

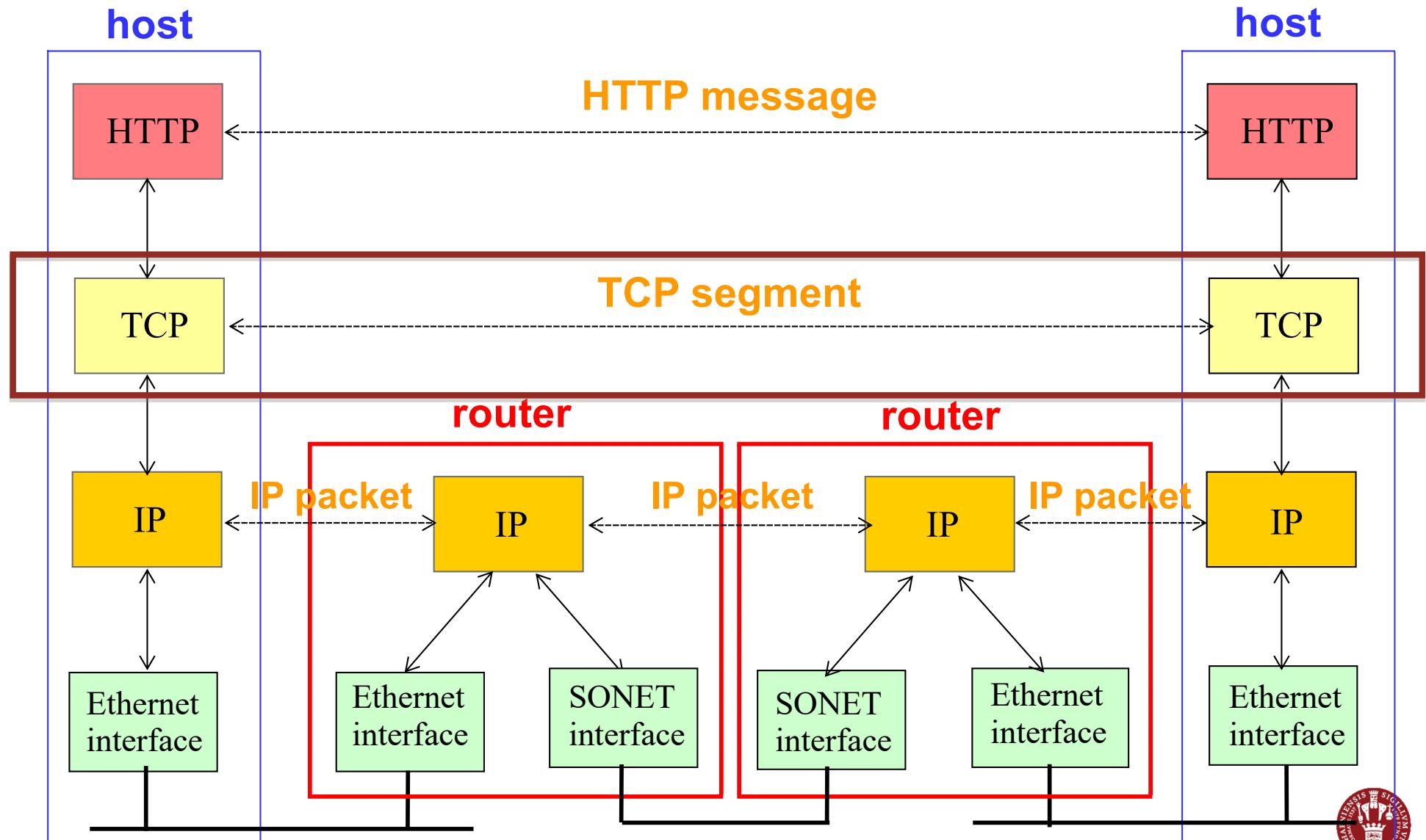


Transport Layer: Reliable Data Transfer + TCP

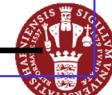
Michael Kirkedal Thomsen

Based on slides compiled by Marcos Vaz Salles, with
adoptions by Vivek Shah

Internet Layering Model



Source: Freedman



Transport Layer

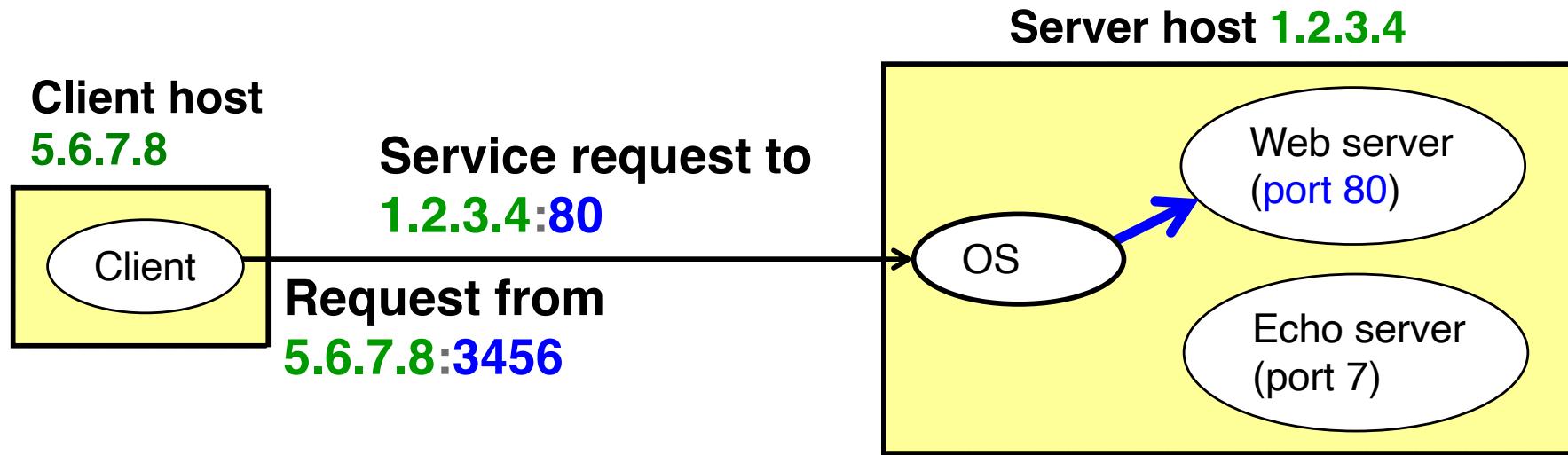
- Logical Communication between processes
 - Sender divides messages into segments.
 - Receiver re-assembles messages into segments.
- Principles underlying transport-layer services
 - (De)multiplexing
 - Detecting corruption
 - Optional: Reliable delivery, Flow control, Congestion control
- Transport-layer protocols in the Internet
 - **User Datagram Protocol (UDP)**
 - Simple (unreliable) message delivery
 - **Transmission Control Protocol (TCP)**
 - Reliable bidirectional stream of bytes

Source: Freedman



Recap: Two Basic Transport Features

- **Demultiplexing:** port numbers



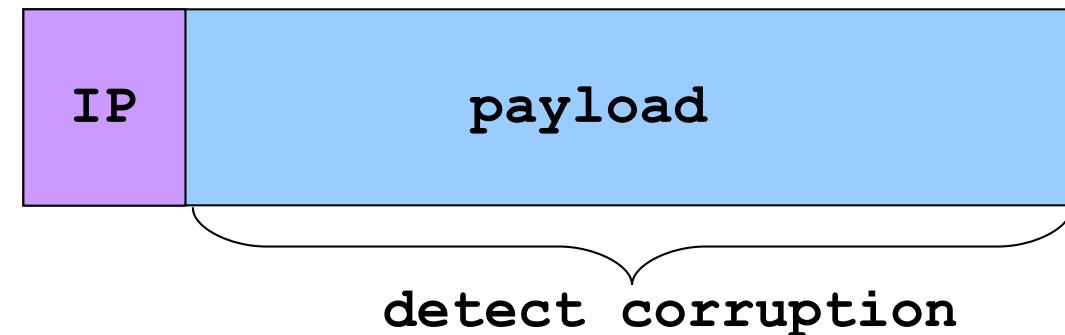
Demux table ("5 tuple")	Socket
$\langle *, *, 1.2.3.4, 80, \text{TCP} \rangle$	5
$\langle 5.6.7.8, 3456, 1.2.3.4, 80, \text{TCP} \rangle$	6

Source: Freedman



Recap: Two Basic Transport Features

- **Error detection:** checksums



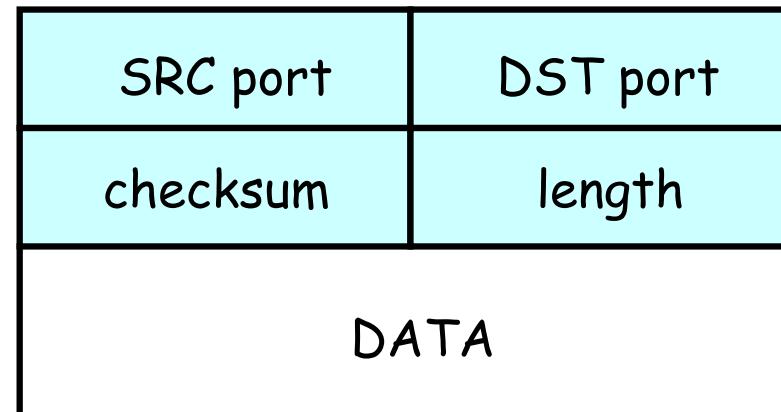
- Optional for IPv4
 - 16-bit one's complement of the sum of a pseudo header of information from the IP header, the UDP header, and the data

Source: Freedman



Recap: User Datagram Protocol (UDP)

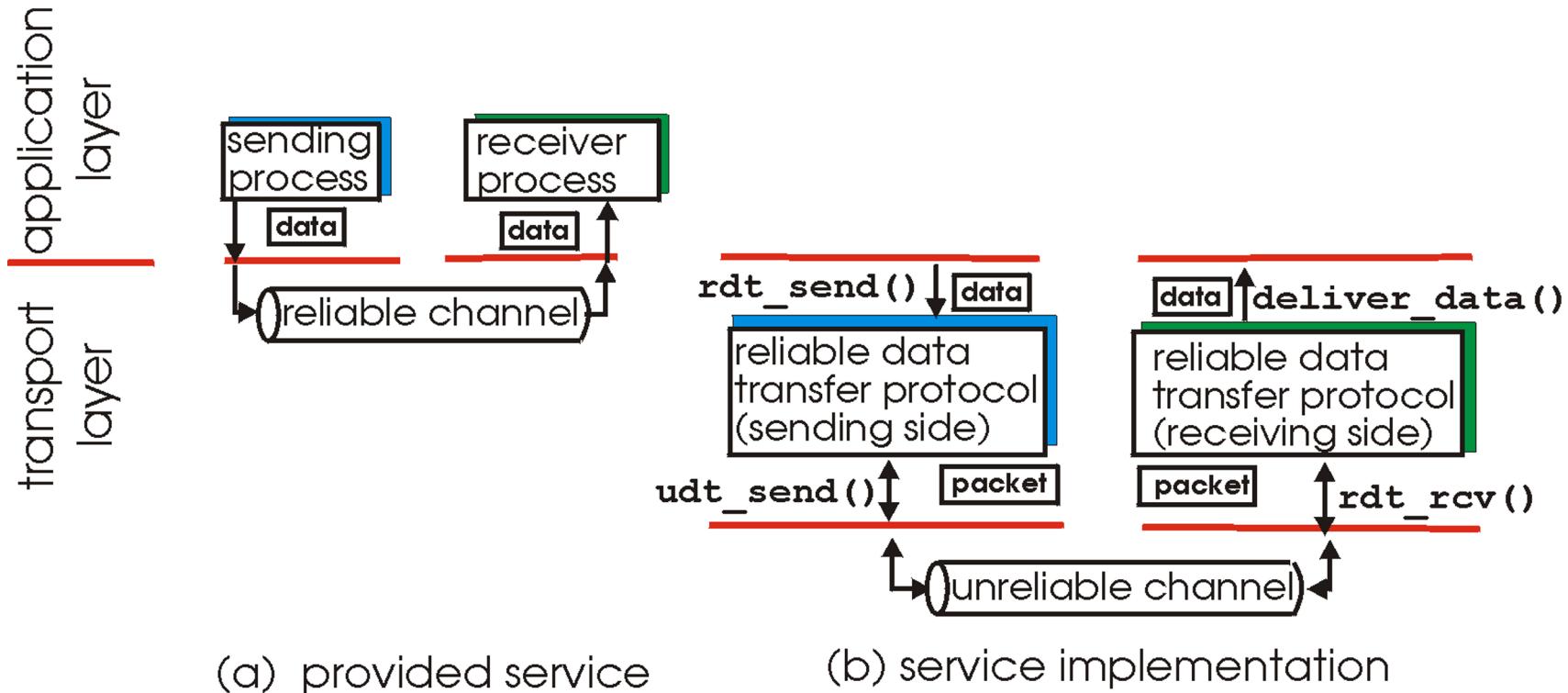
- Datagram messaging service
 - Demultiplexing of messages: port numbers
 - Detecting corrupted messages: checksum
- Lightweight communication between processes
 - Send messages to and receive them from a socket
- Avoid overhead and delays of ordered, reliable delivery



Source: Freedman



Reliable Data Transfer



Source: Kurose & Ross

- What can go wrong on the unreliable channel?
- How can you deal with it?
- Suppose you want to transfer TCP segments, reliably and in order! ☺



Challenges of Reliable Data Transfer

- Over a perfectly reliable channel: Done
- Over a channel with bit errors
 - Receiver detects errors and requests re-transmission
- Over a lossy channel with bit errors
 - Some data missing, others corrupted
 - Receiver cannot easily detect loss
- Over a channel that may reorder packets
 - Receiver cannot easily distinguish loss vs. out-of-order

Source: Freedman



An Analogy

- Alice and Bob are talking
 - What if Alice couldn't understand Bob?
 - Alice asks Bob to repeat what he said
- What if Bob hasn't heard Alice for a while?
 - Is Alice just being quiet? Has she lost reception?
 - How long should Bob just keep on talking?
 - Maybe Alice should periodically say "uh huh"
 - ... or Bob should ask "Can you hear me now?"



Source: Freedman



Take Aways from the Example

- Acknowledgments from receiver
 - Positive: “okay” or “uh huh” or “ACK”
 - Negative: “please repeat that” or “NACK”
- Retransmission by the sender
 - After *not* receiving an “ACK”
 - After receiving a “NACK”
- Timeout by the sender (“stop and wait”)
 - Don’t wait forever without some acknowledgment

Source: Freedman



TCP Support for Reliable Delivery

- **Detect bit errors:** checksum
 - Used to detect corrupted data at the receiver
 - ...leading the receiver to drop the packet
- **Detect missing data:** sequence number
 - Used to detect a gap in the stream of bytes
 - ... and for putting the data back in order
- **Recover from lost data:** retransmission
 - Sender re-transmits lost or corrupted data
 - Two main ways to detect lost packets

Source: Freedman



Transmission Control Protocol (TCP)

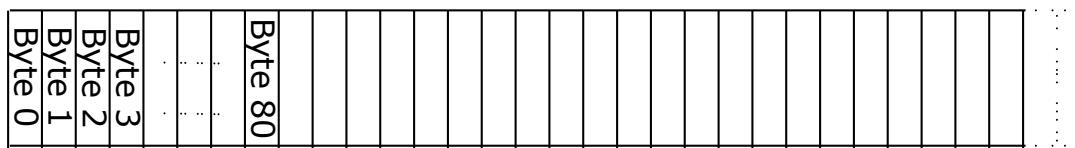
- **Stream-of-bytes service:** Send/recv streams, not msgs
- **Reliable, in-order delivery**
 - Checksums to detect corrupted data
 - Sequence numbers to detect losses and reorder data
 - Acknowledgments & retransmissions for reliable delivery
- **Connection oriented:** Explicit set-up and tear-down
- **Flow control:** Prevent overload of receiver's buffer
- **Congestion control:** Adapt for greater good

Source: Freedman

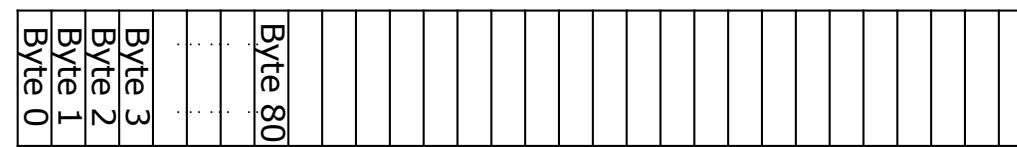


TCP “Stream of Bytes” Service

Host A



Host B



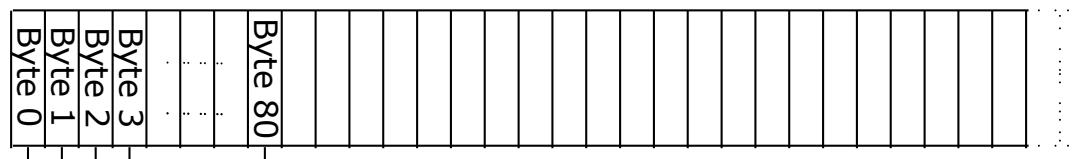
Byte 80
Byte 3
Byte 2
Byte 1
Byte 0

Source: Freedman



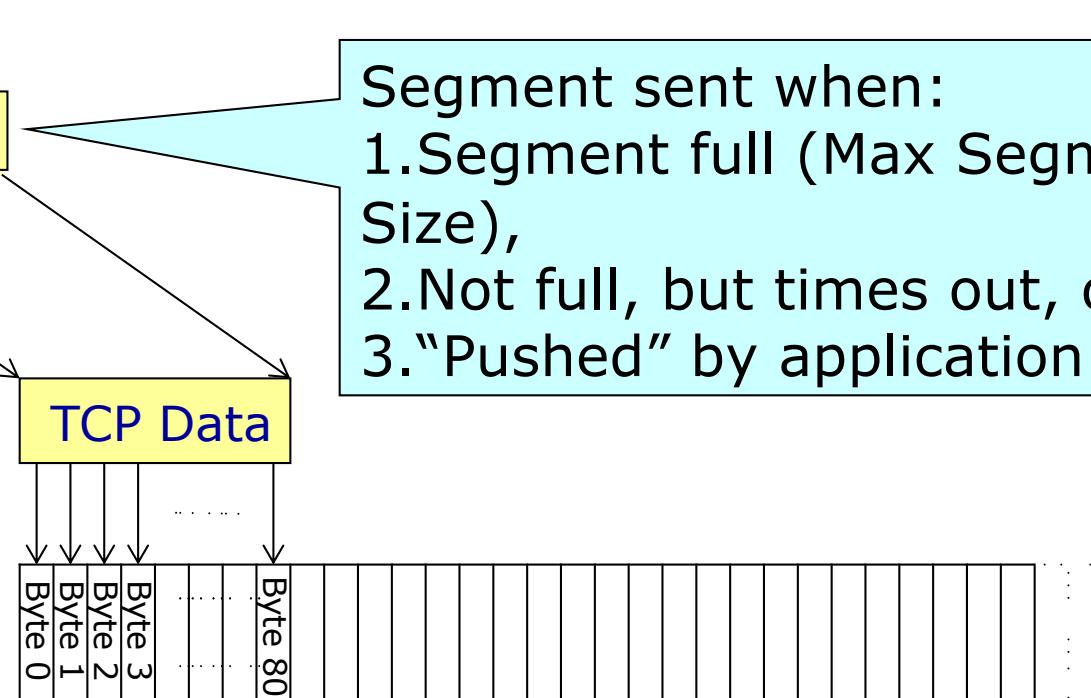
... Emulated Using TCP “Segments”

Host A



Segment sent when:
1. Segment full (Max Segment Size),
2. Not full, but times out, or
3. “Pushed” by application

Host B

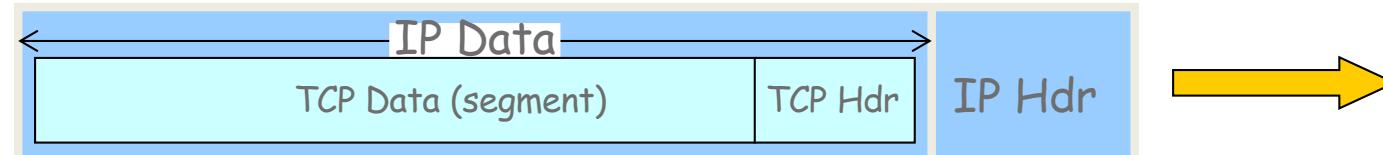


Source: Freedman



TCP Segment

- IP packet
 - No bigger than Maximum Transmission Unit (MTU)
 - E.g., up to 1500 bytes on an Ethernet link
- TCP packet
 - IP packet with a TCP header and data inside
 - TCP header is typically 20 bytes long
- TCP segment
 - No more than Maximum Segment Size (MSS) bytes
 - E.g., up to 1460 consecutive bytes from the stream

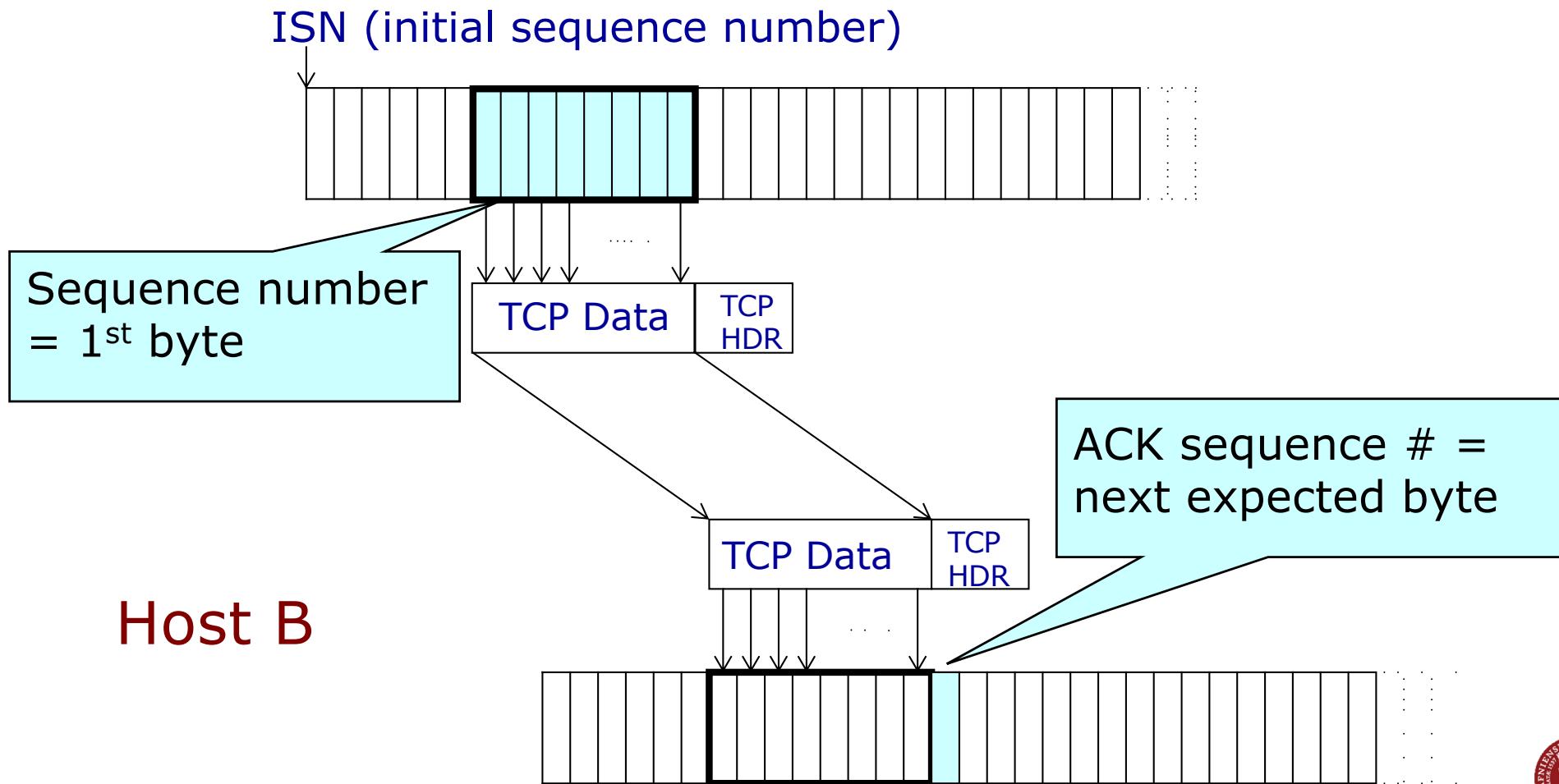


Source: Freedman



TCP Acknowledgements

Host A

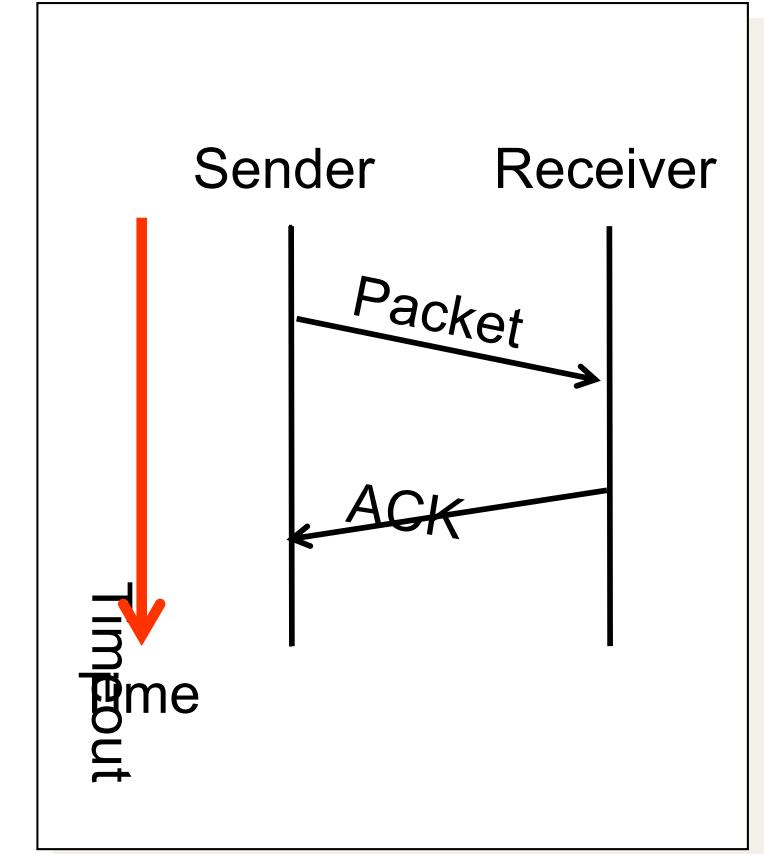


Source: Freedman



Automatic Repeat Request (ARQ)

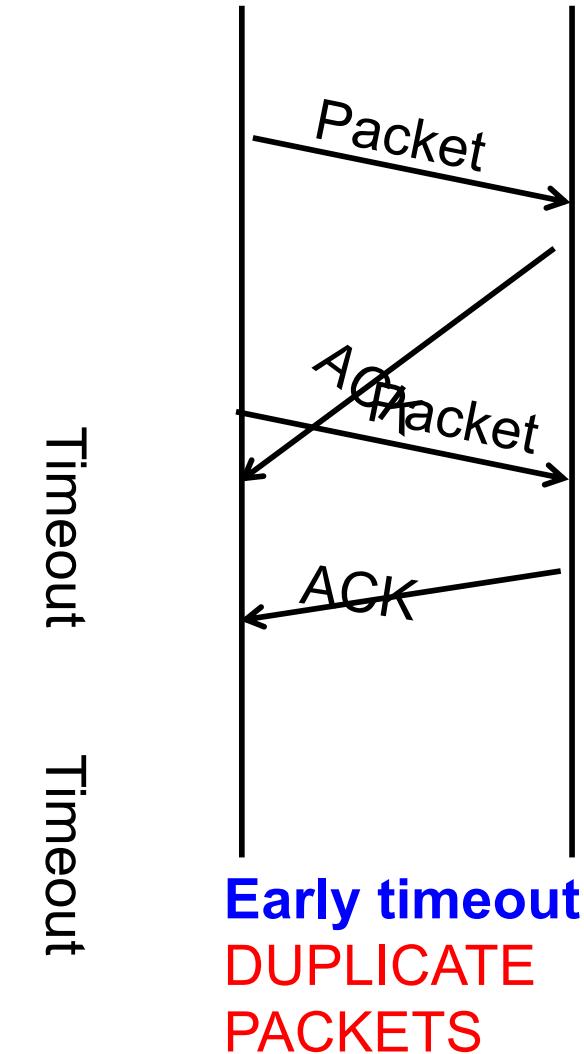
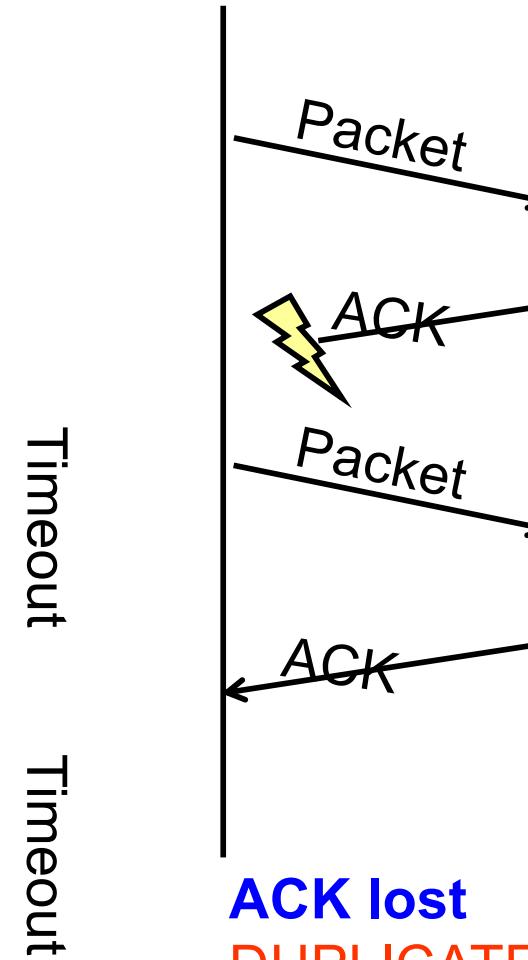
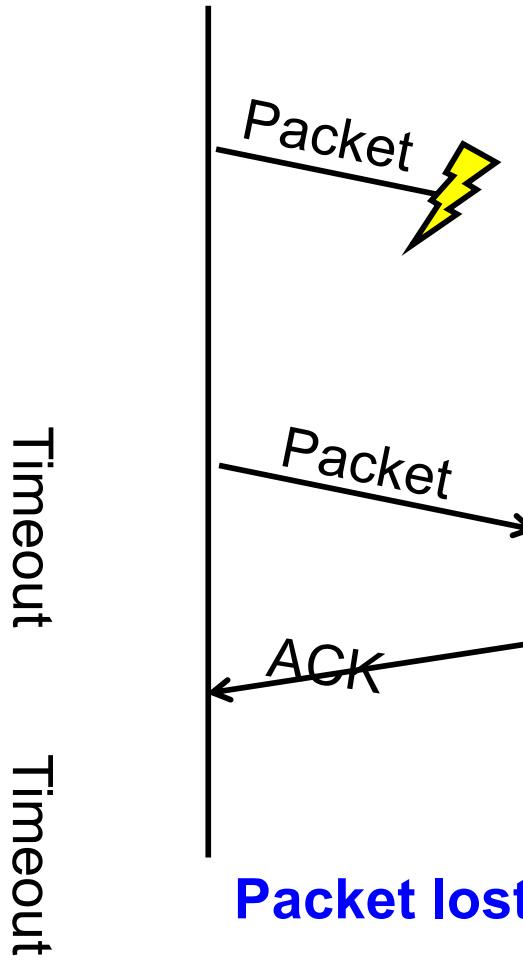
- Receiver sends ACK when it receives packet
- Sender waits for ACK.
- If ACK not received within some timeout period, resend packet
- “stop and wait”
 - One packet at a time...



Source: Freedman (partial)



Reasons for Retransmission



Source: Freedman



How Long Should Sender Wait?

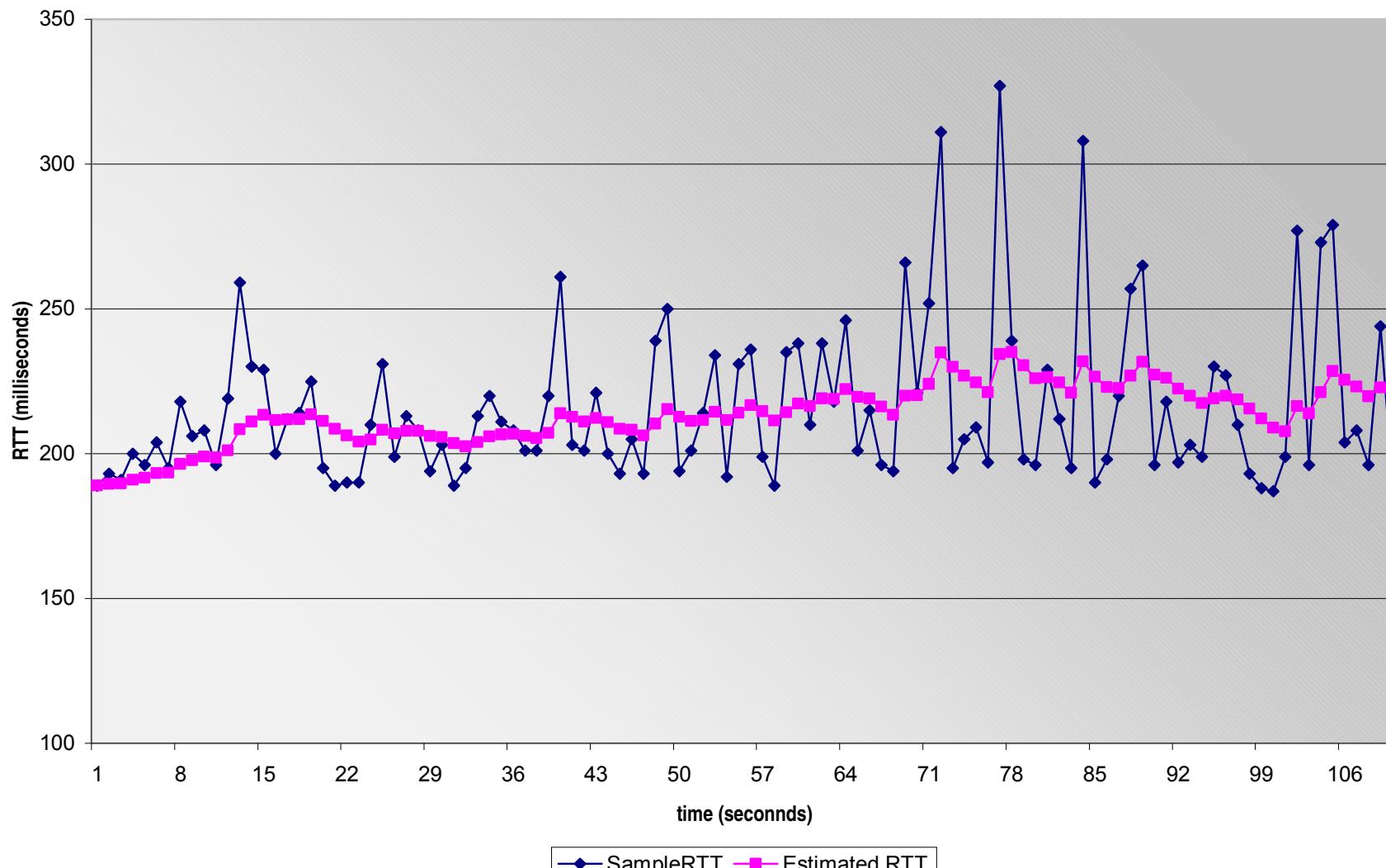
- Too short? Wasted re-transmissions
- Too long? Excessive delays when packet lost
- TCP sets timeout as function of Round Trip Time
 - ACK should arrive after RTT + fudge factor for queuing
- How does sender know RTT?
 - Can estimate RTT by watching the ACKs
 - Smooth estimate: Exponentially-weighted moving avg (EWMA)
 - $\text{EstimatedRTT} = (1-a) * \text{EstimatedRTT} + a * \text{SampleRTT}$
 - Typical value: $a = 0.125$

Source: Freedman (partial) + Kurose & Ross (partial)



Example RTT Estimation

RTT: gaia.cs.umass.edu to fantasia.eurecom.fr



Source: Kurose & Ross



TCP Round Trip Time and Timeout

Setting the timeout

- **EstimatedRTT** plus “safety margin”
 - large variation in **EstimatedRTT** → larger safety margin
- first estimate of how much SampleRTT deviates from EstimatedRTT:

$$\text{DevRTT} = (1-\beta) * \text{DevRTT} + \beta * |\text{SampleRTT} - \text{EstimatedRTT}|$$

(typically, $\beta = 0.25$)

- Then set timeout interval:

$$\text{TimeoutInterval} = \text{EstimatedRTT} + 4 * \text{DevRTT}$$



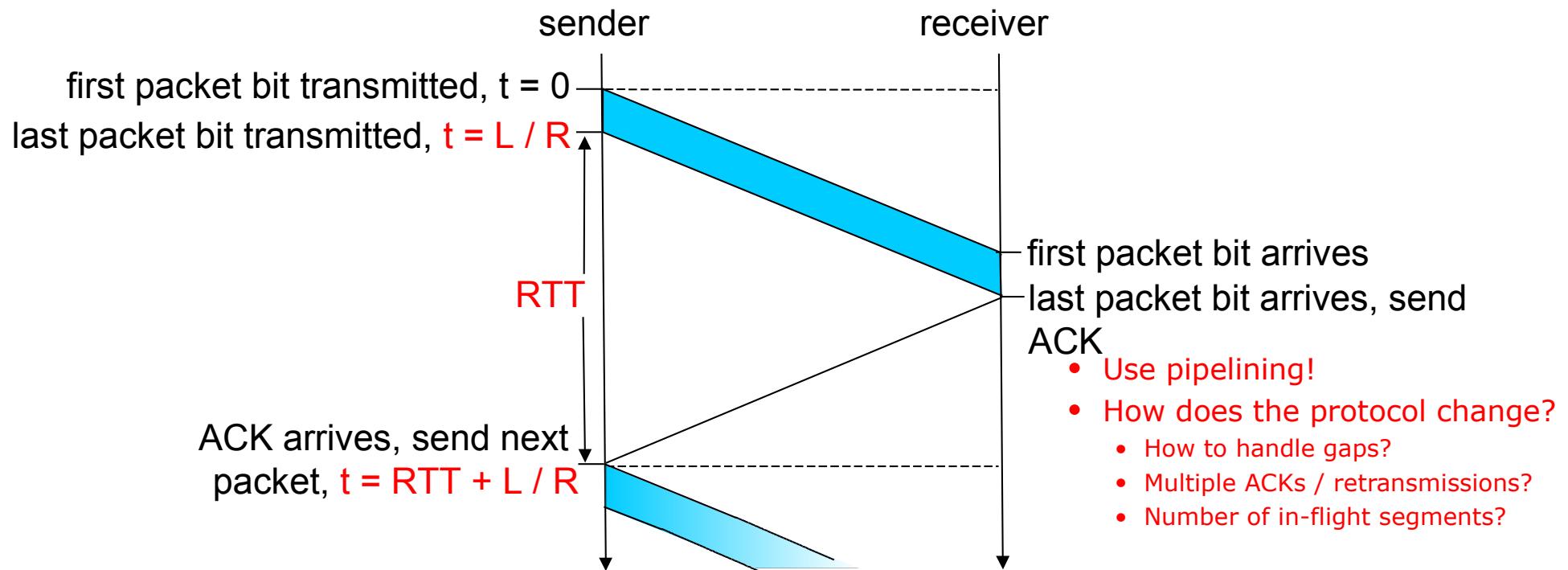
Source: Kurose & Ross

A Flaw in This Approach

- ACK acknowledges receipt to data, not transmission
- Consider a retransmission of a lost packet
 - If assume ACK with 1st transmission, SampleRTT too large
- Consider a duplicate packet
 - If assume ACK with 2nd transmission, SampleRTT too small
- Simple solution in the Karn/Partridge algorithm
 - Only collect samples for segments sent one single time
 - On retransmission, **new_timeout = 2 * timeout**



Well tuned timeouts help, but...

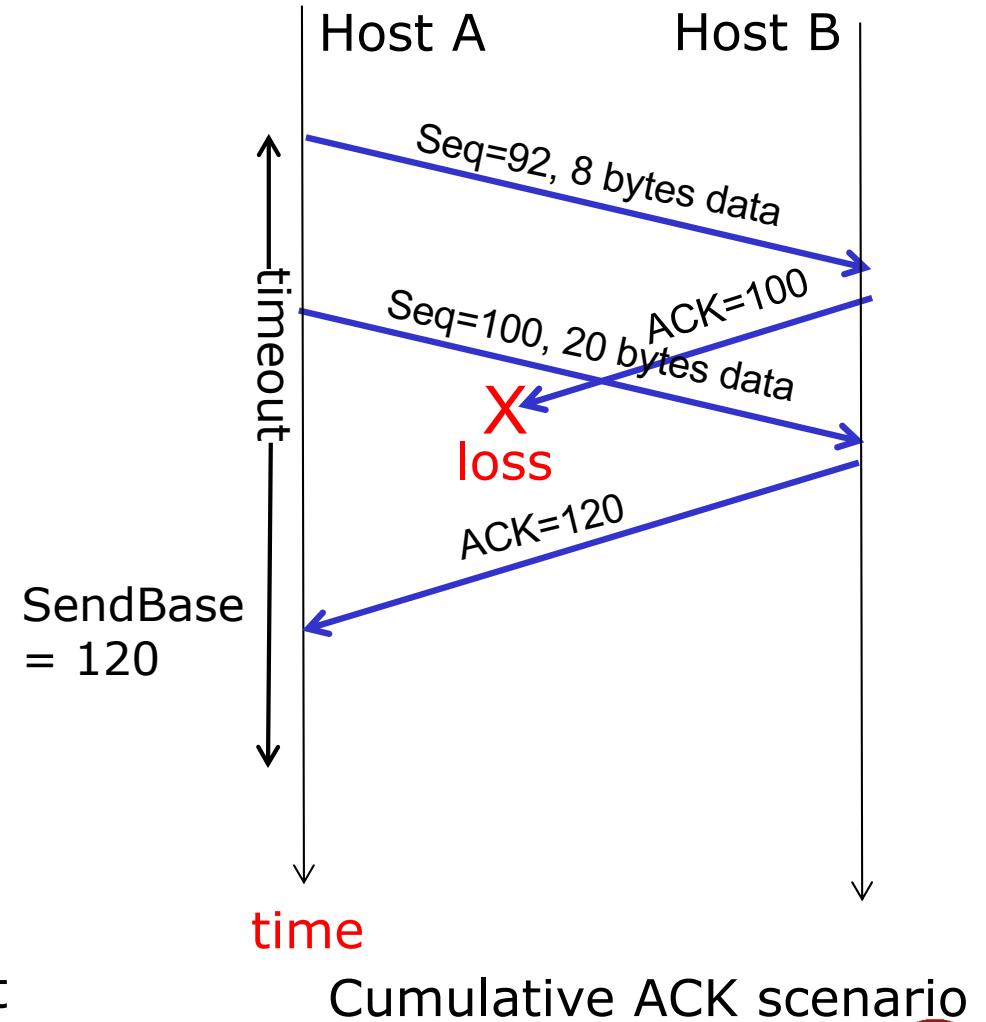
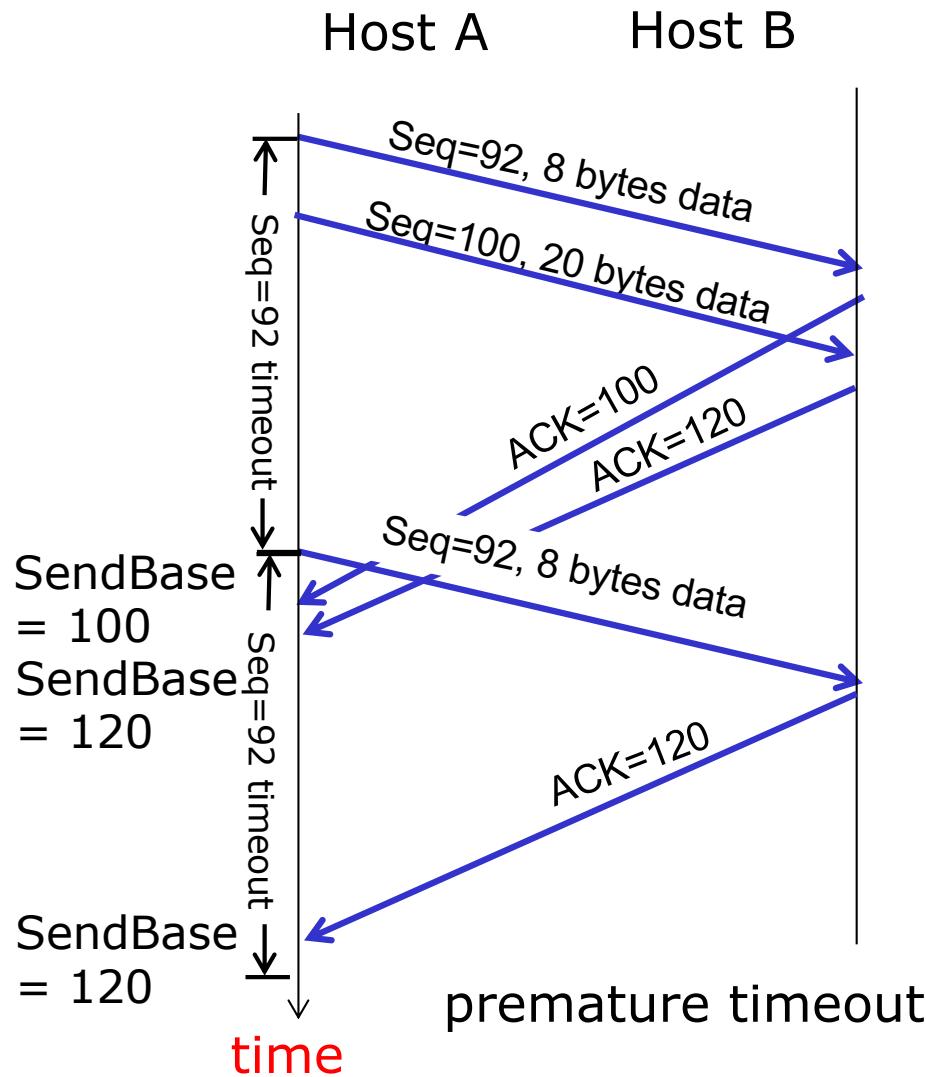


$$U_{\text{sender}} = \frac{L / R}{RTT + L / R} = \frac{.008}{30.008} = 0.00027$$



Source: Freedman (partial)

TCP Retransmission and Cumulative ACK



Source: Kurose & Ross (partial)



TCP Fast Retransmit

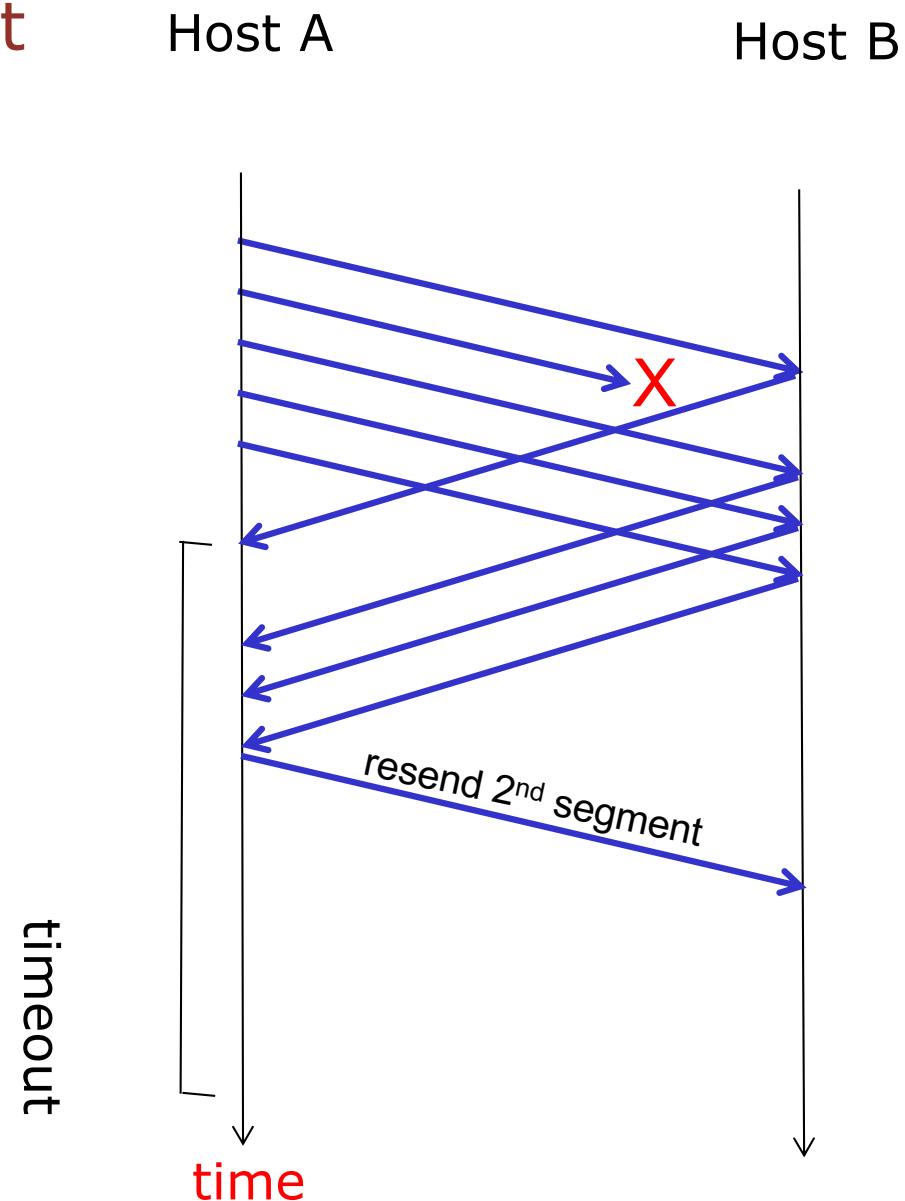
- time-out period often relatively long:
 - long delay before resending lost packet
- detect lost segments via duplicate ACKs.
 - sender often sends many segments back-to-back
 - if segment is lost, there will likely be many duplicate ACKs.
- if sender receives 3 ACKs for the same data, it supposes that segment after ACKed data was lost:
 - **fast retransmit:** resend segment before timer expires

Source: Kurose & Ross



TCP Fast Retransmit

- Resending a segment after triple duplicate ACK
- Triple duplicate ACK works as a logical **NACK**



Source: Kurose & Ross (partial)



Effectiveness of Fast Retransmit

- When does Fast Retransmit work best?
 - Long transfers: High likelihood of many pkts in flight
 - Large window: High likelihood of many packets in flight
 - Low loss burstiness: Higher likelihood that later pkts arrive
- Implications for Web traffic
 - Most Web objects are short (e.g., 10 packets)
 - So, often aren't many packets in flight
 - ... making fast retransmit less likely to "kick in"
 - ... another reason for persistent connections!

Source: Freedman



Increasing TCP throughput

- **Problem:** Stop-and-wait + timeouts are inefficient
 - Only one TCP segment “in flight” at time
 - **Solution:** Send multiple packets at once
- ✓
- **Problem:** How many w/o overwhelming receiver?
 - **Solution:** Determine “window size” dynamically

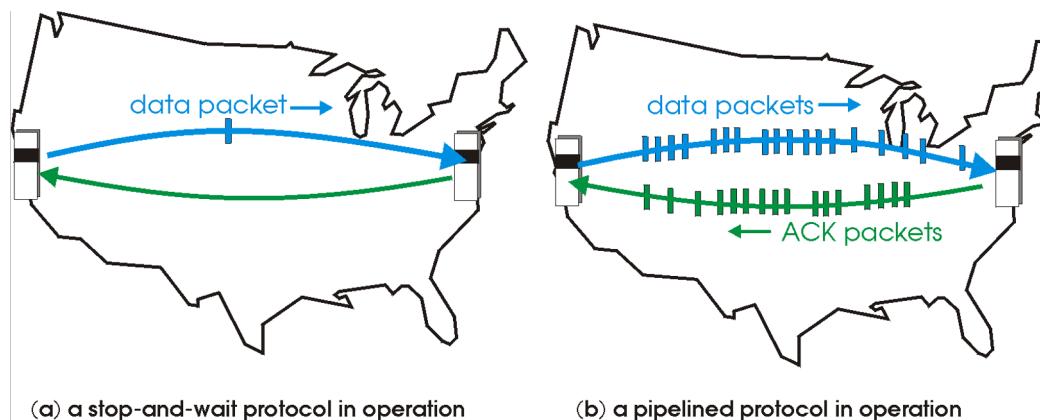


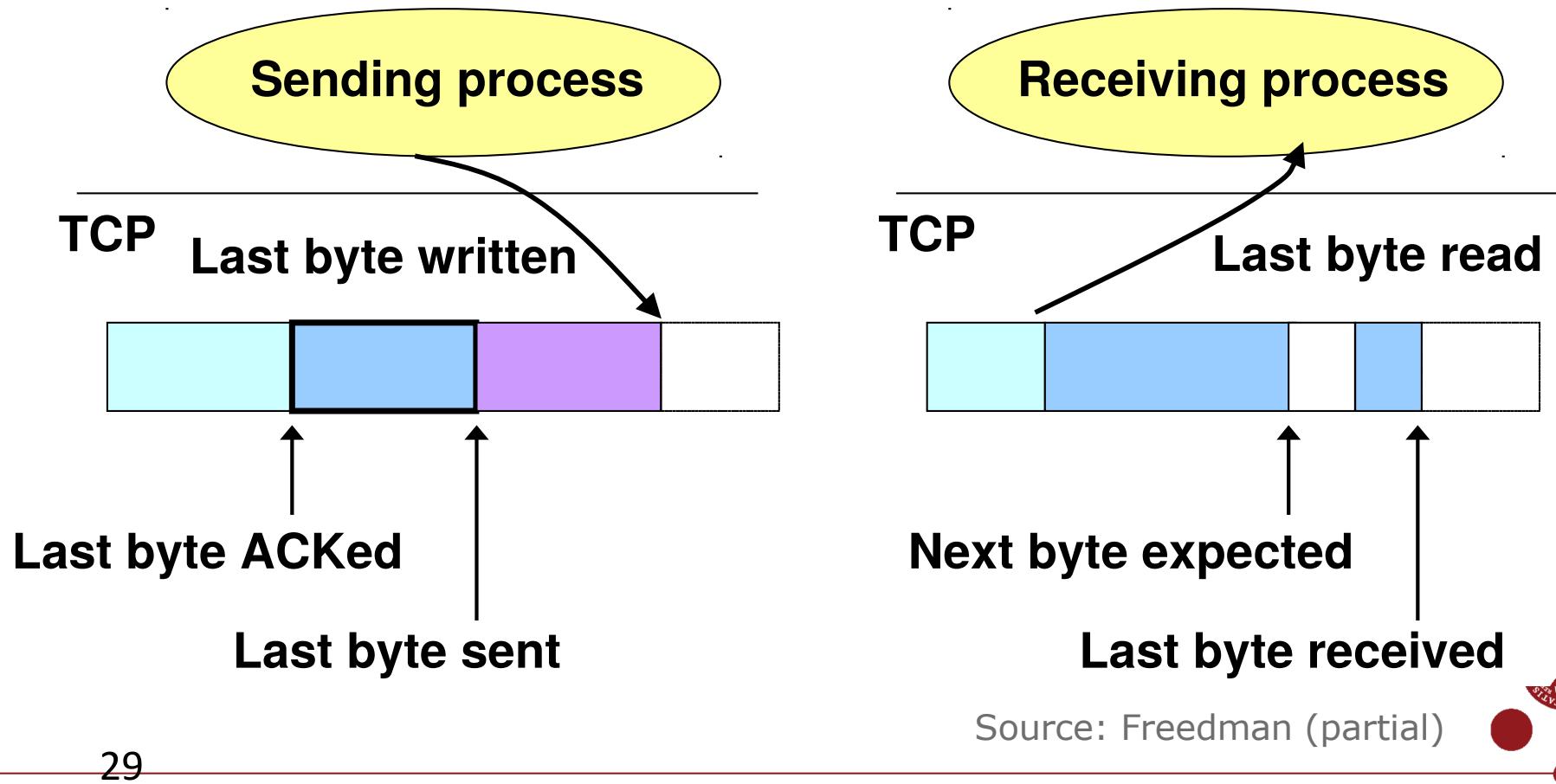
Image Source:
Kurose & Ross



Source: Freedman (partial)

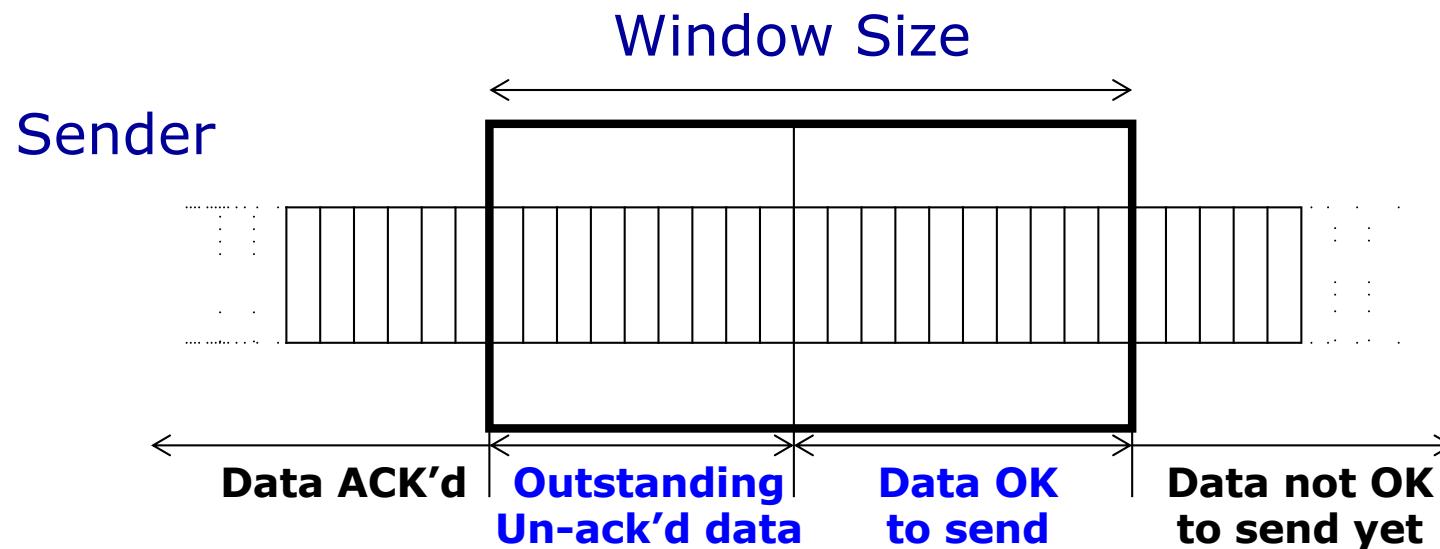
Flow Control: Sliding Window

- Allow a larger amount of data “in flight”
 - Sender can get ahead of receiver, though not *too far*



Flow Control: Receiver Buffering

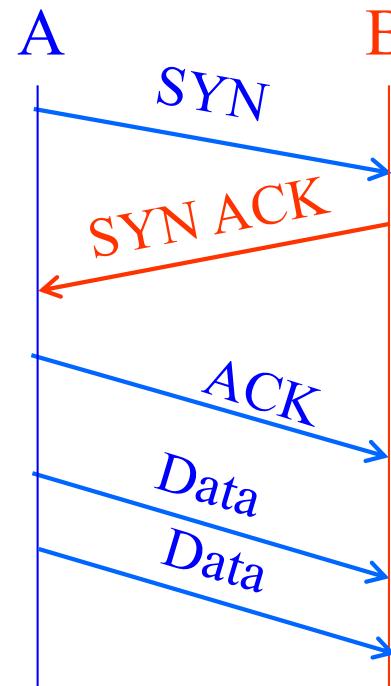
- Window size
 - Amount that can be sent w/o ACK, because receiver can buffer
- Receiver advertises window to sender
 - Tells amount of free space left (in **bytes**)
 $\text{RcvWindow} = \text{RcvBuffer} - [\text{LastByteRcvd} - \text{LastByteRead}]$
 - Sender agrees not to exceed this amount



Source: Freedman (partial)



Establishing a TCP Connection



Each host tells its ISN
to other host

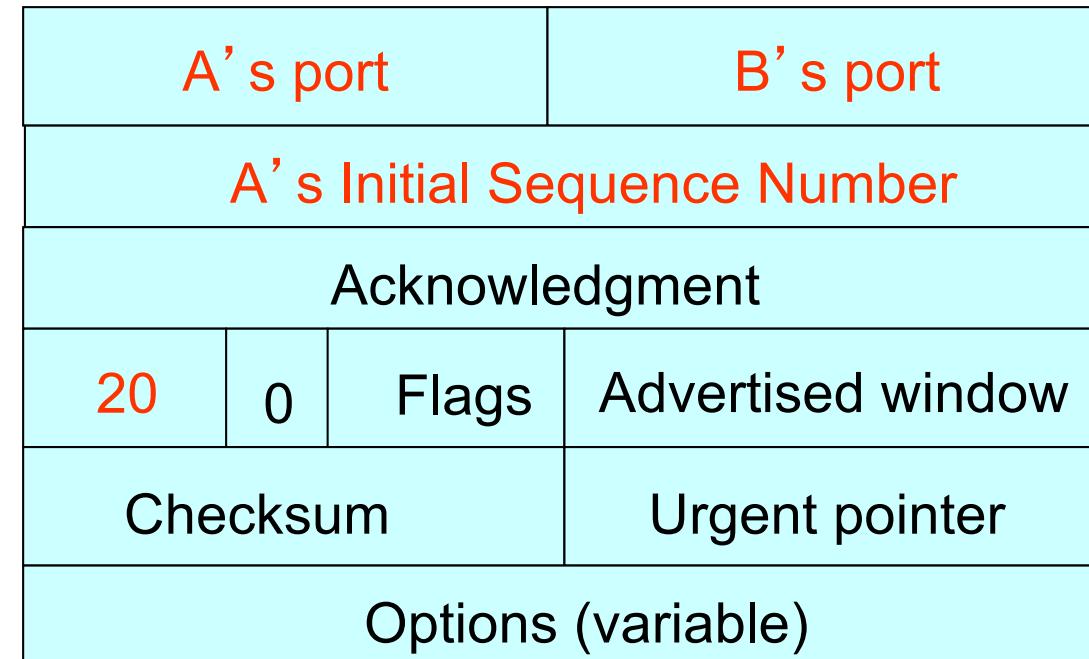
- Three-way handshake to establish connection
 - Host A sends a **SYN**chronize (open) to the host B
 - Host B returns a SYN **ACK**nowledgment (**SYN ACK**)
 - Host A sends an **ACK** to acknowledge the SYN ACK



Source: Freedman

Step 1: A's Initial SYN Packet

Flags: **SYN**
FIN
RST
PSH
URG
ACK



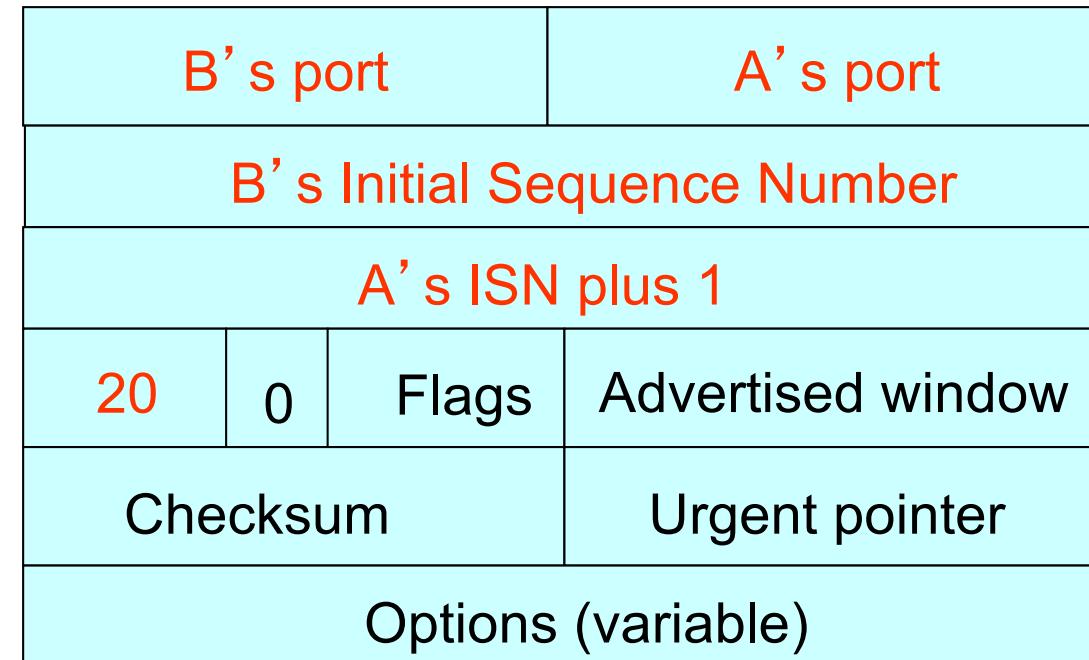
A tells B it wants to open a connection...

Source: Freedman



Step 2: B's SYN-ACK Packet

Flags: **SYN**
FIN
RST
PSH
URG
ACK



B tells A it accepts, and is ready to hear the next byte...

... upon receiving this packet, A can start sending data

Source: Freedman



Step 3: A's ACK of the SYN-ACK

Flags: SYN
FIN
RST
PSH
URG
ACK

A's port	B's port		
Sequence number			
B's ISN plus 1			
20	0	Flags	Advertised window
Checksum			
Urgent pointer			
Options (variable)			

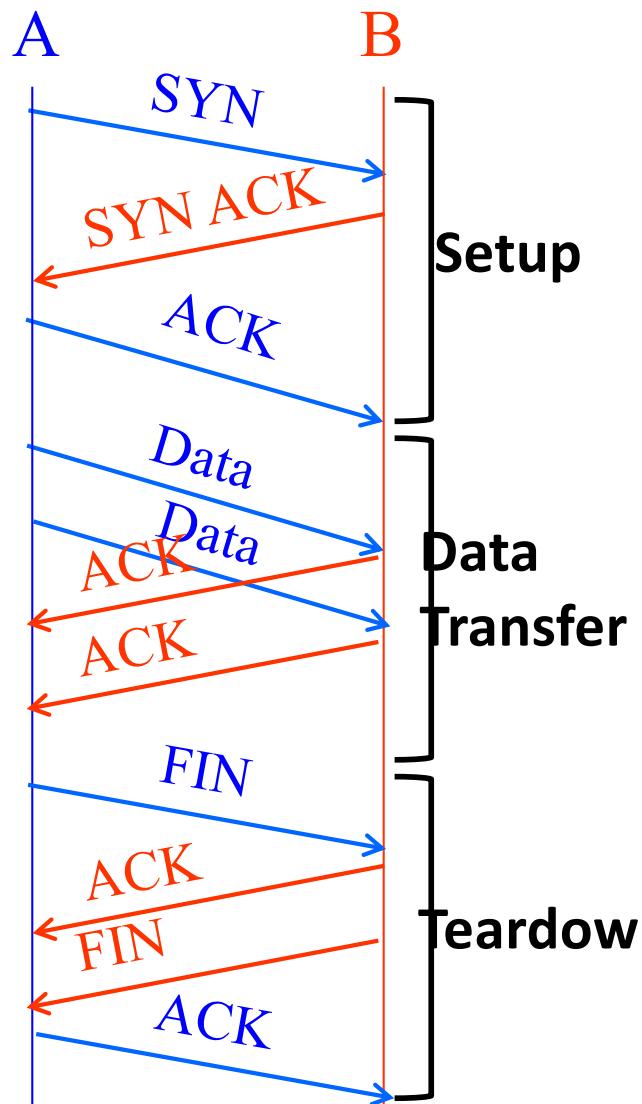
A tells B it is okay to start sending...

... upon receiving this packet, B can start sending data

Source: Freedman



Tearing Down the Connection



- **Closing a connection**
 - Process done writing: invokes `close()`
 - Once TCP sends all outstanding byte, TCP sends a FINish message
- **Receiving a FINish**
 - Process reading data from socket
 - Eventually, read attempt returns EOF
- **Tear-down is two-way**
 - FIN to close, but receive remaining
 - Other host ACKs the FIN
 - Reset (RST) to close and not receive remaining: error condition

Source: Freedman



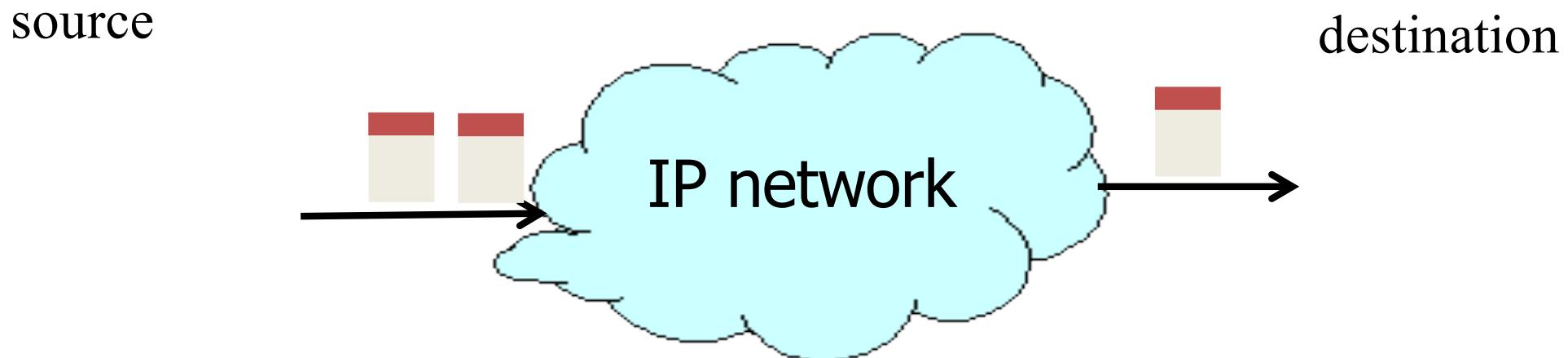
Congestion Control

- Congestion in IP networks
 - Unavoidable due to best-effort service model
 - IP philosophy: decentralized control at end hosts
- Congestion control by the TCP senders
 - Infers congestion is occurring (e.g., from packet losses)
 - Slows down to alleviate congestion, for the greater good
- TCP congestion-control algorithm
 - Additive-increase, multiplicative-decrease
 - Slow start and slow-start restart



IP Best-Effort Design Philosophy

- Best-effort delivery
 - Let everybody send
 - Network tries to deliver what it can
 - ... and just drop the rest

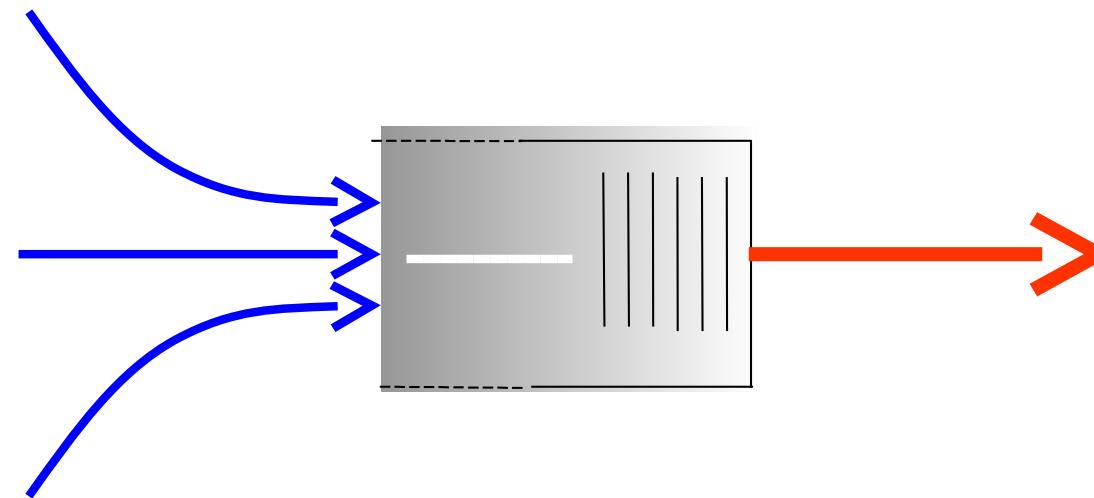


Source: Freedman



Congestion is Unavoidable

- Two packets arrive at same time
 - Router can only transmit one: must buffer or drop other
 - If many packets arrive in short period of time
- Router cannot keep up with the arriving traffic
 - Buffer may eventually overflow

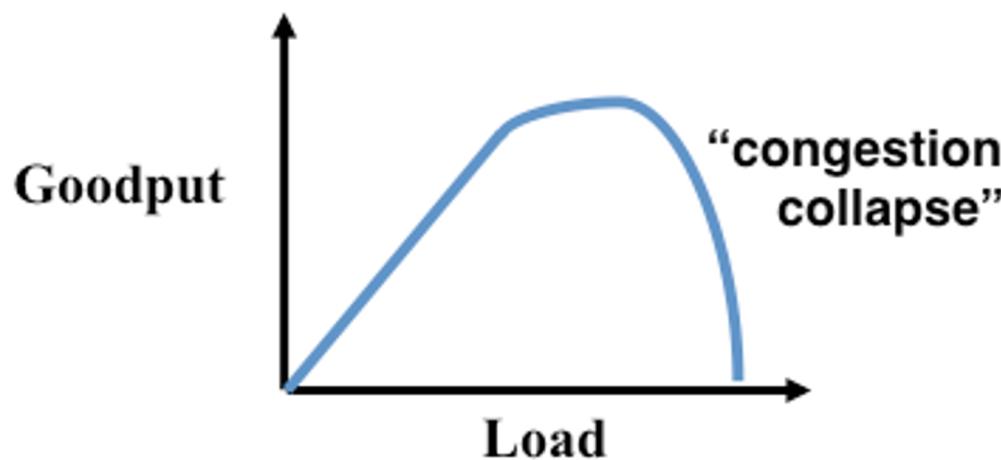


Source: Freedman



The Problem of Congestion

- What is congestion?
 - Load is higher than capacity
- What do IP routers do?
 - Drop the excess packets
- Why is this bad?
 - Wasted bandwidth for re-transmissions



Increase in load that results in a *decrease* in useful work done.



Source: Freedman

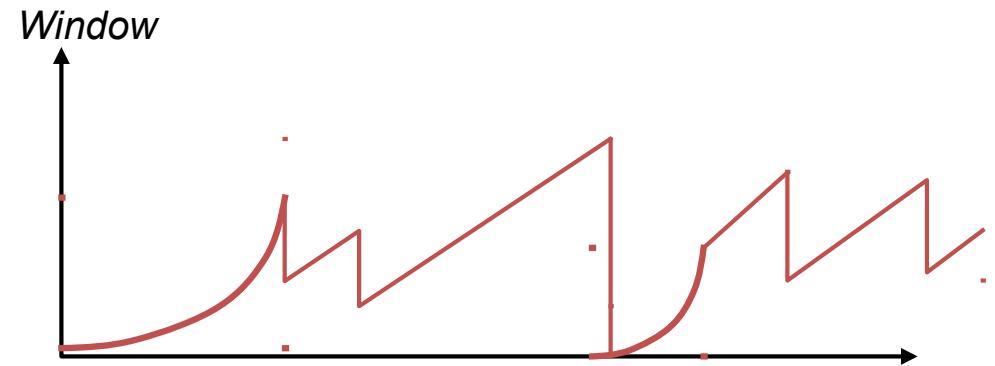
Ways to Deal With Congestion

- Ignore the problem
 - Many dropped (and retransmitted) packets
 - Can cause congestion collapse
- Reservations, like in circuit switching
 - Pre-arrange bandwidth allocations
 - Requires negotiation before sending packets
- Pricing
 - Don't drop packets for the high-bidders
 - Requires a payment model, and low-bidders still dropped
- Dynamic adjustment (TCP)
 - Every sender infers the level of congestion
 - Each adapts its sending rate “for the greater good”

Source: Freedman



Inferring From Implicit Feedback



- What does the end host see?
- What can the end host change?
- What if conditions change?
- TCP keeps congestion window, as in the graph
- Can you explain behavior? Why are there increases and drops?
- Why is there a “sawtooth”?

Source: Freedman



TCP Congestion Window

- Each TCP sender maintains a congestion window
 - Max number of bytes to have in transit (not yet ACK'd)
- Adapting the congestion window
 - Decrease upon losing a packet: backing off
 - Increase upon success: optimistically exploring
 - Always struggling to find right transfer rate
- Tradeoff
 - Pro: avoids needing explicit network feedback
 - Con: continually under- and over-shoots “right” rate

Source: Freedman



Additive Increase, Multiplicative Decrease (AIMD)

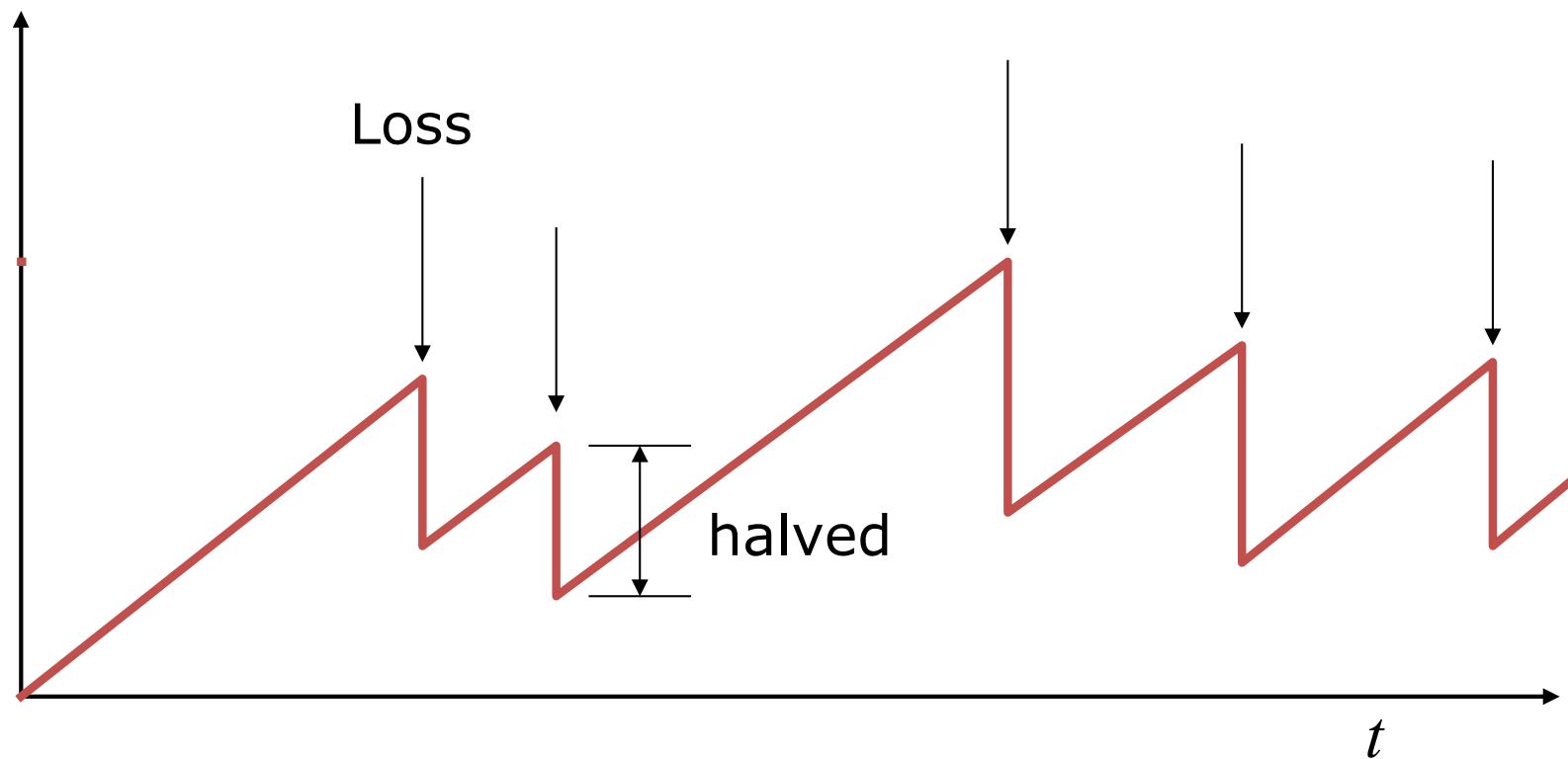
- How much to adapt?
 - **Additive increase:** On success of last window of data, increase window by 1 Max Segment Size (MSS)
 - **Multiplicative decrease:** On loss of packet, divide congestion window in half
- Much quicker to slow than speed up!
 - Over-sized windows (causing loss) are much worse than under-sized windows (causing lower throughput)
 - AIMD: A necessary condition for stability of TCP



Source: Freedman (partial)

Leads to TCP "Sawtooth"

Window



Source: Freedman



Receiver Window vs. Congestion Window

- Flow control
 - Keep a *fast sender* from overwhelming a *slow receiver*
- Congestion control
 - Keep a set of senders from overloading the *network*
- Different concepts, but similar mechanisms
 - TCP flow control: receiver window
 - TCP congestion control: congestion window
 - Sender TCP window =
 $\min \{ \text{congestion window}, \text{receiver window} \}$

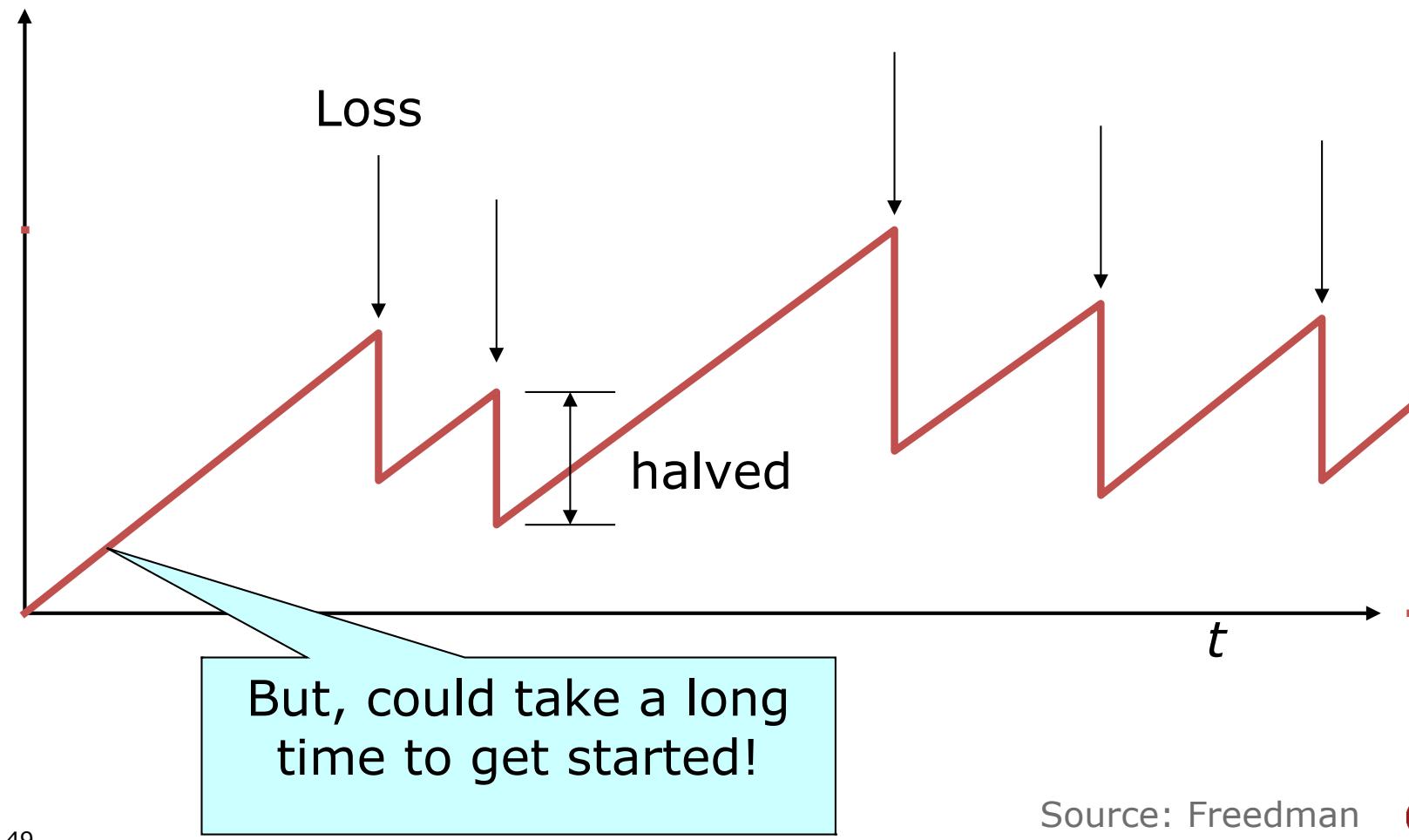
Source: Freedman



How Should a New Flow Start?

Start slow (a small CWND) to avoid overloading network

Window



“Slow Start” Phase

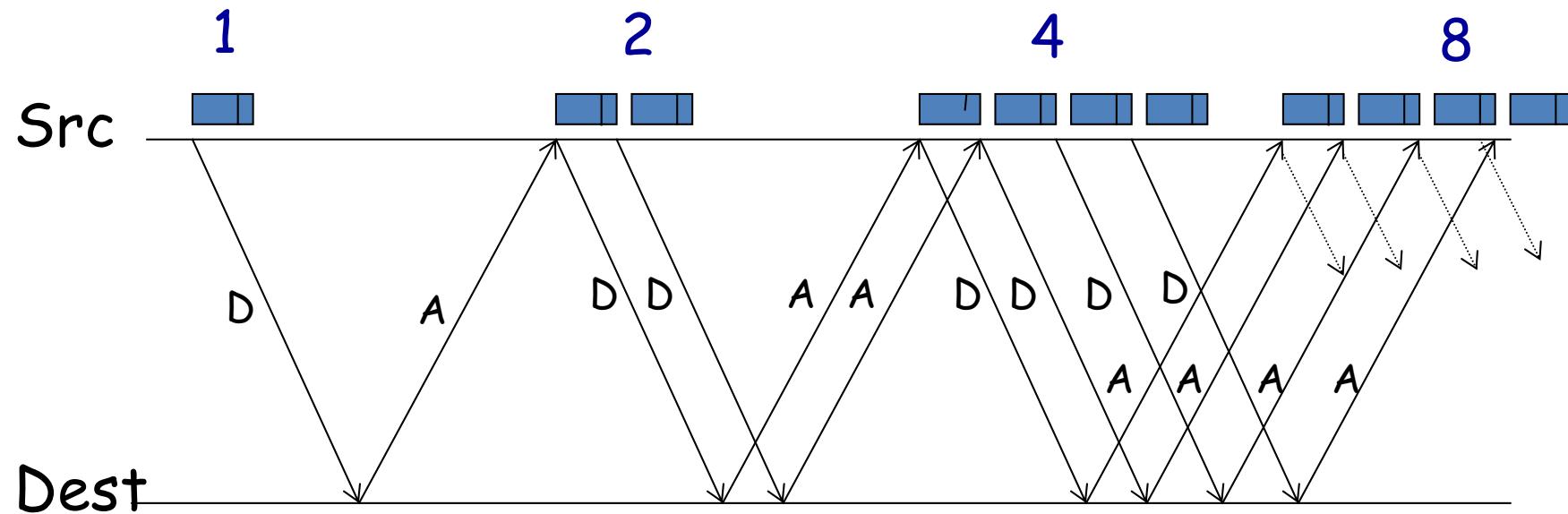
- Start with a small congestion window
 - Initially, CWND is 1 MSS
 - So, initial sending rate is MSS / RTT
- Could be pretty wasteful
 - Might be much less than actual bandwidth
 - Linear increase takes a long time to accelerate
- Slow-start phase (really “fast start”)
 - Sender starts at a slow rate (hence the name)
 - ... but increases rate exponentially until the first loss

Source: Freedman



Slow Start in Action

Double CWND per round-trip time

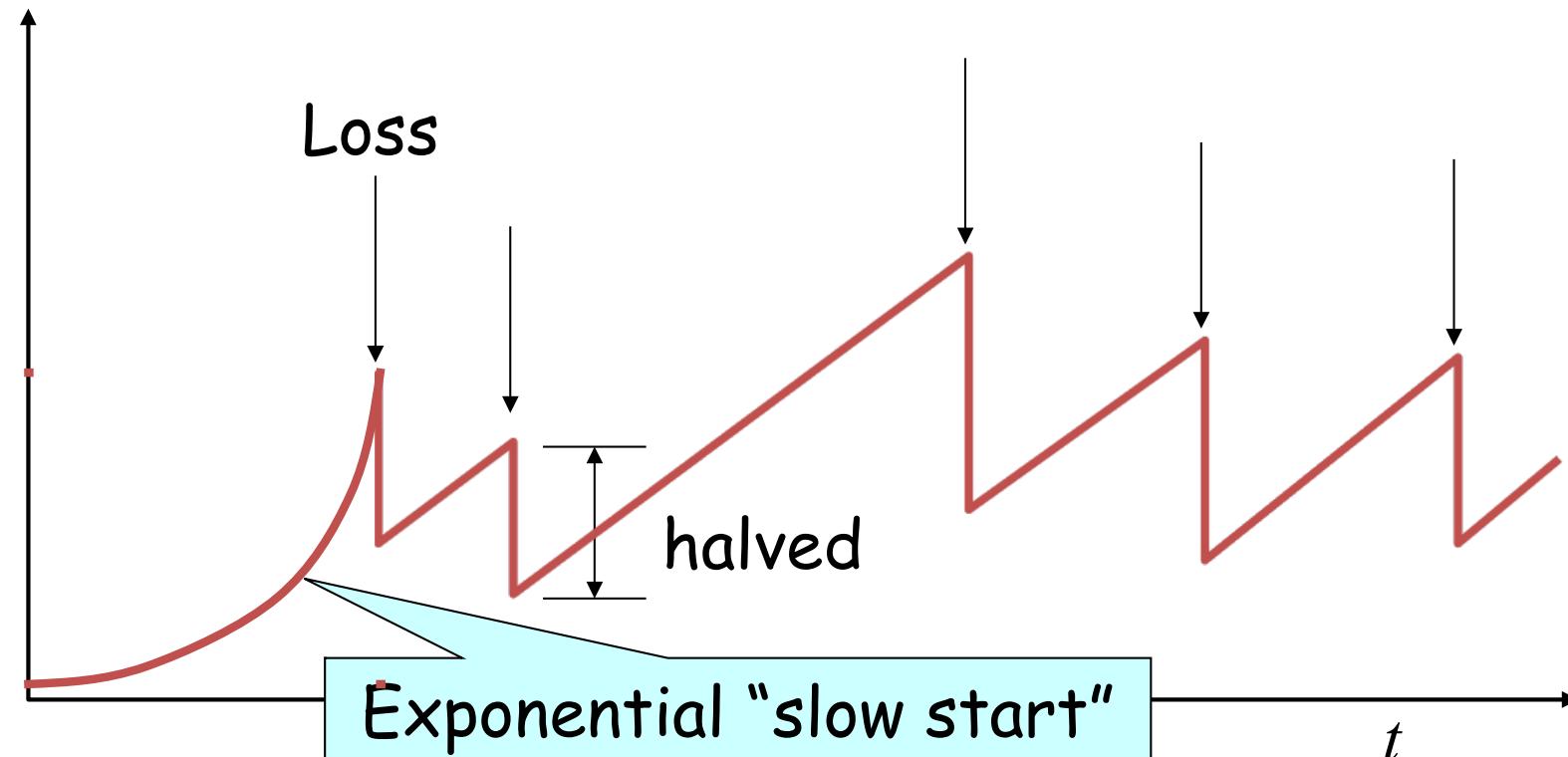


Source: Freedman



Slow Start and the TCP Sawtooth

Window



- So-called because TCP originally had no congestion control
 - Source would start by sending an entire receiver window
 - Led to congestion collapse!

Source: Freedman



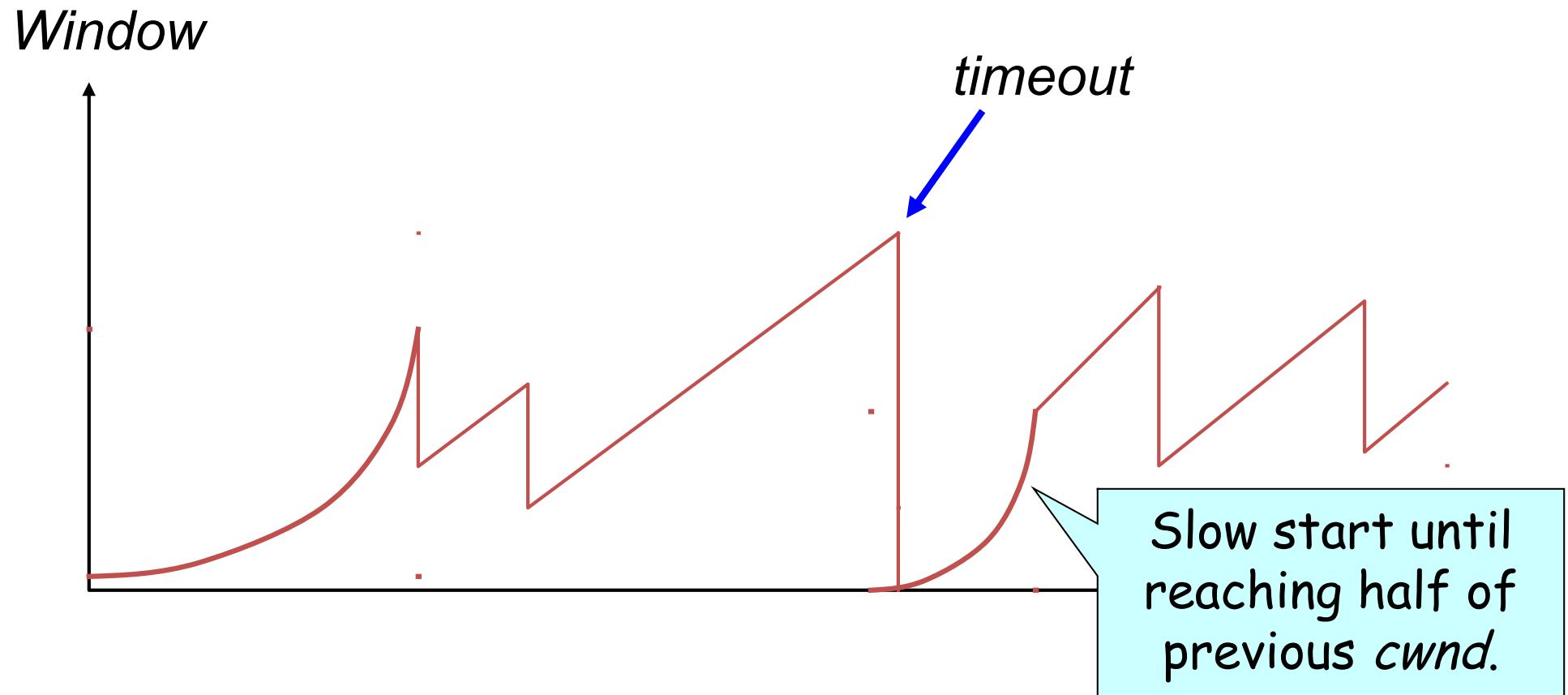
Two Kinds of Loss in TCP

- Timeout
 - Packet n is lost and detected via a timeout
 - When? n is last packet in window, or all packets in flight lost
 - After timeout, blasting entire CWND would cause another burst
 - Better to start over with a low CWND
- Triple duplicate ACK
 - Packet n is lost, but packets n+1, n+2, etc. arrive
 - How detected? Multiple ACKs that receiver waiting for n
 - When? Later packets after n received
 - After triple duplicate ACK, sender quickly resends packet n
 - Do a multiplicative decrease and keep

Source: Freedman



Repeating Slow Start After Timeout



Slow-start restart: Go back to CWND of 1, but take advantage of knowing the previous value of CWND.

Source: Freedman



Repeating Slow Start After Idle Period

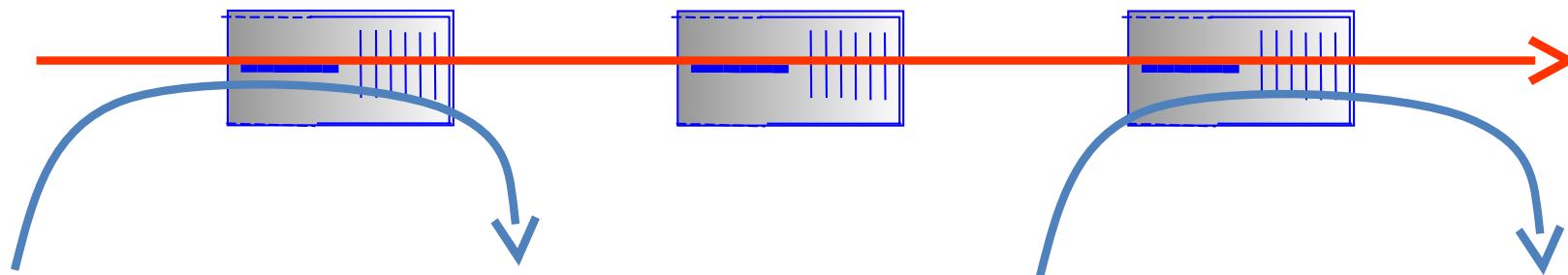
- Suppose a TCP connection goes idle for a while
- Eventually, the network conditions change
 - Maybe many more flows are traversing the link
- Dangerous to start transmitting at the old rate
 - Previously-idle TCP sender might blast network
 - ... causing excessive congestion and packet loss
- So, some TCP implementations repeat slow start
 - Slow-start restart after an idle period

Source: Freedman



TCP Achieves Some Notion of Fairness

- Effective utilization is not only goal
 - We also want to be *fair* to various flows
 - ... but what does *that* mean?
- Simple definition: equal shares of the bandwidth
 - N flows that each get $1/N$ of the bandwidth?
 - But, what if flows traverse different paths?
 - Result: bandwidth shared in proportion to RTT



Source: Freedman



What About Cheating?

- Some folks are more fair than others
 - Running multiple TCP connections in parallel (BitTorrent)
 - Modifying the TCP implementation in the OS
 - Some cloud services start TCP at > 1 MSS
 - Use the User Datagram Protocol
- What is the impact
 - Good guys slow down to make room for you
 - You get an unfair share of the bandwidth
- Possible solutions?
 - Routers detect cheating and drop excess packets?
 - Per user/customer fairness?
 - Peer pressure?

Source: Freedman



Summary

- UDP
 - basic multiplexing, checksums
- TCP & reliable transfer
 - Segments, sequence numbers, automatic repeat requests
 - Timeout estimation
 - Pipelining, cumulative ACK, fast retransmit
 - Flow control: receiver window
 - Congestion control: congestion window, AIMD, slow start, slow start restart

