Problem / Overview

Course: Networking Fundamentals
Module: Transport

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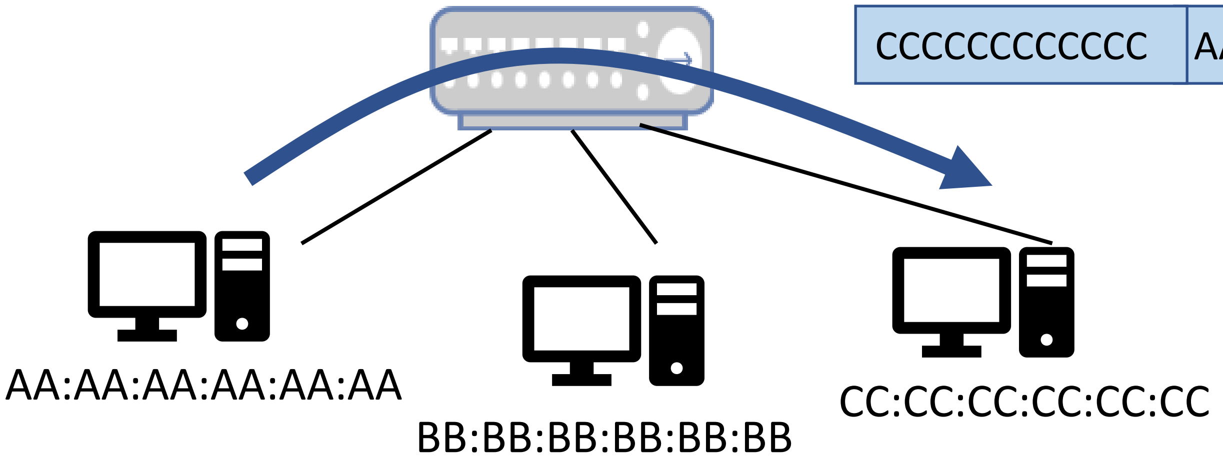
Ethernet Addressing

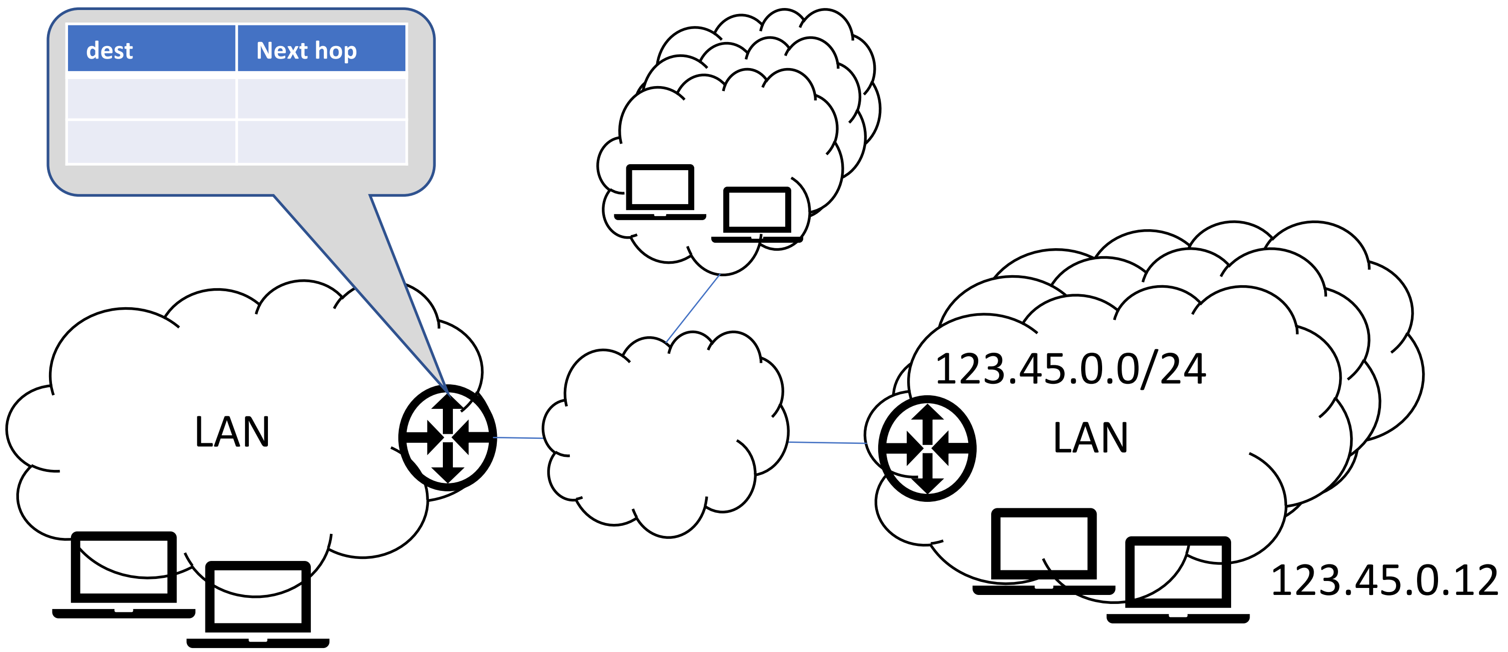
- Recall:
  - Each NIC has a MAC address
  - Each frame contains src and dest MAC address



Dest	Src	Type	Payload	FCS
CCCCCCCCCCCC	AAAAAAAAAAAA	0800	F10FE23…	102F

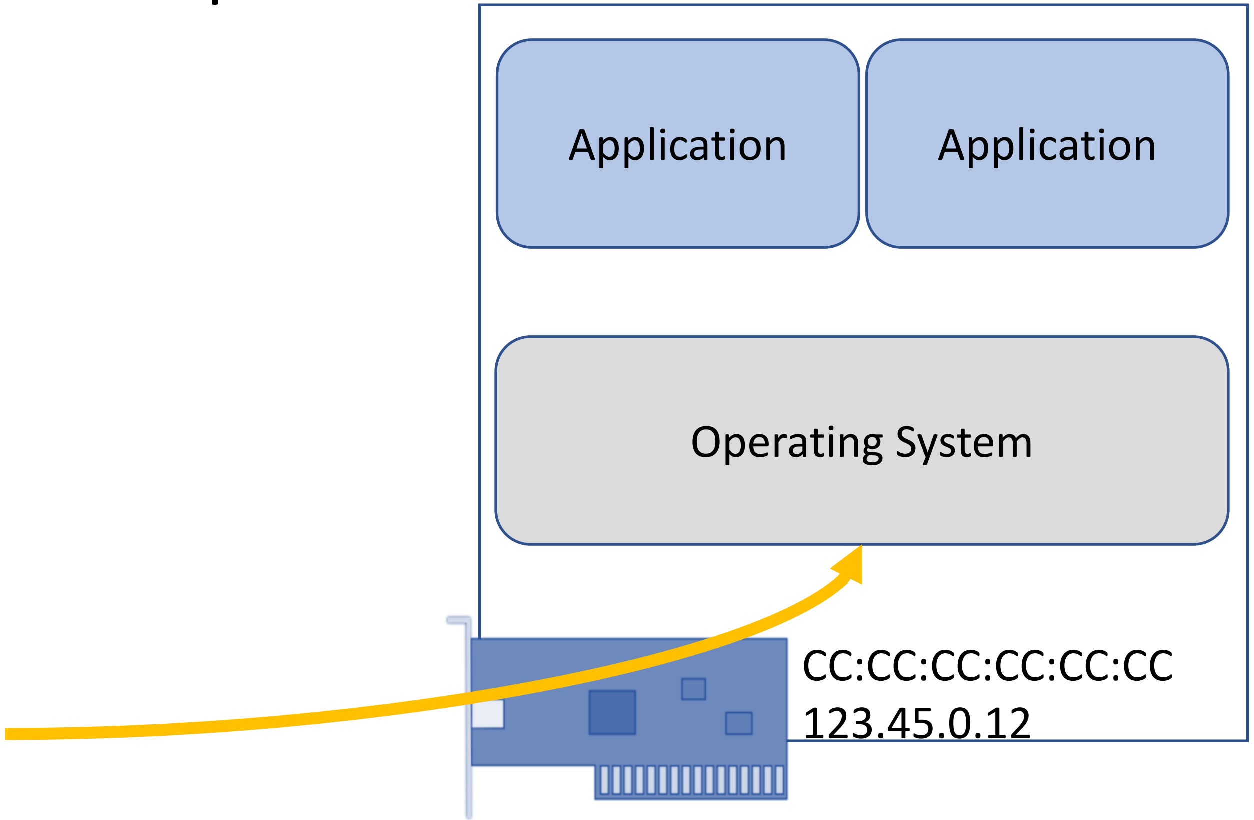
IP Addressing

- In Ethernet we saw table had 1 entry per destination
- That doesn't scale to billions of devices worldwide
- Solution – add structure to addresses so devices can be grouped



Problem 1: Multiplexing

- We have multiple applications running – which application is a packet for?



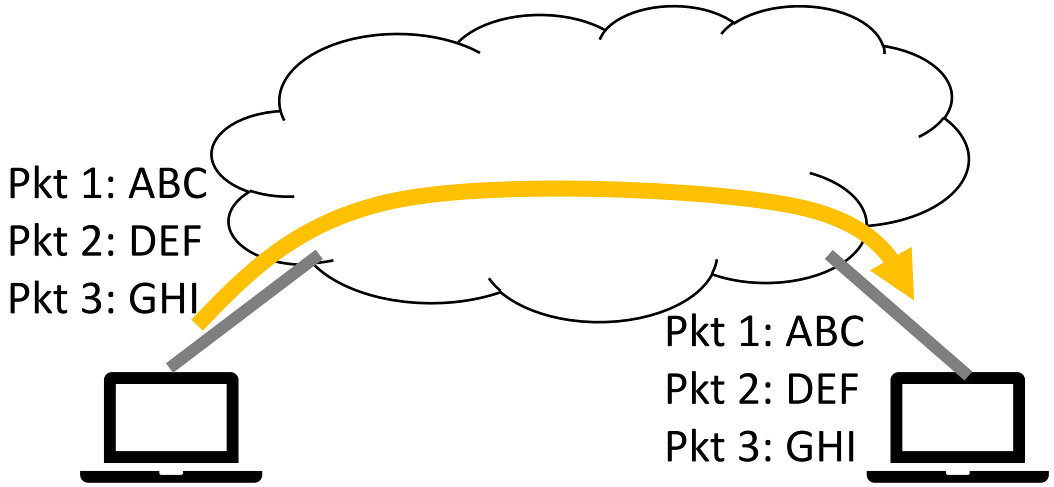
Service Model of the Internet Protocol

- Best Effort
  - Delivery – packets may get dropped
  - Timing – no guarantee on how long it takes to deliver a packet
  - Order – packets may get re-ordered in the network

- Reasoning: inter-connecting different link layers, so needs to be lowest common denominator

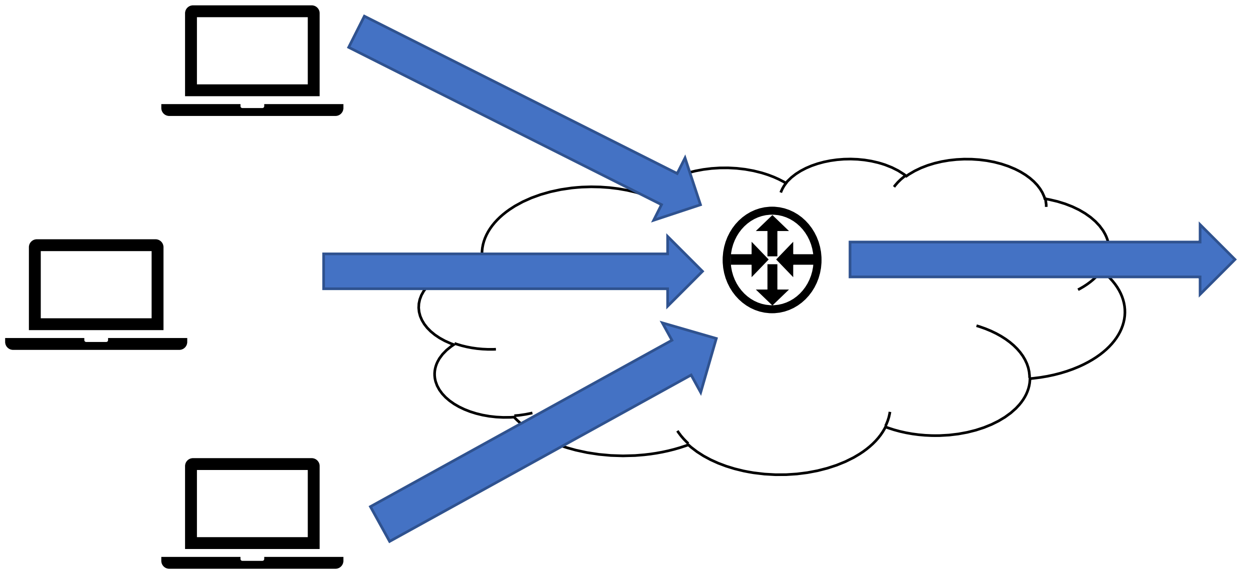
Problem 2: Reliable Transfer

- Goal - Allow an application to be assured that what they send is what is received (same data, same order).



Problem 3: Congestion Control

- Congestion in the network will occur – leading to packets being dropped
- Goal: What if senders could detect this and backoff as needed?



Transport Overview

- Multiplexing
- Reliable Transfer
- Congestion Control

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Multiplexing

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Module: Transport

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Ethernet Addressing

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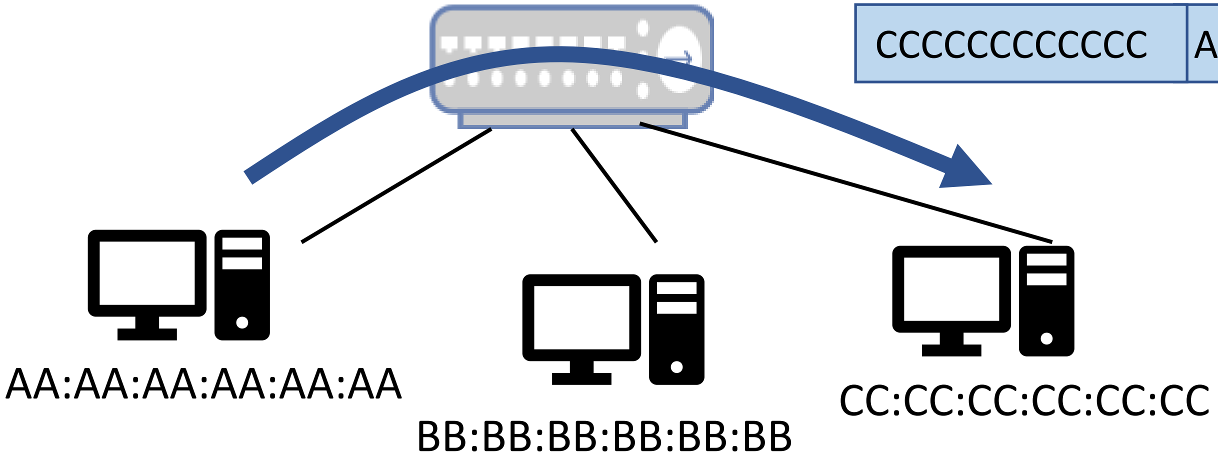

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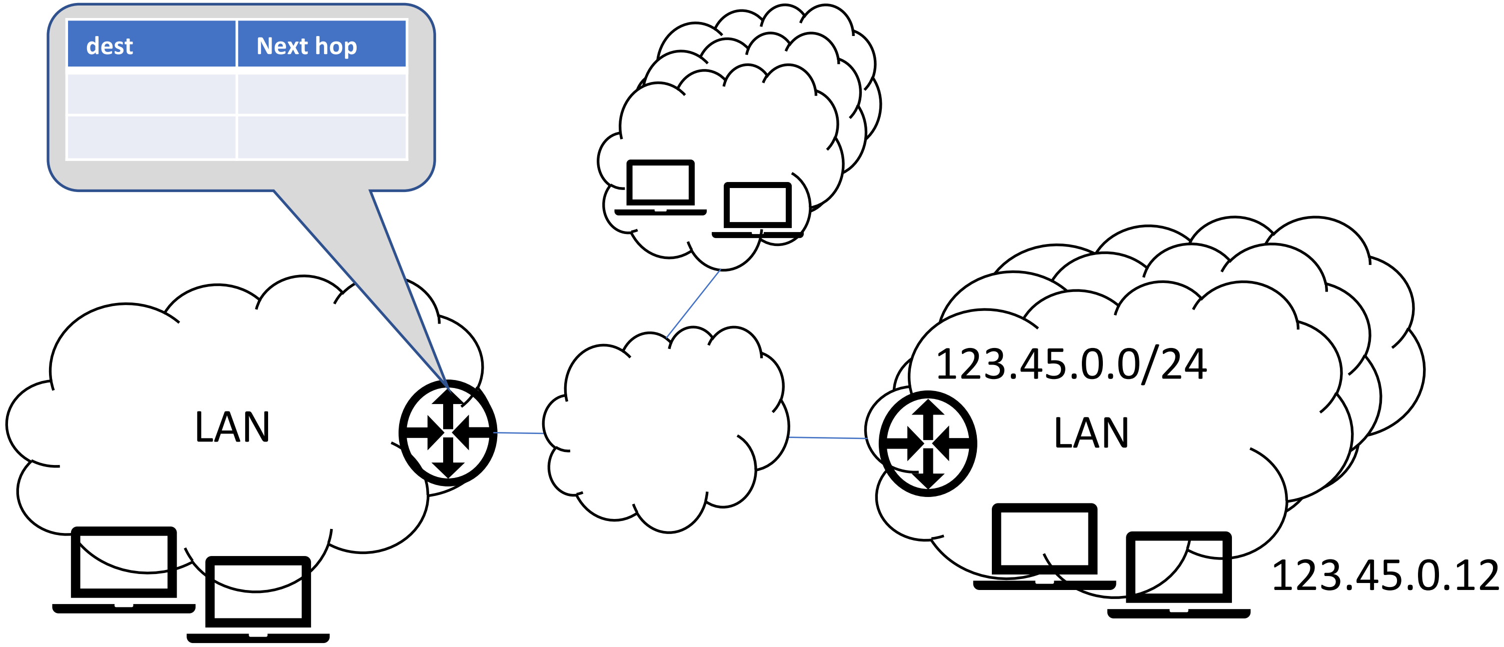

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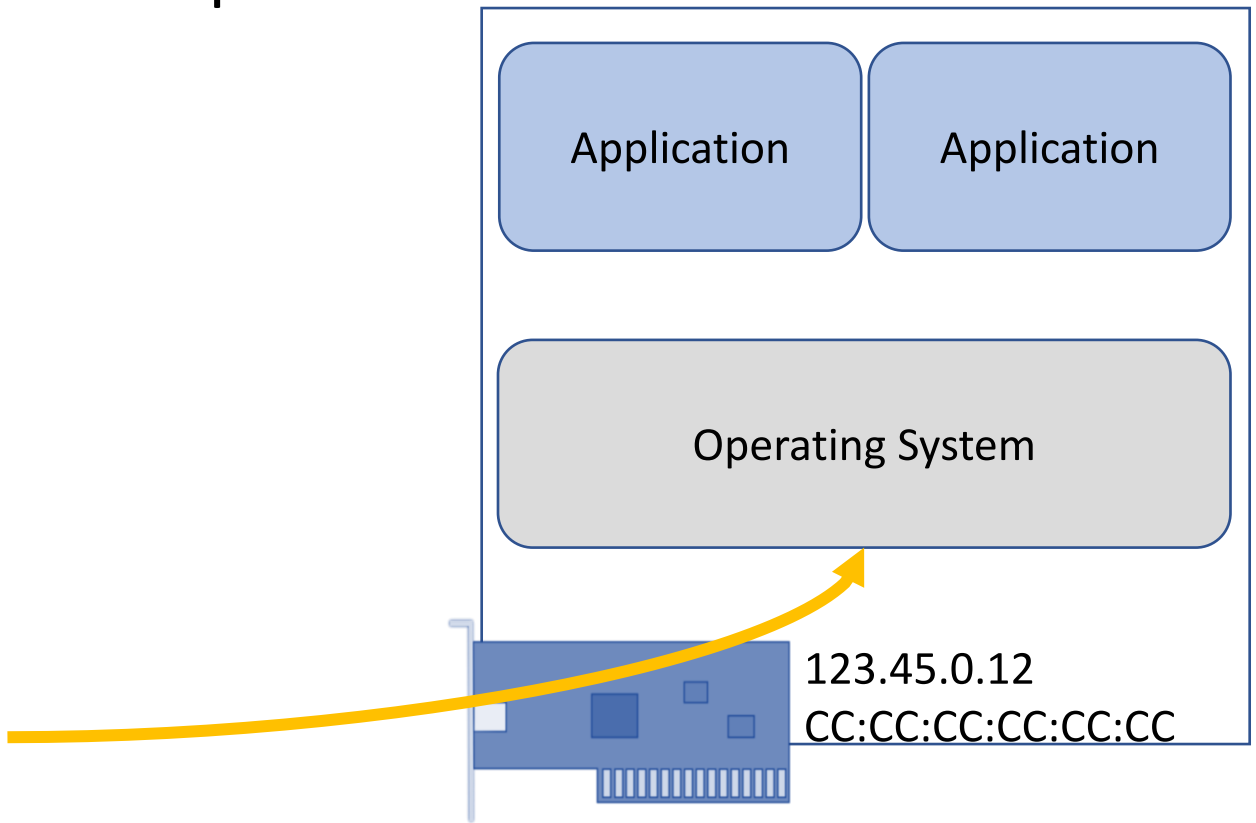
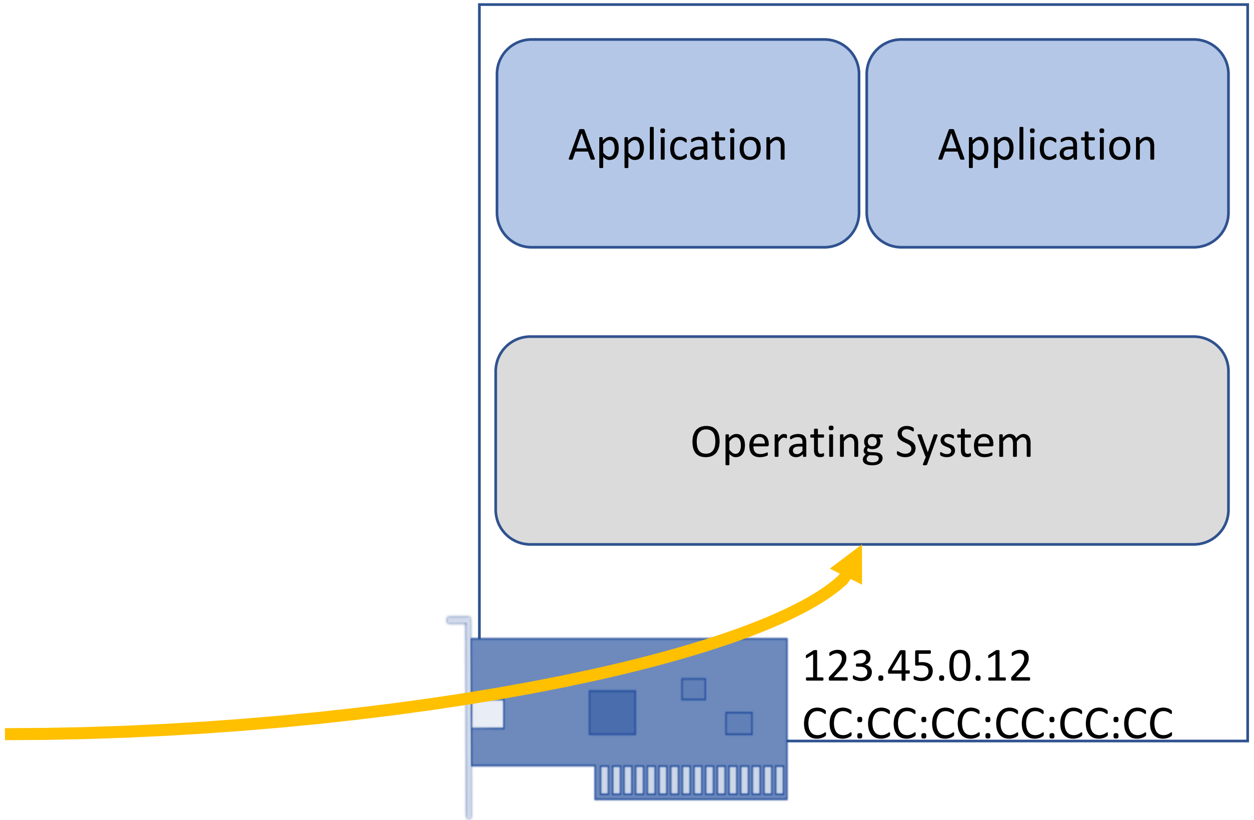
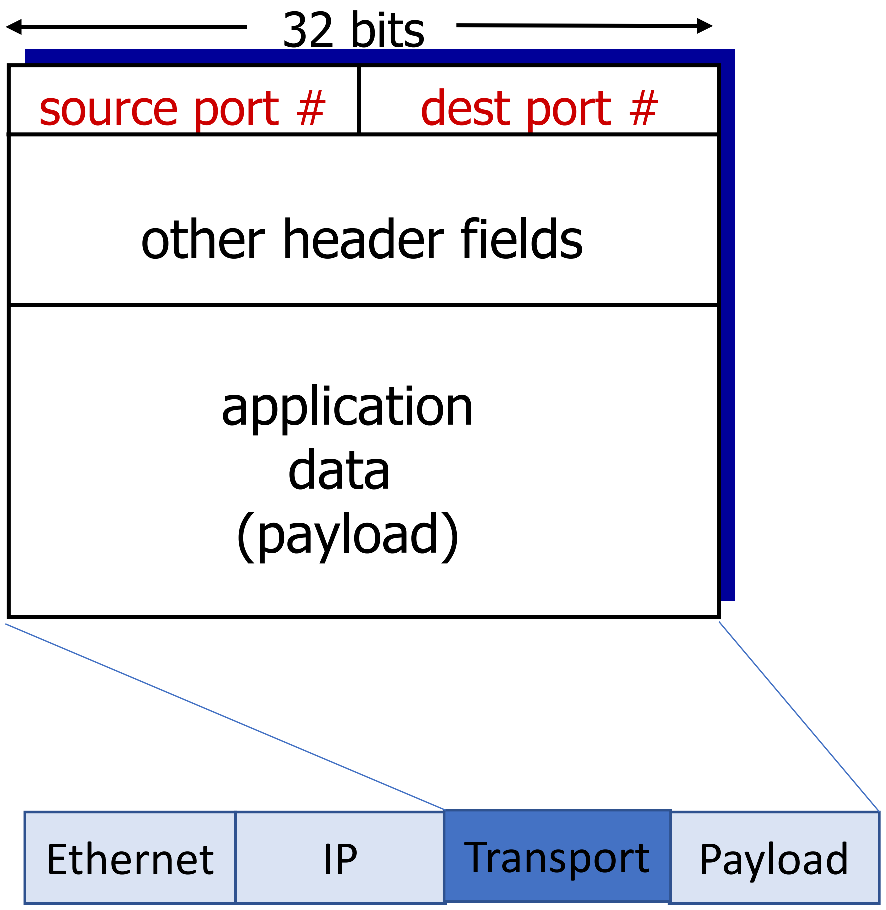


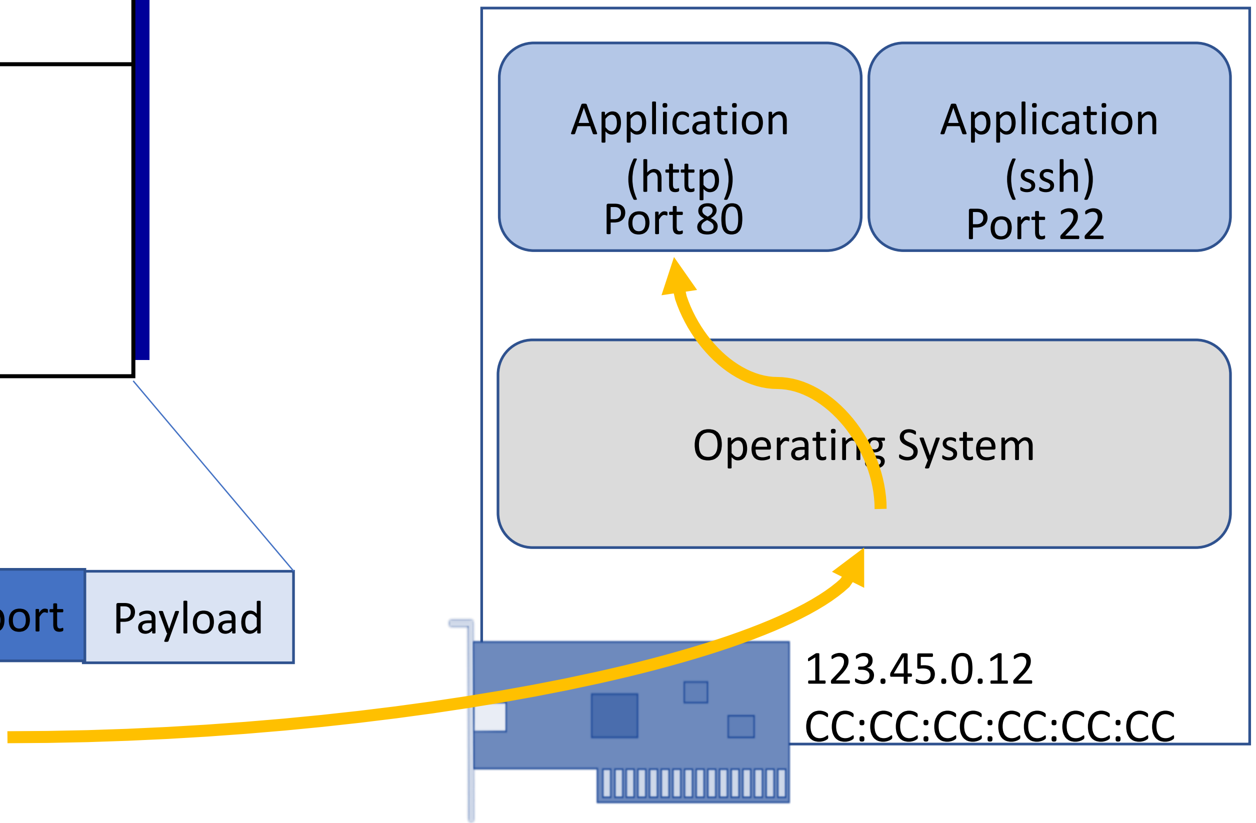
Transport

- Networking layer is for communication between hosts
- Transport layer is for communication between processes



Transport Addressing - Ports





Main Transport Protocols

- UDP
- TCP

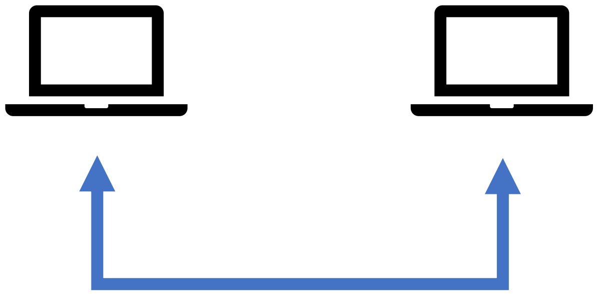
Aside – Message Naming

Ethernet	IP	Transport	Payload

- Link layer – Frame
- Network layer – Packet
- Tansport layer – Datagram
- Application layer (next module) - Message

Connectionless vs Connection-oriented

- Connectionless
  - Host uses Dest IP and Dest Port to demultiplex to specific process
  - Doesn't require establishment
  - Only state is (IP, port) → process mapping
- Connection-oriented
  - 4 tuple of Src IP, Dest IP, Src Port, Dest Port identifies the connection
  - Requires establishment before data transfer
  - Host keeps more state about the connection



User Datagram Protocol (UDP)

- Connectionless
- Simple multiplexing / demultiplexing
- Inherits IP’s service – best effort delivery of each datagram

UDP datagram header

Offsets	Octet	0								1								2								3							
Octet	Bit	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0	0	Source port																Destination port															
4	32	Length																Checksum															

Pic: https://en.wikipedia.org/wiki/User_Datagram_Protocol

Transport Control Protocol (TCP)

- Connection-oriented
- Single process can have multiple connections
  - (src IP, dest IP, src Port, dest Port) identifies the connection
- In-order reliable stream (more in next lessons)

TCP segment header

<table>
<tr><th colspan="2">Offsets</th><th colspan="8">0</th><th colspan="8">1</th><th colspan="8">2</th><th colspan="8">3</th></tr>
<tr><th>Octet</th><th>Bit</th><th>0</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>0</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>0</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>0</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
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Reliable Transfer

Course: Networking Fundamentals
Module: Transport

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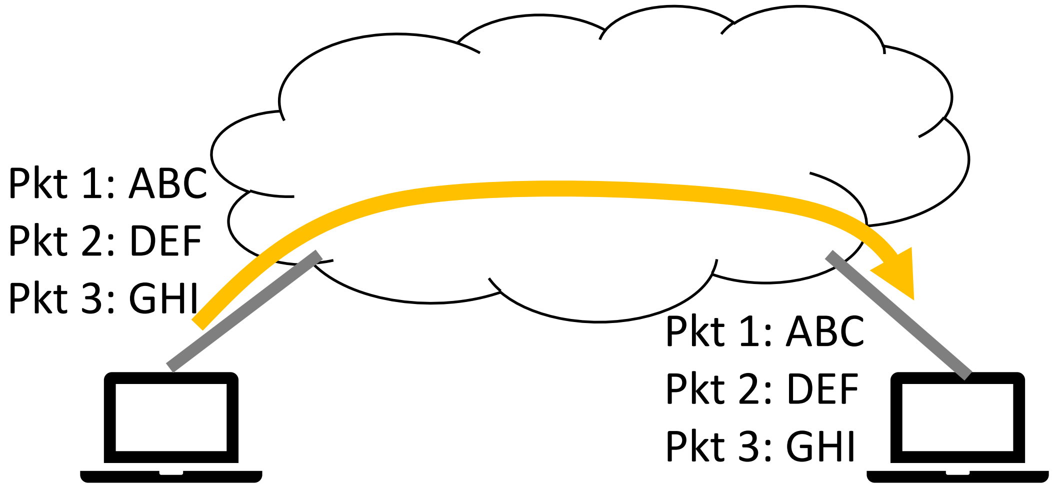
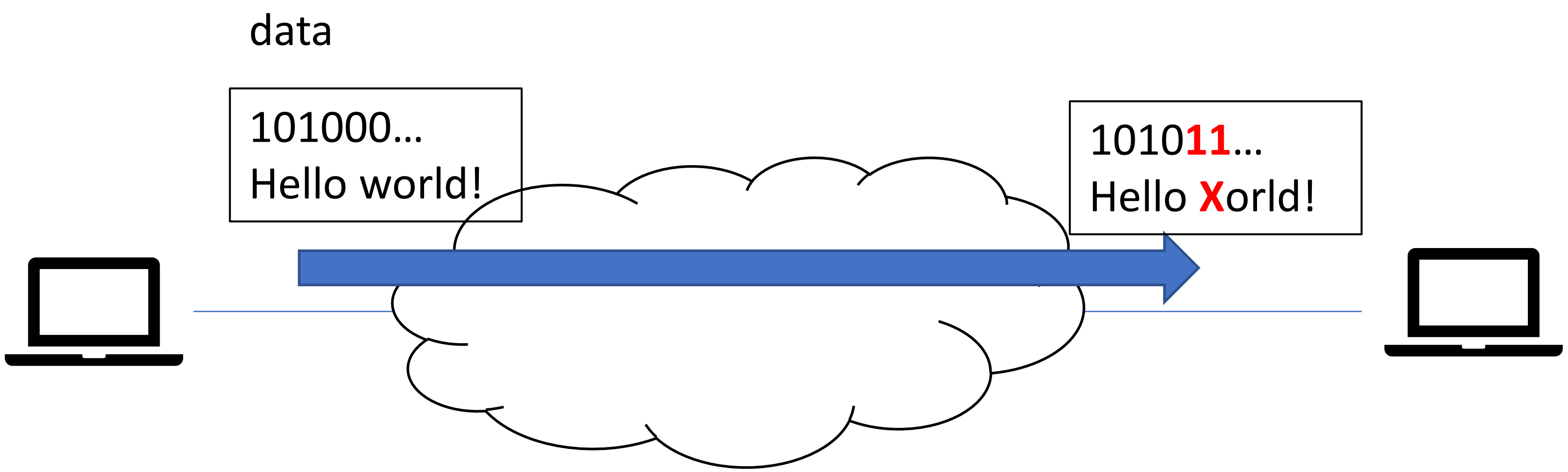
Problem 2: Reliable Transfer

- Goal - Allow an application to be assured that what they send is what is received (same data, same order).



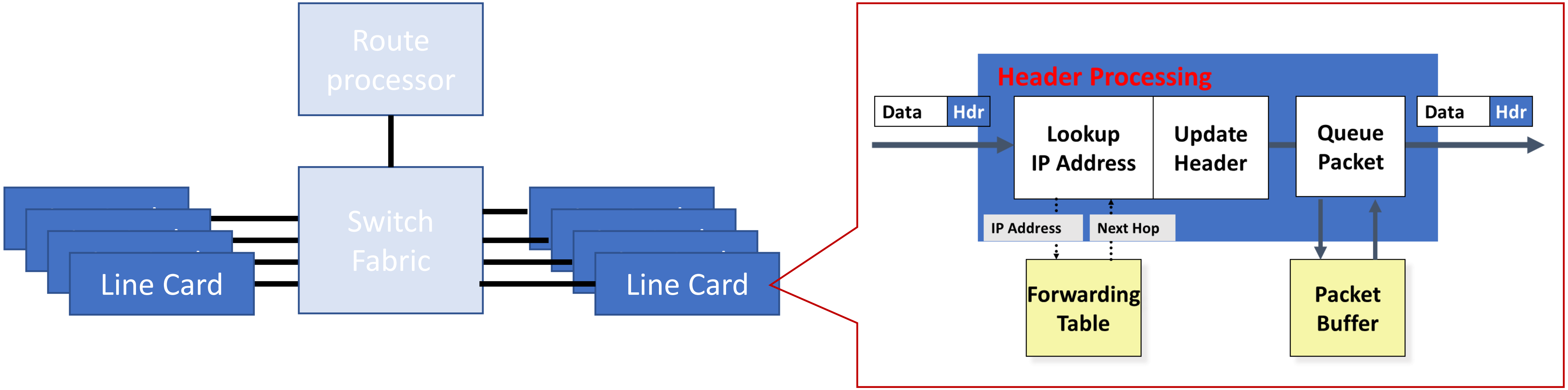
Motivation 1: Frame/Packet Error

- Recall – at link layer errors may occur (e.g., from interference)
- Ethernet has a CRC field to be able to detect errors
- But not fix errors – so, drop frames that are in error



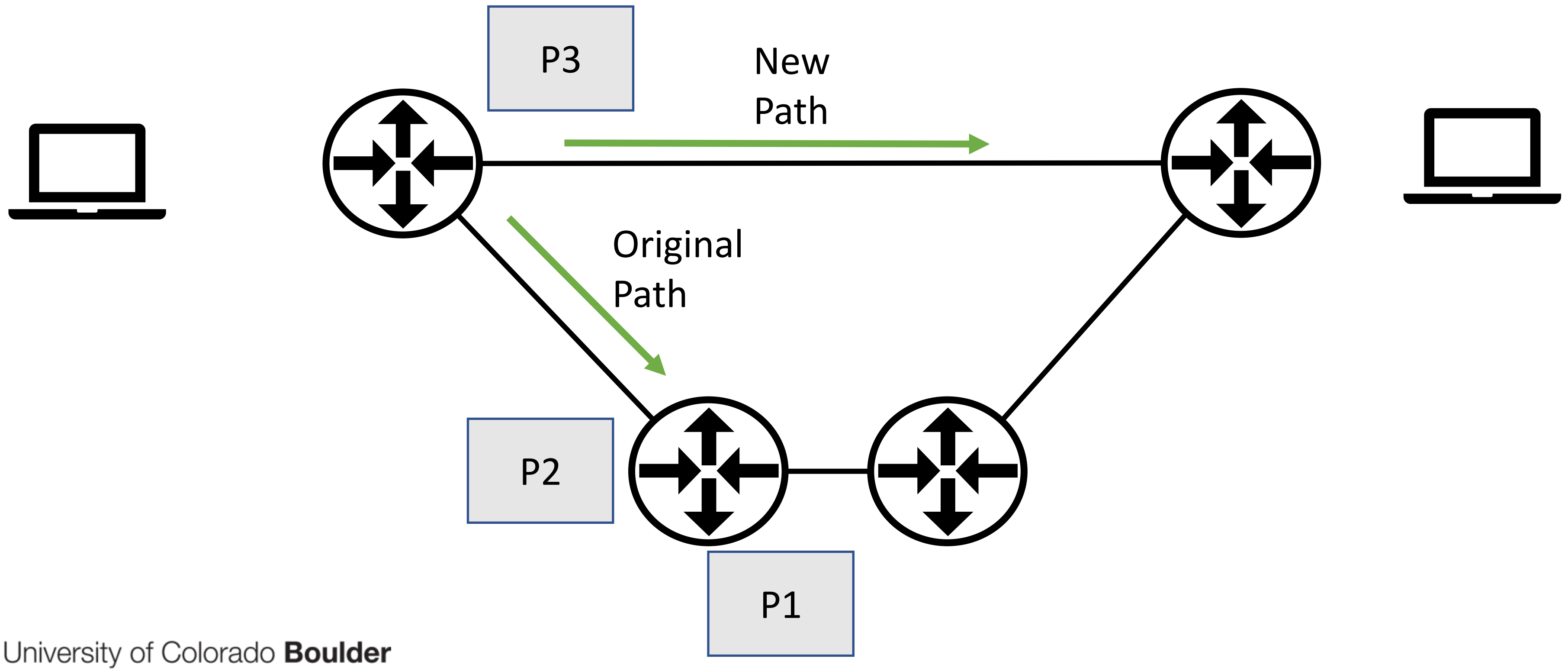
Motivation 2: Dropping due to Congestion

- Recall – router architecture queues packets for transmission.
- If incoming rate > outgoing rate then buffer will fill up



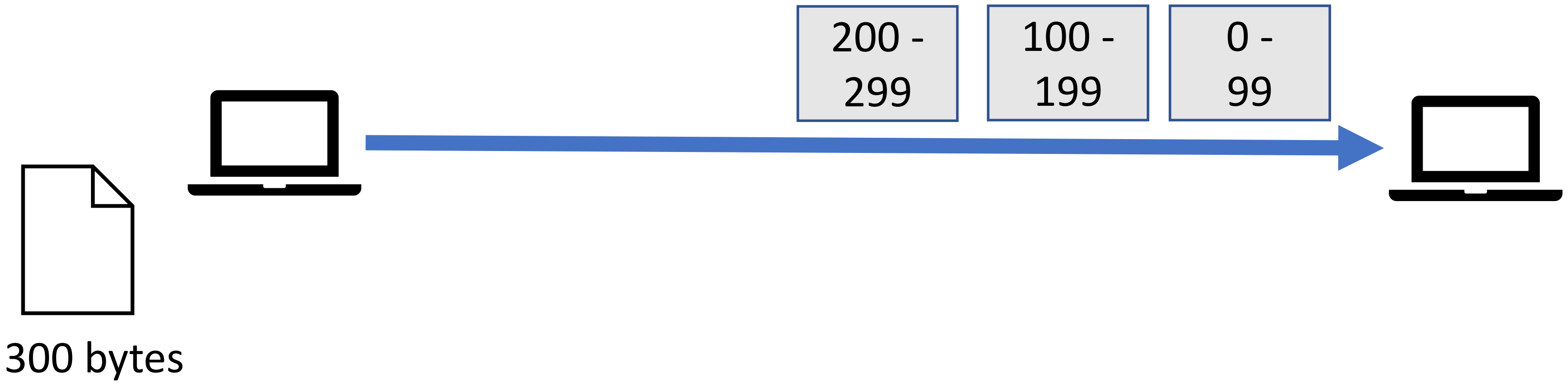
Motivation 3: Packet Re-ordering

- Recall – routing calculates best path, and can change over time
- In example – new path is shorter transmission delay than old



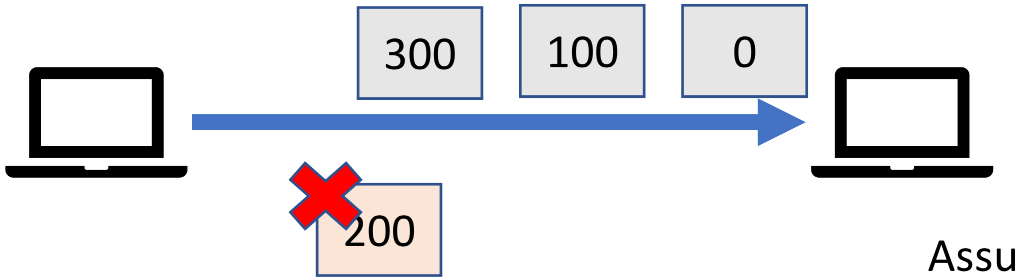
TCP Mechanisms for Reliable Transfer

- Recall – TCP provides abstraction of a reliable in order stream



TCP Mechanisms for Reliable Transfer (1)

- Sequence Number
  - Indicates which bytes in the stream the datagram contains



Assume each is length 100 bytes

TCP segment header

Offsets		0								1								2								3							
Octet	**Bit**	0	1	2	3	4	5	6	7	0	1	2	3	4	5	6	7	0	1	2	3	4	5	6	7	0	1	2	3	4	5	6	7
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12	**96**	Data offset				Reserved 0 0 0 0				C W R	E C E	U R G	A C K	P S H	R S T	S Y N	F I N	Window Size															
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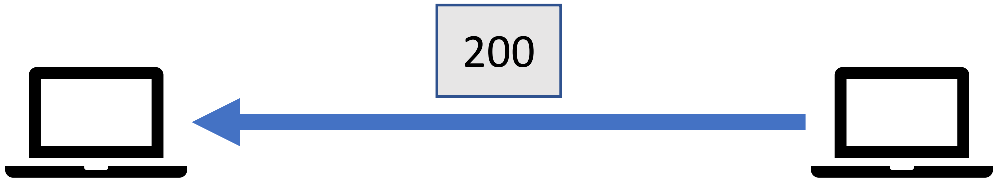
⋮	**⋮**																																
56	**448**																																

TCP Mechanisms for Reliable Transfer (2)

- Acknowledgement Number
  - Specifies what is the next byte in the stream receiver expects



TCP segment header

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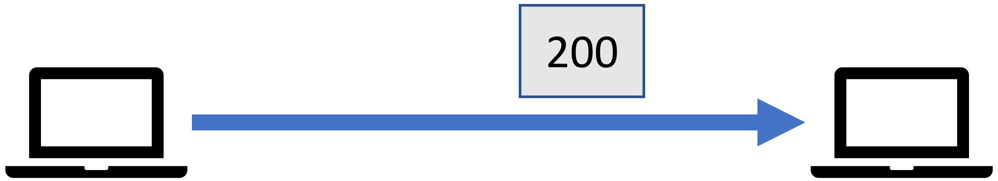
TCP Mechanisms for Reliable Transfer (3)

- Re-transmission
  - Sender can re-send unacknowledged bytes in the stream



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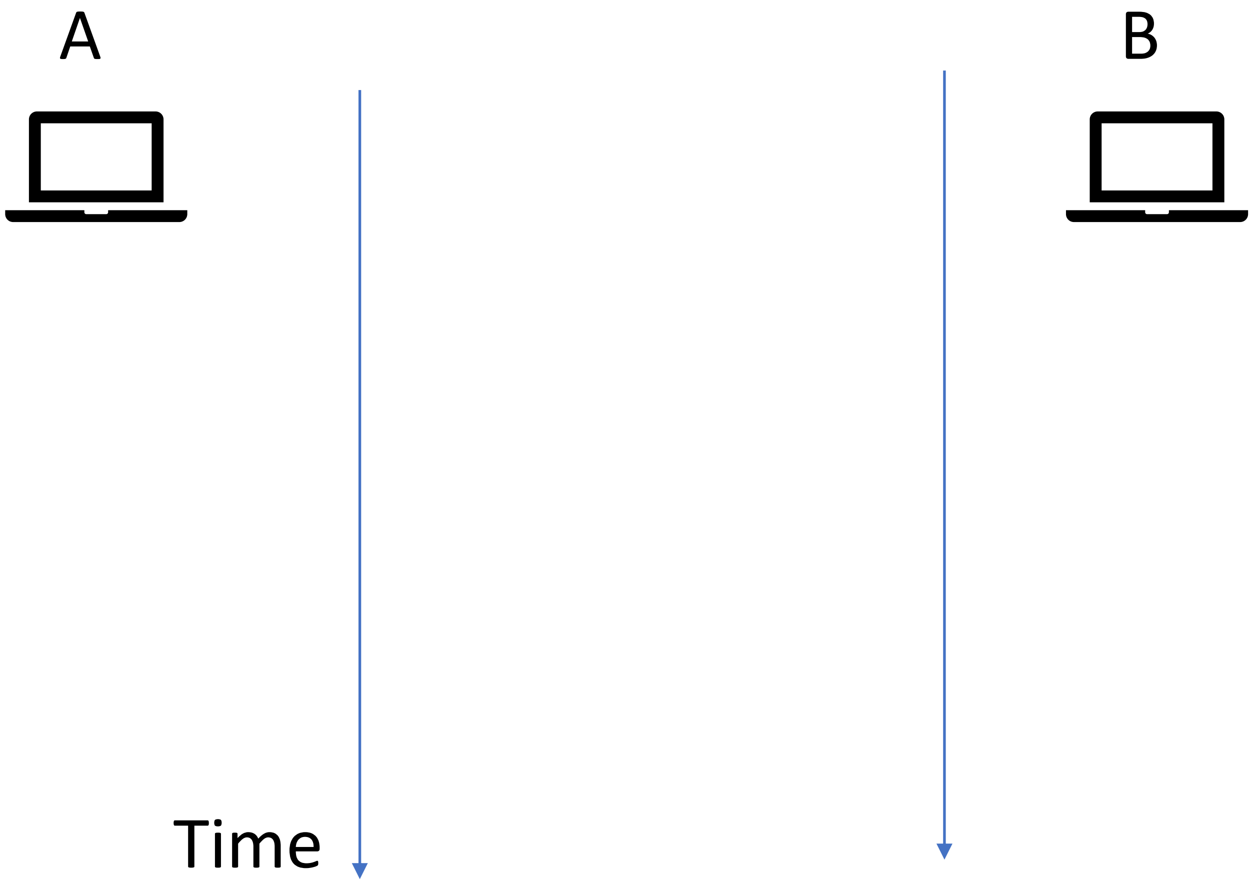
When to Re-transmit

- Timeout
- ACK

Aside – Message Exchange Diagram



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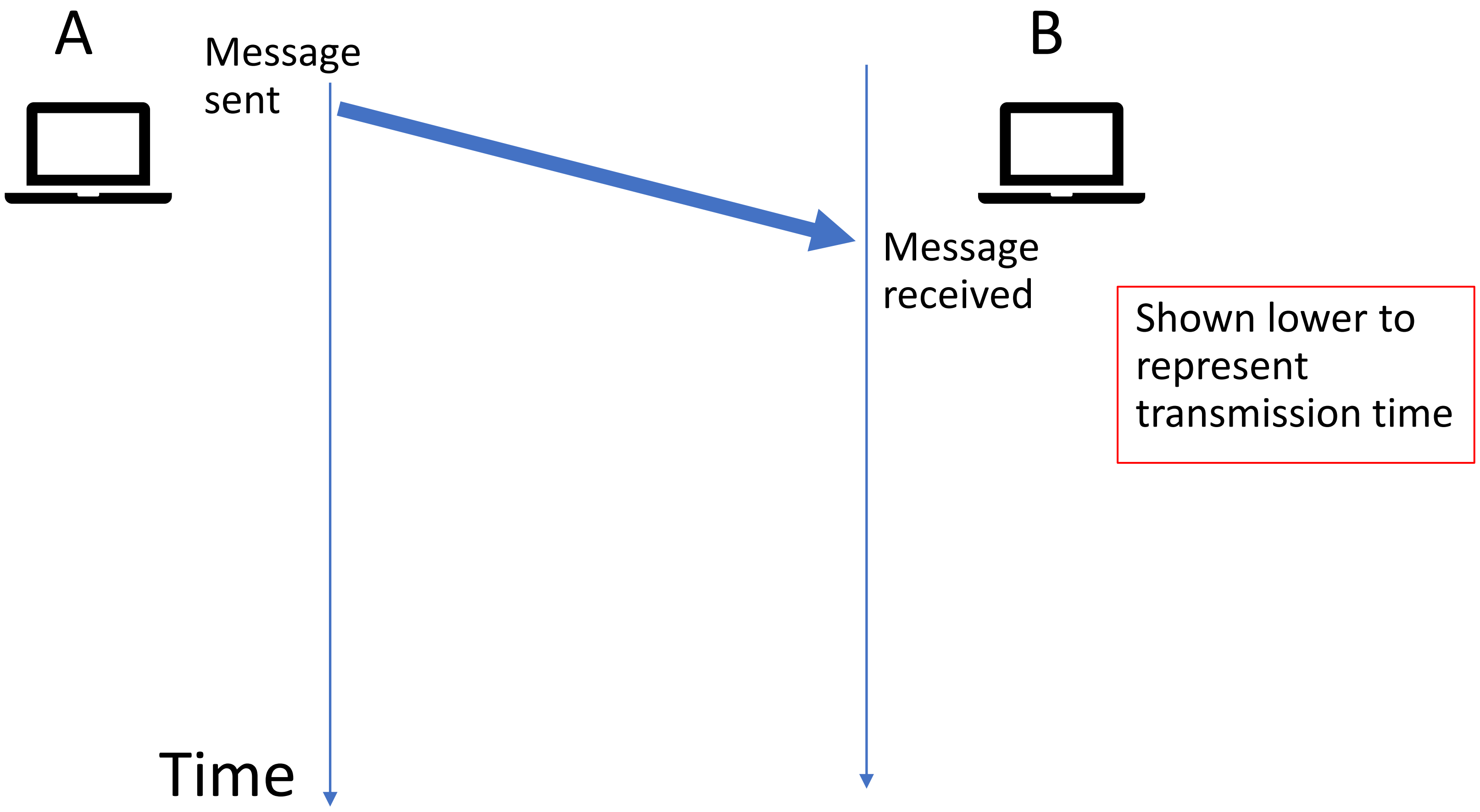

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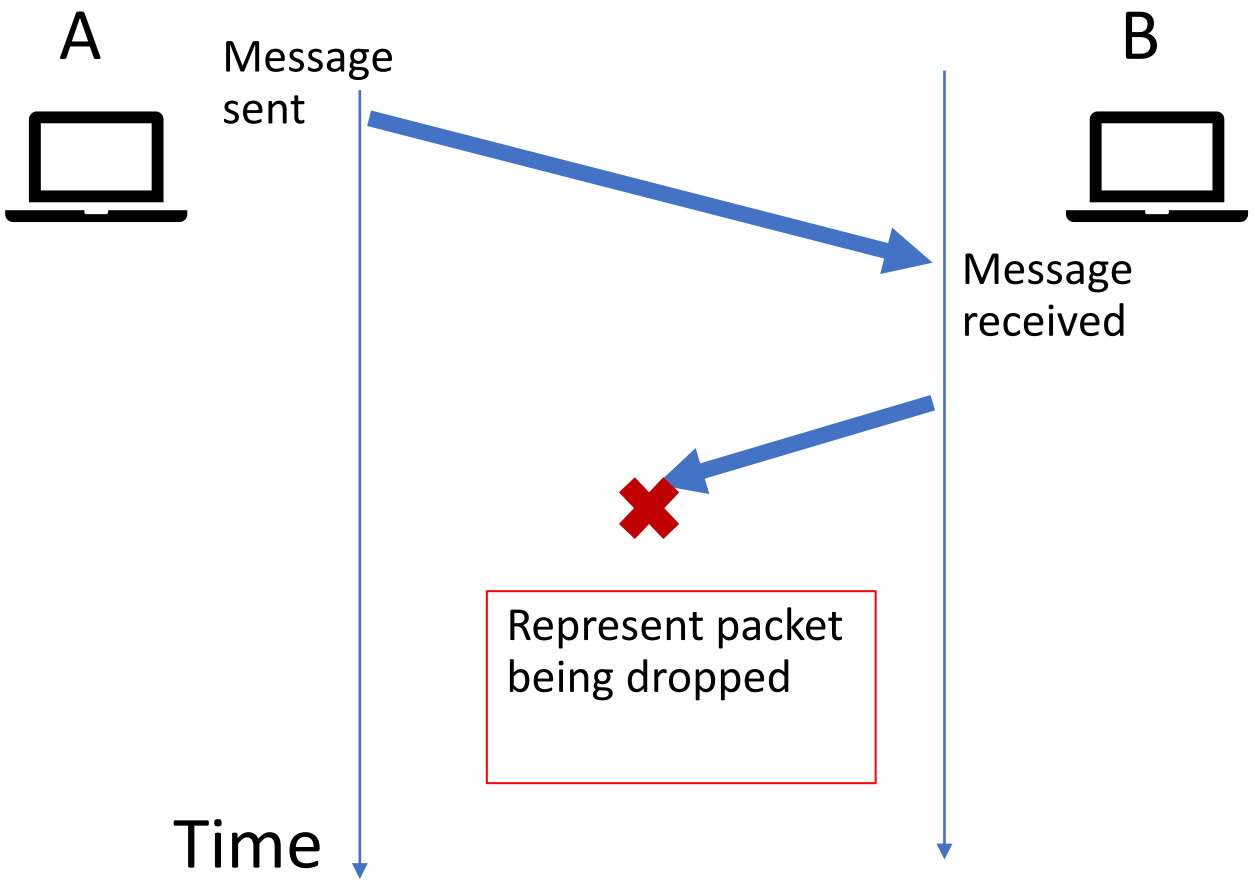
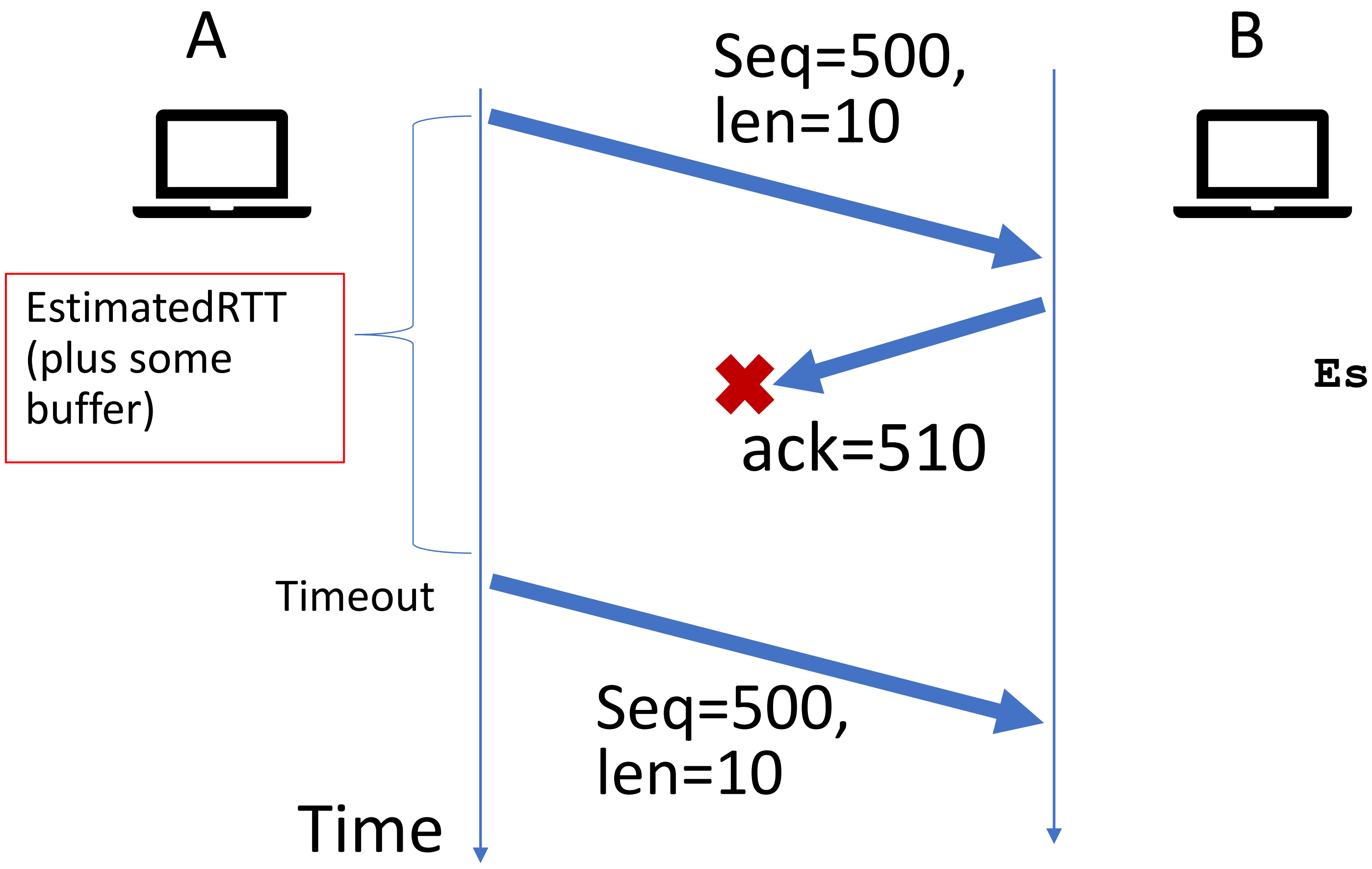
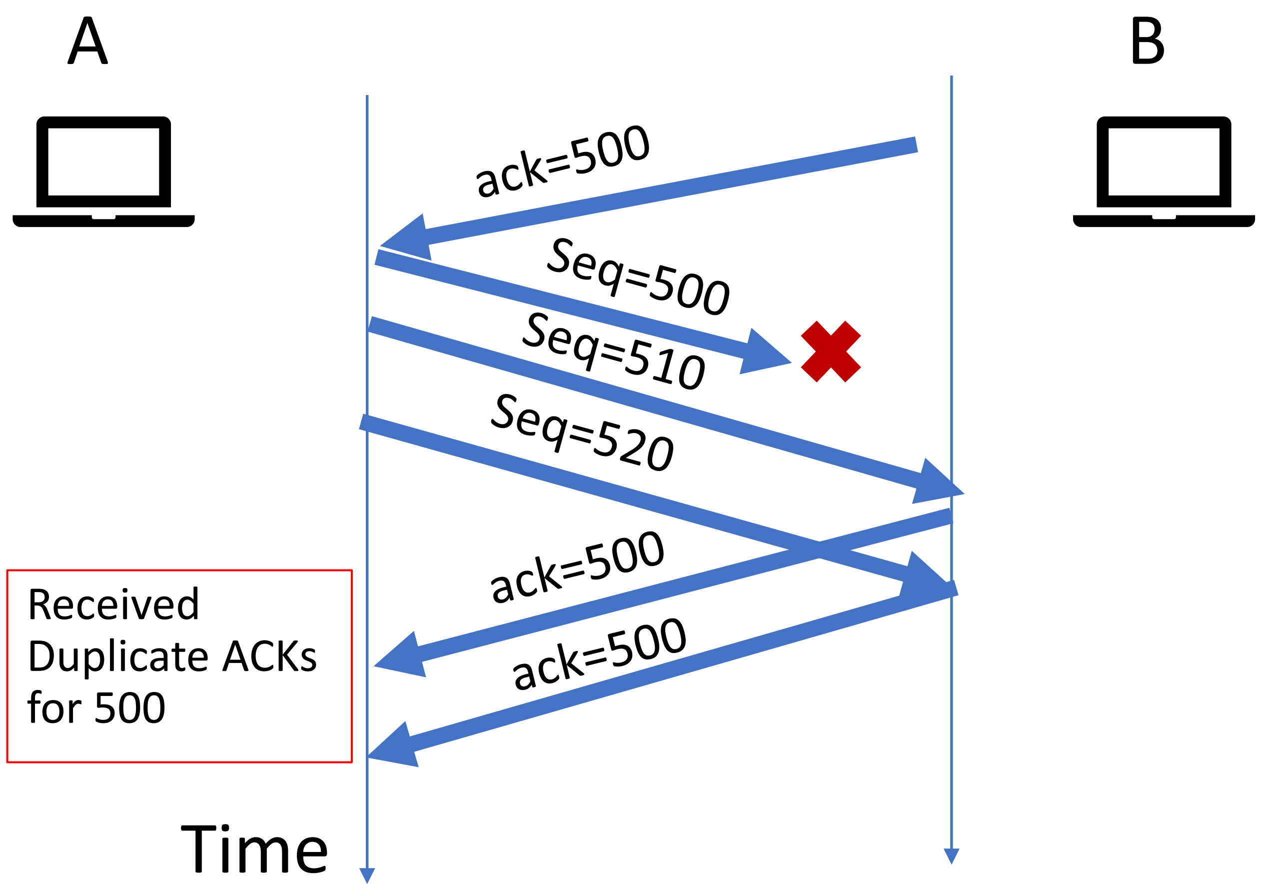


When to Re-transmit - Timeout



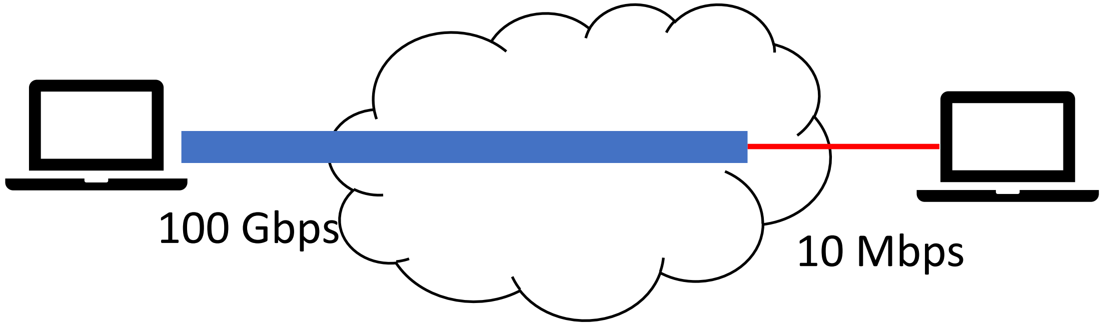
$$\texttt{EstimatedRTT} = (1-\alpha)\texttt{*EstimatedRTT} + \alpha\texttt{*SampleRTT}$$

When to Re-transmit – Duplicate Ack



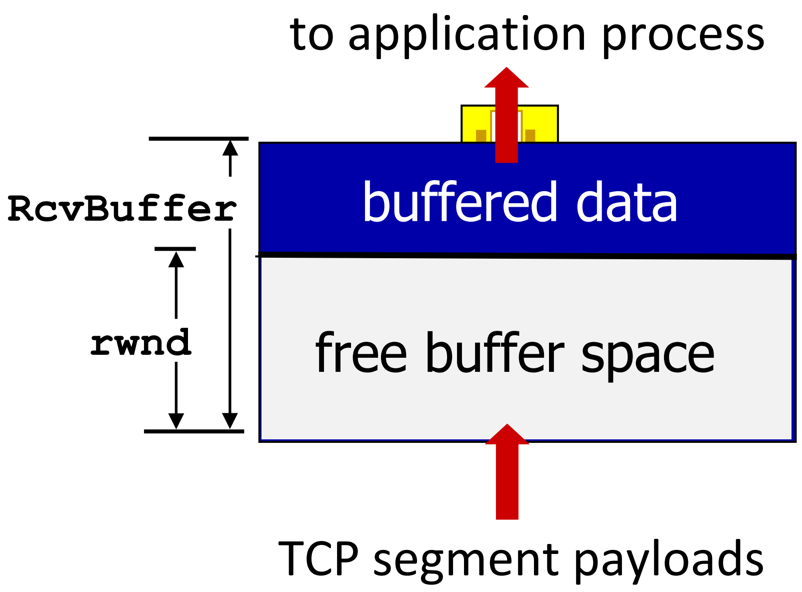
What about drops at the Receiver?

- Sender may be able to send at higher rates than receiver can accept
- Goal: Make it so the sender cannot overwhelm the receiver



Flow Control

- TCP receiver "advertises" free buffer space in rwnd field in TCP header
- sender limits amount of unACKed ("in-flight") data to received rwnd



TCP receiver-side buffering

Flow Control – TCP Header

- Window Size field –how many bytes the host is currently able to receive

TCP segment header

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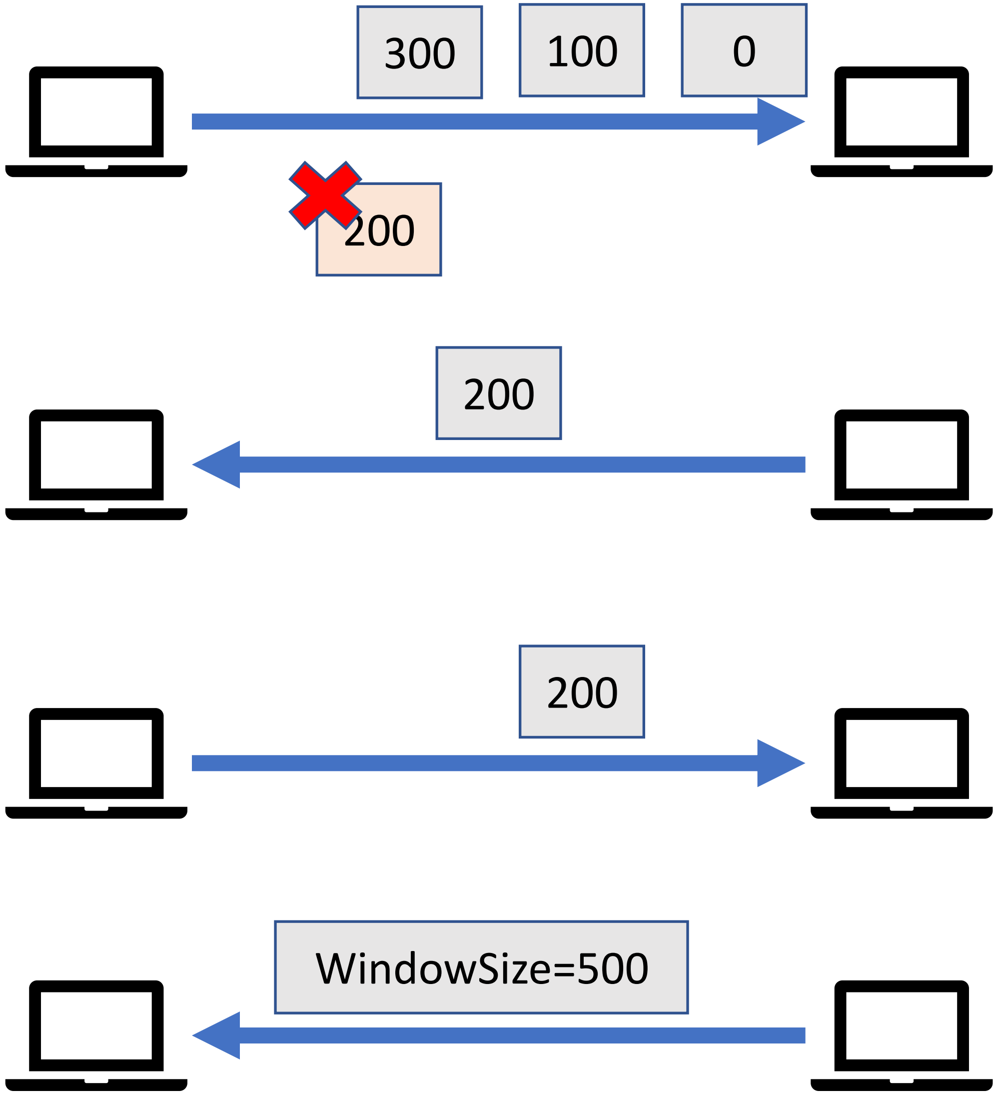
Summary – Reliable Transfer

- Sequence Number
- Acknowledgement Number
- Re-transmission
- Flow Control



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TCP Connection Establishment

Course: Networking Fundamentals
Module: Transport

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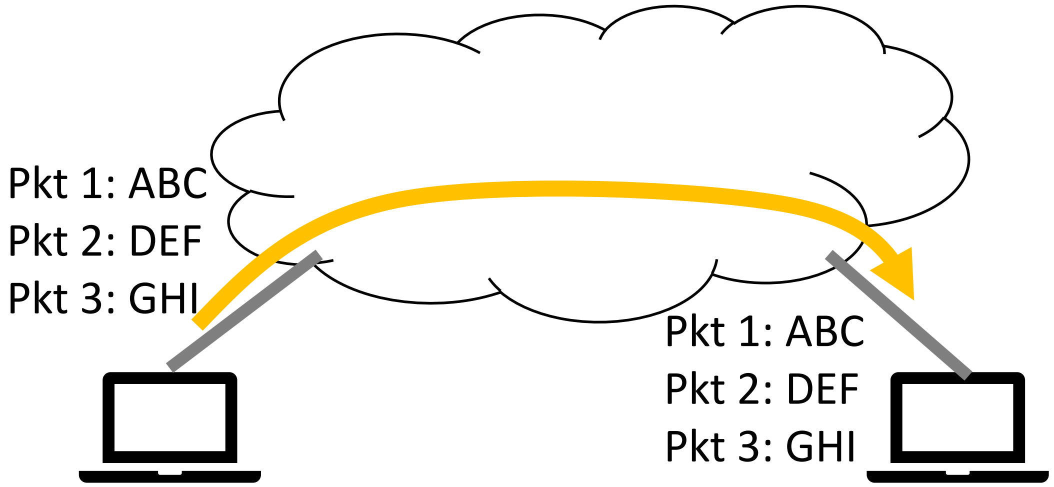
Problem 2: Reliable Transfer

- Goal - Allow an application to be assured that what they send is what is received (same data, same order).



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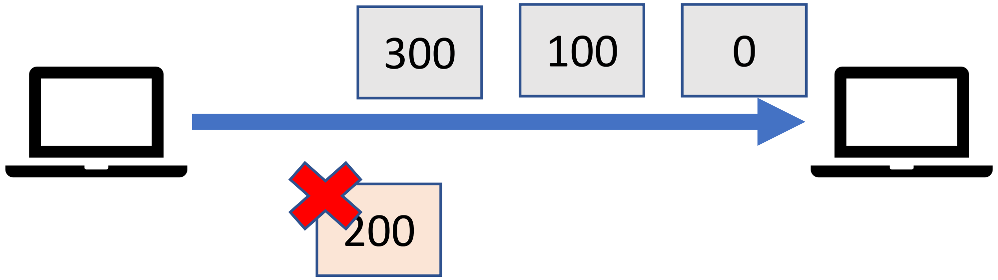
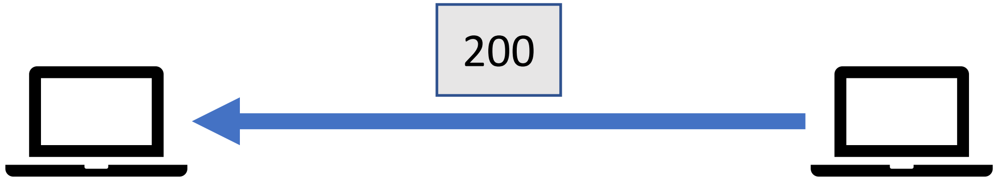
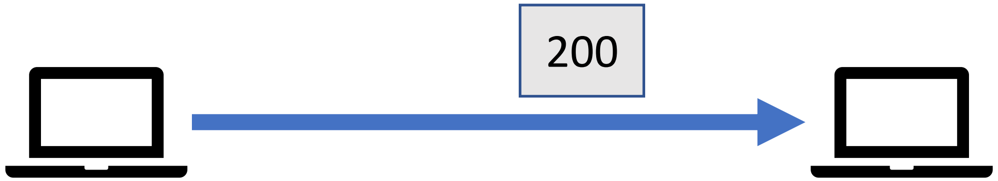


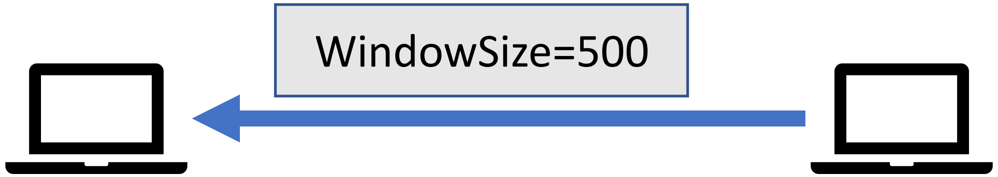
- Acknowledgement Number



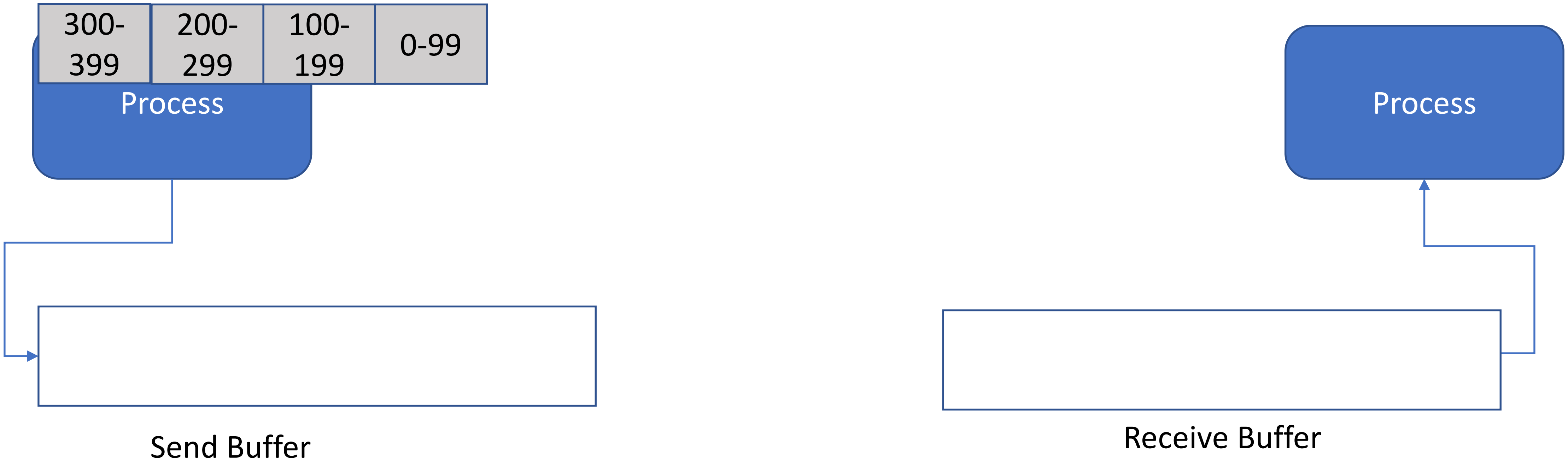
- Re-transmission



- Flow Control



Each Side Needs to Store State



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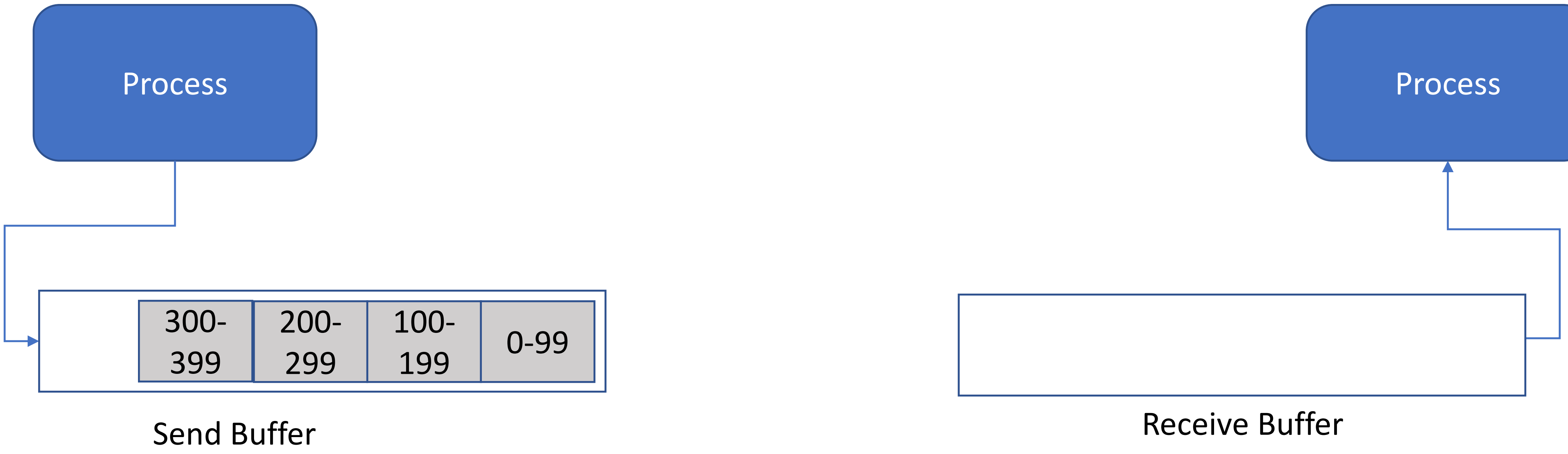
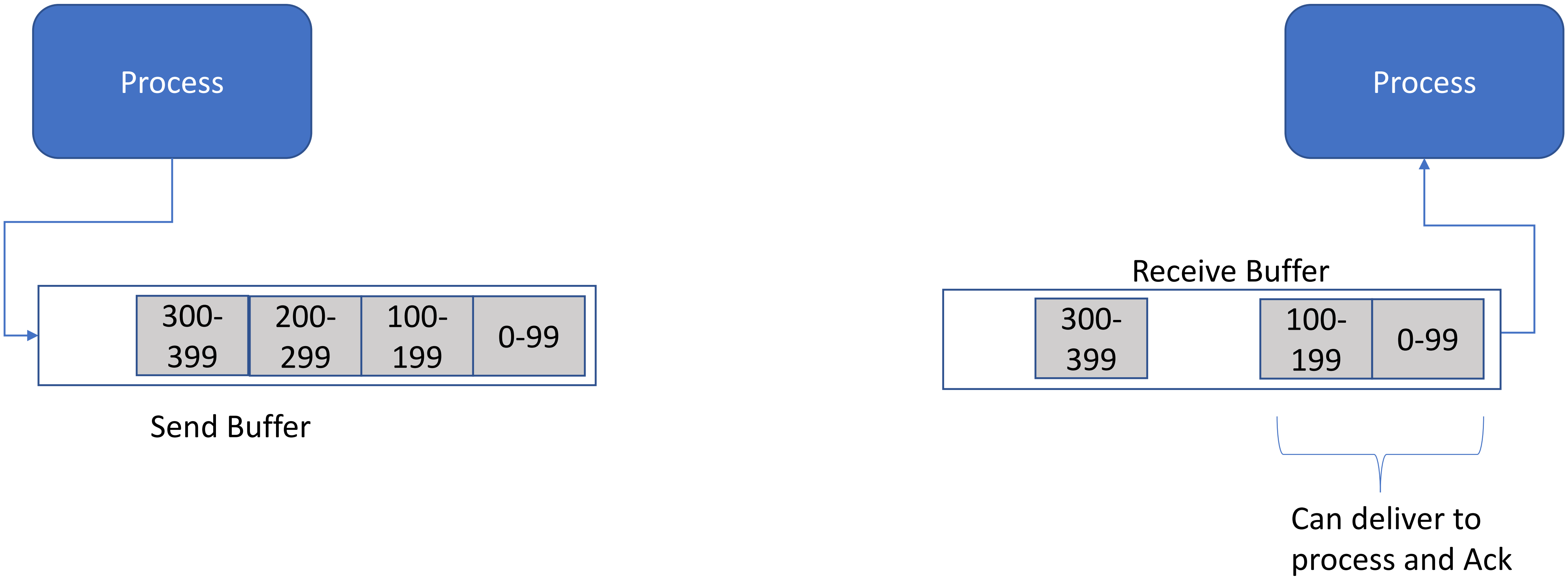


Each Side Needs to Store State



Each Side Needs to Store State

Received Ack for 0-199, still has 200-299 in buffer to re-transmit

Connection Establishment

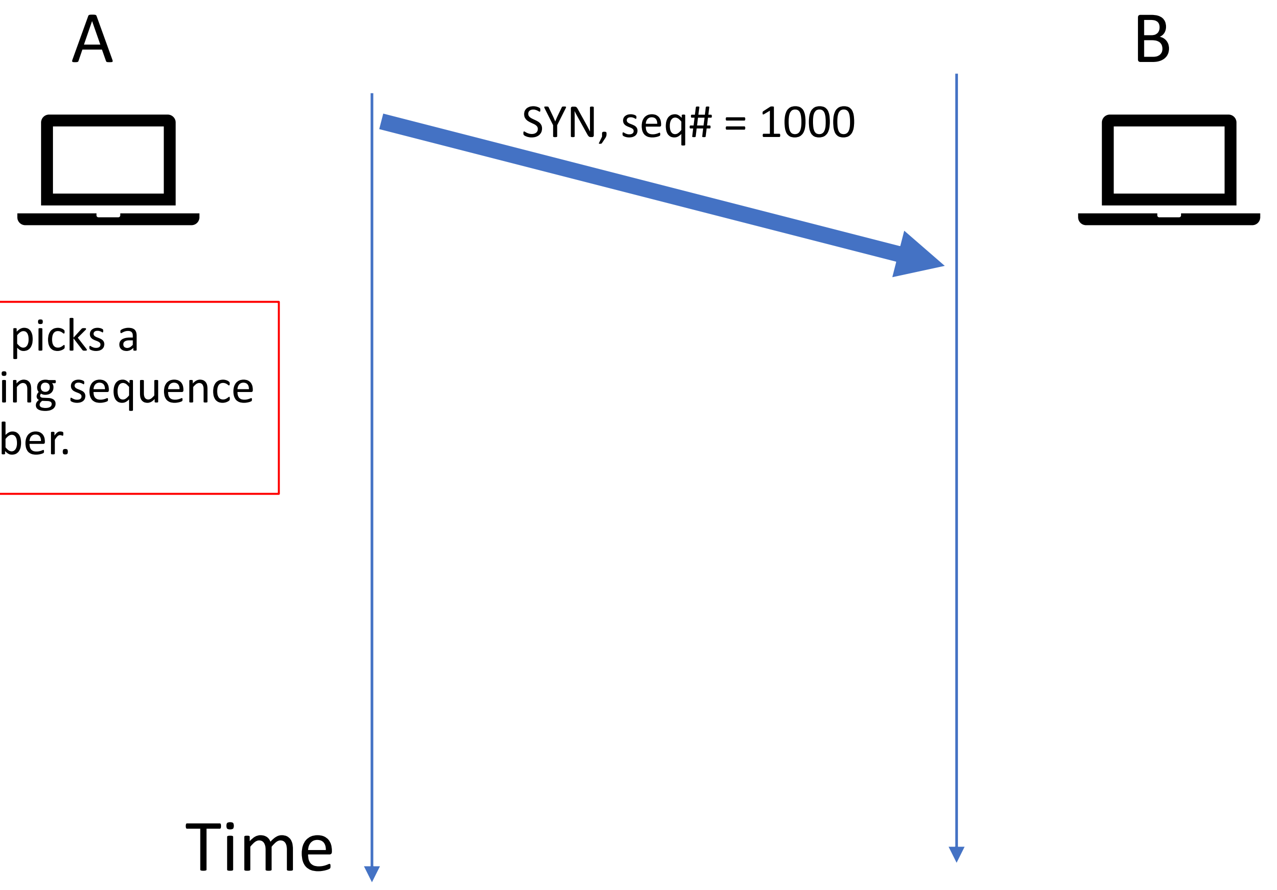
- TCP is connection oriented
- Connection establishment is an exchange of messages where each process agree to form a connection
- Uniquely identified by (src IP, dest IP, src Port, dest Port)
- Three way handshake
  Basically: A to B) I'd like to connect, B to A) Ok, A to B) Thanks.

TCP Flags Used in Connection Establishment

- SYN – synchronize sequence number
- ACK – the acknowledgement number field is valid

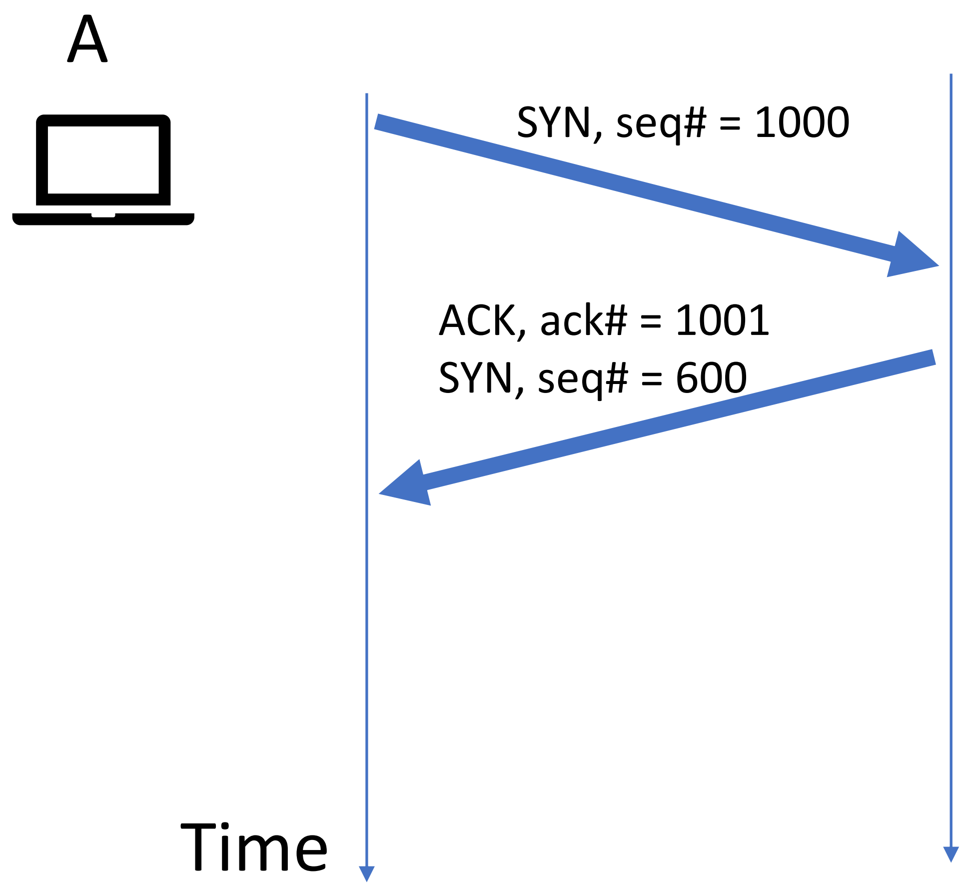
<table>
<caption>TCP segment header</caption>
<tr><th colspan="2">Offsets</th><th colspan="8">0</th><th colspan="8">1</th><th colspan="8">2</th><th colspan="8">3</th></tr>
<tr><th>Octet</th><th>Bit</th><th>0</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>0</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>0</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>0</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th></tr>
<tr><th>0</th><th>0</th><td colspan="16">Source port</td><td colspan="16">Destination port</td></tr>
<tr><th>4</th><th>32</th><td colspan="32">Sequence number</td></tr>
<tr><th>8</th><th>64</th><td colspan="32">Acknowledgment number (if ACK set)</td></tr>
<tr><th>12</th><th>96</th><td colspan="4">Data offset</td><td colspan="4">Reserved
0 0 0 0</td><td>C
W
R</td><td>E
C
E</td><td>U
R
G</td><td>A
C
K</td><td>P
S
H</td><td>R
S
T</td><td>S
Y
N</td><td>F
I
N</td><td colspan="16">Window Size</td></tr>
<tr><th>16</th><th>128</th><td colspan="16">Checksum</td><td colspan="16">Urgent pointer (if URG set)</td></tr>
<tr><th>20</th><th>160</th><td colspan="32" rowspan="3">Options (if data offset > 5. Padded at the end with "0" bits if necessary.)</td></tr>
<tr><th>⋮</th><th>⋮</th></tr>
<tr><th>56</th><th>448</th></tr>
</table>

TCP Connection Establishment (3-way handshake)



Host picks a starting sequence number.

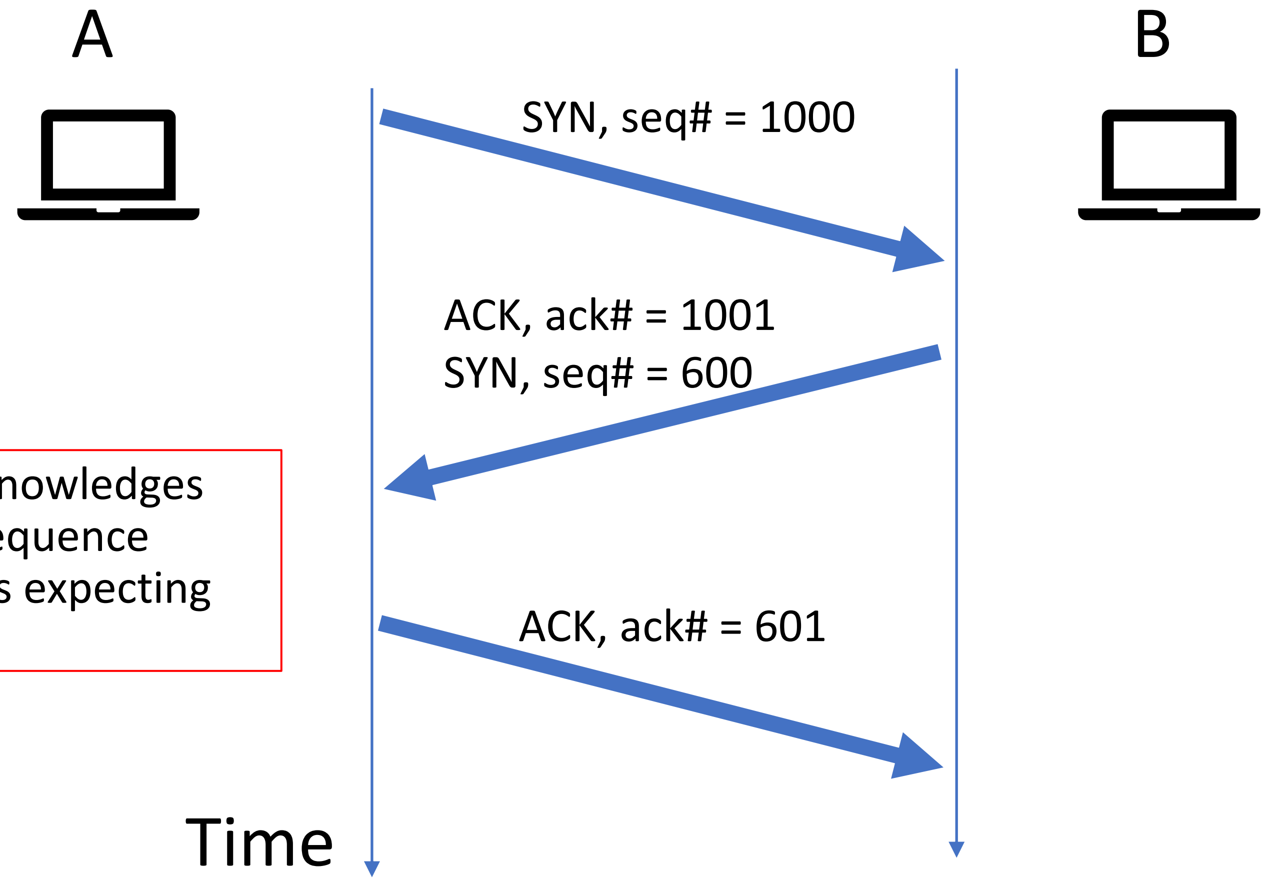
TCP Connection Establishment (3-way handshake)



Host B picks its own starting sequence number.

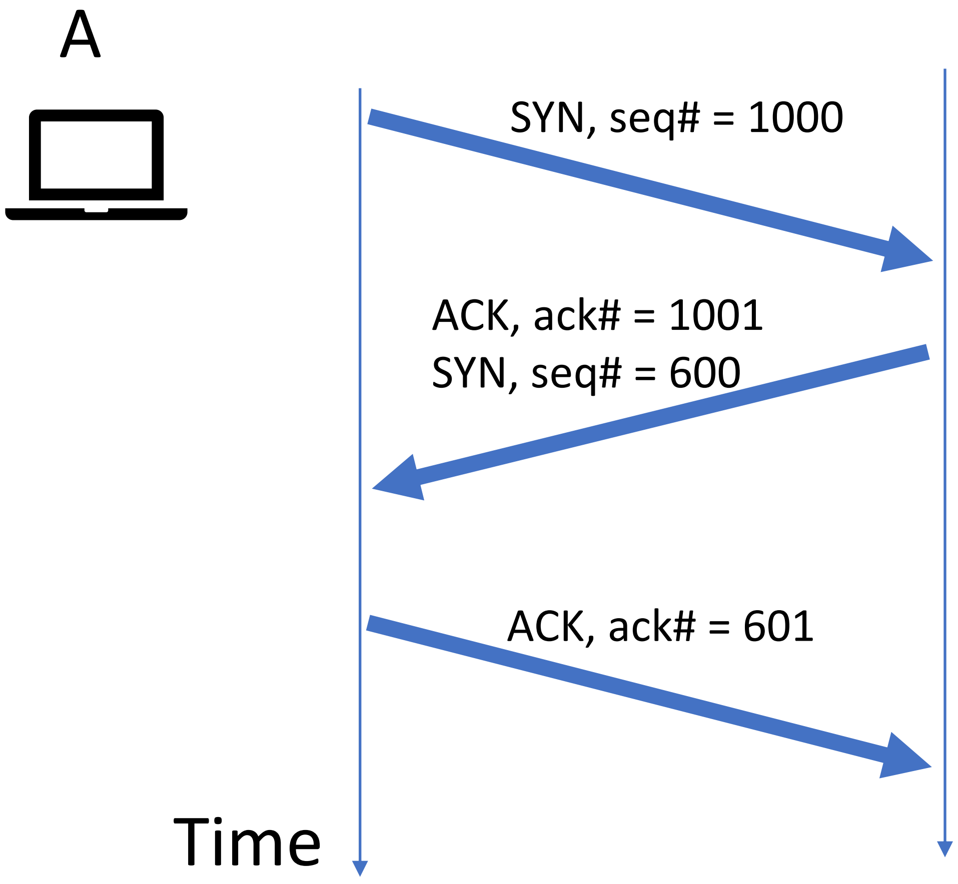
Acknowledge with the next sequence number its expecting

TCP Connection Establishment (3-way handshake)



Host A acknowledges the next sequence number it's expecting

What if Packets are Lost during Connection Establishment?



Pkt 1 lost - A won't get an ACK, will resend

Pkt 2 lost - A won't get an ACK (for pkt1), will resend pkt 1.
B will ACK re-transmitted pkt1

Pkt 3 lost - B won't get an ACK (for pkt2), will resend pkt 2.
A will ACK retransmitted pkt2

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Congestion Control

Course: Networking Fundamentals
Module: Transport

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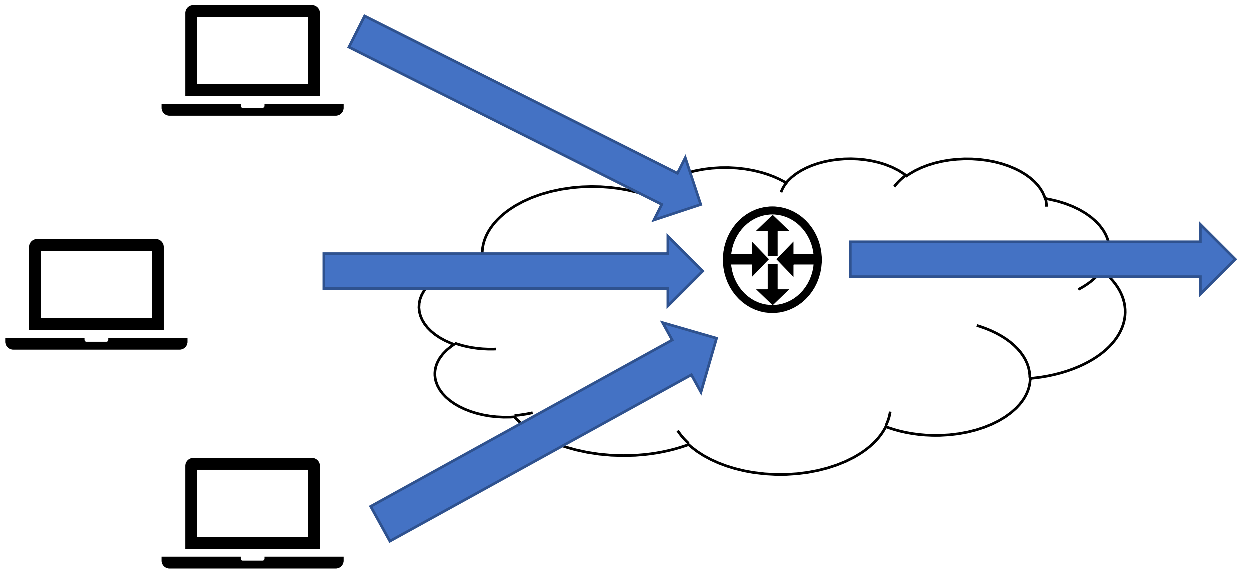
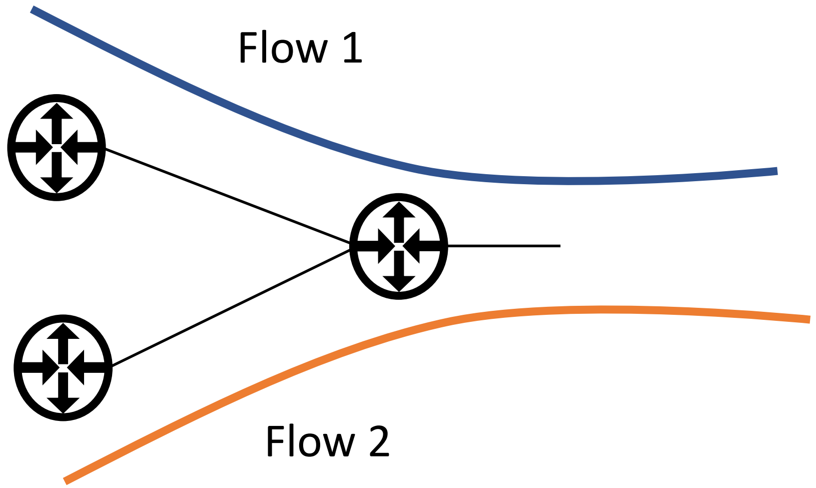
Problem 3: Congestion Control

- Congestion in the network will occur – leading to packets being dropped
- Goal: What if senders could detect this and backoff as needed?

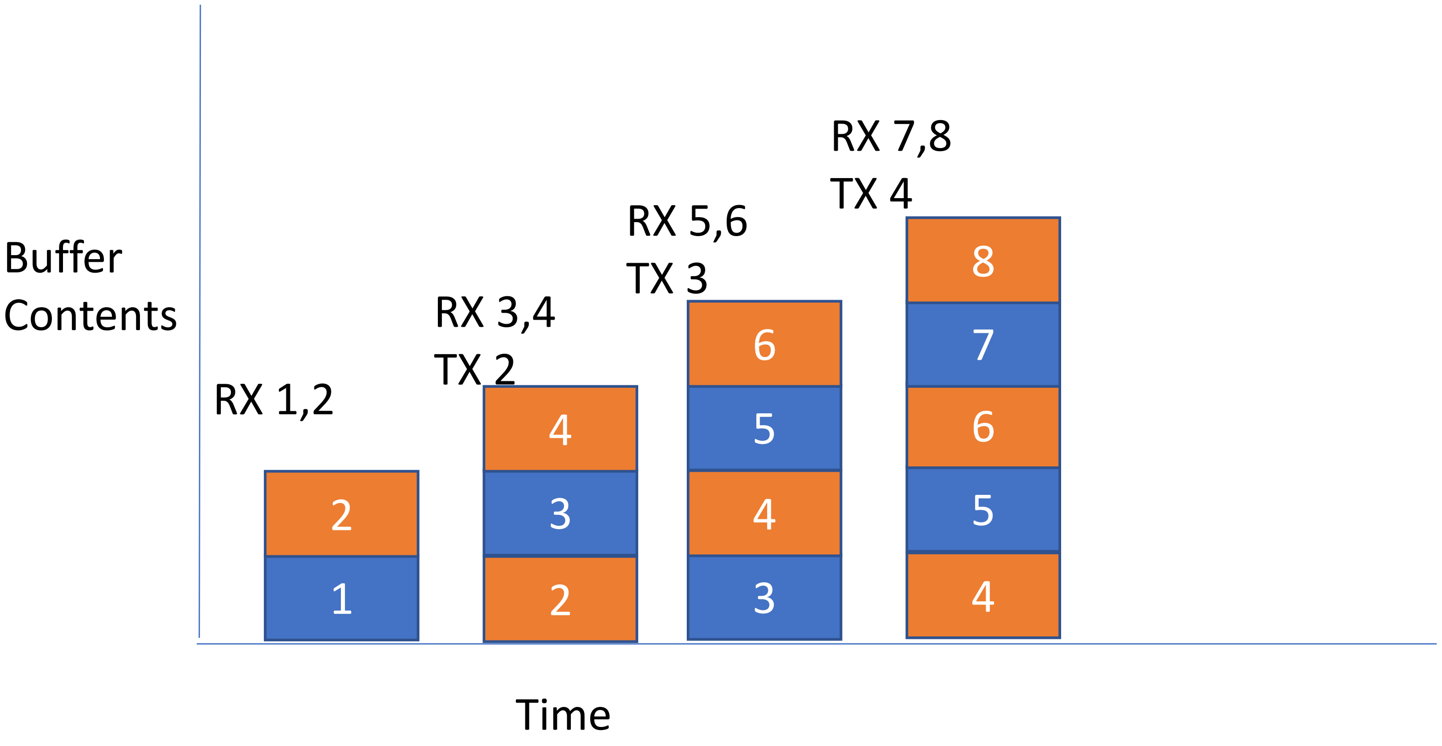


How Congestion Happens

- Send rate out of a link lower than the receive rate
  (e.g., different bandwidths, or forwarding from multiple ports to one)

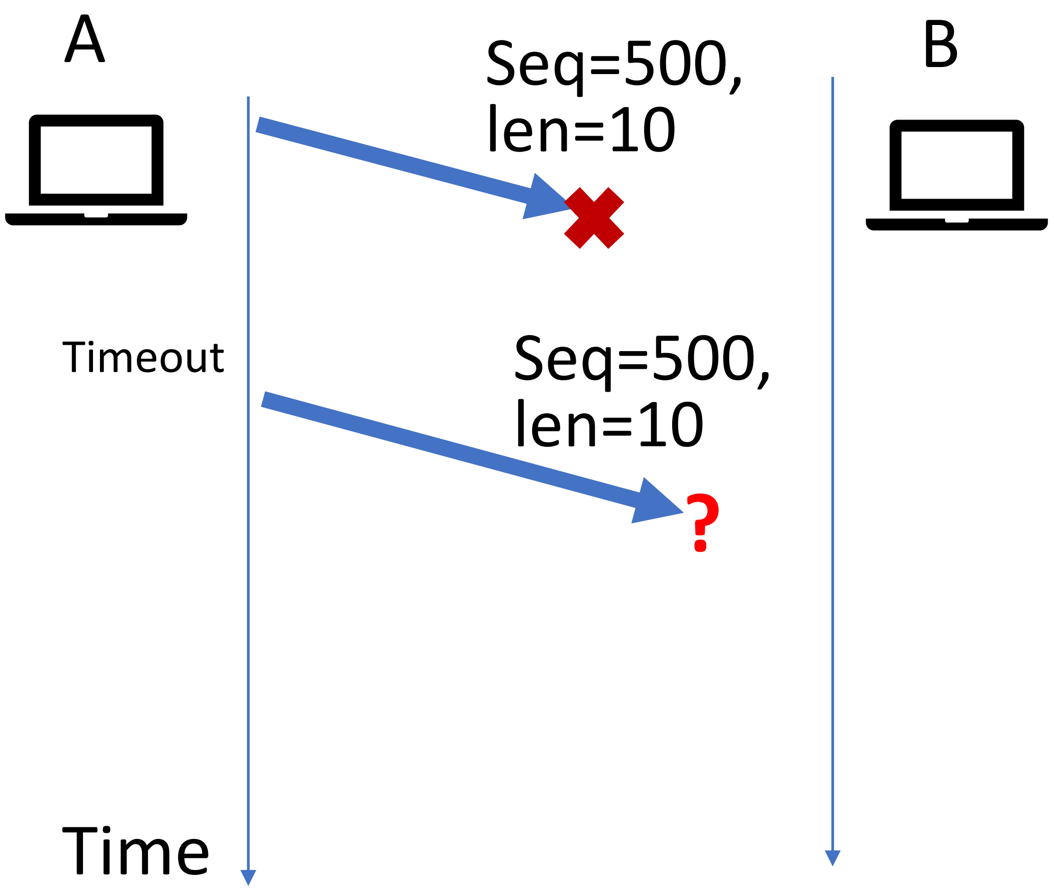


Each link can transfer 1 pkt per unit time



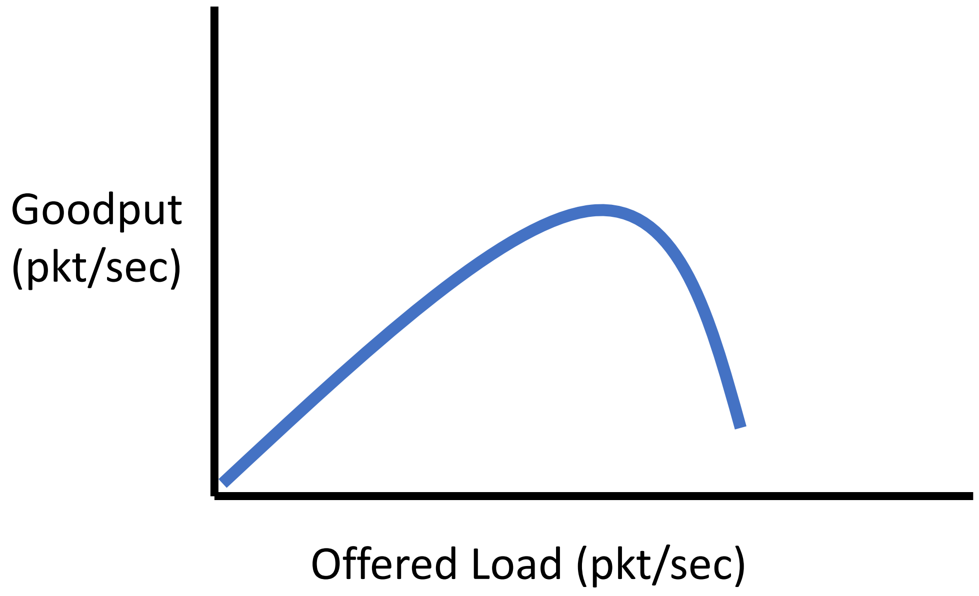
What Happens When Congestion Occurs

- Packets get dropped (by router)
- Then re-transmitted (by host)



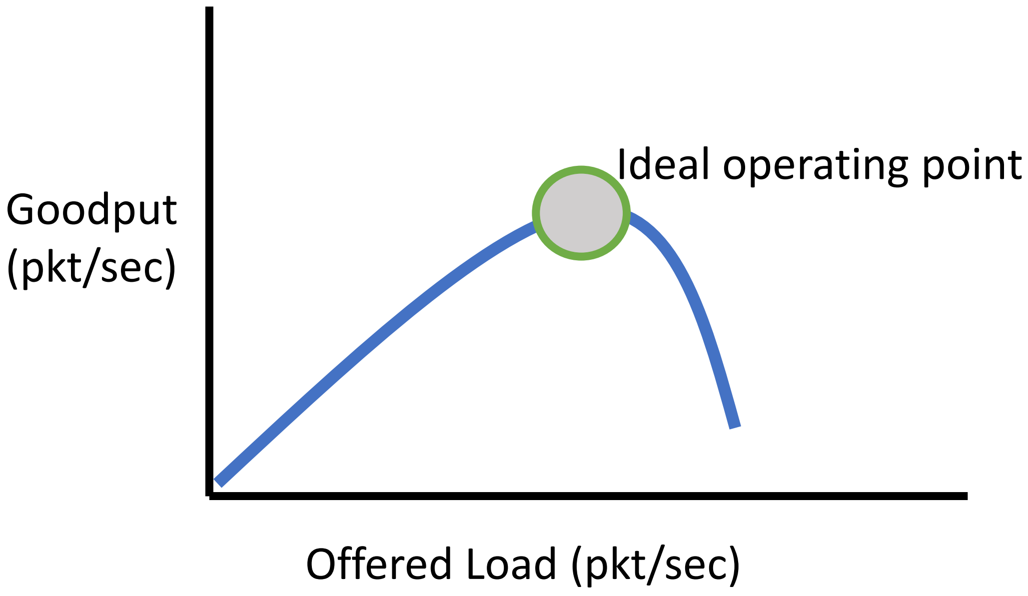
End Result – Congestion Collapse

- When nearing capacity, goodput decreases rapidly
- Buffers get full, but sending keeps overloading them, so more and more packets getting dropped and re-transmitted



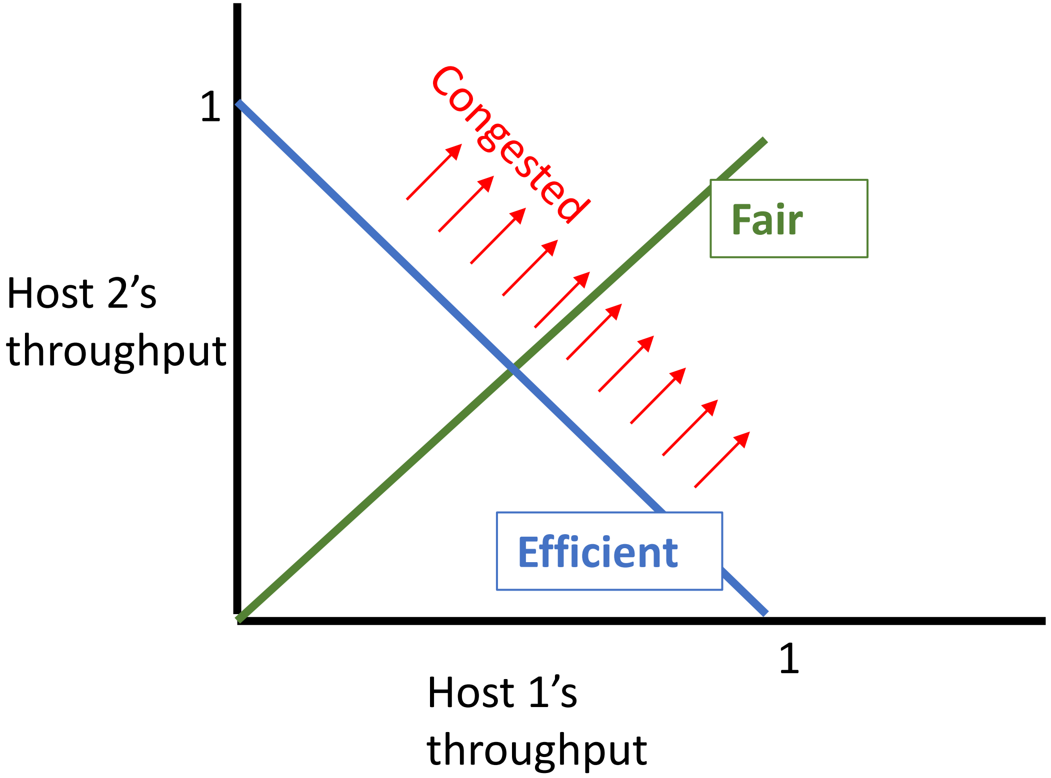
Congestion Control

- Can we get the network to operate just before it collapses?
- Goal – efficient, fair



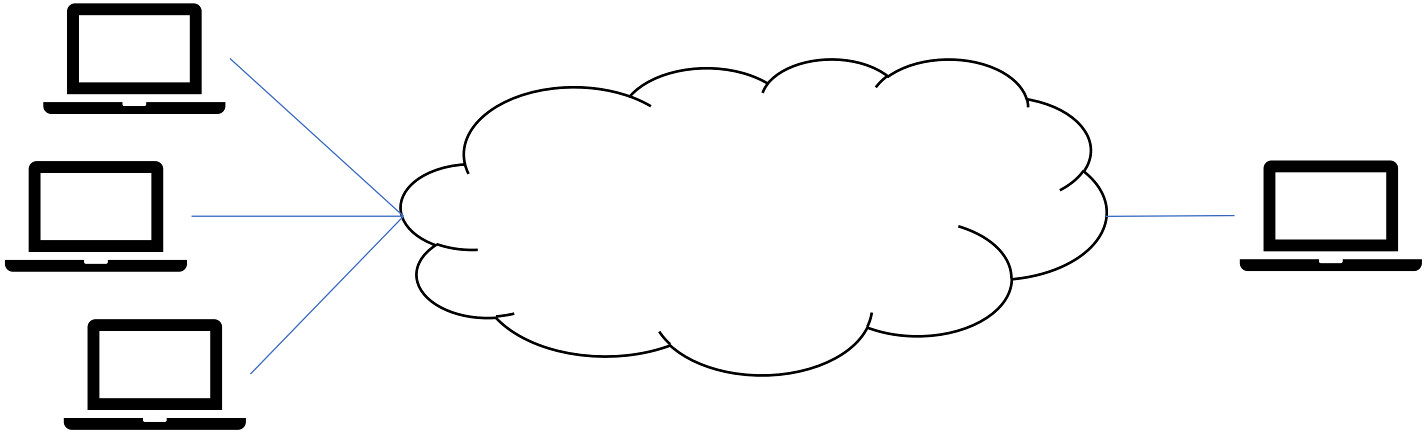
Fair and Efficient Illustrated

- Fair – each flow receives an equal share of the bandwidth of a link
- Efficient – full bandwidth of link is used



Resource Allocation Approaches

- Reservation – in network, reserve bandwidth on each router
- Feedback and Adjust – on hosts, detect congestion and adjust send rate



TCP Congestion Control Overview

Senders can increase sending rate until congestion occurs, then decrease sending rate

- Feedback – implicit
- Adjust – window-based

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TCP Congestion Control

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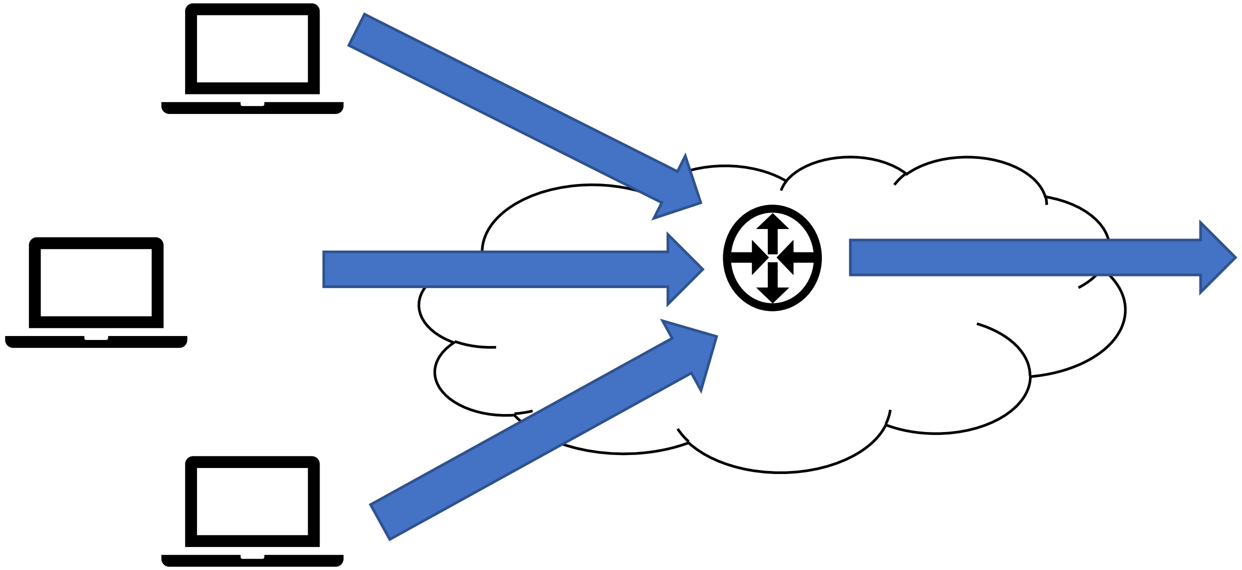
Problem 3: Congestion Control

- Congestion in the network will occur – leading to packets being dropped
- Goal: What if senders could detect this and backoff as needed?



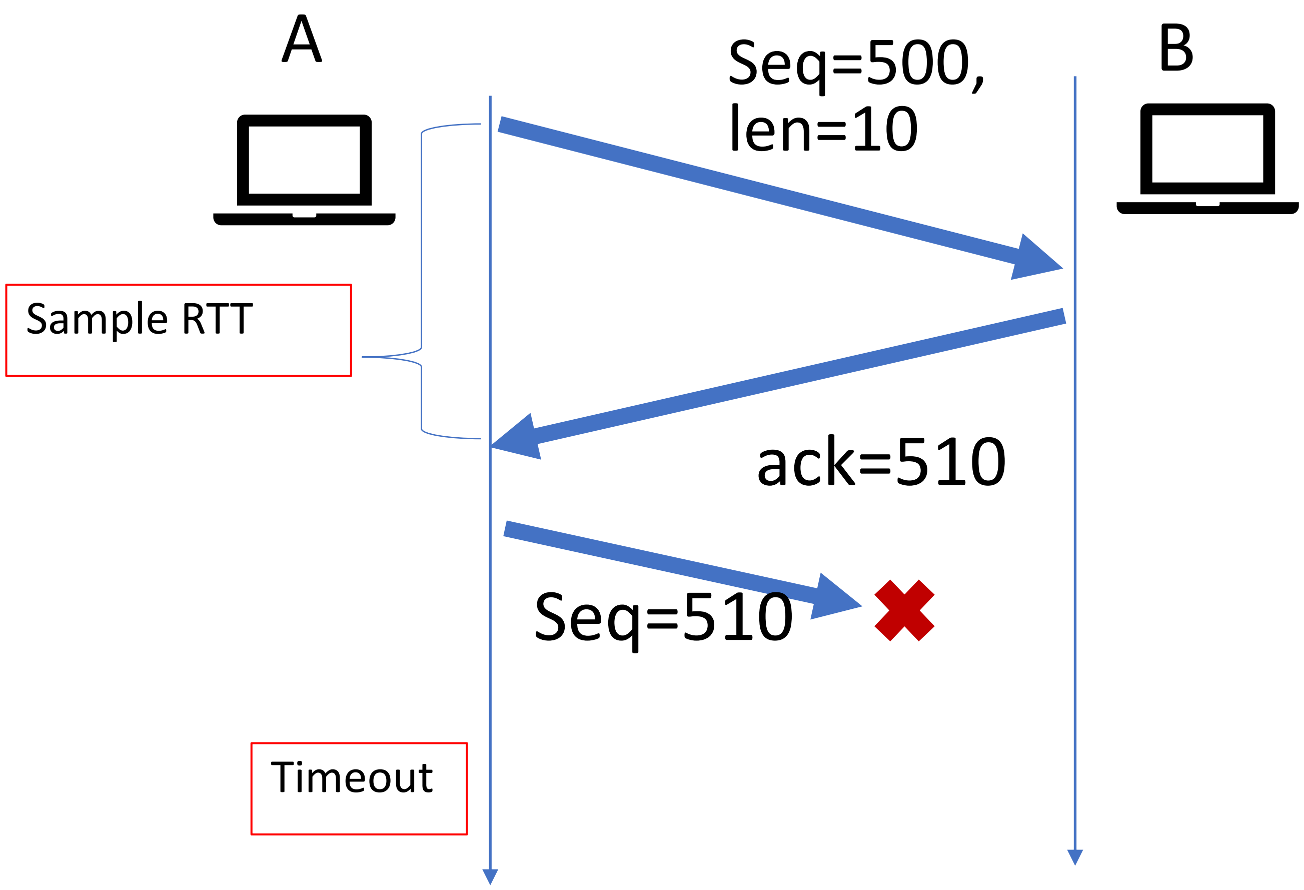
TCP Congestion Control Overview

Senders can increase sending rate until congestion occurs, then decrease sending rate

- Feedback – implicit
- Adjust – window-based

Feedback

- Packet Loss
  - Timeout
  - Duplicate ACK
- Packet Delay
- Explicit Congestion Notification (requires router support)



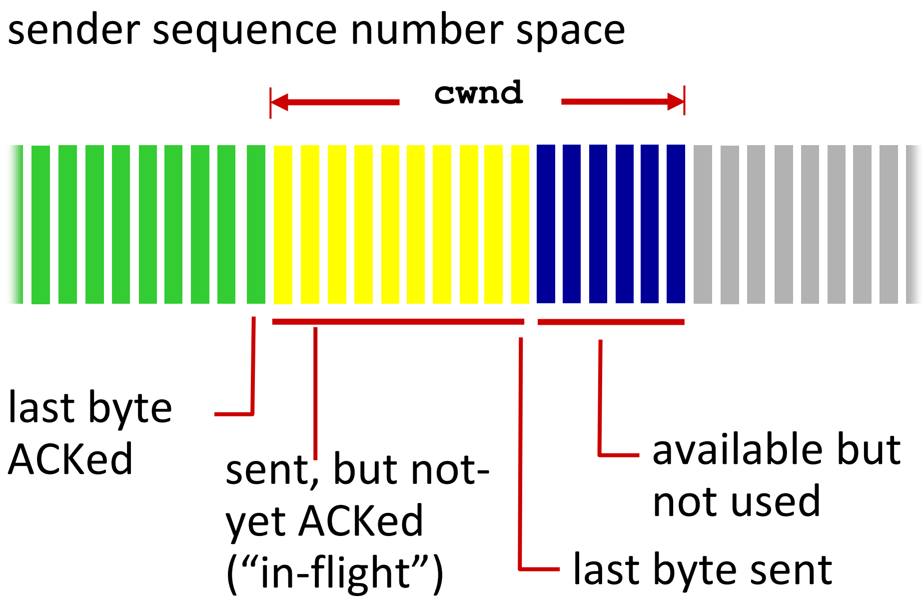
Window

- Host limits sending through a Congestion Window (cwnd)

lastByteSent – lastByteAck ≤ cwnd

Note: recall flow control – window size TCP header field. (rwnd)

cwnd is internal state on host



Pic: https://gaia.cs.umass.edu/kurose_ross/index.php

Adjusting Congestion Window

- Additive Increase Multiplicative Decrease (AIMD)
- Shown to:
  - optimize congested flow rates network wide!
  - have desirable stability properties

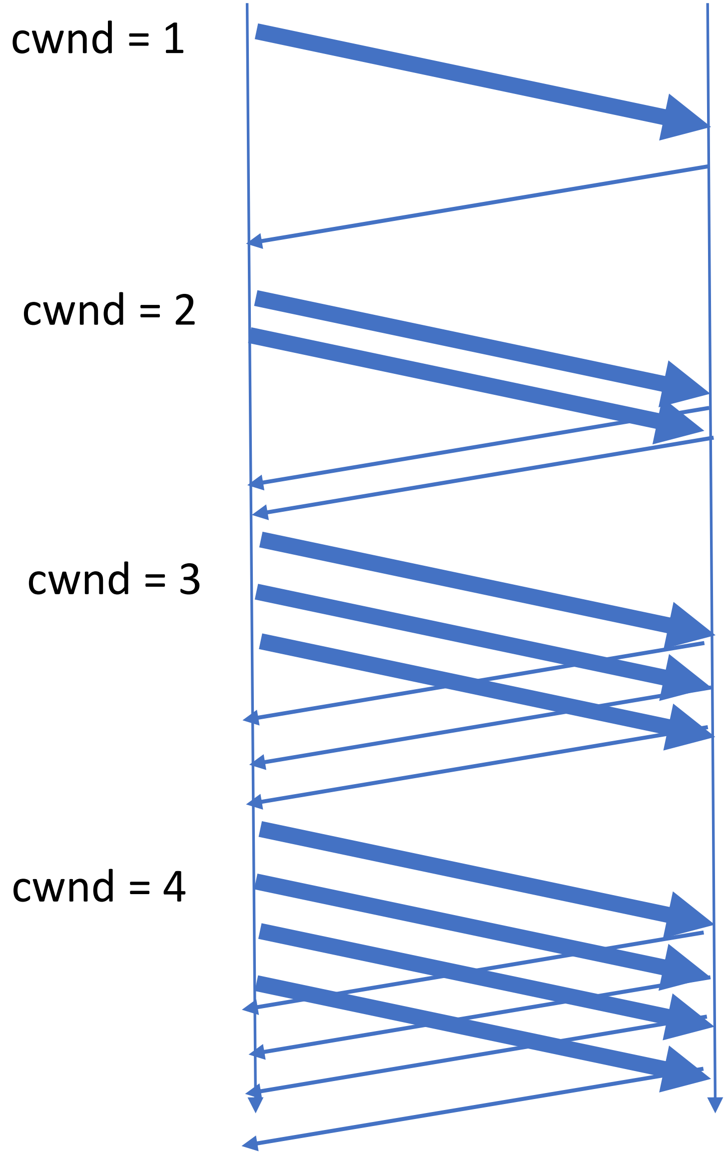
Additive Increase
increase sending rate by 1 maximum segment size every RTT until loss detected

Multiplicative Decrease
decrease sending rate by some multiplicative factor (e.g., by half) when loss detected

Additive Increase

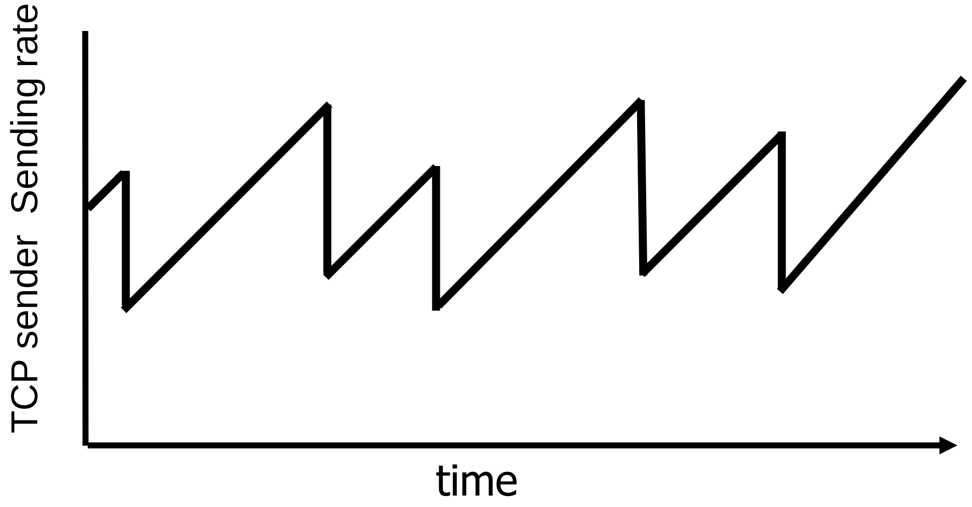
- Timeline with increase cwnd by MSS for each RTT
  (but, do it partially with each ACK)

Increment = MSS x (MSS/CongestionWindow)
CongestionWindow += Increment



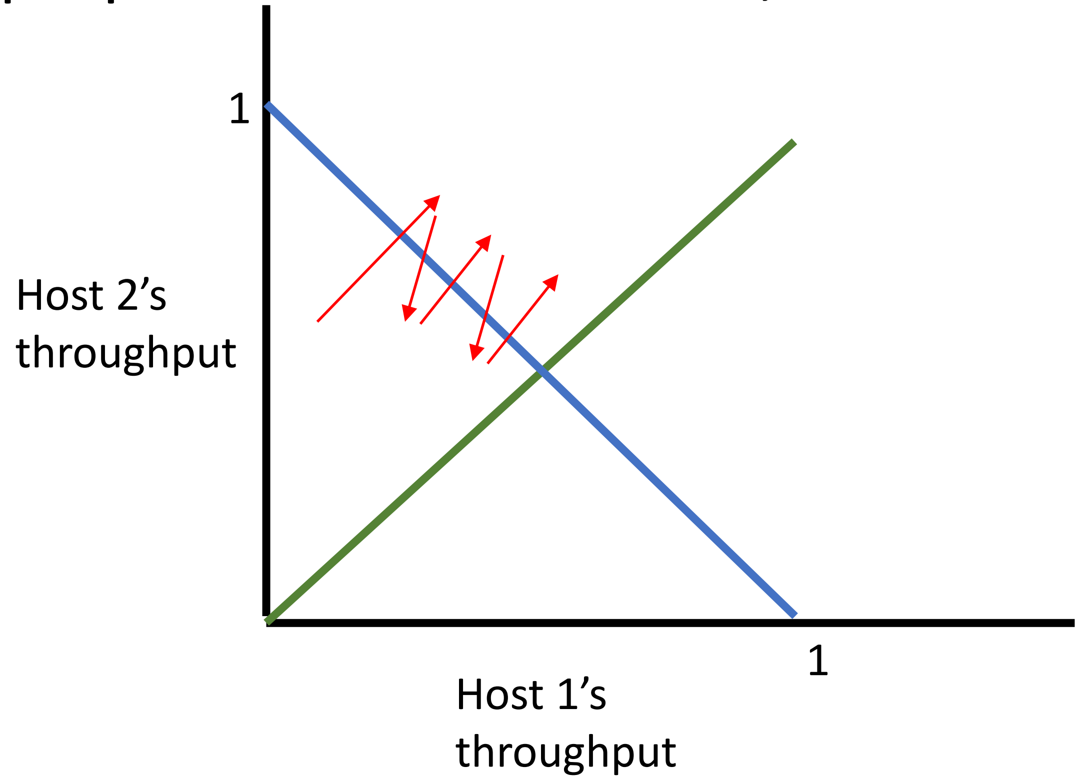
Multiplicative Decrease

- When detect congestion, decrease send rate
- Leads to sawtooth pattern
  - AI (probe for bandwidth), MD (rapidly correct)
- Multiplicative has been shown to be a necessary condition for stability



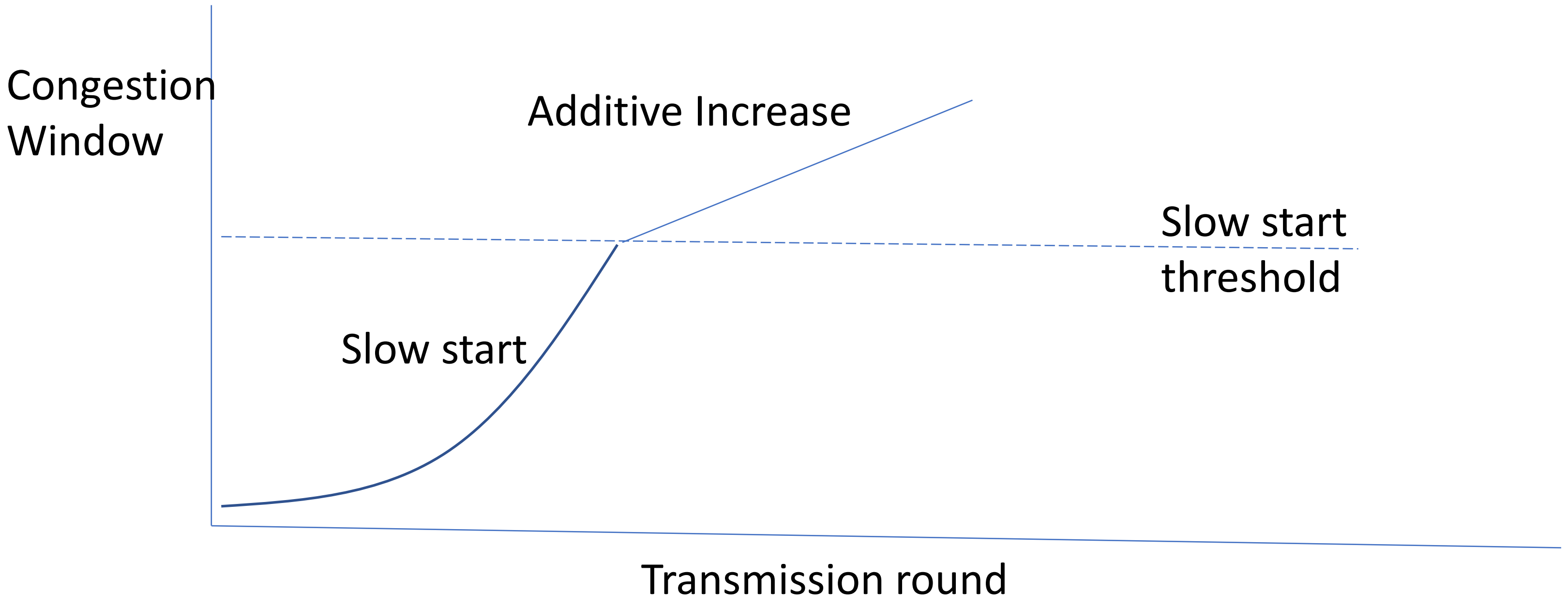
Why AIMD Conceptually Works

- Increase is linear (all increase the same)
- Decrease is proportional to send rate, so converge towards fair line



TCP Slow Start

- Additive increase is too conservative (too slow to get to congestion)
- TCP Slow Start - Increase cwnd every Ack (instead of every RTT)



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