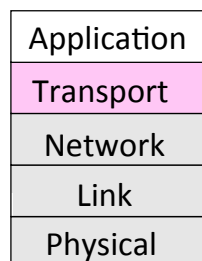# Operating Systems and Networks

Network Lecture 8: Transport Layer

Adrian Perrig
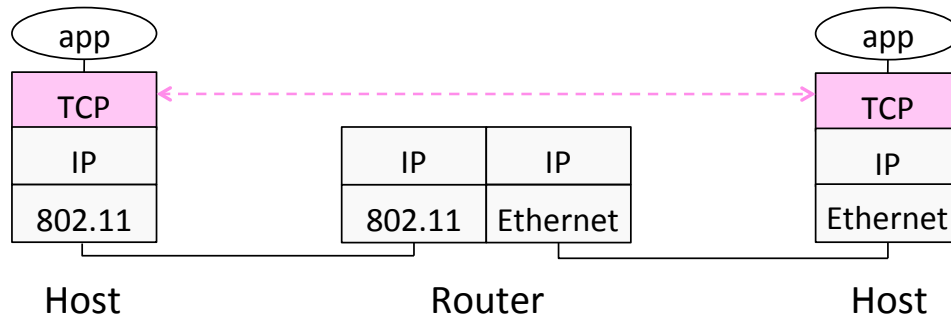Network Security Group
ETH Zürich

Where we are in the Course

- Starting the Transport Layer!
  - Builds on the network layer to deliver data across networks for applications with the desired reliability or quality

Application
Transport
Network
Link
Physical

Computer Networks

Recall

- Transport layer provides end-to-end connectivity across the network

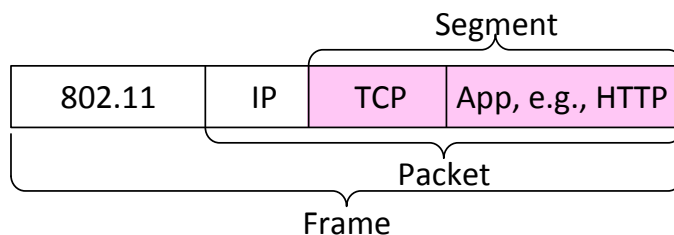| app			app
TCP			TCP
IP	IP	IP	IP
802.11	802.11	Ethernet	Ethernet

Host Router Host

Computer Networks

3

Recall (2)

- Segments carry application data across the network
- Segments are carried within packets within frames

Segment

| 802.11 | IP | TCP | App, e.g., HTTP |

Packet

Frame

Computer Networks

4

Transport Layer Services

- Provide different kinds of data delivery across the network to applications

	Unreliable	Reliable
Messages	Datagrams (UDP)	
Bytestream		Streams (TCP)

Computer Networks

5

Comparison of Internet Transports

- TCP is full-featured, UDP is a glorified packet

TCP (Streams)	UDP (Datagrams)
Connections	Datagrams
Bytes are delivered once, reliably, and in order	Messages may be lost, reordered, duplicated
Arbitrary length content	Limited message size
Flow control matches sender to receiver	Can send regardless of receiver state
Congestion control matches sender to network	Can send regardless of network state

Computer Networks

6

3

Socket API

- Simple abstraction to use the network
  - The "network" API (really Transport service) used to write all Internet apps
  - Part of all major OSes and languages; originally Berkeley (Unix) ~1983

- Supports both Internet transport services (Streams and Datagrams)

7

Socket API (2)

- Sockets let apps attach to the local network at different ports

Socket, Port #1

Socket, Port #2

8
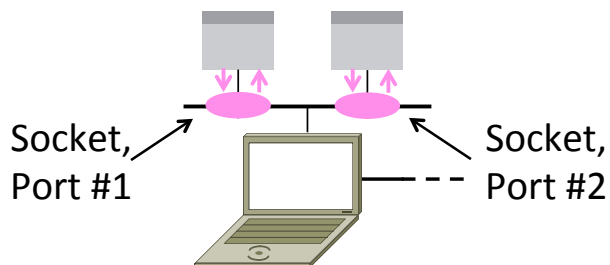
Socket API (3)

- Same API used for Streams and Datagrams

Primitive	Meaning
SOCKET	Create a new communication endpoint
BIND	Associate a local address (port) with a socket
LISTEN	Announce willingness to accept connections
ACCEPT	Passively establish an incoming connection
CONNECT	Actively attempt to establish a connection
SEND(TO)	Send some data over the socket
RECEIVE(FROM)	Receive some data over the socket
CLOSE	Release the socket

Only needed for Streams

To/From forms for Datagrams

Computer Networks

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Ports

- Application process is identified by the tuple IP address, protocol, and port
  - Ports are 16-bit integers representing local "mailboxes" that a process leases

- Servers often bind to "well-known ports"
  - <1024, require administrative privileges
- Clients often assigned "ephemeral" ports
 - Chosen by OS, used temporarily

Computer Networks

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Some Well-Known Ports

Port	Protocol	Use
20, 21	FTP	File transfer
22	SSH	Remote login, replacement for Telnet
25	SMTP	Email
80	HTTP	World Wide Web
110	POP-3	Remote email access
143	IMAP	Remote email access
443	HTTPS	Secure Web (HTTP over SSL/TLS)
543	RTSP	Media player control
631	IPP	Printer sharing

Computer Networks

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Topics

- Service models
  - Socket API and ports
  - Datagrams, Streams
- User Datagram Protocol (UDP)   } This
- Connections (TCP)   time
- Sliding Window (TCP)
- Flow control (TCP)
- Retransmission timers (TCP)

- Congestion control (TCP)   } Later

Computer Networks

12
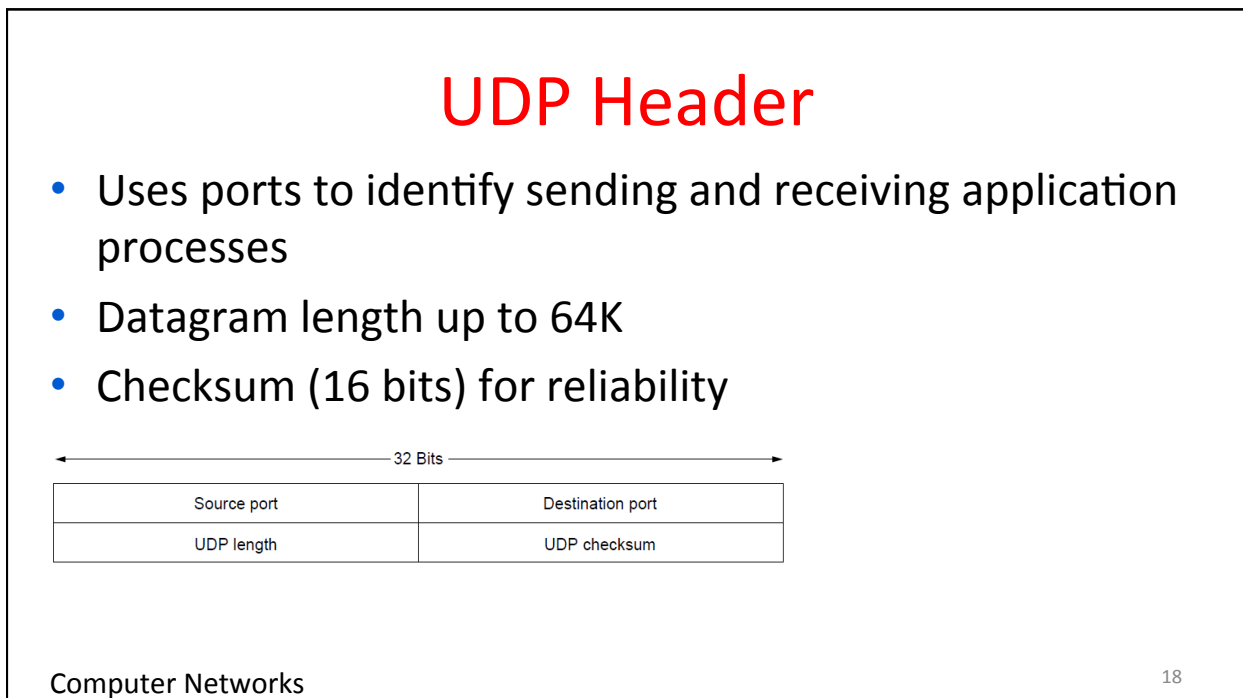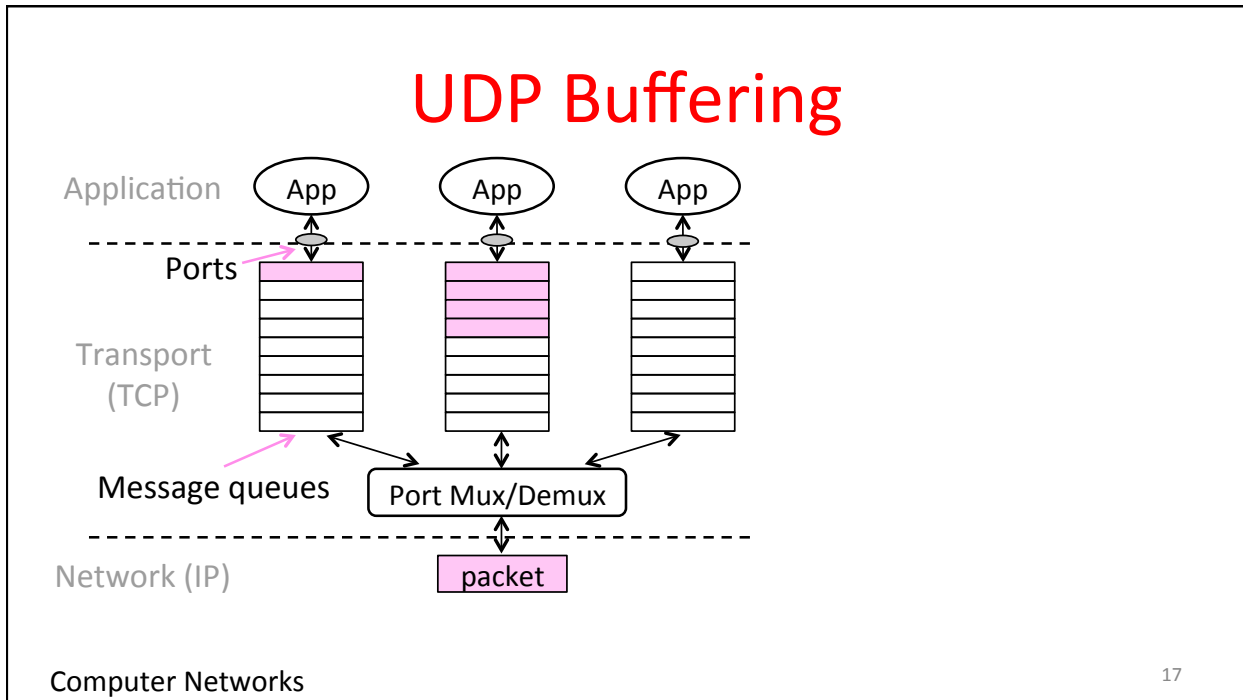
User Datagram Protocol (UDP) (§6.4)

- Sending messages with UDP
  - A shim layer on packets

Computer Networks
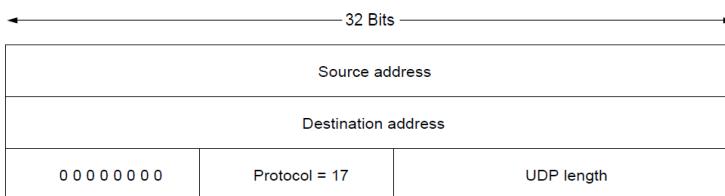
13
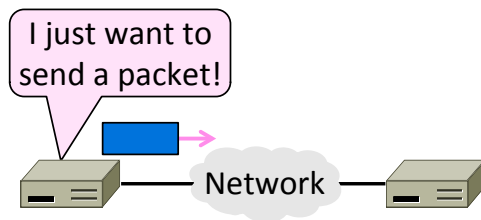
User Datagram Protocol (UDP)

- Used by apps that don't want reliability or bytestreams
  - Voice-over-IP (unreliable)
  - DNS, RPC (message-oriented)
  - DHCP (bootstrapping)

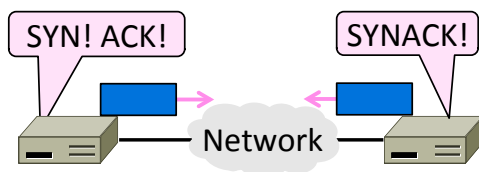(If application wants reliability and messages then it has work to do!)

Computer Networks

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Datagram Sockets

Client (host 1)   Time   Server (host 2)

request →

← reply

Computer Networks

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Datagram Sockets (2)

Client (host 1)   Time   Server (host 2)

1: socket

1: socket
2: bind
3: recvfrom*

4: sendto   request →

5: recvfrom*   reply ←   6: sendto

7: close   7: close

*= call blocks

Computer Networks

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8

UDP Buffering

Application   App   App   App

Ports

Transport
(TCP)

Message queues   Port Mux/Demux

Network (IP)   packet

Computer Networks

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UDP Header

- Uses ports to identify sending and receiving application processes
- Datagram length up to 64K
- Checksum (16 bits) for reliability

32 Bits	
Source port	Destination port
UDP length	UDP checksum

Computer Networks

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UDP Header (2)

- Optional checksum covers UDP segment and IP pseudoheader
  - Checks key IP fields (addresses)
  - Value of zero means "no checksum"

32 Bits		
Source address		
Destination address		
0 0 0 0 0 0 0 0	Protocol = 17	UDP length

Computer Networks

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Connection Establishment (6.5.5, 6.5.7, 6.2.2)

- How to set up connections
  - We'll see how TCP does it

SYN! ACK!

SYNACK!

Network

Computer Networks

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Connection Establishment

- Both sender and receiver must be ready before we start the transfer of data
  - Need to agree on a set of parameters
  - e.g., the Maximum Segment Size (MSS)

- This is signaling
  - It sets up state at the endpoints
  - Like "dialing" for a telephone call

Computer Networks

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Three-Way Handshake

- Used in TCP; opens connection for data in both directions

- Each side probes the other with a fresh Initial Sequence Number (ISN)
  - Sends on a SYNchronize segment
  - Echo on an ACKnowledge segment

- Chosen to be robust even against delayed duplicates

Active party
(client)

Passive party
(server)

Computer Networks

22
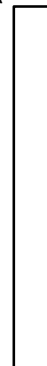
Three-Way Handshake (2)

- Three steps:
  - Client sends SYN(x)
  - Server replies with SYN(y)ACK(x+1)
  - Client replies with ACK(y+1)
  - SYNs are retransmitted if lost

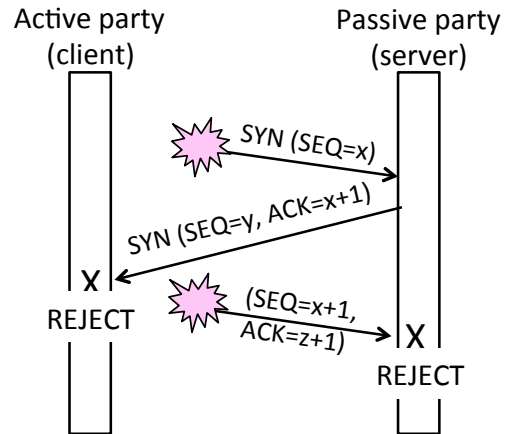- Sequence and ack numbers carried on further segments

Active party (client)   Passive party (server)

1
SYN (SEQ=x)

2
SYN (SEQ=y, ACK=x+1)

3
(SEQ=x+1, ACK=y+1)

Time

Computer Networks

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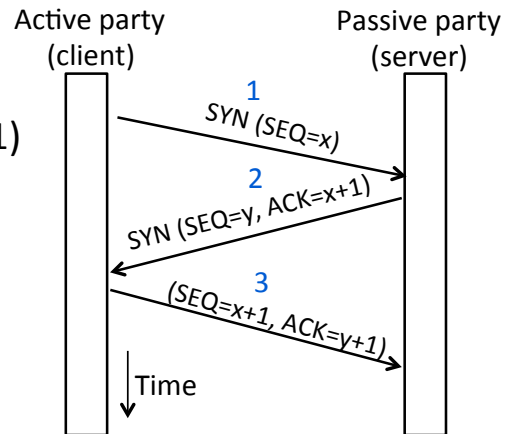
Three-Way Handshake (3)

- Suppose delayed, duplicate copies of the SYN and ACK arrive at the server!
  - Improbable, but anyhow …

Active party (client)   Passive party (server)

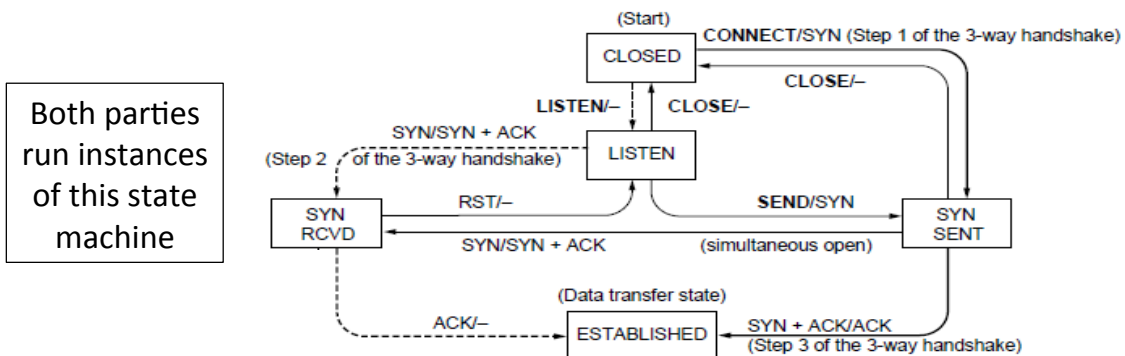SYN (SEQ=x)

(SEQ=x+1, ACK=z+1)

Computer Networks

24
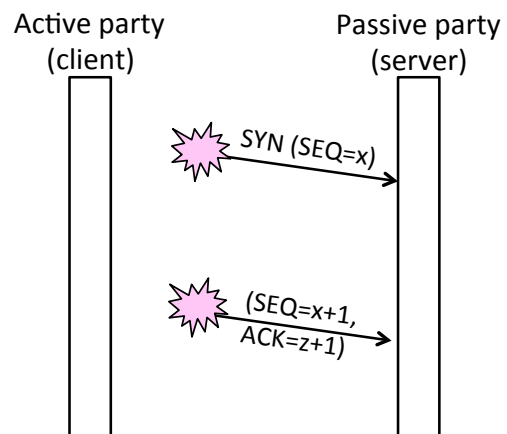
Three-Way Handshake (4)

- Suppose delayed, duplicate copies of the SYN and ACK arrive at the server!
  - Improbable, but anyhow …
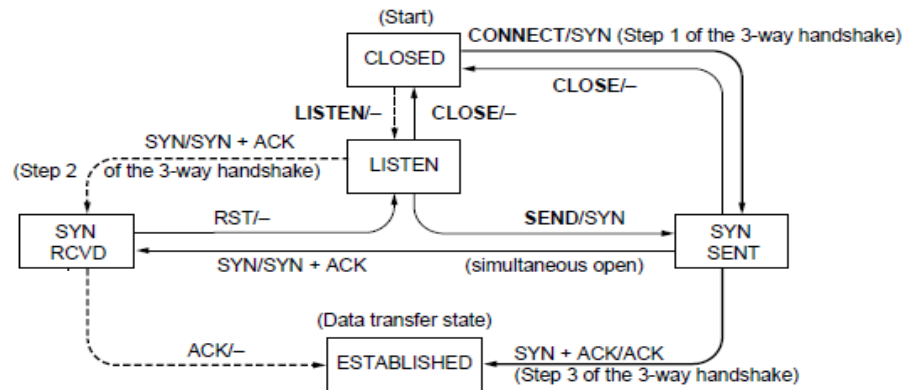
- Connection will be cleanly rejected on both sides ☺

Active party (client)   Passive party (server)

SYN (SEQ=x)

SYN (SEQ=y, ACK=x+1)

X
REJECT

(SEQ=x+1, ACK=z+1)

X
REJECT

Computer Networks   25

TCP Connection State Machine

- Captures the states (rectangles) and transitions (arrows)
  - A/B means event A triggers the transition, with action B

Both parties run instances of this state machine

(Start)
CLOSED
CONNECT/SYN (Step 1 of the 3-way handshake)
CLOSE/–
LISTEN/–
CLOSE/–
SYN/SYN + ACK
LISTEN
(Step 2 of the 3-way handshake)
SYN RCVD
RST/–
SEND/SYN
SYN SENT
SYN/SYN + ACK
(simultaneous open)
(Data transfer state)
ACK/–
ESTABLISHED
SYN + ACK/ACK
(Step 3 of the 3-way handshake)

Computer Networks   26

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TCP Connections (2)

- Follow the path of the client:

TCP Connections (3)

- And the path of the server:
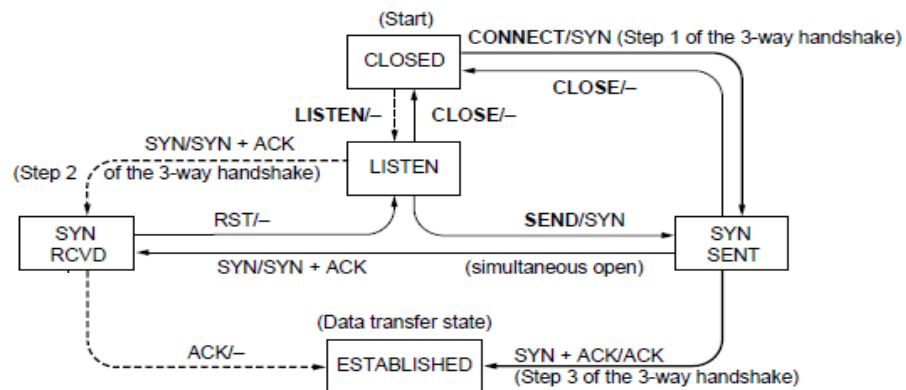
TCP Connections (4)

- Again, with states …

Active party (client)   Passive party (server)

CLOSED   CLOSED
SYN_SENT   LISTEN

1   *SYN (SEQ=x)*

2   *SYN (SEQ=y, ACK=x+1)*   SYN_RCVD

ESTABLISHED   3   *(SEQ=x+1, ACK=y+1)*

Time   ESTABLISHED
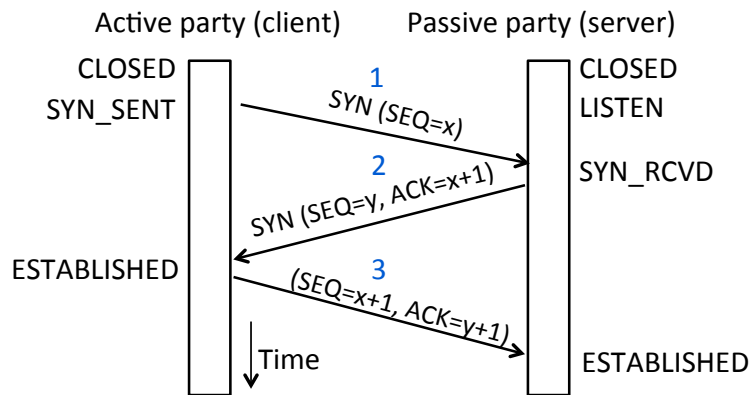
Computer Networks   29

TCP Connections (5)

- Finite state machines are a useful tool to specify and check the handling of all cases that may occur

- TCP allows for simultaneous open
  - i.e., both sides open at once instead of the client-server pattern
  - Try at home to confirm it works ☺

Computer Networks   30

Connection Release (6.5.6-6.5.7, 6.2.3)

- How to release connections
  - We'll see how TCP does it
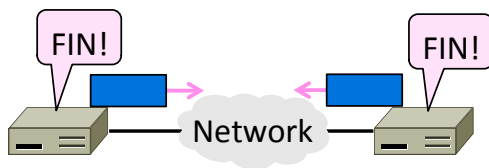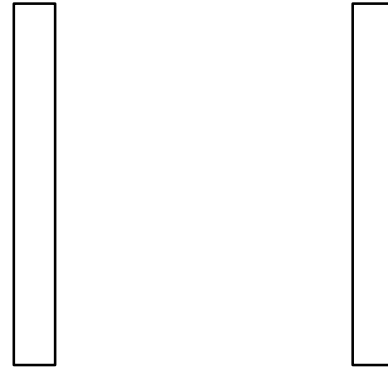
Connection Release

- Orderly release by both parties when done
  - Delivers all pending data and "hangs up"
  - Cleans up state in sender and receiver

- Key problem is to provide reliability while releasing
  - TCP uses a "symmetric" close in which both sides shutdown independently

TCP Connection Release

- Two steps:
  - Active sends FIN(x), passive ACKs
  - Passive sends FIN(y), active ACKs
  - FINs are retransmitted if lost

- Each FIN/ACK closes one direction of data transfer
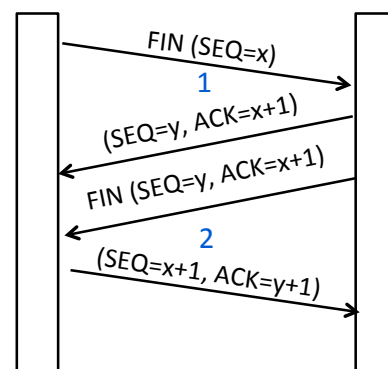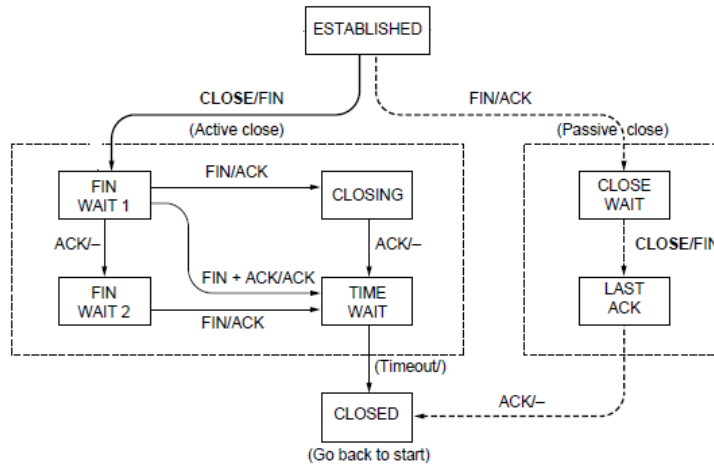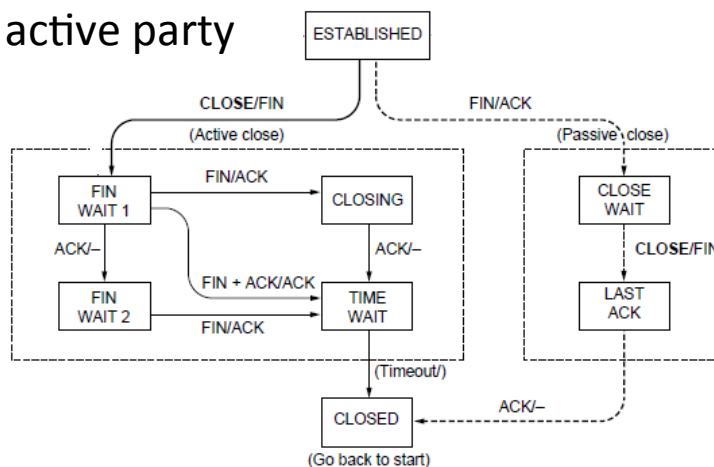
Active party   Passive party

Computer Networks

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TCP Connection Release (2)

- Two steps:
  - Active sends FIN(x), passive ACKs
  - Passive sends FIN(y), active ACKs
  - FINs are retransmitted if lost

- Each FIN/ACK closes one direction of data transfer

Active party   Passive party

FIN (SEQ=x)
1
(SEQ=y, ACK=x+1)
FIN (SEQ=y, ACK=x+1)
2
(SEQ=x+1, ACK=y+1)

Computer Networks

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TCP Connection State Machine

Both parties run instances of this state machine

Computer Networks

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TCP Release

- Follow the active party

Computer Networks

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TCP Release (2)

- Follow the passive party

ESTABLISHED

CLOSE/FIN
(Active close)

FIN/ACK
(Passive close)

FIN
WAIT 1

FIN/ACK

CLOSING

CLOSE
WAIT

ACK/–

ACK/–

CLOSE/FIN

FIN
WAIT 2

FIN + ACK/ACK

TIME
WAIT

LAST
ACK

FIN/ACK

(Timeout/)

CLOSED

ACK/–

(Go back to start)

Computer Networks

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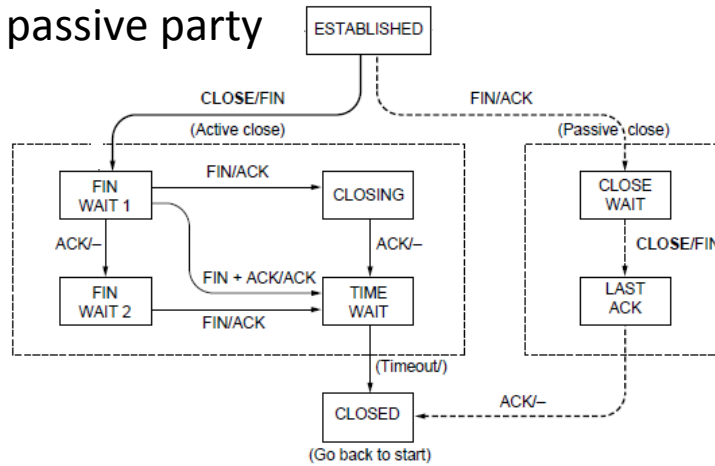
TCP Release (3)

- Again, with states …

Active party   Passive party

ESTABLISHED   ESTABLISHED

FIN_WAIT_1

$FIN\ (SEQ=x)$

1

$(SEQ=y, ACK=x+1)$

CLOSE_WAIT

FIN_WAIT_2

$FIN\ (SEQ=y, ACK=x+1)$

2

LAST_ACK

$(SEQ=x+1, ACK=y+1)$

TIME_WAIT

(timeout)

CLOSED

CLOSED

Computer Networks

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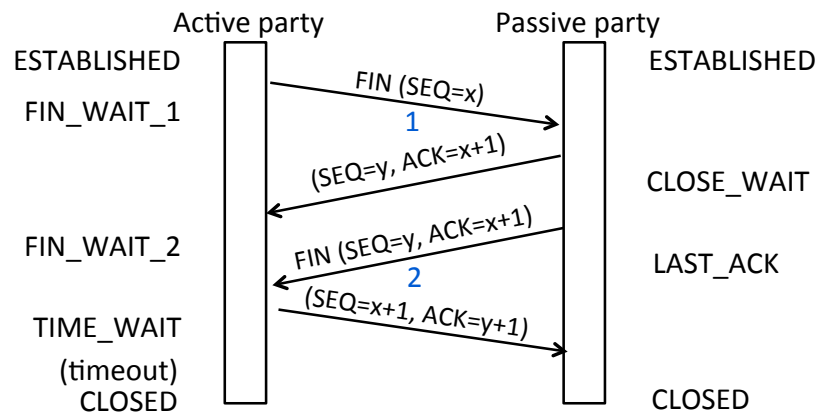
TIME_WAIT State

- We wait a long time (two times the maximum segment lifetime of 60 seconds) after sending all segments and before completing the close

- Why?
  - ACK might have been lost, in which case FIN will be resent for an orderly close
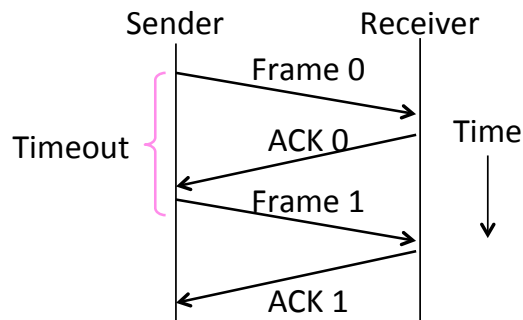 - Could otherwise interfere with a subsequent connection

Computer Networks

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Sliding Windows (§3.4, §6.5.8)

- The sliding window algorithm
  - Pipelining and reliability
  - Building on Stop-and-Wait

Computer Networks

40
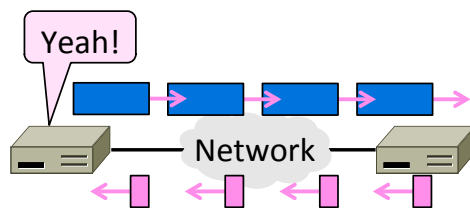
Recall

- ARQ with one message at a time is Stop-and-Wait (normal case below)

Sender   Receiver

Timeout { Frame 0 → ACK 0 ← Frame 1 → ACK 1 ← }   Time

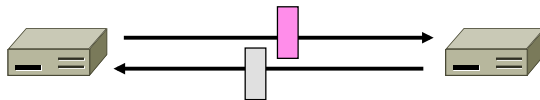Computer Networks   41

Limitation of Stop-and-Wait

- It allows only a single message to be outstanding from the sender:
  - Fine for LAN (only one frame fit)
  - Not efficient for network paths with BD >> 1 packet
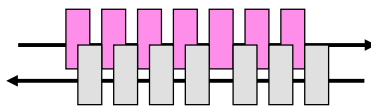

Computer Networks   42

Limitation of Stop-and-Wait (2)

- Example: R=1 Mbps, D = 50 ms
  - RTT (Round Trip Time) = 2D = 100 ms
  - How many packets/sec?

  - What if R=10 Mbps?

Computer Networks

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Sliding Window

- Generalization of stop-and-wait
  - Allows W packets to be outstanding
  - Can send W packets per RTT (=2D)

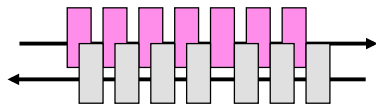 - <u>Pipelining</u> improves performance
  - Need W=2BD to fill network path

Computer Networks

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Sliding Window (2)

- What W will use the network capacity?
- Ex: R=1 Mbps, D = 50 ms

- Ex: What if R=10 Mbps?

Computer Networks

45

Sliding Window (3)

- Ex: R=1 Mbps, D = 50 ms
  - 2BD = 10^6 b/sec x 100. 10^{-3} sec = 100 kbit
  - W = 2BD = 10 packets of 1250 bytes

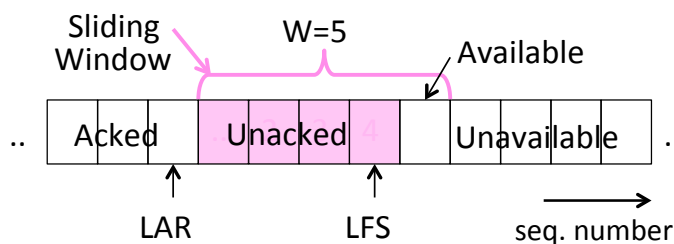- Ex: What if R=10 Mbps?
  - 2BD = 1000 kbit
  - W = 2BD = 100 packets of 1250 bytes

Computer Networks

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Sliding Window Protocol

- Many variations, depending on how buffers, acknowledgements, and retransmissions are handled

- <u>Go-Back-N</u>
  - Simplest version, can be inefficient
- <u>Selective Repeat</u>
 - More complex, better performance

Computer Networks

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Sliding Window – Sender

- Sender buffers up to W segments until they are acknowledged
  - LFS=LAST FRAME SENT, LAR=LAST ACK REC'D
  - Sends while LFS − LAR ≤ W

Sliding
Window

W=5

Available

.. | Acked | Unacked | | Unavailable | ..

LAR

LFS

seq. number

Computer Networks

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24

Sliding Window – Sender (2)

- Transport accepts another segment of data from the Application …
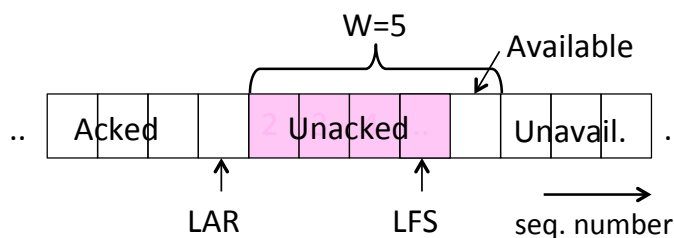 - Transport sends it (as LFS–LAR → 5)

W=5

.. | Acked | | Unacked | 4 | 4 | Unavailable | .. |

LAR   LFS

seq. number
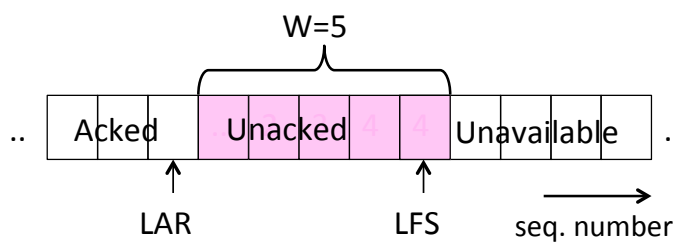
49

Sliding Window – Sender (3)

- Next higher ACK arrives from peer…
  - Window advances, buffer is freed
  - LFS–LAR → 4 (can send one more)

W=5

Available

.. | Acked | | 2 | Unacked | 2 | Unavail. | .. |

LAR   LFS

seq. number

50

Sliding Window – Go-Back-N

- Receiver keeps only a single packet buffer for the next segment
  - State variable, LAS = LAST ACK SENT

- On receive:
  - If seq. number is LAS+1, accept and pass it to app, update LAS, send ACK
  - Otherwise discard (as out of order)

Computer Networks

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Sliding Window – Selective Repeat

- Receiver passes data to app in order, and buffers out-of-order segments to reduce retransmissions

- ACK conveys highest in-order segment, plus hints about out-of-order segments

- TCP uses a selective repeat design; we'll see the details later

Computer Networks

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Sliding Window – Selective Repeat (2)

- Buffers W segments, keeps state variable, LAS = LAST ACK SENT

- On receive:
  - Buffer segments [LAS+1, LAS+W]
  - Pass up to app in-order segments from LAS+1, and update LAS
  - Send ACK for LAS regardless

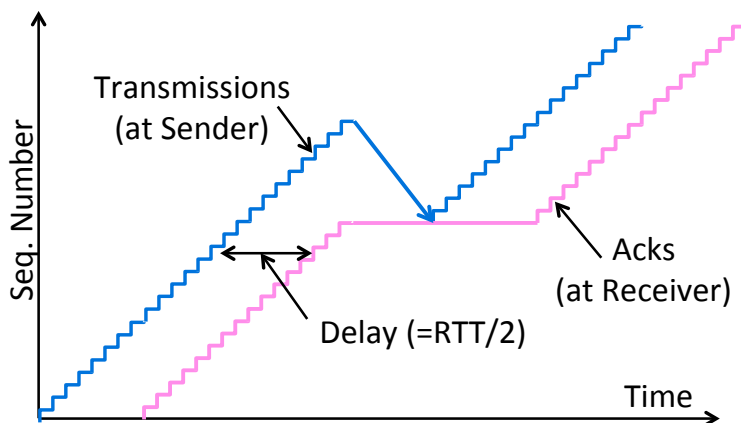Computer Networks   53

Sliding Window – Retransmissions

- Go-Back-N sender uses a single timer to detect losses
  - On timeout, resends buffered packets starting at LAR+1

- Selective Repeat sender uses a timer per unacked segment to detect losses
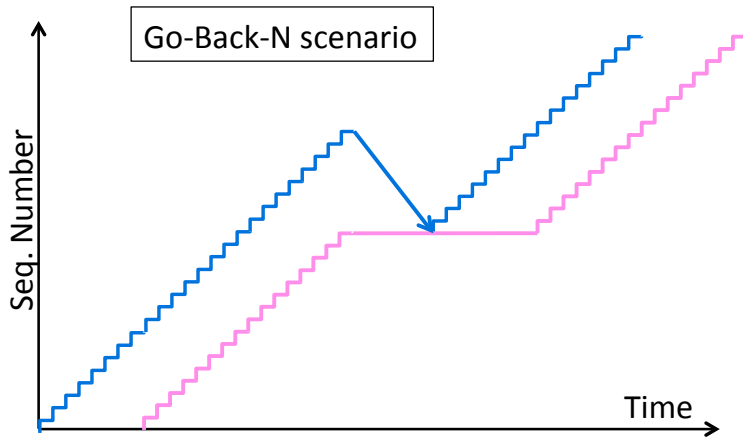 - On timeout for segment, resend it
  - Hope to resend fewer segments

Computer Networks   54

Sequence Numbers

- Need more than 0/1 for Stop-and-Wait …
  - But how many?

- For Selective Repeat, need W numbers for packets, plus W for acks of earlier packets
  - 2W seq. numbers
  - Fewer for Go-Back-N (W+1)

- Typically implement seq. number with an N-bit counter that wraps around at 2^N-1
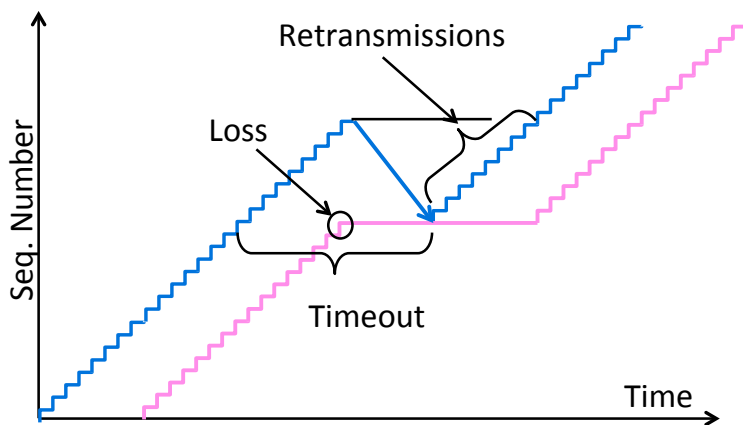 - E.g., N=8:   …, 253, 254, 255, 0, 1, 2, 3, …

Computer Networks

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Sequence Time Plot

Seq. Number

Transmissions (at Sender)

Acks (at Receiver)

Delay (=RTT/2)

Time

Computer Networks

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Sequence Time Plot (2)

Go-Back-N scenario

Seq. Number

Time

Computer Networks

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Sequence Time Plot (3)
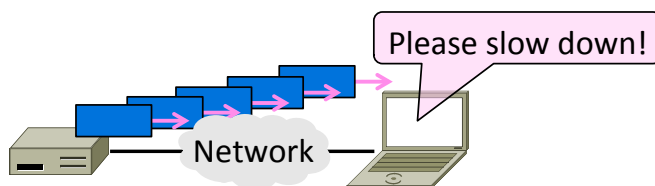
Retransmissions

Loss

Seq. Number

Timeout

Time

Computer Networks

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Flow Control (§6.5.8)

- Adding flow control to the sliding window algorithm
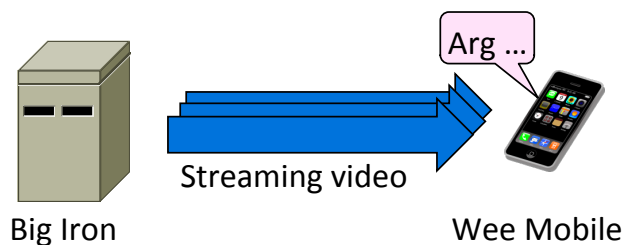 - To slow the over-enthusiastic sender

Please slow down!

Network

Computer Networks

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Problem

- Sliding window uses pipelining to keep the network busy
  - What if the receiver is overloaded?

Arg …

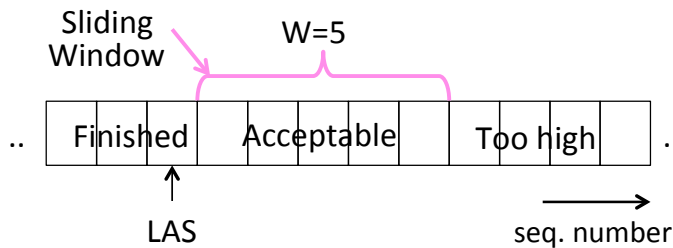Streaming video

Big Iron   Wee Mobile

Computer Networks

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Sliding Window – Receiver

- Consider receiver with W buffers
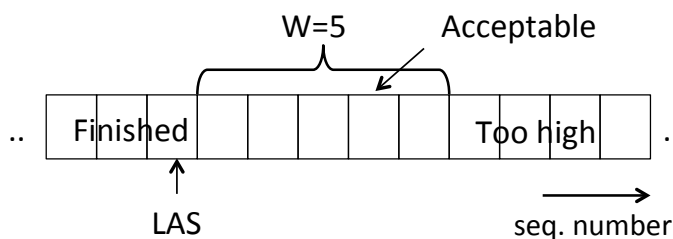 - LAS=LAST ACK SENT, app pulls in-order data from buffer with recv() call

Sliding Window   W=5

.. | Finished | Acceptable | Too high | ..

↑
LAS

seq. number

Computer Networks

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Sliding Window – Receiver (2)

- Suppose the next two segments arrive but app does not call recv()

W=5   Acceptable

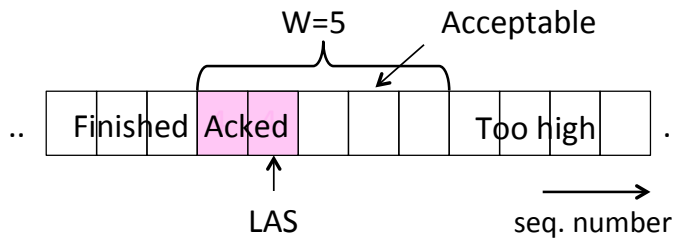.. | Finished | | | | | | Too high | ..
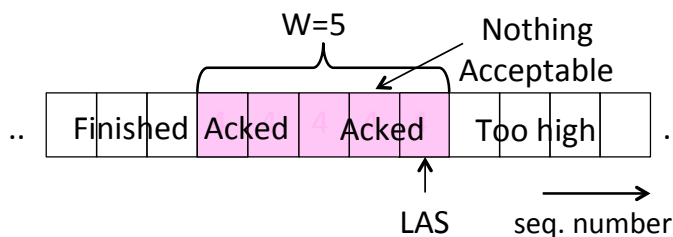
↑
LAS

seq. number

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Sliding Window – Receiver (3)

- Suppose the next two segments arrive but app does not call recv()
  - LAS rises, but we can't slide window!

W=5   Acceptable

.. | Finished | Acked | | | | Too high | | ..

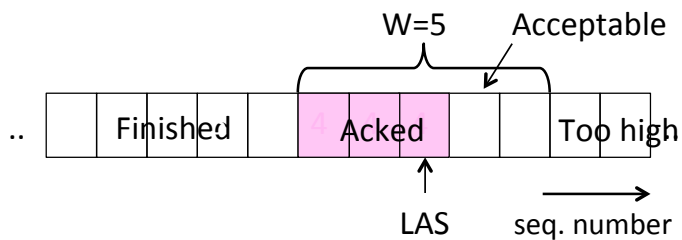LAS   seq. number

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Sliding Window – Receiver (4)

- If further segments arrive (even in order) we can fill the buffer
  - Must drop segments until app recvs!

W=5   Nothing
             Acceptable

.. | Finished | Acked | | Acked | | Too high | | ..

LAS   seq. number

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Sliding Window – Receiver (5)

- App recv() takes two segments
  - Window slides (phew)

W=5   Acceptable

.. | Finished | 4 Acked | | Too high

LAS   seq. number
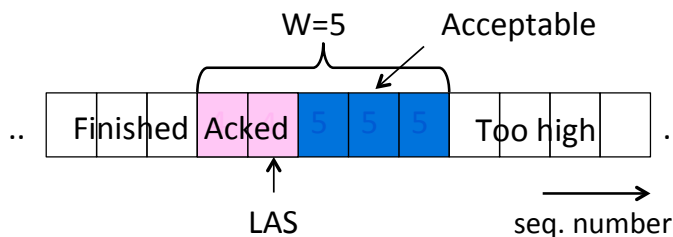
Flow Control

- Avoid loss at receiver by telling sender the available buffer space
  - WIN=#Acceptable, not W (from LAS)

W=5   Acceptable

.. | Finished | Acked | 5 5 5 | Too high | ..

LAS   seq. number
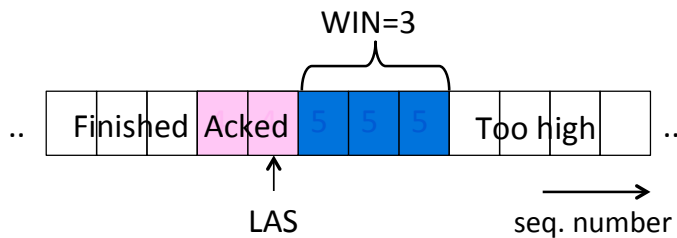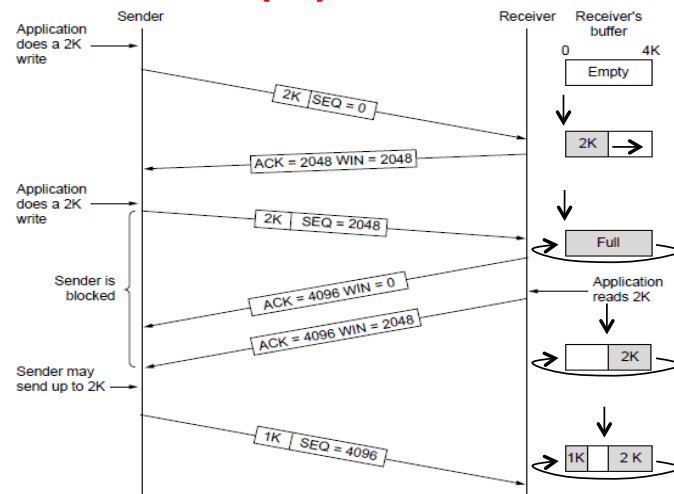
Flow Control (2)

- Sender uses the lower of the sliding window and <u>flow control window </u>(WIN) as the effective window size

WIN=3

| .. | Finished | Acked | 5 | 5 | 5 | Too high | | .. |

LAS

seq. number

Flow Control (3)

- TCP-style example
  - SEQ/ACK sliding window
  - Flow control with WIN
  - SEQ + length < ACK+WIN
  - 4KB buffer at receiver
  - Circular buffer of bytes

Sender   Receiver   Receiver's buffer

Application does a 2K write

0   4K

Empty

2K | SEQ = 0

2K

ACK = 2048 WIN = 2048

Application does a 2K write

2K | SEQ = 2048

Full

Sender is blocked

ACK = 4096 WIN = 0

Application reads 2K

ACK = 4096 WIN = 2048

2K

Sender may send up to 2K

1K | SEQ = 4096

1K | 2 K

Retransmission Timeouts (§6.5.9)

- How to set the timeout for sending a retransmission
  - Adapting to the network path
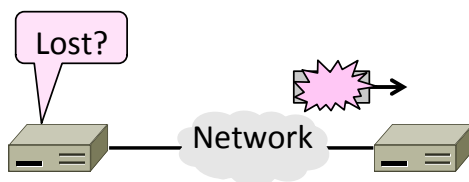
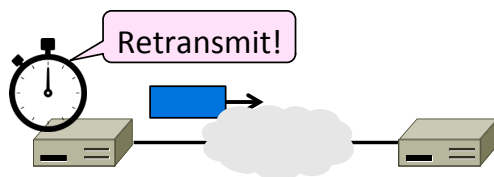Computer Networks

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Retransmissions

- With sliding window, the strategy for detecting loss is the <u>timeout</u>
  - Set timer when a segment is sent
  - Cancel timer when ack is received
  - If timer fires, <u>retransmit</u> data as lost

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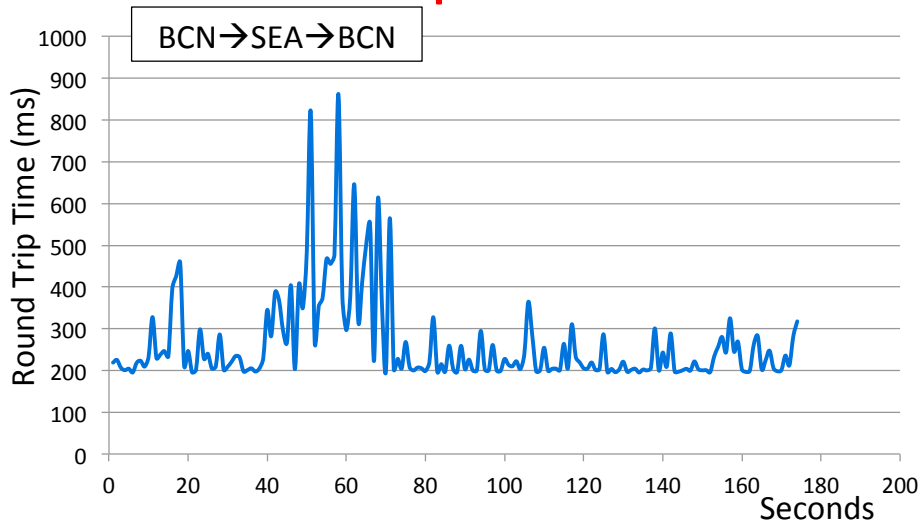# Timeout Problem

- Timeout should be "just right"
  - Too long wastes network capacity
  - Too short leads to spurious resends
  - But what is "just right"?

- Easy to set on a LAN (Link)
  - Short, fixed, predictable RTT
- Hard on the Internet (Transport)
  - Wide range, variable RTT

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Example of RTTs

BCN→SEA→BCN

Round Trip Time (ms)

Seconds

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Example of RTTs (2)

BCN→SEA→BCN

Variation due to queuing at routers, changes in network paths, etc.

Propagation (+transmission) delay ≈ 2D

Round Trip Time (ms)

Seconds
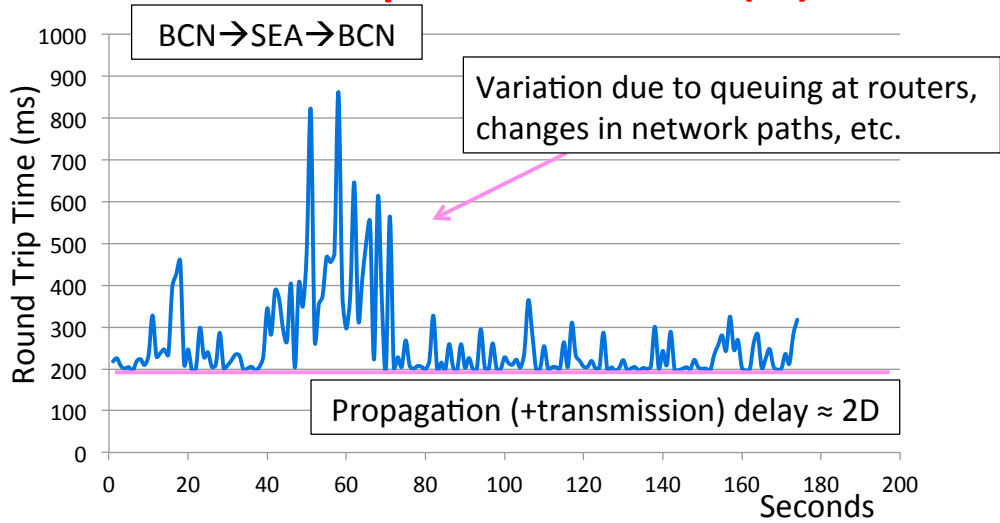
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Example of RTTs (3)

Timer too high!

Need to adapt to the network conditions

Timer too low!

Round Trip Time (ms)

Seconds
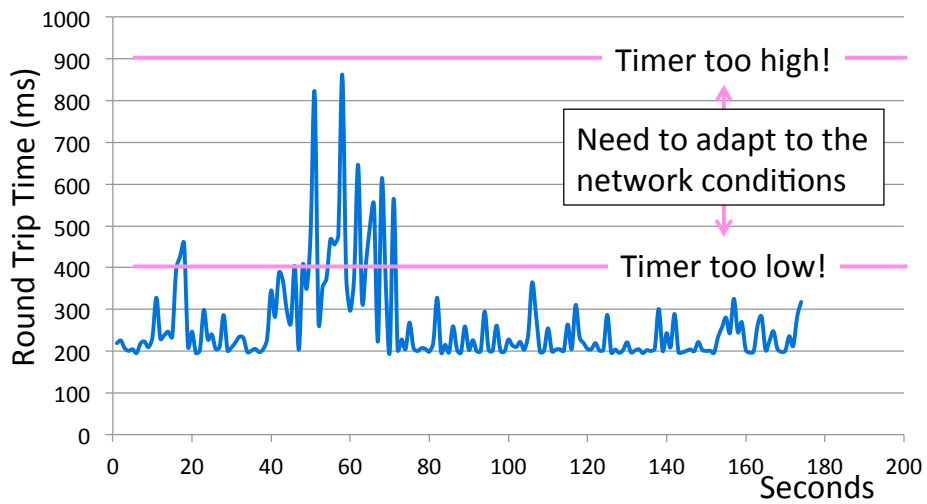
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Adaptive Timeout

- Keep smoothed estimates of the RTT (1) and variance in RTT (2)
  - Update estimates with a moving average
  1. $SRTT_{N+1} = 0.9*SRTT_N + 0.1*RTT_{N+1}$
  2. $Svar_{N+1} = 0.9*Svar_N + 0.1*|RTT_{N+1} - SRTT_{N+1}|$

- Set timeout to a multiple of estimates
  - To estimate the upper RTT in practice
  - TCP $Timeout_N = SRTT_N + 4*Svar_N$

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Example of Adaptive Timeout

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Example of Adaptive Timeout (2)

- Early timeout
- Timeout (SRTT + 4*Svar)

RTT (ms) vs Seconds
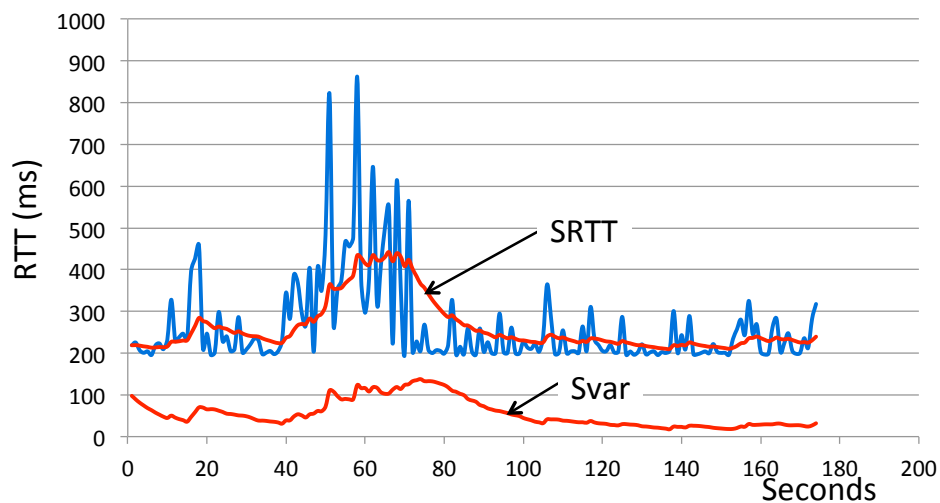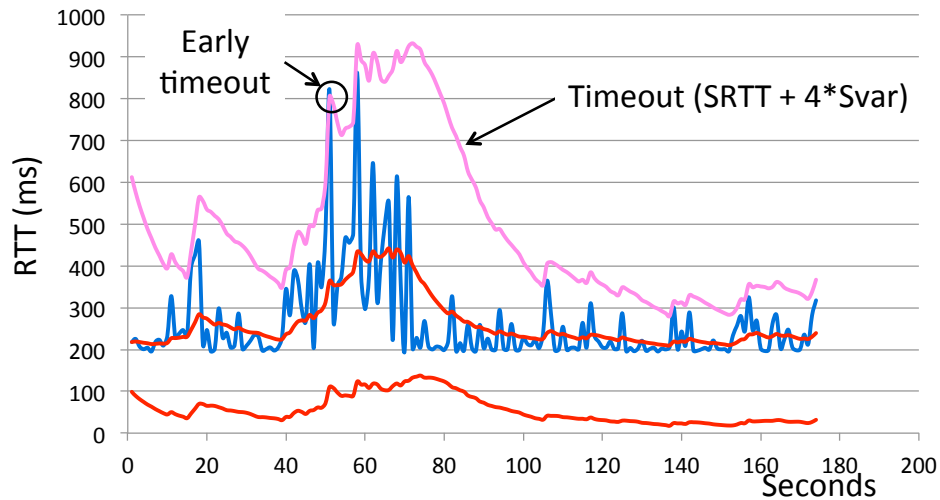
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Adaptive Timeout (2)

- Simple to compute, does a good job of tracking actual RTT
  - Little "headroom" to lower
  - Yet very few early timeouts

- Turns out to be important for good performance and robustness

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Transmission Control Protocol (TCP) (§6.5)

- How TCP works!
  - The transport protocol used for most content on the Internet

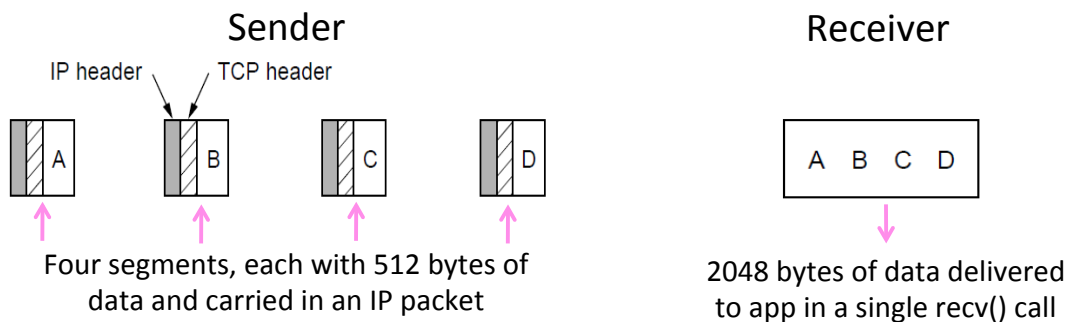
We ♥ TCP/IP!
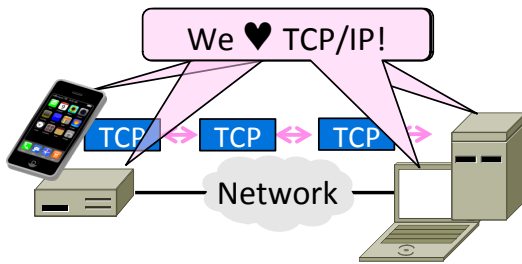
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TCP Features

- A reliable bytestream service
- Based on connections
- Sliding window for reliability
  - With adaptive timeout
- Flow control for slow receivers

This time

- Congestion control to allocate network bandwidth

Next time

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Reliable Bytestream

- Message boundaries not preserved from send() to recv()
  - But reliable and ordered (receive bytes in same order as sent)

Sender   Receiver

IP header   TCP header

| A | | B | | C | | D |

Four segments, each with 512 bytes of
data and carried in an IP packet

| A B C D |

2048 bytes of data delivered
to app in a single recv() call

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Reliable Bytestream (2)

- Bidirectional data transfer
  - Control information (e.g., ACK) piggybacks on data segments in reverse direction

ACK B→A

ACK A→B   data A→B

A ———————————————————————— B

data B→A

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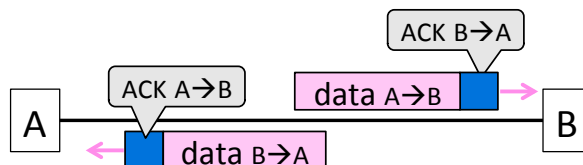
TCP Header (1)

- Ports identify apps (socket API)
  - 16-bit identifiers

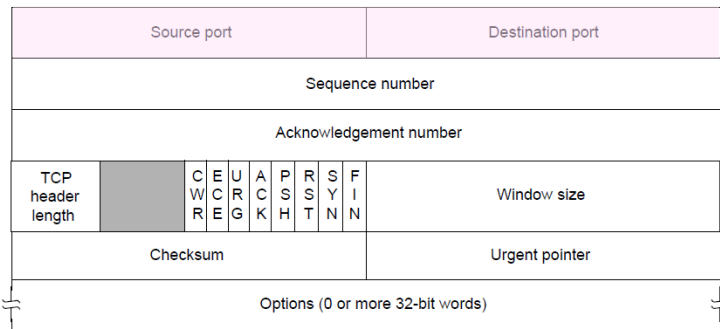| Source port	Destination port
Sequence number	
Acknowledgement number	
TCP header length	[C W R][E C E][U R G][A C K][P S H][R S T][S Y N][F I N]	Window size
Checksum	Urgent pointer
Options (0 or more 32-bit words)	

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TCP Header (2)

- SEQ/ACK used for sliding window
  - Selective Repeat, with byte positions

| Source port	Destination port
Sequence number	
Acknowledgement number	
TCP header length	[C W R][E C E][U R G][A C K][P S H][R S T][S Y N][F I N]	Window size
Checksum	Urgent pointer
Options (0 or more 32-bit words)	
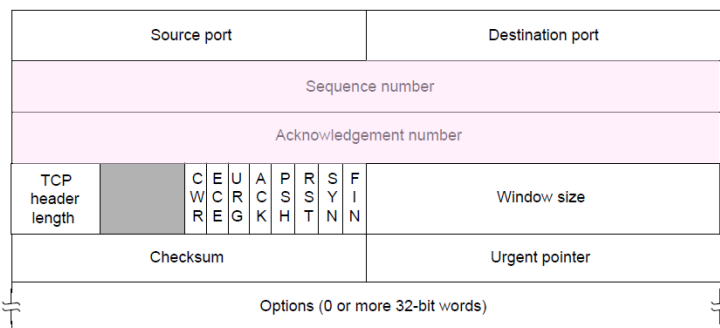
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TCP Sliding Window – Receiver

- <u>Cumulative</u> ACK tells next expected byte sequence number ("LAS+1")

- Optionally, <u>selective</u> ACKs (SACK) give hints for receiver buffer state
  - List up to 3 ranges of received bytes
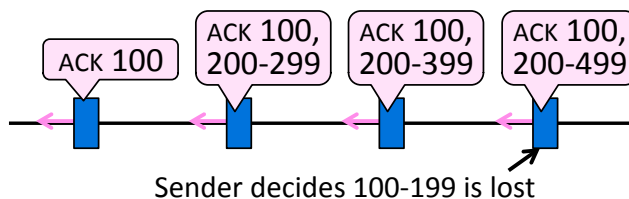
ACK up to 100 and 200-299
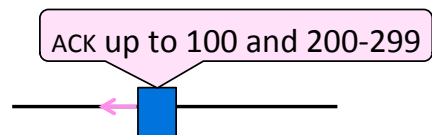
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TCP Sliding Window – Sender

- Uses adaptive retransmission timeout to resend data from LAS+1
- Uses heuristics to infer loss quickly and resend to avoid timeouts
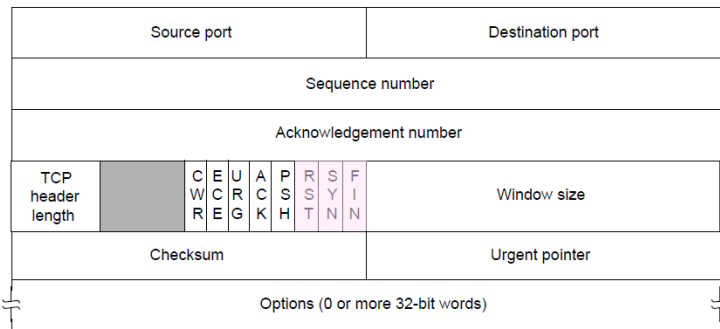 - "Three duplicate ACKs" treated as loss

ACK 100

ACK 100, 200-299

ACK 100, 200-399

ACK 100, 200-499

Sender decides 100-199 is lost

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TCP Header (3)

- SYN/FIN/RST flags for connections
  - Flag indicates segment is a SYN etc.

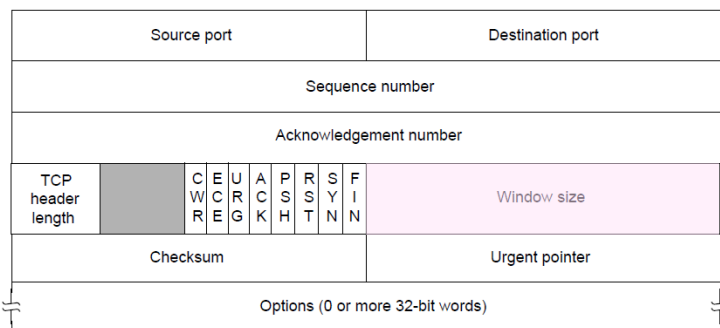| Source port										Destination port
Sequence number										
Acknowledgement number										
TCP header length		C W R	E C E	U R G	A C K	P S H	R S T	S Y N	F I N	Window size
Checksum										Urgent pointer
Options (0 or more 32-bit words)										

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TCP Header (4)

- Window size for flow control
  - Relative to ACK, and in bytes

Source port										Destination port
Sequence number										
Acknowledgement number										
TCP header length		C W R	E C E	U R G	A C K	P S H	R S T	S Y N	F I N	Window size
Checksum										Urgent pointer
Options (0 or more 32-bit words)										

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Other TCP Details

- Many, many quirks you can learn about its operation
  - But they are the details

- Biggest remaining mystery is the workings of congestion control
  - We'll tackle this next time!

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