

Leonard Kleinrock

Leonard Kleinrock is a professor of computer science at the University of California, Los Angeles. In 1969, his computer at UCLA became the first node of the Internet. His creation of packet-switching principles in 1961 became the technology behind the Internet. He received his B.E.E. from the City College of New York (CCNY) and his masters and PhD in electrical engineering from MIT.



What made you decide to specialize in networking/Internet technology?

As a PhD student at MIT in 1959, I looked around and found that most of my classmates were doing research in the area of information theory and coding theory. At MIT, there was the great researcher, Claude Shannon, who had launched these fields and had solved most of the important problems already. The research problems that were left were hard and of lesser consequence. So I decided to launch out in a new area that no one else had yet conceived of. Remember that at MIT I was surrounded by lots of computers, and it was clear to me that soon these machines would need to communicate with each other. At the time, there was no effective way for them to do so, so I decided to develop the technology that would permit efficient and reliable data networks to be created.

What was your first job in the computer industry? What did it entail?

I went to the evening session at CCNY from 1951 to 1957 for my bachelor's degree in electrical engineering. During the day, I worked first as a technician and then as an engineer at a small, industrial electronics firm called Photobell. While there, I introduced digital technology to their product line. Essentially, we were using photoelectric devices to detect the presence of certain items (boxes, people, etc.) and the use of a circuit known then as a *bistable multivibrator* was just the kind of technology we needed to bring digital processing into this field of detection. These circuits happen to be the building blocks for computers, and have come to be known as *flip-flops* or *switches* in today's vernacular.

What was going through your mind when you sent the first host-to-host message (from UCLA to the Stanford Research Institute)?

Frankly, we had no idea of the importance of that event. We had not prepared a special message of historic significance, as did so many inventors of the past (Samuel Morse with "What hath God wrought." or Alexander Graham Bell with "Watson, come here! I want you." or Neal Armstrong with "That's one small step for a man, one giant leap for mankind.") Those guys were *smart*! They understood media and public relations. All we wanted to do was to login to the SRI computer. So we typed the "L", which was correctly received, we typed the "o" which was received, and then we typed the "g" which caused the SRI host computer to

crash! So, it turned out that our message was the shortest and perhaps the most prophetic message ever, namely “Lo!” as in “Lo and behold!”

Earlier that year, I was quoted in a UCLA press release saying that once the network was up and running, it would be possible to gain access to computer utilities from our homes and offices as easily as we gain access to electricity and telephone connectivity. So my vision at that time was that the Internet would be ubiquitous, always on, always available, anyone with any device could connect from any location, and it would be invisible. However, I never anticipated that my 99-year-old mother would use the Internet—and indeed she did!

What is your vision for the future of networking?

The easy part of the vision is to predict the infrastructure itself. I anticipate that we see considerable deployment of nomadic computing, mobile devices, and smart spaces. Indeed, the availability of lightweight, inexpensive, high-performance, portable computing, and communication devices (plus the ubiquity of the Internet) has enabled us to become nomads. Nomadic computing refers to the technology that enables end users who travel from place to place to gain access to Internet services in a transparent fashion, no matter where they travel and no matter what device they carry or gain access to. The harder part of the vision is to predict the applications and services, which have consistently surprised us in dramatic ways (email, search technologies, the world-wide-web, blogs, social networks, user generation, and sharing of music, photos, and videos, etc.). We are on the verge of a new class of surprising and innovative mobile applications delivered to our hand-held devices.

The next step will enable us to move out from the netherworld of cyberspace to the physical world of smart spaces. Our environments (desks, walls, vehicles, watches, belts, and so on) will come alive with technology, through actuators, sensors, logic, processing, storage, cameras, microphones, speakers, displays, and communication. This embedded technology will allow our environment to provide the IP services we want. When I walk into a room, the room will know I entered. I will be able to communicate with my environment naturally, as in spoken English; my requests will generate replies that present Web pages to me from wall displays, through my eyeglasses, as speech, holograms, and so forth.

Looking a bit further out, I see a networking future that includes the following additional key components. I see intelligent software agents deployed across the network whose function it is to mine data, act on that data, observe trends, and carry out tasks dynamically and adaptively. I see considerably more network traffic generated not so much by humans, but by these embedded devices and these intelligent software agents. I see large collections of self-organizing systems controlling this vast, fast network. I see huge amounts of information flashing across this network instantaneously with this information undergoing enormous processing and filtering. The Internet will essentially be a pervasive global nervous system. I see all these things and more as we move headlong through the twenty-first century.

What people have inspired you professionally?

By far, it was Claude Shannon from MIT, a brilliant researcher who had the ability to relate his mathematical ideas to the physical world in highly intuitive ways. He was on my PhD thesis committee.

Do you have any advice for students entering the networking/Internet field?

The Internet and all that it enables is a vast new frontier, full of amazing challenges. There is room for great innovation. Don't be constrained by today's technology. Reach out and imagine what could be and then make it happen.



Application Layer

Network applications are the *raison d'être* of a computer network—if we couldn't conceive of any useful applications, there wouldn't be any need for networking protocols that support these applications. Since the Internet's inception, numerous useful and entertaining applications have indeed been created. These applications have been the driving force behind the Internet's success, motivating people in homes, schools, governments, and businesses to make the Internet an integral part of their daily activities.

Internet applications include the classic text-based applications that became popular in the 1970s and 1980s: text email, remote access to computers, file transfers, and newsgroups. They include *the* killer application of the mid-1990s, the World Wide Web, encompassing Web surfing, search, and electronic commerce. They include instant messaging and P2P file sharing, the two killer applications introduced at the end of the millennium. Since 2000, we have seen an explosion of popular voice and video applications, including: voice-over-IP (VoIP) and video conferencing over IP such as Skype; user-generated video distribution such as YouTube; and movies on demand such as Netflix. During this same period we have also seen the emergence of highly engaging multi-player online games, including Second Life and World of Warcraft. And most recently, we have seen the emergence of a new generation of social networking applications, such as Facebook and Twitter, which have created engaging human networks on top of the Internet's network of routers and communication links. Clearly, there has been no slowing down of new

and exciting Internet applications. Perhaps some of the readers of this text will create the next generation of killer Internet applications!

In this chapter we study the conceptual and implementation aspects of network applications. We begin by defining key application-layer concepts, including network services required by applications, clients and servers, processes, and transport-layer interfaces. We examine several network applications in detail, including the Web, e-mail, DNS, and peer-to-peer (P2P) file distribution (Chapter 8 focuses on multimedia applications, including streaming video and VoIP). We then cover network application development, over both TCP and UDP. In particular, we study the socket API and walk through some simple client-server applications in Python. We also provide several fun and interesting socket programming assignments at the end of the chapter.

The application layer is a particularly good place to start our study of protocols. It's familiar ground. We're acquainted with many of the applications that rely on the protocols we'll study. It will give us a good feel for what protocols are all about and will introduce us to many of the same issues that we'll see again when we study transport, network, and link layer protocols.

2.1 Principles of Network Applications

Suppose you have an idea for a new network application. Perhaps this application will be a great service to humanity, or will please your professor, or will bring you great wealth, or will simply be fun to develop. Whatever the motivation may be, let's now examine how you transform the idea into a real-world network application.

At the core of network application development is writing programs that run on different end systems and communicate with each other over the network. For example, in the Web application there are two distinct programs that communicate with each other: the browser program running in the user's host (desktop, laptop, tablet, smartphone, and so on); and the Web server program running in the Web server host. As another example, in a P2P file-sharing system there is a program in each host that participates in the file-sharing community. In this case, the programs in the various hosts may be similar or identical.

Thus, when developing your new application, you need to write software that will run on multiple end systems. This software could be written, for example, in C, Java, or Python. Importantly, you do not need to write software that runs on network-core devices, such as routers or link-layer switches. Even if you wanted to write application software for these network-core devices, you wouldn't be able to do so. As we learned in Chapter 1, and as shown earlier in Figure 1.24, network-core devices do not function at the application layer but instead function at lower layers—specifically at the network layer and below. This basic design—namely, confining application software to the end systems—as shown in Figure 2.1, has facilitated the rapid development and deployment of a vast array of network applications.

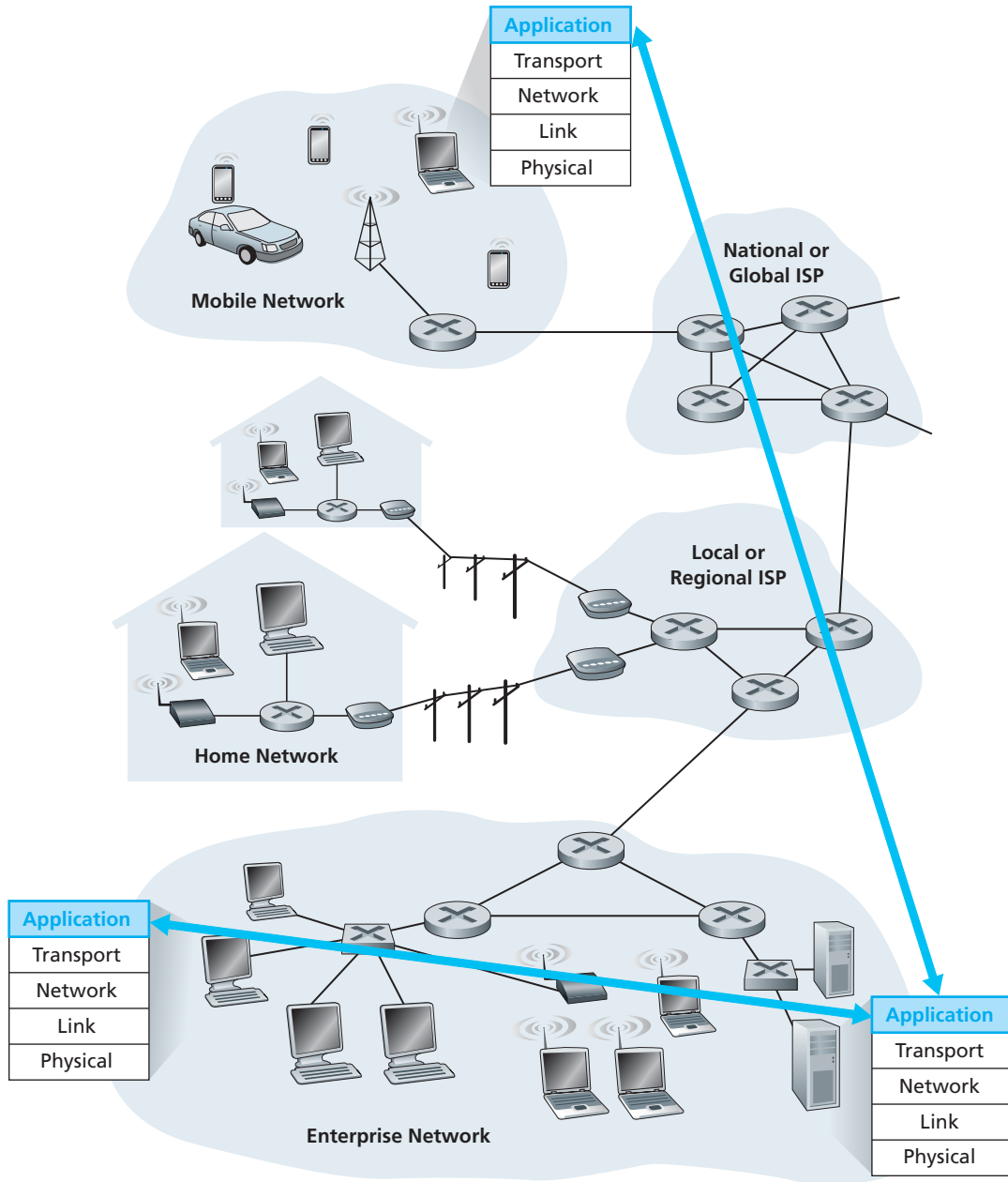


Figure 2.1 ♦ Communication for a network application takes place between end systems at the application layer