Announcements:

- Assign 1 is due next Tuesday
Nodal delay

\[ d_{\text{nodal}} = d_{\text{proc}} + d_{\text{queue}} + d_{\text{trans}} + d_{\text{prop}} \]

- \( d_{\text{proc}} \) = processing delay
  - typically a few microsecs or less
- \( d_{\text{queue}} \) = queuing delay
  - depends on congestion
- \( d_{\text{trans}} \) = transmission delay
  - \( = L/R \), significant for low-speed links
- \( d_{\text{prop}} \) = propagation delay
  - a few microsecs to hundreds of msecs
Queueing delay (more insight)

- Every second: \(aL\) bits arrive to queue
- Every second: \(R\) bits leave the router
- **Question**: what happens if \(aL > R\) ?
- **Answer**: queue will fill up, and packets will get dropped!!

\[aL/R\] is called traffic intensity
Queueing delay: illustration

Arrival rate: \( a = \frac{1}{(L/R)} = \frac{R}{L} \) (packet/second)

Traffic intensity = \( aL/R = (R/L)(L/R) = 1 \)

Average queueing delay = 0
(queue is initially empty)
Queueing delay: illustration

N packet arrive simultaneously every LN/R seconds

Arrival rate: \( a = \frac{N}{LN/R} = \frac{R}{L} \) packet/second

Traffic intensity = \( \frac{aL}{R} = \frac{(R/L)}{(L/R)} = 1 \)

Average queueing delay (queue is empty is time 0) ?
\[
\frac{0 + L/R + 2L/R + \ldots + (N-1)L/R}{N} = \frac{L}{RN} \left\{ 1 + 2 + \ldots + (N-1) \right\} = \frac{L(N-1)}{2R}
\]

Note: traffic intensity is same as previous scenario, but queueing delay is different
Queueing delay: behavior

- $La/R \sim 0$: avg. queueing delay small
- $La/R \to 1$: delays become large
- $La/R > 1$: more "work" than can be serviced, average delay infinite!
  (this is when $a$ is random!)

Packet arrival rate $a$ packets/sec
Packet length $L$ bits
Link bandwidth $R$ bits/sec
Packet-switching: store-and-forward

Entire packet must arrive at router before it can be transmitted on next link: *store and forward*

- Takes $L/R$ seconds to transmit (push out) packet of $L$ bits on to link of $R$ bps
- delay = $3L/R$ (assuming zero propagation delay)

more on this next...
Store-and-forward: illustration

- distance = \( d \) meters; speed of propagation = \( s \) m/sec
- transmission rate of link = \( R \) bits/s

- delay (one packet only)
  \[= \frac{L}{R} + \frac{d}{s}\]

Example:
- \( d/s = 0.5 \) sec
- \( L = 10 \) Mbits
- \( R = 1 \) Mbps
- delay = 10.5 sec

Example:
- \( d/s = 0.5 \) sec
- \( L = 10 \) Mbits
- \( R = 1 \) Mbps
- delay = 20.5 sec
Store-and-forward & queuing delay

- distance = d meters; speed of propagation = s m/sec
- transmission rate of link = R1 and R2 bits/s
- Consider sending two packets A and B back to back

Case 1: Assume R1 < R2

- Case 2: Assume R1 > R2

Q: is there a queuing delay? how much is this delay?

Answer (queue is empty initially):
Time for last bit of 2\textsuperscript{nd} pkt to arrive at router: \(d_1 = \frac{L}{R_1} + \frac{L}{R_1} + \frac{d}{2s}\)
Time for last bit of 1\textsuperscript{st} pkt to leave router: \(d_2 = \frac{L}{R_1} + \frac{d}{2s} + \frac{L}{R_2}\)
Queueing delay = \(d_2 - d_1 = \frac{L}{R_2} - \frac{L}{R_1}\) if positive, otherwise 0. Hence:
when R1 < R2, queueing delay = \(d_2 - d_1 = 0\)
when R1 > R2, queueing delay = \(d_2 - d_1 = \frac{L}{R_2} - \frac{L}{R_1}\)
Throughput analysis

- Suppose: Host A has huge file of size $F$ bits to send to Host B
- File is split into $N$ packets, each of length $L$ bits (i.e., $N=F/L$)
- Ignore propagation delay for now

- **Question 1:** how long it takes to send the file?
  - **A:** $(N+2)L/R = (F+2L)/R$

- **Question 2:** what is the average throughput achieved when sending the file?
  - **A:** $NL/[(N+2)L/R] = NR/(N+2) = FR/(F+2L) = R/(1+2L/F)$

Note: throughput = number of total bits sent / total time taken
Throughput analysis

Suppose: Host A has huge file of size $F$ bits to send to Host B
- File is split into $N$ packets, each of length $L$ bits (i.e., $N=F/L$)
- Do NOT ignore propagation delay (assume prop. speed = $s$ m/s)

**Question 1:** how long it takes to send the file?

$A$: \( (N+2)L/R + d/s = (F+2L)/R + d/s \)

**Question 2:** what is the average throughput achieved when sending the file?

Introduction: Summary

Covered a ton of material!
- Internet overview
- Network protocol
- Network edge, core, access network
- Packet-switching versus circuit-switching
- Internet/ISP structure
- Layering and service models
- Performance: delay and throughput analysis