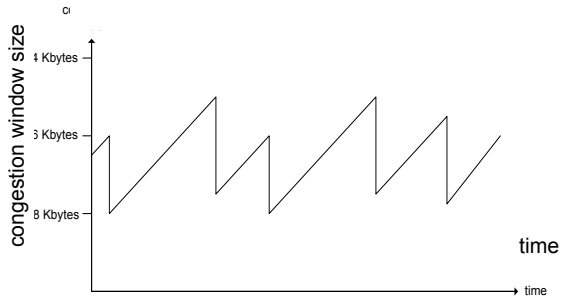
TCP congestion control:

- "Probing" for usable bandwidth:
  - Ideally: transmit as fast as possible (`cwnd` as large as possible) without loss
  - *Increase* `cwnd` until loss (congestion)
  - Loss: *decrease* `cwnd`, then begin probing (increasing) again
- Two "phases"
  - Slow start
  - Congestion avoidance
- Important variables:
  - `Cwnd (congwin)`
  - `Threshold:` defines threshold between two slow start phase, congestion control phase

TCP congestion control: Additive increase, multiplicative decrease

- *Approach:* Increase transmission rate (window size), probing for usable bandwidth, until loss occurs
  - *Additive increase:* Increase **cwnd** by 1 MSS every RTT until loss detected
  - *Multiplicative decrease*: Cut **cwnd** in half after loss

Saw tooth behavior: probing for bandwidth



TCP congestion control: Details

- Sender limits transmission:
  `LastByteSent-LastByteAcked`
  `≤ cwnd`
- Roughly,

$$\text{rate} = \frac{\text{cwnd}}{\text{RTT}} \text{ Bytes/sec}$$

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

How does sender perceive congestion?

- Loss event = timeout *or* 3 duplicate acks
- TCP sender reduces rate (**`cwnd`**) after loss event

Three mechanisms:

- AIMD
- Slow start
- Conservative after timeout events

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TCP slow start

- How do we get the clocking behavior to start?
  - Initialize cwnd = 1 MSS (typically 1460 bytes)
  - Upon receipt of every ack, cwnd = cwnd + 1 MSS
- Implications
  - Window actually increases to W in RTT * $\log_2(W)$
  - Exponential increase up to first loss event
  - Can overshoot window and cause packet loss
- Summary: initial rate is slow but ramps up exponentially fast

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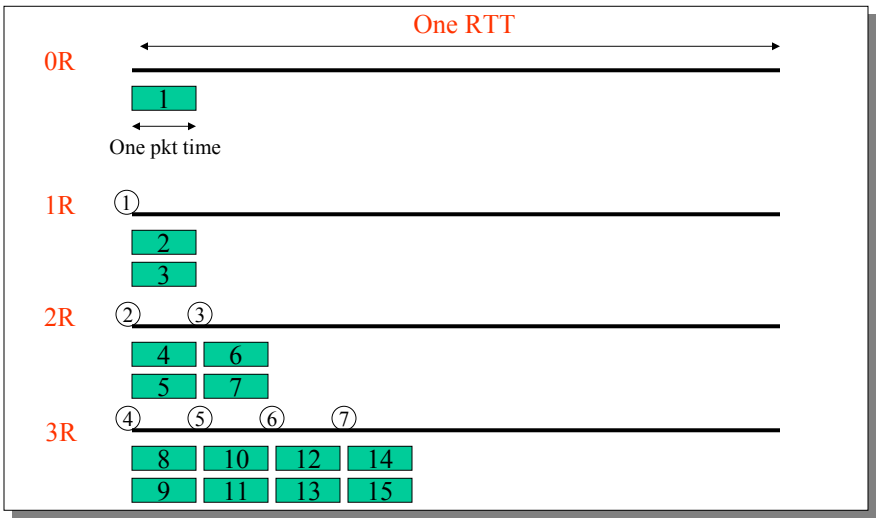
Slow start example



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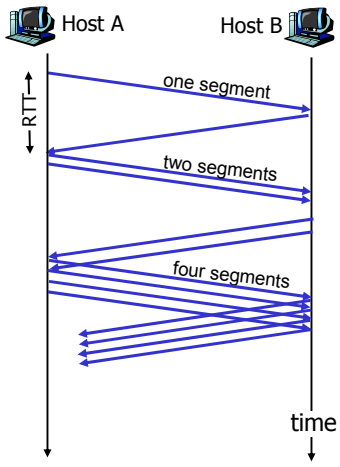
Slow start example (cont.)



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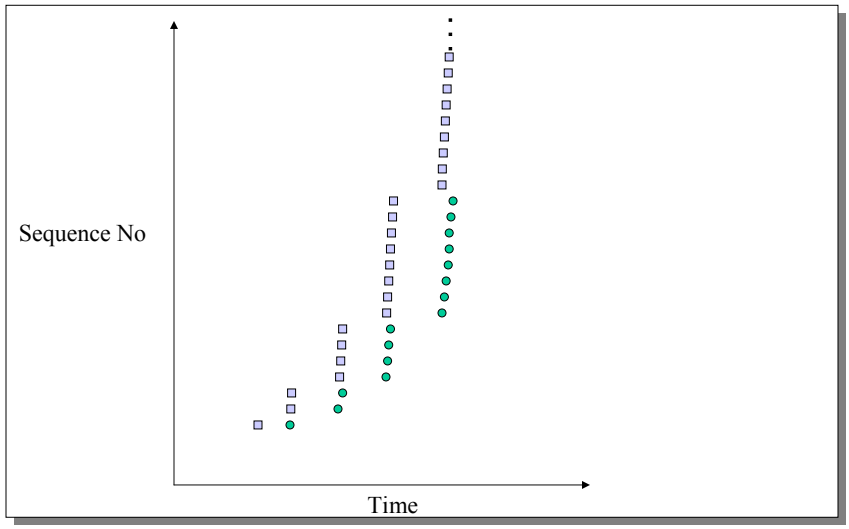
Slow start sequence number plot



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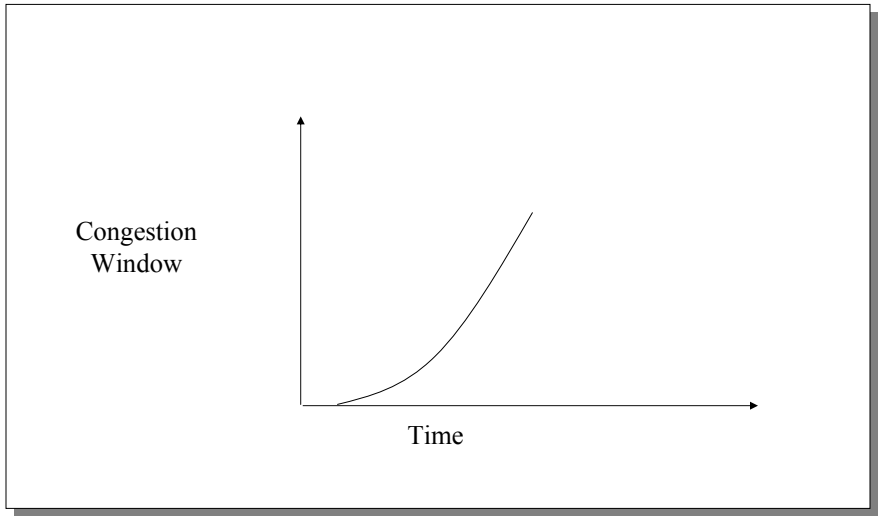
Congestion window



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Congestion avoidance

- Upon receiving ACK
  - Increase cwnd by MSS/cwnd
  - Results in additive increase
- Loss implies congestion – why?
  - Not necessarily true on all link types
- If loss occurs when cwnd = W
  - Network can handle 0.5W ~ W segments
  - Set cwnd to 0.5W (multiplicative decrease)

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Return to slow start

- If packet is lost we lose our self clocking as well
  - Need to implement slow-start and congestion avoidance together

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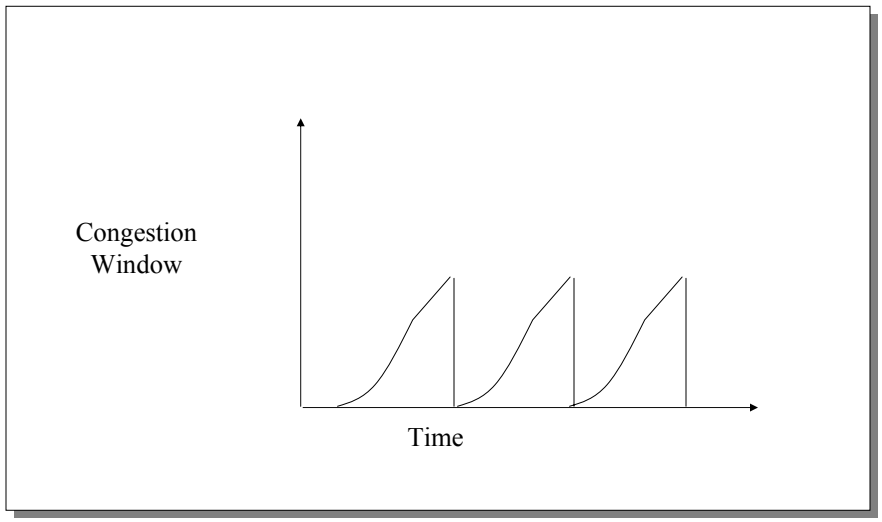
Congestion window



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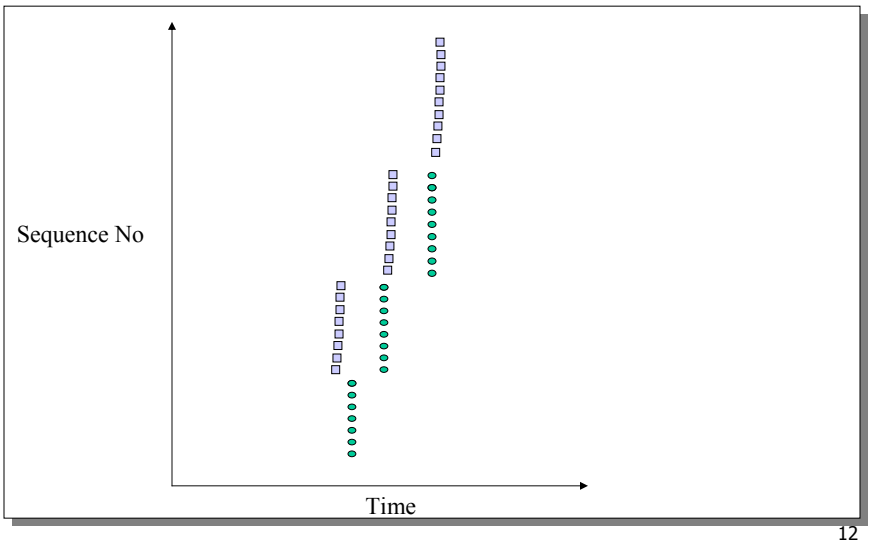
Congestion avoidance sequence plot



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Return to slow start (cont.)

- If packet is lost we lose our self clocking as well
  - Need to implement slow-start and congestion avoidance together
- When timeout occurs set ssthresh to 0.5w
  - If cwnd < ssthresh, use slow start
  - Else use congestion avoidance

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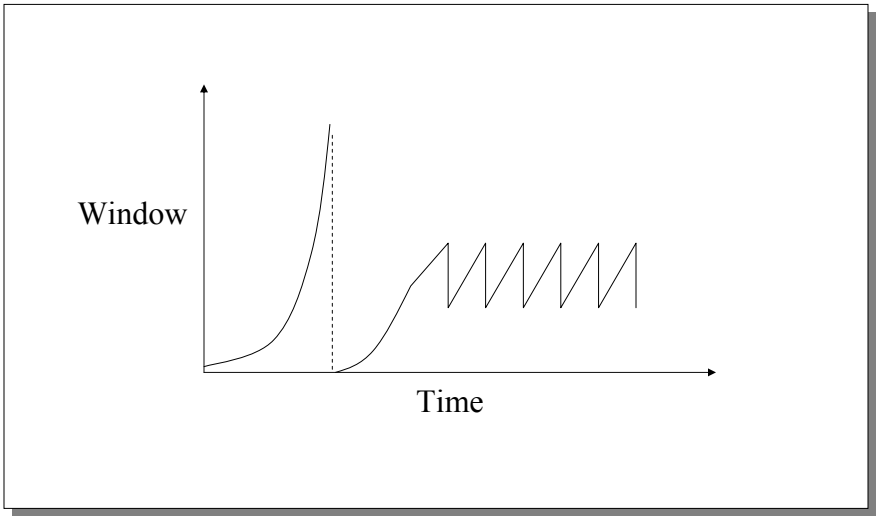
Overall TCP behavior



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How to change window

- When a loss occurs have W packets outstanding
- New cwnd = 0.5 * cwnd
  - How to get to new state?

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Fast recovery

- Each duplicate ack notifies sender that single packet has cleared network
- When < cwnd packets are outstanding
  - Allow new packets out with each new duplicate acknowledgement
- Behavior
  - Sender is idle for some time – waiting for ½ cwnd worth of dupacks
  - Transmits at original rate after wait
    - Ack clocking rate is same as before loss

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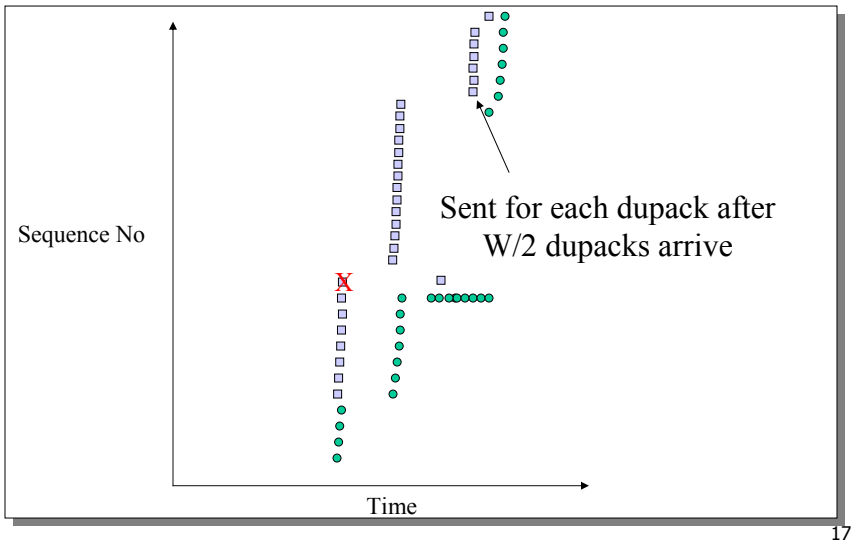
Fast recovery



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TCP congestion control: Summary

- "Probing" for usable bandwidth:
  - Ideally: transmit as fast as possible (**`cwnd`** as large as possible) without loss
  - *Increase* **`cwnd`** until loss (congestion)
  - Loss: *decrease* **`cwnd`**, then begin probing (increasing) again
- Two "phases"
  - Slow start
  - Congestion avoidance
- Important variables:
  - **`Cwnd`**
  - **`Threshold:`** defines threshold between two slow start phase, congestion control phase

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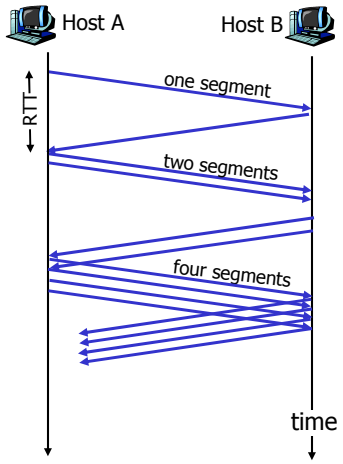
TCP slow start

Slowstart algorithm

initialize: **cwnd** = 1 MSS
for (each segment ACKed)
 cwnd += 1MSS
until (loss event OR
 cwnd > threshold)

- Exponential increase (per RTT) in window size (not so slow!)
- Loss event: timeout (Tahoe TCP) and/or or three duplicate ACKs (Reno TCP)



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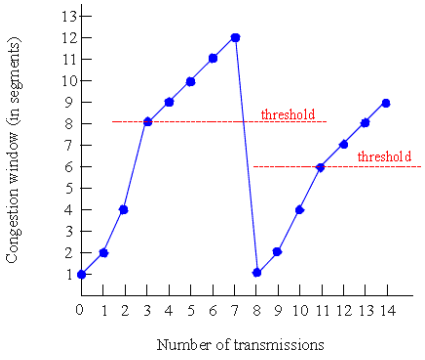
TCP congestion avoidance

Congestion avoidance

/* slowstart is over */
/* **cwnd** > threshold */
Until (loss event) {
 every w segments ACKed:
 cwnd += 1 MSS
 }
threshold = **cwnd** /2
cwnd = 1 MSS
perform slow start[1]



1: TCP Reno skips slowstart (fast recovery) after three duplicate ACKs

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TCP sender congestion control

State	Event	TCP Sender Action	Commentary
Slow Start (SS)	ACK receipt for previously unacked data	cwnd = cwnd + MSS, If (cwnd > Threshold) set state to "Congestion Avoidance"	Resulting in a doubling of cwnd every RTT
Congestion Avoidance (CA)	ACK receipt for previously unacked data	cwnd = cwnd +MSS / (cwnd)	Additive increase, resulting in increase of cwnd by 1 MSS every RTT
SS or CA	Loss event detected by triple duplicate ACK	Threshold = cwnd /2, cwnd = Threshold, Set state to "Congestion Avoidance"	Fast recovery, implementing multiplicative decrease. cwnd will not drop below 1 MSS.
SS or CA	Timeout	Threshold = cwnd /2, cwnd = 1 MSS, Set state to "Slow Start"	Enter slow start
SS or CA	Duplicate ACK	Increment duplicate ACK count for segment being acked	cwnd and Threshold not changed

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TCP flavors

- Tahoe, Reno, Vegas, SACK
- TCP Tahoe (distributed with 4.3BSD Unix)
  - Original implementation of Van Jacobson's mechanisms
  - Includes:
    - Slow start
    - Congestion avoidance
    - Fast retransmit

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Fast retransmit

- What are duplicate acks (dupacks)?
  - Repeated acks for the same sequence
- When can duplicate acks occur?
  - Loss
  - Packet re-ordering
  - Window update – advertisement of new flow control window
- Assume re-ordering is infrequent and not of large magnitude
  - Use receipt of 3 or more duplicate acks as indication of loss
  - Don't wait for timeout to retransmit packet

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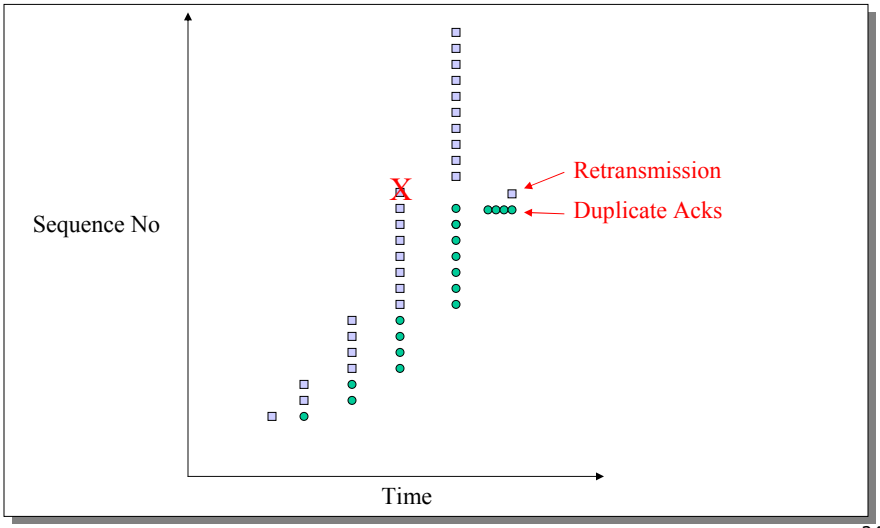
Fast retransmit



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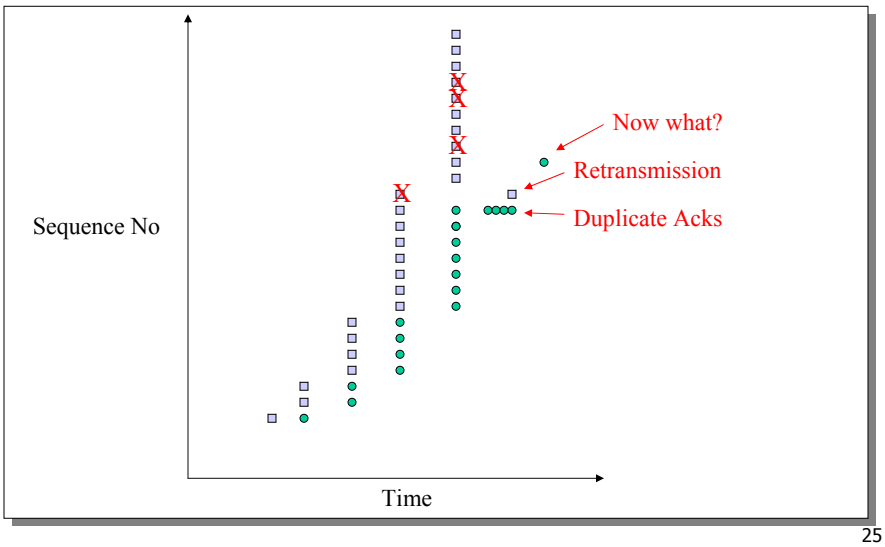
Multiple losses



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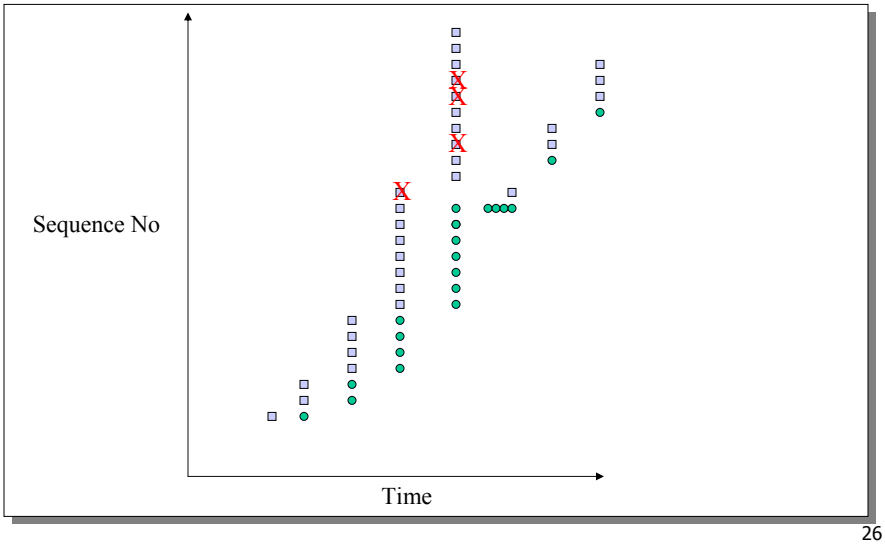
Tahoe



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TCP Reno (1990)

- All mechanisms in Tahoe
- Addition of fast-recovery
  - Opening up congestion window after fast retransmit
- Delayed acks
- Header prediction
  - Implementation designed to improve performance
  - Has common case code inlined
- With multiple losses, Reno typically timeouts because it does not see duplicate acknowledgements

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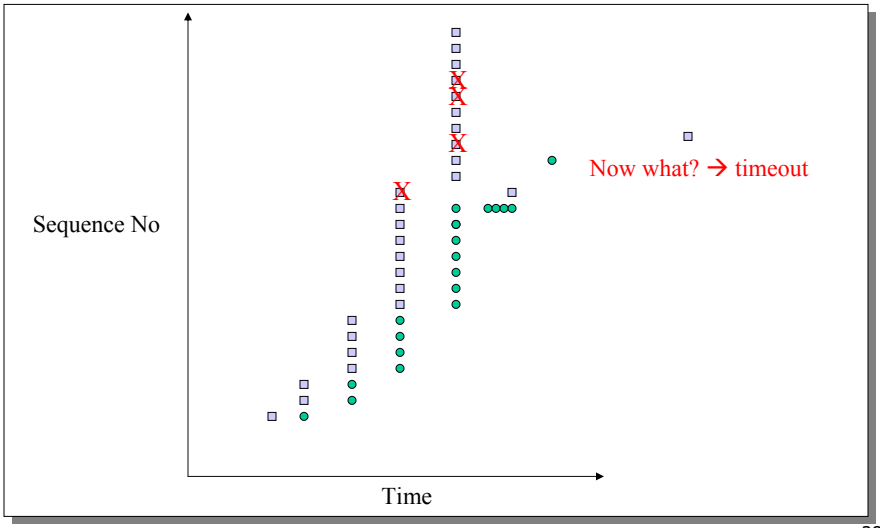
Reno



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NewReno

- The ack that arrives after retransmission (partial ack) should indicate that a second loss occurred
- When does NewReno timeout?
  - When there are fewer than three dupacks for first loss
  - When partial ack is lost
- How fast does it recover losses?
  - One per RTT

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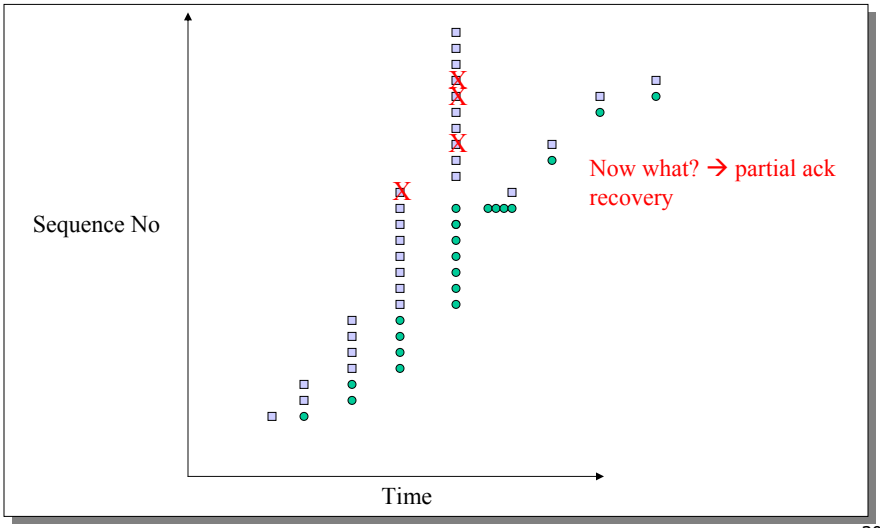
NewReno



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SACK

- Basic problem is that cumulative acks only provide little information
  - Ack for just the packet received
    - What if acks are lost? → carry cumulative also
    - Not used
  - Bitmask of packets received
    - Selective acknowledgement (SACK)
- How to deal with reordering

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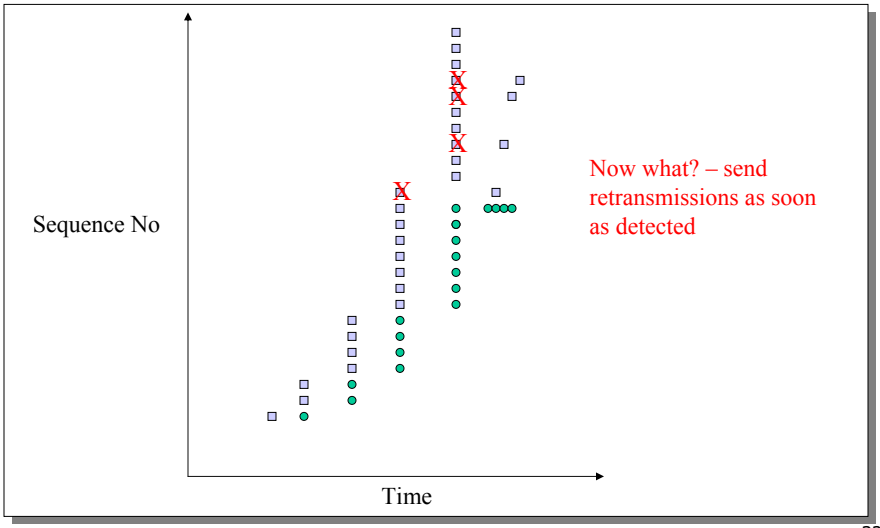
SACK (cont.)



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Performance issues

- Timeout >> fast rexmit
  - Need 3 dupacks/sacks
  - Not great for small transfers
    - Don't have 3 packets outstanding
  - What are real loss patterns like?
- Right edge recovery
  - Allow packets to be sent on arrival of first and second duplicate ack
  - Helps recovery for small windows
- How to deal with reordering?

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TCP extensions

- Implemented using TCP options
  - Timestamp
  - Protection from sequence number wraparound
  - Large windows

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Protection from wraparound

- Wraparound time vs. link speed
  - 1.5Mbps: 6.4 hours
  - 10Mbps: 57 minutes
  - 45Mbps: 13 minutes
  - 100Mbps: 6 minutes
  - 622Mbps: 55 seconds → < MSL!
  - 1.2Gbps: 28 seconds
- Use timestamp to distinguish sequence number wraparound

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Large windows

- Delay-bandwidth product for 100ms delay
  - 1.5Mbps: 18KB
  - 10Mbps: 122KB > max 16bit window
  - 45Mbps: 549KB
  - 100Mbps: 1.2MB
  - 622Mbps: 7.4MB
  - 1.2Gbps: 14.8MB
- Scaling factor on advertised window
  - Specifies how many bits window must be shifted to the left
  - Scaling factor exchanged during connection setup

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Maximum segment size (MSS)

- Exchanged at connection setup
  - Typically pick MTU of local link
- What all does this effect?
  - Efficiency
  - Congestion control
  - Retransmission
- Path MTU discovery
  - Why should MTU match MSS?

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Effects of TCP latencies

Q: client latency from object request from WWW server to receipt?

- TCP connection establishment
- Data transfer delay

Notation, assumptions:

- Assume: fixed congestion window, W, giving throughput of R bps
- S: MSS (bits)
- O: oject size (bits)
- No retransmissions (no loss, no corruption)

Two cases to consider:

- WS/R > RTT + S/R: ACK for first segment in window before window's worth of data sent
- WS/R < RTT + S/R: wait for ACK after sending window's worth of data sent

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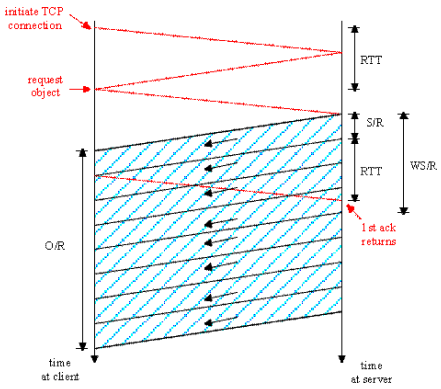
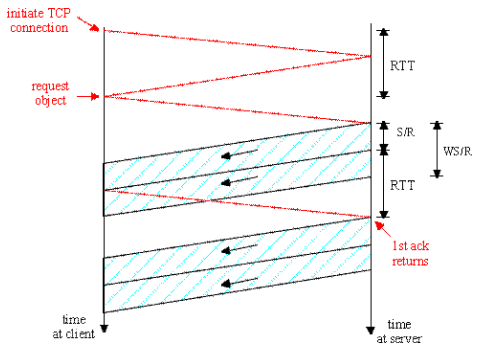
Effects of TCP latencies (cont.)



Case 1: latency = 2RTT + O/R



Case 2: latency = 2RTT + O/R + (K-1)[S/R + RTT - WS/R]

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Transport layer: Summary

- Principles behind transport layer services:
  - Multiplexing/demultiplexing
  - Reliable data transfer
  - Flow control
  - Congestion control
- Instantiation and implementation in the Internet
  - UDP
  - TCP

Next:

- Leaving the network "edge" (application transport layer)
- Into the network "core"

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