15-441/641: Computer Networks
The Transport Layer, Part 1 of 3

15-441 Fall 2019

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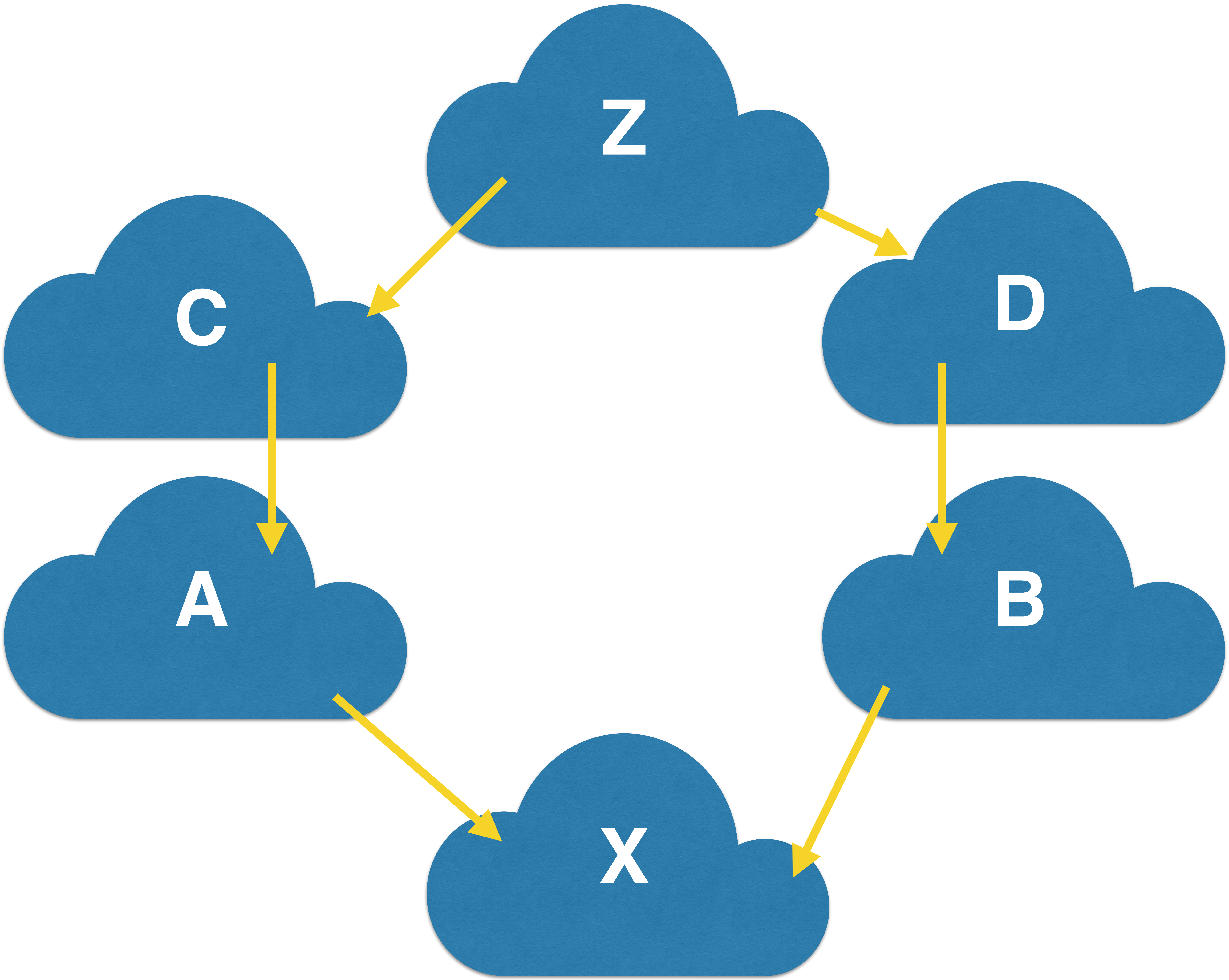
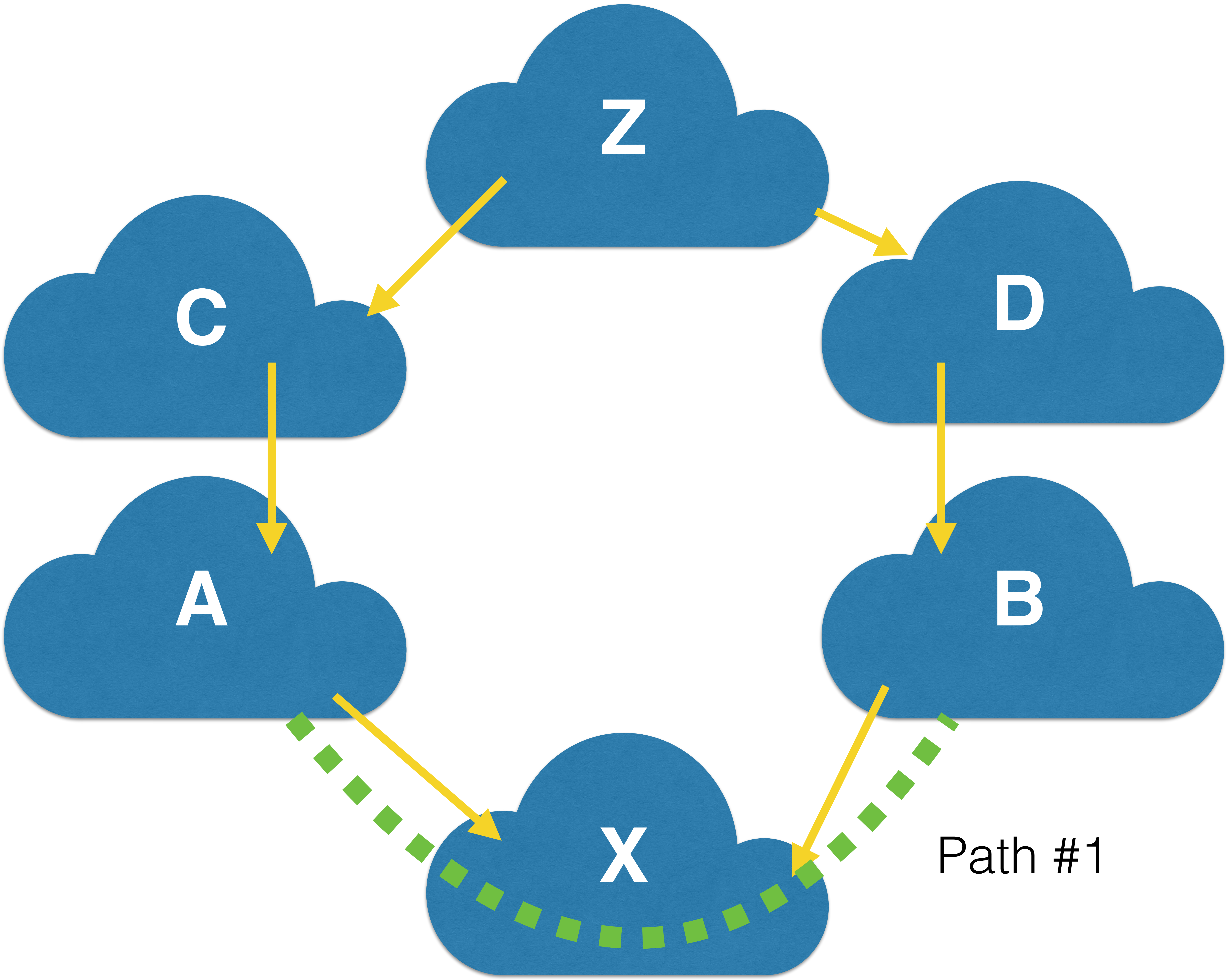
Warmup: BGP Refresh

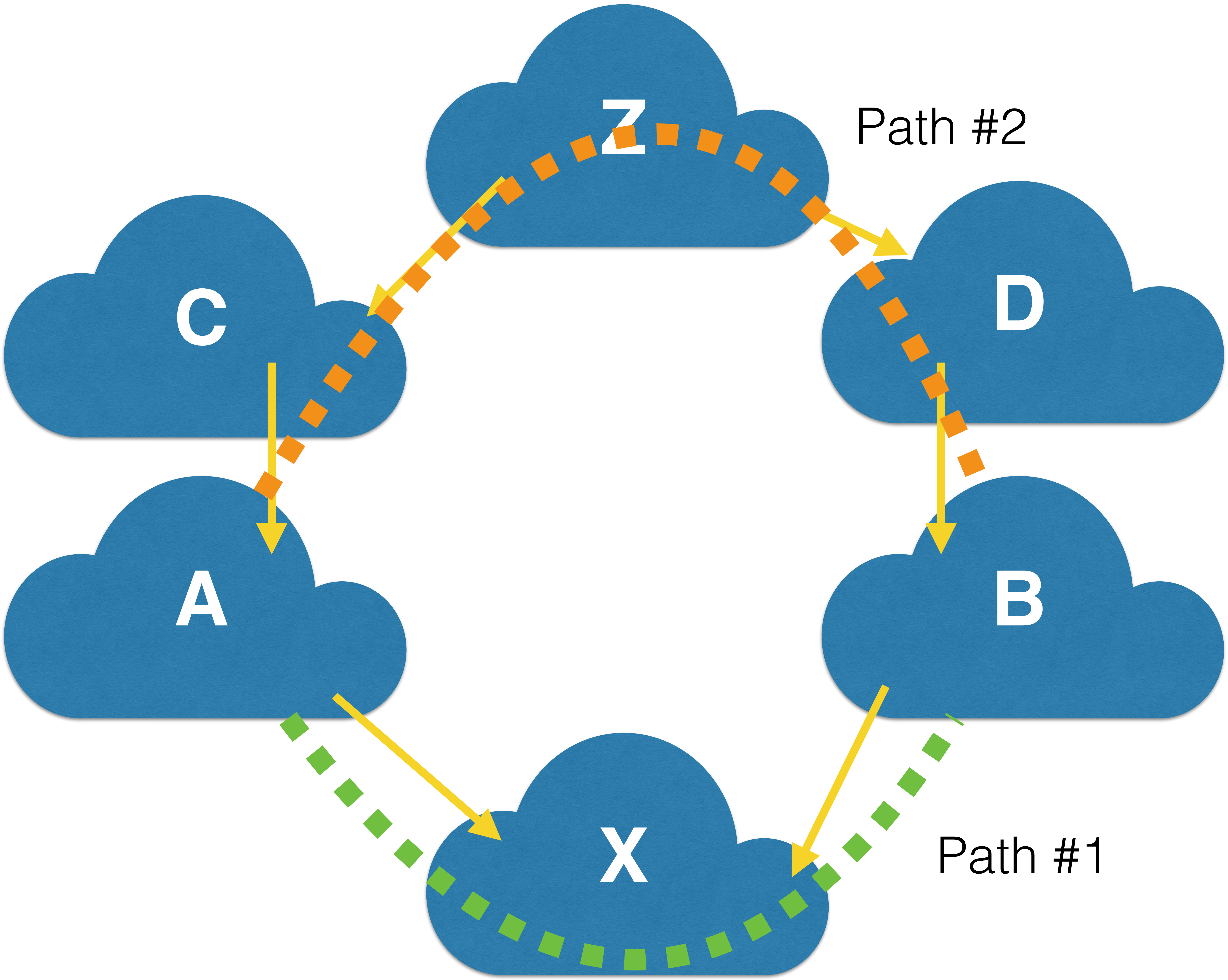
- X is a small university network with two providers, A and B.
- A’s provider is C.
- B’s provider is D.
- C’s provider is Z.
- D’s provider is Z.

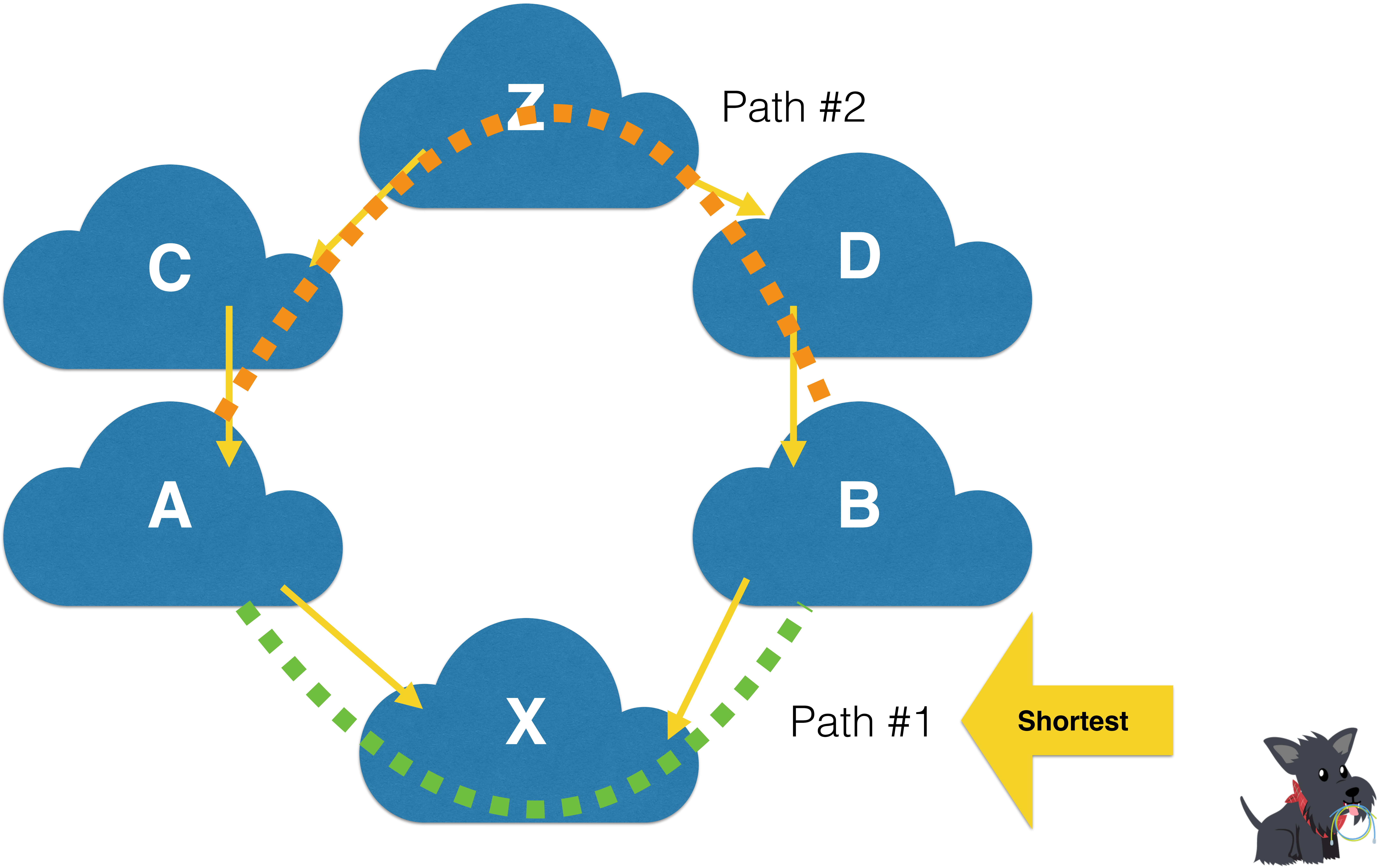
What AS path does traffic take from A to B?

- Why?


Z
C
D
A
B
X


Z
C
D
A
B
X
Path #1


Z
Path #2
C
D
A
B
X
Path #1


Z
Path #2
C
D
A
B
X
Path #1
Shortest

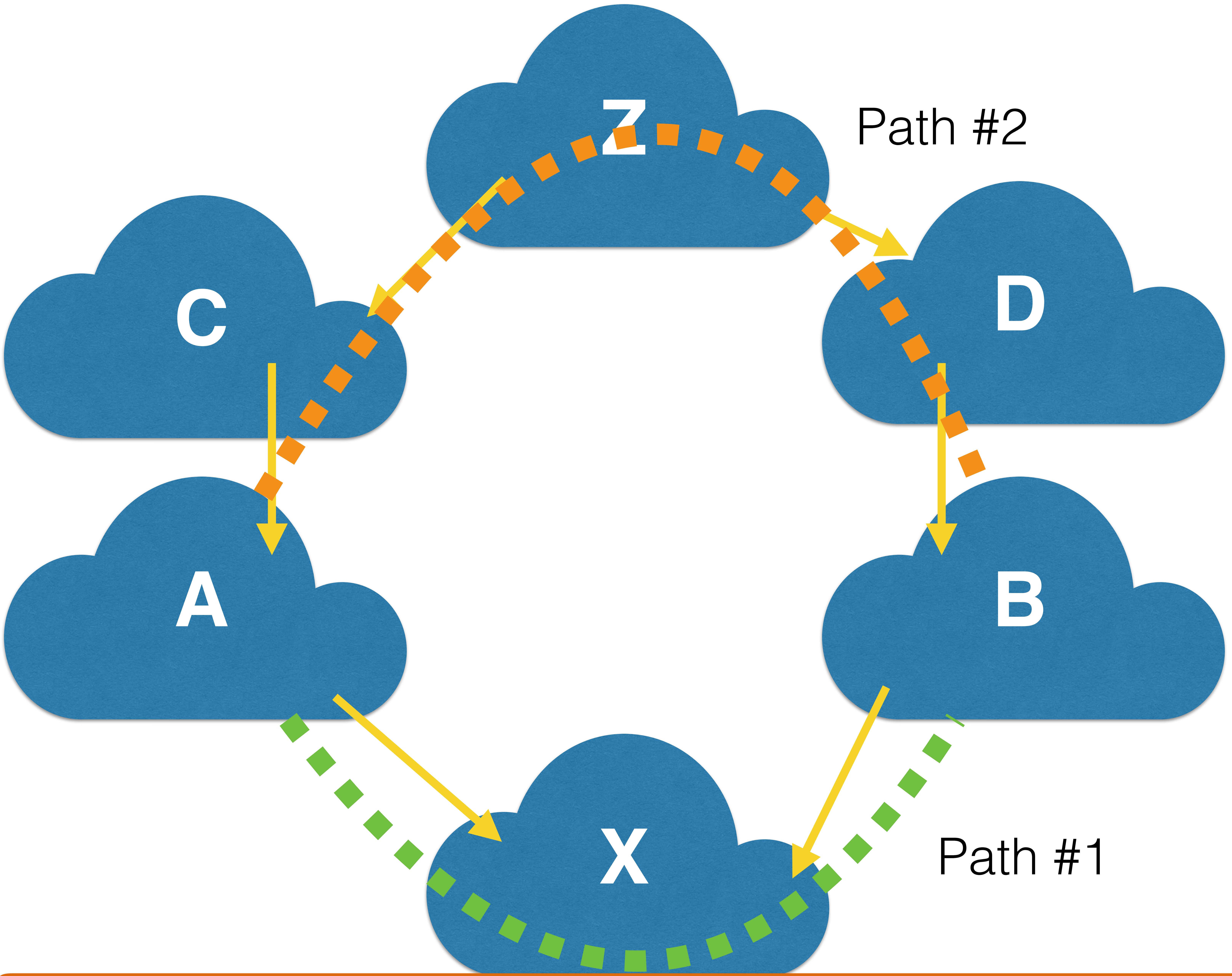

That's illegal.

Gao-Rexford Conditions

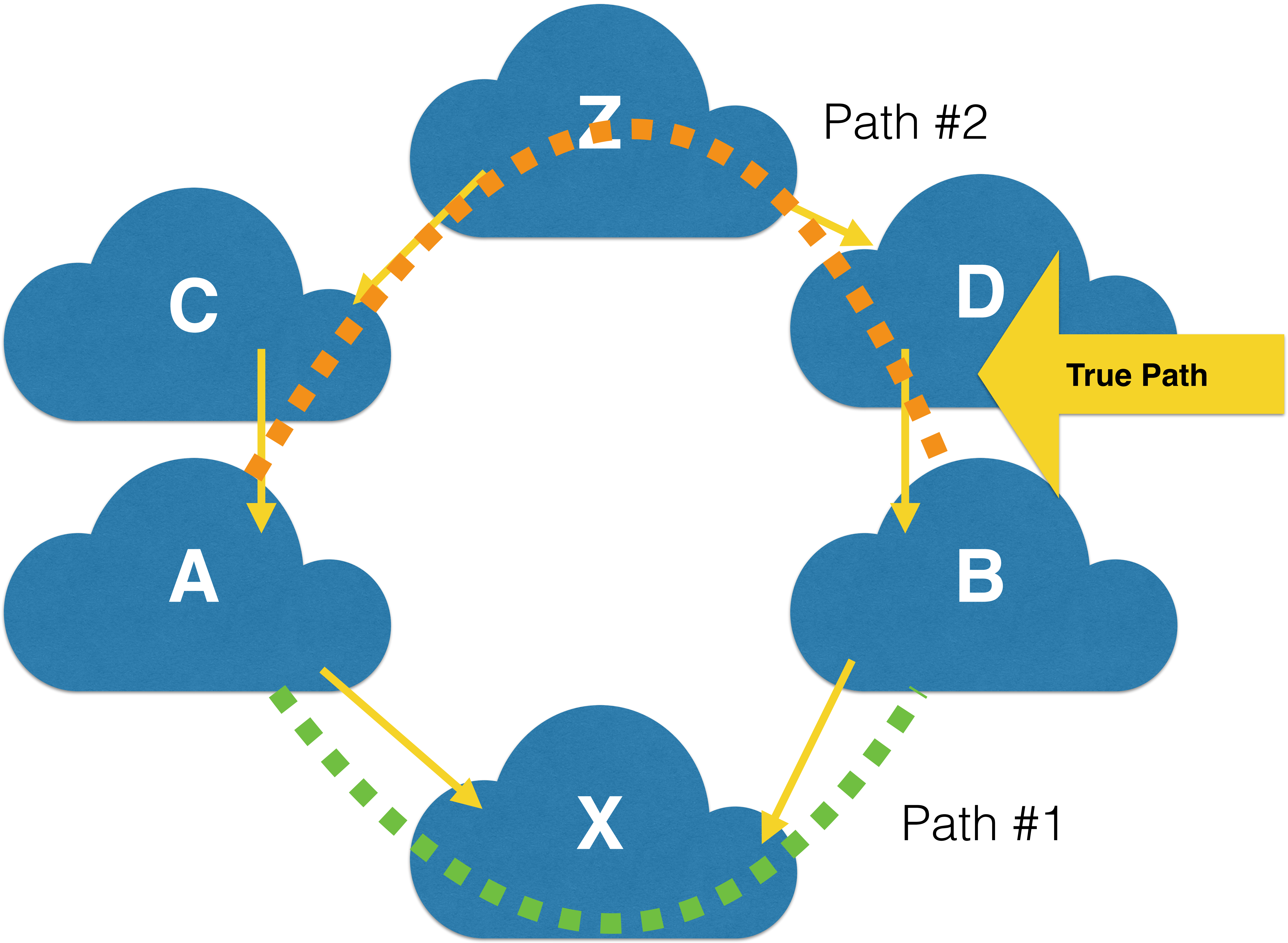
- If I receive a route announcement from my *customer*, I will announce that route to my customers, peers, and my providers.
- If I receive a route announcement from my *peer*, I will announce that route only to my customers.
- If I receive a route announcement from my *provider*, I will announce that route only to my customers.

I only want to carry traffic that will earn me a profit!

Gao-Rexford: “Scrooge McDuck Policy”



X would never announce a route for B to A

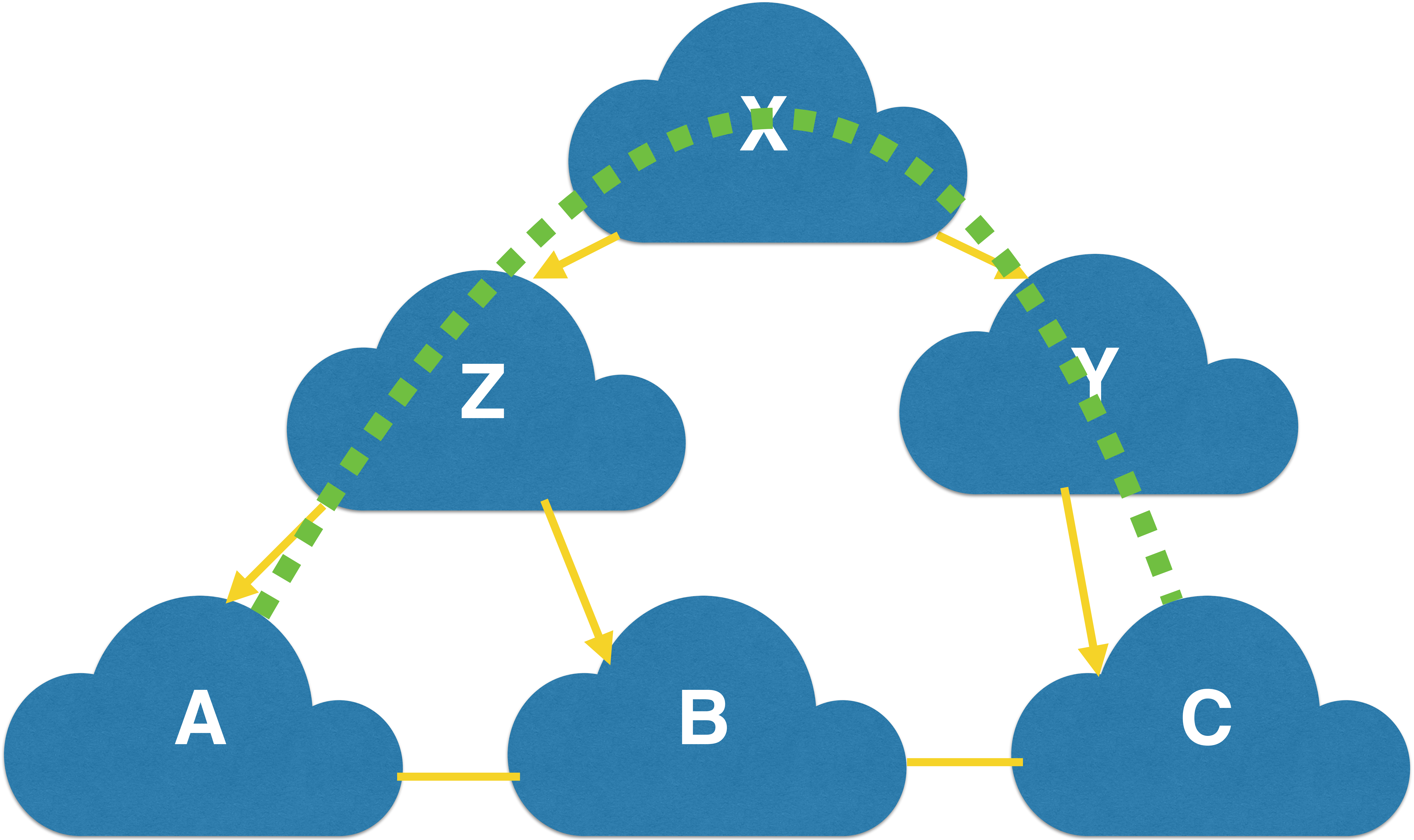

Z
Path #2
C
D
True Path
A
B
X
Path #1

Another BGP Warmup

- A's provider is Z. A peers with B.
- B's provider is Z. B peers with A and C.
- C's provider is Y. C peers with B.
- Z's provider is X.
- Y's provider is X.

What AS path does traffic take from A to C?

- Why?



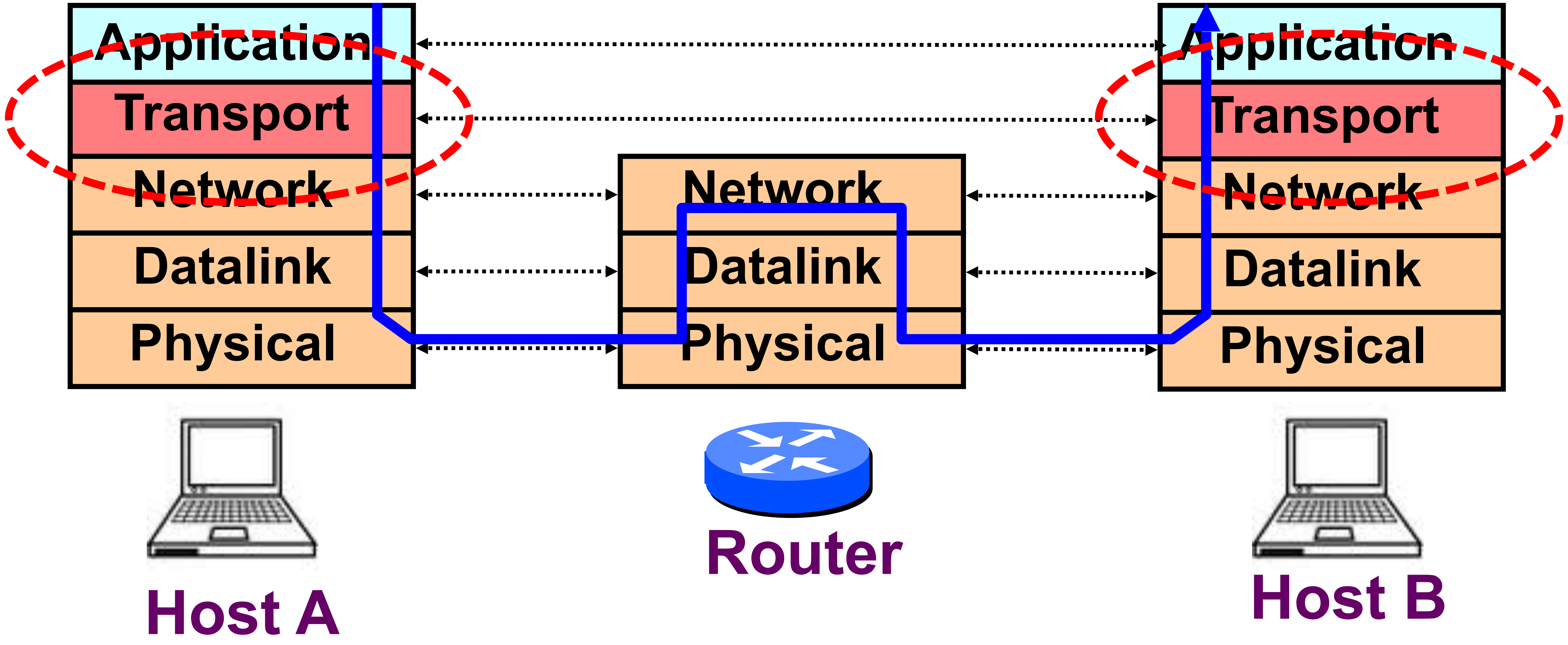
Follow the money!

Today

- Starting three lectures on the transport layer.
- The transport layer is currently one of my primary areas of research.
- I'll teach you the basics….
- For lecture #3, our TA Ranysha is going to tell you about her PhD research on modern transport on the Internet.
    - Including new protocols from companies like Google and Akamai

Quick Review

Transport Layer in the Internet Model



Why a transport layer?

- IP packets are addressed to a host but end-to-end communication is between application processes at hosts
  - Need a way to decide which packets go to which applications (*multiplexing/demultiplexing*)

Why a transport layer?

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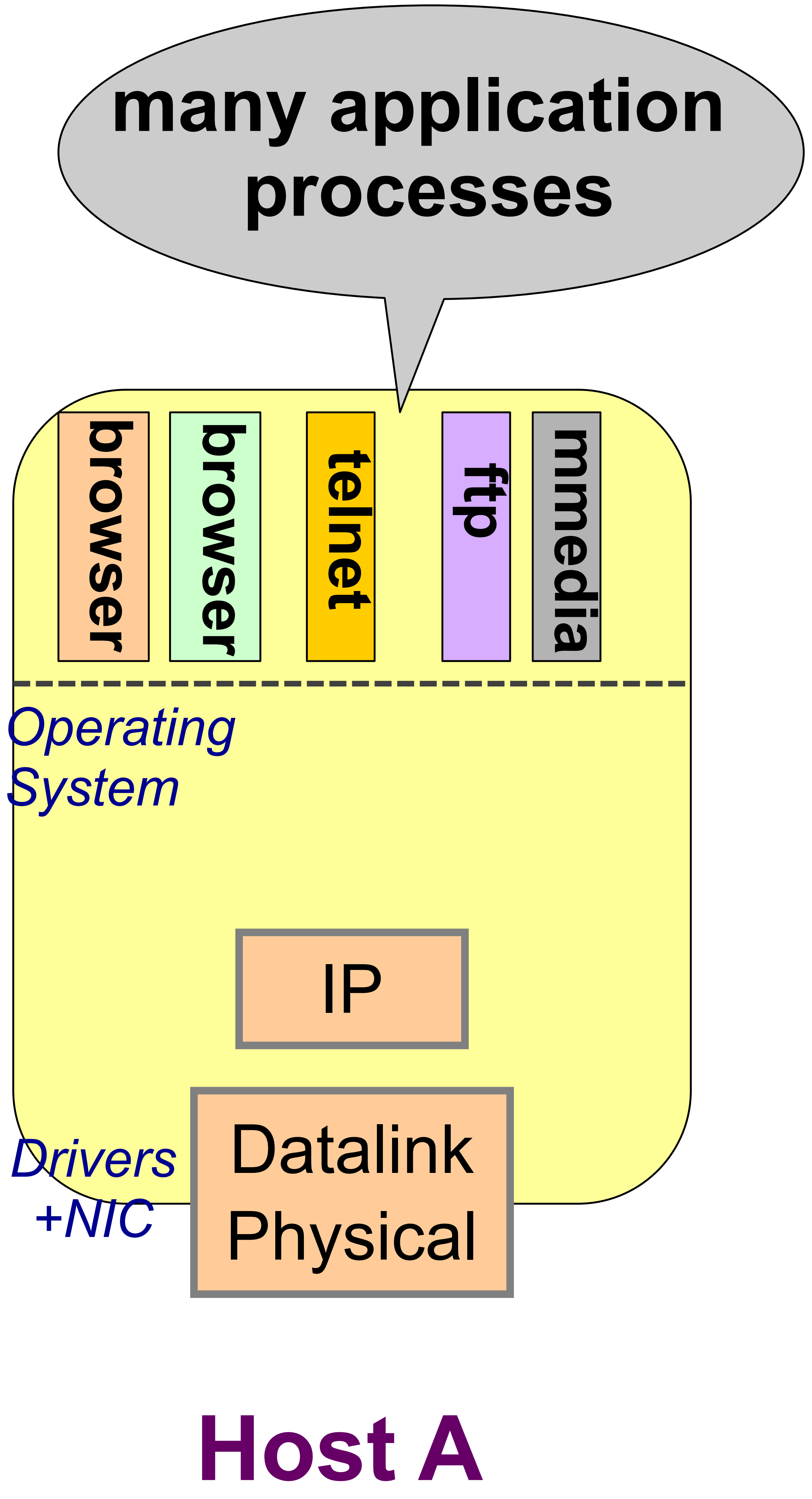
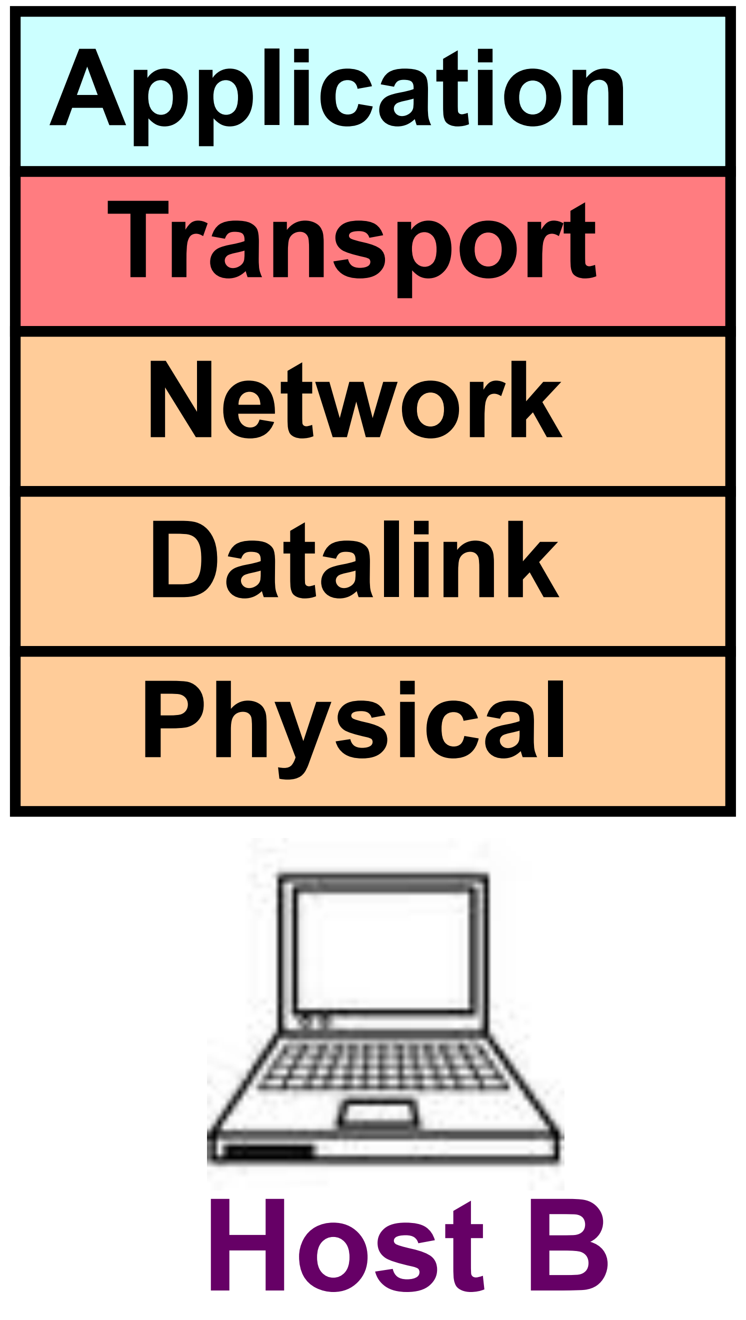
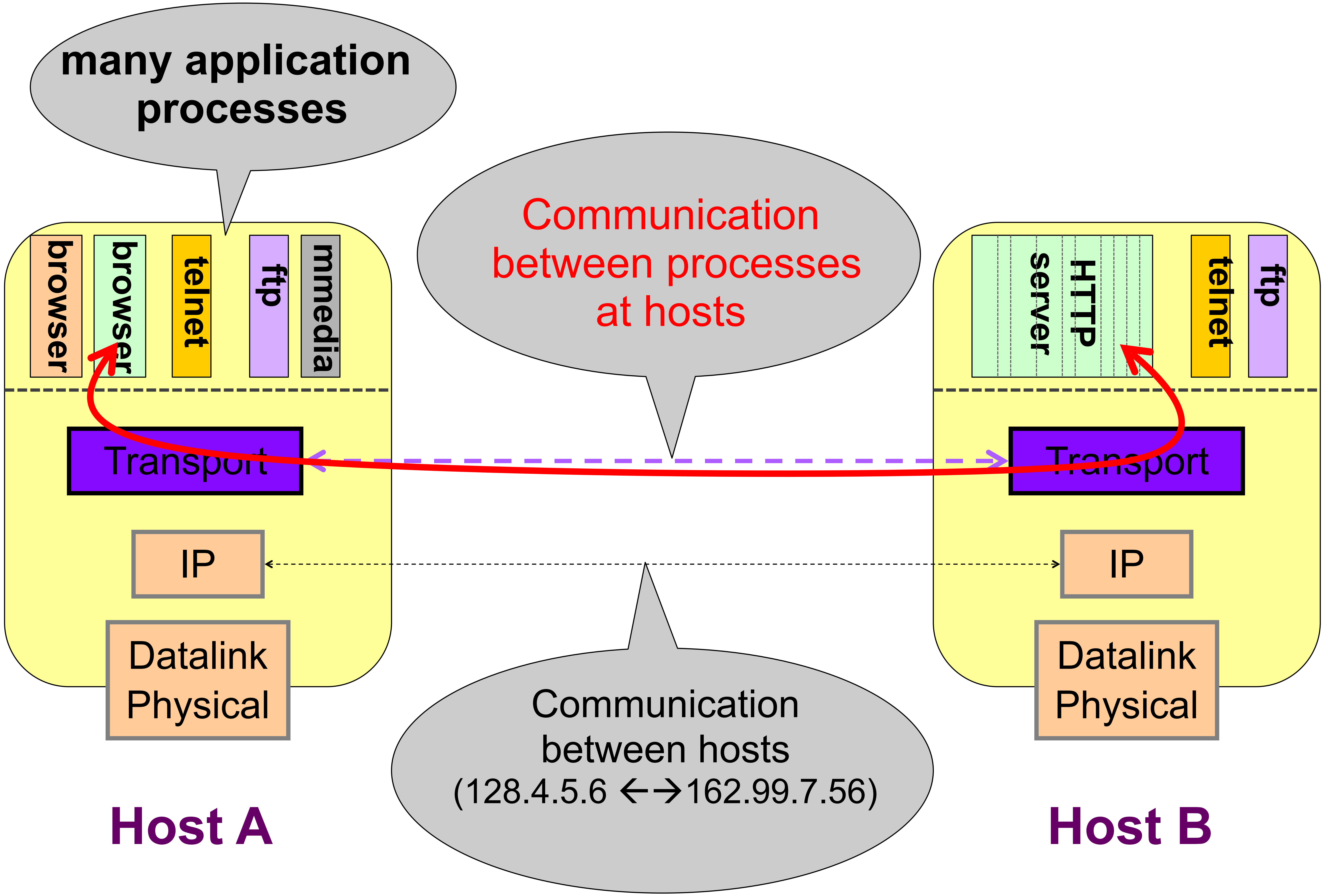




Why a transport layer?



Role of the Transport Layer

- Communication between application processes
  - Mux and demux from/to application processes
  - Implemented using *ports*
- *You know this from Liso project!*

Why a transport layer?

- IP packets are addressed to a host but end-to-end communication is between application processes at hosts
  - Need a way to decide which packets go to which applications (mux/demux)
- IP provides a weak service model (*best-effort*)
  - Packets can be corrupted, delayed, dropped, reordered, duplicated
  - No guidance on how much traffic to send and when
  - Dealing with this is tedious for application developers

Role of the Transport Layer

- Communication between application processes

- Provide common end-to-end services for app layer [optional]
  - Reliable, in-order data delivery
  - Well-paced data delivery
    - too fast may overwhelm the network
    - too slow is not efficient

Role of the Transport Layer

- Communication between processes
- Provide common end-to-end services for app layer [optional]
- TCP and UDP are the common transport protocols
  - also SCTP, MTCP, SST, RDP, DCCP, …

Context: Applications and Sockets

- Socket: software abstraction by which an application process exchanges network messages with the (transport layer in the) operating system
  - socketID = socket(…, socket.TYPE)
  - socketID.sendto(message, …)
  - socketID.recvfrom(…)

- Two important types of sockets
  - UDP socket: TYPE is SOCK_DGRAM
  - TCP socket: TYPE is SOCK_STREAM

Role of the Transport Layer

- Communication between processes
- Provide common end-to-end services for app layer [optional]
- TCP and UDP are the common transport protocols
- UDP is a minimalist, no-frills transport protocol
    - only provides mux/demux capabilities

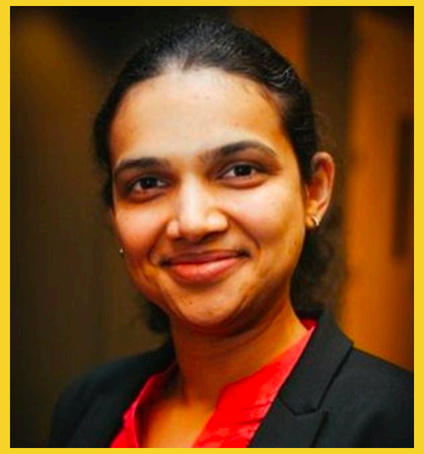
UDP: User Datagram Protocol

- Lightweight communication between processes
  - Avoid overhead and delays of ordered, reliable delivery
- UDP described in RFC 768 – (1980!)
  - Destination IP address and port to support demultiplexing
  - Optional error checking on the packet contents
    - (**checksum** field = 0 means “don’t verify checksum”)

SRC port	DST port
checksum	length
DATA	

What is a checksum?

- Wikipedia: “A checksum is a small-sized c digital data for the purpose of detecting errors th during its transmission or storage.”



Take a class from Prof. Vinayak to learn more about information theory and how to use it to build systems!

- Simplest checksum:
  - Take every, say, 32-bit word and XOR them all ether
  - Append the result to the end of the packet (add overhead!)
  - At the receiver, re-compute the XOR. If it does n t match the appended checksum, you know some of the data has beer corrupted.
- There is a huge literature on “coding” checksumming schemes.

UDP

- That's literally the entire protocol.
- If a packet gets lost, it's up to the application developer to decide what to do about it.

Role of the Transport Layer

- Communication between processes
- Provide common end-to-end services for app layer [optional]
- TCP and UDP are the common transport protocols
- UDP is a minimalist, no-frills transport protocol
- TCP is the whole-hog protocol
  - offers apps a reliable, in-order, bytestream abstraction
  - with congestion control
  - but no performance guarantees (delay, bw, etc.)

Why a transport layer?

- IP packets are addressed to a host but end-to-end communication is between application processes at hosts
  - Need a way to decide which packets go to which applications (mux/demux)
- IP provides a weak service model (*best-effort*)
  - Packets can be corrupted, delayed, dropped, reordered, duplicated

TCP, literally the next three lectures

Getting this right is *hard* and hence it is an active area of research.

Let’s get started understanding why this is challenging…

I need two volunteers.

Team Structure

- I have ten beanbags labeled 1 to 10.
- Your job is to transport them from one end of the classroom to the other.
- Like Professor Sherry, you must throw them — you can't simply carry them to the other side of the classroom.
  - Unlike Professor Sherry, you may have better aim.
  - Or they might fall to the ground. If they fall, you can't pick them back up!
- If you determine that a beanbag is lost, you can grab another beanbag, label it with the missing number, and re-transmit it.

Team Structure

- Two of you are the end points (sender/receiver) who decide what packets to transmit, and whether or not to re-transmit. The endpoints must face the wall — they can't see the network. But, they can talk!

- The other two represent the network in the middle. You can see everything, but you can't talk or signal in any way to the endpoints.

    - The sender will will hold up a bean bag in the air if they have a bag they want you deliver.

    - They receiver will hold up their hand so you can put beanbags into it.

    - But otherwise no talking! Just try not to let the beanbags fall!

PRIZES

- The winner is whoever successfully gets beanbags numbered 1…10 to their receiver first.
- Winning team gets t-shirts
- Losing team still gets candy!

Back to the real Internet…

How do we tell that a packet has been lost?

- The packet was sent a long time ago, but still has not arrived
- Packet arrives at receiver, but data does not match its checksum

A basic protocol: Stop and Wait

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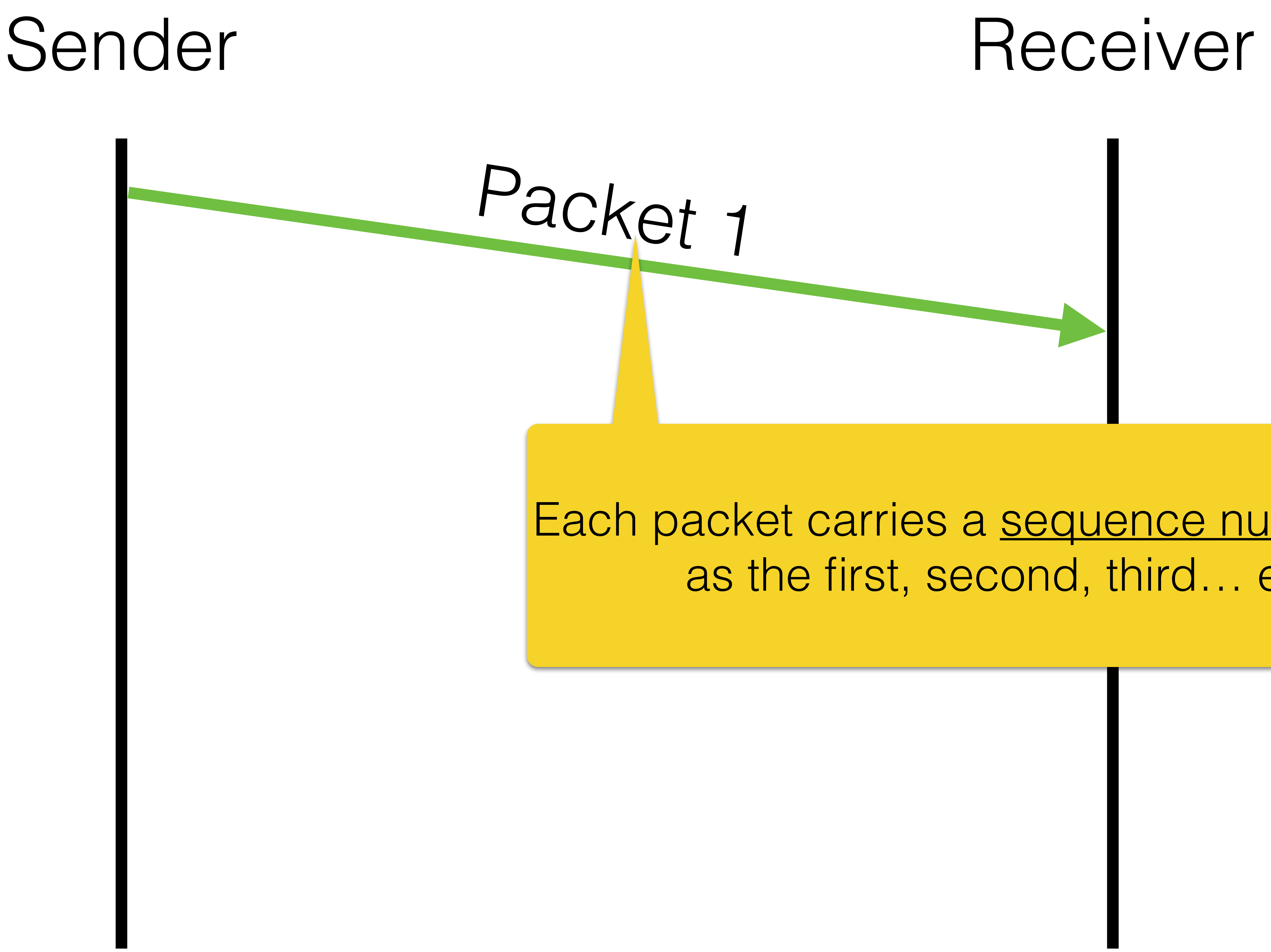
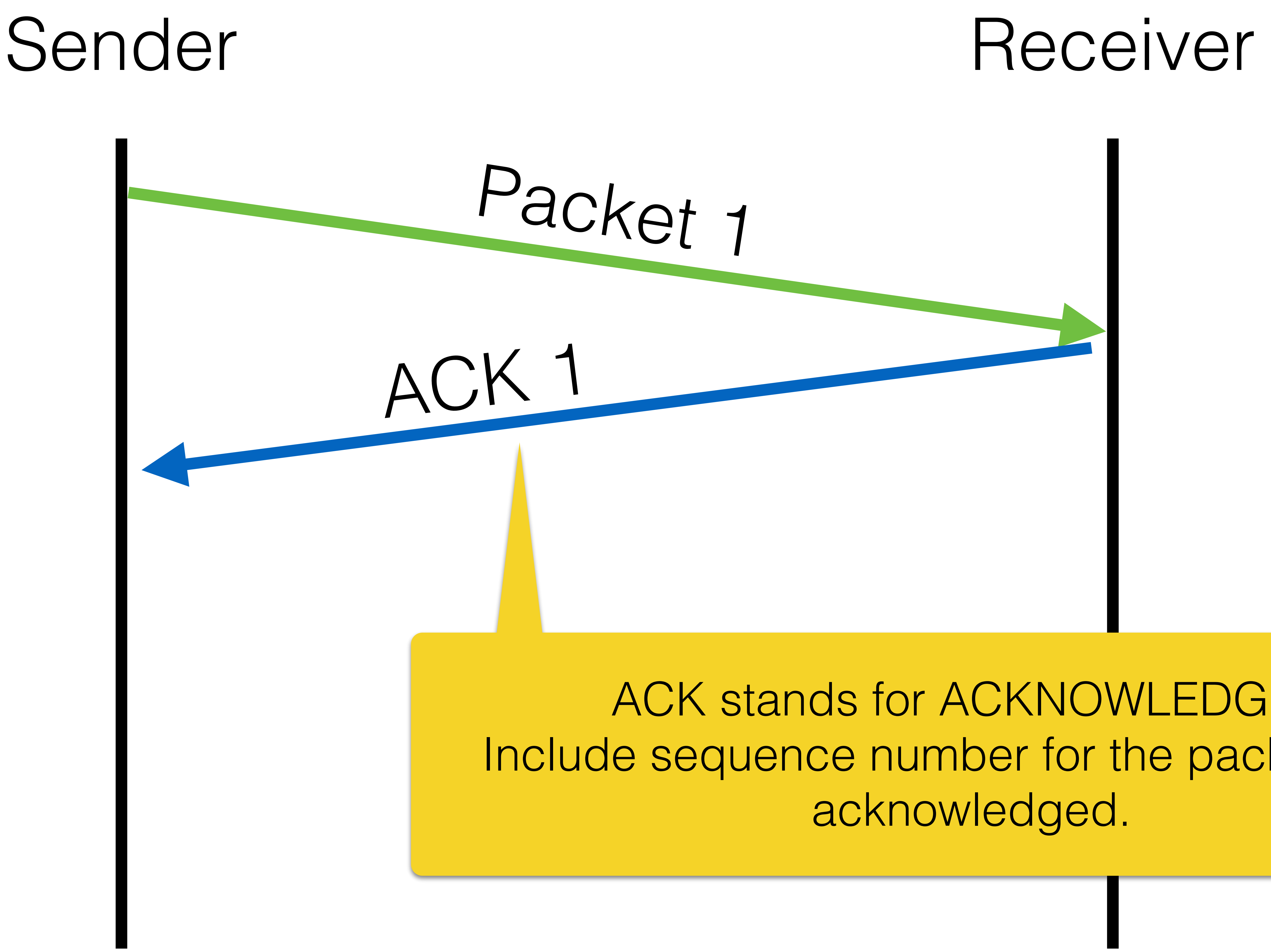


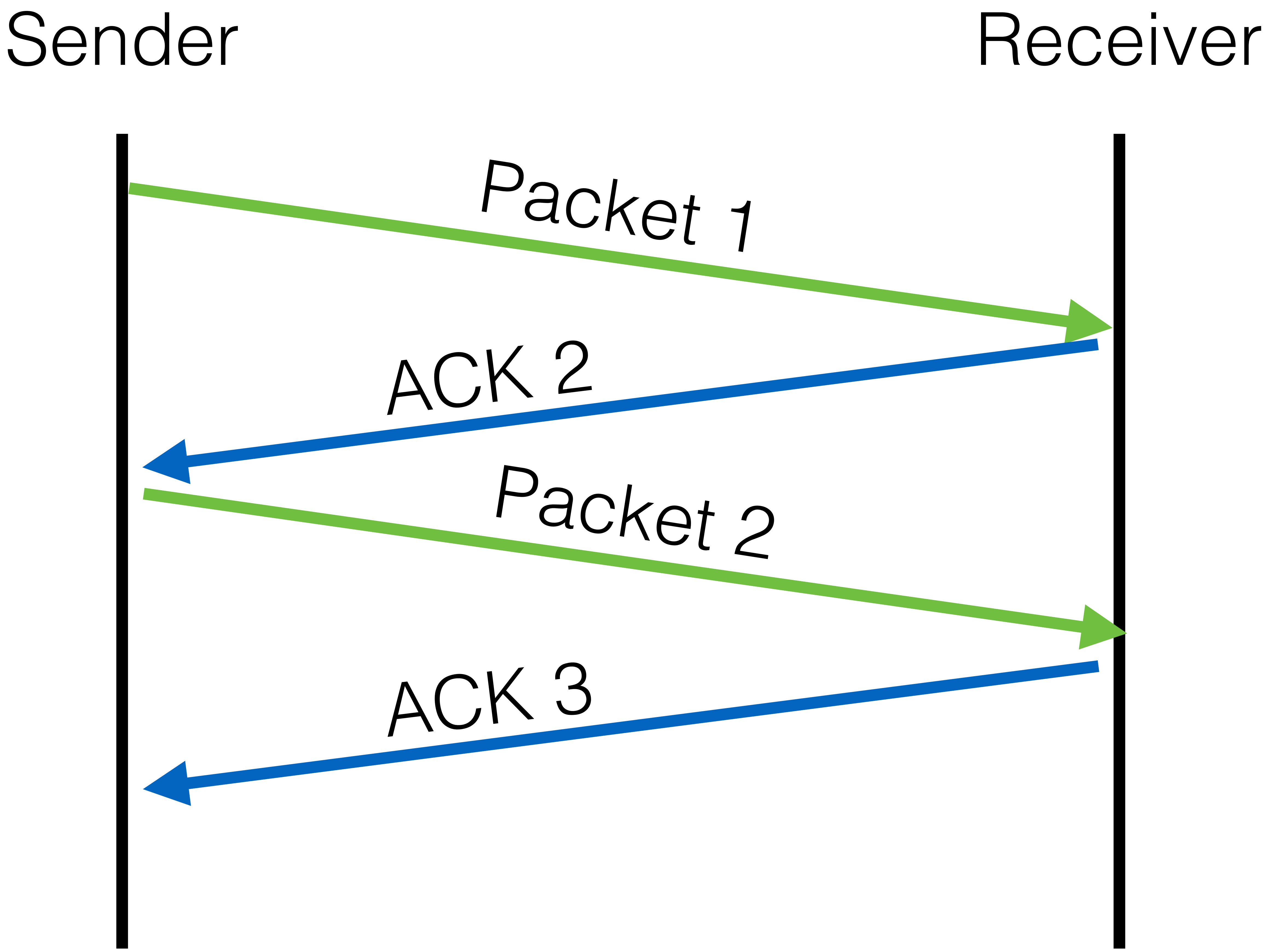
Each packet carries a sequence number identifying it as the first, second, third… etc packet.

A basic protocol: Stop and Wait



ACK stands for ACKNOWLEDGED
Include sequence number for the packet being acknowledged.

A basic protocol: Stop and Wait



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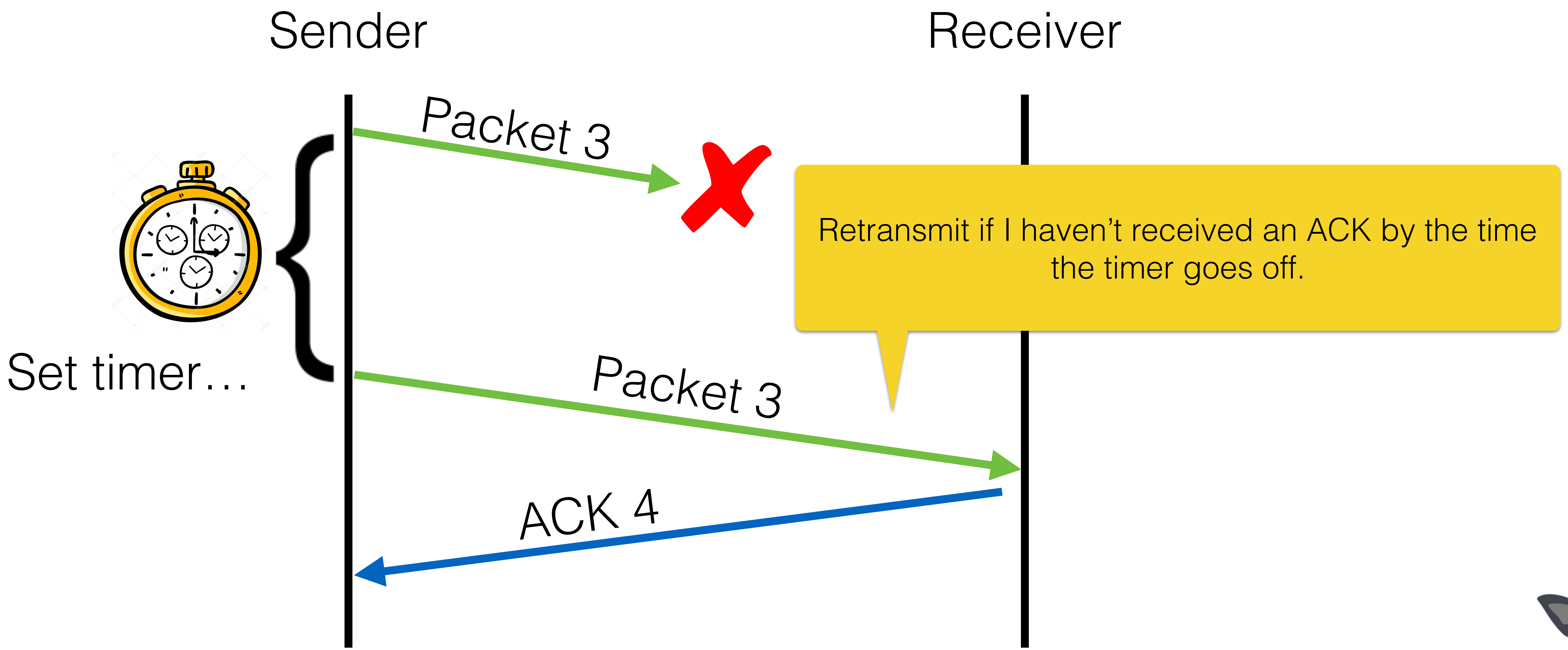

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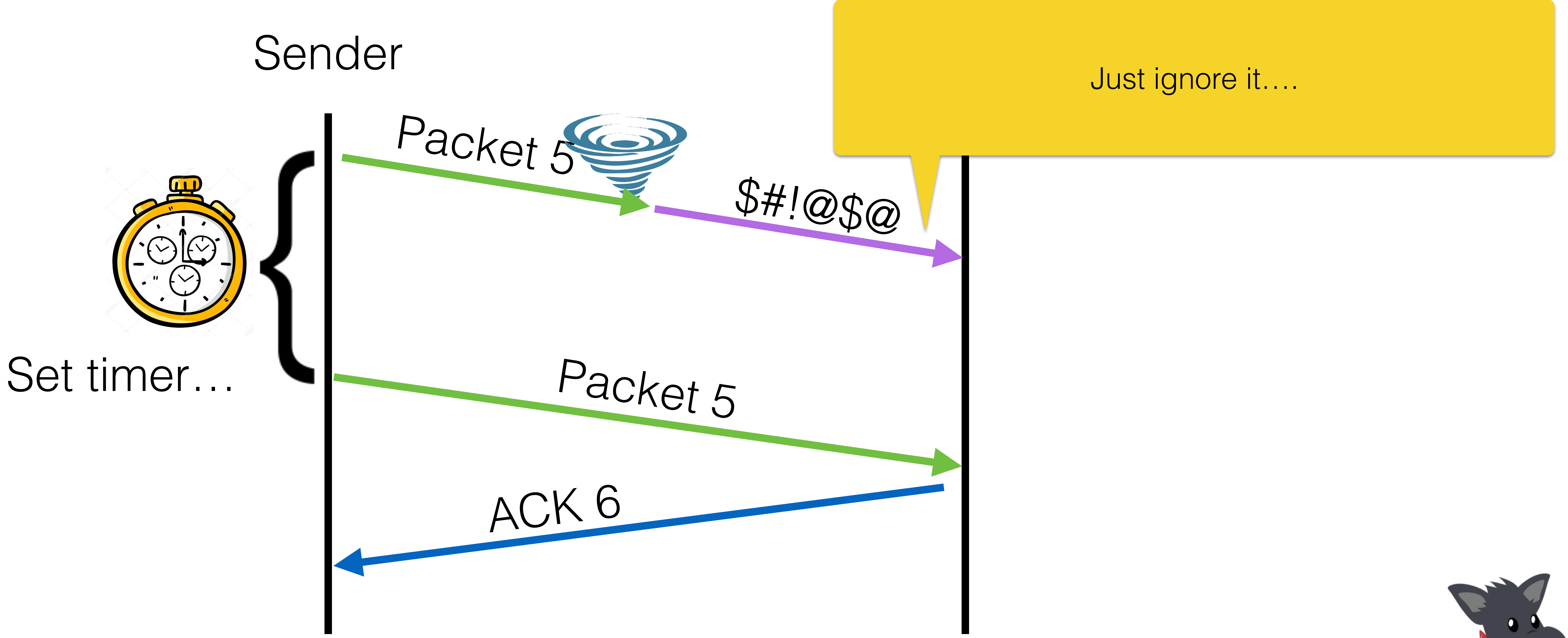


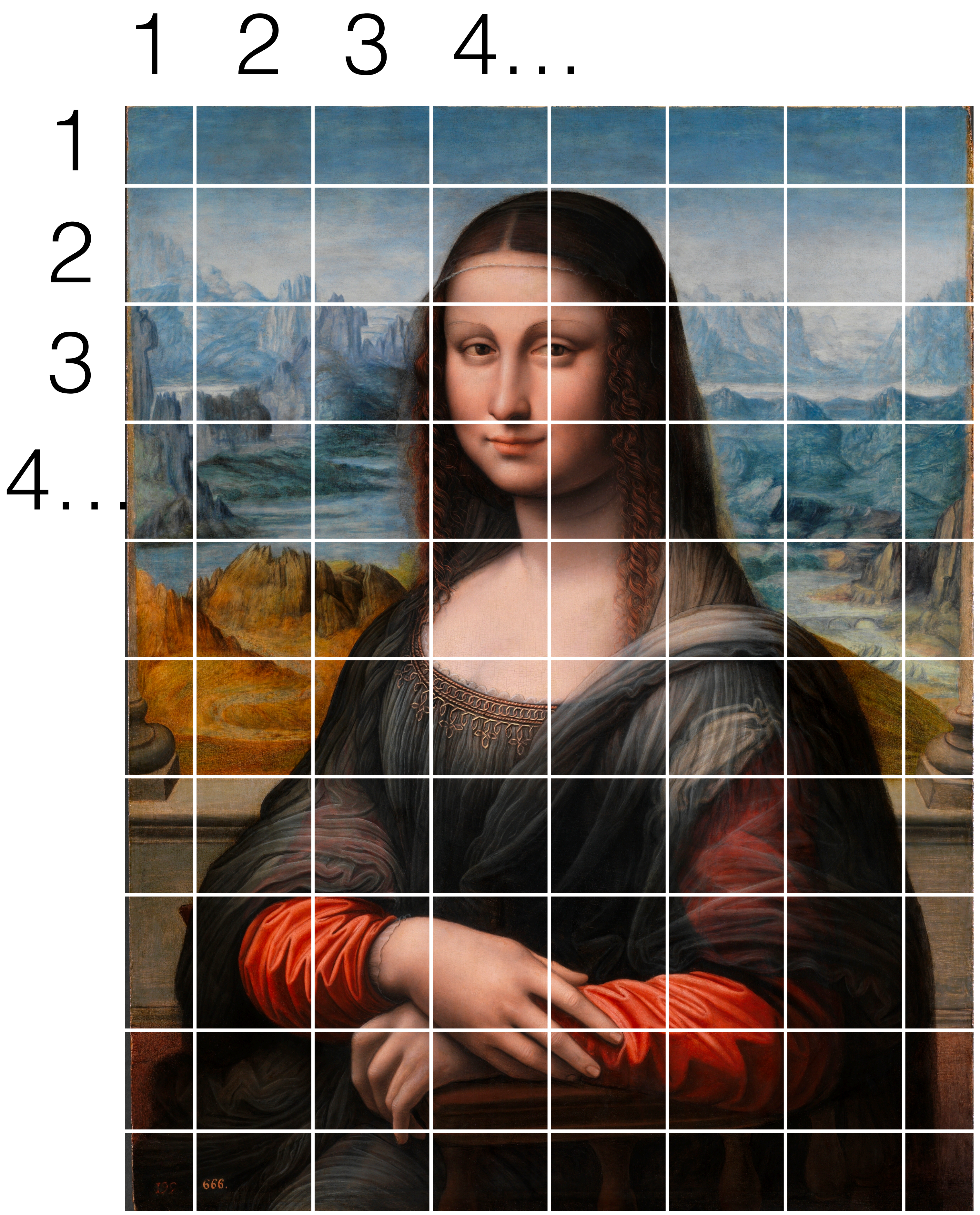
Stop-and-Wait: Summary

- **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.

Why do we need sequence numbers? Could we use Stop-and-Wait without them?

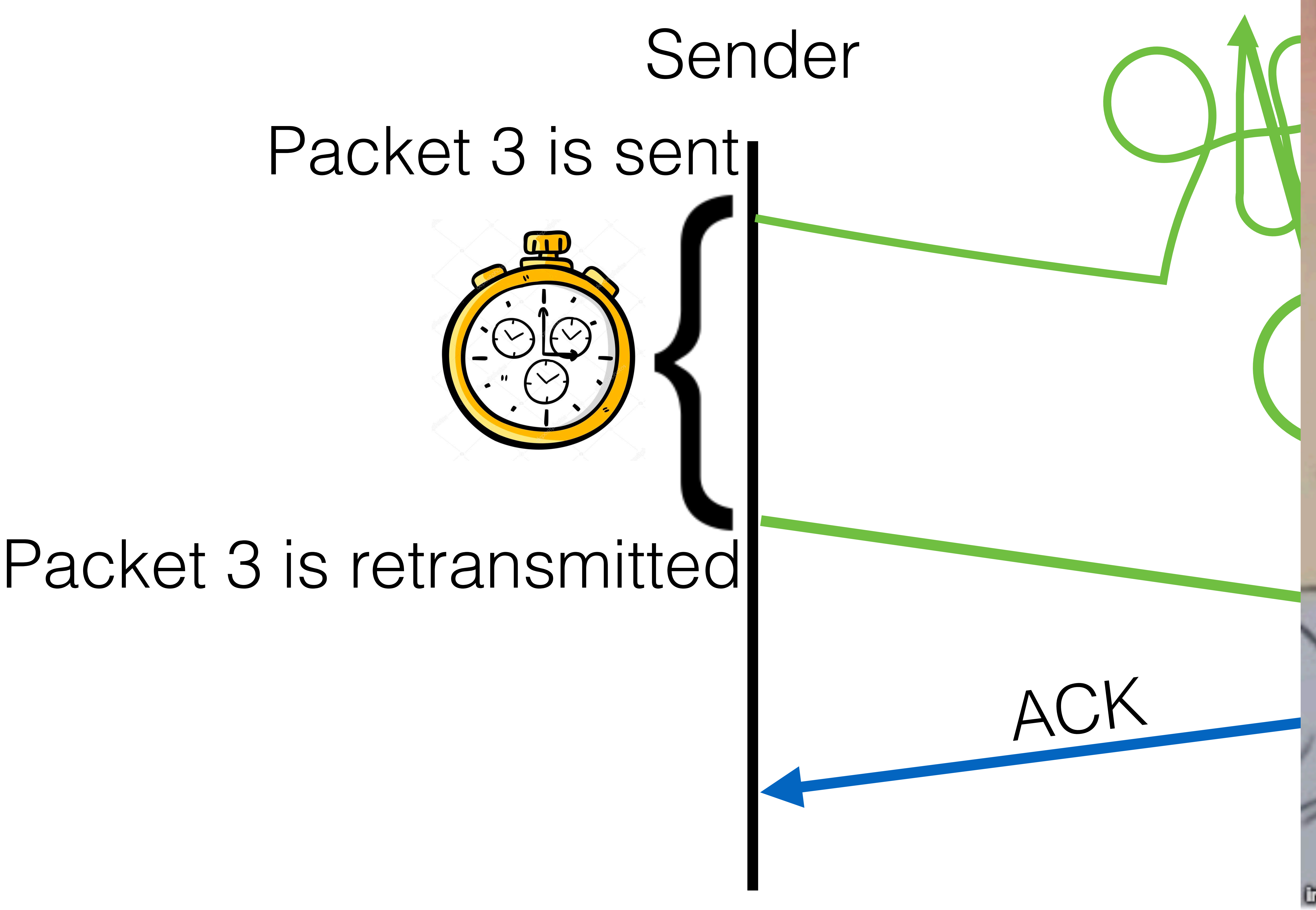
Intuitive Need for Sequence Numbers…

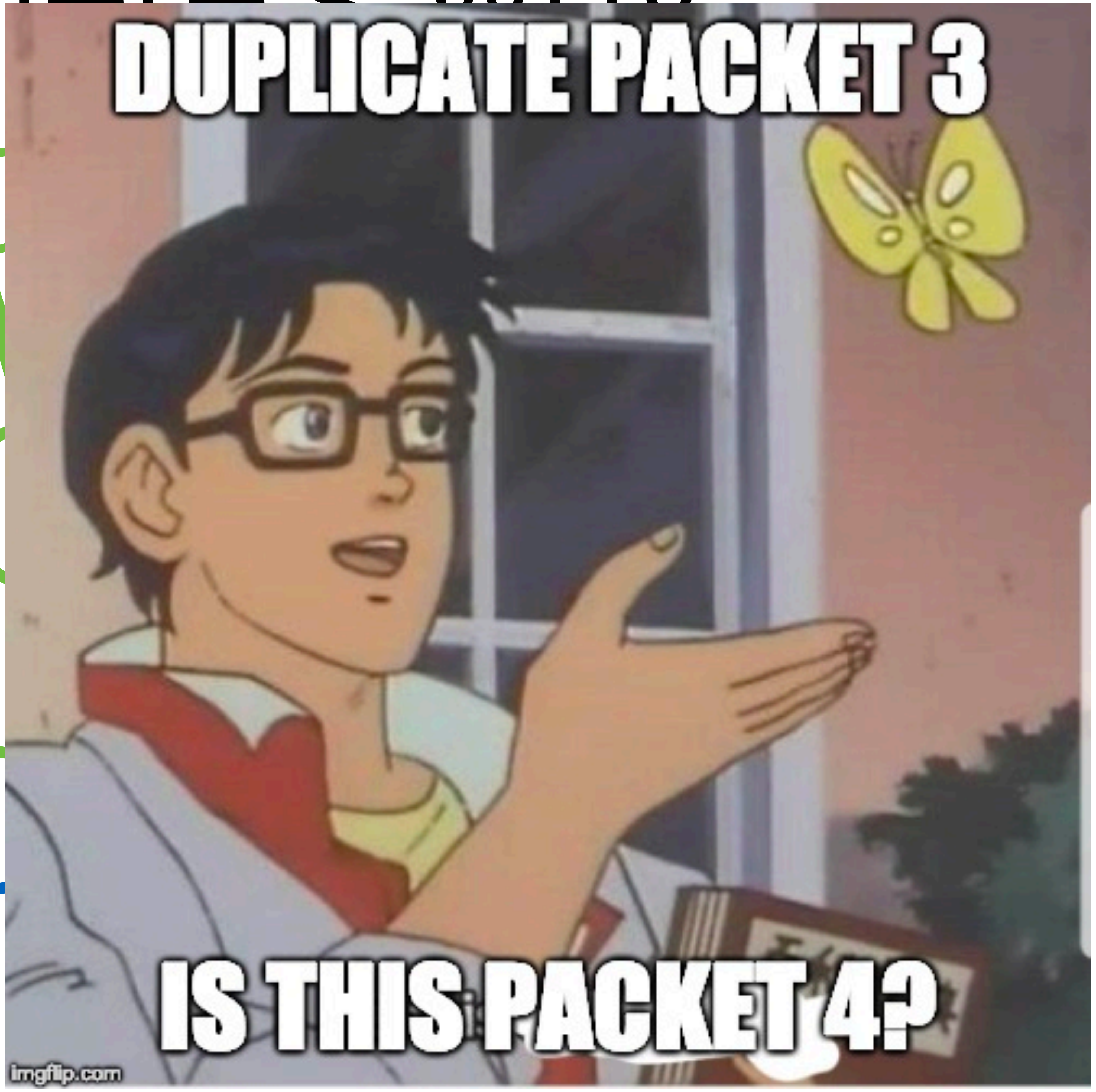
How do we put the file back together again after packetization?



But maybe we could just standardize this —- say each packet is in row-order starting from top left. Would we still need sequence numbers for the protocol?

We do, and here’s why





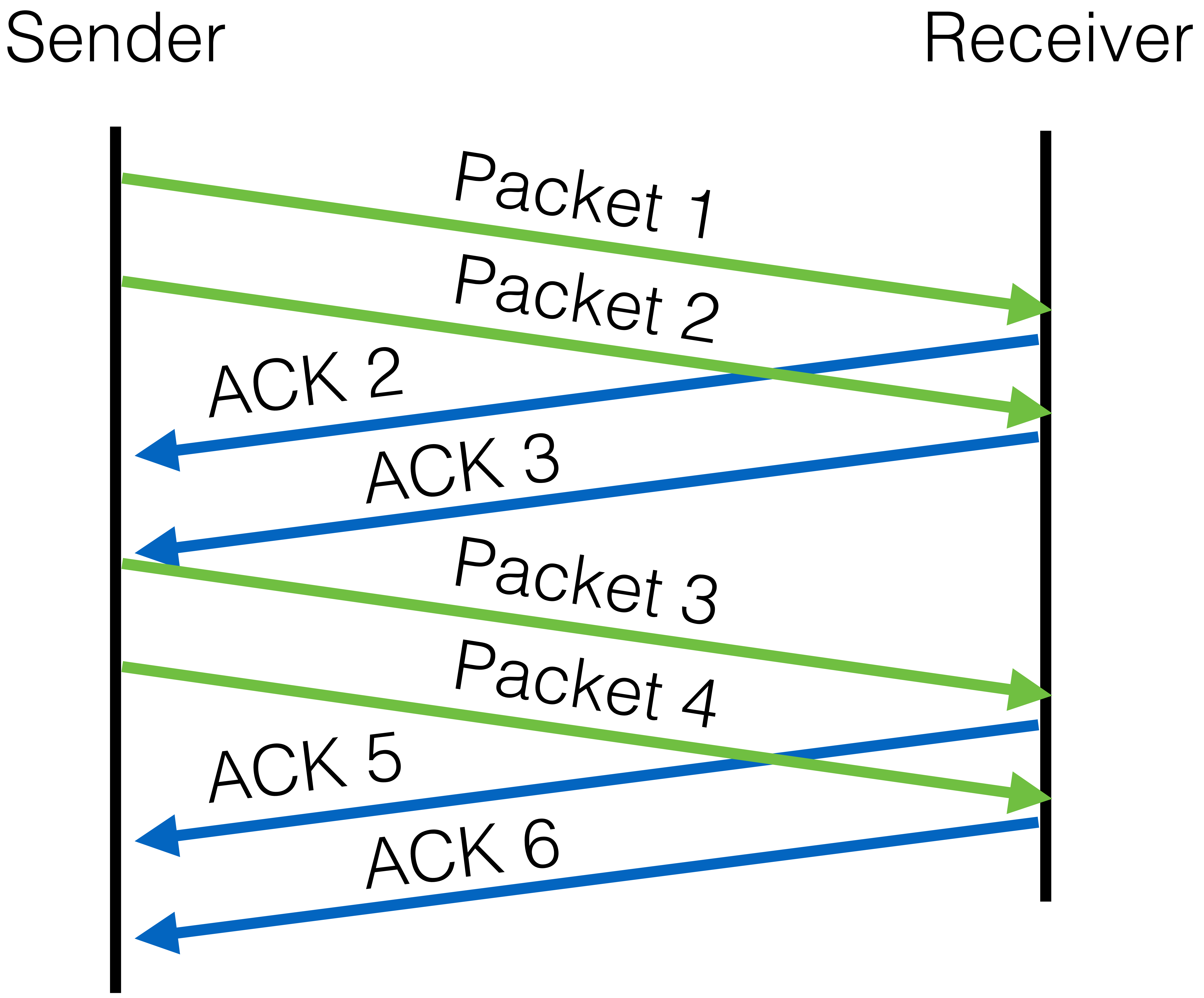
Sequence numbers are needed for reliability.

What's wrong with stop-and-wait?

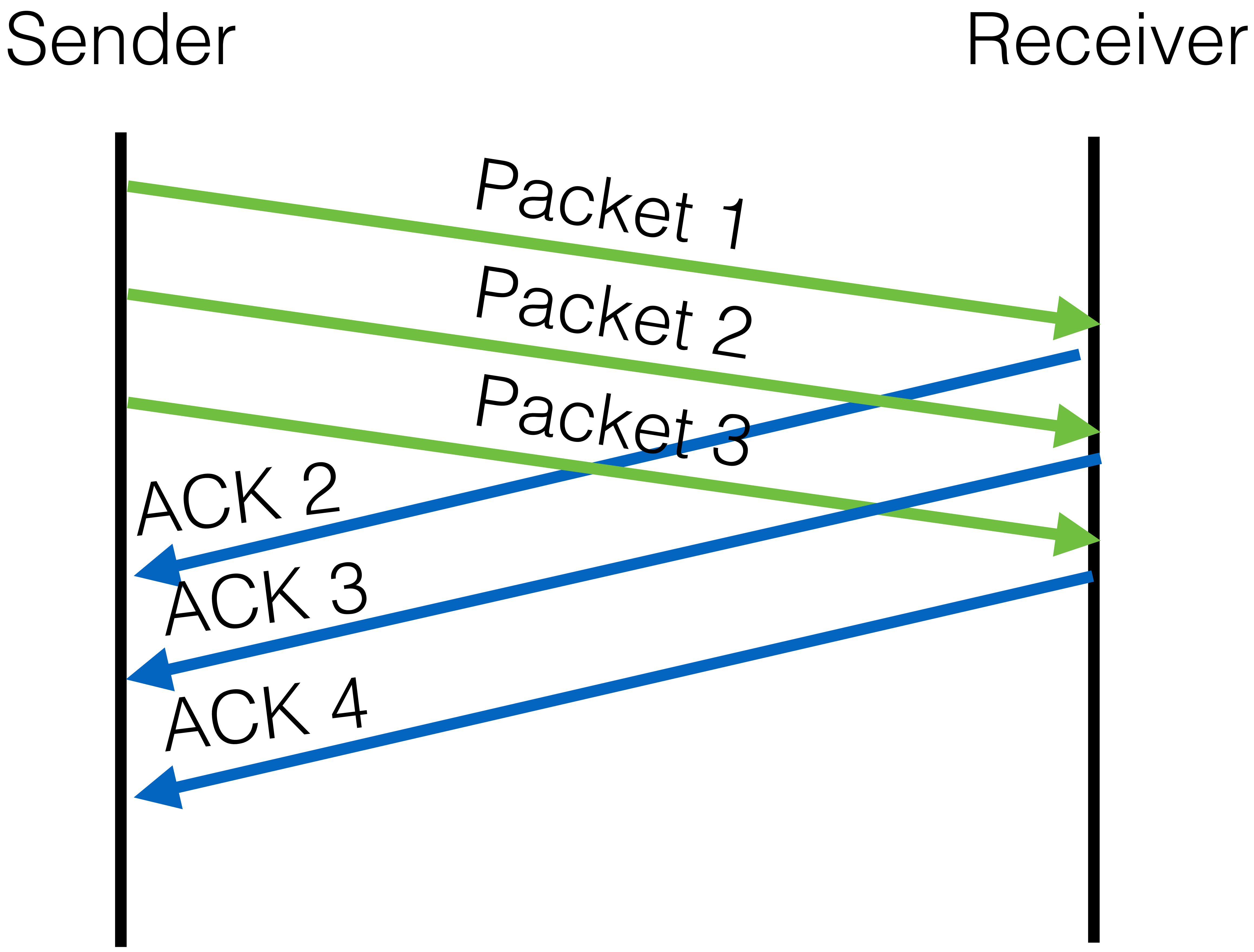
It’s slow!

How might we fix it?

Making Stop and Wait faster…

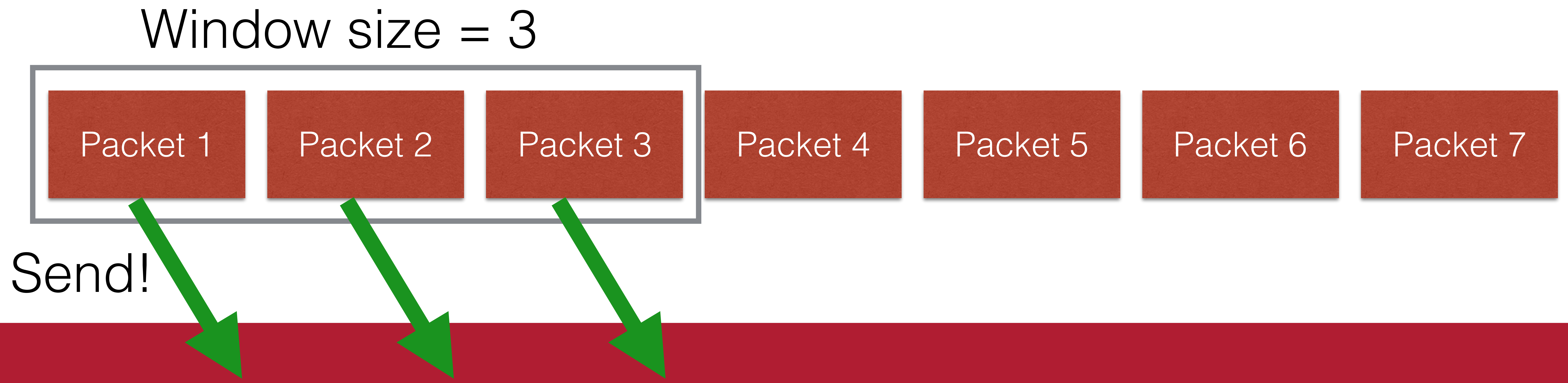


…and faster…



Sliding Windows

- A sender's "window" contains a set of packets that have been transmitted but not yet acked.
- Windowing improves the efficiency of a transport protocol.
- We say the window "slides" when a packet is asked.



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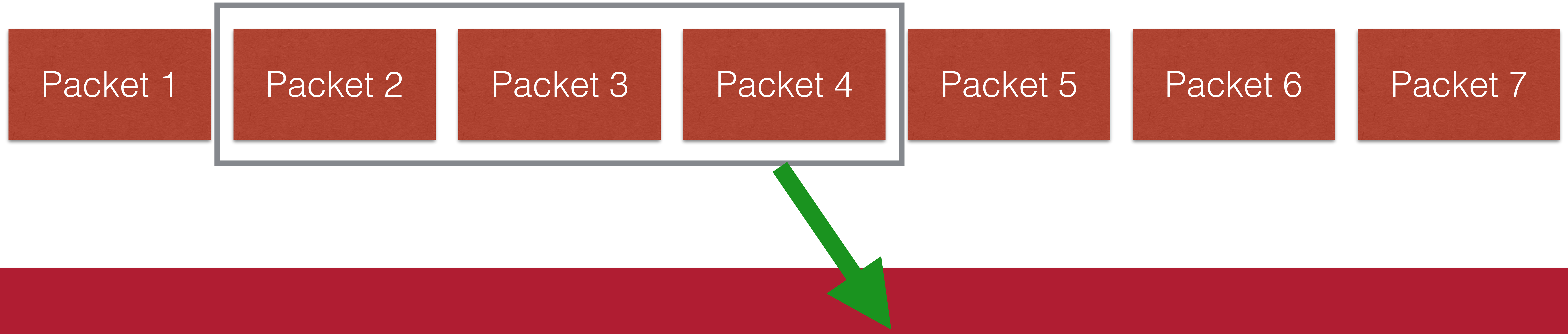

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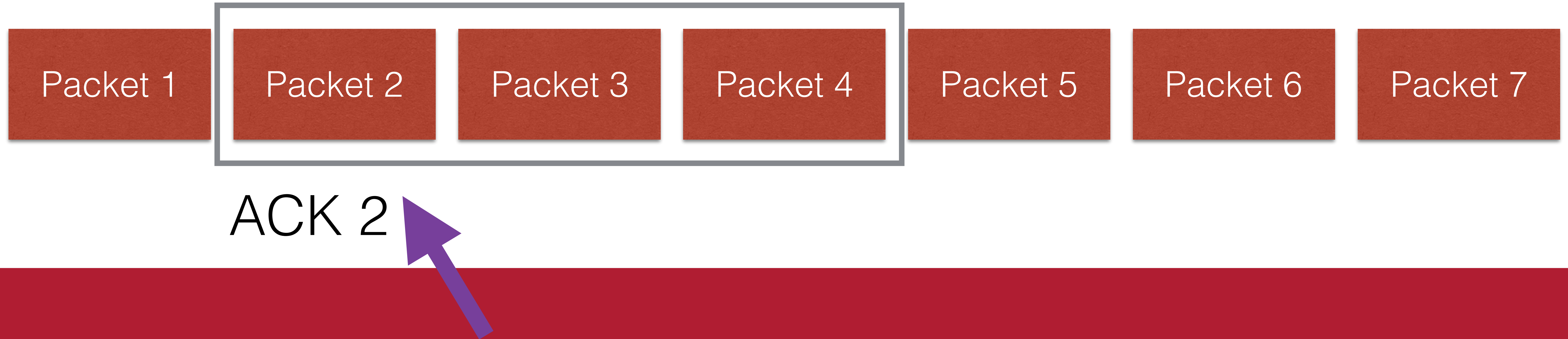

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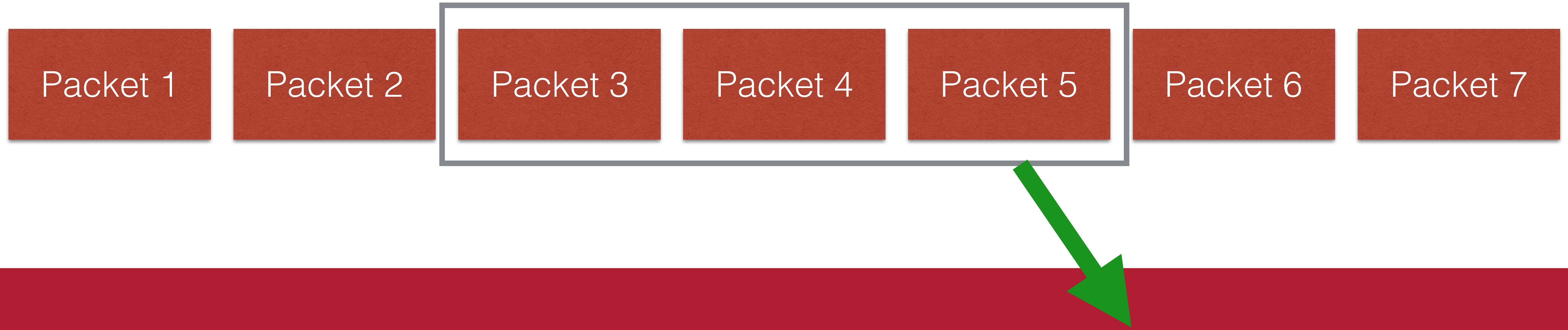

Sliding Windows

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- 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?

Sliding Windows

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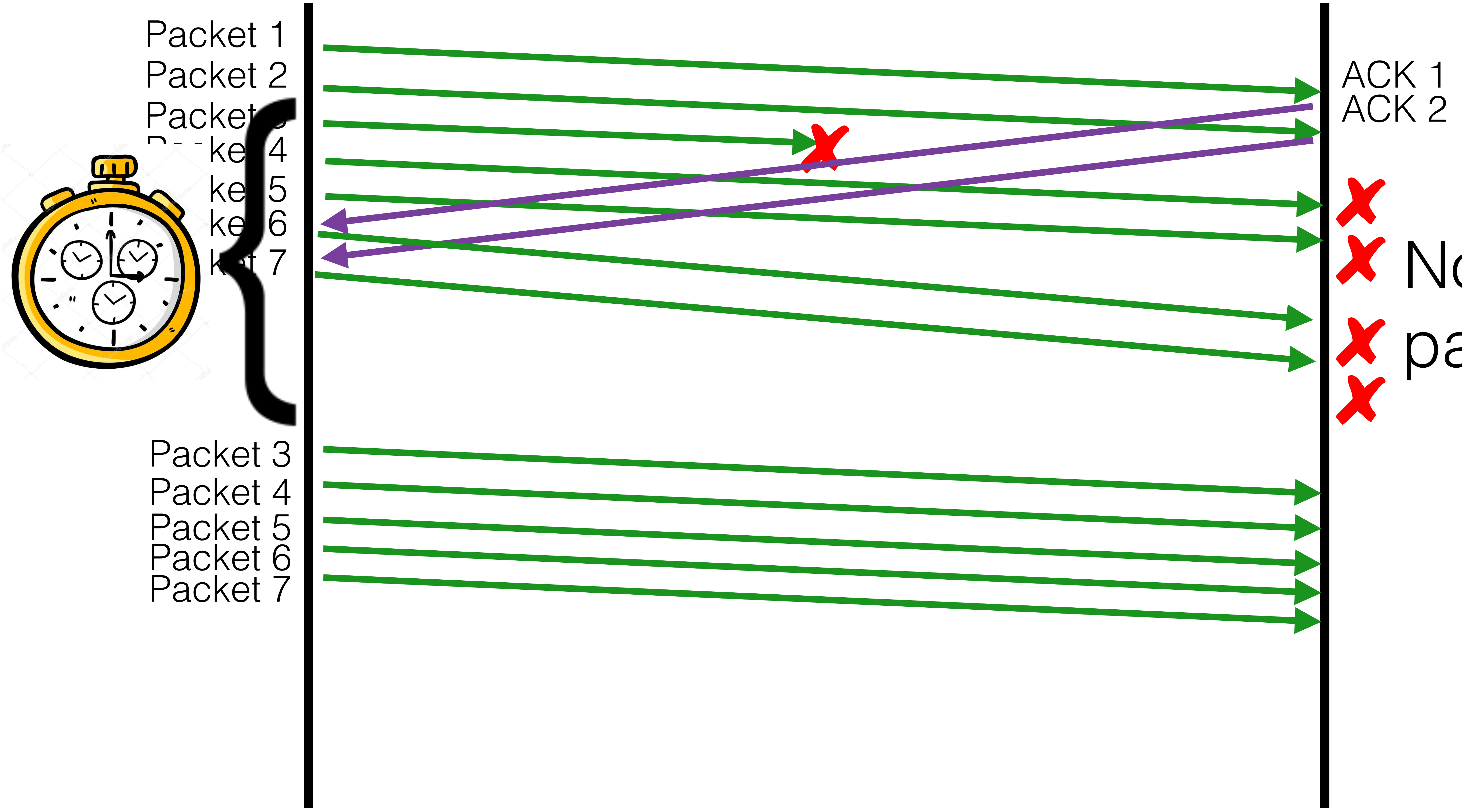
Approach #1: Go Back N



Not the expected packet — 3 — so ignore.

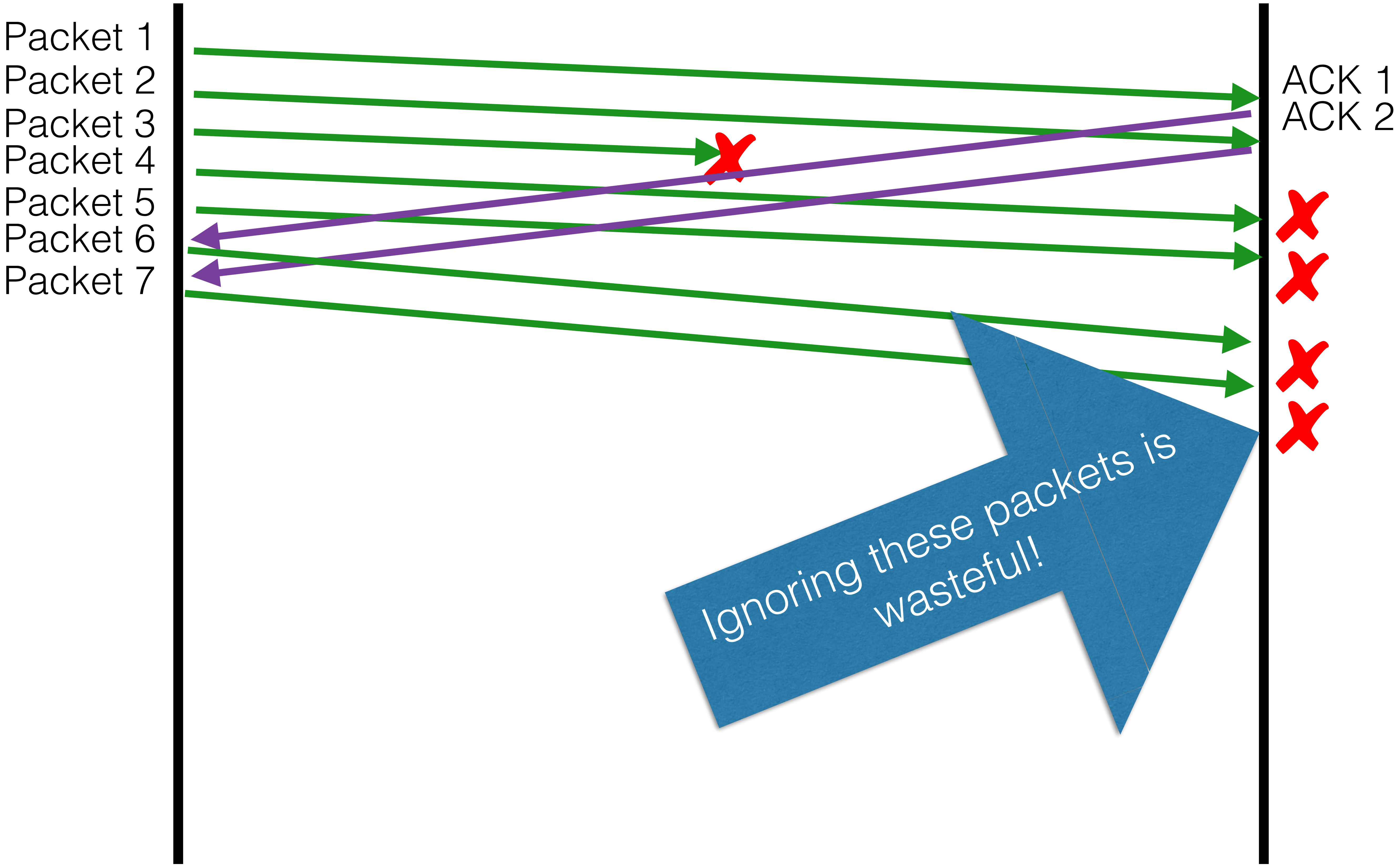
Go Back N

- **Sender:**
  - Send up to {n} packets at a time. Set a timeout timer for every packet.
  - On receiving an ACK, slide the window forward.
  - On timeout, retransmit the timeout packet, and everything after it in the window.
- **Receiver:**
  - On receive next expected sequence number, send an ACK
  - If packet is corrupted or has an unexpected sequence number, ignore it.

We don’t use Go Back N on the Internet… why not?

Loss recovery *works*… but it's not very efficient.

Approach #1: Go Back N



Approach #2: Selective Repeat

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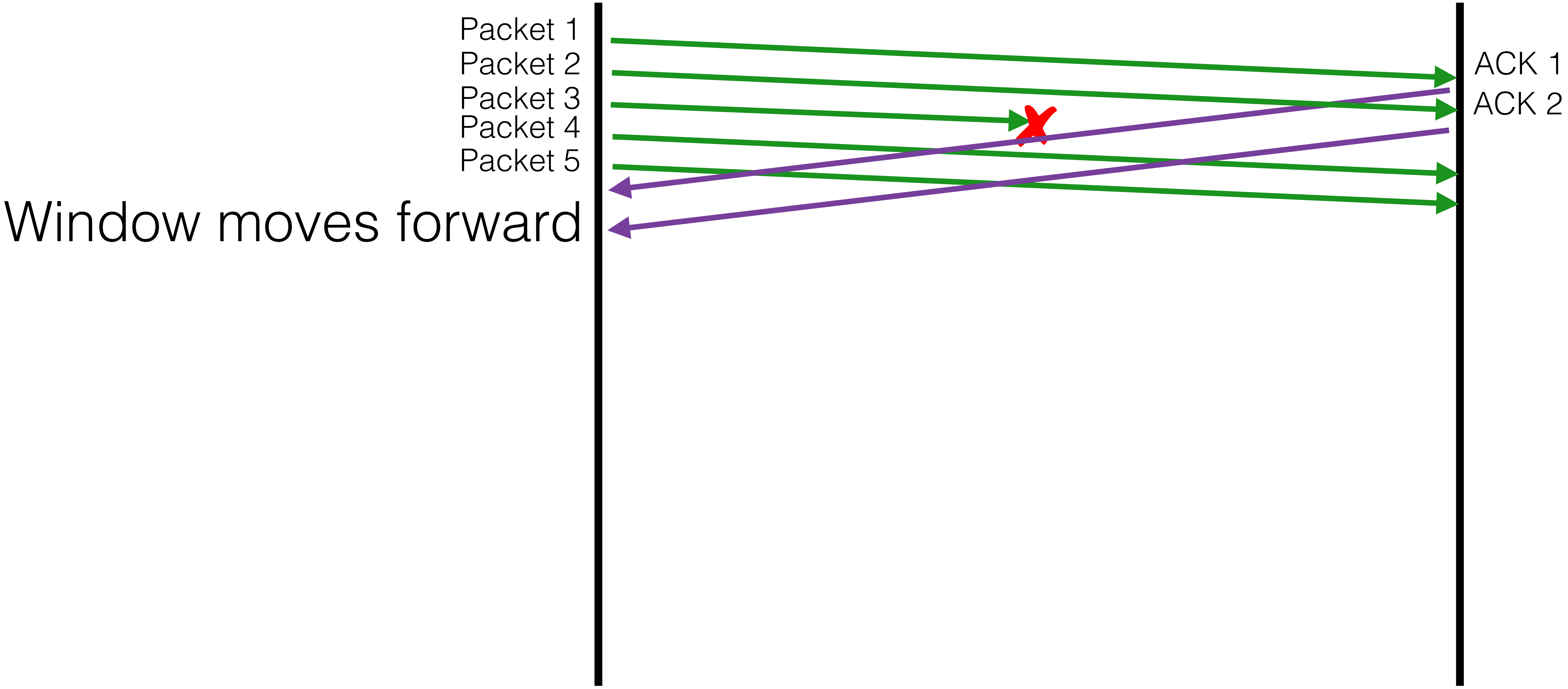

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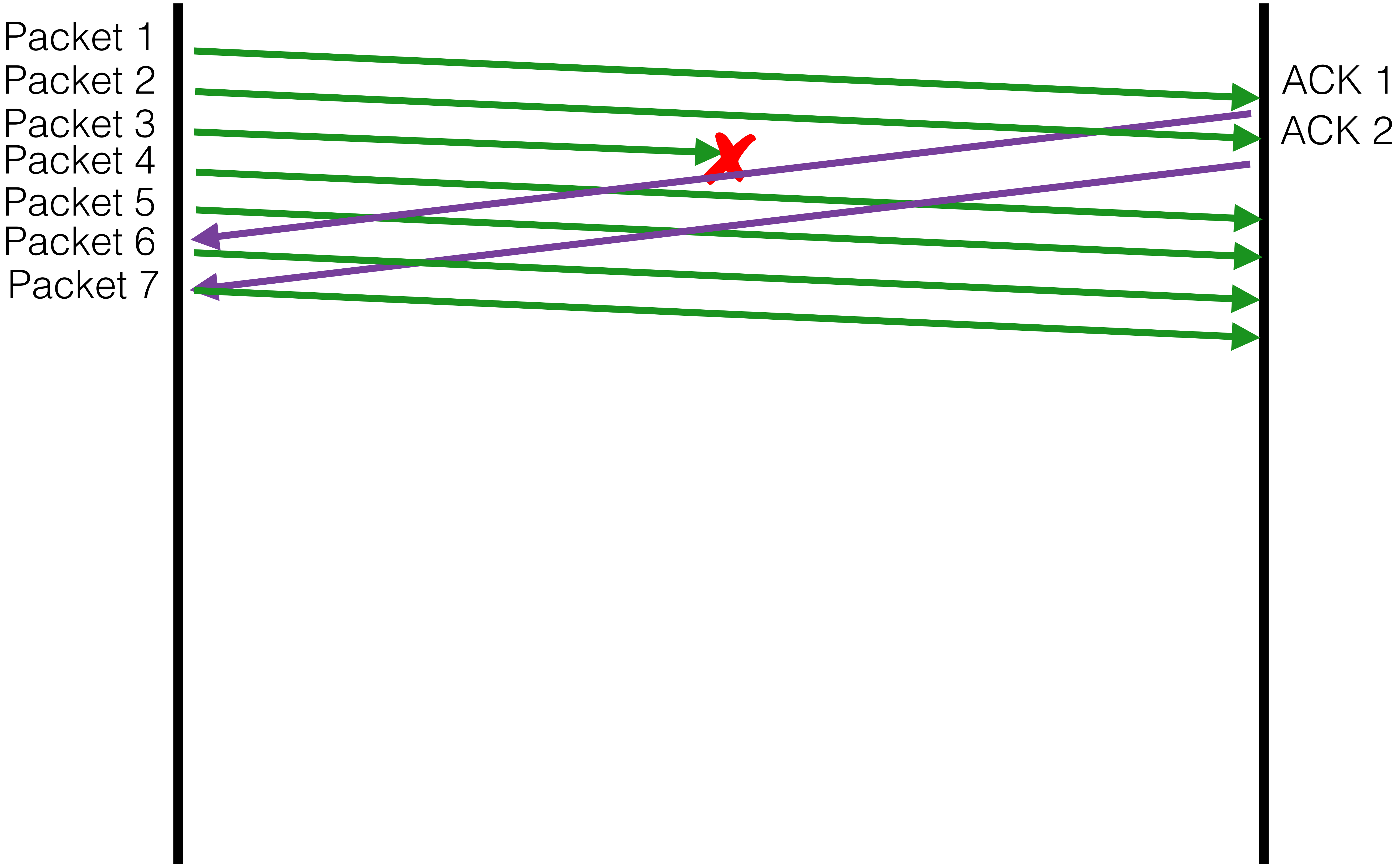

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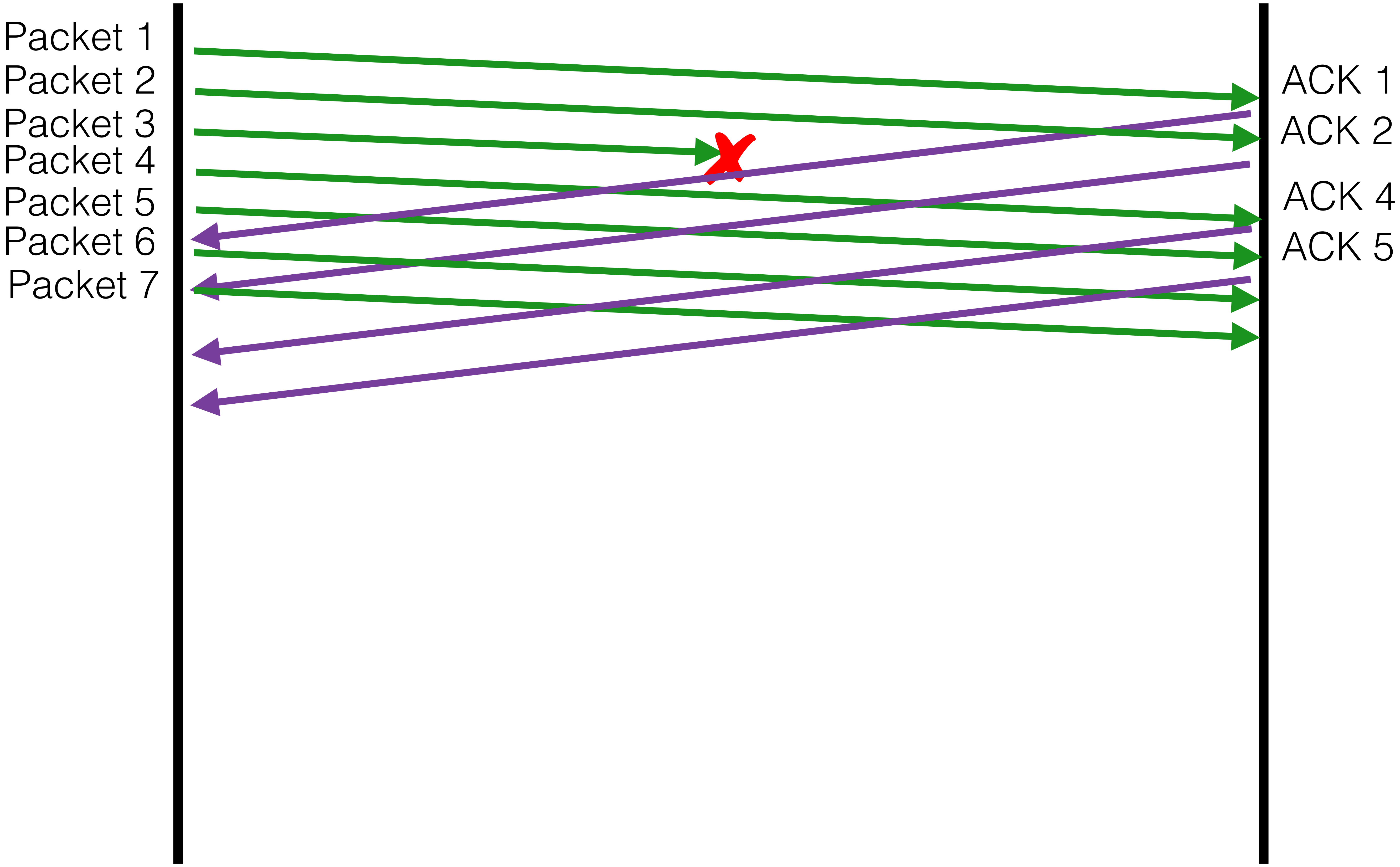

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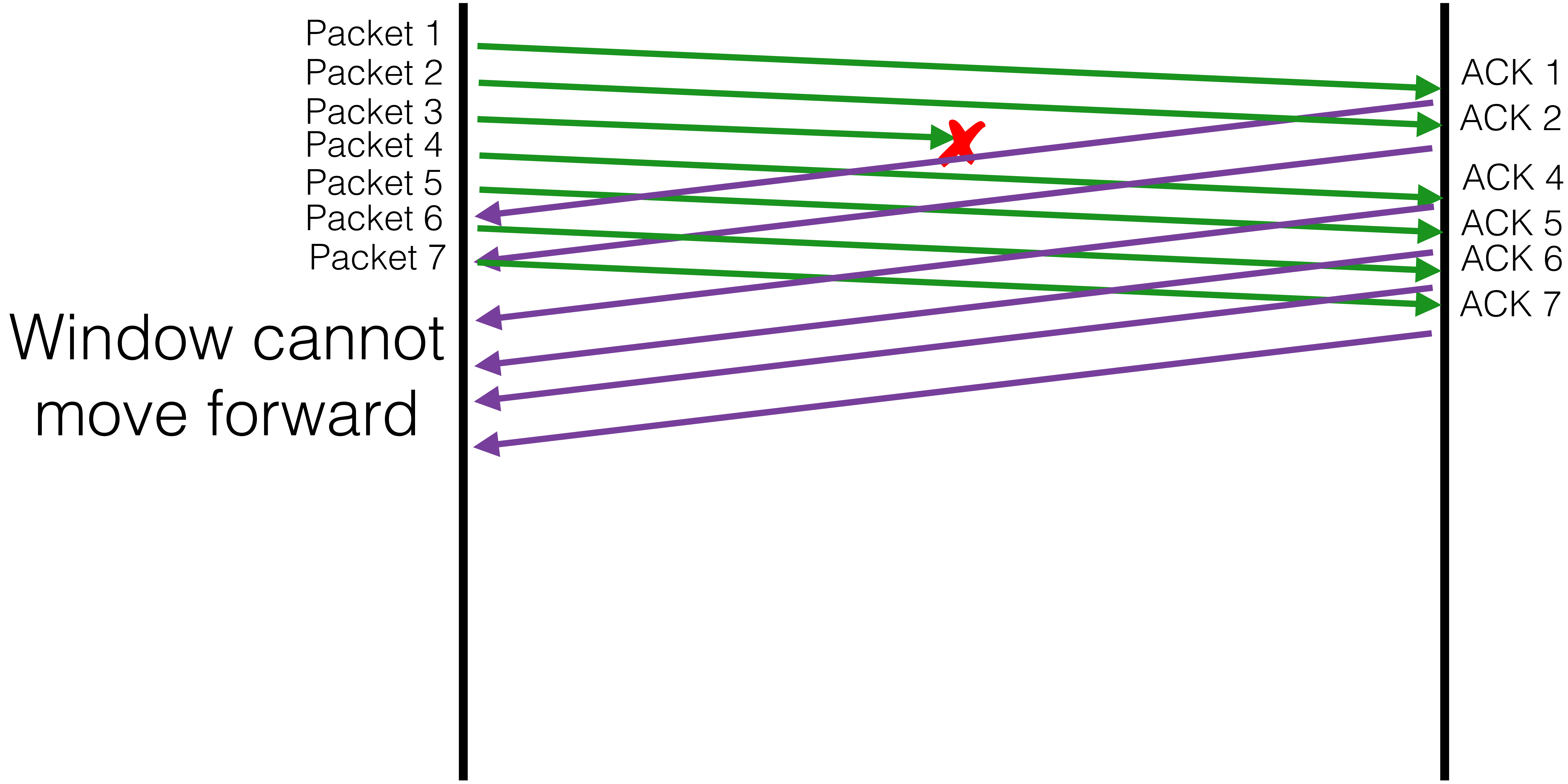

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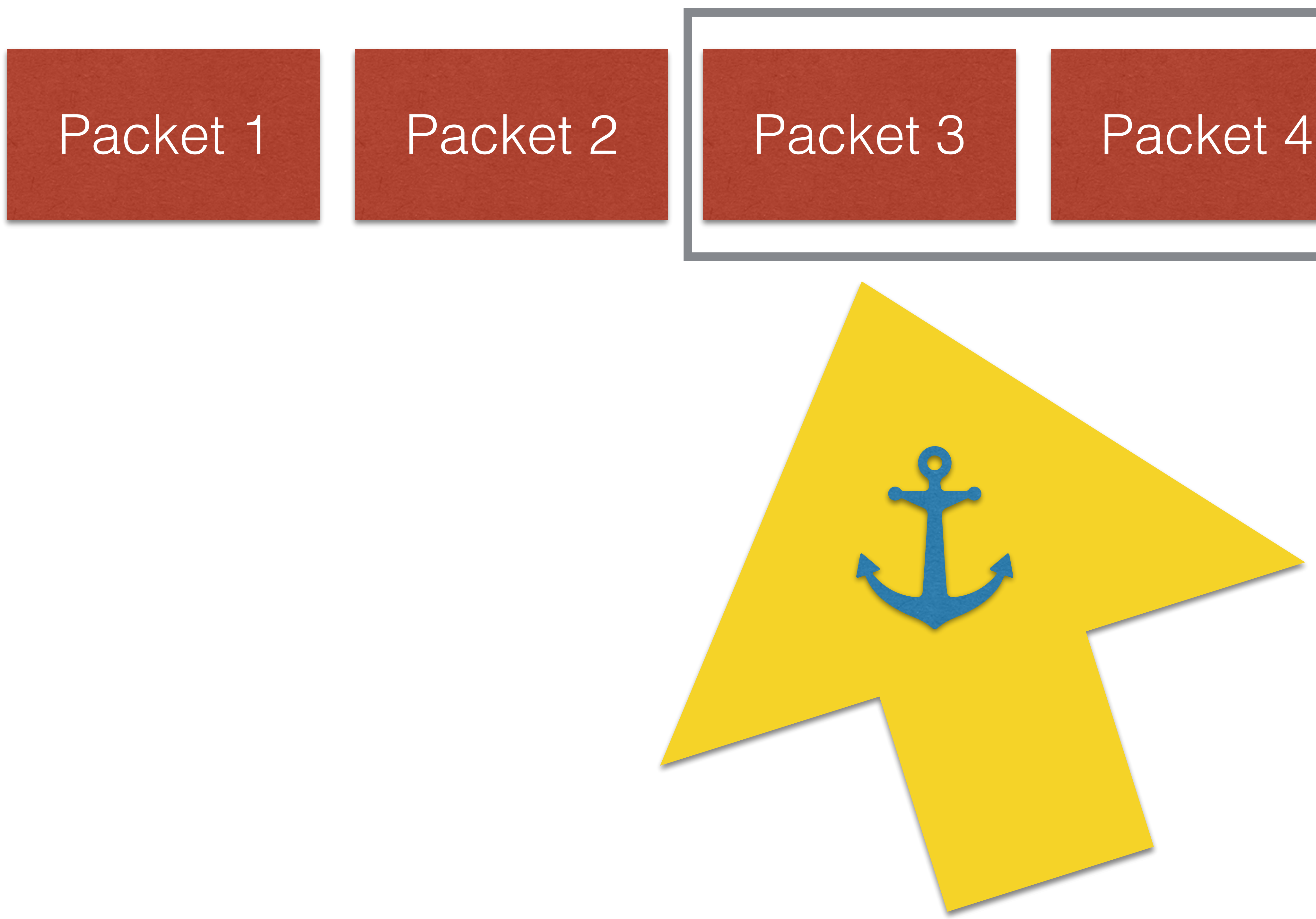
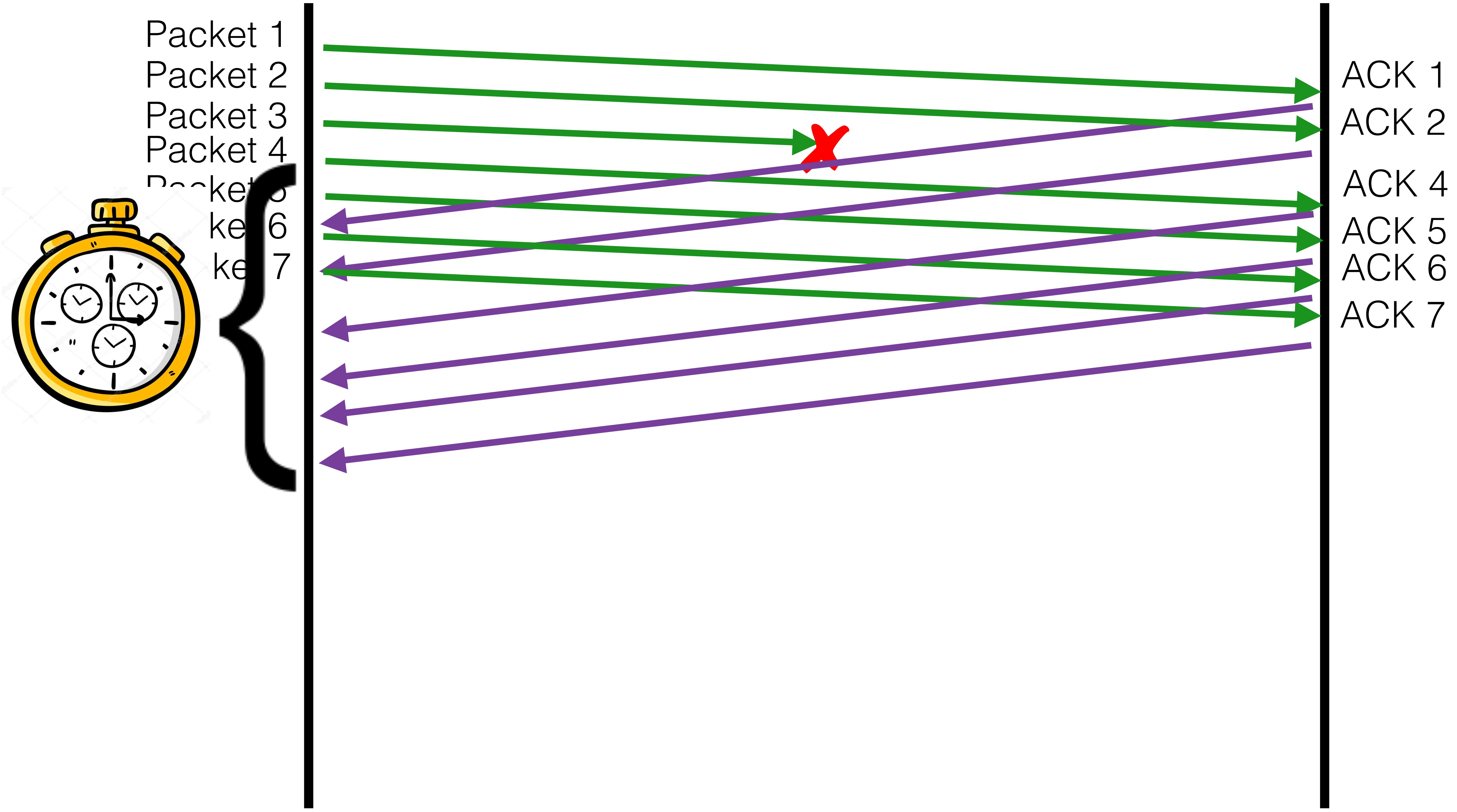


Missing packet 3 stops the window from moving forward

Approach #2: Selective Repeat



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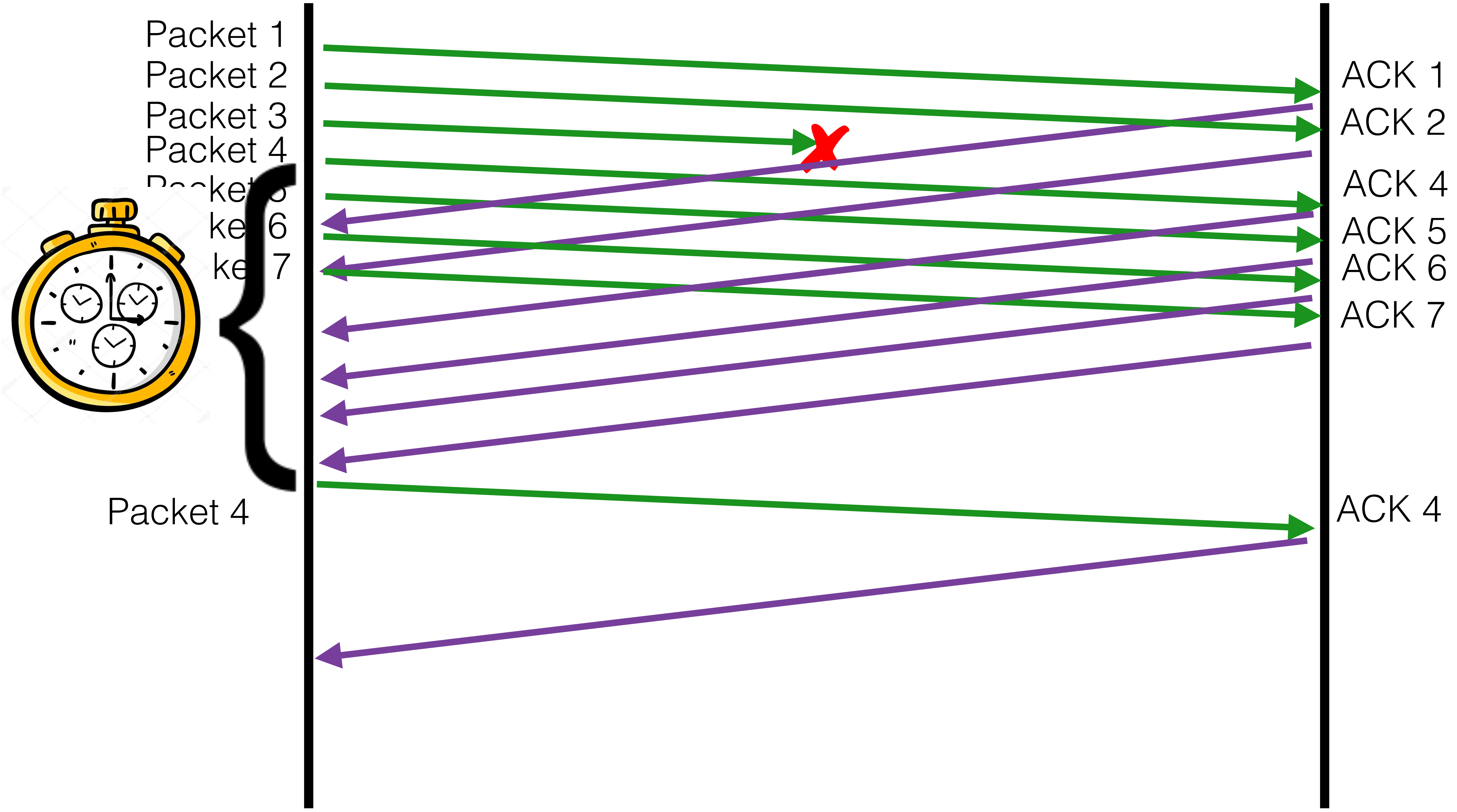

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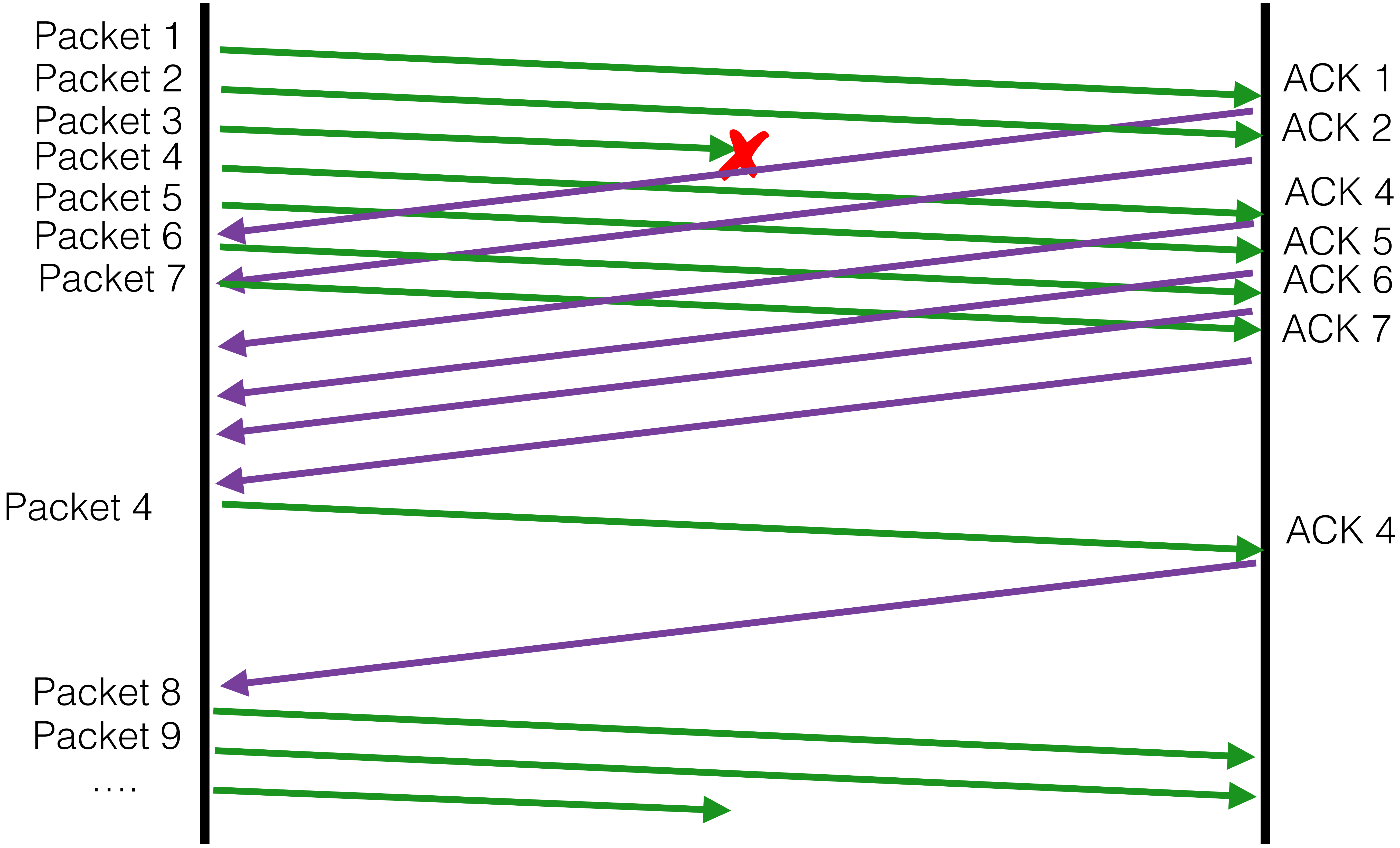
Packet 1 | Packet 2 | Packet 3 | Packet 4 | Packet 5 | Packet 6 | Packet 7 | Packet 8 | Packet 9

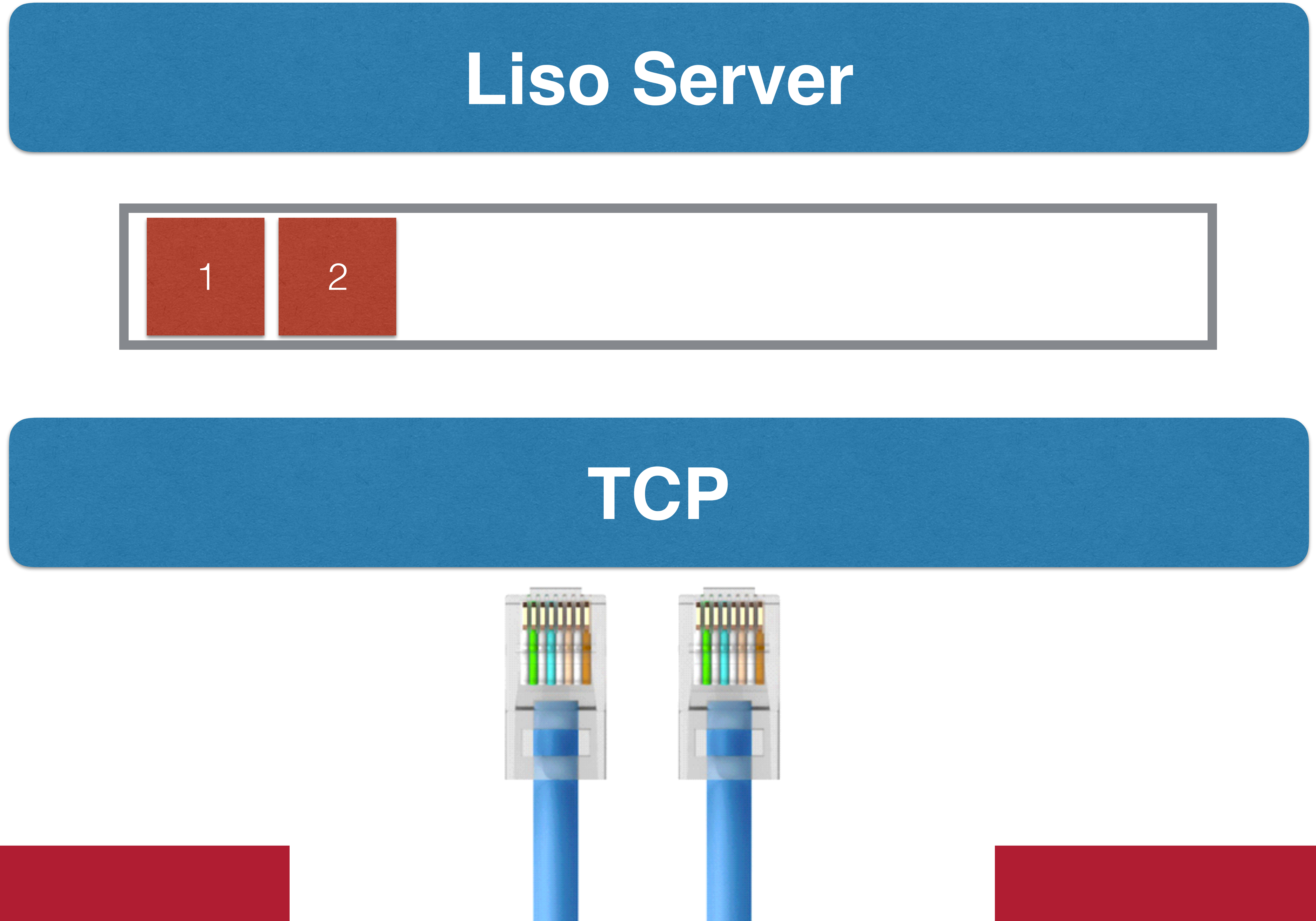
Approach #2: Selective Repeat



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.

Receive Buffer



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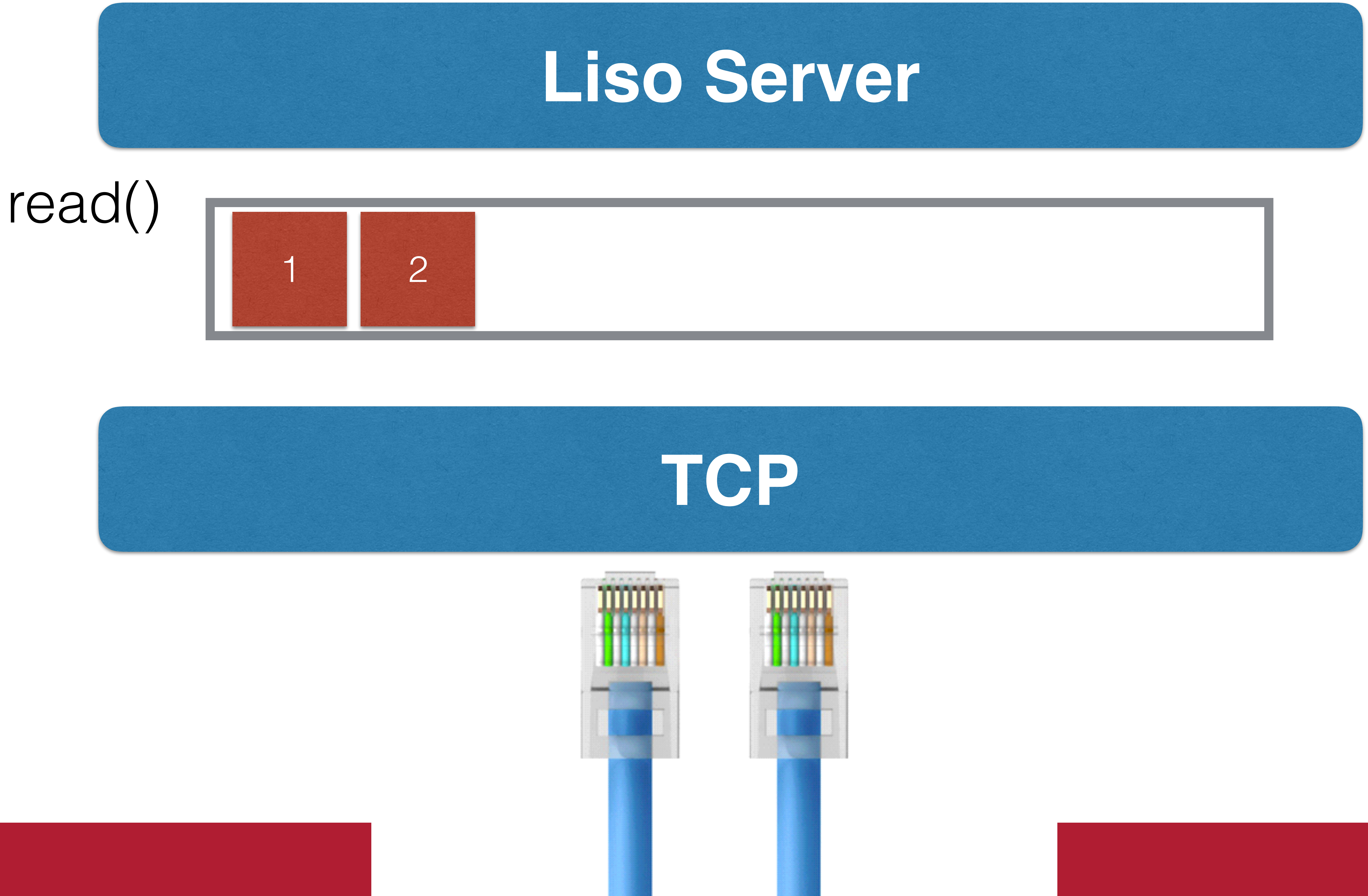

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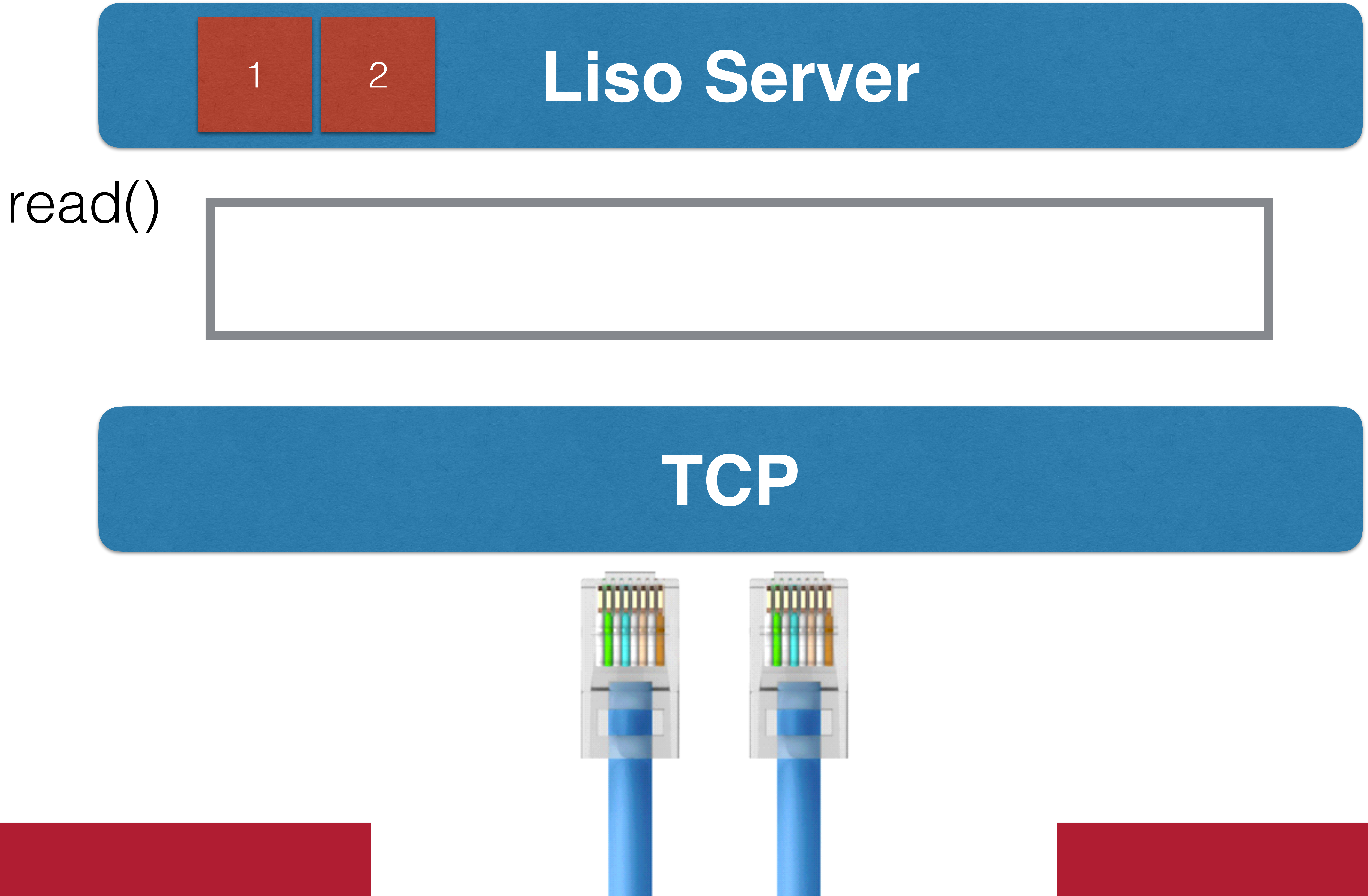

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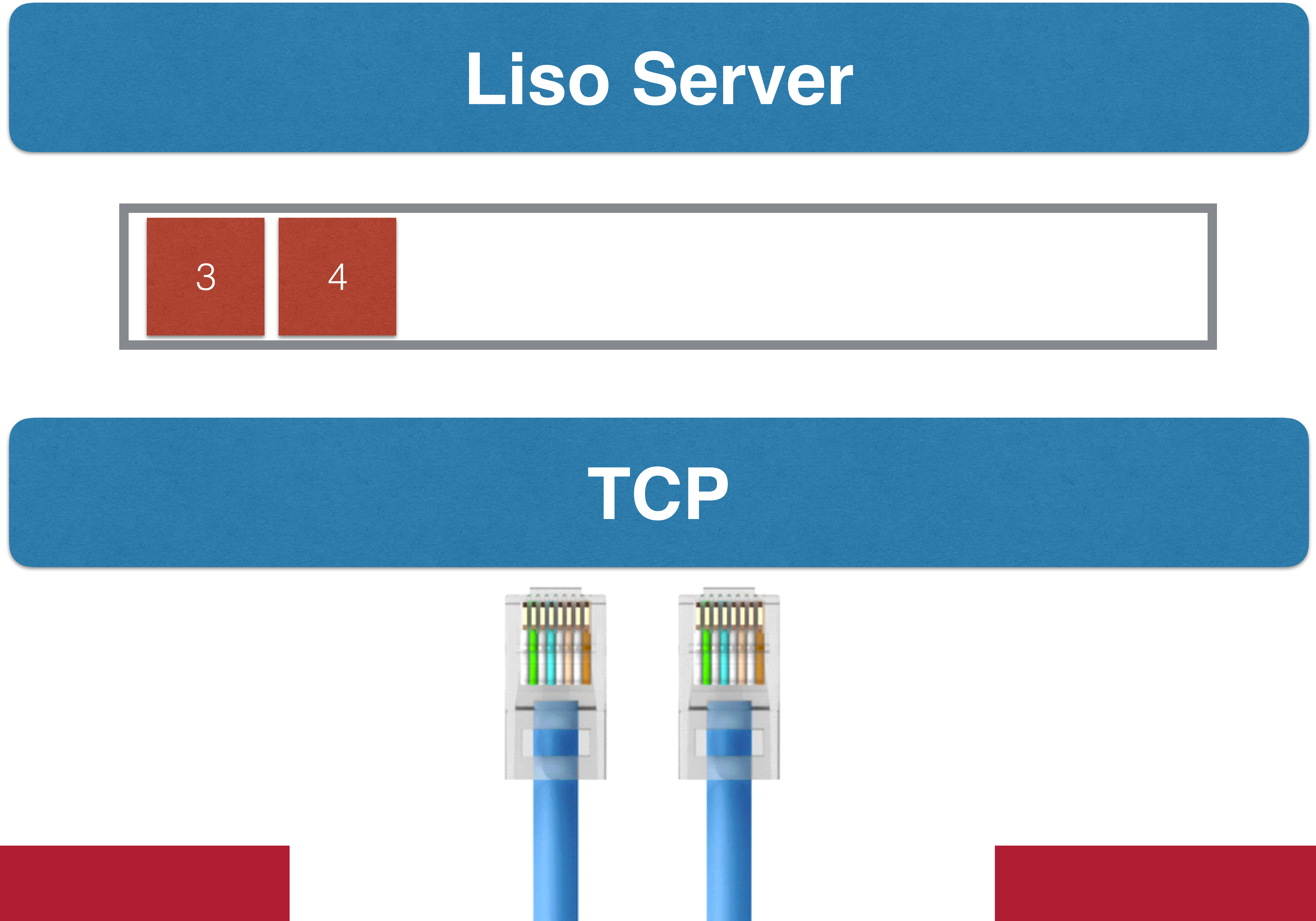

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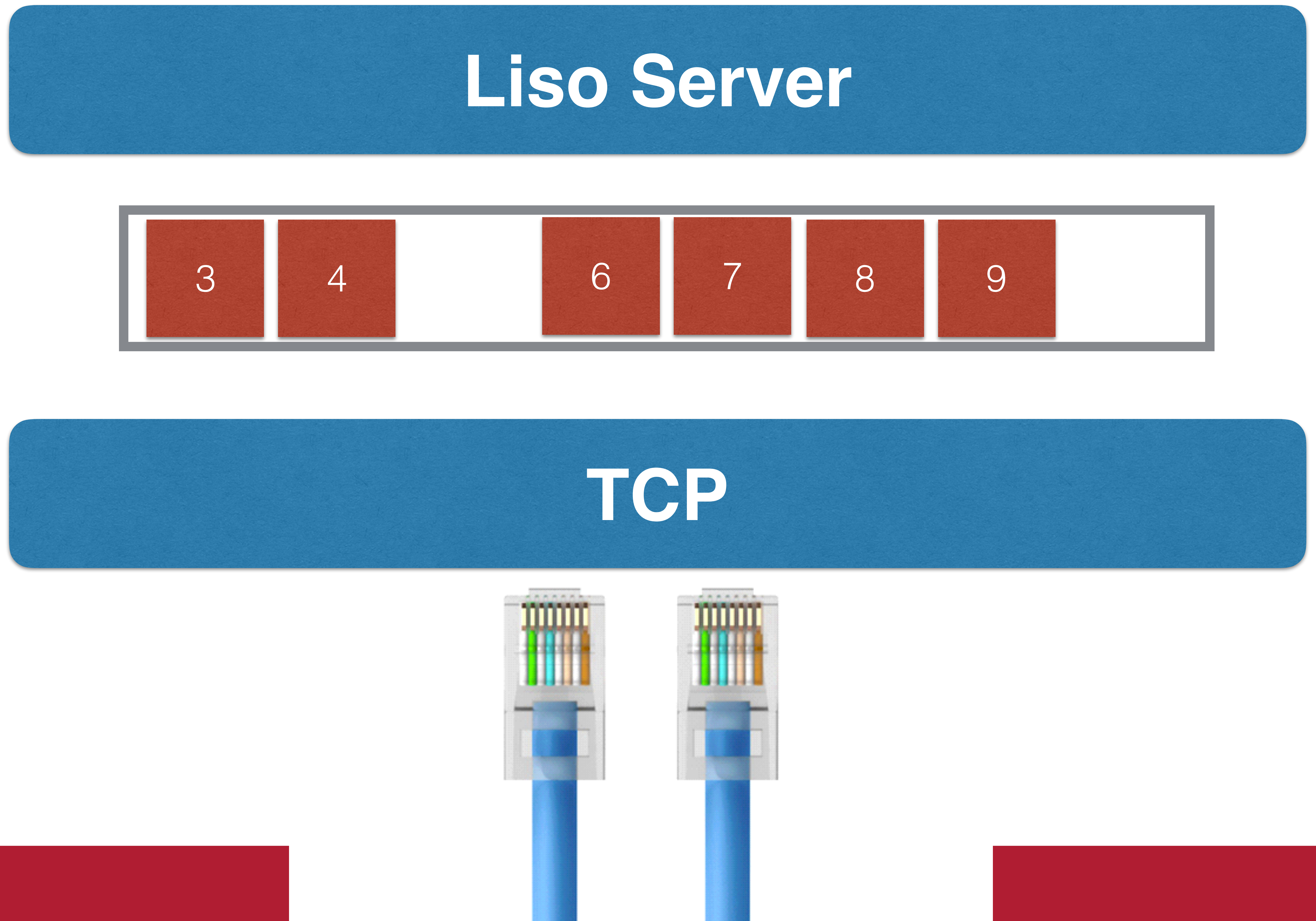

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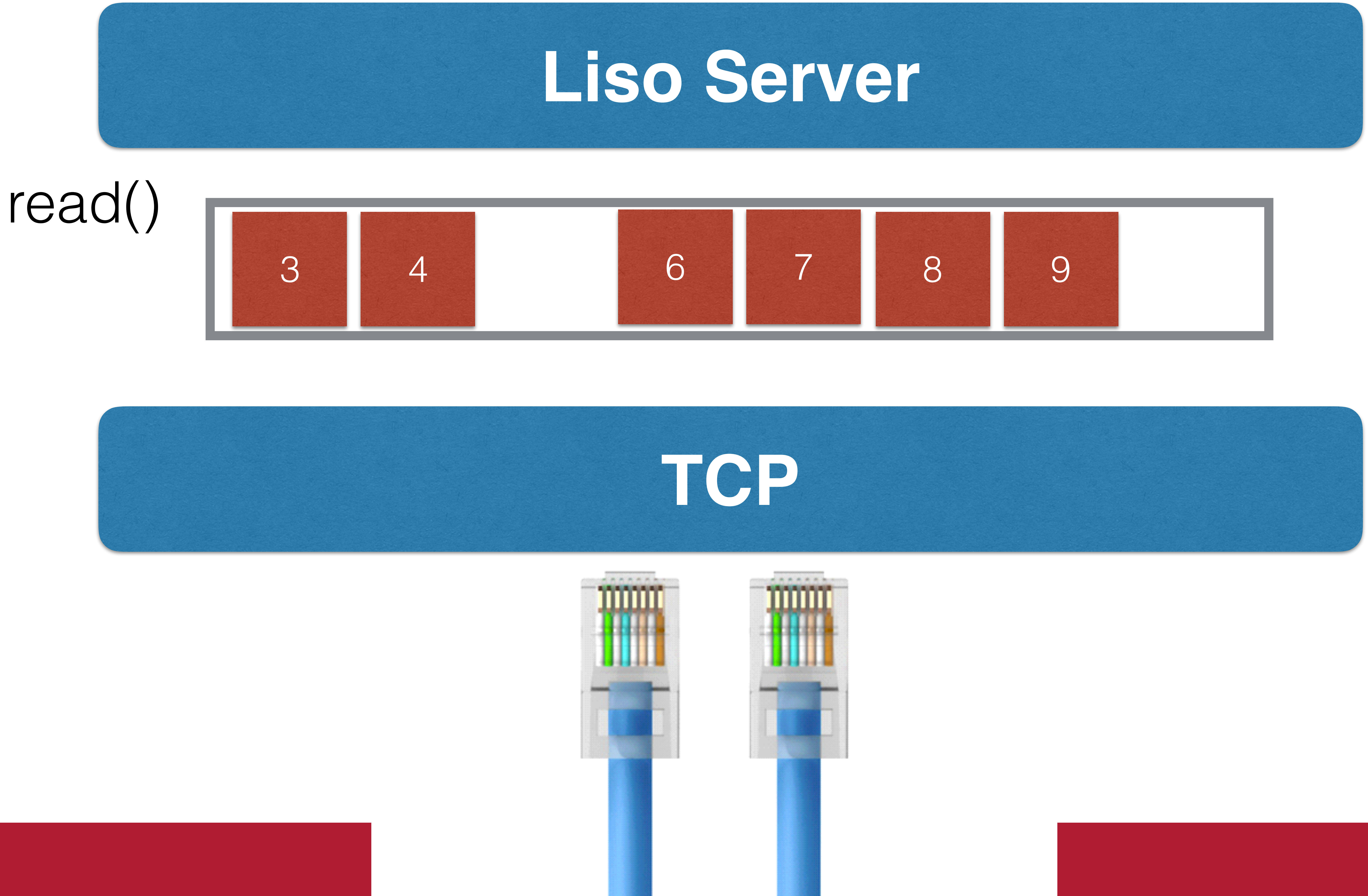

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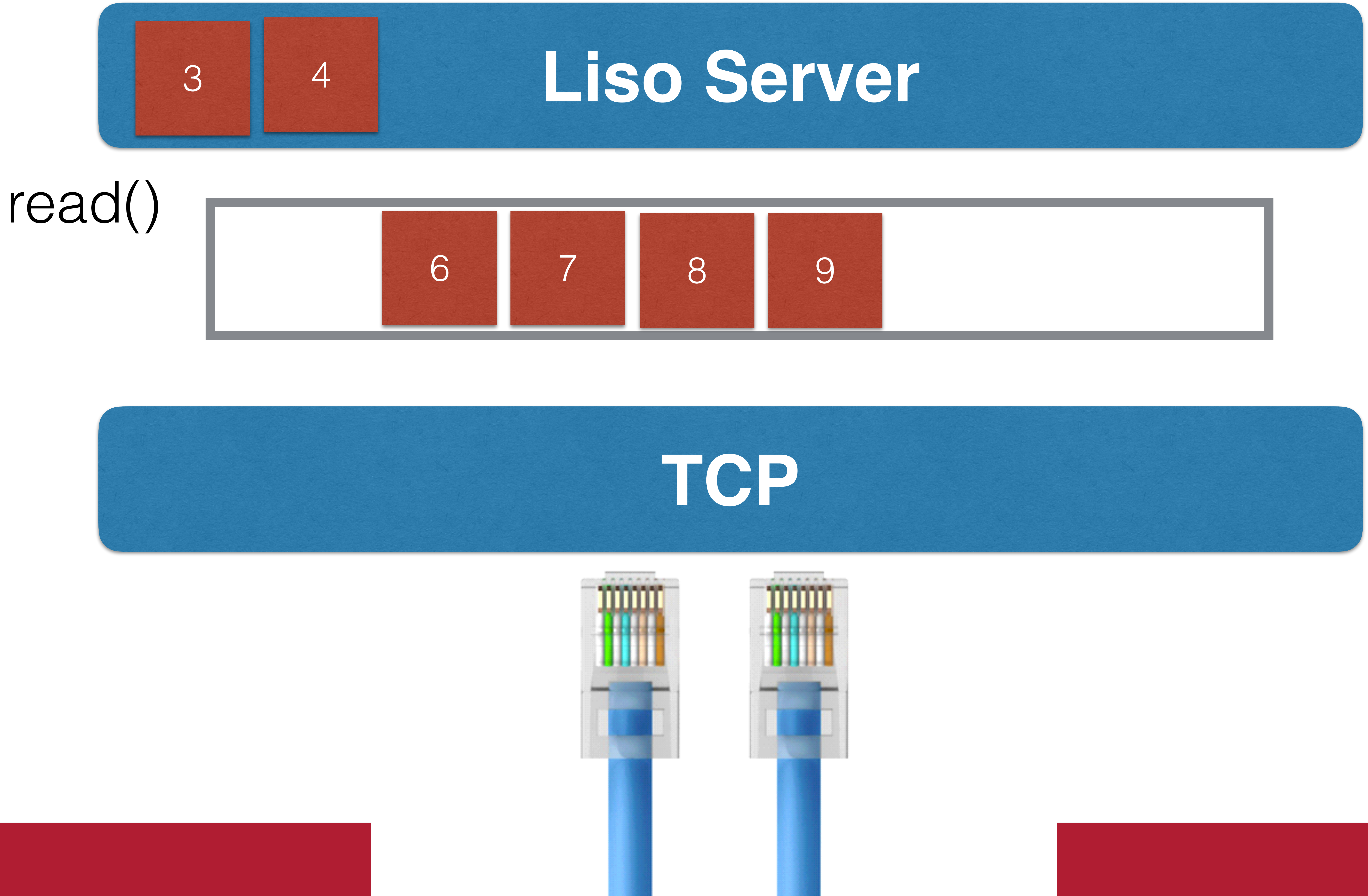

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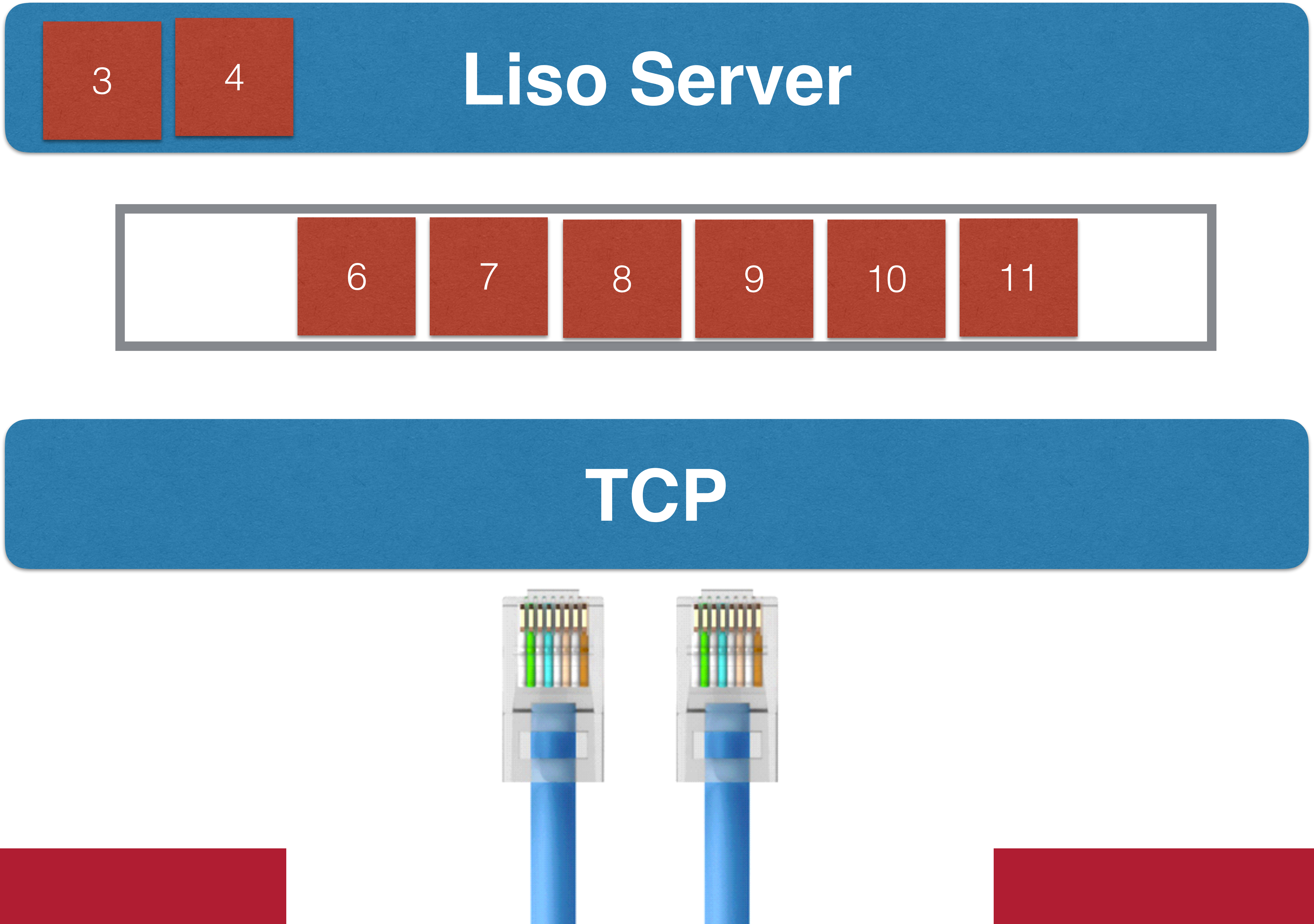
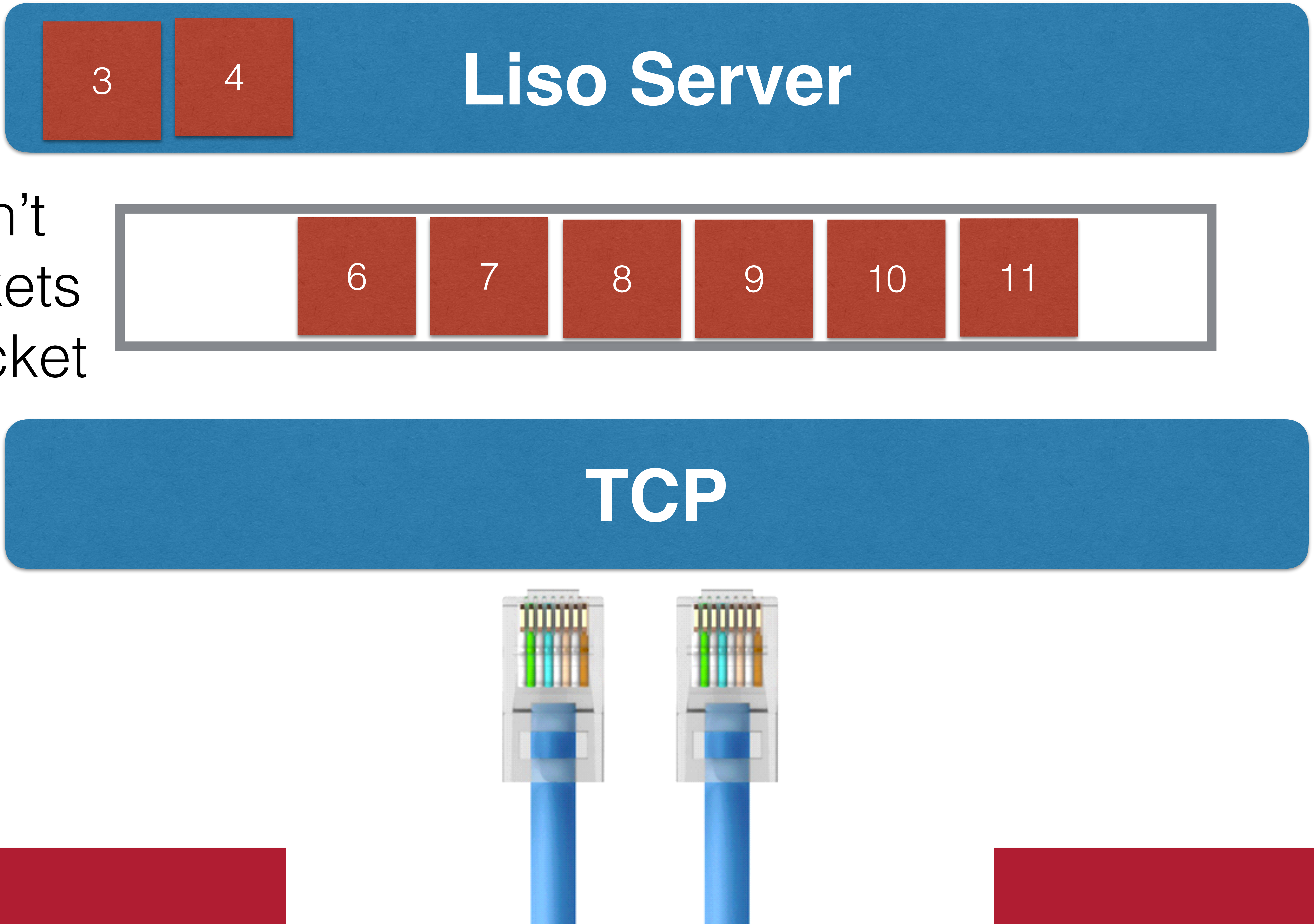


Receive Buffer

Application can’t take in any packets until missing packet comes in



Handling Loss

- Go-Back-N and Selective Repeat both handle loss, while allowing lots of packets in flight.
- Selective repeat is more efficient at recovering from failure.

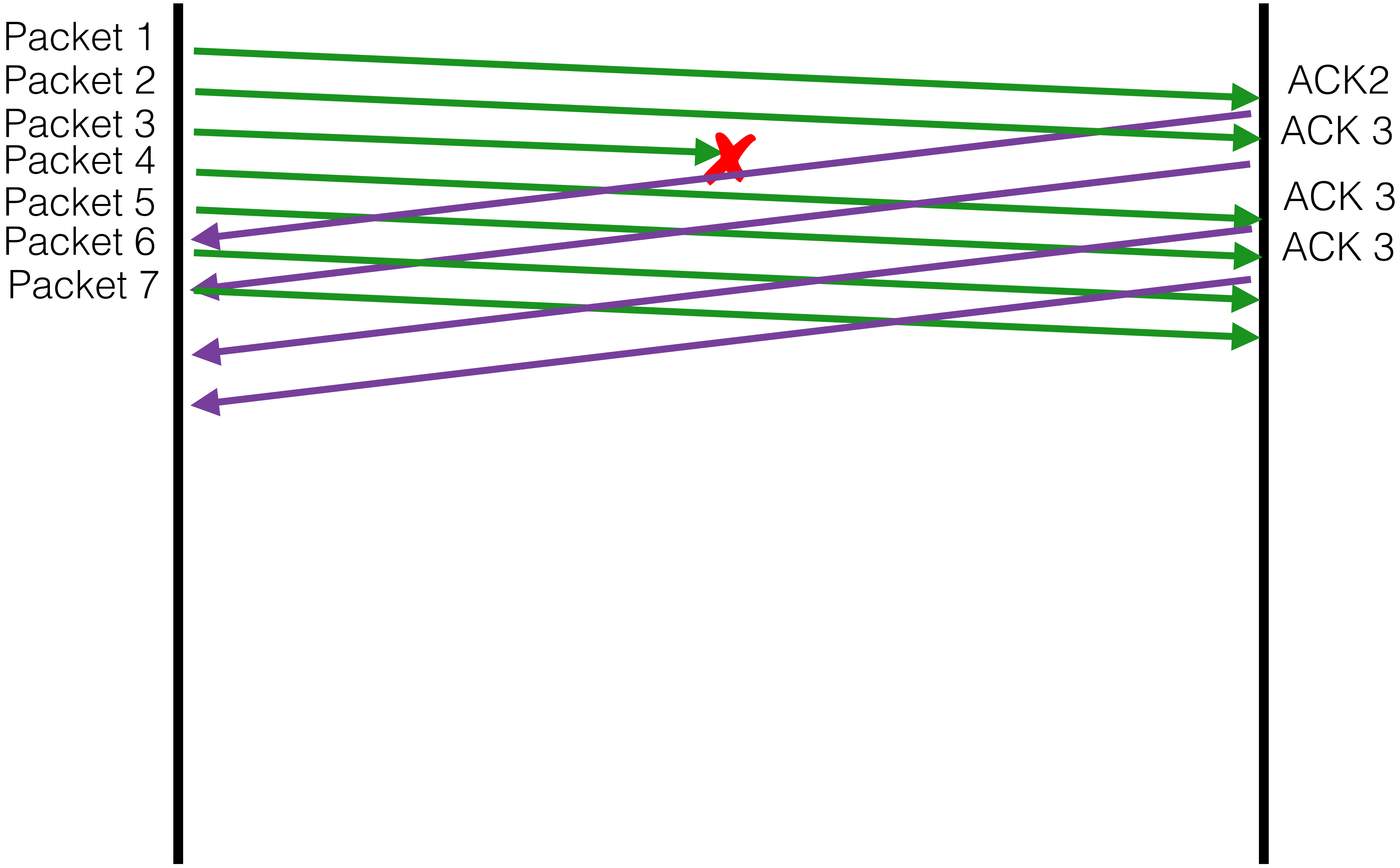
What does TCP Do?

- TCP is like Selective Repeat, but…
  - It uses *cumulative ACKs*
  - Instead of using per-packet sequence numbers, it uses per-byte sequence numbers.
    - e.g. if packet #1 has 1000 bytes of payload data, packet #2 will have the sequence number 1001
  - It implements *fast recovery (we'll discuss this on Tuesday)*

Basic ACKs vs Cumulative ACKs

- Basic ACKs: “ACK n” means “I just received packet n”
- Cumulative ACKs: “ACK n” means, “I have received all packets up to (but not including) n”

Cumulative ACK



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Sliding Windows

- A sender's "window" contains a set of packets that have been transmitted but not yet acked.

You now know most of this

- Sliding windows improve the effic… a transport protocol.
- Two questions we need to answer … windows:
  - (1) How do we handle loss with a windowed approach?
  - (2) How big should we make the window?

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?

We’ll figure this out on Thursday.

Have a great afternoon!