee claims that his efforts in 1991 to encourage a French research group at the INRIA laboratory to commercialize an application that could have been the first commercial browser met with failure because of the researchers' concern that gaining funding from the EU Commission to undertake the necessary integration tasks would take too long (Berners-Lee, 2000, pp. 44–45).

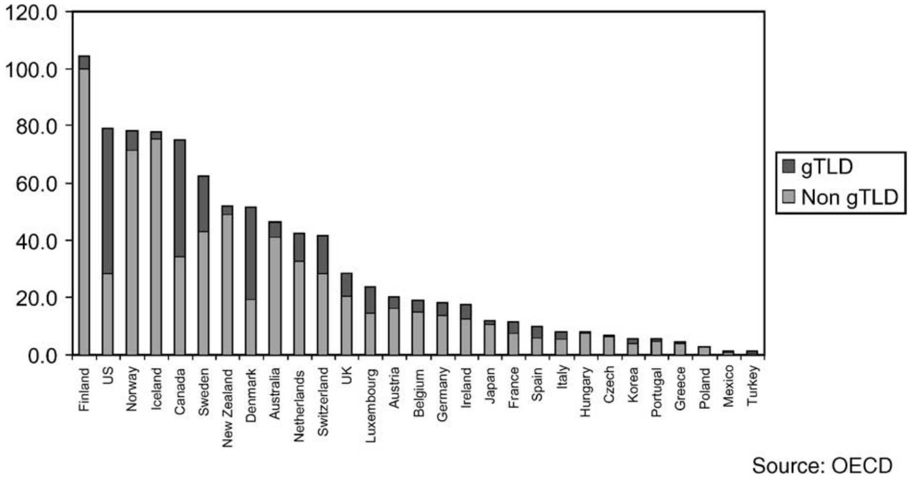

Fig. 6. Hosts per capita (July 1998).

and commercialized primarily in the US. The US was the first country to deploy a large national research-computing network, the first country to standardize on TCP/IP, and the first to develop a large, competitive market for individual access. Commercial exploitation of the Internet, indeed the development of the browser that drew on fundamental European advances, occurred first and most extensively in the US. The US remains an international leader in overall network penetration and its national network continues to grow rapidly (see Figs. 6 and 7).

The US role in invention, diffusion and commercialization of computer networking technology reflects the unusual mix of institutions and policies that characterize the post-1945 US national innovation system, while also exploiting long-established characteristics of the US economy that were important to economic growth and innovation in the first half of the 20th century (Mowery and Rosenberg, 1993, 1998). Even as

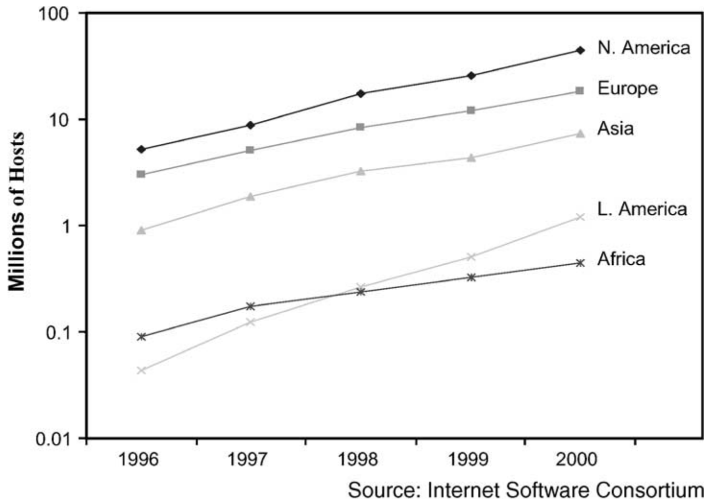

Fig. 7. Internet hosts by region.

the international "uniqueness" of many characteristics of the US national innovation system has diminished somewhat in the face of globalization, several remaining and internationally unique characteristics of the US system have arguably had a major impact on its performance, especially in information technologies.

3.1. 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 US. Inasmuch as the US government was not the only national government supporting domestic R&D in computer networking during the 1960s and 1970s, the benefits of government-sponsored R&D in the US flowed as much from the scale and structure of these programs as from any first-mover advantages.

Federal R&D spending, much of which was defense-related, played an important role in the creation of a diverse array of information technology industries (including semiconductors, computers, and computer software) in the postwar US. The earliest US research on what became the Internet was supported by these programs. 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 15-year DoD investment in hardware and software technology that began with the earliest work on numerical computing. Federal R&D investments strengthened US universities' research capabilities in computer science, facilitated the formation of university "spinoffs" such as BBN and Sun Microsystems, and trained a large cohort of technical experts who aided in the development, adoption, and commercialization of the Internet.

Although reliable estimates of the total federal investment in Internet-related R&D do not exist, federal investments in academic computer science research and training infrastructure during the postwar period were substantial. According to a report from the National Research Council's Computer Science and Telecommunications Board, federal investments in computer science research increased fivefold during the 1976–1995 period, from US$ 190 million in 1976 to slightly more than US$ 1 billion in 1995 in constant (1996) dollars. (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 US$ 411 million (1996 dollars). And according to Vinton Cerf, the NSF spent roughly US$ 200 million to expand the NSFNET between 1986 and 1995 (Cerf, 2000). The sizable investments by DARPA and the NSF almost certainly constitute a majority of Internet-related R&D funding.

The large scale of the US defense-related programs in computer science research and networking distinguished them from those in the UK and France; but the contrasts extend beyond the matter of size. Unlike their counterparts in the Soviet Union or the UK, DoD program managers in information technologies sought to establish a broad national research infrastructure in computer science that was accessible to both civilian and defense-related firms and applications, and disseminated technical information to academic, industrial, and defense audiences. (Flamm, 1988, pp. 224–226; Rees, 1982, pp. 110–111) Classified R&D was important, but a great deal of US defense-related R&D consisted of long-term research that was conducted in universities, which by their nature are relatively open institutions. In contrast, Hendry (1990) argues that a lack of interchange between military and civilian researchers and engineers weakened the early postwar British computer industry.[19]

Even within the nonmilitary component of the UK's public R&D system, Donald Davies's proposal for a national computer network failed to gain support. Paradoxically, the unwillingness of UK government officials to support the deployment of a large prototype computer network reflected their focus at the time on commercial technologies for the "white heat"

[19] "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, 1990, p. 162).

of innovation sought by the Wilson government to improve British economic performance (Abbate, 1999). Davies's proposal was viewed as too distant from the market for public support. Meanwhile, in France, Louis Pouzin's CYCLADES packet network research program, though financed by the French government through the Institute Recherche d'Informatique et d'Automatique (INRIA), experienced similar difficulties with funding.

The Department of Defense's procurement policy in the development of computer networking complemented DARPA's broad-based approach to R&D funding.[20] 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 in emerging industries, supporting competition and innovation. NSF's subsequent support for the development of its NSFNET infrastructure also emphasized university-industry collaboration.

Another factor in the success of US R&D programs was their neutrality with respect to specific commercial applications. These US programs generally avoided the promotion of specific product architectures, technologies, or suppliers, in contrast to efforts in other industrial economies, such as the French Minitel program or Britain's national champion policies in the computer industry. Reflecting their support by defense-related or basic research agencies, US R&D programs also avoided excessive pressure for early commercialization. DARPA was willing to fund projects such as TCP/IP that made current networking standards obsolete, despite the absence at the time of a clear military or commercial application for the technology.

The diversity of the federal Internet R&D portfolio reflected the fact that federal R&D investments were not coordinated by any central agency (even within DoD), 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 1970s. The NSFNET program was initiated and carried out during a period of declining defense-related investments in information technology R&D. In an environment of technological uncertainty, this diversified and pluralistic program structure, however inefficient, appears to have been beneficial.

Our emphasis on the role of public policies and public R&D funding 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 in the US. Privately financed research led to the development of several basic networking technologies, including networking hardware, Unix and the Ethernet protocol. Start-up firms were crucial to the commercialization of Internet-related innovations. Equally important were the heavy investments by US industry in information technology during the 1980s that supported the rapid diffusion of the TCP/IP network. But in many respects, this private investment complemented and responded to the incentives created by public policies and larger market forces. Although private investments were indispensable to the development and deployment of the Internet, their effects were mediated by the constellation of institutions and policies within the US national innovation system.

3.2. *Other government policies*

In addition to supporting Internet-related R&D, the US government influenced the development and diffusion of the Internet through 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 firms.

US antitrust policy influenced the evolution of the Internet by limiting the activities of two of the leading sources of technological innovation in the information technology sector during the postwar period, AT&T and IBM. The Department of Justice's 1949 antitrust lawsuit against AT&T was settled by a 1956 consent decree, and a second antitrust suit, brought in 1974, was not concluded until 1982. Meanwhile, 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 and Oettinger, 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

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

of Bell Laboratories' major information technology innovations, including the transistor and related technologies as well as 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.

A 1956 consent decree in a federal antitrust lawsuit against IBM similarly promoted the licensing of important advances in computer technology. The threat of antitrust action in the late 1960s also encouraged IBM to "unbundle" its pricing of hardware and software products, creating opportunities for the growth of the US commercial software industry that in turn produced many of the entrepreneurs and some of the firms that were active in the commercialization of the Internet.

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 US. The 1984 Modified Final Judgment stipulated that the Regional Bell Operating Companies (RBOCs) could not offer long distance services until they established competitive local markets. The creation of such markets required that competitive local exchange carriers (CLECs) be allowed to connect to the network infrastructure on reasonable terms. 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.[21] The Telecommunications Act of 1996 sought to further reinforce competition in markets for broadband data communication.

State and federal regulation of telecommunications prices aided the domestic diffusion of the Internet by maintaining 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, which established their modem-banks within the local loop and were classified by the FCC as "enhanced service providers."[22] Unmetered access for residential telephone services encouraged the growth of the ISP industry in local markets and the widespread diffusion of the network among US 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.

Other industrial economies have been slower to institute deregulatory and other structural changes in telecommunications that promote the diffusion of the Internet by encouraging competition in infrastructure markets, and lowering the price of Internet access. Strong competition in domestic telecommunications services is associated with lower prices and higher Internet penetration (see Fig. 8, which is based on OECD data). 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 US, the four OECD countries with unmetered pricing of local telecommunications services (OECD, 2000, p. 30).

Although their influence has been less obvious and direct than that of antitrust policy or telecommunications deregulation, US intellectual property rights (IPR) policies also influenced the evolution of the Internet. Many of the key technical advances embodied in the Internet, such as TCP/IP and HTTP/HTML, were placed in the public domain from their inception. This relatively weak IPR regime reflected the network's academic origins, the US Defense Department's support for placing research in 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 entry by networking firms in hardware, software and services. The strengthening of patent rights in the US during the 1980s did not initially affect the software-based architecture and protocols at the heart of the Internet, though it has played a role in the subsequent commercialization of the Internet.[23]

[21] 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.

[22] This classification was reaffirmed in the FCCs May 1997 "Access Reform Order," which 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.

[23] The Internet helped to spawn the free or open source software movement, which has taken an extremely strong stance against the

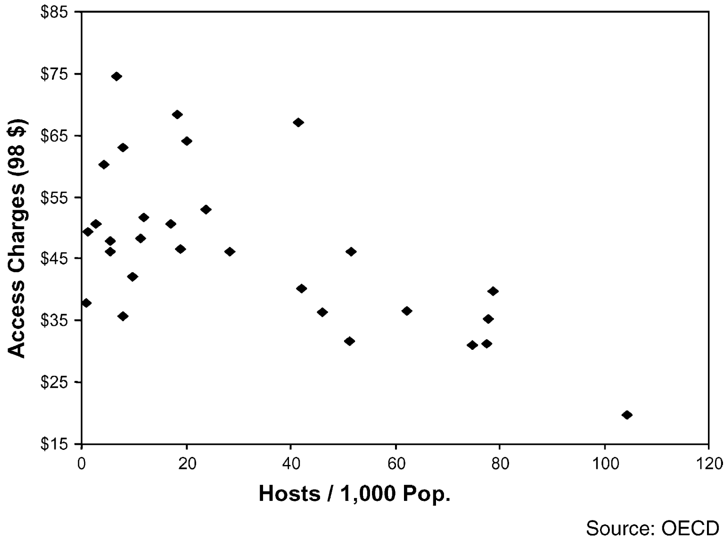

Fig. 8. Access pricing and Internet hosts.

Even the expanded role of US venture capital in Internet and related investments during the 1980s and 1990s was affected by changes in federal policy. In 1979 the US Department of Labor clarified the "prudent man" provisions of the Employee Retirement Income Security Act, which had previously placed limitations on the ability of pensions and large institutional investors to invest in risky asset classes, including venture capital. In 1980, "safe harbor" provisions that shielded venture capital fund managers from assuming the full liability for pension fund investments were put in place. These regulatory changes helped US venture capitalists raise money from large institutional investors and grow their industry more quickly than European counterparts during the 1990s.

3.3. Internet commercialization and the changing US national innovation system

The commercial exploitation of the Internet that began in the 1990s drew on federal investments 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 the transition in the technology underpinning the Internet from development to application, as well as changes in the structure of the US innovation system. Although antitrust and deregulatory telecommunications policies remained influential, defense R&D spending was overshadowed by private sector R&D investment by the 1990s. And one of the most important mechanisms for Internet commercialization was the US VC industry, which assumed a larger role in the commercial exploitation of the Internet than had been true during the formative years of other postwar US high-technology industries. As we noted earlier, the large size of the US domestic market and heavy industrial investments in information technology also accelerated Internet commercialization.

The Internet explosion of the 1990s in the US relied on close university-industry links, an abundant supply of VC, an active antitrust policy, and a deregulatory posture in telecommunications. Most if not all of these elements have been important factors within the US innovation system since 1945, although the importance of some institutions, such as VC and regulatory policy,

use of patents and copyright in the software industry. Paradoxically, however, the Internet also has created great incentives for entrepreneurs to pursue patents in "business methods" that have applications on the Internet. Recent judicial decisions upholding the validity of such patents seem likely to affect the future evolution of the Internet (Graham and Mowery, 2000).

has clearly expanded in recent years. 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).

Finally, the relatively open IPR regime that typified the development of Internet infrastructure during the 1970s and early 1980s shifted during the late 1980s and 1990s towards a "pro-patent" posture. US universities, which during the 1960s and 1970s were important sources of new firms and innovations that often were placed in the public domain, now seek to profit from faculty inventions for the Internet through elaborate patenting and licensing policies. Universities such as Carnegie-Mellon University have invested in faculty-founded firms, such as Lycos, that have profited from the growth of the Internet. Finally, the shift in US macroeconomic policy from its destabilizing posture during the 1970s and 1980s toward a more stable position assuredly contributed to the capital investment boom that underpinned the domestic diffusion of the Internet.

4. Conclusion

Although it drew on important technical advances from foreign sources, the development of the Internet was primarily a US-based phenomenon. Moreover, the creation of the Internet drew on many of the same institutions and policies of the post-war US "national innovation system" that were influential in other post-war high-technology industries. But the four-decade history of the Internet's development reveals change in the role of many of these institutions. 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 IPR, whose relative weakness in Internet-related technologies arguably supported the Internet's rapid development, also have been extended considerably since the early 1990s, with uncertain effects on the future development of the Internet and related technologies. The vibrant equity-finance system long characteristic of the US "innovation system" has expanded greatly and played a key role in the "Internet bubble" of the late 1990s and the "Internet bust" of the early 21st century. The historically central role of US universities in industrial innovation also has shifted somewhat, as universities now seek stronger IPR and investment positions in faculty-founded firms exploiting the Internet.

In a recent review of the "New Economy" debate, the OECD pointed out that the 1990s were characterized by growing divergence in GDP per capita among OECD member economies (OECD, 2000), and argued that information technologies, including the Internet, played a key role in facilitating these developments.[24] The report argued that the divergence in economic performance among member economies could prove to be enduring, because the first-mover advantages enjoyed by US firms in exploiting the Internet rely in part on domestic demand-side scale economies. One of the most important sources of such "scale economies" is the involvement of users as innovators in developing new applications for Internet and networking technologies. For this reason, the economic importance of the large domestic market of demanding and innovative users that emerged from a combination of factors in the US proved to be a powerful impetus in the commercialization of the Internet. Moreover, this particular "asset" remains nationally embedded by virtue of linguistic, regulatory, and other constraints.

Nevertheless, the ultimate effects of early US leadership in commercial Internet applications are far from clear. In 2001, a slowing US economy and slumping equity market have been accompanied by declining investment in information technology and the Internet. The rapid growth of the Internet outside the US may allow other industrial economies to "catch up" in the development of commercial applications. The arrival of new platforms, including wireless technologies (cell phones) in which the US lags much of the developed world, may provide opportunities for other

[24] 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).

nations to leapfrog the US in developing commercial applications for data networks.

Ultimately, although many other industrial economies now seek to emulate the remarkable success of US firms in commercializing the Internet, the limited "transferability" of the web of US policies and institutions, as well as the importance of the large US domestic market, may impede 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 US national innovation system remain unusual, if not unique, by comparison with those of other industrial economies. But as the history of the Internet reveals, these institutions themselves continue to change in unexpected ways.

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References

Abbate, J., 1999. Inventing the Internet. MIT Press, Cambridge.

Berners-Lee, T., 2000. Weaving the Web. HarperCollins, New York.

Brand, S., Founding Father: An Interview with Paul Baran. Wired Magazine, March 2001.

Bresnahan, T.F., Trajtenberg, M., 1995. General Purpose Technologies: Engine of Growth? Journal of Econometrics 65, 83–108.

Cerf, V., et al., 2000. A Brief History of the Internet, <www.isoc.org/internet/history/>.

Cusumano, M., Yoffie, D.B., 1998. Competing on Internet Time: Lessons from Netscape and its Battle with Microsoft. Free Press, New York.

Economist, 2001. What a Peculiar Cycle, 8 March 2001.

European Venture Capital Association <www.evca.com/pdf/WhitePaper.pdf>.

Gompers, S., Lerner, J., 1999. The Venture Capital Cycle. MIT Press, Cambridge.

Graham, S., Mowery, D.C., 2000. Intellectual property protection in the software industry. In: Proceedings of the National Research Council Conference on Intellectual Property and Policy, Washington, DC, 2–3 February.

Greenstein, S., 2000a. Framing empirical work on the evolving structure of commercial Internet markets. In: Brynjolffson, E., Kahin, B. (Eds.), Understanding the Digital Economy. MIT Press, Cambridge, MA.

Hendry, J., 1990. Innovating for Failure. MIT Press, Cambridge.

Internet Society: www.isoc.org.

Kuan, J., 2000. Open-Source Software as Consumer Integration into Production, Haas School of Business, U.C. Berkeley, in press.

Langlois, R.N., Mowery, D.C., 1996. The federal government role in the development of the US software industry. In: Mowery, D.C. (Ed.), The International Computer Software Industry: A Comparative Study of Industry Evolution and Structure. Oxford University Press, New York.

Lee, G.K., Cole, R.E., 2000. The Linux Kernel Development as a Model of Open Source Knowledge Creation. Haas School of Business, U.C. Berkeley, in press.

Lipsey, R.G., Bekar, C. Carlaw, K. 1998. What requires explanation? In: Helpman, E. (Ed.), General Purpose Technologies and Economic Growth. MIT Press, Cambridge.

Mowery, D.C., Rosenberg, N., 1998. Paths of Innovation: Technological Change in 20th Century America. Cambridge University Press, New York.

Mowery, D.C., Rosenberg, N., 1993. The US National Innovation System. In: Nelson, R.R. (Eds.), National Innovation Systems: A Comparative Analysis. Oxford University Press, New York.

National Research Council, 1999a. Funding a Revolution: Government Support for Computing Research, National Academy Press.

National Research Council, 1999b. Securing America's Industrial Strength. National Academy Press.

OECD (Organization for Economic Cooperation and Development), 2000. A New Economy? The Changing Role of Innovation and Information Technology in Growth. OECD, Paris.

OECD, 1998. France's Experience with the Minitel: Lessons for Electronic Commerce over the Internet. OECD, Paris.

Request for Comments (various). In: Postel, J. (Ed.), <www.faqs.org/rfcs/>.

US Department of Commerce, 2002. E-stats, www.census.gov/estats.

Wildes, K.L., Lindgren, N.A., 1985. A Century of Electrical Engineering and Computer Science at MIT, 1882–1982. MIT Press, Cambridge.

Weinhaus, C.L., Oettinger, A.G., 1988. Behind the Telephone Debates, Ablex Publishing, Norwood, NJ.

Zakon, R.H., 2001. Hobbe's Internet Timeline http://www.zakon.org/robert/internet/timeline.