Computer Networking

Global Infrastructure for the 21st Century

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THE INTERNET PHENOMENON

The Internet has gone from near-invisibility to near-ubiquity in little more than a year. (Near-ubiquity may be a bit of an over-statement, but Valvoline's promotion of its Internet World Wide Web home page in its Indianapolis 500 television advertisements speaks worlds about the phenomenon that we are witnessing!) In fact, though, today's multi-billion dollar industry in Internet hardware and software is the direct descendant of strategically-motivated fundamental research begun in the 1960s with federal sponsorship. A fertile mixture of high-risk ideas, stable research funding, visionary leadership, extraordinary grass-roots cooperation, and vigorous entrepreneurship has led to an emerging Global Information Infrastructure unlike anything that has ever existed.

Although not easy to estimate with accuracy, the 1994 data communications market approached roughly $15 billion/year if one includes private line data services ($9 billion/year), local area network and bridge/router equipment ($3 billion/year), wide area network services ($1 billion/year), electronic messaging and online services ($1 billion/year), and proprietary networking software and hardware ($1 billion/year). Some of these markets show annual growth rates in the 35-50% range, and the Internet itself has doubled in size each year since 1988.

The Internet now encompasses an estimated 50,000 networks worldwide, about half of which are in the United States. There are over 5 million computers permanently attached to the Internet, plus at least that many portable and desktop systems which are only intermittently online. (There were only 4 computers on the ARPANET in 1969, and only 200 on the Internet in 1983!) Traffic rates measured in the recently "retired" NSFNET backbone approached 20 trillion bytes per month and were growing at a 100% annual rate.

What triggered this phenomenon? What sustains it? How is its evolution managed? The answers to these questions have their roots in ARPA-sponsored research in the 1960s into a then-risky new approach to data communication: packet switching. The U.S. government has played a critical role in the evolution and application of advanced computer networking technology and deserves credit for stimulating wide-ranging exploration and experimentation over the course of several decades.

EVOLUTIONARY STAGES

Packet Switching

Today's computer communication networks are based on a technology called packet switching. This technology, which arose from ARPA-sponsored researching the 1960s, is fundamentally different from the technology that was then employed by the telephone system (which was based on "circuit switching") or by the military messaging system (which was based on "message switching").

In a packet switching system, data to be communicated is broken into small chunks that are labeled to show where they come from and where they are to go, rather like postcards in the postal system. Like postcards, packets have a maximum length and are not necessarily reliable. Packets are forwarded from one computer to another until they arrive at their destination. If any are lost, they are re-sent by the originator. The recipient acknowledges receipt of packets to eliminate unnecessary re-transmissions.

The earliest packet switching research was sponsored by the Information Processing Techniques Office of the Department of Defense Advanced Research Projects Agency, which acted as a visionary force shaping the evolution of computer networking as a tool for coherent harnessing of far-flung computing resources. The first experiments were conducted around 1966.

Shortly thereafter, similar work began at the National Physical Laboratory in the UK. In 1968 ARPA developed and released a Request for Quotation for a communication system based on a set of small, interconnected computers it called "Interface Message Processors" or "IMPs." The competition was won by Bolt Beranek and Newman (BBN), a research firm in Cambridge, MA, and by September 1969 BBN had developed and delivered the first IMP to the Network Measurement Center located at UCLA. The "ARPANET" was to touch off an explosion of networking research that continues to the present.

Apart from exercising leadership by issuing its RFQ for a system that many thought was simply not feasible (AT&T was particularly pessimistic), ARPA also set a crucial tone by making the research entirely unclassified and by engaging some of the most creative members of the computer science community who tackled this communication problem without the benefit of the experience (and hence bias) of traditional telephony groups. Even within the computer science community, though, the technical approach was not uniformly well-received, and it is to ARPA's credit that it persevered despite much advice to the contrary.

ARPANET

The ARPANET grew from four nodes in 1969 to roughly one hundred by 1975. In the course of this growth, a crucial public demonstration was held during the first International Conference on Computer Communication in October 1972. Many skeptics were converted by witnessing the responsiveness and robustness of the system. Out of that pivotal meeting came an International Network Working Group (INWG) composed of researchers who had begun to explore packet switching concepts in earnest. Several INWG participants went on to develop an international standard for packet communication known as X.25, and to lead the development of commercial packet switching in the U.S., Canada, France, and the UK, specifically for systems such as Telenet, Datapac, Experimental Packet Switching System, Transpac, and Reseau Communication par Paquet (RCP).

By mid-1975, ARPA had concluded that the ARPANET was stable and should be turned over to a separate agency for operational management. Responsibility was therefore transferred to the Defense Communications Agency (now known as the Defense Information Systems Agency).

New Packet Technologies

ARPANET was a single terrestrial network. Having seen that ARPANET was not only feasible but powerfully useful, ARPA began a series of research programs intended to extend the utility of packet switching to ships at sea and ground mobile units through the use of synchronous satellites (SATNET) and ground mobile packet radio (PRNET). These programs were begun in 1973, as was a prophetic effort known as "Internetting" which was intended to solve the problem of linking different kinds of packet networks together without requiring the users or their computers to know much about how packets moved from one network to another.

Also in the early 1970s, ARPA provided follow-on funding for a research project originated in the late 1960s by the Air Force Office of Scientific Research to explore the use of radio for a packet switched network. This effort, at the University of Hawaii, led to new mobile packet radio ideas and also to the design of the now-famous Ethernet. The Ethernet concept arose when a researcher from Xerox PARC spent a sabbatical period at the University of Hawaii and had the insight that the random access radio system could be operated on a coaxial cable, but at data rates thousands of times faster than could then be supported over the air. Ethernet has become a cornerstone of the multi-billion dollar local area network industry.

These efforts came together in 1977 when a four-network demonstration was conducted linking ARPANET, SATNET, Ethernet and the PRNET. The satellite effort, in particular, drew international involvement from participants in the UK, Norway, and later Italy and Germany.

The Internet Protocols

A third ARPA effort of the early 1970s involved research at Stanford to design a new set of computer communication protocols that would allow multiple packet networks to be interconnected in a flexible and dynamic way.

In defense settings, circumstances often prevented detailed planning for communication system deployment, and a dynamic, packet-oriented, multiple-network design provided the basis for a highly robust and flexible network to support command-and-control applications.

The first phase of this work culminated in a demonstration in July 1977, the success of which led to a sustained effort to implement robust versions of the basic Internet protocols (called TCP/IP for the two main protocols: Transmission Control Protocol and Internet Protocol).

The roles of ARPA and the Defense Communications Agency were critical both in supplying sustained funding for implementing the protocols on various computers and operating systems and for the persistent and determined application of the new protocols to real needs.

By 1980, sufficient experience had been gained that the design of the protocols could be frozen and a serious effort mounted to require all computers on the ARPANET to adopt TCP/IP. This effort culminated in a switch to the new protocols in January 1983. ARPANET had graduated to production use, but it was still an evolving experimental testbed under the leadership of ARPA and DCA.

ARPANET - SFNET - Internet

As ARPA and DCA were preparing to convert the organizations they supported to TCP/IP, the National Science Foundation started an effort called CSNET (for Computer Science Network) to interconnect the nation's computer science departments, many of which did not have access to ARPANET. CSNET adopted TCP/IP, but developed a dial-up "Phone-mail" capability for electronic mail exchange among computers that were not on ARPANET, and pioneered the use of TCP/IP over the X.25 protocol standard that emerged from commercial packet switching efforts. Thus, the beginning of the 1980s marked the expansion of U.S. government agency interest in networking, and by the mid-1980s the Department of Energy and NASA also had become involved.

NSF's interest in high-bandwidth attachment was ignited in 1986 after the start of the Supercomputer Centers program. NSF paved the way to link researchers to the Centers through its sponsorship of NSFNET, which augmented ARPANET as a major network backbone and eventually replaced ARPANET when ARPANET was retired in 1990. Then-Senator Gore's 1986 legislation calling for the interconnection of the Centers using fiber optic technology ultimately led the administration to respond with the **High Performance Computing and Communications** (HPCC) Initiative.

Among the most critical decisions that NSF made was to support the creation of "regional" or "intermediate-level" networks that would aggregate demand from the nation's universities and feed it to the NSFNET backbone. The backbone itself was initially implemented using gateways (systems used to route traffic) developed at the University of Delaware and links operating at the ARPANET speed of 56K bps. Because of rapidly increasing demand, though, NSF in 1988 selected MERIT (at the University of Michigan) to lead a cooperative agreement with MCI and IBM to develop a 1.5M bps backbone. IBM developed new routers and MCI supplied 1.5M bps circuits, and **NSFNET was reborn roughly 30 times faster than its predecessor**.

The regional networks quickly became the primary means by which universities and other research institutions linked to the NSFNET backbone. NSF wisely advised these networks that their seed funding would have limited duration and they would have to become self-sustaining. Although this took longer than originally expected, most of the regional networks (such as BARNET, SURANET, JVNCNET, CICNET, NYSERNET, and so on) now have either gone into for-profit mode or have spun off for-profit operations.

Because of continued increases in demand, NSF recently re-visited the cooperative agreement with MCI, IBM and MERIT. A non-profit organization, Advanced Networks and Services (ANS) was born, and has satisfied the current demand for Internet capacity using 45M bps circuits. The name "Internet" refers to the global seamless interconnection of networks made possible by the protocols devised in the 1970s through ARPA-sponsored research -- the Internet protocols, still in use today.

A Commercial Market Emerges

By the mid-1980s there was sufficient interest in the use of Internet in the research, educational, and defense communities that it was possible to establish businesses making equipment for Internet implementation. Companies such as Cisco Systems, Proteon, and later Wellfleet (now Bay Networks) and 3Com became interested in manufacturing and selling "routers," the commercial equivalents of the "gateways" that had been built by BBN in the early ARPANET experiments. Cisco alone is already a $1 billion business, and others seem headed rapidly toward that level.

The previous subsection noted the "privatization" of the NSF regional networks. NYSERNET (the New York State regional network) was the first to spin out a for-profit company, Performance Systems International, which now is one of the more successful Internet service providers. Other Internet providers actually began as independent entities; one of these is UUNET, which started as a private non-profit but turned for-profit and began offering an Internet service it calls ALTERNET; another is CERFNet, a for-profit operation initiated by General Atomic in 1989; a third is NEARNet, started in the Boston area and recently absorbed into a cluster of for-profit services operated as BBN Planet (recall that BBN was the original developer of the ARPANET IMP; BBN also created the Telenet service, which it sold to GTE and which subsequently became Sprintnet).

In 1988, in a conscious effort to test Federal policy on commercial use of Internet, the Corporation for National Research Initiatives approached the Federal Networking Council (actually its predecessor, the Federal Research Internet Coordinating Committee) for permission to experiment with the interconnection of MCI Mail with the Internet. An experimental electronic mail relay was built and put into operation in 1989, and shortly thereafter Compuserve, ATTMail and Sprintmail (Telemail) followed suit. Once again, a far-sighted experimental effort coupled with a wise policy choice stimulated investment by industry and expansion of the nation's infrastructure. In the past year, commercial use of the Internet has exploded.

The Roaring '90s: Privatization, and the World Wide Web

The Internet is experiencing exponential growth in the number of networks, number of hosts, and volume of traffic. NSFNET backbone traffic more than doubled annually from a terabyte per month in March 1991 to eighteen terabytes a month in November 1994. (**A terabyte is a thousand billion bytes**!) The number of host computers increased from 200 to 5,000,000 in the 12 years between 1983 and 1995 -- a factor of 25,000!

As 1995 unfolds, many Internet service providers have gone public and others have merged or grown by acquisition. Market valuations of these companies are impressive. America Online purchased Advanced Networks and Services for $35 million. Microsoft supplied more than $20 million in capital to UUNET for expansion. UUNET and PSI have gone public. MCI has unveiled a major international Internet service, as well as an information and electronic commerce service called marketplace MCI. AT&T is expected to announce a major new service later in the year. Other major carriers such as British Telecom, France Telecom, Deutsche Telekom, Swedish Telecom, Norwegian Telecom, and Finnish Telecom, among many others, have announced Internet services. An estimated 300 service providers are in operation, ranging from very small resellers to large telecom carriers.

In an extraordinary development, the NSFNET backbone was retired at the end of April 1995, with almost no visible effects from the point of view of users (it was hard work for the Internet service providers!). A fully commercial system of backbones has been erected where a government sponsored system once existed. Indeed, the key networks that made the Internet possible (ARPANET, SATNET, PRNET and NSFNET) are now gone -- but the Internet thrives!

One of the major forces behind the exponential growth of the Internet is a variety of new capabilities in the network -- particularly directory, indexing, and searching services that help users discover information in the vast sea of the Internet. Many of these services have started as university research efforts and evolved into businesses. Examples include the Wide Area Information Service, Archie (which spawned a company called Bunyip in Canada), LYCOS from Carnegie Mellon, YAHOO from Stanford, and INFOSEEK. Aiding and stimulating these services is the recent arrival of a "**killer ap**" for the Internet: the World Wide Web.

Developed at the European Center for Particle Research (CERN), the World Wide Web was first used in experimental form in 1989. Around 1992 it came to the attention of a young programming team at the National Center for Supercomputing Applications (NCSA) at the University of Illinois. This team developed a graphical browser for the Web, called Mosaic. In accordance with NCSA policies, this software was made widely available on the Internet for free. It took the world by storm. The excitement of being able to provide images, sound, video clips and multifont text in a hypertext system was irresistible. Between 1992 and 1995 a number of commercial versions of Web browsers and servers emerged, among them Netscape Communications, which was founded by the former chairman of Silicon Graphics, Inc., who instantly realized that the Web would dramatically magnify the utility of the Internet by replacing its rather arcane interface with something anyone could do ("point and click").

Today (May 1995) there are over 30,000 Web sites on the Internet and the number is doubling every two months. Companies that were formerly unsure about the utility of the Internet have rushed to use the Web as a means of resenting products and services. The rest of the 1990s belongs to the content providers, who will use the rapidly evolving infrastructure to bring increasingly sophisticated material to consumers.

The Future

It's risky to predict the future of something as dynamic as the Internet. It seems safe to say that we will see a continuing explosion of new services. Today, at least a dozen companies are engaged in providing electronic funds transfers on the Internet in support of electronic commerce. Other companies are exploring the provision of packetized video, videoconferencing, packetized voice (packet telephone!), and increasingly sophisticated tools for securing Internet operation for intra- and inter-corporate use.

Projections of Internet-related business range to $50 billion at the end of the decade. While this is still small compared to the total telecommunications business (estimated at about $300 billion today), its rapid growth and the rich evolution of new products and services suggest that the modest research investments of the federal government have paid off in myriad ways, not all of them merely monetary. There is every reason to believe that the Internet will transform education, business, government, and personal activities in ways we cannot fully fathom. Virtually none of this would have happened as rapidly, or in the same open and inclusive fashion, had not the federal government consciously provided sustained research funding and encouragement of open involvement and open standards, and then wisely stepped out of the picture as the resulting systems became self-sustaining.

The Internet is truly a global infrastructure for the 21st century -- the first really new infrastructure to develop in nearly a century.

The Author

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Cerf's career in computer communications began nearly 30 years ago, and has included stops as an independent consultant, Principal Programmer on the ARPANET Project at UCLA, faculty member in Electrical Engineering and Computer Science at Stanford University, Principal Scientist (Internet Research) at the Department of Defense Advanced Research Projects Agency, Vice President of Engineering for the MCI Digital Information Services Company, and Vice President of the Corporation for National Research Initiatives, prior to his current position. Cerf, together with Robert E. Kahn, is the co-inventor of the TCP/IP protocols, and led the Internet development effort at Stanford and ARPA from 1973 to 1982.

Cerf is a Fellow of the Association for Computing Machinery, a Fellow of the Institute of Electrical and Electronics Engineers, a Fellow of the American Association for the Advancement of Science, and a recently-elected member of the National Academy of Engineering. He is a member of the American Association for the Arts and Sciences and a 1995 recipient of the Kilby Award. He has served as chairman of the Internet Architecture Board, the ACM Special Interest Group on Computer Communications (SIGCOMM), and as chair or member of a number of National Research Council panels. He chairs the NATO Networking subcommittee of its Science Committee. Cerf is married, has two sons, and has an abiding interest in fine foods, fine wine, and mind-rotting science fiction.
