CSCI 460
Networks and Communications

Transport Layer

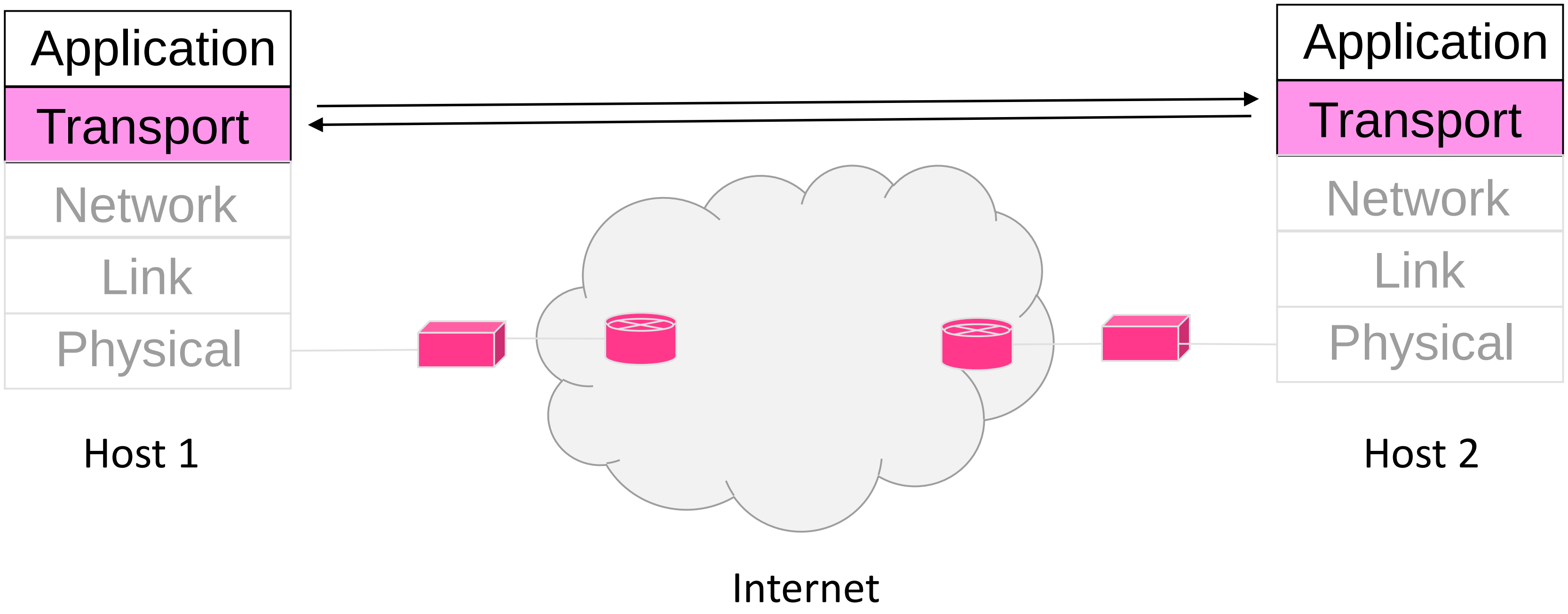
Humayun Kabir
Professor, CS, Vancouver Island University, BC, Canada

Outline

- User Datagram Protocol (UDP)
- Transport Control Protocol (TCP)
  - TCP Segment Header
  - TCP Connection
  - TCP Flow Control
  - TCP Congestion Control
  - TCP Retransmission Timer

The Transport Layer

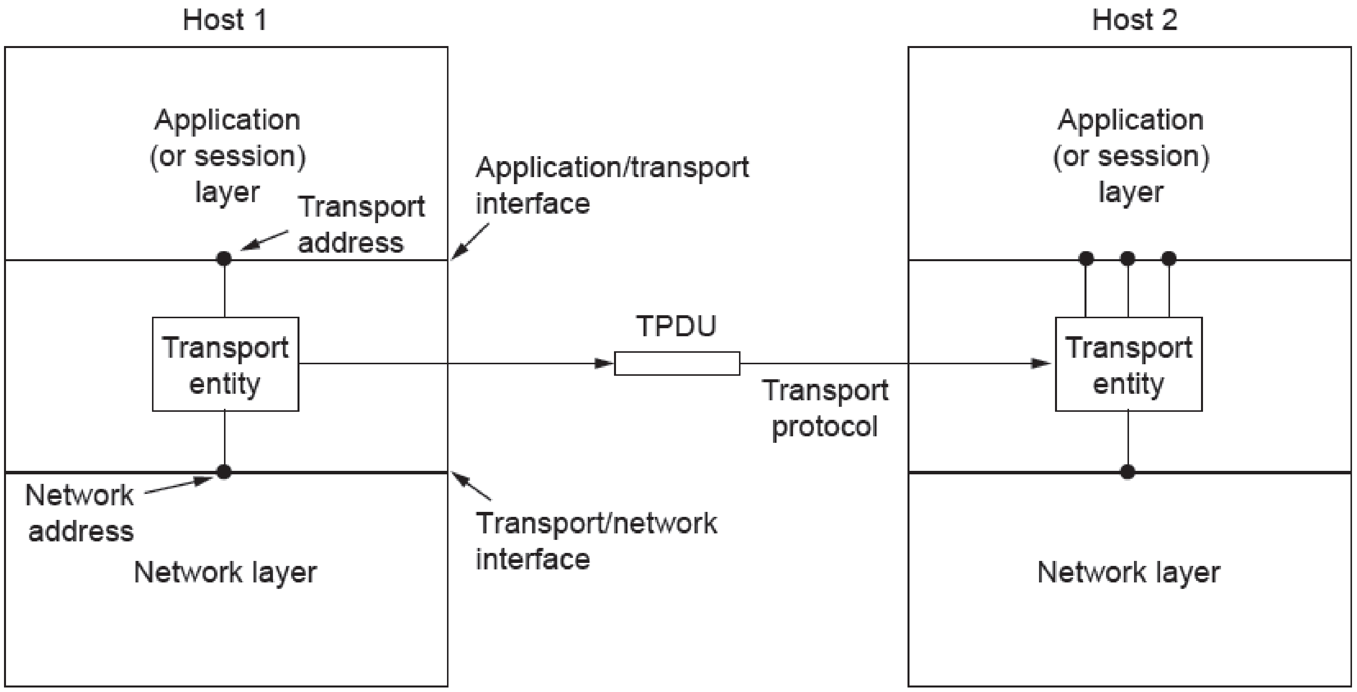
Responsible for delivering data from source to destination nodes (across networks) with the desired reliability or quality



Services Provided to Application Layer

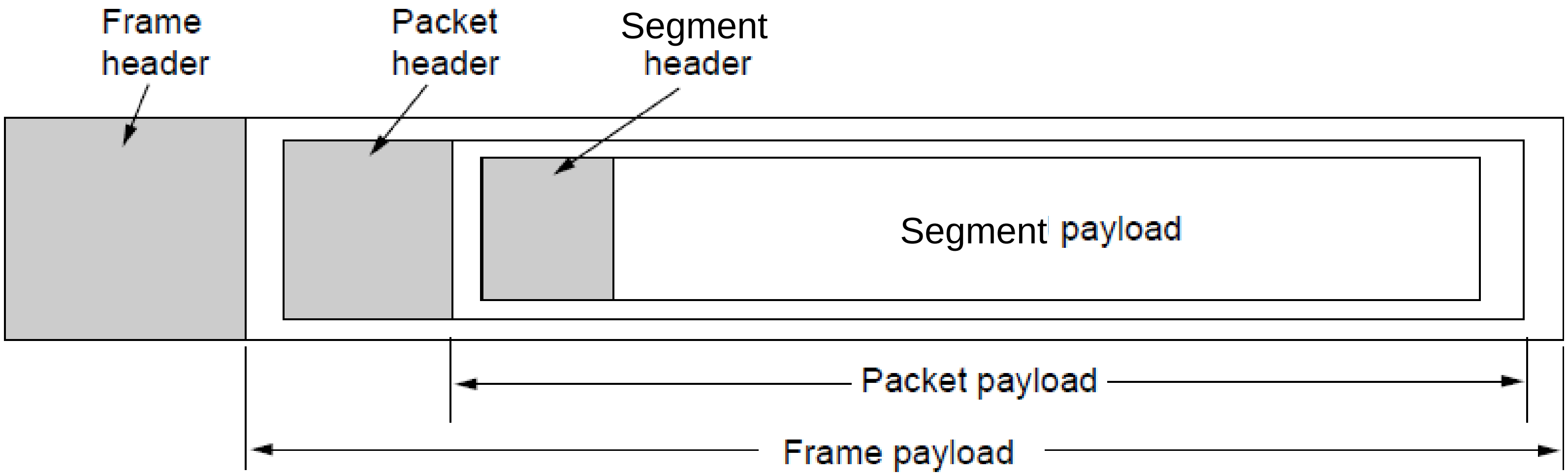
Transport layer adds reliability to the network layer

- Offers connectionless (e.g., UDP) and connection-oriented (e.g, TCP) service to applications



Services Provided to Application Layer

Transport layer sends transport segments inside network packets (inside datalink frames)



UDP in TCP/IP Protocol Stack

UDP (User Datagram Protocol) is a shim over IP

- Header has ports (TSAPs), length and checksum.

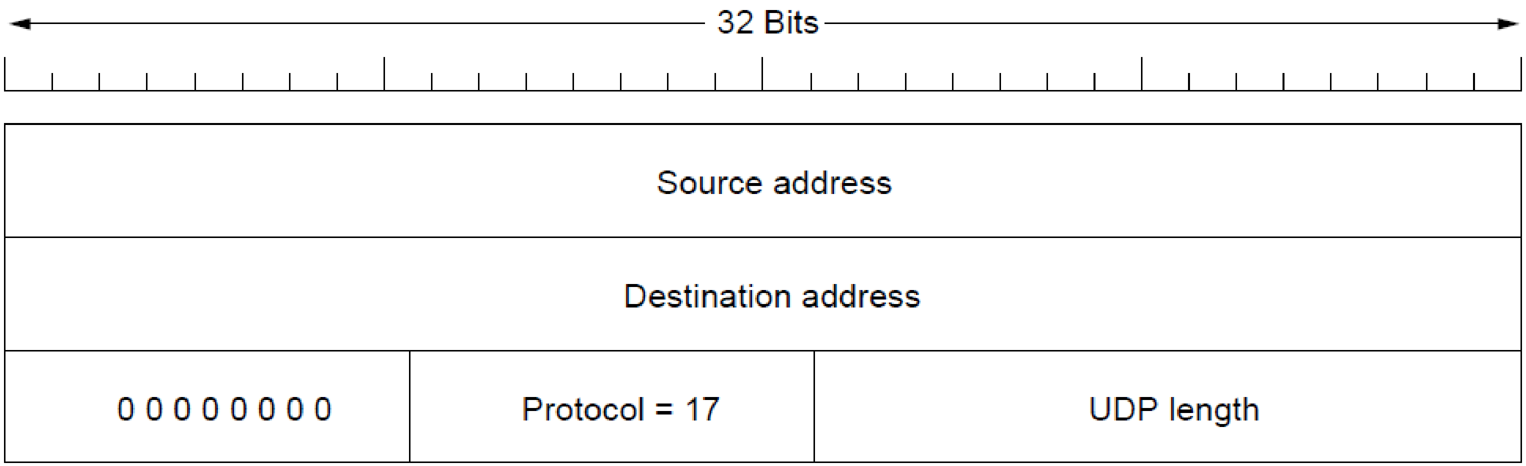
32 Bits

Source port	Destination port
UDP length	UDP checksum

UDP in TCP/IP Protocol Stack

Checksum covers UDP segment and IP pseudoheader

- Fields that change in the network are zeroed out
- Provides an end-to-end delivery check



TCP in TCP/IP Protocol Stack

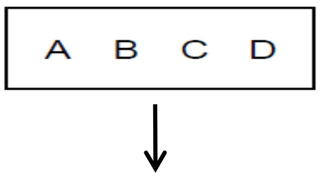
TCP provides applications with a reliable byte stream between processes; it is the workhorse of the Internet

- Popular servers run on well-known ports

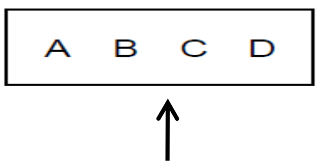
Port	Protocol	Use
20, 21	FTP	File transfer
22	SSH	Remote login, replacement for Telnet
25	SMTP	Email
80	HTTP	World Wide Web
110	POP-3	Remote email access
143	IMAP	Remote email access
443	HTTPS	Secure Web (HTTP over SSL/TLS)
543	RTSP	Media player control
631	IPP	Printer sharing

TCP in TCP/IP Protocol Stack

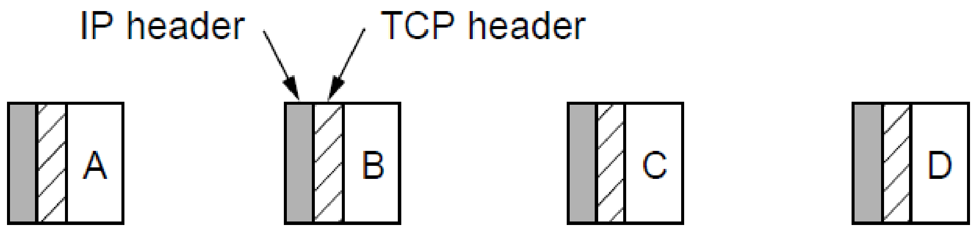
Applications using TCP see only the byte stream and not the segments sent as separate IP packets



2048 bytes of data
handed by application



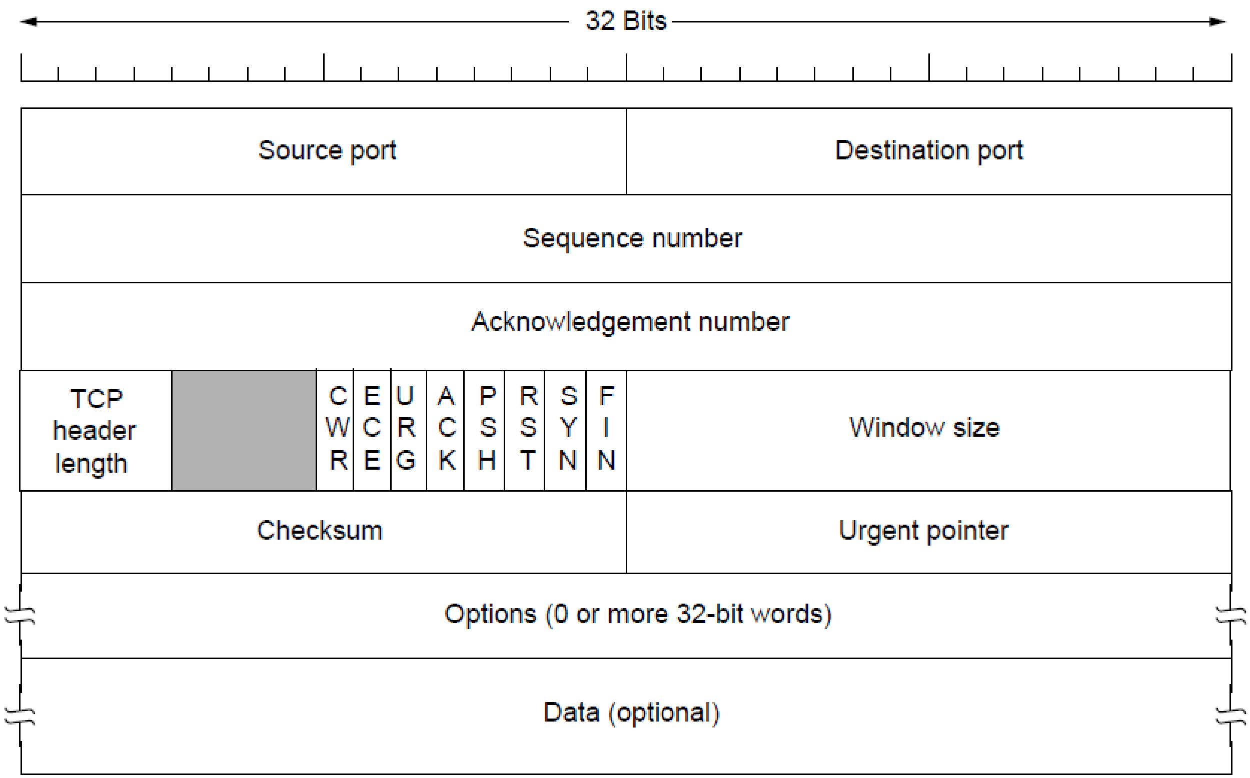
2048 bytes of data
delivered to application



Four TCP segments, each with 512 bytes of data and carried in an IP packet

TCP Segment Header

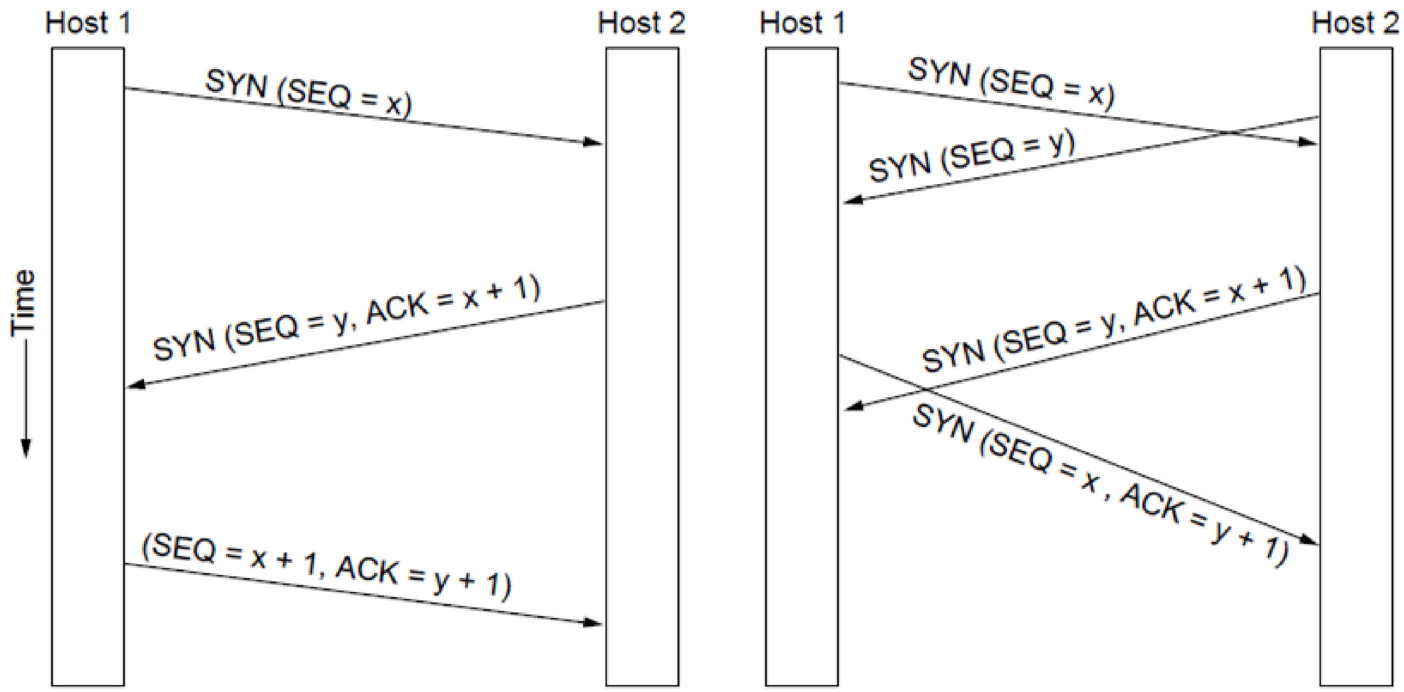
TCP header includes addressing (ports), sliding window (seq. / ack. number), flow control (window), error control (checksum) and more.



TCP Connection Establishment

TCP sets up connections with the three-way handshake

- Release is symmetric, also as described before

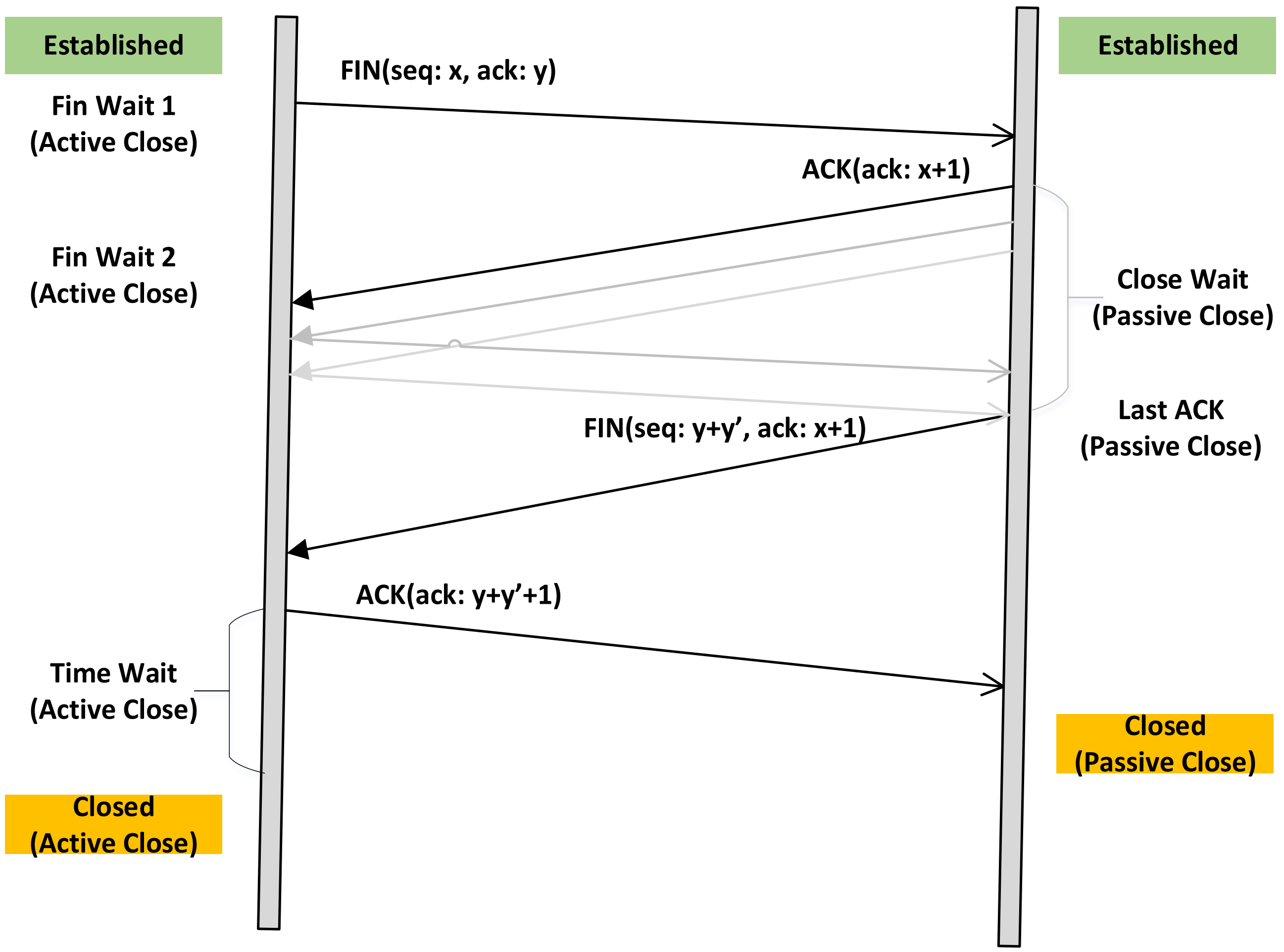


Normal case

Simultaneous connect

TCP Connection Release

TCP release connections with the three-way handshake.



TCP Connection State Modeling

The TCP connection finite state machine has more states than our simple example from earlier.

State	Description
CLOSED	No connection is active or pending
LISTEN	The server is waiting for an incoming call
SYN RCVD	A connection request has arrived; wait for ACK
SYN SENT	The application has started to open a connection
ESTABLISHED	The normal data transfer state
FIN WAIT 1	The application has said it is finished
FIN WAIT 2	The other side has agreed to release
TIME WAIT	Wait for all packets to die off
CLOSING	Both sides have tried to close simultaneously
CLOSE WAIT	The other side has initiated a release
LAST ACK	Wait for all packets to die off

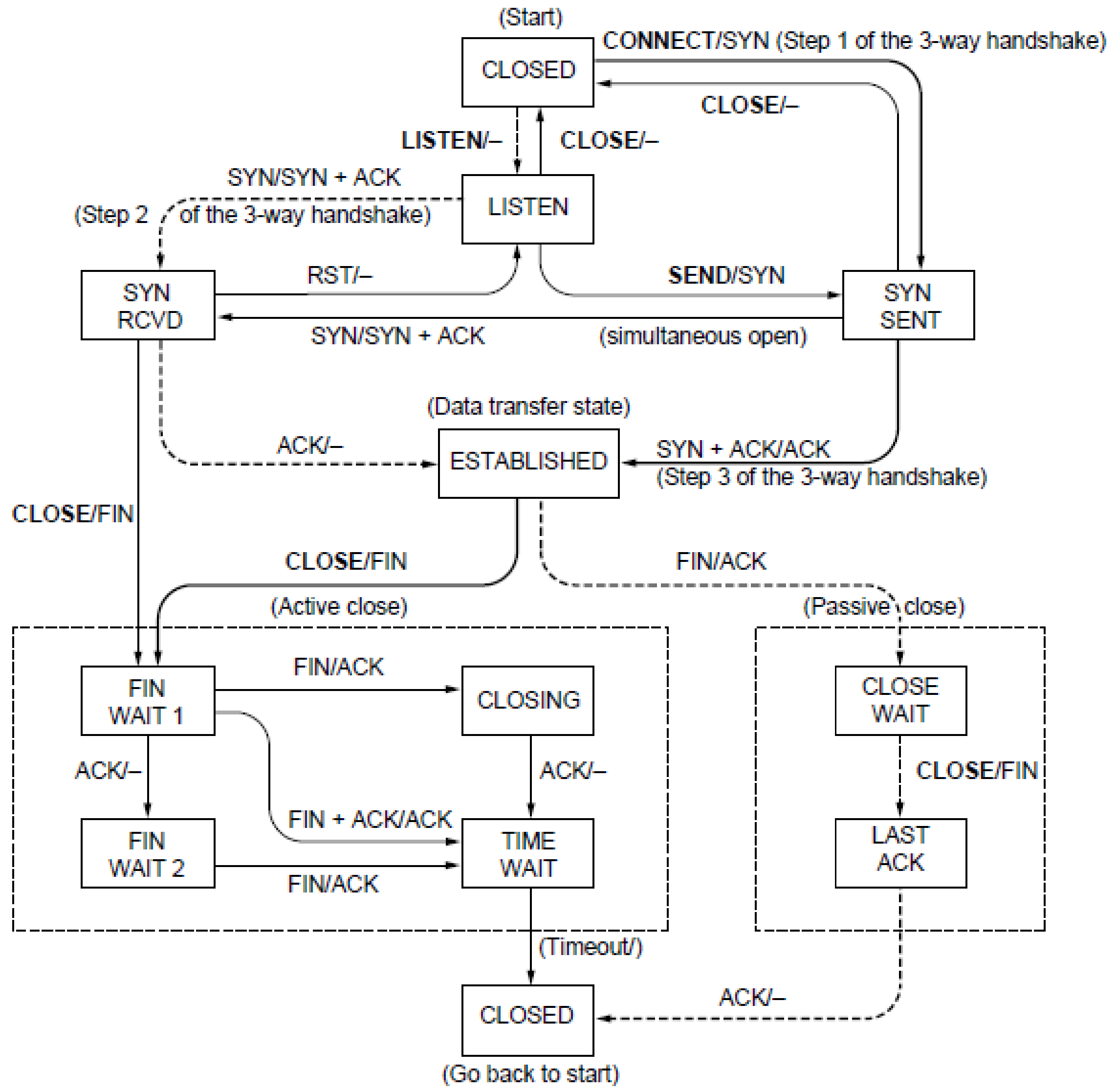
TCP Connection State Modeling

Solid line is the normal path for a client.

Dashed line is the normal path for a server.

Light lines are unusual events.

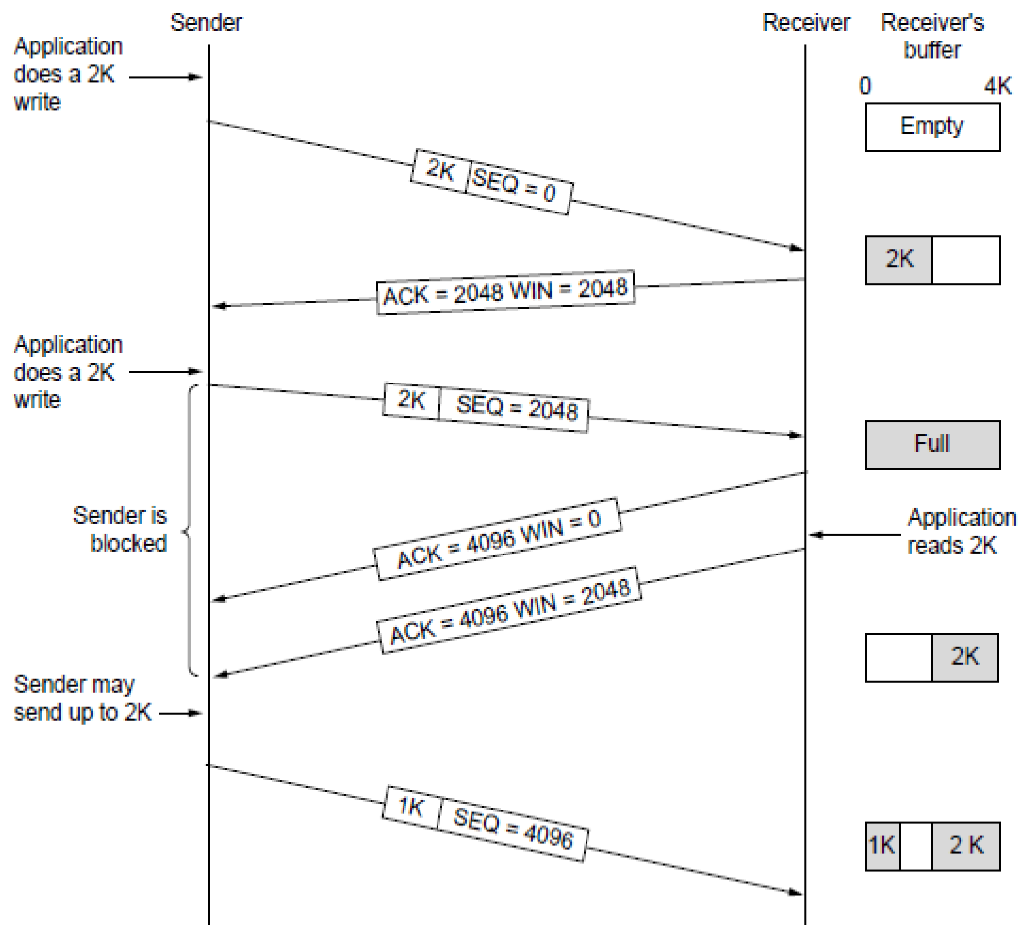
Transitions are labeled by the cause and action, separated by a slash.



TCP Sliding Window (Flow Control)

TCP adds flow control to the sliding window as before

- ACK + WIN is the sender's limit



TCP Sliding Window (Flow Control)

- **Delayed Acknowledgements**
  - TCP receiver delays the acknowledgments for 500 msec with the hope to acquire enough data from the sender.
  - Minimizes the number of TCP segments over the network.
  - Longers the response time to interactive applications.

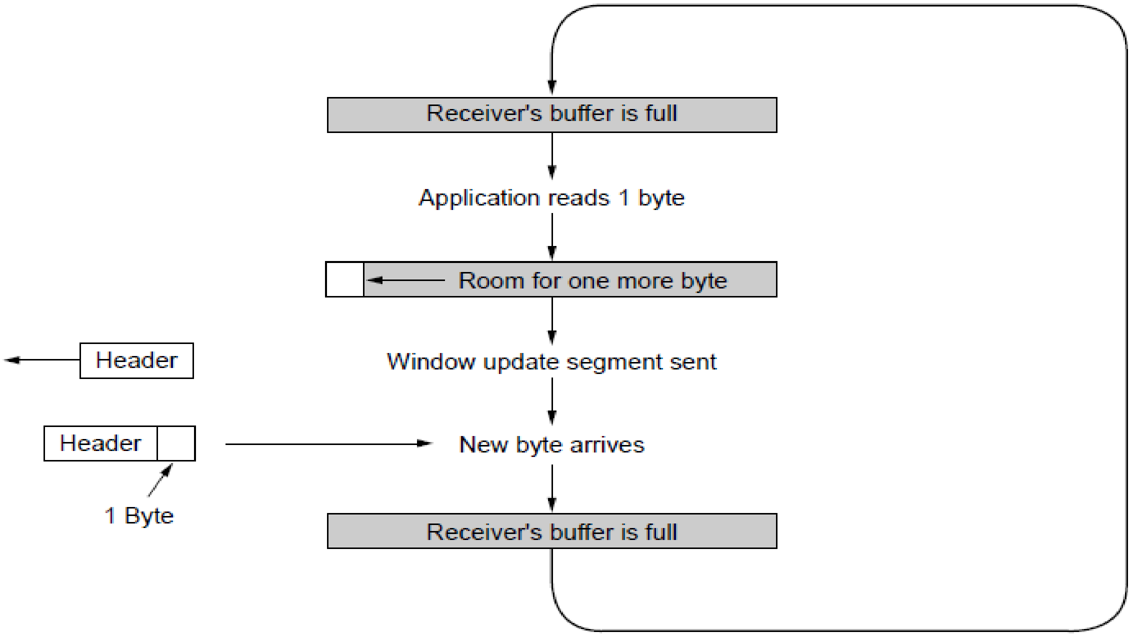
TCP Sliding Window (Flow Control)

- **Nagle's Algorithm**
  - When data from the applications comes at TCP sender in small pieces send the first piece and buffer the rest until the first acknowledgement is returned.
  - Minimizes the number of TCP segments over the network.
  - Longers the response time to interactive applications, it can be deactivated using TCP_NODELAY option.

TCP Sliding Window (Flow Control)

Need to add special cases to avoid unwanted behavior

- E.g., silly window syndrome [below]



Receiver application reads single bytes, so sender always sends one byte segments

TCP Sliding Window (Flow Control)

- **Cark Solution to Silly Window Syndrome**
  - TCP receiver delays the acknowledgments until either the half or an MSS equivalent of the receiver buffer is empty.
  - TCP sender instead of sending tiny segments it sends segments whose size is at least one MSS or half of the receiver window size.
  - Longers the response time to interactive applications.

TCP Congestion Control

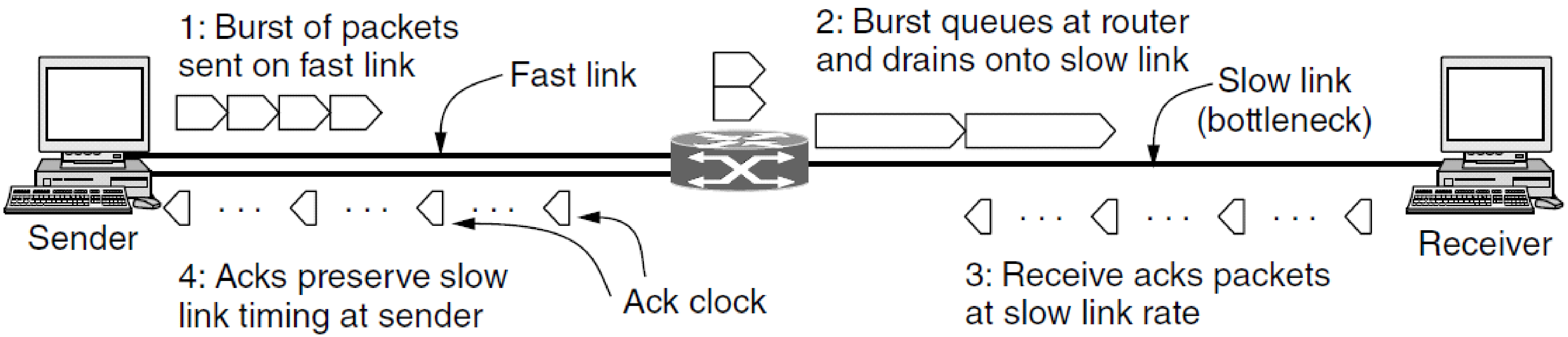
TCP uses AIMD with loss signal to control congestion

- Implemented as a **congestion window** (cwnd) for the number of unacknowledged segments that may be in the network.
- Congestion window controls the **sending rate**, cwnd / RTT; window can stop sender quickly.
- Uses several mechanisms that work together.

TCP Congestion Control

Name	Mechanism	Purpose
ACK clock	Congestion window (cwnd)	Smooth out packet bursts
Slow-start	Double cwnd each RTT	Rapidly increase send rate to reach roughly the right level
Additive Increase	Increase cwnd by 1 segment each RTT	Slowly increase send rate to probe at about the right level
Fast retransmit	Resend lost segment after 3 duplicate ACKs	Recover from a lost segment as soon as possible
Fast recovery	Send new packet for each new ACK	Recover from a lost segment without stopping ACK clock

TCP Congestion Control



ACKs pace new segments into the network and smooth bursts

- **ACK Clock** : The rate at which TCP sender receives the acknowledgements, reflects the rate of the slowest link in the network. Paces traffic and smooths out sender bursts.
- TCP **congestion window** is regulated on ACK Clock.

TCP Congestion Control Slow Start

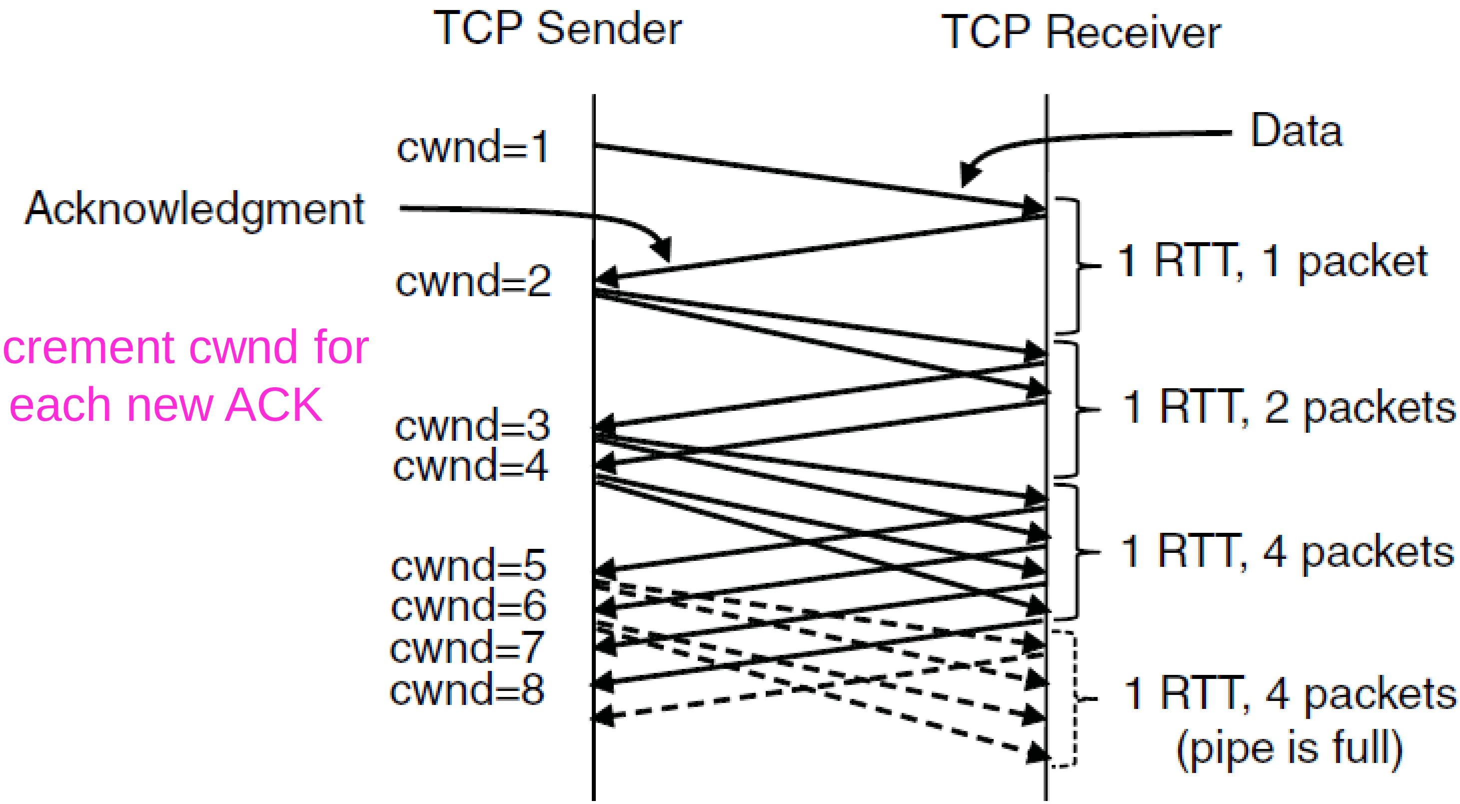
- Congestion window (**cwind**) starts with 1 MSS (at most 4 MSS).
- At the reception of each acknowledgement sender increments the cwind1 MSS and sends 2 MSS, i.e., the window is doubled in every **round-trip-time** (RTT). This **exponential growth** continues until it reaches a threshold called **slow-start-threshold**. Initial slow-start-threshold is set to receiver window size and the sender enters into **additive increase mode**.
- When a segment is lost and the **retransmission timer** times out, sender sets the slow-start-threshold to the half of the current congestion window and repeats the slow start mode.

TCP Congestion Control

Slow start grows congestion window exponentially

- Doubles every RTT while keeping ACK clock going

Increment cwnd for each new ACK



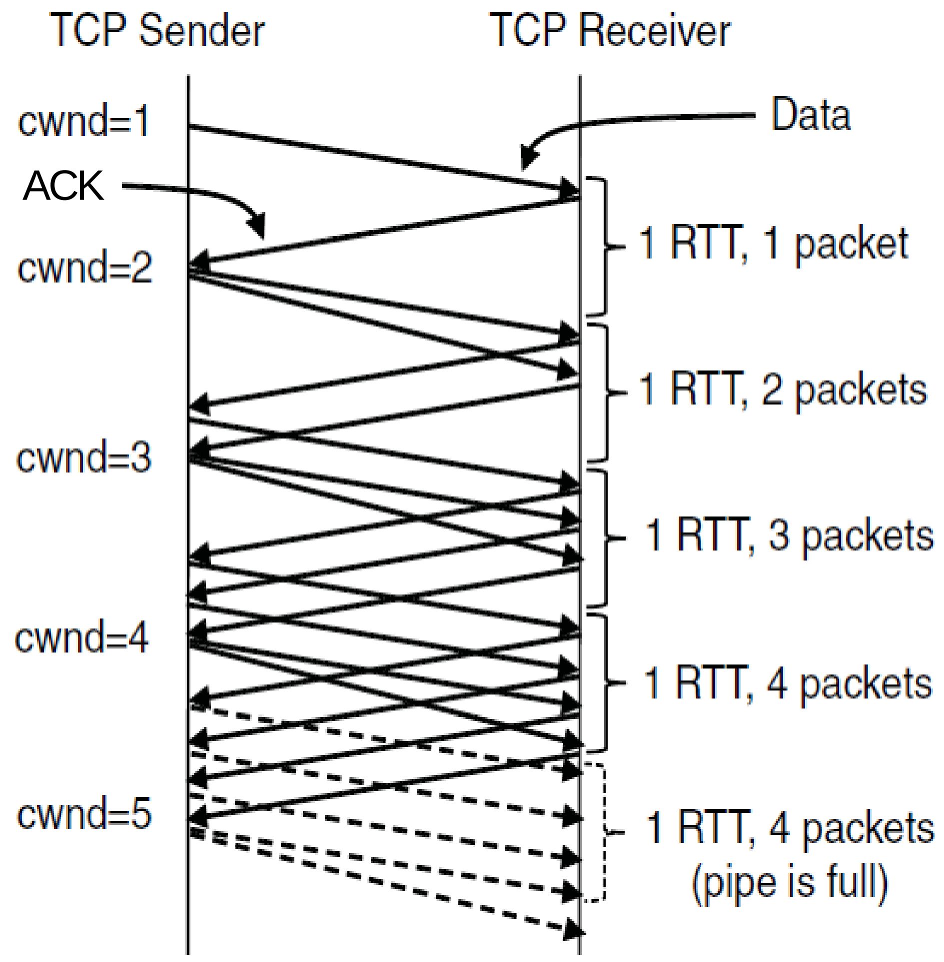
TCP Congestion Control Additive Increase

- Congestion window grows linearly instead of exponentially. Congestion window is incremented 1 MSS in every RTT.
- At the reception of each acknowledgement sender increments the congestion window **MSSxMSS/cwind**.
- When a segment is lost and the **retransmission timer** times out, sender sets the slow-start-threshold to the half of the current congestion window and repeats the slow start mode.

TCP Congestion Control

Additive increase grows cwnd slowly

- Adds 1 every RTT
- Keeps ACK clock



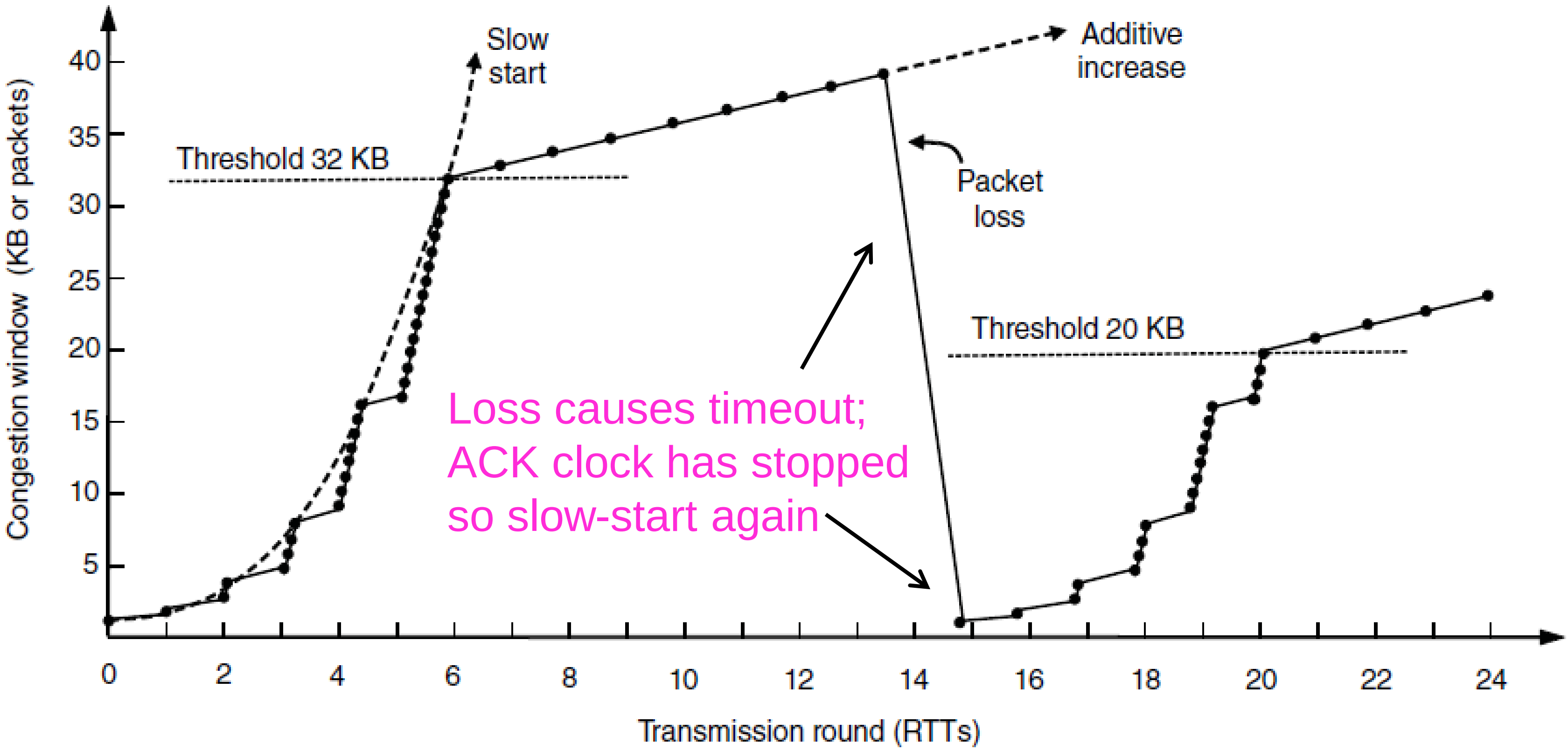
TCP Congestion Control Fast Retransmission

- Sender assumes **segment loss** after receiving **3 duplicate acknowledgements**.
- Retransmits the lost segment, resets the slow-start-threshold to the half of the current congestion window, and repeats the slow start mode.
- Segment lost detection does not wait for the **retransmission timer to** time out, i.e., recovers from the loss quicker.

TCP Congestion Control

Slow start followed by additive increase (TCP Tahoe)

- Threshold is half of previous loss cwnd



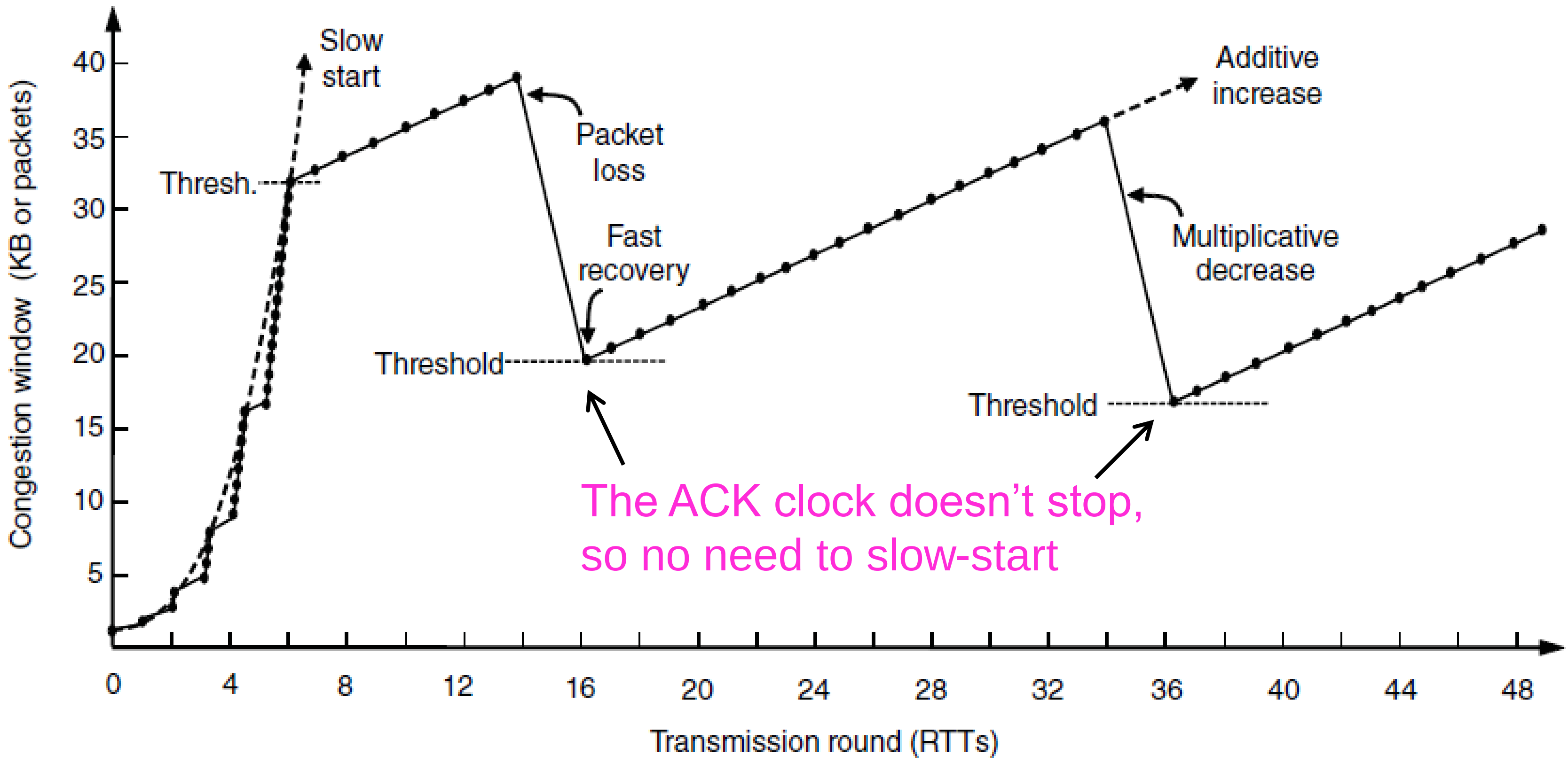
TCP Congestion Control Fast Recovery

- After receiving **3 duplicate acknowledgements** retransmits the lost segment, resets both the congestion window and the slow-start-threshold to the half of the current congestion window, and enters into fast recovery mode for a short period of time.
- Counts all the duplicate acknowledgments and transmits a new segment against each duplicate acknowledgement until the segments in the network reaches the new slow-start-threshold.
- Exits from the fast recovery mode when duplicate acknowledgements ceases and repeats **additive mode**.

TCP Congestion Control

With fast recovery, we get the classic sawtooth (TCP Reno)

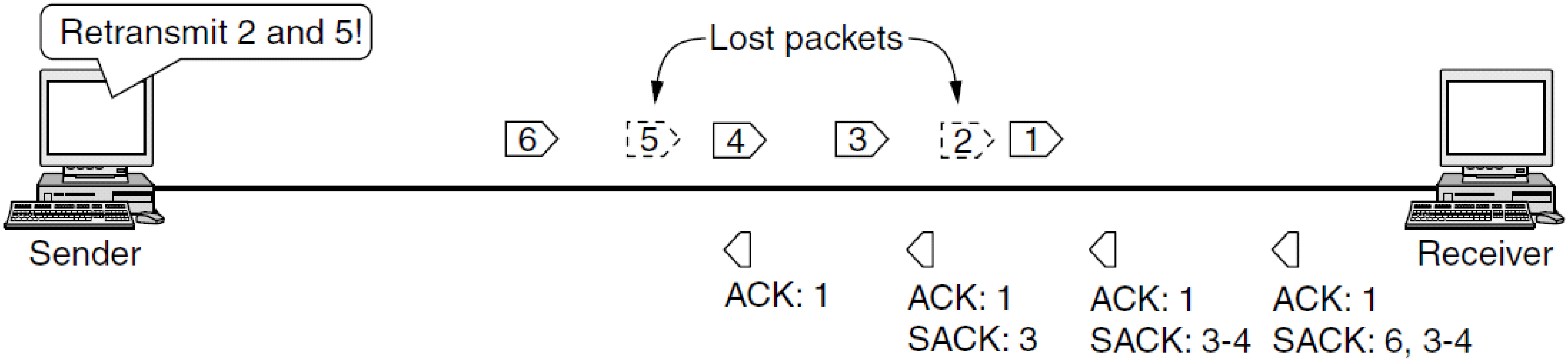
- Retransmit lost packet after 3 duplicate ACKs
- New packet for each dup. ACK until loss is repaired



TCP Congestion Control

SACK (Selective ACKs) extend ACKs with a vector to describe received segments and hence losses

- Allows for more accurate retransmissions / recovery



No way for us to know that 2 and 5 were lost with only ACKs

Explicit Congestion Notification (ECN)

- Both TCP and IP layers work in synergy.
- **ECN** is **negotiated** between TCP sender and receiver while establishing TCP connection.
- ECN negotiated sender marks the outgoing IP packets with **ECN Capable Transport** (either 01 or 10).
- If a router on the path supports ECN and experiences congestion, it changes ECN marker of the IP packets to **Congestion Experienced** (11).

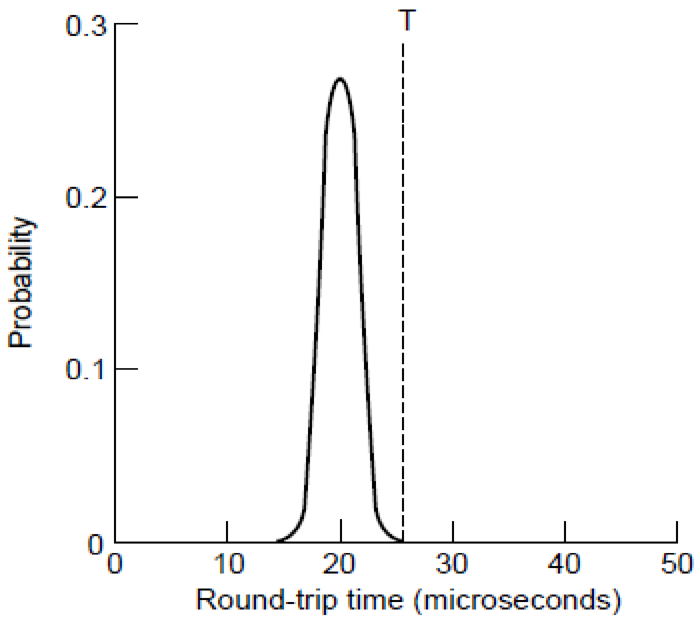
Explicit Congestion Notification (ECN)

- ECN negotiated TCP receiver keeps replying with **ECE (ECN-Echo)** bit set TCP segments until it receives a TCP segment with **CWR (Congestion Window Reduced)** bit set.
- Upon receiving a TCP segment with ECE bit set, TCP sender reduces the **congestion window** as for a segment drop and sends a TCP segment with CWR bit set.

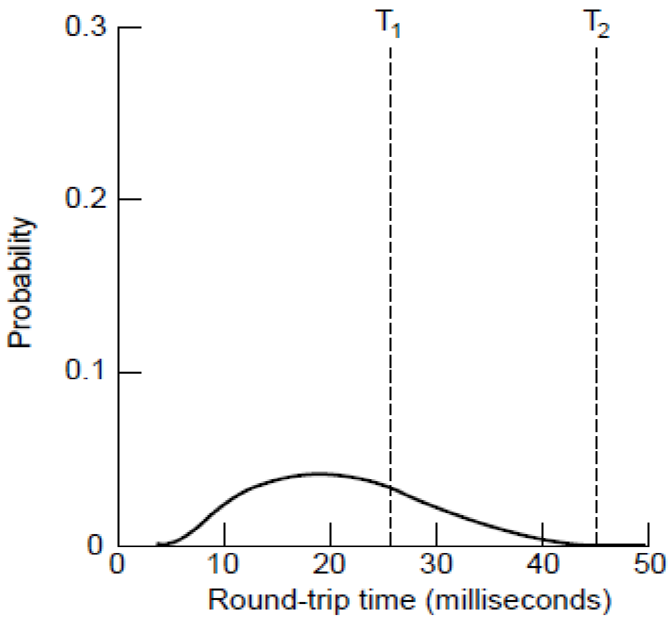
TCP Timer Management

TCP estimates retransmit timer from segment RTTs

- Tracks both average and variance (for Internet case)
- Timeout is set to average plus 4 x variance



LAN case – small, regular RTT



Internet case – large, varied RTT

TCP Timer Management

$R_0, R_1, R_2, R_3, \ldots. R_n$

$SRTT_0 = R_0$

$SRTTVAR_0 = R_0/2$

$\alpha = 0.0 \ldots 1.0$

$\beta = 0.0 \ldots 1.0$

$SRTT_n = \alpha * SRTT_{n-1} + (1-\alpha) * R_n$

$SRTTVAR_n = \beta * SRTTVAR_{n-1} + (1-\beta) * |(SRTT_n - R_n)|$

$RTT = SRTT_n + 4 * SRTTVAR_n$

Summary

– User Datagram Protocol (UDP)
– Transport Control Protocol (TCP)
  - TCP Segment Header
  - TCP Connection
  - TCP Flow Control
  - TCP Congestion Control
  - TCP Retransmission Timer

Next

Application Layer

- DNS
  - Name Space
  - Resource Record
  - DNS Server
- HTTP
  - URL
  - HTML
  - HTTP Methods
  - HTTP Headers
- FTP
  - Control and Data Connections
  - Commands and Replies