国外计算机科学教材系列

Pearson

Douglas E. Comer

用TCP/IP进行网际互连

（第一卷）（第六版）

[美] Douglas E. Comer 著

英文版 **Internetworking With TCP/IP Volume One**

Pearson New International Edition, Sixth Edition

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Internetworking With TCP/IP
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内容简介

本书是计算机网络领域的著名经典教材，美国众多大学的计算机网络课程将其作为主要参考书。作者是TCP/IP协议和因特网的国际公认专家。本书强调原理、概念准确。所有各章均反映了协议的新版本和新技术，删除和压缩了一些陈旧内容，对现在因特网中用得较多的协议则适当增加篇幅。全书结构分成五部分。第一部分为概述，包括第1章和第2章；第二部分从单个主机来看TCP/IP互联网，包括第3章至第11章；第三部分则从全局来看互联网的结构，包括第12章至第14章；第四部分讨论一些扩展技术，包括第15章至第19章；第五部分讨论因特网提供的应用层服务，包括第20章至第29章。

本书可供计算机和通信专业的高年级本科生和研究生作为教科书和参考书，也可供从事科研和技术开发的人员参考。

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Introduction And Overview

1.1 The Motivation For Internetworking

Internet communication has become a fundamental part of life. Social networks, such as Facebook, provide connections among a group of friends and allow them to share interests. The World Wide Web contains information about such diverse subjects as politics, atmospheric conditions, stock prices, crop production, and airline fares. Family and friends use the Internet to share photos and keep in touch with VoIP telephone calls and live video chats. Consumers use the Internet to purchase goods and services and for personal banking. Companies take orders and make payments electronically. The move to cloud computing will put more information and services online.

Although it appears to operate as a unified network, the Internet is not engineered from a single networking technology because no technology suffices for all uses. Instead, networking hardware is designed for specific situations and budgets. Some groups need high-speed wired networks to connect computers in a single building. Others need a low-cost wireless network for a private home. Because low-cost hardware that works well inside a building cannot span large geographic distances, an alternative must be used to connect sites that are thousands of miles apart.

In the 1970s, a technology was created that makes it possible to interconnect many disparate individual networks and operate them as a coordinated unit. Known as *internetworking,* the technology forms the basis for the Internet by accommodating multiple, diverse underlying hardware technologies, providing a way to interconnect the networks, and defining a set of communication conventions that the networks use to interoperate. The internet technology hides the details of network hardware, and permits computers to communicate independent of their physical network connections.

Internet technology is an example of *open system interconnection*. It is called *open* because, unlike proprietary communication systems available from one specific vendor, the specifications are publicly available. Thus, any individual or company can build the hardware and software needed to communicate across the Internet. More important, the entire technology has been designed to foster communication among machines with diverse hardware architectures, to use almost any packet switched network hardware, to accommodate a wide variety of applications, and to accommodate arbitrary computer operating systems.

1.2 The TCP/IP Internet

In the 1970s and 1980s, U.S. government agencies realized the importance and potential of internet technology, and funded research that made possible a global Internet†. This book discusses principles and ideas that resulted from research funded by the *Defense Advanced Research Projects Agency* (*DARPA*‡). The DARPA technology includes a set of network standards that specify the details of how computers communicate, as well as a set of conventions for interconnecting networks and forwarding traffic. Officially named the *TCP/IP Internet Protocol Suite* and commonly referred to as *TCP/IP* (after the names of its two main standards), it can be used to communicate across any set of interconnected networks. For example, TCP/IP can be used to interconnect a set of networks within a single building, within a physical campus, or among a set of campuses.

Although the TCP/IP technology is noteworthy by itself, it is especially interesting because its viability has been demonstrated on a large scale. It forms the base technology for the global Internet that connects approximately two billion individuals in homes, schools, corporations, and governments in virtually all populated areas of the planet. An outstanding success, the Internet demonstrates the viability of the TCP/IP technology and shows how it can accommodate a wide variety of underlying hardware technologies.

1.3 Internet Services

One cannot appreciate the technical details underlying TCP/IP without understanding the services it provides. This section reviews internet services briefly, highlighting the services most users access, and leaves to later chapters the discussion of how computers connect to a TCP/IP internet and how the functionality is implemented.

Much of our discussion of services will focus on standards called *protocols*. Protocol specifications, such as those for TCP and IP, define the syntactic and semantic rules for communication. They give the details of message formats, describe how a computer responds when a message arrives, and specify how a computer handles errors or other abnormal conditions. Most important, protocols allow us to discuss computer communication independent of any particular vendor's network hardware. In a sense, protocols

†We will follow the usual convention of capitalizing *Internet* when referring specifically to the global Internet, and use lower case to refer to private internets that use TCP/IP technology.

‡At various times, *DARPA* has been called the *Advanced Research Projects Agency* (*ARPA*).

are to communication what algorithms are to computation. An algorithm allows one to specify or understand a computation without knowing the details of a particular programming language or CPU instruction set. Similarly, a communication protocol allows one to specify or understand data communication without depending on detailed knowledge of a particular vendor's network hardware.

Hiding the low-level details of communication helps improve productivity in several ways. First, because they can use higher-level protocol abstractions, programmers do not need to learn or remember as many details about a given hardware configuration. Thus, they can create new network applications quickly. Second, because software built using higher-level abstractions are not restricted to a particular computer architecture or a particular network hardware, the applications do not need to be changed when computers or networks are replaced or reconfigured. Third, because applications built using higher-level protocols are independent of the underlying hardware, they can be ported to arbitrary computers. That is, a programmer does not need to build a special version of an application for each type of computer or each type of network. Instead, applications that use high-level abstractions are more general-purpose — the same code can be compiled and run on an arbitrary computer.

We will see that the details of each service available on the Internet are given by a separate protocol. The next sections refer to protocols that specify some of the application-level services as well as those used to define network-level services. Later chapters explain each of the protocols in detail.

1.3.1 Application Level Internet Services

From a user's point of view, the Internet appears to consist of a set of application programs that use the underlying network to carry out useful tasks. We use the term *interoperability* to refer to the ability of diverse computing systems to cooperate in solving computational problems. Because the Internet was designed to accommodate heterogeneous networks and computers, interoperability was a key requirement. Consequently, Internet application programs usually exhibit a high degree of interoperability. In fact, most users access applications without understanding the types of computers or networks being used, the communication protocols, or even the path data travels from its source to its destination. Thus, a user might access a web page from a desktop system connected to a cable modem or from an iPad connected to a 4G wireless network.

The most popular and widespread Internet application services include:

- *World Wide Web.* The Web became the largest source of traffic on the global Internet between 1994 and 1995, and remains so. Many popular services, including Internet search (e.g., Google) and social networking (e.g., Facebook), use web technology. One estimate attributes approximately one quarter of all Internet traffic to Facebook. Although users distinguish among various web-based services, we will see that they all use the same application-level protocol.

- *Cloud Access And Remote Desktop.* Cloud computing places computation and storage facilities in *cloud data centers*, and arranges for users to access the services over the Internet. One access technology, known as a *remote desktop service*, allows a user to access a computer in a remote data center as if the computer is local. The user only needs an interface device with a screen, keyboard, mouse or touchpad, and a network connection. When the data center computer updates the video display, the remote desktop service captures the information, sends it across the Internet, and displays it on the user's screen. When the user moves the mouse or presses a key, the remote desktop service sends the information to the data center. Thus, the user has full access to a powerful PC, but only needs to carry a basic interface device such as a tablet.

- *File Transfer.* The file transfer protocol allows users to send or receive a copy of a data file. Many file downloads, including movie downloads, invoke a file transfer mechanism. Because they often invoke file transfer from a web page, users may not be aware that a file transfer application has run.

- *Electronic Mail (email).* Electronic mail, which once accounted for large amounts of Internet traffic, has largely been replaced by web applications. Many users now access email through a web application that allows a user to read messages in their mailbox, select a message for processing, and forward the message or send a reply. Once a user specifies sending a message, the underlying system uses an email transfer protocol to send the message to the recipient's mailbox.

- *Voice And Video Services.* Both streaming video and audio already account for a nontrivial fraction of bits transported across the global Internet, and the trend will continue. More important, a significant change is occurring; video upload is increasing, especially because users are using mobile devices to send video of live events.

We will return to a discussion of applications in later chapters and examine them in more detail. We will see exactly how applications use the underlying TCP/IP protocols, and why having standards for application protocols has helped ensure that they are widespread.

1.3.2 Network-Level Internet Services

A programmer who creates network applications has an entirely different view of the Internet than a user who merely runs applications such as web browsers. At the network level, the Internet provides two broad services that all application programs use. While it is unimportant at this time to understand the details of the services, they are fundamental to an overview of TCP/IP:

- *Connectionless Packet Delivery Service.* Packet delivery, explained in detail throughout the text, forms the basis for all internet services. Connectionless delivery is an abstraction of the service that most packet-switching networks offer. It means simply that a TCP/IP internet forwards small messages from one computer to another based on address information carried in the message. Because it forwards each packet independently, an internet does not guarantee reliable, in-order delivery. However, because it maps directly onto most of the underlying hardware technologies, a connectionless delivery service is extremely efficient. More important, because the design makes connectionless packet delivery the basis for all internet services, the TCP/IP protocols can accommodate a wide range of network hardware.

- *Reliable Stream Transport Service.* Most applications require the communication software to recover automatically from transmission errors, lost packets, or failures of intermediate switches along the path between sender and receiver. Consequently, most applications need a reliable transport service to handle problems. The Internet's reliable stream service allows an application on one computer to establish a "connection" to an application on another computer, and allows the applications to transfer arbitrarily large amounts of data across the connection as if it were a permanent, direct hardware link. Underneath, the communication protocols divide the stream of data into small packets and send them one at a time, waiting for the receiver to acknowledge reception.

Many networks provide basic services similar to those outlined above, so one might wonder what distinguishes TCP/IP services from others. The primary distinguishing features are:

- *Network Technology Independence.* Although it is based on conventional packet switching technology, TCP/IP is independent of any particular brand or type of hardware; the global Internet includes a variety of network technologies. TCP/IP protocols define the unit of data transmission, called a *datagram*, and specify how to transmit datagrams on a particular network, but nothing in a datagram is tied to specific hardware.

- *Universal Interconnection.* The Internet allows any arbitrary pair of computers to communicate. Each computer is assigned an *address* that is universally recognized throughout the Internet. Every datagram carries the addresses of its source and destination. Intermediate devices use the destination address to make forwarding decisions; a sender only needs to know the address of a recipient and the Internet takes care of forwarding datagrams.

- *End-to-End Acknowledgements.* The TCP/IP Internet protocols provide acknowledgements between the original source and ultimate destination instead of between successive machines along the path, even if the source and destination do not connect to a common physical network.

- *Application Protocol Standards.* In addition to the basic transport-level services (like reliable stream connections), the TCP/IP protocols include standards for many common applications, including protocols that specify how to access a web page, transfer a file, and send email. Thus, when designing applications that use TCP/IP, programmers often find that existing application protocols provide the communication services they need.

Later chapters discuss the details of the services provided to the programmer as well as examples of application protocol standards.

1.4 History And Scope Of The Internet

Part of what makes the TCP/IP technology so exciting is its universal adoption, as well as the size and growth rate of the global Internet. DARPA began working toward an internet technology in the mid 1970s, with the architecture and protocols taking their current form around 1977–79. At that time, DARPA was known as the primary funding agency for packet-switched network research, and pioneered many ideas in packet-switching with its well-known *ARPANET*. The ARPANET used conventional point-to-point leased line interconnections, but DARPA also funded exploration of packet-switching over radio networks and satellite communication channels. Indeed, the growing diversity of network hardware technologies helped force DARPA to study network interconnection, and pushed internetworking forward.

The availability of research funding from DARPA caught the attention and imagination of several research groups, especially those researchers who had previous experience using packet switching on the ARPANET. DARPA scheduled informal meetings of researchers to share ideas and discuss results of experiments. Informally, the group was known as the *Internet Research Group*. By 1979, so many researchers were involved in the TCP/IP effort that DARPA created an informal committee to coordinate and guide the design of the protocols and architecture of the emerging Internet. Called the *Internet Control and Configuration Board* (*ICCB*), the group met regularly until 1983, when it was reorganized.

The global Internet began around 1980 when DARPA started converting computers attached to its research networks to the new TCP/IP protocols. The ARPANET, already in place, quickly became the backbone of the new Internet and was used for many of the early experiments with TCP/IP. The transition to Internet technology became complete in January 1983 when the Office of the Secretary of Defense mandated that all computers connected to long-haul networks use TCP/IP. At the same time, the *Defense Communication Agency* (*DCA*) split the ARPANET into two separate networks, one for further research and one for military communication. The research part retained the name ARPANET; the military part, which was somewhat larger, became known as the *military network* (*MILNET*).

To encourage university researchers to adopt and use the new protocols, DARPA made an implementation available at low cost. At that time, most university computer science departments were running a version of the UNIX operating system available in the University of California's *Berkeley Software Distribution*, commonly called *BSD UNIX*. By funding Bolt Beranek and Newman, Incorporated (*BBN*) to implement its TCP/IP protocols for use with UNIX and funding Berkeley to integrate the protocols with its software distribution, DARPA was able to reach over 90% of university computer science departments. The new protocol software came at a particularly significant time because many departments were just acquiring second or third computers and connecting them together with local area networks. The departments needed communication protocols that provided application services such as file transfer.

Besides a set of utility programs, Berkeley UNIX created a new operating system abstraction known as a *socket* to allow applications to access the Internet protocols. A generalization of the UNIX mechanism for I/O, the socket interface has options for other network protocols besides TCP/IP. The introduction of the socket abstraction was important because it allowed programmers to use TCP/IP protocols with little effort. The socket interface has become a de facto standard, and is now used in most operating systems.

Realizing that network communication would soon be a crucial part of scientific research, the National Science Foundation (NSF) took an active role in expanding the TCP/IP Internet to reach as many scientists as possible. In the late 1970s, NSF funded a project known as the *Computer Science NETwork* (*CSNET*), which had as its goal connecting all computer scientists. Starting in 1985, NSF began a program to establish access networks centered around its six supercomputer centers, and in 1986 expanded networking efforts by funding a new wide area backbone network, known as the *NSFNET backbone*. NSF also provided seed money for regional networks, each of which connected major scientific research institutions in a given area.

By 1984, the Internet reached over 1,000 computers. In 1987, the size grew to over 10,000. By 1990, the size topped 100,000, and by 1993, exceeded 1,000,000. In 1997, more than 10,000,000 computers were permanently attached to the Internet, and in 2001, the size exceeded 100,000,000. In 2011, the Internet reached over 800,000,000 permanently-attached computers.

The early growth of the Internet did not occur merely because universities and government-funded groups adopted the protocols. Major computer corporations connected to the Internet, as did many other large corporations including oil companies, the auto industry, electronics firms, pharmaceutical companies, and telecommunications carriers. Medium and small companies began connecting in the 1990s. In addition, many companies experimented by using TCP/IP protocols on their internal corporate intranets before they chose to be part of the global Internet.

1.5 The Internet Architecture Board

Because the TCP/IP Internet protocol suite did not arise from a specific vendor or from a recognized professional society, it is natural to ask, "who set the technical direction and decided when protocols became standard?" The answer is a group known as the *Internet Architecture Board* (*IAB*†) that was formed in 1983 when DARPA reorganized the Internet Control and Configuration Board. The IAB provided the focus and coordination for much of the research and development underlying the TCP/IP protocols, and guided the evolution of the Internet. The IAB decided which protocols were a required part of the TCP/IP suite and set official policies.

†IAB originally stood for *Internet Activities Board*.

1.6 The IAB Reorganization

By the summer of 1989, both the TCP/IP technology and the Internet had grown beyond the initial research project into production facilities upon which thousands of people depended for daily business. It was no longer possible to introduce new ideas by changing a few installations overnight. To a large extent, the hundreds of commercial companies that offered TCP/IP products determined whether their products would interoperate by deciding when to incorporate protocol changes in their software. Researchers who drafted specifications and tested new ideas in laboratories could no longer expect instant acceptance and use of the ideas. It was ironic that the researchers who designed and watched TCP/IP develop found themselves overcome by the commercial success of their brainchild. In short, the TCP/IP protocols and the Internet became a successful production technology, and the marketplace began to dominate its evolution.

To reflect the political and commercial realities of both TCP/IP and the Internet, the IAB was reorganized in the summer of 1989. Researchers were moved from the IAB itself to a subsidiary group known as the *Internet Research Task Force* (*IRTF*), and a new IAB board was constituted to include representatives from the wider community. Responsibility for protocol standards and other technical aspects passed to a group known as the *Internet Engineering Task Force* (*IETF*).

The IETF existed in the original IAB structure, and its success provided part of the motivation for reorganization. Unlike most IAB task forces, which were limited to a few individuals who focused on one specific issue, the IETF was large — before the reorganization, it had grown to include dozens of active members who worked on many problems concurrently. Following the reorganization, the IETF was divided into over 20 *working groups*, each of which focused on a specific problem.

Because the IETF was too large for a single chairperson to manage, it has been divided into a set of approximately one dozen areas, each with its own manager. The IETF chairperson and the area managers constitute the *Internet Engineering Steering Group* (*IESG*), the individuals responsible for coordinating the efforts of IETF working groups. The name *IETF* now refers to the entire body, including the chairperson, area managers, and all members of working groups.

1.7 Internet Request For Comments (RFCs)

We have said that no vendor owns the TCP/IP technology, nor does any professional society or standards body. Thus, the documentation of protocols, standards, and policies cannot be obtained from a vendor. Instead, the IETF manages the standardization process. The resulting protocol documents are kept in an on-line repository and made available at no charge.

Documentation of work on the Internet, proposals for new or revised protocols, and TCP/IP protocol standards all appear in a series of technical reports called Internet *Requests For Comments*, or *RFCs*. RFCs can be short or long, can cover broad concepts or details, and can be standards or merely proposals for new protocols. There are references to RFCs throughout the text. While RFCs are not refereed in the same way as academic research papers, they are reviewed and edited. For many years, a single individual, the late Jon Postel, served as the RFC editor. The task of editing RFCs now falls to area managers of the IETF; the IESG as a whole approves new RFCs.

The RFC series is numbered sequentially in the chronological order RFCs are written. Each new or revised RFC is assigned a new number, so readers must be careful to obtain the highest numbered version of a document; an RFC index is available to help identify the correct version. In addition, preliminary versions of RFC documents, which are known as *Internet drafts*, are available.

RFCs and Internet Drafts can be obtained from:

www.ietf.org

1.8 Internet Growth

The Internet has grown rapidly and continues to evolve. New protocols are being proposed; old ones are being revised. The most significant demand on the underlying technology does not arise from added network connections, but from additional traffic. As new users connect to the Internet and new applications appear, traffic patterns change. For example, when the *World Wide Web* was introduced, it became incredibly popular, and Internet traffic increased dramatically. Later, when music sharing became popular, traffic patterns changed again. More changes are occurring as the Internet is used for telephone, video, and social networking.

Figure 1.1 summarizes expansion of the Internet, and illustrates an important component of growth: much of the change in complexity has arisen because multiple groups now manage various parts of the whole.

	Number of networks	Number of computers	Number of users	Number of managers
1980	10	10^2	10^2	10^0
1990	10^3	10^5	10^6	10^1
2000	10^5	10^7	10^8	10^2
2010	10^6	10^8	10^9	10^3

Figure 1.1 Growth of the Internet. In addition to increases in traffic, complexity has resulted from decentralized management.

The number of computers attached to the Internet helps illustrate the growth. Figure 1.2 contains a plot.

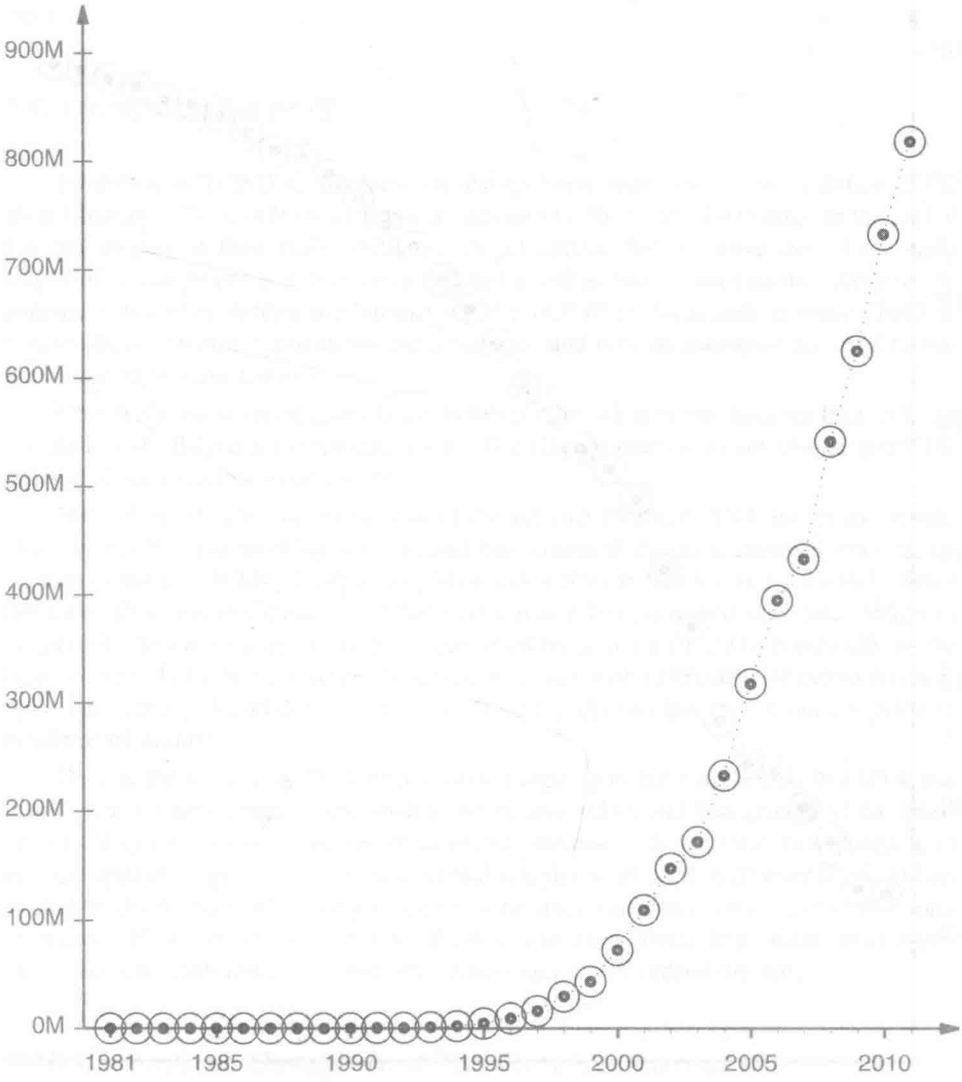

Figure 1.2 Computers on the Internet as a function of the year (linear scale).

The plot makes it appear that the Internet did not start to grow until the late 1990s. However, the linear scale hides an important point: even in the early Internet, the growth rate was high. Figure 1.3 shows the same data plotted on a log scale. The figure reveals that although the count of computers was much smaller, some of the most rapid growth occurred in the late 1980s when the Internet grew from 1,000 computers to over 10,000 computers.

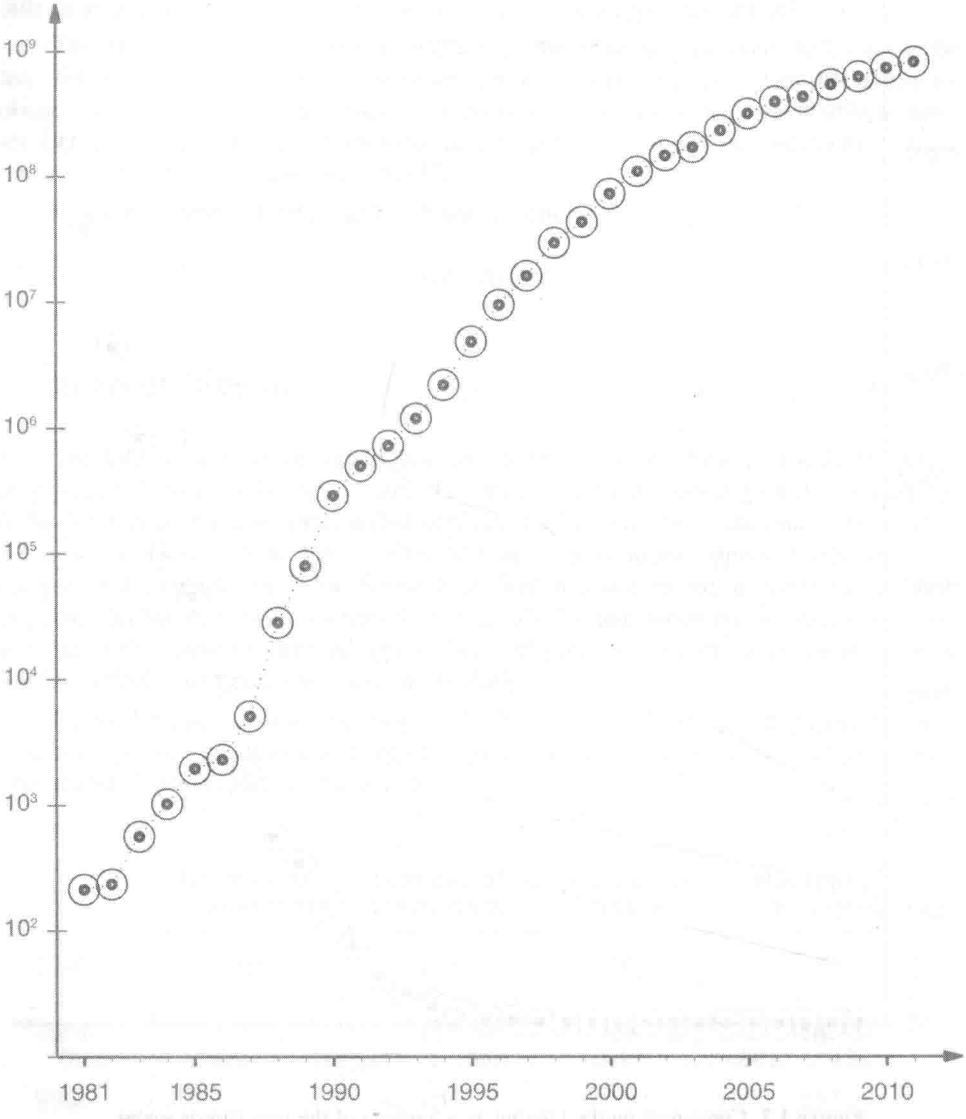

Figure 1.3 Computers on the Internet as a function of the year (log scale).

The count of computers is not the only significant change. Because the technology was developed when a single person at DARPA had control of all aspects of the Internet, the designs of many subsystems depended on centralized management and control.