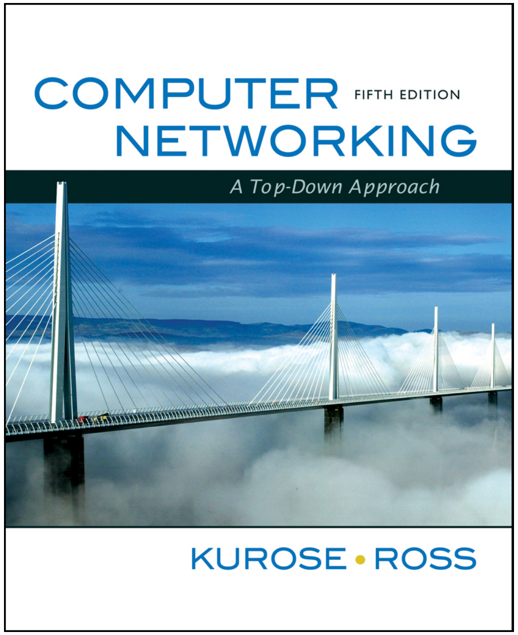
Chapter 3
Transport Layer



Computer Networking: A Top Down Approach
6th edition
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Addison-Wesley
April 2012

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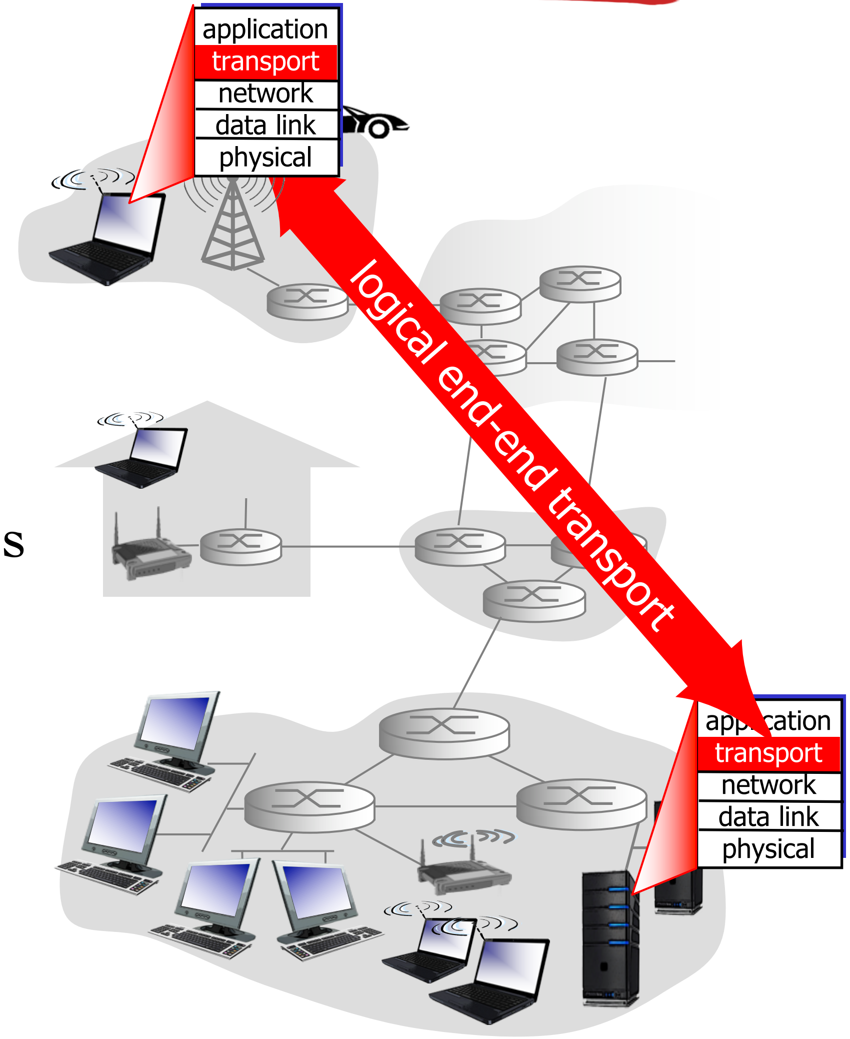
Chapter 3: Transport Layer

- learn about Internet transport layer protocols:
  - UDP: connectionless transport, brief not much to say
  - TCP: connection-oriented reliable transport
  - TCP congestion control

Transport services and protocols

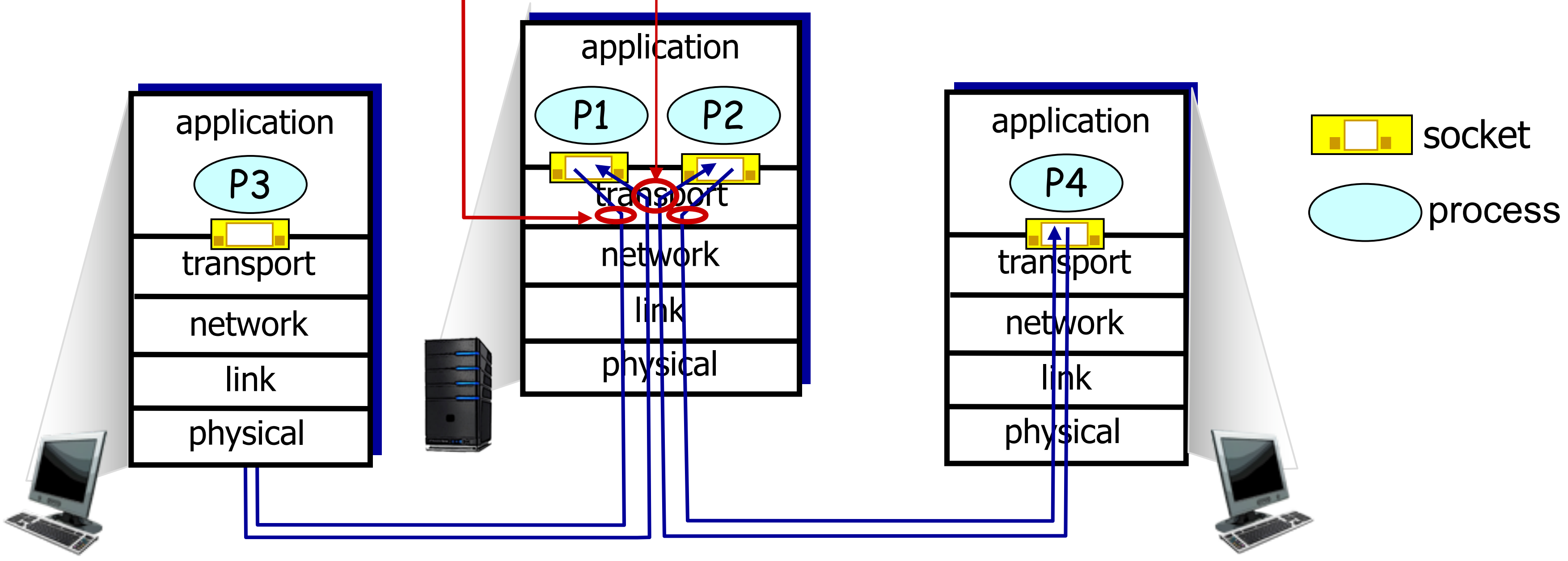
- provide *logical communication* between app processes running on different hosts
- transport protocols run in end systems
  - send side: breaks app messages into *segments*, passes to network layer
  - rcv side: reassembles segments into messages, passes to app layer
- more than one transport protocol available to apps
  - Internet: TCP and UDP
- no delay/service guarantees



Multiplexing/demultiplexing

multiplexing at sender:
handle data from multiple sockets, add transport header (later used for demultiplexing)

demultiplexing at receiver:
use header info to deliver received segments to correct socket

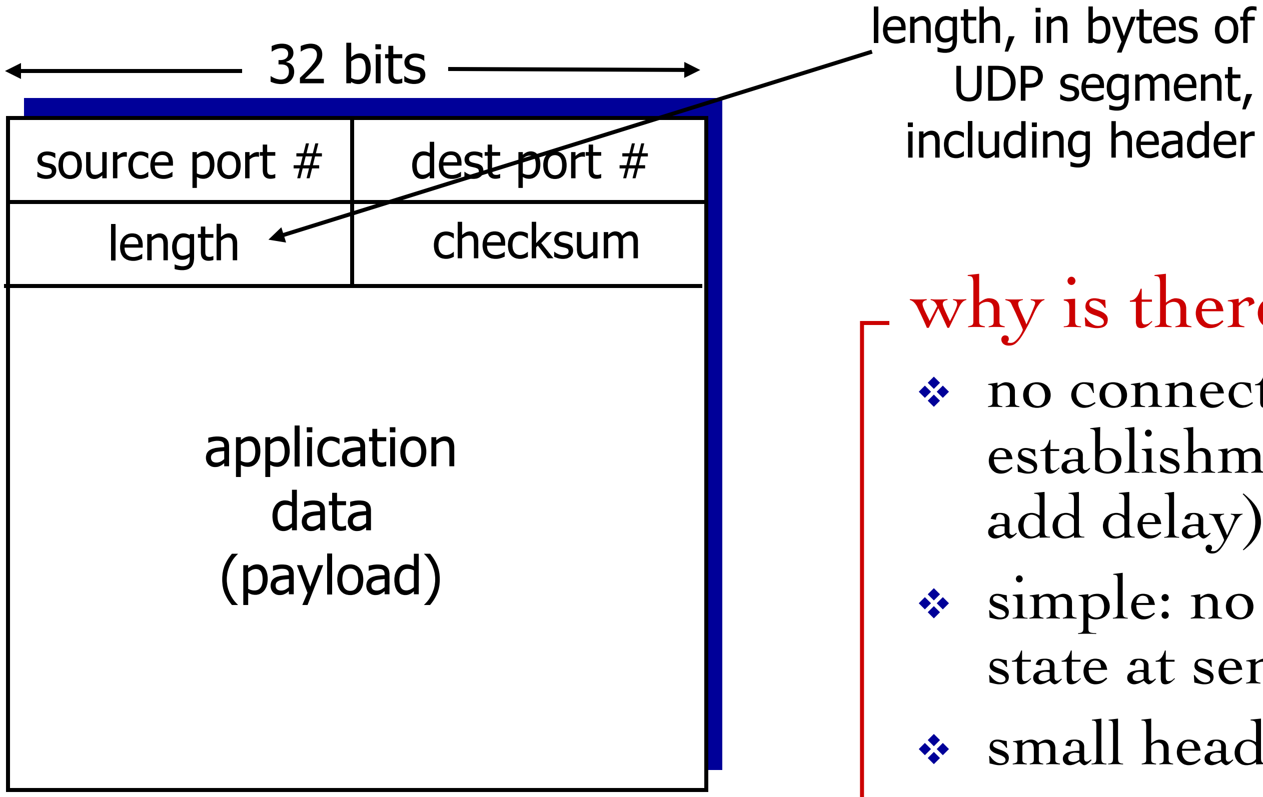


UDP: User Datagram Protocol [RFC 768]

- "no frills," "bare bones" Internet transport protocol
- "best effort" service, UDP segments may be:
  - lost
  - delivered out-of-order to app
- *connectionless:*
  - no handshaking between UDP sender, receiver
  - each UDP segment handled independently of others

- UDP use:
  - streaming multimedia apps (loss tolerant, rate sensitive)
  - DNS
  - SNMP
- reliable transfer over UDP:
  - add reliability at application layer
  - application-specific error recovery!

UDP: segment header



32 bits

source port # | dest port #

length | checksum

application data (payload)

length, in bytes of UDP segment, including header

UDP segment format

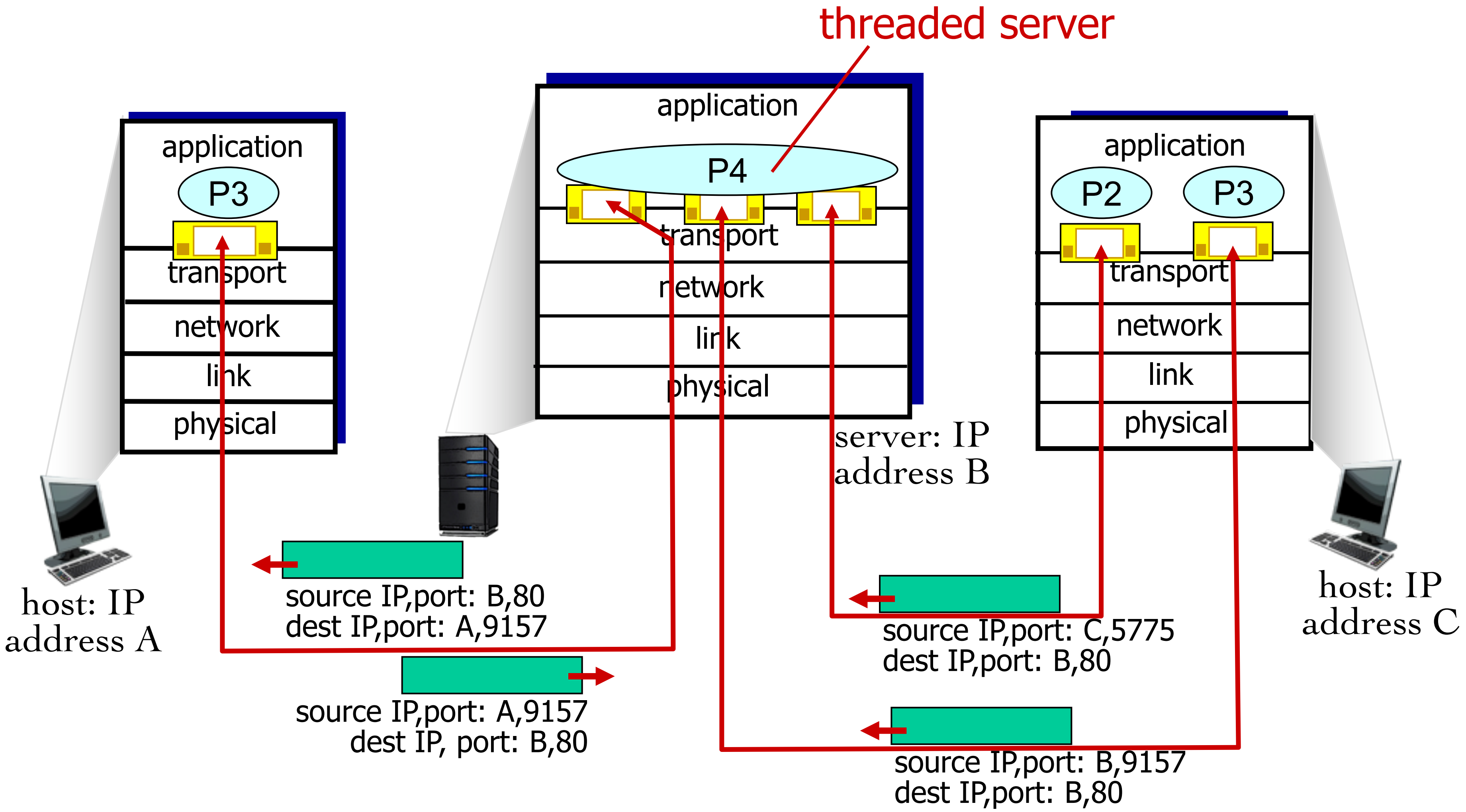
why is there a UDP?

- no connection establishment (which can add delay)
- simple: no connection state at sender, receiver
- small header size
- no congestion control: UDP can blast away as fast as desired

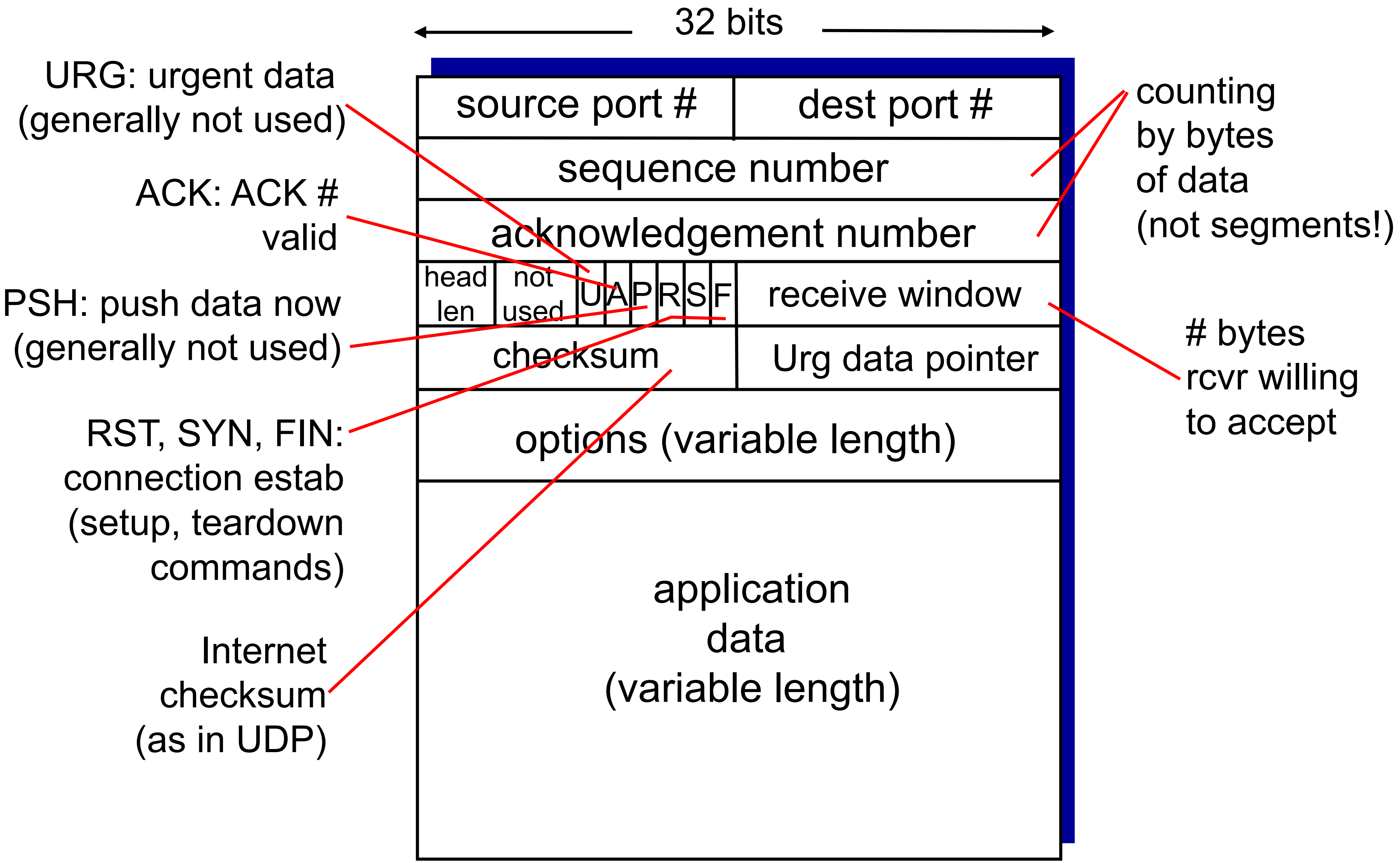
Connection-oriented demux

- TCP socket identified by 4-tuple:
  - source IP address
  - source port number
  - dest IP address
  - dest port number
- demux: receiver uses all four values to direct segment to appropriate socket
- server host may support many simultaneous TCP sockets:
  - each socket identified by its own 4-tuple
- web servers have different sockets for each connecting client
  - non-persistent HTTP will have different socket for each request

Connection-oriented demux



TCP segment structure



32 bits

source port #								dest port #
sequence number								
acknowledgement number								
head len	not used	U	A	P	R	S	F	receive window
checksum								Urg data pointer
options (variable length)								
application data (variable length)								

URG: urgent data (generally not used)

ACK: ACK # valid

PSH: push data now (generally not used)

RST, SYN, FIN: connection estab (setup, teardown commands)

Internet checksum (as in UDP)

counting by bytes of data (not segments!)

# bytes rcvr willing to accept

TCP: Overview RFCs: 793,1122,1323, 2018, 2581

- point-to-point:
  - one sender, one receiver
- reliable, in-order *byte steam:*
  - no "message boundaries"
- pipelined:
  - TCP congestion and flow control set window size
  - *Hybrid of go back n and selective repeat*
- full duplex data:
  - bi-directional data flow in same connection
  - MSS: maximum segment size
- connection-oriented:
  - handshaking (exchange of control msgs) inits sender, receiver state before data exchange
- flow controlled:
  - sender will not overwhelm receiver

channels with errors *and* loss

assumption: underlying channel can lose packets (data, ACKs)

- checksum, seq. #, ACKs, retransmissions will be of help … but not enough

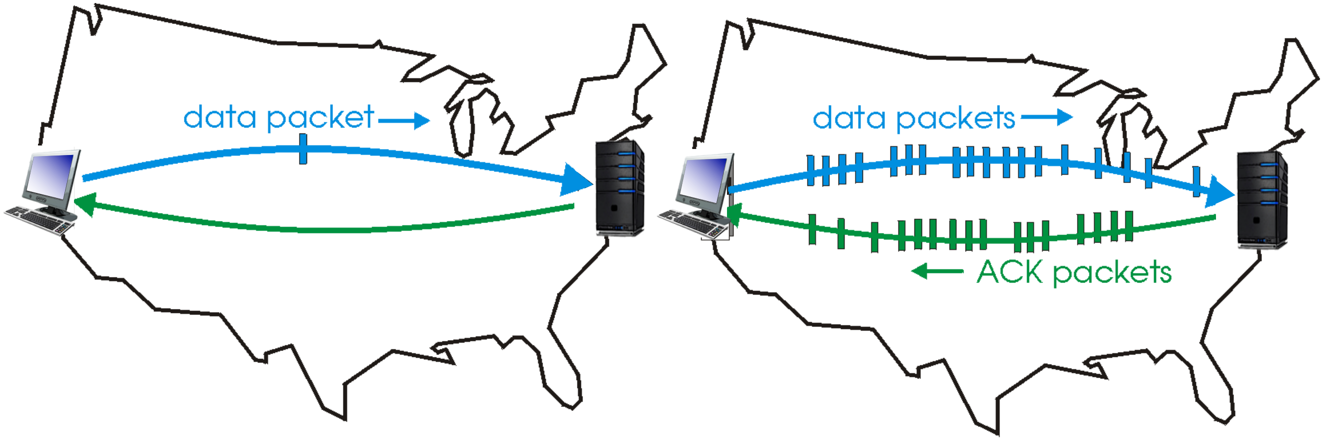
approach: sender waits "reasonable" amount of time for ACK

- retransmits if no ACK received in this time
- if pkt (or ACK) just delayed (not lost):
  - retransmission will be duplicate, but seq. #'s already handles this
  - receiver must specify seq # of pkt being ACKed
- requires countdown timer

Pipelined protocols

pipelining: sender allows multiple, "in-flight", yet-to-be-acknowledged pkts

- range of sequence numbers must be increased
- buffering at sender and/or receiver



(a) a stop-and-wait protocol in operation

(b) a pipelined protocol in operation

- two generic forms of pipelined protocols: *go-Back-N, selective repeat*

Pipelined protocols: concepts

Go-back-N:

- sender can have up to N unacked packets in pipeline
- receiver only sends *cumulative ack*
  - doesn' t ack packet if there' s a gap
- sender has timer for oldest unacked packet
  - when timer expires, retransmit *all* unacked packets

Selective Repeat:

- sender can have up to N unack' ed packets in pipeline
- rcvr sends *individual ack* for each packet
- sender maintains timer for each unacked packet
  - when timer expires, retransmit only that unacked packet

TCP seq. numbers, ACKs

sequence numbers:

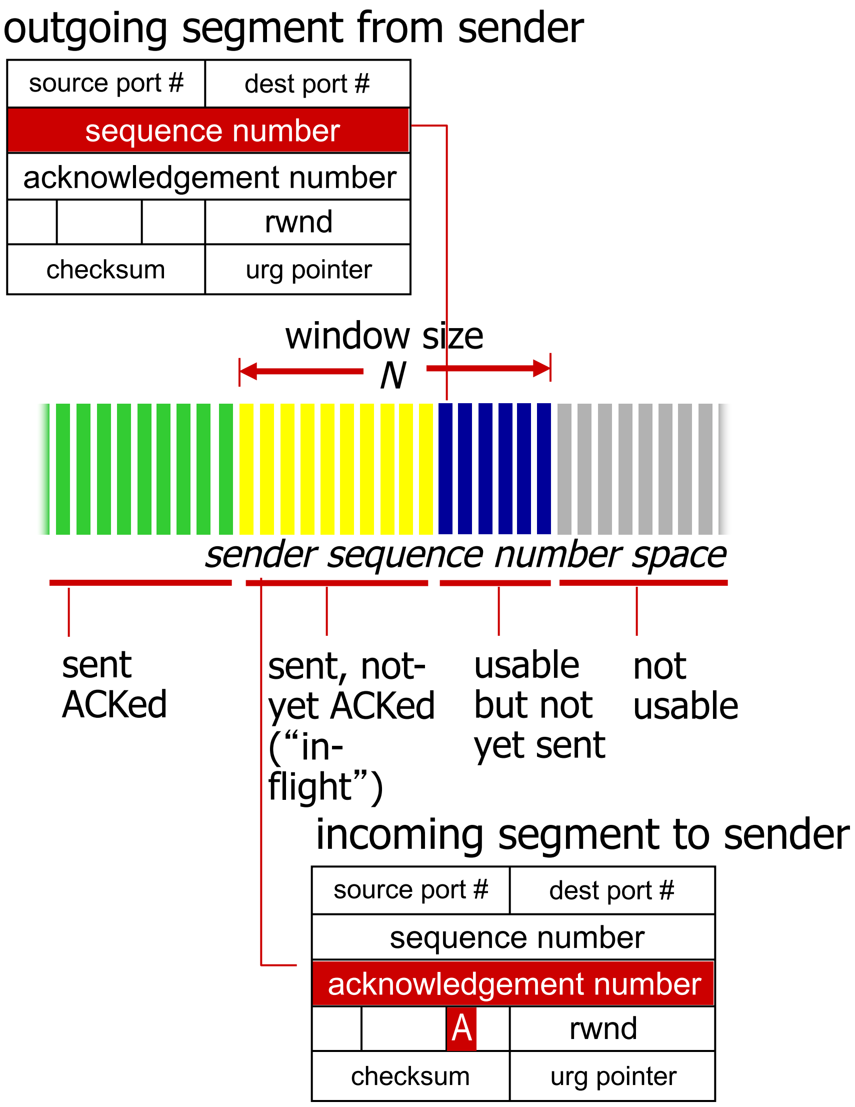
- byte stream "number" of first byte in segment's data

acknowledgements:

- seq # of next byte expected from other side
- cumulative ACK

Q: how receiver handles out-of-order segments

- A: TCP spec doesn't say, - up to implementor



outgoing segment from sender

source port #	dest port #
sequence number	
acknowledgement number	
	rwnd
checksum	urg pointer

window size

N

sender sequence number space

sent ACKed

sent, not-yet ACKed ("in-flight")

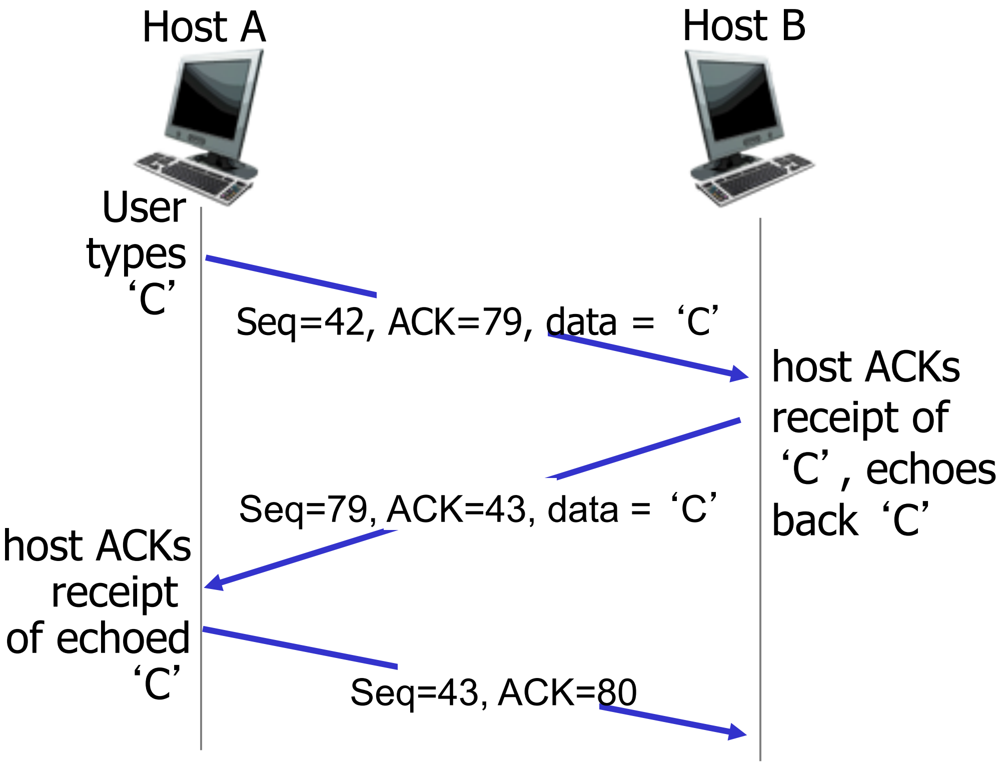
usable but not yet sent

not usable

incoming segment to sender

source port #	dest port #
sequence number	
acknowledgement number	
A	rwnd
checksum	urg pointer

TCP seq. numbers, ACKs


Host A
Host B
User types 'C'
Seq=42, ACK=79, data = 'C'
host ACKs receipt of 'C', echoes back 'C'
Seq=79, ACK=43, data = 'C'
host ACKs receipt of echoed 'C'
Seq=43, ACK=80

simple telnet scenario

TCP round trip time, timeout

Q: how to set TCP timeout value?

- longer than RTT
  - but RTT varies
- *too short:* premature timeout, unnecessary retransmissions
- *too long:* slow reaction to segment loss

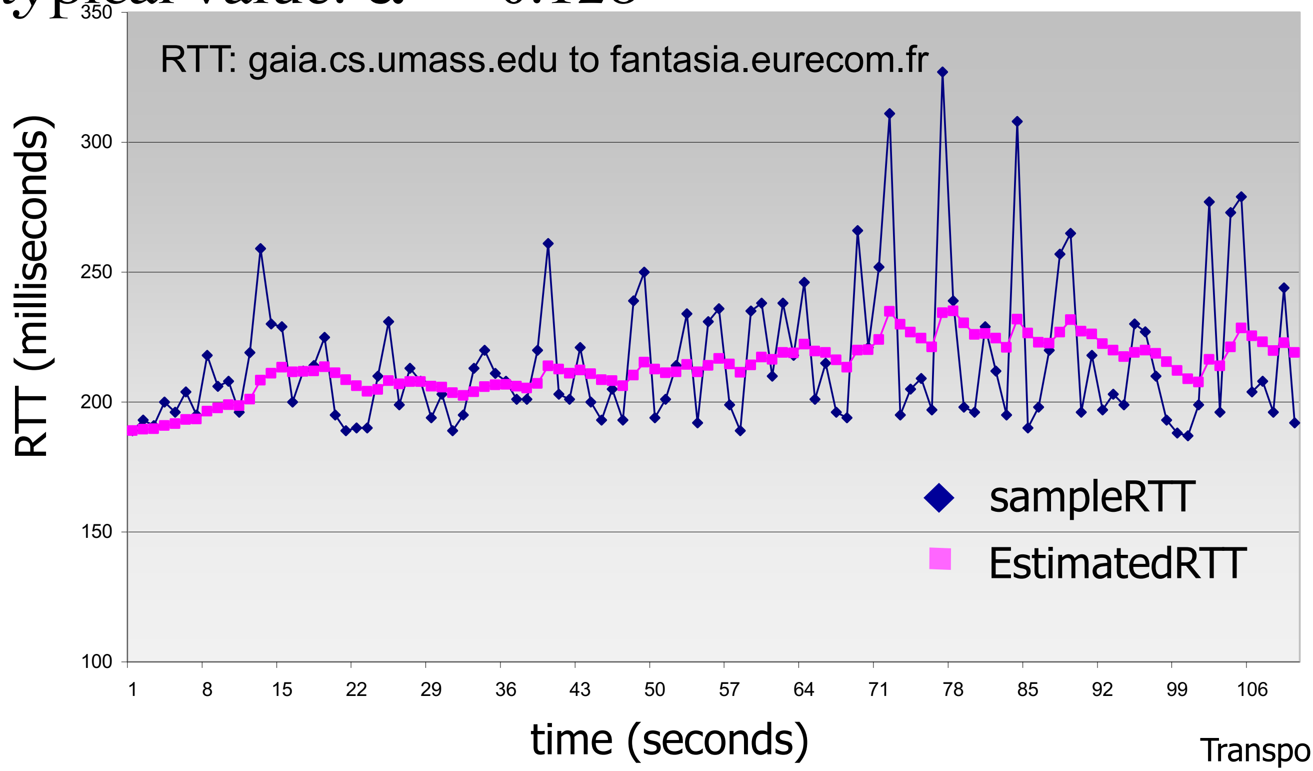
Q: how to estimate RTT?

- **`SampleRTT`**: measured time from segment transmission until ACK receipt
  - ignore retransmissions
- **`SampleRTT`** will vary, want estimated RTT "smoother"
  - average several *recent* measurements, not just current **`SampleRTT`**

TCP round trip time, timeout

`EstimatedRTT = (1- α)*EstimatedRTT + α*SampleRTT`

- exponential weighted moving average
- influence of past sample decreases exponentially fast
- typical value: **α = **0.125



TCP round trip time, timeout

- timeout interval: **`EstimatedRTT`** plus "safety margin"
  - large variation in **`EstimatedRTT ->`** larger safety margin
- estimate SampleRTT deviation from EstimatedRTT:

```
DevRTT = (1-β)*DevRTT +
               β*|SampleRTT-EstimatedRTT|

         (typically, β = 0.25)
```

$$\texttt{TimeoutInterval = } \underbrace{\texttt{EstimatedRTT}}_{\text{estimated RTT}} \texttt{ + } \underbrace{\texttt{4*DevRTT}}_{\text{“safety margin”}}$$

TCP simple sender (no optimizations, congestion control):

data rcvd from app:

- create segment with seq #
- seq # is byte-stream number of first data byte in segment
- start timer if not already running
  - think of timer as for oldest unacked segment
  - expiration interval: **`TimeOutInterval`**

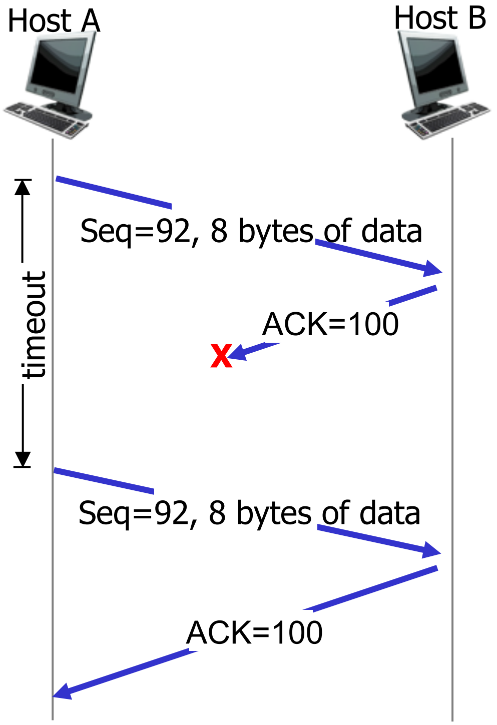
timeout:

- retransmit segment that caused timeout
- restart timer

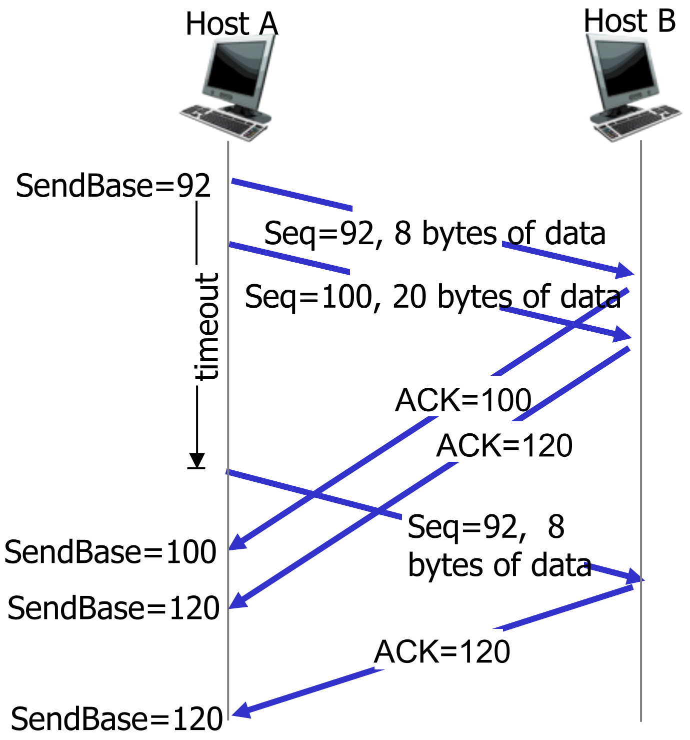
ack rcvd:

- if ack acknowledges previously unacked segments
  - update what is known to be ACKed
  - start timer if there are still unacked segments

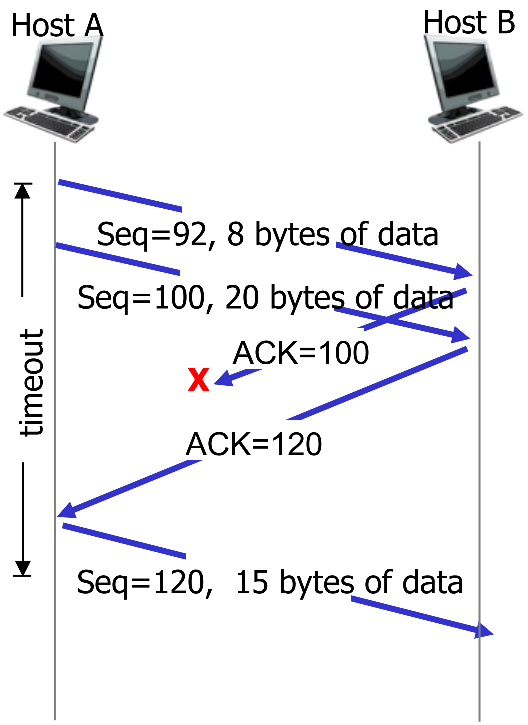
TCP: retransmission scenarios



lost ACK scenario



premature timeout



cumulative ACK

TCP ACK original generation

[RFC 1122, RFC 2581]

event at receiver	*TCP receiver action*
arrival of in-order segment with expected seq #. All data up to expected seq # already ACKed	delayed ACK. Wait up to 500ms for next segment. If no next segment, send ACK
arrival of in-order segment with expected seq #. One other segment has ACK pending	immediately send single cumulative ACK, ACKing both in-order segments
arrival of out-of-order segment higher-than-expect seq. # . Gap detected	immediately send *duplicate ACK,* indicating seq. # of next expected byte
arrival of segment that partially or completely fills gap	immediate send ACK, provided that segment starts at lower end of gap

TCP fast retransmit—detect loss before timeout

- 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.

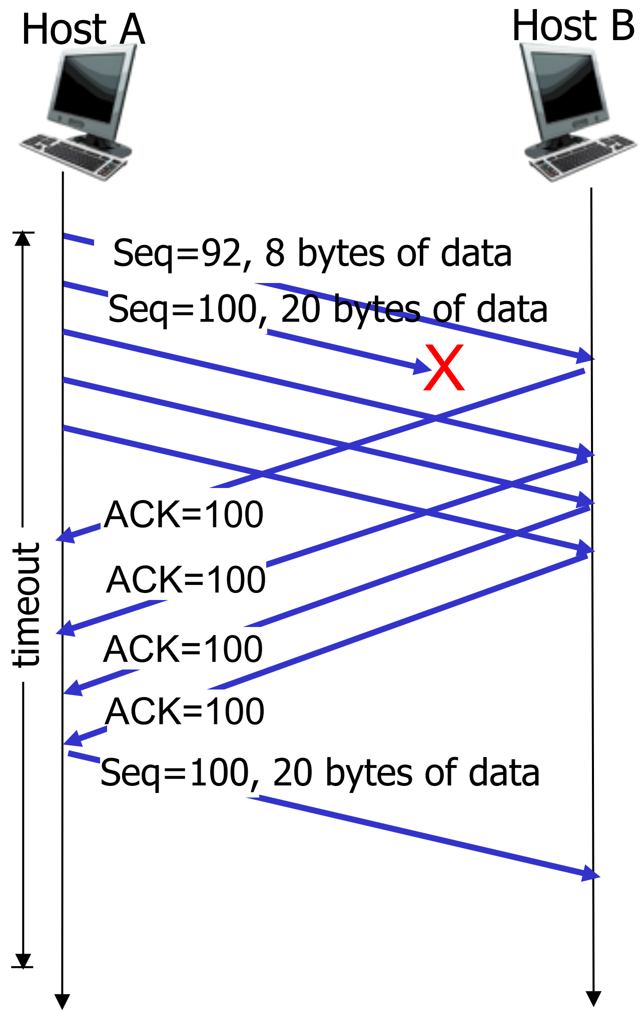
TCP fast retransmit

if sender receives 3 ACKs for same data

("triple duplicate ACKs"), resend unacked segment with smallest seq #

- likely that unacked segment lost, so don't wait for timeout

TCP fast retransmit

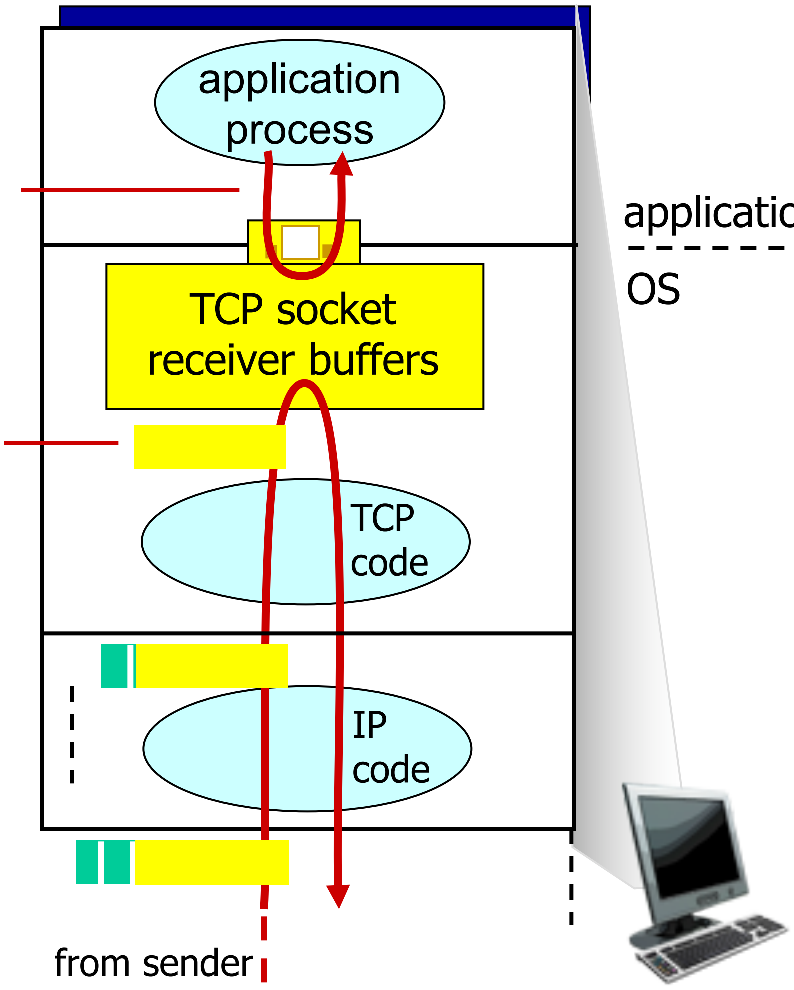


fast retransmit after sender receipt of triple duplicate ACK

TCP flow control

application may remove data from TCP socket buffers ….

… slower than TCP receiver is delivering (sender is sending)



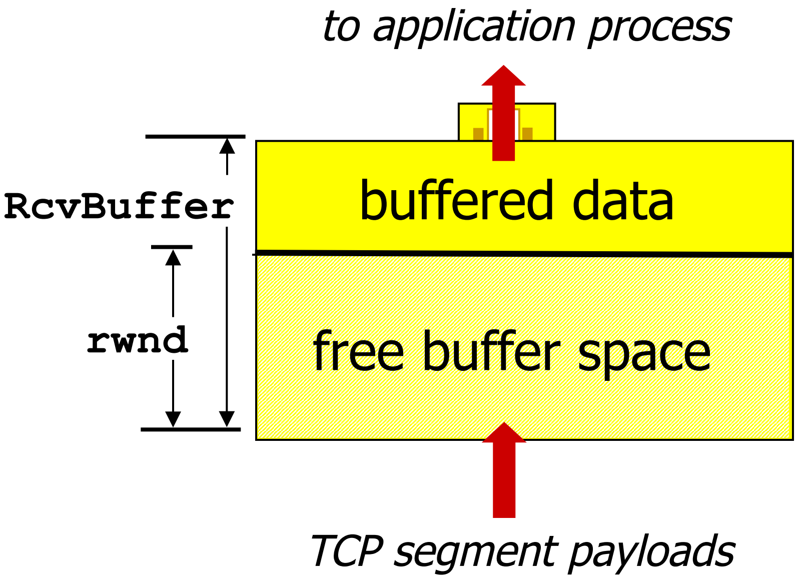
receiver protocol stack

flow control

receiver controls sender, so sender won't overflow receiver's buffer by transmitting too much, too fast

TCP flow control

- receiver "advertises" free buffer space by including **`rwnd`** value in TCP header of receiver-to-sender segments
  - **`RcvBuffer`** size set via socket options (typical default is 4096 bytes)
  - many operating systems autoadjust **`RcvBuffer`**
- sender limits amount of unacked ("in-flight") data to receiver's **`rwnd`** value
- guarantees receive buffer will not overflow

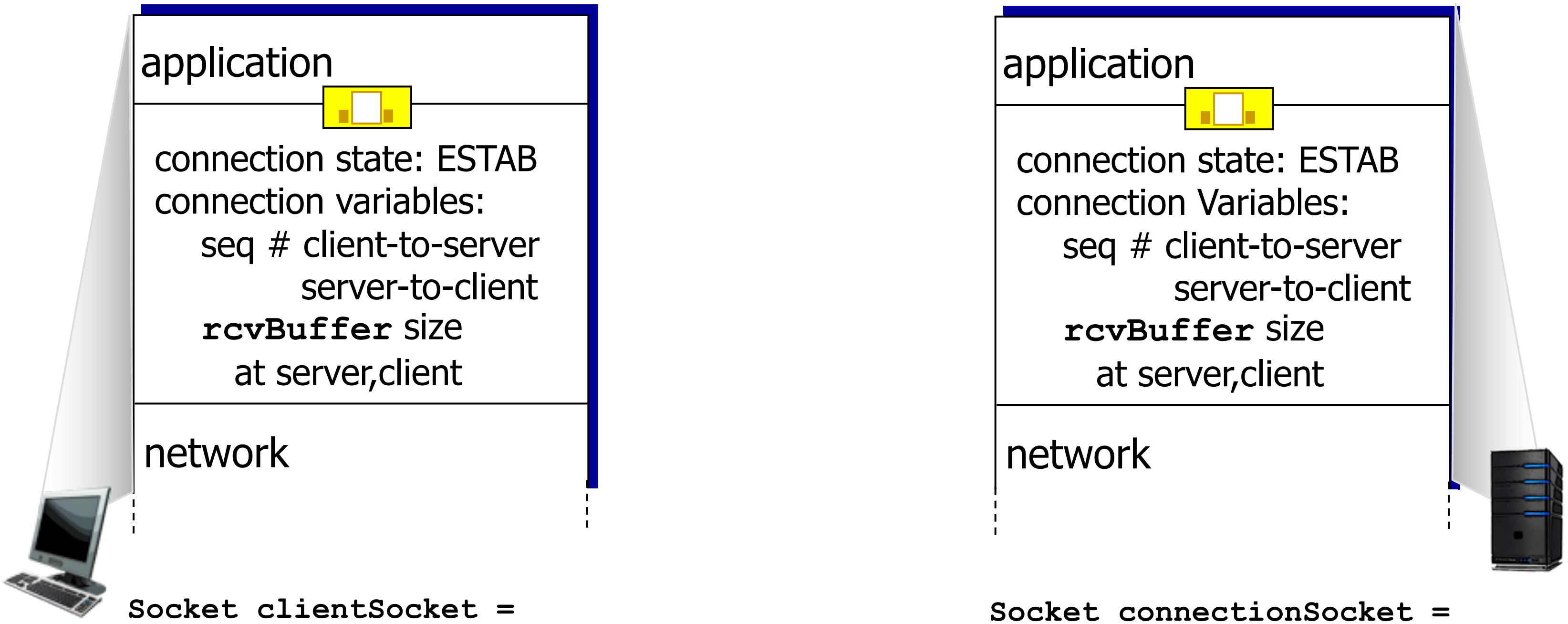


receiver-side buffering

Connection Management

before exchanging data, sender/receiver "handshake":

- agree to establish connection (each knowing the other willing to establish connection)
- agree on connection parameters – sequence number



application

connection state: ESTAB
connection variables:
seq # client-to-server
server-to-client
rcvBuffer size
at server,client

network

application

connection state: ESTAB
connection Variables:
seq # client-to-server
server-to-client
rcvBuffer size
at server,client

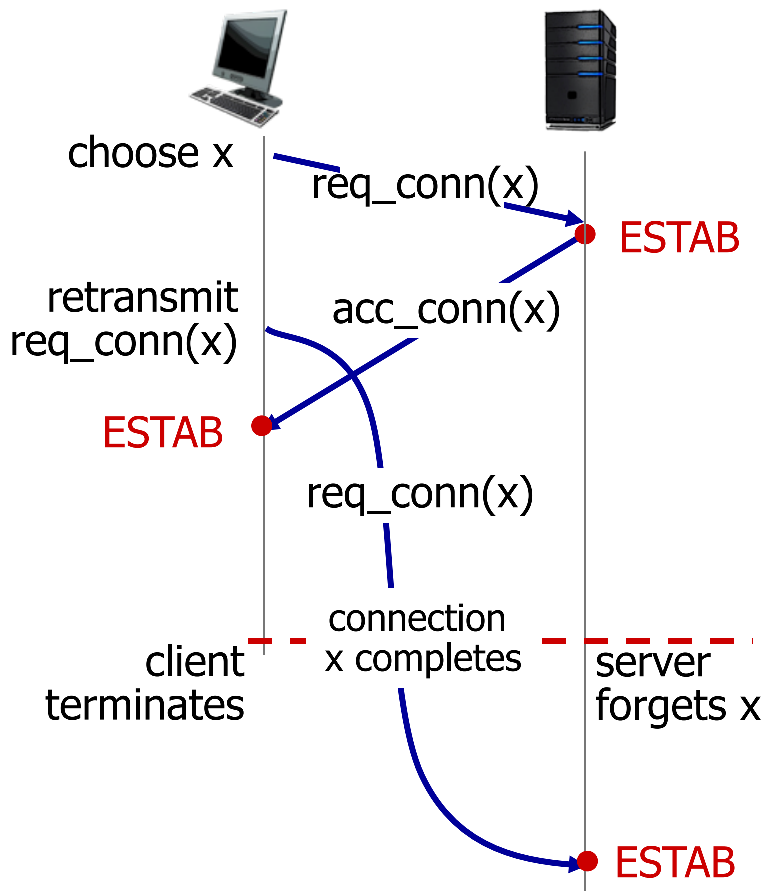
network

```
Socket clientSocket =
  newSocket("hostname","port
   number");
```

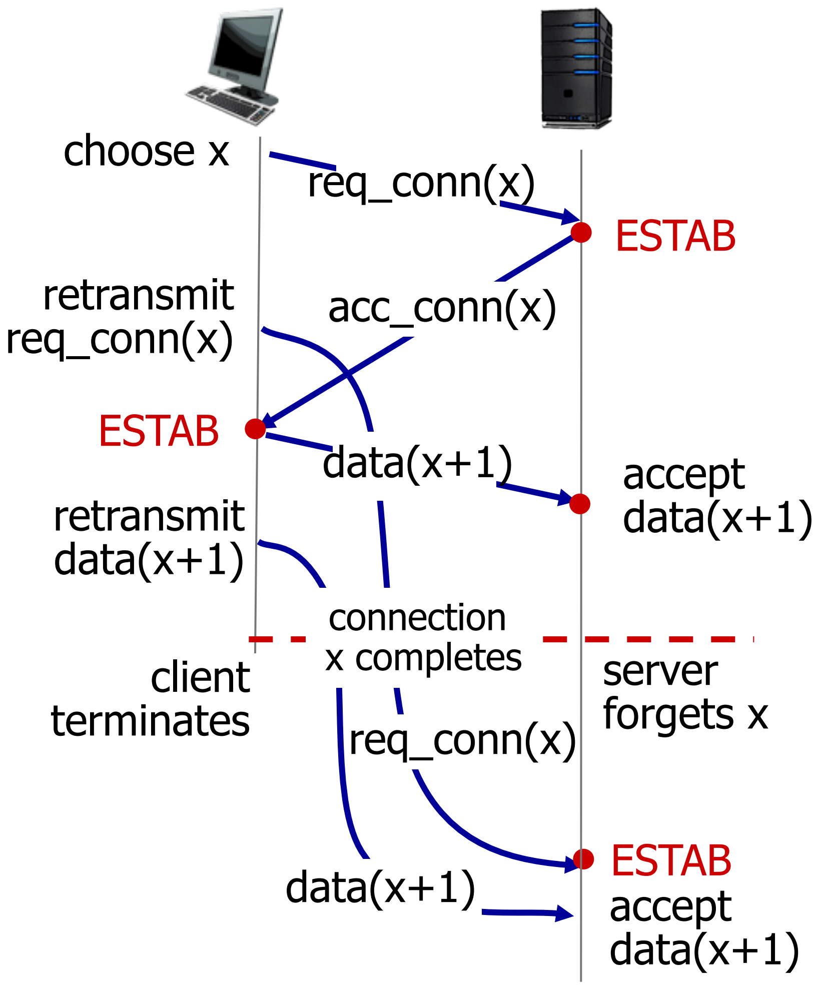
```
Socket connectionSocket =
   welcomeSocket.accept();
```

Agreeing to establish a connection

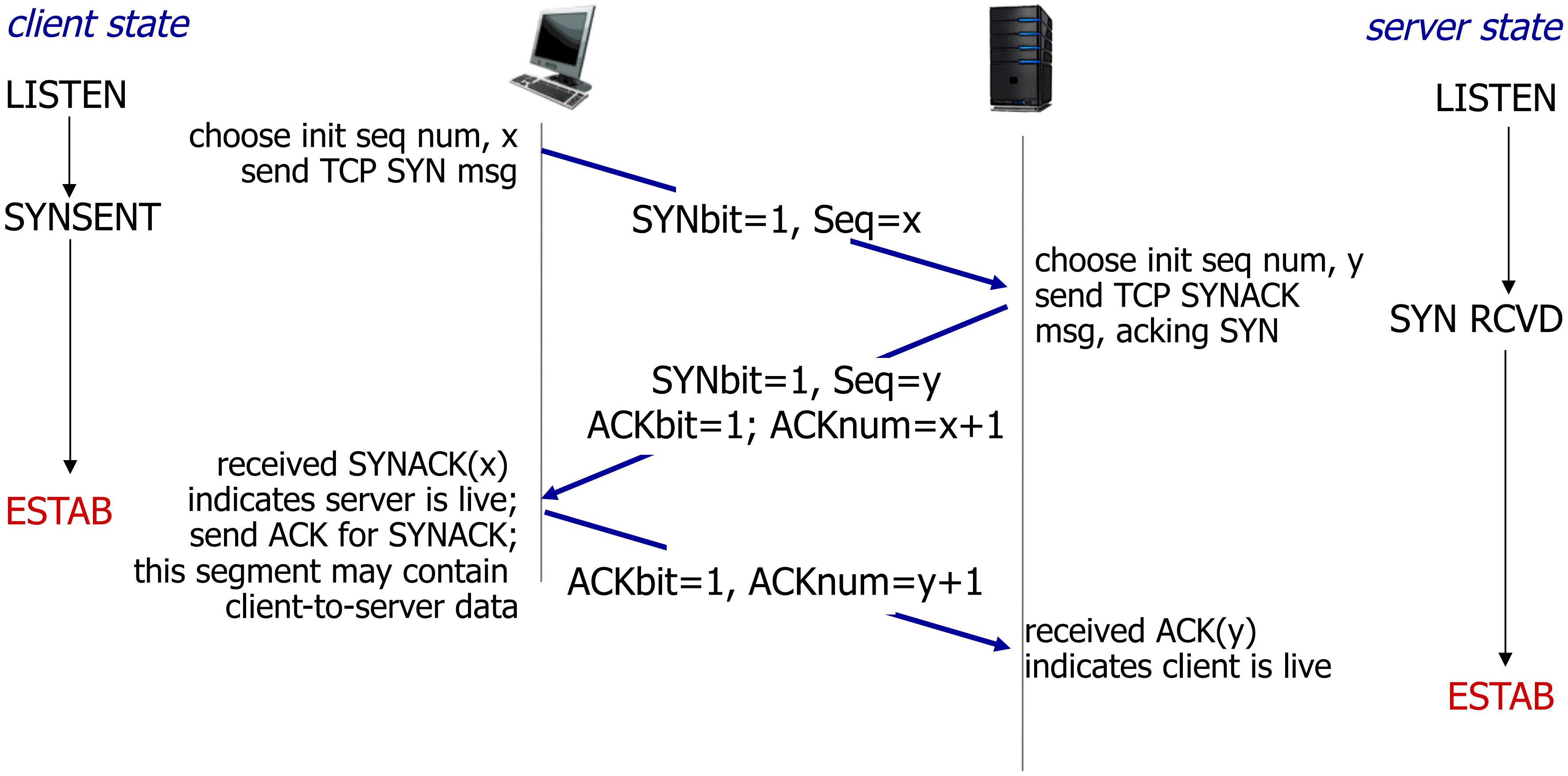
2-way handshake failure scenarios:



half open connection!
(no client!)



TCP 3-way handshake



client state

LISTEN

SYNSENT

ESTAB

choose init seq num, x
send TCP SYN msg

SYNbit=1, Seq=x

server state

LISTEN

SYN RCVD

ESTAB

choose init seq num, y
send TCP SYNACK
msg, acking SYN

SYNbit=1, Seq=y
ACKbit=1; ACKnum=x+1

received SYNACK(x)
indicates server is live;
send ACK for SYNACK;
this segment may contain
client-to-server data

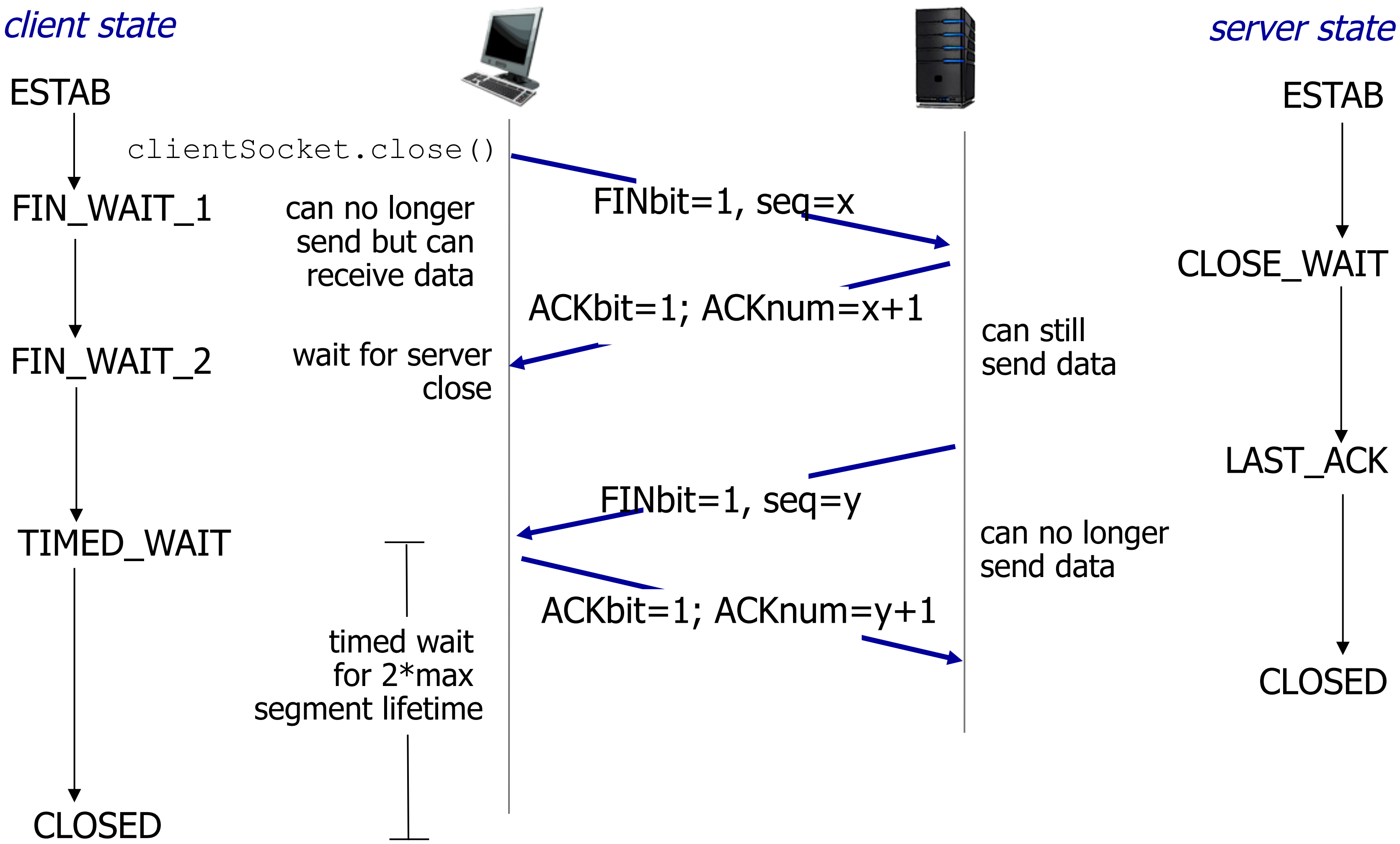
ACKbit=1, ACKnum=y+1

received ACK(y)
indicates client is live

TCP: closing a connection

- client, server each close their side of connection
  - send TCP segment with FIN bit = 1
- respond to received FIN with ACK
  - on receiving FIN, ACK can be combined with own FIN
- simultaneous FIN exchanges can be handled

TCP: closing a connection



client state

server state

ESTAB

ESTAB

clientSocket.close()

FIN_WAIT_1

can no longer send but can receive data

FINbit=1, seq=x

CLOSE_WAIT

ACKbit=1; ACKnum=x+1

FIN_WAIT_2

wait for server close

can still send data

LAST_ACK

FINbit=1, seq=y

TIMED_WAIT

can no longer send data

ACKbit=1; ACKnum=y+1

timed wait for 2*max segment lifetime

CLOSED

CLOSED

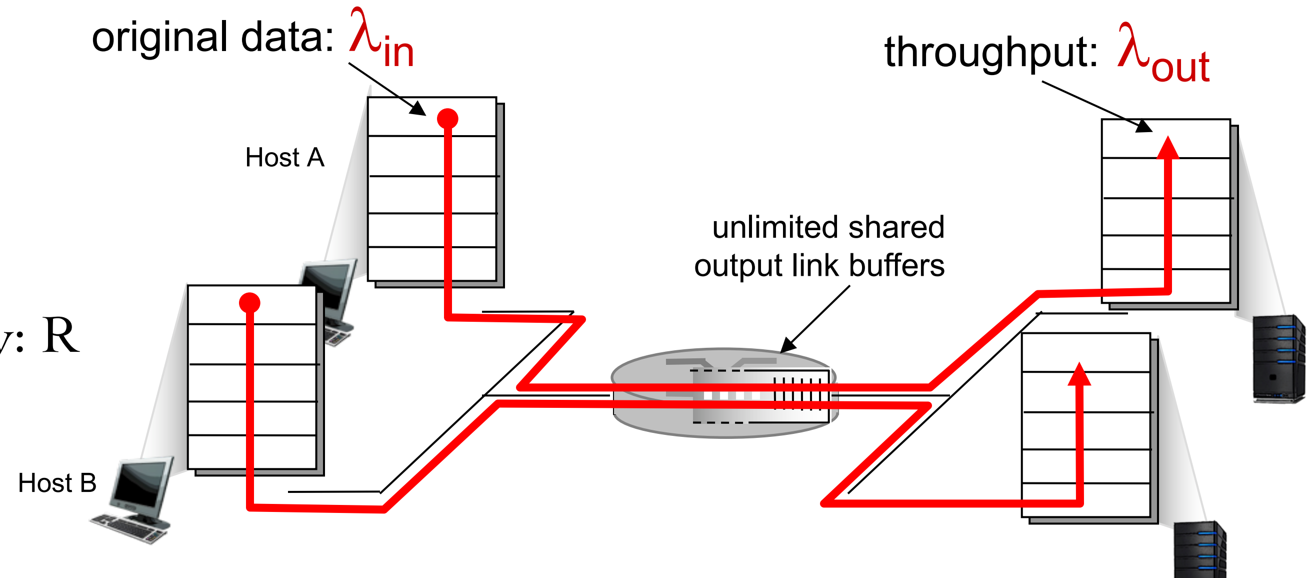
Principles of congestion control

congestion:

- informally: "too many sources sending too much data too fast for *network* to handle"
- different from flow control!
- manifestations:
  - lost packets (buffer overflow at routers)
  - long delays (queueing in router buffers)
- a top-10 problem!

Causes/costs of congestion: delay

- two senders, two receivers
- one router, infinite buffers
- output link capacity: R
- no retransmission



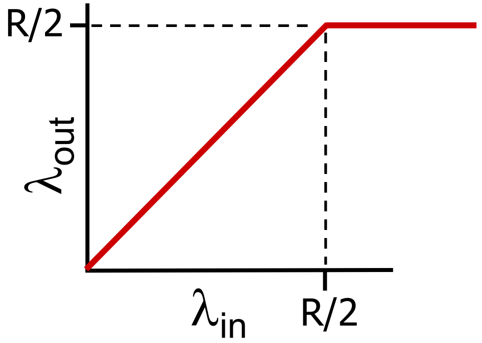
original data: λ_{in}

throughput: λ_{out}

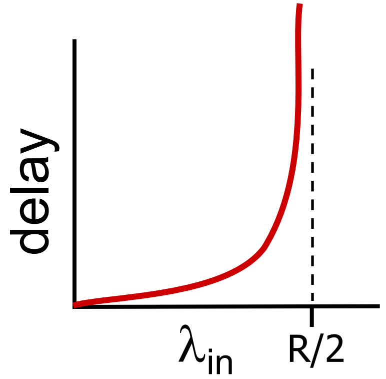
Host A

Host B

unlimited shared output link buffers



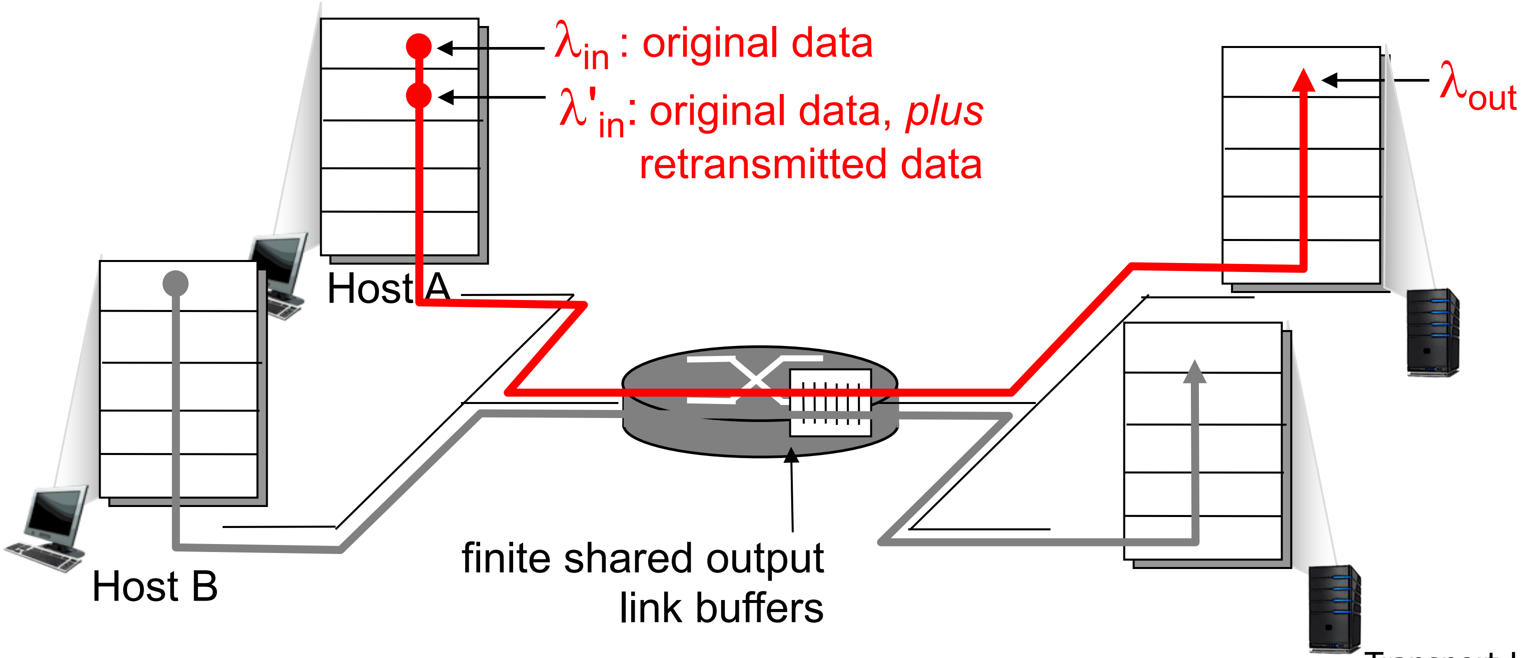
- maximum per-connection throughput: R/2



- large delays as arrival rate, λ_{in}, approaches capacity

Causes/costs of congestion: drop + duplicate

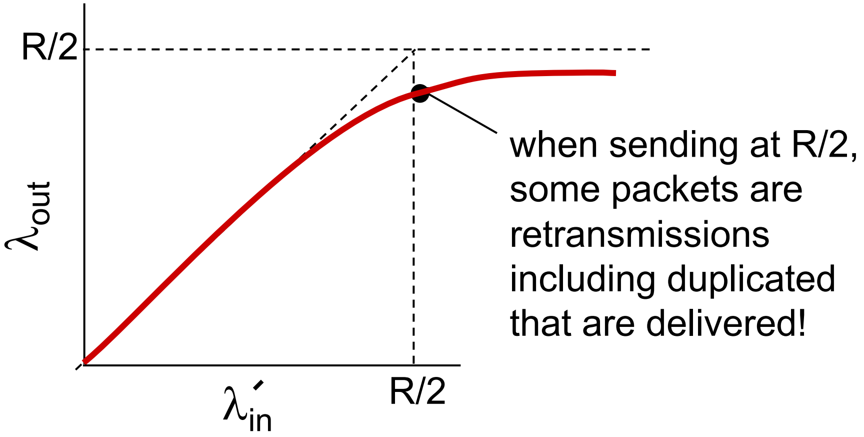
- one router, *finite* buffers
- sender retransmission of timed-out packet
  - application-layer input = application-layer output: $\lambda_{\text{in}} = \lambda_{\text{out}}$
  - transport-layer input includes *retransmissions* : $\lambda'_{\text{in}} \geq \lambda_{\text{in}}$


λ_{in} : original data
λ'_{in}: original data, *plus* retransmitted data
λ_{out}
Host A
Host B
finite shared output link buffers

Causes/costs of congestion:

duplicates

- packets can be lost, dropped at router due to full buffers
- sender times out prematurely, sending two copies, both of which are delivered

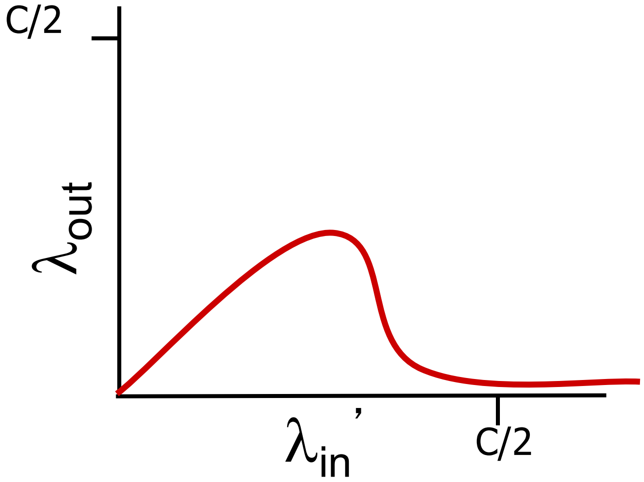


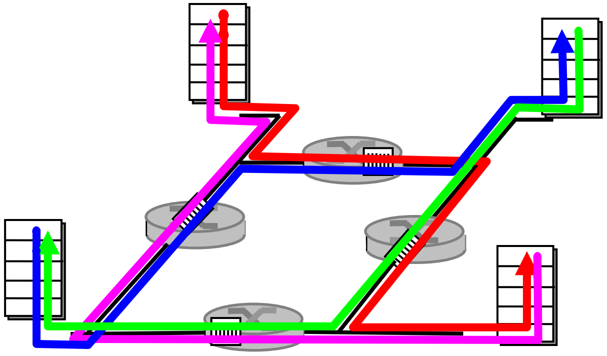
when sending at R/2, some packets are retransmissions including duplicated that are delivered!

"costs" of congestion:

- more work (retrans) for given "goodput"
- unneeded retransmissions: link carries multiple copies of pkt
  - decreasing goodput

Causes/costs of congestion: multi-hop paths





another "cost" of congestion:

- when packet dropped, any "upstream transmission capacity used for that packet was wasted!

Approaches towards congestion control

two broad approaches towards congestion control:

end-end congestion control:

- no explicit feedback from network
- congestion inferred from end-system observed loss, delay, Ack signals from receiver
- approach taken by TCP

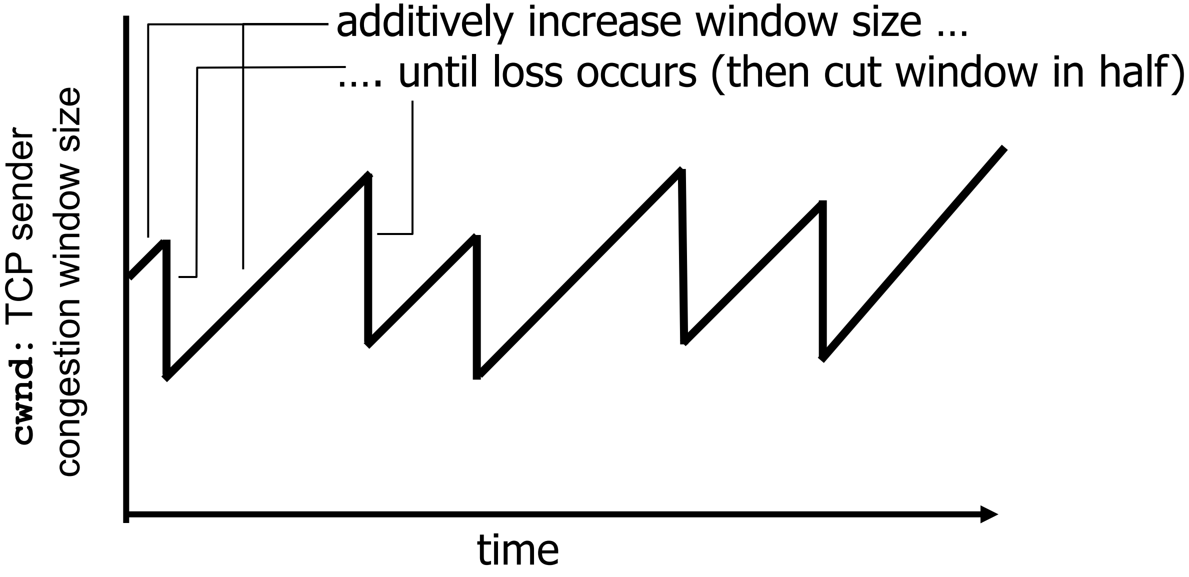
network-assisted congestion control:

- routers provide feedback to end systems
  - single bit indicating congestion as packet forwarded (SNA, DECbit, TCP/IP ECN)

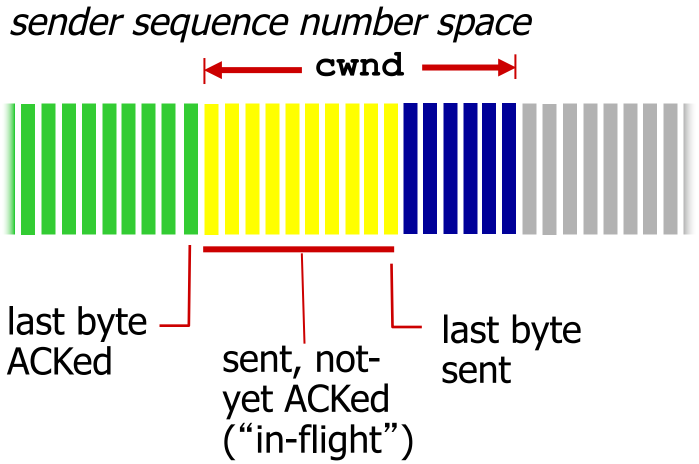
TCP congestion control basics:
additive increase multiplicative decrease

- approach: sender increases transmission rate (window size), probing for usable bandwidth, until loss occurs
  - additive increase: increase **`cwnd`** by 1 MSS (max segment size, default 536 bytes) every RTT until loss detected
  - multiplicative decrease: cut **`cwnd`** in half after loss

AIMD saw tooth behavior: probing for bandwidth



TCP Congestion Control: window


sender sequence number space
cwnd
last byte ACKed
sent, not-yet ACKed ("in-flight")
last byte sent

- sender limits transmission:

$$\boxed{\texttt{LastByteSent-}\ \texttt{LastByteAcked} \leq \texttt{cwnd}}$$

- **`cwnd`** is dynamic, function of perceived network congestion

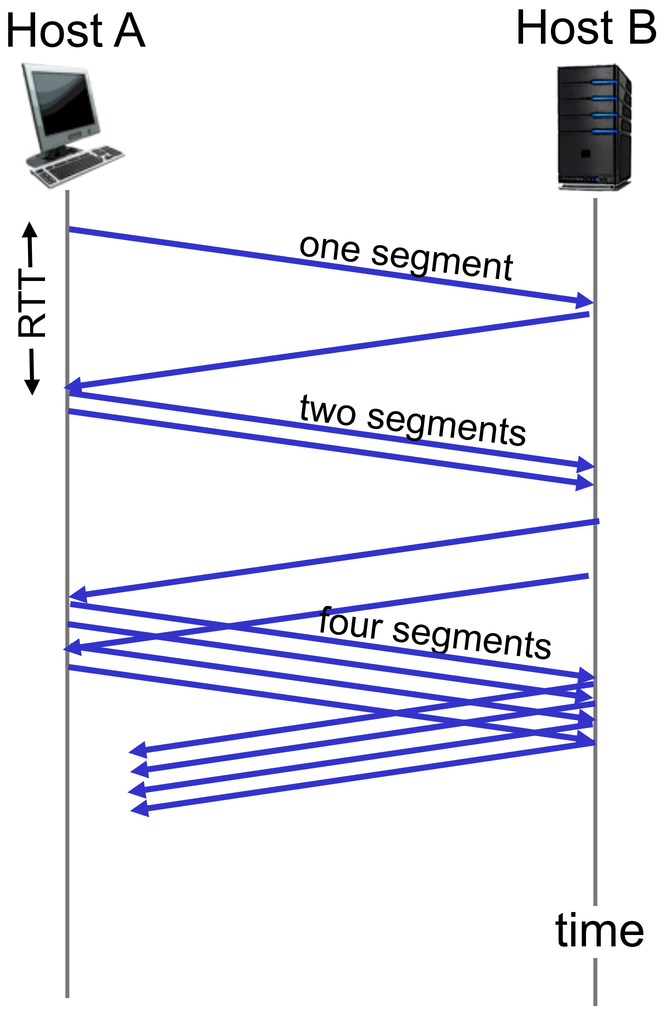
TCP sending rate:

- *roughly:* send cwnd bytes, wait RTT for ACKS, then send more bytes

$$\boxed{\text{rate} \approx \frac{\text{cwnd}}{\text{RTT}} \text{ bytes/sec}}$$

TCP Slow Start

- when connection begins, rate (window) small but increase rate (window) exponentially until first loss event:
  - initially **cwnd** = 1 MSS
  - double **cwnd** every RTT
  - done by incrementing **cwnd** for every ACK received
- summary: initial rate is slow but ramps up exponentially fast



TCP: detecting and responding to loss

- If loss detected by timeout:
  - **`cwnd`** set to 1 MSS
  - window initially grows exponentially to threshold (ssthresh), then grows linearly

- Fast Retransmit (reminder): Faster loss detection signaled by duplicate ACKs from receiver;
  - Receiver adjusted to send Ack each time packet received even if it's a duplicate (no advance in seq number)
  - Sender waits for 3 duplicate Acks (not just one in case slightly out of order delivery)

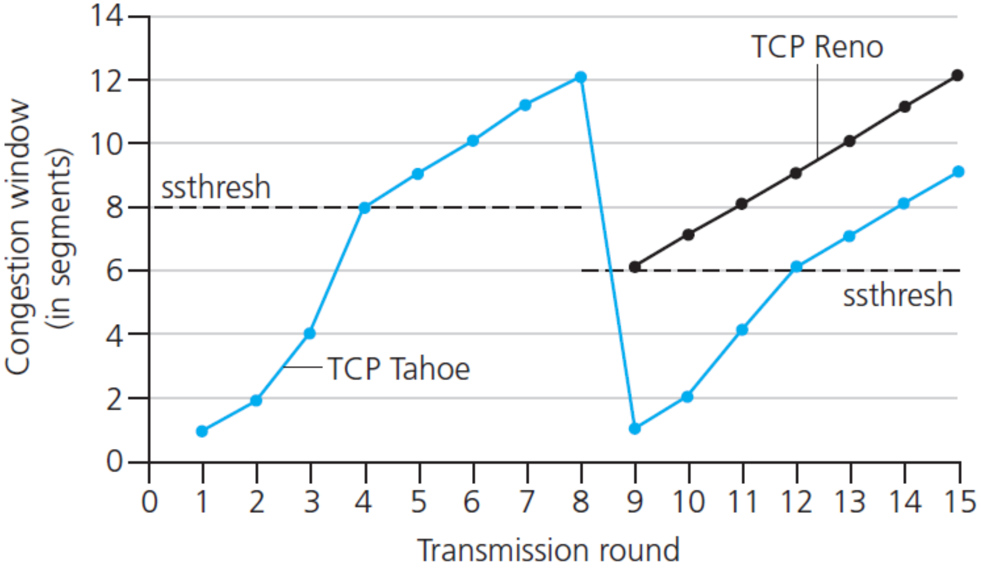
TCP: reacting to loss

- If loss detected by timeout **`cwnd`** set to 1 MSS
- If lost detected by duplicate ACKS: can be less reactive since ACKs indicate network able to deliver packets to receiver
  - TCP Reno: **`cwnd`** is only cut in half (not set to 1); then window grows linearly
  - TCP New Reno: improves retransmit during fast recovery given wireless link loss is not usually due to network congestion
    - for every ACK that advances sequence space, send next packet beyond the ACKed sequence number as well

TCP: switching from slow start to CA

Q: when should the exponential increase switch to linear?

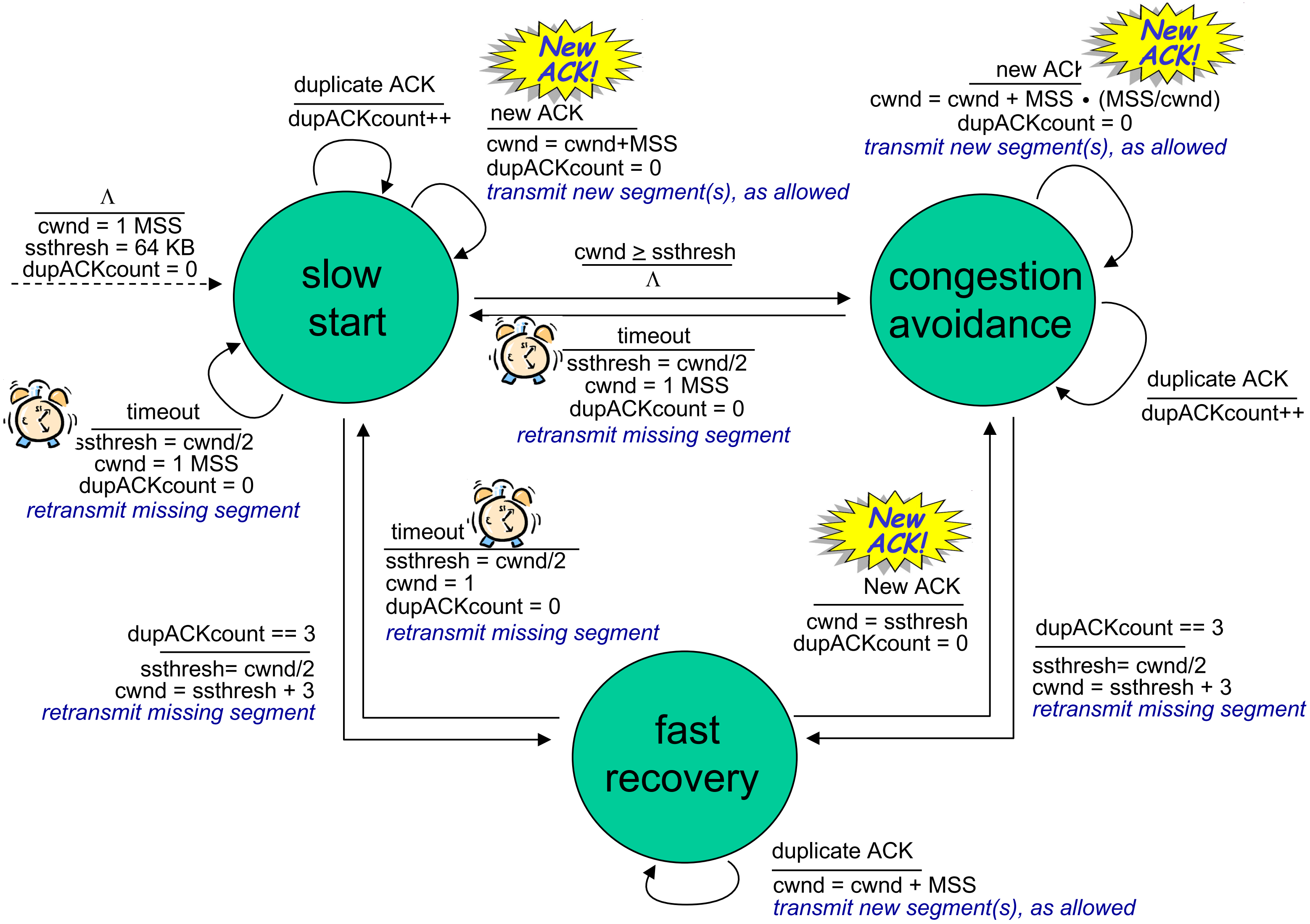
A: when **cwnd** gets to 1/2 of its value before timeout.



Implementation:

- variable **ssthresh**
- on loss event, **ssthresh** is set to 1/2 of **cwnd** just before loss event

Summary: TCP Congestion Control



slow start

congestion avoidance

fast recovery

Λ
cwnd = 1 MSS
ssthresh = 64 KB
dupACKcount = 0

duplicate ACK
dupACKcount++

New ACK!
new ACK
cwnd = cwnd+MSS
dupACKcount = 0
transmit new segment(s), as allowed

cwnd ≥ ssthresh
Λ

timeout
ssthresh = cwnd/2
cwnd = 1 MSS
dupACKcount = 0
retransmit missing segment

New ACK!
new ACK
cwnd = cwnd + MSS • (MSS/cwnd)
dupACKcount = 0
transmit new segment(s), as allowed

duplicate ACK
dupACKcount++

timeout
ssthresh = cwnd/2
cwnd = 1 MSS
dupACKcount = 0
retransmit missing segment

timeout
ssthresh = cwnd/2
cwnd = 1
dupACKcount = 0
retransmit missing segment

dupACKcount == 3
ssthresh= cwnd/2
cwnd = ssthresh + 3
retransmit missing segment

New ACK!
New ACK
cwnd = ssthresh
dupACKcount = 0

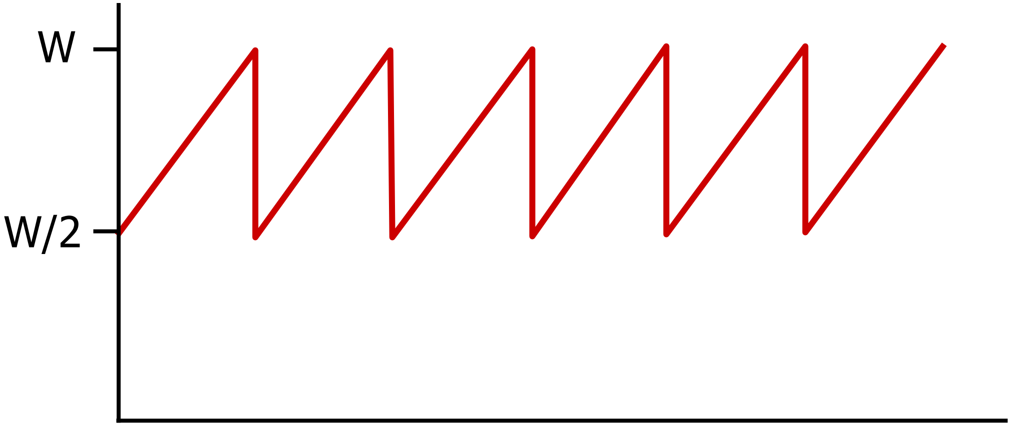
dupACKcount == 3
ssthresh= cwnd/2
cwnd = ssthresh + 3
retransmit missing segment

duplicate ACK
cwnd = cwnd + MSS
transmit new segment(s), as allowed

TCP throughput

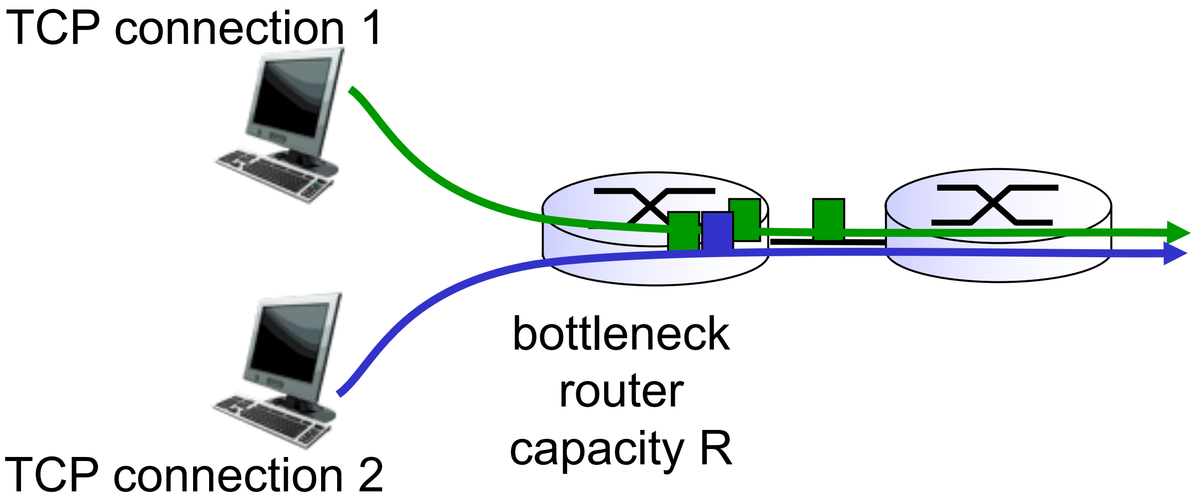
- avg. TCP thruput as function of window size, RTT?
  - ignore transient of slow start, assume always data to send
- W: window size (measured in bytes) where loss occurs
  - avg. window size (# in-flight bytes) is ¾ W
  - avg. thruput is 3/4W per RTT

$$\text{avg TCP thruput} = \frac{3}{4}\frac{W}{RTT} \text{ bytes/sec}$$



TCP Fairness

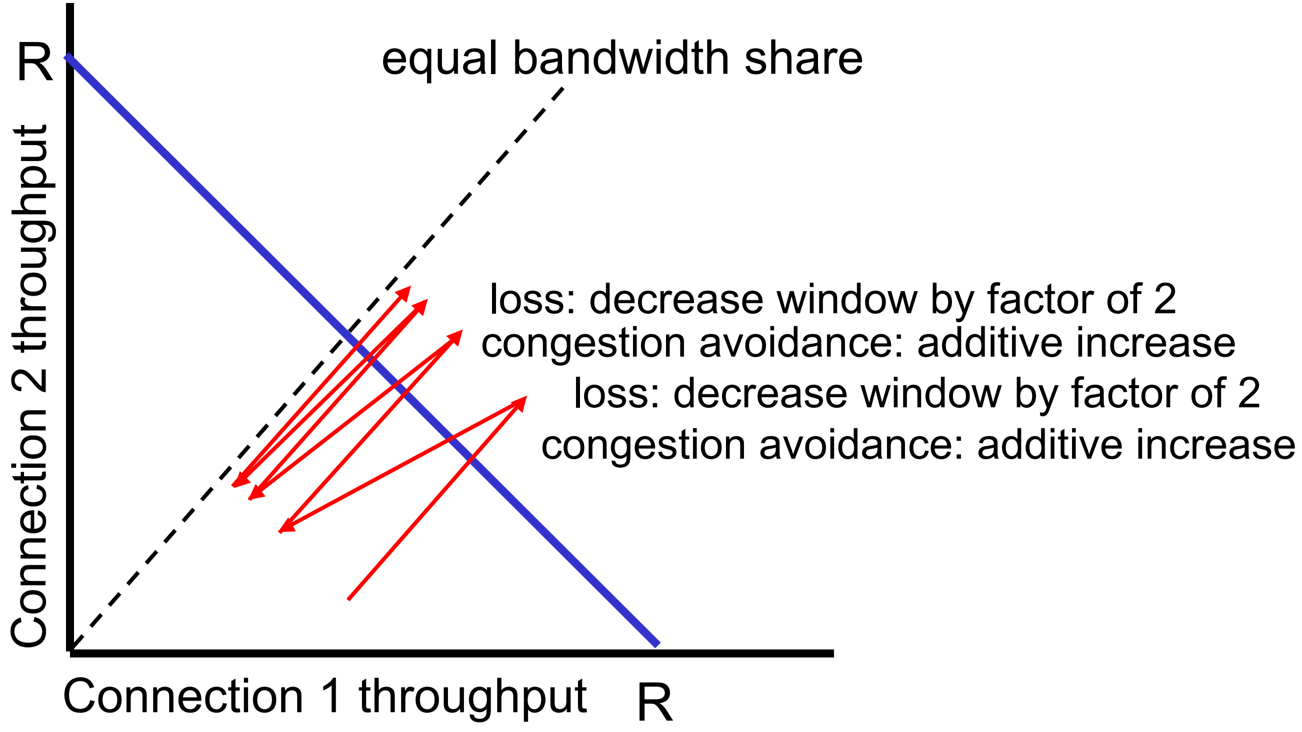
fairness goal: if K TCP sessions share same bottleneck link of bandwidth R, each should have average rate of R/K



Why is TCP fair, in concept?

two competing sessions:

- additive increase gives slope of 1, as throughout increases
- multiplicative decrease decreases throughput proportionally


R
equal bandwidth share
loss: decrease window by factor of 2
congestion avoidance: additive increase
loss: decrease window by factor of 2
congestion avoidance: additive increase
Connection 2 throughput
Connection 1 throughput
R