CS 3640: Introduction to Networks and Their Applications

Fall 2023, Lecture 5/6: Performance metrics

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You should have…

- Submitted assignment 1.
  - Add Prof. and TA as “Maintainer” or “Developer”. “Guest” does not work.

- Assignment 2 coming soon.

- Class on Thursday may be canceled. Please stay tuned to your inboxes tomorrow.

Assessing performance in packet-switched networks

- **Delay**
  - How long does it take a packet to get to its destination?
    - Transmission delay: How fast can your link interface convert bits into link signals?
    - Propagation delay: How fast can your link send bits from one end to the other?
    - Processing delay: How fast can your processor handle an incoming packet?
    - Queueing delay: How full is the buffer?

- **Loss**
  - What fraction of packets that are sent end up getting dropped?

- **Throughput**
  - At what rate is data being received by the destination?

This week

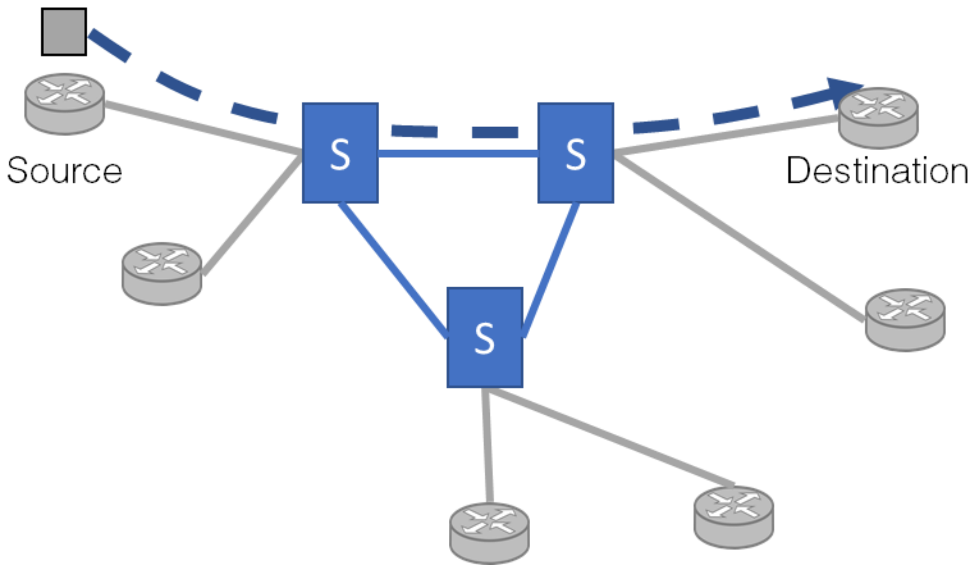
1. Performance metrics

2. Q&A: Wrapping up “design principles”

IOWA

End-to-end delay of a packet-switched network

- End-to-end delay is the sum of all the delays added by each switch/link between the source & destination.
  - $d_{e2e} = (total_{switch\ delays} + total_{link\ delays}) \quad = \sum_{i=1}^{n} (d^{i}{}_{trans} + d^{i}{}_{prop} + d^{i}{}_{proc} + d^{i}{}_{queue})$
  - Here, $d^{\,i}$ is the delay associated with the i^{th} of n switches/links.



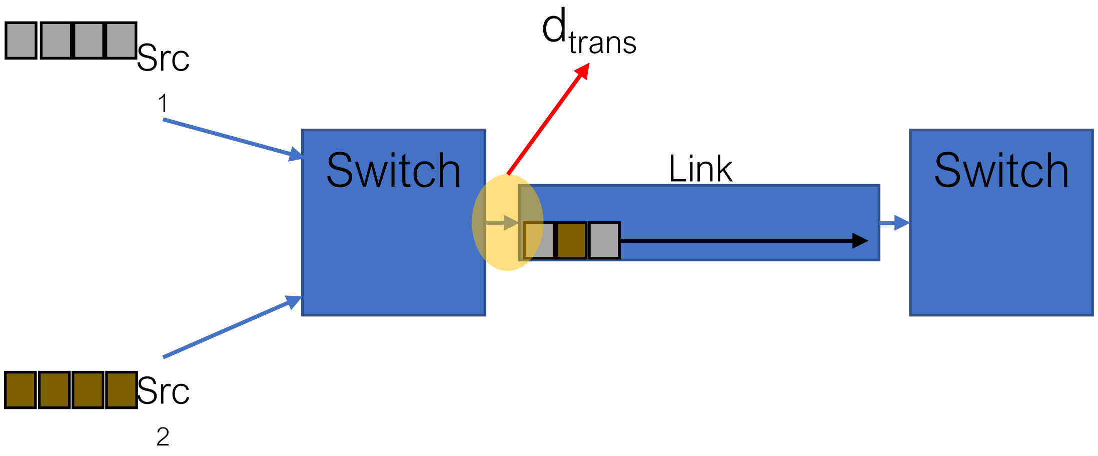
IOWA

$$\boldsymbol{d^i}_{\boldsymbol{trans}} + d^i_{prop} + d^i_{proc} + d^i_{queue}$$

- Transmission delay of a link
  - Q: How many bits can you write to the link in one second?
    A: How much $$$ can you spend?

$$d^i_{trans} + d^i_{prop} + d^i_{proc} + d^i_{queue}$$

- **Discuss: Need to send a 1000KB packet over a 1, 10, and 100 Gbps link adapter. What is the transmission delay over each one?**



8000 Kbits = 8 x 10^6 bits
100 Gbps = 100 x 10^9 bits/sec
10 Gbps = 10 x 10^9 bits/sec
1 Gbps = 10^9 bits/sec

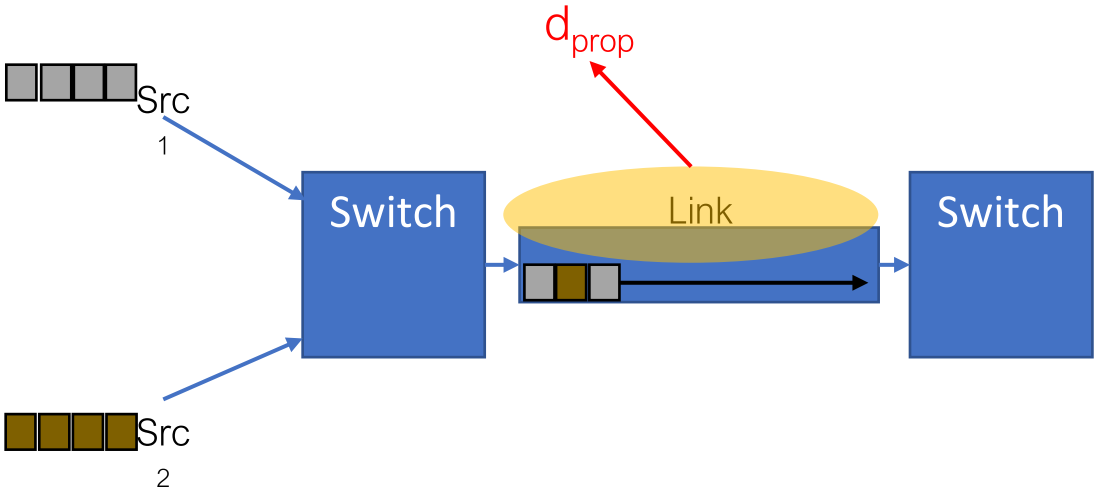
Transmission delay for a 1000KB packet:
@100Gbps: 8×10^{-5} sec
@10 Gbps: 8×10^{-4} sec
@1 Gbps: 8×10^{-3} sec

Transmission delay = data size/transmission rate of link interface

IOWA

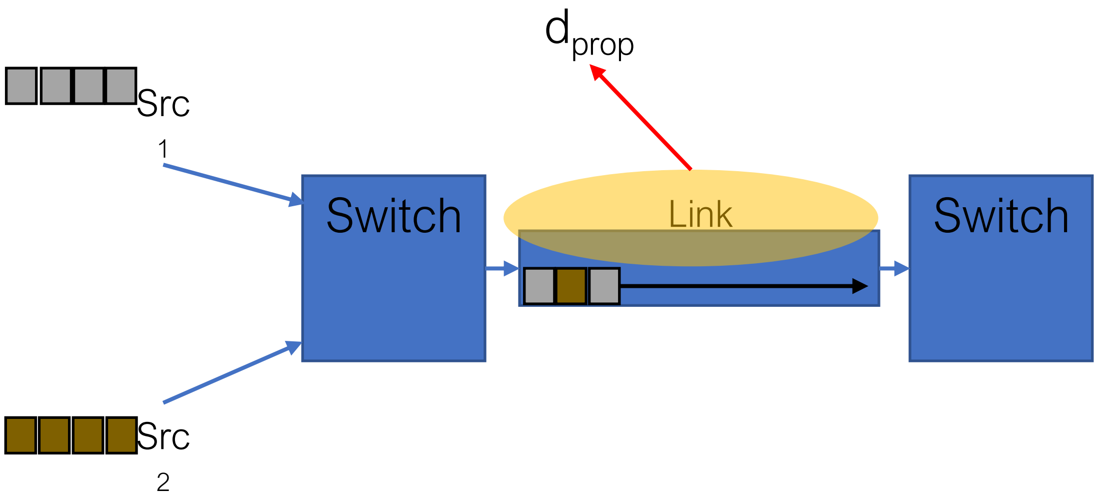
$$d^{i}{}_{trans} + \boldsymbol{d^{i}{}_{prop}} + d^{i}{}_{proc} + d^{i}{}_{queue}$$

- Propagation delay of a link
  - How long does it take to move one bit from one end of the link to the other?
    - Depends on how long the link is.
    - Depends on the material used by the link.
    - Since links are usually optic fiber, they propagate bits at $2x10^8$ mps.
      - This is the speed of light in glass.
      - If we could cost-effectively send bits in vacuum, this would be $3x10^8$ mps.



$$d^{i}{}_{trans} + \boldsymbol{d^{i}{}_{prop}} + d^{i}{}_{proc} + d^{i}{}_{queue}$$

- **Discuss: What is the propagation delay of a 100m optic fiber link? (speed of light in glass: $2\text{x}10^8$ mps)**
  - Time to travel 100 meters @ $2\text{x}10^8$ mps = $100\text{m}/2\text{x}10^8$ mps= $.5\text{x}10^{-6}$ sec



Propagation delay = length of link/propagation speed of link

Propagation delay = length of link/propagation speed of link

Transmission delay = data size/transmission rate of link interface

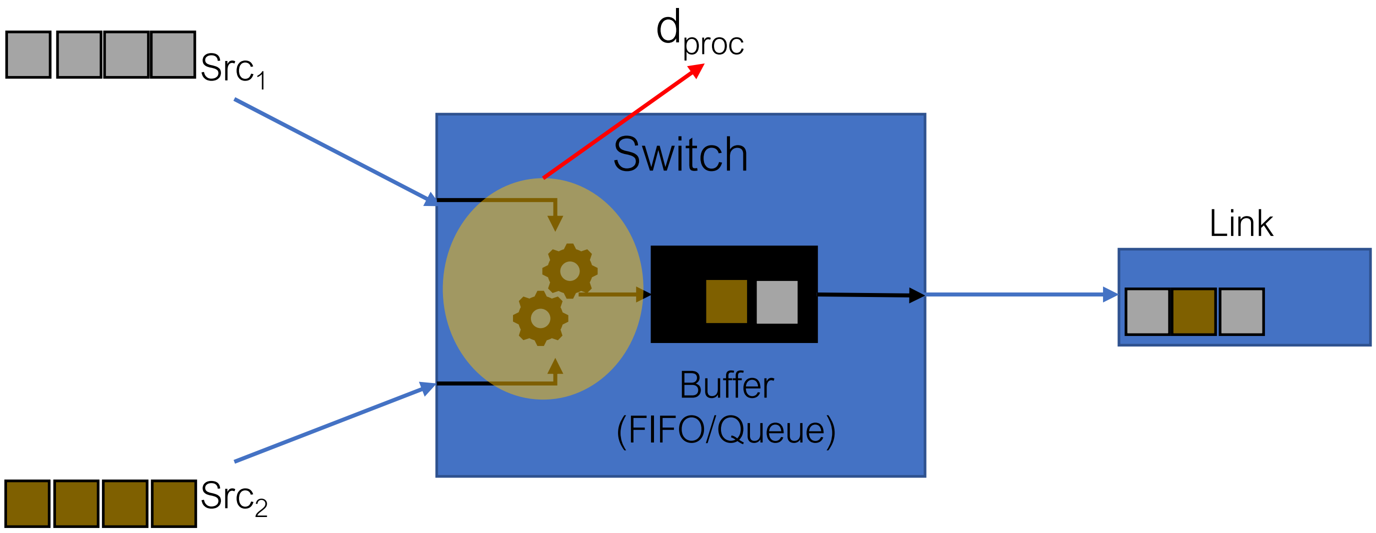
$$\boldsymbol{d^i}_{\boldsymbol{trans}} + \boldsymbol{d^i}_{\boldsymbol{prop}} + d^i{}_{proc} + d^i{}_{queue}$$

- **Discuss: Assume we have no switch-induced delays.**
  - **Link propagation speed: $2x10^8$ mps. Link length: $20x10^3$ m**
  - **Two different networks. When should you invest in a faster link interface card?**
  - **Scenario 1:**
    - **Link adapter: 1 Gbps, Data: 1 GB? What is d_{trans}? What is d_{prop}?**
      - $d_{trans} = 1x8x10^9/1x10^9 = 8s$, $d_{prop} = 20x10^3/2x10^8 = 10^{-4}s$,
      - $d_{e2e} = 8+10^{-4}s$
      - d_{trans} is dominant. Investing in a faster link interface card is a good idea.
  - **Scenario 2:**
    - **Link adapter: 1 Gbps, Data: 100 B? What is d_{trans}? What is d_{prop}?**
      - $d_{trans} = 8x10^2/1x10^9 = 8x10^{-7}$ s, $d_{prop} = 20x10^3/2x10^8 = 10^{-4}$ s,
      - $d_{e2e} = (8x10^{-7}) + 10^{-4}$ s
      - d_{prop} is dominant. Investing in a faster link interface card a waste.

IOWA

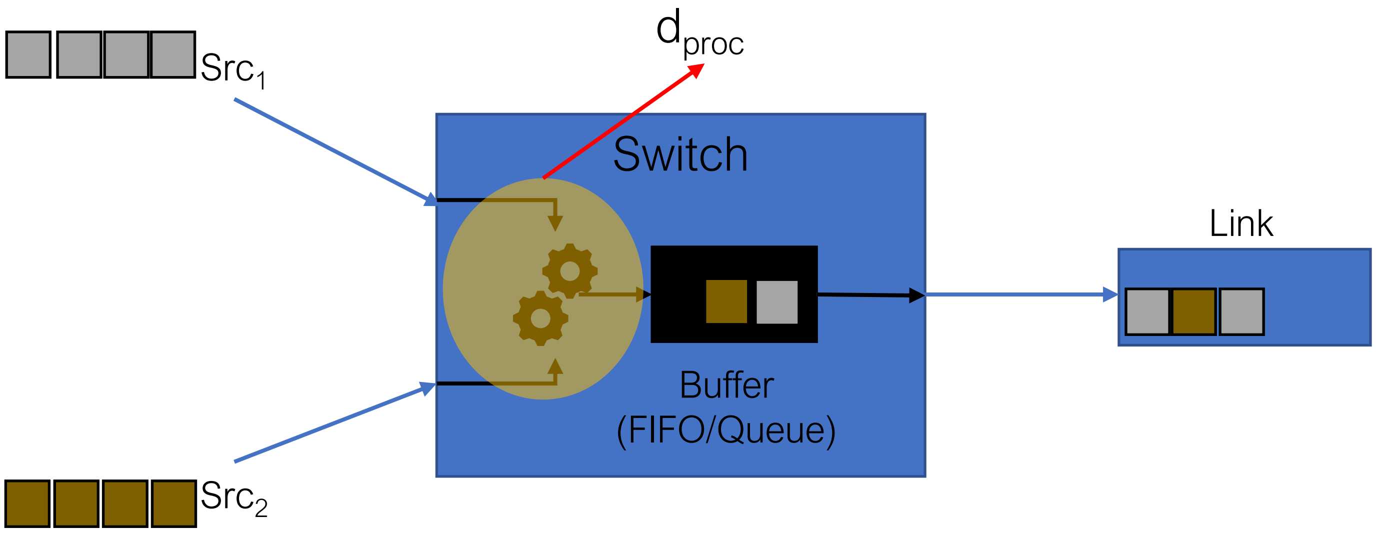
$$d^i{}_{trans} + d^i{}_{prop} + \boldsymbol{d^i{}_{proc}} + d^i{}_{queue}$$

- **Processing delay of a switch**
  - How long does a switch take to error check and figure out which link to send the packet on?
    - Depends on the switch CPU.
      - CPUs are typically multi-core 2-3GHz.
    - Depends on the per-packet operations required.
      - Operations per packet usually require O(10^3) CPU cycles.



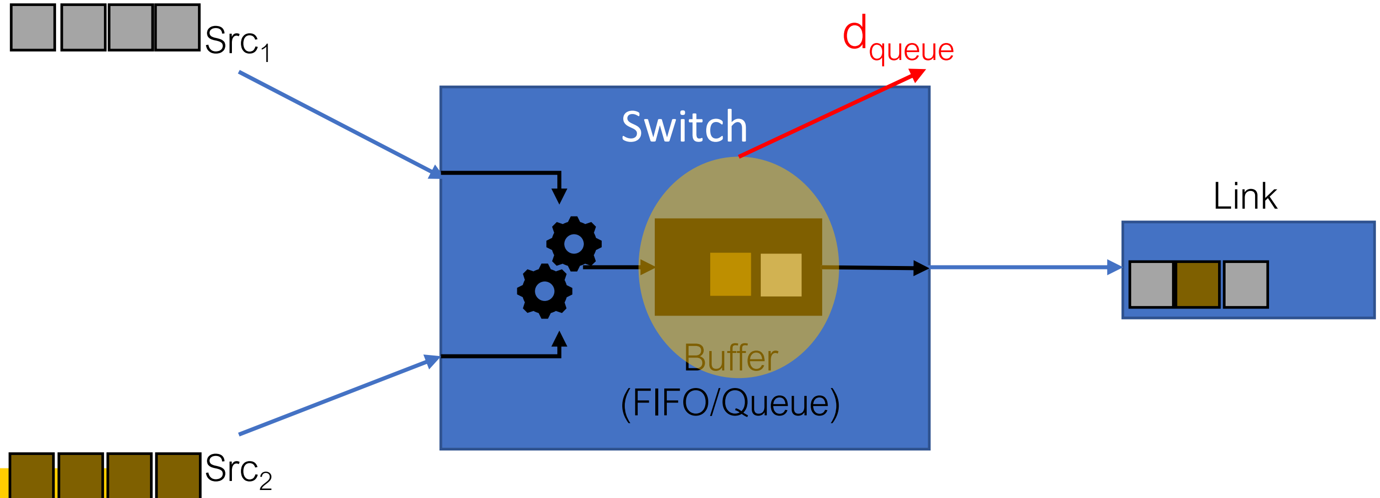
$$d^i{}_{trans} + d^i{}_{prop} + \boldsymbol{d^i{}_{proc}} + d^i{}_{queue}$$

- **Discuss: What is the per packet processing delay of a 3 GHz switch using 3x10³ cycles per packet?**
  - Time to process a packet = $3\text{x}10^3$ cpp/$3\text{x}10^9$ cps = 10^{-6} s
  - Currently, this is never the bottleneck. CPUs are way faster than networks.
  - Adding too much functionality at the link/network layer could make it one, however.



$$d^i{}_{trans} + d^i{}_{prop} + d^i{}_{proc} + \boldsymbol{d^i{}_{queue}}$$

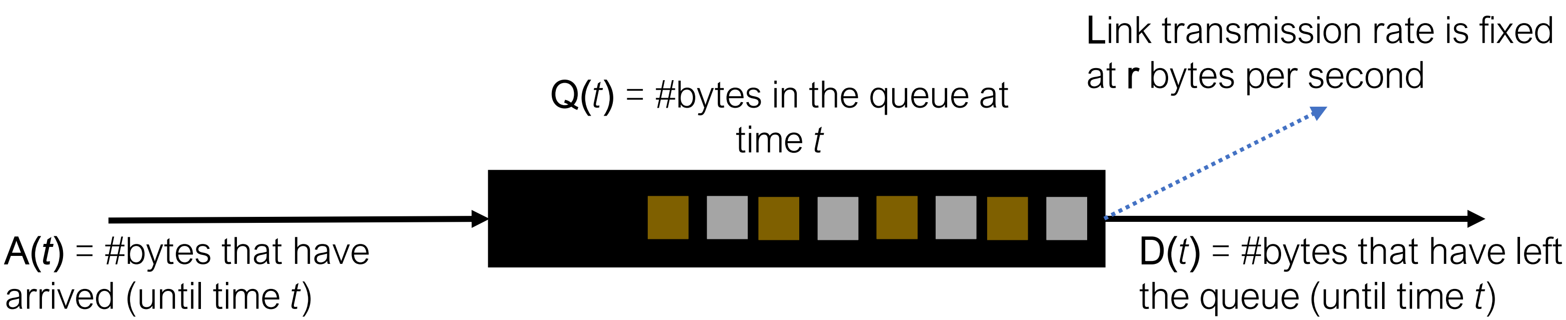
- **Queueing delay of a switch**
  - How long does a packet need to be buffered before the link can handle it?
    - Depends on packet arrival rate.
      - How many packets are already queued?
      - Bursty traffic is likely to have a longer time in the buffer.
    - Depends on packet dispatch rate.
      - How fast can things be removed from the buffer? Depends on d_{trans}.
  - A lot messier to calculate.
    - Queueing theory: A whole research area with 100s of PhD dissertations.

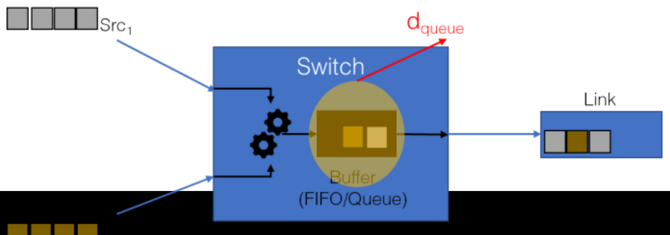


IOWA

$$d^{i}{}_{trans} + d^{i}{}_{prop} + d^{i}{}_{proc} + \boldsymbol{d^{i}{}_{queue}}$$

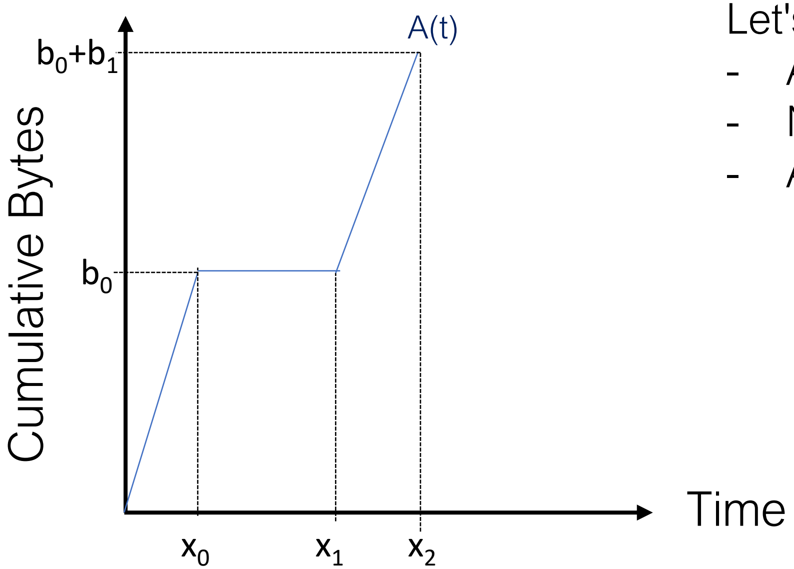
- **Queueing delay of a switch: A simple deterministic model**
  - Part of the complication is that $\mathbf{d}_{\mathbf{queue}}$ changes over time and is different even for packets arriving at the same time.
  - At time *t*, here is what we do know:





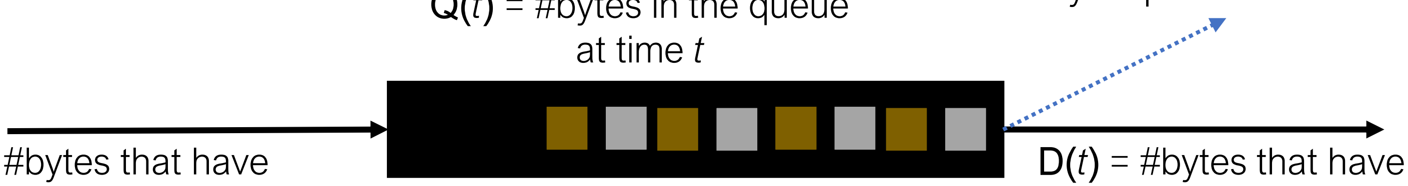
$$d^i{}_{trans} + d^i{}_{prop} + d^i{}_{proc} + \boldsymbol{d^i{}_{queue}}$$

- **Queueing delay of a switch: A simple deterministic model**



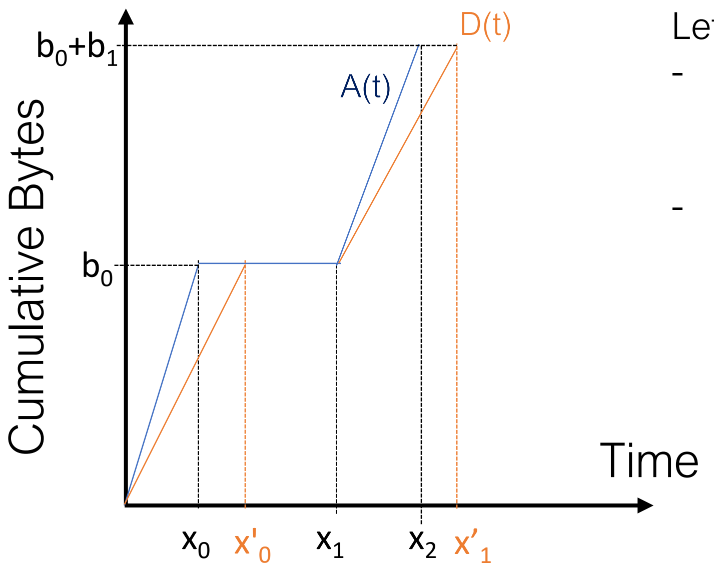
Let's plot A(t) for bursty traffic from a single source.

- At time 0 to x_0, a bunch of packets arrive (b_0 bytes).
- Nothing happens until x_1.
- At time x_1 to x_2, a bunch of packets arrive (b_1 bytes).



$$d^{i}_{trans} + d^{i}_{prop} + d^{i}_{proc} + \boldsymbol{d^{i}_{queue}}$$

- **Queueing delay of a switch: A simple deterministic model**



Lets plot D(t) for link transmission rate r bytes/sec.

- When are the first b_0 bytes sent?

$$x_0' = \frac{b_0}{r}$$

- When are the next b_1 bytes sent?

$$x_1' = x_1 + \frac{b_1}{r}$$

Link transmission rate is fixed at **r** bytes per second

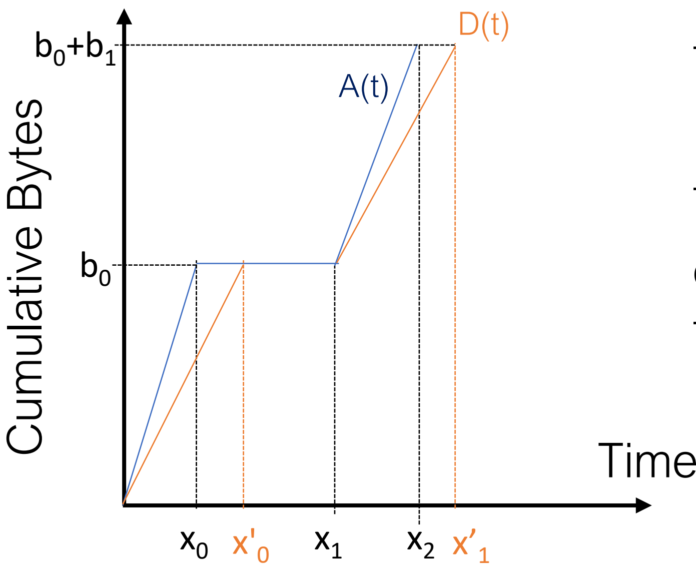
Q(*t*) = #bytes in the queue at time *t*

A(*t*) = #bytes that have arrived (until time *x*)

D(*t*) = #bytes that have left the queue (until time *t*)

$$d^{i}{}_{trans} + d^{i}{}_{prop} + d^{i}{}_{proc} + \boldsymbol{d^{i}{}_{queue}}$$

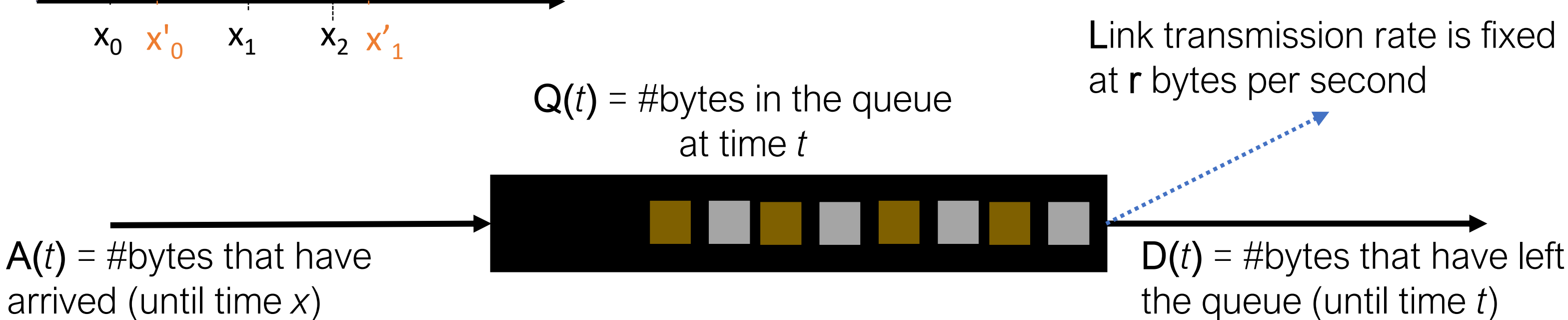
- **Queueing delay of a switch: A simple deterministic model**



What is the size of the queue at time t? [Q(t)]
- At time x, the vertical distance between D(t) and A(t).

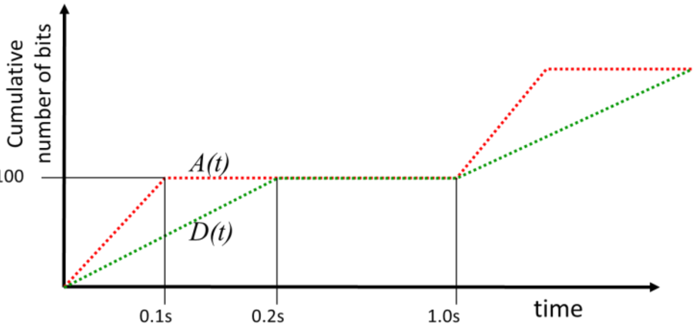
For byte b, what is the queuing delay? [$d_{queue,\ b}$]
- At byte b, the horizontal distance between D(t) and A(t).

Ok, but this isn't so useful for understanding network performance.
- Let's use aggregate queue statistics instead.
    - Average queue occupancy, average queueing delay



$$d^i{}_{trans} + d^i{}_{prop} + d^i{}_{proc} + \boldsymbol{d^i}{}_{\boldsymbol{queue}}$$

- **Queueing delay of a switch: A simple deterministic model**
  - Queue statistic: Average queue occupancy over time.
    - How full is the queue, on average? This is the average vertical distance between A and D.
  - Scenario: At the start of every second, 100 bits arrive to a queue at rate 1000 bits/second. The transmission rate is 500 bits/second.
    - What is the maximum queue occupancy (required buffer size to not have packet loss)?
    - What is the average occupancy over time?



0s to 0.1s: For every 2 bits that arrive into the queue, 1 bit leaves from the queue. 100 bits arrive. [occupancy: 0->50 bits].
Average queue occupancy = (1 + 2 + … + 49 + 50)/50

0.1s to 0.2s: No bits arrive, queue empties. [occupancy: 50->0 bits].
Average queue occupancy = (49 + 48 + … + 1 + 0)/50

Average occupancy from 0s to 0.2s = $\sum_{i=1}^{50} \frac{\frac{i}{50}+\frac{50-i}{50}}{2} = \mathbf{25}\boldsymbol{bits}$

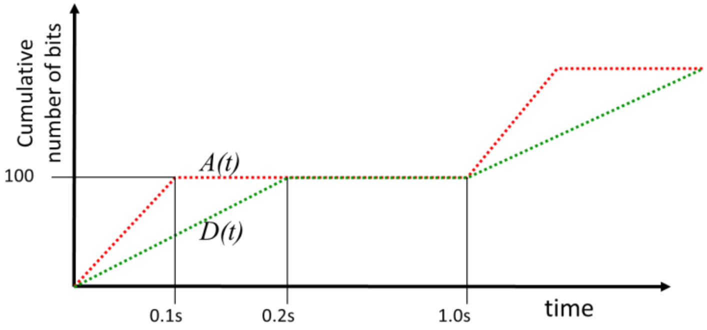
0.2s to 1.0s: No bits arrive, no bits leave. [occupancy: 0 bits]. Average queue occupancy = 0

Average queue occupancy (per second): 25x0.2 + 0x0.8 = 5 bits

IOWA

$$d^i{}_{trans} + d^i{}_{prop} + d^i{}_{proc} + \boldsymbol{d^i{}_{queue}}$$

- **Queueing delay of a switch: A simple deterministic model**
  - Queue statistic: Average queuing delay per bit.
    - How long is the queueing delay, on average? The average horizontal distance between A and D.
  - Scenario: At the start of every second, 100 bits arrive to a queue at rate 1000 bits/second. The transmission rate is 500 bits/second.
    - What is the maximum queueing delay for a bit? What is the average queuing delay per bit?



Maximum delay = 0.1 s (the last packet arrives at 0.1s, leaves at 0.2s)

Average delay = delay for each bit/#bits

Bit 1: Arrives at t=1/1000, leaves at t=1/500. Delay: 1/1000
Bit 2: Arrives at t=2/1000, leaves at t=2/500. Delay: 2/1000
Bit n: Arrives at t=n/1000, leaves at t=n/500. Delay: n/1000
Bit 100: Arrives at t=.1, leaves at t=.2. Delay: .1s

Average delay: (100*101*.5)/(100*1000) ~ .05s

$$d^{i}{}_{trans} + d^{i}{}_{prop} + d^{i}{}_{proc} + \boldsymbol{d^{i}{}_{queue}}$$

- **Queueing delay of a switch and traffic intensity**
  - Intensity (I) = bit arrival rate/bit departure rate
  - Let L be average packet length (depends on content being delivered).
  - Let a be packet arrival rate.
  - Let R be transmission rate of link adapter.
  - I = La/R

- **Why do people spend their time studying queueing theory?**
  - Packets don't arrive in regularly spaced intervals.
    - Their arrival times are randomly distributed (IRL).
  - Unless you are the owner or exclusive user of the switch, you don't know A(t) or D(t). We need models based on incomplete information.
  - We assumed infinitely long queues --- things get more complicated when we restrict this.

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Packet loss in packet-switched networks

- Let L be average packet length (depends on content being delivered).
- Let a be packet arrival rate.
- Let R be transmission rate of link adapter.
- I = La/R

- **Packet Loss**
  - What fraction of packets that are sent end up getting dropped?
  - What can impact this?
    - Buffer sizes and traffic intensity (I = La/R).
  - What can we say about the case where:
    - $I \leq 1$ and uniform packet arrivals?
      - The queue never fills up, average queueing delay is 0.
    - $I > 1$ and uniform packet arrivals?
      - For every La bits coming in, only R are sent out.
        - Every second, (La-R) bits are added to the queue!
      - Queue needs to be big enough to handle t(La-R) bits.
        - t is estimated duration of intensity (I).
  - Rule of network design: Never let I > 1.
    - Increase R or provision other switches to reduce the maximum L x a.

Packet loss in packet-switched networks

- Let L be average packet length (depends on content being delivered).
- Let a be packet arrival rate.
- Let R be transmission rate of link adapter.
- I = La/R

- **Packet Loss**
  - What fraction of packets that are sent end up getting dropped?
  - What can impact this?
    - Buffer sizes and traffic intensity (I = La/R).
  - What can we say about the case where a = 1, but:
    - $I \leq 1$ and bursty packet arrivals (N simultaneous packets/N seconds)?
      - Packets still go out faster than they come in.
        - The queue never needs to hold more than N packets.
      - Queueing delay increases by (L/R) for each packet after the first.
        - Average queueing delay of n packets: (0 + L/R + 2L/R + … + (n-1)L/R)/n
    - $I > 1$ and bursty packet arrivals (N simultaneous packets/N seconds)?
      - You're toast.
      - After N seconds, you still have N(L – R) bits in the queue.
      - After 2N seconds, you still have 2N(L – R) bits in the queue.
      - If queue size < tN(L-R) after tN seconds, everything coming in is dropped.

End-to-end throughput in packet-switched networks

- **End-to-end Throughput**
  - At what rate is data being received by the destination?
  - What can impact this?
    - Slowest link on path and packet loss.
    - Limit (upper-bound on end-to-end throughput): You can never receive data faster than the transmission rate of the slowest link in your network.
    - How could you do worse than this limit? Packet loss. If a packet is lost/dropped, it does not count as received.

  - Like queueing delays and packet loss, this is also a function of time.
    - Congested networks have lower throughput.
    - We use similar analysis using random variables and distributions to analyze end-to-end throughput, but things get a bit messier.

IOWA

Summary: Performance metrics in packet-switched networks

- End-to-end delays:
  - Transmission (link adapter limited)
    - d_{trans} = data size/transmission rate of link adapter
  - Propagation (link material limited)
    - d_{prop} = length of link/propagation speed of link
  - Processing (switch processor limited)
    - d_{proc} = clock cycles per packet/clock speed
  - Queueing (traffic intensity dependent)
    - Time dependent random variable.
    - D(t) and A(t):
      - Horizontal difference at bit “b”: delay for bit “b”.
      - Vertical difference at time “t”: queue occupancy for time “t”
      - Can be used to compute average/maximum delays/occupancy.
    - Limitations of modeling as a uniform arrival rate.
    - Traffic intensity (I = La/R) can give an intuition about delay growth.

Summary: Performance metrics in packet-switched networks

- Packet loss:
  - Depends on buffer sizes and traffic arrival/departure rates.
  - Bursty traffic is much worse than uniform traffic on the same network.
    - Queueing delays increase when I <= 1.
    - Queue size requirements increase very fast when I > 1.
  - Remember: Traffic intensity (I) > 1: very bad. Always.

- End-to-end throughput:
  - Limited by transmission rate of slowest link on path.
  - Can be made worse by packet loss.

This week

1.

Performance metrics

2.

Q&A: Wrapping up "design principles"

IOWA

Discussion

- In groups, produce two questions:
  - Q1: Something that was genuinely confusing to you about the topics we covered in class.
  - Q2: Something that you want to know more about regarding design principles.

- Topics: Layering and 4-layer model, end-to-end principle, fate-sharing, circuit switching, packet switching, performance metrics.