CSCI-1680
Transport Layer II

Data over TCP: Flow Control

Nick DeMarinis

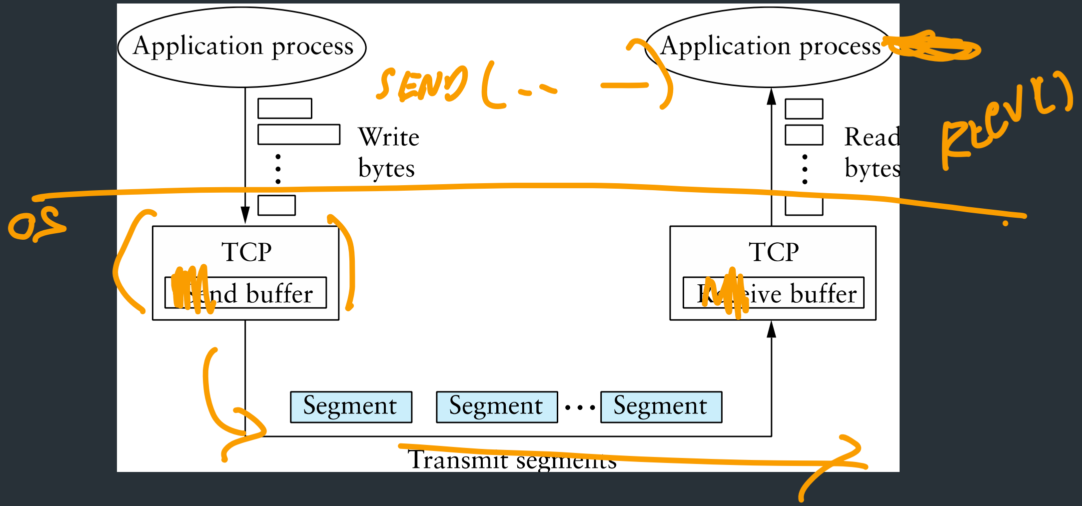
Based partly on lecture notes by Rodrigo Fonseca, David Mazières, Phil Levis, John Jannotti

"Hi, I'd like to hear a TCP joke."
"Hello, would you like to hear a TCP joke?"
"Yes, I'd like to hear a TCP joke."
"OK, I'll tell you a TCP joke."
"Ok, I will hear a TCP joke."
"Are you ready to hear a TCP joke?"
"Yes, I am ready to hear a TCP joke."
"Ok, I am about to send the TCP joke. It will last 10 seconds, it has two characters, it does not have a setting, it ends with a punchline."
"Ok, I am ready to get your TCP joke that will last 10 seconds, has two characters, does not have an explicit setting, and ends with a punchline."
"I'm sorry, your connection has timed out. ... Hello, would you like to hear a TCP joke?"

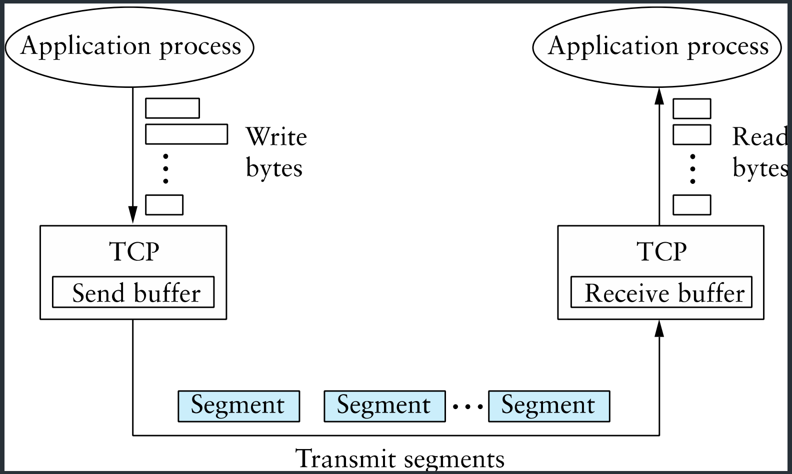
Administrivia

- IP project grading: happening now! Sign up for a meeting if you haven't already
- **TCP assignment: out now—<u>start early</u>!**
  - Gearup I: Thursday 10/26 5-7pm CIT 368 (+ Zoom, Rec)
  - Milestone 1: schedule meeting on/before Thursday, November 2

TCP – Transmission Control Protocol

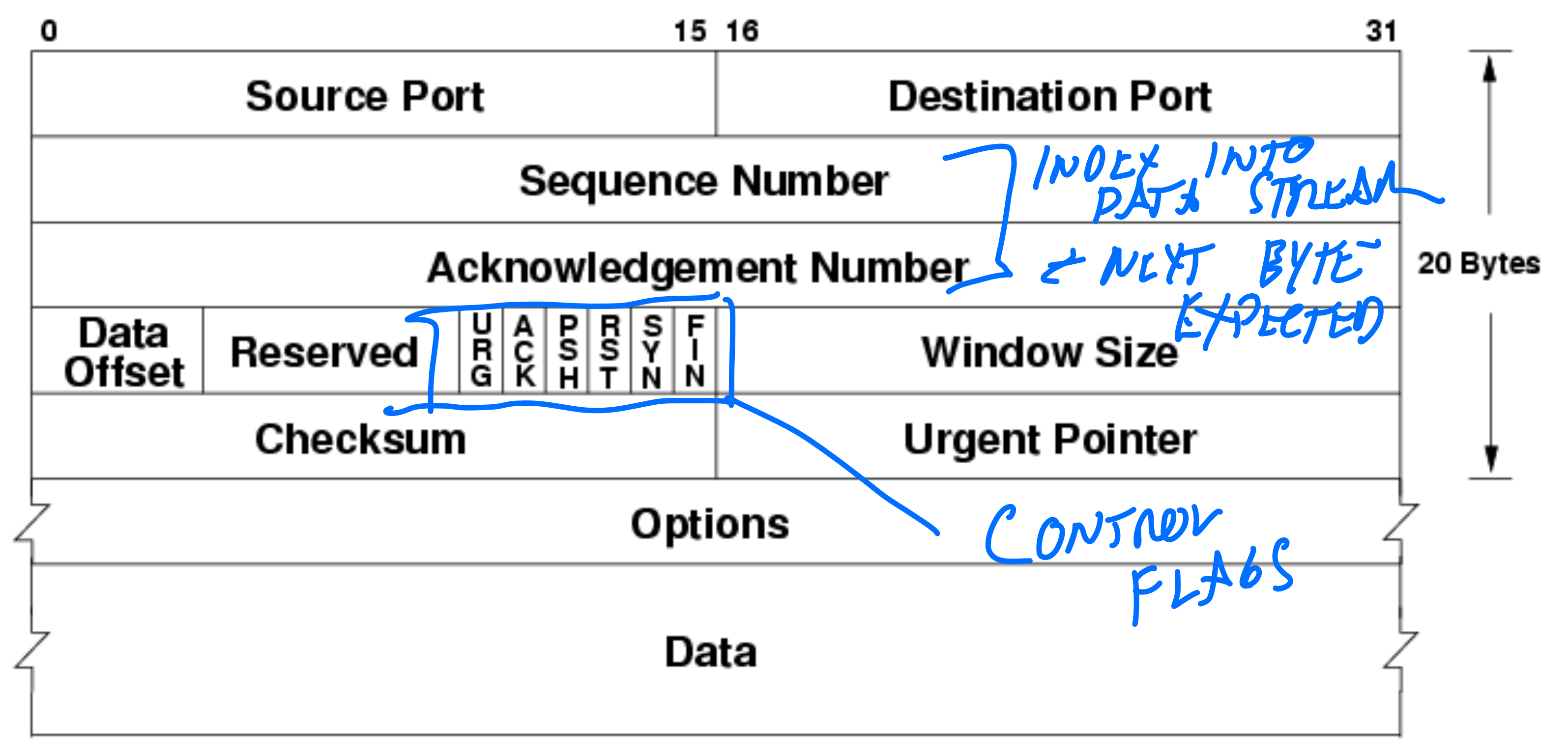


TCP – Transmission Control Protocol

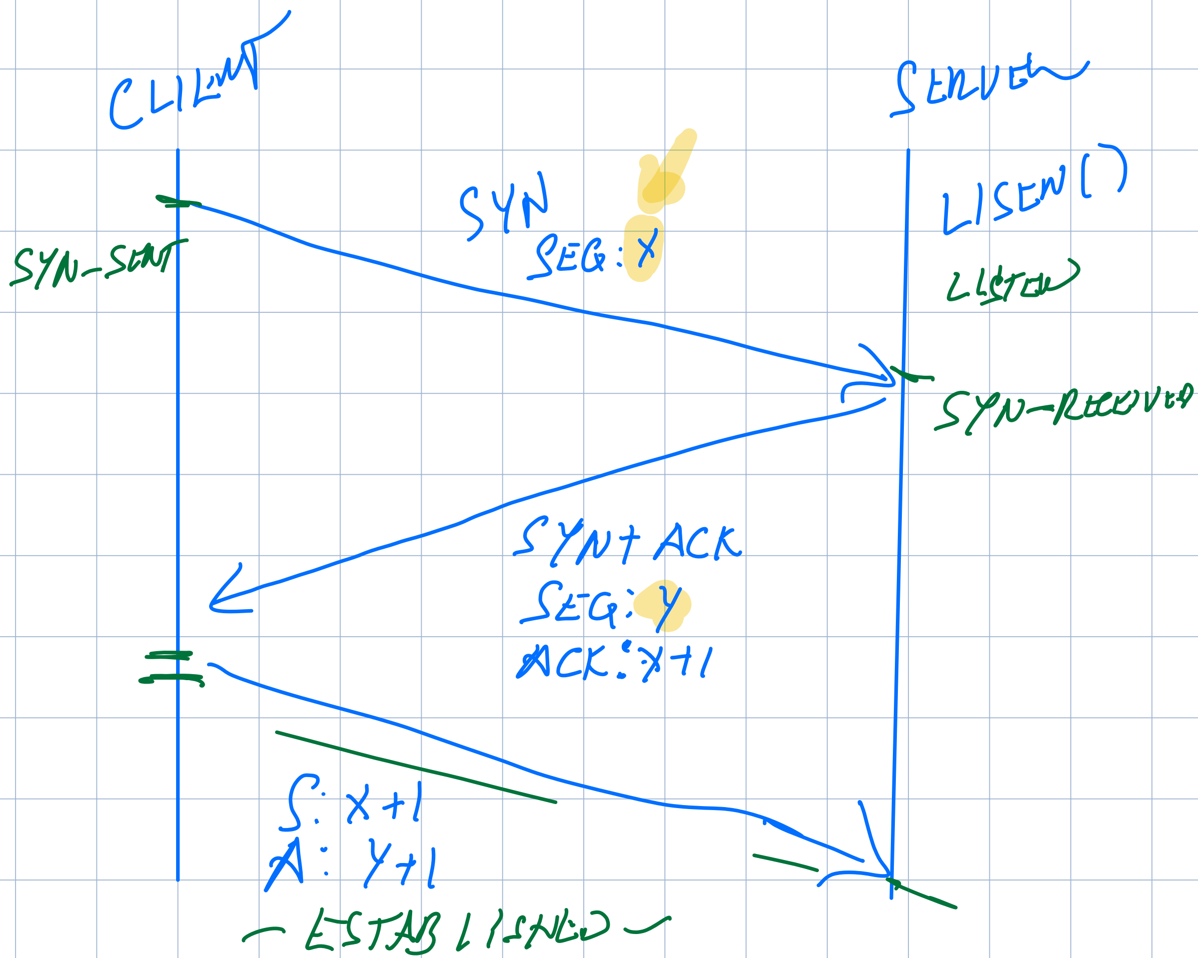


TCP provides a "reliable, connection oriented, full duplex ordered byte stream"

TCP Header



0
15
16
31
Source Port
Destination Port
Sequence Number
Acknowledgement Number
Data Offset
Reserved
URG
ACK
PSH
RST
SYN
FIN
Window Size
Checksum
Urgent Pointer
Options
Data
20 Bytes
INDEX INTO DATA STREAM
& NEXT BYTE EXPECTED
CONTROL FLAGS



– BOTH SIDES NEED TO AGREE ON THEIR STARTING SEQ NUMBERS

Important Header Fields: Flags

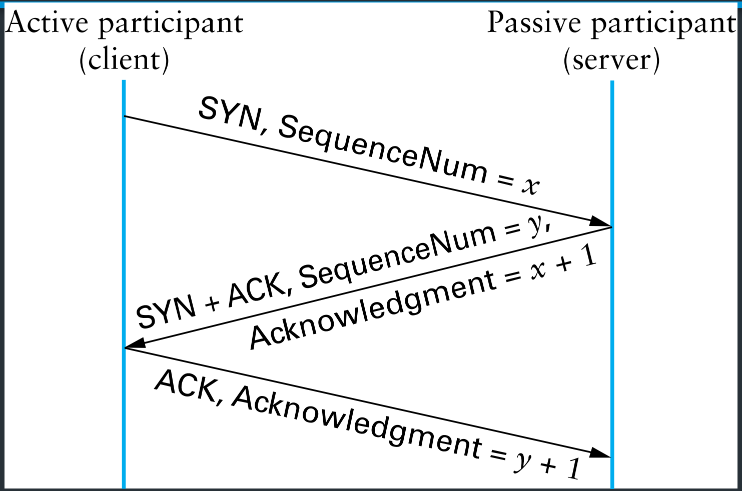
- SYN: establishes connection (“synchronize”)
- ACK: this segment ACKs some data (all packets except first)
- FIN: close connection (gracefully)

- RST: reset connection (used for errors)
- PSH: push data to the application immediately
- URG: whether there is urgent data

Less important header fields

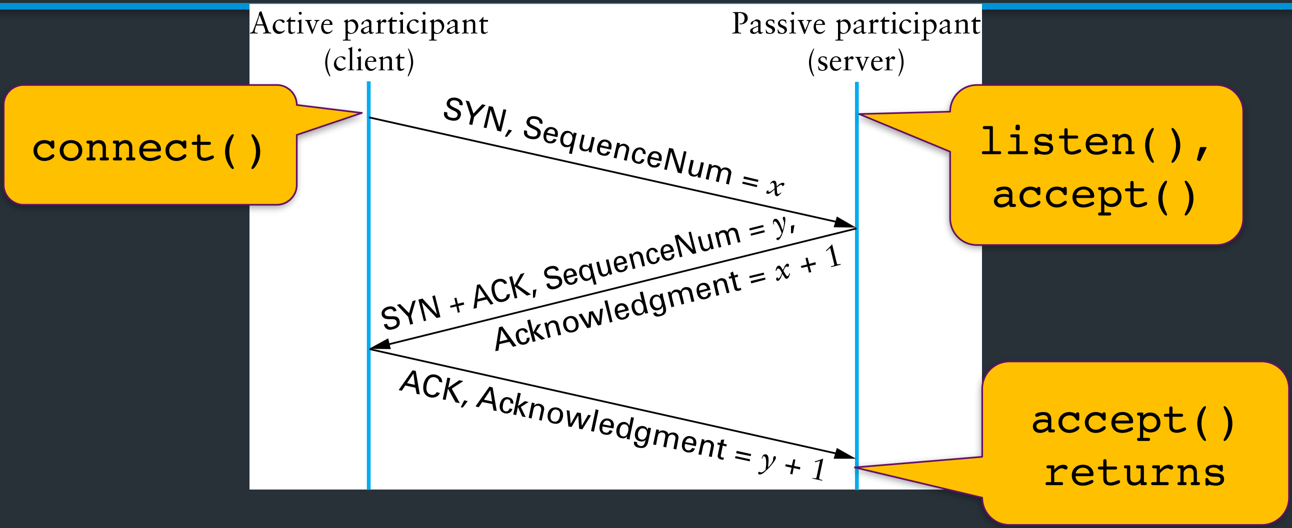
- Checksum: Very weak, like IP
  - Has weird semantics ("pseudo header"), more on this later…
- Data Offset: used to indicate TCP options (mostly unused)
- Urgent Pointer

Establishing a Connection



- Three-way handshake
  - Two sides agree on respective initial sequence nums
- If no one is listening on port: OS may send RST
- If server is overloaded: ignore SYN
- If no SYN-ACK: retry, timeout

Establishing a Connection



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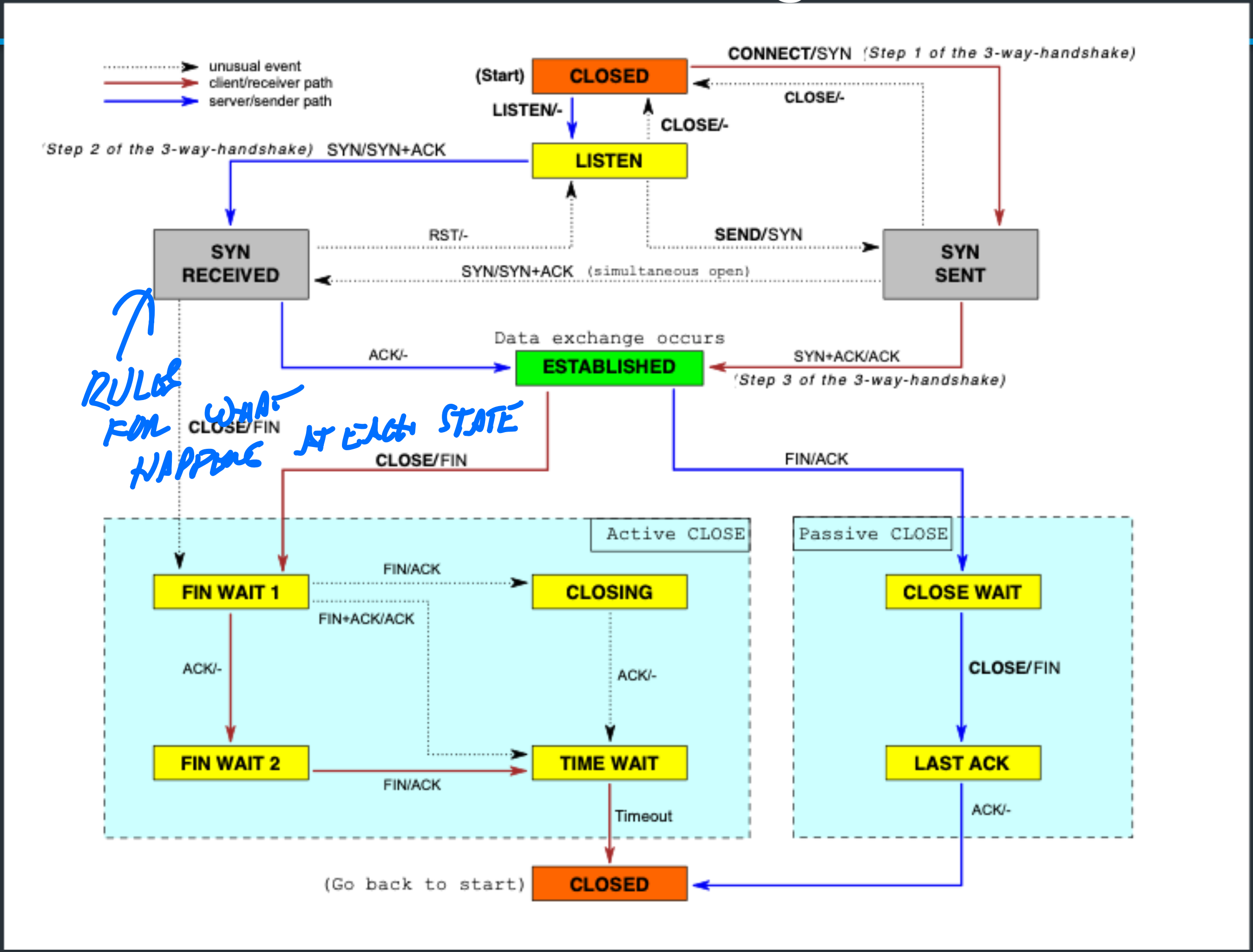
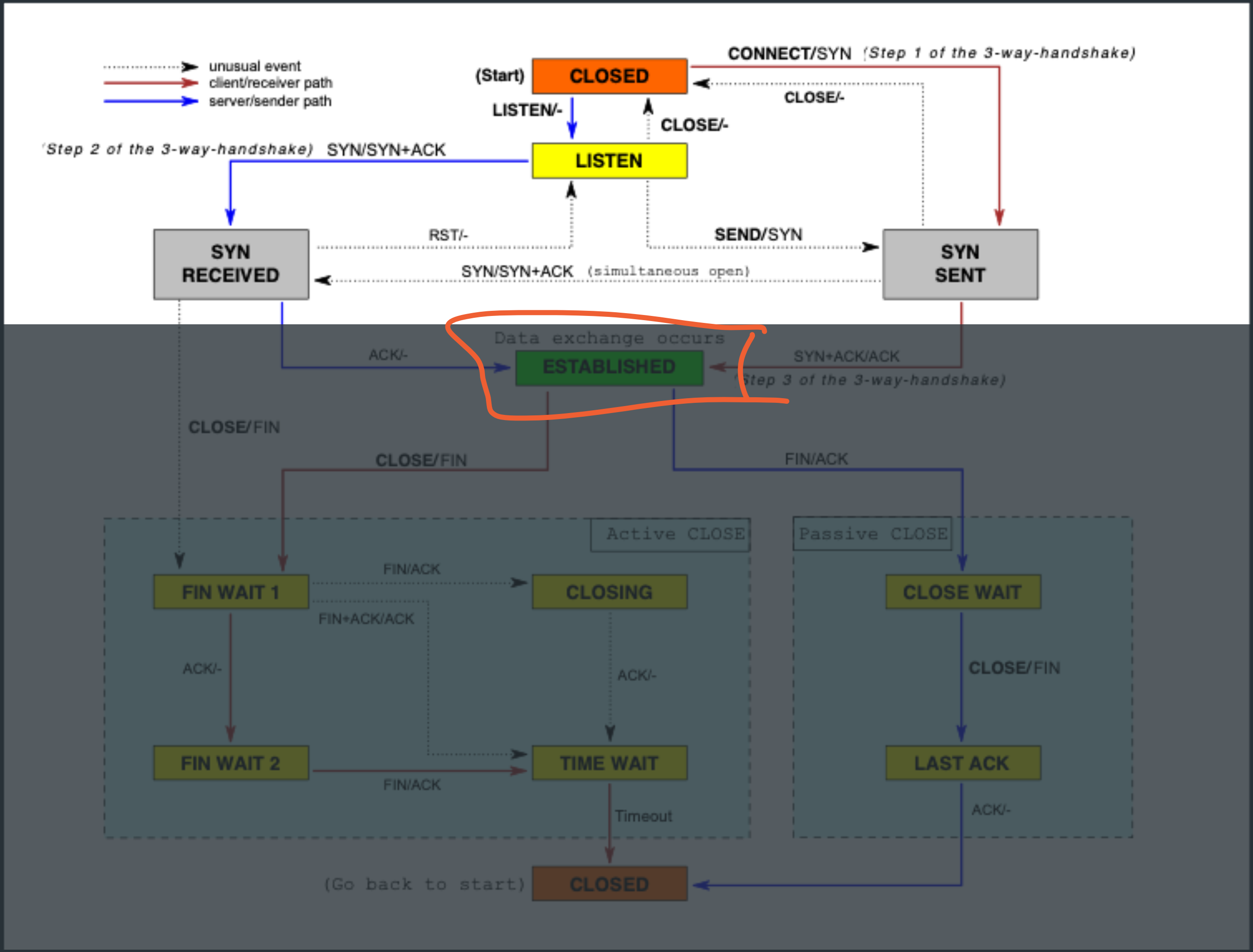
TCP State Diagram



We are now here



State for a TCP connection kept in <u>Transmission Control Buffer (TCB)</u>

- Keeps initial sequence numbers, connection state, send/recv buffers, status of unACK'd segments, …

x, y

<u>When to allocate?</u>

<u>SERVER</u>: LISTENING ON CONNECTION (LISTEN)

CLIENT: INITIATING CONNECTION (SYN)

<u>SERVER</u>: AFTER EACH CLIENT CONNECTS (ACCEPT)

State for a TCP connection kept in Transmission Control Buffer (TCB)

- Keeps initial sequence numbers, connection state, send/recv buffers, status of unACK'd segments, …

When to allocate?

- Server: listening on a connection*
- Client: Initiating a connection (sending a SYN)
- Server: accepting a new connection (receiving SYN)

⇒ When to deallocate?

↳ UNTIL ALL DATA HAS BEEN ACK'D, CLOSE PROCESS IS DONE.

State for a TCP connection kept in Transmission Control Buffer (TCB)

- Keeps initial sequence numbers, connection state, send/recv buffers, status of unACK'd segments, …

When to allocate?

- Server: listening on a connection*
- Client: Initiating a connection (sending a SYN)
- Server: accepting a new connection (receiving SYN)

When to deallocate?

Only after connection termination is fully completed (CLOSED state)

=> If no state, can't meaningfully respond to packet!

NOTA BENE: This diagram is only a summary and must not be taken as the total specification. Many details are not included.

```
                            +---------+ ---------\      active OPEN
                            |  CLOSED |            \    -----------
                            +---------+<---------\   \   create TCB
                              |     ^              \   \  snd SYN
                 passive OPEN |     |   CLOSE        \   \
                 ------------ |     | ----------       \   \
                  create TCB  |     | delete TCB         \   \
                              V     |                      \   \
          rcv RST (note 1)  +---------+            CLOSE    |    \
       -------------------->|  LISTEN |          ---------- |     |
      /                     +---------+          delete TCB |     |
     /           rcv SYN      |     |     SEND              |     |
    /           -----------   |     |    -------            |     V
+--------+      snd SYN,ACK  /       \   snd SYN          +--------+
|        |<-----------------           ------------------>|        |
|  SYN   |                    rcv SYN                     |  SYN   |
|  RCVD  |<-----------------------------------------------|  SENT  |
|        |                  snd SYN,ACK                   |        |
|        |------------------           -------------------|        |
+--------+   rcv ACK of SYN  \       /  rcv SYN,ACK       +--------+
   |         --------------   |     |   -----------
   |                x         |     |     snd ACK
   |                          V     V
   |  CLOSE                 +---------+
   | -------                |  ESTAB  |
   | snd FIN                +---------+
```

RFC 9293, Sec 3.3.2

Recall: the socket table

```
deemer@vesta ~ % netstat -anl
Active Internet connections (including servers)
Proto Recv-Q Send-Q  Local Address          Foreign Address        (state)
tcp4       0      0  172.17.48.121.56915    192.168.1.58.7000      SYN_SENT
tcp4       0      0  172.17.48.121.56908    142.250.80.35.443      ESTABLISHED
tcp4       0      0  172.17.48.121.56887    13.225.231.50.80       ESTABLISHED
                                      . . .
tcp4       0      0  *.22                   *.*                    LISTEN
```

TCB
TCB
TCB
TCB

KEY

VALUE

- Each connection has an associated TCB in the kernel
- Depending on socket type, socket contains TCB

⇒ For each packet, kernel maps the 5-tuple
(tcp/udp, local IP, local port, remote IP, remote port) => socket

5-tuple (proto., source IP, source port, dest IP, dest port) => 1 Conn

– Kernel maintains socket table: maps (5-tuple) => Socket

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- If a 5-tuple is reused => new ISN, so sequence numbers likely out of range from past connection

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tcp4       0      0  172.17.48.121:22     192.168.1.58:34452     SYN_SENT



tcp4       0      0  *.22                   *.*                    LISTEN
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tcp4       0      0  172.17.48.121:22      142.250.80.35:11435      ESTABLISHED
tcp4       0      0  172.17.48.121:22      13.225.231.50:12345      ESTABLISHED
                                     . . .
tcp4       0      0  *.22                    *.*                     LISTEN
```

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Two "types" of sockets:

- "Normal" sockets

- Listen sockets

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tcp4       0      0  172.17.48.121.56887    13.225.231.50.80       ESTABLISHED
                                       . . .
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```

"Normal" sockets

– Connection between two specific endpoints
– Can send/recv data

Listen sockets

– Created by receiver to accept new connections
– When a client connects, client info gets queued by kernel
– When server process calls accept(), **a new ("normal") socket is created between the server and that client**

How to pick the initial sequence number?

- Protocols based on <u>relative</u> seq. numbers based on starting value
- Why not start at 0?

How to pick the initial sequence number?

- Protocols based on relative seq. numbers based on starting value
- Why not start at 0?

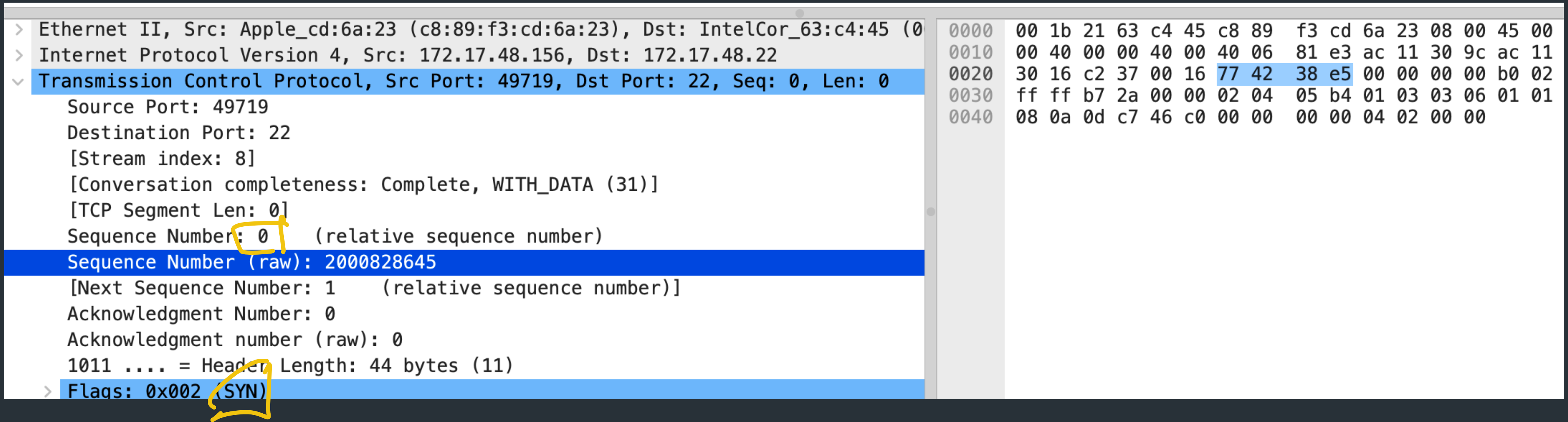
=> Someone might guess the value!

=> IF NUMBER ~~RE~~ REUSED (SYSTEM RESTART), CAN'T TELL IP PACKET IS FOR DIFF CONNECTION.

=> RFC9293, Sec 3.4.1: Procedure for picking ISN, based on timer and cryptographic hash

=> For project, just pick a random integer :)

Relative Sequence Numbering



Observation: new connections use memory!

What happens if you send a someone lots of SYN packets?

SYN flood => type of Denial of Service (DOS) attack

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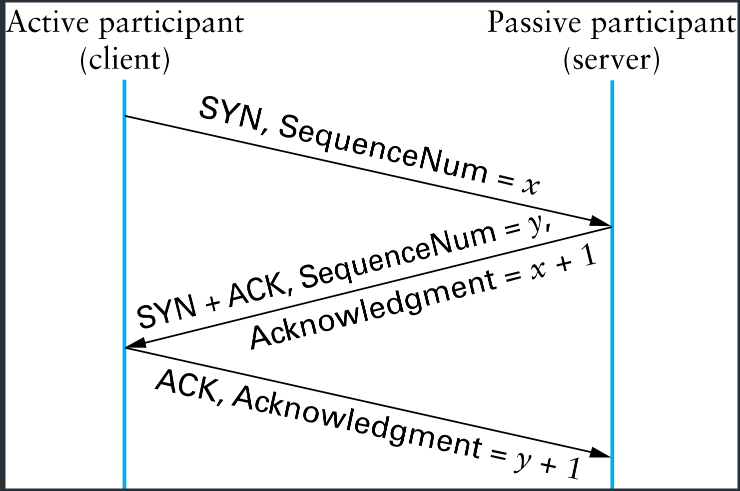
=> Especially bad when attack traffic comes from multiple sources (more on this later)

A hacky solution: SYN cookies

- Don't allocate TCB on first SYN
- Encode some state inside the initial sequence number that goes back to the client (in the SYN+ACK)
- What gets encoded?
  - Coarse timestamp
  - Hash of connection IP/port
  - Other stuff (implementation dependent)
- Better ideas?



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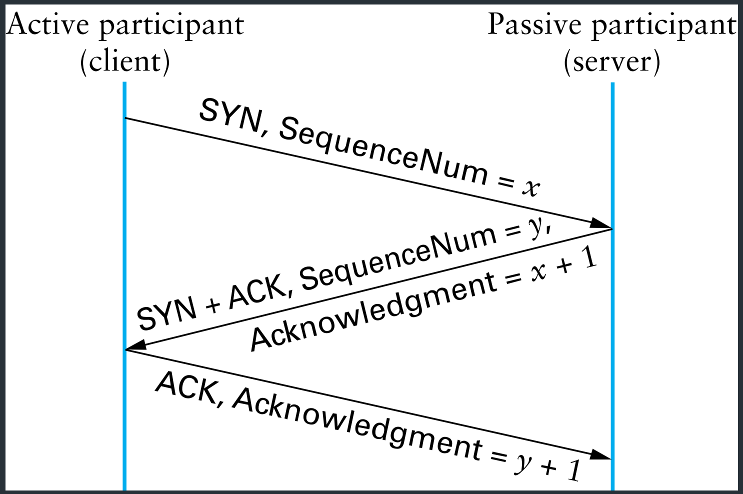
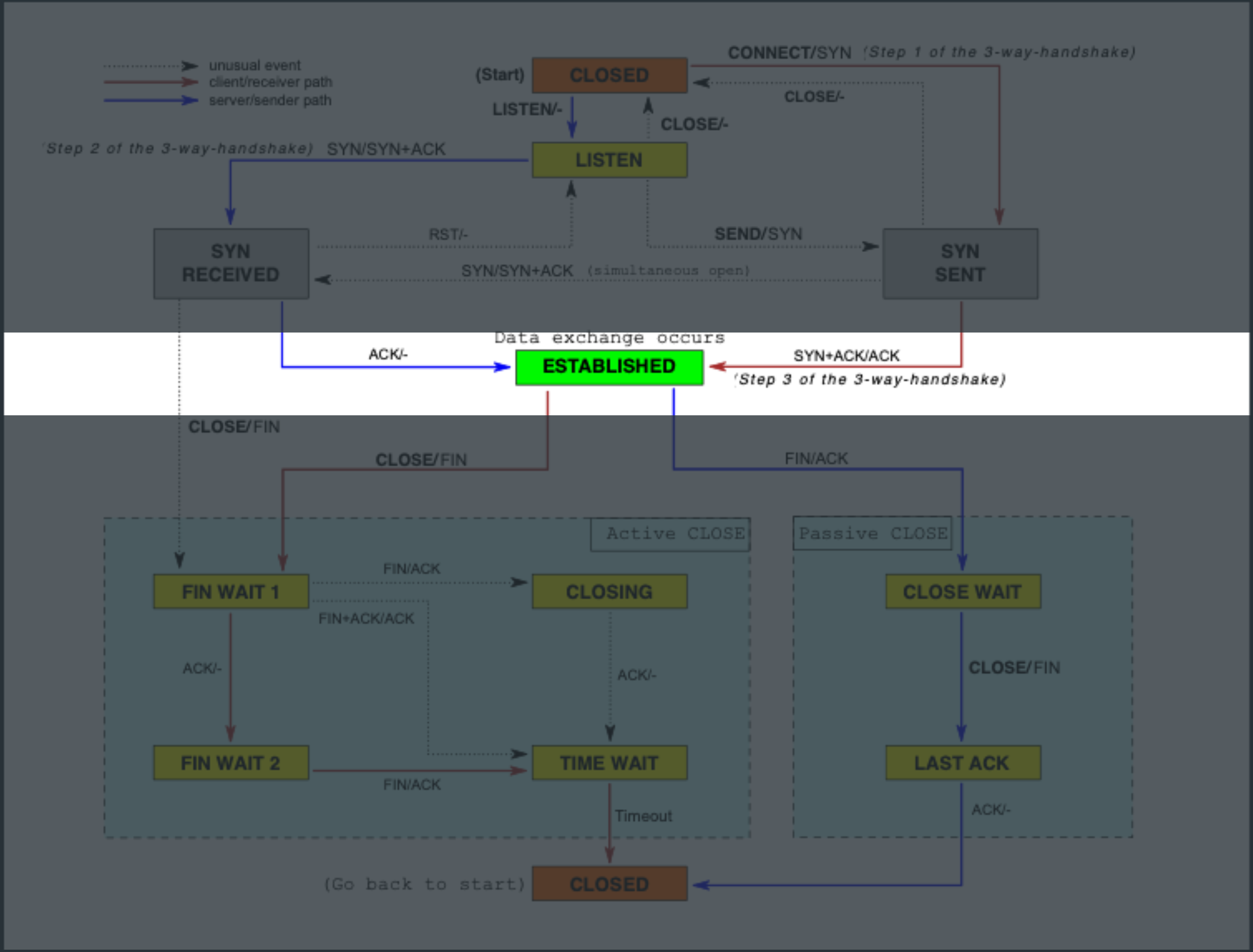


- Nowadays: filtering in kernel (or in network) on number of new connections per time (esp. on servers)
  = > More on this later!

Sending data



DROP PACKET: RETRANSMIT IF TIMEOUT (RTO)

LOST ACK: //

DUP ACK/PACKET:

⇒ ALWAYS KNOW WHAT SEGMENT OR ACK TO EXPECT NEXT. IF YOU DON'T RECEIVE AN EXPECTED SEGMENT, IGNORE IT.

"IN THE WINDOW" (OF EXPECTED PKTS/ACKS)

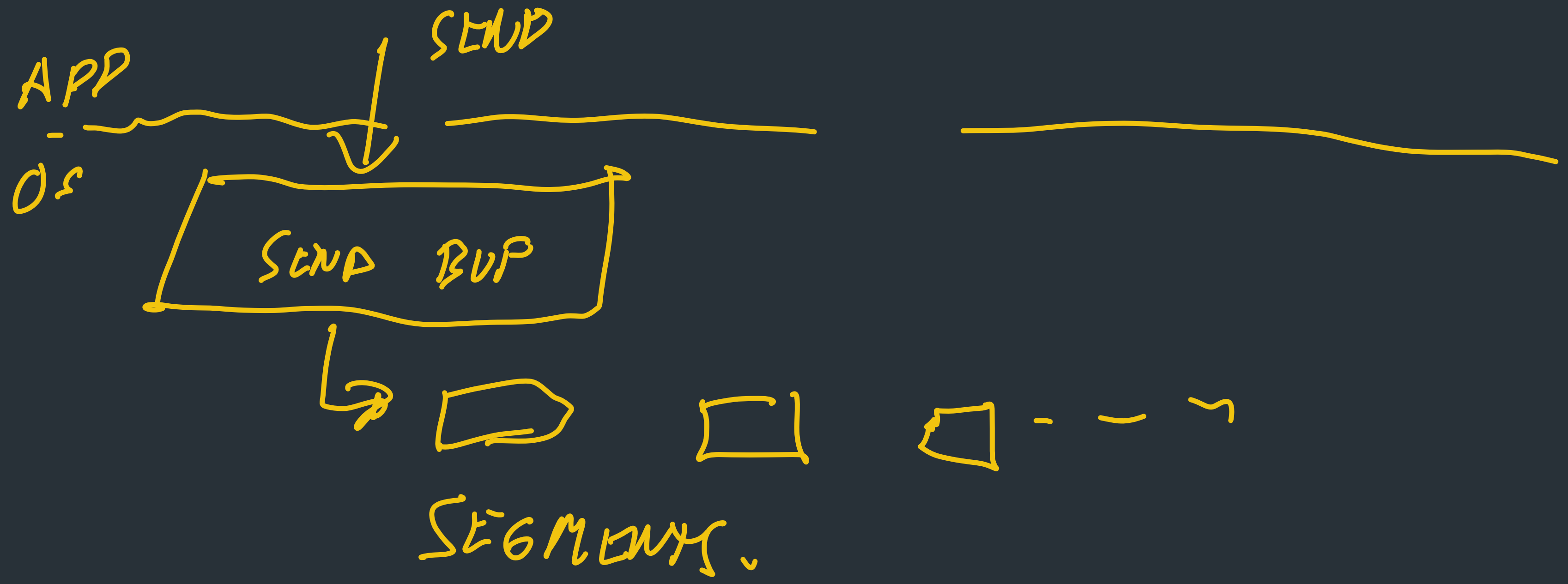
Sending data: the basic idea

- Start: app calls Send(), loads send buffer

→ PART OF TCB

Sending data: the basic idea

- Start: app calls Send(), loads send buffer
- TCP stack divides data into packets called segments



Sending data: the basic idea

- Start: app calls Send(), loads send buffer
- TCP stack divides data into packets called segments

Key challenges

"(FLOW CONTROL)

- When to send data?
- How much data to send?

WINDOW SIZE"

⇒ Flow control (now): don't send more data than the receiver can handle

⇒ Congestion control (much later) don't send more data than the network can handle (LATER)

Terminology: MSS

MSS: Maximum segment size

LARGEST POSSIBLE SEGMENT

- Largest segment a TCP can send
- Can be configurable

- Nowadays: sender and receiver negotiate using TCP options (out of scope for this class)

Terminology: MSS

MSS: Maximum segment size

- Largest segment a TCP can send
- Can be configurable

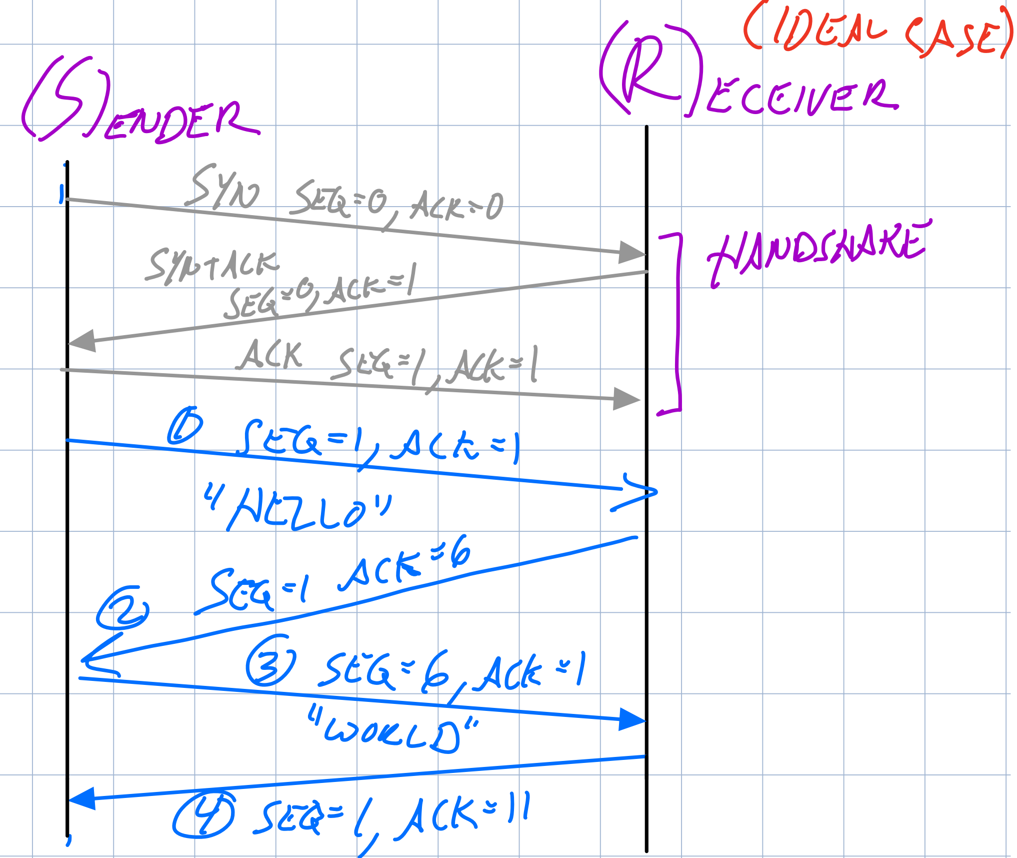
- Nowadays: sender and receiver negotiate using TCP options (out of scope for this class)

(≈ 1000 BYTES)

=> For project: just a fixed value

Simplest TCP sender: stop and wait

SIMPLEST SENDER: STOP + WAIT



- S: SEND SEGMENT, WAIT FOR ACK (EX. ①, ③)
- R: WAIT FOR SEGMENT, SEND ACK (EX. ②, ④)

KEY FIELDS (FOR SOME X, Y)

- SEQ: SEGMENT STARTS AT POSITION X IN DATA STREAM
- ACK: "I HAVE UP TO BYTE (Y-1), I EXPECT BYTE Y NEXT
- WINDOW: HOW MANY BYTES LEFT IN R'S RECV BUFFER (MORE ON THIS SOON!)

Simplest method: Stop and Wait

Consider sending one packet at a time

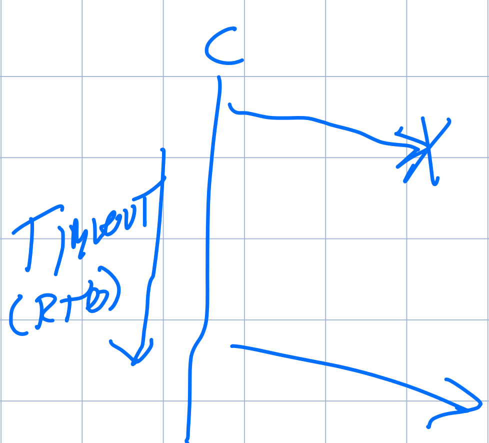
- S: Send packet, wait
- R: Receive packet, send ACK
- S: Receive ACK, send next packet

OR

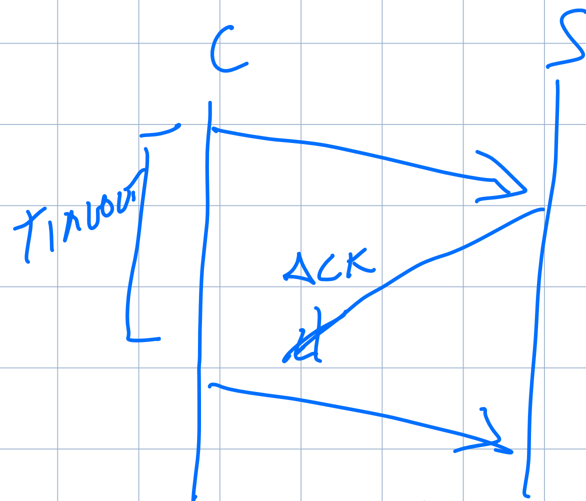
IF No ACK within some time (RTO), timeout and retransmit

(RTO TIME ADAPTS TO NETWORK CONDITIONS, MORE ON THIS LATER.)

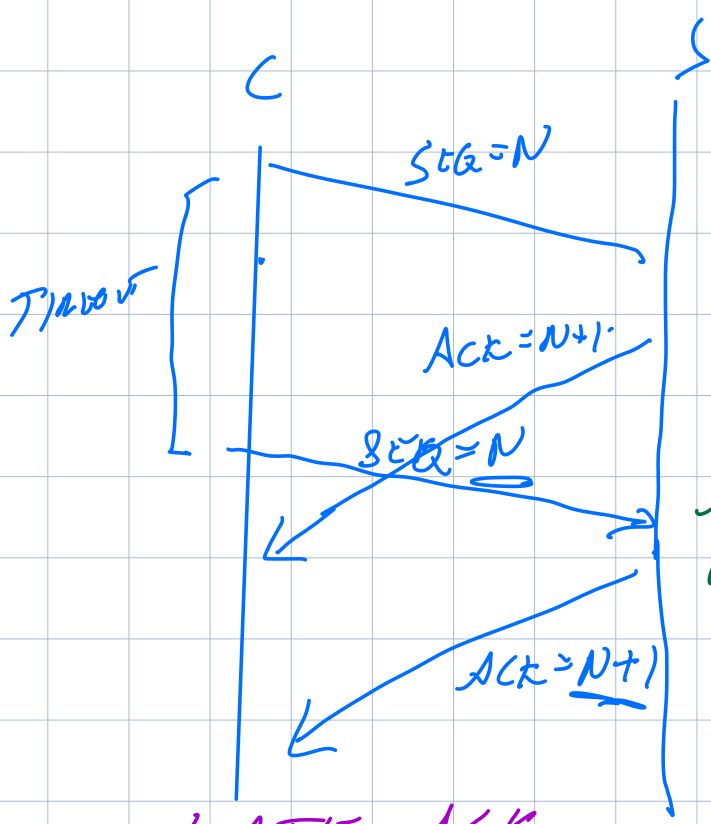
STOP + WAIT: WHAT CAN GO WRONG?



LOST DATA



LOST ACK



LATE ACK

SEQUENCE NUMBERS + RETRANSMISSIONS ALLOW US TO RECOVER FROM ALL OF THESE!

Simplest method: Stop and Wait

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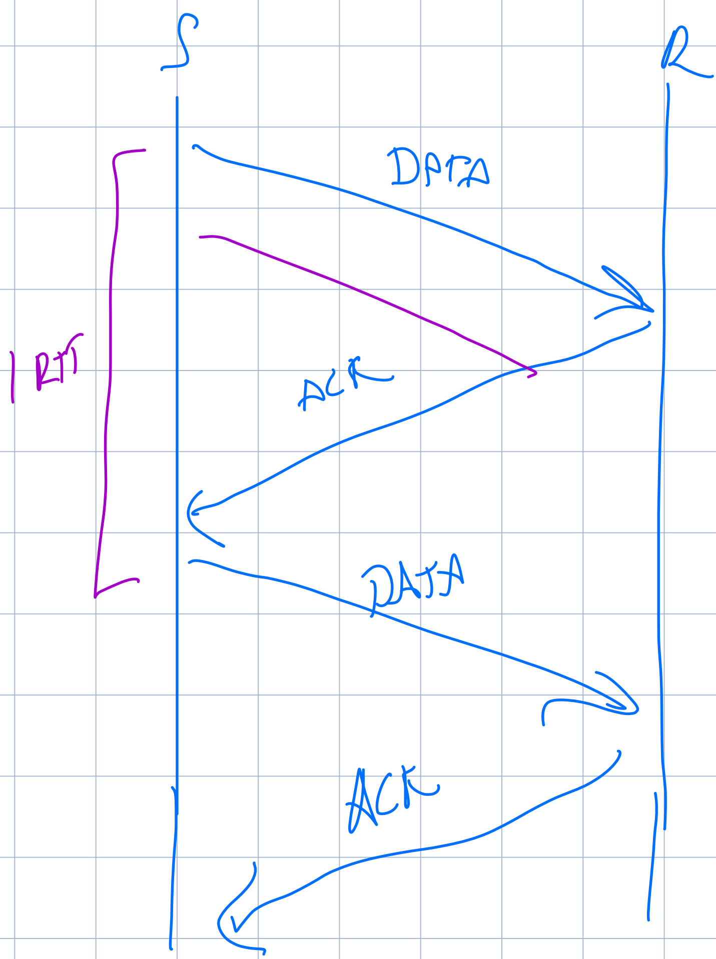
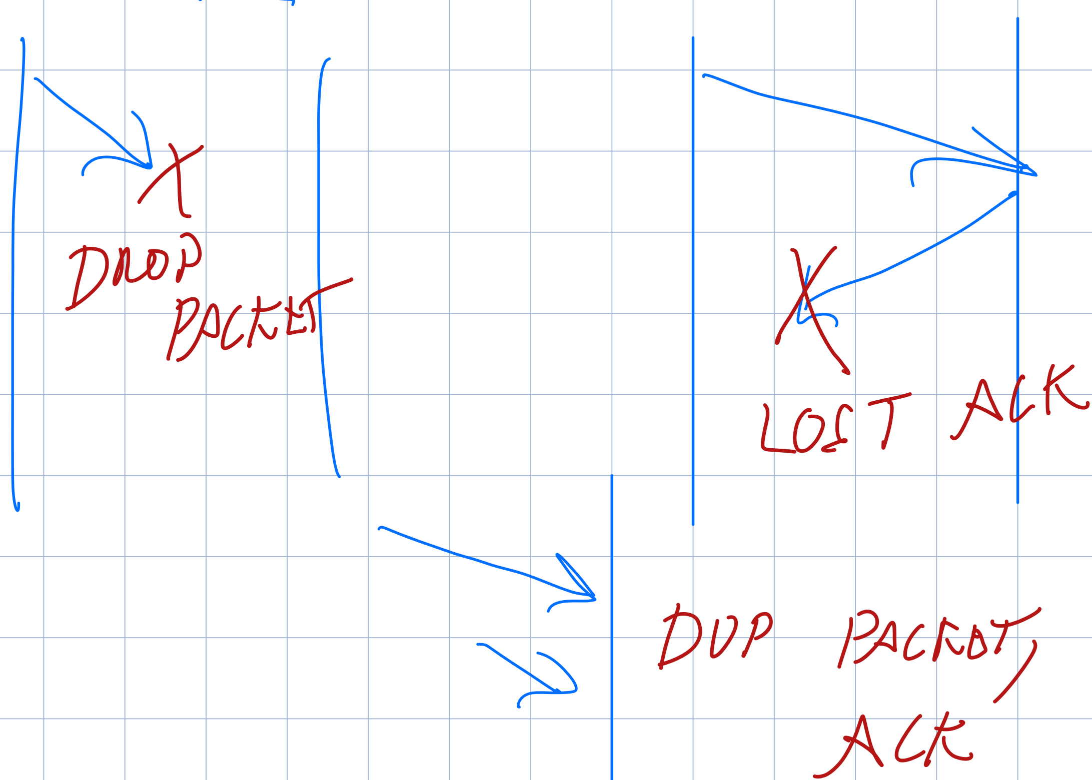
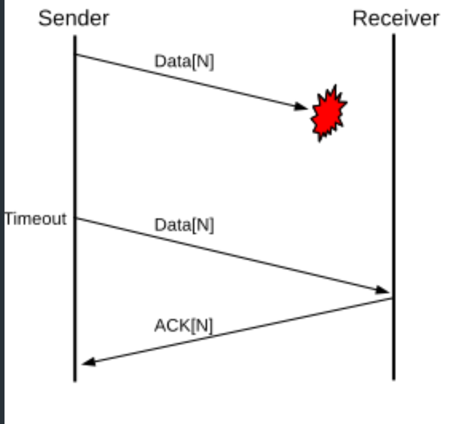


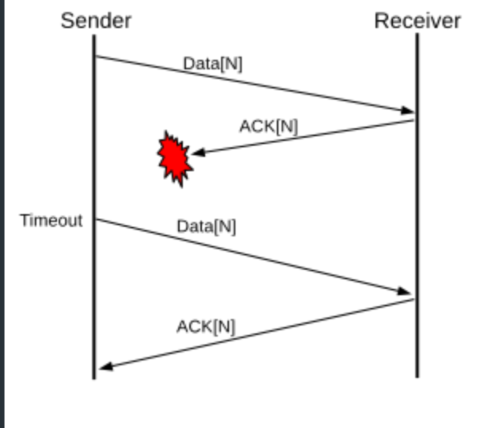
ONLY ONE SEGMENT "IN FLIGHT" (PENDING) AT ANY ONE TIME



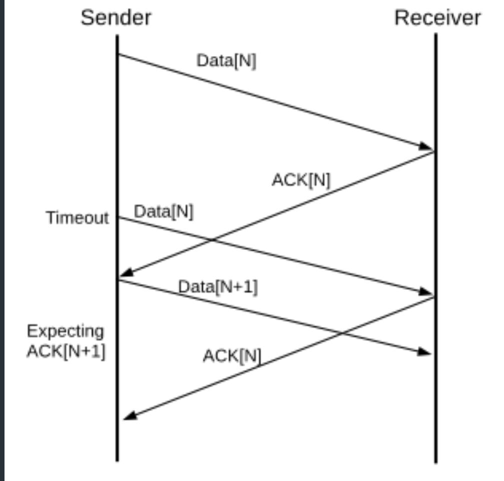
What can go wrong?



Lost Data

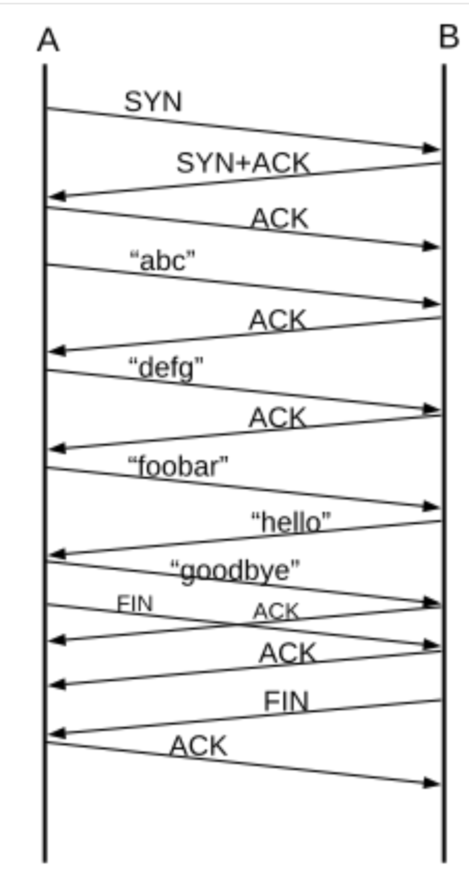


Lost ACK



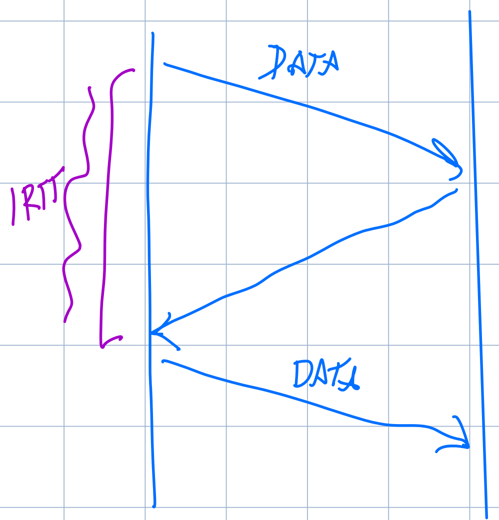
Late ACK

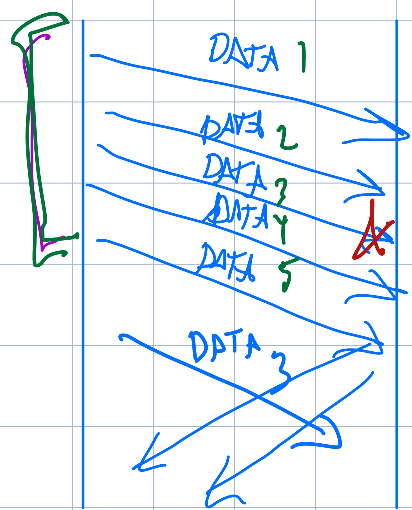
Sequence number example

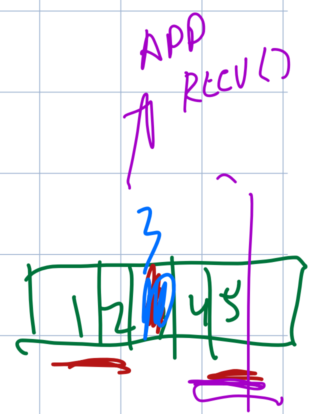


	A sends	B sends
1	SYN, **seq=0**	
2		SYN+ACK, seq=0, **ack=1** (expecting)
3	ACK, **seq=1**, ack=1 (ACK of SYN)	
4	"abc", **seq=1**, ack=1	
5		ACK, seq=1, **ack=4**
6	"defg", **seq=4**, ack=1	
7		seq=1, **ack=8**
8	"foobar", **seq=8**, ack=1	
9		seq=1, **ack=14**, "hello"
10	**seq=14**, ack=6, "goodbye"	
11,12	**seq=21**, ack=6, FIN	seq=6, **ack=21** ;; ACK of "goodbye", crossing packets
13		seq=6, **ack=22** ;; ACK of FIN
14		seq=6, **ack=22**, FIN
15	**seq=22**, ack=7 ;; ACK of FIN	

STOP + WAIT







WOULD LIKE TO HAVE MORE SEGMENTS "IN FLIGHT" AT ONE TIME TO USE MORE NETWORK BANDWIDTH

CHALLENGES:

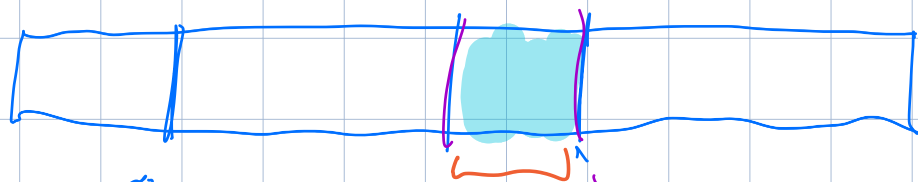
- RECEIVER NEEDS TO PUT SEGMENTS IN ORDER
- ~~R~~ SEGMENTS MIGHT BE RECEIVED OUT OF ORDER

SEQ

- SENDER: FLOW CONTROL

HOW WE THINK ABOUT BUFFERING

SEND BUFFER (CIRCULAR BUFFER)



APP LOADS DATA
CONN.WRITE

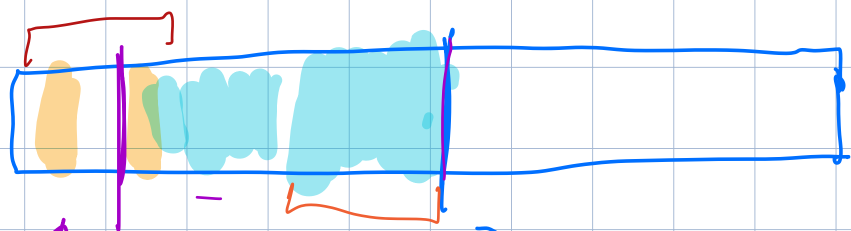
TCP STACK
DECIDES HOW
TO SEND OUT

"IN-FLIGHT"
⇒ SENT, BUT NOT
ACK'D.

REMOVE AFTER ACK
RECEIVED.

RECV BUFFER (CIRCULAR BUFFER)

EARLY ARRIVALS



TCP STACK ADDS DATA WHEN SEGMENTS RECEIVED

APP READS DATA FROM BUFFER (CONN.READ)

DATA RECV'D IN ORDER, READY FOR APP

MAX AMOUNT APP CAN READ.

WHAT'S THIS ABOUT A BUFFER?

~~TCP BUFFERING: HIGH-LEVEL OVERVIEW~~

SEND BUFFER (CIRCULAR)

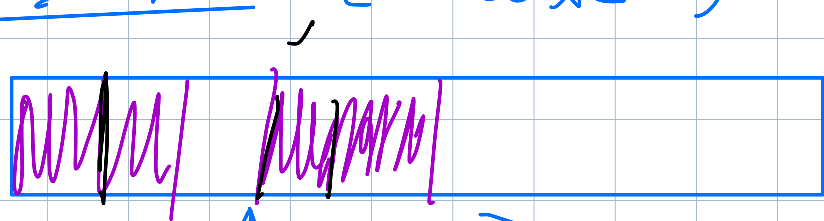
APP ADDS DATA TO BUFFER.

CONN.WRITE.

TCP STACK DECIDES HOW/WHEN TO SEND OUT

(REMOVES DATA ONCE RECEIVER ACKS IT)

RECV BUFFER (CIRCULAR)



TCP STACK ADDS DATA AS IT'S RECV'D

(MIGHT BE OUT OF ORDER ... MORE ON THIS LATER!)

CONN.READ() READS DATA FROM BUFFER (REMOVING IT)

MORE NOTES

IF YOU WANT

TO READ

AHEAD

Better Flow Control: Sliding window

- Part of TCP specification (even before 1988)
- Send multiple packets at once, based on a window
- Receiver uses window header field to tell sender how much space it has

TCP and buffering

Recall: TCP stack responsibilities

- Sender: breaking application data into segments
- Receiver: receiving segments, reassembling them in order

- Need to buffer data

Sliding window: in abstract terms

- Window of size w
- Can send at most w packets before waiting for an ACK

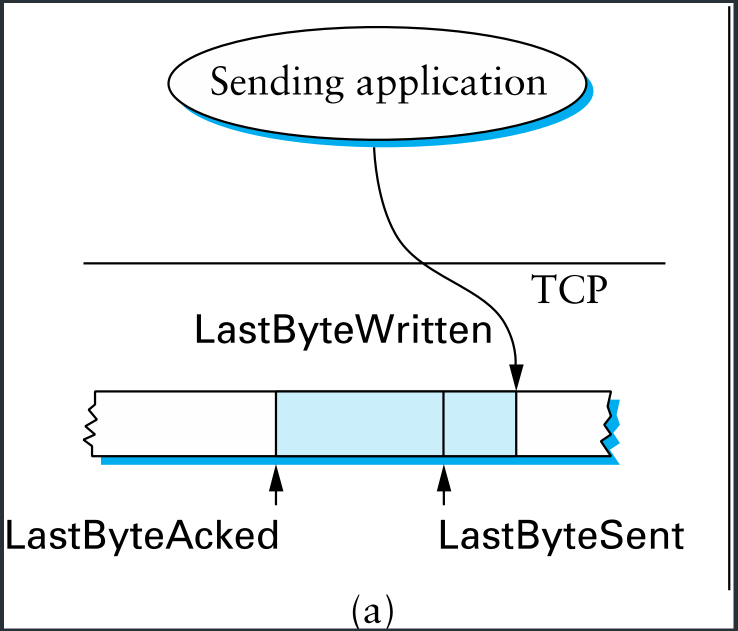
Sliding window: in abstract terms

- Window of size w
- Can send at most w packets before waiting for an ACK
- Goal
  - Network "pipe" always filled with data
  - ACKs come back at rate data is delivered => "self-clocking"

Sender example

Receiver example

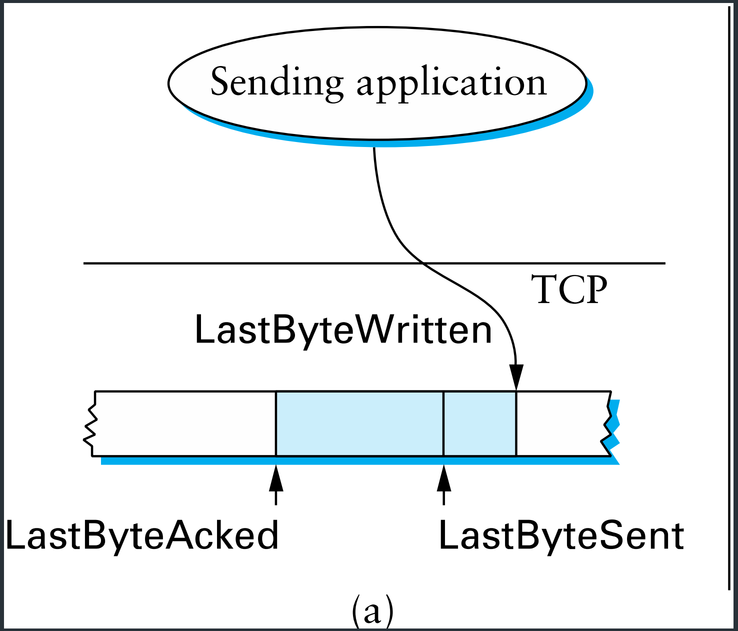
Flow Control: Sender



Invariants

- LastByteSent – LastByteAcked <= AdvertisedWindow
- EffectiveWindow = AdvertisedWindow – (BytesInFlight)
- LastByteWritten – LastByteAcked <= MaxSendBuffer

Flow Control: Sender



Invariants

- LastByteSent – LastByteAcked <= AdvertisedWindow
- EffectiveWindow = AdvertisedWindow – (BytesInFlight)
- LastByteWritten – LastByteAcked <= MaxSendBuffer

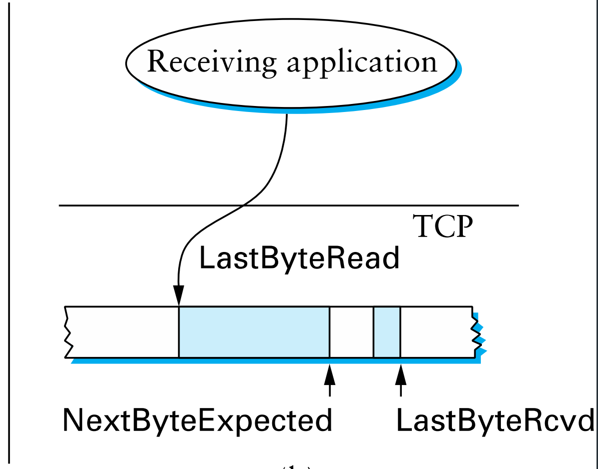
Useful Sliding Window Terminology:
RFC 9293, Sec 3.3.1

Flow control: receiver

- Can accept data if space in window
- Available window =
  BufferSize– ((NextByteExpected-1) - LastByteRead

- On receiving segment for byte S
  - if s is outside window, ignore packet
  - if s == NextByteExpected:
    - Deliver to application (Update LastByteReceived)
    - If next segment was early arrival, deliver it too
  - If s > NextByteExpected, but within window
    - Queue as early arrival

- Send ACK for highest contiguous byte received, available window



(b)

Flow control: receiver

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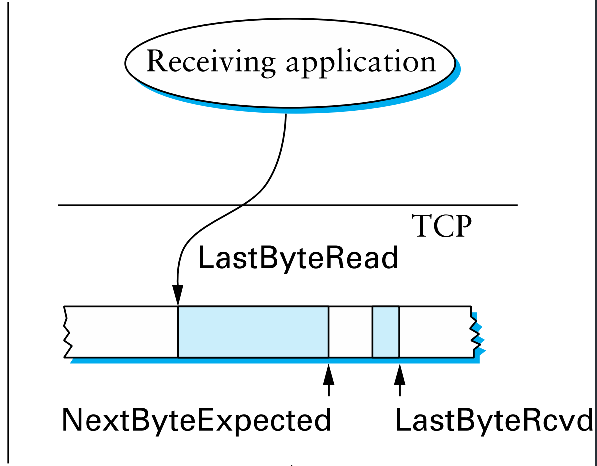
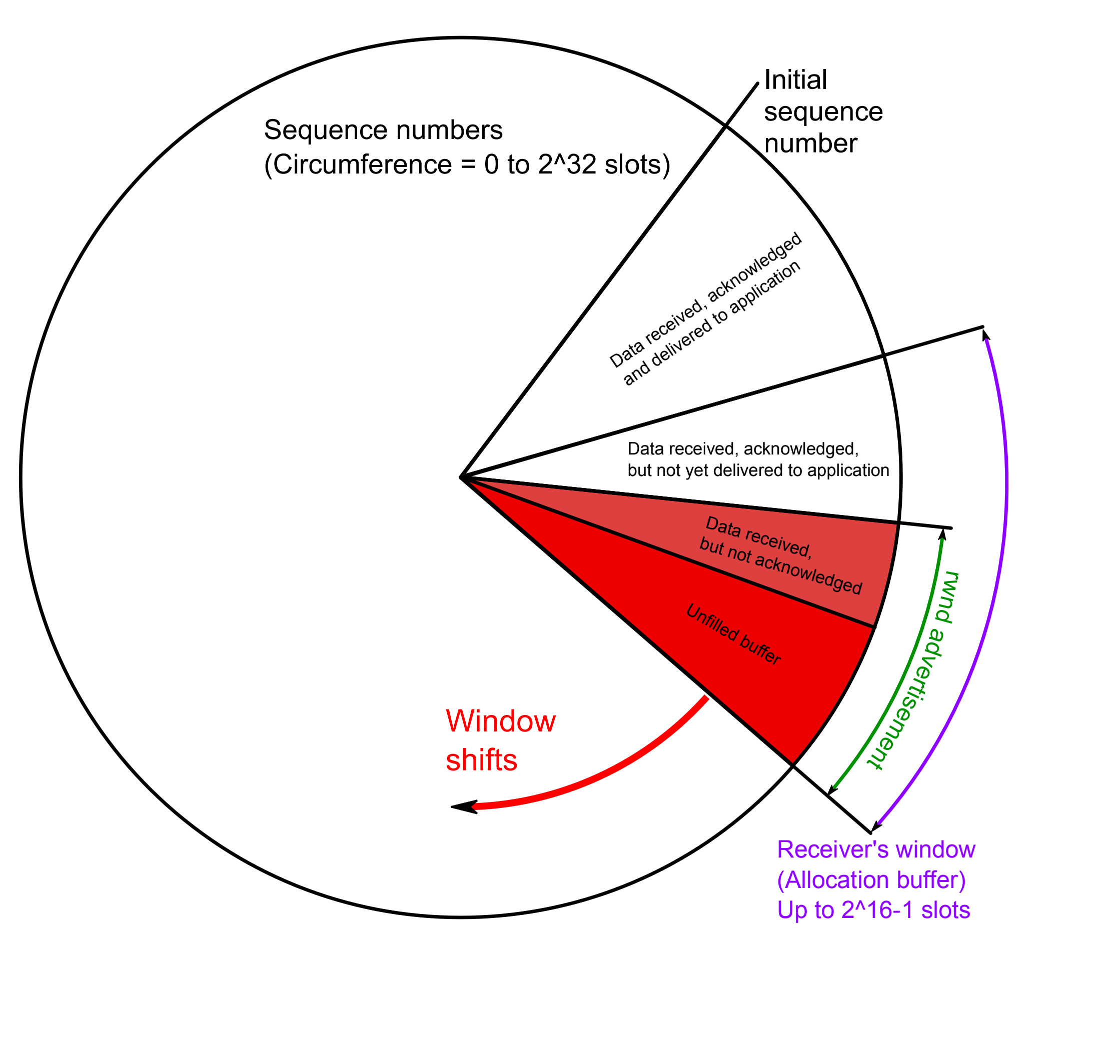


(b)

Flow Control

- Advertised window can fall to 0
  - How?
  - Sender eventually stops sending, blocks application

- Resolution: zero window probing: sender sends 1-byte segments until window comes back > 0


Sequence numbers
(Circumference = 0 to 2^32 slots)
Initial sequence number
Data received, acknowledged and delivered to application
Data received, acknowledged, but not yet delivered to application
Data received, but not acknowledged
Unfilled buffer
rwnd advertisement
Window shifts
Receiver's window
(Allocation buffer)
Up to 2^16-1 slots

Some Visualizations

- Normal conditions: https://www.youtube.com/watch?v=zY3Sxvj8kZA

- With packet loss: https://www.youtube.com/watch?v=lk27yiITOvU

How do ACKs work?

- ACK contains next expected sequence number
- If one segment is missed but new ones received, send duplicate ACK
- Retransmit when:
  - Receive timeout (RTO) expires
  - Possibly other conditions, for certain TCP variants (eg. 3 dup ACKs)

- How to set RTO?

When to time out?

RFC793, Sec 3.7

Should expect an ACK within one Round Trip Time (RTT)

- Problem: RTT can be highly variable

- Strategy: expected RTT based on ACKs received
  - Use exponentially weighted moving average (EWMA)
  - RFC793 version ("smoothed RTT"):

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  - RFC793 version ("smoothed RTT"):

$$SRTT = (\alpha * SRTT) + (1 - \alpha) * RTT_{Measured}$$

$$RTO = \max(RTO_{Min}, \min(\beta * SRTT, RTO_{Max}))$$

α = "Smoothing factor": .8-.9

β = "Delay variance factor": 1.3—2.0

This is only the beginning…

- Problem 1: what if segment is a retransmission?

This is only the beginning…

- Problem 1: what if segment is a retransmission?
  - Solution: don't update RTT if segment was retransmitted