AinShams University
Faculty of Engineering

CSE 351s: Computer networks
Section 1

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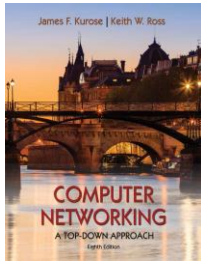
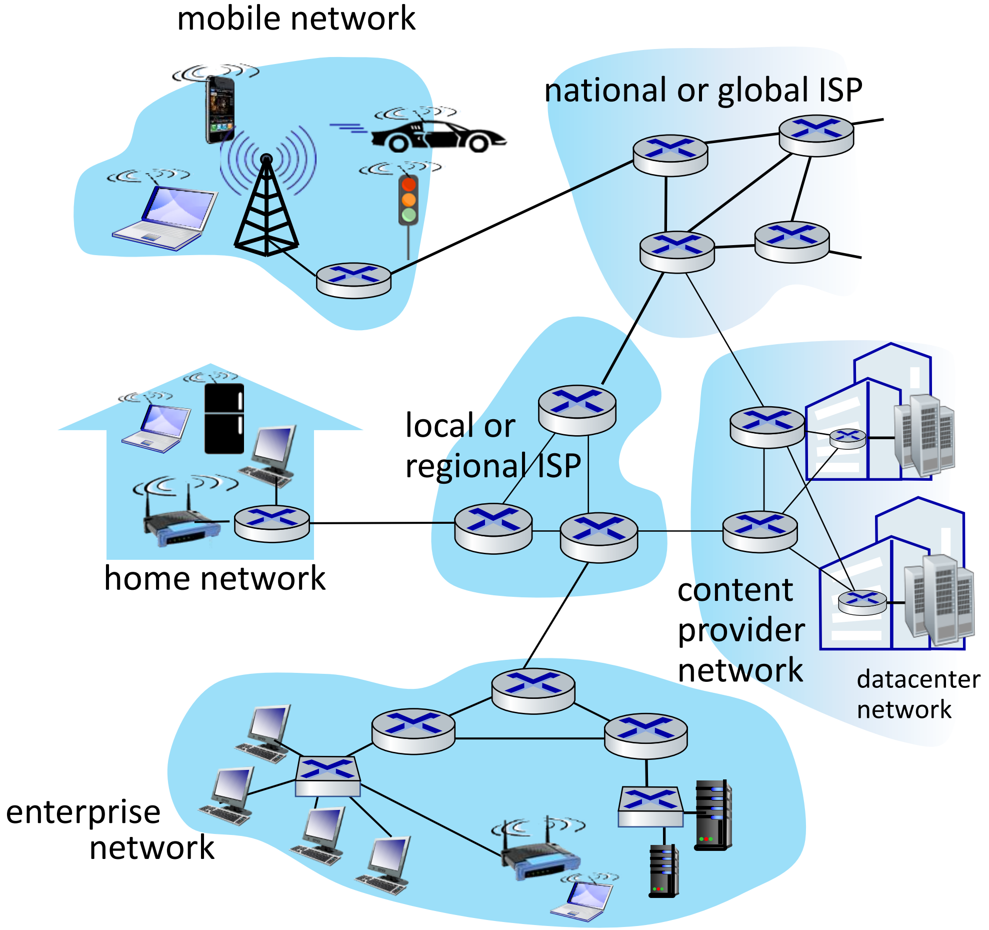
Class textbook:
Computer Networking: A Top-Down Approach (*8th ed.*)
J.F. Kurose, K.W. Ross
Pearson, 2020
http://gaia.cs.umass.edu/kurose_ross



Internet structure: a "network of networks"

- hosts connect to Internet via access Internet Service Providers (ISPs)
- access ISPs in turn must be interconnected
  - so that *any* two hosts *(anywhere!)* can send packets to each other
- resulting network of networks is very complex
  - evolution driven by economics, national policies



Let's take a stepwise approach to describe current Internet structure

Sheet 1: Question 1

- What is the difference between a host and an end system?

There is no difference. Throughout this text, the words “host” and “end system” are used interchangeably.

- List several different types of end systems.

End systems include PCs, Web servers, and mail servers.

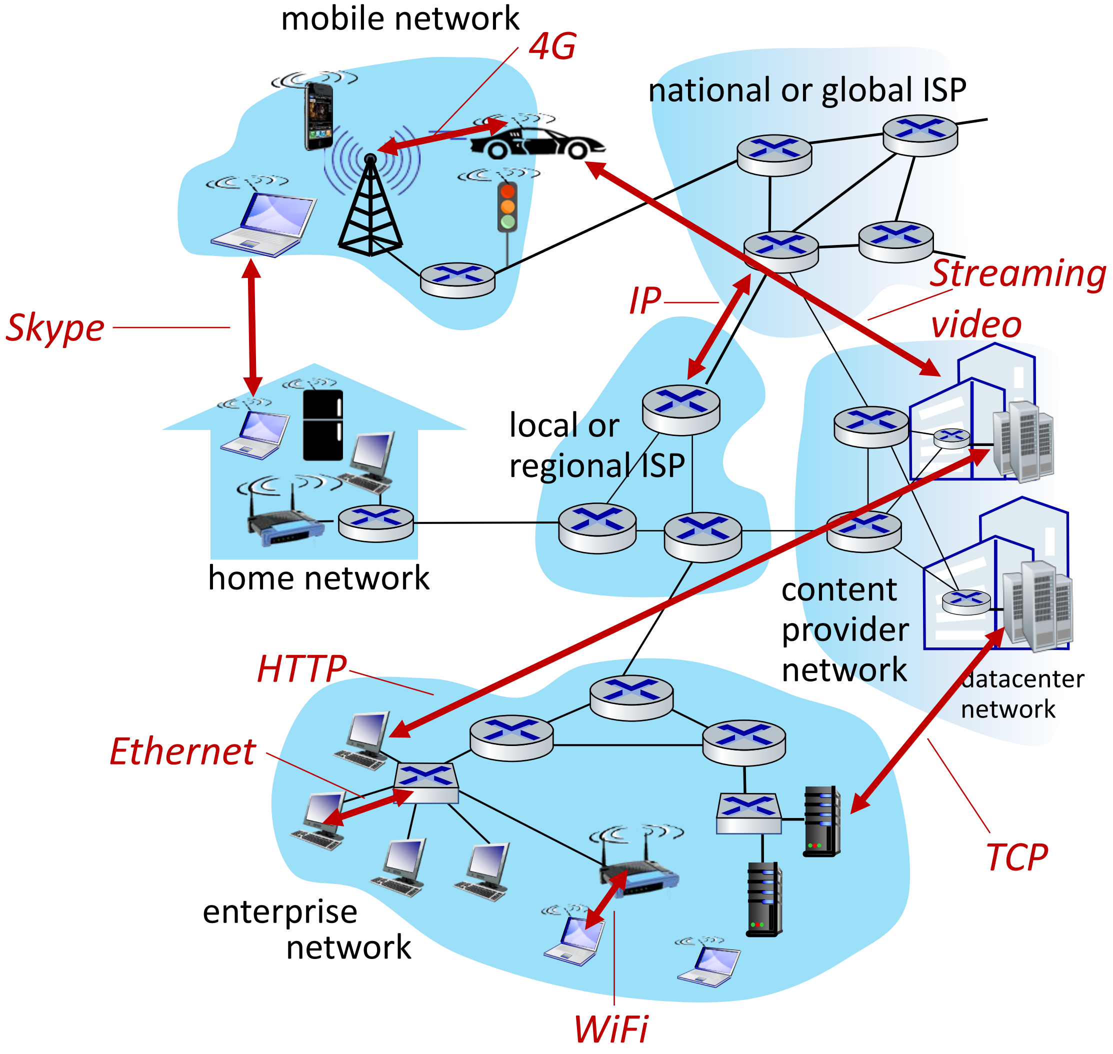
- Is a Web server an end system?

Yes

What's a protocol?

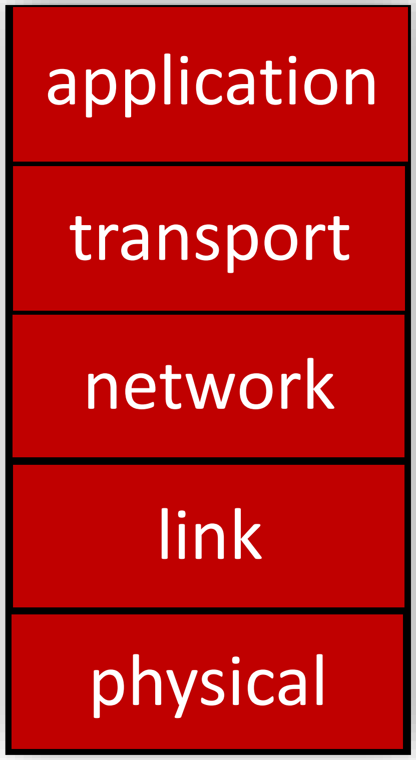
Protocols define the format, order of messages sent and received among network entities, and actions taken on message transmission, receipt

- *protocols* are *everywhere*
  - control sending, receiving of messages
  - e.g., HTTP (Web), streaming video, Skype, TCP, IP, WiFi, 4G, Ethernet



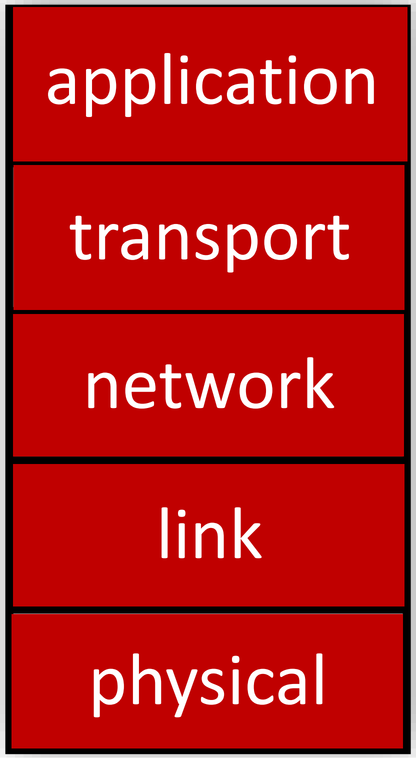
Layered Internet protocol stack

- *application:* supporting network applications
  - HTTP, IMAP, SMTP, DNS
- *transport:* process-process data transfer
  - TCP, UDP
- *network:* routing of datagrams from source to destination
  - IP, routing protocols
- *link:* data transfer between neighboring network elements
  - Ethernet, 802.11 (WiFi), PPP
- *physical:* bits “on the wire”



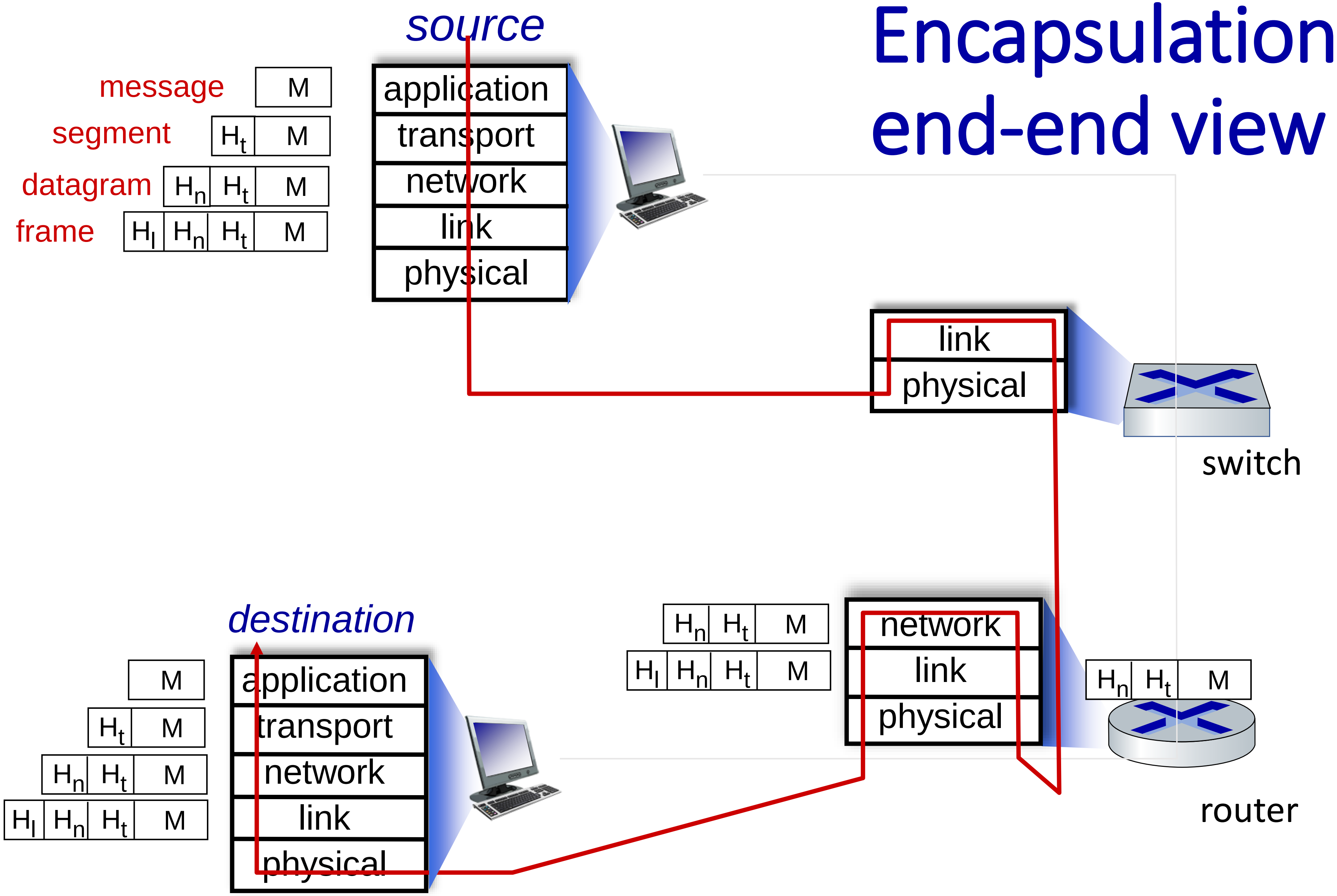
Sheet 1: Question 6

What are the five layers in the Internet protocol stack? What are the principal responsibilities of each of these layers?



- *Application layer:* exchange messages between network applications that are distributed over various end systems
- *Transport layer:* process-process data(segment) transfer
- *Network layer:* routing of datagrams from source to destination (finding best route, load balancing)
- *Link layer:* data transfer between neighboring network elements (next hop)
- *Physical layer:* bits “on the wire”

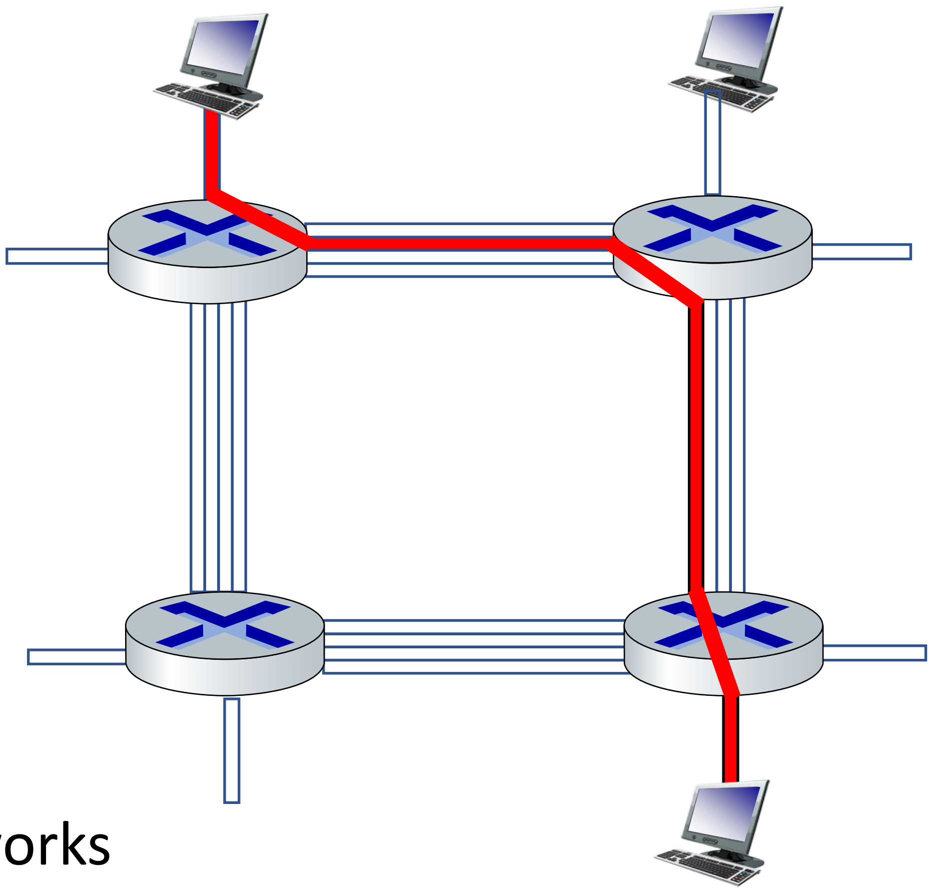
Encapsulation: an end-end view



Circuit switching

end-end resources allocated to, reserved for “call” between source and destination

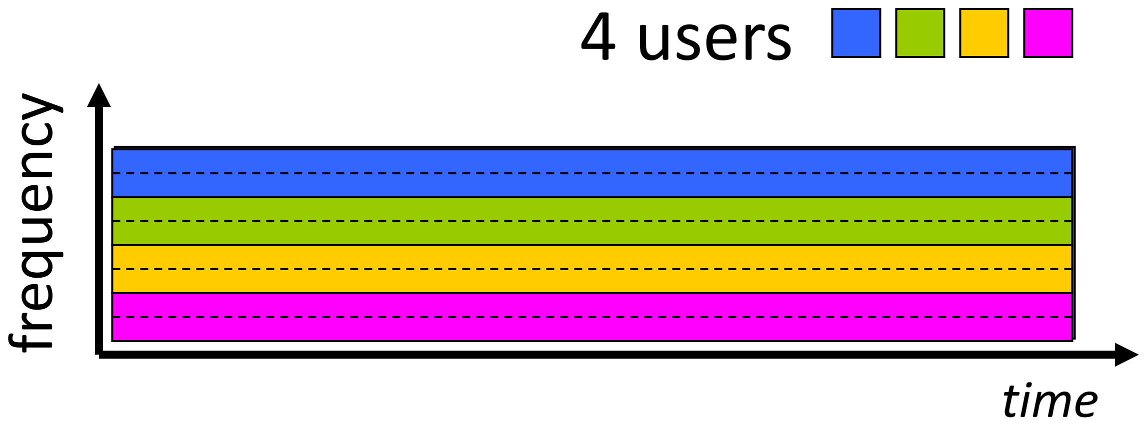
- in diagram, each link has four circuits.
  - call gets 2nd circuit in top link and 1st circuit in right link.
- dedicated resources: no sharing
  - circuit-like (guaranteed) performance
- circuit segment idle if not used by call (no sharing)
- commonly used in traditional telephone networks



Circuit switching: FDM and TDM

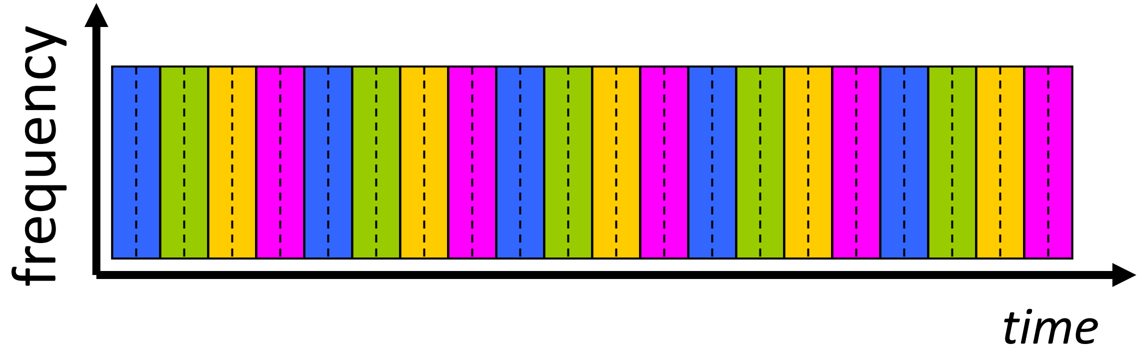
Frequency Division Multiplexing (FDM)

- optical, electromagnetic frequencies divided into (narrow) frequency bands
- each call allocated its own band, can transmit at max rate of that narrow band

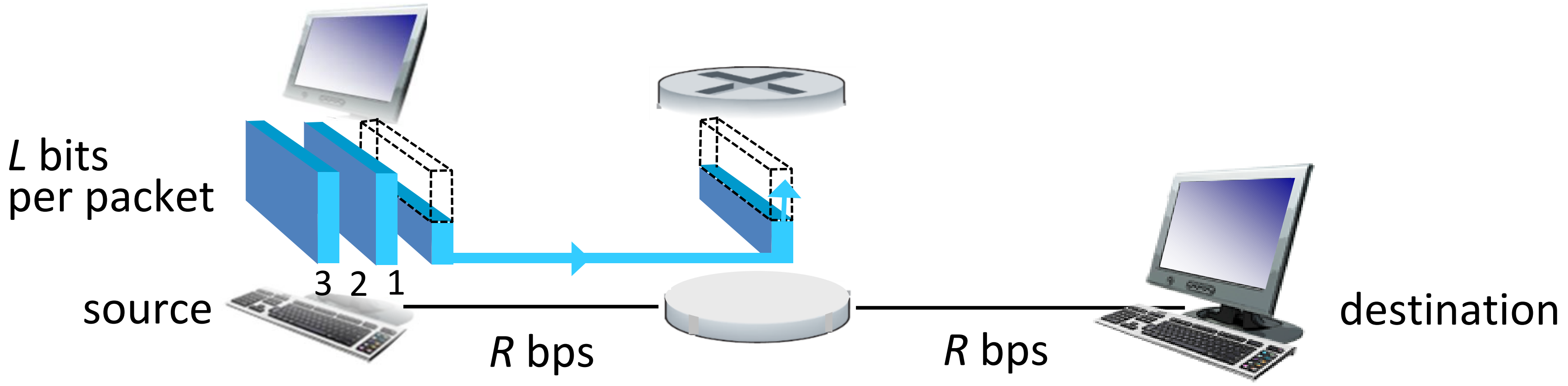


Time Division Multiplexing (TDM)

- time divided into slots
- each call allocated periodic slot(s), can transmit at maximum rate of (wider) frequency band (only) during its time slot(s)



Packet-switching: store-and-forward

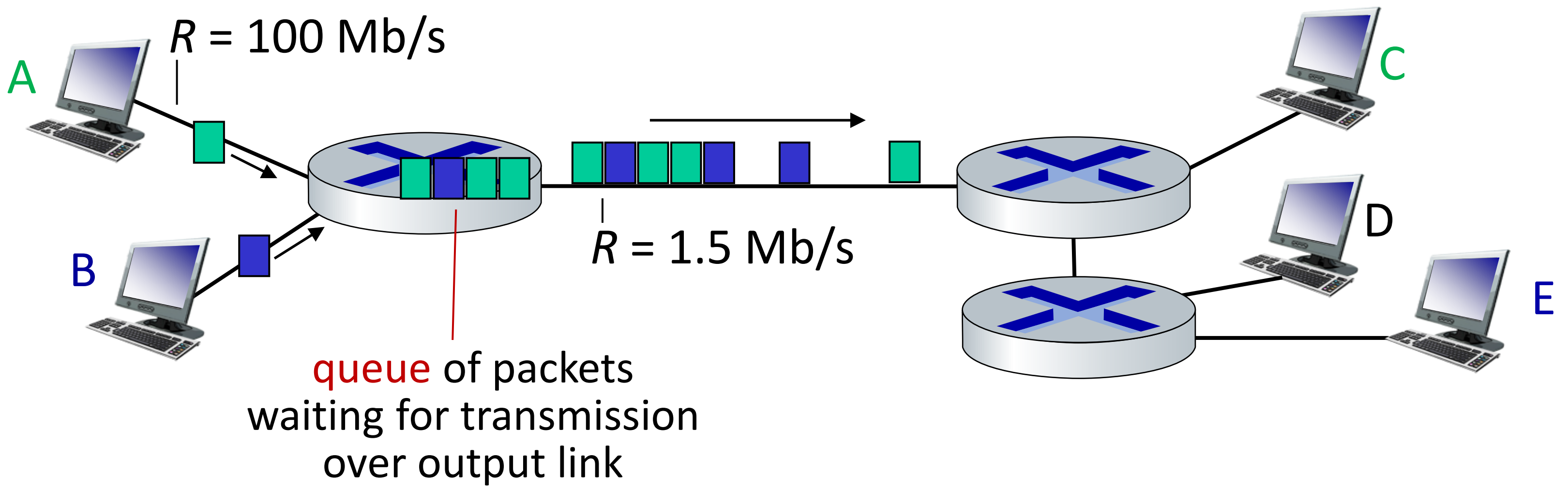


- packet transmission delay: takes *L*/*R* seconds to transmit (push out) *L*-bit packet into link at *R* bps
- *store and forward: entire* packet must arrive at router before it can be transmitted on next link

One-hop numerical example:

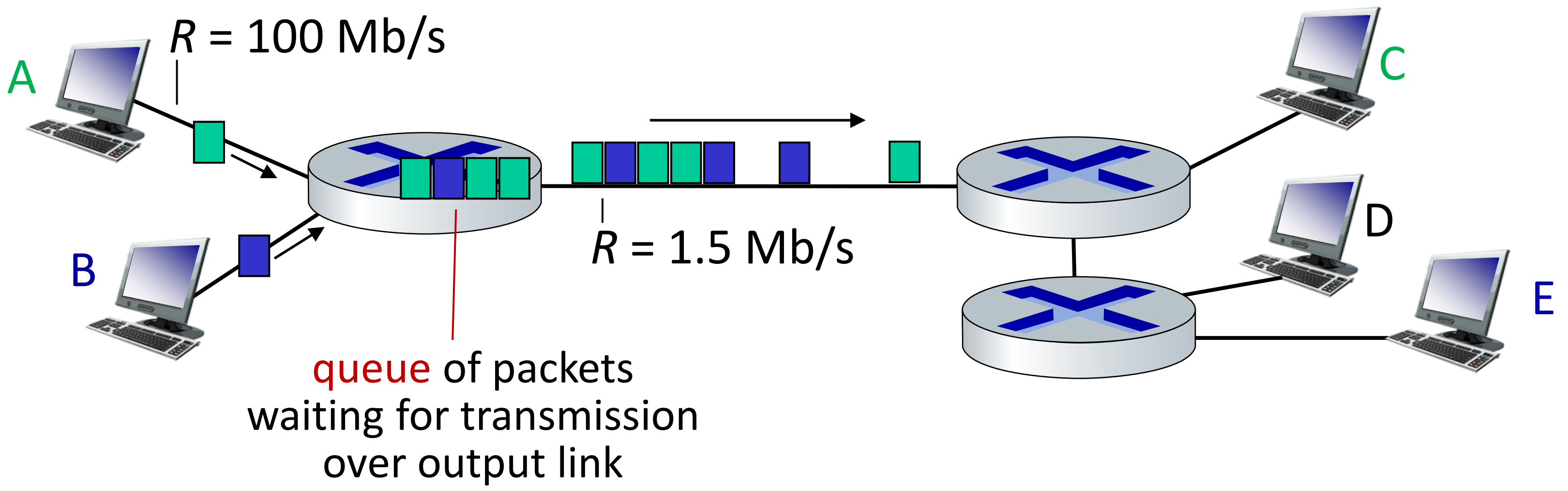
- *L* = 10 Kbits
- *R* = 100 Mbps
- one-hop transmission delay = 0.1 msec

Packet-switching: queueing



Queueing occurs when work arrives faster than it can be serviced:

Packet-switching: queueing

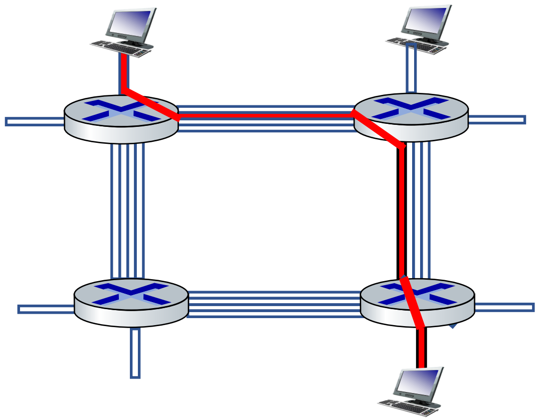


Packet queuing and loss: if arrival rate (in bps) to link exceeds transmission rate (bps) of link for some period of time:

- packets will queue, waiting to be transmitted on output link
- packets can be dropped (lost) if memory (buffer) in router fills up

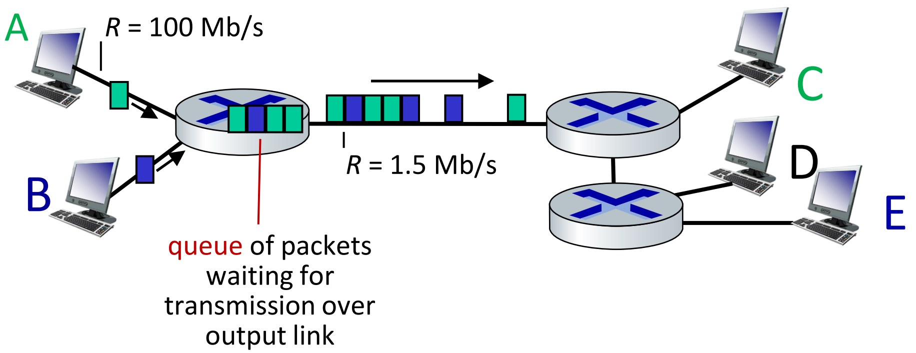
Packet switching versus circuit switching

circuit-switching:



- dedicated resources: no sharing
  - ⬆ circuit-like (guaranteed) performance.
  - ⬇ circuit segment idle if not used by call (no sharing)

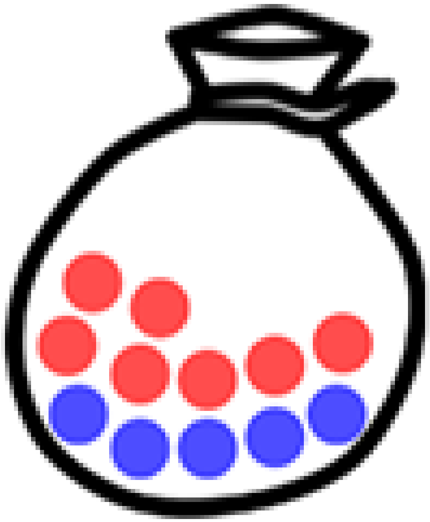
packet switching:



- ⬆ No dedicated resources
- ⬆ No call setup
- ⬆ Great for bursty data
- ⬇ Needs protocols for congestion control

Simple Probability

$$\text{Probabilty} = \frac{\text{Favorable outcomes}}{\text{Total outcomes}}$$



Example:

$$P(red) = \frac{7}{12}$$

Number of red marbles

Total number of marbles (sample space)

$$P(blue) = \frac{5}{12}$$

Number of blue marbles

Total number of marbles (sample space)

Probability Rules Cheat Sheet

complement rule

$P(A) = 1 - P(A')$

multiplication rules (joint probability) **AND**

dependent $P(A \cap B) = P(A) * P(B|A)$

independent $P(A \cap B) = P(A) * P(B)$

mutually exclusive $P(A \cap B) = 0$

addition rules (union of events) **OR**

$P(A \cup B) = P(A) + P(B) - P(A \cap B)$

mutually exclusive $P(A \cup B) = P(A) + P(B)$

Sheet 1: Question 4

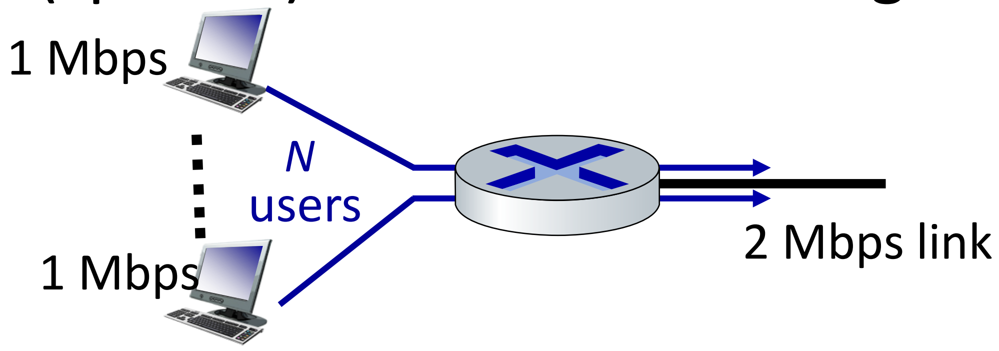
Suppose users share a 2 Mbps link. Also suppose each user transmits continuously at 1 Mbps when transmitting, but each user transmits only 20 percent of the time.

- When circuit switching is used, how many users can be supported?

  2 users can be supported because each user requires half of the link bandwidth

- For the remainder of this problem, suppose packet switching is used. Find the probability that a given (specific) user is transmitting.

  P= 0.2



Sheet 1: Question 4 (Cont'd)

- Suppose now there are three users. Find the probability that at any given time, all three users are transmitting simultaneously.

  $p^N = 0.2^3 = 0.008$ → (probability of worst case)

- 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?
  - each user → requires → 1Mbps.
  - users ≤ 2 → require → 2Mbps max. → Which is $<$ → available bandwidth
    - ❖ no queuing delay before the link.
  - Users ≥ 3 → require → 3Mbps or larger when transmit simultaneously, → Which is $>$ → available bandwidth
    - ❖ there will be queuing delay before the link

Notes if we have N users, and each of them can transmit at any time with probability p:

- The probability that all users transmit at the same time = Probability (User_1 transmitting **and** User_2 transmitting **and** User_3 transmitting …. **and** User_N transmitting) = p^N

- The probability that all users will not transmit at a given time = Probability (User_1 not transmitting **and** User_2 not transmitting **and** User_3 not transmitting …. **and** User_N not transmitting) = $(1-p)^N$

- The probability that a **specific** user (e.g. 1st user) is transmitting while others are not = Probability (User_1 transmitting **and** User_2 not transmitting **and** User_3 not transmitting …. **and** User_N not transmitting) = $p(1 – p)^{N-1}$

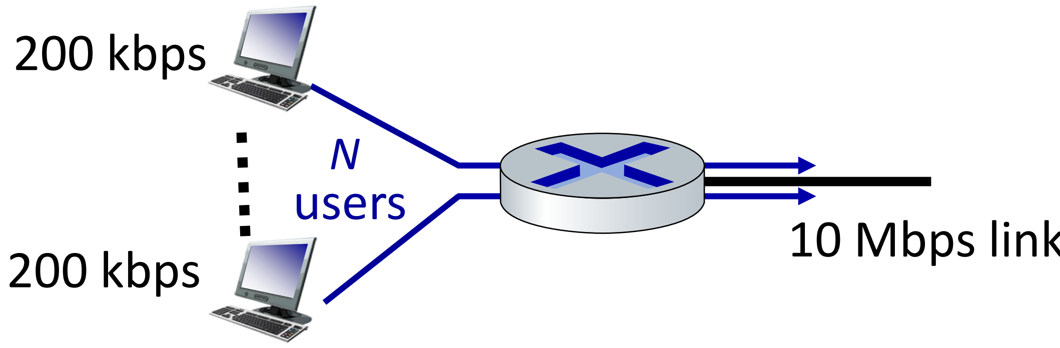
- The probability that **any** user is transmitting while others not = Probability (User_1 only transmits **OR** User_2 only transmits **OR** ….. **OR** User_N only transmits) = Probability (User_1 transmitting and all other users not transmitting) + Probability (User_2 transmitting and all other users not transmitting) + …. + Probability (User_N transmitting and all other users not transmitting) = $N \times p\,(1-p)^{N-1}$

Sheet 1: Question 10

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.

- When circuit switching is used, how many users can be supported?

Number of users = $\frac{10\times10^6}{200\times10^3} = 50 \text{ users}$



- Suppose packet switching is used. Find the probability that a given user is transmitting.

P= 0.1

Sheet 1: Question 10 (Cont'd)

- Suppose there are 120 users. Find the probability that at any given time, exactly n users are transmitting simultaneously.

$$P = \binom{120}{n} \times p^n \times (1-p)^{120-n}$$

Sheet 1: Question 10 (Cont'd)

- Find the probability that there are 51 or more users transmitting simultaneously.

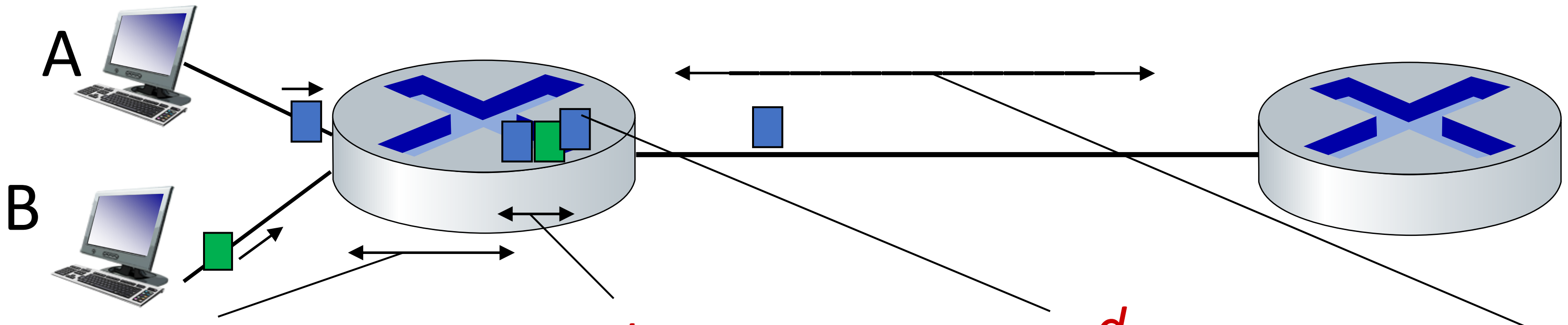
$$= \sum_{n=51}^{120} \binom{120}{n} \times p^n \times (1-p)^{120-n}$$

$$= \sum_{n=51}^{120} \binom{120}{n} \times 0.1^n \times 0.9^{120-n}$$

This is the same as:

$$= 1 - \sum_{n=0}^{50} \binom{120}{n} \times 0.1^n \times 0.9^{120-n}$$

Packet delay: four sources



d_{proc} Processing delay

- check bit errors
- determine o/p link
- typically < microsecs

d_{queue} queueing delay

- time waiting at output link for transmission
- depends on congestion level of router

d_{trans} transmission delay

- *L*: packet length (bits)
- *R*: link *transmission rate (bps)*
- $d_{trans} = L/R$

d_{prop} propagation delay

- *d*: length of physical link
- *s*: propagation speed (~2×10^8 m/sec)
- $d_{prop} = d/s$

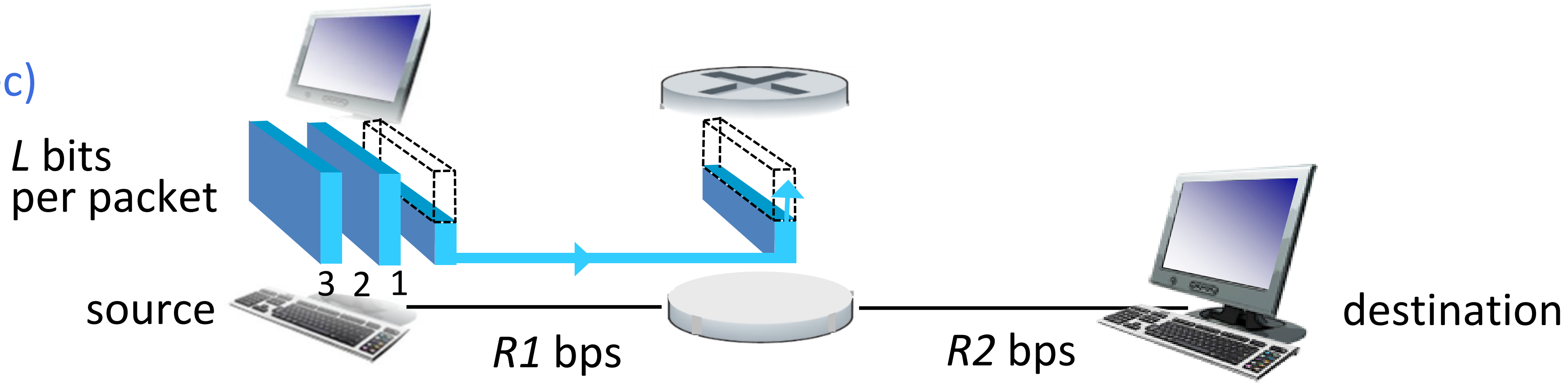
$$d_{nodal} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$$

Sheet 1: Question 3

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, and there is no propagation, processing and queuing delays.

what is the total end-to-end delay to send a packet of length *L*?

$$\frac{L \text{ (bits)}}{R1 \text{ (bits/sec)}} + \frac{L \text{ (bits)}}{R2 \text{ (bits/sec)}}$$



Sheet 1: Question 5

How long does it take a packet of length 1000 bytes to propagate over a link of distance 2500 km, propagation speed 2.5×10^8 m/s, and transmission rate 2 Mbps? More generally, how long does it take a packet of length L to propagate over a link of distance d, propagation speed s, and transmission rate R bps? Does this delay depend on packet length? Does this delay depend on transmission rate?

$D_{prop} = d / s = (2500 \times 10^3) / (2.5 \times 10^8) = 0.01$ sec

It doesn't depend on packet length or transmission rate.

Sheet 1: Question 11

Consider a **packet of length L** that begins at end system A and travels over three links to a destination end system. These **three links** are connected by two packet switches. Let **di, si, and Ri denote the length, propagation speed, and the transmission rate of link i**, for i = 1, 2, 3. The packet switch delays each packet by **dproc**.

- Assuming no queuing delays, in terms of di, si, Ri, (i = 1, 2, 3), and L, what is the total end-to-end delay for the packet?

$$d_{end\text{-}end} = L/R_1 + L/R_2 + L/R_3 + d_1/s_1 + d_2/s_2 + d_3/s_3 + d_{proc} + d_{proc}$$

Sheet 1: Question 11 (cont'd)

- Suppose now **the packet is 1,500 bytes**, the **propagation speed on all three links is 2.5x10^8m/s**, the **transmission rates of all three links are 2.5 Mbps**, the **packet switch processing delay is 3 msec**, the length of the first link is **5,000 km**, the length of the second link is **4,000 km**, and the length of the last link is **1,000 km**. For these values, what is the end-to-end delay?

$$d_{end\text{-}end} = L/R_1 + L/R_2 + L/R_3 + d_1/s_1 + d_2/s_2 + d_3/s_3 + d_{proc} + d_{proc}$$

$$= 3 * ((1500*8)/(2.5*10^6))$$

$$+ ((5000+4000+1000)*10^3) / (2.5*10^8) + 2 * 0.003$$

$$= 60.4 \text{ msec}$$

Sheet 1: Question 12

In the above problem, suppose R1 = R2 = R3 = R and dproc = 0. Further suppose that the packet switch does not store-and-forward packets but instead immediately transmits each bit it receives before waiting for the entire packet to arrive. What is the end-to-end delay?

Because bits are immediately transmitted, the packet switch does not introduce any delay; in particular, it does not introduce a transmission delay. Thus,

$d_{end\text{-}end} = L/R + d_1/s_1 + d_2/s_2 + d_3/s_3$

For the values in Problem 11, we get 4.8 + 20 + 16 + 4 = 44.8 msec.

Sheet 1: Question 8

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_p in terms of m and S.

  $D_p = m / \mathrm{S}$

- Express the transmission delay, D_t in terms of L and R.

  $D_t = L / \mathrm{R}$

Sheet 1: Question 8 (Cont'd)

- Suppose Host A begins to transmit the packet at time t = 0. At time t = $d$trans, where is the last bit of the packet?

The bit is just leaving Host A.

- Suppose $d$prop is greater than $d$trans. At time t = $d$trans, where is the first bit of the packet?

The first bit is in the link and has not reached Host B.

- Suppose $d$prop is less than $d$trans. At time t = $d$trans, where is the first bit of the packet?

The first bit has reached Host B.

Sheet 1: Question 8 (Cont'd)

- Ignoring processing and queuing delays, obtain an expression for the end-to-end delay.

$$D_T = D_p + D_t = m / S + L / R$$

- Suppose S $= 2.5x10^8$ m/s, $L=1500$ bytes and $R=10$ Mbps. Find the distance m so that $D_p = D_t$.

$$D_t = L / R = (1500 \text{ x } 8) / (10 \text{ x} 10^6)$$

$$D_p = m / (2.5x10^8)$$

$$\text{for } D_{\text{prop}} = D_{trans}$$

Distance (m) = $(1500 \text{ x } 8 \text{ x } 2.5 \text{ x } 10^8) / (10 \text{ x} 10^6) = 300$ km.

Sheet 1: Question 14

Suppose you would like to urgently deliver 50 terabytes data from Boston to Los Angeles. You have available a 100 Mbps dedicated link for data transfer. Would you prefer to transmit the data via this link or instead use FedEx overnight delivery? Explain.

*50 terabytes = 50 * 10^12 * 8 bits.*

So, if using the dedicated link, it will take
*(50 * 10^12 * 8) / (100 *10^6)*
=4000000 seconds = 46 days.

But with FedEx overnight delivery, you can guarantee the data arrives in one day, and it should cost less than $100.

Sheet 1: Question 7

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.

Let's now consider the general case of sending one packet from source to destination over a path consisting of N links each of rate R (thus, there are N-1 routers between source and destination). Applying the same logic as above, we see that the end-to-end delay is:

$$d_{\text{end-to-end}} = N\frac{L}{R} \tag{1.1}$$

Sheet 1: Question 7

$$d_{\text{end-to-end}} = N\frac{L}{R} \quad (1.1)$$

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.

The transmission time ends when all P packets have reached the destination (assuming no other sources of delay).

If there are P packets, the P_{th} packet is transmitted by the sending host on the 1^{st} link at time P*(L/R).

It will then be transmitted over (N-1) links until it reaches the destination. Thus, it will take an additional time of (N-1)*(L/R).

Thus, at time P*(L/R) + (N-1)*(L/R) = **(N+P-1)*(L/R)** all packets have reached the destination.

Sheet 1: Question 9

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)?

Sheet 1: Question 9

Consider the first bit in a packet. Before this bit can be transmitted, all of the bits in the packet must be generated. This requires:

$(56*8)/(64*10^3)$ sec =7 msec.

The time required to transmit the packet is $\mathbf{(56 \times 8)/\,(10 \times 10^6\,)}$ **sec=** $\mathbf{44.8\ \mu sec.}$

Propagation delay = **10 msec.**

The delay until decoding is $\mathbf{7 + 0.0448 + 10 = 17.0448\ msec}$.

Sheet 1: Question 13

A packet switch receives a packet and determines the outbound link to which the packet should be forwarded. **When the packet arrives, one other packet is halfway done being transmitted** on this outbound link and **four other packets are waiting to be transmitted.** Packets are transmitted in order of arrival. Suppose **all packets are 1,500 bytes** and **the link rate is 2.5 Mbps.** What is the queuing delay for the packet? More generally, what is the queuing delay when all packets have length L, the transmission rate is R, x bits of the currently-being-transmitted packet have been transmitted, and n packets are already in the queue?

Sheet 1: Question 13

The arriving packet must first wait for the link to transmit 4.5 *1,500 bytes = 6,750 bytes or 54,000 bits.

Since these bits are transmitted at 2.5 Mbps, the queuing delay is $54{,}000/(2.5*10^6) = 21.6$ msec.

Generally, the queuing delay is n * (L/R) + (L-x)/R
$=(nL + (L - x))/R$.

Sheet 1: Question 15

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 **2.5×10^8 meters/sec**.

- Calculate the bandwidth-delay product, *R.d*prop.

Propagation delay = $\frac{distance}{propagation\ speed} = \frac{20000 \times 10^3}{2.5 \times 10^8} = 0.08\ sec$

*R.d*prop = bandwidth $\times$ propagation delay
$= 5 \times 10^6 \times 0.08 = 400{,}000$ bits

- Provide an interpretation of the bandwidth-delay product.

The bandwidth-delay product is the maximum number of bits that can be in the link at any given time.

Sheet 1: Question 15 (Cont'd)

- 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?

Hint: The maximum number of bits that will be in the link at any given time = min(bandwidth-delay product, data size)

Theoretically, Bandwidth-delay product is the maximum number of bits that can be in the link at any given time.

Here we want to send 800,000 bits > Bandwidth-delay product (400,000 bits).

Thus, the maximum number of bits in the link at any a given time is 400,000 bits.

Sheet 1: Question 15 (Cont'd)

- What is the width (in meters) of a bit in the link?

The width of a bit in the link = $\frac{Line\ length}{Maximum\ number\ of\ bits\ in\ the\ line} =$

$$\frac{Line\ length}{\text{bandwidth}-\text{delay product}} = \frac{20{,}000\times 10^{3}}{400{,}000} = 50\ meters/bit$$

Sheet 1: Question 15 (Cont'd)

- 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*.

The width of a bit in the link =

$$\frac{Line\ length}{\mathrm{bandwidth-delay\ product}} = \frac{\mathrm{m}}{\mathrm{R}\times\frac{m}{s}} = \frac{s}{R}\ meters$$

Sheet 1: Question 16

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.

Number of packets = F/S packets

Number of links = 3 links

From the equation in Problem no. 7:

$$D_{\text{end-to-end}} = \left(3 + \frac{F}{S} - 1\right) \times \frac{80+S}{R} = \left(2 + \frac{F}{S}\right) \times \frac{80+S}{R}$$

Sheet 1: Question 16 (Cont'd)

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.

$$D_{\text{end-to-end}} = \left(3 + \frac{F}{S} - 1\right) \times \frac{80+S}{R} = \left(2 + \frac{F}{S}\right) \times \frac{80+S}{R}$$

To calculate the value of S which leads to the minimum delay:

$$\frac{d}{dS} delay = 0 \Rightarrow S = \sqrt{40F}$$

Thanks