15-441/641: Computer Networks
The Transport Layer, Part 2 of 3

15-441 Spring 2019

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Questions to discuss with a friend

- What are some things that make reliable transmission hard?
    - *Think: what went wrong in our reliable transmission race?*
- What is the difference between a “cumulative ACK” and a “basic ACK”?
    - What is one benefit of each?
- How do Selective Repeat and Go-back-N improve upon Stop-and-Wait?
- Can the transport layer guarantee:
    - That all packets will arrive at their destination?
    - That packets will be delivered at a certain throughput?
    - That packets will be delivered with a certain latency?

Last Time: Reliable Transmission

- When transmitting across the Internet, how can we be sure that every message reaches its destination?
  - Retransmit!
- Three approaches:
  - Stop and Wait
  - Go Back N
  - Selective Repeat

Stop-and-Wait: Summary

- **Sender:**
  - Transmit packets one by one. Label each with a sequence number. Set timer after transmitting.
  - If receive ACK, send the next packet.
  - If timer goes off, re-send the previous packet.
- **Receiver:**
  - When receive packet, send ACK.
  - If packet is corrupted, just ignore it — sender will eventually re-send.

Can I get some volunteers to act it out?

Selective Repeat

- **Sender:**
  - Send packets from the window. Set timeout for each packet.
  - On receiving ACKs for the “left side” of the window, slide forward.
    - Send packets that have now entered the window.
  - On timeout, retransmit only the timed out packet
- **Receiver**
  - Keep a buffer of size of the window.
  - On receiving packets, send ACKs for every packet.
  - If packets come in out of order, just store them in the buffer and send ACK anyway.

Can I get some volunteers to act it out?

Today’s Agenda

- #1: How big should we size the window?
- #2: How should we determine the BDP?
- #3: How does “plain” TCP work?

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Sliding Windows

- A sender's "window" contains a set of packets that have been transmitted but not yet acked.
- Sliding windows improve the efficiency of a transport protocol.
- Two questions we need to answer to use windows:
  - (1) How do we handle loss with a windowed approach?
  - (2) How big should we make the window?

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Why not send as fast as we can?

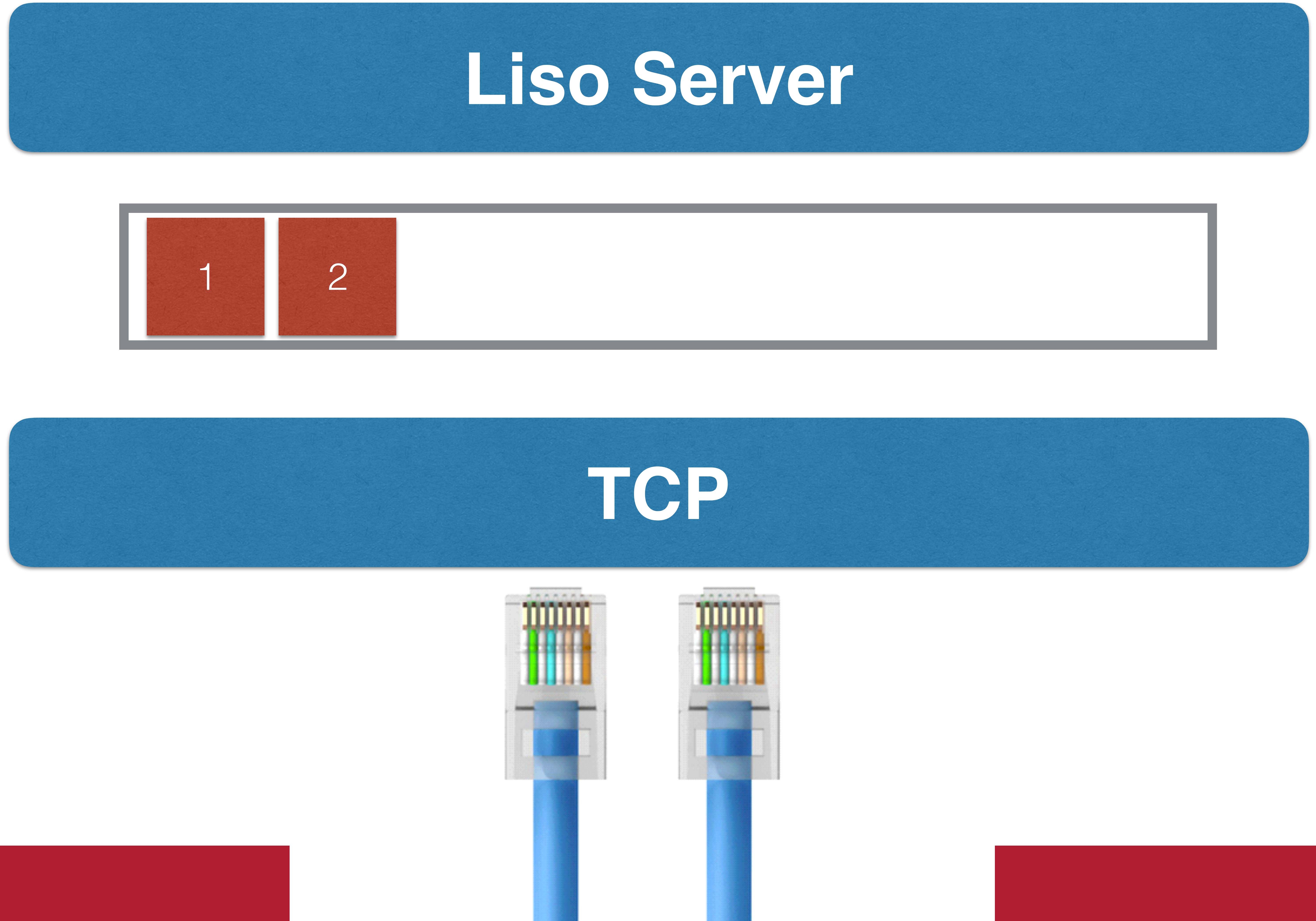
Problem #1: Flow Control

Yet another demo…
I need two volunteers, one of whom is confident reading out loud in English!

Flow Control: Don’t overload the receiver.

Bonus candy: who wrote the essay in the packets? What is the essay named?

Receive Buffer



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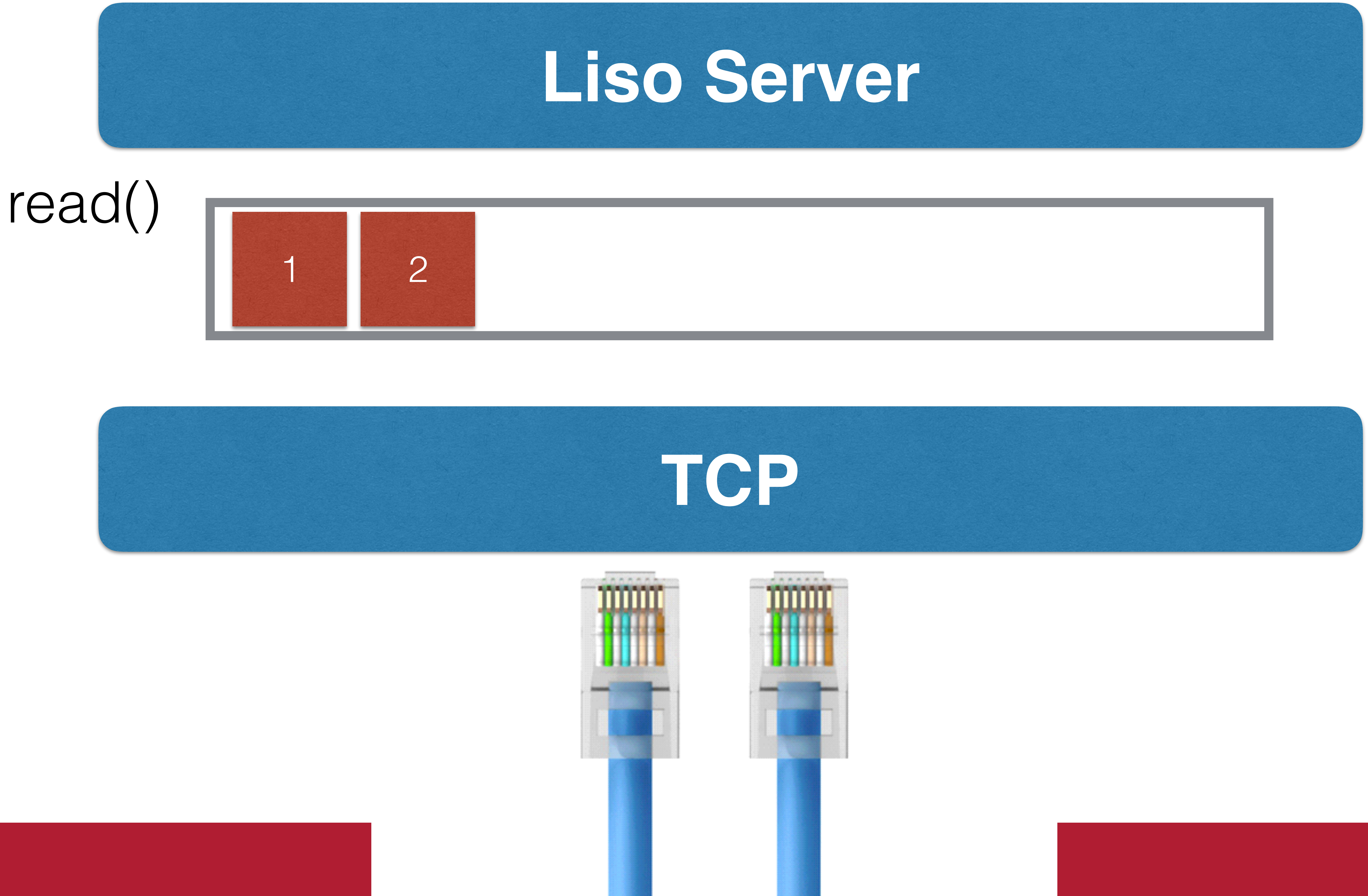

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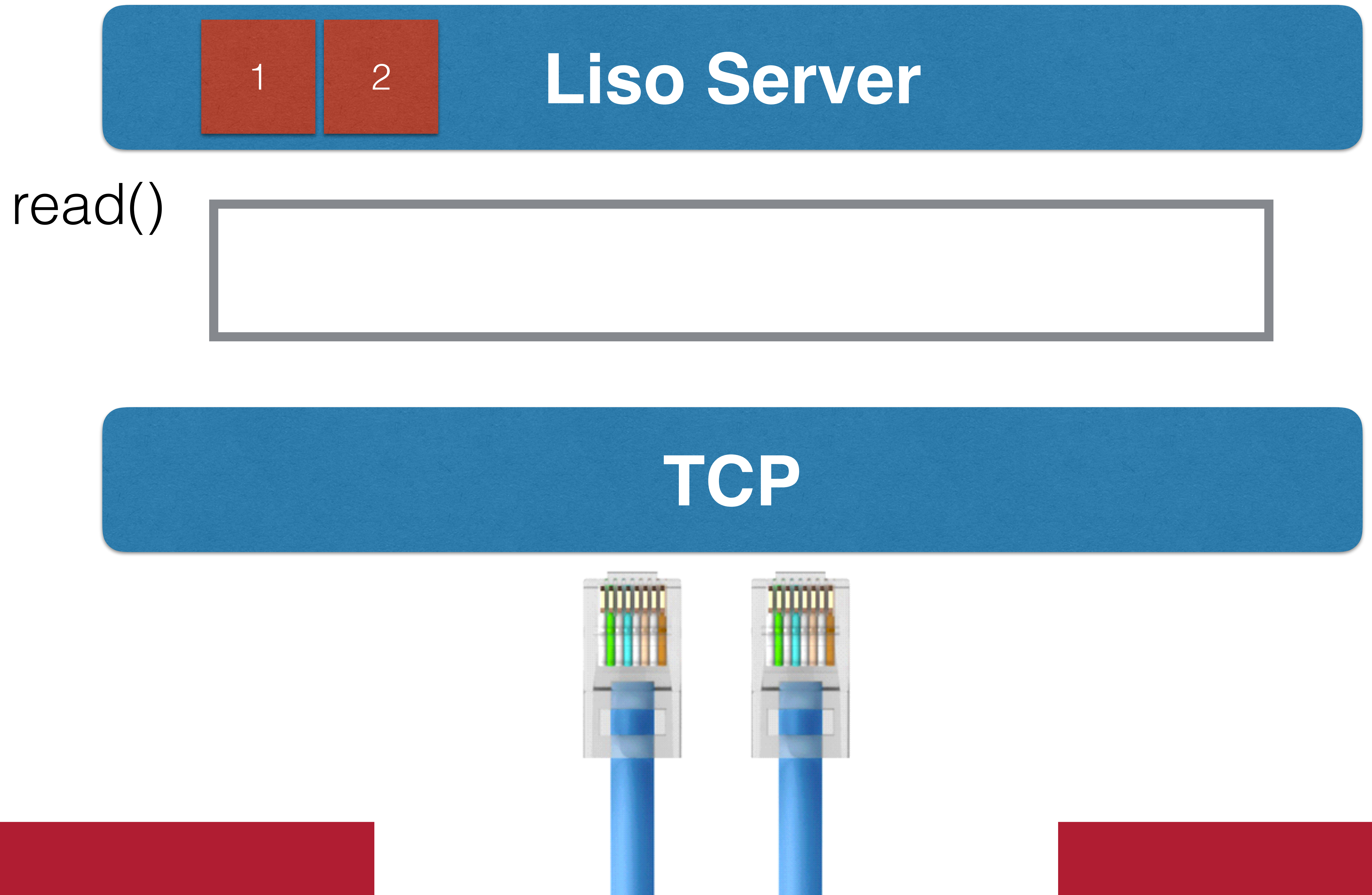

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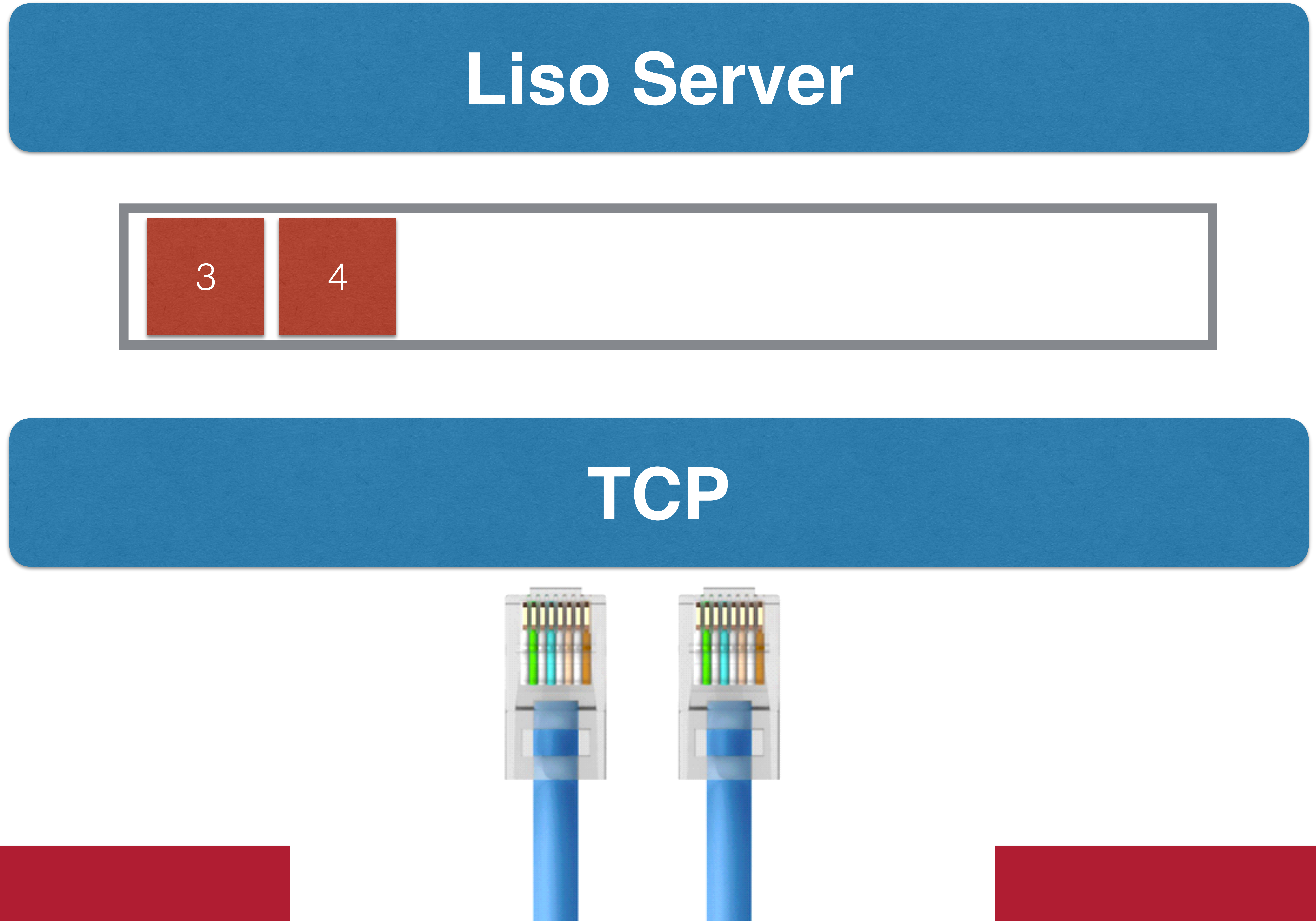

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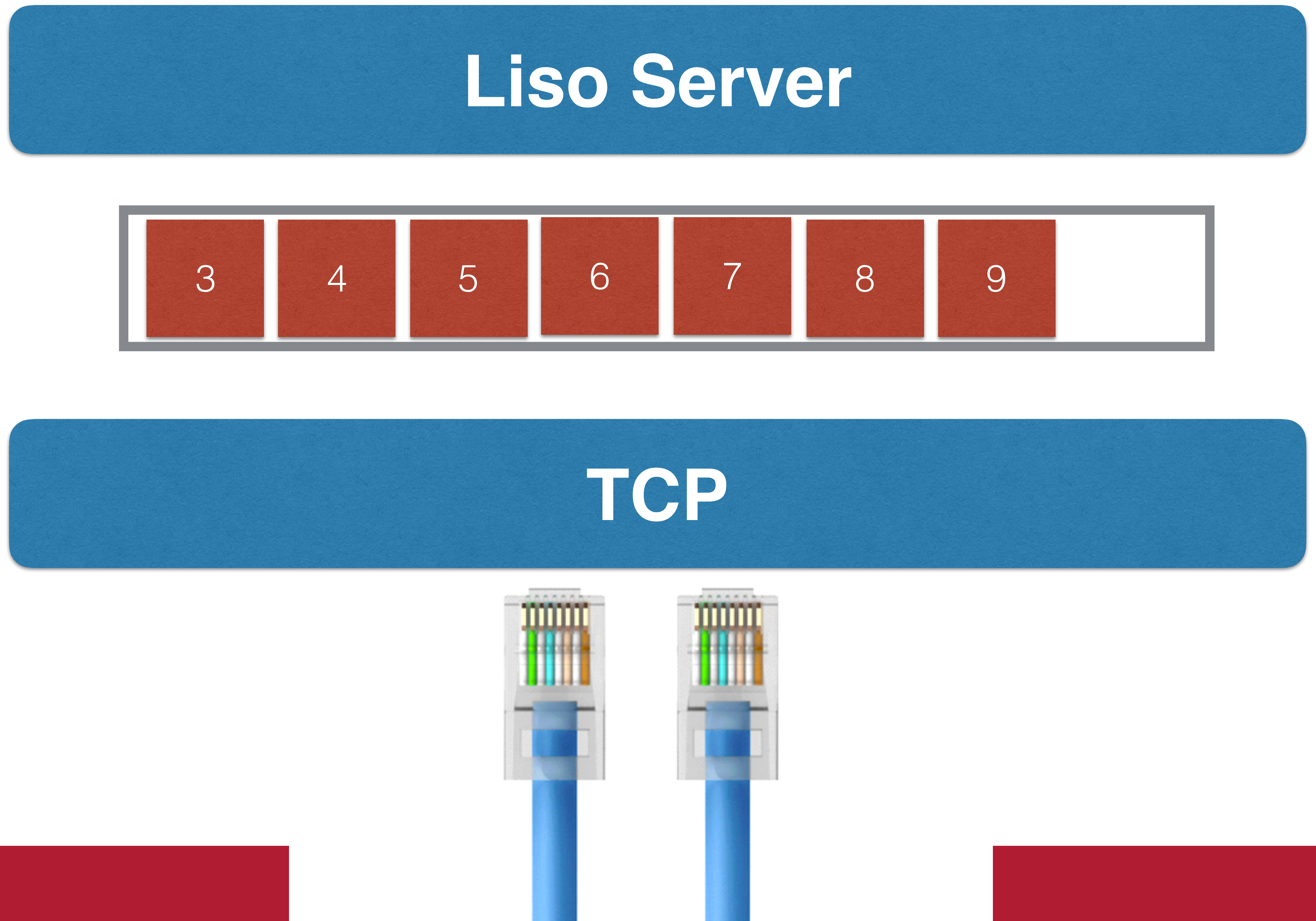

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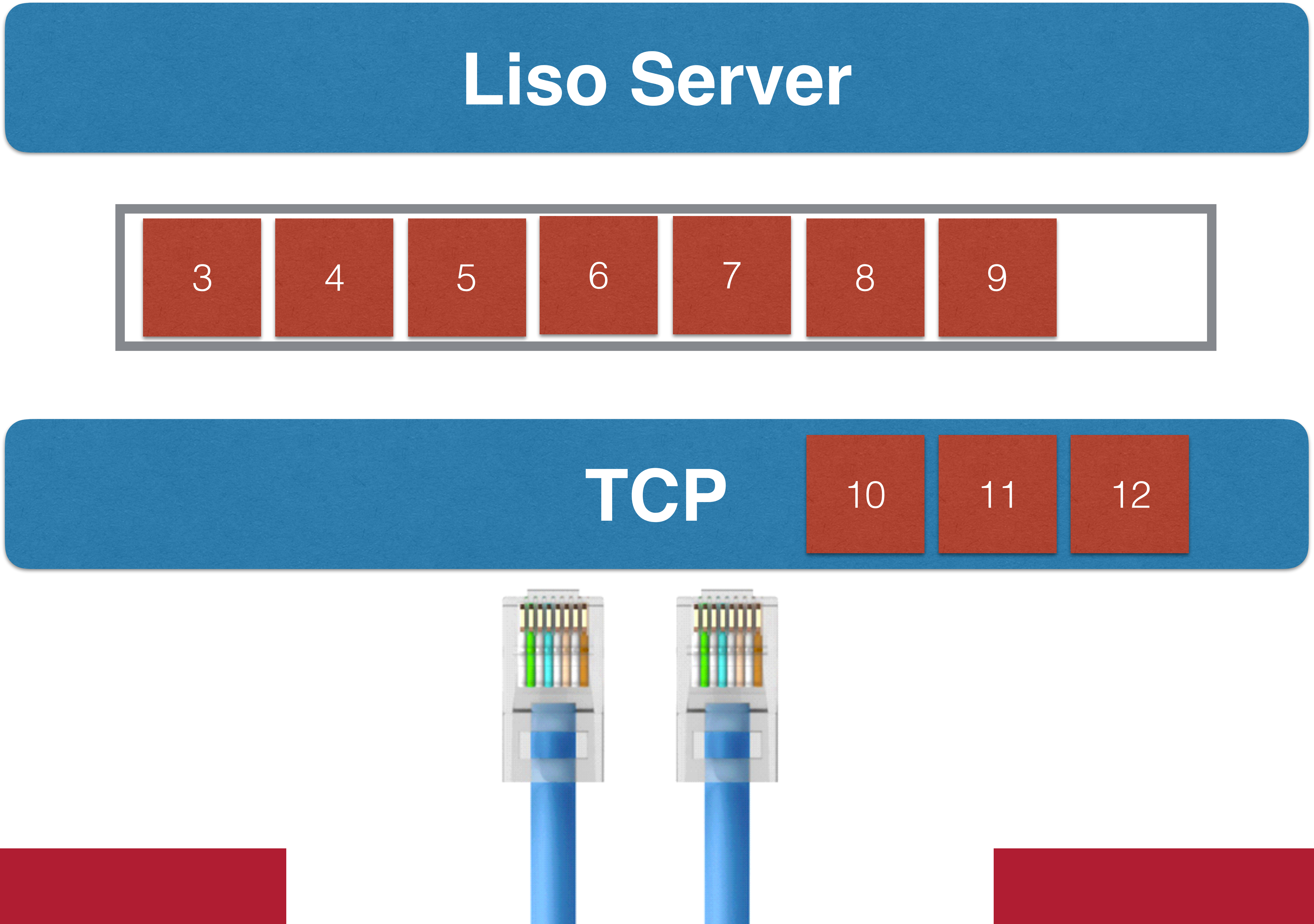

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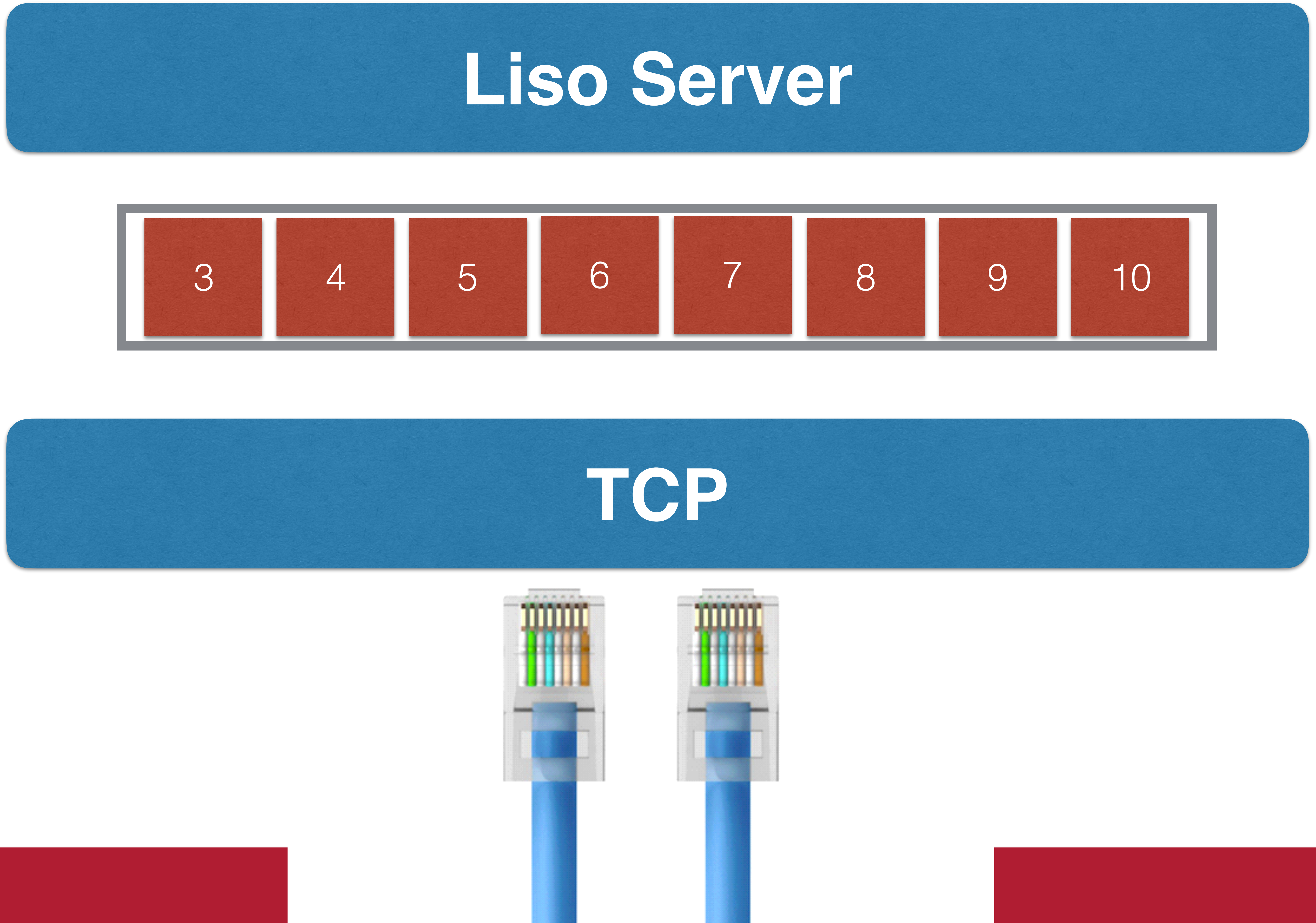


11 and 12 just get dropped :(

Solution: Advertised Window

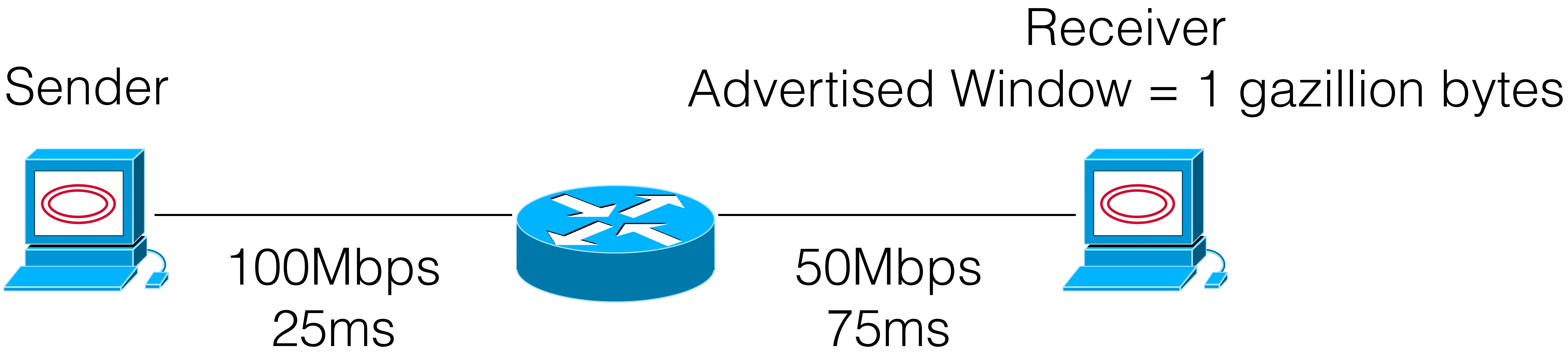
- Receiver uses an “Advertised Window” (W) to prevent sender from overflowing its window
  - Receiver indicates value of W in ACKs
  - Sender limits number of bytes it can have in flight <= W
- If I only have 10KB left in my buffer, tell the receiver in my next ACK!

How big should we make the window?

- Window should be:
    - Less than or equal to the advertised window so that we do not overload the receiver.
        - This is called Flow Control.

Alright, so let's set the window to W?

What will happen here?



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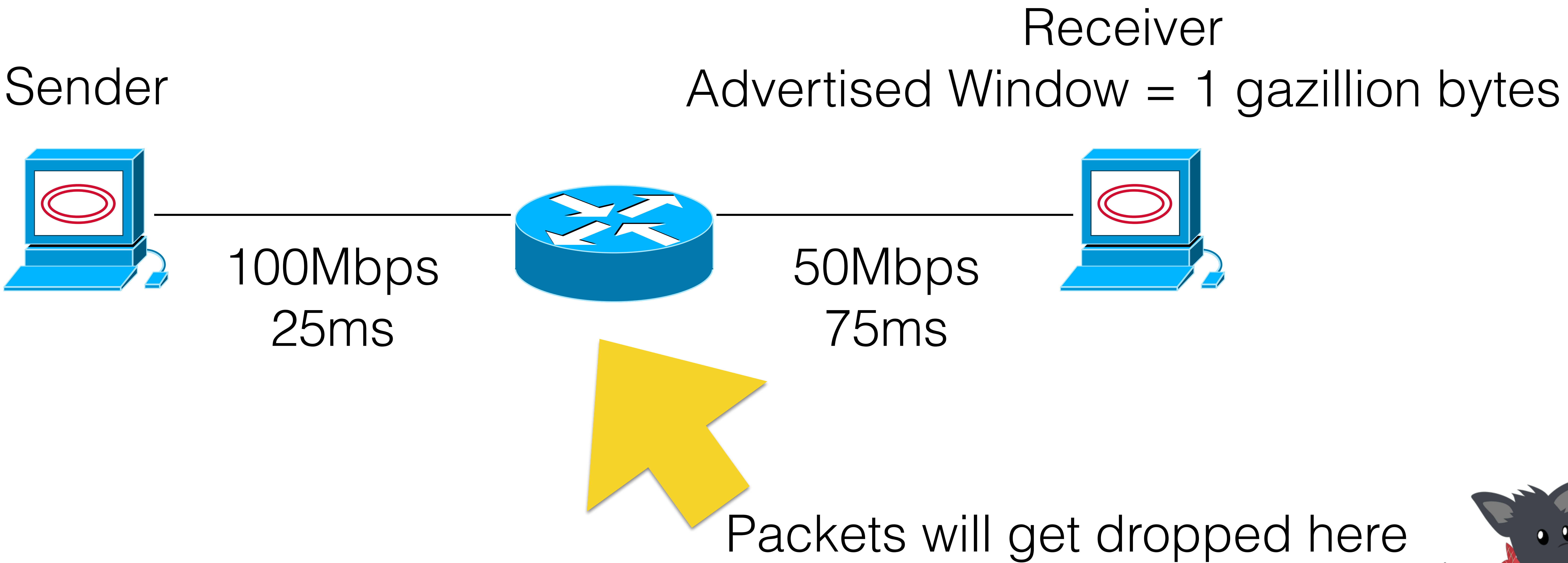

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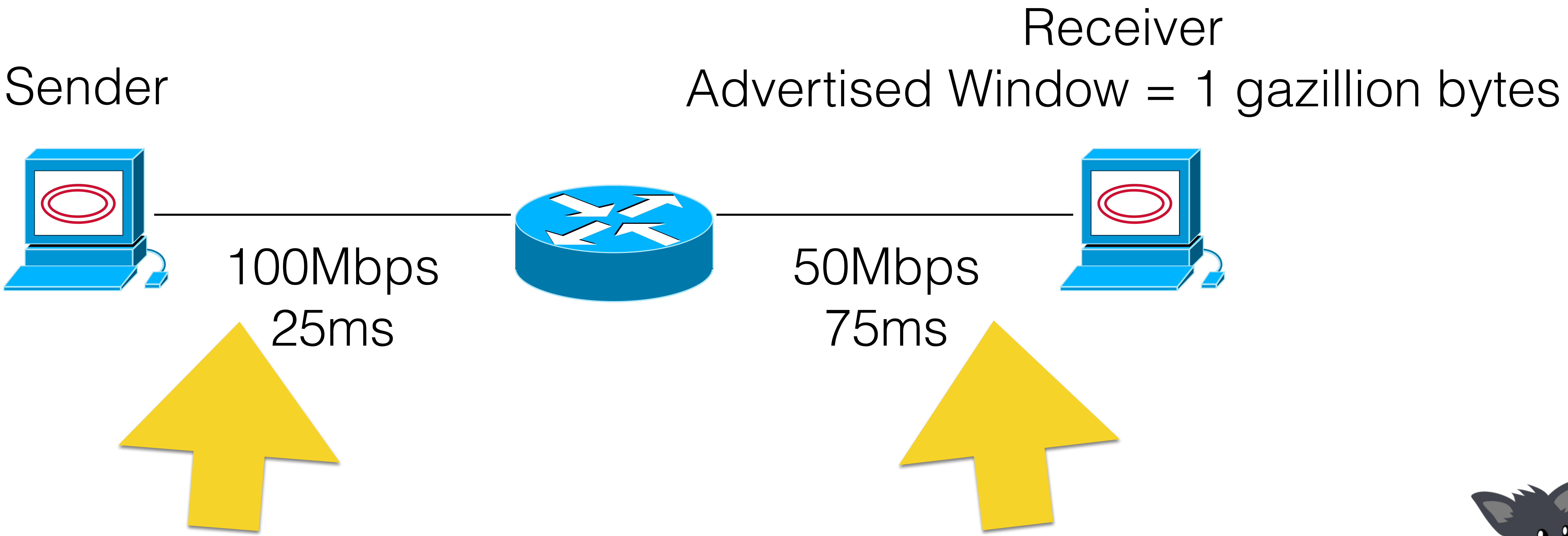
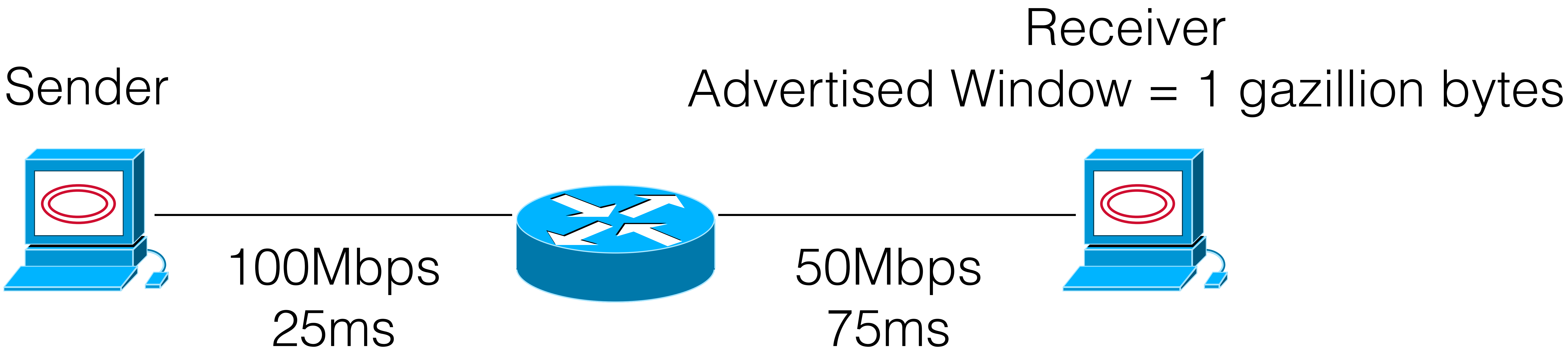


Arrival rate is faster than departure rate

How big should we set the window to be?

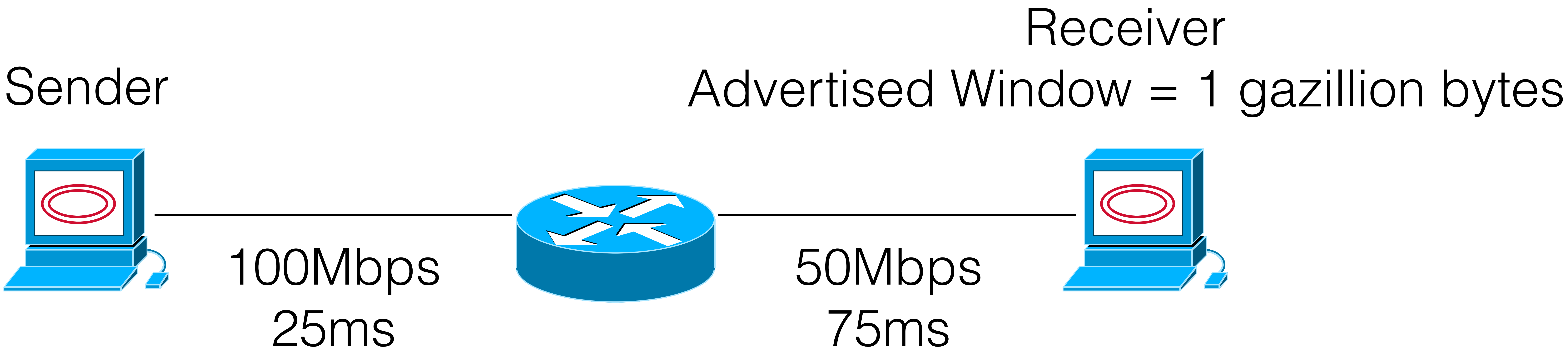
“I just want to send at 50Mbps — how does that translate into a window size?”



Remind me: what is the definition of a Window?

Recall: Window is the number of bytes I may have transmitted but not yet received an ACK for.

How long will it take for me to receive an ACK back for the first packet?



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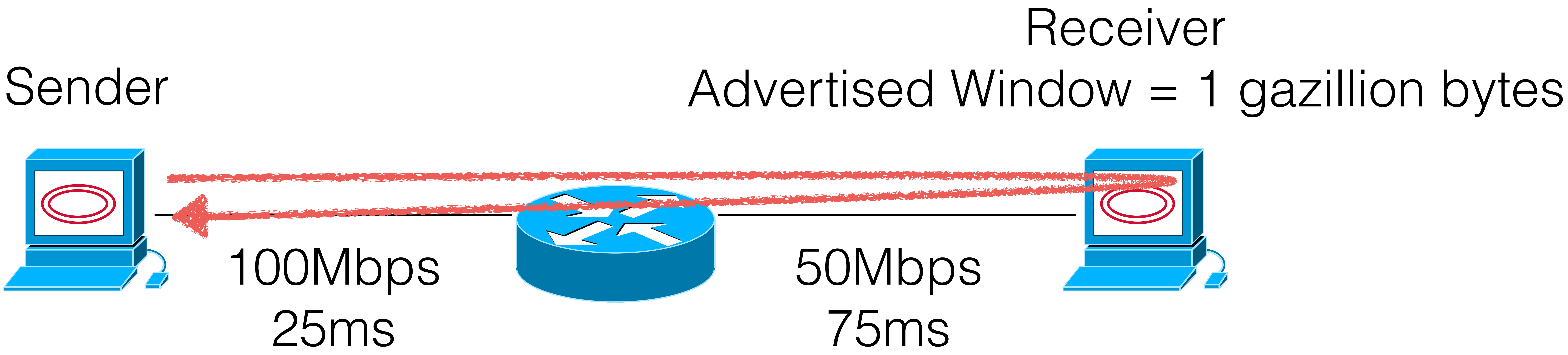


One round-trip-time (RTT) = 200 milliseconds

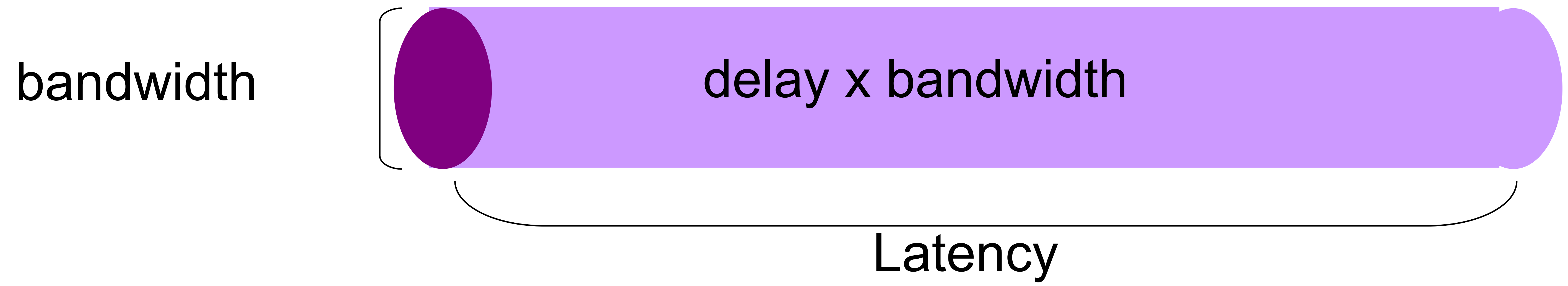
How much data will I send, at 50Mbps, in 200ms?

50Mbps * 200ms = 1.25 MB

We call this the

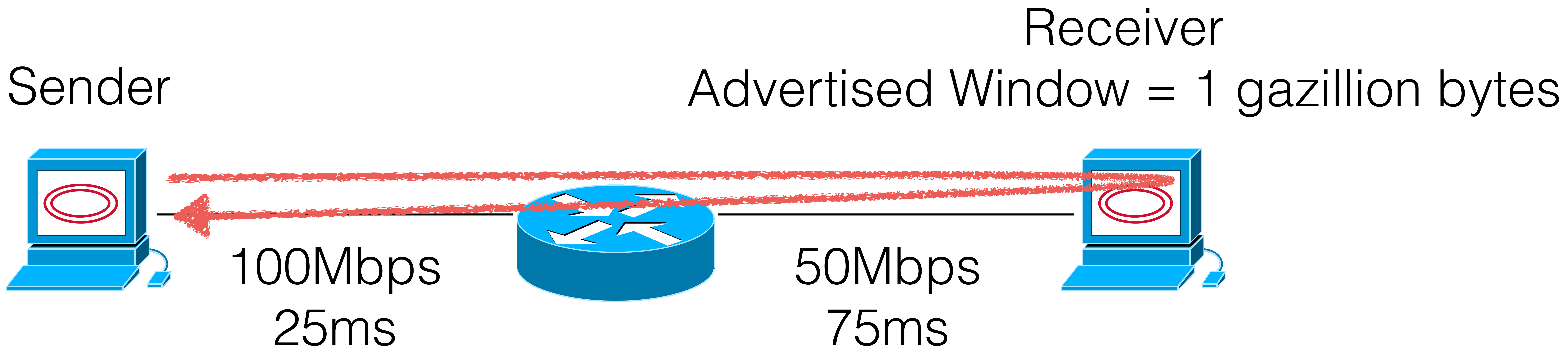
bandwidth-delay product.

Pipe Model



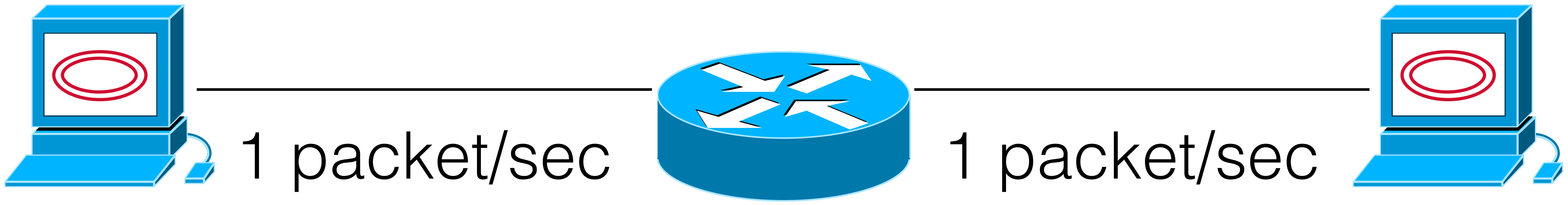
- Bandwidth-Delay Product (BDP): “volume” of the link
  - amount of data that can be “in flight” at any time
  - propagation delay × bits/time = total bits in link

When we set our window to the BDP, we get into a very convenient loop called "ACK Clocking"

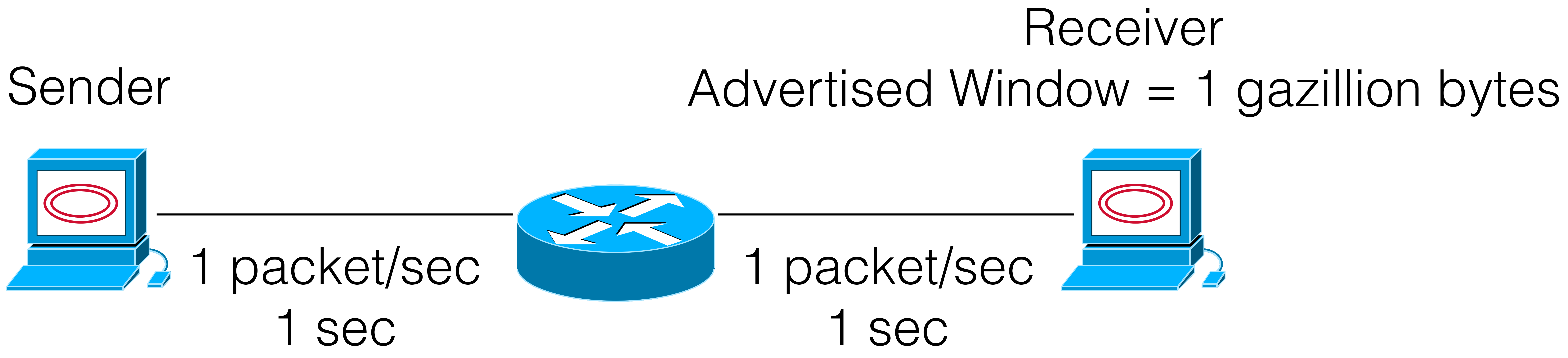


One round-trip-time (RTT) = 200 milliseconds

Yes, yet another demo….



I receive new ACKs back at *just* the right rate so that I can keep transmitting at 1 packet/sec.



How big should we make the window?

- Window should be:
    - Less than or equal to the advertised window so that we do not overload the receiver.
        - This is called Flow Control.
    - Less than or equal to the bandwidth-delay product so that we do not overload the network.
        - This is called Congestion Control.
- (That's it).

What are we missing?

How do we actually figure out the BDP?!?!

Today’s Agenda

- #1: How big should we size the window?
- **#2: How should we determine the BDP?**
- #3: How does “plain” TCP work?

Problem Constraints

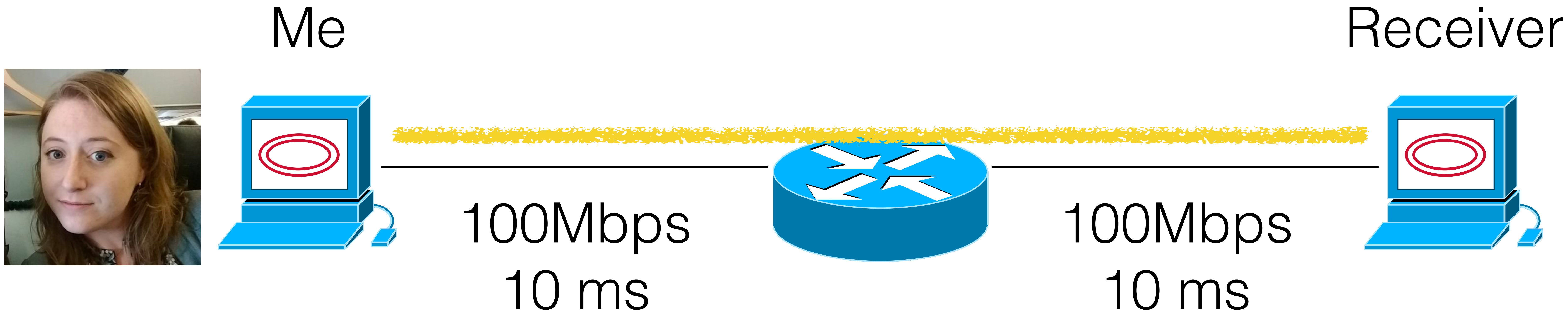
- The network does not tell us the bandwidth or the round trip time.
    - *Implication: Need to infer appropriate window size from the transmitted packets.*

Let’s make it harder…

Problem Constraints

- The network does not tell us the bandwidth or the round trip time.
- My share of bandwidth is dependent on the other users on the network.

My window size: 100Mbps x 10ms



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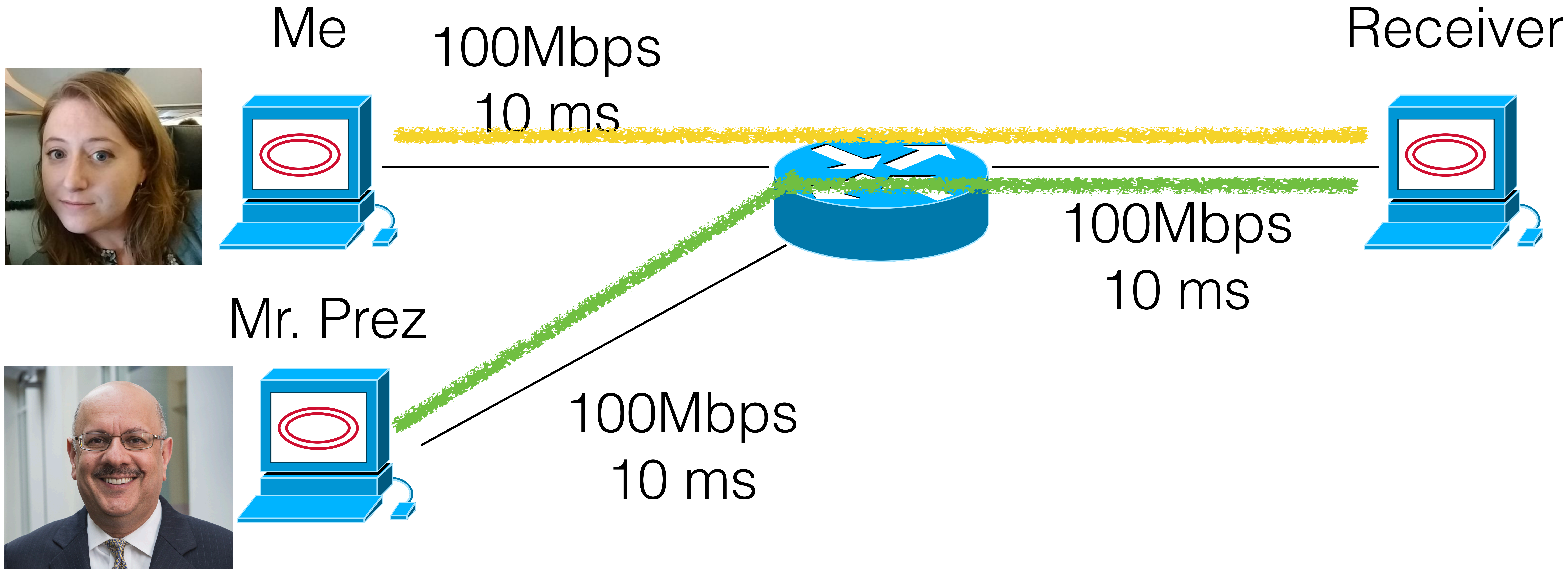

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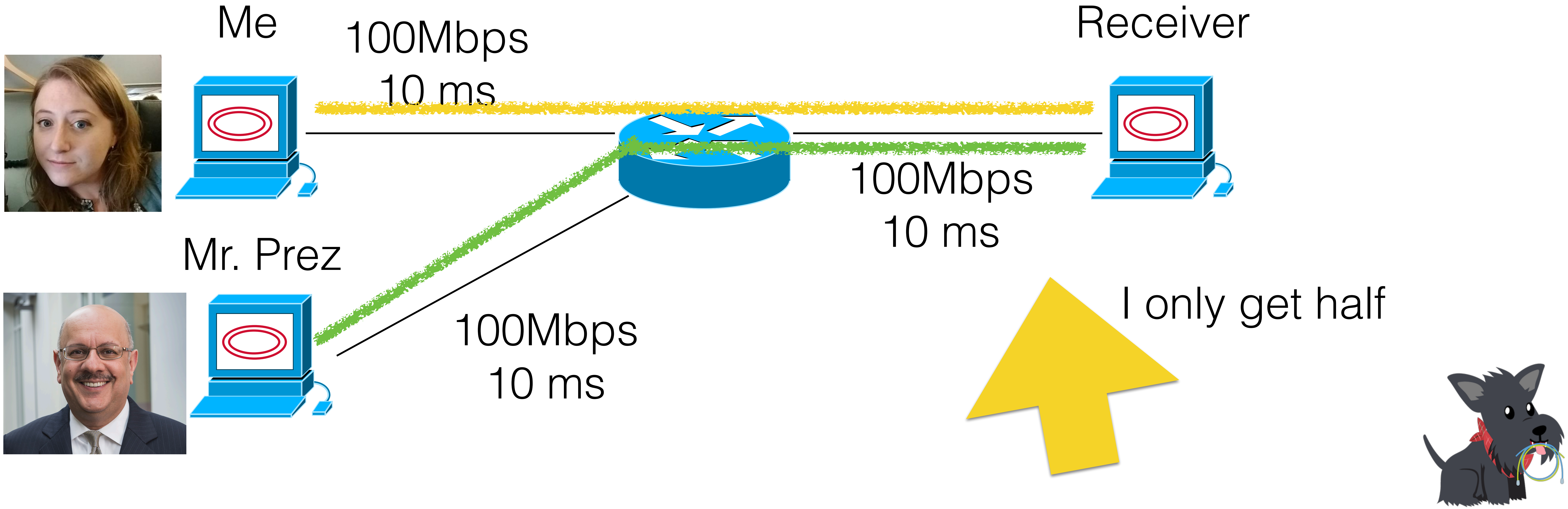
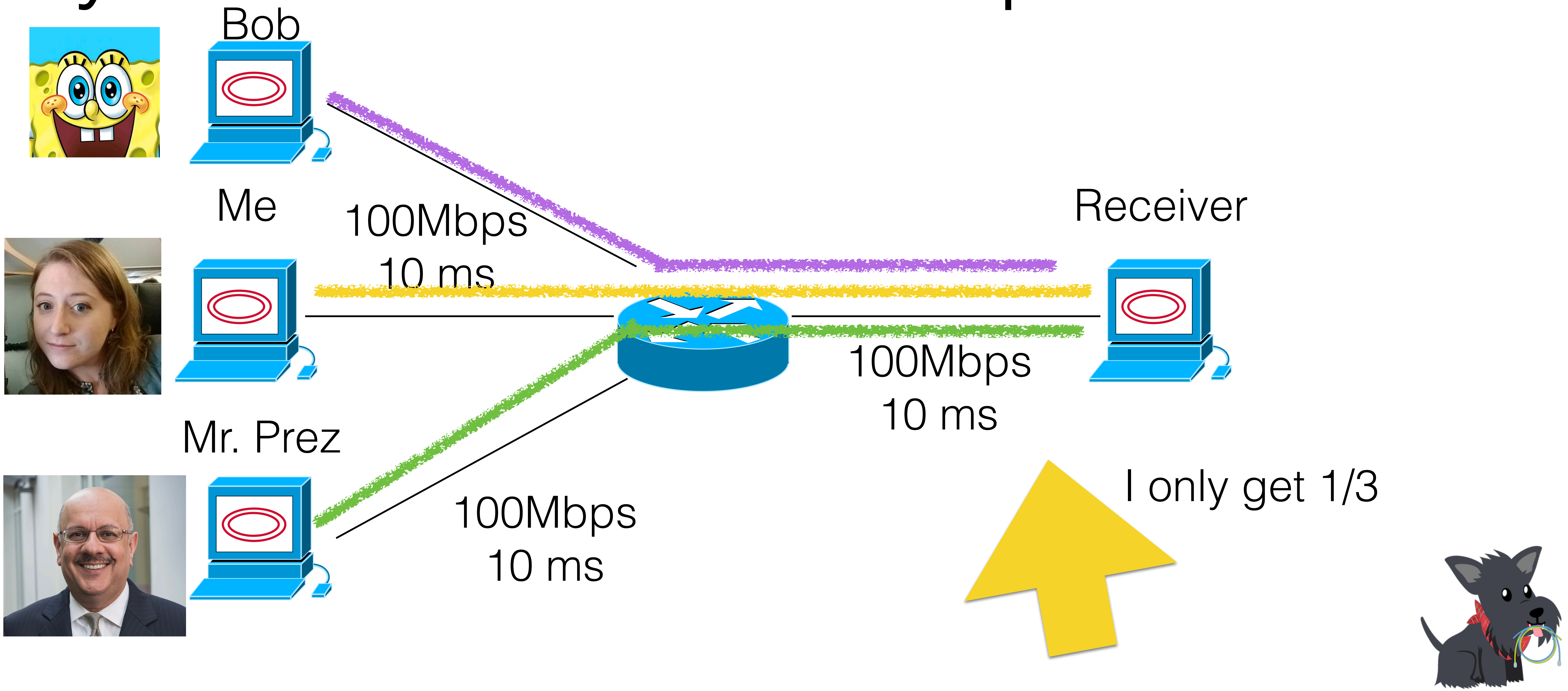


My window size: 33Mbps x 10ms



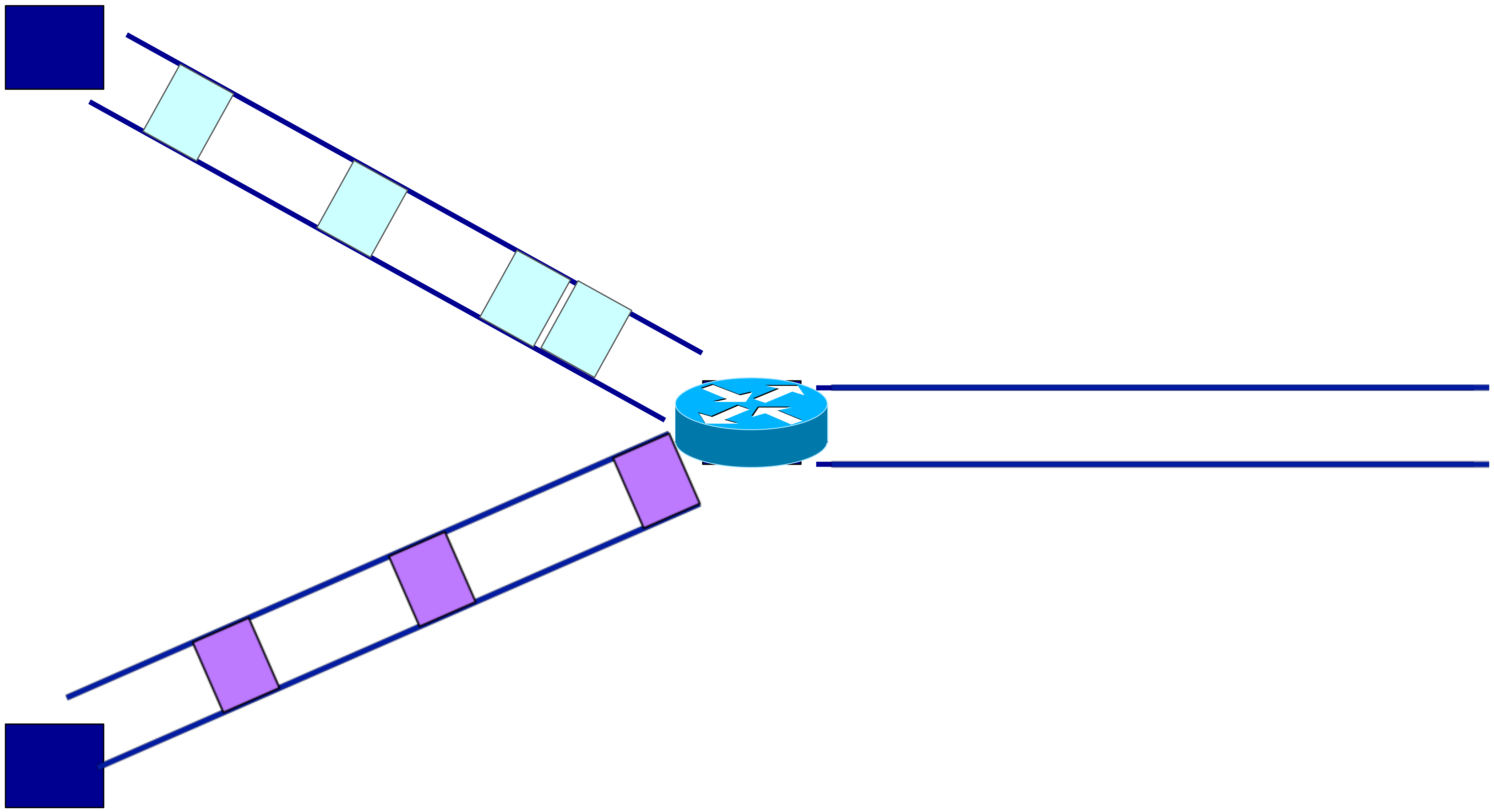
Problem Constraints

- The network does not tell us the bandwidth or the round trip time.
- My share of bandwidth is dependent on the other users on the network.
  - *Implication: my window size will change as other users start or stop sending.*

Problem Constraints

- The network does not tell us the bandwidth or the round trip time.
- My share of bandwidth is dependent on the other users on the network.
- Excess packets may not be dropped, but instead stalled in a bottleneck queue.

All routers have queues to avoid packet drops.



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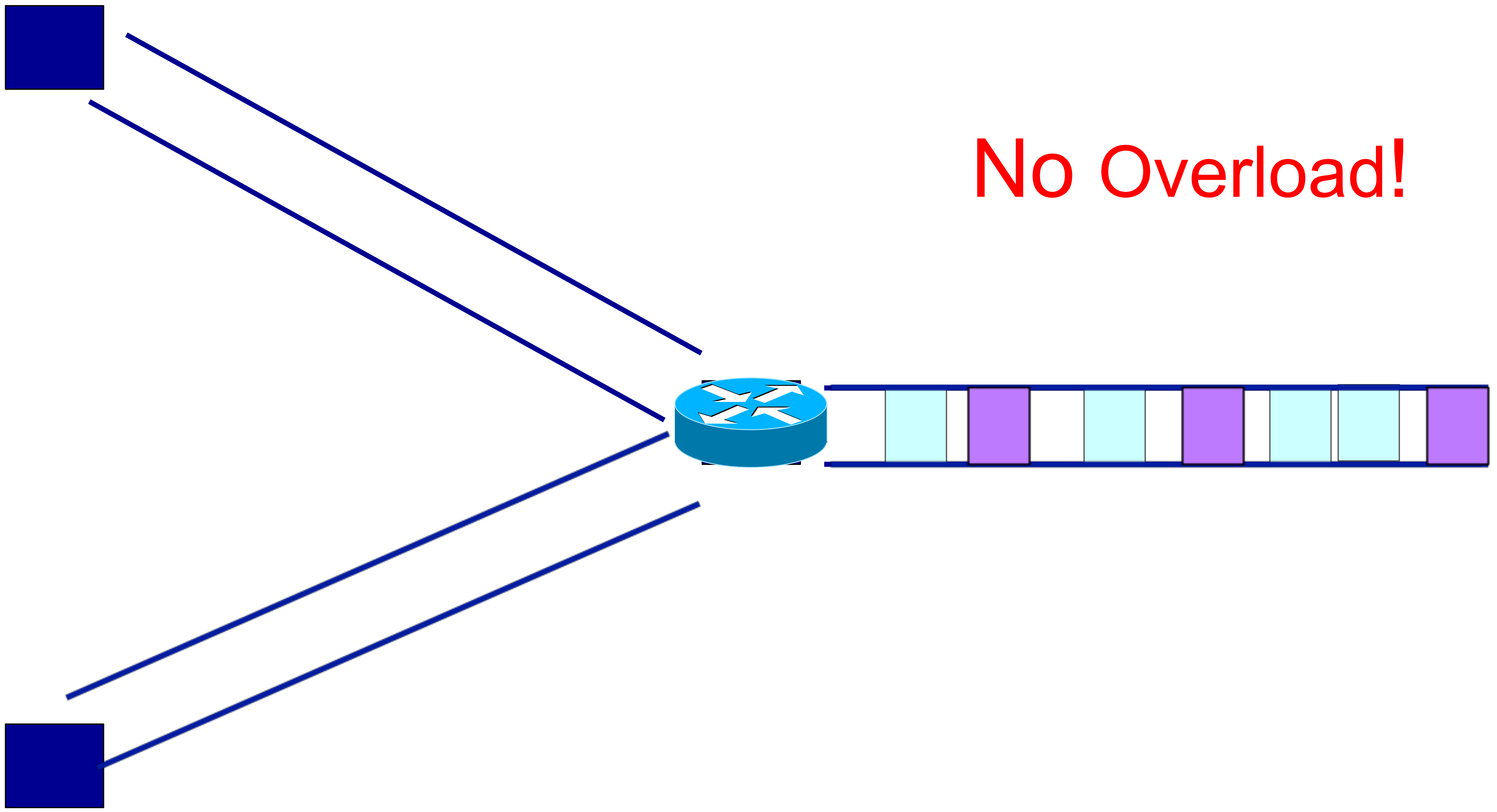
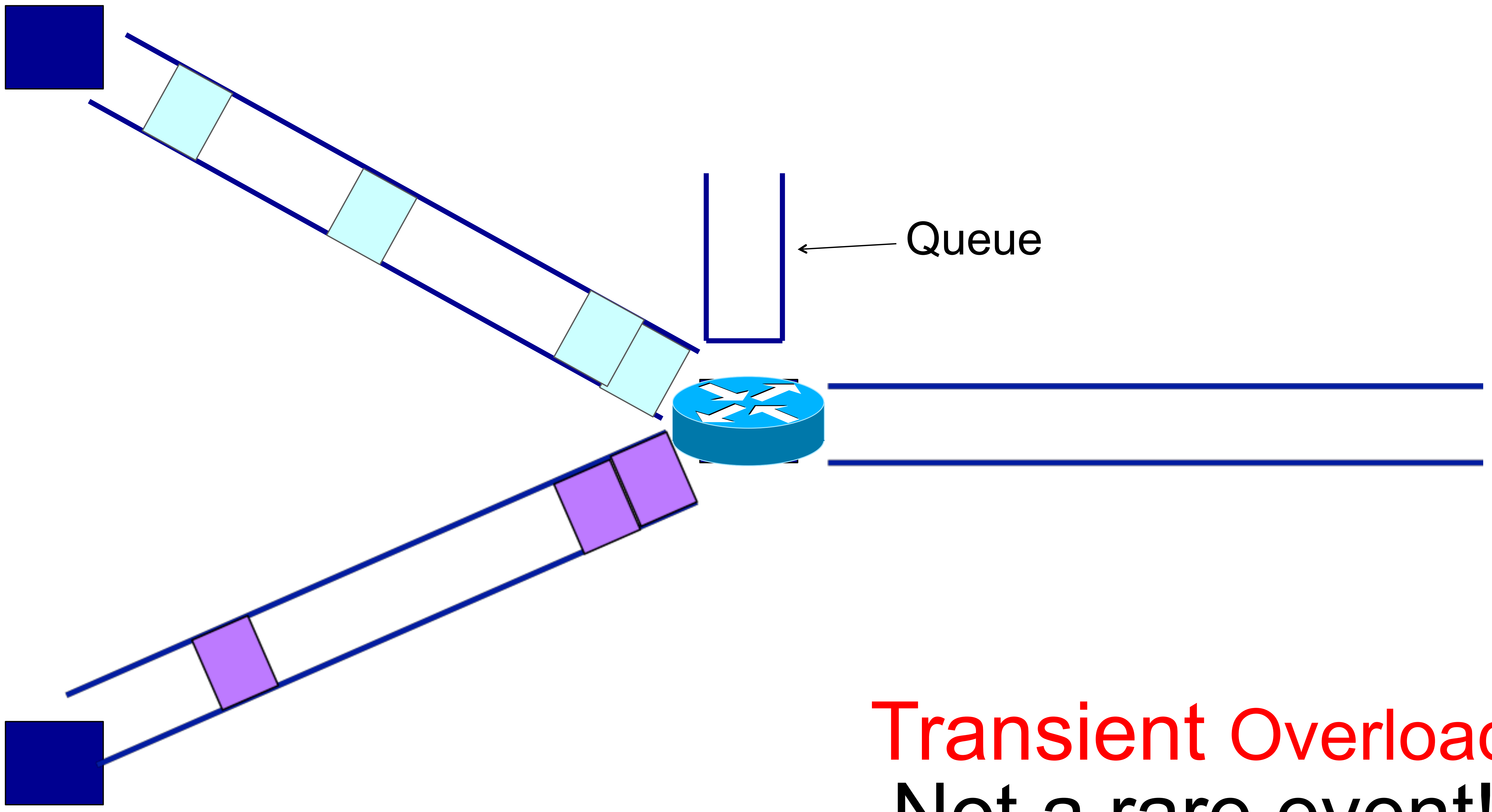


Statistical multiplexing: pipe view



Transient Overload
Not a rare event!

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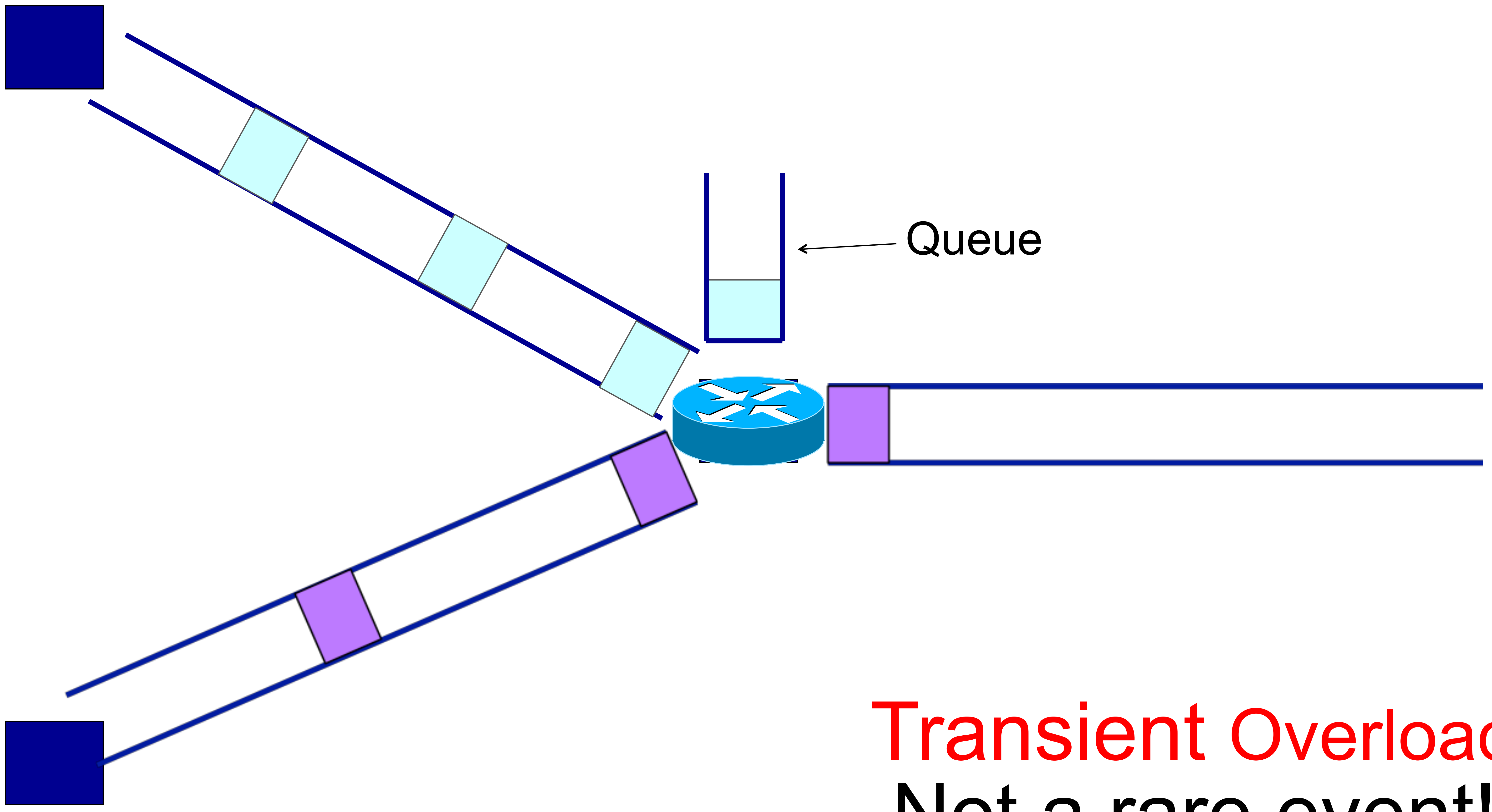

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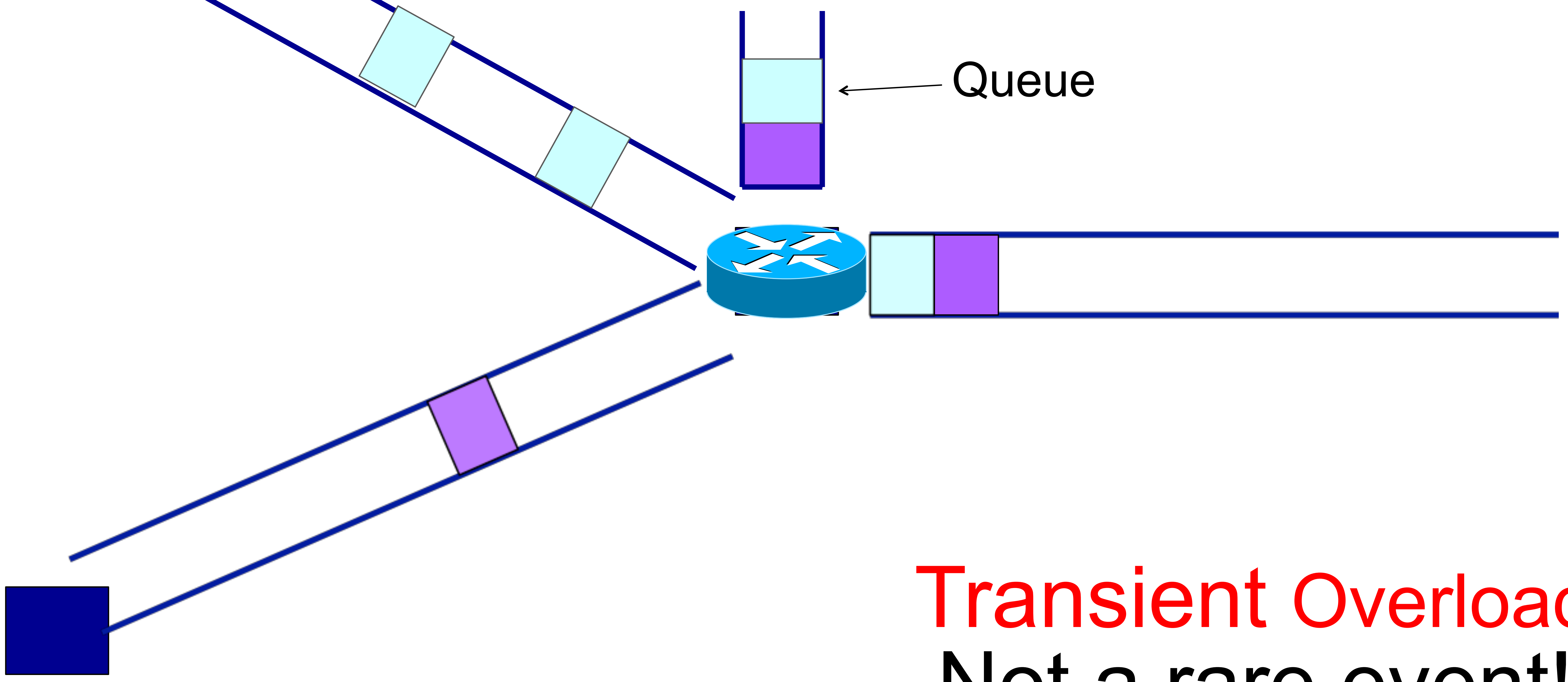

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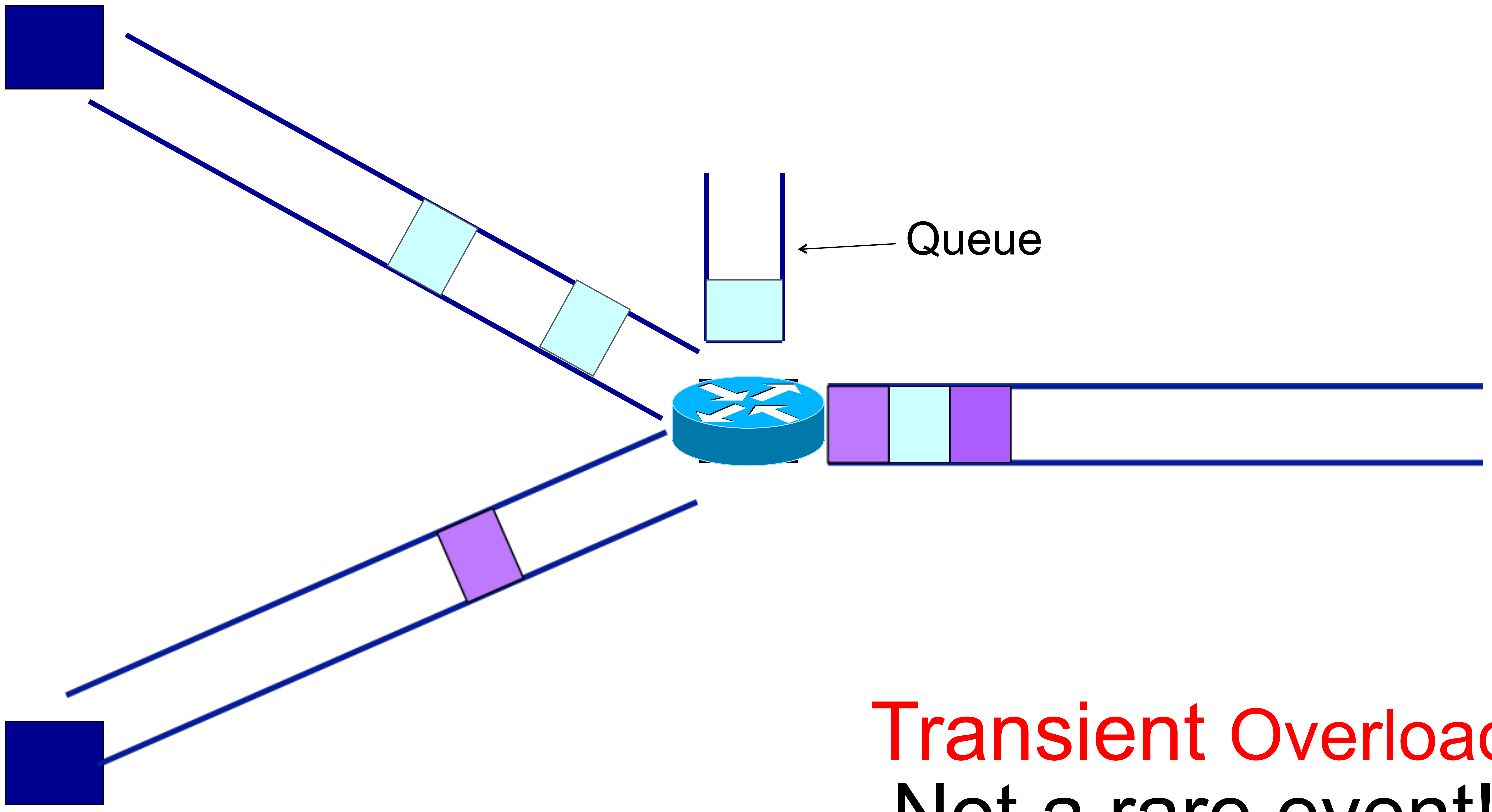

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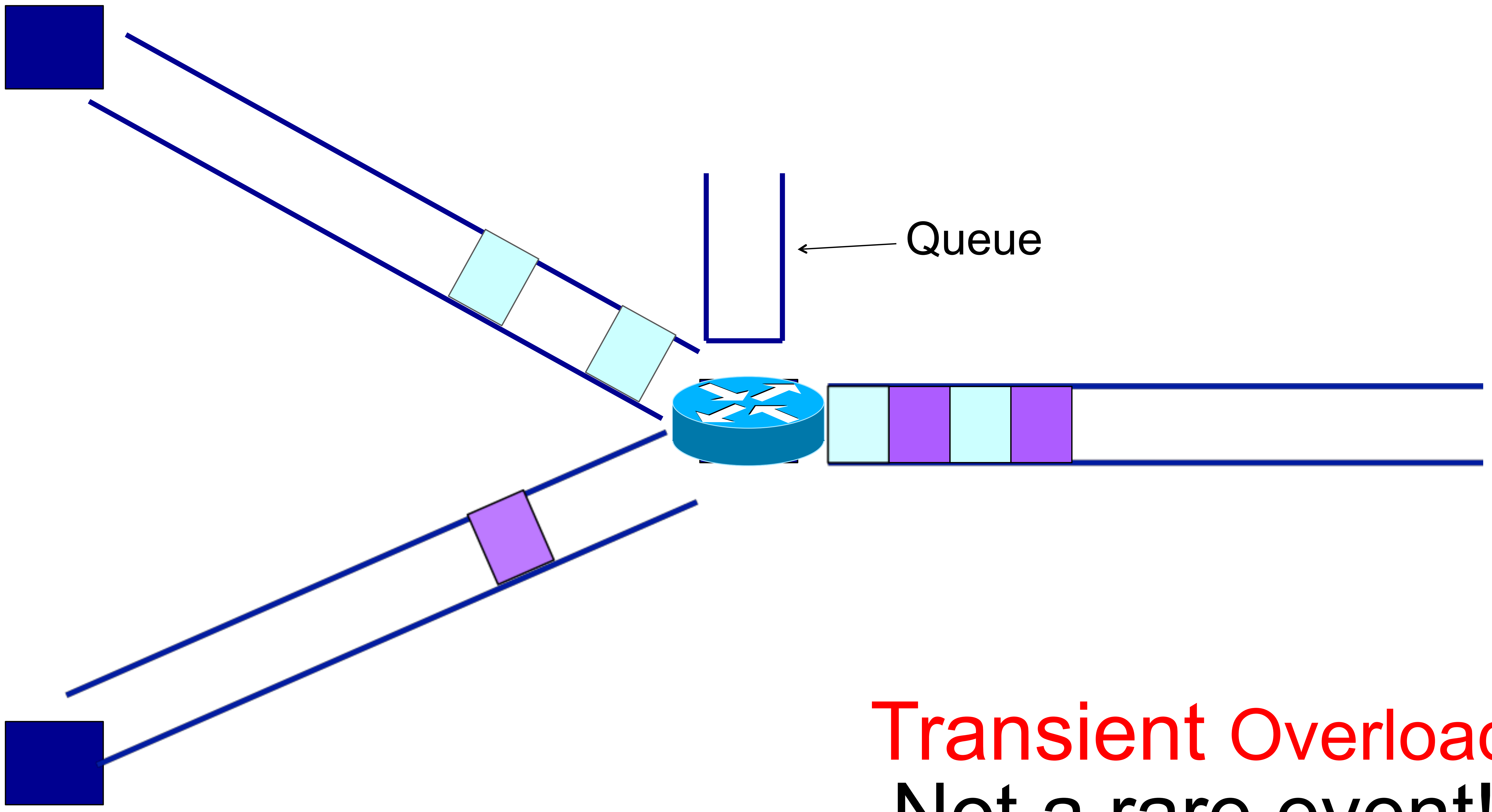

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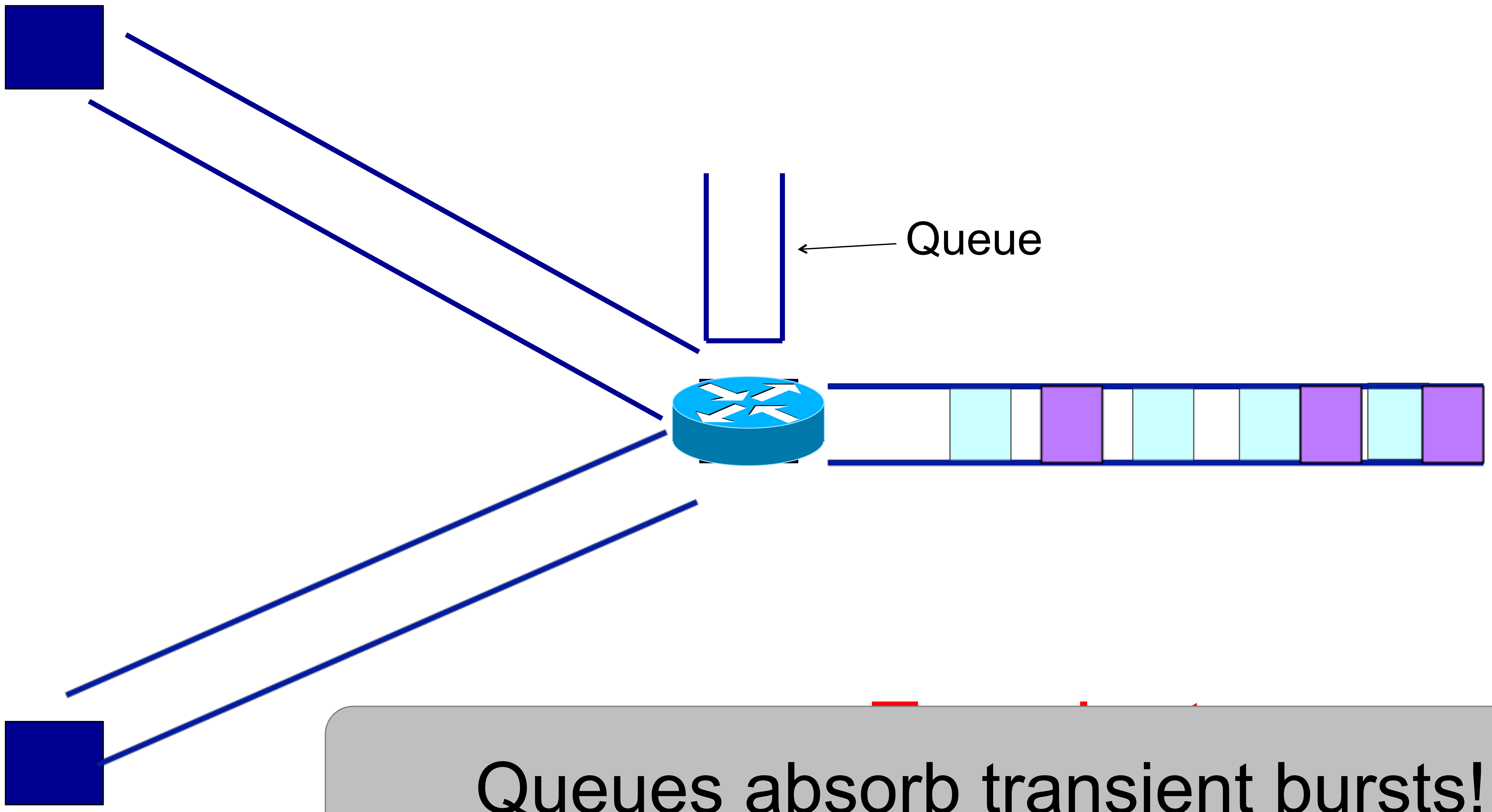
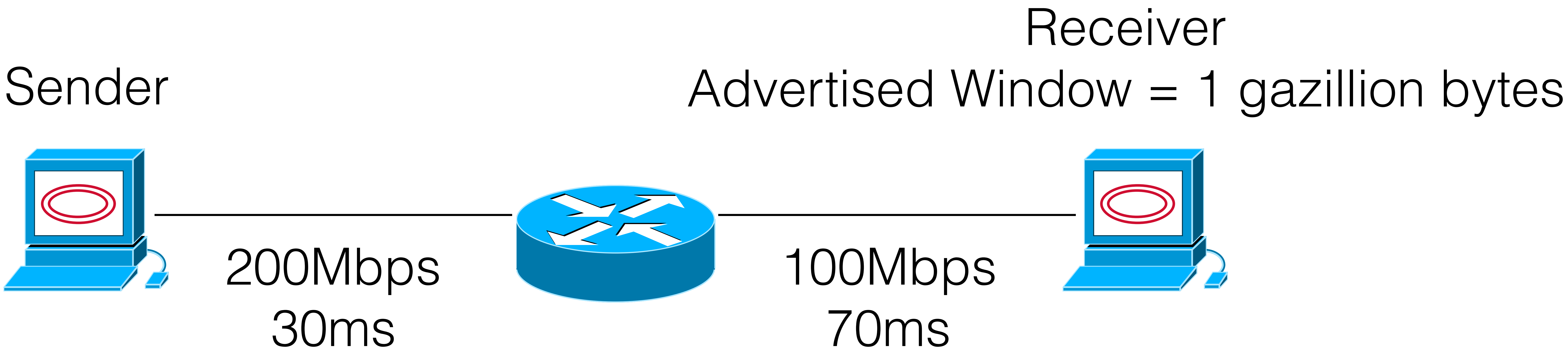


Queues absorb transient bursts!

BDP: 100Mbps * 200ms = 2.5MB



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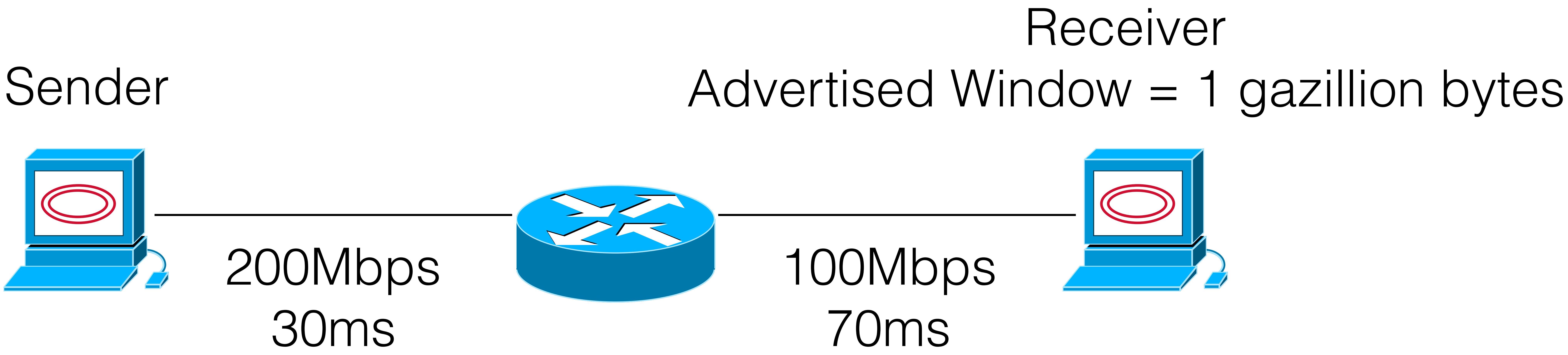
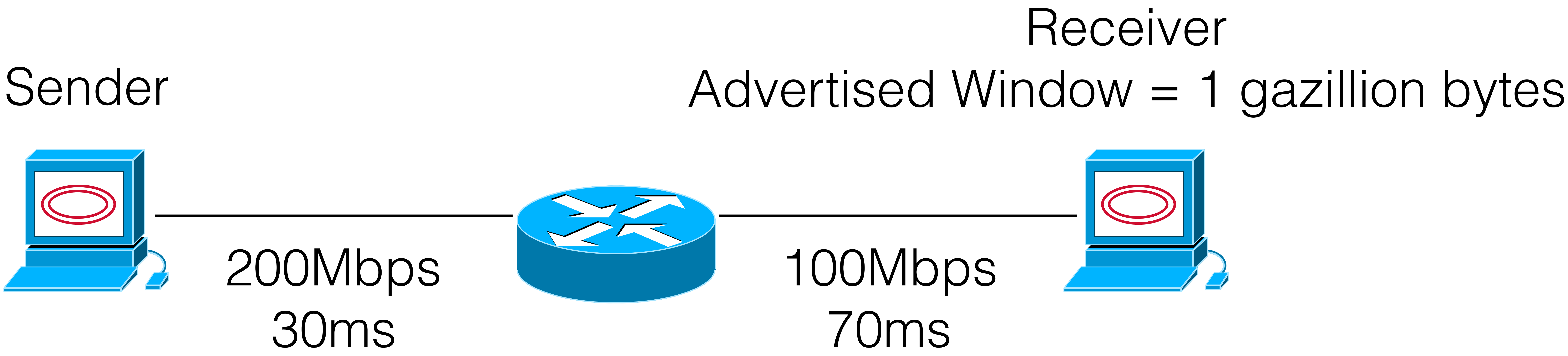


If I have 1000B payloads, my window will be 2500 packets.

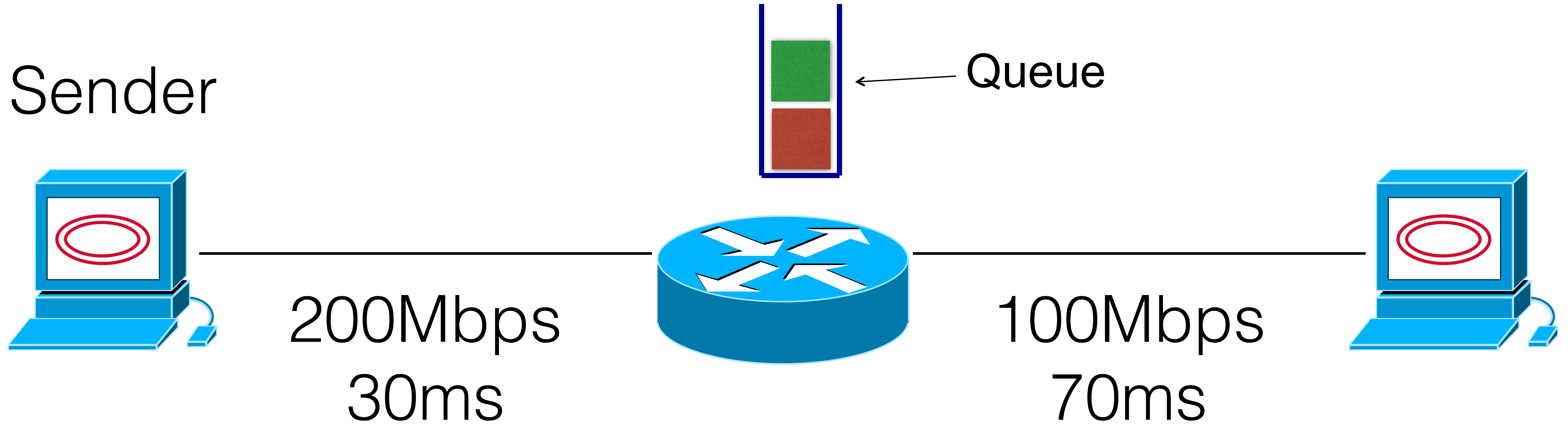
BDP: 100Mbps * 200ms = 2.5MB



Will packets get dropped if I set my window to, say, 2.6MB or 2600 packets?

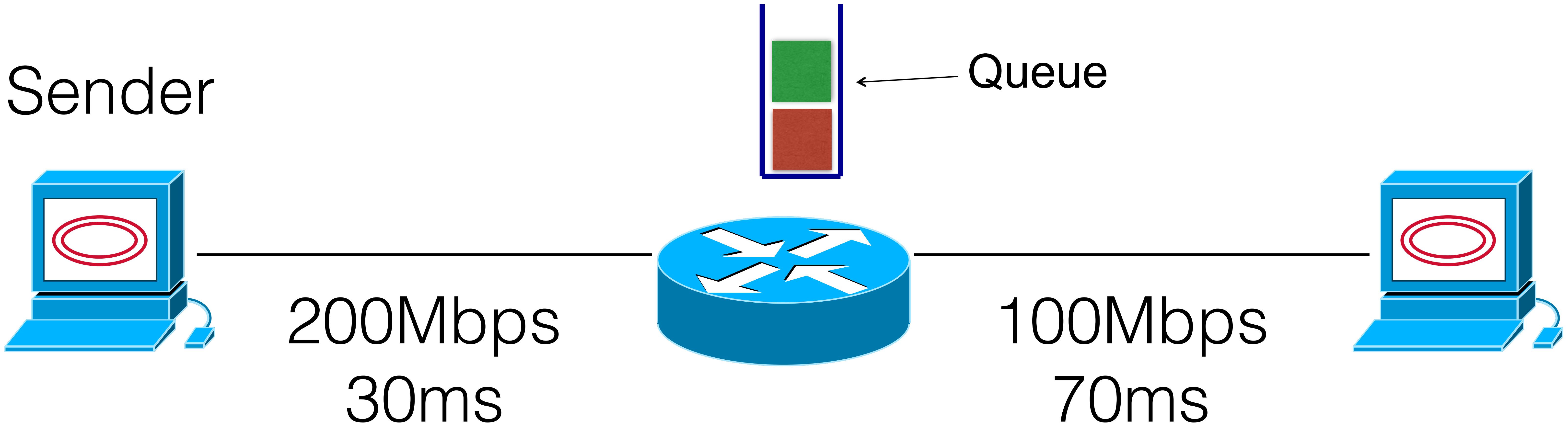
What do you think?

BDP: 100Mbps * 200ms = 2.5MB



If the queue can hold 100 more packets, none will be dropped!

BDP: 100Mbps * 200ms = 2.5MB



If the queue cannot “absorb” the extra packets, they will be dropped.

Problem Constraints

- The network does not tell us the bandwidth or the round trip time.
- My share of bandwidth is dependent on the other users on the network.
- Excess packets may not be dropped, but instead stalled in a bottleneck queue.
  - *Implication: It's okay to "overshoot" the window size, a little bit, and you still won't suffer packet loss.*

Congestion Control Algorithm: An algorithm to determine the appropriate window size, given the prior constraints.

There are *many* congestion control algorithms.

- TCP Reno and NewReno (the OG originals)
- Cubic (Linux, OSX)
- BBR (Google)
- LEDBAT (BitTorrent)
- Compound (Windows)
- FastTCP (Akamai)
- DCTCP (Microsoft Datacenters)
- TIMELY (Google Datacenters)
- Other weird stuff (ask Ranysha on Thursday)

Some History: TCP in the 1980s

- Sending rate only limited by flow control
  - Packet drops → senders (repeatedly!) retransmit a full window's worth of packets
- Led to "congestion collapse" starting Oct. 1986
  - Throughput on the NSF network dropped from 32Kbits/s to 40bits/sec
- "Fixed" by Van Jacobson's development of TCP's congestion control (CC) algorithms

Van Jacobsen

Internet Hall of Fame
Kobayashi Award
SIGCOMM Lifetime Achievement Award

- Inventor of TCP Congestion Control
- “TCP Tahoe”
- More recently, one of the co-inventors of Google’s BBR
- Author of many networking tools (traceroute, tcpdump)

LITERALLY SAVED THE INTERNET FROM COLLAPSE

Jacobson's Approach

- Extend TCP's existing window-based protocol but adapt the window size in response to congestion
    - required no upgrades to routers or applications!
    - patch of a few lines of code to TCP implementations

- A pragmatic and effective solution
    - but many other approaches exist

- Extensively improved upon
    - topic now sees less activity in ISP contexts
    - but is making a comeback in datacenter environments

The default TCP everyone teaches is TCP Reno, so that is what we will teach in this class.

* Even though Reno isn’t what Jacobsen invented.

** Even though our research at CMU suggests that it’s extinct — no one uses it anymore

*** On Thursday you’ll learn about “living” TCPs

TCP Reno: General Blueprint

- If a packet is lost, slow down! The packet is a signal that you are sending *too fast.*

- If you have been sending for a while and no packets are lost, speed up! No loss is a signal that you are probably are sending less than the link capacity.

How much should we slow down? Speed up?

- AIAD: Additive Increase, Additive Decrease
  - Every RTT, I increase my window by one. Every time I have a loss, I decrease my window by one.
- MIAD: Multiplicative Increase, Additive Decrease
  - Every RTT, I increase my window by 2x. Every time I have a loss, I decrease my window by one.
- AIMD: Additive Increase, Multiplicative Decrease
  - Every RTT, I increase my window by 1. Every time I have a loss, I decrease my window by 2x.
- MIMD: Additive Increase, Multiplicative Decrease
  - Every RTT, I increase my window by 2x. Every time I have a loss, I decrease my window by 2x.

Let’s Try It

- Turn to a partner. One of you will be “the network”, the other will be “the sender.”

- Network:
    - Choose a random number between 1 and 30. This is your BDP.
    - Every time your partner guesses, tell them “drop” if they overshoot, or “no drop” if they undershoot.
    - On a piece of paper, keep track of how many times your partner guessed, and keep track of how many packets are “lost”
        - If my partner guesses 40, and my secret number is 28, we “lost” 12 packets and transmitted 28.

- Sender:
    - Choose an algorithm (AIMD, MIMD, MIAD, or AIAD) and an *initial window size* — a random number from 1-30 that is your first window size.
    - Tell your partner “I transmit $windowsize packets”
        - Your partner will tell you whether there were dropped packets or no dropped packets.
    - Adjust your window according to the algorithm and then make another guess.

Who thinks they had a good algorithm/initial window size?

- What algorithm did you choose?
    - Why is it a good algorithm?
- What initial window size did you choose?
    - Why is it a good initial window size?

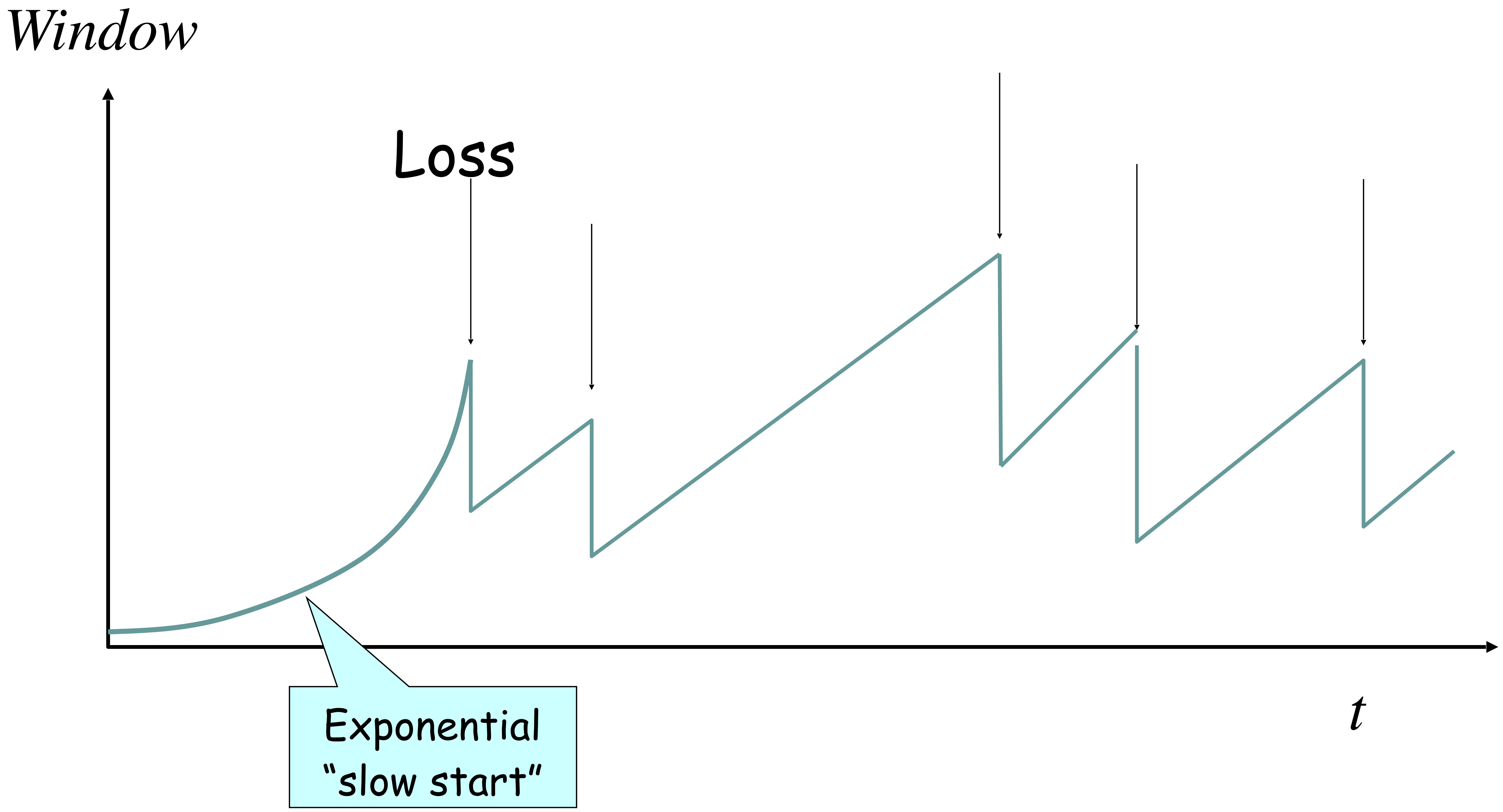
Challenges

- If you overshoot, lots of packets can be lost — for you and anyone else sharing the link!
    - Wastes network resources
    - Slows down transmission overall (have to wait for timers to go off)
    - Wastes CPU time (complicates book-keeping at sender and receiver)
- If you undershoot your transmission is slower than it could be…. :(

TCP Reno

- Uses Multiplicative Increase at startup to find the “right” sending rate quickly. Initial window size is set to 4.
    - For historical reasons this is called “slow start” — senders used to just pick an insane high initial window size and this was “slower” than that.
- Under normal operation, uses Additive Increase/Multiplicative Decrease (AIMD) to adjust the sending rate over time.

Leads to the TCP “Sawtooth”



Slow-Start vs. AIMD

- When does a sender stop Slow-Start and start Additive Increase?

- Introduce a "slow start threshold" (ssthresh)
  - Initialized to a large value

- When window = ssthresh, sender switches from slow-start to AIMD-style increase

  - Or if a drop happens.

Why AIMD?

- Key idea:
  - Be cautious in consuming new resources
    - So we don’t cause another congestion collapse!
  - Be aggressive in slowing down at packet drops.
    - So we don’t cause another congestion collapse!
- Other nice properties: AIMD is guaranteed to converge to a *fair share* between two senders sharing the same link with the same RTT.
  - More on this on Thursday.

Today's Agenda

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- #2: How should we determine the BDP?
- **#3: How does "plain" TCP work?**

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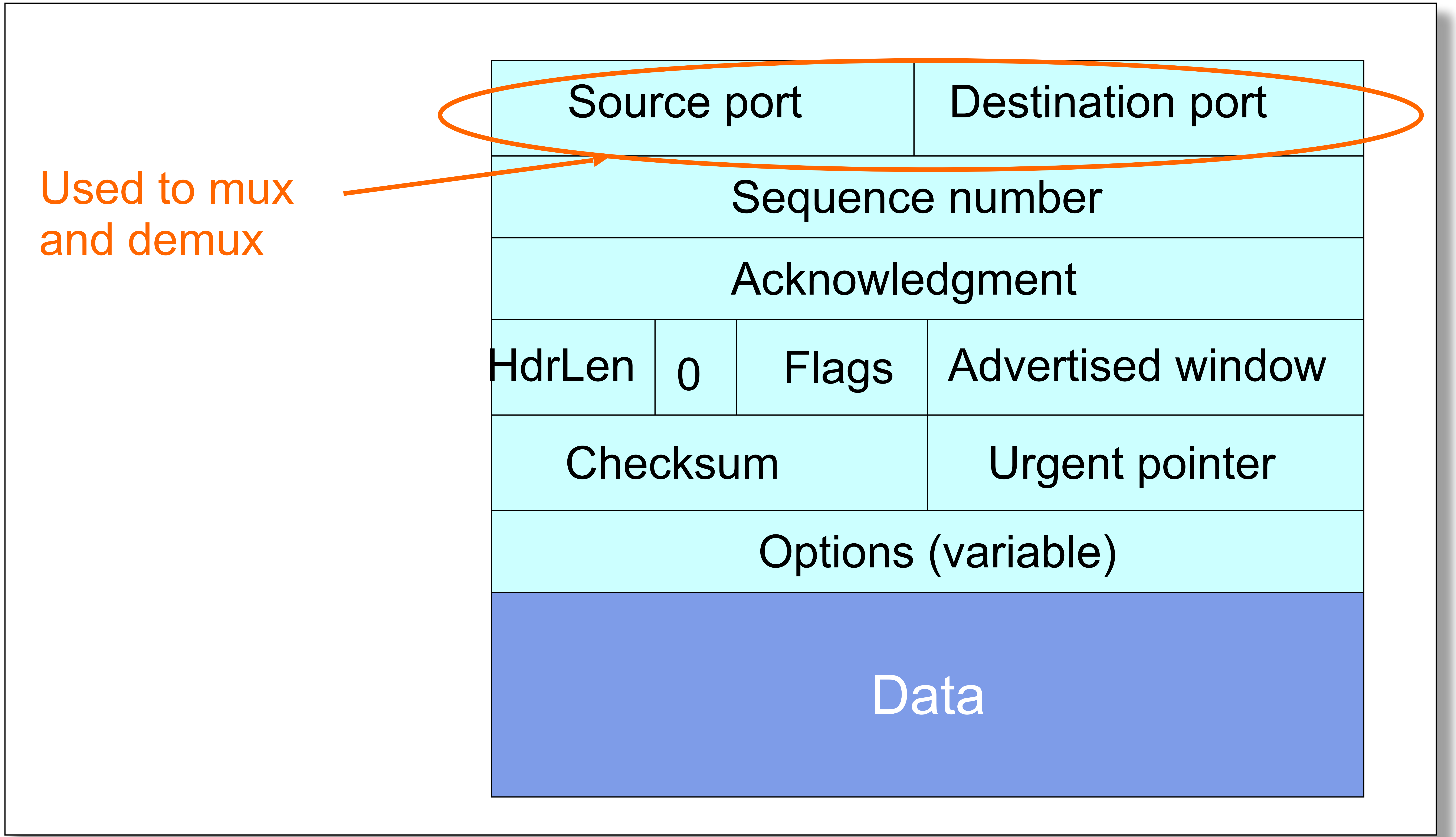
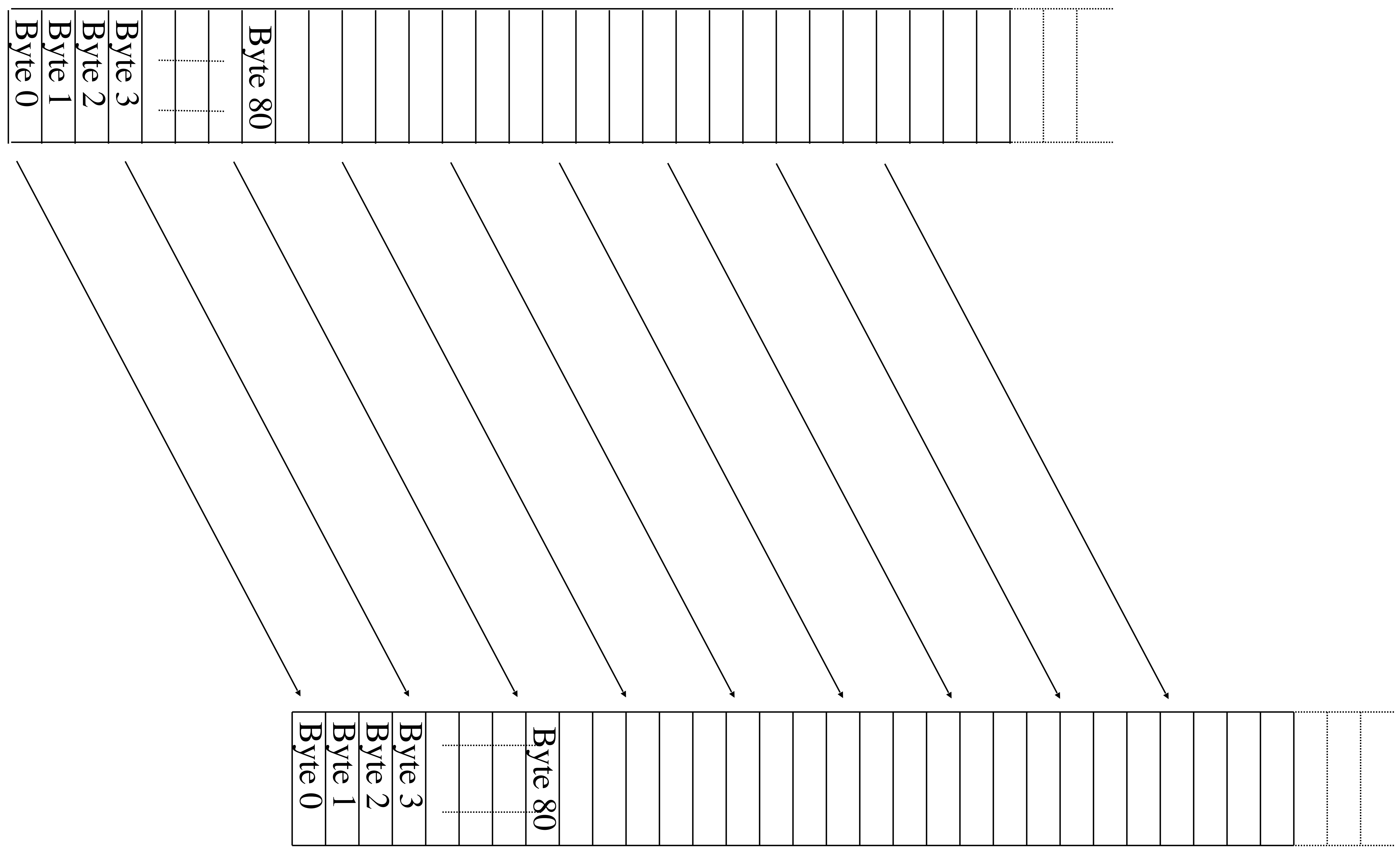
- #2: How should we determine the BDP?
- **#3: How does "~~plain~~" TCP Reno work?**

TCP Header


Used to mux
and demux
Source port
Destination port
Sequence number
Acknowledgment
HdrLen
0
Flags
Advertised window
Checksum
Urgent pointer
Options (variable)
Data

TCP “Stream of Bytes” Service…

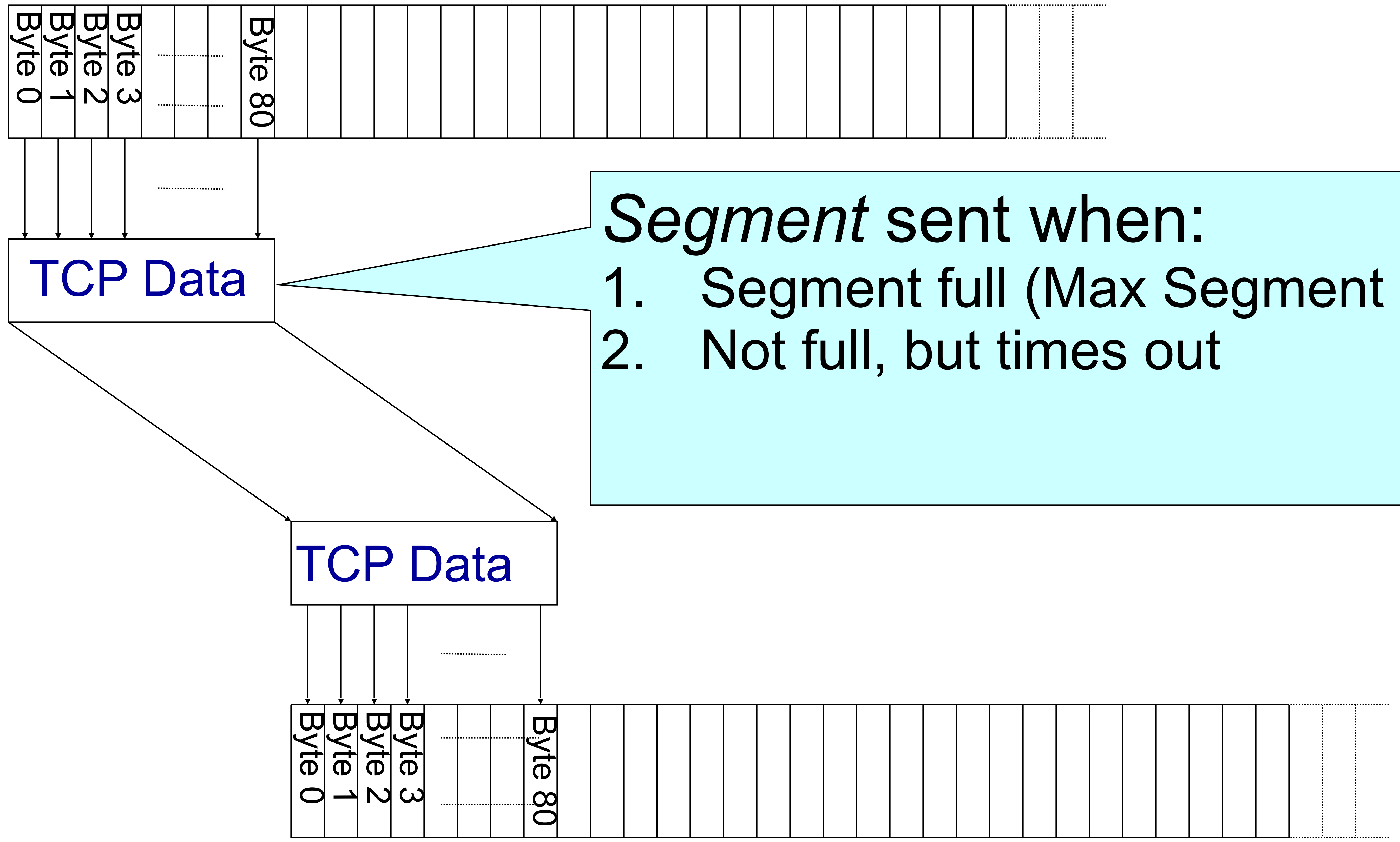
Application @ Host A



Application @ Host B

… Provided Using TCP "Segments"

Host A

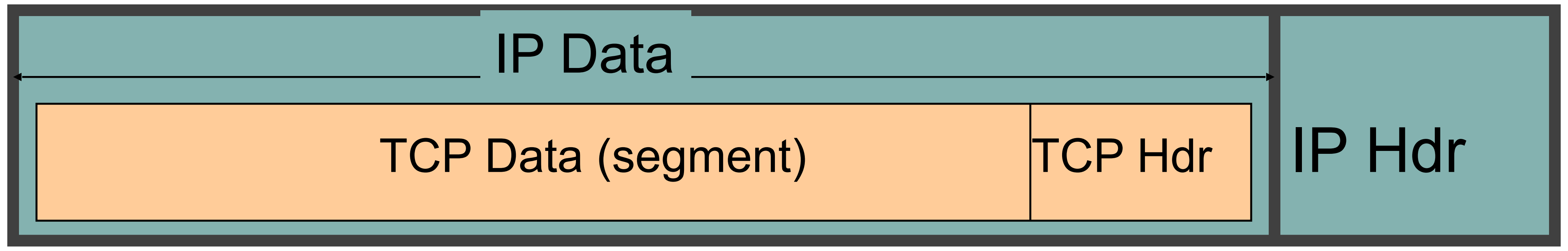


Segment sent when:

1. Segment full (Max Segment Size),
2. Not full, but times out

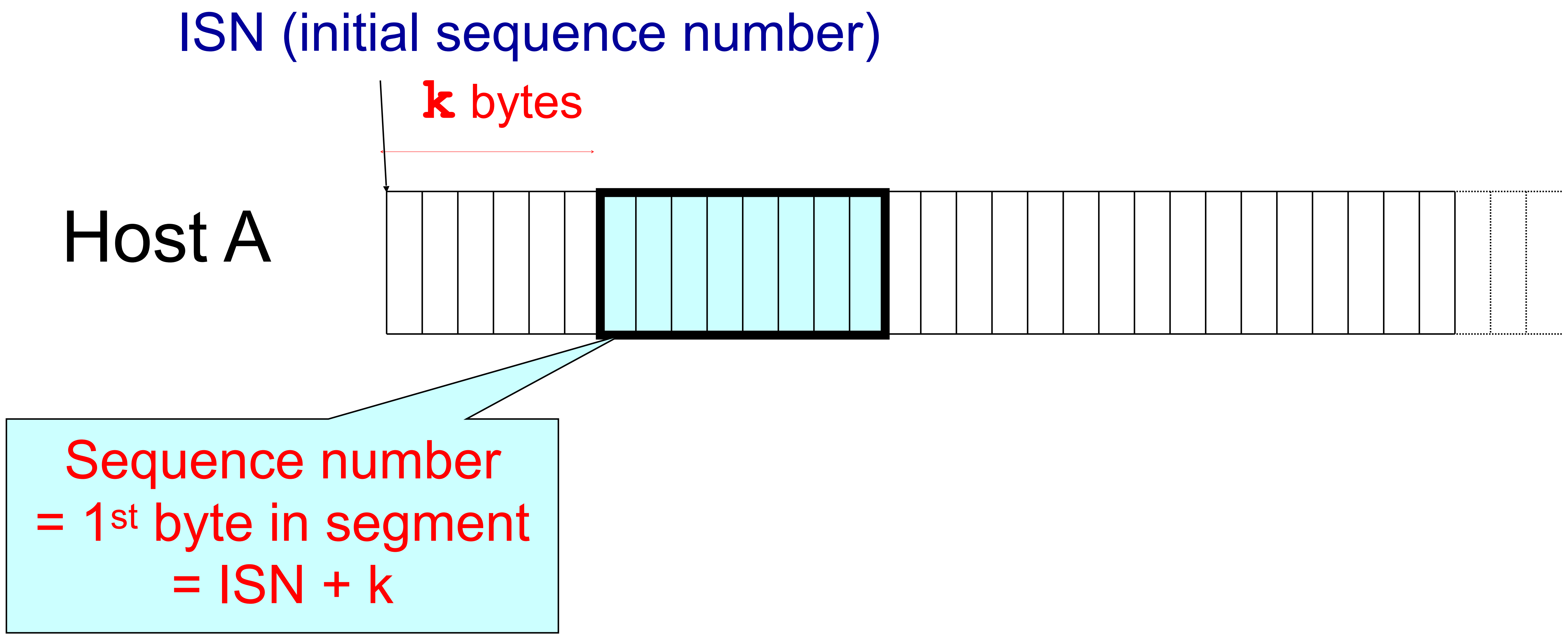
Host B

TCP Segment

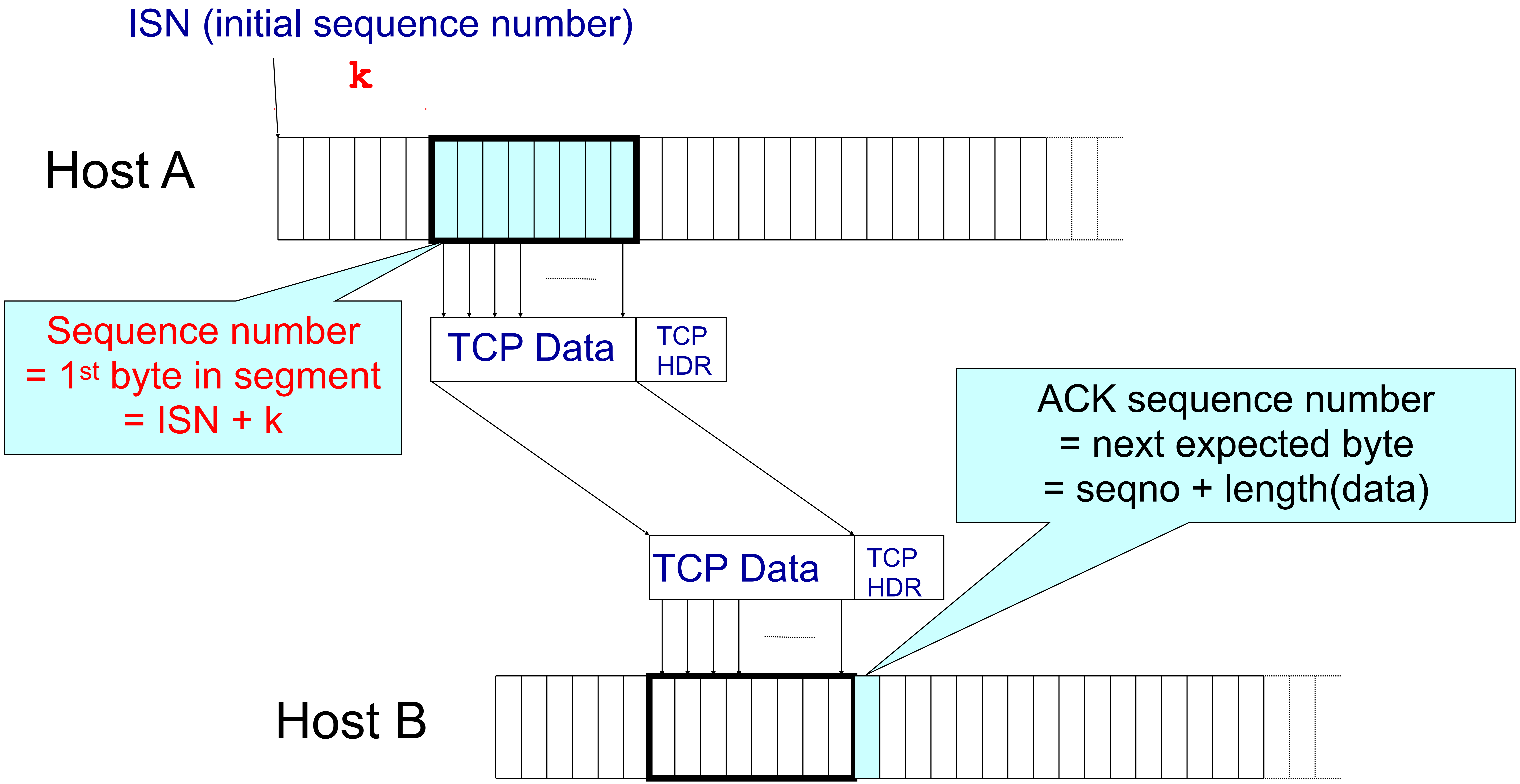


- IP packet
  - No bigger than Maximum Transmission Unit (MTU)
  - E.g., up to 1500 bytes with Ethernet
- TCP packet
  - IP packet with a TCP header and data inside
  - TCP header ≥ 20 bytes long
- TCP **segment**
  - No more than Maximum Segment Size (MSS) bytes
  - E.g., up to 1460 consecutive bytes from the stream
  - MSS = MTU – (IP header) – (TCP header)

Sequence Numbers

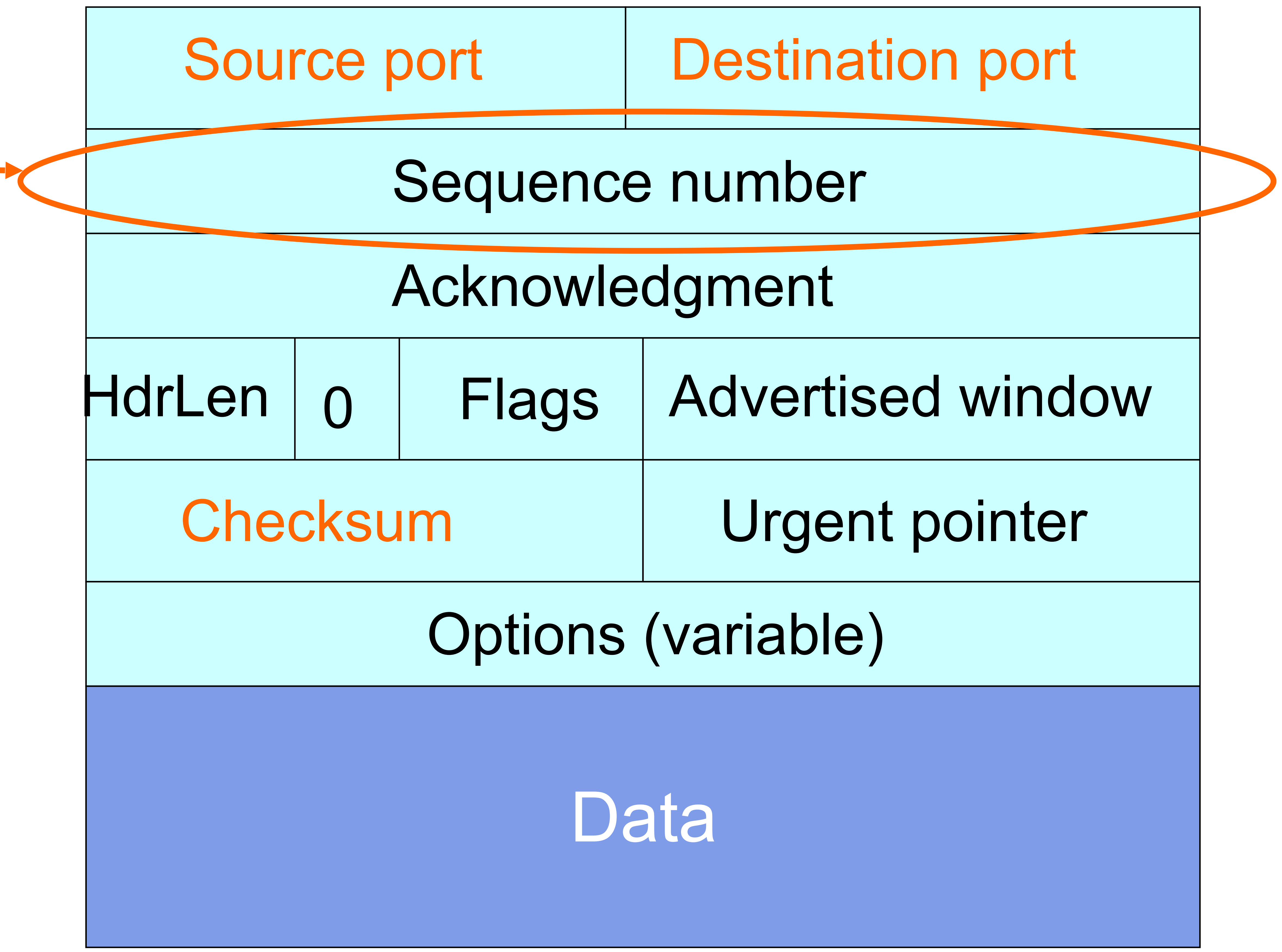


Sequence Numbers



TCP Header

Starting byte offset of data carried in this segment



TCP Header

Acknowledgment gives seqno just beyond highest seqno received **in order**
("What Byte is Next")

Remember: CUMULATIVE — this means I have every byte before this sequence number

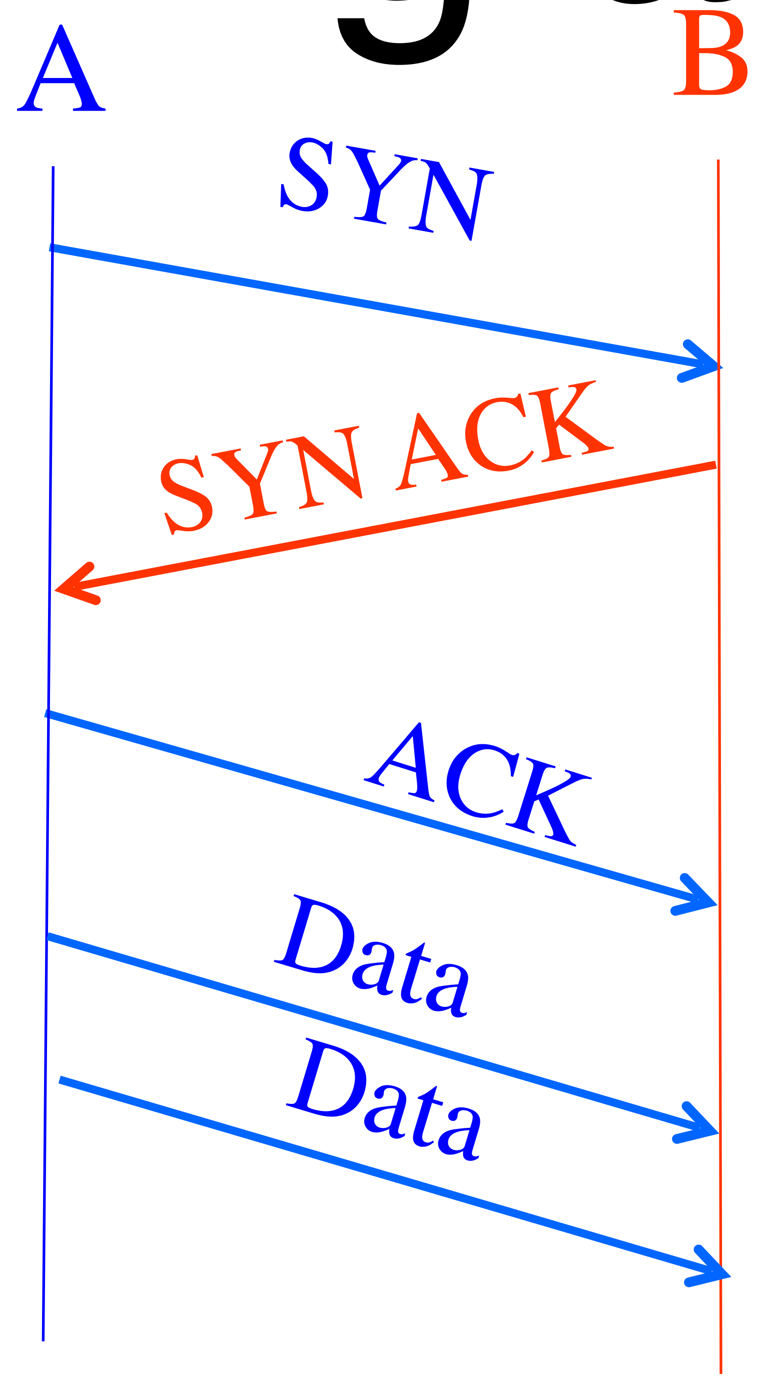
Source port		Destination port	
Sequence number			
Acknowledgment			
HdrLen	0	Flags	Advertised window
Checksum		Urgent pointer	
Options (variable)			
Data			

TCP Connection Establishment and Initial Sequence Numbers

Initial Sequence Number (ISN)

- Sequence number for the very first byte
- Why not just use ISN = 0?
- Practical issue
  - IP addresses and port #s uniquely identify a connection
  - Eventually, though, these port #s do get used again
  - … small chance an old packet is still in flight
- TCP therefore requires changing ISN
- Hosts exchange ISNs when they establish a connection

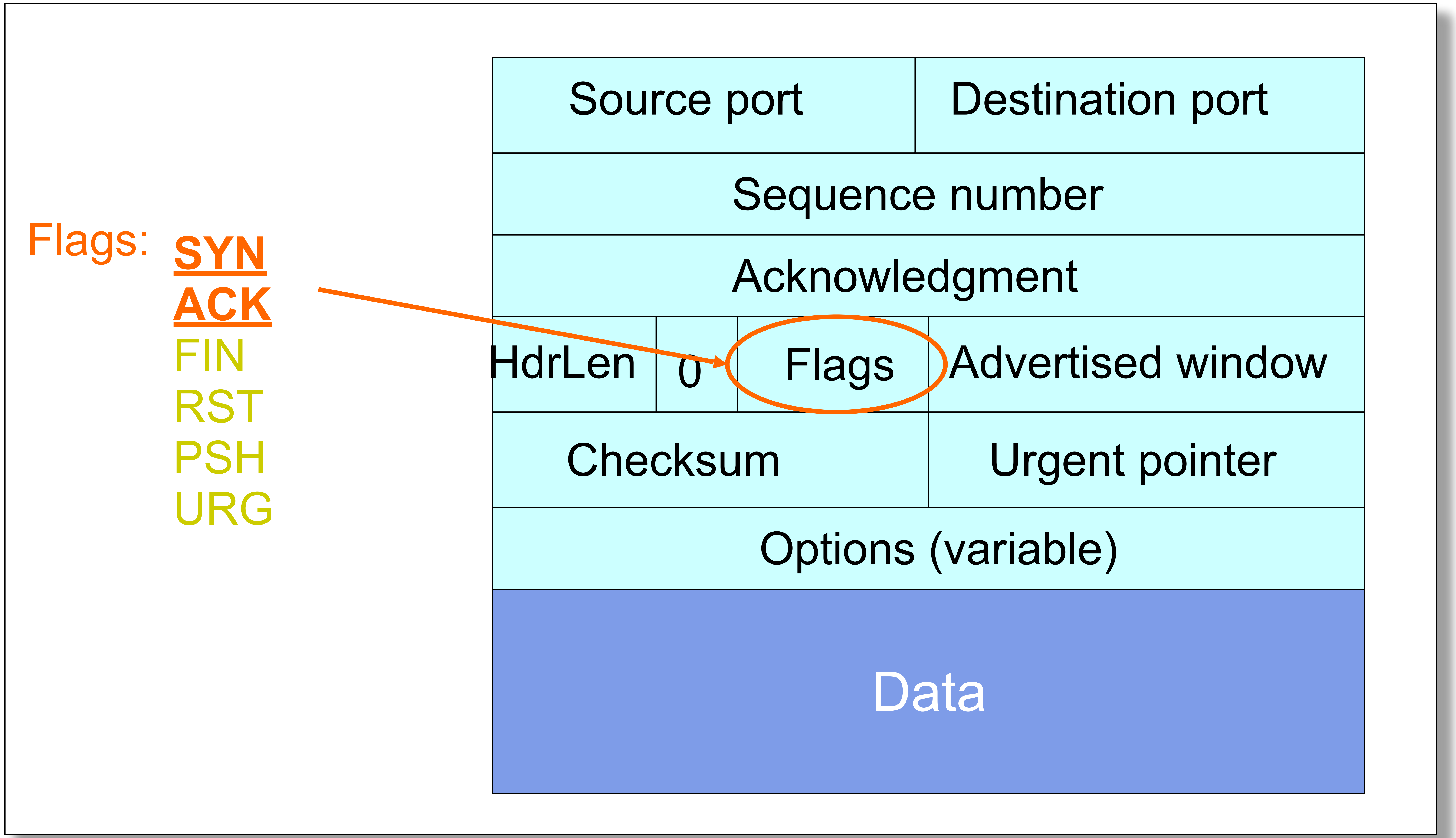
Establishing a TCP Connection



Each host tells its ISN to the other host.

- Three-way handshake to establish connection
  - Host A sends a **SYN** (open; “synchronize sequence numbers”) to host B
  - Host B returns a SYN acknowledgment (**SYN ACK**)
  - Host A sends an **ACK** to acknowledge the SYN ACK

TCP Header


Flags: SYN
ACK
FIN
RST
PSH
URG
Source port
Destination port
Sequence number
Acknowledgment
HdrLen
0
Flags
Advertised window
Checksum
Urgent pointer
Options (variable)
Data

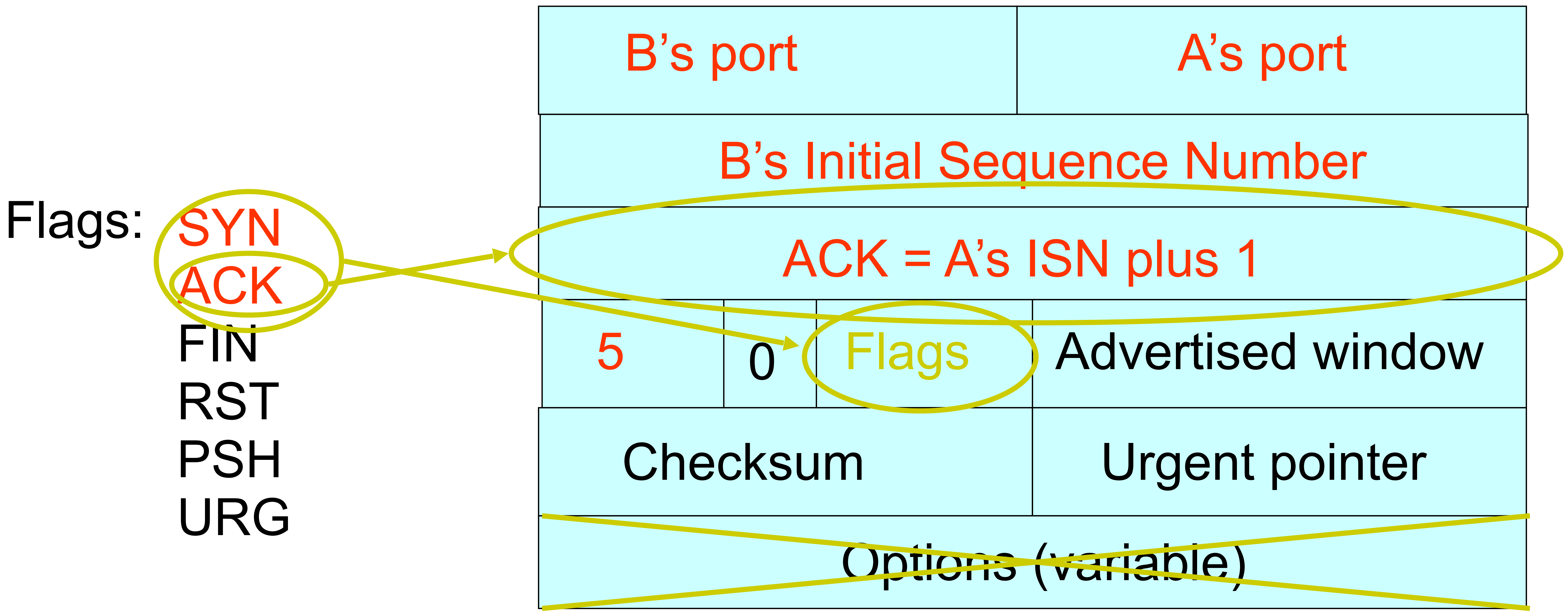
Step 1: A's Initial SYN Packet

Flags: SYN
ACK
FIN
RST
PSH
URG

A's port		B's port	
A's Initial Sequence Number			
(Irrelevant since ACK not set)			
5	0	Flags	Advertised window
Checksum		Urgent pointer	
~~Options (variable)~~			

A tells B it wants to open a connection…

Step 2: B's SYN-ACK Packet



B tells A it accepts, and is ready to hear the next byte…

… upon receiving this packet, A can start sending data

Step 3: A's ACK of the SYN-ACK

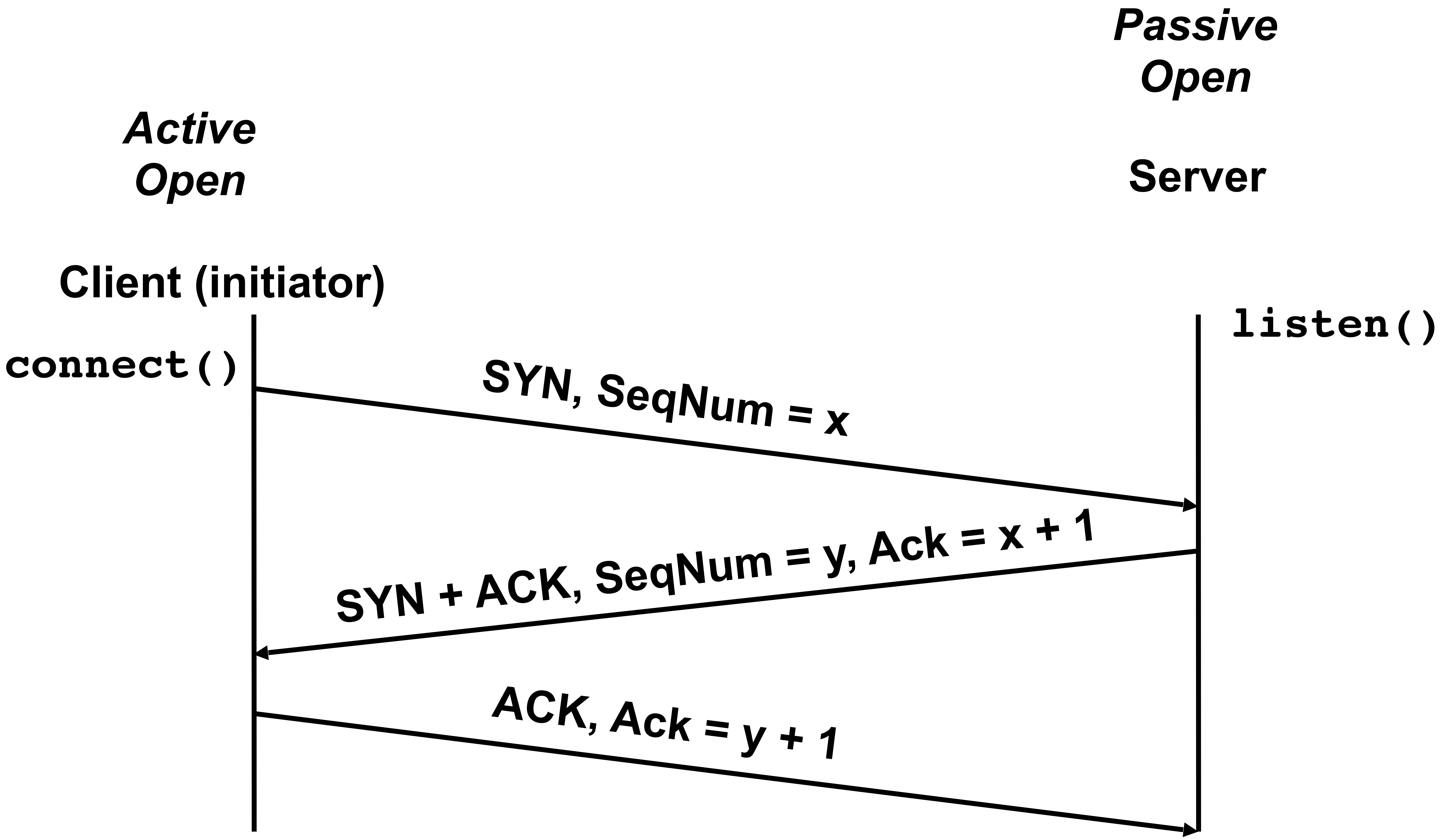
Flags: SYN
ACK
FIN
RST
PSH
URG

A's port			B's port
A's Initial Sequence Number			
B's ISN plus 1			
20B	0	Flags	Advertised window
Checksum			Urgent pointer
~~Options (variable)~~			

A tells B it's likewise okay to start sending

… upon receiving this packet, B can start sending data

Timing Diagram: 3-Way Handshaking



What if the SYN Packet Gets Lost?

- Suppose the SYN packet gets lost
  - Packet is lost inside the network, or:
  - Server discards the packet (e.g., it's too busy)

- Eventually, no SYN-ACK arrives
  - Sender sets a timer and waits for the SYN-ACK
  - … and retransmits the SYN if needed

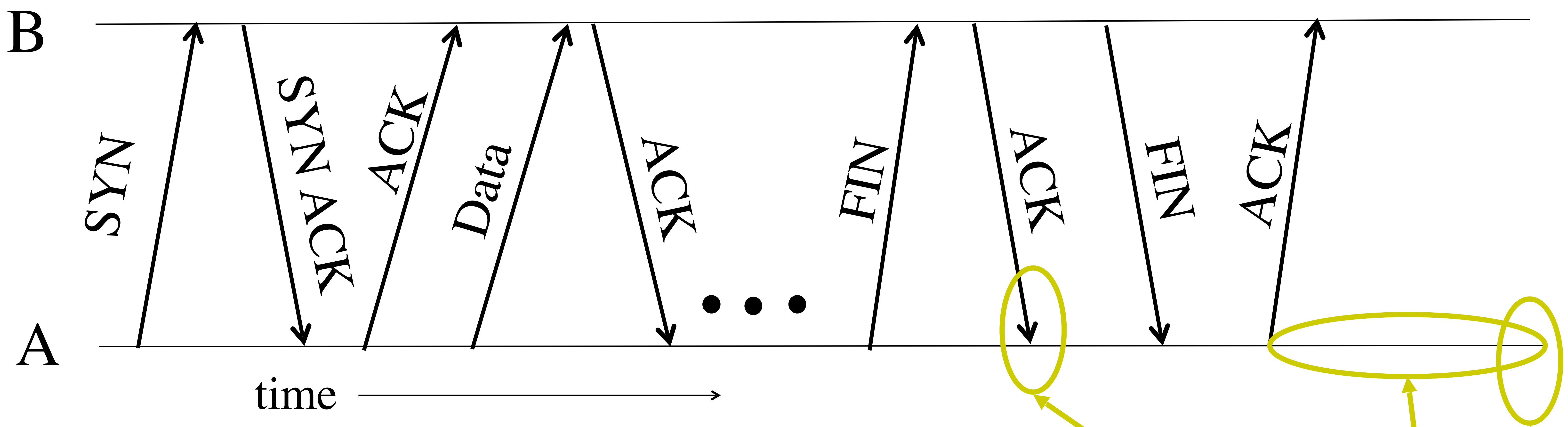
- How should the TCP sender set the timer?
  - Sender has no idea how far away the receiver is
  - Hard to guess a reasonable length of time to wait
  - **SHOULD** (RFCs 1122 & 2988) use default of 3 seconds
    - Some implementations instead use 6 seconds

SYN Loss and Web Downloads

- User clicks on a hypertext link
  - Browser creates a socket and does a "connect"
  - The "connect" triggers the OS to transmit a SYN
- If the SYN is lost…
  - 3-6 seconds of delay: can be very long
  - User may become impatient
  - … and click the hyperlink again, or click "reload"
- User triggers an "abort" of the "connect"
  - Browser creates a new socket and another "connect"
  - Essentially, forces a faster send of a new SYN packet!
  - Sometimes very effective, and the page comes quickly

Tearing Down the Connection

Normal Termination, One Side At A Time



- Finish (**FIN**) to close and receive remaining bytes
  - **FIN** occupies one byte in the sequence space
- Other host acks the byte to confirm
- Closes A's side of the connection, but not B's
  - Until B likewise sends a **FIN**
  - Which A then acks

Connection now **closed**

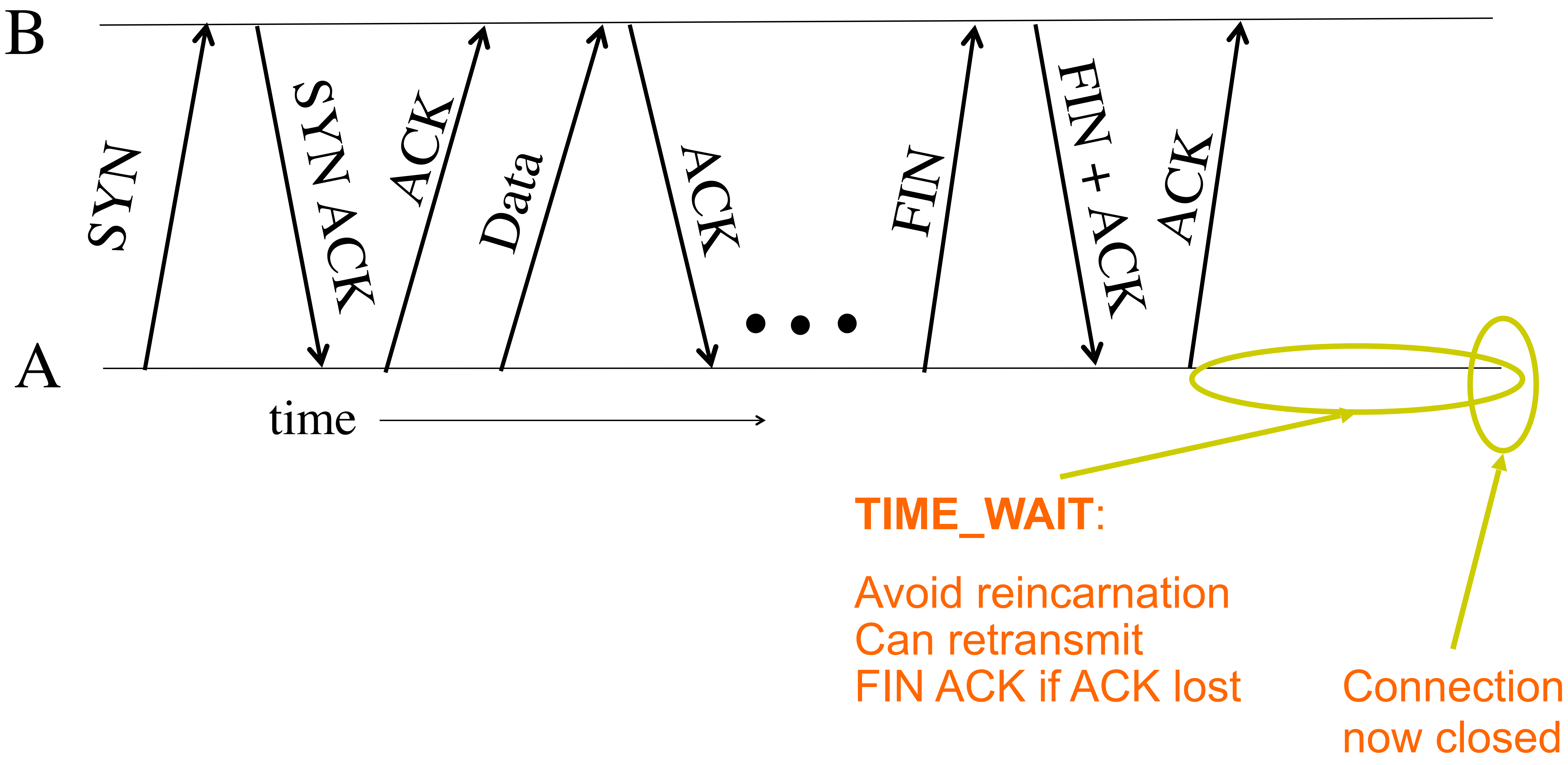
Connection now **half-closed**

TIME_WAIT:

Avoid reincarnation

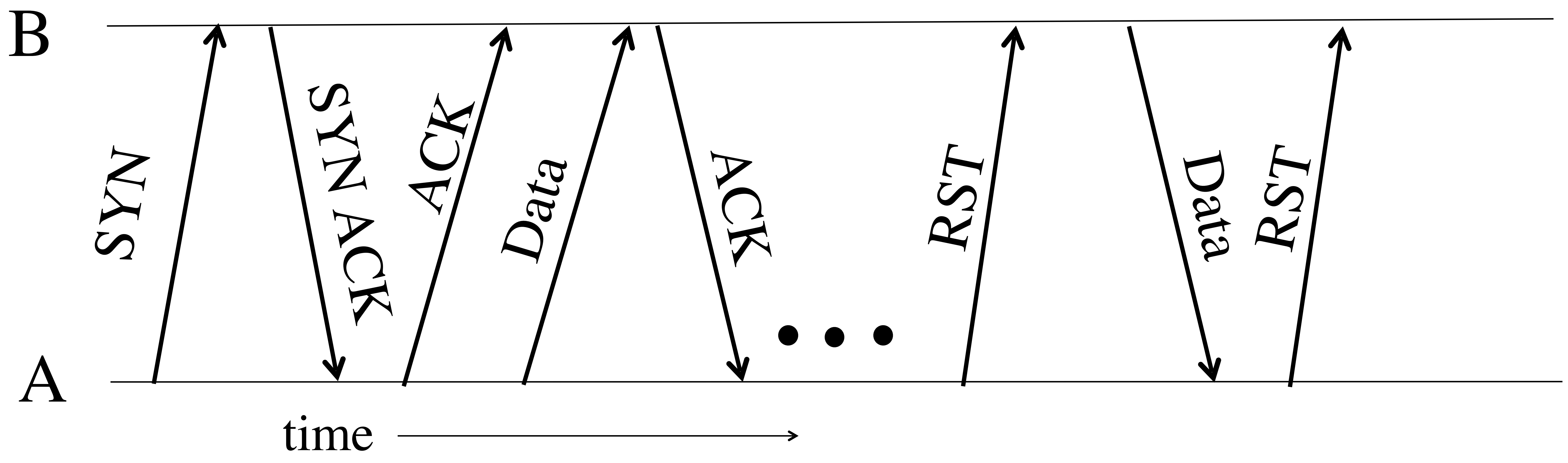
B will retransmit FIN if ACK is lost

Normal Termination, Both Together



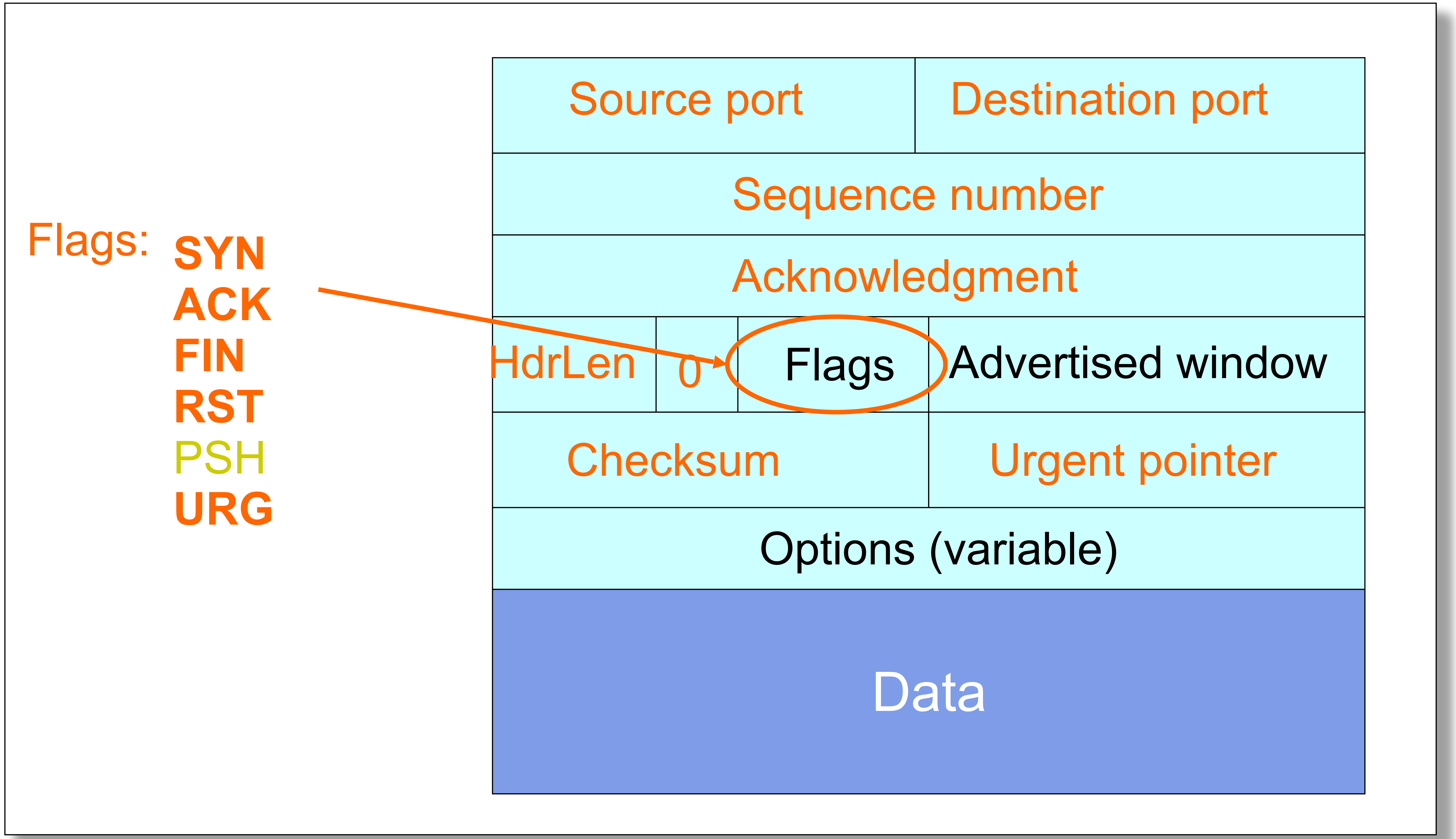
- Same as before, but B sets **FIN** with their ack of A's **FIN**

Abrupt Termination

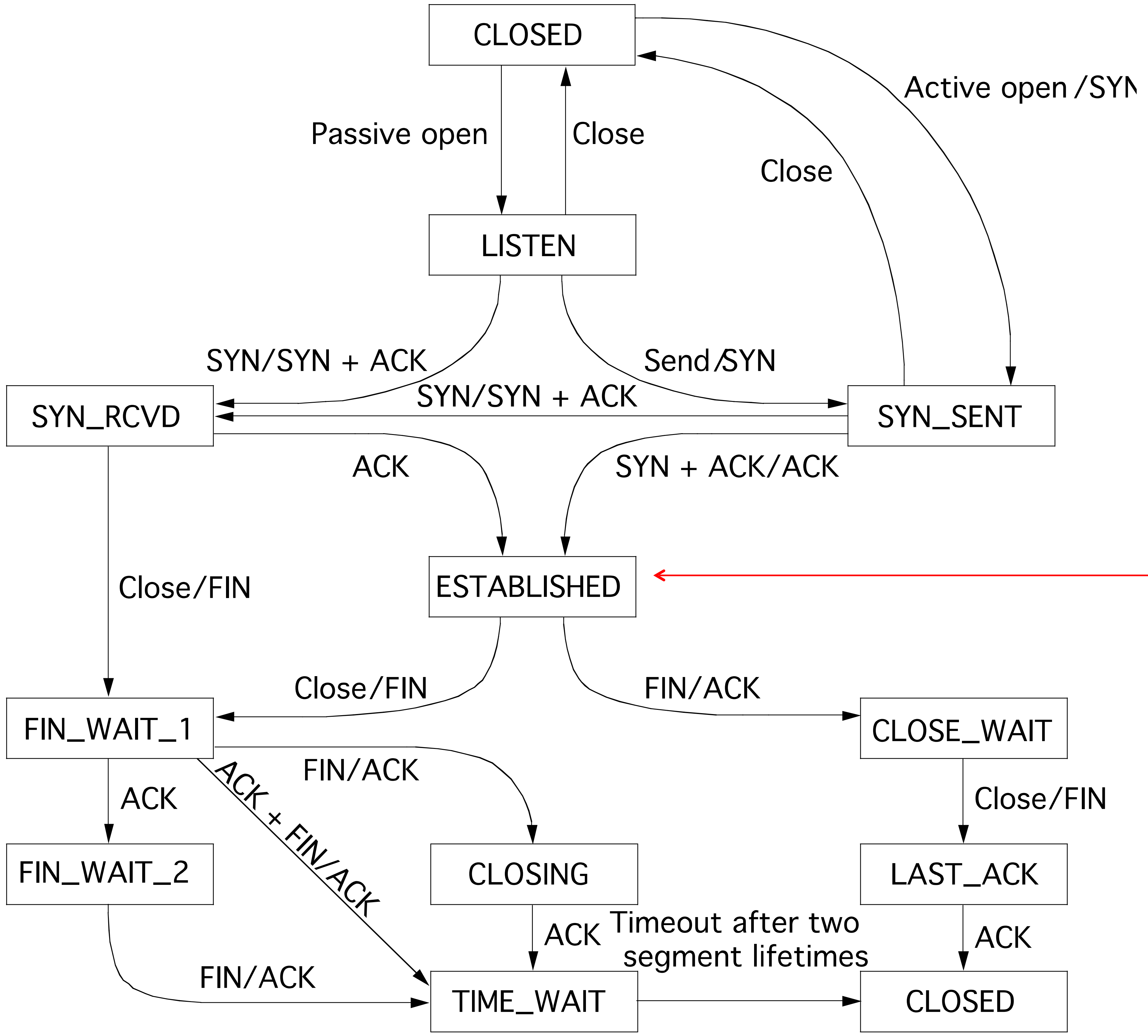


- A sends a RESET (**RST**) to B
  - E.g., because application process on A crashed
- That's it
  - B does not ack the **RST**
  - Thus, **RST** is not delivered reliably
  - And: any data in flight is lost
  - But: if B sends anything more, will elicit another **RST**

TCP Header


Flags:
SYN
ACK
FIN
RST
PSH
URG
Source port
Destination port
Sequence number
Acknowledgment
HdrLen
0
Flags
Advertised window
Checksum
Urgent pointer
Options (variable)
Data

TCP State Transitions



Data, ACK exchanges are in here

After all that work…

- ESTABLISHED is the part where we transmit data.
- When our congestion control algorithm runs.

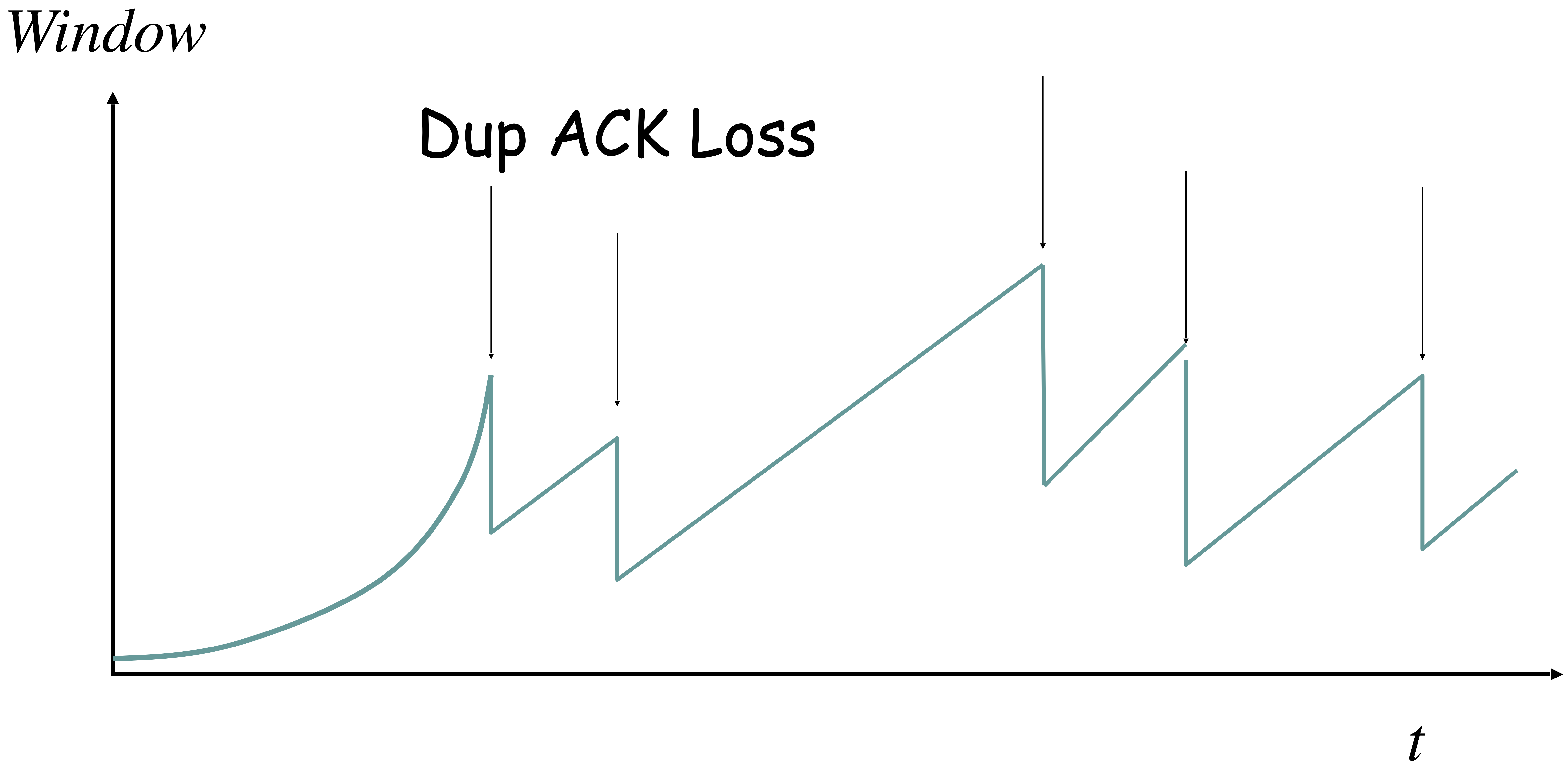
AIMD Mechanics in Reno

- "CWND" is the measured "congestion window"
  - Sending window is min(CWND, Advertised Window)
- Reno follows three key stages to determine CWND:
  - (1) Slow start, where it uses multiplicative increase
  - (2) Congestion avoidance, where it uses additive increase
  - (3) Fast recovery, where it "recovers" from "easy" packet losses.
    - *What do you mean, Easy Packet Losses?*

Duplicate ACKs

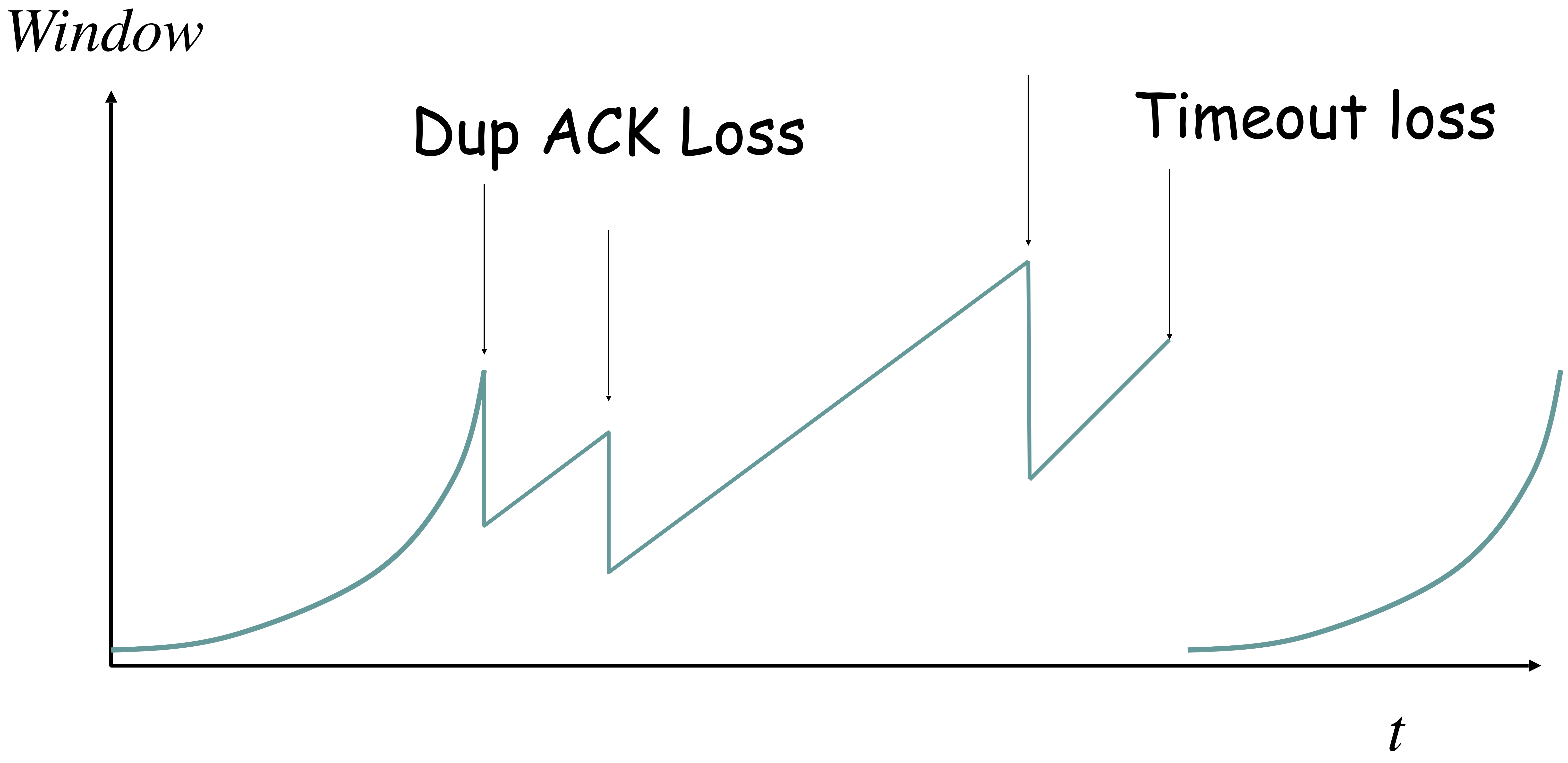
- I can pre-emptively figure out that loss has happened without a timer going off.
- How?
    - Say I receive packets with MSS 1000, sequence numbers 1000, 2000, 4000, 5000, 6000….
    - I know I missed 3000!
- Recall that TCP uses cumulative ACKs — I ACK the next byte such that I have the data for all bytes lower than that.
    - If I see the same “dup” ACK three times, I determine there is a loss.

Leads to the TCP "Sawtooth"

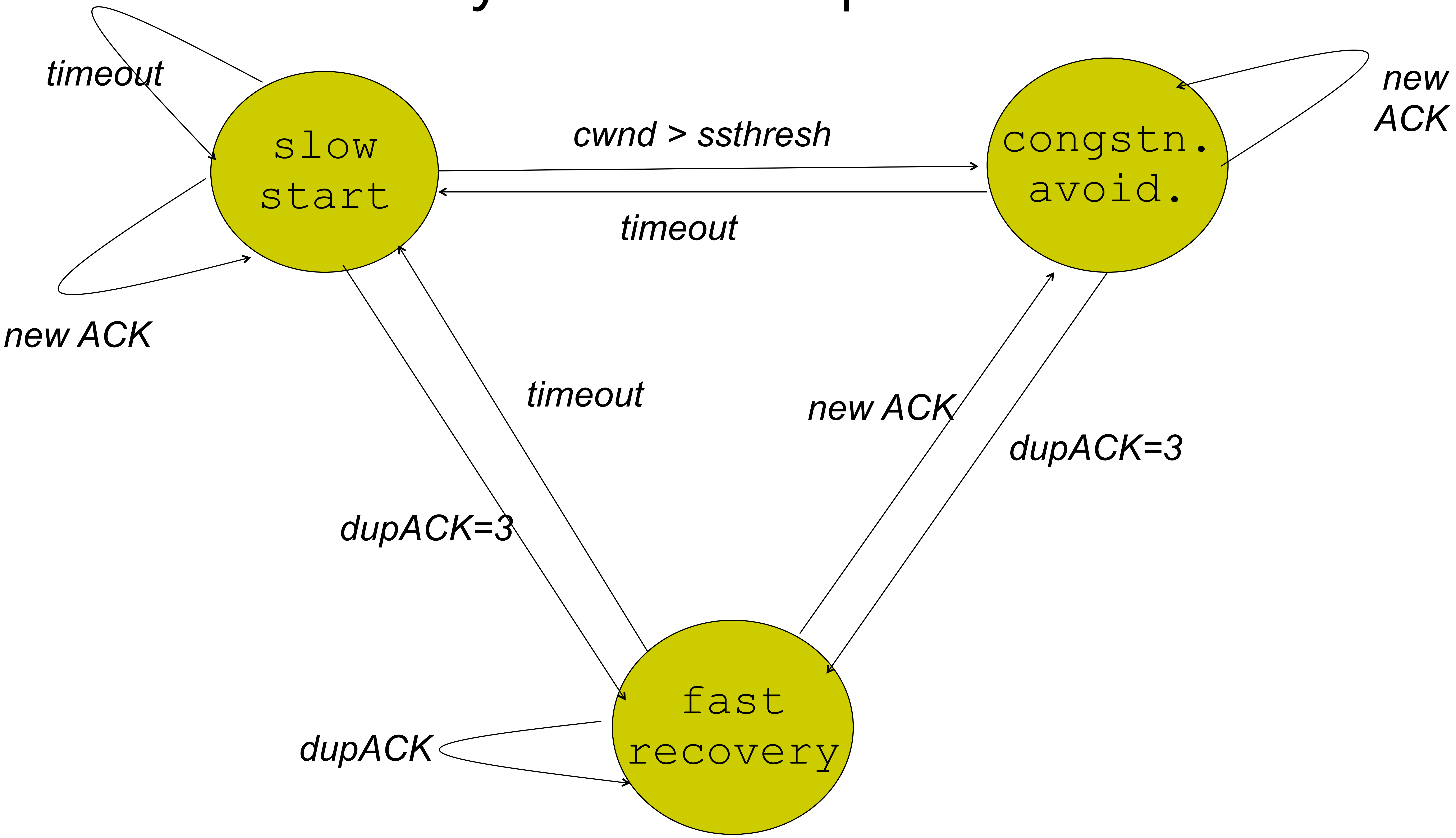


Assumption: Timeout Losses are Worse

- Timeout *can mean* (but not always) that lots of packets were lost and I have severely overshot.
- So I should react more severely to a timeout.
- Instead of halving my window, I will go all the way back to slow start and start over again!


Window
Dup ACK Loss
Timeout loss
t

Print this out and tape it above your bed. This is what you will implement for P2!



Summary

- All TCP connections use the same handshake, initial sequence number exchange, etc.
- But determining the right window size is *hard* because the network does not tell us directly how much capacity is available to us!
  - There are lots of algorithms to measure “CWND”
  - Reno is the classic algorithm, and it uses AIMD.

Thursday

- Why AIMD converges to fairness
- Calculating TCP throughput with loss
- Problems with TCP Reno
- New TCPs: Cubic, BBR
- Is the Internet fair?