

## Chapter 1 Problems

### Problem 1

There is no single right answer to this question. Many protocols would do the trick. Here's a simple answer below:

#### Messages from ATM machine to Server

Msg name	purpose
-----	-----
HELO <userid>	Let server know that there is a card in the ATM machine
	ATM card transmits user ID to Server
PASSWD <passwd>	User enters PIN, which is sent to server
BALANCE	User requests balance
WITHDRAWL <amount>	User asks to withdraw money
BYE	user all done

#### Messages from Server to ATM machine (display)

Msg name	purpose
-----	-----
PASSWD	Ask user for PIN (password)
OK	last requested operation (PASSWD, WITHDRAWL) OK
ERR	last requested operation (PASSWD, WITHDRAWL) in ERROR
AMOUNT <amt>	sent in response to BALANCE request
BYE	user done, display welcome screen at ATM

#### Correct operation:

client		server
HELO (userid)	----->	(check if valid userid)
	<-----	PASSWD
PASSWD <passwd>	----->	(check password)
	<-----	OK (password is OK)
BALANCE	----->	
	<-----	AMOUNT <amt>
WITHDRAWL <amt>	----->	check if enough \$ to cover withdrawl
	<-----	OK
ATM dispenses \$		
BYE	----->	
	<-----	BYE

In situation when there's not enough money:

```

HELO (userid) -----> (check if valid userid)
<----- PASSWD
PASSWD <passwd> -----> (check password)
<----- OK (password is OK)
BALANCE ----->
<----- AMOUNT <amt>
WITHDRAWL <amt> -----> check if enough $ to cover
withdrawl
<----- ERR (not enough funds)
error msg displayed
no $ given out
BYE ----->
<----- BYE

```

## Problem 2

At time  $N \cdot (L/R)$  the first packet has reached the destination, the second packet is stored in the last router, the third packet is stored in the next-to-last router, etc. At time  $N \cdot (L/R) + L/R$ , the second packet has reached the destination, the third packet is stored in the last router, etc. Continuing with this logic, we see that at time  $N \cdot (L/R) + (P-1) \cdot (L/R) = (N+P-1) \cdot (L/R)$  all packets have reached the destination.

## Problem 3

- a) A circuit-switched network would be well suited to the application, because the application involves long sessions with predictable smooth bandwidth requirements. Since the transmission rate is known and not bursty, bandwidth can be reserved for each application session without significant waste. In addition, the overhead costs of setting up and tearing down connections are amortized over the lengthy duration of a typical application session.
- b) In the worst case, all the applications simultaneously transmit over one or more network links. However, since each link has sufficient bandwidth to handle the sum of all of the applications' data rates, no congestion (very little queuing) will occur. Given such generous link capacities, the network does not need congestion control mechanisms.

## Problem 4

- a) Between the switch in the upper left and the switch in the upper right we can have 4 connections. Similarly we can have four connections between each of the 3 other pairs of adjacent switches. Thus, this network can support up to 16 connections.
- b) We can 4 connections passing through the switch in the upper-right-hand corner and another 4 connections passing through the switch in the lower-left-hand corner, giving a total of 8 connections.

- c) Yes. For the connections between A and C, we route two connections through B and two connections through D. For the connections between B and D, we route two connections through A and two connections through C. In this manner, there are at most 4 connections passing through any link.

### Problem 5

Tollbooths are 75 km apart, and the cars propagate at 100km/hr. A tollbooth services a car at a rate of one car every 12 seconds.

- a) There are ten cars. It takes 120 seconds, or 2 minutes, for the first tollbooth to service the 10 cars. Each of these cars has a propagation delay of 45 minutes (travel 75 km) before arriving at the second tollbooth. Thus, all the cars are lined up before the second tollbooth after 47 minutes. The whole process repeats itself for traveling between the second and third tollbooths. It also takes 2 minutes for the third tollbooth to service the 10 cars. Thus the total delay is 96 minutes.
- b) Delay between tollbooths is  $8 \cdot 12$  seconds plus 45 minutes, i.e., 46 minutes and 36 seconds. The total delay is twice this amount plus  $8 \cdot 12$  seconds, i.e., 94 minutes and 48 seconds.

### Problem 6

- a)  $d_{prop} = m / s$  seconds.
- b)  $d_{trans} = L / R$  seconds.
- c)  $d_{end-to-end} = (m / s + L / R)$  seconds.
- d) The bit is just leaving Host A.
- e) The first bit is in the link and has not reached Host B.
- f) The first bit has reached Host B.
- g) Want

$$m = \frac{L}{R} s = \frac{120}{56 \times 10^3} (2.5 \times 10^8) = 536 \text{ km.}$$

### Problem 7

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

$$\frac{56 \cdot 8}{64 \times 10^3} \text{ sec} = 7 \text{ msec.}$$

The time required to transmit the packet is

$$\frac{56 \cdot 8}{2 \times 10^6} \text{ sec} = 224 \mu \text{ sec}.$$

Propagation delay = 10 msec.  
The delay until decoding is

$$7 \text{ msec} + 224 \mu \text{ sec} + 10 \text{ msec} = 17.224 \text{ msec}$$

A similar analysis shows that all bits experience a delay of 17.224 msec.

### Problem 8

a) 20 users can be supported.

b)  $p = 0.1$ .

$$\text{c) } \binom{120}{n} p^n (1-p)^{120-n}.$$

$$\text{d) } 1 - \sum_{n=0}^{20} \binom{120}{n} p^n (1-p)^{120-n}.$$

We use the central limit theorem to approximate this probability. Let  $X_j$  be independent random variables such that  $P(X_j = 1) = p$ .

$$P(\text{“21 or more users”}) = 1 - P\left(\sum_{j=1}^{120} X_j \leq 21\right)$$

$$\begin{aligned} P\left(\sum_{j=1}^{120} X_j \leq 21\right) &= P\left(\frac{\sum_{j=1}^{120} X_j - 12}{\sqrt{120 \cdot 0.1 \cdot 0.9}} \leq \frac{9}{\sqrt{120 \cdot 0.1 \cdot 0.9}}\right) \\ &\approx P\left(Z \leq \frac{9}{3.286}\right) = P(Z \leq 2.74) \\ &= 0.997 \end{aligned}$$

when  $Z$  is a standard normal r.v. Thus  $P(\text{“21 or more users”}) \approx 0.003$ .

### Problem 9

a) 10,000

$$\text{b) } \sum_{n=N+1}^M \binom{M}{n} p^n (1-p)^{M-n}$$

## Problem 10

The first end system requires  $L/R_1$  to transmit the packet onto the first link; the packet propagates over the first link in  $d_1/s_1$ ; the packet switch adds a processing delay of  $d_{proc}$ ; after receiving the entire packet, the packet switch connecting the first and the second link requires  $L/R_2$  to transmit the packet onto the second link; the packet propagates over the second link in  $d_2/s_2$ . Similarly, we can find the delay caused by the second switch and the third link:  $L/R_3$ ,  $d_{proc}$ , and  $d_3/s_3$ .

Adding these five delays gives

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

To answer the second question, we simply plug the values into the equation to get  $6 + 6 + 6 + 20 + 16 + 4 + 3 + 3 = 64$  msec.

## Problem 11

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

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

For the values in Problem 10, we get  $6 + 20 + 16 + 4 = 46$  msec.

## Problem 12

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 Mbps, the queuing delay is 27 msec. Generally, the queuing delay is  $(nL + (L - x))/R$ .

## Problem 13

- a) The queuing delay is 0 for the first transmitted packet,  $L/R$  for the second transmitted packet, and generally,  $(n-1)L/R$  for the  $n^{th}$  transmitted packet. Thus, the average delay for the  $N$  packets is:

$$\begin{aligned} & (L/R + 2L/R + \dots + (N-1)L/R)/N \\ &= L/(RN) * (1 + 2 + \dots + (N-1)) \\ &= L/(RN) * N(N-1)/2 \\ &= LN(N-1)/(2RN) \\ &= (N-1)L/(2R) \end{aligned}$$

Note that here we used the well-known fact:

$$1 + 2 + \dots + N = N(N+1)/2$$

- b) It takes  $LN/R$  seconds to transmit the  $N$  packets. Thus, the buffer is empty when a each batch of  $N$  packets arrive. Thus, the average delay of a packet across all batches is the average delay within one batch, i.e.,  $(N-1)L/2R$ .

### Problem 14

- a) The transmission delay is  $L/R$ . The total delay is

$$\frac{IL}{R(1-I)} + \frac{L}{R} = \frac{L/R}{1-I}$$

- b) Let  $x = L/R$ .

$$\text{Total delay} = \frac{x}{1-ax}$$

For  $x=0$ , the total delay  $=0$ ; as we increase  $x$ , total delay increases, approaching infinity as  $x$  approaches  $1/a$ .

### Problem 15

$$\text{Total delay} = \frac{L/R}{1-I} = \frac{L/R}{1-aL/R} = \frac{1/\mu}{1-a/\mu} = \frac{1}{\mu-a}.$$

### Problem 16

The total number of packets in the system includes those in the buffer and the packet that is being transmitted. So,  $N=10+1$ .

Because  $N = a \cdot d$ , so  $(10+1)=a \cdot (\text{queuing delay} + \text{transmission delay})$ . That is,  $11=a \cdot (0.01+1/100)=a \cdot (0.01+0.01)$ . Thus,  $a=550$  packets/sec.

### Problem 17

- a) There are  $Q$  nodes (the source host and the  $Q-1$  routers). Let  $d_{proc}^q$  denote the processing delay at the  $q$ th node. Let  $R^q$  be the transmission rate of the  $q$ th link and let

$d_{trans}^q = L/R^q$ . Let  $d_{prop}^q$  be the propagation delay across the  $q$ th link. Then

$$d_{end-to-end} = \sum_{q=1}^Q [d_{proc}^q + d_{trans}^q + d_{prop}^q].$$

b) Let  $d_{queue}^q$  denote the average queuing delay at node  $q$ . Then

$$d_{end-to-end} = \sum_{q=1}^Q [d_{proc}^q + d_{trans}^q + d_{prop}^q + d_{queue}^q].$$

## Problem 18

On linux you can use the command

```
traceroute www.targethost.com
```

and in the Windows command prompt you can use

```
tracert www.targethost.com
```

In either case, you will get three delay measurements. For those three measurements you can calculate the mean and standard deviation. Repeat the experiment at different times of the day and comment on any changes.

Here is an example solution:

```
traceroute to www.poly.edu (128.238.24.40), 30 hops max, 40 byte packets
 1 thunder.sdsc.edu (132.249.20.5)  2.802 ms  0.645 ms  0.484 ms
 2 dolphin.sdsc.edu (132.249.31.17)  0.227 ms  0.248 ms  0.239 ms
 3 dc-sdg-aggr1--sdsc-1.cenic.net (137.164.23.129)  0.360 ms  0.260 ms  0.240 ms
 4 dc-riv-core1--sdg-aggr1-10ge-2.cenic.net (137.164.47.14)  8.847 ms  8.497 ms  8.230 ms
 5 dc-lax-core1--lax-core2-10ge-2.cenic.net (137.164.46.64)  9.969 ms  9.920 ms  9.846 ms
 6 dc-lax-px1--lax-core1-10ge-2.cenic.net (137.164.46.151)  9.845 ms  9.729 ms  9.724 ms
 7 hurricane--lax-px1-ge.cenic.net (198.32.251.86)  9.971 ms  16.981 ms  9.850 ms
 8 10gigabitethernet4-3.core1.nyc4.he.net (72.52.92.225)  72.796 ms  80.278 ms  72.346 ms
 9 10gigabitethernet3-4.core1.nyc5.he.net (184.105.213.218)  71.126 ms  71.442 ms  73.623 ms
10 lighttower-fiber-networks.10gigabitethernet3-2.core1.nyc5.he.net (216.66.50.106)  70.924 ms  70.959 ms  71.072 ms
11 ae0.nycmnyzrj91.lighttower.net (72.22.160.156)  70.870 ms  71.089 ms  70.957 ms
12 72.22.188.102 (72.22.188.102)  71.242 ms  71.228 ms  71.102 ms
```

```
traceroute to www.poly.edu (128.238.24.40), 30 hops max, 40 byte packets
 1 thunder.sdsc.edu (132.249.20.5)  0.478 ms  0.353 ms  0.308 ms
 2 dolphin.sdsc.edu (132.249.31.17)  0.212 ms  0.251 ms  0.238 ms
 3 dc-sdg-aggr1--sdsc-1.cenic.net (137.164.23.129)  0.237 ms  0.246 ms  0.240 ms
 4 dc-riv-core1--sdg-aggr1-10ge-2.cenic.net (137.164.47.14)  8.628 ms  8.348 ms  8.357 ms
 5 dc-lax-core1--lax-core2-10ge-2.cenic.net (137.164.46.64)  9.934 ms  9.963 ms  9.852 ms
 6 dc-lax-px1--lax-core1-10ge-2.cenic.net (137.164.46.151)  9.831 ms  9.814 ms  9.676 ms
 7 hurricane--lax-px1-ge.cenic.net (198.32.251.86)  10.194 ms  10.012 ms  16.722 ms
 8 10gigabitethernet4-3.core1.nyc4.he.net (72.52.92.225)  73.856 ms  73.196 ms  73.979 ms
 9 10gigabitethernet3-4.core1.nyc5.he.net (184.105.213.218)  71.247 ms  71.199 ms  71.646 ms
10 lighttower-fiber-networks.10gigabitethernet3-2.core1.nyc5.he.net (216.66.50.106)  70.987 ms  71.073 ms  70.985 ms
11 ae0.nycmnyzrj91.lighttower.net (72.22.160.156)  71.075 ms  71.042 ms  71.328 ms
12 72.22.188.102 (72.22.188.102)  71.626 ms  71.299 ms  72.236 ms
```

```

1 thunder.sdsc.edu (132.249.20.5) 0.403 ms 0.347 ms 0.358 ms
2 dolphin.sdsc.edu (132.249.31.17) 0.225 ms 0.244 ms 0.237 ms
3 dc-sdg-aggr1--sdsc-1.cenic.net (137.164.23.129) 0.362 ms 0.256 ms 0.239 ms
4 dc-riv-core1--sdg-aggr1-10ge-2.cenic.net (137.164.47.14) 8.850 ms 8.358 ms 8.227 ms
5 dc-lax-core1--lax-core2-10ge-2.cenic.net (137.164.46.64) 10.096 ms 9.869 ms 10.351 ms
6 dc-lax-px1--lax-core1-10ge-2.cenic.net (137.164.46.151) 9.721 ms 9.621 ms 9.725 ms
7 hurricane--lax-px1-ge.cenic.net (198.32.251.86) 11.345 ms 10.048 ms 13.844 ms
8 10gigabitethernet4-3.core1.nyc4.he.net (72.52.92.225) 71.920 ms 72.977 ms 77.264 ms
9 10gigabitethernet3-4.core1.nyc5.he.net (184.105.213.218) 71.273 ms 71.247 ms 71.291 ms
10 lighttower-fiber-networks.10gigabitethernet3-2.core1.nyc5.he.net (216.66.50.106) 71.114 ms 82.516 ms 71.136 ms
11 ae0.nycmnyzrj91.lighttower.net (72.22.160.156) 71.232 ms 71.071 ms 71.039 ms
12 72.22.188.102 (72.22.188.102) 71.585 ms 71.608 ms 71.493 ms

```

### Traceroutes between San Diego Super Computer Center and www.poly.edu

- The average (mean) of the round-trip delays at each of the three hours is 71.18 ms, 71.38 ms and 71.55 ms, respectively. The standard deviations are 0.075 ms, 0.21 ms, 0.05 ms, respectively.
- In this example, the traceroutes have 12 routers in the path at each of the three hours. No, the paths didn't change during any of the hours.
- Traceroute packets passed through four ISP networks from source to destination. Yes, in this experiment the largest delays occurred at peering interfaces between adjacent ISPs.

```

traceroute to www.poly.edu (128.238.24.40), 30 hops max, 60 byte packets
1 62-193-36-1.stella-net.net (62.193.36.1) 0.500 ms 0.415 ms 0.440 ms
2 62.193.33.29 (62.193.33.29) 0.910 ms 1.065 ms 1.026 ms
3 bg1.stella-net.net (62.193.32.254) 0.972 ms 1.026 ms 1.078 ms
4 62.193.32.66 (62.193.32.66) 1.021 ms 0.988 ms 0.947 ms
5 10gigabitethernet-2-2.par2.he.net (195.42.144.104) 1.537 ms 1.752 ms 1.714 ms
6 10gigabitethernet7-1.core1.ash1.he.net (184.105.213.93) 80.273 ms 80.103 ms 79.971 ms
7 10gigabitethernet1-2.core1.nyc4.he.net (72.52.92.85) 86.494 ms 85.872 ms 86.223 ms
8 10gigabitethernet3-4.core1.nyc5.he.net (184.105.213.218) 85.248 ms 85.424 ms 85.388 ms
9 lighttower-fiber-networks.10gigabitethernet3-2.core1.nyc5.he.net (216.66.50.106) 86.194 ms 85.864 ms 86.116 ms
10 ae0.nycmnyzrj91.lighttower.net (72.22.160.156) 85.796 ms 85.823 ms 85.766 ms
11 72.22.188.102 (72.22.188.102) 87.717 ms 86.817 ms 86.774 ms

```



```

traceroute to www.poly.edu (128.238.24.40), 30 hops max, 60 byte packets
 1 62-193-36-1.stella-net.net (62.193.36.1) 0.375 ms 0.397 ms 0.355 ms
 2 62.193.33.29 (62.193.33.29) 0.810 ms 0.877 ms 0.836 ms
 3 bg1.stella-net.net (62.193.32.254) 1.098 ms 0.991 ms 1.055 ms
 4 62.193.32.66 (62.193.32.66) 0.994 ms 0.960 ms 1.157 ms
 5 10gigabitethernet-2-2.par2.he.net (195.42.144.104) 1.679 ms 1.816 ms 1.768 ms
 6 10gigabitethernet7-1.core1.ash1.he.net (184.105.213.93) 80.416 ms 90.573 ms 90.659 ms
 7 10gigabitethernet1-2.core1.nyc4.he.net (72.52.92.85) 85.933 ms 95.987 ms 96.087 ms
 8 10gigabitethernet3-4.core1.nyc5.he.net (184.105.213.218) 90.268 ms 90.229 ms 90.030 ms
 9 lighttower-fiber-networks.10gigabitethernet3-2.core1.nyc5.he.net (216.66.50.106) 85.833 ms 85.448 ms 85.418 ms
10 ae0.nycmnyzrj91.lighttower.net (72.22.160.156) 87.067 ms 86.025 ms 85.962 ms
11 72.22.188.102 (72.22.188.102) 86.542 ms 86.369 ms 86.170 ms

```

```

traceroute to 128.238.24.40 (128.238.24.40), 30 hops max, 60 byte packets
 1 62-193-36-1.stella-net.net (62.193.36.1) 0.396 ms 0.284 ms 0.239 ms
 2 62.193.33.29 (62.193.33.29) 0.817 ms 0.786 ms 0.848 ms
 3 bg1.stella-net.net (62.193.32.254) 1.150 ms 1.216 ms 1.265 ms
 4 62.193.32.66 (62.193.32.66) 1.002 ms 0.963 ms 0.923 ms
 5 10gigabitethernet-2-2.par2.he.net (195.42.144.104) 1.573 ms 1.534 ms 1.643 ms
 6 10gigabitethernet7-1.core1.ash1.he.net (184.105.213.93) 88.738 ms 82.866 ms 82.783 ms
 7 10gigabitethernet1-2.core1.nyc4.he.net (72.52.92.85) 94.888 ms 90.936 ms 90.877 ms
 8 10gigabitethernet3-4.core1.nyc5.he.net (184.105.213.218) 90.498 ms 90.543 ms 90.482 ms
 9 lighttower-fiber-networks.10gigabitethernet3-2.core1.nyc5.he.net (216.66.50.106) 85.716 ms 85.408 ms 85.637 ms
10 ae0.nycmnyzrj91.lighttower.net (72.22.160.156) 85.779 ms 85.290 ms 85.252 ms
11 72.22.188.102 (72.22.188.102) 86.217 ms 86.652 ms 86.588 ms

```

### Traceroutes from www.stella-net.net (France) to www.poly.edu (USA).

- d) The average round-trip delays at each of the three hours are 87.09 ms, 86.35 ms and 86.48 ms, respectively. The standard deviations are 0.53 ms, 0.18 ms, 0.23 ms, respectively. In this example, there are 11 routers in the path at each of the three hours. No, the paths didn't change during any of the hours. Traceroute packets passed three ISP networks from source to destination. Yes, in this experiment the largest delays occurred at peering interfaces between adjacent ISPs.

### Problem 19

An example solution:

```

traceroute to www.poly.edu (128.238.24.30), 30 hops max, 60 byte packets
 1 62-193-36-1.stella-net.net (62.193.36.1) 0.426 ms 0.329 ms 0.284 ms
 2 62.193.33.25 (62.193.33.25) 0.810 ms 0.771 ms 0.878 ms
 3 62.193.32.66 (62.193.32.66) 0.815 ms 0.840 ms 0.801 ms
 4 10gigabitethernet-2-2.par2.he.net (195.42.144.104) 1.387 ms 1.506 ms 1.467 ms
 5 10gigabitethernet7-1.core1.ash1.he.net (184.105.213.93) 85.402 ms 85.553 ms 85.353 ms
 6 10gigabitethernet1-2.core1.nyc4.he.net (72.52.92.85) 94.360 ms 96.220 ms 96.355 ms
 7 10gigabitethernet3-4.core1.nyc5.he.net (184.105.213.218) 90.279 ms 87.459 ms 87.709 ms
 8 lighttower-fiber-networks.10gigabitethernet3-2.core1.nyc5.he.net (216.66.50.106) 85.474 ms 85.450 ms 85.983 ms
 9 ae0.nycmnyzrj91.lighttower.net (72.22.160.156) 86.160 ms 85.768 ms 86.016 ms
10 72.22.188.102 (72.22.188.102) 124.111 ms 89.340 ms 89.556 ms

```

```

 1 vl200.hs01.mar01.jaguar-network.net (85.31.192.253) 0.552 ms 0.414 ms
 2 ae1.cr01.mar01.jaguar-network.net (85.31.194.9) 0.340 ms 0.213 ms
 3 xe2-0-0.cr01.par02.jaguar-network.net (78.153.231.201) 9.933 ms 9.841 ms
 4 te1-3.er01.par02.jaguar-network.net (85.31.194.14) 9.828 ms 9.962 ms
 5 10gigabitethernet-2-2.par2.he.net (195.42.144.104) 10.456 ms 10.332 ms
 6 10gigabitethernet7-1.core1.ash1.he.net (184.105.213.93) 88.793 ms 96.781 ms
 7 10gigabitethernet1-2.core1.nyc4.he.net (72.52.92.85) 94.651 ms 99.654 ms
 8 10gigabitethernet3-4.core1.nyc5.he.net (184.105.213.218) 94.786 ms 94.755 ms
 9 lighttower-fiber-networks.10gigabitethernet3-2.core1.nyc5.he.net (216.66.50.106) 91.935 ms 91.776 ms
10 ae0.nycmnyzrj91.lighttower.net (72.22.160.156) 91.909 ms 91.784 ms
11 72.22.188.102 (72.22.188.102) 93.791 ms 93.515 ms

```

## Traceroutes from two different cities in France to New York City in United States

- a) In these traceroutes from two different cities in France to the same destination host in United States, seven links are in common including the transatlantic link.

```

traceroute to www.poly.edu (128.238.24.30), 30 hops max, 60 byte packets
 1
 2 hos-tr3.juniper2.rz10.hetzner.de 213.239.224.65 de 0.224 ms * *
   hos-tr2.juniper1.rz10.hetzner.de 213.239.224.33 de 0.174 ms 0.176 ms
 3 hos-bb1.juniper1.ffm.hetzner.de 213.239.240.224 de 4.746 ms 4.780 ms
   hos-bb1.juniper4.ffm.hetzner.de 213.239.240.230 de 4.823 ms
 4 20gigabitethernet4-3.core1.fra1.he.net 80.81.192.172 de 5.462 ms 5.461 ms 5.456 ms
 5 10gigabitethernet1-4.core1.ams1.he.net 72.52.92.94 us 12.899 ms
   10gigabitethernet5-3.core1.ams1.he.net 72.52.92.77 us 13.197 ms
   10gigabitethernet5-3.core1.lon1.he.net 184.105.213.145 us 26.110 ms
 6 10gigabitethernet1-4.core1.lon1.he.net 72.52.92.81 us 18.720 ms 18.871 ms 18.862 ms
 7 10gigabitethernet7-4.core1.nyc4.he.net 72.52.92.241 us 86.677 ms 85.580 ms 86.560 ms
 8 lighttower-fiber-networks.10gigabitethernet3-2.core1.nyc5.he.net 216.66.50.106 us 118.500 ms
   10gigabitethernet3-4.core1.nyc5.he.net 184.105.213.218 us 90.346 ms
   lighttower-fiber-networks.10gigabitethernet3-2.core1.nyc5.he.net 216.66.50.106 us 118.500 ms
 9 ae0.nycmnyzrj91.lighttower.net 72.22.160.156 us 85.289 ms 85.552 ms 85.283 ms

```



```

traceroute to www.poly.edu (128.238.24.30), 30 hops max, 60 byte packets
 1 62-193-36-1.stella-net.net (62.193.36.1) 0.426 ms 0.329 ms 0.284 ms
 2 62.193.33.25 (62.193.33.25) 0.810 ms 0.771 ms 0.878 ms
 3 62.193.32.66 (62.193.32.66) 0.815 ms 0.840 ms 0.801 ms
 4 10gigabitethernet-2-2.par2.he.net (195.42.144.104) 1.387 ms 1.506 ms 1.467 ms
 5 10gigabitethernet7-1.core1.ash1.he.net (184.105.213.93) 85.402 ms 85.553 ms 85.353 ms
 6 10gigabitethernet1-2.core1.nyc4.he.net (72.52.92.85) 94.360 ms 96.220 ms 96.355 ms
 7 10gigabitethernet3-4.core1.nyc5.he.net (184.105.213.218) 90.279 ms 87.459 ms 87.709 ms
 8 lighttower-fiber-networks.10gigabitethernet3-2.core1.nyc5.he.net (216.66.50.106) 85.474 ms 85.450 ms 85.983 ms
 9 ae0.nycmnyzrj91.lighttower.net (72.22.160.156) 86.160 ms 85.768 ms 86.016 ms
10 72.22.188.102 (72.22.188.102) 124.111 ms 89.340 ms 89.556 ms

```

- b) In this example of traceroutes from one city in France and from another city in Germany to the same host in United States, three links are in common including the transatlantic link.

```

Tracing route to www.autoisp.shu.edu.cn [27.115.83.251]
over a maximum of 30 hops:
 1      9 ms      8 ms      10 ms      10.40.32.1
 2      12 ms     12 ms      9 ms      gig-3-0-4-nycmnyj-rtr1.nyc.rr.com [24.29.119.189]
 3      21 ms     20 ms     22 ms      tenge-0-6-0-0-nyquny91-rtr001.nyc.rr.com [24.29.100.122]
 4      19 ms     21 ms     22 ms      bun6-nyquny91-rtr002.nyc.rr.com [24.29.148.254]
 5      11 ms     11 ms     19 ms      ae-3-0-cr0.nyc20.tbone.rr.com [66.109.6.76]
 6      14 ms     18 ms     14 ms      ae-0-0-pr0.nyc30.tbone.rr.com [66.109.6.159]
 7      14 ms     11 ms     10 ms      xe-9-0-0-edge2.Newark1.Level3.net [4.59.20.29]
 8      12 ms     10 ms     13 ms      ae-31-51.ebr1.Newark1.Level3.net [4.69.156.30]
 9      10 ms     15 ms     13 ms      ae-2-2.ebr1.NewYork1.Level3.net [4.69.132.97]
10      11 ms     17 ms     14 ms      ae-81-81.csw3.NewYork1.Level3.net [4.69.134.74]
11      12 ms     14 ms     11 ms      ae-82-82.ebr2.NewYork1.Level3.net [4.69.148.41]
12      83 ms     83 ms     88 ms      ae-2-2.ebr4.SanJose1.Level3.net [4.69.135.185]
13      91 ms     87 ms     84 ms      ae-71-71.csw2.SanJose1.Level3.net [4.69.153.6]
14      83 ms     83 ms     88 ms      ae-2-70.edge3.SanJose1.Level3.net [4.69.152.82]
15      595 ms    593 ms    600 ms      CHINA-NETCO.edge3.SanJose1.Level3.net [4.79.54.6]
16      594 ms    591 ms    592 ms      219.158.96.213
17      539 ms    540 ms    540 ms      219.158.11.173
18      593 ms    586 ms    585 ms      219.158.19.93
19      585 ms    585 ms    584 ms      219.158.21.246
20      568 ms    587 ms    569 ms      112.64.243.62
21      570 ms    566 ms    568 ms      112.64.243.146
22      342 ms    341 ms    347 ms      112.65.183.106
23      574 ms    571 ms    573 ms      27.115.83.251

Trace complete.

```

```

Tracing route to www.lb.pku.edu.cn [162.105.131.113]
over a maximum of 30 hops:
 1      8 ms      8 ms      8 ms      10.40.32.1
 2      14 ms     9 ms      10 ms      gig-0-3-0-18-nycmnyj-rtr1.nyc.rr.com [24.168.138.85]
 3      21 ms     10 ms     11 ms      tenge-0-6-0-0-nyquny91-rtr001.nyc.rr.com [24.29.100.122]
 4      13 ms     22 ms     22 ms      bun6-nyquny91-rtr002.nyc.rr.com [24.29.148.254]
 5      11 ms     18 ms     12 ms      ae-3-0-cr0.nyc20.tbone.rr.com [66.109.6.76]
 6      43 ms     38 ms     41 ms      ae-8-0-cr0.chi10.tbone.rr.com [66.109.6.25]
 7      86 ms     88 ms     88 ms      ae-6-0-cr0.sjc30.tbone.rr.com [66.109.6.14]
 8      86 ms     89 ms     91 ms      ae-1-0-pr0.sjc10.tbone.rr.com [66.109.6.137]
 9      87 ms     86 ms     86 ms      66.109.10.210
10      257 ms    258 ms    258 ms      ge3-0-0.gw4.hkg3.asianetcom.net [61.14.157.250]
11      298 ms    296 ms    295 ms      CER-0002.gw4.hkg3.asianetcom.net [203.192.137.198]
12      297 ms    305 ms    305 ms      202.112.61.13
13      295 ms    296 ms    296 ms      202.112.61.157
14      *        *        *        Request timed out.
15      298 ms    302 ms    298 ms      202.112.41.178
16      308 ms    300 ms    300 ms      202.112.41.182

```

### Traceroutes to two different cities in China from same host in United States

- c) Five links are common in the two traceroutes. The two traceroutes diverge before reaching China

### Problem 20

Throughput =  $\min\{R_s, R_c, R/M\}$

### Problem 21

If only use one path, the max throughput is given by:

$$\max\{\min\{R_1^1, R_2^1, \dots, R_N^1\}, \min\{R_1^2, R_2^2, \dots, R_N^2\}, \dots, \min\{R_1^M, R_2^M, \dots, R_N^M\}\}.$$

If use all paths, the max throughput is given by  $\sum_{k=1}^M \min\{R_1^k, R_2^k, \dots, R_N^k\}.$

### Problem 22

Probability of successfully receiving a packet is:  $p_s = (1-p)^N.$

The number of transmissions needed to be performed until the packet is successfully received by the client is a geometric random variable with success probability  $p_s$ . Thus, the average number of transmissions needed is given by:  $1/p_s$ . Then, the average number of re-transmissions needed is given by:  $1/p_s - 1$ .

### Problem 23

Let's call the first packet A and call the second packet B.

- a) If the bottleneck link is the first link, then packet B is queued at the first link waiting for the transmission of packet A. So the packet inter-arrival time at the destination is simply  $L/R_s$ .
- b) If the second link is the bottleneck link and both packets are sent back to back, it must be true that the second packet arrives at the input queue of the second link before the second link finishes the transmission of the first packet. That is,

$$L/R_s + L/R_s + d_{prop} < L/R_s + d_{prop} + L/R_c$$

The left hand side of the above inequality represents the time needed by the second packet to *arrive at* the input queue of the second link (the second link has not started

transmitting the second packet yet). The right hand side represents the time needed by the first packet to finish its transmission onto the second link.

If we send the second packet  $T$  seconds later, we will ensure that there is no queuing delay for the second packet at the second link if we have:

$$L/R_s + L/R_s + d_{prop} + T \geq L/R_s + d_{prop} + L/R_c$$

Thus, the minimum value of  $T$  is  $L/R_c - L/R_s$ .

## Problem 24

40 terabytes =  $40 * 10^{12} * 8$  bits. So, if using the dedicated link, it will take  $40 * 10^{12} * 8 / (100 * 10^6) = 3200000$  seconds = 37 days. But with FedEx overnight delivery, you can guarantee the data arrives in one day, and it should cost less than \$100.

## Problem 25

- a) 160,000 bits
- b) 160,000 bits
- c) The bandwidth-delay product of a link is the maximum number of bits that can be in the link.
- d) the width of a bit = length of link / bandwidth-delay product, so 1 bit is 125 meters long, which is longer than a football field
- e)  $s/R$

## Problem 26

$$s/R = 20000 \text{ km}, \text{ then } R = s/20000 \text{ km} = 2.5 * 10^8 / (2 * 10^7) = 12.5 \text{ bps}$$

## Problem 27

- a) 80,000,000 bits
- b) 800,000 bits, this is because that the maximum number of bits that will be in the link at any given time =  $\min(\text{bandwidth delay product, packet size}) = 800,000$  bits.
- c) .25 meters

## Problem 28

- a)  $t_{trans} + t_{prop} = 400 \text{ msec} + 80 \text{ msec} = 480 \text{ msec}$ .
- b)  $20 * (t_{trans} + 2 t_{prop}) = 20 * (20 \text{ msec} + 80 \text{ msec}) = 2 \text{ sec}$ .

- c) Breaking up a file takes longer to transmit because each data packet and its corresponding acknowledgement packet add their own propagation delays.

### Problem 29

Recall geostationary satellite is 36,000 kilometers away from earth surface.

- a) 150 msec
- b) 1,500,000 bits
- c) 600,000,000 bits

### Problem 30

Let's suppose the passenger and his/her bags correspond to the data unit arriving to the top of the protocol stack. When the passenger checks in, his/her bags are checked, and a tag is attached to the bags and ticket. This is additional information added in the Baggage layer in Figure 1.20 that allows the Baggage layer to implement the service of separating the passengers and baggage on the sending side, and then reuniting them (hopefully!) on the destination side. When a passenger then passes through security and additional stamp is often added to his/her ticket, indicating that the passenger has passed through a security check. This information is used to ensure (e.g., by later checks for the security information) secure transfer of people.

### Problem 31

- a) Time to send message from source host to first packet switch =  $\frac{8 \times 10^6}{2 \times 10^6} \text{ sec} = 4 \text{ sec}$

With store-and-forward switching, the total time to move message from source host to destination host =  $4 \text{ sec} \times 3 \text{ hops} = 12 \text{ sec}$

- b) Time to send 1<sup>st</sup> packet from source host to first packet switch =  $\frac{1 \times 10^4}{2 \times 10^6} \text{ sec} = 5 \text{ msec}$ . Time at which 2<sup>nd</sup> packet is received at the first switch = time at which 1<sup>st</sup> packet is received at the second switch =  $2 \times 5 \text{ msec} = 10 \text{ msec}$

- c) Time at which 1<sup>st</sup> packet is received at the destination host =  $5 \text{ msec} \times 3 \text{ hops} = 15 \text{ msec}$ . After this, every 5msec one packet will be received; thus time at which last (800<sup>th</sup>) packet is received =  $15 \text{ msec} + 799 \times 5 \text{ msec} = 4.01 \text{ sec}$ . It can be seen that delay in using message segmentation is significantly less (almost 1/3<sup>rd</sup>).

- d)
- i. Without message segmentation, if bit errors are not tolerated, if there is a single bit error, the whole message has to be retransmitted (rather than a single packet).
  - ii. Without message segmentation, huge packets (containing HD videos, for example) are sent into the network. Routers have to accommodate these huge

packets. Smaller packets have to queue behind enormous packets and suffer unfair delays.

e)

- i. Packets have to be put in sequence at the destination.
- ii. Message segmentation results in many smaller packets. Since header size is usually the same for all packets regardless of their size, with message segmentation the total amount of header bytes is more.

### Problem 32

Yes, the delays in the applet correspond to the delays in the Problem 31. The propagation delays affect the overall end-to-end delays both for packet switching and message switching equally.

### Problem 33

There are  $F/S$  packets. Each packet is  $S=80$  bits. Time at which the last packet is received at the first router is  $\frac{S+80}{R} \times \frac{F}{S}$  sec. At this time, the first  $F/S-2$  packets are at the destination, and the  $F/S-1$  packet is at the second router. The last packet must then be transmitted by the first router and the second router, with each transmission taking  $\frac{S+80}{R}$  sec. Thus delay in sending the whole file is  $delay = \frac{S+80}{R} \times (\frac{F}{S} + 2)$

To calculate the value of  $S$  which leads to the minimum delay,

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

### Problem 34

The circuit-switched telephone networks and the Internet are connected together at "gateways". When a Skype user (connected to the Internet) calls an ordinary telephone, a circuit is established between a gateway and the telephone user over the circuit switched network. The skype user's voice is sent in packets over the Internet to the gateway. At the gateway, the voice signal is reconstructed and then sent over the circuit. In the other direction, the voice signal is sent over the circuit switched network to the gateway. The gateway packetizes the voice signal and sends the voice packets to the Skype user.