Order Number 9503730

From ARPANET to Internet: A history of ARPA-sponsored computer networks, 1966–1988

Abbate, Janet Ellen, Ph.D.

University of Pennsylvania, 1994

U·M·I
300 N. Zeeb Rd.
Ann Arbor, MI 48106

FROM ARPANET TO INTERNET:
A HISTORY OF ARPA-SPONSORED COMPUTER NETWORKS, 1966-1988

Janet Abbate

A DISSERTATION

in

American Civilization

Presented to the Faculties of the University of Pennsylvania

in Partial Fulfillment of the Requirements for the

Degree of Doctor of Philosophy

1994

Thomas P Hughes

Supervisor of Dissertation

Peter Conn

Graduate Group Chairperson

To my parents, Anne and Mario Abbate, for years of patient support;

to Matthew and Beth, for providing supper and sanity;

and to Sonya, who was always there

Acknowledgments

I gratefully acknowledge the intellectual sustenance and moral support of the students and faculty, particularly Karin Calvert and Murray G. Murphey, of the University of Pennsylvania Department of American Civilization. Financial support and access to invaluable materials on the history of ARPA's networking programs were provided by the Charles Babbage Institute at the University of Minnesota; I wish to thank Arthur Norberg and Judy O'Neill for their assistance. The MIT Program in Science, Technology, and Society offered a collegial welcome and a chance to participate in many stimulating discussions during my residence in Cambridge. Thomas P. Hughes of the University of Pennsylvania has been a source of theoretical insight, mentor, and friend; his unfailing advice and encouragement helped make the long and often difficult process of creating this work a rewarding one as well.

ABSTRACT

FROM ARPANET TO INTERNET:

A HISTORY OF ARPA-SPONSORED COMPUTER NETWORKS, 1966-1988

JANET ABBATE

THOMAS P. HUGHES

The ARPANET and Internet were pioneering computer networks that established the technical groundwork and social expectations for wide-area networking in the United States today. Created by the U.S. Defense Advanced Research Projects Agency (ARPA), the ARPANET was a testing ground for innovative concepts such as packet switching, distributed topology and routing, and the connection of heterogeneous computer systems. ARPA dealt with the complexities of this project using a management style that fostered collegial interaction and a technical strategy known as "layering" that allowed network components to be developed independently. The highly visible success of the ARPANET brought its techniques into the computer science mainstream and made it an influential model for subsequent research and commercial networks. ARPA followed the ARPANET with experimental packet radio and satellite networks; the need to connect these diverse systems led ARPA to begin its Internet Program, which developed techniques for interconnecting networks. These techniques were used to connect other research networks to the ARPANET, forming the basis for today's Internet, a worldwide "network of networks."

The ARPANET and Internet were socially constructed artifacts whose design was shaped by the interests and worldviews of their creators. Different networking techniques had different implications for the performance, economics, and social dynamics of the resulting system, so that technical choices

can be understood as trade-offs between competing values. Analysis of the ARPANET design decisions reveals how the network was shaped by social considerations such as a preference for decentralized organization and a concern for military "survivability." Network users were also instrumental in constructing the ARPANET's identity: their unexpected enthusiasm for electronic mail turned a system intended primarily for remote computing into a medium for communication between people. The social values embodied in the ARPANET and Internet are further illuminated by contrast with alternative networking systems representing different social aims and interests that were introduced in the 1970s by international standards organizations.

Table of Contents

List of Illustrations

Chapter 1

Introduction

In October 1972, over a thousand people who had traveled to Washington, D.C., for the First International Conference on Computer Communications witnessed a remarkable technological feat. From a demonstration area containing dozens of computer terminals, conference attendees were able to access computers located hundreds or thousands of miles across the United States; there was even a temporary link to Paris. Participants could use interactive software programs including meteorological models, an air traffic simulator, conferencing systems, MIT's MACSYMA mathematics system, experimental data bases, a system for displaying Chinese characters, even a computerized chess player (Roberts and Kahn, 1972). The combined variety of terminals, computers, and programs, all operating successfully and responsively from across the country, made a powerful impression. One observer described visiting engineers as "just as excited as little kids, because all these neat things were going on," while another recalled, "There was more than one person exclaiming, 'Wow! What is this thing?'" (Cerf, 1990, 25; Lynch and Rose, 1993, 10).

The technology showcased at the ICCC conference was the brand-new ARPANET, the world's first wide-area computer-to-computer network. A creation of the U.S. Department of Defense, the ARPANET represented a turning point in computer communications. Most of the computing experts at the conference had never attempted to combine computers from different manufacturers in a single network or to maintain continuous long-distance data connections. The ARPANET did both, and accomplished this using complex and little understood techniques whose feasibility had been doubted by many in the communications industry. The array of concrete benefits the ARPANET made available to researchers in their daily work raised public and professional awareness of what networks could do. The trade journal *Electronics* reported that "with the great interest in computer networks indicated by . . . the crowds in the Arpanet demonstration room, networks clearly are the wave of the future" (Electronics, 1972, 36).

Computer networks surround us today in many guises. They may be local, regional, or wide-area, and make use of such varying transmission media as cables, telephone lines, microwave transmitters, radios, and satellites. Specialized networks exist for different purposes, including research networks, automation networks that control factory machines, and remote transaction networks linking central offices with bank machines, reservation systems, and point-of-sale terminals. We take it for granted that data can travel long distances instantaneously. But computer communication before networking was analogous to human communication before the telegraph: it was difficult to share information without moving a human being or a physical storage device, such as a reel of magnetic tape or a stack of punch cards, from one location to another. Incompatibilities between machines compounded the problems of distance. The ARPANET was the first to break these barriers and allow routine long-distance data transfers between different types of computers.

Throughout America's history the development of communications and information technologies has been a critical factor in social and economic change, with the twentieth century often characterized as the era of a communications or information "revolution." Computer networks, a product of both "revolutions," have played an important role in America as a highly visible information resource, with the potential to become as essential to American life as the highway or telephone systems to which they are often compared. In the past decade there have been several important social studies of computers and of computer networks. Most of these focus on the ways computers are used and their ability to reinforce or challenge social relationships and power; examples include Turkle (1984), Kling (1991), Marvin and Winther (1983), Zuboff (1988), Kramerae (1988), Sproull and Kiesler (1991), and Taylor et al. (1993). These works demonstrate the myriad competing ways in which the technology has been imagined and used. Most, however, take the technology itself as a given, rarely exploring the technical and non-technical factors that shape the *production* of networks. But without knowing how computer networks came to be as they are, our ability to understand current technologies and guide their future development is limited. The cultural history of the ARPANET and Internet that follows is a first step toward filling this gap.

Since the history of networks is not well known, a brief overview may be useful. The ARPANET was the brainchild of the U.S. Defense Department's Advanced Research Projects Agency (ARPA), a research arm of the Department of Defense.[1] Founded in 1958 in response to the Soviet Sputnik launch, ARPA's mission is to keep the U.S. ahead of its military rivals by pursuing research that promises a significant advance in defense-related fields. ARPA is a small agency with no laboratories of its own; ARPA staff initiate and manage projects, but the actual research and development is done by academic and industry contractors. Successful technologies are turned over to the armed services for operational use. The private sector is also encouraged to exploit ARPA's research results,

[1] In 1972 ARPA was given the status of a separate Defense agency and its name was changed to DARPA (Defense Advanced Research Projects Agency). The name was changed back to ARPA in 1993, apparently to signal a renewed commitment to research that would benefit civilian as well as defense industries. For consistency I will use *ARPA* throughout this work except in direct quotations that use *DARPA*.

most of which are unclassified; this serves the military indirectly by making advanced technologies commercially available to it.

ARPA has several project offices that fund research in different areas, such as behavioral sciences, materials sciences, and ballistic missile defense; these offices are created or disbanded as defense priorities change. When ARPA established its Information Processing Techniques Office (IPTO) in 1962 it became a major funder of computer science in the United States. IPTO's record in conceiving and managing computing research projects is remarkable: the office has been the driving force behind several important areas of computing research in the U.S., including graphics, artificial intelligence, time-sharing operating systems, and networking (Norberg and O'Neill, 1992, 96). The agency is recognized even by critics for its good management and rapid development of new technologies (Pollack, 1989, 8). IPTO's expertise at managing research and development would be crucial to the success of the ARPANET.

In 1966 IPTO director Robert Taylor began planning a network to connect the computing centers of ARPA contractors. The proposed ARPANET would have two main goals: to save computing costs by allowing contractors across the country to share computer resources, and to advance the state of the art in the transfer of information between machines and over distances, known as *data communications*. ARPA also hoped the network would encourage collaboration between researchers in different locations. Taylor's successor, Lawrence Roberts, managed the project, beginning development in 1968. The first four ARPANET sites were installed by the end of 1969, and from 1970 to 1972 the ARPANET team expanded, tested, and modified the network hardware and software. The public demonstration at the International Conference on Computer

Communications marked the network's transition from an experiment to an operational system.

IPTO built on the success of the ARPANET with several new projects. First it adapted ARPANET technologies for use with radio and satellite transmission. Then in 1973 IPTO began its Internet program to develop technologies to connect or "internetwork" different computer networks. Program managers Vinton Cerf and Robert Kahn developed a set of networking *protocols* (rules guiding the interaction between computers) called TCP/IP, which allowed ARPA to connect its radio and satellite networks to the ARPANET. The set of connected networks that communicated using TCP/IP became known as the Internet. The TCP/IP protocols were widely adopted by commercial and research network builders, and during the 1980s the protocols became a *de facto* standard in the United States. When the National Science Foundation decided in 1985 to build the NSFNET to connect its supercomputers, it chose to use the ARPA internet protocols.

The ARPANET proved extremely popular with its users, and traffic increased steadily until by the late 1980s it had outgrown the network's capacity to provide fast and reliable service. ARPA decided the network had become obsolete, and began decommissioning the original ARPANET hardware in 1988. To provide continued support for researchers, NSF arranged to have the NSFNET take over as the backbone of the Internet, which had grown into a world-wide network of networks linking millions of computer users. Though the original ARPANET no longer exists, the Internet perpetuates both its technology and its role in bringing together computer users.

The ARPANET reshaped standards and expectations in the computing profession. By its very existence the ARPANET proved the validity of novel techniques such as packet switching and distributed communications (described in Chapter 2), as well as the feasibility of linking heterogeneous groups of computers. Project manager Roberts had claimed that the ARPANET would advance by an order of magnitude the nation's experience and expertise in computer networking, and this expectation was met (Roberts, 1967, 1). Many of those who had worked on the ARPANET went on to provide commercial networking systems or consulting services; the universities involved became centers of networking research; and by making technical specifications and implementations freely available, ARPA significantly lowered the learning curve for those who followed. At the same time, the ARPANET's influence incorporated military priorities into civilian technologies, and established norms for computer communications that favored independent, technically sophisticated computer owners and users.

The ARPANET changed the scope and nature of computing for the users it served. Before, people had typically shared computer resources within a single campus; with the ARPANET and Internet they could access resources across the country or around the world. Incompatibilities between manufacturers' standards no longer determined the limits of connectivity. Collaboration became more feasible both within the U.S. and across national borders. Network services such as electronic mail, news, and bulletin boards allowed people to create "virtual communities"—geographically separated communities of interest linked via the network—that spread from academic and business uses to the personal realm. By the late 1980s networking had become a household word and ordinary people were struggling with the implications for personal rights and responsibilities, government regulation, business opportunities, questions of funding, control, and access of public networks, and their own hopes and fears for the kinds of human interactions made possible by computers. The evolution of the ARPANET in the period from 1966 to 1988, as it first pioneered a new technology and then ushered in the era of internetworking, established the technical groundwork and social expectations for wide-area networking in the United States today.

*****

My theoretical approach draws on two currents that have been prominent in recent scholarship in the history of technology: systems theory and social construction. Systems, as described by Hughes (1983), join people, material things, and ideas in the service of a goal set by the "system builder." Systems follow a life cycle from invention through development into maturation and finally obsolescence. I use systems theory as a framework for identifying and organizing the disparate elements that have gone into building the ARPANET and its successors, and for describing the evolution of the system from invention to obsolescence. The theory of social construction, introduced by LaTour (1979) and applied to technological systems by Bijker et al (1987), posits that technical choices are based not on an unmediated understanding of natural facts, but rather on a "construction" of the technical situation that is shaped by the designers' training and goals as well as the influence of competing social actors who have a stake in the system. Social construction provides a vocabulary for discussing how computer networks are shaped by social conditions and discourses. Taking the idea of social construction beyond the initial creation of the system, I also advance the argument that in interactive systems such as computer networks, part of the design process takes place in the act of using them.

The most important sources for this work have been first-hand accounts by ARPANET participants, especially those gathered for the Charles Babbage Institute's DARPA oral history project, and the technical literature on computer networking. Key technical journals include the *Proceedings of the Institute for Electrical and Electronics Engineers* (IEEE), *Communications of the Association for Computing Machinery* (ACM), *ACM Computer Communication Review*, *Computer Networking*, *Proceedings* of American Federation of Information Processing Societies (AFIPS) Conferences, International Conference on Computer Communication (ICCC) *Proceedings*, as well as minutes from International Telecommunication Union (ITU) meetings. I have made extensive use of the Internet itself to retrieve official ARPANET documents, correspond electronically with informants, and exchange information with on-line technical and historical communities. As well as an invaluable resource, my contact with the network has provided a constant reminder of its growing influence.

Throughout this dissertation I emphasize how social and technical factors are interwoven in computer networking, while individual chapters explore several specific ways in which the ARPANET is, in Lévi-Strauss's term, "good to think with." Chapter 2 surveys the inventions underlying the ARPANET and explores some of the social implications of different data communications practices. It describes the issues that drove computer users to experiment with networking, the different goals they pursued, the problems they encountered, and a variety of approaches they employed to solve them. With many networking techniques available and none universally recognized as "best," network builders often made choices based on their interpretation of how the available alternatives would serve particular social interests.

Chapter 3 focuses on the development of the ARPANET. The central problem faced by ARPA's network builders was the complexity of the system. Their response was twofold: nurturing a social environment that encouraged cooperative problem solving, and adopting a technical strategy of viewing the network as a set of distinct but interacting layers of hardware and software. The resulting ARPANET system was in many ways a physical analog of the social network within which it was created.

Chapter 4 charts the transition from the ARPANET to the Internet. During this period ARPANET technology was transferred in several directions: to the military, to commercial systems, and to new ARPA networking projects. As ARPA researchers experimented with different network media, including radio and communications satellites, ARPA saw a need to connect these diverse systems, and began its Internet Program. Just as the ARPANET had entailed a new way of thinking about computers, so the Internet required a new way of thinking about networks: in both cases, ARPA had to answer the question of how to connect heterogeneous systems, and how to manage the resulting "meta-system."

ARPA's approach to internetworking reflected the technical constraints and social organization of ARPA's own network systems. During the 1970s data networks embodying a different set of values were being built in other countries, especially Canada, the countries of western Europe, and Japan. Unlike the ARPANET, systems in these countries were usually controlled by and modeled after the national telecommunications monopolies. Chapter 5 describes how networking issues became internationalized, focusing on a series of debates over network protocol standards that brought the networking paradigms of ARPA and the telecommunications carriers into conflict. The contrast highlights the cultural assumptions that underlay the U.S. system, as well as political and economic factors in the international standards arena.

Network design decisions have never been purely technical—or purely social. System builders choose techniques on the basis of their perceptions of technical and economic constraints, as well as their own tacit or explicit social goals. Users further shape the system by choosing certain applications over others. Understanding the history behind the networks we use today can help us evaluate and participate in the choices that must be made in building networks for the future.

Chapter 2

The Drive to Build Networks

> Like distant islands sundered by the sea,
> we had no sense of one community.
> We lived and worked apart and rarely knew
> that others searched with us for knowledge, too. . . .
>
> But, could these new resources not be shared?
> Let links be built; machines and men be paired!
> Let distance be no barrier! They set
> that goal: design and build the ARPANET!
>
> Vint Cerf, "Requiem for the ARPANET"

The drive to build networks was part of a general movement to make computers more accessible. Networking needed no inventor; for computer owners of the 1960s, linking their "distant islands" was a common goal that was brought a step closer by each advance in computing or communications equipment and by each awkward attempt at in connecting computers. But networking did not have a single fixed meaning, technique, or purpose. Many choices existed for building networks, based on different technical paradigms and representing different aims and interests.

The significance of network design decisions can be understood in terms of the social construction of technology. This theoretical approach, presented in Bijker et al (1987) and deriving from LaTour's work on the social construction of science (LaTour, 1979), holds that, just as scientific theories do not necessarily prevail because they are the "best" description of reality, so technological artifacts or processes are not necessarily adopted because they are the best (or easiest or most obvious) solution to a problem. Pinch and Bijker (1987) propose that new technologies begin in a state of "interpretive flexibility" in which their form and cultural function are still uncertain (40-42). Multiple variations of an artifact compete for acceptance by "relevant social groups"—aggregates of producers, users, or interested observers for whom the technology has a shared meaning (30-34). When a critical mass of these groups adopts a particular design as being consistent with their goals, they construct a stable form for the artifact (39, 44).

The concept of social construction is useful in explaining the significance of design variations in computer networking. Early network designs were indeed characterized by interpretive flexibility. Computer owners such as corporations or universities who wanted to build networks had differing goals for their systems and competing views on appropriate methods for achieving a given end or avoiding a particular problem. Many of the technical options were not well known or understood even by computer experts; thus network builders evaluated these techniques based not only on their goals but also on their technical training and experience and their attitudes toward adopting unproven techniques. In addition, many design features that were desirable in themselves interacted adversely with other parts of the total network system, forcing designers to weigh trade-offs between different objectives (such as low cost and high capacity, or simplicity and robustness). Thus the design of any network was the result of a series of choices that reflected the resources and goals of the relevant social groups, which might include computer owners, computer manufacturers, or telecommunications providers.

The state of computing in mid-1960s America

Computing in the mid-1960s was a rapidly expanding field. The number of computers in use worldwide rose from a few hundred in 1955 to several thousand in 1959; it quadrupled between 1960 and 1965 and again between 1965 and 1970 (Phister, 1979, 42). General-purpose computers were becoming more common and better adapted to the needs of their users. In 1964 IBM introduced its extremely System/360 series, the first "modular" line of computers: each computer in the series could use the same software, consoles, tape drives, and printers, so that owners could switch models without worrying about compatibility. The integrated circuit, patented in 1961, ushered in the era of minicomputers, smaller, cheaper machines that did not have to be confined to special machine rooms. Introduced commercially in the late 1960s, minicomputers gave many smaller enterprises their first taste of the power of computers. Government and business were also developing special-purpose "supercomputers" with increased speed and power to perform massive calculations.

In software, high-level languages such as FORTRAN (FORmula TRANslator, for scientific applications) and COBOL (COmmon Business-Oriented Language) had been developed in the 1950s and were now in general use. Computer science was also gaining recognition as a distinct discipline. It began to be taught in universities, and several professional organizations published journals and organized conferences, the most prominent being the Association for Computing Machinery (ACM), the American Federation of Information Processing Societies (AFIPS), and the Computer Society of the Institute for Electrical and Electronics Engineers (IEEE).

Despite these rapid advances, there were many obstacles to using computers easily and efficiently. The hardware and software used to interact with the computer (the *user interface*) were awkward to work with; people were rarely able to type commands directly to the computer, and "user-friendly" interfaces featuring graphical icons to represent data or input devices such as the mouse