0. Introduction
- Last time: TCP CC. Massive success. Doesn't require us to change the network, is something machines can opt-in to (don't have to have reliable transport if you don't need it), lets us prevent congestion in a distributed manner.
- But:
  - Can result in long delays when routers have too much buffering (Bufferbloat)
  - Doesn't work well in some scenarios (DCTCP)
  - Most important for today: doesn't react to congestion until queues are full.
- Full queues = long delay
- Queues = necessary to absorb bursts
- Goal: Transient queues, not persistent queues
- Idea: drop packets *before* the queues are full. TCP senders will back off before congestion is too bad.

1. DropTail
- The original queue management scheme. When a packet arrives, if the queue is full, drop it; else, enqueue it.
- Simple (+)
- Only drops packets when it needs to (+/-)
- Remember: dropped packet => retransmission, which wastes resources
- Synchronizes sources (-)

Consider the following scenario, where one source sends a burst of traffic: x x x x [ |x|x|x|x]

Queue will drop three packets at the tail of the burst. TCP sender will (likely) timeout, drop its window to 1.

If multiple senders do this: all sources bursts, packets dropped from all, all sources throttle back (reduces utilization), sources increase, cycle repeats.

Flow synchronization = decreased utilization
- Not very fair (-)
- Tends to result in mostly-full queues (-)
- Bad for bursty traffic (-)

2. RED
- Active queue management scheme
- Idea: drop packets before the queue is full to give senders an early signal
- Requires a measure of the average queue size, $q_{avg}$.
  \[ q_{avg} = a \cdot q_{instant} + (1-a) \cdot q_{avg} \quad ; \quad 0 < a \ll 1 \]
- Drop packets with probability $p$. What is $p$?
  \[
  \begin{align*}
  q_{avg} &\leq \min_q; \quad p = 0 \\
  \min_q < q_{avg} &\leq \max_q; \quad p \text{ increases linearly} \\
  q_{avg} &> \max_q; \quad p = 1
  \end{align*}
\]
  (see slides for diagram)
- Results:
  - Queue length doesn't oscillate as much (+)
    - Because $q_{avg}$ is a low-pass filter, and because of the next point
  - Smooth change in drop rate with congestion (+)
    - As $q_{avg}$ increases, so does $p$. Keeps $q_{avg}$ stable
  - Flows are desynchronized (+)
    - Spreads the drops out
  - But, it still drops packets (-)

3. ECN
- RED, but "mark" packets instead of dropping them
  - "Mark" = set a bit in the header to 1. Sources learn about congestion via marked ACKs
  - Seems great! But sources have to know to do this. They already know to react to packet drops, but not to marks.

4. RED/ECN vs. DropTail
- Advantages of RED/ECN
  - Smaller persistent queues $\Rightarrow$ smaller delays
  - Less dramatic queue oscillation
  - Less biased against bursty traffic (in theory)
- Disadvantages
  - More complex
  - Hard to pick parameters ($q_{min}$, $q_{max}$, etc.)
    - "Right" parameters depend on number of flows, bottleneck, etc.
    - Bad parameters make things worse
- Neither RED nor ECN are the final word on active queue management

5. Traffic Differentiation
- As long as we're changing the switches themselves, why stop at queue management?
- Idea of traffic differentiation: put different types of traffic in different queues, and do something fancy with the queues.

6. Delay-based scheduling
- Suppose we want to prioritize latency-sensitive traffic. Say, Xbox live traffic (latency-sensitive) over email (not)
- Solution: priority queueing
  - Two queues: Xbox queue, email queue. Serve Xbox queue if it has a packet. If not, serve email queue.
  - (Can extend this idea to more than two queues)
- "What queue to send a packet from" is the problem of scheduling. That's different from queue management: "When to drop/mark packets in a single queue"
- Lingering problem: a lot of xbox traffic => starving out the email traffic. We'll come back to that.

7. Bandwidth-based scheduling
- What if we, instead, want to allocate a certain amount of bandwidth to each queue?

8. Round-robin

(Note: in class, all of my examples used Skype/Spotify and Dropbox. Below you have the same examples, just with different apps.)

- First case: want xbox and email traffic to each get 50% of bandwidth
- Solution: round-robin scheduler
- Take a packet from the xbox queue, then the email queue, then the xbox queue, then the email queue, ...
- But, what if packet sizes are different:

  \[
  \begin{array}{cccc}
  \text{xbox:} & 10 & 10 & 10 & 10 \\
  \text{email:} & 100 & 100 & 100 & 100 \\
  \end{array}
  \]

  With this scheme we'll send 10 bytes of xbox traffic for every 100 bytes of email traffic. Not what we want!
  => Can't handle variable packet sizes (-)
  - Also, in its purest form, RR doesn't allow us to weight traffic differently (e.g., 66% xbox 33% email instead of a 50/50 split)

9. Weighted RR
- Take the weights, but factor packet size in as well.
- Algorithm:

  in each round:
  for each queue q:
    \[ q.\text{norm} = \frac{q.\text{weight}}{q.\text{mean\_packet\_size}} \]
    \[ \text{min} = \text{min of } q.\text{norm}'s \text{ over all flows} \]
  for each queue q:
    \[ q.\text{n\_packets} = \frac{q.\text{norm}}{\text{min}} \]
    send \( q.\text{n\_packets} \) from queue q

  - Example 1:

    \[
    \begin{array}{cccc}
    \text{xbox:} & 10 & 10 & 10 & 10 \\
    \text{email:} & 100 & 100 & 100 & 100 \\
    \end{array}
    \]

    \[
    \text{xbox\.weight} = \frac{2}{3} \quad \text{email\.weight} = \frac{1}{3} \quad \text{--- normalize weights}
    \]
xbox.mean = 10     email.mean = 100   <-- mean packet size
xbox.norm = 2/3/10   email.norm = 1/3/100
= 1/15               = 1/300

min norm = 1/300

xbox.packets = 1/15/(1/300)  email.packets = 1/300/(1/300)
= 20                   = 1

So we send 20 packets = 20*10 bytes = 200 bytes of xbox traffic
for every 1 packet = 1*100 bytes = 100 bytes of email traffic.

- Example 2:

  xbox: [ 5 | 5 | 10 | 10 ]
  email: [ 1 | 1 | 1 | 1 ]

  xbox.weight = 2/3    email.weight = 1/3
  xbox.mean = 7.5      email.mean = 1
  xbox.norm = 4/45     email.norm = 1/3

  min norm = 4/45

  xbox.packets = 1     email.packets = 3-4

So for every 3-4 bytes of email, we'll send 5-10 bytes of xbox.
Not quite what we want..

- Also: how do we calculate mean packet size?  Over last n packets?
  Over all packets ever?

10. Deficit round-robin
- Queues accumulate "credit" which specifies how many bytes they're
  allowed to send in the next round. Credit carries over to handle
  larger packet sizes.
- Algorithm:

  in each round:
  for each queue q:
    q.credit += q.quantum
    while q.credit >= size of next packet p:
      q.credit -= size of p
      send p

- Example 1:

  xbox: [10 | 10 | 5 | 5 | 10 | 10]
  email: [10 | 10 | 10 | 10 | 10 | 10]

  xbox.Quantum = 20     <-- note: 20;10 not 2/3;1/3 (see below)
email.Quantum = 10
xbox.credit = 0
eemail.credit = 0

round 1:
xbox.credit += xbox.Quantum = 20
while xbox.credit > next packet size:
    send next packet
decrement packet size from credit
=> we'll send 2 xbox packets, and xbox.credit = 0
    xbox queue is now: [10 | 10 | 5 | 5]

email.credit += email.Quantum = 10
=> we'll send just the first packet, and email.credit = 0
    email queue is now [10 | 10 | 10 | 10 | 10]

round 2:
xbox.credit += 20 = 20
=> have enough credit to send the next four packets
    xbox.credit = 0
    xbox.queue = [ ]

eemail.credit += 10
=> have enough credit to send next packet
    email.credit = 0
    email.queue = [ 10 | 10 | 10 | 10 | 10 ]

So we sent 20 bytes for every 10 bytes of email, even with variable packet sizes within the queue.

- Quantums are larger because they reflect a packet size
- Small quantums: go through a lot of rounds before sending a packet
- Large quantums: potentially send a lot of packets from one queue before moving onto the next

- Example 2:

  xbox = [ 20 | 750 | 200 ]   xbox.Quantum = 500
eemail = [ 500 | 500 ]       email.Quantum = 500

round 1:

xbox.credit = 500
can send first packet; xbox.credit = 300
cannot send next packet

eemail.credit = 500
can send first packet; email.credit = 0
round 2:

\[
xbox.credit = 300 + 500 = 800 \quad \text{--- credit carries over!}
\]

Can send first packet; \(xbox.credit = 50\)
Can send second packet; \(xbox.credit = 30\)

\[
email.credit = 500
\]
Can send first packet; \(email.credit = 0\)

- Credit carrying over helps deal with variable (and large) packet sizes
- Pros of DRR:
  - Don't need mean packet size
  - Give near-perfect fairness (we won't prove this)
  - \(O(1)\) packet processing
  - In fact: schemes that increase fairness also increase packet processing.

11. Discussion

- Traffic differentiation: a good idea? In theory, sure. But:
  - Hard to decide what granularity of isolation makes sense
    (per-app? per-flow?)
  - Per-app also requires deep packet inspection. Expensive and thwarted by encryption.
  - Per-flow = lots of state.
- For fair queueing:
  - Schemes (except deficit RR) are expensive
  - Have to change switches
  - How to you choose which traffic gets priority? And who should make that decision?
- For priority queueing:
  - Unclear how multiple methods of priority queueing would interact across the Internet
  - *Should* we allow traffic to be prioritized at all?
- Depressing conclusion: there's enough bandwidth that usually a single FIFO queue works fine :/
- Queue-management: a good idea? Again, in theory, yes.
  - In fact, RED/ECN -- or their ideas -- are used in some environments (DCTCP).
  - ..But not on the entire Internet
    - Hard to set parameters
    - Hard to figure out interactions between schemes
    - Have to change switches
- In-network resource-management: a good idea?
  - Should we do any of this? Who should make these decisions?
  - Should the network "help" the endpoints, possibly providing better performance, but also possibly providing unnecessary functionality?