UNIVERSITY OF WATERLOO

CS 456/656
Computer Networks

Lecture 7: Transport Layer – Part 3

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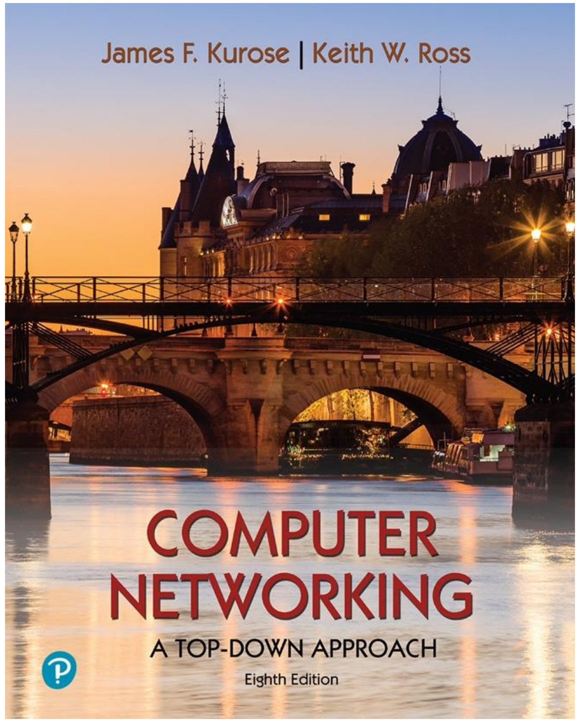
Fall 2025

A note on the slides

Adapted from the slides that accompany this book.



Computer Networking: A Top-Down Approach
8th edition
Jim Kurose, Keith Ross
Pearson, 2020

Transport layer: roadmap

- Transport-layer services
- Multiplexing and demultiplexing
- Connectionless transport: UDP
- Principles of reliable data transfer
- Connection-oriented transport: TCP
  - segment structure
  - connection management
  - reliable data transfer
  - flow control
- Principles of congestion control
- TCP congestion control

TCP: a widely-used reliable transport protocol

- Guarantees reliable, in-order *byte steam:*
  - no "message boundaries"

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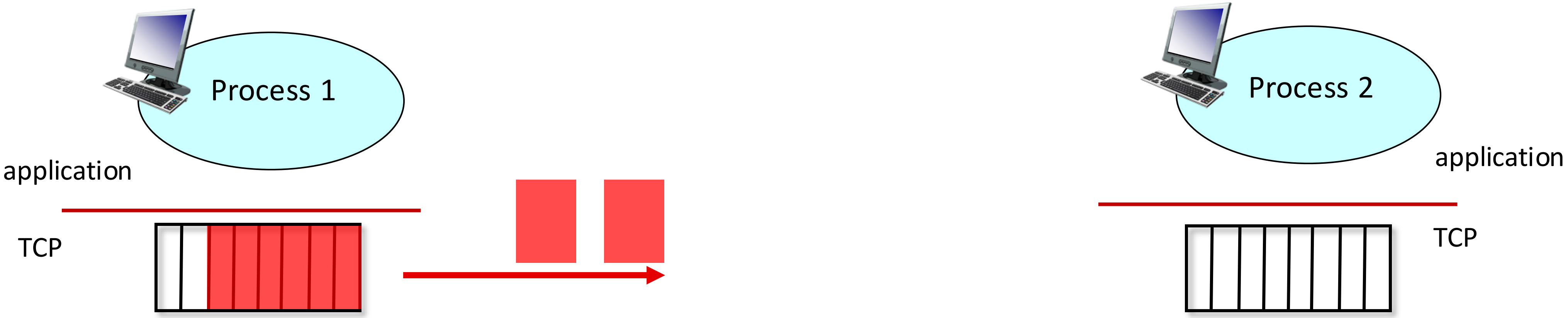

I’ll fit them into 2 packets,
each with 3 bytes of the data

TCP: a widely-used reliable transport protocol

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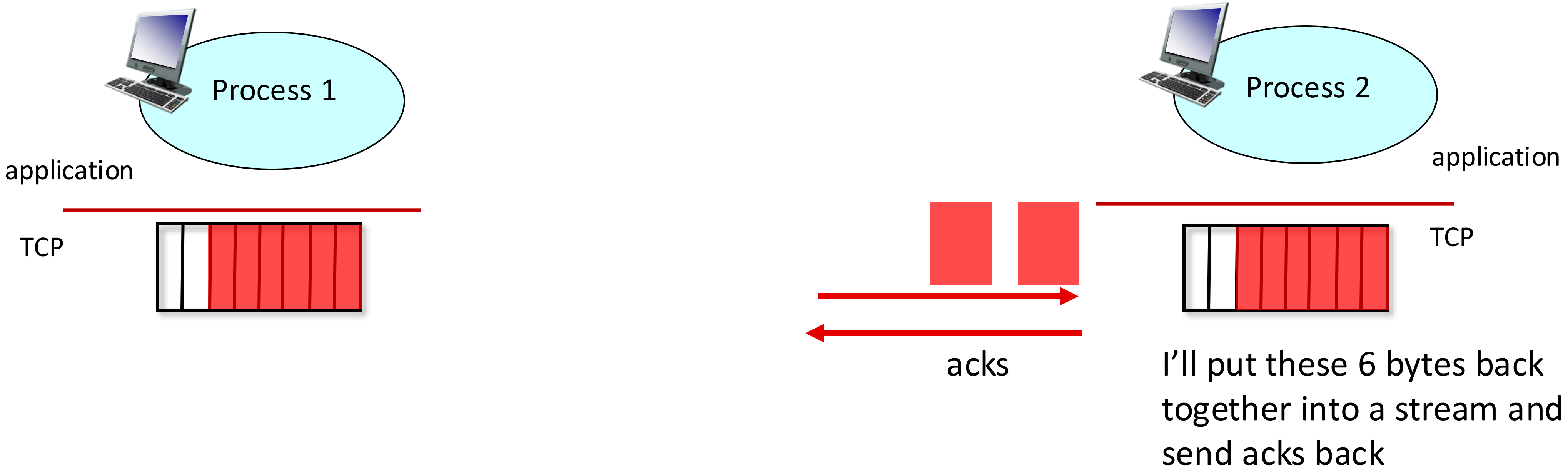

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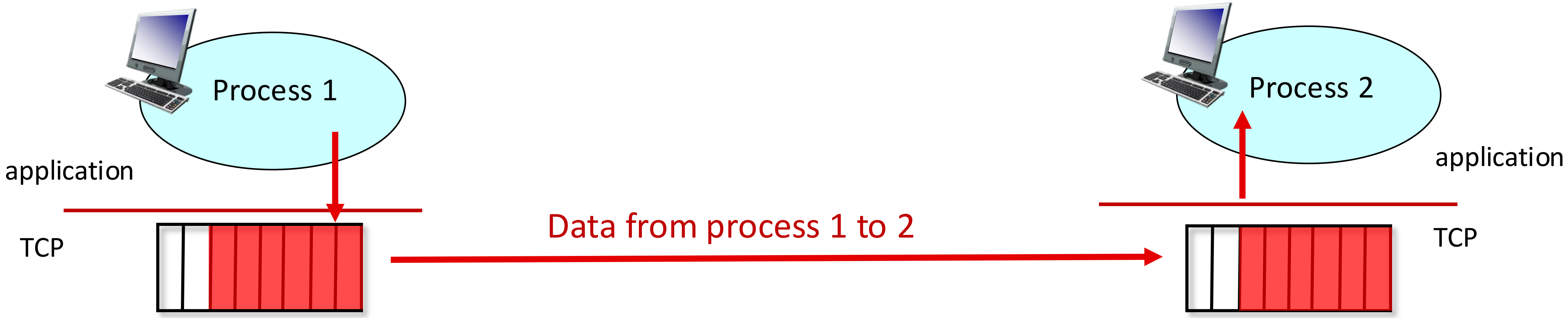

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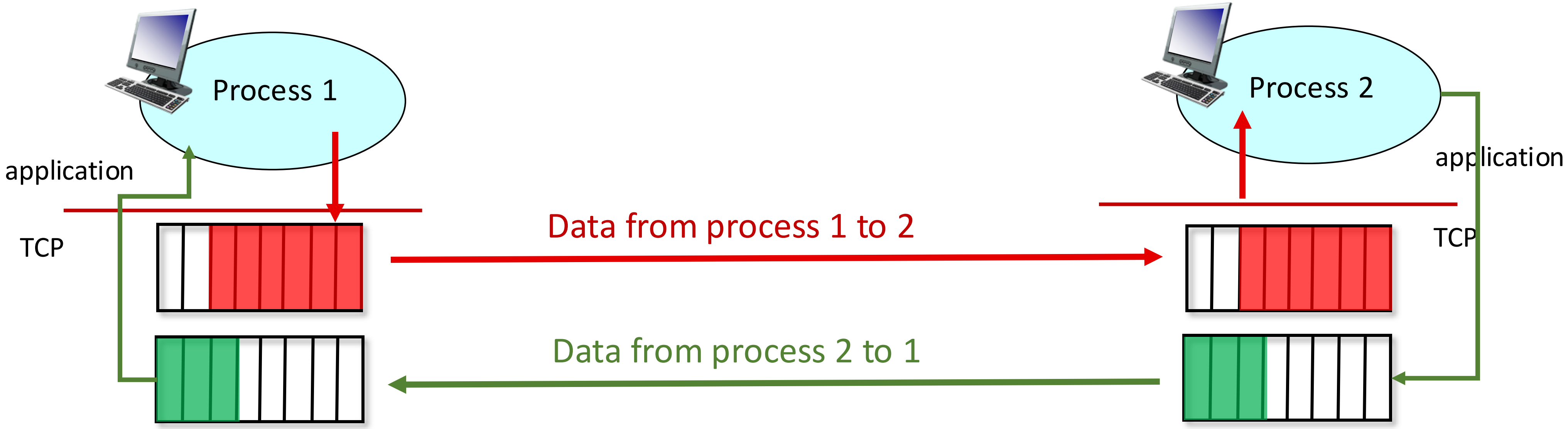

TCP: a widely-used reliable transport protocol

- Guarantees reliable, in-order *byte steam:*
  - no “message boundaries”
- full duplex data:
  - Possible to send data both ways once the two processes establish a connection
- Uses the pipelining approach to reliable data transfer
  - A combination of techniques from Go-Back-N (cumulative acks) and Selective Repeat (only retransmitting presumably lost segment)
  - Performance optimizations like fast retransmit and delayed acks.

TCP: a widely-used reliable transport protocol

- Connection-oriented
  - Connection establishment: Control messages prior to data exchange to initialize the proper state in the communication endpoints
  - Connection tear-down: Control messages after data exchange to end connection
- Flow controlled
  - sender will not overwhelm receiver

Transport layer: roadmap

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  - reliable data transfer
  - flow control
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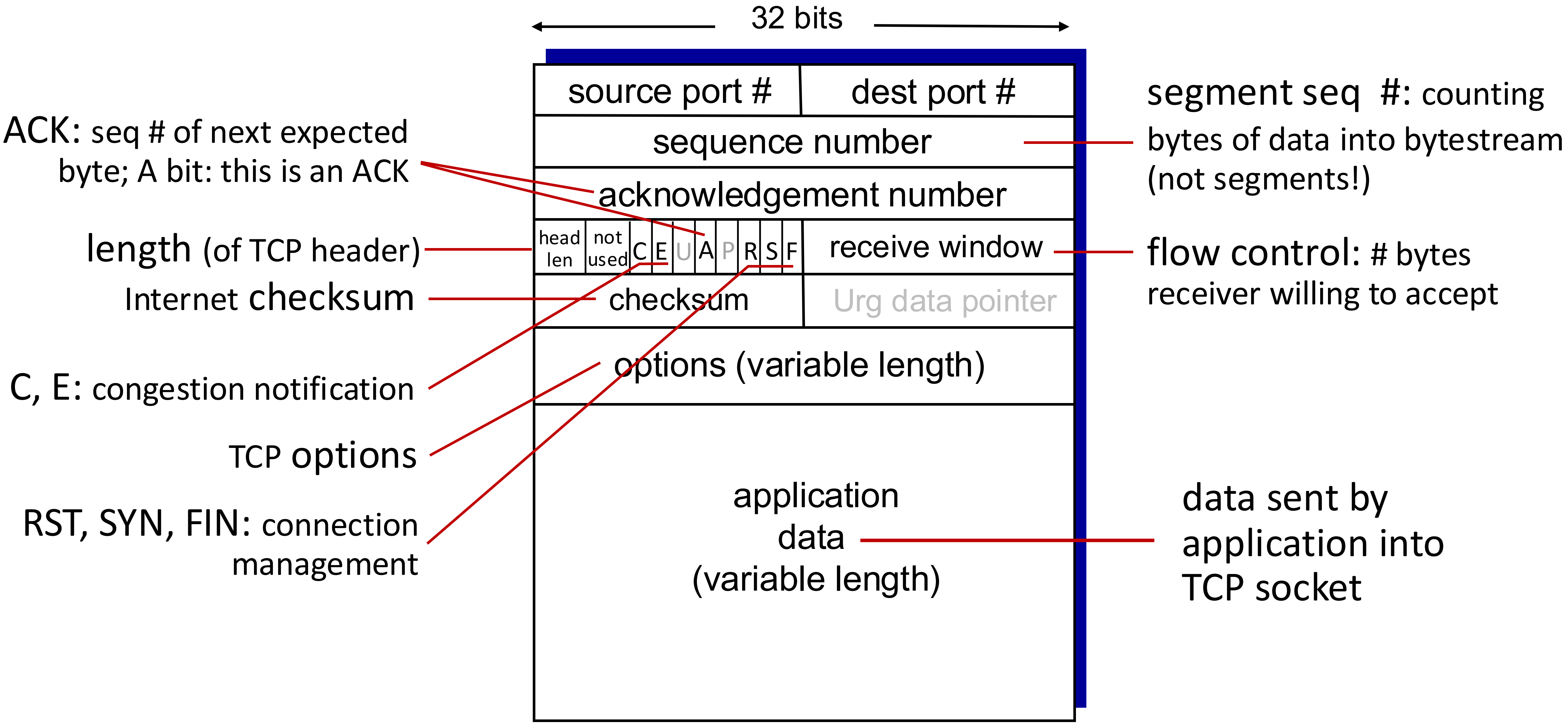
- TCP congestion control

TCP segment structure



Transport layer: roadmap

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TCP reliable data transfer

TCP uses all the reliable data transfer tools we have discussed!

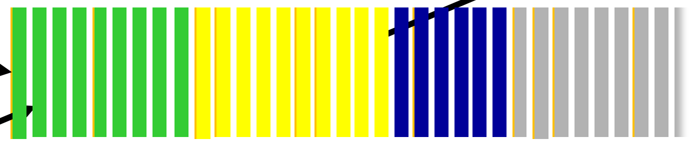
- Checksum
- Sequence number
- Receiver feedback (ACK)
- Timer
- Sliding window/pipelining

TCP sequence numbers – one for every byte

- The interface between a sending process and TCP is a byte stream.
- TCP assigns a sequence number to ***<u>every byte</u>***
  - <u>As opposed to every segment</u>, as we discussed in the last lecture
- It keeps track of the “status” of every byte
  - Is it sent yet? Is it acknowledged yet?

The Nth <u>byte</u> has sequence number init_seq + N - 1

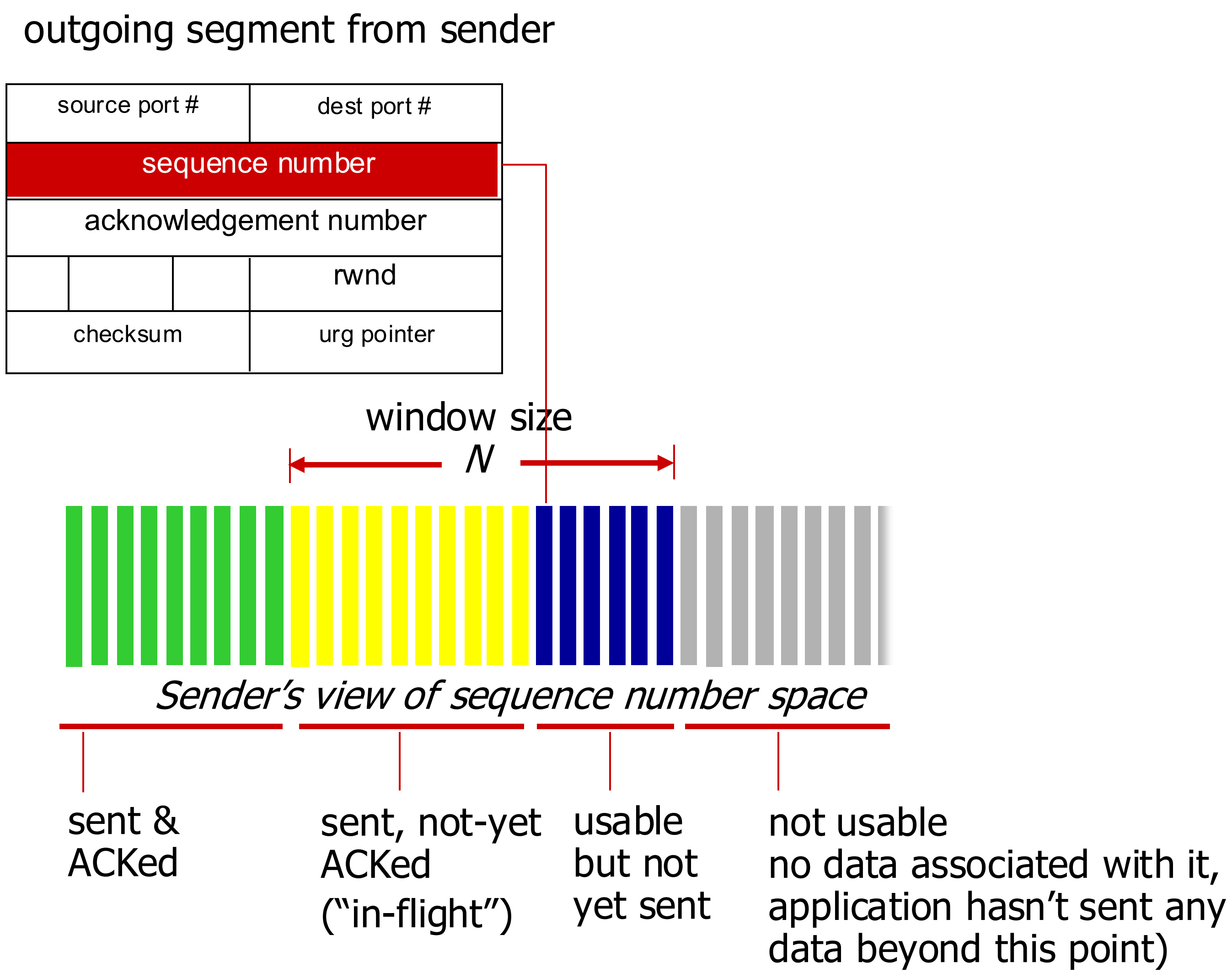
First <u>byte</u> has sequence number init_seq (initial sequence number)



Sender’s view of sequence number space

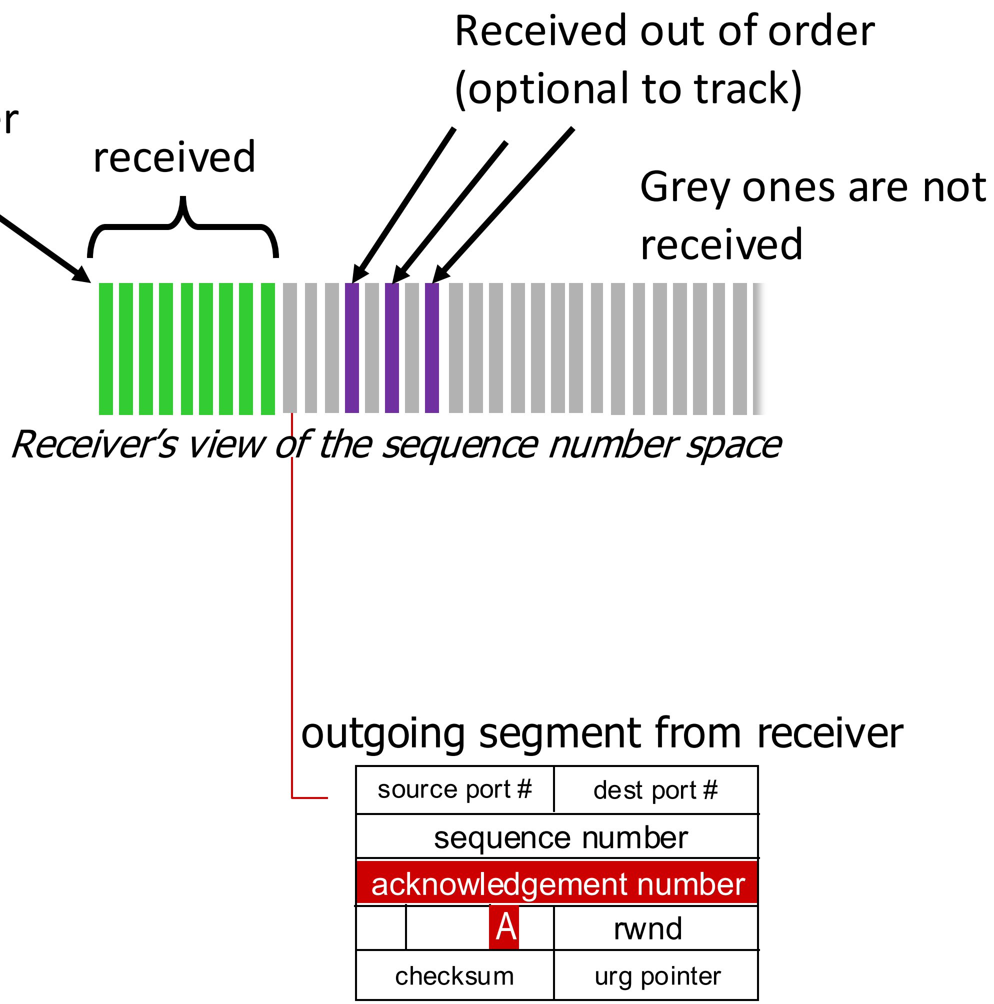
Next <u>byte</u> has sequence number init_seq + 1

TCP sequence numbers



TCP ACKs

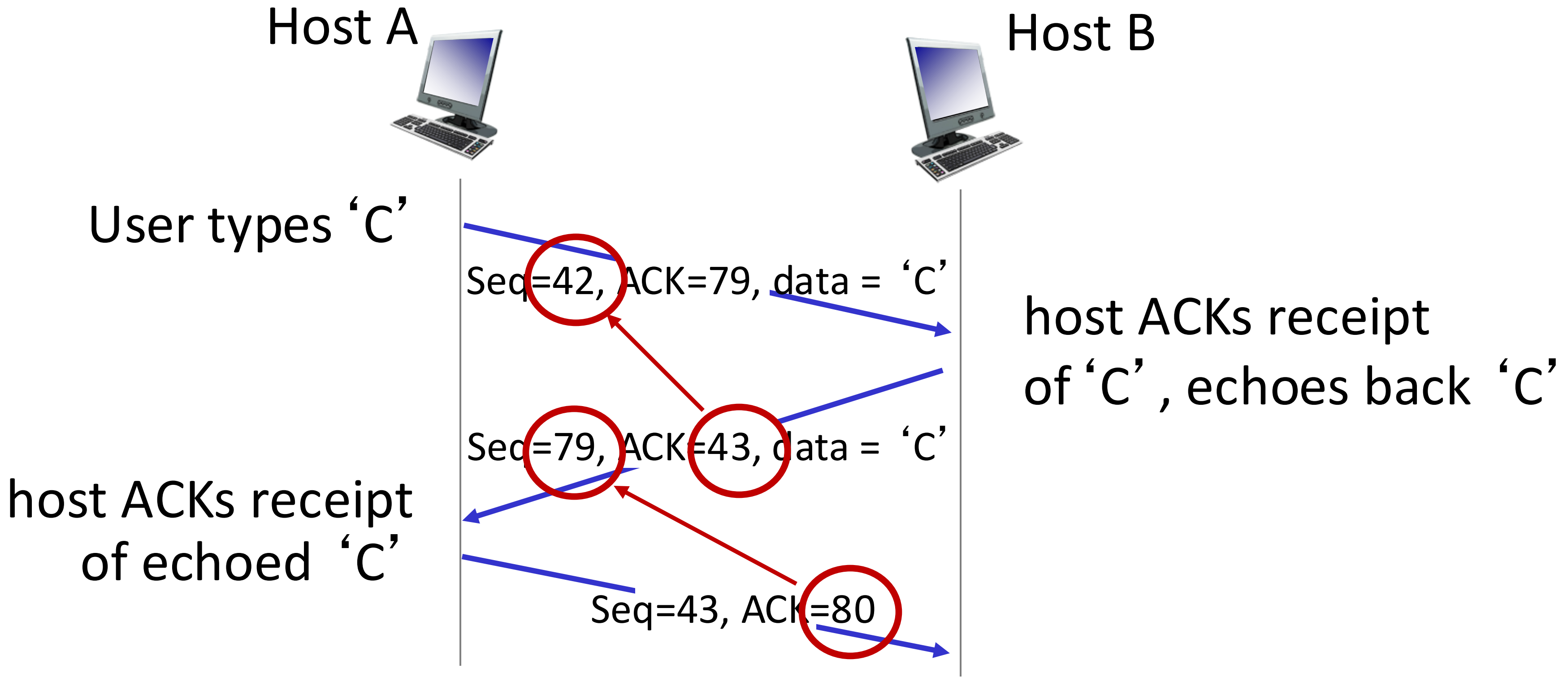
- Cumulative ACK
  - Has seq number of next expected in-order byte
- ACK(n) means:
  - All bytes in [init_seq, n – 1] are received.
  - The receiver is expecting byte n next
- Note the difference from Go-Back-N ack



Q: What about out-of-order segments?

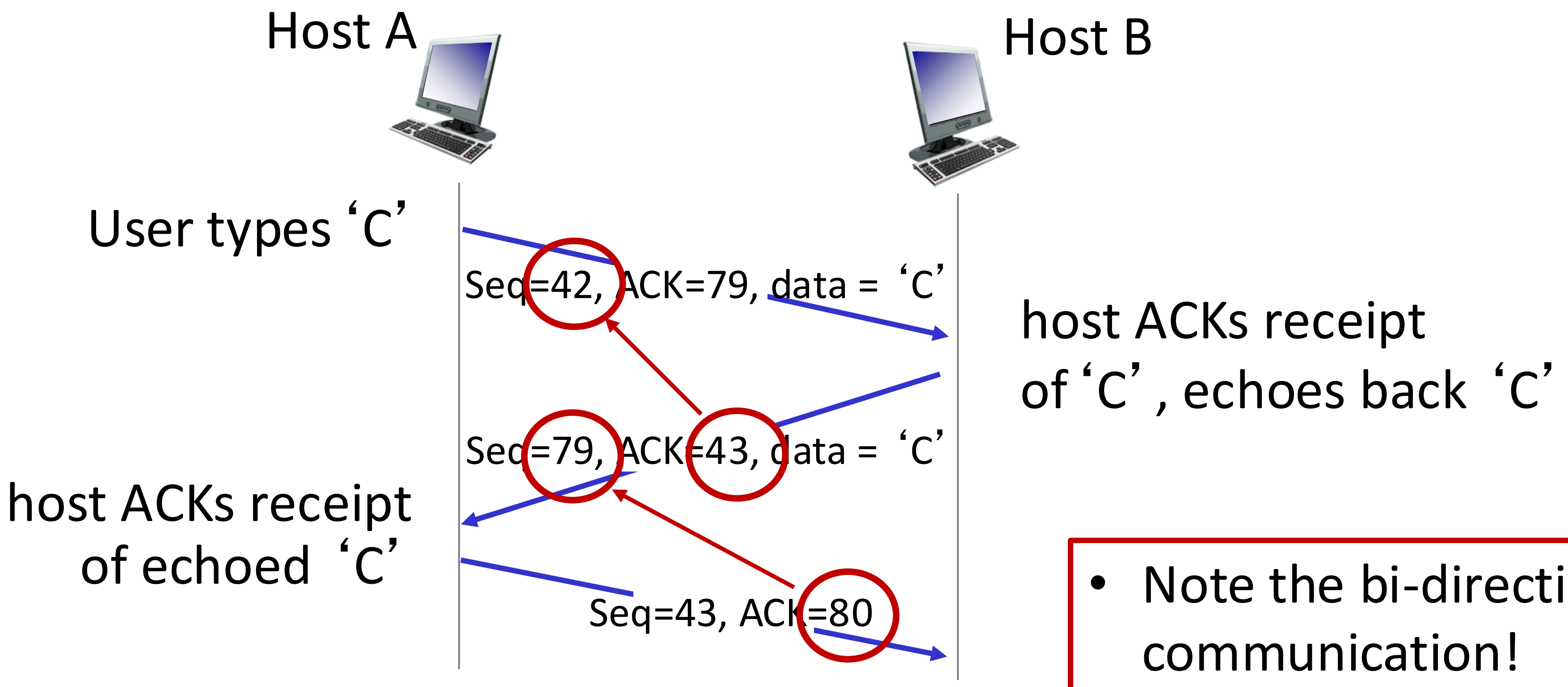
- *A:* TCP spec doesn't specify, - up to implementor

TCP sequence numbers, ACKs



simple telnet scenario

TCP sequence numbers, ACKs



simple telnet scenario

- Note the bi-directional communication!
- There are two data streams:
  - one in each direction
  - each with its own sequence number space

TCP Sender (simplified)

event: data received from application

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

event: timeout

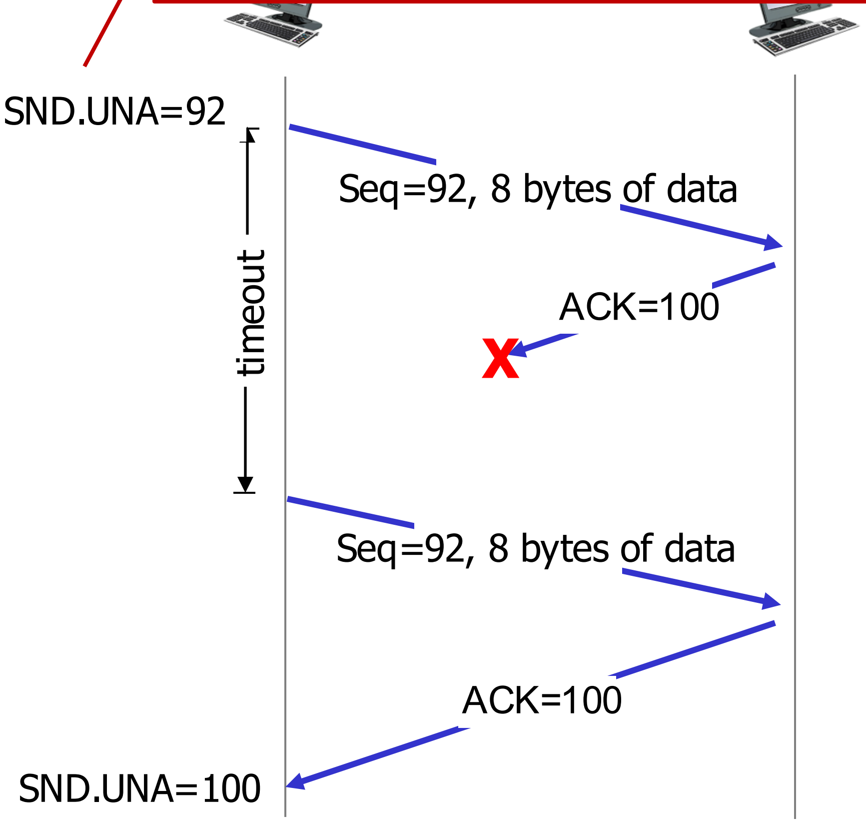
- retransmit segment that caused timeout
- restart timer

event: ACK received

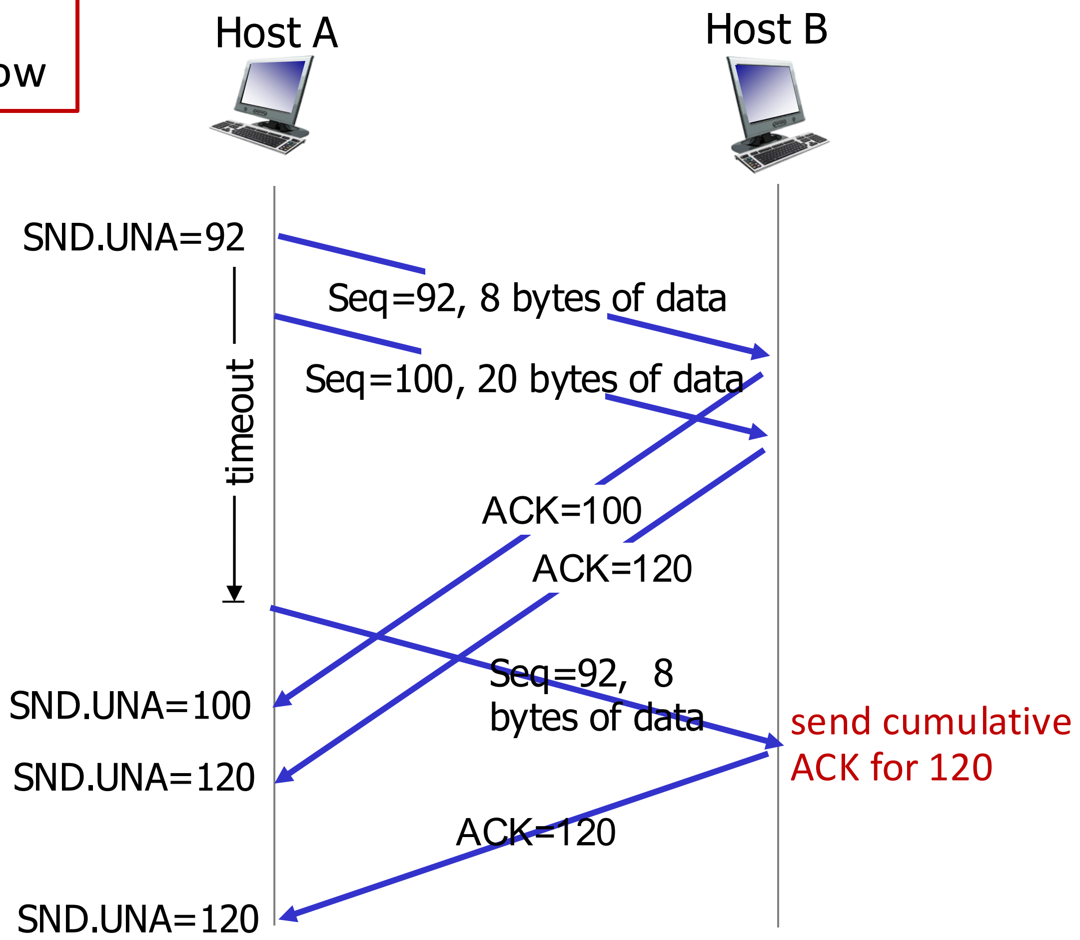
- if ACK acknowledges previously unACKed segments
  - update what is known to be ACKed
  - restart timer if there are still unACKed segments

TCP: retransmission scenarios

First Sent but unacknowledged sequence number
The sequence number at the beginning of the window

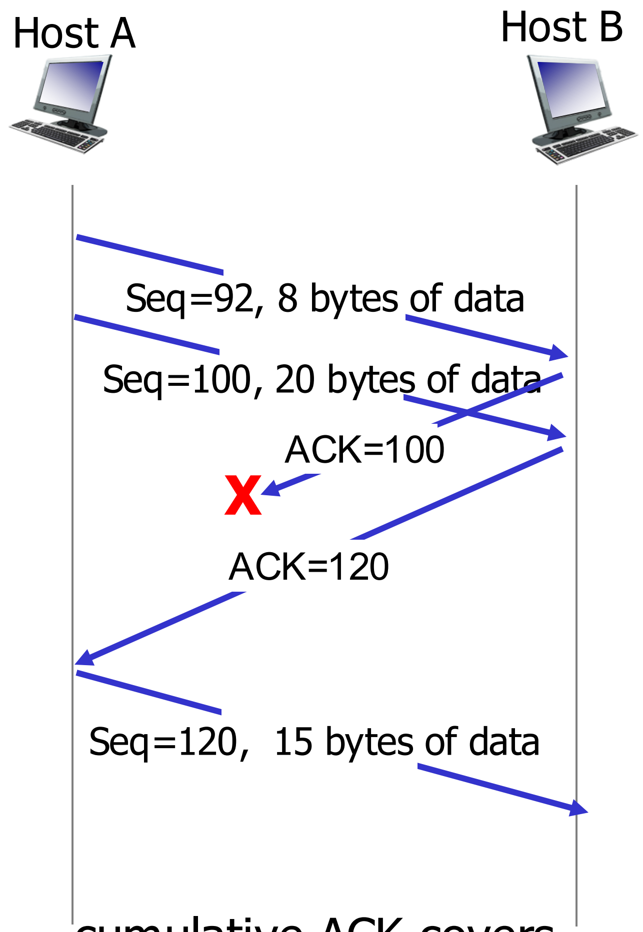


lost ACK scenario



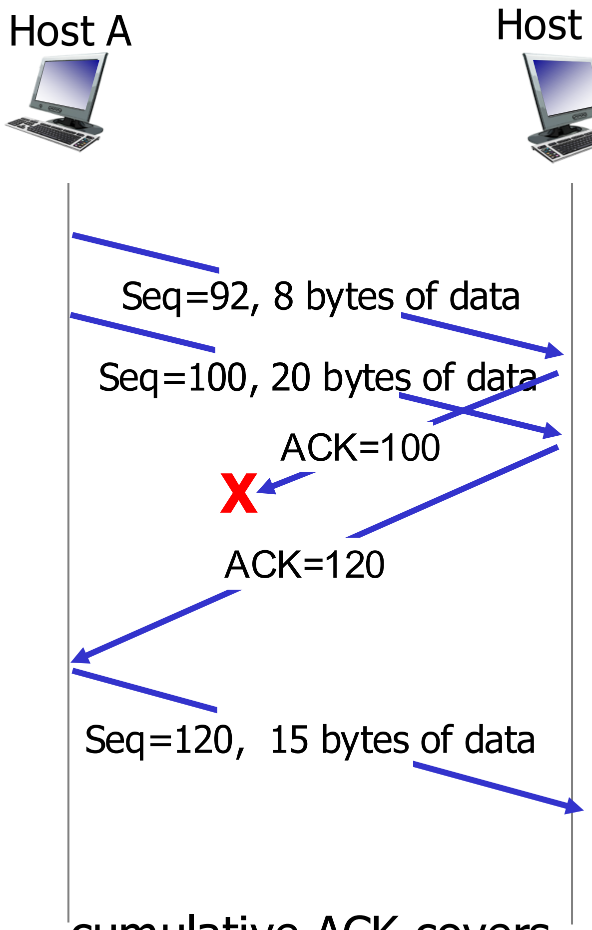
premature timeout

TCP: retransmission scenarios



cumulative ACK covers
for earlier lost ACK

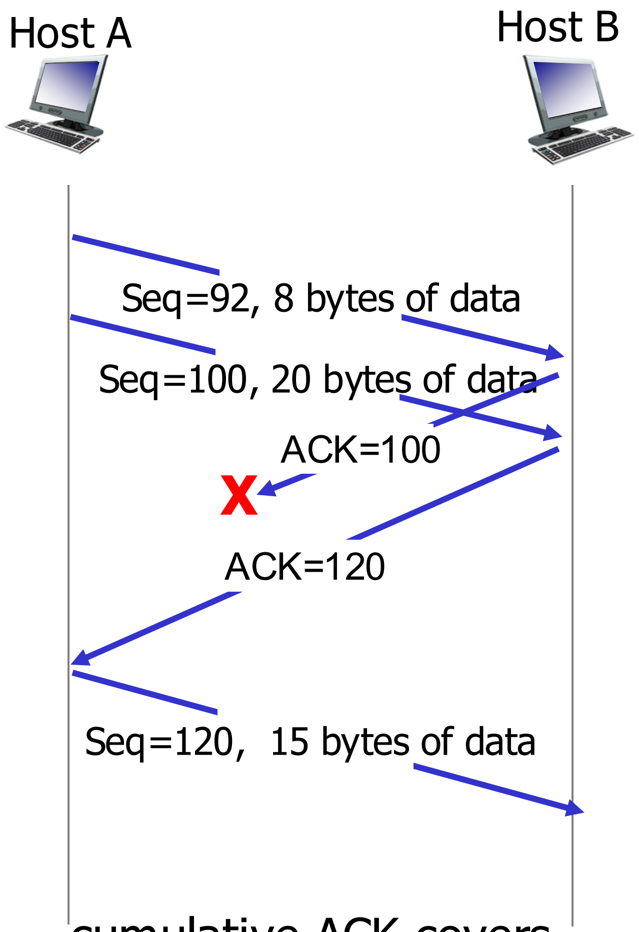
TCP: retransmission scenarios



cumulative ACK covers for earlier lost ACK

- (short) in class exercise:
    - What is the value of SND.UNA after sending and receiving each packet?

TCP: retransmission scenarios



cumulative ACK covers for earlier lost ACK

- Q: How is TCP similar to Go-Back-N? How is it different? How about Selective Repeat?

Knowledge Check

- Make sure you understand and can complete a TCP send and receive timeline.
- This includes, but is not limited to
  - sequence and acknowledgement numbers on packets going back and forth
  - how the sender and receiver view of the sequence number space changes as a result of packets being sent and received (e.g., status of the bytes, position of the sliding window, etc.)

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

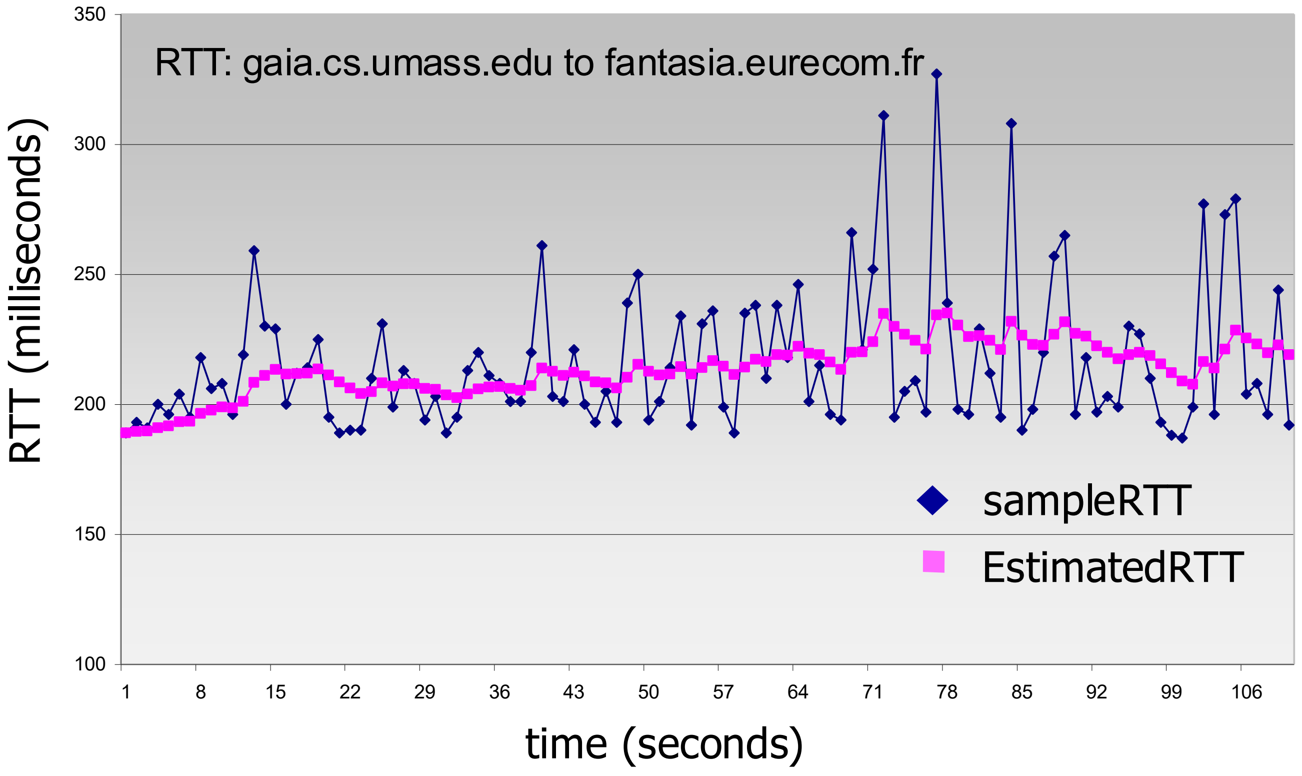
Q: how to estimate RTT?

- `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 (EWMA)
- 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**: want a larger safety margin

```
TimeoutInterval = EstimatedRTT + 4*DevRTT
```

estimated RTT   “safety margin”

- **DevRTT**: EWMA of **SampleRTT** deviation from **EstimatedRTT**:

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

(typically, $\beta = 0.25$)

* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive/

Performance optimizations for TCP

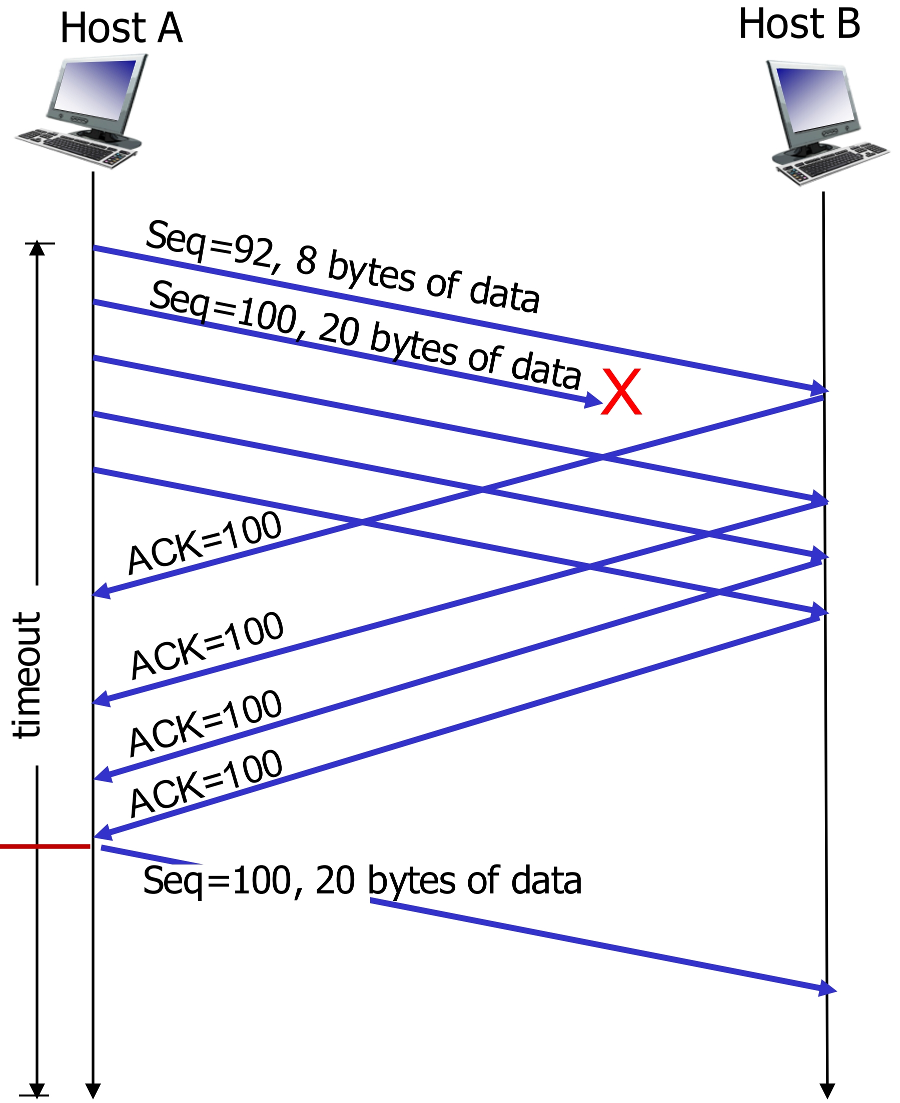
- So far, we have covered “the basics” of TCP’s rdt
  - Sequence number
  - Cumulative ACKs
  - Pipelined segments
  - Retransmission timer
- Next, we will discuss some optimizations

Optimization 1: Fast Retransmit

TCP fast retransmit

if sender receives 3 additional ACKs for same data ("triple duplicate ACKs"), resend unACKed segment with smallest seq #

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



Receipt of three duplicate ACKs indicates 3 segments received after a missing segment – lost segment is likely. So retransmit!

Optimization 2: Delayed ACKs

- Instead of generating an ACK in response to every segment the moment it arrives
  - Wait for some time to see if there is another segment right afterwards
  - Create one ACK for both.
- Benefits?
  - Saves bandwidth
- Disadvantages?
  - Increases delay in responding to the sender.

TCP Receiver: ACK generation [RFC 5681]

Event at receiver	*TCP receiver action*

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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

Optimizations 2: Delays ACKs (cont.)

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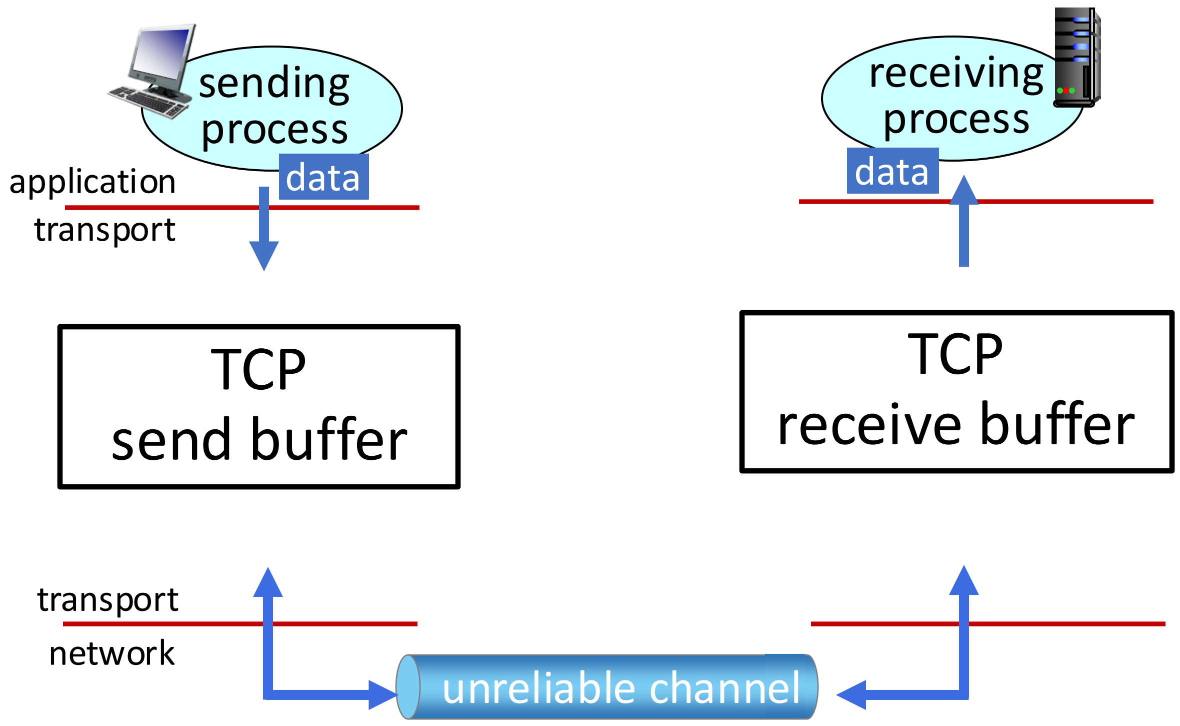
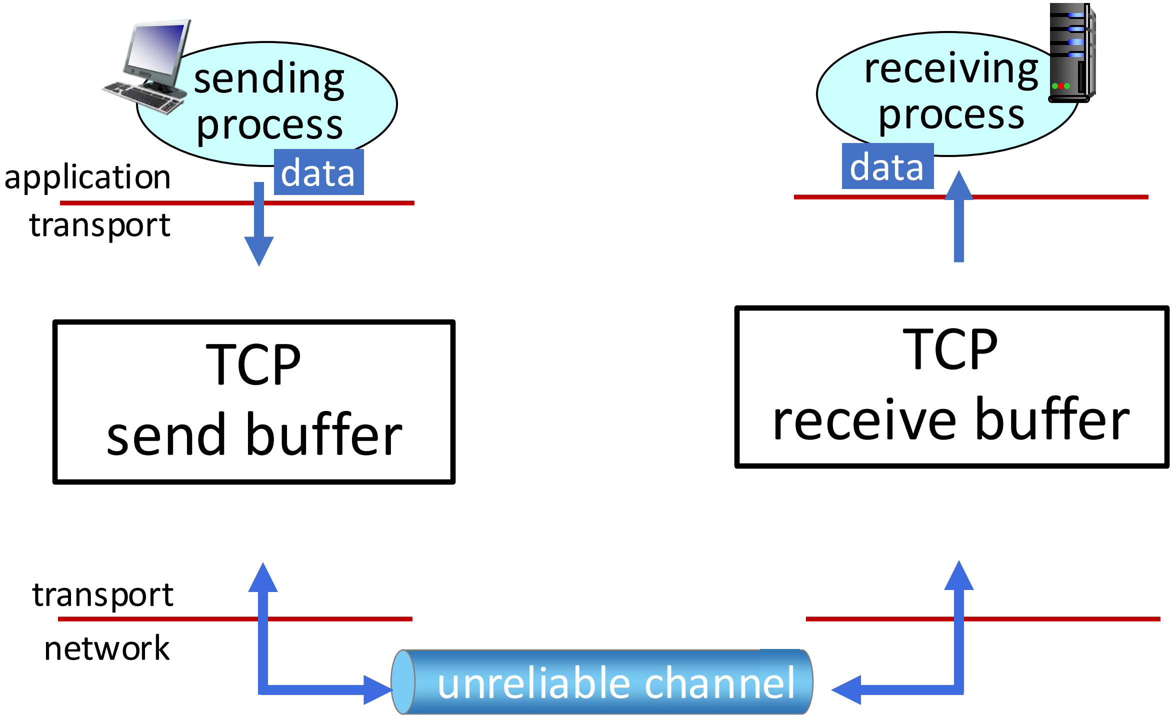
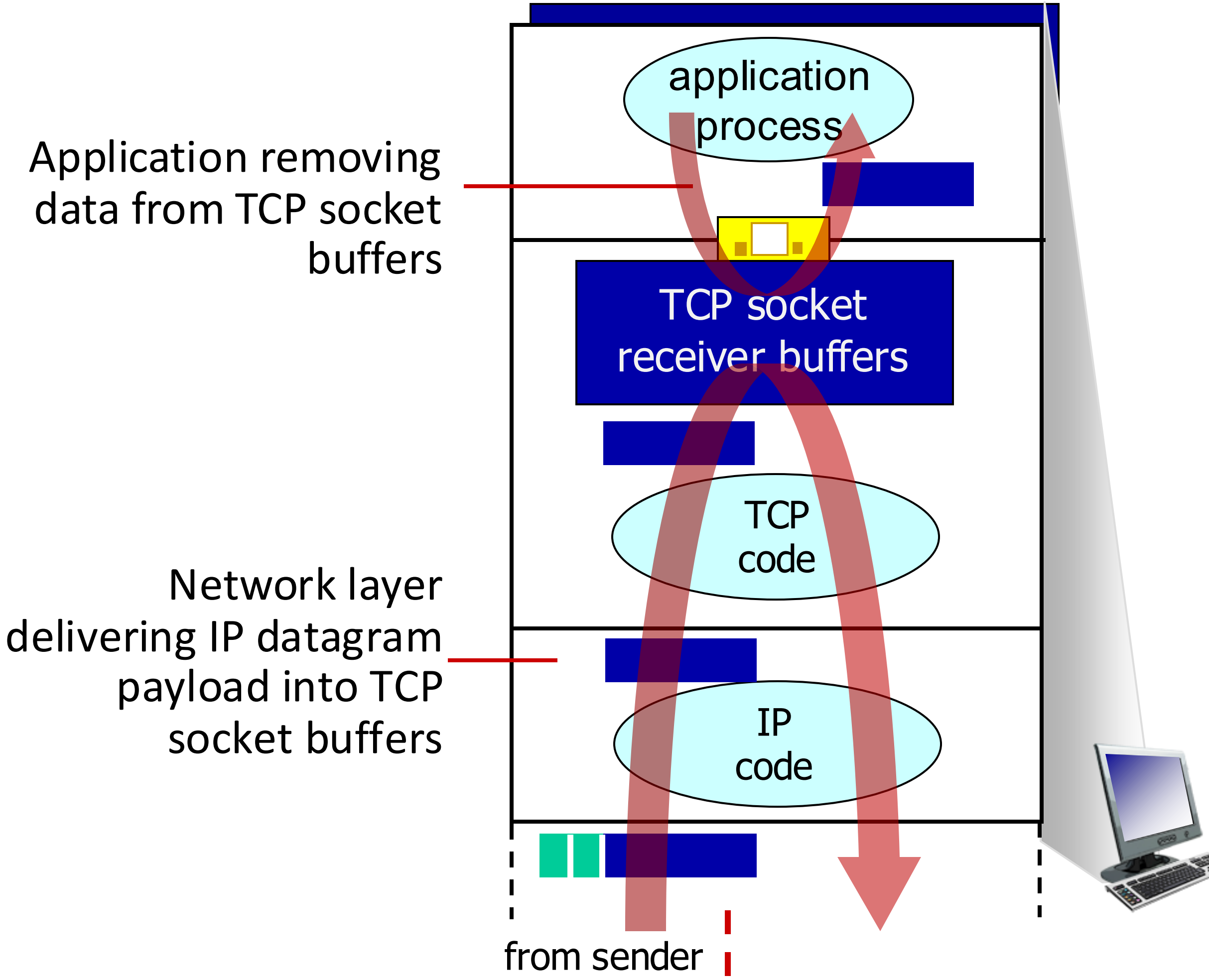
TCP flow control



- The send buffer holds the data the application sends to TCP until it is delivered
- The receive buffer holds the data TCP receives from the network until it is delivered to the application

TCP flow control





receiver protocol stack

Q: What happens if network layer delivers data faster than application layer removes data from socket buffers?

TCP flow control

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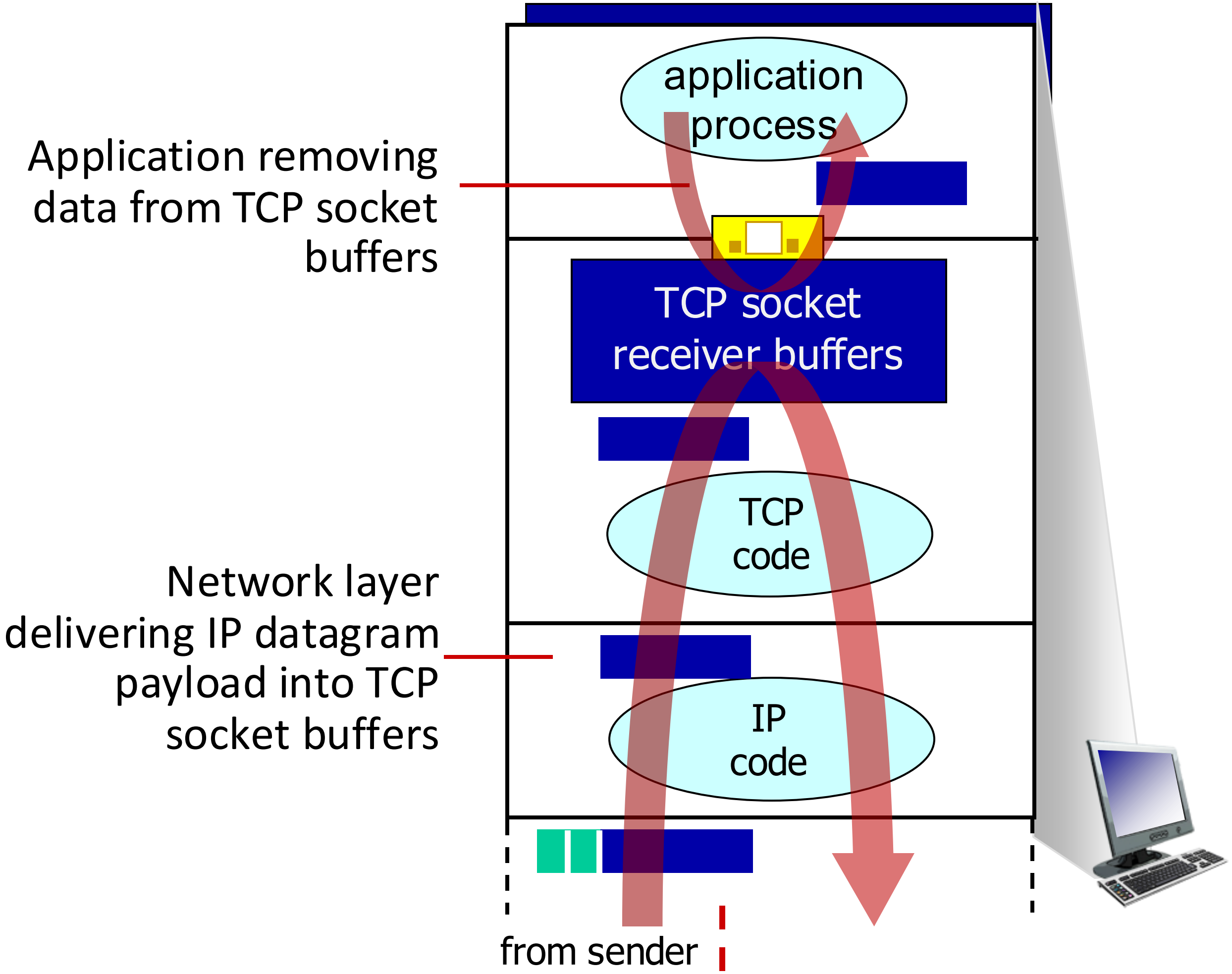

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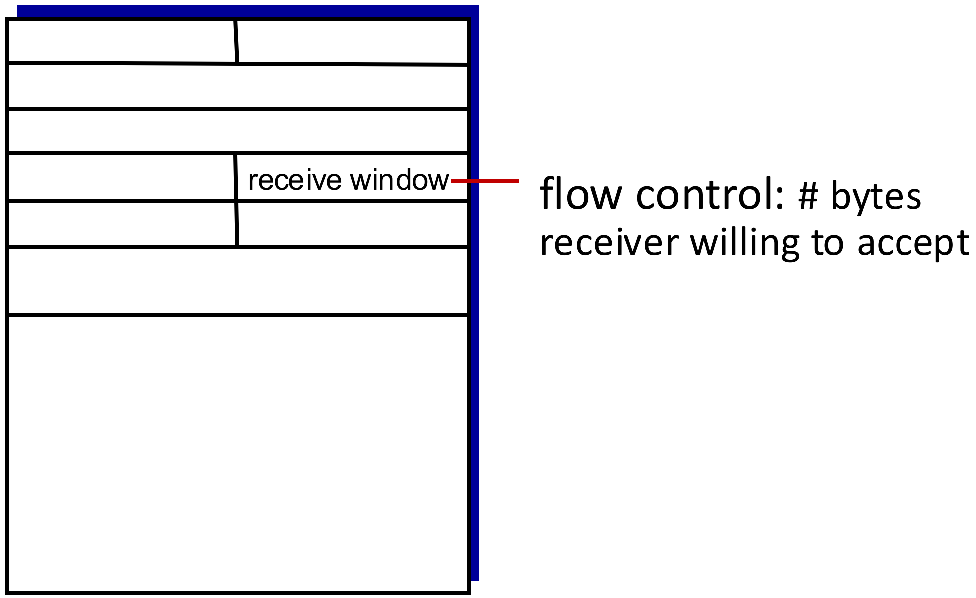

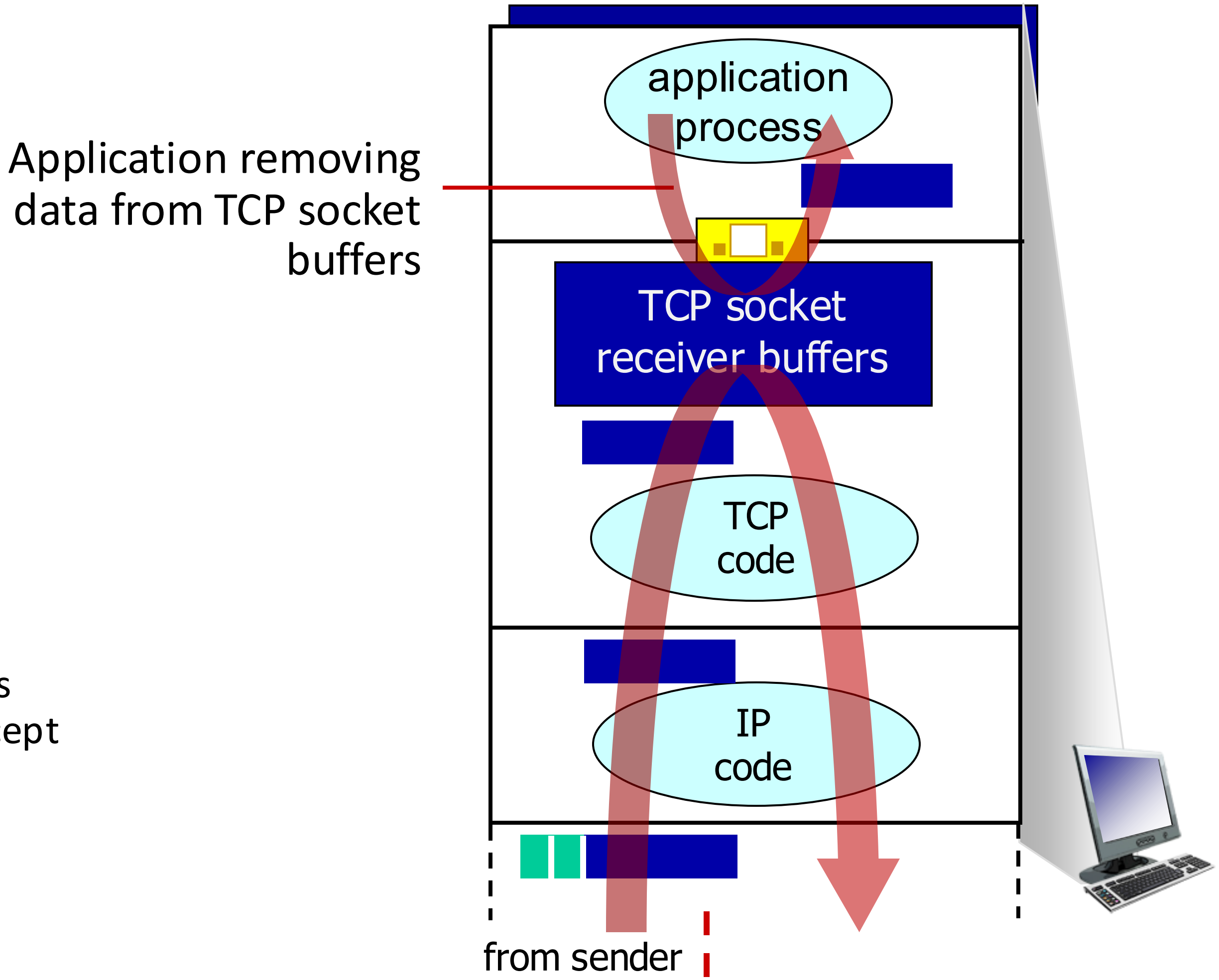

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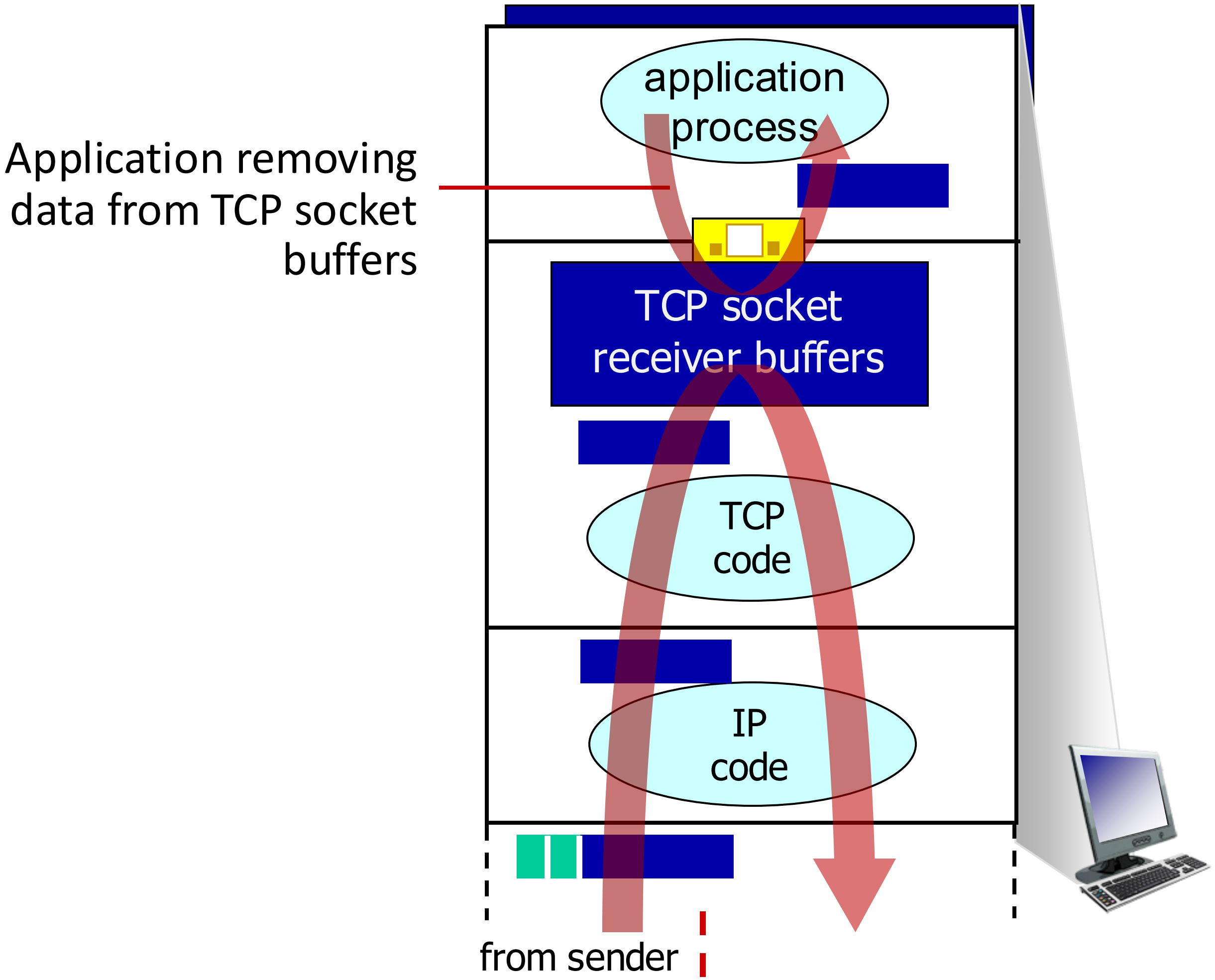


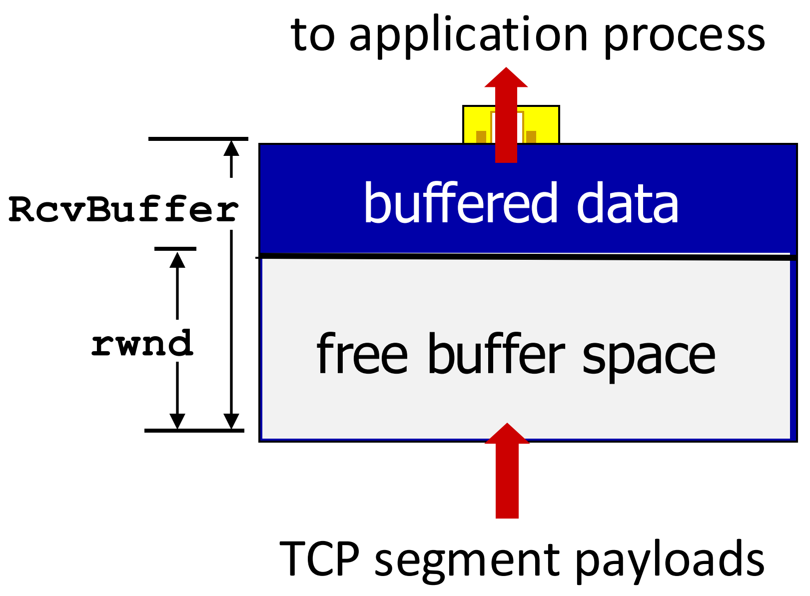
receiver protocol stack

flow control

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

TCP flow control

- **`RcvBuffer`** size set via socket options
  - many operating systems auto-adjust **`RcvBuffer`**
- TCP receiver "advertises" free buffer space in **`rwnd`** field in TCP header
- sender limits amount of unACKed ("in-flight") data to received **`rwnd`**
- guarantees receive buffer will not overflow



TCP receiver-side buffering

TCP flow control

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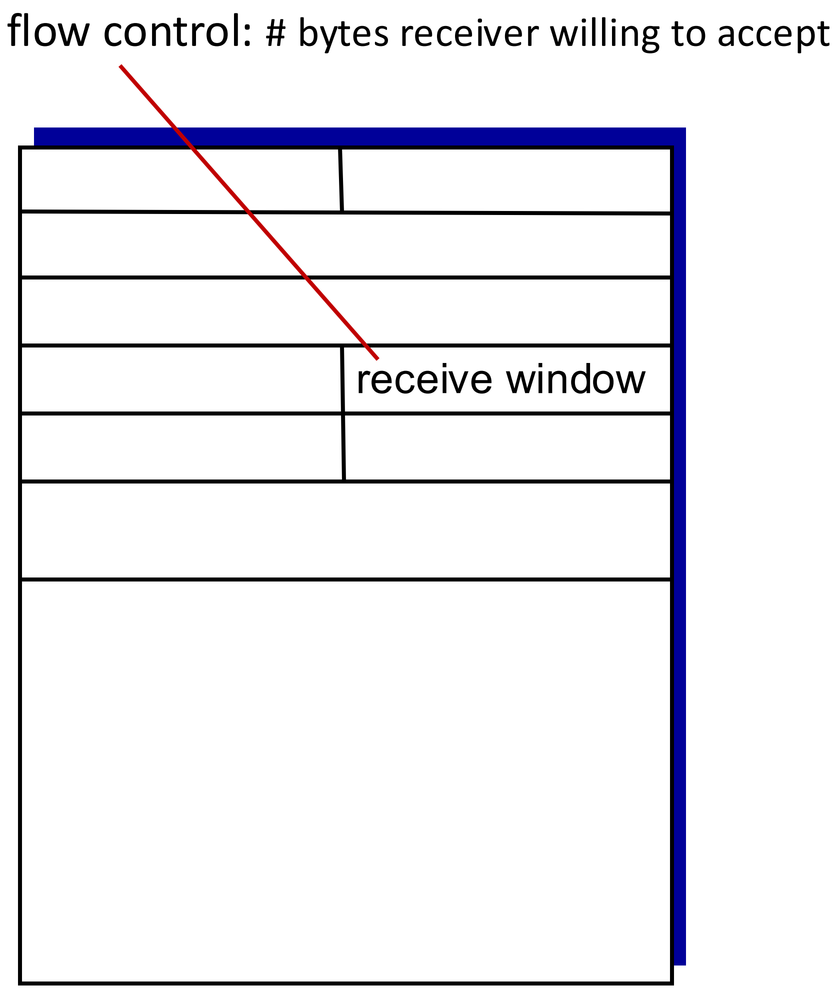

TCP segment format

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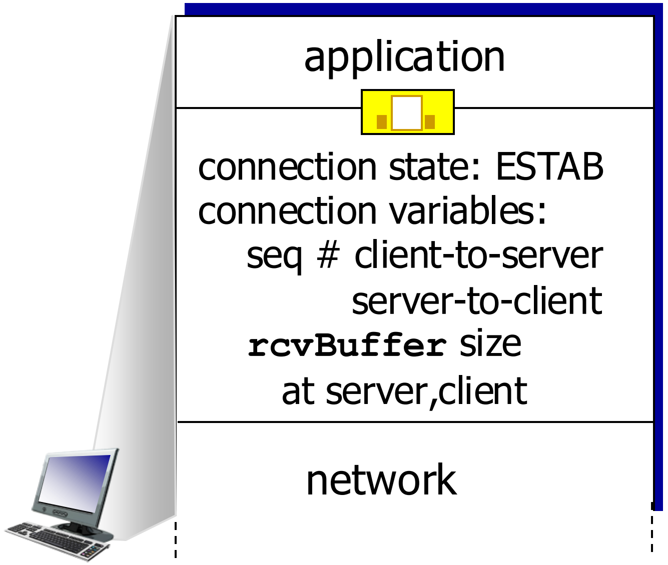
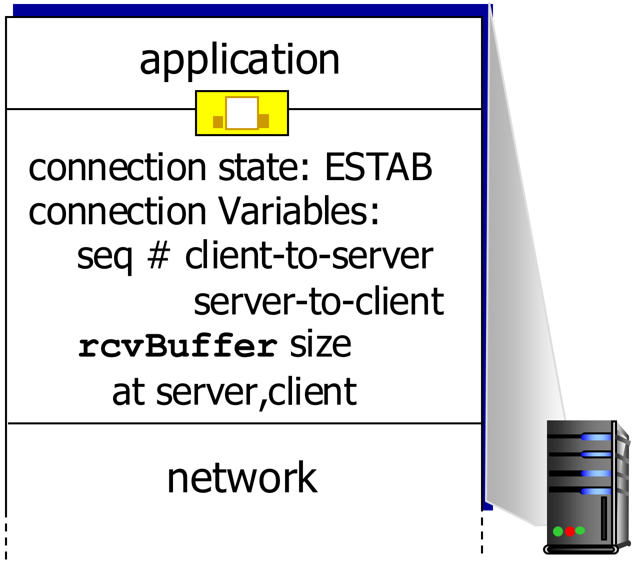
TCP connection management

before exchanging data, sender/receiver “handshake”:

- agree to establish connection (each knowing the other willing to establish connection)
- agree on connection parameters (e.g., starting seq #s)

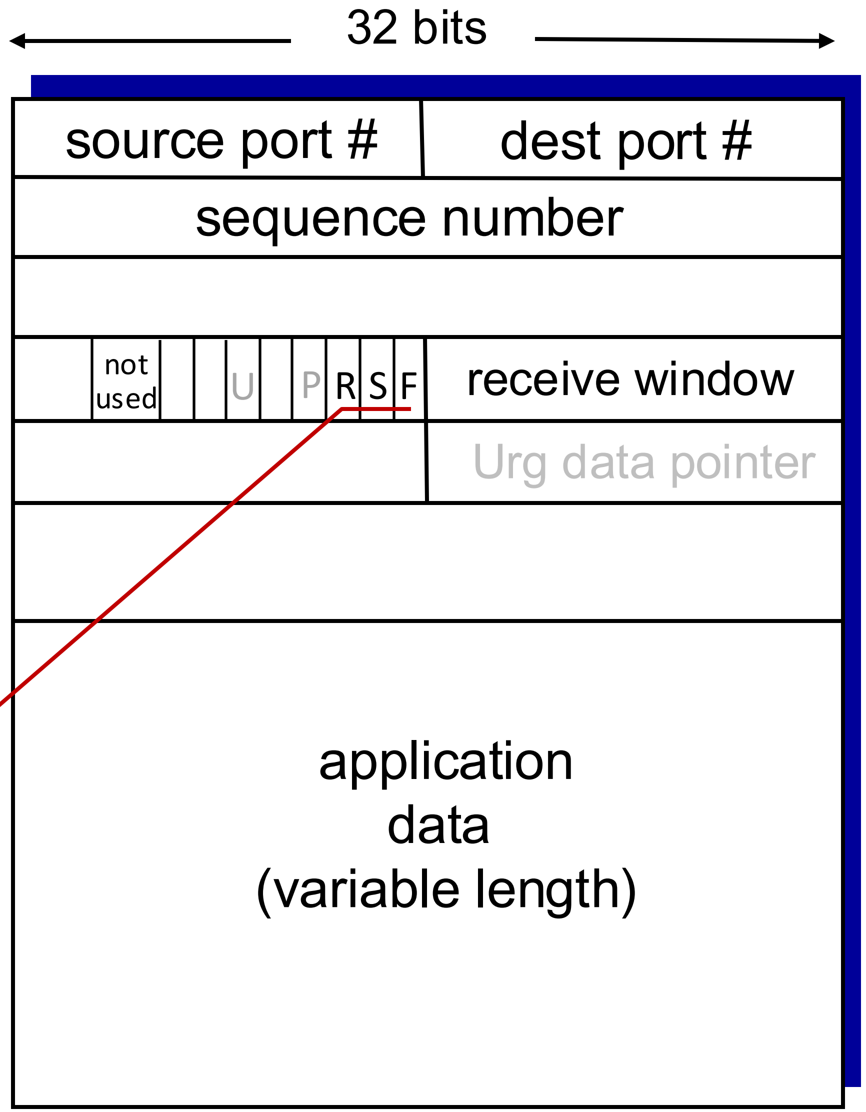



```
Socket clientSocket =
  newSocket("hostname","port number");
clientSocket.connect()
```



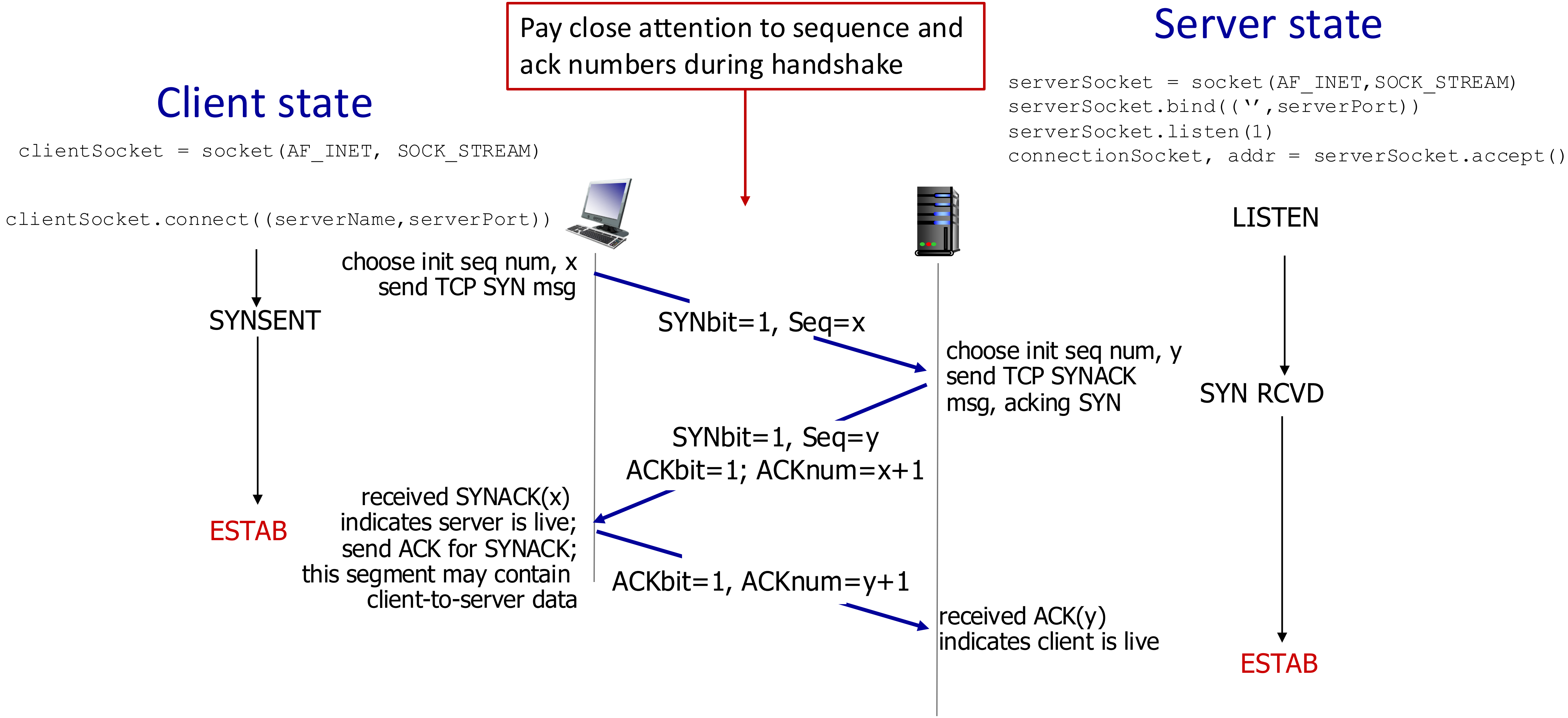

```
Socket connectionSocket =
  welcomeSocket.accept();
```

TCP segment structure



RST, SYN, FIN: connection management

TCP 3-way handshake



A human 3-way handshake protocol

Closing a TCP 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

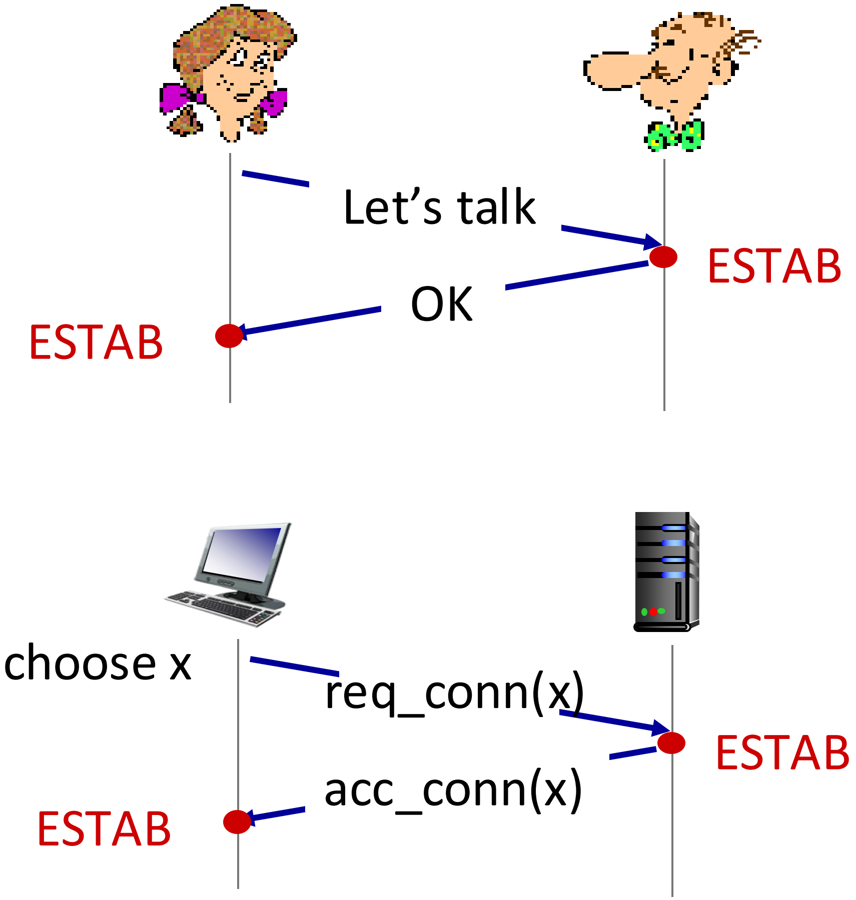
Knowledge Check

- Make sure you understand and can complete a TCP connection timeline
  - From connection establishment, through reliable data transfer (with optimizations and flow control), to connection tear-down
- This includes, but is not limited to
  - sequence and acknowledgement numbers on packets going back and forth
  - how the sender and receiver view of the sequence number space changes as a result of packets being sent and received (e.g., status of the bytes, position of the sliding window, etc.)

Additional Slides

Agreeing to establish a connection

2-way handshake:

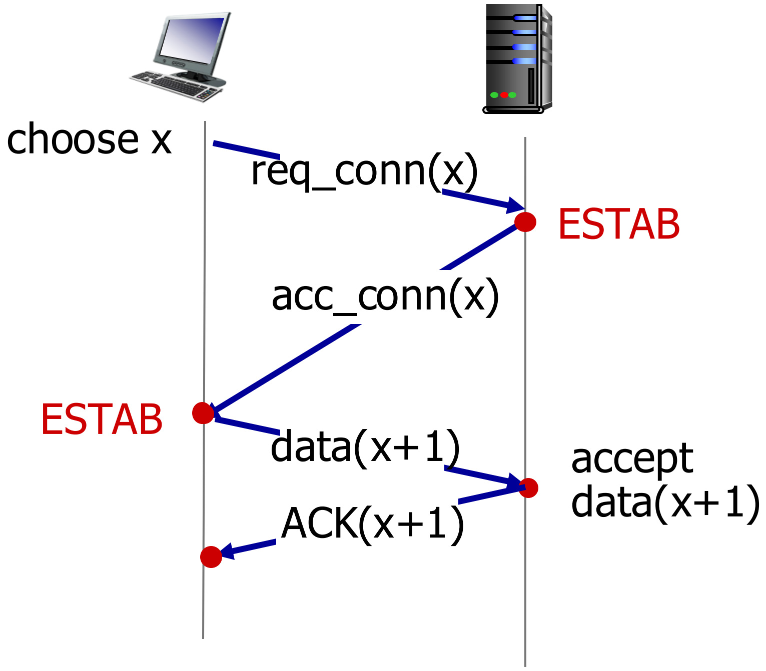


Q: will 2-way handshake always work in network?

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

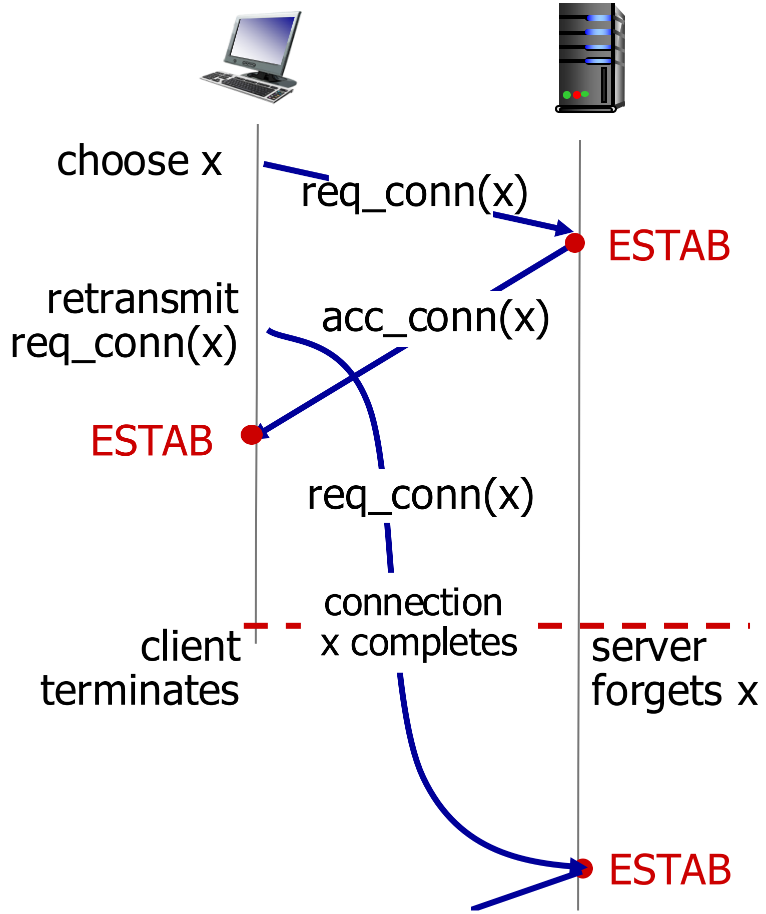
x completes

2-way handshake scenarios



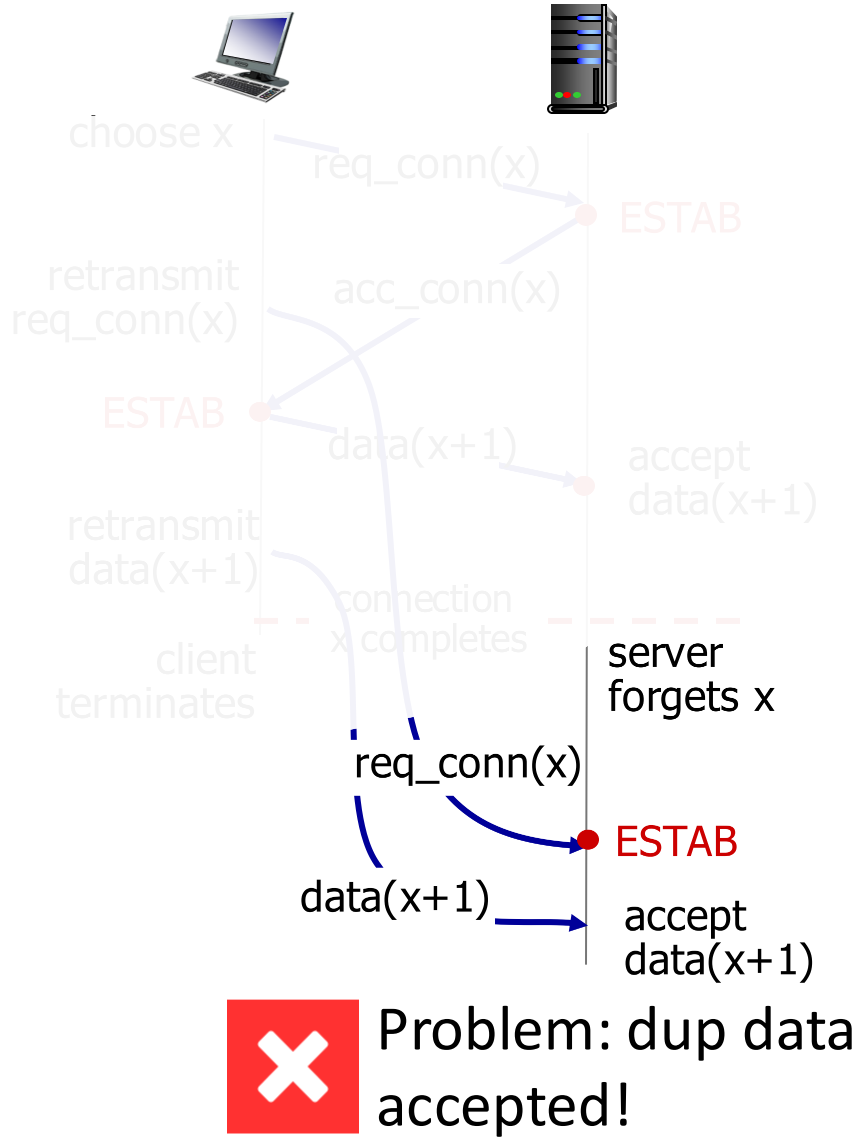
No problem!

2-way handshake scenarios



Problem: half open connection! (no client)

2-way handshake scenarios



SYN flood attack

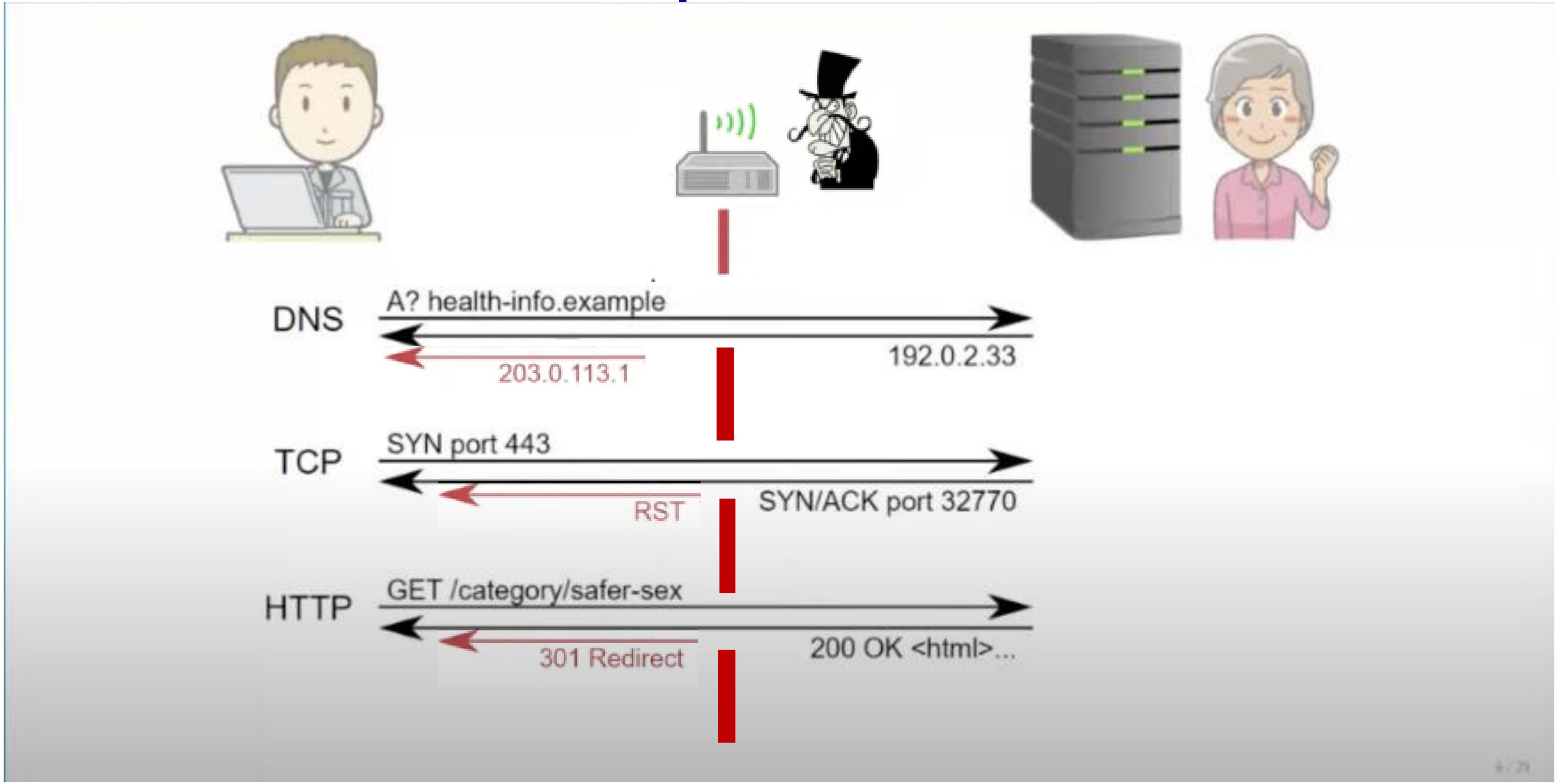
- A common DoS attack

Nmap-port scanning tool

- say port 6789, on a target host, nmap will send a TCP SYN segment
- Three possible outcomes:

1. Receives a TCP synack segment
2. Receives a TCP RST segment
    - Syn segment reached the target host, but the target host is not running an application with tcp port 6789.
    - But the sender at least knows that the segments destined to the host at port 6789 are not blocked
3. Receives nothing

Internet Censorship



Source: https://www.youtube.com/watch?v=6iJ7KczFArw

ICLab: Detailed Probes for Network Censorship

Internet Measurement Village 2020
Presenter: Zachary Weinberg

https://iclab.org/ • info@iclab.org

Arian Akhavan Niaki | Shinyoung Cho | Zachary Weinberg | Nguyen Phong Hoang | Abbas Razaghpanah | Diogo Barradas | Nicolas Christin | Phillipa Gill

University of Massachusetts Amherst · Stony Brook University · International Computer Science Institute · CyLab Carnegie Mellon University Security and Privacy Institute · Técnico Lisboa · inesc id lisboa