Operating Systems and Networks

TCP Summary

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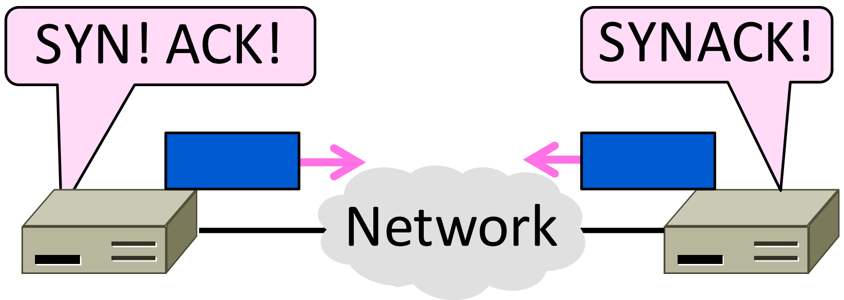
Connection Establishment (6.5.5, 6.5.7, 6.2.2)

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

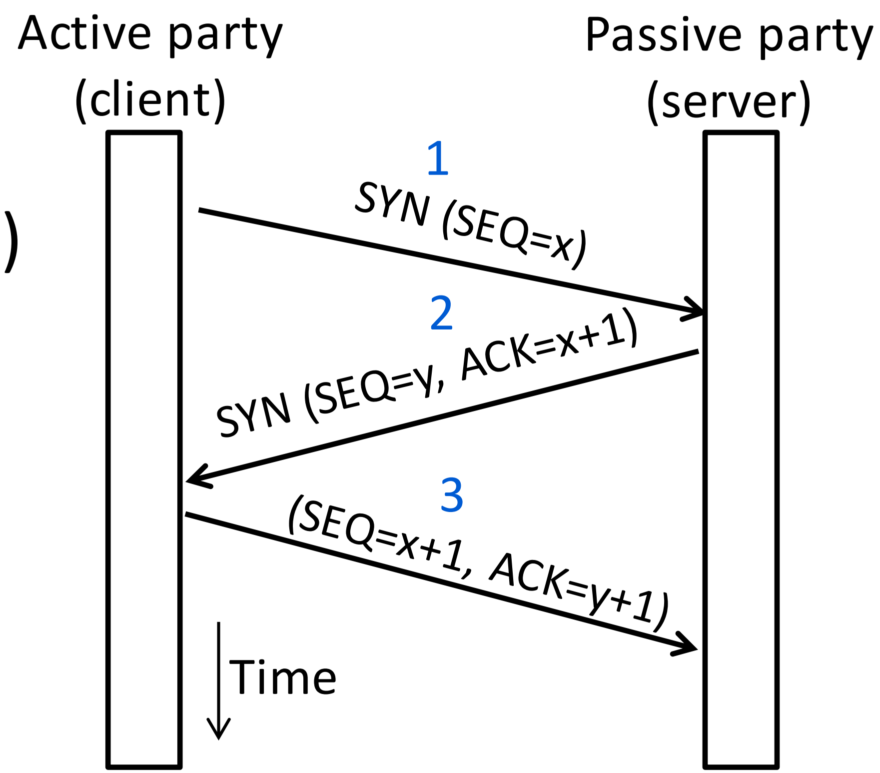


Connection Establishment

- 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

Three-Way Handshake

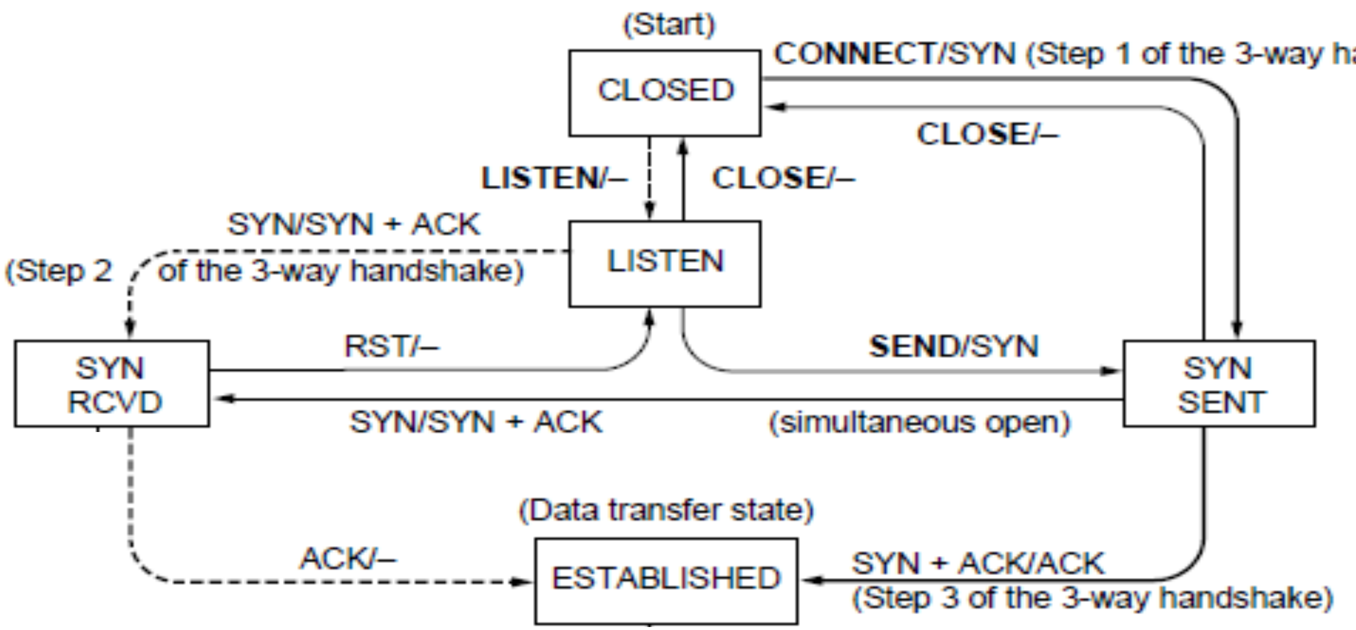
- Three steps:
  - Client sends SYN(x)
  - Server replies with SYN(y)ACK(x+1)
  - Client replies with ACK(y+1)
  - SYNs are retransmitted if lost
- Sequence and ack numbers carried on further segments



TCP Connection State Machine

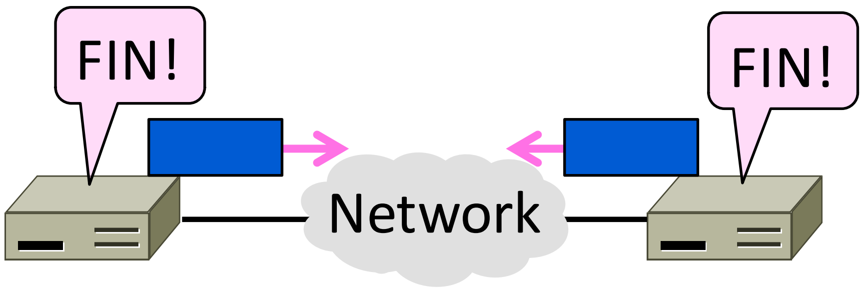
- Captures the states (rectangles) and transitions (arrows)
  - A/B means event A triggers the transition, with action B

Both parties run instances of this state machine



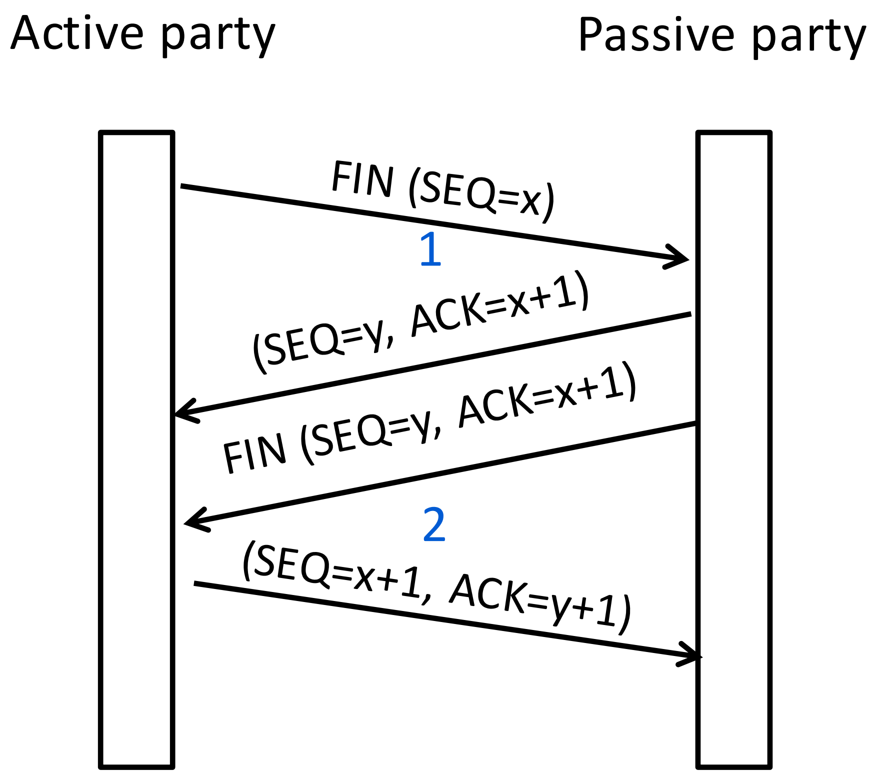
Connection Release (6.5.6-6.5.7, 6.2.3)

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



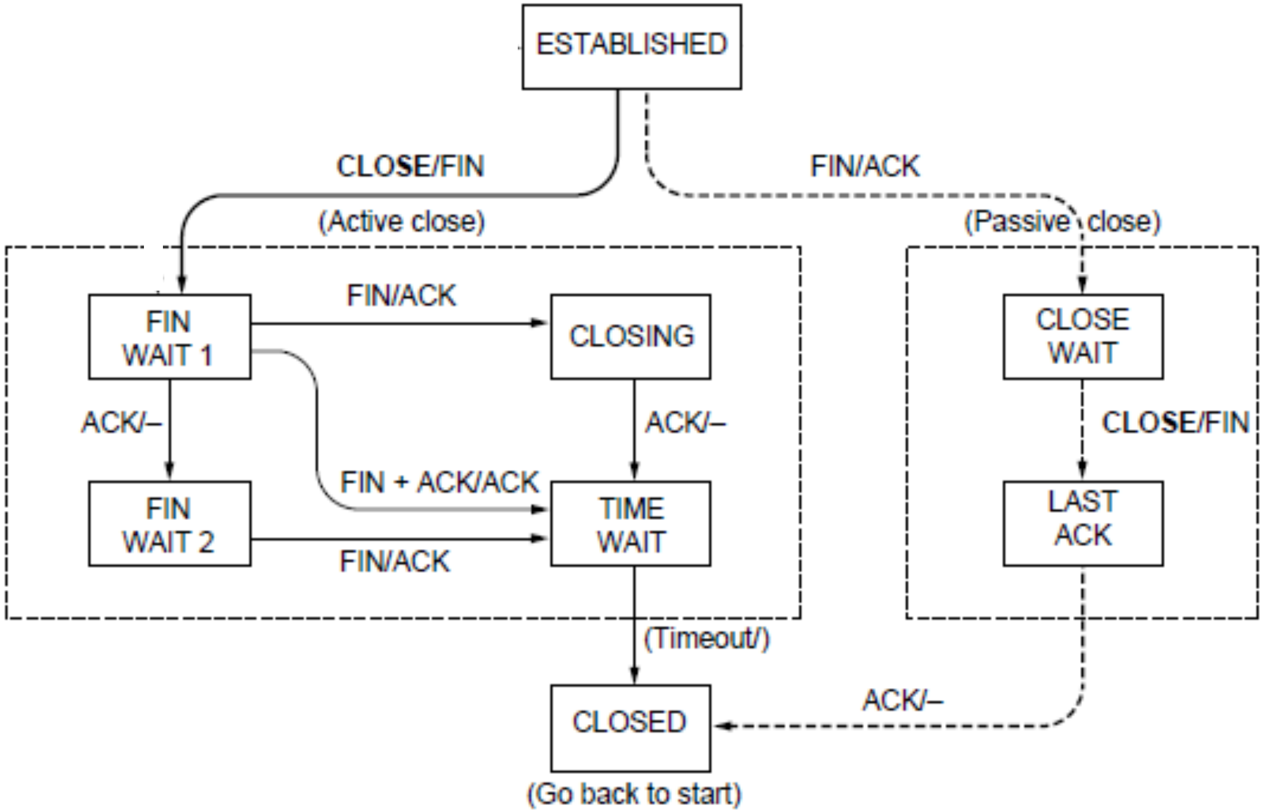
TCP Connection Release

- Two steps:
  - Active party sends FIN(x), passive party sends ACK
  - Passive party sends FIN(y), active party sends ACK
  - FINs are retransmitted if lost
- Each FIN/ACK closes one direction of data transfer



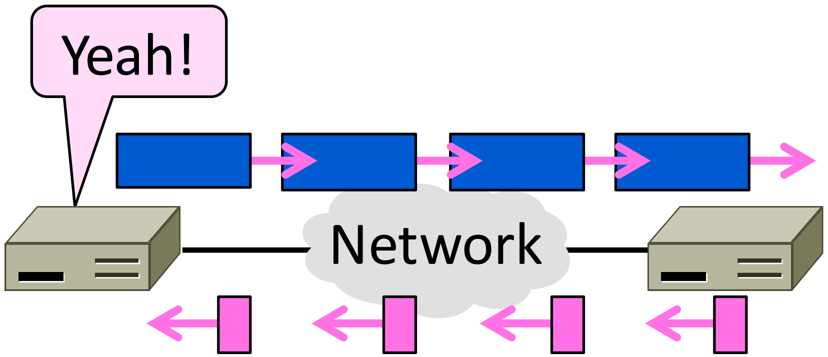
TCP Connection State Machine

Both parties run instances of this state machine



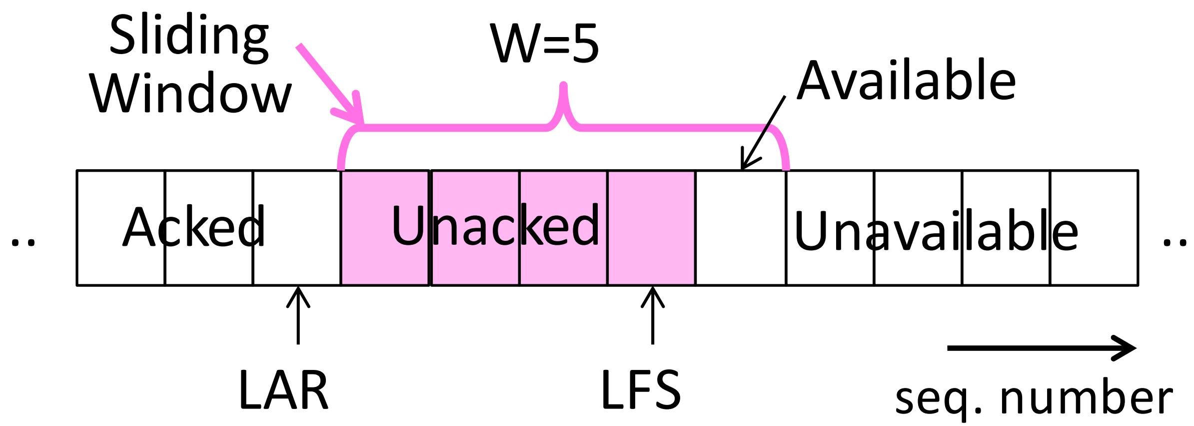
Sliding Windows (§3.4, §6.5.8)

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



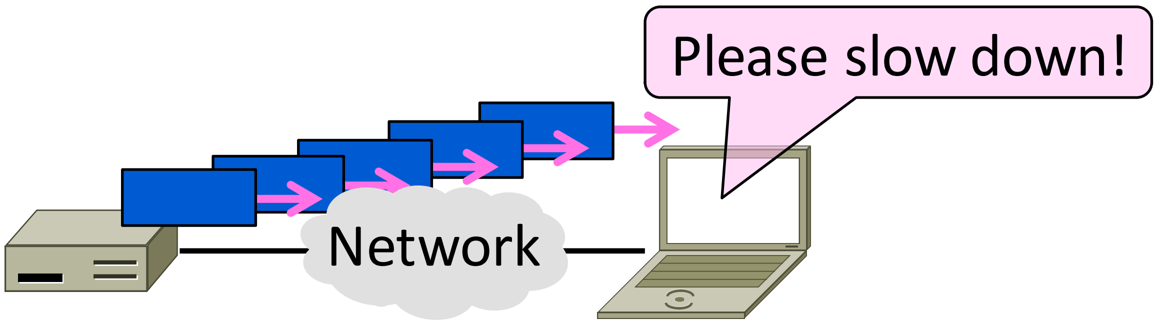
Sliding Window – Sender

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



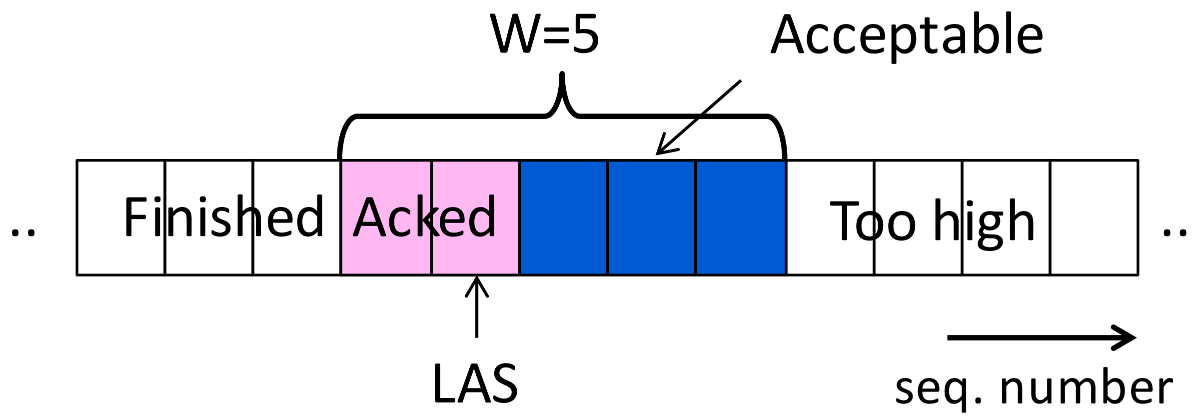
Flow Control (§6.5.8)

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



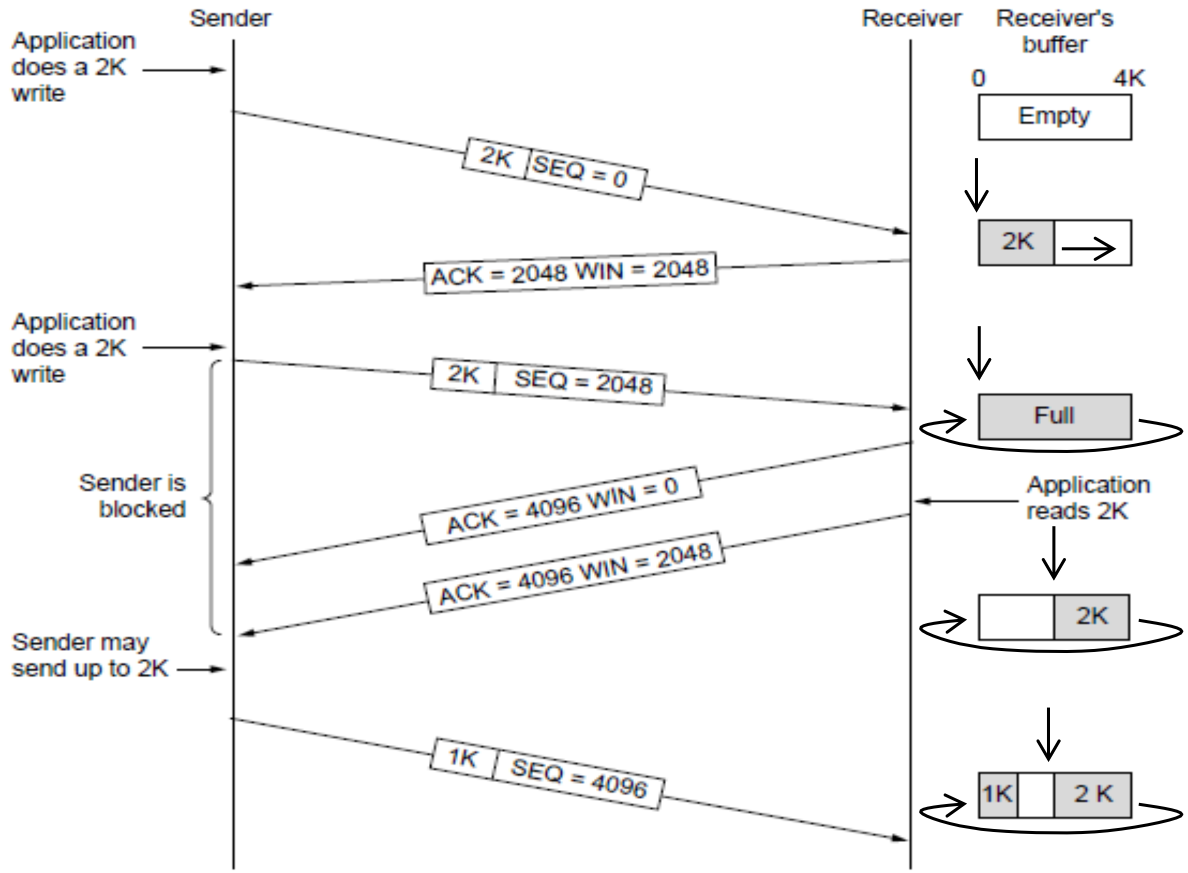
Flow Control

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



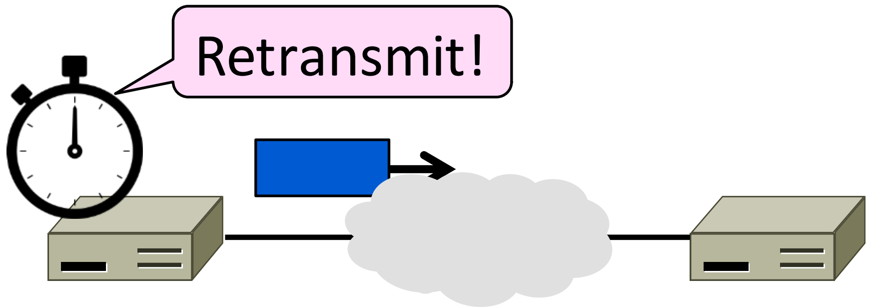
Flow Control (3)

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



Retransmissions

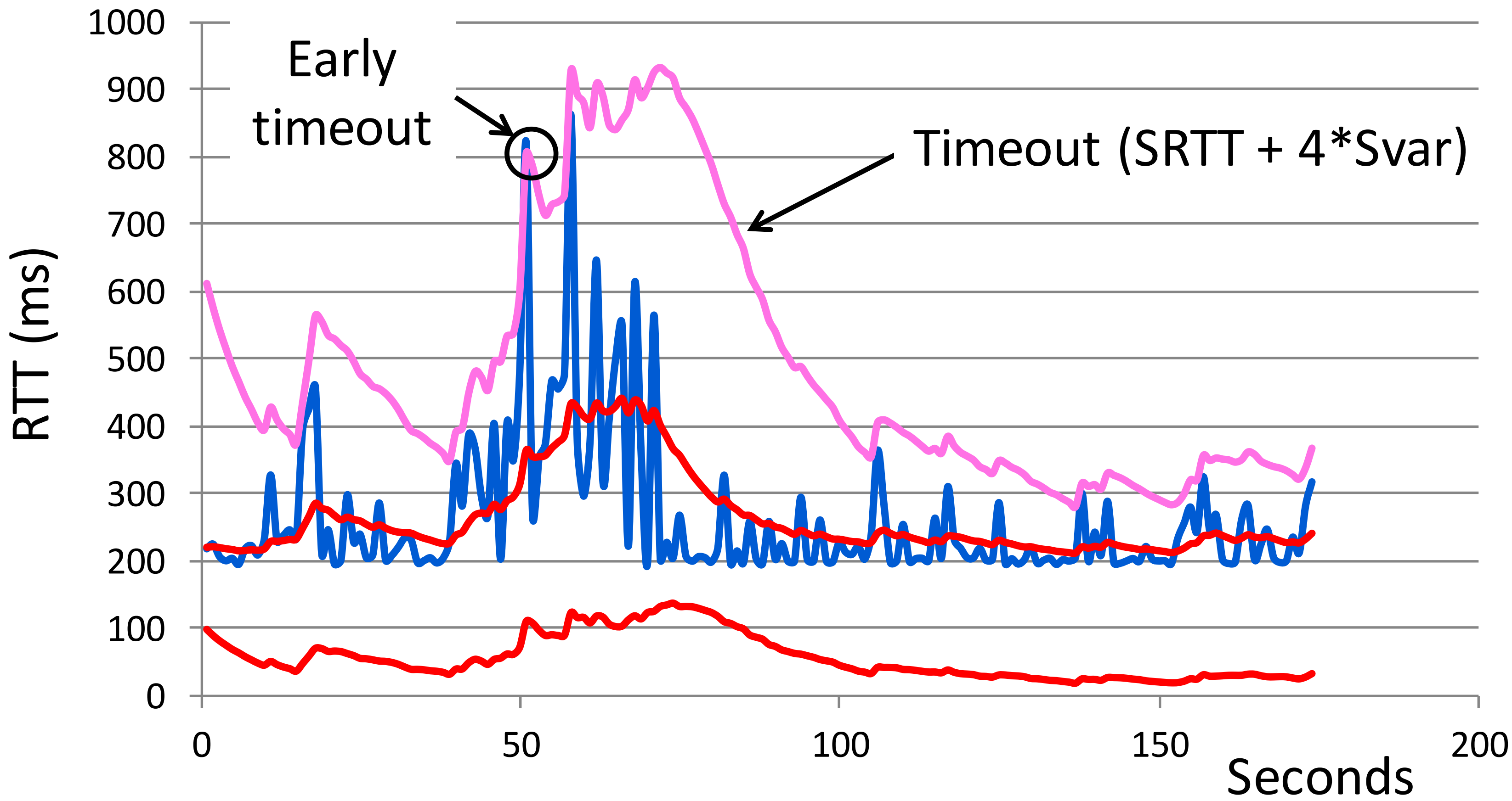
- With sliding window, the strategy for detecting loss is the <u>timeout</u>
  - Set timer when a segment is sent
  - Cancel timer when ack is received
  - If timer fires, <u>retransmit</u> data as lost



Adaptive Timeout

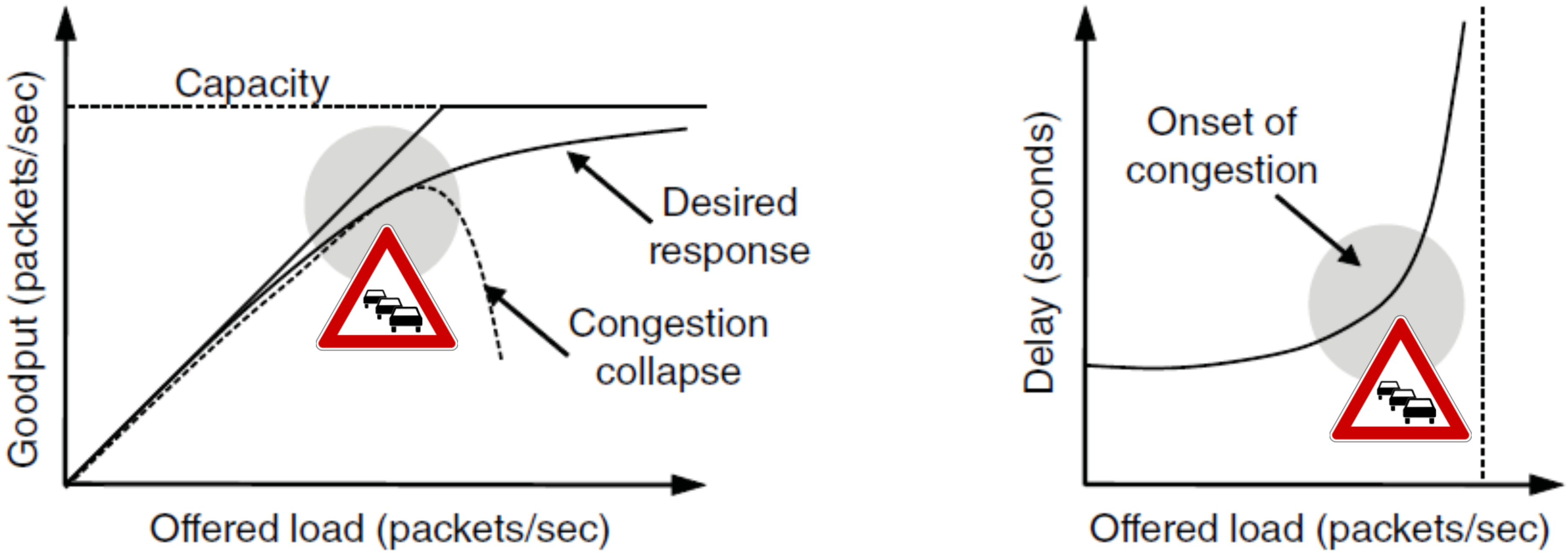
- Keep smoothed estimates of the RTT (1) and variance in RTT (2)
  - Update estimates with a moving average
  1. $SRTT_{N+1} = 0.9*SRTT_N + 0.1*RTT_{N+1}$
  2. $Svar_{N+1} = 0.9*Svar_N + 0.1*|RTT_{N+1} - SRTT_{N+1}|$
- Set timeout to a multiple of estimates
  - To estimate the upper RTT in practice
  - TCP $Timeout_N = SRTT_N + 4*Svar_N$

Example of Adaptive Timeout (2)



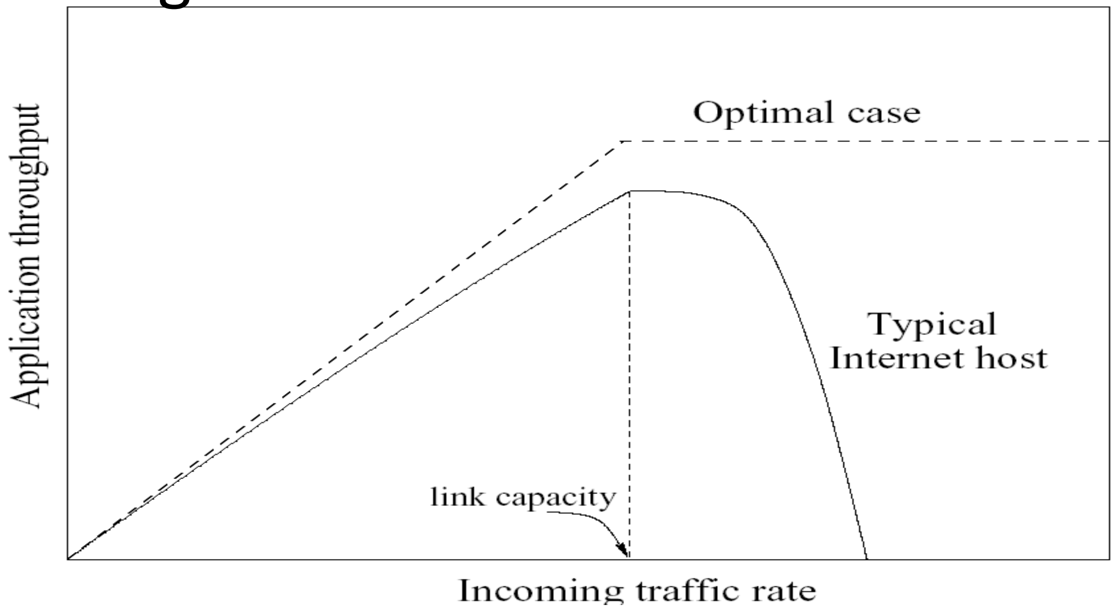
Effects of Congestion

- What happens to performance as we increase the load?



Congestion Characteristics

- Link flooding causes high loss rates for incoming traffic
- Mathis, Semke, Mahdavi, Ott [Sigcomm ’97]:
  TCP Throughput ~ $MSS/RTT*c*q^{-1/2}$
  q is loss prob, c is constant close to 1
- Note: very low throughput for high loss rate
- Result
  - Few legitmate clients served during congestion



Bandwidth Allocation

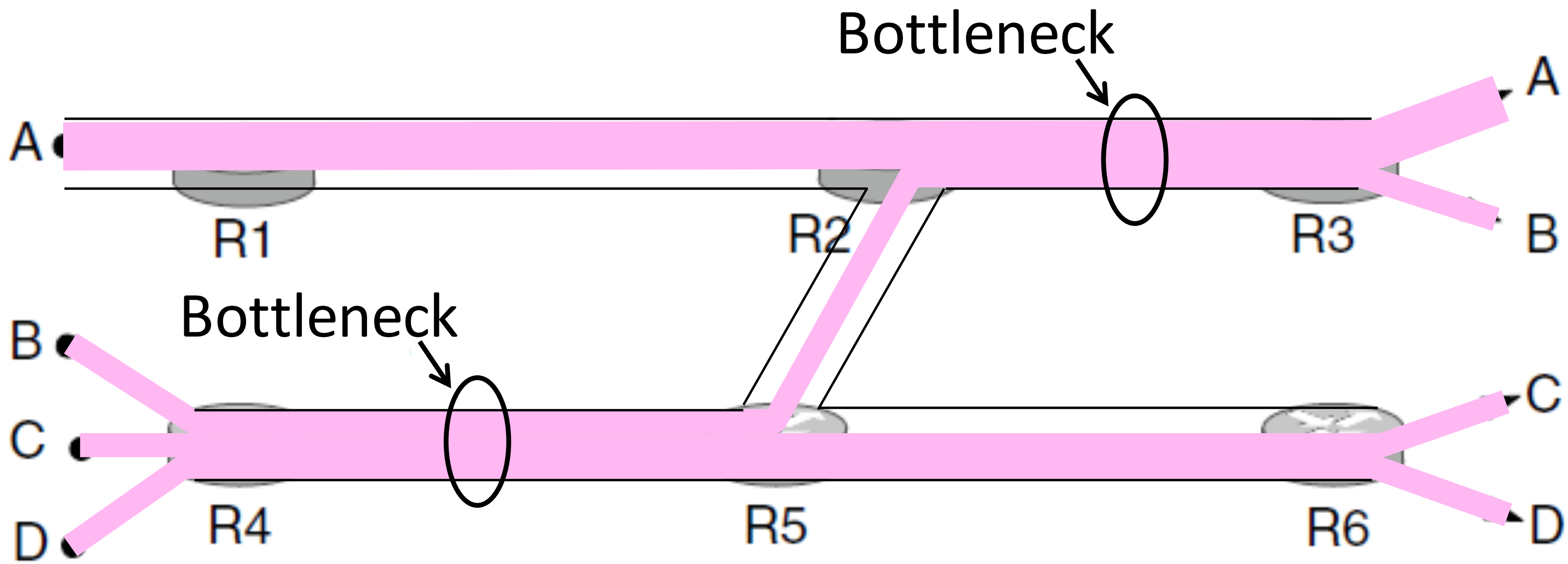
- Important task for network is to allocate its capacity to senders
  - Good allocation is efficient and fair
- Efficient means most capacity is used but there is no congestion
- Fair means every sender gets a reasonable share the network

Max-Min Fairness

- Intuitively, flows bottlenecked on a link get an equal share of that link
- Max-min fair allocation is one that:
  - Increasing the rate of one flow will decrease the rate of a smaller flow
  - This "maximizes the minimum" flow

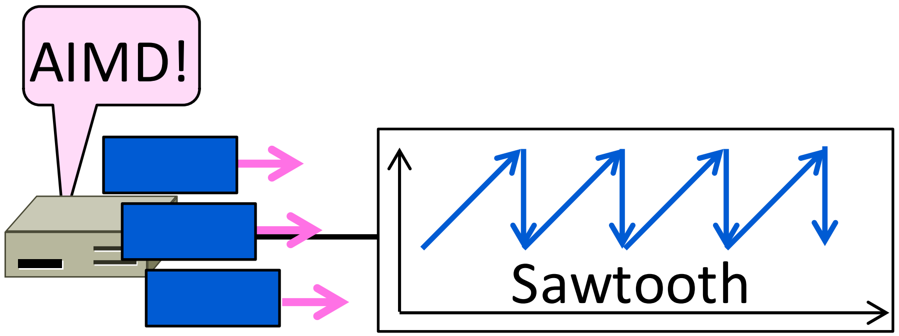
Max-Min Example

- When rate=2/3, flow A bottlenecks R2—R3. Done.



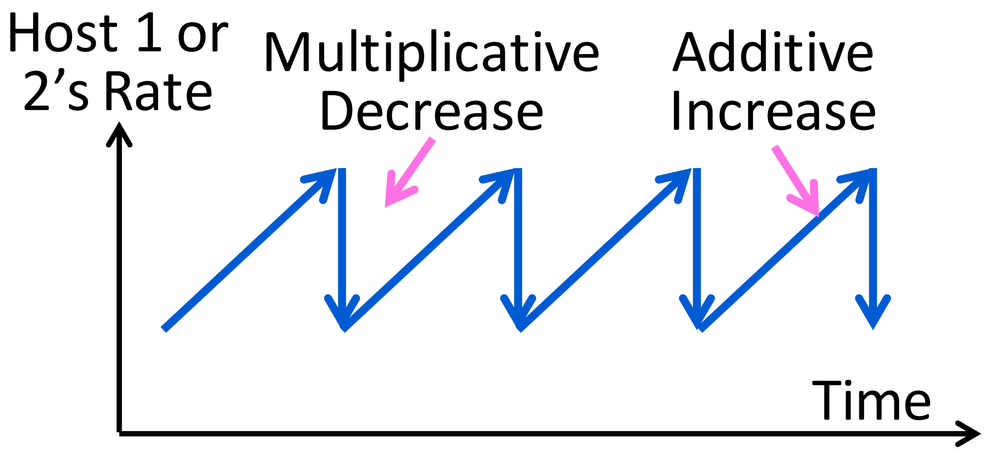
Additive Increase Multiplicative Decrease (AIMD) (§6.3.2)

- Bandwidth allocation models
  - Additive Increase Multiplicative Decrease (AIMD) control law



AIMD Sawtooth

- Produces a “sawtooth” pattern over time for rate of each host
  - This is the TCP sawtooth (later)



AIMD Properties

- Converges to an allocation that is efficient and fair when hosts run it
  - Holds for more general topologies
- Other increase/decrease control laws do not! (Try MIAD, MIMD, AIAD)
- Requires only binary feedback from the network

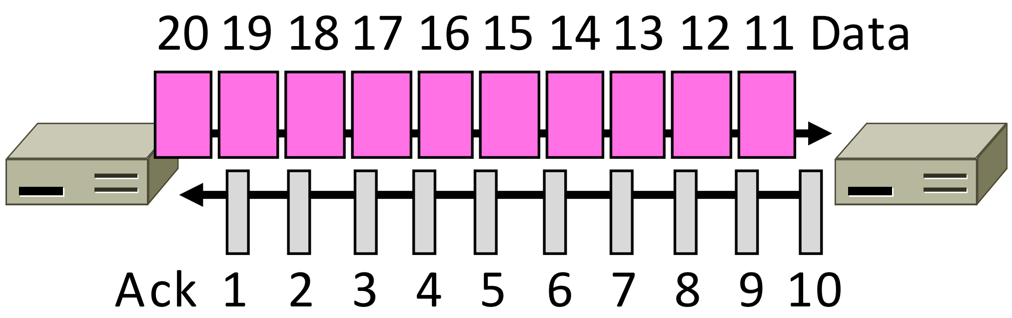
Feedback Signals

- Several possible signals, with different pros/cons
  - We'll look at classic TCP that uses packet loss as a signal

Signal	Example Protocol	Pros / Cons
Packet loss	TCP NewReno Cubic TCP (Linux)	+Hard to get wrong -Hear about congestion late
Packet delay	Compound TCP (Windows)	+Hear about congestion early -Need to infer congestion
Router indication	TCPs with Explicit Congestion Notification	+Hear about congestion early -Require router support

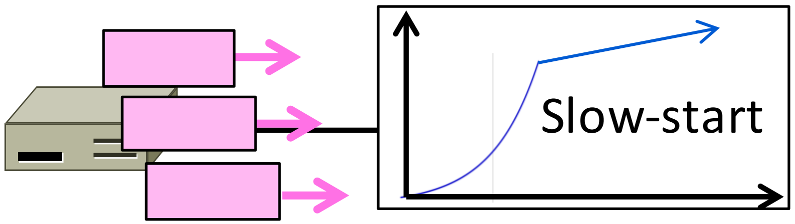
Sliding Window ACK Clock

- Each in-order ACK advances the sliding window and lets a new segment enter the network
  - ACKs "clock" data segments



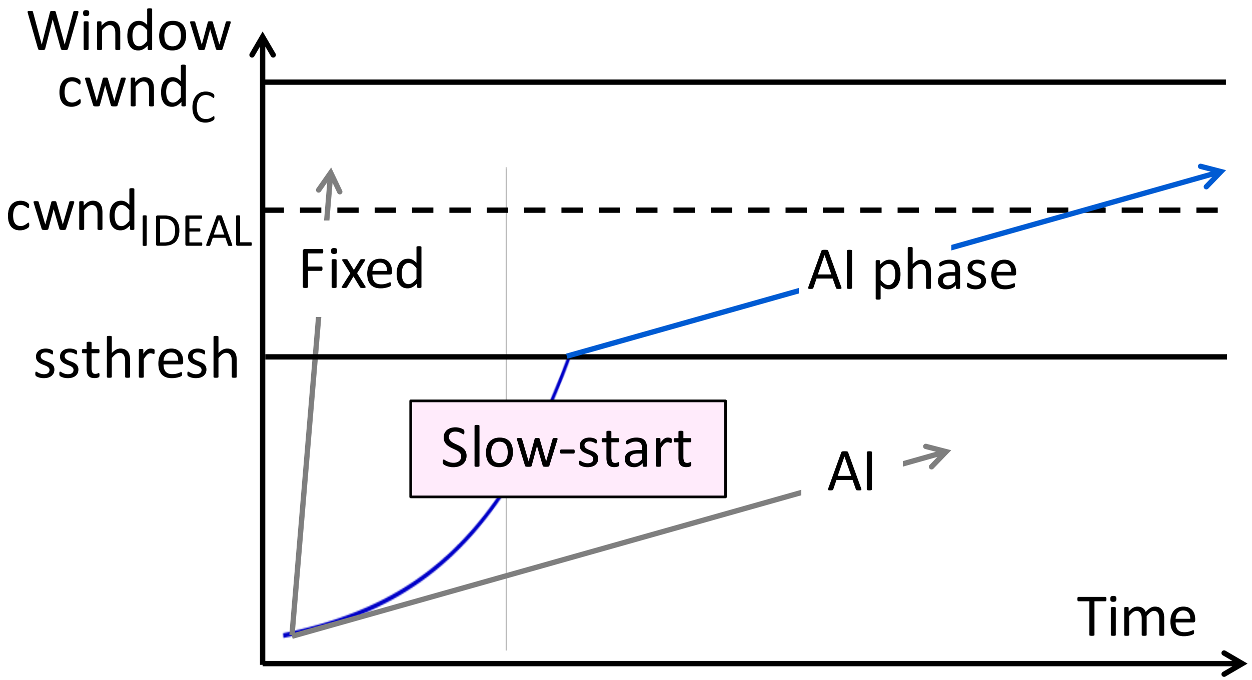
TCP Slow Start (§6.5.10)

- How TCP implements AIMD, part 1
  - "Slow start" is a component of the AI portion of AIMD



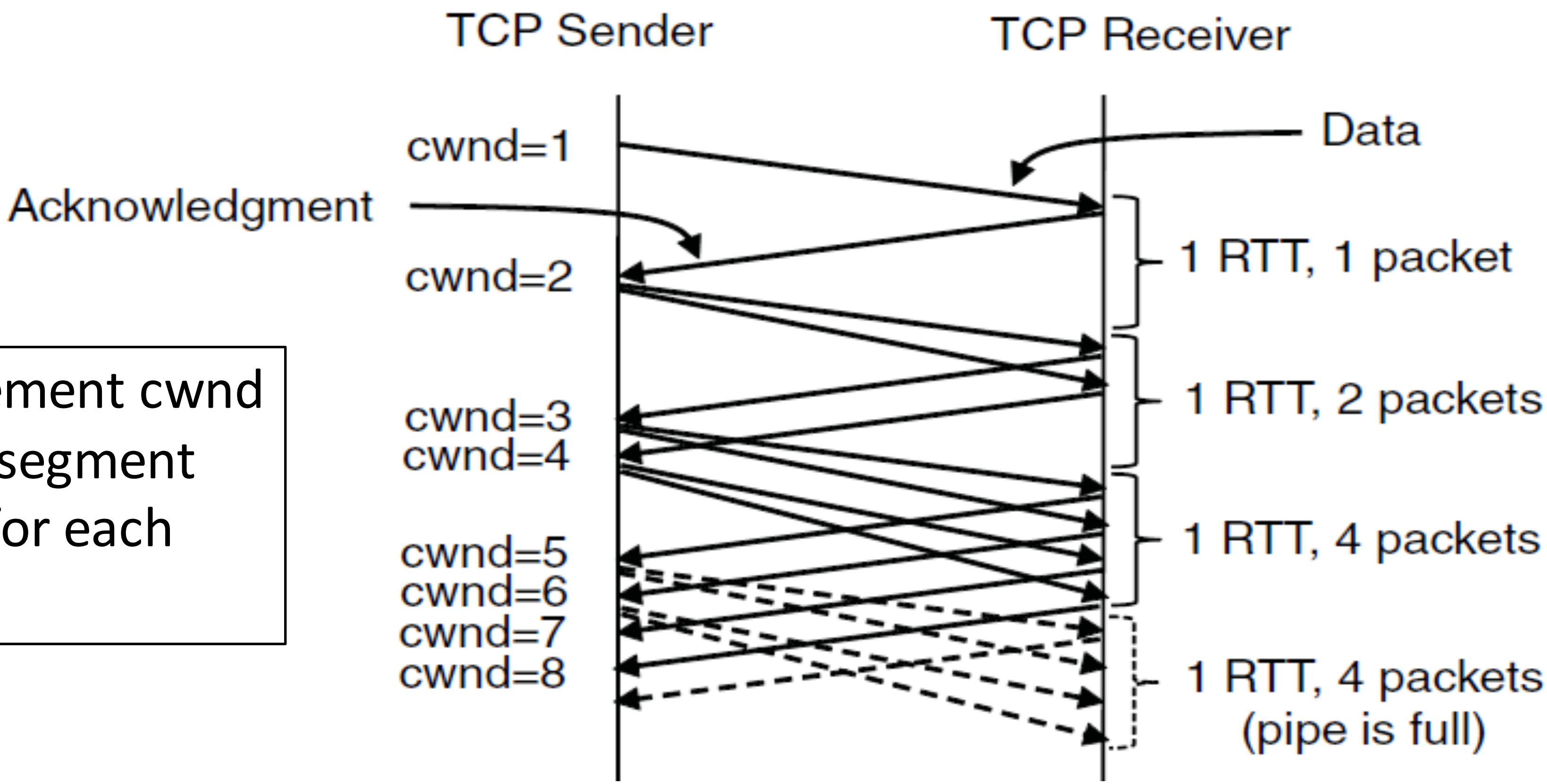
Slow-Start Solution

- Combined behavior, after first time
  - Most time spend near right value

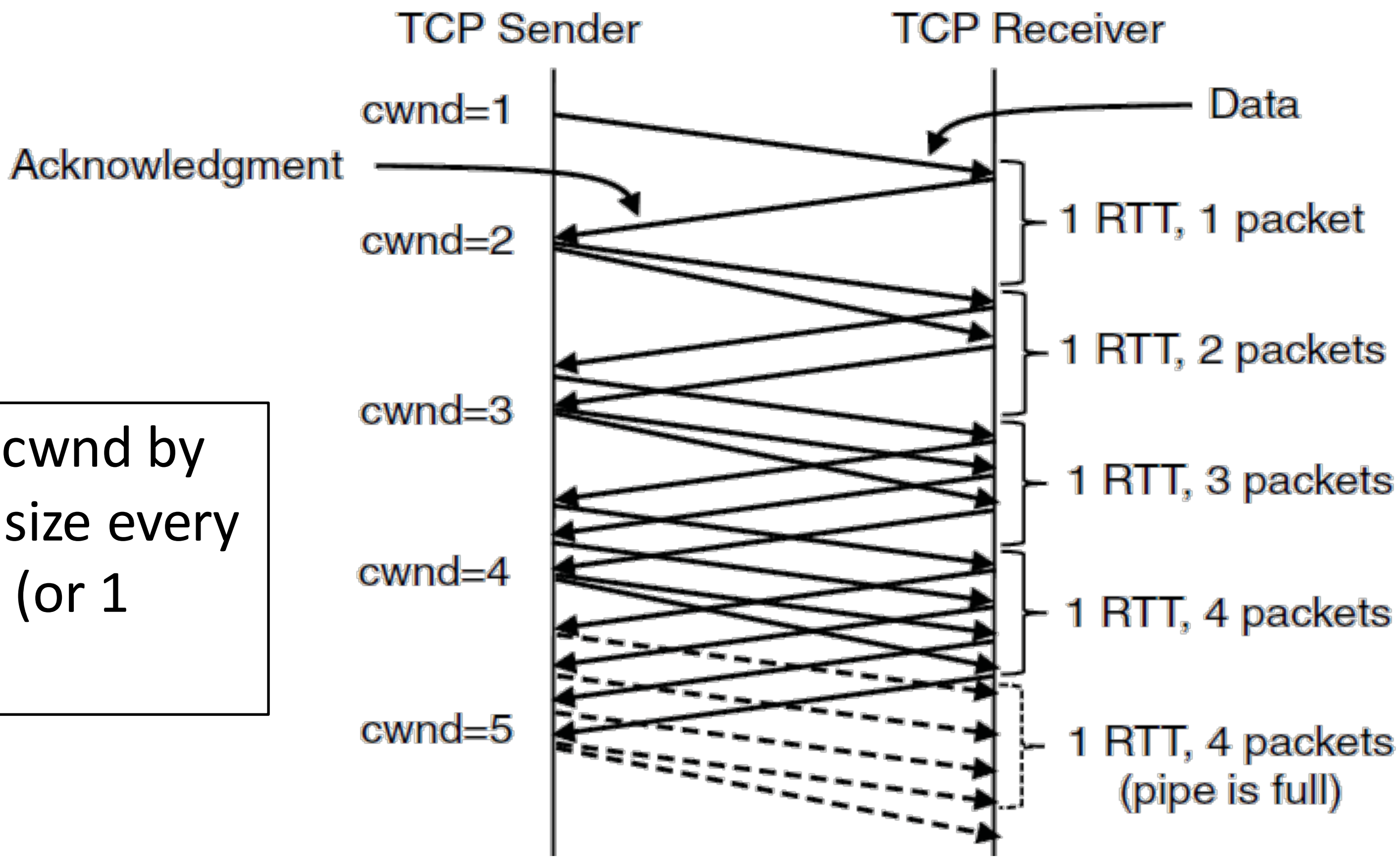


Slow-Start (Doubling) Timeline

Increment cwnd by 1 segment size for each ACK



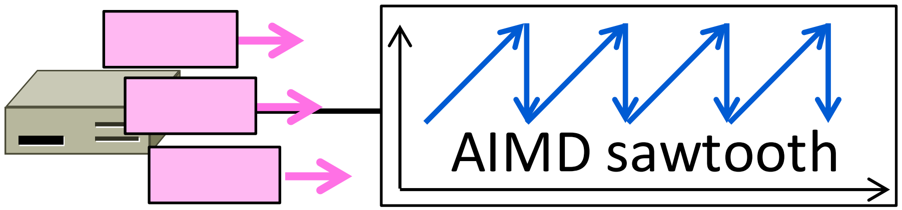
Additive Increase Timeline



Increment cwnd by 1 segment size every cwnd ACKs (or 1 RTT)

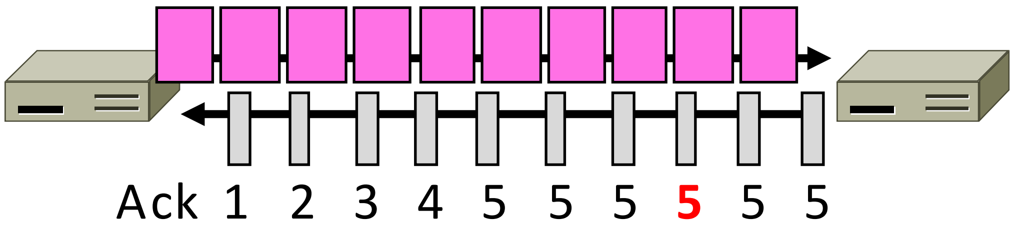
TCP Fast Retransmit / Fast Recovery (§6.5.10)

- How TCP implements AIMD, part 2
  - "Fast retransmit" and "fast recovery" are the MD portion of AIMD

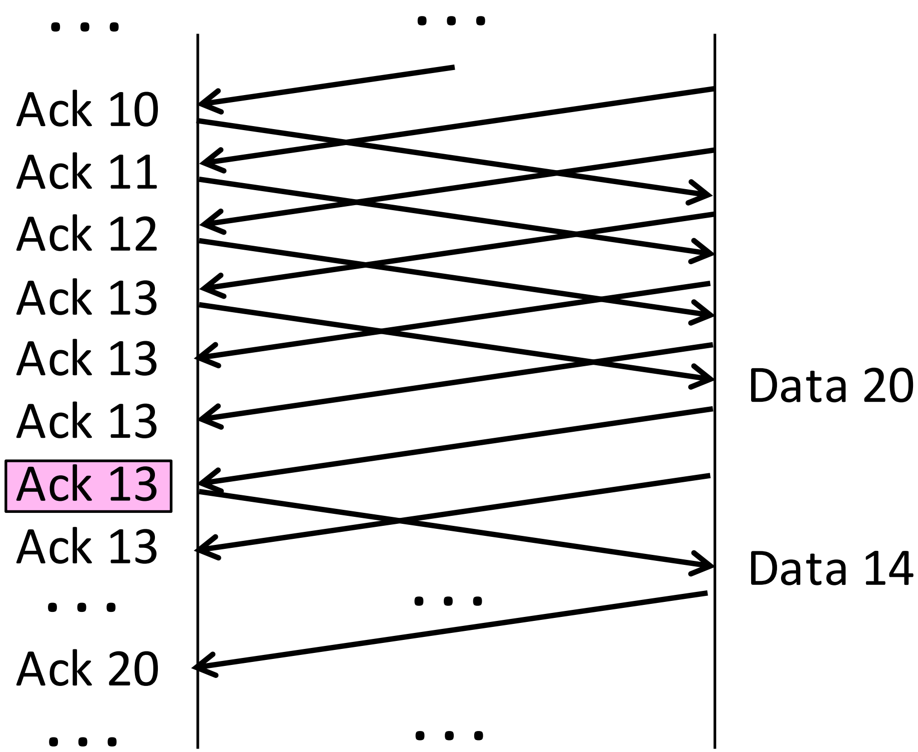


Fast Retransmit

- Treat three duplicate ACKs as a loss
  - Retransmit next expected segment
  - Some repetition allows for reordering, but still detects loss quickly



Fast Retransmit (2)



Data 14 was lost earlier, but got 15 to 20

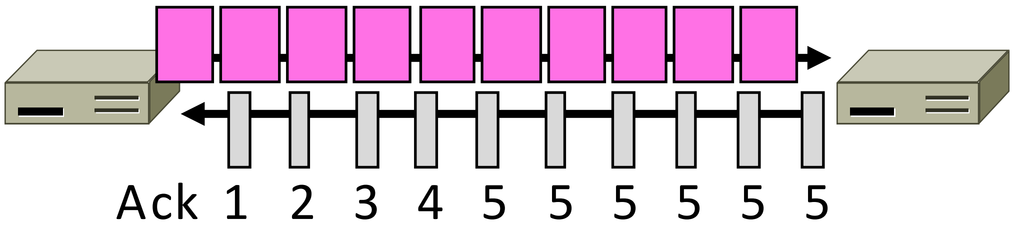
Third duplicate ACK, so send 14

Retransmission fills in the hole at 14

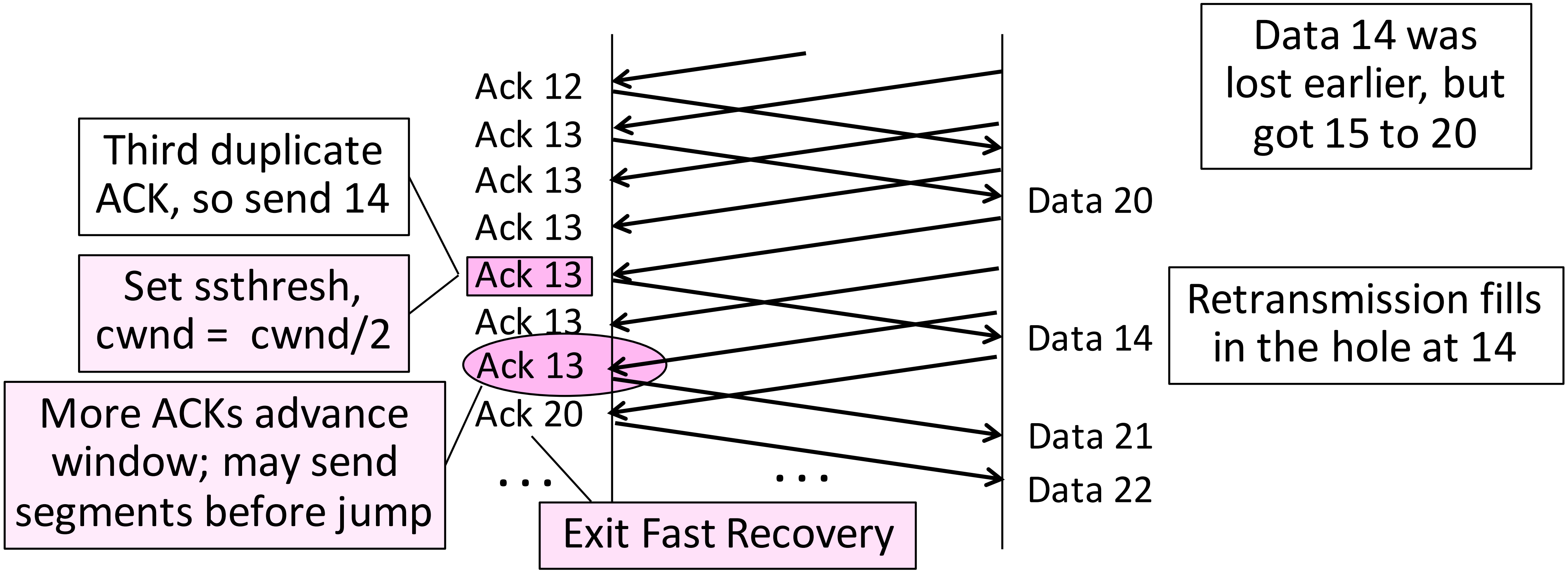
ACK jumps after loss is repaired

Fast Recovery

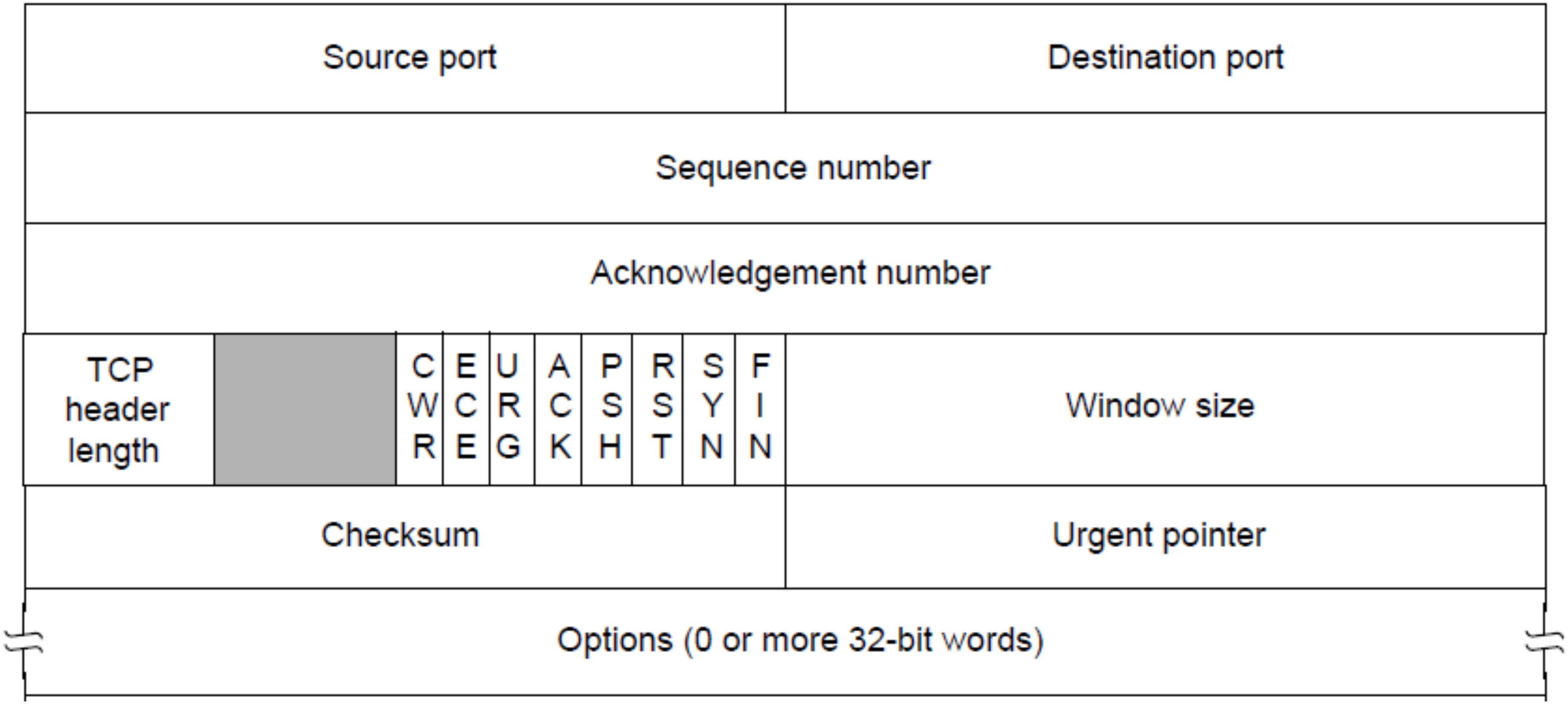
- First fast retransmit, and MD cwnd
- Then pretend further duplicate ACKs are the expected ACKs
  - Lets send new segments for received ACKs
  - Reconcile views when the ACK jumps



Fast Recovery (2)



TCP Header


Source port
Destination port
Sequence number
Acknowledgement number
TCP header length
CWR
ECE
URG
ACK
PSH
RST
SYN
FIN
Window size
Checksum
Urgent pointer
Options (0 or more 32-bit words)

Interesting Questions

- How is MSS / MTU determined?
- What happens if UDP does not implement congestion control?
  - Do modern UDP applications need to implement congestion control?
  - What is the relationship with network neutrality?
- What if different congestion control schemes are used concurrently? What can go wrong?
- Can a malicious host obtain an unfair advantage?
- Why size would you pick for router buffers? Large or small? Which one will result in better performance if standard TCP is used?