

understand the network services needed to support these applications. We can then, in turn, examine the various ways in which such services might be implemented by a network architecture. Covering applications early thus provides motivation for the remainder of the text.

The second half of the book—Chapters 7 and 8—zooms in on two enormously important (and somewhat independent) topics in modern computer networking. In Chapter 7, we examine wireless and mobile networks, including wireless LANs (including WiFi and Bluetooth), Cellular networks (including 4G and 5G), and mobility. Chapter 8, which addresses security in computer networks, first looks at the underpinnings of encryption and network security, and then we examine how the basic theory is being applied in a broad range of Internet contexts.

Homework Problems and Questions

Chapter 1 Review Questions

SECTION 1.1

- R1. What is the difference between a host and an end system? List several different types of end systems. Is a Web server an end system?
- R2. Describe the protocol that might be used by two people having a telephonic conversation to initiate and end the conversation, i.e., the way that they talk.
- R3. Why are standards important for protocols?

SECTION 1.2

- R4. List four access technologies. Classify each one as home access, enterprise access, or wide-area wireless access.
- R5. Is HFC transmission rate dedicated or shared among users? Are collisions possible in a downstream HFC channel? Why or why not?
- R6. What access network technologies would be most suitable for providing internet access in rural areas?
- R7. Dial-up modems and DSL both use the telephone line (a twisted-pair copper cable) as their transmission medium. Why then is DSL much faster than dial-up access?
- R8. What are some of the physical media that Ethernet can run over?
- R9. HFC, DSL, and FTTH are all used for residential access. For each of these access technologies, provide a range of transmission rates and comment on whether the transmission rate is shared or dedicated.
- R10. Describe the different wireless technologies you use during the day and their characteristics. If you have a choice between multiple technologies, why do you prefer one over another?

SECTION 1.3

- R11. Suppose there is exactly one packet switch between a sending host and a receiving host. The transmission rates between the sending host and the switch and between the switch and the receiving host are R_1 and R_2 , respectively. Assuming that the switch uses store-and-forward packet switching, what is the total end-to-end delay to send a packet of length L ? (Ignore queuing, propagation delay, and processing delay.)
- R12. What advantage does a circuit-switched network have over a packet-switched network? What advantages does TDM have over FDM in a circuit-switched network?
- R13. Suppose users share a 2 Mbps link. Also suppose each user transmits continuously at 1 Mbps when transmitting, but each user transmits only 20 percent of the time. (See the discussion of statistical multiplexing in Section 1.3.)
- When circuit switching is used, how many users can be supported?
 - For the remainder of this problem, suppose packet switching is used. Why will there be essentially no queuing delay before the link if two or fewer users transmit at the same time? Why will there be a queuing delay if three users transmit at the same time?
 - Find the probability that a given user is transmitting.
 - Suppose now there are three users. Find the probability that at any given time, all three users are transmitting simultaneously. Find the fraction of time during which the queue grows.
- R14. Why will two ISPs at the same level of the hierarchy often peer with each other? How does an IXP earn money?
- R15. Why is a content provider considered a different Internet entity today? How does a content provider connect to other ISPs? Why?

SECTION 1.4

- R16. Consider sending a packet from a source host to a destination host over a fixed route. List the delay components in the end-to-end delay. Which of these delays are constant and which are variable?
- R17. Visit the Transmission Versus Propagation Delay interactive animation at the Companion Website. Among the rates, propagation delay, and packet sizes available, find a combination for which the sender finishes transmitting before the first bit of the packet reaches the receiver. Find another combination for which the first bit of the packet reaches the receiver before the sender finishes transmitting.
- R18. A user can directly connect to a server through either long-range wireless or a twisted-pair cable for transmitting a 1500-bytes file. The transmission rates of the wireless and wired media are 2 and 100 Mbps, respectively. Assume that the propagation speed in air is 3×10^8 m/s, while the speed in the twisted

pair is 2×10^8 m/s. If the user is located 1 km away from the server, what is the nodal delay when using each of the two technologies?

- R19. Suppose Host A wants to send a large file to Host B. The path from Host A to Host B has three links, of rates $R_1 = 500$ kbps, $R_2 = 2$ Mbps, and $R_3 = 1$ Mbps.
- Assuming no other traffic in the network, what is the throughput for the file transfer?
 - Suppose the file is 4 million bytes. Dividing the file size by the throughput, roughly how long will it take to transfer the file to Host B?
 - Repeat (a) and (b), but now with R_2 reduced to 100 kbps.
- R20. Suppose end system A wants to send a large file to end system B. At a very high level, describe how end system A creates packets from the file. When one of these packets arrives to a router, what information in the packet does the router use to determine the link onto which the packet is forwarded? Why is packet switching in the Internet analogous to driving from one city to another and asking directions along the way?
- R21. Visit the Queuing and Loss interactive animation at the Companion Website. What is the maximum emission rate and the minimum transmission rate? With those rates, what is the traffic intensity? Run the interactive animation with these rates and determine how long it takes for packet loss to occur. Then repeat the experiment a second time and determine again how long it takes for packet loss to occur. Are the values different? Why or why not?

SECTION 1.5

- R22. If two end-systems are connected through multiple routers and the data-link level between them ensures reliable data delivery, is a transport protocol offering reliable data delivery between these two end-systems necessary? Why?
- R23. What are the five layers in the Internet protocol stack? What are the principal responsibilities of each of these layers?
- R24. What do encapsulation and de-encapsulation mean? Why are they needed in a layered protocol stack?
- R25. Which layers in the Internet protocol stack does a router process? Which layers does a link-layer switch process? Which layers does a host process?

SECTION 1.6

- R26. What is self-replicating malware?
- R27. Describe how a botnet can be created and how it can be used for a DDoS attack.
- R28. Suppose Alice and Bob are sending packets to each other over a computer network. Suppose Trudy positions herself in the network so that she can capture all the packets sent by Alice and send whatever she wants to Bob; she can also capture all the packets sent by Bob and send whatever she wants to Alice. List some of the malicious things Trudy can do from this position.

Problems

- P1. Design and describe an application-level protocol to be used between an automatic teller machine and a bank's centralized computer. Your protocol should allow a user's card and password to be verified, the account balance (which is maintained at the centralized computer) to be queried, and an account withdrawal to be made (that is, money disbursed to the user). Your protocol entities should be able to handle the all-too-common case in which there is not enough money in the account to cover the withdrawal. Specify your protocol by listing the messages exchanged and the action taken by the automatic teller machine or the bank's centralized computer on transmission and receipt of messages. Sketch the operation of your protocol for the case of a simple withdrawal with no errors, using a diagram similar to that in Figure 1.2. Explicitly state the assumptions made by your protocol about the underlying end-to-end transport service.
- P2. Equation 1.1 gives a formula for the end-to-end delay of sending one packet of length L over N links of transmission rate R . Generalize this formula for sending P such packets back-to-back over the N links.
- P3. Consider an application that transmits data at a steady rate (for example, the sender generates an N -bit unit of data every k time units, where k is small and fixed). Also, when such an application starts, it will continue running for a relatively long period of time. Answer the following questions, briefly justifying your answer:
- Would a packet-switched network or a circuit-switched network be more appropriate for this application? Why?
 - Suppose that a packet-switched network is used and the only traffic in this network comes from such applications as described above. Furthermore, assume that the sum of the application data rates is less than the capacities of each and every link. Is some form of congestion control needed? Why?
- P4. Consider the circuit-switched network in Figure 1.13. Recall that there are four circuits on each link. Label the four switches A, B, C, and D, going in the clockwise direction.
- What is the maximum number of simultaneous connections that can be in progress at any one time in this network?
 - Suppose that all connections are between switches A and C. What is the maximum number of simultaneous connections that can be in progress?
 - Suppose we want to make four connections between switches A and C, and another four connections between switches B and D. Can we route these calls through the four links to accommodate all eight connections?



VideoNote
Exploring propagation
delay and transmission
delay

- P5. Review the car-caravan analogy in Section 1.4. Assume a propagation speed of 100 km/hour.
- Suppose the caravan travels 175 km, beginning in front of one tollbooth, passing through a second tollbooth, and finishing just after a third tollbooth. What is the end-to-end delay?
 - Repeat (a), now assuming that there are eight cars in the caravan instead of ten.
- P6. This elementary problem begins to explore propagation delay and transmission delay, two central concepts in data networking. Consider two hosts, A and B, connected by a single link of rate R bps. Suppose that the two hosts are separated by m meters, and suppose the propagation speed along the link is s meters/sec. Host A is to send a packet of size L bits to Host B.
- Express the propagation delay, d_{prop} , in terms of m and s .
 - Determine the transmission time of the packet, d_{trans} , in terms of L and R .
 - Ignoring processing and queuing delays, obtain an expression for the end-to-end delay.
 - Suppose Host A begins to transmit the packet at time $t = 0$. At time $t = d_{\text{trans}}$, where is the last bit of the packet?
 - Suppose d_{prop} is greater than d_{trans} . At time $t = d_{\text{trans}}$, where is the first bit of the packet?
 - Suppose d_{prop} is less than d_{trans} . At time $t = d_{\text{trans}}$, where is the first bit of the packet?
 - Suppose $s = 2.5 \cdot 10^8$, $L = 1500$ bytes, and $R = 10$ Mbps. Find the distance m so that d_{prop} equals d_{trans} .
- P7. In this problem, we consider sending real-time voice from Host A to Host B over a packet-switched network (VoIP). Host A converts analog voice to a digital 64 kbps bit stream on the fly. Host A then groups the bits into 56-byte packets. There is one link between Hosts A and B; its transmission rate is 10 Mbps and its propagation delay is 10 msec. As soon as Host A gathers a packet, it sends it to Host B. As soon as Host B receives an entire packet, it converts the packet's bits to an analog signal. How much time elapses from the time a bit is created (from the original analog signal at Host A) until the bit is decoded (as part of the analog signal at Host B)?
- P8. Suppose users share a 10 Mbps link. Also suppose each user requires 200 kbps when transmitting, but each user transmits only 10 percent of the time. (See the discussion of packet switching versus circuit switching in Section 1.3.)
- When circuit switching is used, how many users can be supported?
 - For the remainder of this problem, suppose packet switching is used. Find the probability that a given user is transmitting.

- c. Suppose there are 120 users. Find the probability that at any given time, exactly n users are transmitting simultaneously. (*Hint*: Use the binomial distribution.)
 - d. Find the probability that there are 51 or more users transmitting simultaneously.
- P9. Consider the discussion in Section 1.3 of packet switching versus circuit switching in which an example is provided with a 1 Mbps link. Users are generating data at a rate of 100 kbps when busy, but are busy generating data only with probability $p = 0.1$. Suppose that the 1 Mbps link is replaced by a 1 Gbps link.
- a. What is N , the maximum number of users that can be supported simultaneously under circuit switching?
 - b. Now consider packet switching and a user population of M users. Give a formula (in terms of p , M , N) for the probability that more than N users are sending data.
- P10. Consider the network illustrated in Figure 1.16. Assume the two hosts on the left of the figure start transmitting packets of 1500 bytes at the same time towards Router B. Suppose the link rates between the hosts and Router A is 4-Mbps. One link has a 6-ms propagation delay and the other has a 2-ms propagation delay. Will queuing delay occur at Router A?
- P11. Consider the scenario in Problem P10 again, but now assume the links between the hosts and Router A have different rates R_1 and R_2 byte/s in addition to different propagation delays d_1 and d_2 . Assume the packet lengths for the two hosts are of L bytes. For what values of the propagation delay will no queuing delay occur at Router A?
- P12. Consider a client and a server connected through one router. Assume the router can start transmitting an incoming packet after receiving its first h bytes instead of the whole packet. Suppose that the link rates are R byte/s and that the client transmits one packet with a size of L bytes to the server. What is the end-to-end delay? Assume the propagation, processing, and queuing delays are negligible. Generalize the previous result to a scenario where the client and the server are interconnected by N routers.
- P13. (a) Suppose N packets arrive simultaneously to a link at which no packets are currently being transmitted or queued. Each packet is of length L and the link has transmission rate R . What is the average queuing delay for the N packets?

- (b) Now suppose that N such packets arrive to the link every LN/R seconds. What is the average queuing delay of a packet?
- P14. Consider the queuing delay in a router buffer. Let I denote traffic intensity; that is, $I = La/R$. Suppose that the queuing delay takes the form $IL/R(1 - I)$ for $I < 1$.
- Provide a formula for the total delay, that is, the queuing delay plus the transmission delay.
 - Plot the total delay as a function of L/R .
- P15. Let a denote the rate of packets arriving at a link in packets/sec, and let μ denote the link's transmission rate in packets/sec. Based on the formula for the total delay (i.e., the queuing delay plus the transmission delay) derived in the previous problem, derive a formula for the total delay in terms of a and μ .
- P16. Consider a router buffer preceding an outbound link. In this problem, you will use Little's formula, a famous formula from queuing theory. Let N denote the average number of packets in the buffer plus the packet being transmitted. Let a denote the rate of packets arriving at the link. Let d denote the average total delay (i.e., the queuing delay plus the transmission delay) experienced by a packet. Little's formula is $N = a \cdot d$. Suppose that on average, the buffer contains 100 packets, and the average packet queuing delay is 20 msec. The link's transmission rate is 100 packets/sec. Using Little's formula, what is the average packet arrival rate, assuming there is no packet loss?
- P17. Consider the network illustrated in Figure 1.12. Would Equation 1.2 hold in such a scenario? If so, under which conditions? If not, why? (Assume N is the number of links between a source and a destination in the figure.)
- P18. Perform a Traceroute between source and destination on the same continent at three different hours of the day.
- Find the average and standard deviation of the round-trip delays at each of the three hours.
 - Find the number of routers in the path at each of the three hours. Did the paths change during any of the hours?
 - Try to identify the number of ISP networks that the Traceroute packets pass through from source to destination. Routers with similar names and/or similar IP addresses should be considered as part of the same ISP. In your experiments, do the largest delays occur at the peering interfaces between adjacent ISPs?
 - Repeat the above for a source and destination on different continents. Compare the intra-continent and inter-continent results.



VideoNote
Using Traceroute to
discover network
paths and measure
network delay

- P19. Metcalfe's law states the value of a computer network is proportional to the square of the number of connected users of the system. Let n denote the number of users in a computer network. Assuming each user sends one message to each of the other users, how many messages will be sent? Does your answer support Metcalfe's law?
- P20. Consider the throughput example corresponding to Figure 1.20(b). Now suppose that there are M client-server pairs rather than 10. Denote R_s , R_c , and R for the rates of the server links, client links, and network link. Assume all other links have abundant capacity and that there is no other traffic in the network besides the traffic generated by the M client-server pairs. Derive a general expression for throughput in terms of R_s , R_c , R , and M .
- P21. Assume a client and a server can connect through either network (a) or (b) in Figure 1.19. Assume that $R_i = (R_c + R_s) / i$, for $i = 1, 2, \dots, N$. In what case will network (a) have a higher throughput than network (b)?
- P22. Consider Figure 1.19(b). Suppose that each link between the server and the client has a packet loss probability p , and the packet loss probabilities for these links are independent. What is the probability that a packet (sent by the server) is successfully received by the receiver? If a packet is lost in the path from the server to the client, then the server will re-transmit the packet. On average, how many times will the server re-transmit the packet in order for the client to successfully receive the packet?
- P23. Consider Figure 1.19(a). Assume that we know the bottleneck link along the path from the server to the client is the first link with rate R_s bits/sec. Suppose we send a pair of packets back to back from the server to the client, and there is no other traffic on this path. Assume each packet of size L bits, and both links have the same propagation delay d_{prop} .
- What is the packet inter-arrival time at the destination? That is, how much time elapses from when the last bit of the first packet arrives until the last bit of the second packet arrives?
 - Now assume that the second link is the bottleneck link (i.e., $R_c < R_s$). Is it possible that the second packet queues at the input queue of the second link? Explain. Now suppose that the server sends the second packet T seconds after sending the first packet. How large must T be to ensure no queuing before the second link? Explain.
- P24. Consider a user who needs to transmit 1.5 gigabytes of data to a server. The user lives in a village where only dial-up access is available. As an alternative, a bus collects data from users in rural areas and transfer them to the Internet through a 1 Gbps link once it gets back to the city. The bus visits the village once a day and stops in front of the user's house just long enough to receive the data. The bus has a 100 Mbps WiFi connection. Suppose the average speed of the bus is 60 km/h and that the distance between the village and the city is 150 km. What is the fastest way the user can transfer the data to the server?

- P25. Suppose two hosts, A and B, are separated by 20,000 kilometers and are connected by a direct link of $R = 5$ Mbps. Suppose the propagation speed over the link is $2.5 \cdot 10^8$ meters/sec.
- Calculate the bandwidth-delay product, $R \cdot d_{\text{prop}}$.
 - Consider sending a file of 800,000 bits from Host A to Host B. Suppose the file is sent continuously as one large message. What is the maximum number of bits that will be in the link at any given time?
 - Provide an interpretation of the bandwidth-delay product.
 - What is the width (in meters) of a bit in the link? Is it longer than a football field?
 - Derive a general expression for the width of a bit in terms of the propagation speed s , the transmission rate R , and the length of the link m .
- P26. Consider problem P25 but now with a link of $R = 1$ Gbps.
- Calculate the bandwidth-delay product, $R \cdot d_{\text{prop}}$.
 - Consider sending a file of 800,000 bits from Host A to Host B. Suppose the file is sent continuously as one big message. What is the maximum number of bits that will be in the link at any given time?
 - What is the width (in meters) of a bit in the link?
- P27. Consider the scenario illustrated in Figure 1.19(a). Assume R_s is 20 Mbps, R_c is 10 Mbps, and the server is continuously sending traffic to the client. Also assume the router between the server and the client can buffer at most four messages. After how many messages sent by the server will packet loss starts occurring at the router?
- P28. Generalize the result obtained in Problem P27 for the case where the router can buffer m messages.
- P29. Suppose there is a 10 Mbps microwave link between a geostationary satellite and its base station on Earth. Every minute the satellite takes a digital photo and sends it to the base station. Assume a propagation speed of $2.4 \cdot 10^8$ meters/sec.
- What is the propagation delay of the link?
 - What is the bandwidth-delay product, $R \cdot d_{\text{prop}}$?
 - Let x denote the size of the photo. What is the minimum value of x for the microwave link to be continuously transmitting?

- P30. Consider the airline travel analogy in our discussion of layering in Section 1.5, and the addition of headers to protocol data units as they flow down the protocol stack. Is there an equivalent notion of header information that is added to passengers and baggage as they move down the airline protocol stack?
- P31. In modern packet-switched networks, including the Internet, the source host segments long, application-layer messages (for example, an image or a music file) into smaller packets and sends the packets into the network. The receiver then reassembles the packets back into the original message. We refer to this process as *message segmentation*. Figure 1.27 illustrates the end-to-end transport of a message with and without message segmentation. Consider a message that is 10^6 bits long that is to be sent from source to destination in Figure 1.27. Suppose each link in the figure is 5 Mbps. Ignore propagation, queuing, and processing delays.
- Consider sending the message from source to destination *without* message segmentation. How long does it take to move the message from the source host to the first packet switch? Keeping in mind that each switch uses store-and-forward packet switching, what is the total time to move the message from source host to destination host?
 - Now suppose that the message is segmented into 100 packets, with each packet being 10,000 bits long. How long does it take to move the first packet from source host to the first switch? When the first packet is being sent from the first switch to the second switch, the second packet is being sent from the source host to the first switch. At what time will the second packet be fully received at the first switch?
 - How long does it take to move the file from source host to destination host when message segmentation is used? Compare this result with your answer in part (a) and comment.

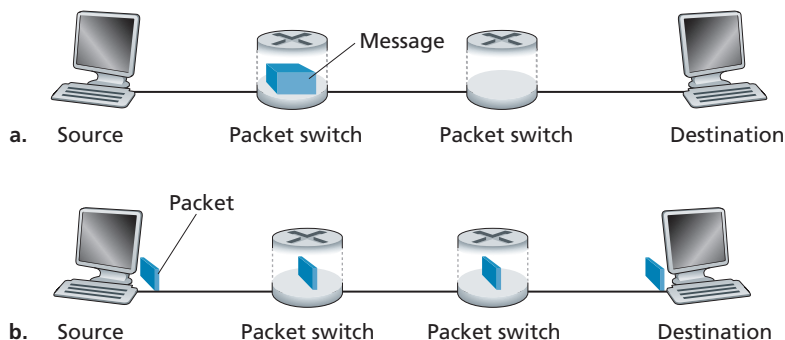


Figure 1.27 ♦ End-to-end message transport: (a) without message segmentation; (b) with message segmentation

- d. In addition to reducing delay, what are reasons to use message segmentation?
 - e. Discuss the drawbacks of message segmentation.
- P32. Consider Problem P31 and assume that the propagation delay is 250 ms. Recalculate the total time needed to transfer the source data with and without segmentation. Is segmentation more beneficial or less if there is propagation delay?
- P33. Consider sending a large file of F bits from Host A to Host B. There are three links (and two switches) between A and B, and the links are uncongested (that is, no queuing delays). Host A segments the file into segments of S bits each and adds 80 bits of header to each segment, forming packets of $L = 80 + S$ bits. Each link has a transmission rate of R bps. Find the value of S that minimizes the delay of moving the file from Host A to Host B. Disregard propagation delay.
- P34. Early versions of TCP combined functions for both forwarding and reliable delivery. How are these TCP variants located in the ISO/OSI protocol stack? Why were forwarding functions later separated from TCP? What were the consequences?

Wireshark Lab

“Tell me and I forget. Show me and I remember. Involve me and I understand.”
Chinese proverb

One’s understanding of network protocols can often be greatly deepened by seeing them in action and by playing around with them—observing the sequence of messages exchanged between two protocol entities, delving into the details of protocol operation, causing protocols to perform certain actions, and observing these actions and their consequences. This can be done in simulated scenarios or in a real network environment such as the Internet. The interactive animations at the textbook Web site take the first approach. In the Wireshark labs, we’ll take the latter approach. You’ll run network applications in various scenarios using a computer on your desk, at home, or in a lab. You’ll observe the network protocols in your computer, interacting and exchanging messages with protocol entities executing elsewhere in the Internet. Thus, you and your computer will be an integral part of these live labs. You’ll observe—and you’ll learn—by doing.

The basic tool for observing the messages exchanged between executing protocol entities is called a **packet sniffer**. As the name suggests, a packet sniffer passively copies (sniffs) messages being sent from and received by your computer; it also displays the contents of the various protocol fields of these captured messages. A screenshot of the Wireshark packet sniffer is shown in Figure 1.28. Wireshark is a