

# Chapter 3 outline

3.1 transport-layer services

3.2 multiplexing and demultiplexing

3.3 connectionless transport: UDP

3.4 principles of reliable data transfer

3.5 connection-oriented transport: TCP

- segment structure
- reliable data transfer
- flow control
- connection management

3.6 principles of congestion control

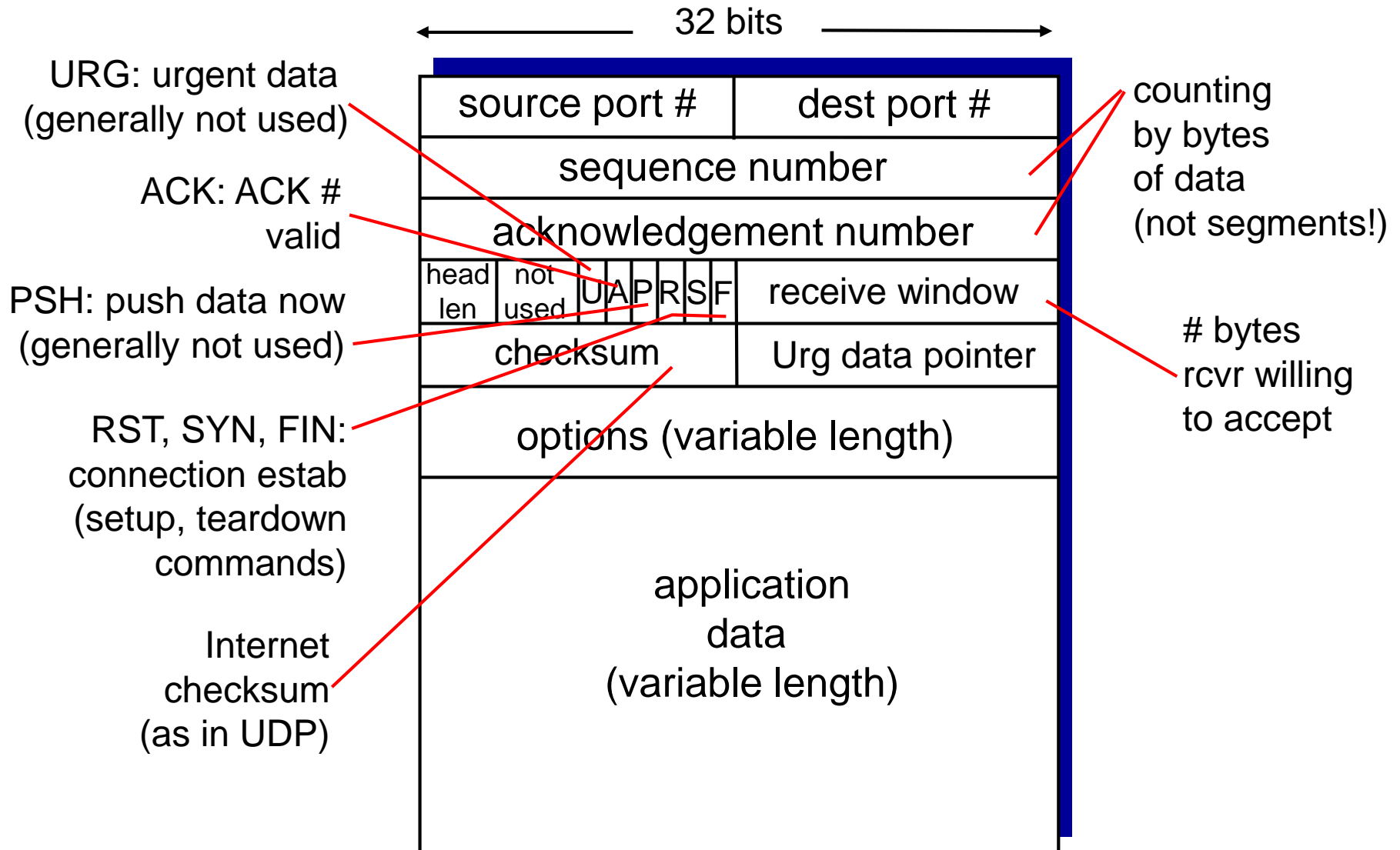
3.7 TCP congestion control

# TCP: Overview

RFCs: 793, 1122, 1323, 2018, 2581

- ❖ **point-to-point:**
  - one sender, one receiver
- ❖ **reliable, in-order *byte stream*:**
  - no “message boundaries”
- ❖ **pipelined:**
  - TCP congestion and flow control set window size
- ❖ **full duplex data:**
  - bi-directional data flow in same connection
  - MSS: maximum segment size
- ❖ **connection-oriented:**
  - handshaking (exchange of control msgs) initializes sender, receiver state before data exchange
- ❖ **flow controlled:**
  - sender will not overwhelm receiver

# TCP segment structure



# TCP seq. numbers, ACKs

## sequence numbers:

- byte stream “number” of first byte in segment’s data

## acknowledgements:

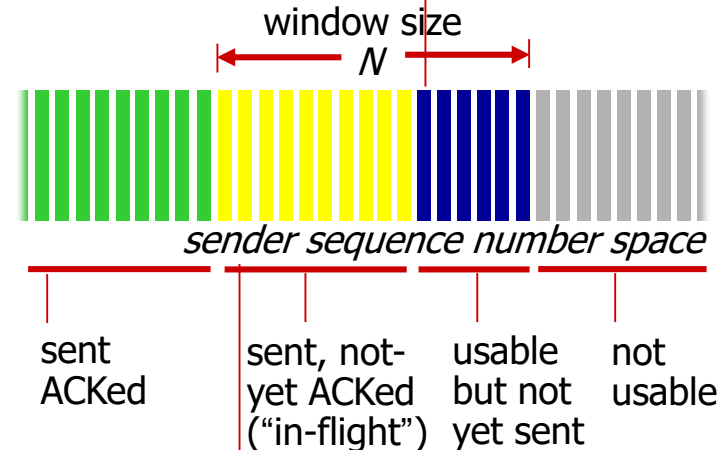
- seq # of next byte expected from other side
- cumulative ACK

**Q:** how receiver handles out-of-order segments

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

outgoing segment from sender

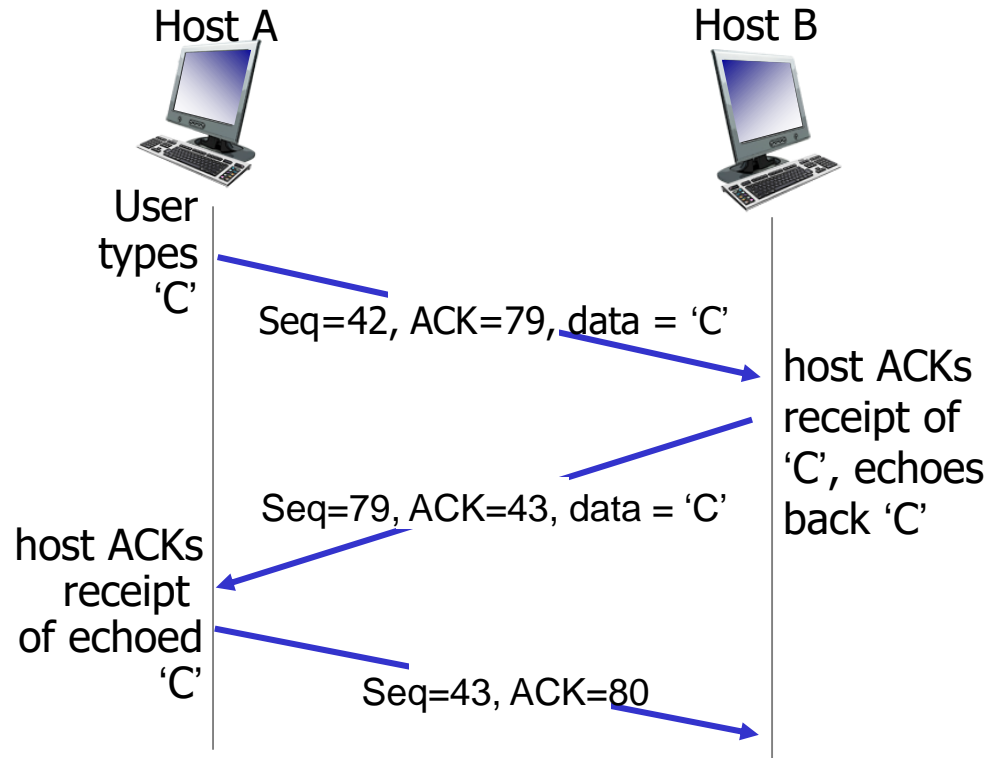
source port #	dest port #
sequence number	
acknowledgement number	
	rwnd
checksum	urg pointer



incoming segment to sender

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

# TCP seq. numbers, ACKs



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

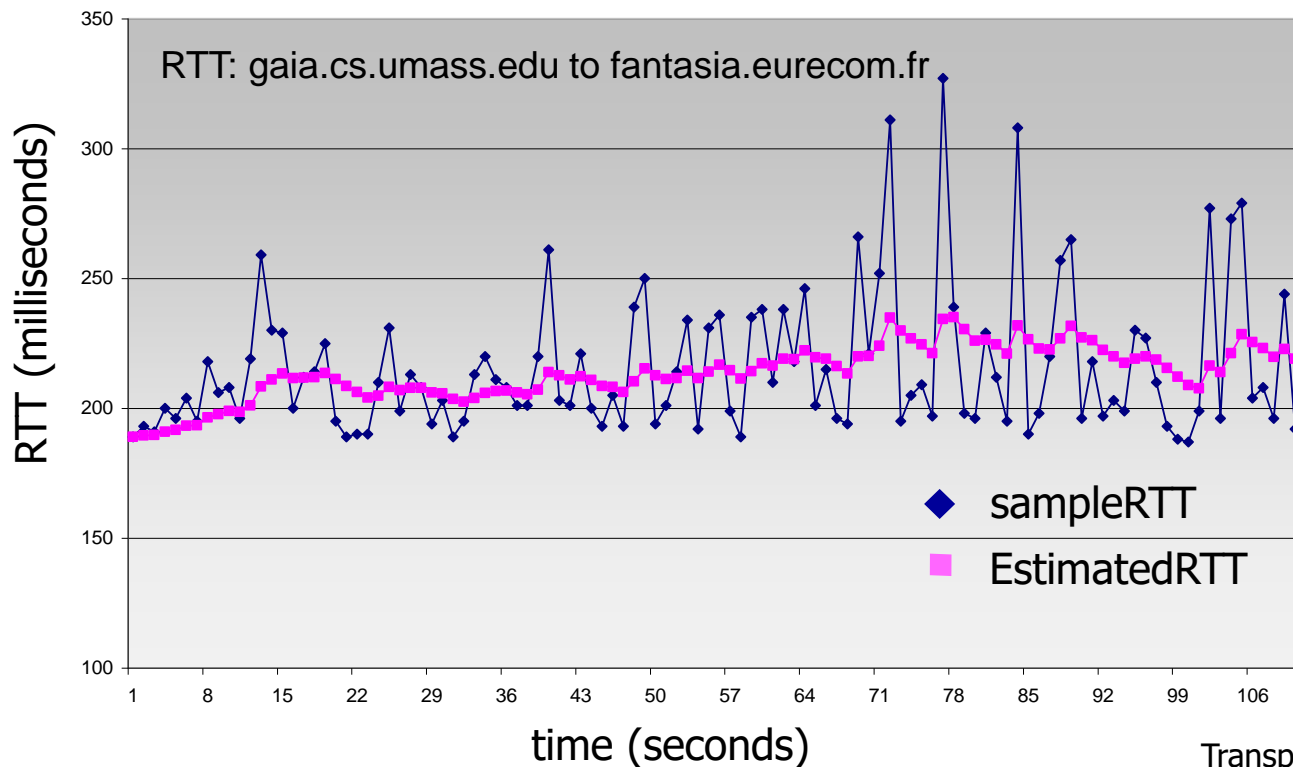
Q: how to estimate RTT?

- ❖ **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

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

- ❖ exponential weighted moving average
- ❖ influence of past sample decreases exponentially fast
- ❖ typical value:  $\alpha = 0.125$



# TCP round trip time, timeout

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

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

(typically,  $\beta = 0.25$ )

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



↑  
estimated RTT

↑  
"safety margin"



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# TCP reliable data transfer

- ❖ TCP creates rdt service on top of IP's unreliable service

- pipelined segments
- cumulative acks
- single retransmission timer

- ❖ retransmissions triggered by:

- timeout events
- duplicate acks

let's initially consider simplified TCP sender:

- ignore duplicate acks
- ignore flow control, congestion control

# TCP sender events:

## *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`

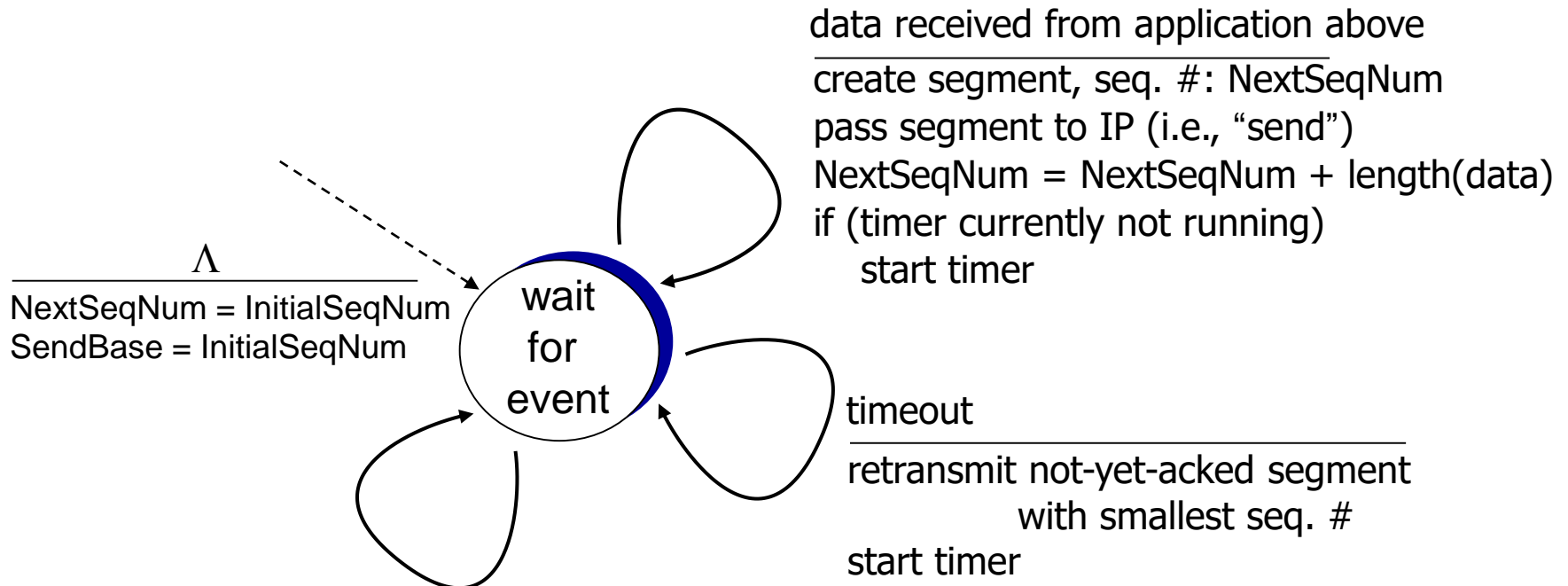
## *timeout:*

- ❖ 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

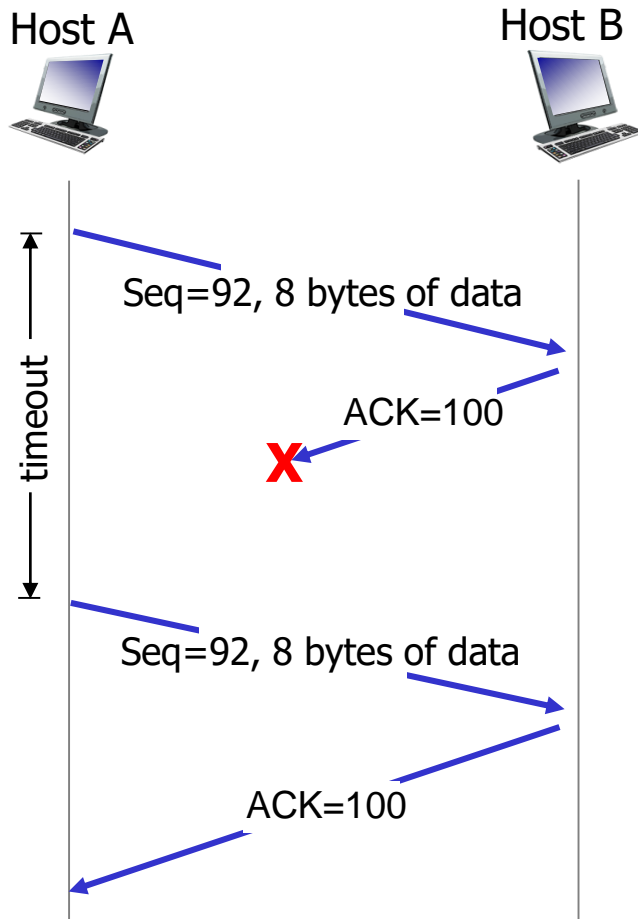
# TCP sender (simplified)



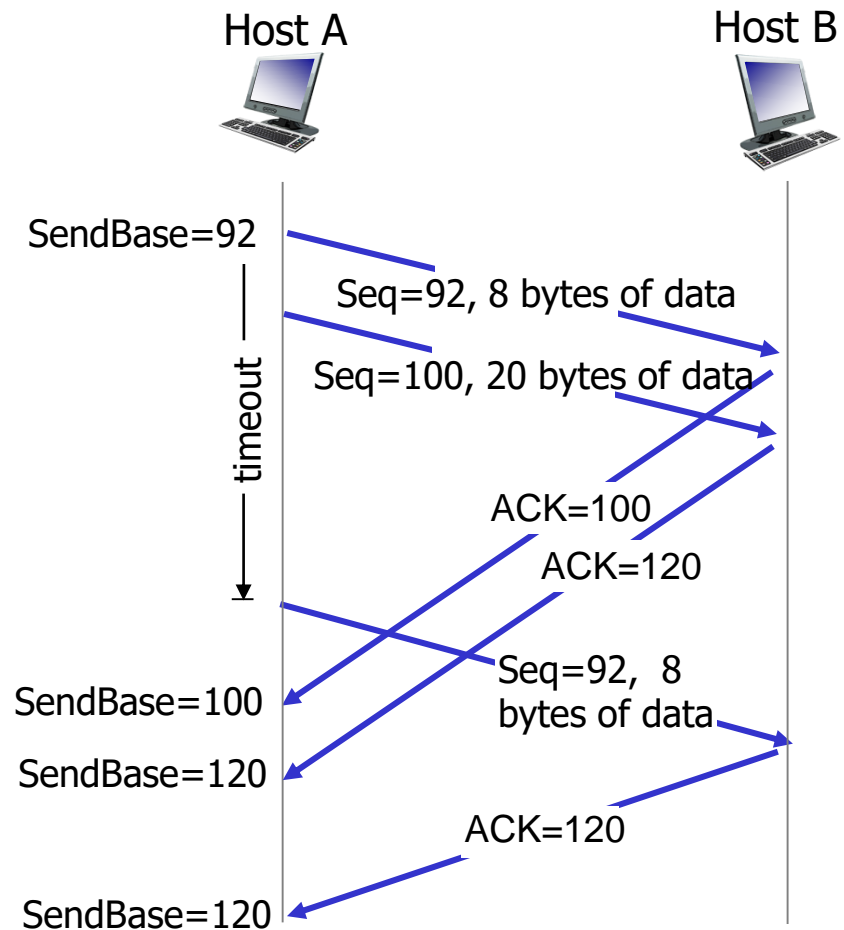
ACK received, with ACK field value y

```
if (y > SendBase) {  
    SendBase = y  
    /* SendBase-1: last cumulatively ACKed byte */  
    if (there are currently not-yet-acked segments)  
        start timer  
    else stop timer  
}
```

# TCP: retransmission scenarios

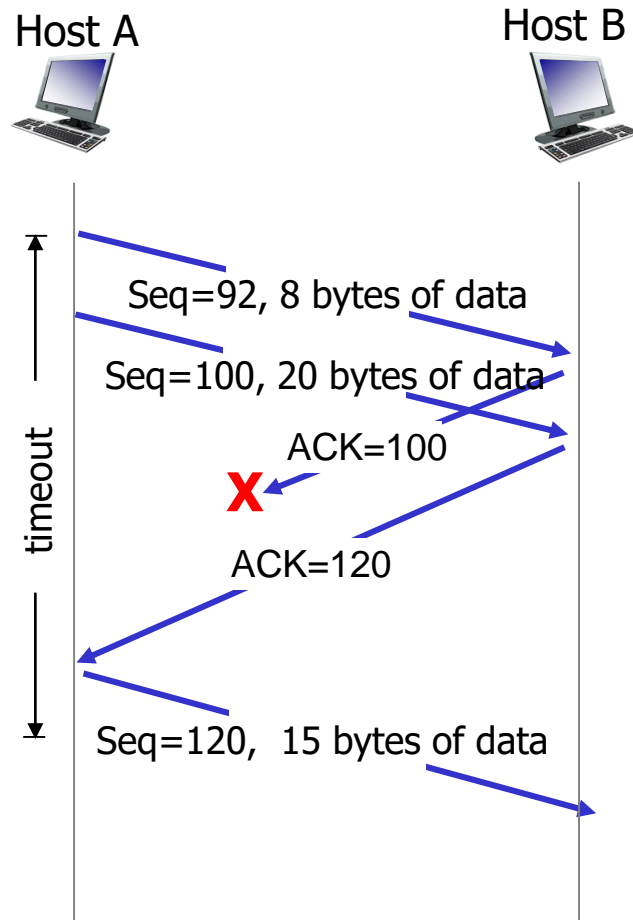


lost ACK scenario



premature timeout

# TCP: retransmission scenarios



cumulative ACK

# TCP ACK generation [RFC 1122, RFC 2581]

<i>event at receiver</i>	<i>TCP receiver action</i>
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 <i>duplicate ACK</i> , 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

- ❖ 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.

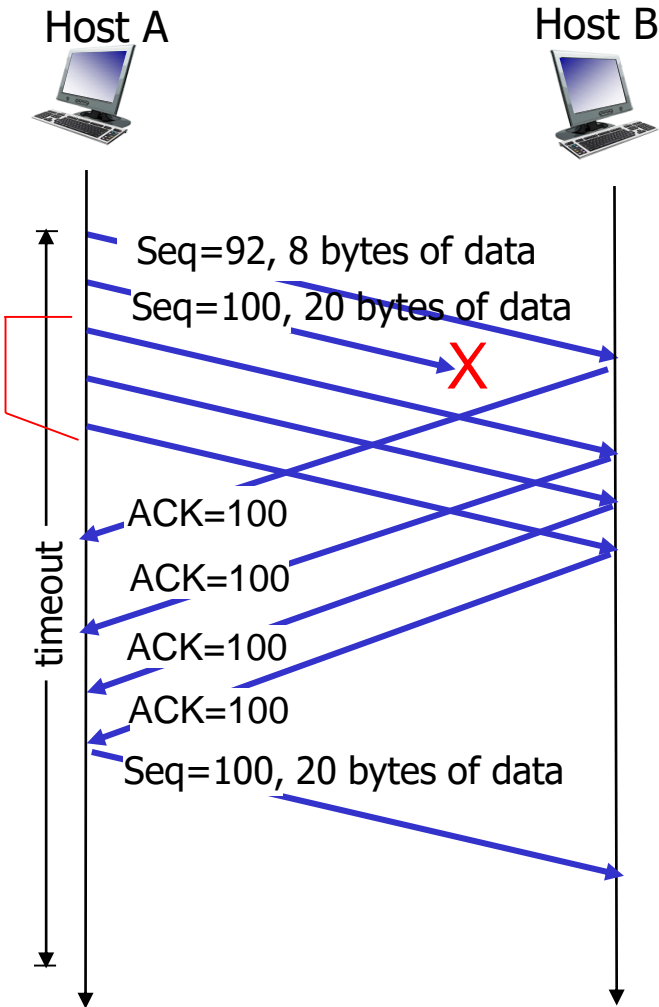
## *TCP fast retransmit*

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



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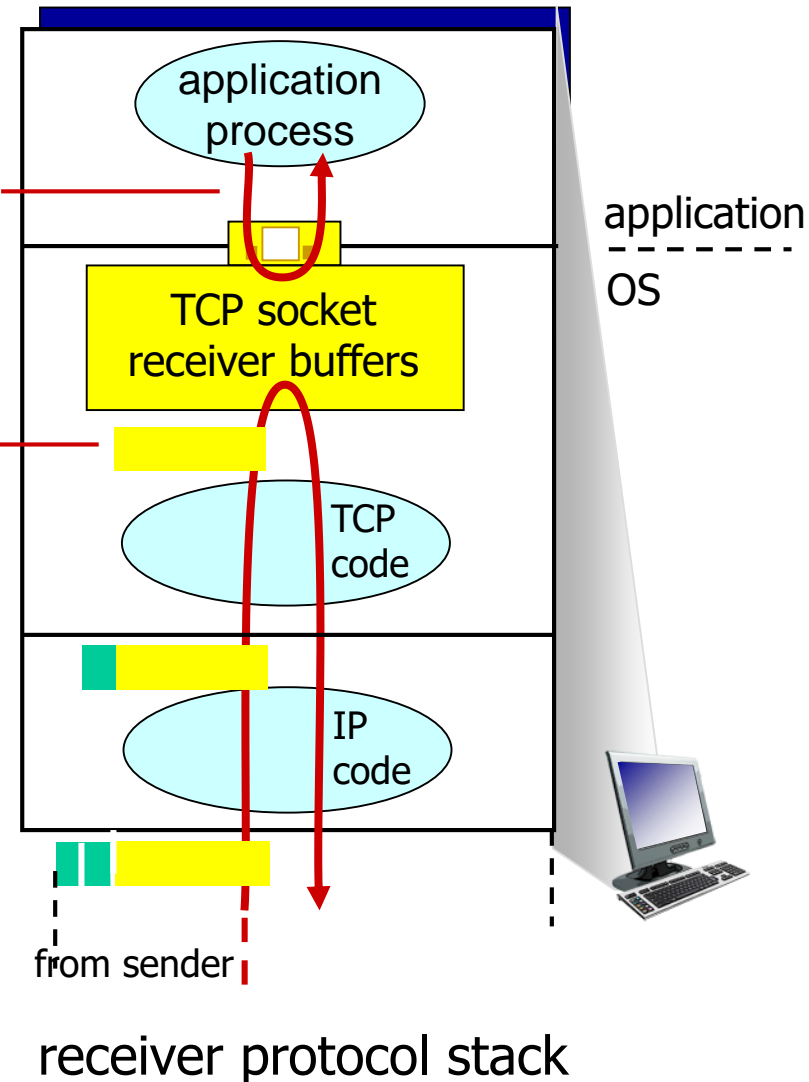
3.7 TCP congestion control

# TCP flow control

application may  
remove data from  
TCP socket buffers ....

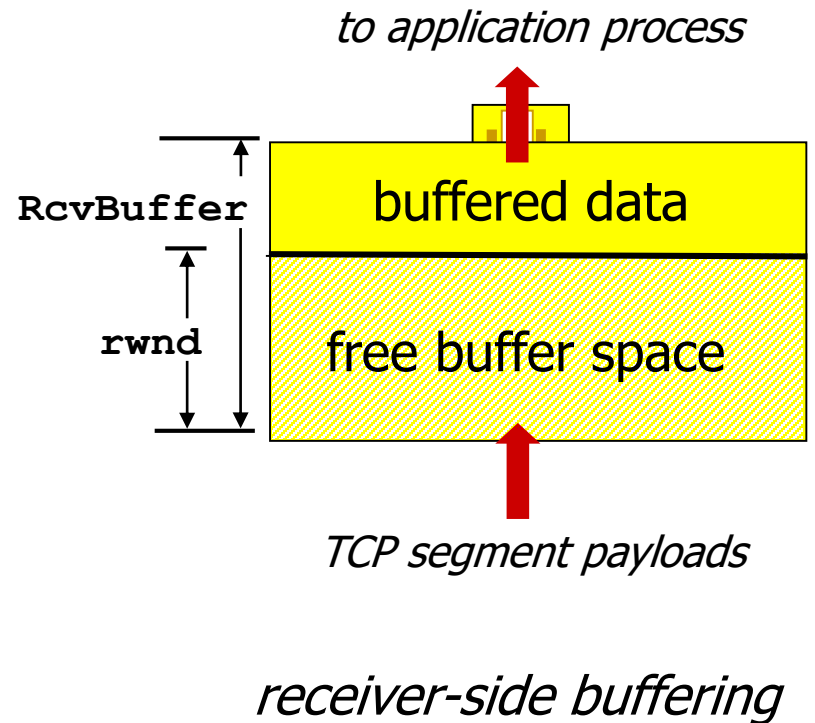
... slower than TCP  
receiver is delivering  
(sender is sending)

***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



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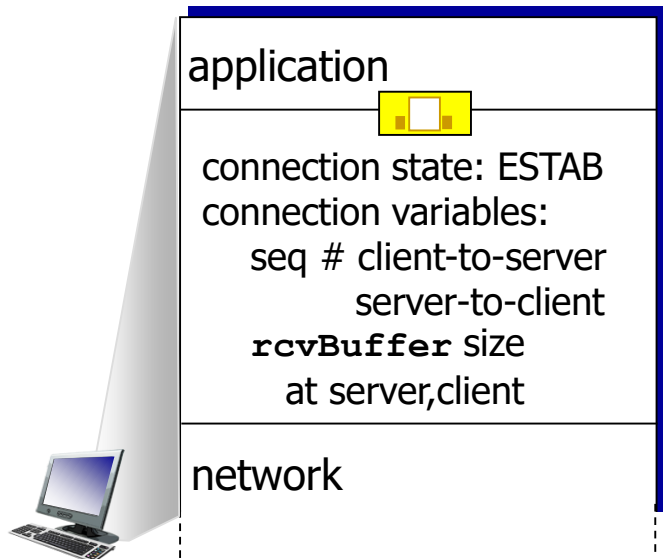
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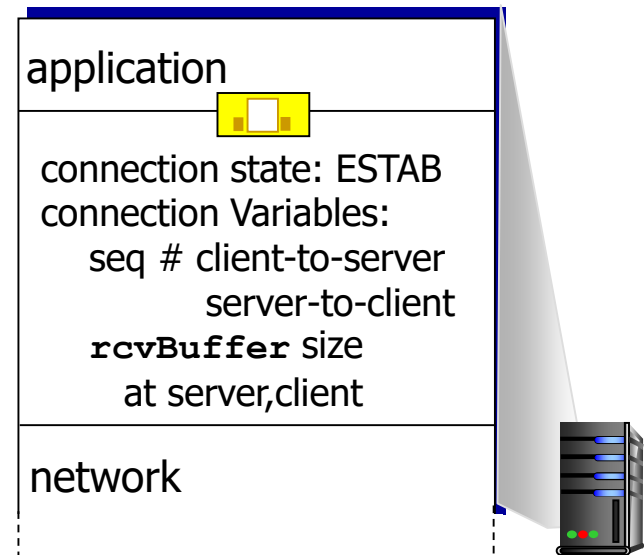
# Connection Management

before exchanging data, sender/receiver “handshake”:

- ❖ agree to establish connection (each knowing the other willing to establish connection)
- ❖ agree on connection parameters



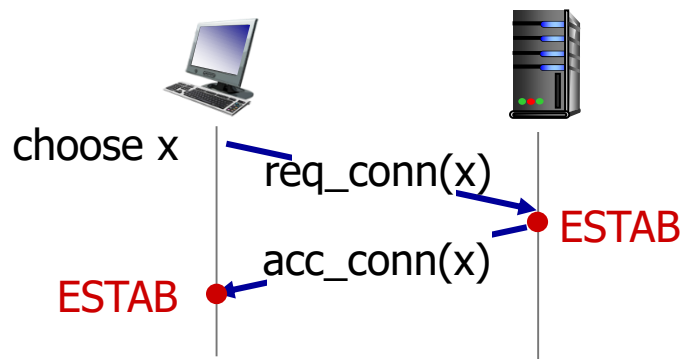
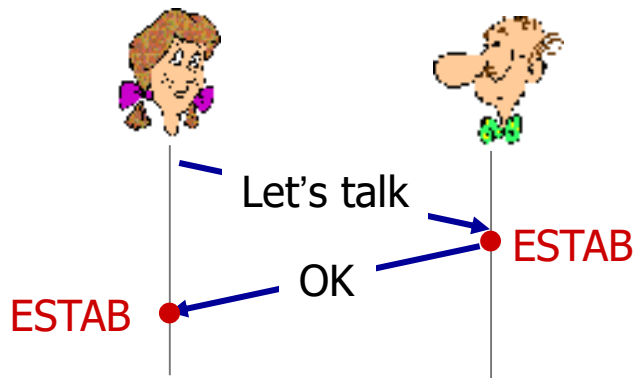
```
Socket clientSocket =  
    newSocket("hostname", "port  
    number");
```



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

# Agreeing to establish a connection

2-way handshake:

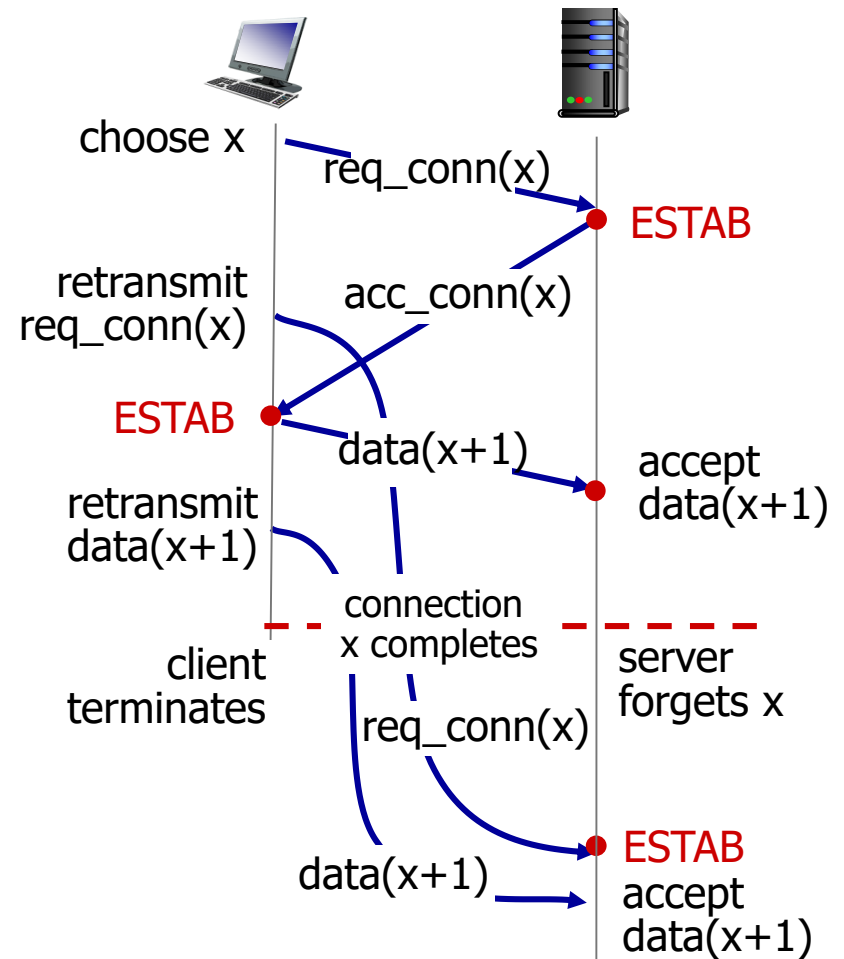
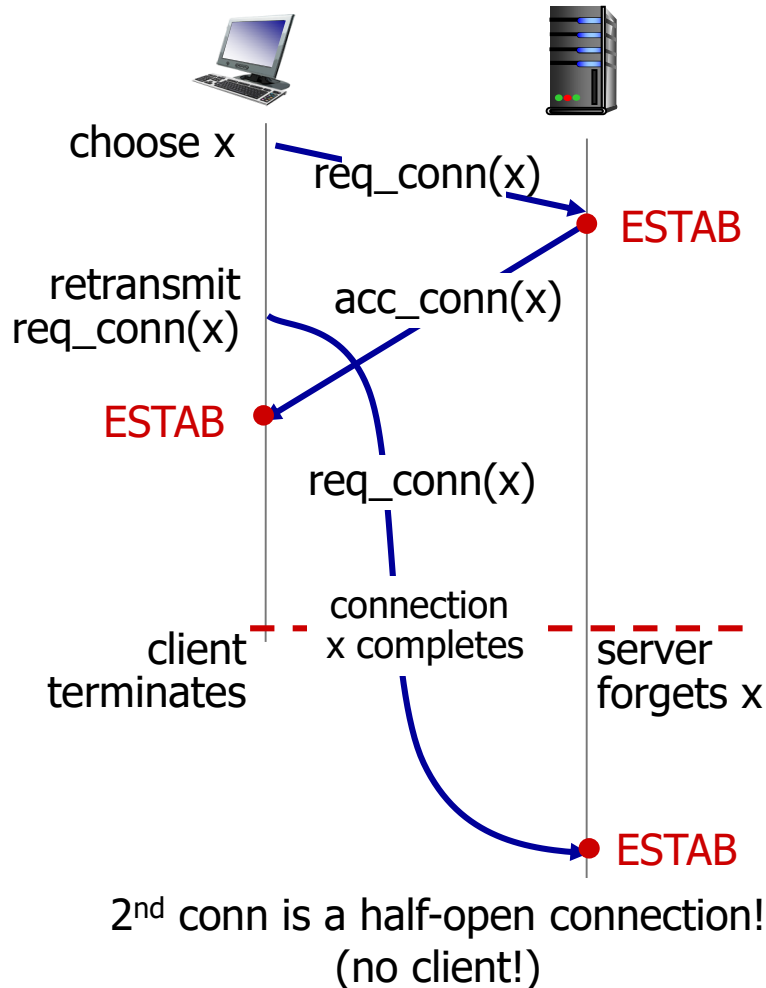


Q: will 2-way handshake always work in network?

- ❖ variable delays
- ❖ retransmitted messages (e.g. req\_conn(x)) due to message loss
- ❖ message reordering
- ❖ can't "see" other side

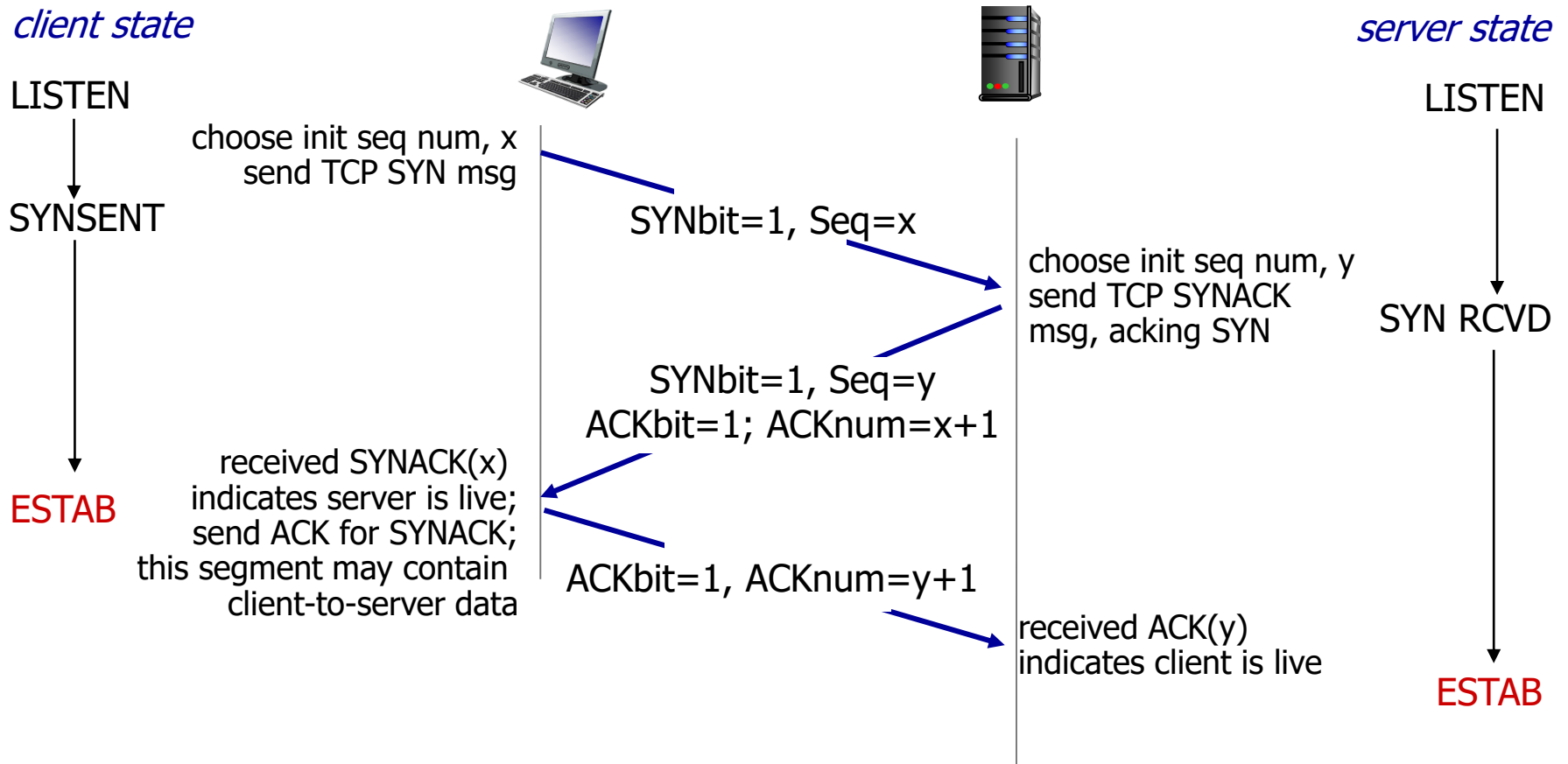
# Agreeing to establish a connection

2-way handshake failure scenarios:

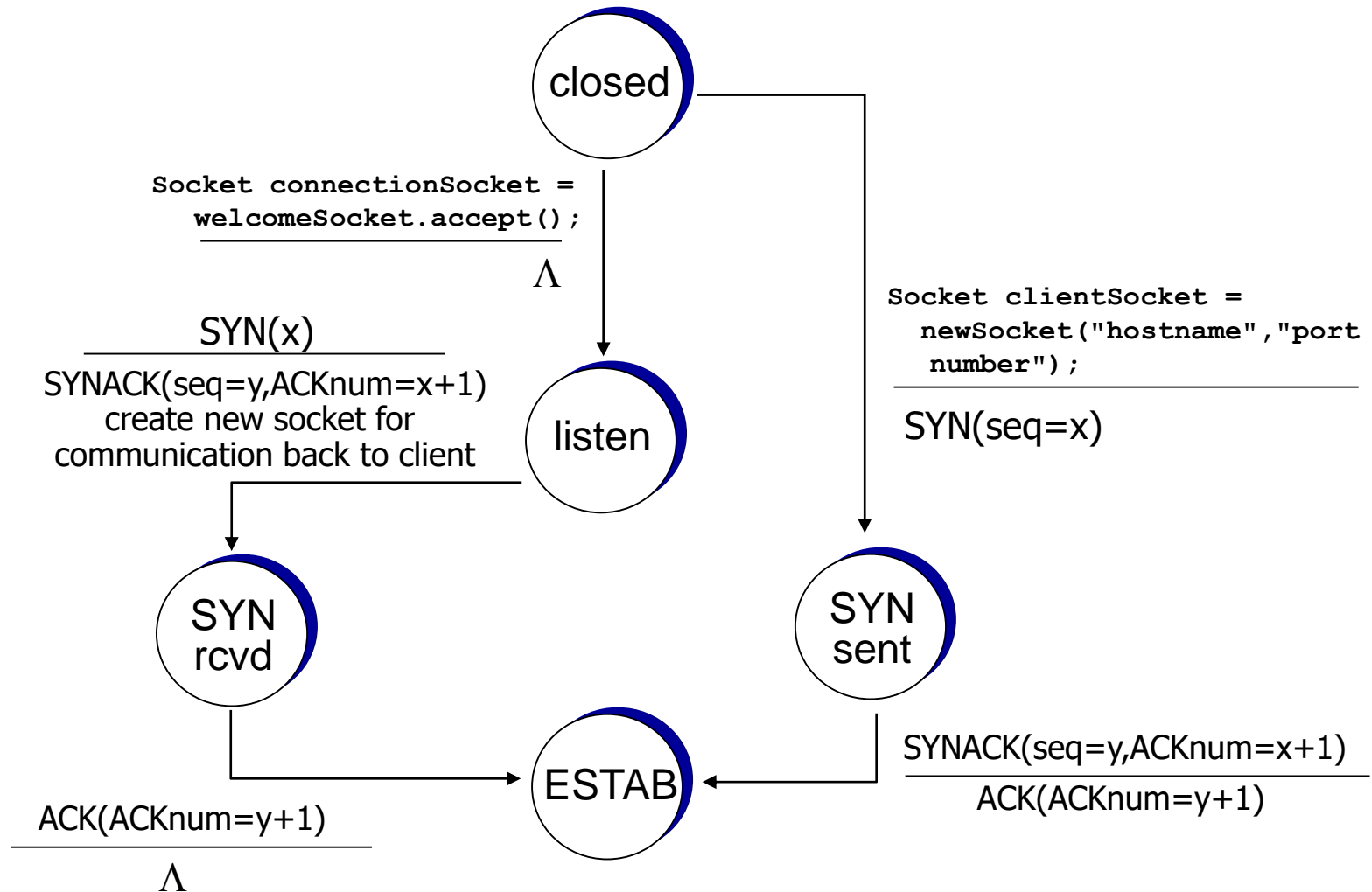




# TCP 3-way handshake



# TCP 3-way handshake: FSM



# 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*

ESTAB

`clientSocket.close()`

FIN\_WAIT\_1

can no longer  
send but can  
receive data

FIN\_WAIT\_2

wait for server  
close

TIMED\_WAIT

timed wait  
for  $2 * \text{max}$   
segment lifetime

CLOSED



FINbit=1, seq=x

ACKbit=1; ACKnum=x+1

FINbit=1, seq=y

ACKbit=1; ACKnum=y+1

can still  
send data

can no longer  
send data

*server state*

ESTAB

CLOSE\_WAIT

LAST\_ACK

CLOSED

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