EECS 489

Computer Networks

Transport Control Protocol - TCP

Material with thanks to Aditya Akella, Sugih Jamin, Philip Levis, Sylvia Ratnasamy, Peter Steenkiste, and many other colleagues.

Agenda

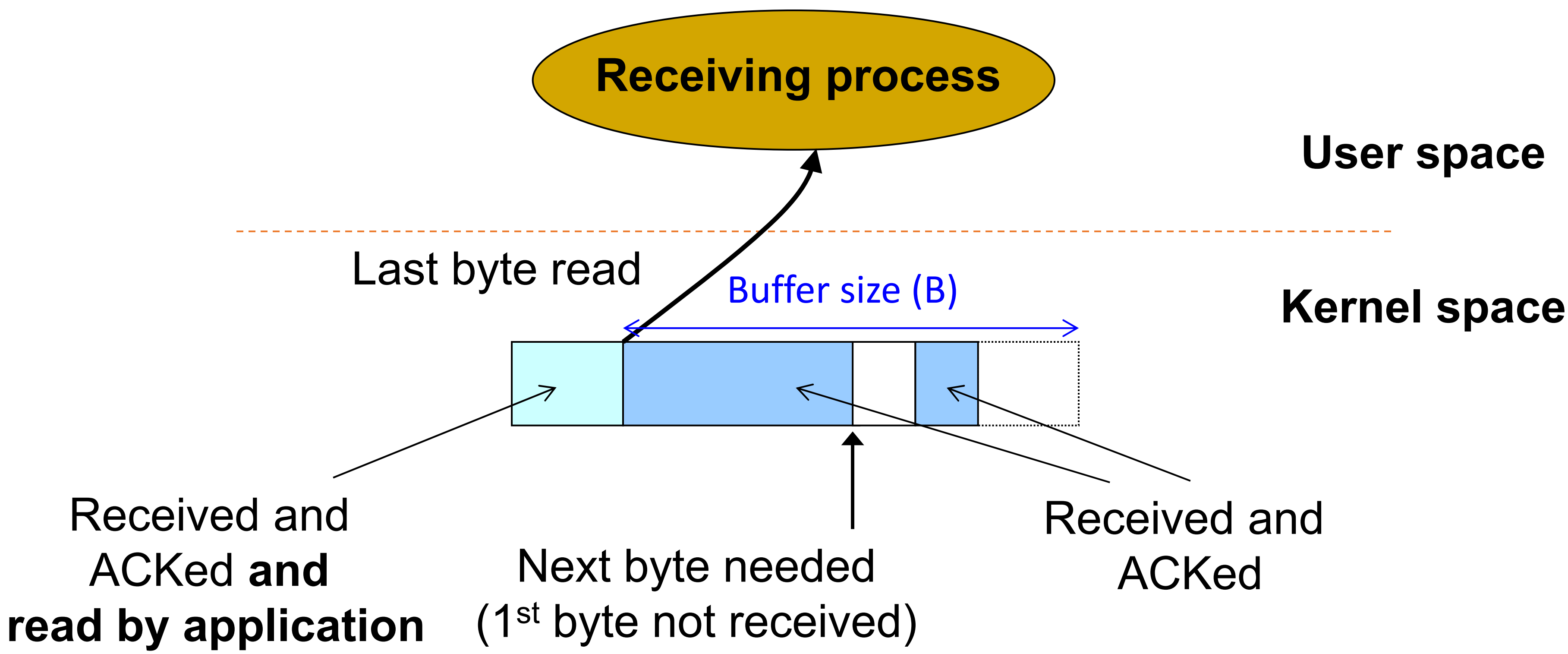
- From reliable data transfer to TCP
- TCP connection setup and teardown

Recap: Designing a reliable transport protocol

- Stop and Wait vs Sliding Window

- Sliding Window
  - Acknowledgements: Cumulative vs Selective
  - Resending packets: Go-Back-N vs Selective Repeat

Sliding window at receiver



TCP: Transmission Control Protocol

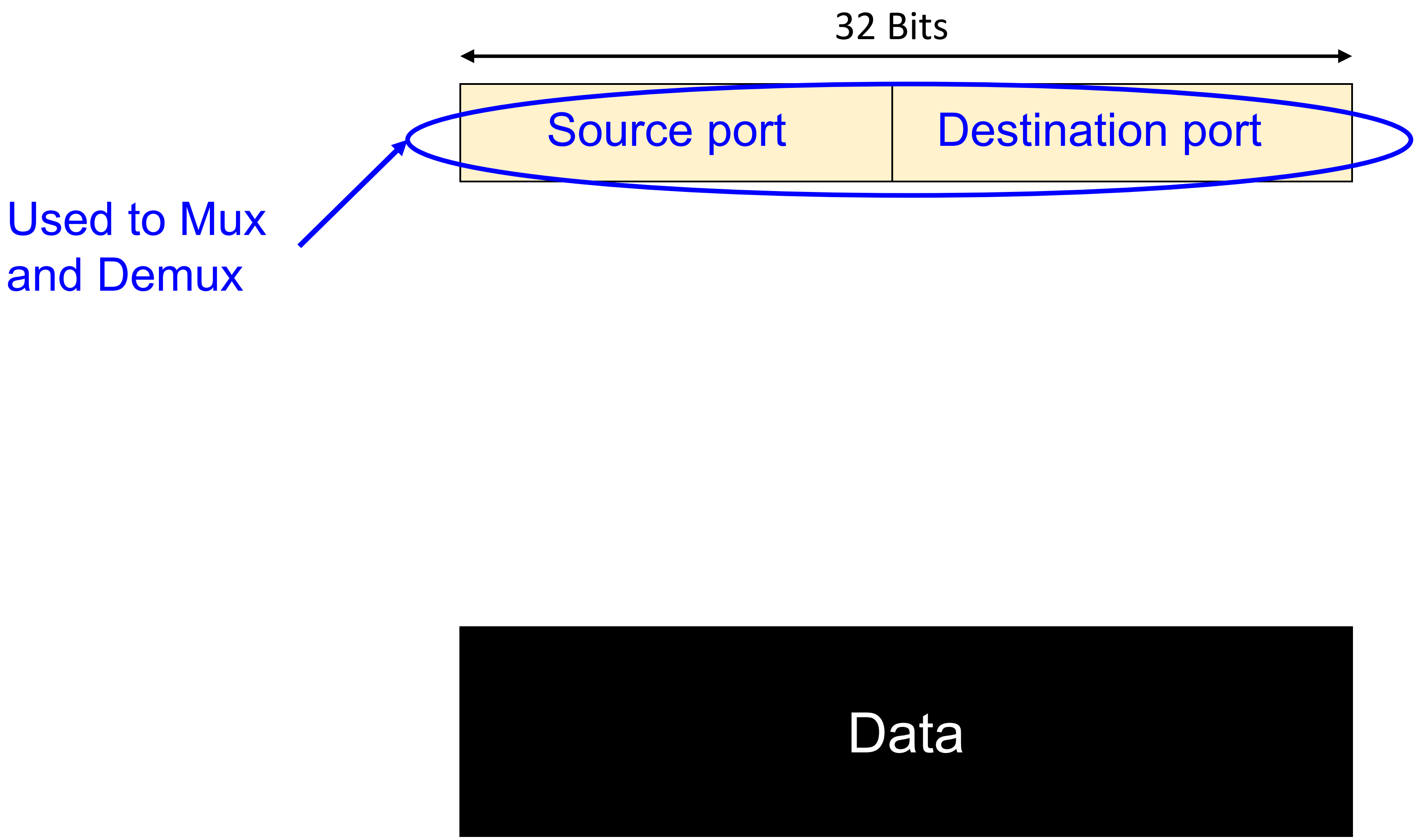
The TCP Abstraction

- TCP delivers a reliable, in-order, byte stream
- Reliable: TCP resends lost packets
  - Until it gives up and shuts down connection
- In-order: TCP only hands consecutive chunks of data to application
- Byte stream: TCP assumes there is an incoming stream of data, and attempts to deliver it to app

What does TCP use from what we've seen so far?

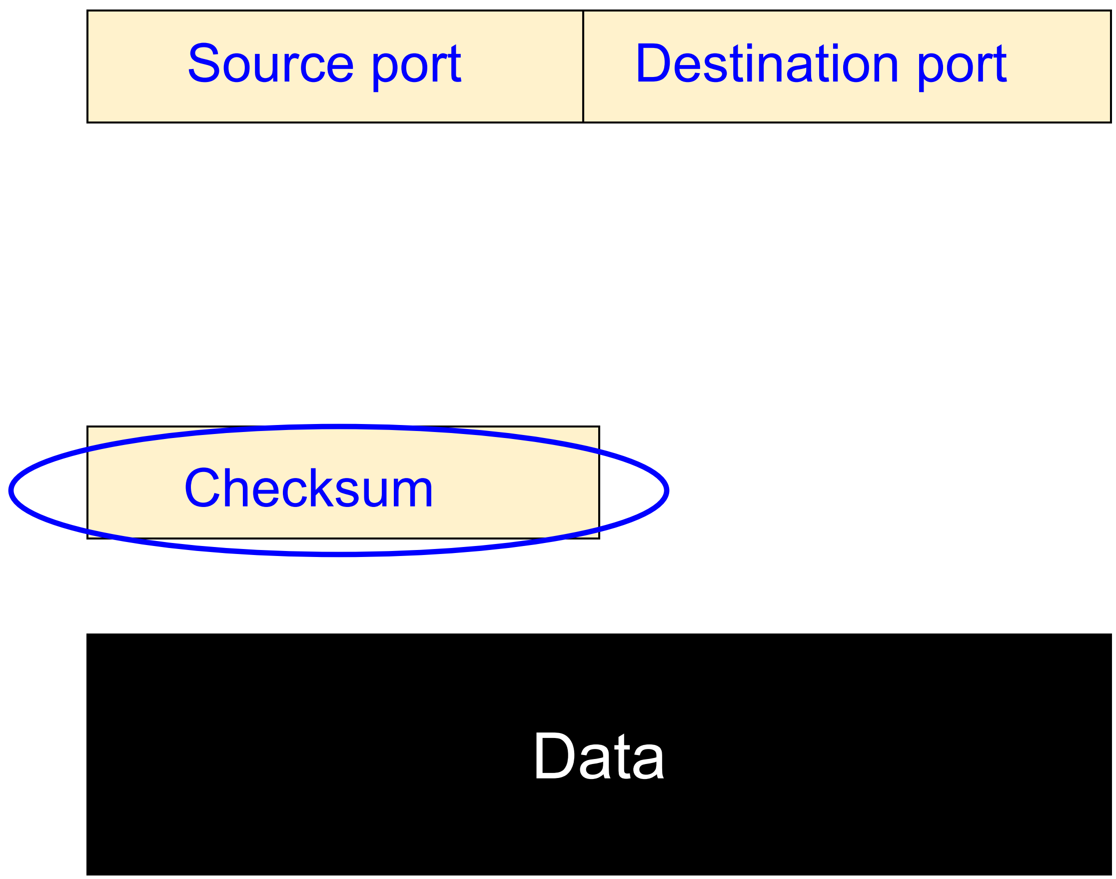
- Most of what we've seen
  - Checksums
  - Sequence numbers are byte offsets
  - Sender and receiver maintain a sliding window
  - Receiver sends cumulative acknowledgements (like GBN)
    - Sender maintains a single retransmission timer
  - Receivers buffer out-of-sequence packets (like SR)
- Few more: fast retransmit, timeout estimation algorithms etc.

Build the TCP header



Build the TCP header

Computed over pseudo-header and data

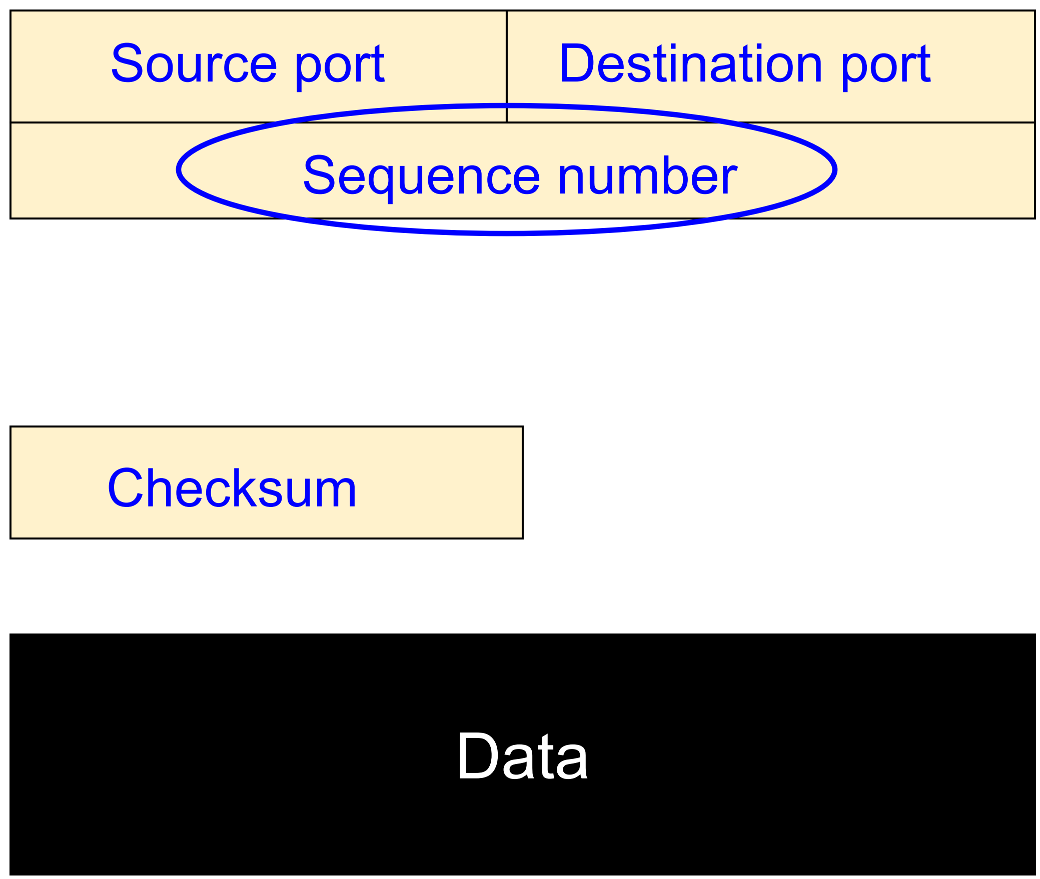


What does TCP do?

- Most of what we've seen
  - Checksum
  - Sequence numbers are byte offsets

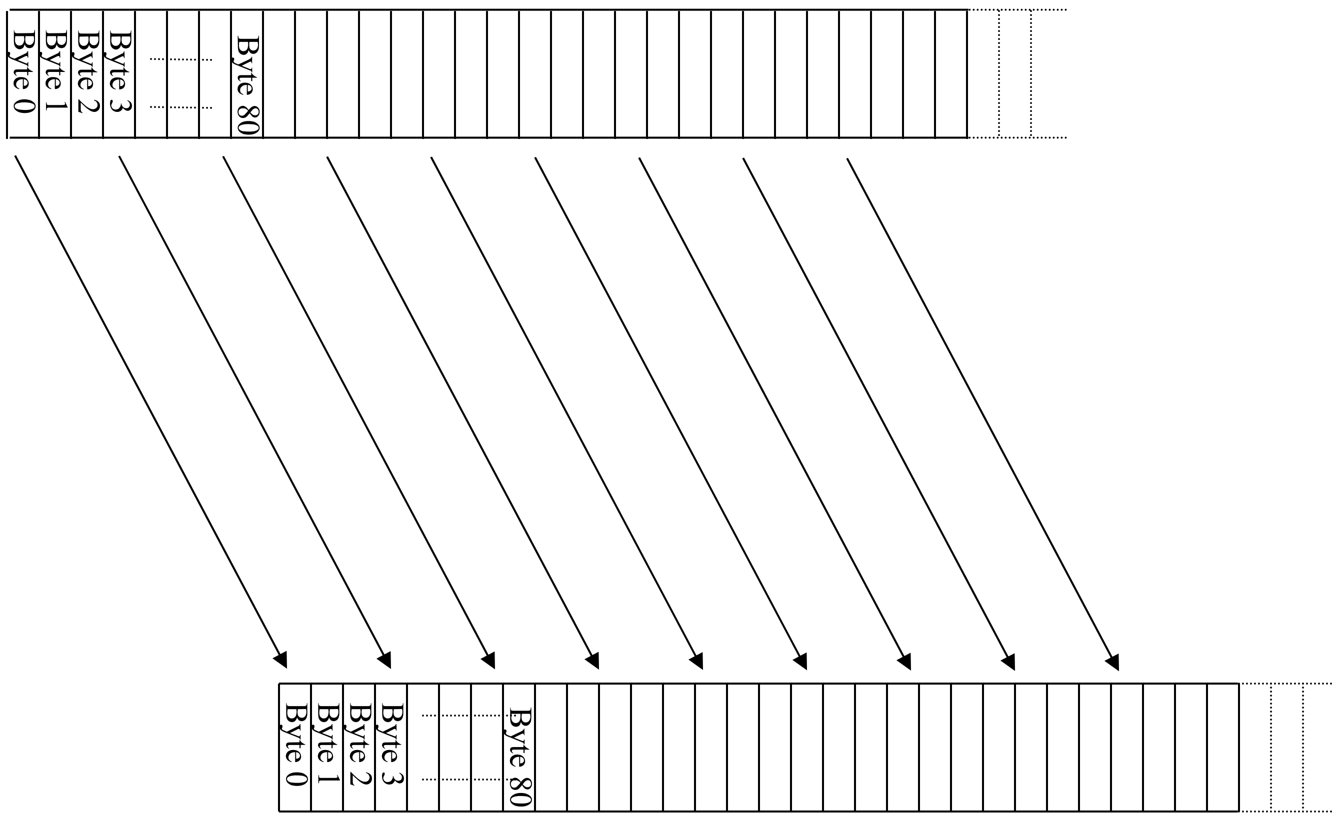
Build the TCP header

Byte offsets
(NOT packet id),
because TCP is a
byte stream



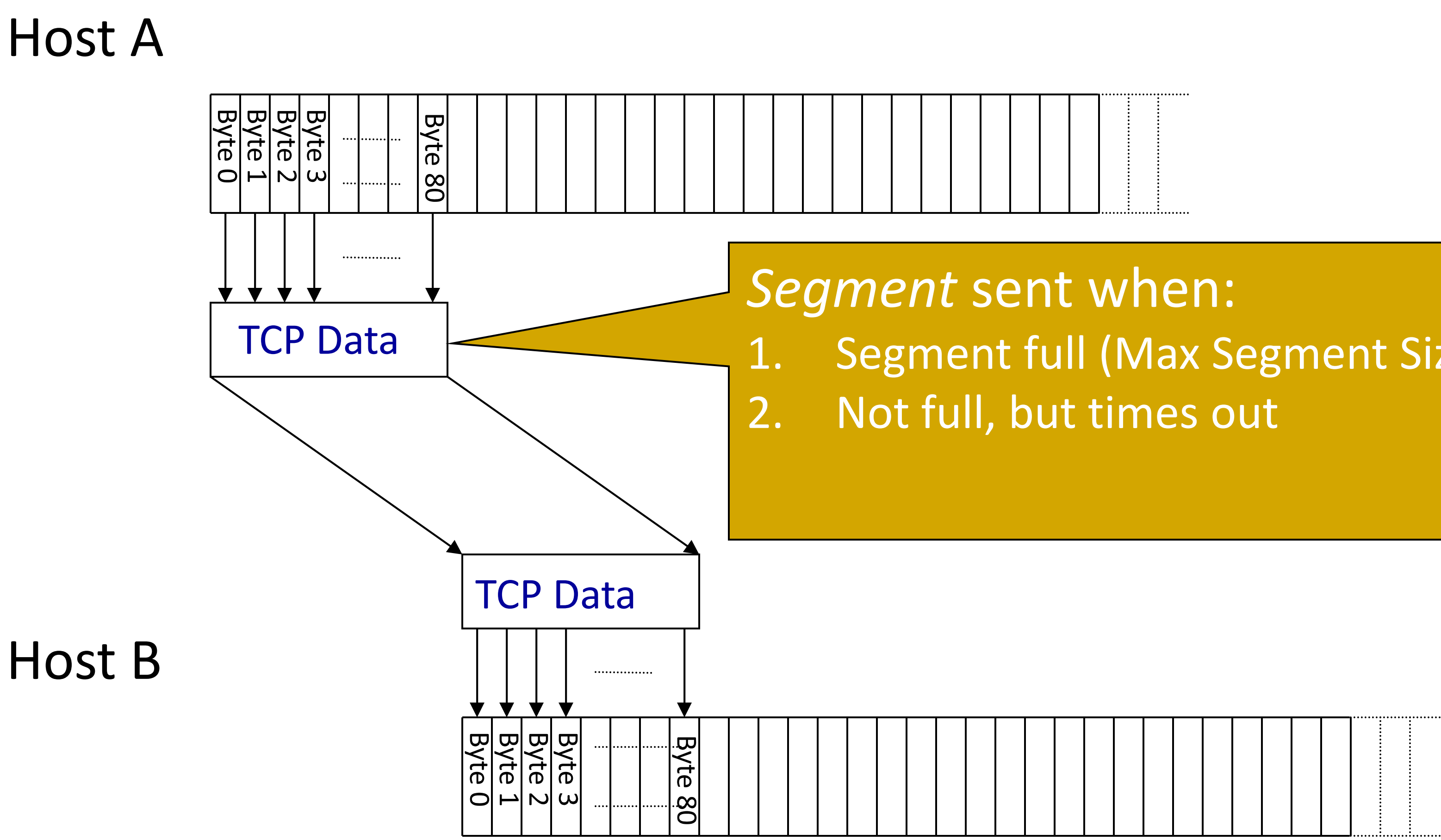
TCP "stream of bytes" service…

Application @ Host A



Application @ Host B

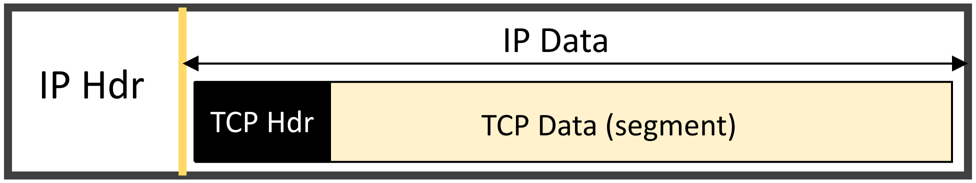
… provided using TCP "segments"



Segment sent when:

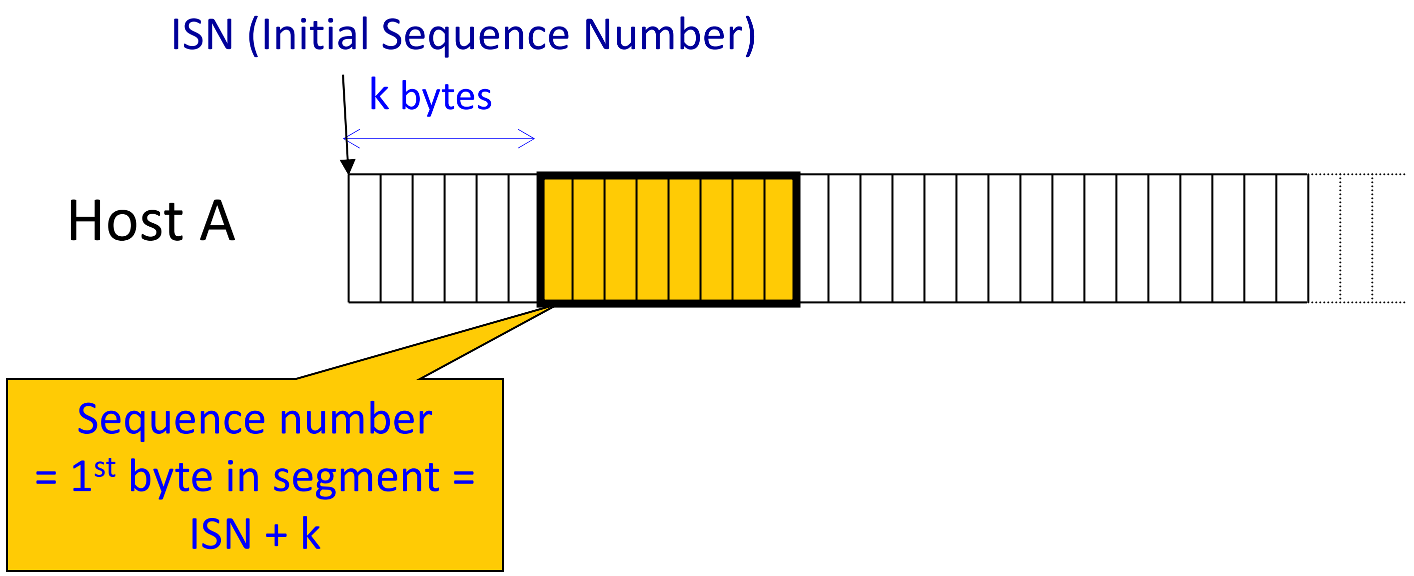
1. Segment full (Max Segment Size),
2. Not full, but times out

TCP segment

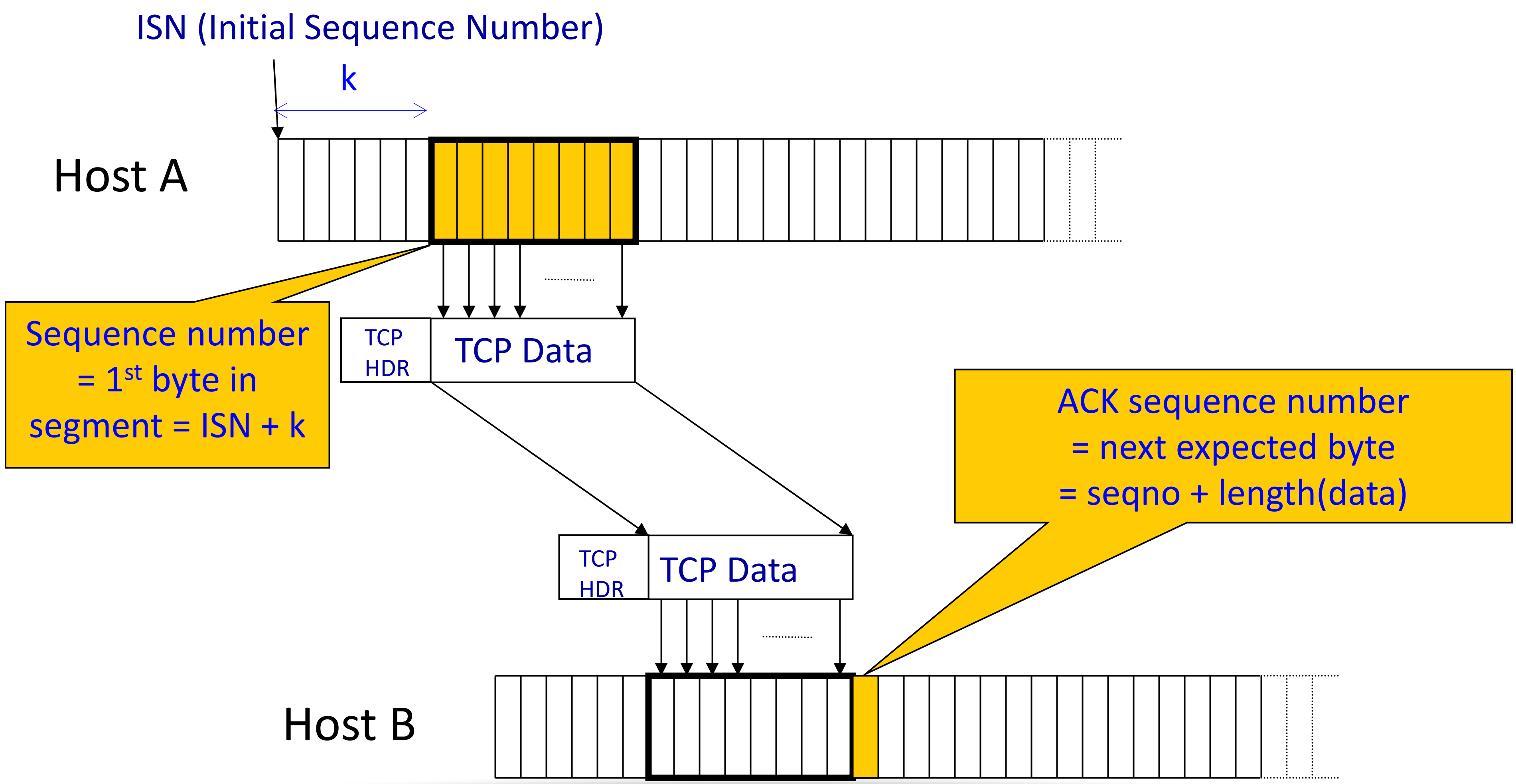


- IP packet
  - No bigger than Maximum Transmission Unit (MTU)
  - E.g., up to 1500 bytes with Ethernet, 9K for high-speed Ethernet
- TCP packet
  - IP packet with a TCP header and data inside
  - TCP header ≥ 20 bytes long
- TCP segment
  - No more than Maximum Segment Size (MSS) bytes
  - E.g., up to 1460 consecutive bytes from the stream
  - MSS = MTU – (IP header) – (TCP header)

Sequence numbers

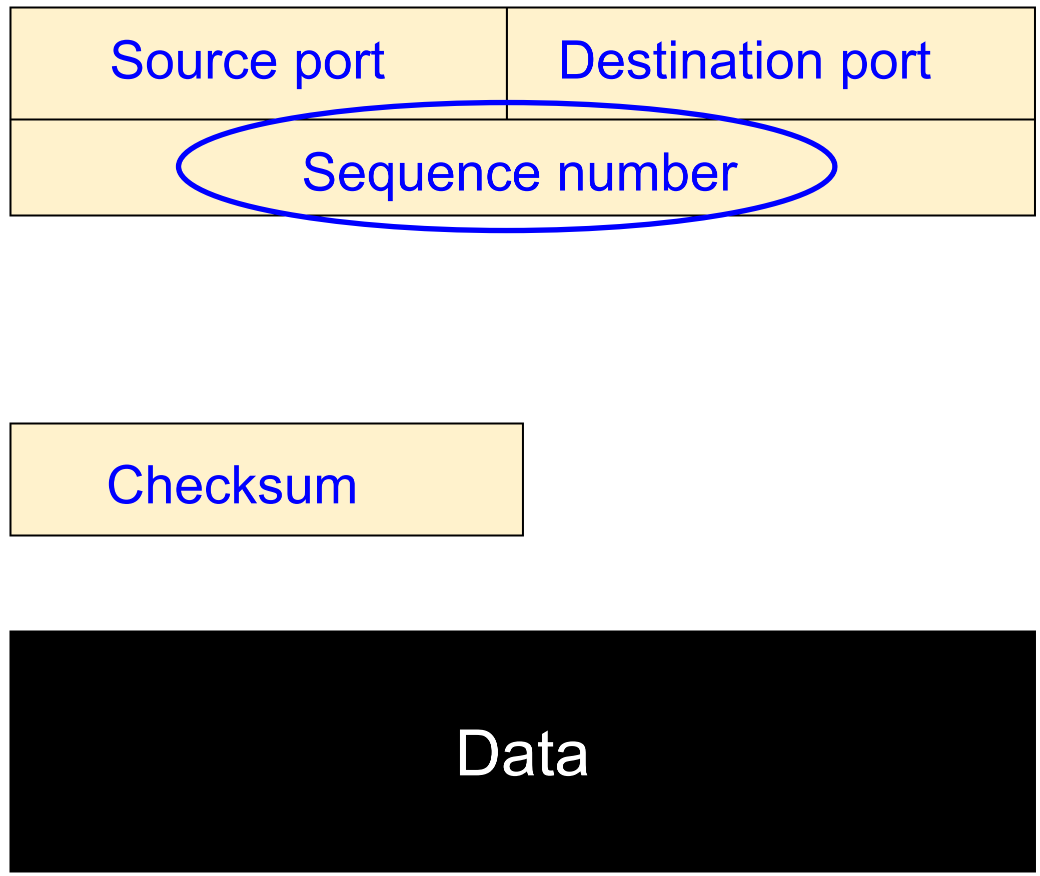


Sequence numbers



Build the TCP header

Starting byte offset of data carried in this segment



What does TCP do?

- Most of what we've seen
  - Checksum
  - Sequence numbers are byte offsets
  - Receiver sends cumulative acknowledgements (like GBN)

ACKs and sequence numbers

- Sender sends packet
  - Data starts with sequence number X
  - Packet contains B bytes [X, X+1, X+2, ….X+B-1]
- Upon receipt of packet, receiver sends an ACK
  - If all data prior to X already received:
    - ACK acknowledges X+B (because that is next expected byte)
  - If highest in-order byte received is Y s.t. (Y+1) < X
    - ACK acknowledges Y+1
    - Even if this has been ACKed before

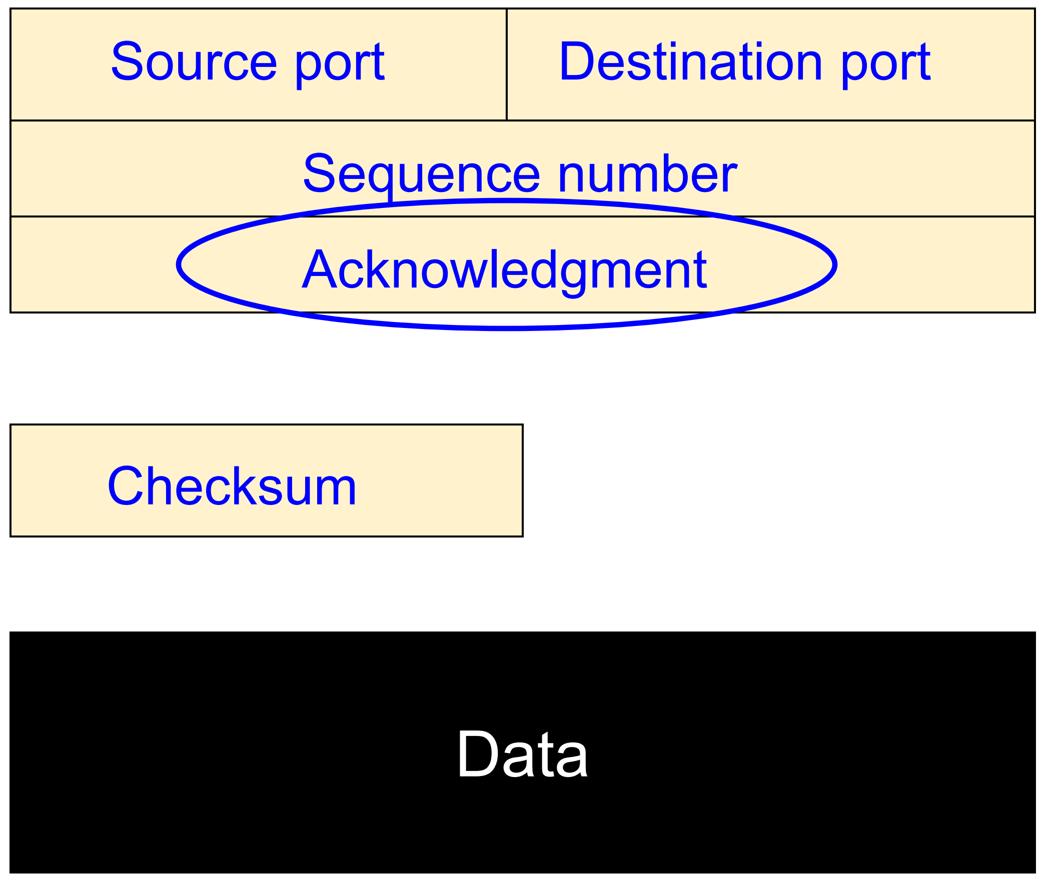
Typical operation

- Sender: seqno=X, length=B
- Receiver: ACK=X+B
- Sender: seqno=X+B, length=B
- Receiver: ACK=X+2B
- Sender: seqno=X+2B, length=B

- Seqno of next packet is same as last ACK field

Build the TCP header

Acknowledgment gives seqno just beyond highest seqno received **in order**



What does TCP do?

- Most of what we've seen
  - Checksum
  - Sequence numbers are byte offsets
  - Receiver sends cumulative acknowledgements (like GBN)
  - Receivers can buffer out-of-sequence packets (like SR)

Loss with cumulative ACKs

- Sender sends packets with 100B and seqnos.:
  - 100, 200, 300, 400, 500, 600, 700, 800, …
- Assume the fifth packet (seqno 500) is lost, but no others
- Stream of ACKs will be:
  - 200, 300, 400, 500, 500, 500, 500,…

What does TCP introduce?

- Most of what we've seen
  - Checksum
  - Sequence numbers are byte offsets
  - Receiver sends cumulative acknowledgements (like GBN)
  - Receivers can buffer out-of-sequence packets (like SR)
- Introduces fast retransmit: duplicate ACKs trigger early retransmission

Loss with cumulative ACKs

- Duplicate ACKs are a sign of an isolated loss
  - The lack of ACK progress means 500 hasn't been delivered
  - Stream of ACKs means some packets are being delivered
- Trigger retransmission upon receiving k duplicate ACKs
  - TCP uses k=3
  - Faster than waiting for timeout

Loss with cumulative ACKs

- Two choices after resending
  - Send missing packet and move sliding window by the number of dup ACKs
    - Speeds up transmission, but might be wrong
  - Send missing packet, and wait for ACK to move sliding window
    - Is slowed down by single dropped packets
- Which should TCP do?
  - Choose correctness

Announcements

- Assignment 2 is posted!

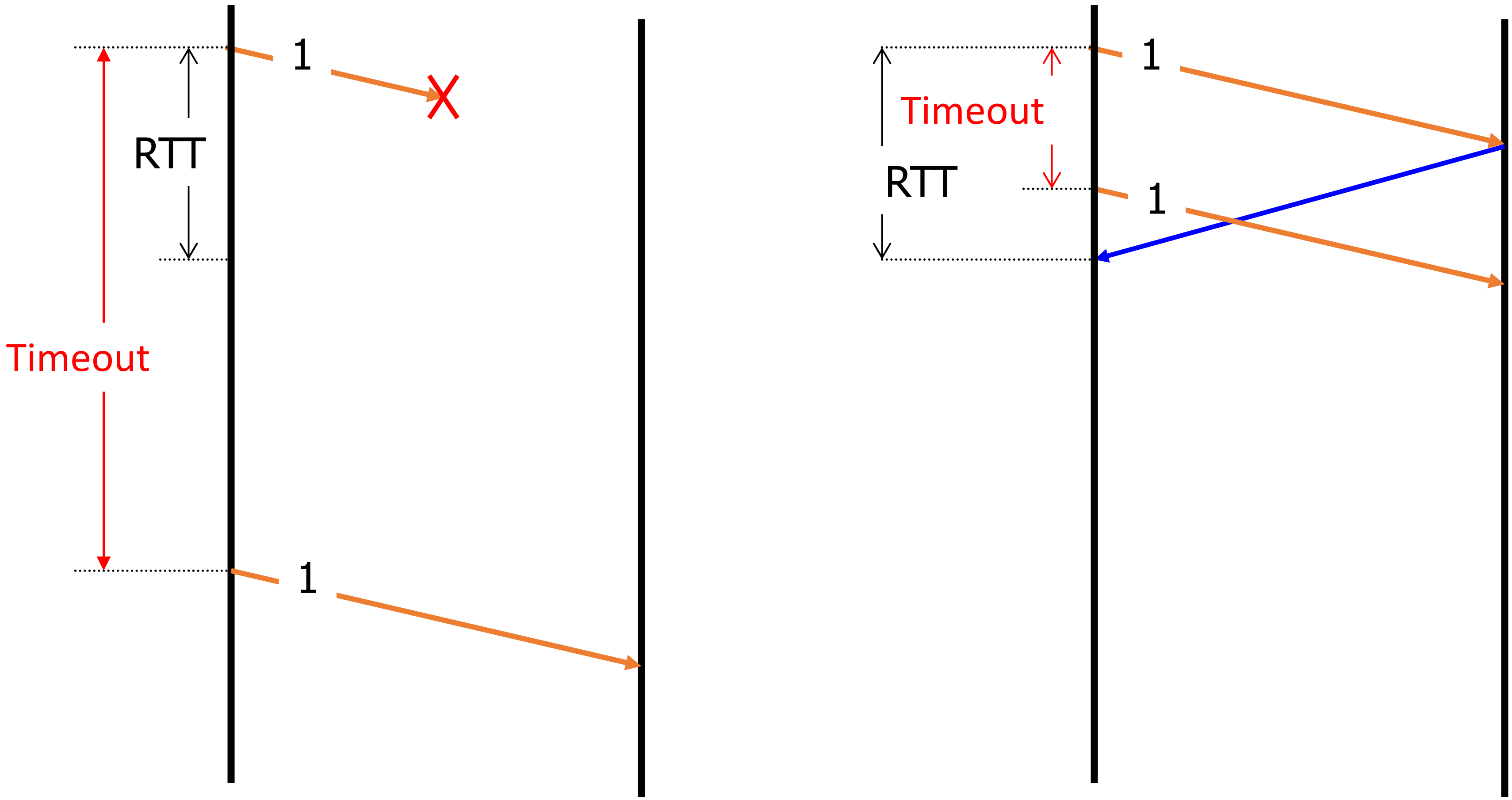
What does TCP introduce?

- Most of what we've seen
  - Checksum
  - Sequence numbers are byte offsets
  - Receiver sends cumulative acknowledgements (like GBN)
  - Receivers buffer out-of-sequence packets (like SR)
- Introduces fast retransmit: duplicate ACKs trigger early retransmission
- Sender maintains a single retransmission timer (like GBN) and retransmits on timeout

Retransmission timeout

- If the sender hasn't received an ACK by timeout, retransmit the first packet in the window
- How do we pick a timeout value?

Timing illustration



Timeout too long → inefficient

Timeout too short → duplicate packets

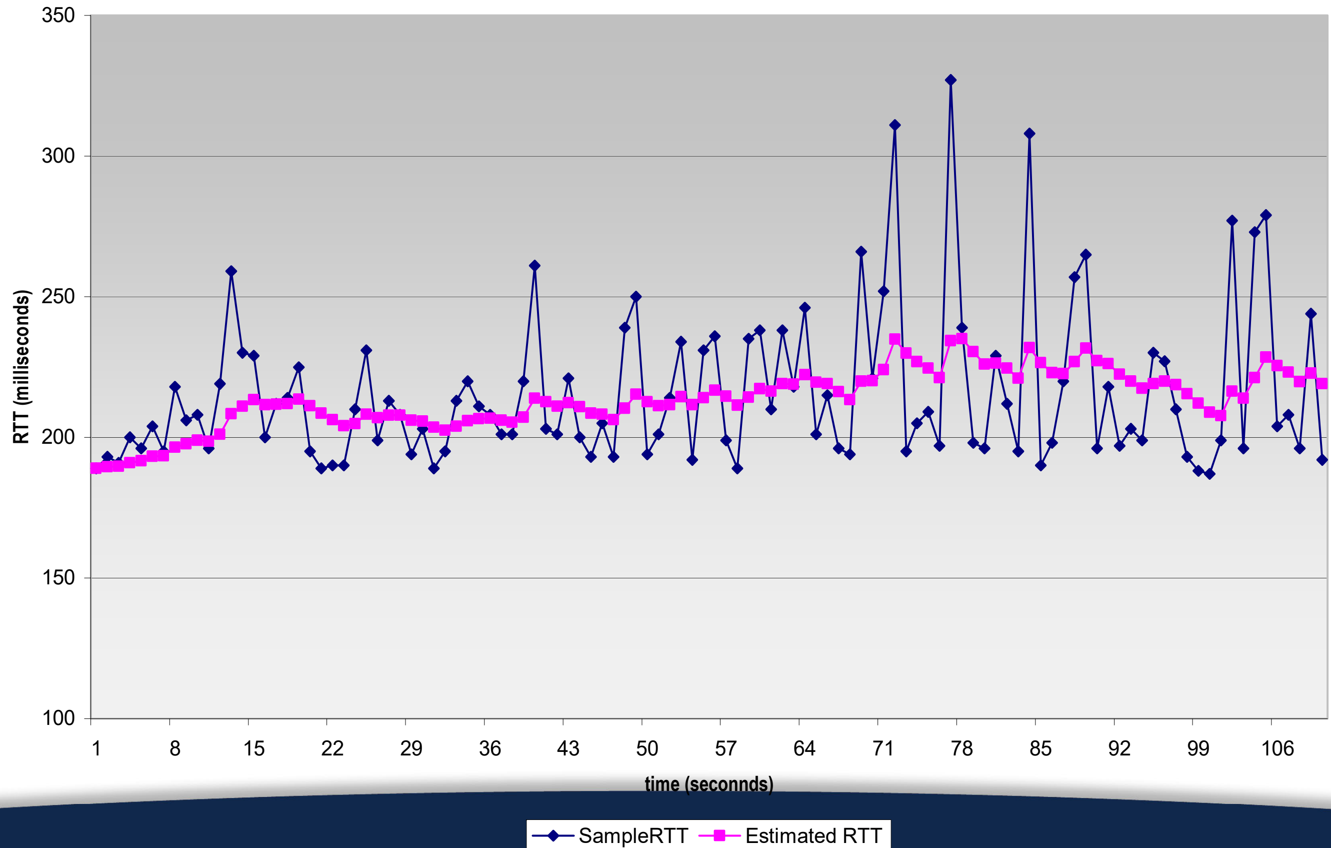
Retransmission timeout

- If the sender hasn't received an ACK by timeout, retransmit the first packet in the window
- How to set timeout?
  - Too long: connection has low throughput
  - Too short: retransmit packet that was just delayed
- Solution: make timeout proportional to RTT
  - But how do we measure RTT?

RTT estimation

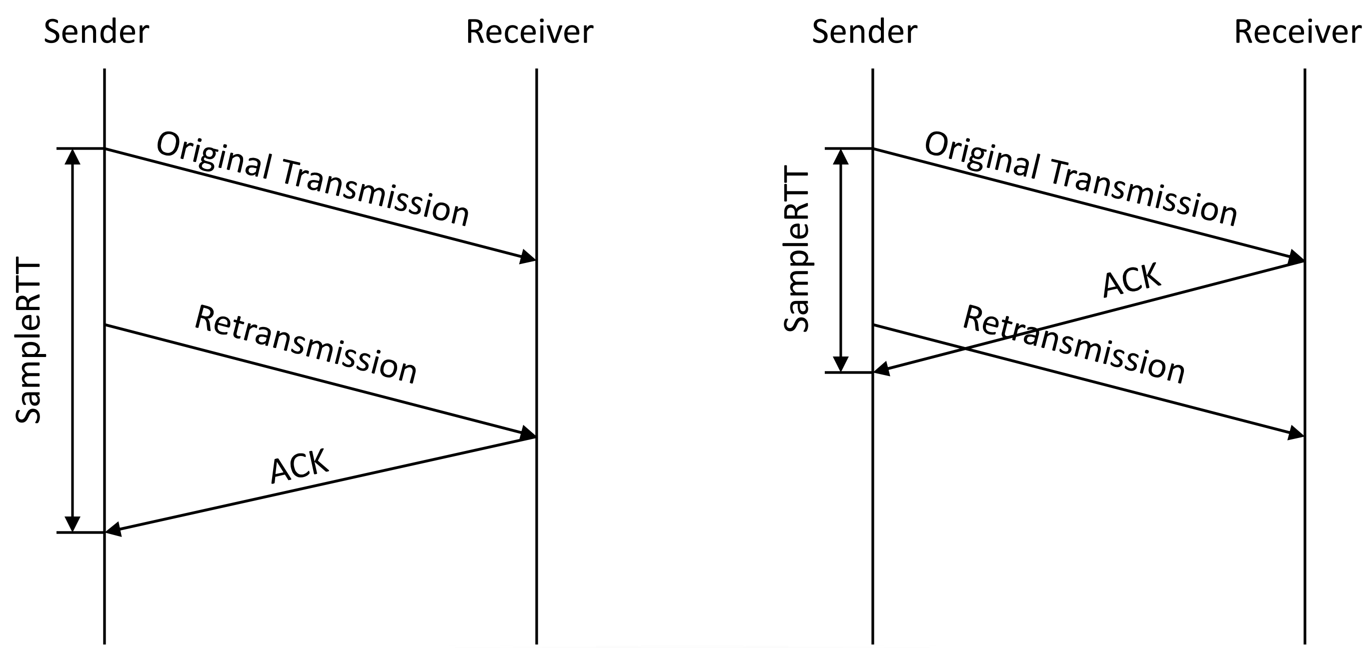
- Exponential weighted average of RTT samples

$$\textbf{EstimatedRTT} = (1- \alpha)*\textbf{EstimatedRTT} + \alpha*\textbf{SampleRTT}$$



Problem: Ambiguous measurements

- How do we differentiate between the real ACK, and ACK of the retransmitted packet?



Karn/Partridge algorithm

- Don't use SampleRTT from retransmissions
  - Once retransmitted, ignore that segment in the future
- Computes EstimatedRTT using $\alpha = 0.125$
- Timeout value (RTO) = $2 \times$ EstimatedRTT
  - Employs exponential backoff
    - Every time RTO timer expires, set RTO $\leftarrow 2 \cdot$RTO
      (Up to maximum $\geq$ 60 sec)
    - Every time new measurement comes in (= successful original transmission), collapse RTO back to $2 \times$ EstimatedRTT
- Sensitive to RTT variations

Jacobson/Karels algorithm

- Problem: need to better capture variability in RTT
  - Directly measure deviation

$$\text{Difference} = \text{SampleRTT} - \text{EstimatedRTT}$$

$$\text{EstimatedRTT} = \text{EstimatedRTT} + (\delta \times \text{Difference})$$

$$\text{Deviation} = \text{Deviation} + \delta(|\text{Difference}| - \text{Deviation})$$

$$\text{TimeOut} = \mu \times \text{EstimatedRTT} + \phi \times \text{Deviation}$$

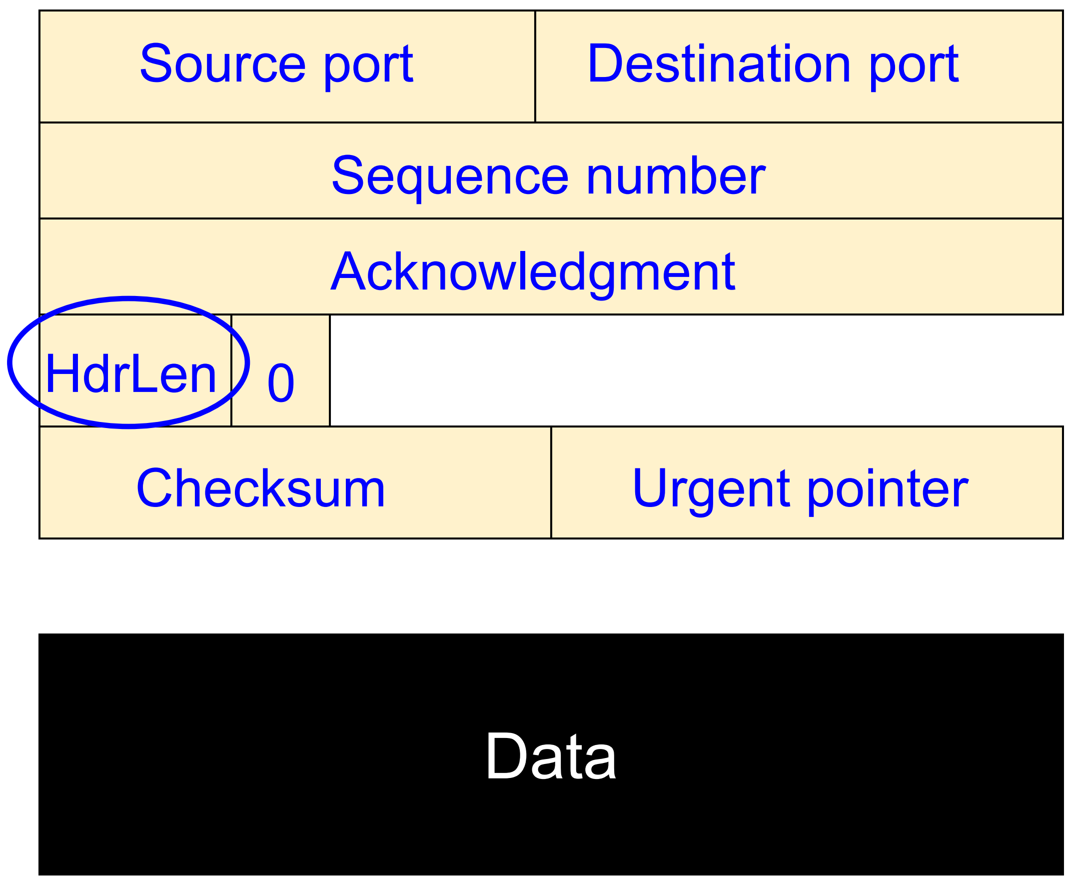
μ is typically set to 1 and ϕ is set to 4*

- RTO = EstimatedRTT + 4 x DeviationRTT

*Peterson and Davie

Build the TCP header

Number of 4-byte words in the header; 5: No options



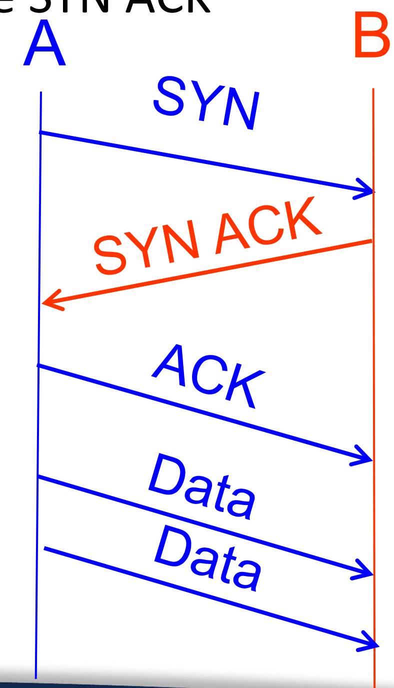
TCP Connection Establishment

Initial Sequence Number (ISN)

- Sequence number for the very first byte
- Why not just use ISN = 0?
  - Practical issue
    - IP addresses and port #s uniquely identify a connection
    - Eventually, though, these port #s do get used again; small chance an old packet is still in flight
    - Also, others might try to spoof your connection
  - Why does using ISN help?
- Hosts exchange ISNs when establishing connection

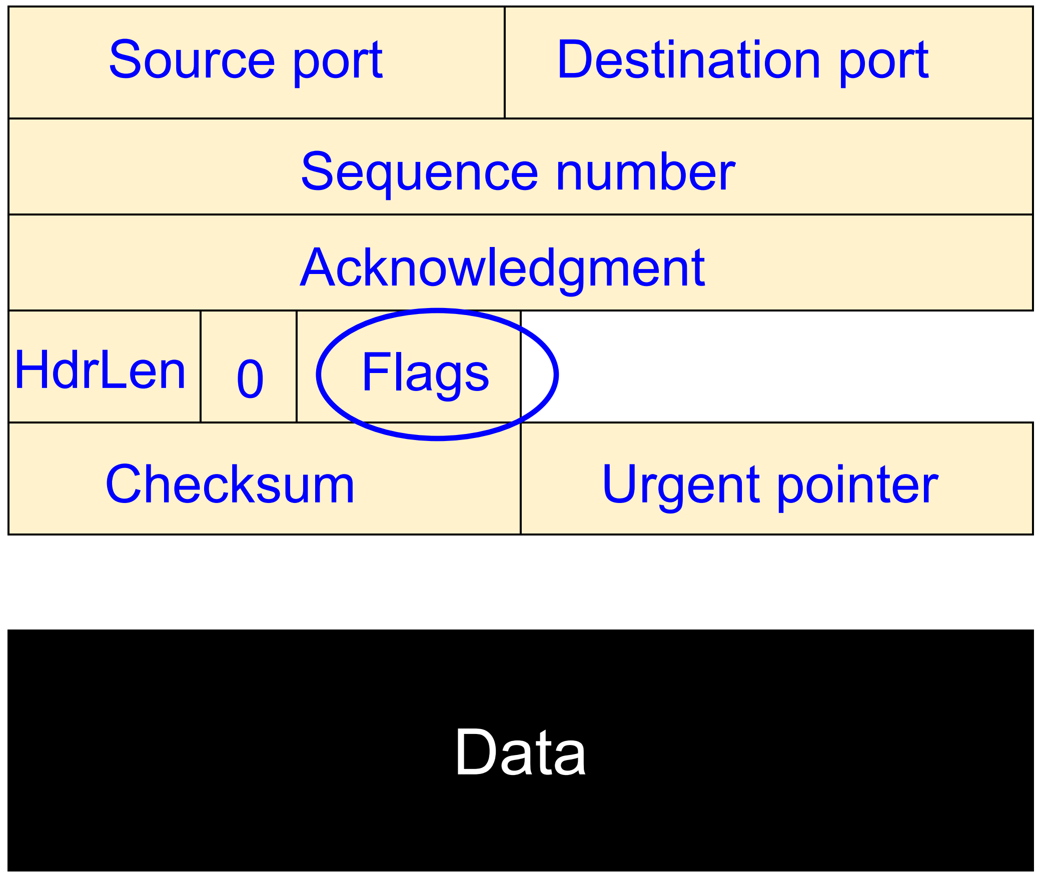
Establishing a TCP connection

- Three-way handshake to establish connection
  - Host A sends a SYN (open; "synchronize sequence numbers") to host B
  - Host B returns a SYN acknowledgment (SYN ACK)
  - Host A sends an ACK to acknowledge the SYN ACK



Build the TCP header

Flags:
SYN
ACK
FIN
RST
PSH
URG



Step 1: A's initial SYN packet

A tells B to open a connection

A's port			B's port
A's Initial Sequence Number			
N/A			
5	0	SYN	
Checksum			Urgent pointer

Step 1: B's SYN-ACK packet

B tells it accepts and is ready to accept next packet

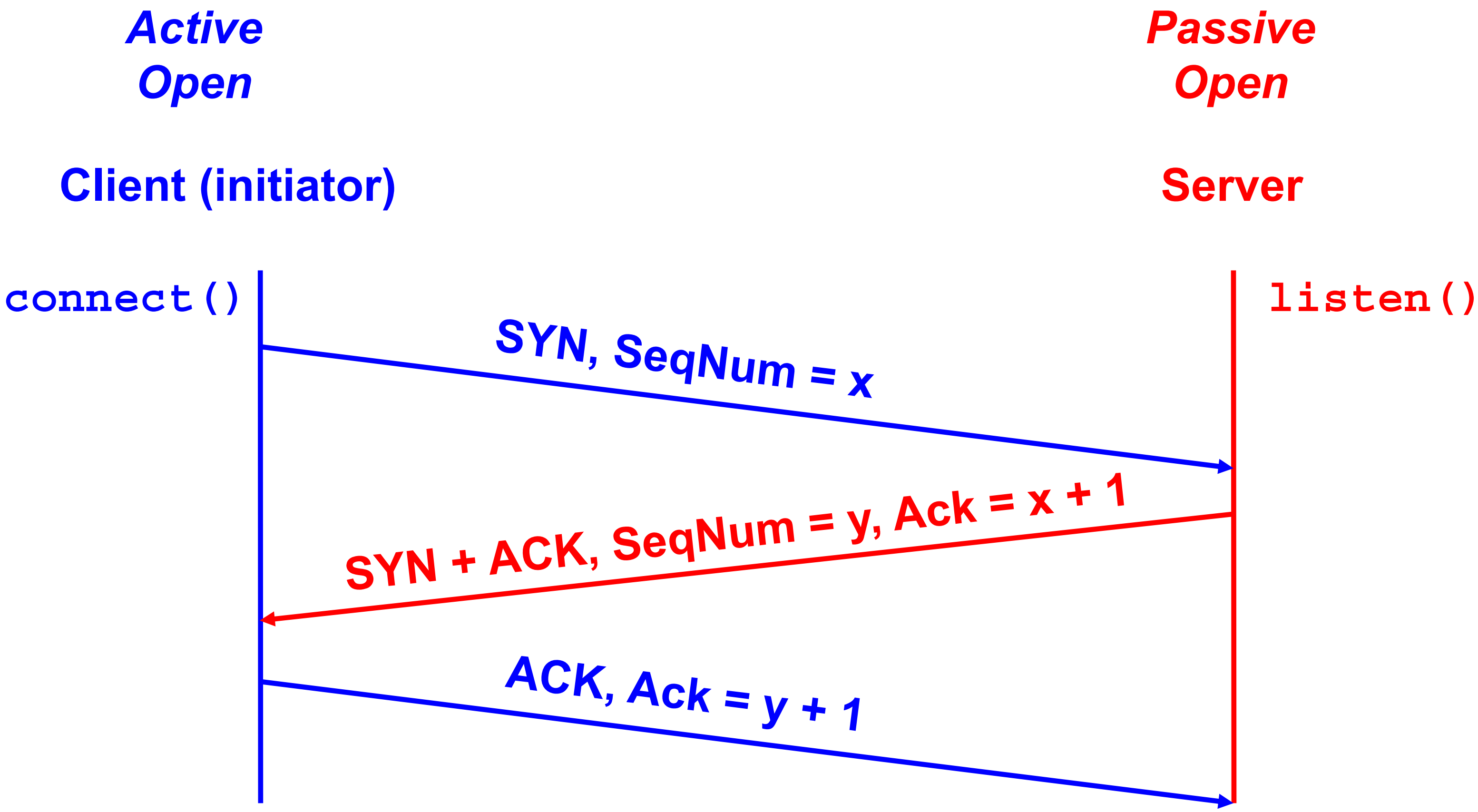
B's port		A's port	
B's Initial Sequence Number			
ACK=A's ISN+1			
5	0	SYN|ACK	
Checksum		Urgent pointer	

Step 1: A’s ACK to SYN-ACK

A tells B to open
a connection

<table>
<tr><td colspan="3">A’s port</td><td>B’s port</td></tr>
<tr><td colspan="4">A’s Initial Sequence Number + 1</td></tr>
<tr><td colspan="4">ACK=B’s ISN+1</td></tr>
<tr><td>5</td><td>0</td><td>ACK</td><td></td></tr>
<tr><td colspan="3">Checksum</td><td>Urgent pointer</td></tr>
</table>

TCP’s 3-Way handshaking



What if the SYN Packet Gets Lost?

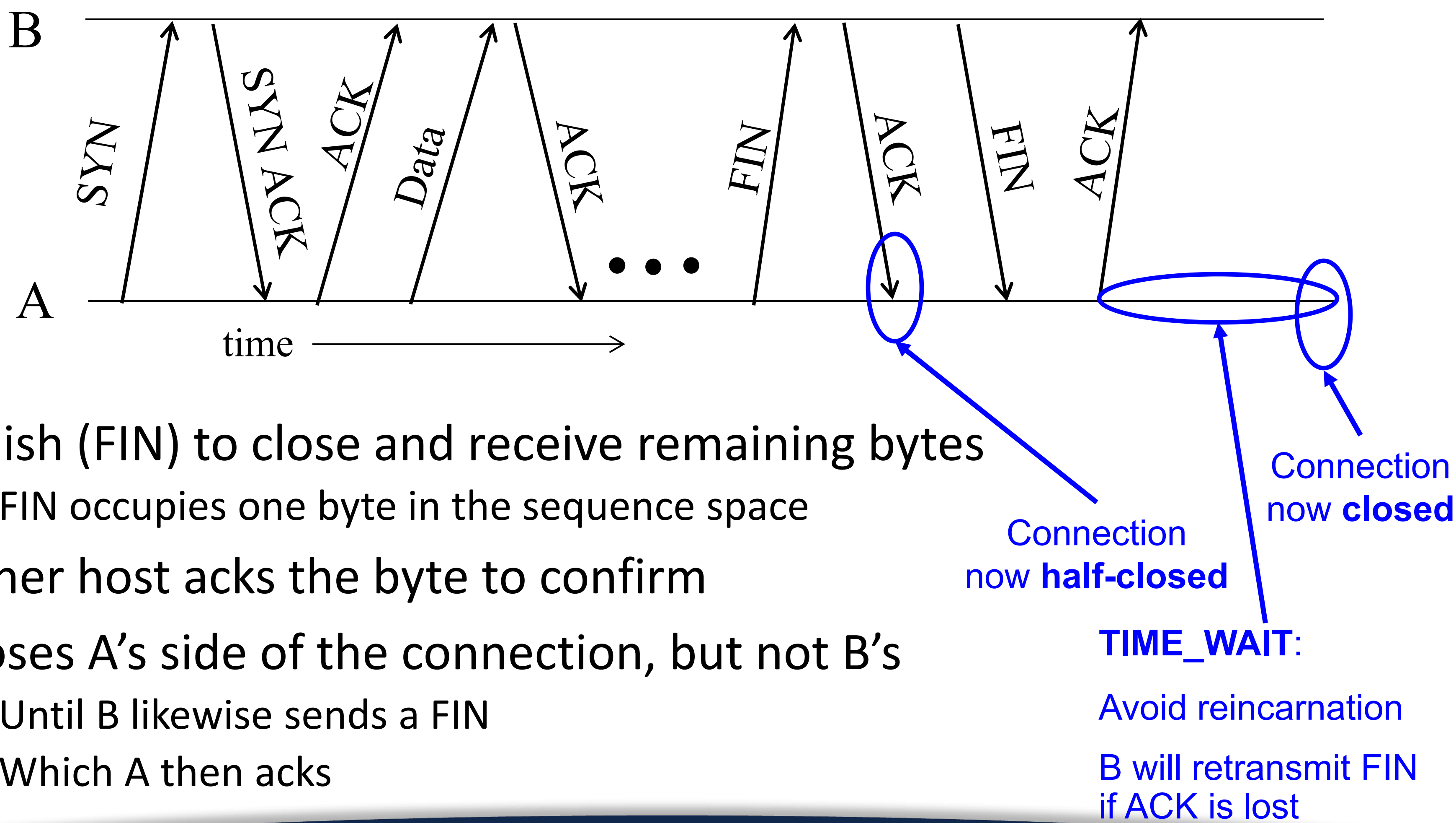
- Suppose the SYN packet gets lost
  - Packet dropped by the network or server is busy
- Eventually, no SYN-ACK arrives
  - Sender retransmits the SYN on timeout
- How should the TCP sender set the timer?
  - Sender has no idea how far away the receiver is
  - Hard to guess a reasonable length of time to wait
  - SHOULD (RFCs 1122 & 2988) use default of 3 seconds
    - Some implementations instead use 6 seconds

SYN loss and web downloads

- User clicks on a hypertext link
  - Browser creates a socket and does a "connect"
  - The "connect" triggers the OS to transmit a SYN
- If the SYN is lost…
  - 3-6 seconds of delay: can be very long
  - User may become impatient and can retry
- User triggers an "abort" of the "connect"
  - Browser creates a new socket and another "connect"
  - Can be effective in some cases

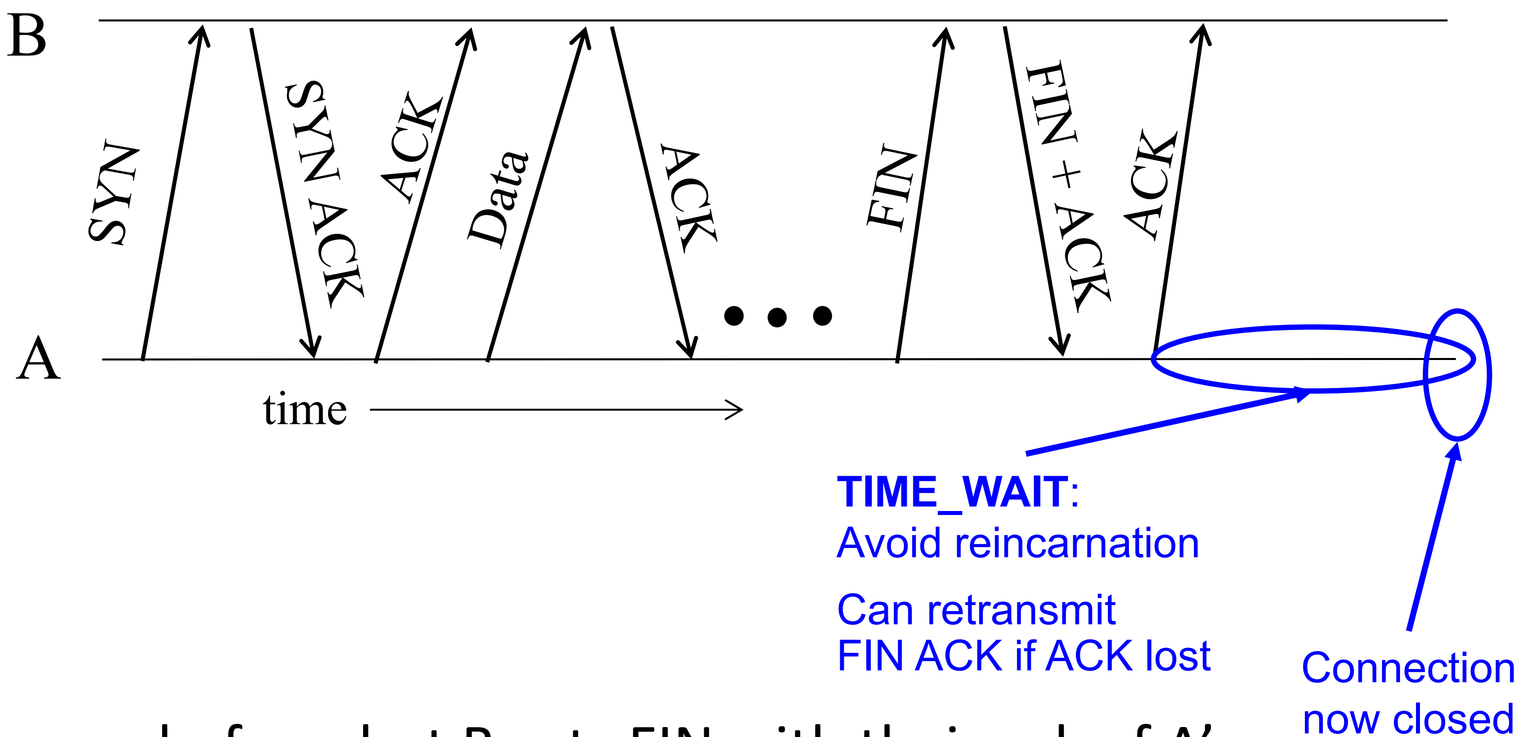
TCP connection teardown

Normal termination, one side at a time



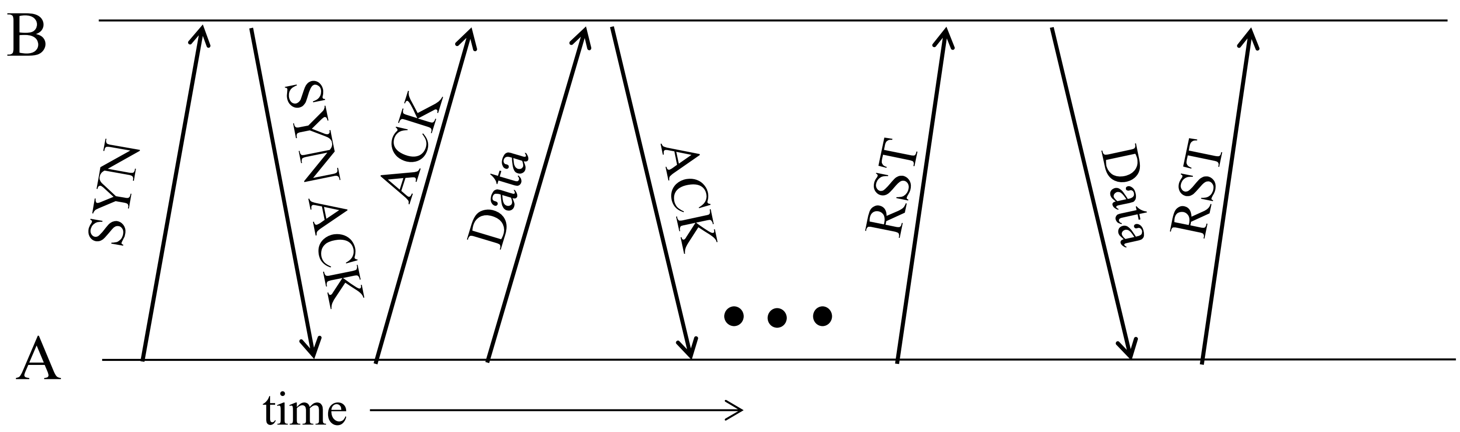
- Finish (FIN) to close and receive remaining bytes
  - FIN occupies one byte in the sequence space
- Other host acks the byte to confirm
- Closes A's side of the connection, but not B's
  - Until B likewise sends a FIN
  - Which A then acks

Normal termination, both together



- Same as before, but B sets FIN with their ack of A's FIN

Abrupt termination



- A sends a RESET (RST) to B
  - E.g., because application process on A crashed
- That’s it
  - B does not ack the RST
  - Thus, RST is not delivered reliably, and any data in flight is lost
  - But: if B sends anything more, will elicit another RST

Summary

- Reliability is not easy!

- Next
  - Flow control
  - LOTs of congestion control

Bonus Quiz 7

- https://forms.gle/iroh9cEyjUxi1L238