

Operating Systems and Networks

Network Lecture 10: Congestion Control

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Where we are in the Course

- More fun in the Transport Layer!
 - The mystery of congestion control
 - Depends on the Network layer too

Application
Transport
Network
Link
Physical

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Topic

- Understanding congestion, a “traffic jam” in the network
 - Later we will learn how to control it

What's the hold up?

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Nature of Congestion

- Routers/switches have internal buffering for contention

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Nature of Congestion (2)

- Simplified view of per port output queues
 - Typically FIFO (First In First Out), discard when full

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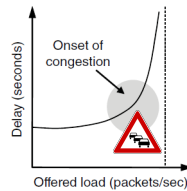
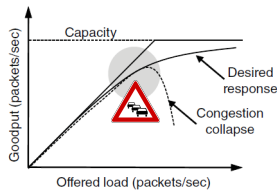
Nature of Congestion (3)

- Queues help by absorbing bursts when input > output rate
- But if input > output rate persistently, queue will overflow
 - This is congestion
- Congestion is a function of the traffic patterns – can occur even if every link has same capacity

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Effects of Congestion

- What happens to performance as we increase the load?



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Effects of Congestion (3)

- As offered load rises, congestion occurs as queues begin to fill:
 - Delay and loss rise sharply with more load
 - Throughput falls below load (due to loss)
 - Goodput may fall below throughput (due to spurious retransmissions)
- None of the above is good! 
 - Want to operate network just before the onset of congestion

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Bandwidth Allocation

- Important task for network is to allocate its capacity to senders
 - Good allocation is efficient and fair
- **Efficient** means most capacity is used but there is no congestion
- **Fair** means every sender gets a reasonable share the network

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Bandwidth Allocation (2)

- Key observation:
 - In an effective solution, Transport and Network layers must work together
- Network layer witnesses congestion
 - Only it can provide direct feedback
- Transport layer causes congestion
 - Only it can reduce offered load

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Bandwidth Allocation (3)

- Why is it hard? (Just split equally!)
 - Number of senders and their offered load is constantly changing
 - Senders may lack capacity in different parts of the network
 - Network is distributed; no single party has an overall picture of its state

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Bandwidth Allocation (4)

- Solution context:
 - Senders adapt concurrently based on their own view of the network
 - Design this adaption so the network usage as a whole is efficient and fair
 - Adaptation is continuous since offered loads continue to change over time

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Topics

- Nature of congestion
- Fair allocations
- AIMD control law
- TCP Congestion Control history
- ACK clocking
- TCP Slow-start
- TCP Fast Retransmit/Recovery
- Congestion Avoidance (ECN)

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Fairness of Bandwidth Allocation (§6.3.1)

- What's a "fair" bandwidth allocation?
 - The max-min fair allocation



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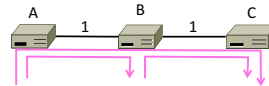
Recall

- We want a good bandwidth allocation to be fair and efficient
 - Now we learn what fair means
- Caveat: in practice, efficiency is more important than fairness

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Efficiency vs. Fairness

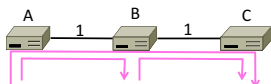
- Cannot always have both!
 - Example network with traffic $A \rightarrow B$, $B \rightarrow C$ and $A \rightarrow C$
 - How much traffic can we carry?



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Efficiency vs. Fairness (2)

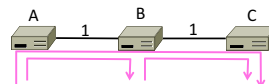
- If we care about fairness:
 - Give equal bandwidth to each flow
 - $A \rightarrow B$: $\frac{1}{2}$ unit, $B \rightarrow C$: $\frac{1}{2}$, and $A \rightarrow C$: $\frac{1}{2}$
 - Total traffic carried is $1 \frac{1}{2}$ units



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Efficiency vs. Fairness (3)

- If we care about efficiency:
 - Maximize total traffic in network
 - $A \rightarrow B$: 1 unit, $B \rightarrow C$: 1, and $A \rightarrow C$: 0
 - Total traffic rises to 2 units!



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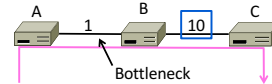
The Slippery Notion of Fairness

- Why is “equal per flow” fair anyway?
 - $A \rightarrow C$ uses more network resources (two links) than $A \rightarrow B$ or $B \rightarrow C$
 - Host A sends two flows, B sends one
- Not productive to seek exact fairness
 - More important to avoid starvation
 - “Equal per flow” is good enough

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Generalizing “Equal per Flow”

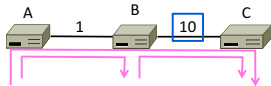
- Bottleneck for a flow of traffic is the link that limits its bandwidth
 - Where congestion occurs for the flow
 - For $A \rightarrow C$, link A–B is the bottleneck



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Generalizing “Equal per Flow” (2)

- Flows may have different bottlenecks
 - For $A \rightarrow C$, link A–B is the bottleneck
 - For $B \rightarrow C$, link B–C is the bottleneck
 - Can no longer divide links equally ...



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Max-Min Fairness

- Intuitively, flows bottlenecked on a link get an equal share of that link
- Max-min fair allocation is one that:
 - Increasing the rate of one flow will decrease the rate of a smaller flow
 - This “maximizes the minimum” flow

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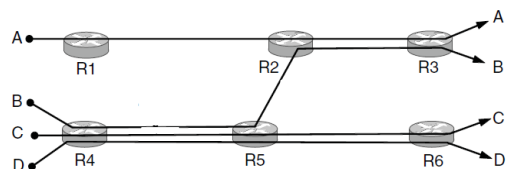
Max-Min Fairness (2)

- To find it given a network, imagine “pouring water into the network”
 1. Start with all flows at rate 0
 2. Increase the flows until there is a new bottleneck in the network
 3. Hold fixed the rate of the flows that are bottlenecked
 4. Go to step 2 for any remaining flows

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Max-Min Example

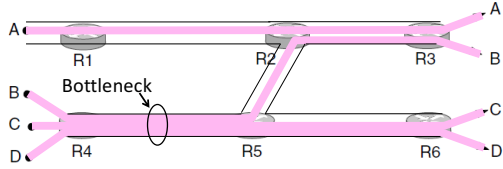
- Example: network with 4 flows, links equal bandwidth
 - What is the max-min fair allocation?



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Max-Min Example (2)

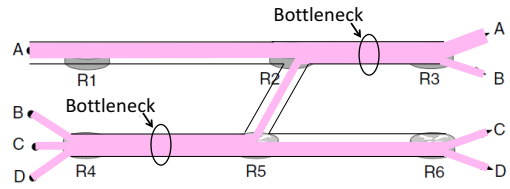
- When rate=1/3, flows B, C, and D bottleneck R4—R5
 - Fix B, C, and D, continue to increase A



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Max-Min Example (3)

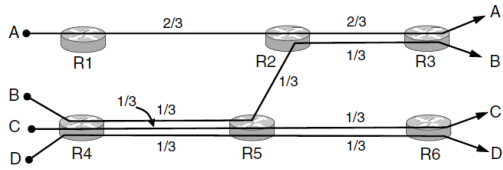
- When rate=2/3, flow A bottlenecks R2—R3. Done.



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Max-Min Example (4)

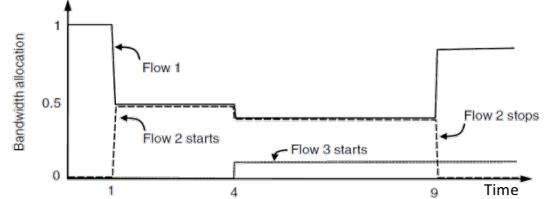
- End with A=2/3, B, C, D=1/3, and R2—R3, R4—R5 full
 - Other links have extra capacity that can't be used



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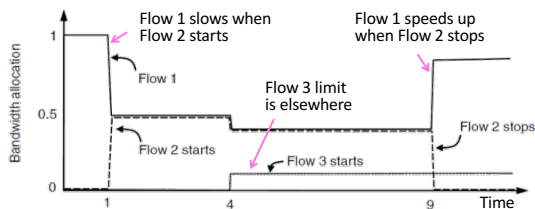
Adapting over Time

- Allocation changes as flows start and stop



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Adapting over Time (2)



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Recall

- Want to allocate capacity to senders
 - Network layer provides feedback
 - Transport layer adjusts offered load
 - A good allocation is efficient and fair
- How should we perform the allocation?
 - Several different possibilities ...

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Bandwidth Allocation Models

- Open loop versus closed loop
 - Open: reserve bandwidth before use
 - Closed: use feedback to adjust rates
- Host versus Network support
 - Who sets/enforces allocations?
- Window versus Rate based
 - How is allocation expressed?

TCP is a closed loop, host-driven, and window-based

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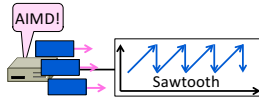
Bandwidth Allocation Models (2)

- We'll look at closed-loop, host-driven, and window-based
- Network layer returns feedback on current allocation to senders
 - At least tells if there is congestion
- Transport layer adjusts sender's behavior via window in response
 - How senders adapt is a control law

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Additive Increase Multiplicative Decrease (AIMD) (§6.3.2)

- Bandwidth allocation models
 - Additive Increase Multiplicative Decrease (AIMD) control law



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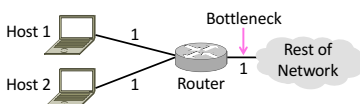
Additive Increase Multiplicative Decrease

- AIMD is a control law hosts can use to reach a good allocation
 - Hosts additively increase rate while network is not congested
 - Hosts multiplicatively decrease rate when congestion occurs
 - Used by TCP ☺
- Let's explore the AIMD game ...

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AIMD Game

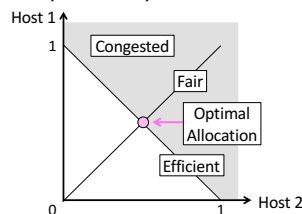
- Hosts 1 and 2 share a bottleneck
 - But do not talk to each other directly
- Router provides binary feedback
 - Tells hosts if network is congested



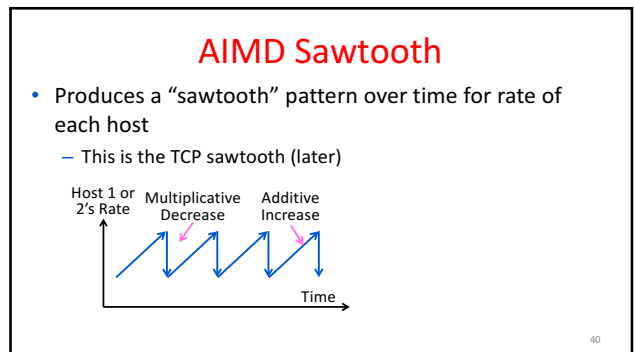
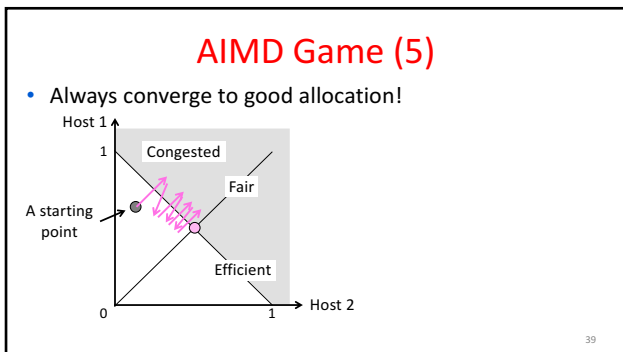
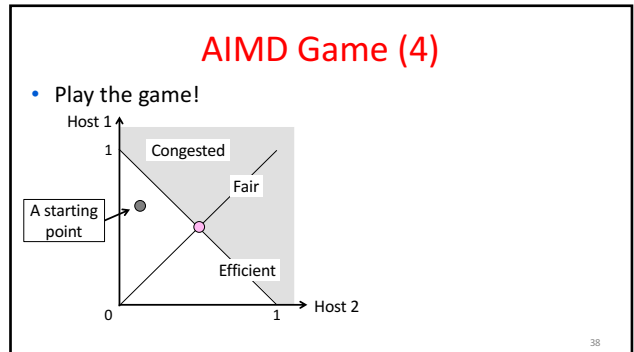
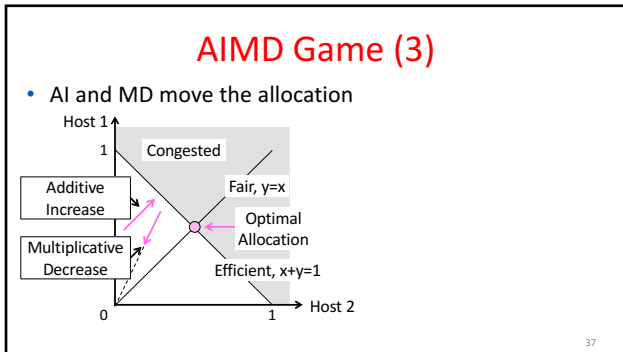
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AIMD Game (2)

- Each point is a possible allocation



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- ### AIMD Properties
- Converges to an allocation that is efficient and fair when hosts run it
 - Holds for more general topologies
 - Other increase/decrease control laws do not! (Try MIAD, MIMD, AIAD)
 - Requires only binary feedback from the network
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Feedback Signals

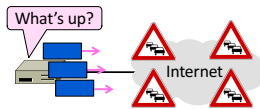
- Several possible signals, with different pros/cons
 - We'll look at classic TCP that uses packet loss as a signal

Signal	Example Protocol	Pros / Cons
Packet loss	TCP NewReno Cubic TCP (Linux)	+Hard to get wrong -Hear about congestion late
Packet delay	Compound TCP (Windows)	+Hear about congestion early -Need to infer congestion
Router indication	TCPs with Explicit Congestion Notification	+Hear about congestion early -Require router support

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History of TCP Congestion Control (§6.5.10)

- The story of TCP congestion control
 - Collapse, control, and diversification



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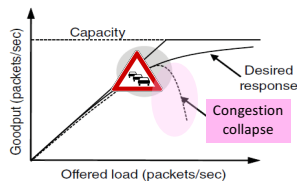
Congestion Collapse in the 1980s

- Early TCP used a fixed size sliding window (e.g., 8 packets)
 - Initially fine for reliability
- But something strange happened as the ARPANET grew
 - Links stayed busy but transfer rates fell by orders of magnitude!

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Congestion Collapse (2)

- Queues became full, retransmissions clogged the network, and **goodput fell**



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Van Jacobson (1950—)

- Widely credited with saving the Internet from congestion collapse in the late 80s
 - Introduced congestion control principles
 - Practical solutions (TCP Tahoe/Reno)
- Much other pioneering work:
 - Tools like traceroute, tcpdump, pathchar
 - IP header compression, multicast tools



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TCP Tahoe/Reno

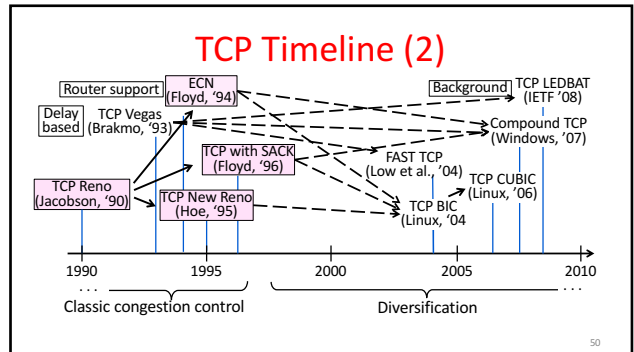
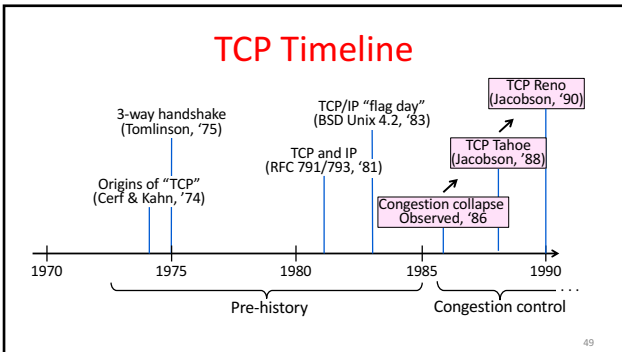
- Avoid congestion collapse without changing routers (or even receivers)
- Idea is to fix timeouts and introduce a congestion window (cwnd) over the sliding window to limit queues/loss
- TCP Tahoe/Reno implements AIMD by adapting cwnd using packet loss as the network feedback signal

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TCP Tahoe/Reno (2)

- TCP behaviors we will study:
 - ACK clocking
 - Adaptive timeout (mean and variance)
 - Slow-start
 - Fast Retransmission
 - Fast Recovery
- Together, they implement AIMD

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TCP Ack Clocking (§6.5.10)

- The self-clocking behavior of sliding windows, and how it is used by TCP
 - The "ACK clock"

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Sliding Window ACK Clock

- Each in-order ACK advances the sliding window and lets a new segment enter the network
 - ACKs "clock" data segments

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Benefit of ACK Clocking

- Consider what happens when sender injects a burst of segments into the network

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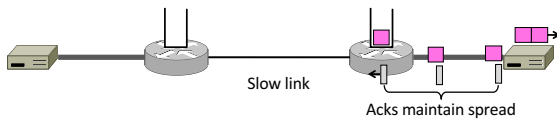
Benefit of ACK Clocking (2)

- Segments are buffered and spread out on slow link

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Benefit of ACK Clocking (3)

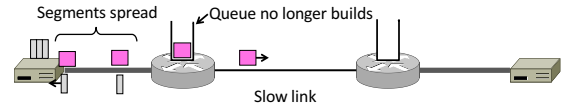
- ACKs maintain the spread back to the original sender



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Benefit of ACK Clocking (4)

- Sender clocks new segments with the spread
 - Now sending at the bottleneck link without queuing!



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Benefit of ACK Clocking (4)

- Helps the network run with low levels of loss and delay!
- The network has smoothed out the burst of data segments
- ACK clock transfers this smooth timing back to the sender
- Subsequent data segments are not sent in bursts so they do **not** queue up in the network

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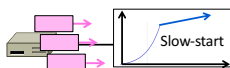
TCP Uses ACK Clocking

- TCP uses a sliding window because of the value of ACK clocking
- Sliding window controls how many segments are inside the network
 - Called the congestion window, or cwnd
 - Rate is roughly $cwnd/RTT$
- TCP only sends small bursts of segments to let the network keep the traffic smooth

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TCP Slow Start (§6.5.10)

- How TCP implements AIMD, part 1
 - “Slow start” is a component of the AI portion of AIMD



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Considerations

- We want TCP to follow an AIMD control law for a good allocation
- Sender uses a congestion window or cwnd to set its rate ($\approx cwnd/RTT$)
- Sender uses packet loss as the network congestion signal
- Need TCP to work across a very large range of rates and RTTs

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TCP Tahoe (Implementation)

- Initial slow-start (doubling) phase
 - Start with $cwnd = 1$ (or small value)
 - $cwnd += 1$ segment size per ACK
- Later Additive Increase phase
 - $cwnd += 1/cwnd$ segments per ACK
 - Roughly adds 1 segment size per RTT
- Switching threshold (initially infinity)
 - Switch to AI when $cwnd > ssthresh$
 - Set $ssthresh = cwnd/2$ after loss
 - Begin with slow-start after timeout

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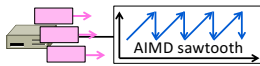
Timeout Misfortunes

- Why do a slow-start after timeout?
 - Instead of MD $cwnd$ (for AIMD)
- Timeouts are sufficiently long that the ACK clock will have run down
 - Slow-start ramps up the ACK clock
- We need to detect loss before a timeout to get to full AIMD
 - Done in TCP Reno

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TCP Fast Retransmit / Fast Recovery (§6.5.10)

- How TCP implements AIMD, part 2
 - “Fast retransmit” and “fast recovery” are the MD portion of AIMD



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Recall

- We want TCP to follow an AIMD control law for a good allocation
- Sender uses a congestion window or cwnd to set its rate ($\approx cwnd/RTT$)
- Sender uses slow-start to ramp up the ACK clock, followed by Additive Increase
- But after a timeout, sender slow-starts again with $cwnd=1$ (as it has no ACK clock)

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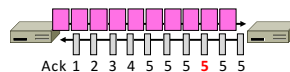
Inferring Loss from ACKs

- TCP uses a cumulative ACK
 - Carries highest in-order seq. number
 - Normally a steady advance
- Duplicate ACKs give us hints about what data hasn't arrived
 - Tell us some new data did arrive, but it was not next segment
 - Thus the next segment may be lost

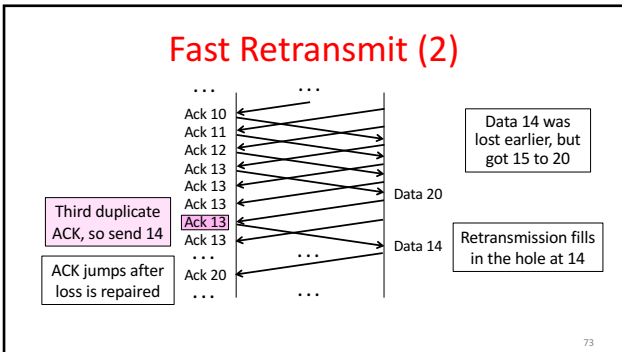
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Fast Retransmit

- Treat three duplicate ACKs as a loss
 - Retransmit next expected segment
 - Some repetition allows for reordering, but still detects loss quickly

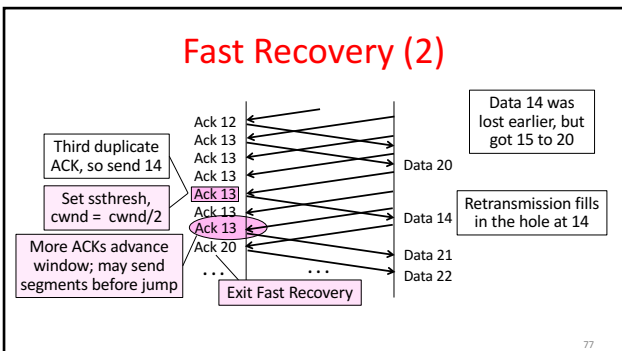
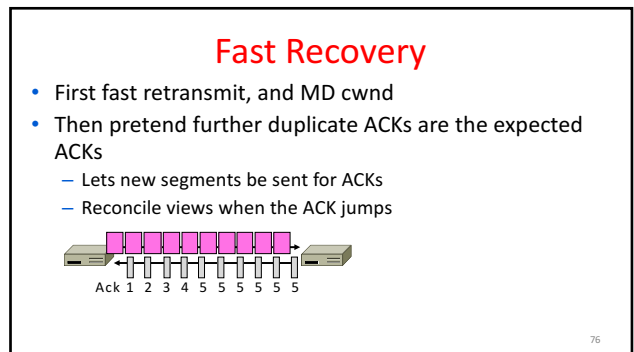


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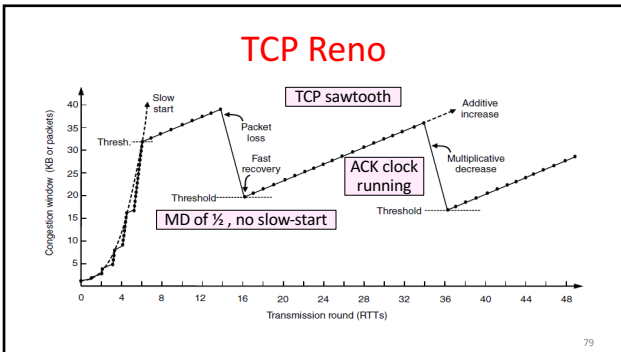


- ### Fast Retransmit (3)
- It can repair single segment loss quickly, typically before a timeout
 - However, we have quiet time at the sender/receiver while waiting for the ACK to jump
 - And we still need to MD cwnd ...
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- ### Inferring Non-Loss from ACKs
- Duplicate ACKs also give us hints about what data has arrived
 - Each new duplicate ACK means that some new segment has arrived
 - It will be the segments after the loss
 - Thus advancing the sliding window will not increase the number of segments stored in the network
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- ### Fast Recovery (3)
- With fast retransmit, it repairs a single segment loss quickly and keeps the ACK clock running
 - This allows us to realize AIMD
 - No timeouts or slow-start after loss, just continue with a smaller cwnd
 - TCP Reno combines slow-start, fast retransmit and fast recovery
 - Multiplicative Decrease is $\frac{1}{2}$
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- ### TCP Reno, NewReno, and SACK
- Reno can repair one loss per RTT
 - Multiple losses cause a timeout
 - NewReno further refines ACK heuristics
 - Repairs multiple losses without timeout
 - SACK is a better idea
 - Receiver sends ACK ranges so sender can retransmit without guesswork
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- ### Explicit Congestion Notification (§5.3.4, §6.5.10)
- How routers can help hosts to avoid congestion
 - Explicit Congestion Notification
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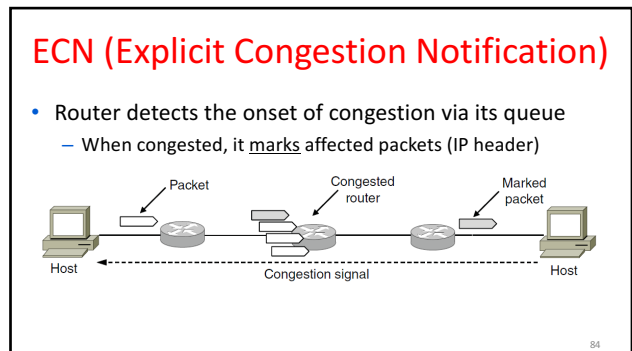
- ### Congestion Avoidance vs. Control
- Classic TCP drives the network into congestion and then recovers
 - Needs to see loss to slow down
 - Would be better to use the network but avoid congestion altogether!
 - Reduces loss and delay
 - But how can we do this?
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Feedback Signals

- Delay and router signals can let us avoid congestion

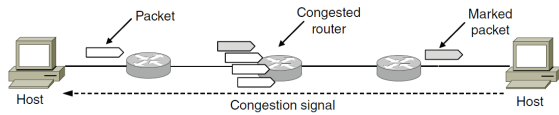
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ECN (2)

- Marked packets arrive at receiver; treated as loss
 - TCP receiver reliably informs TCP sender of the congestion



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ECN (3)

- Advantages
 - Routers deliver clear signal to hosts
 - Congestion is detected early, no loss
 - No extra packets need to be sent
- Disadvantage
 - Routers and both sender and receiver must be upgraded

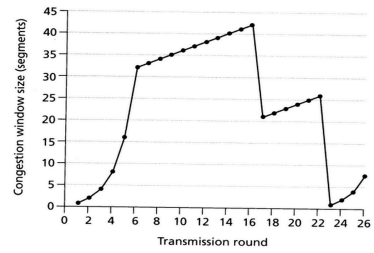
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Example 1

- Assume a TCP sender without fast retransmit, but with slow start and additive increase. Also assume:
- Segments $n, n+1, n+2, \dots, n+10$ transmitted at times $0, 1, 2, \dots, 10$ ms
 - Transmission time / segment = 1 ms
 - RTT ($2 \times$ propagation + transmission + ack processing + ack transmission) = 10 ms
 - Segment n is lost (only)
 - In order segments and ACKs
 - Retransmission timer for segment n is 60 ms, starting at the end of transmission
 - $cwnd = ssthresh = 64$ at time 0
 - $offeredWindow = 70$

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Example 2: Infer Events that Occurred



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