TCP Basics

CPSC 433/533, Spring 2021
Anurag Khandelwal

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  - TCP/IP has been historically co-designed, so the lines are often blurry between them
  - Not necessarily the best idea, in hindsight!

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- **Transport layer has two purposes:**
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  - Multiplexing/demultiplexing: done using *ports* and *sockets*
  - Optional: Reliable delivery
- **Reliable delivery involves many mechanisms**
  - Requires delicate design to get them to work together
  - TCP is the standard example of a reliable transport

Last Time: Components of Reliable Transport

- **Checksums:** for error detection
- **Timers:** for loss detection
- **Sliding Windows:** for efficiency
- **ACKs**
  - Cumulative
  - Selective
- **Sequence numbers:** tracking duplicates, windows
- **Retransmissions:**
  - Go-Back-N (GBN)
  - Selective Repeat

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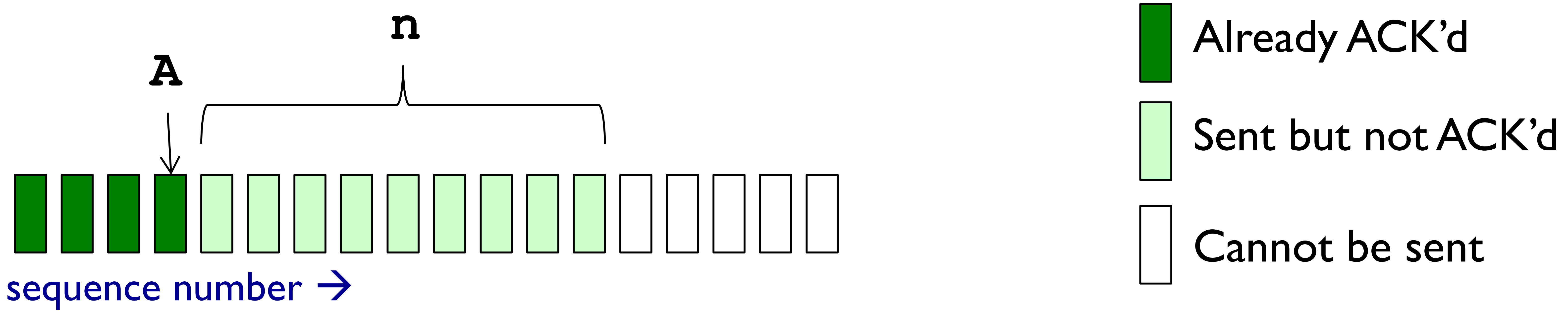
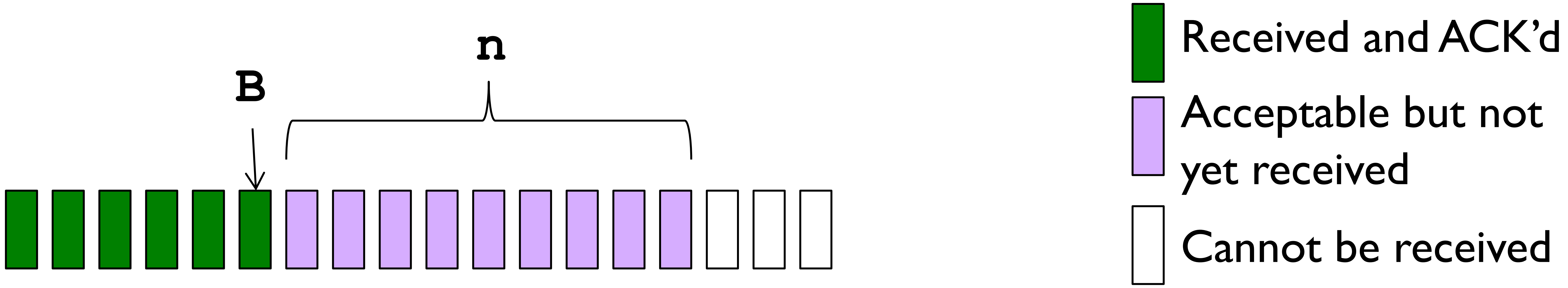
- Sender sets timer for 1st outstanding ACK(A+1)
- If timeout, retransmit A+1, …, A+n

Sliding Window with GBN

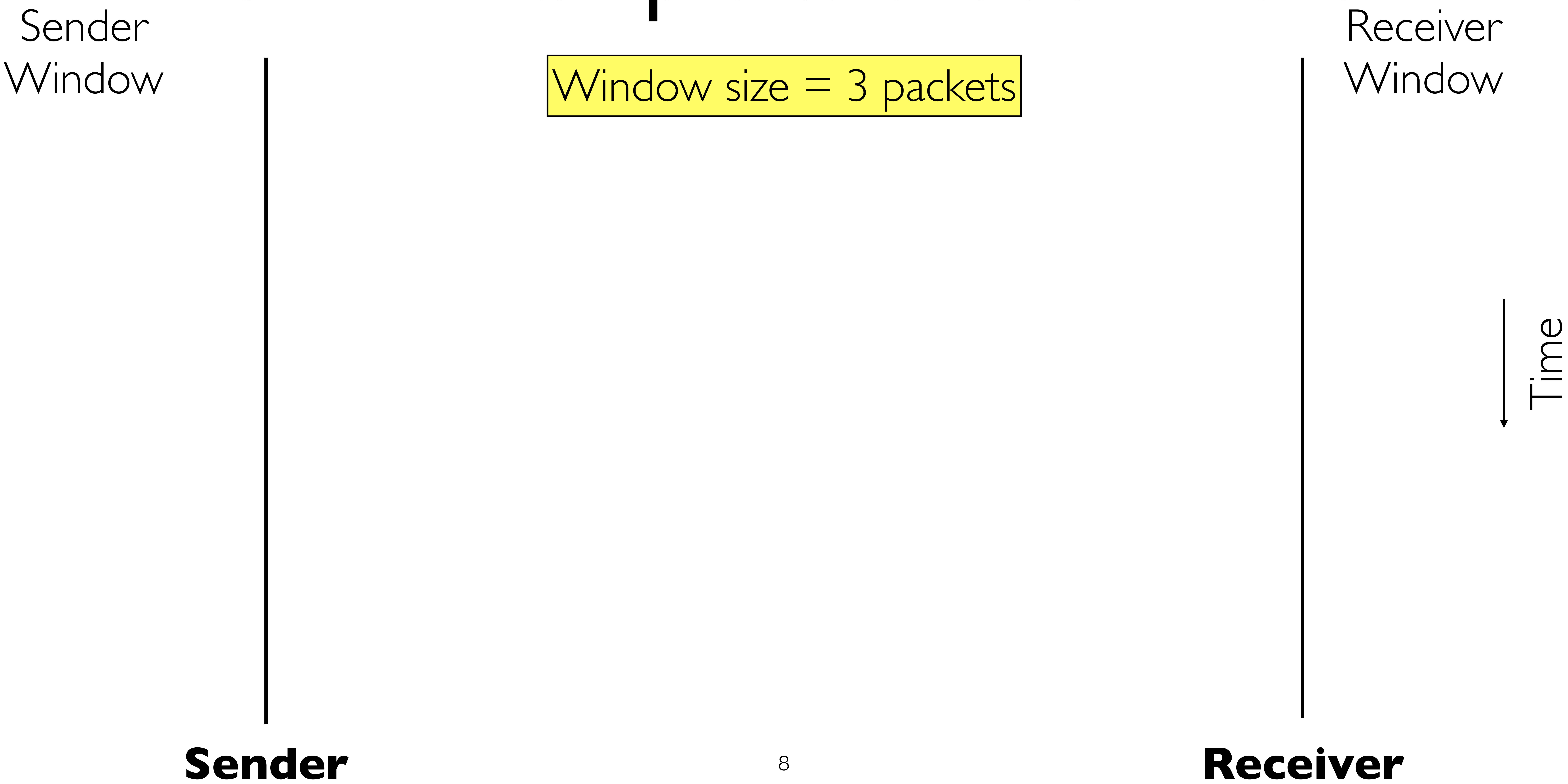
- Let A be the **last ACK'd packet of sender without gap**; then window of sender = {A+1, A+2, …, A+n}



- Let B be the **last received packet without gap** by receiver; then window of receiver = {B+1, …, B+n}



GBN Example without Errors



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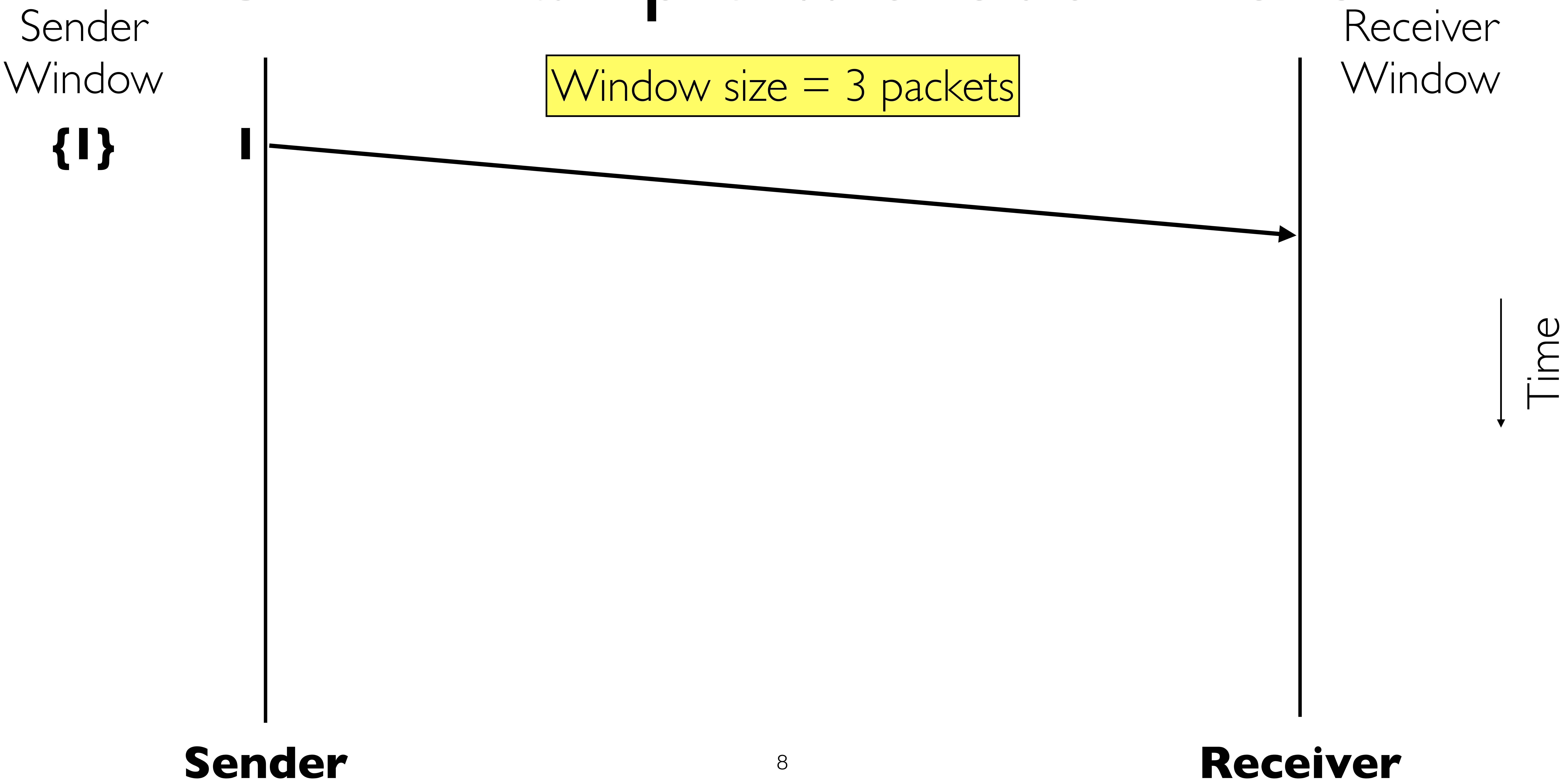

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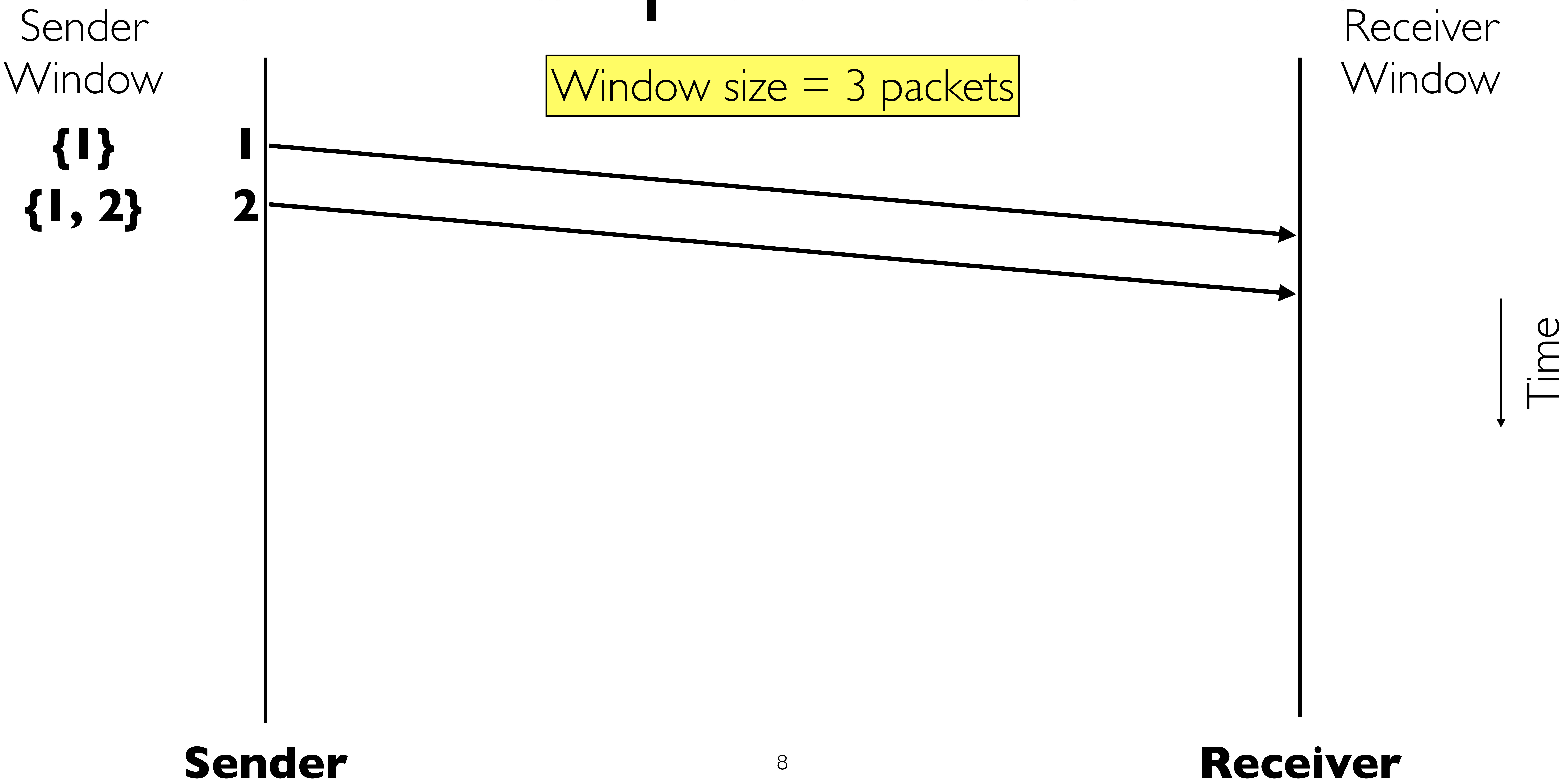

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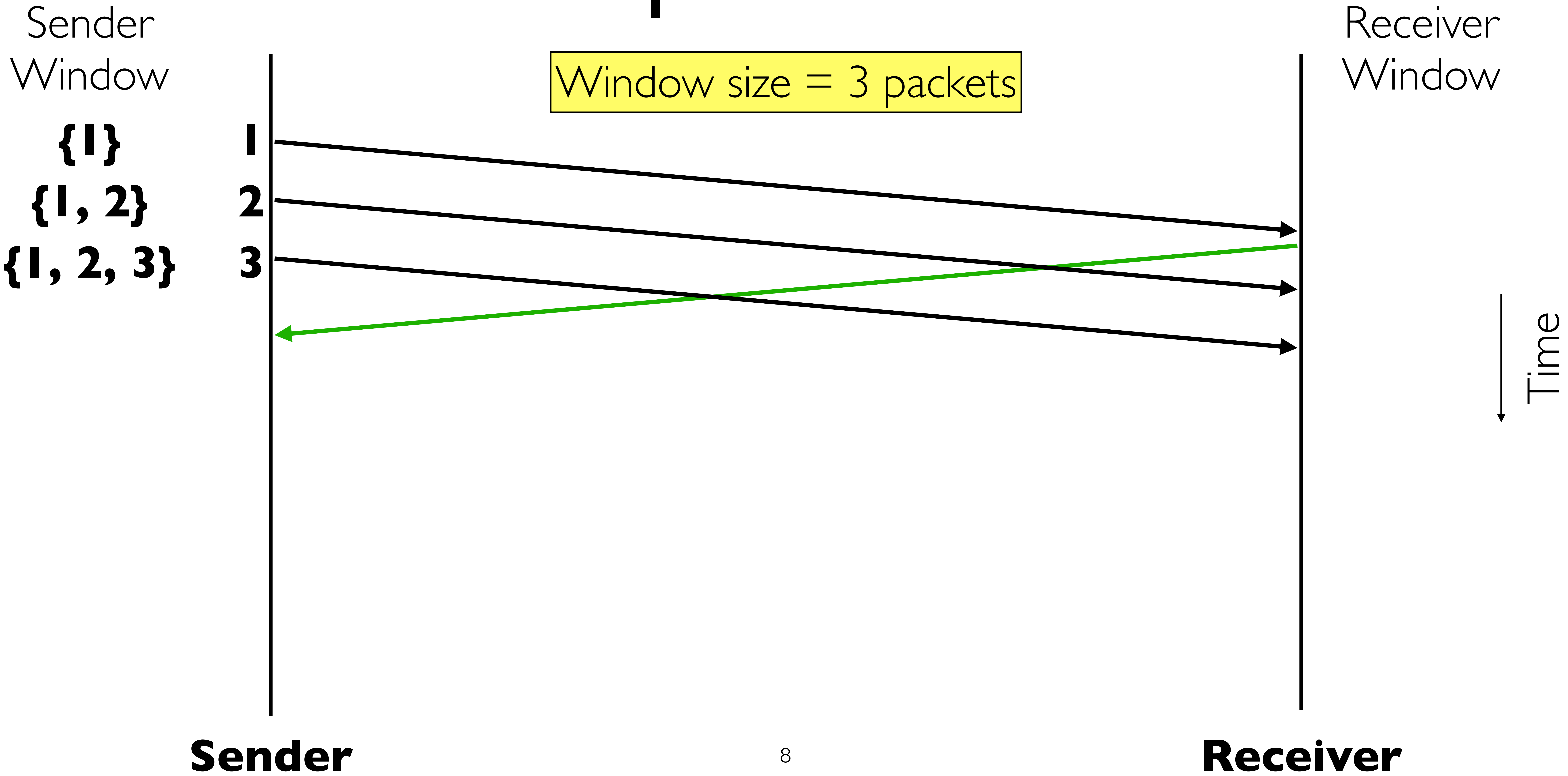

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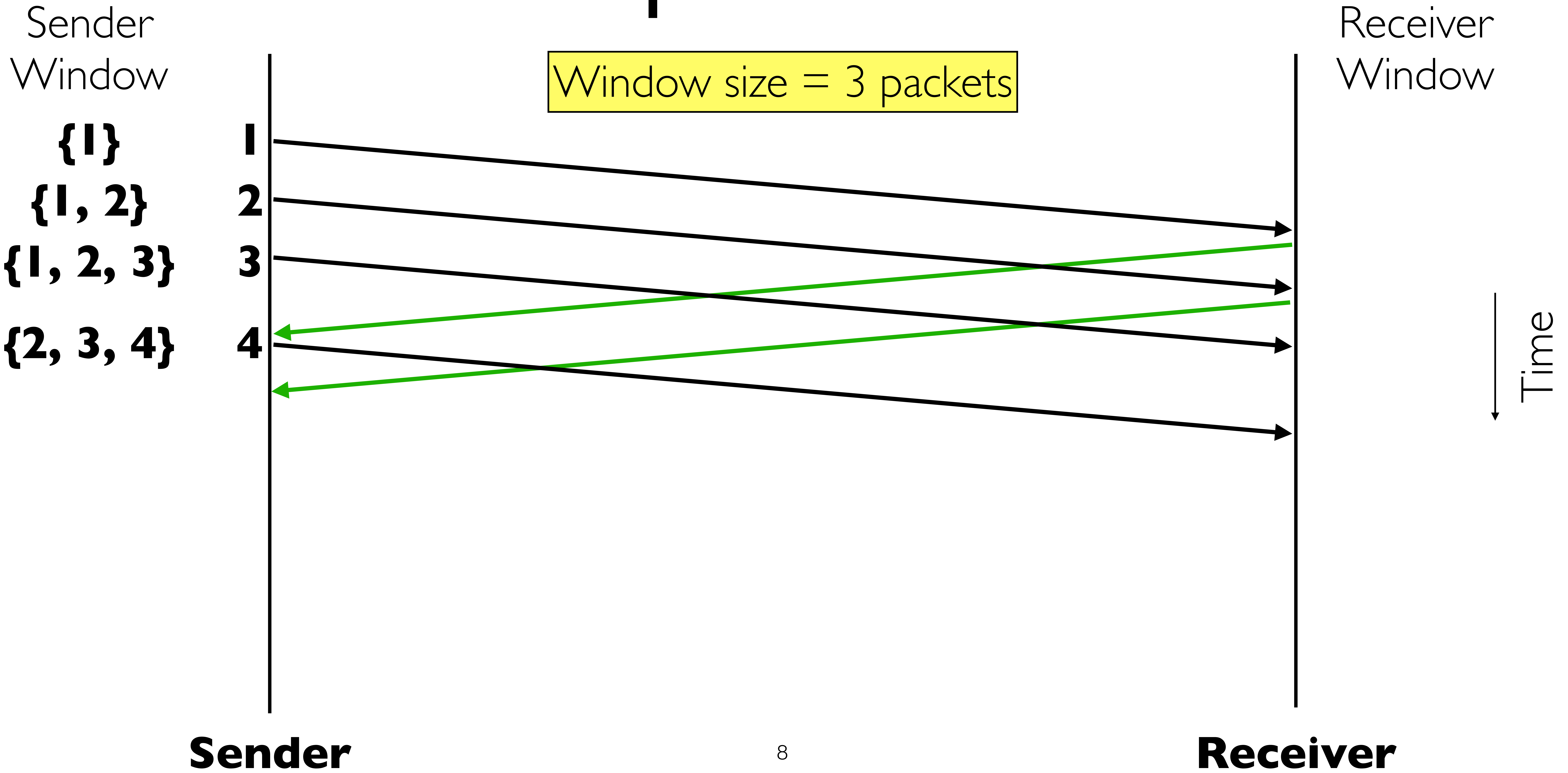

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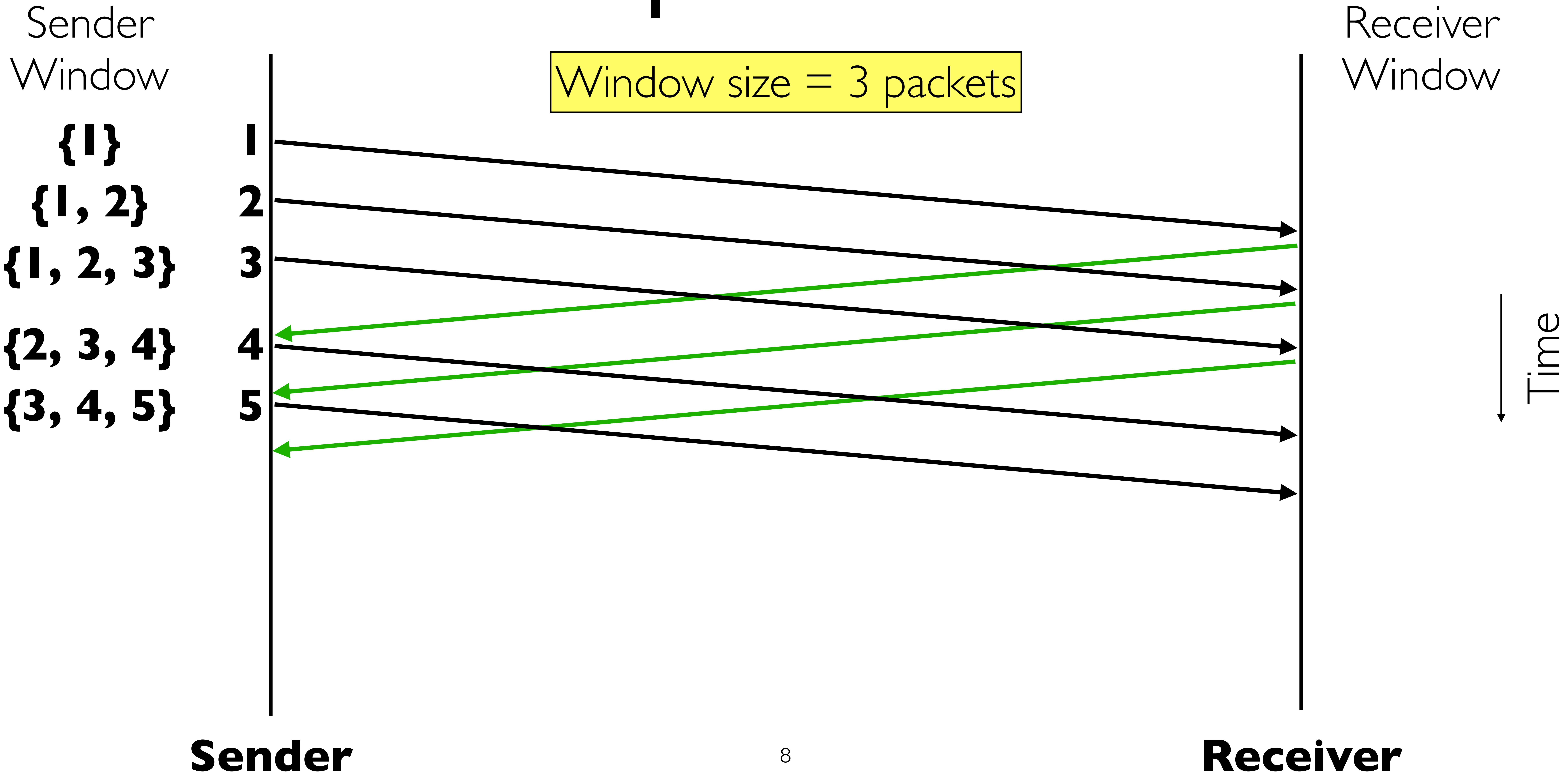

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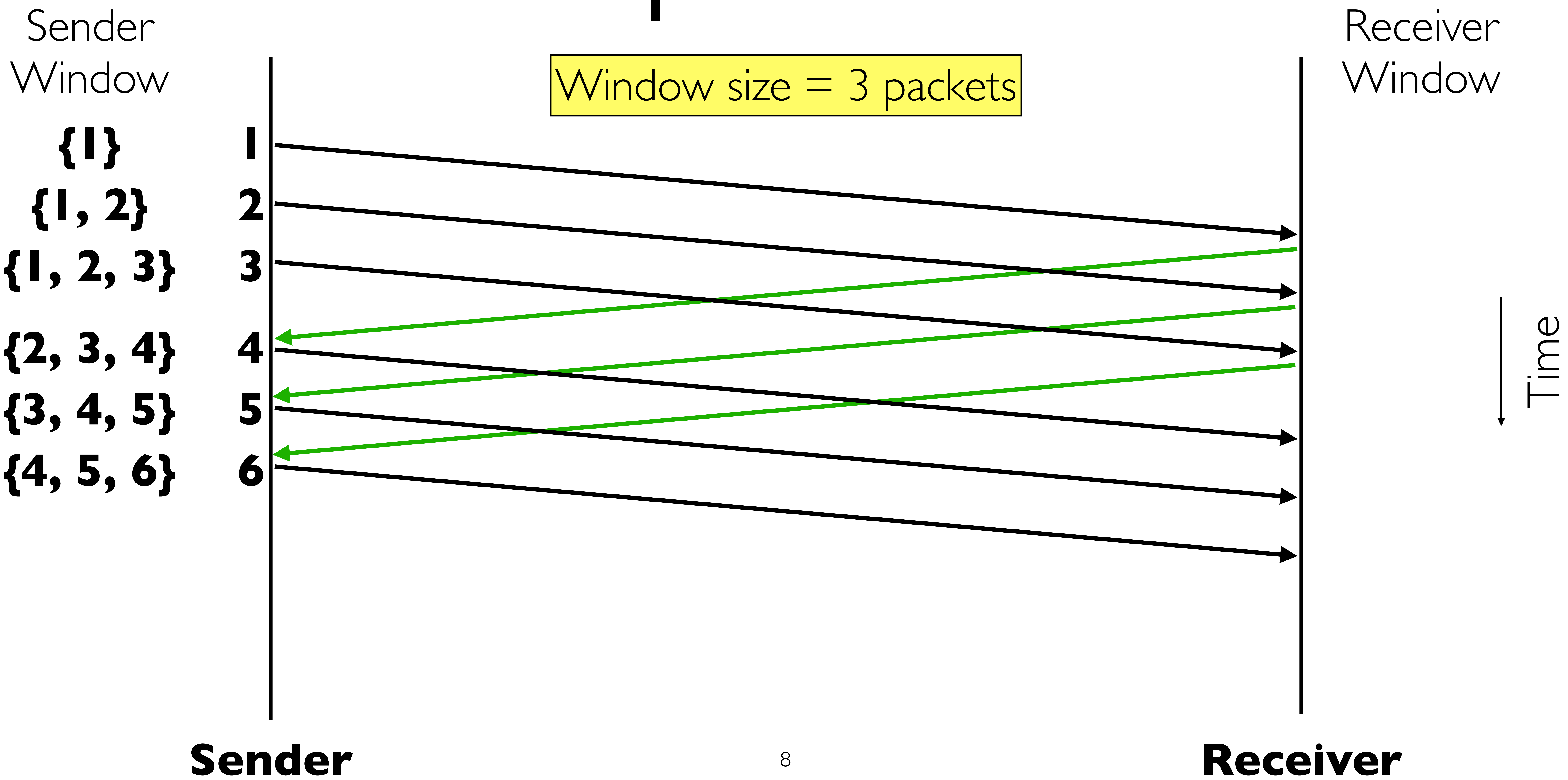

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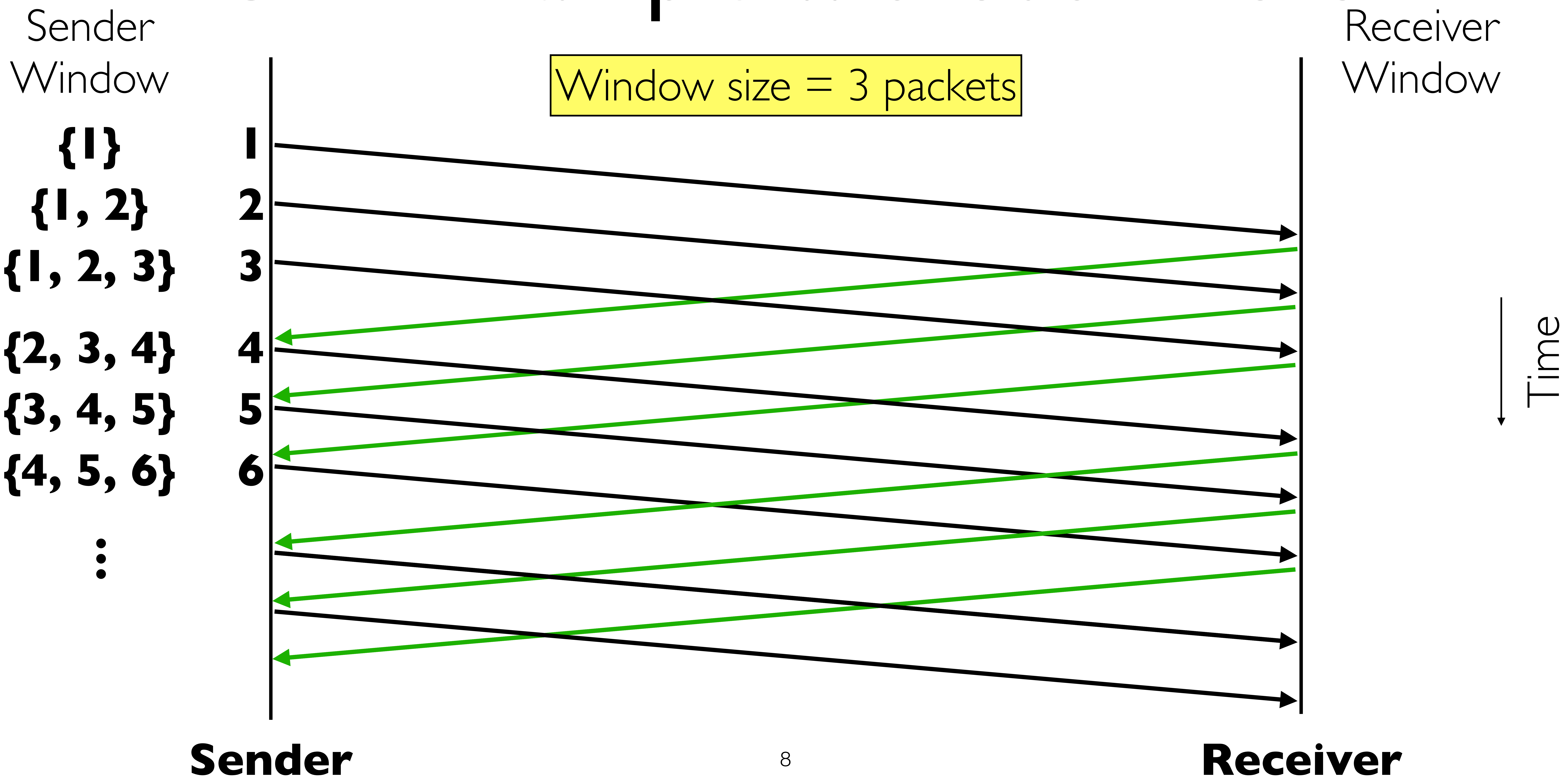

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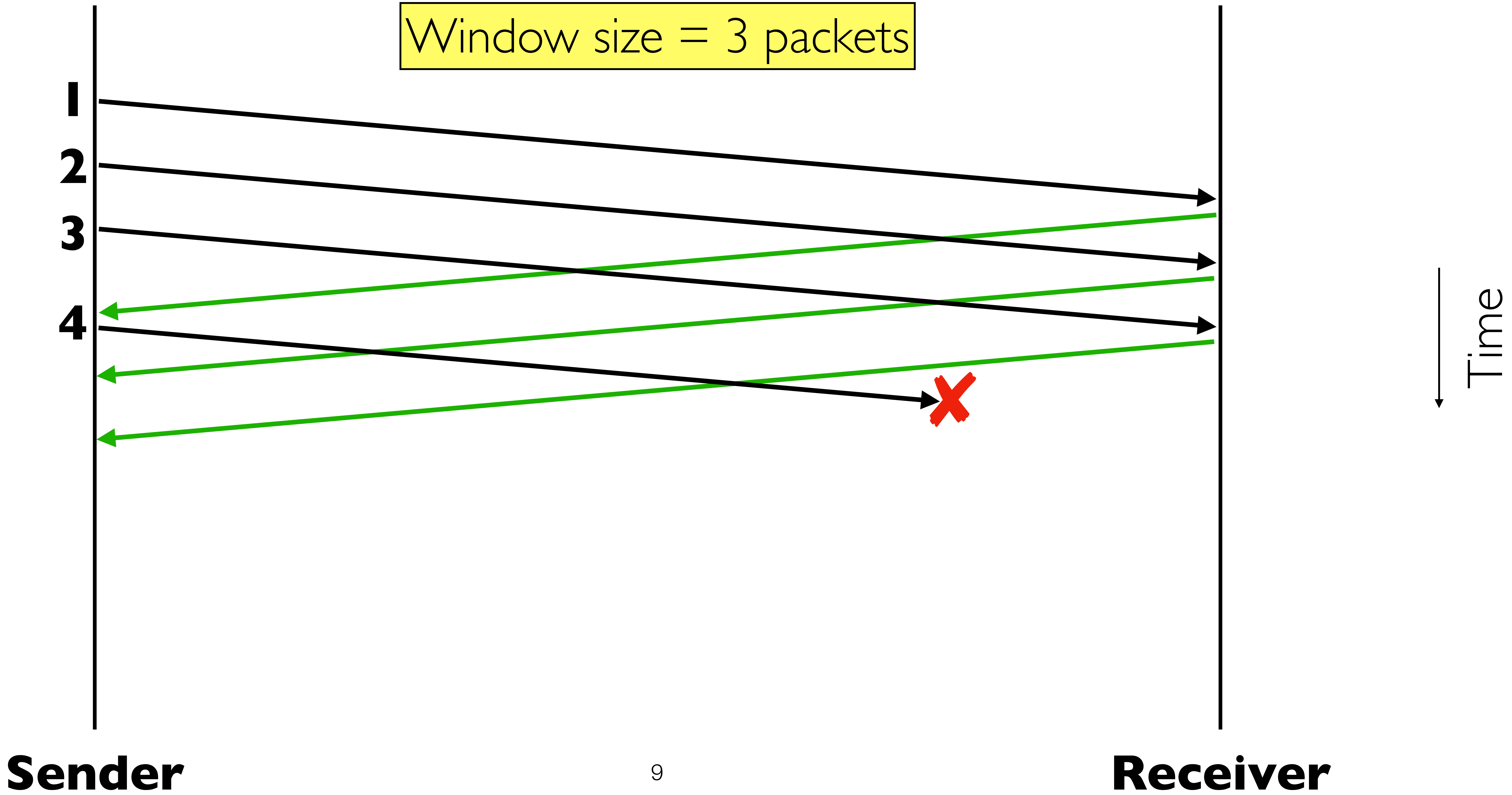

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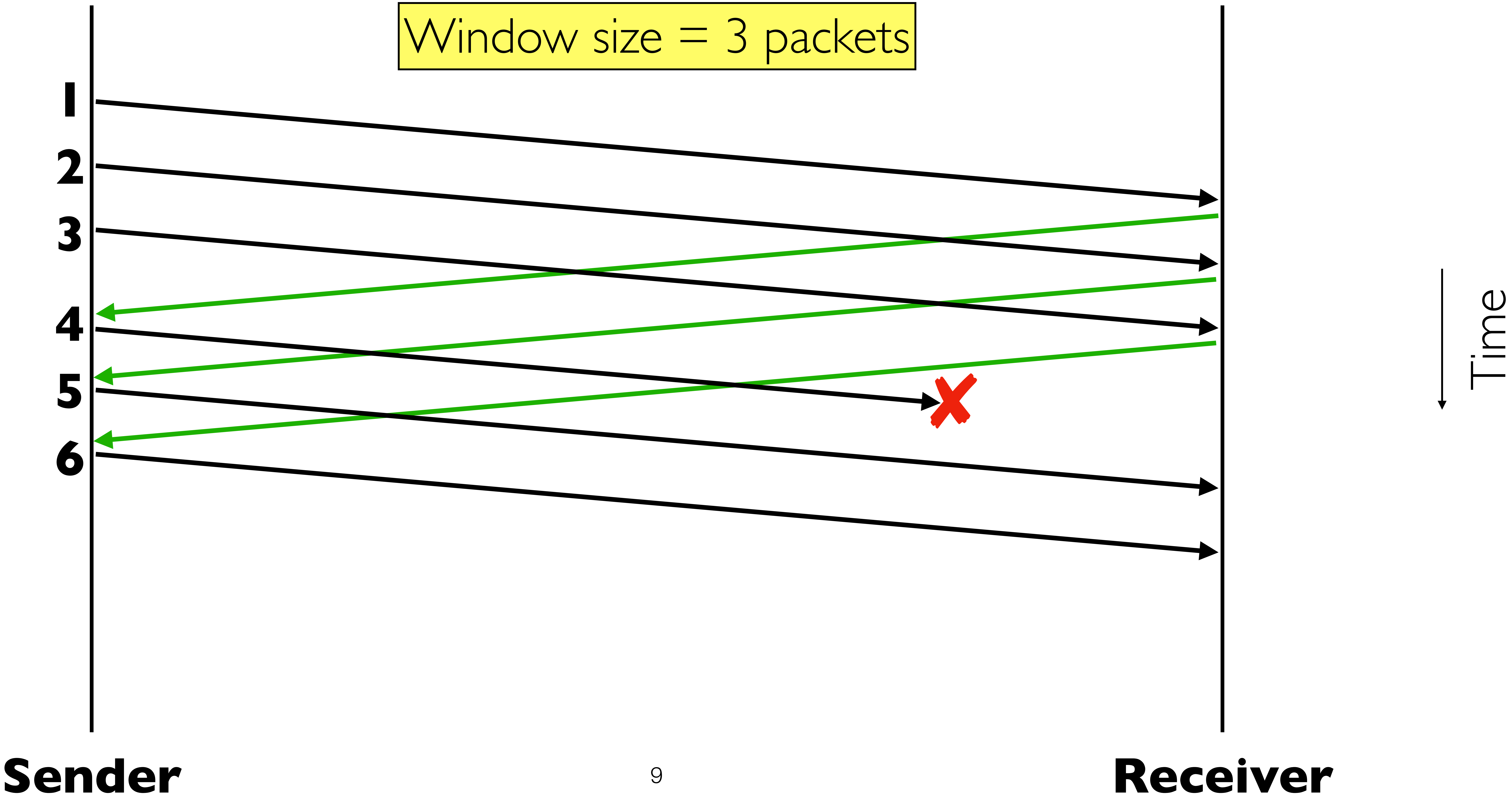

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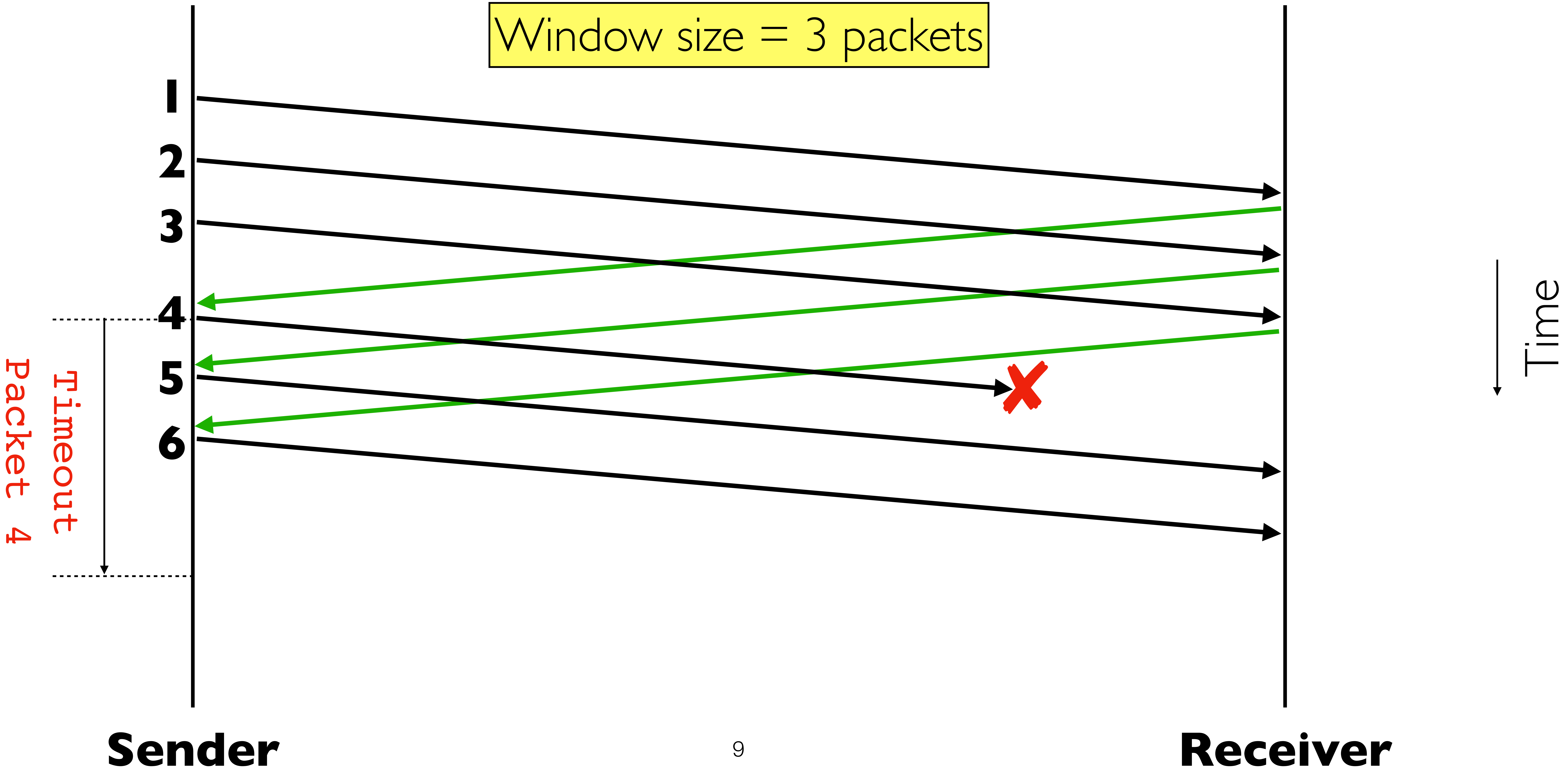

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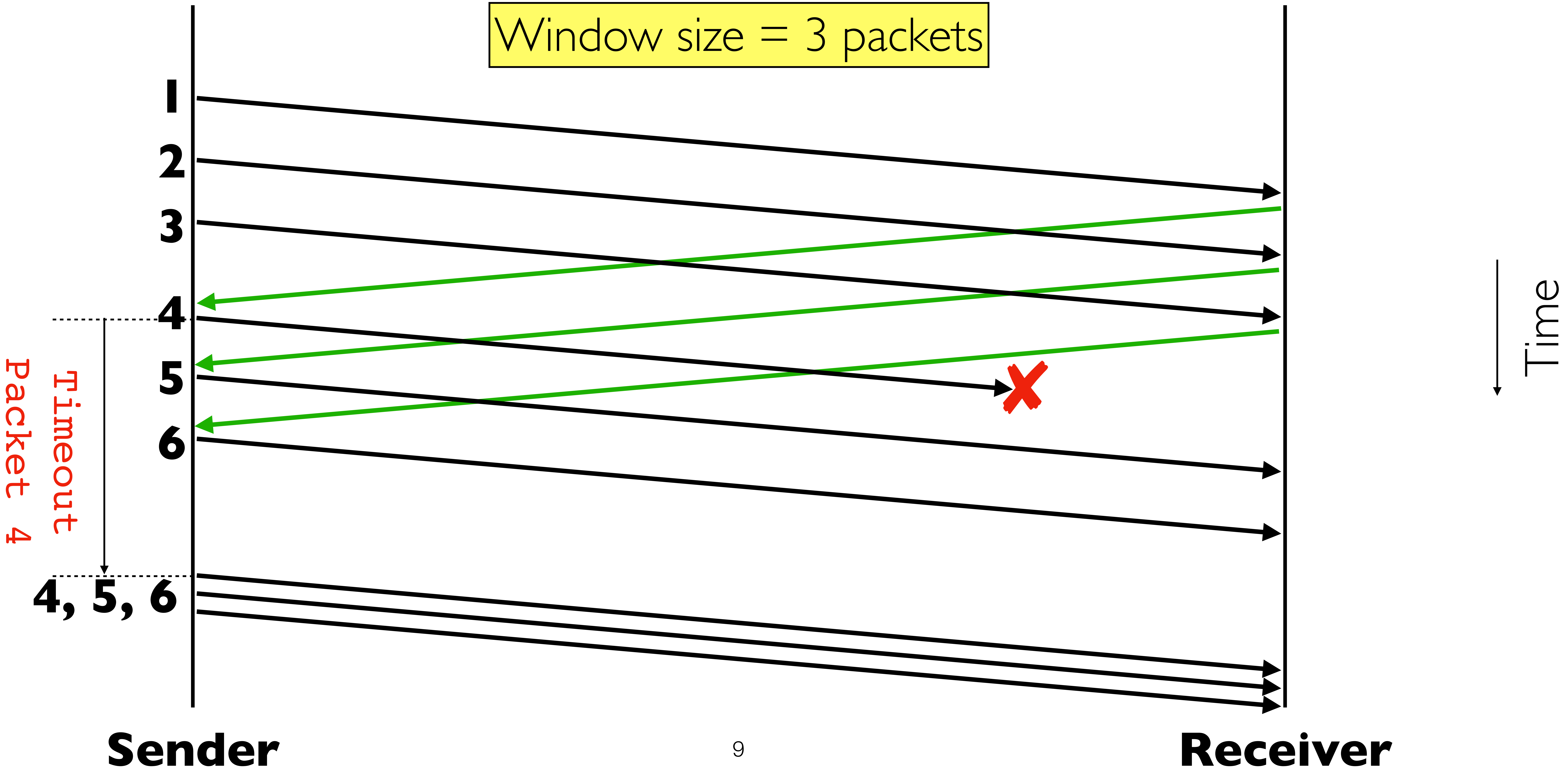

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- Assume packet *k* is lost, *k+1* is not
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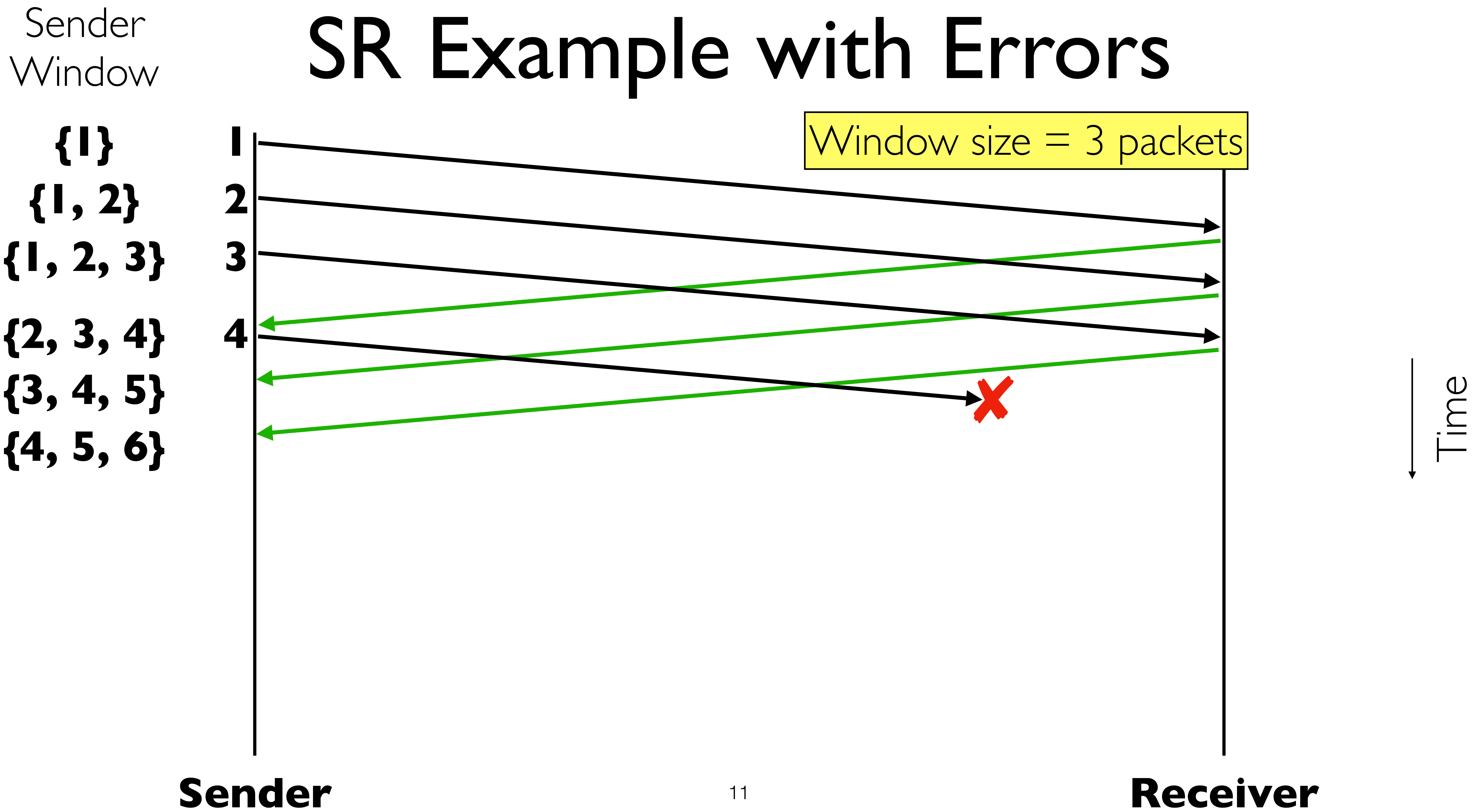
- Efficient in retransmissions but complex bookkeeping
  - Need a timer per packet!

SR Example with Errors



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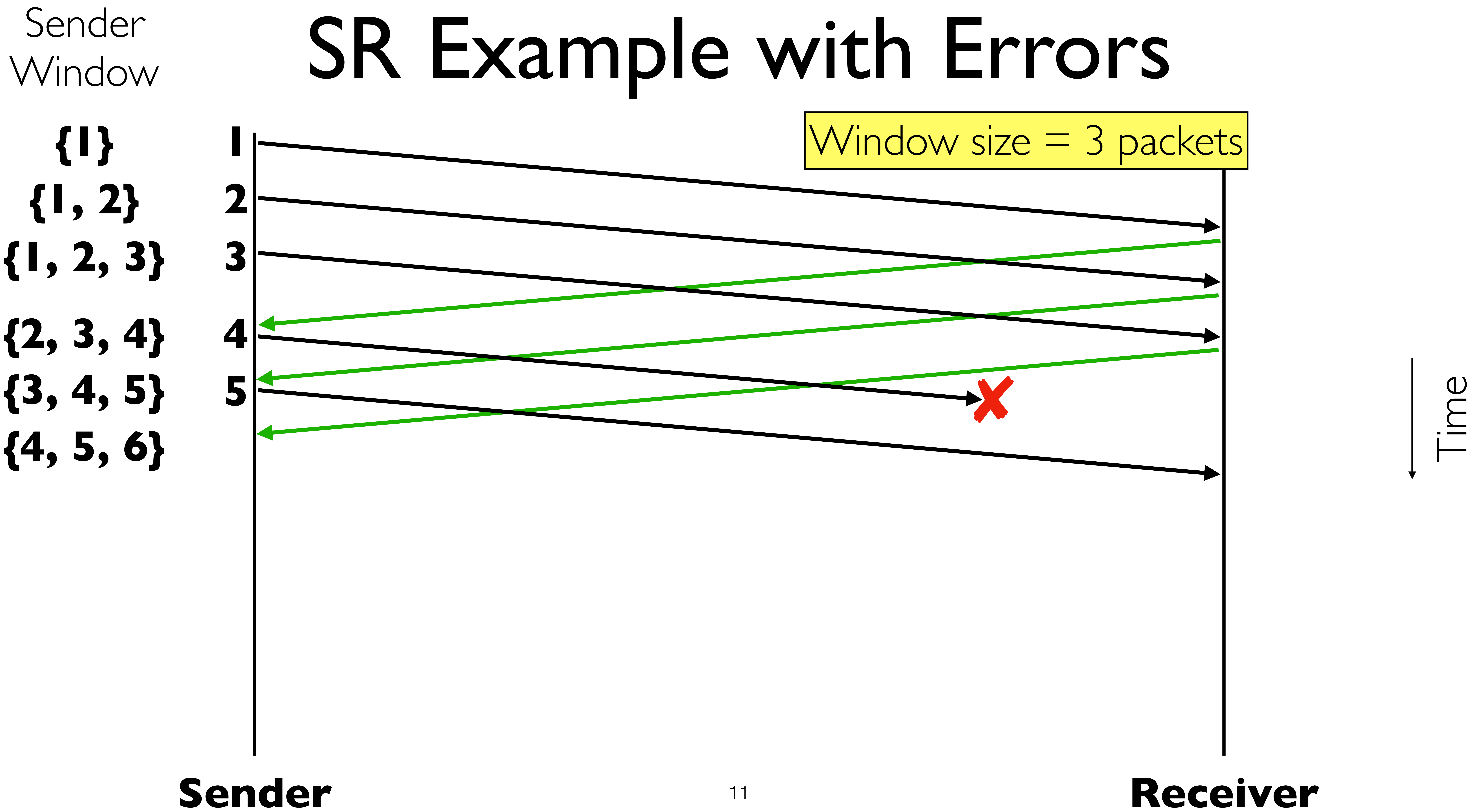

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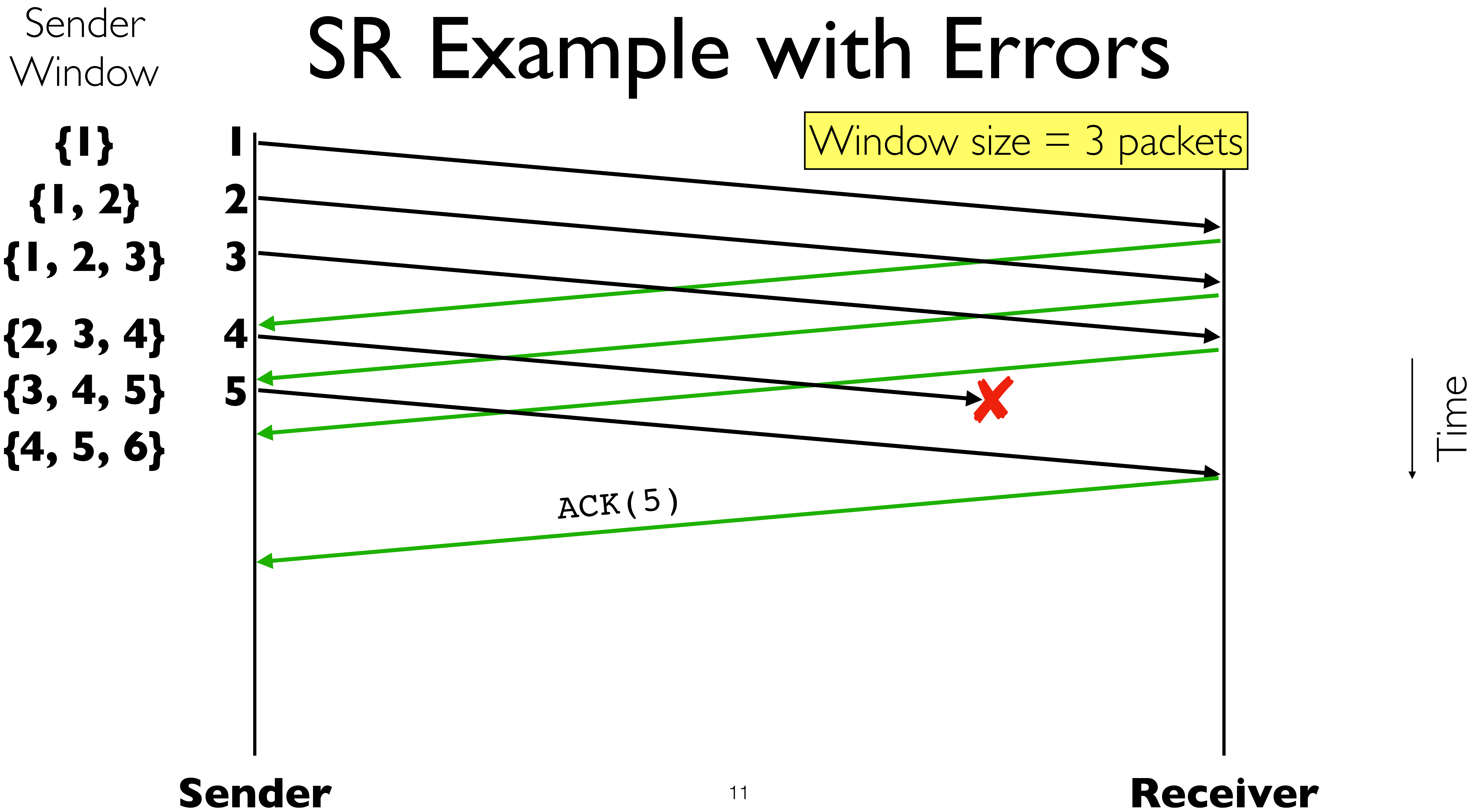

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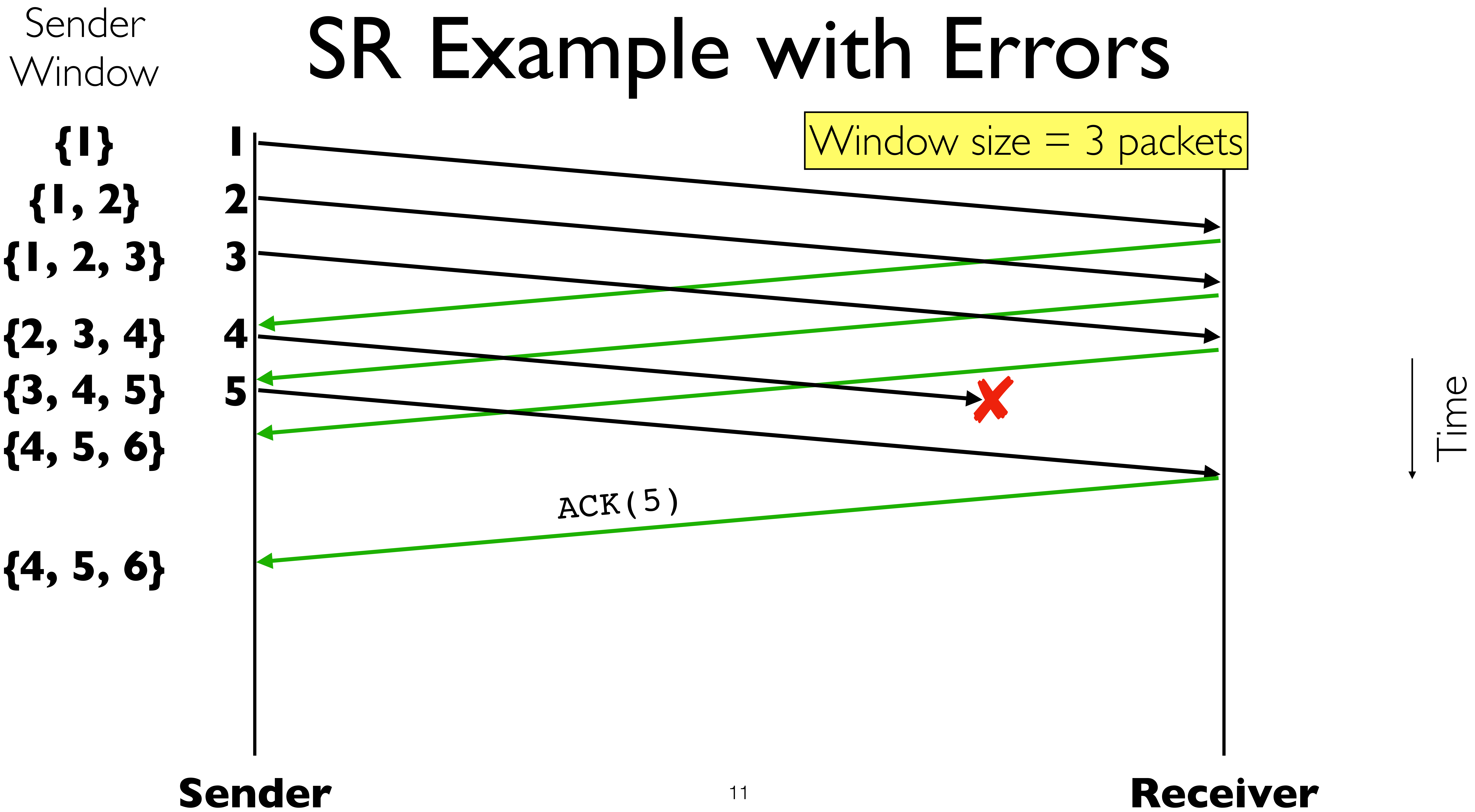
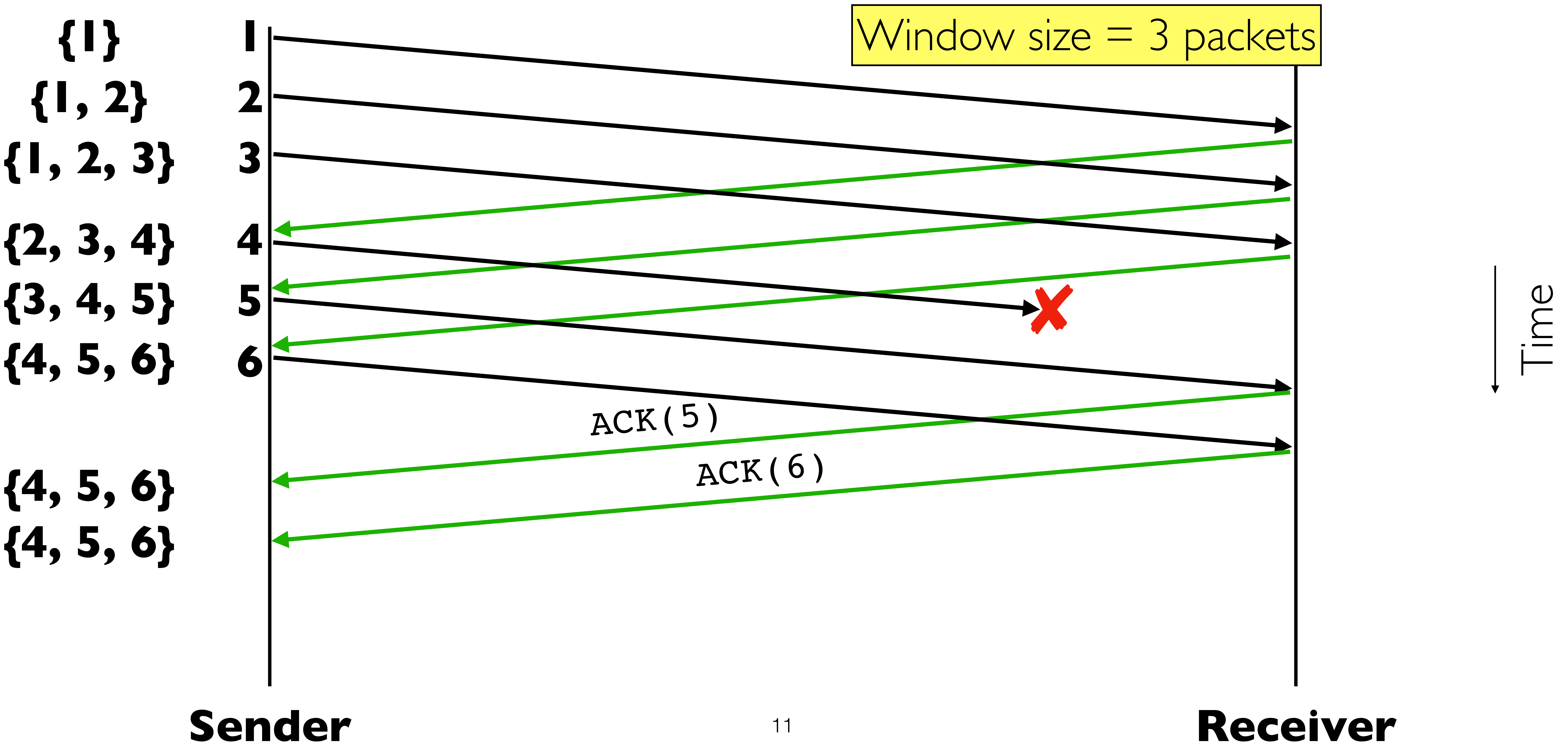


Sender Window

SR Example with Errors



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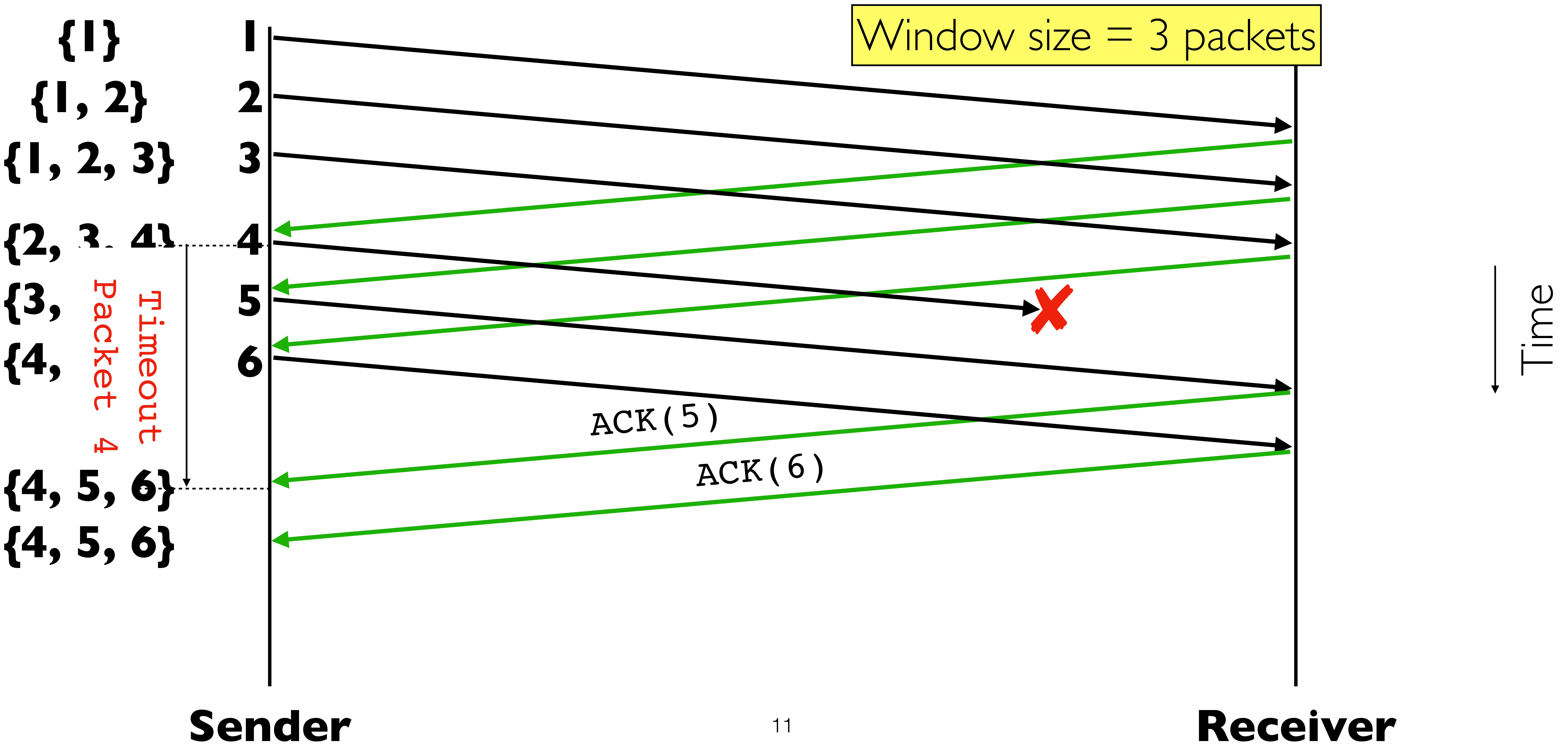

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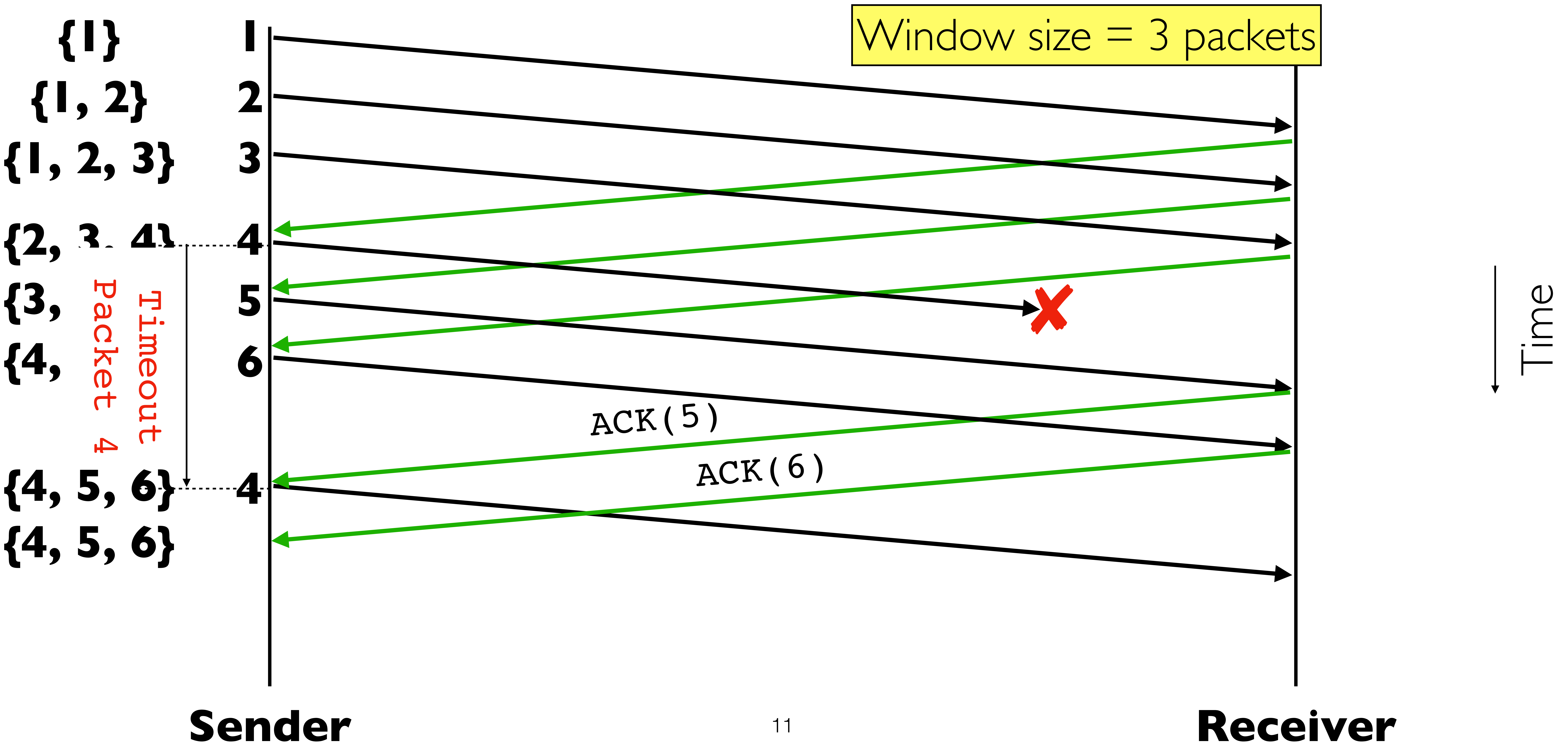

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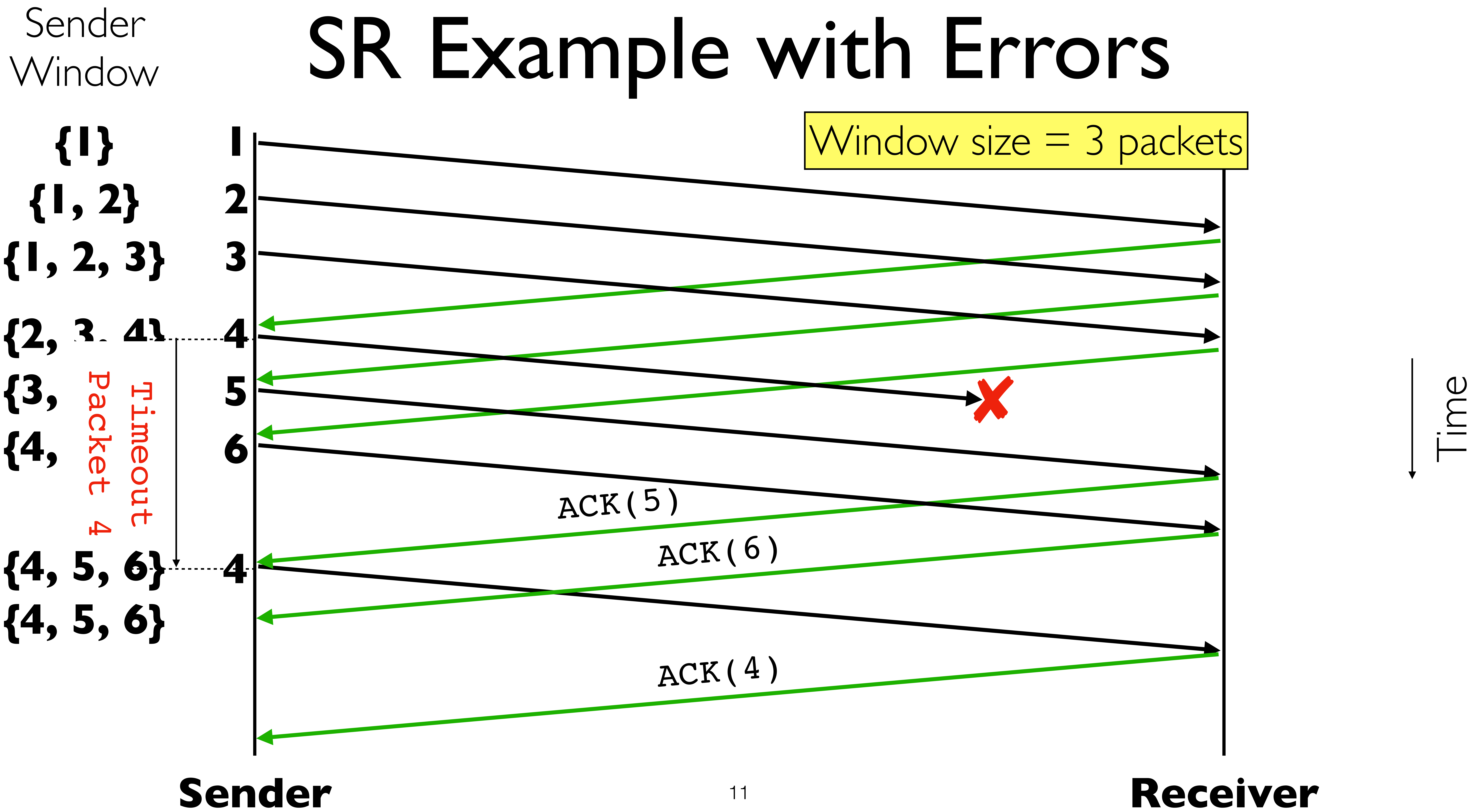

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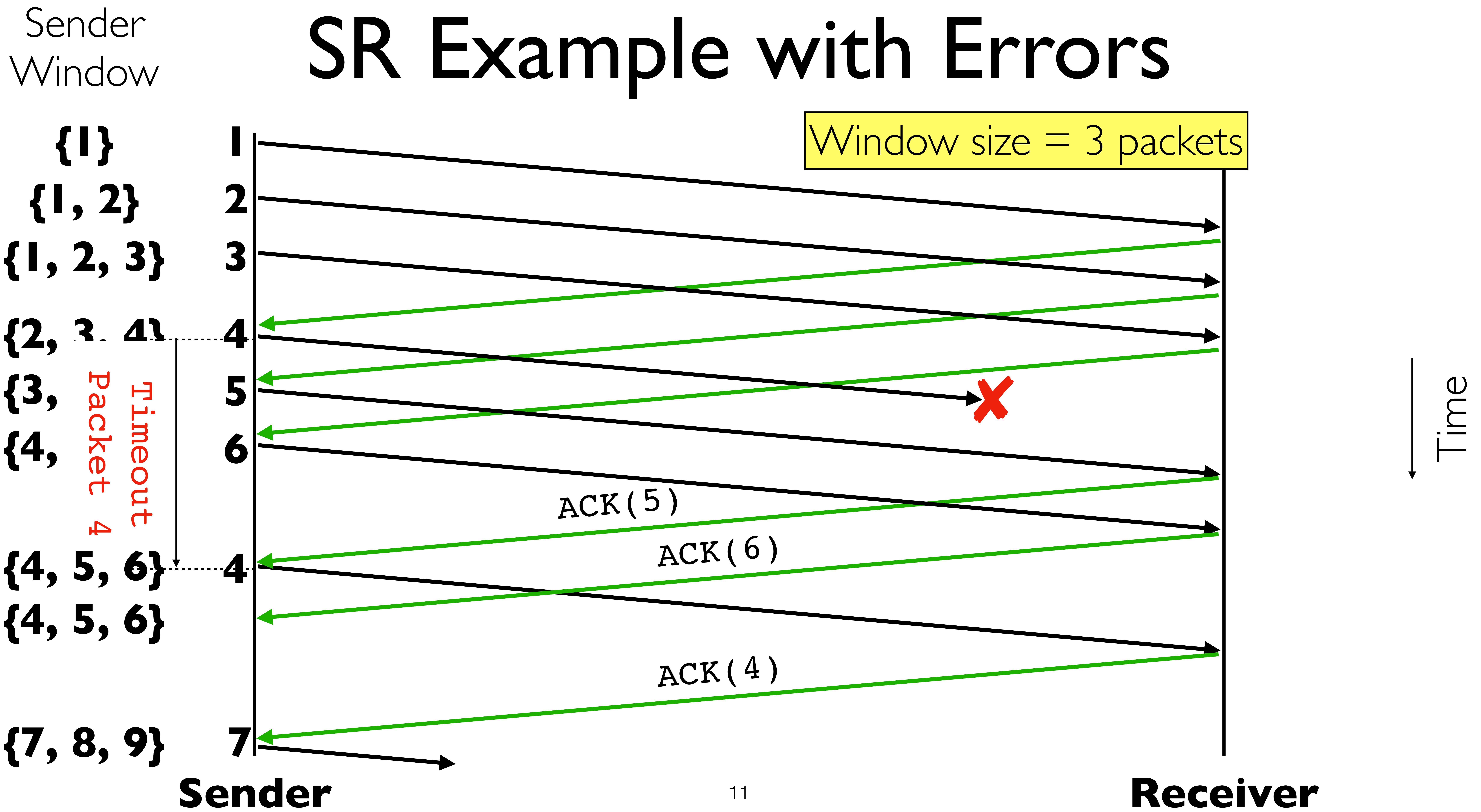

GBN vs Selective Repeat

- When would GBN be better?
- When would SR be better?

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- Implementation complexity depends on protocol details (GBN vs. SR)

Recap: Components of a solution

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- **Reliability protocols use the above to decide when and what to retransmit or acknowledge.**

The TCP Abstraction

- **TCP delivers a *reliable*, *in-order* *byte-stream***
- ***Reliable:*** TCP resends lost packets (recursively)
  - Until it gives up and shuts down connection
- ***In-order:*** TCP only hands consecutive chunks of data to application
- **Byte-stream:** TCP assumes there is an incoming stream of data, and attempts to deliver it to the application

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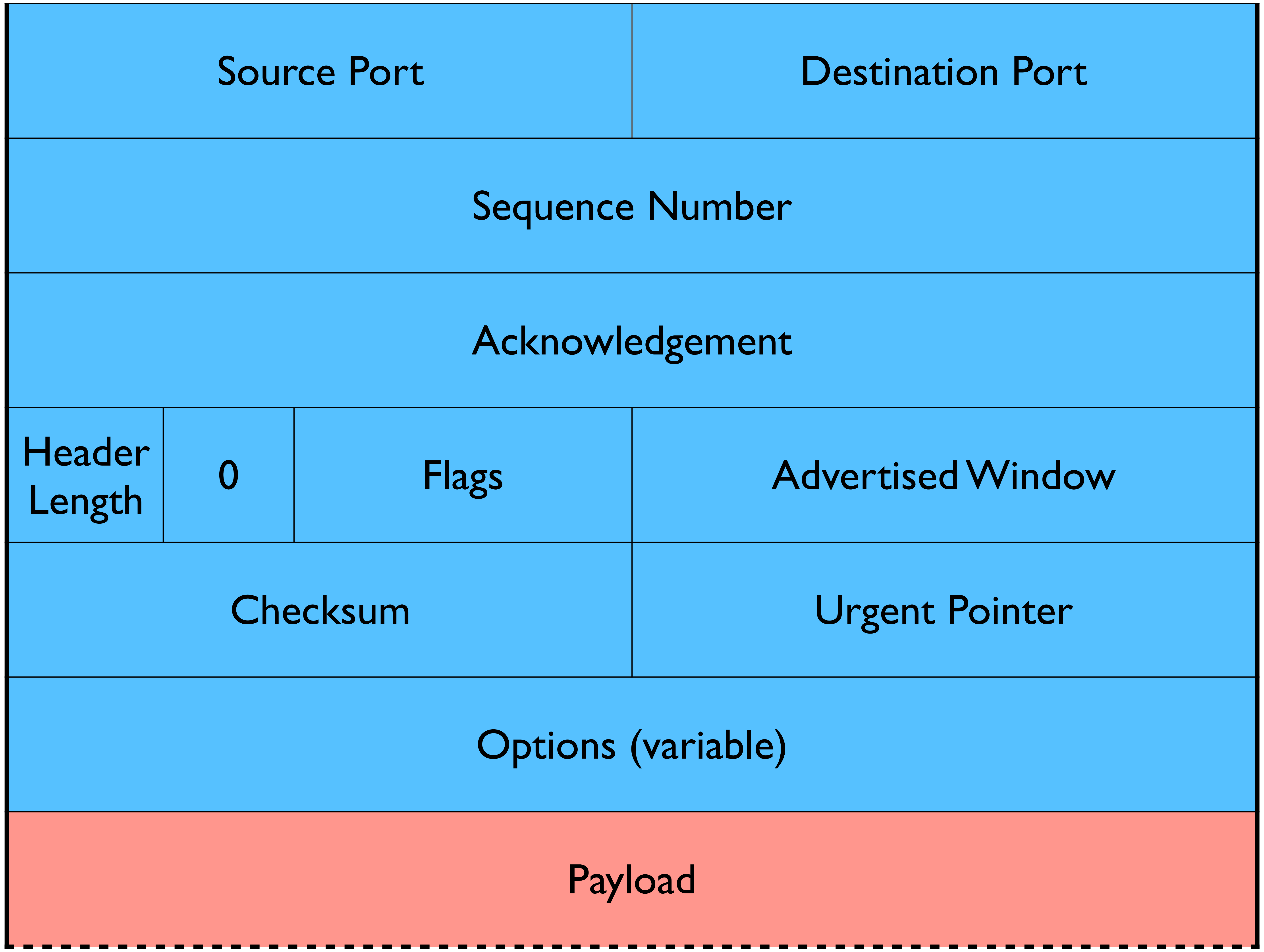
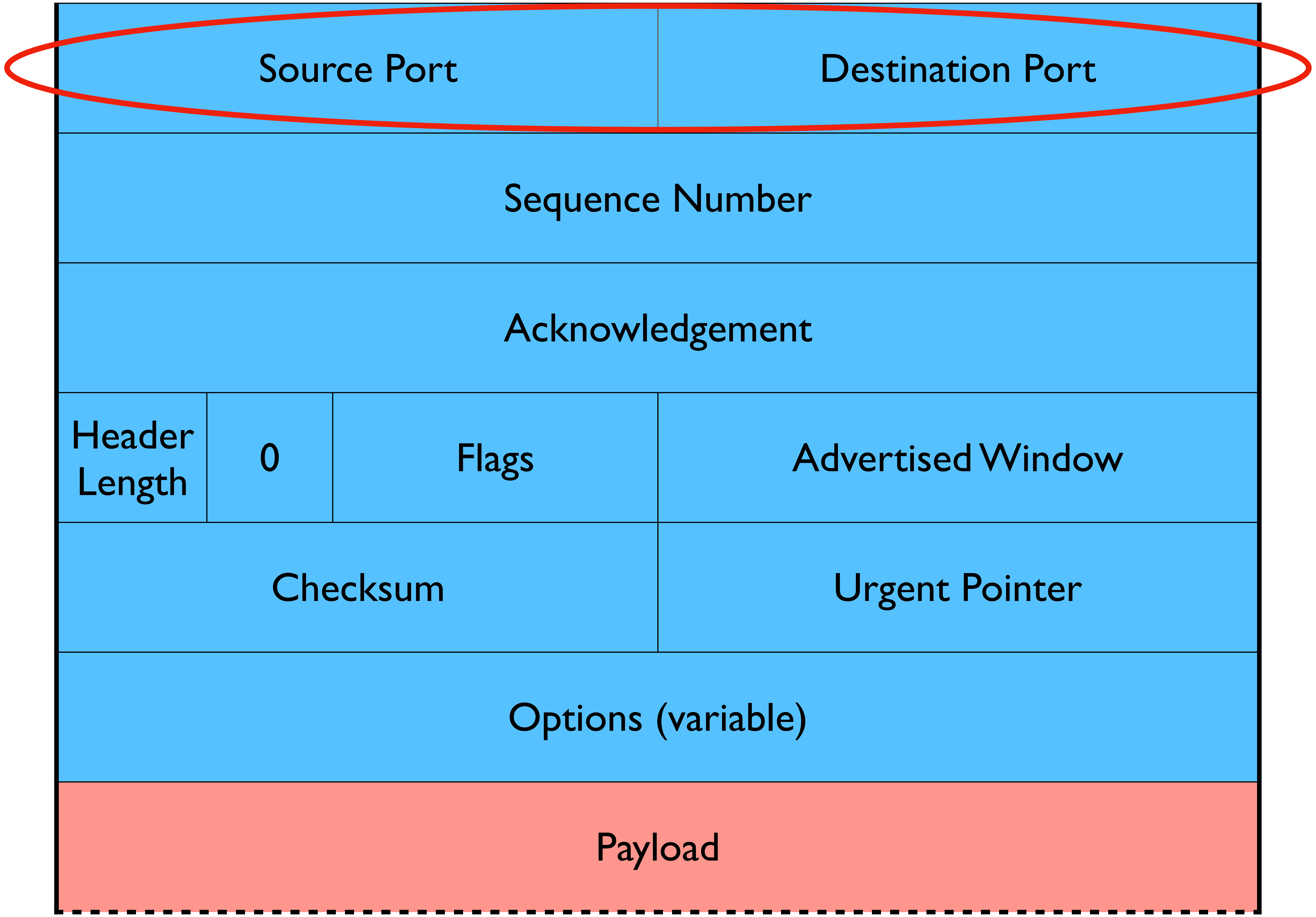
- **TCP is not a perfect design**
  - Probably wouldn't make exactly the same choices today
- **But it is good enough**
  - And is a great example of sweating the details…
  - …and just happens to carry most of your traffic

TCP Header


Source Port
Destination Port
Sequence Number
Acknowledgement
Header Length
0
Flags
Advertised Window
Checksum
Urgent Pointer
Options (variable)
Payload

TCP Header

Used to multiplex/demultiplex



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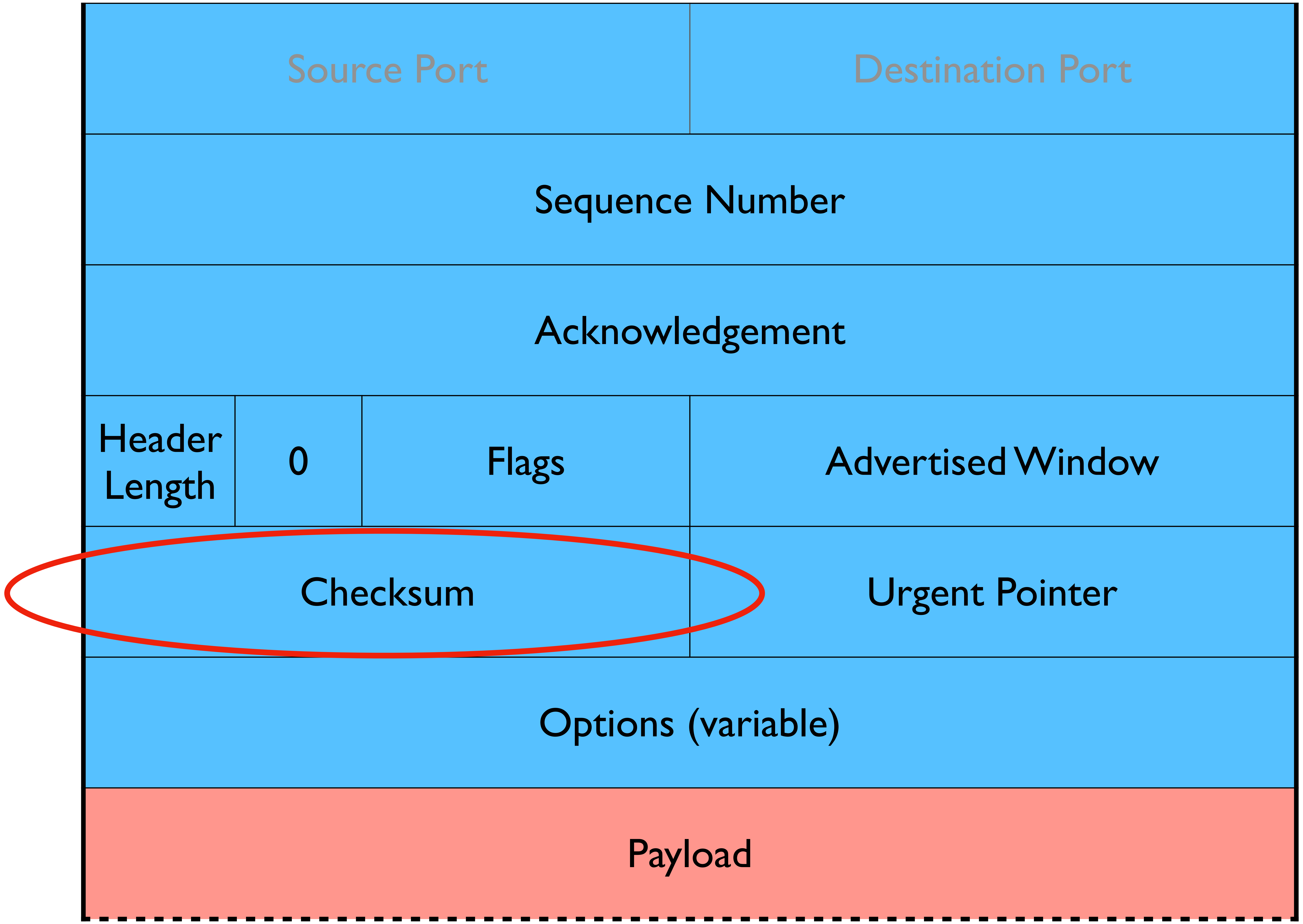
Computed over pseudo-header & data



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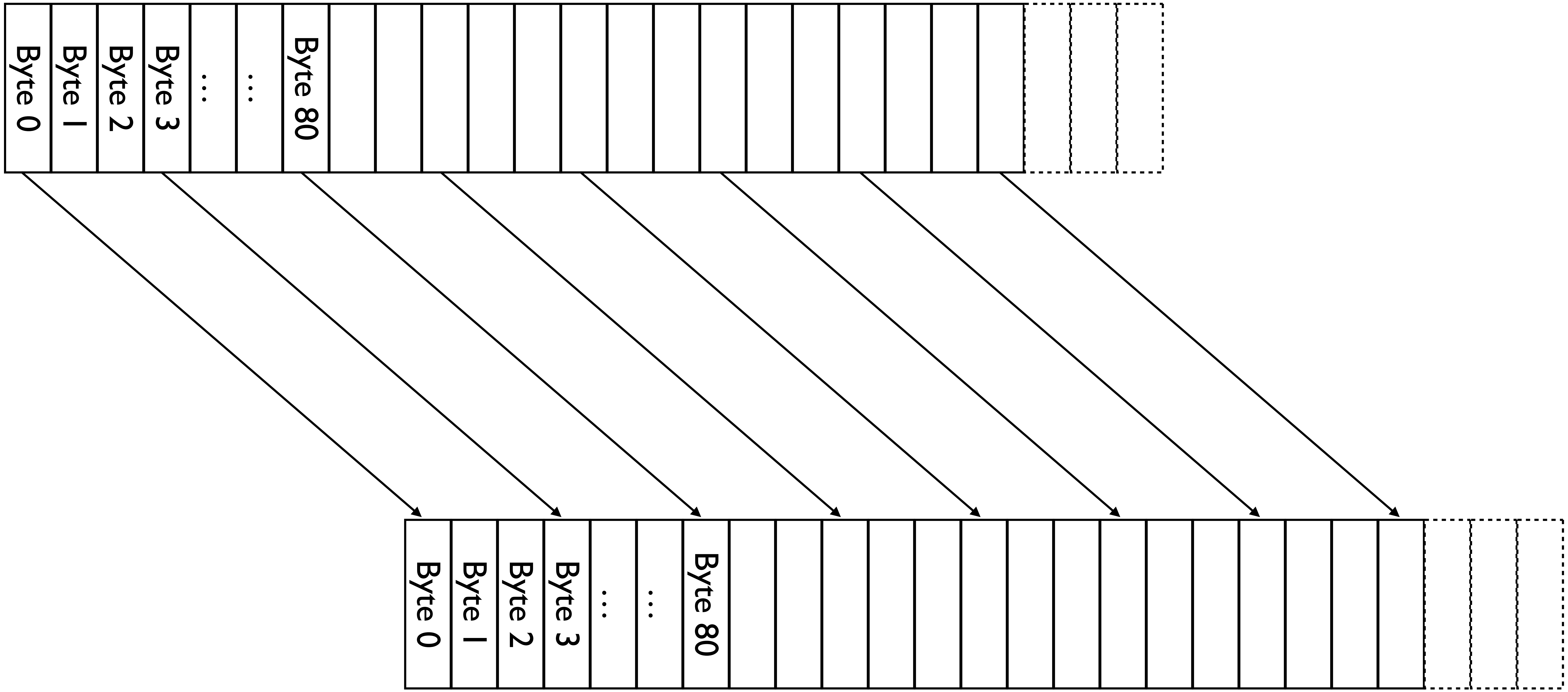
- **Most of our previous tricks + a few differences**
  - Checksum
  - Sequence numbers are byte-offsets
    - And also includes the notion of a "segment" and ISNs
    - Proof that networking is boring: 7 slides on sequence numbers!

TCP: Segments & Sequence Numbers

TCP “Stream-of-Bytes” Service…

Application @ Host A



Application @ Host B

…Provided using TCP "Segments"

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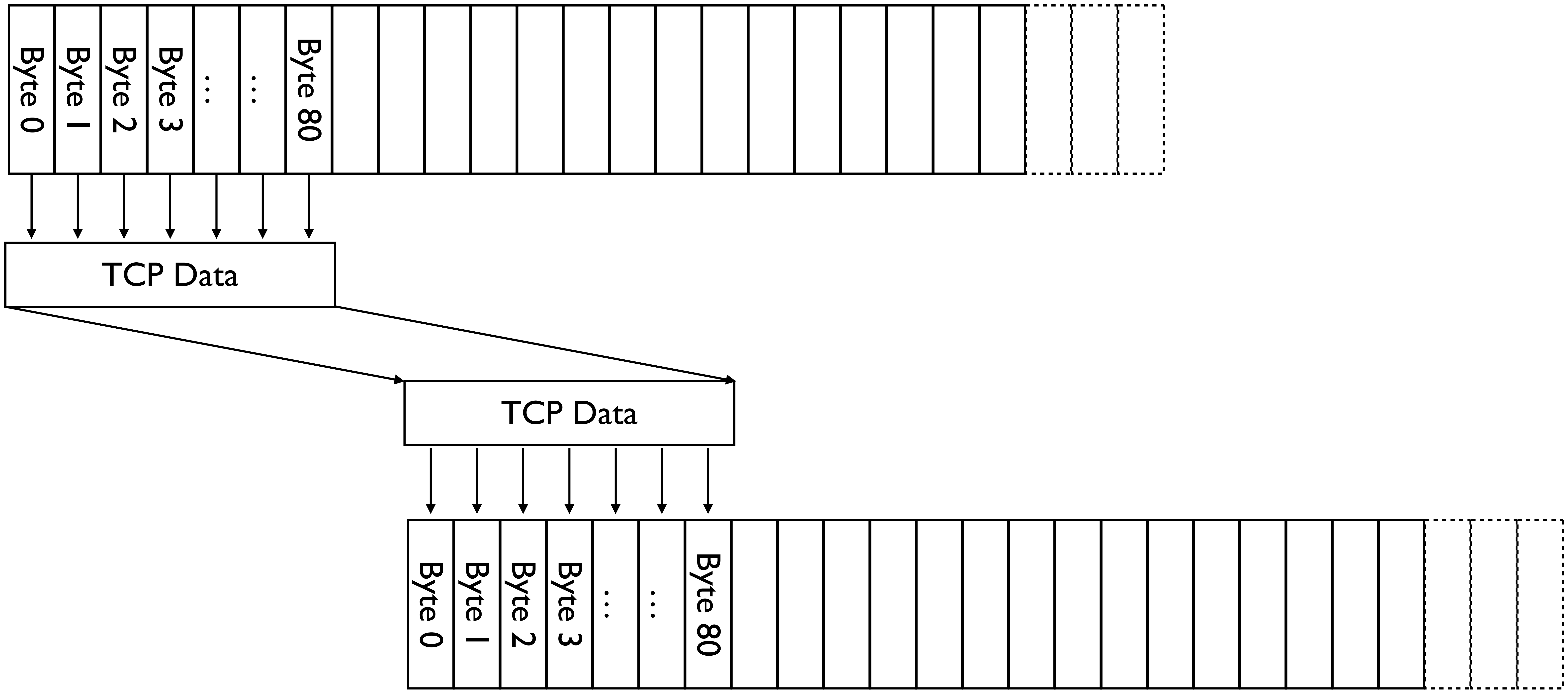

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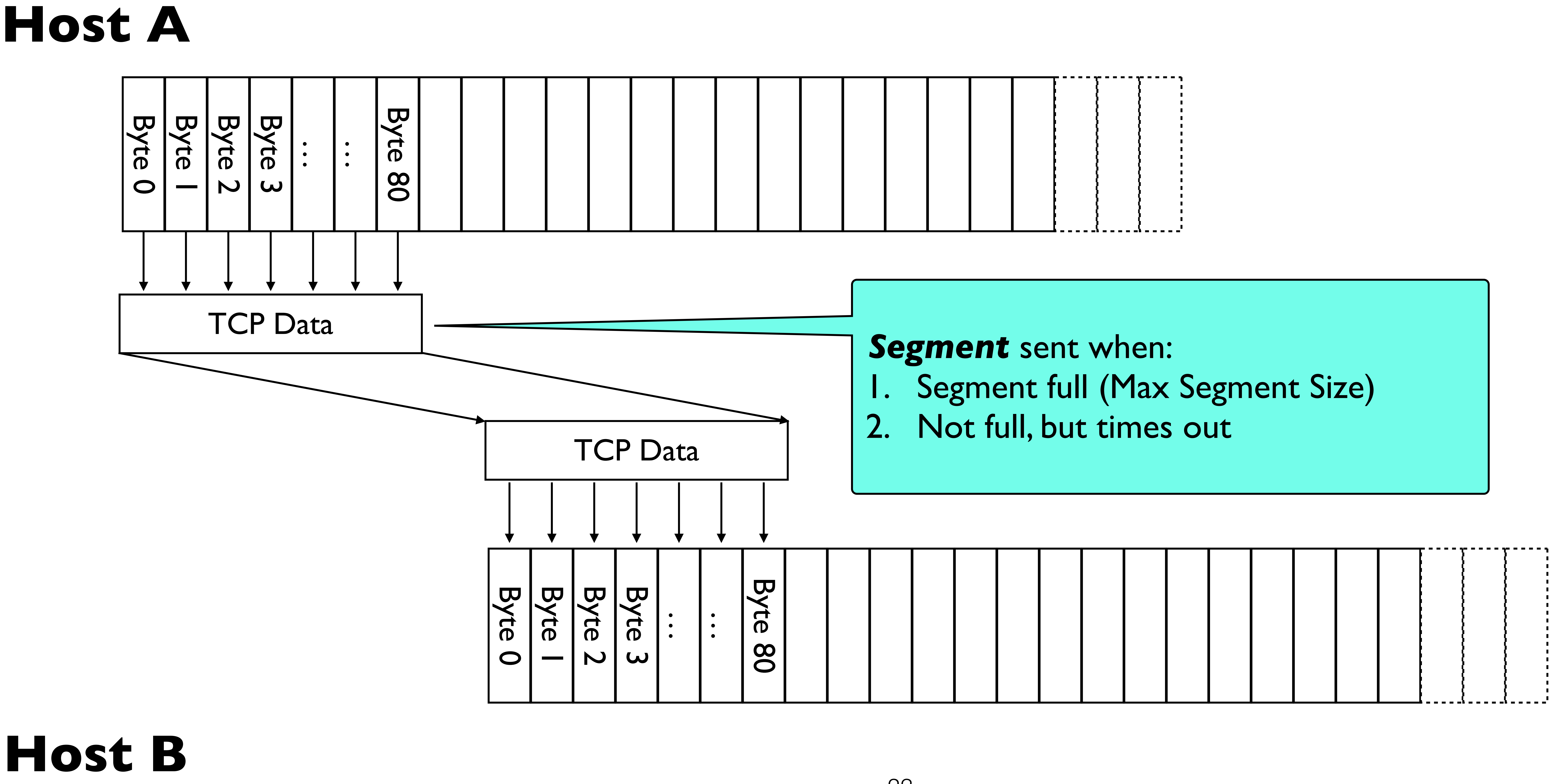
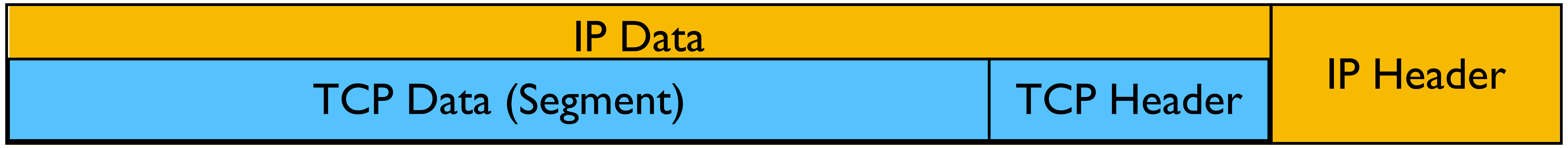


Segment sent when:

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

TCP Segment



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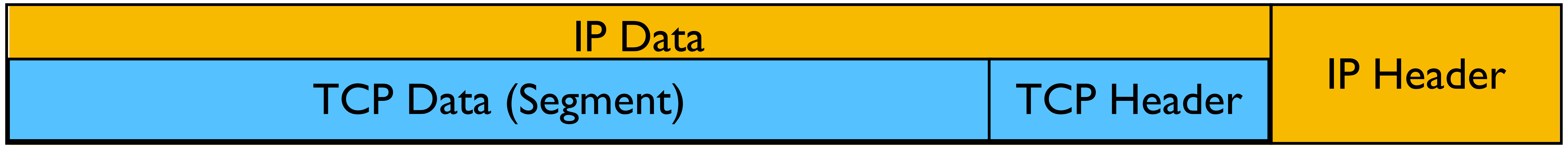

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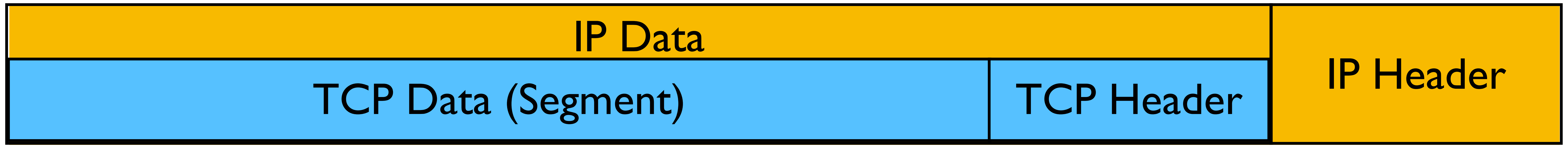

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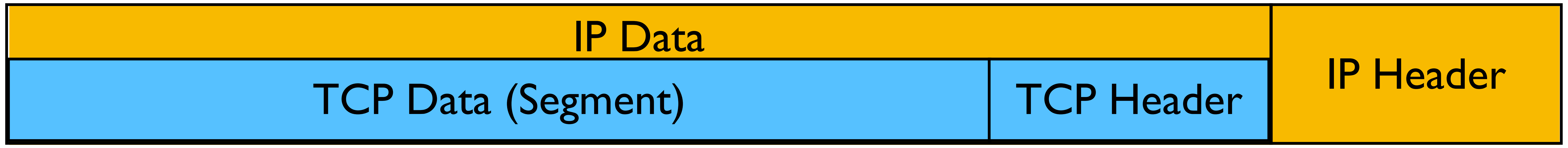

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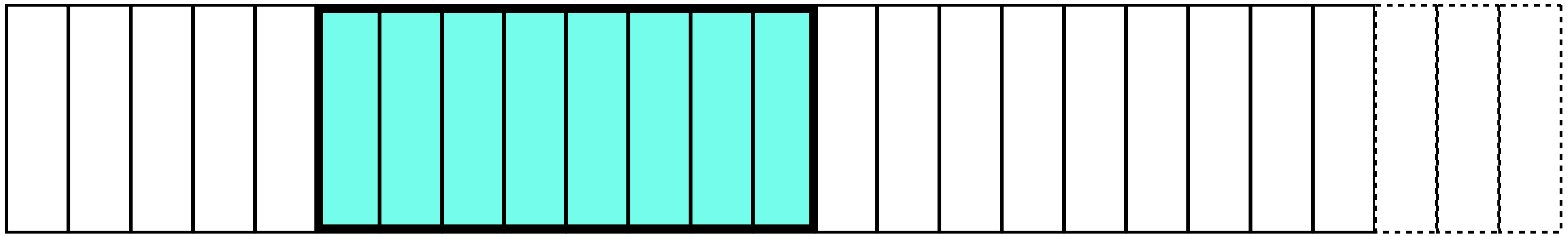
  - IP packet with a TCP header and data inside
  - TCP header >= 20 bytes long
- **TCP Segment**
  - No more than **Maximum Segment Size** (MSS) bytes
  - E.g., up to 1460 consecutive bytes from the stream
  - MSS = MTU - (IP Header Size) - (TCP Header Size)

Sequence Numbers

Host A



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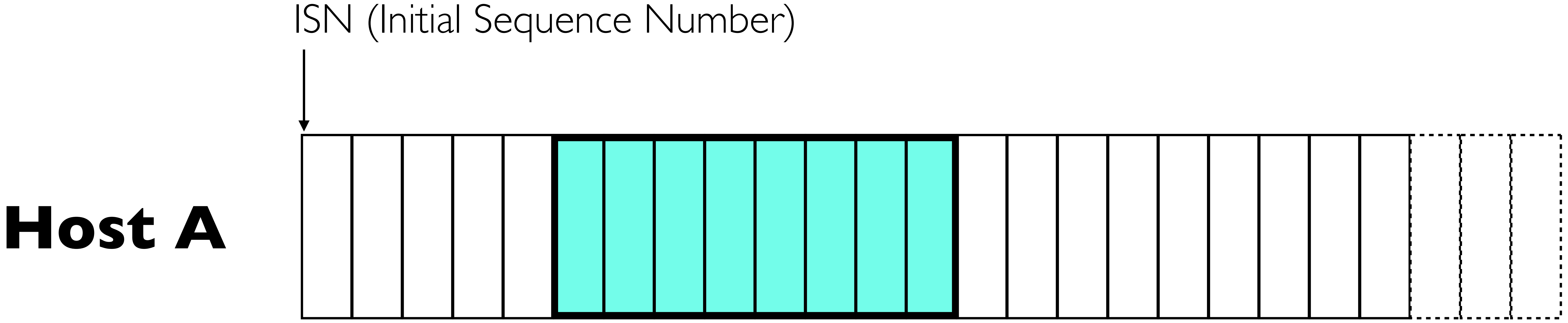

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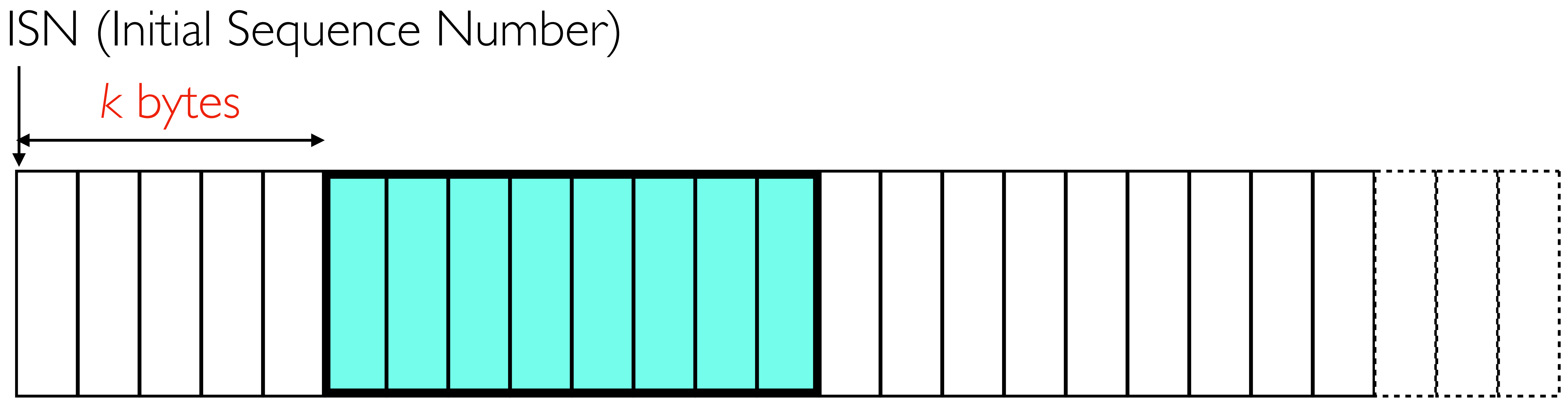

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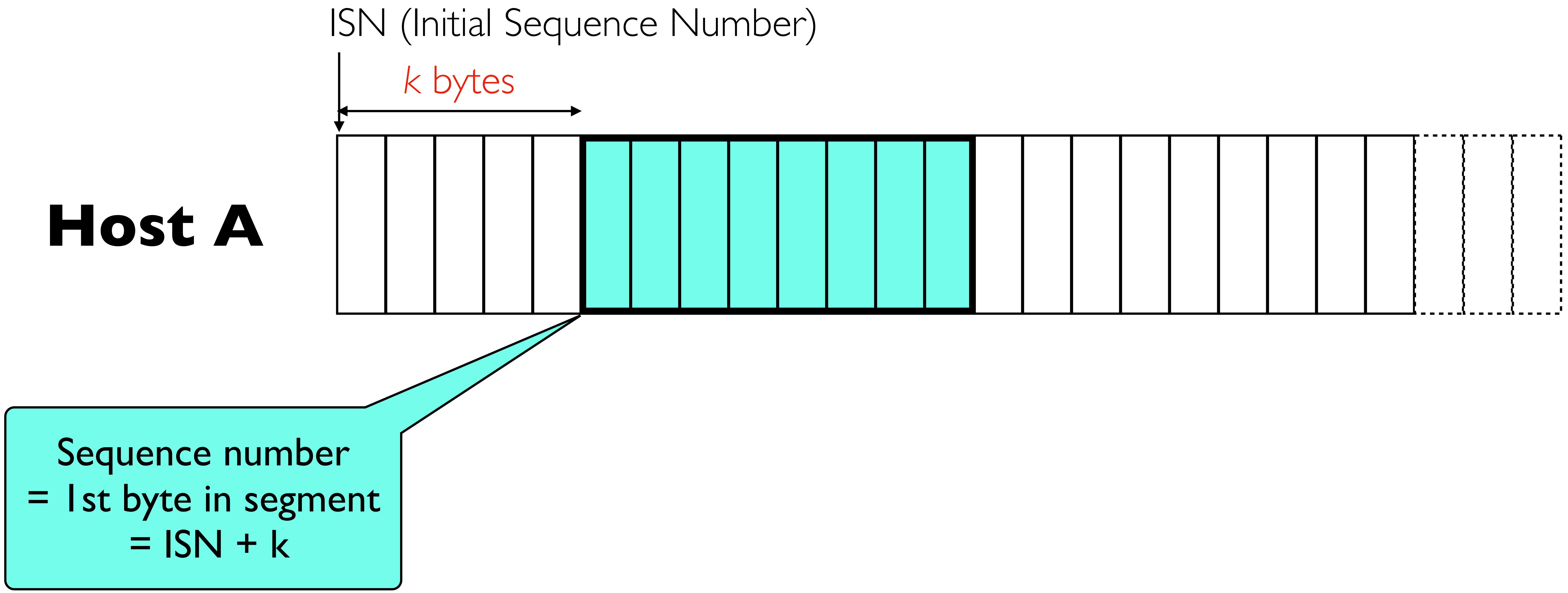

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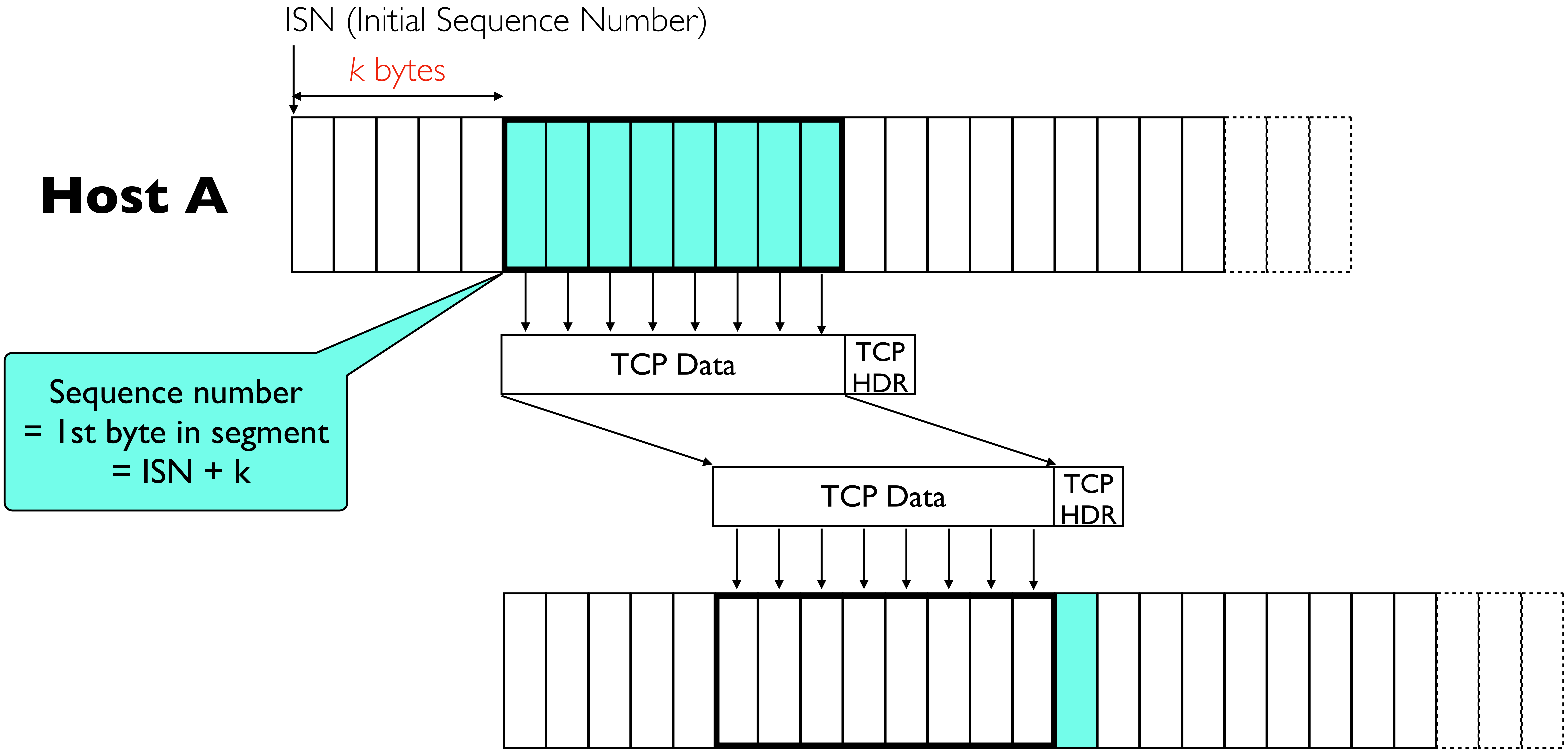

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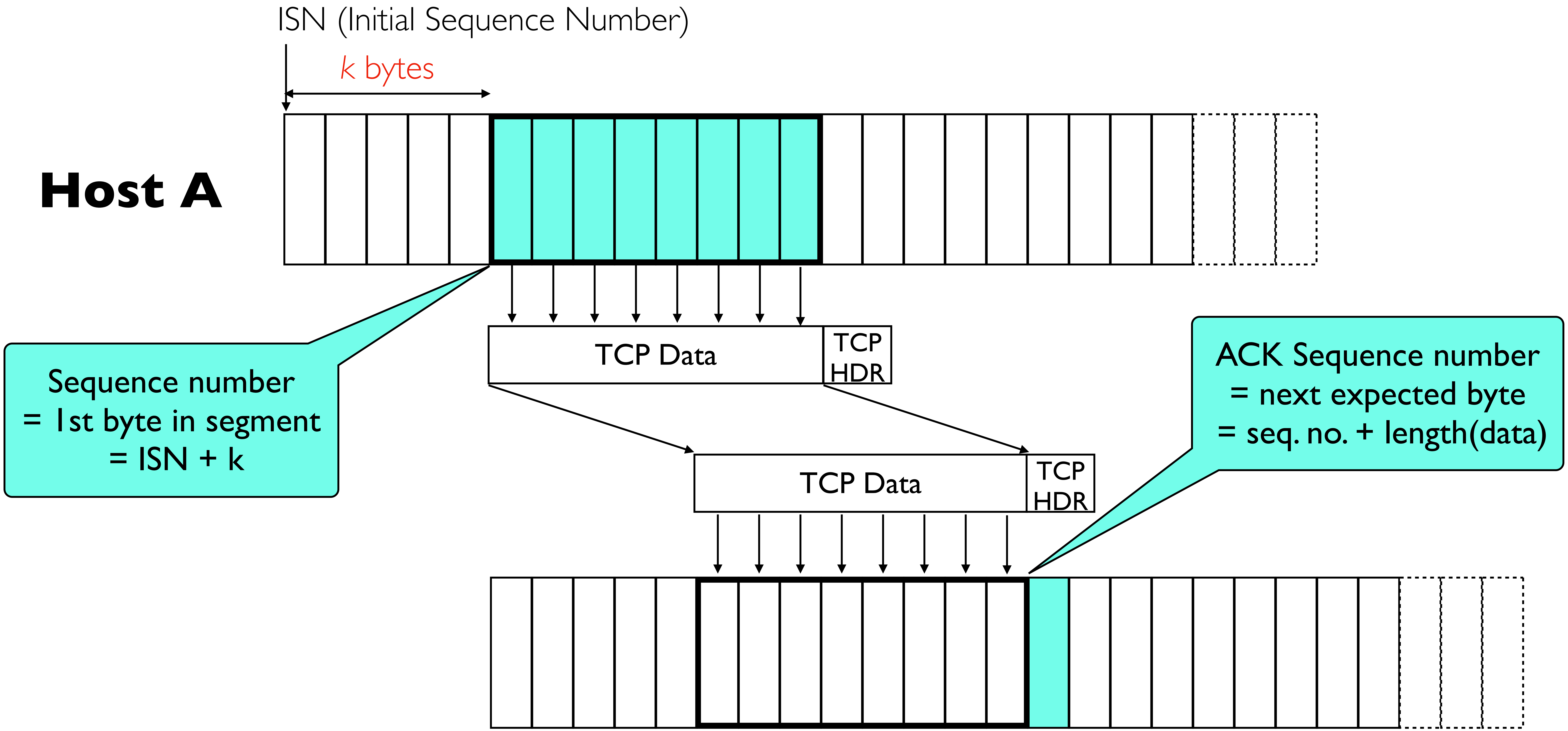
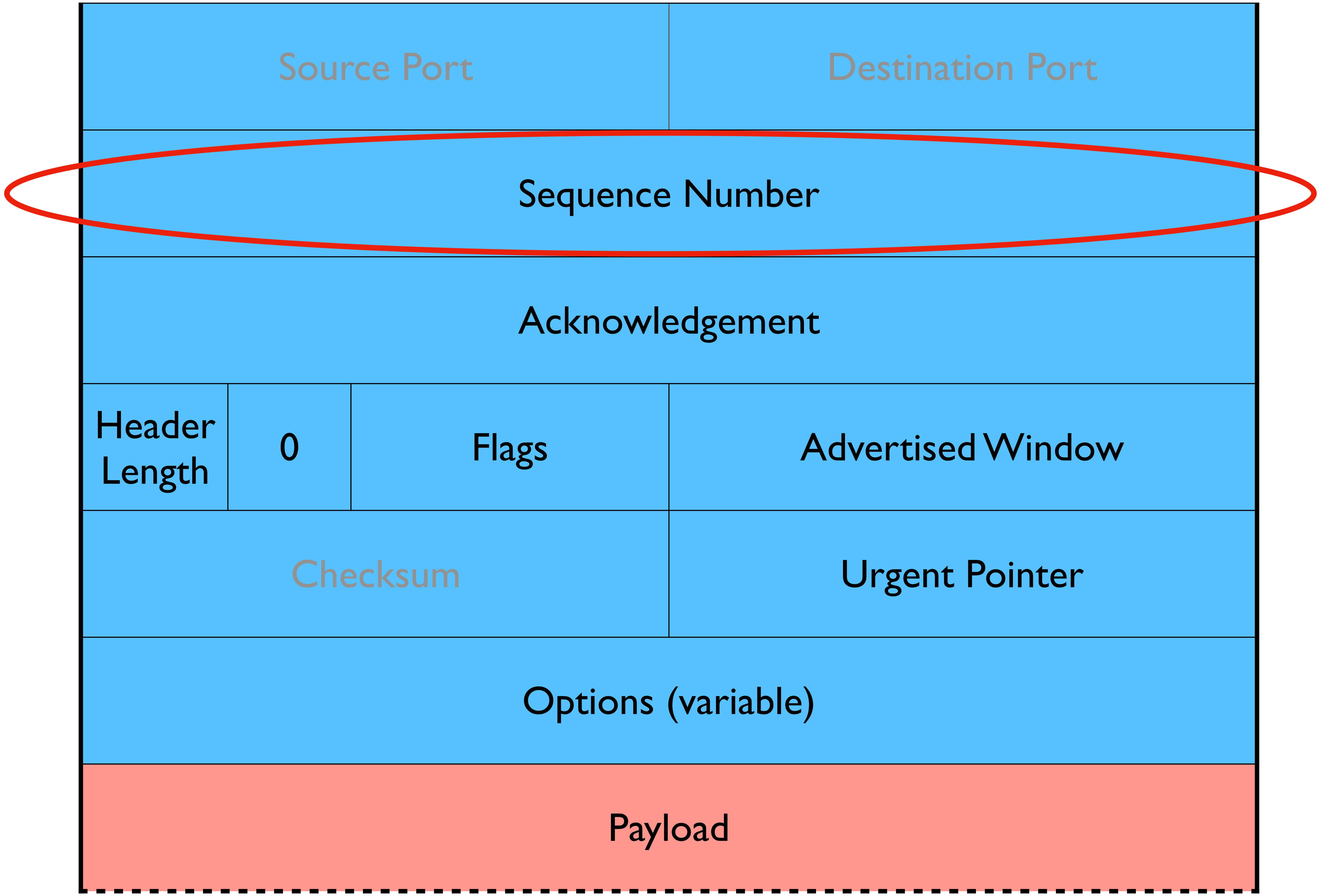


TCP Header

Starting byte offset of
data carried in this segment



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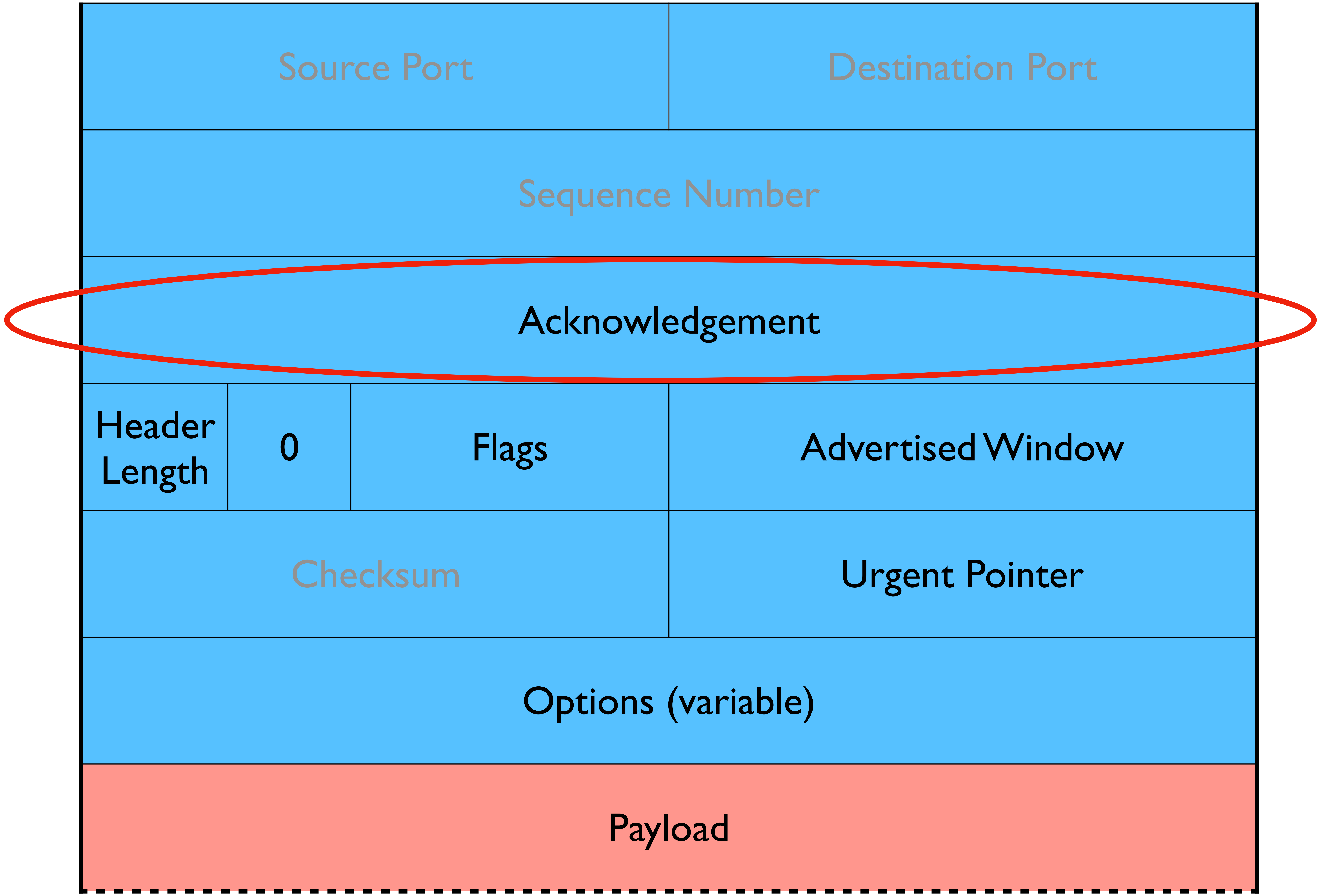
- …
- **seqno** of next packet is same as last **ACK** field

TCP Header

Acknowledgement gives seqno just beyond highest seqno received *in-order*
("What Byte Is Next")



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  - TCP uses k=3 [Fast Retransmit]

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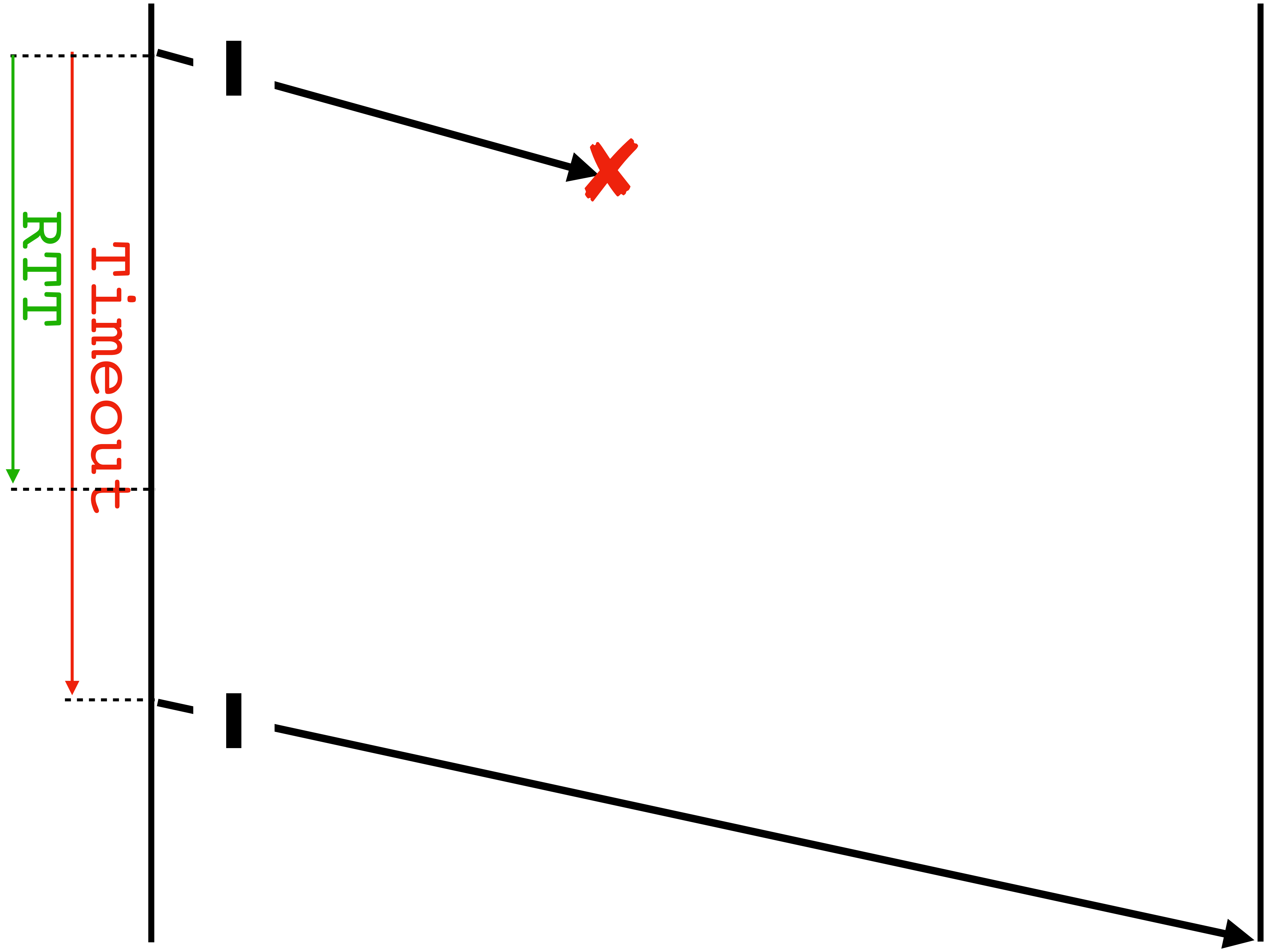

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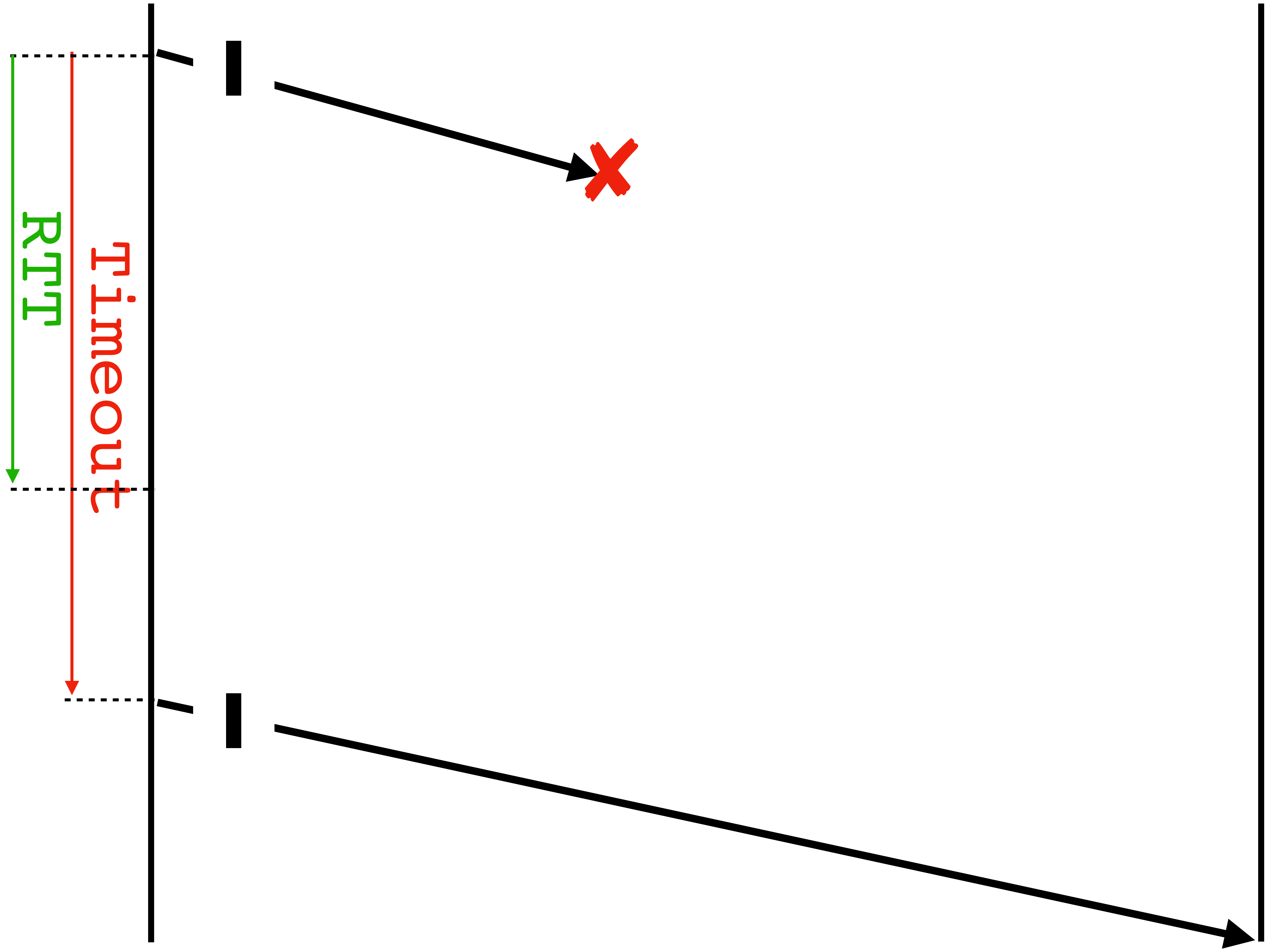

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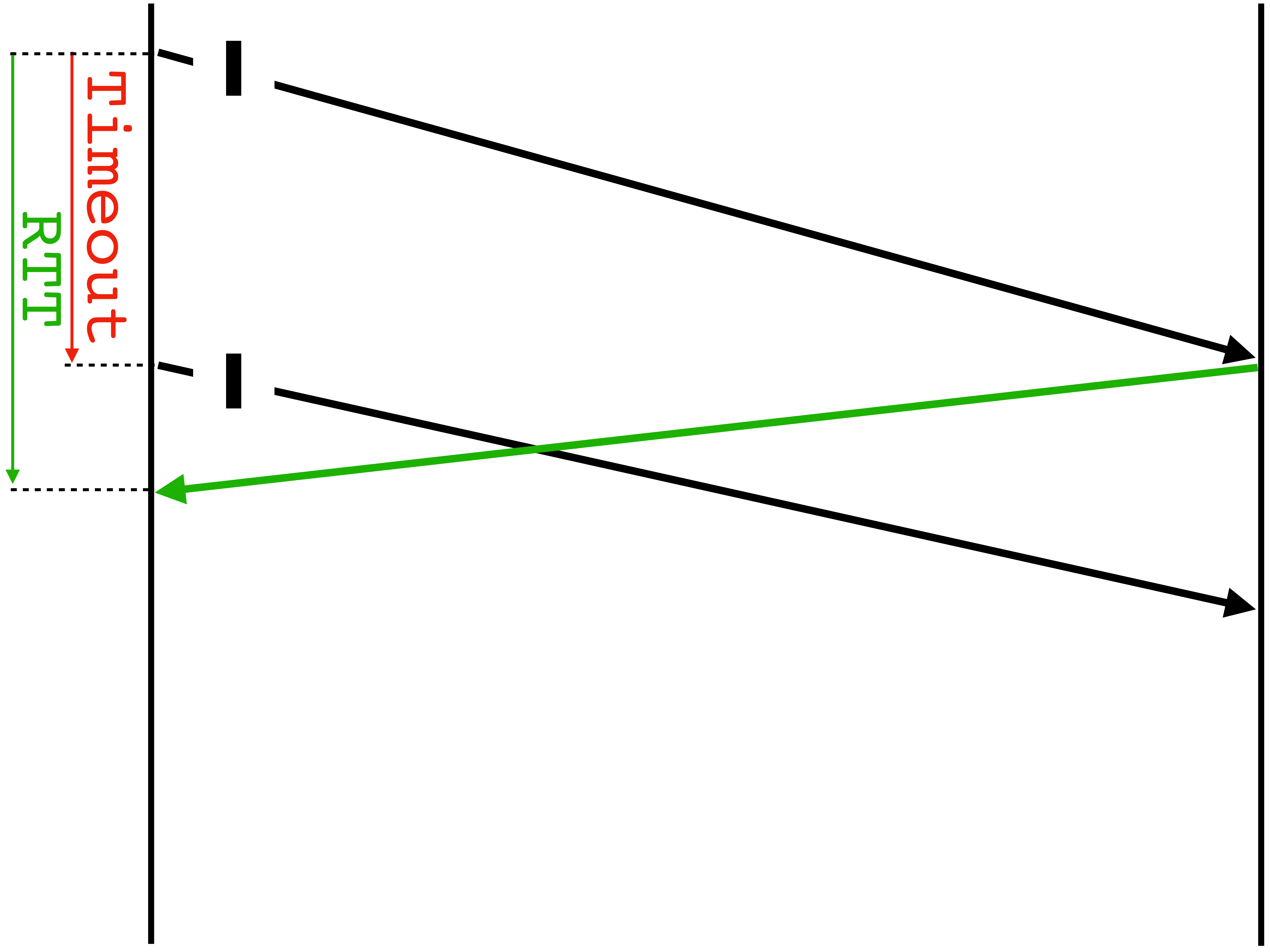

Timeout too short → Duplicate packets

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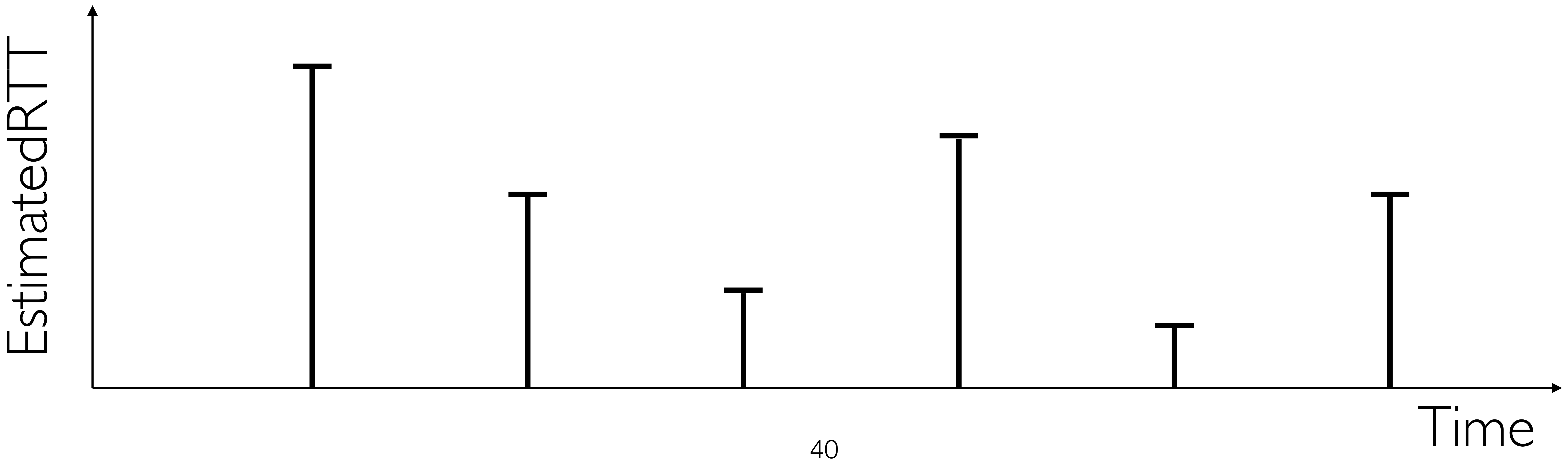
- **But how do we measure RTT?**

RTT Estimation

- **Use exponential averaging of RTT Samples**



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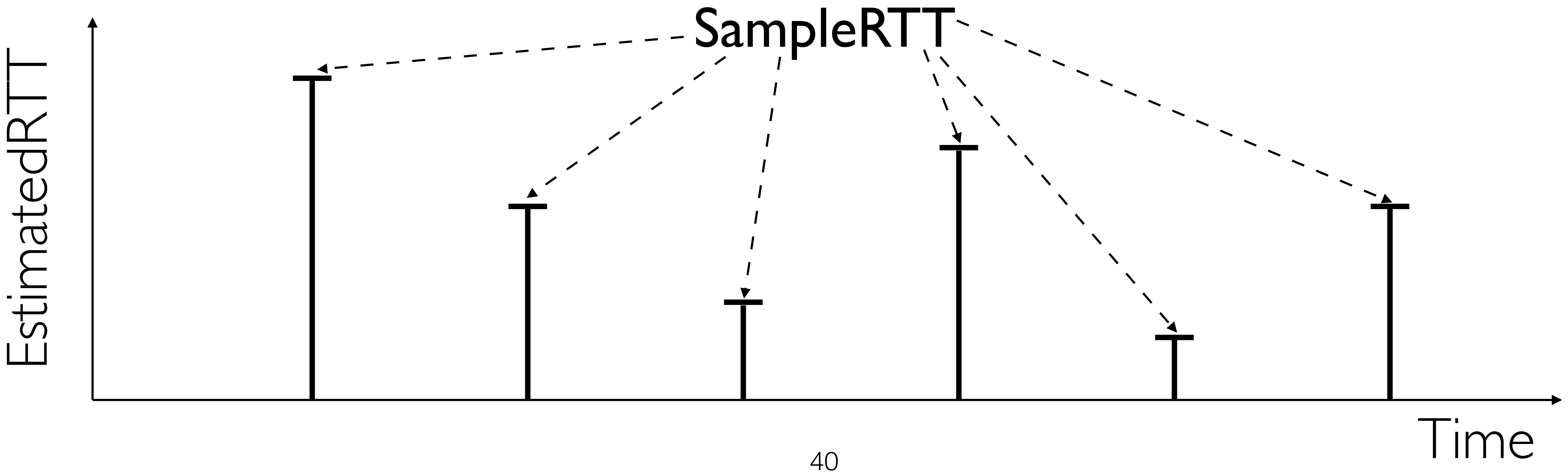

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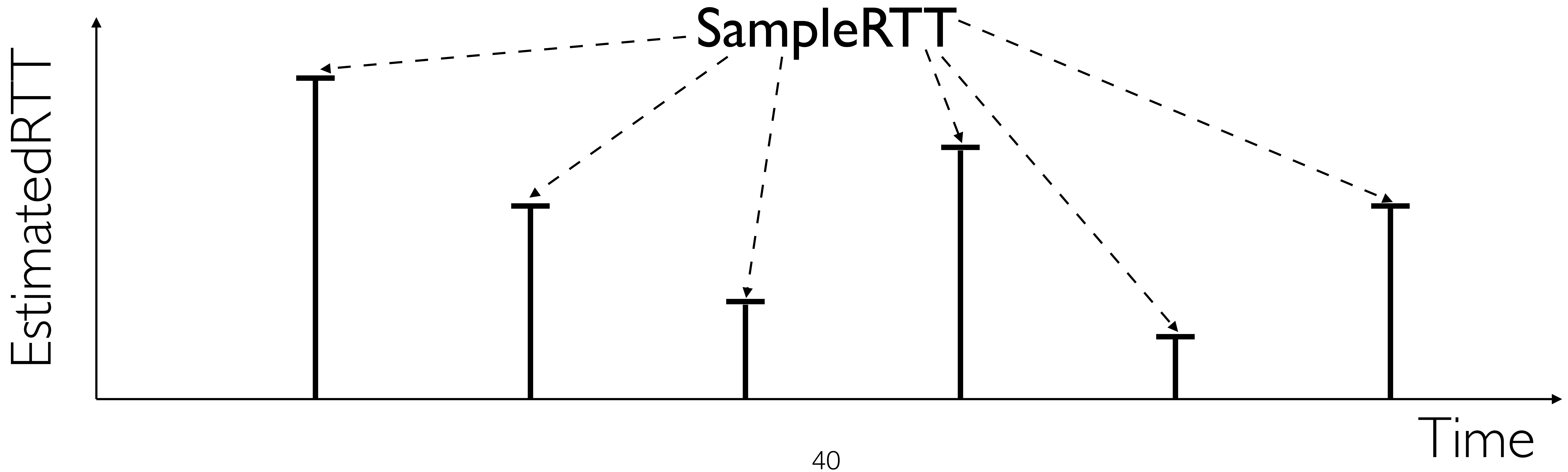
SampleRTT = AckRcvdTime - SendPacketTime
EstimatedRTT = α x EstimatedRTT + (1- α) x SampleRTT
0 < α <= 1



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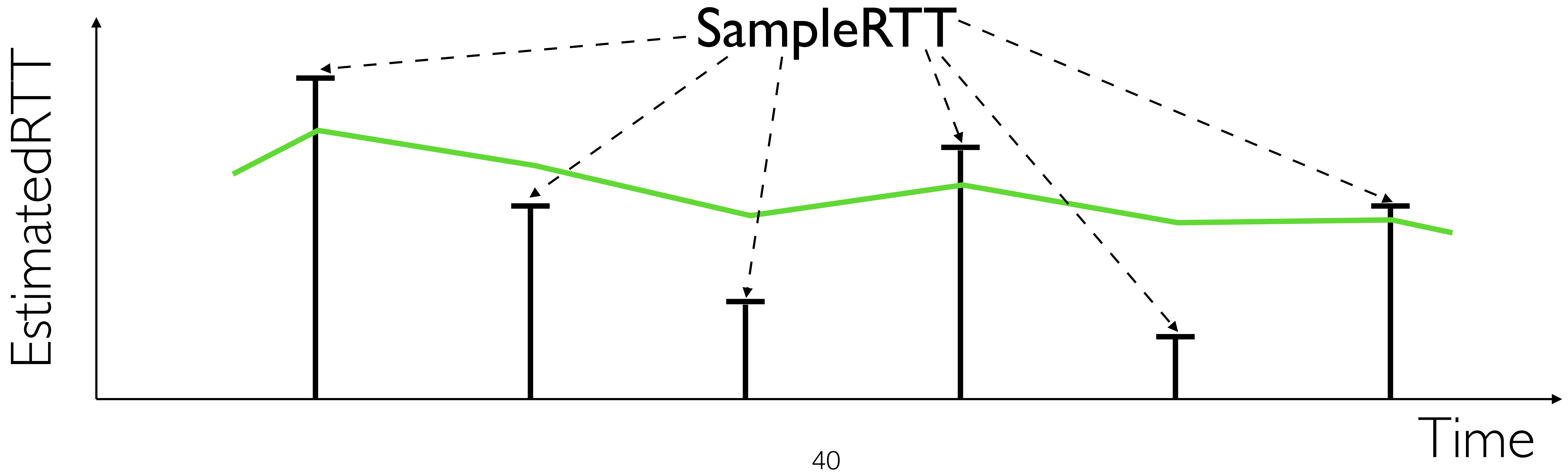

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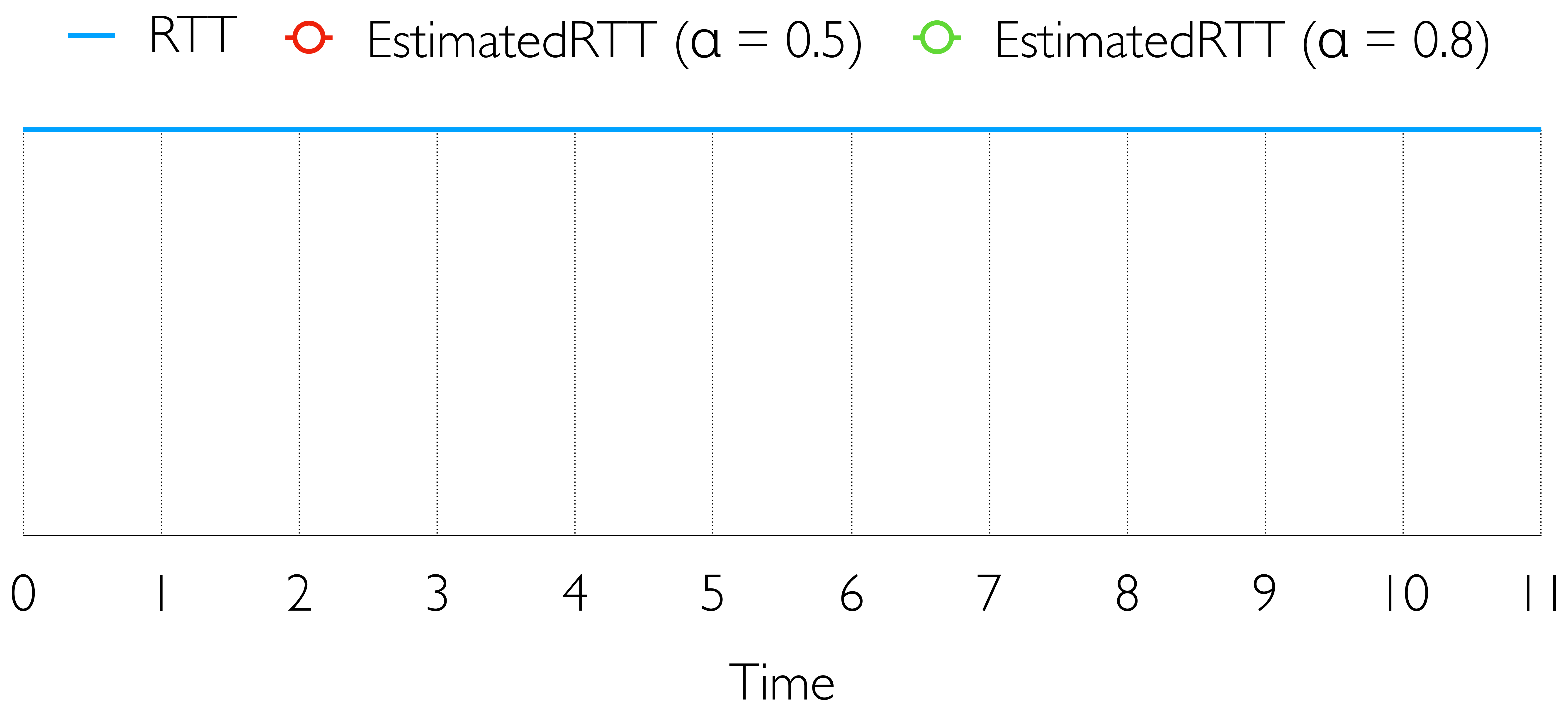

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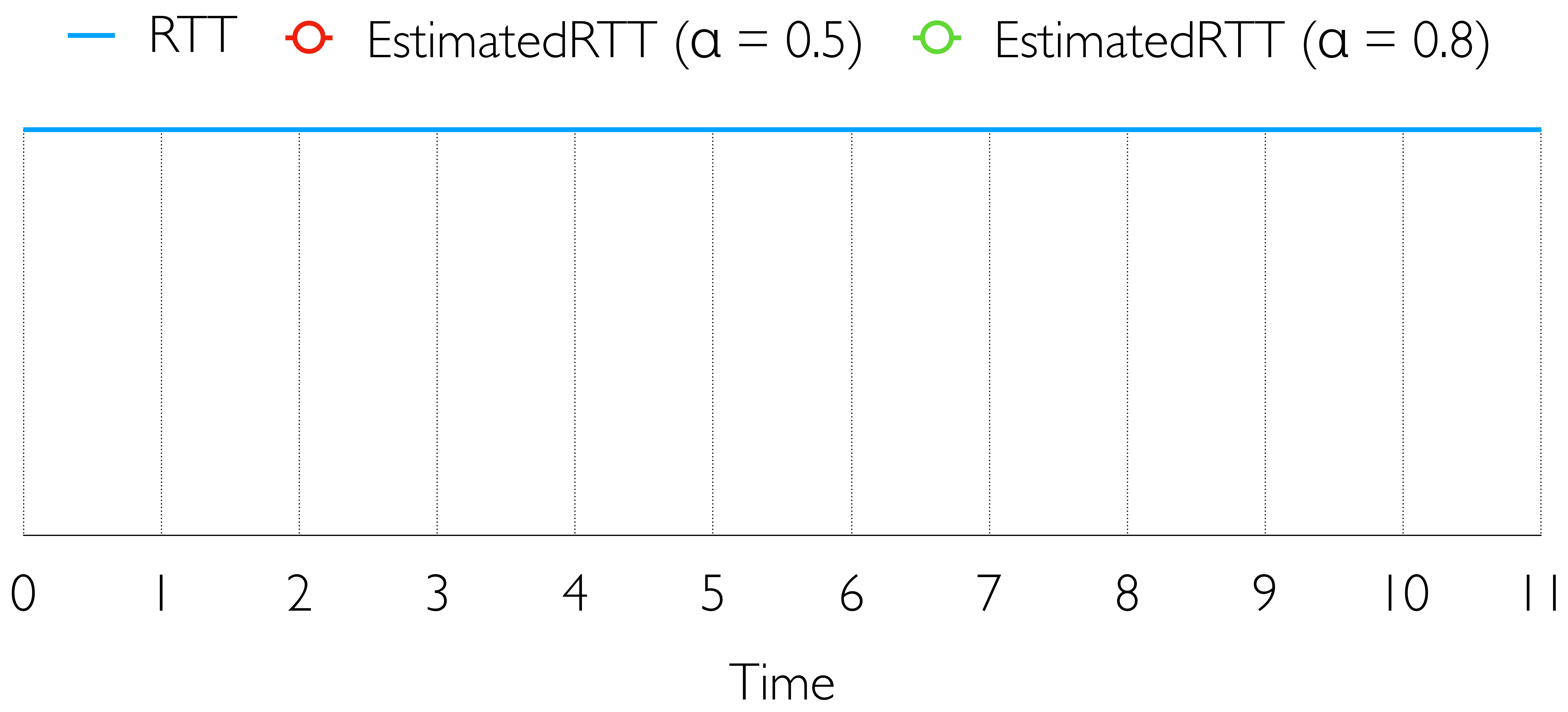

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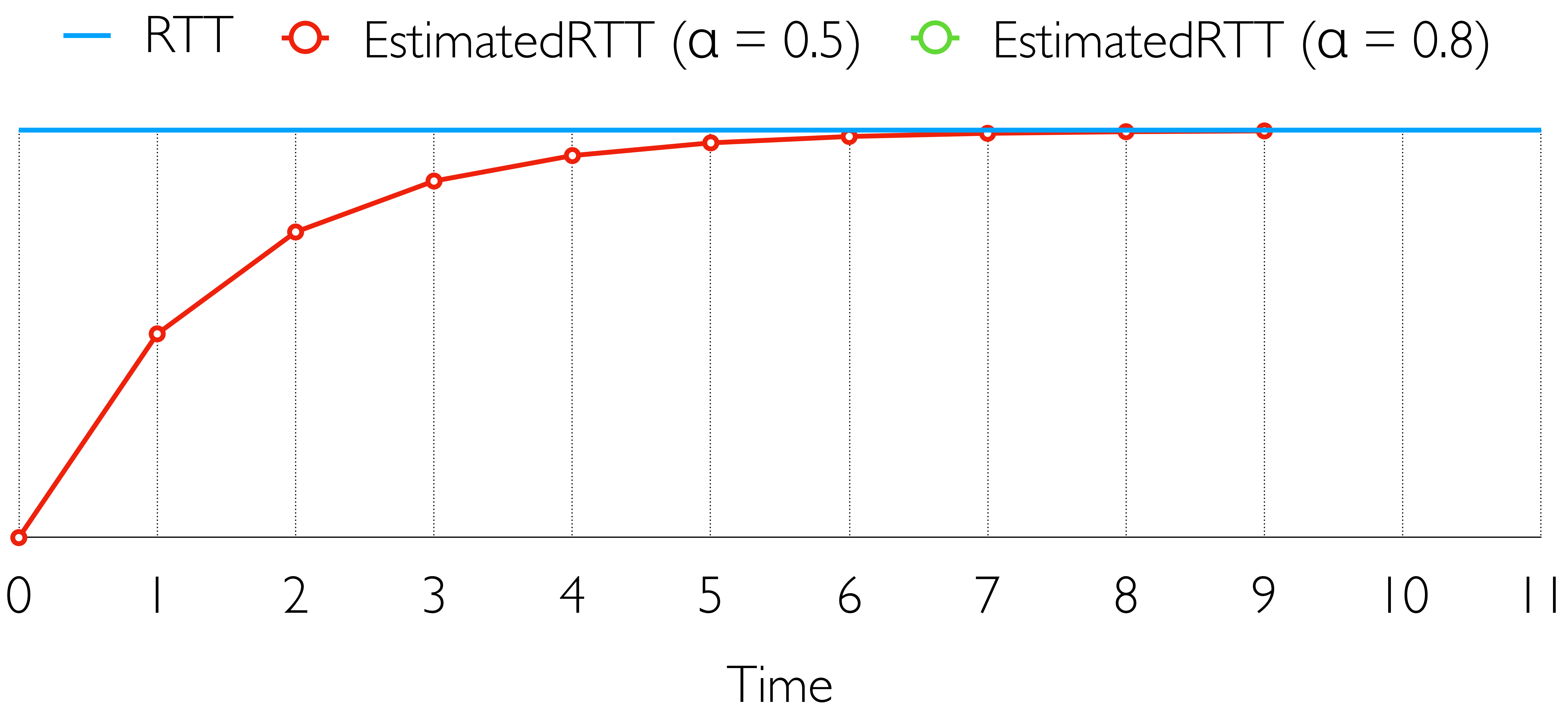

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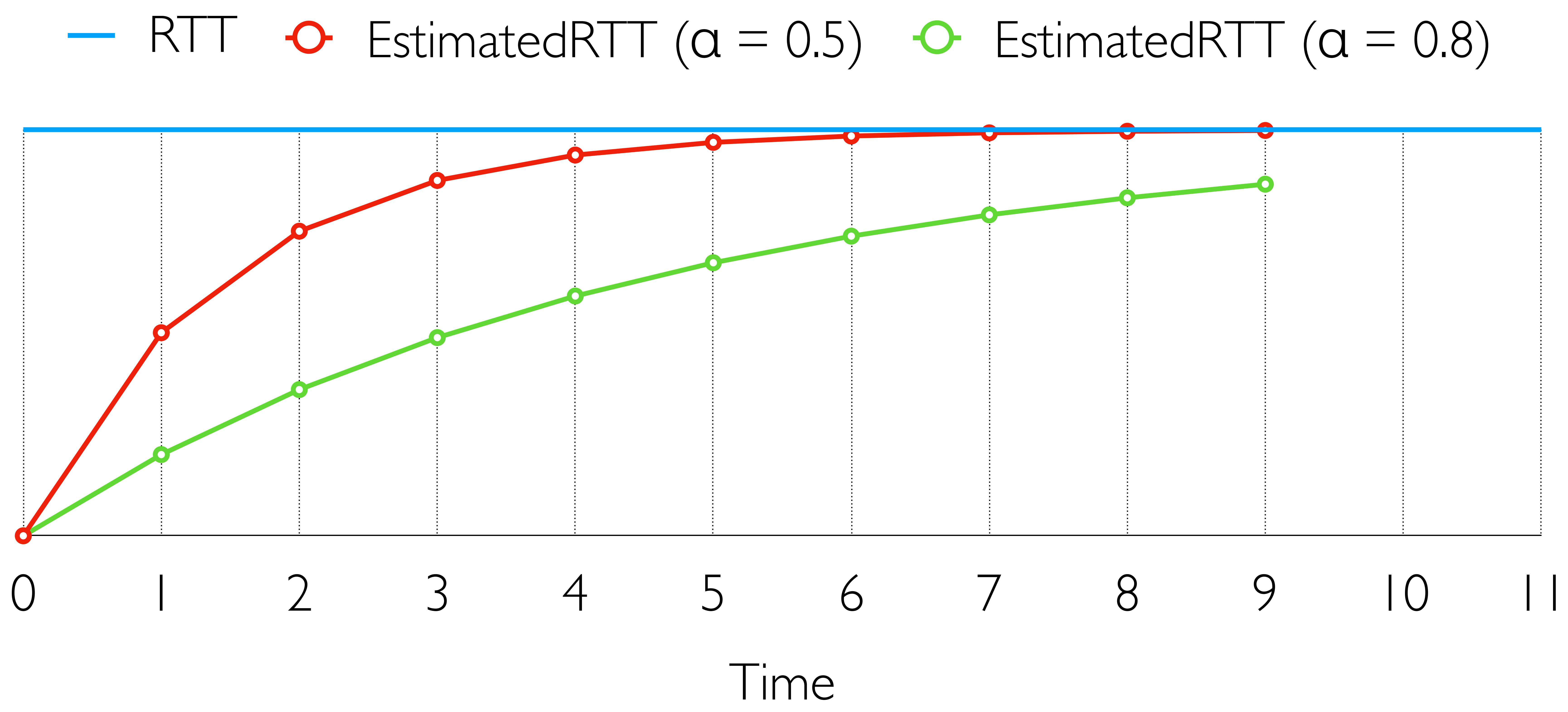

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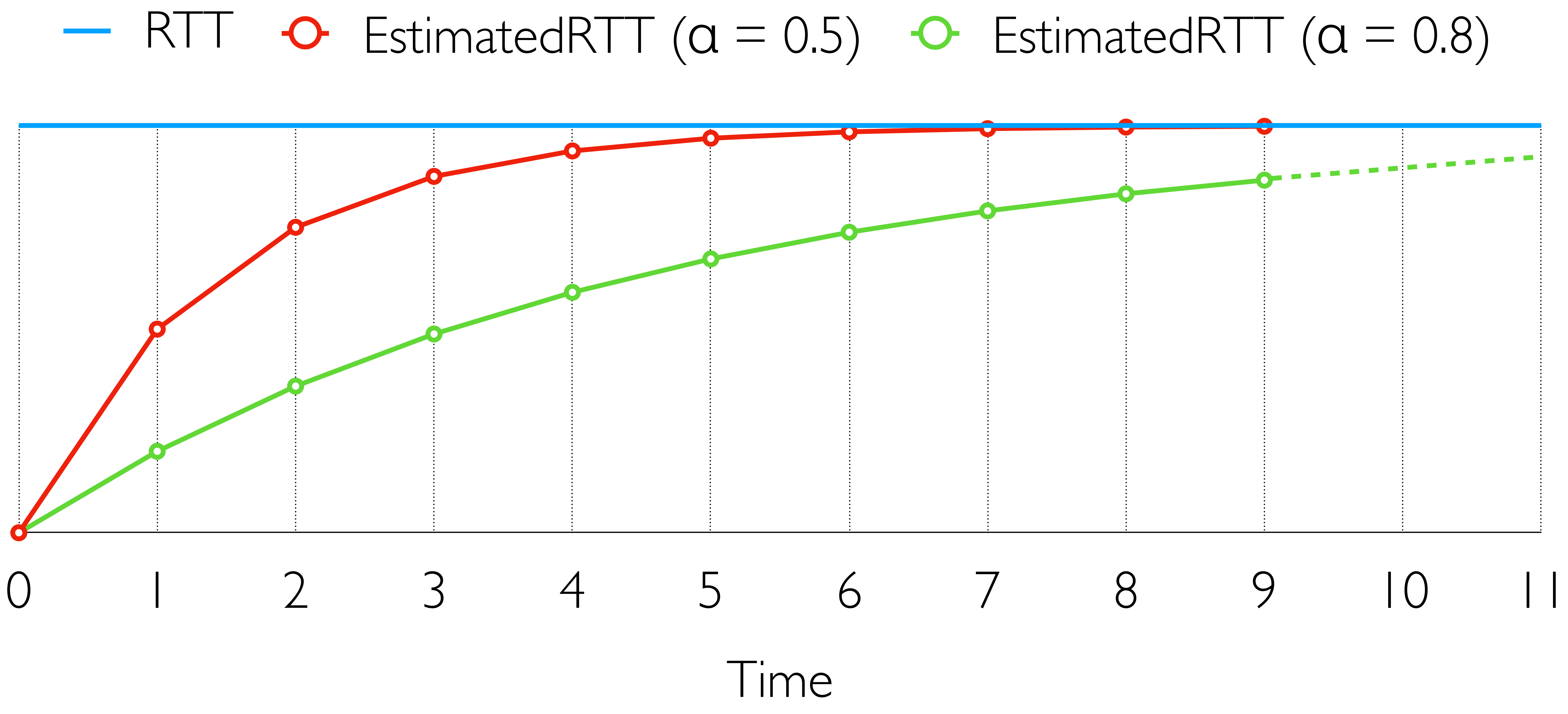

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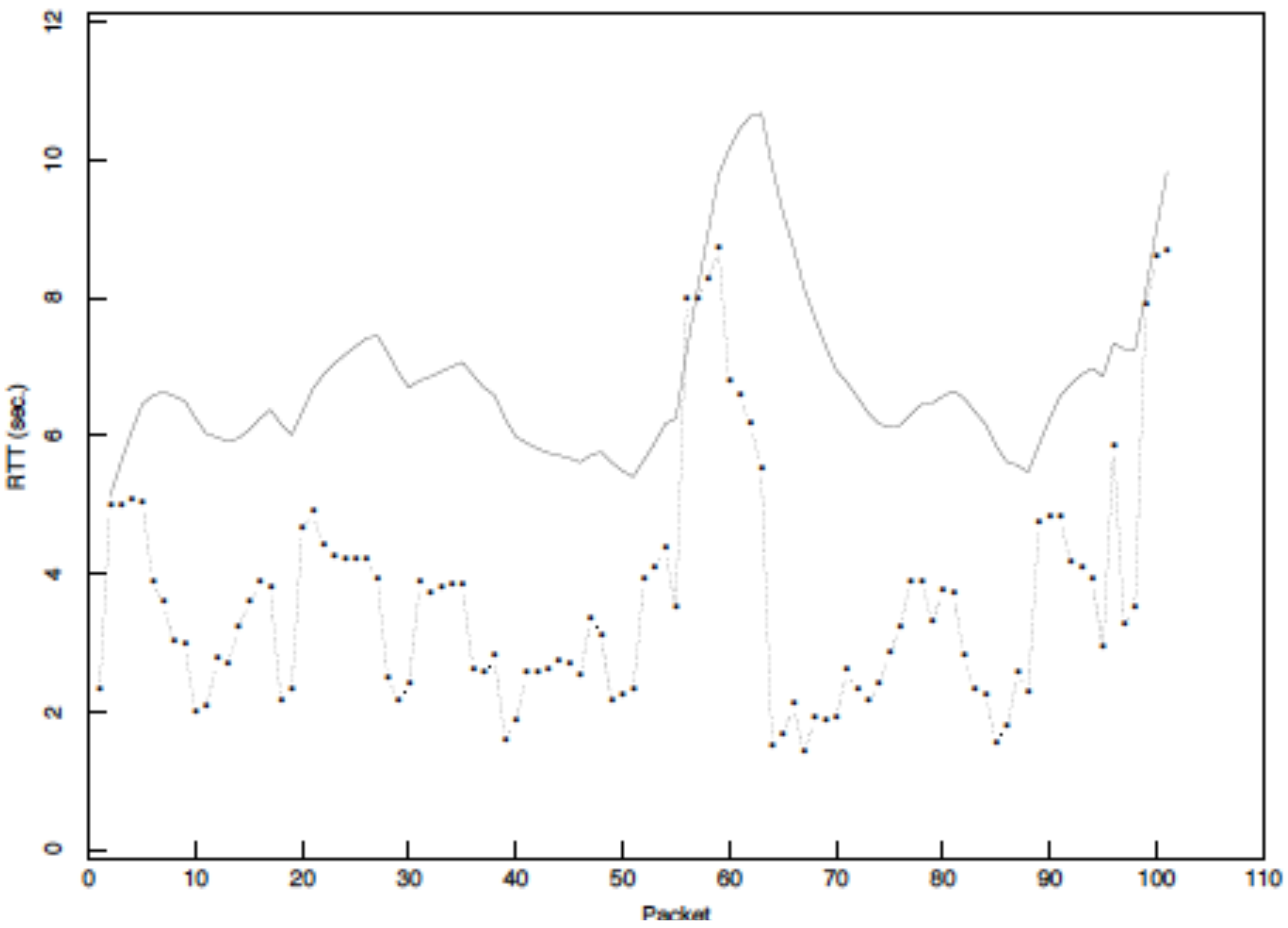
- **Employs *exponential backoff***
  - Every time RTO timer expires, set RTO ← 2 x RTO
  - (Up to a maximum >= 60seconds)
  - Every time new measurement comes in (=successful original transmission)
    - Collapse RTO back to 2 x EstimatedRTT

Karn/Partridge in Action

Figure 5: Performance of an RFC793 retransmit timer



From Jacobson & Karels, SIGCOMM 1988

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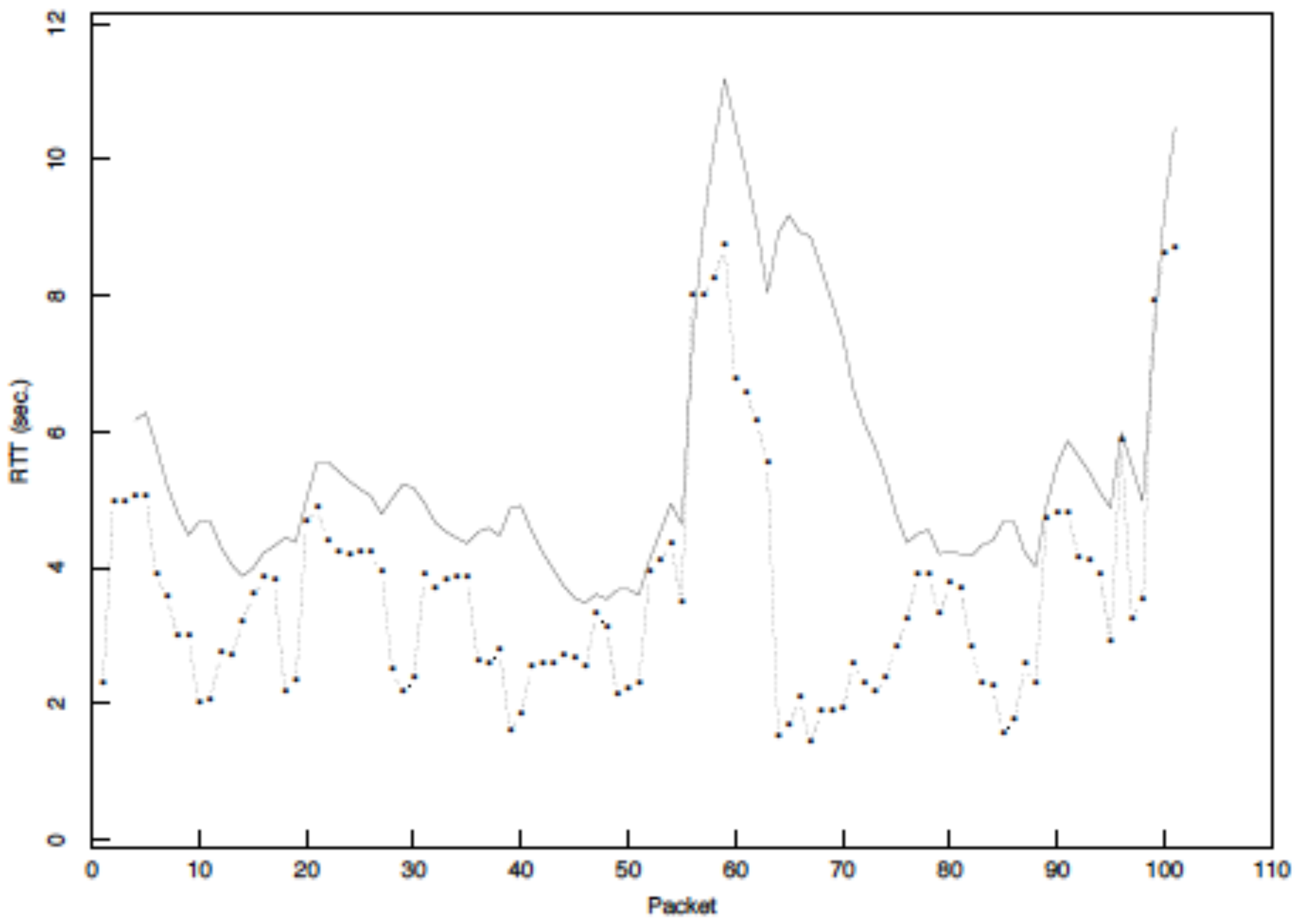
With Jacobson/Karels

Figure 6: Performance of a Mean+Variance retransmit timer



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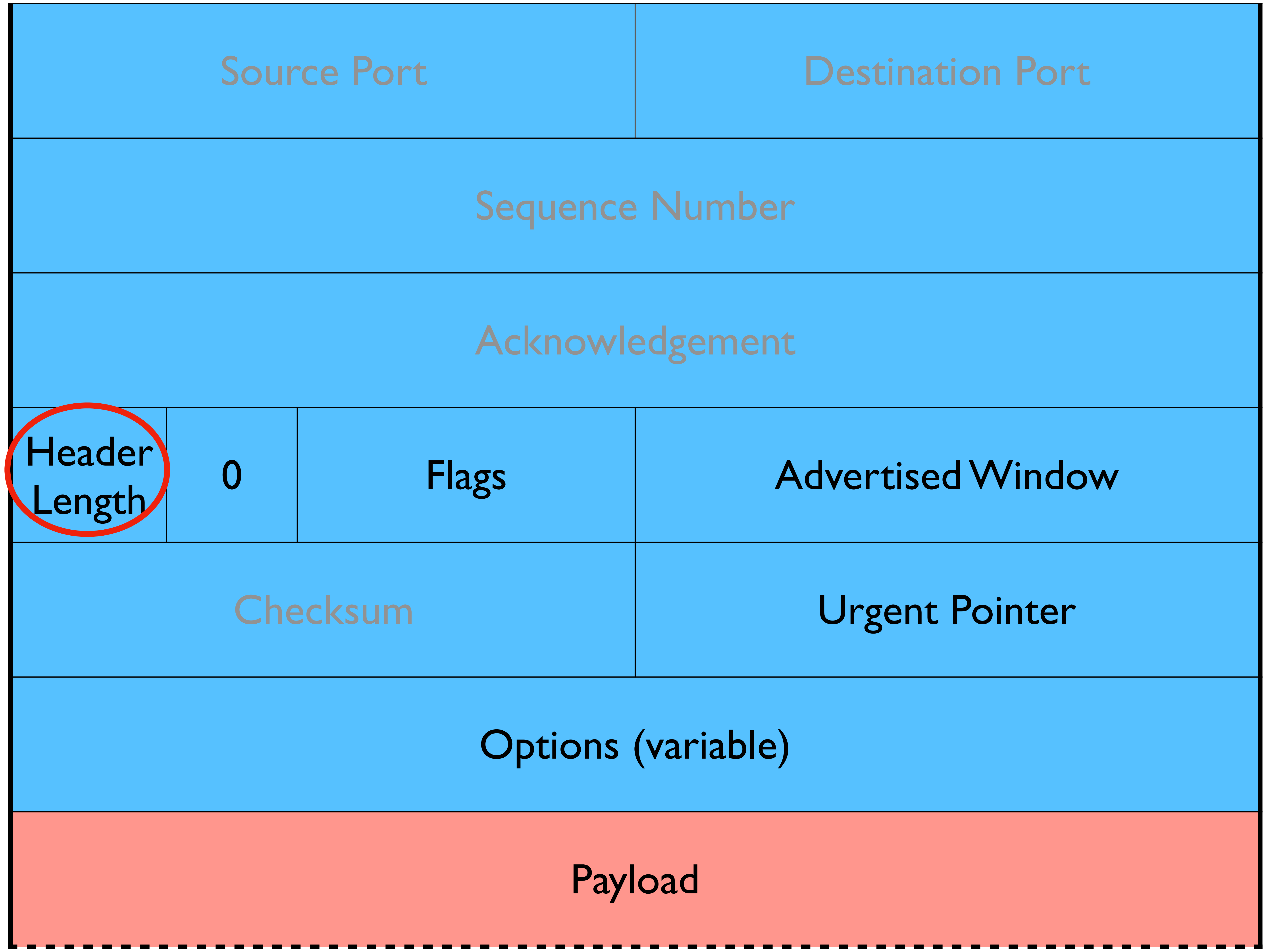
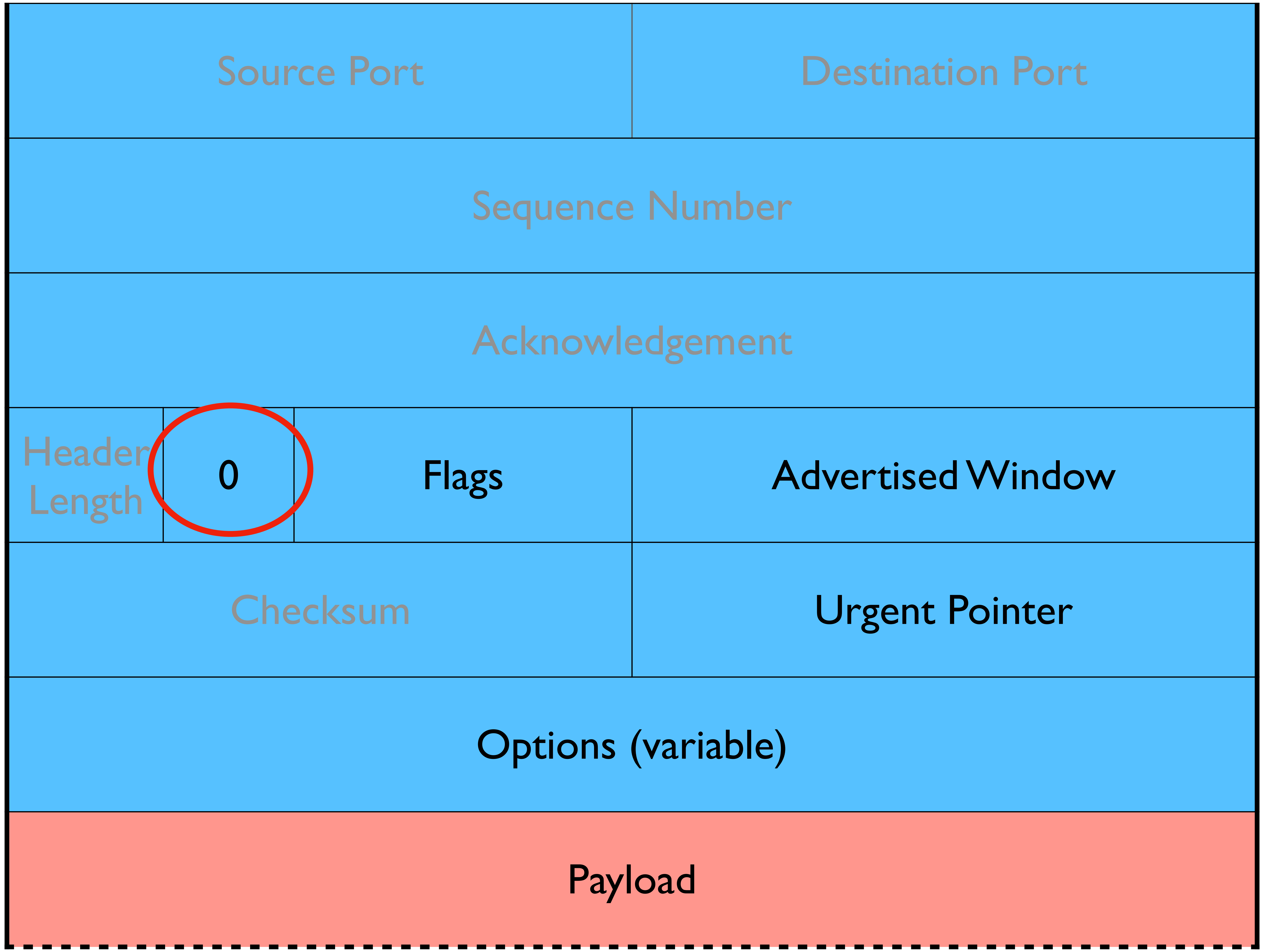
TCP Header: What's Left?

Number of 4-byte words in TCP header; 5 means no options



TCP Header: What's Left?

"Must Be Zero"
6 bits reserved



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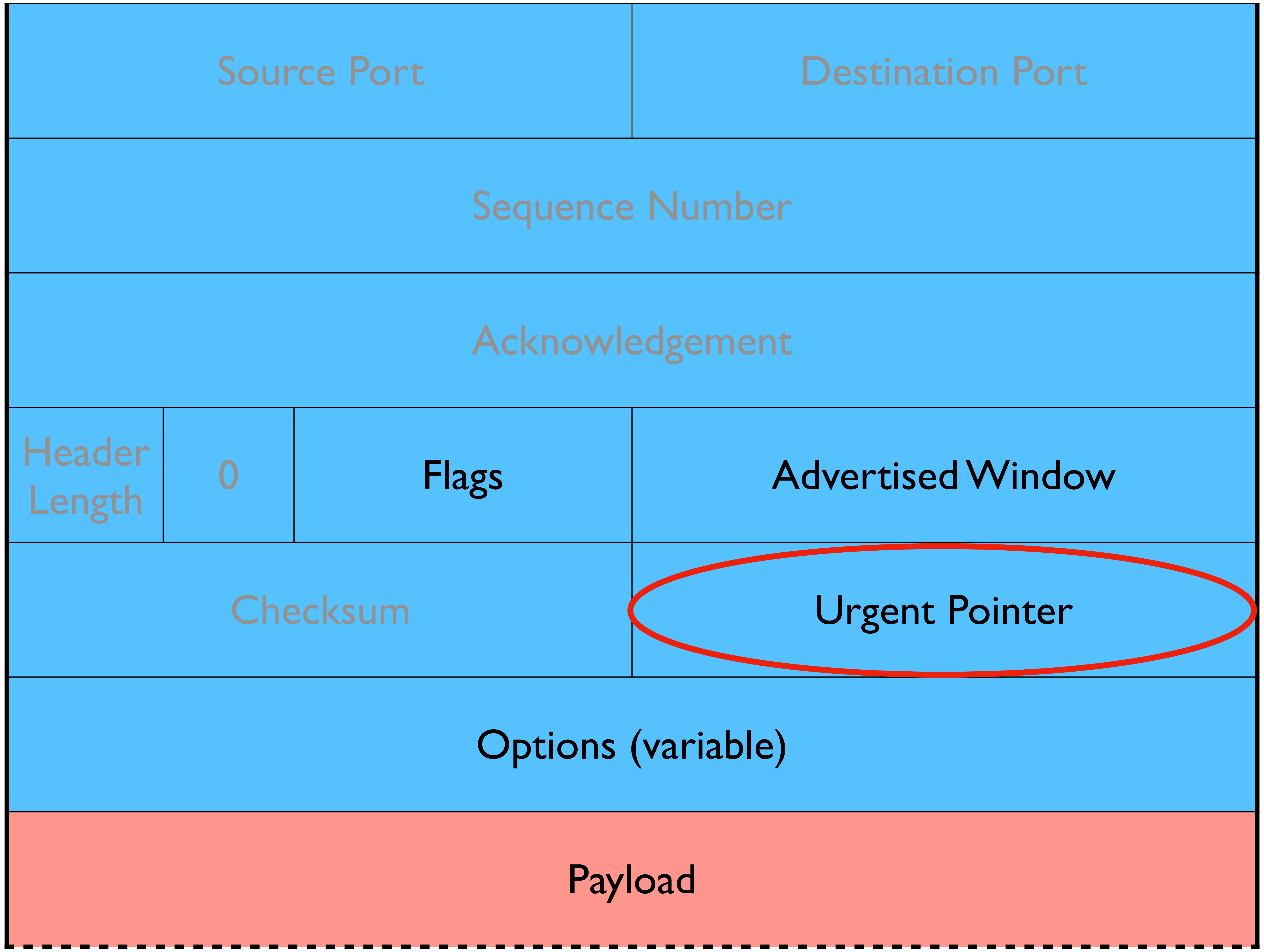
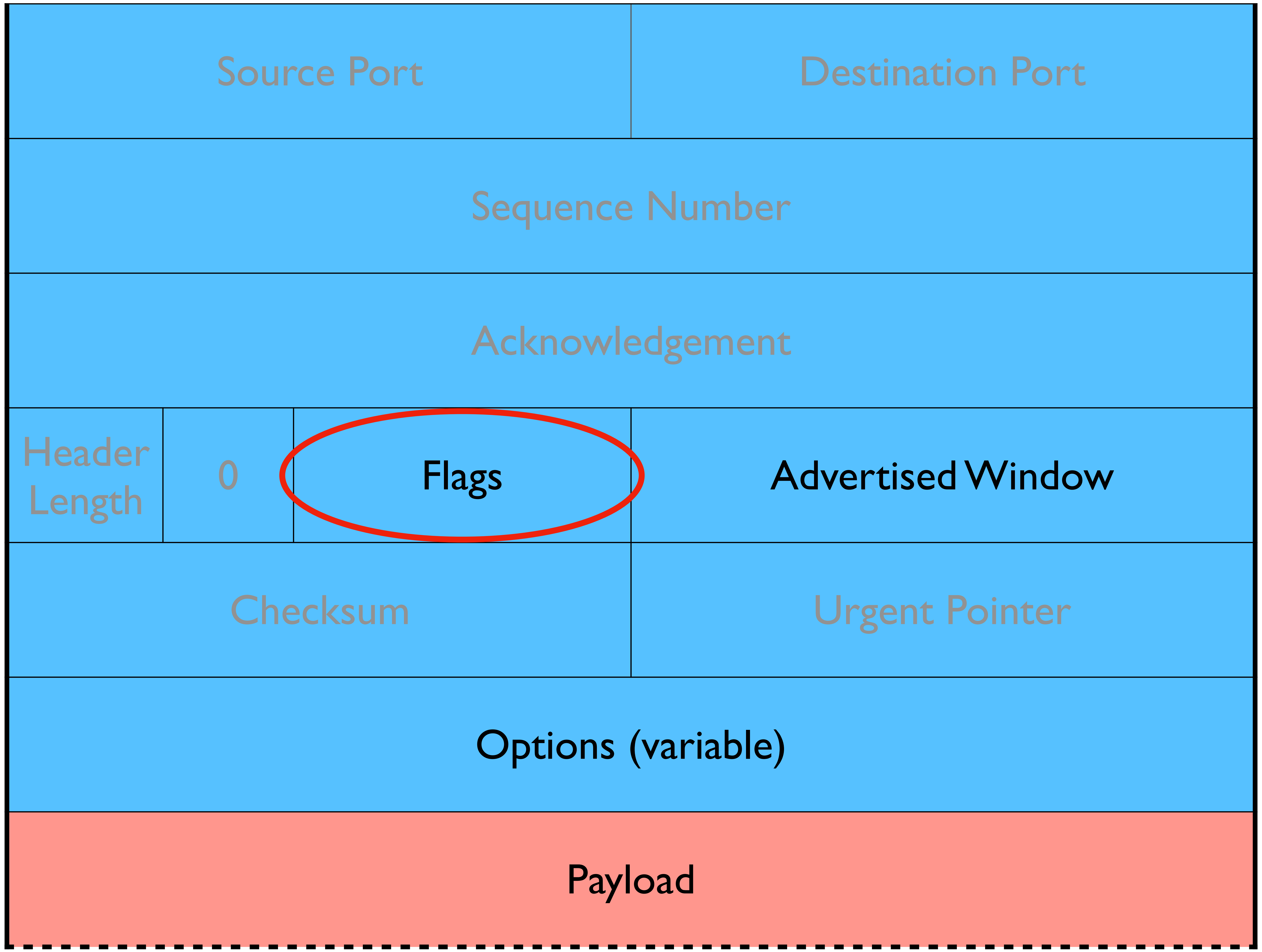


Used with URG flag to indicate urgent data (not discussed further)

TCP Header: What's Left?



TCP Connection Establishment and Initial Sequence Numbers

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- Hosts exchange ISNs when they establish a connection

Establishing a TCP Connection

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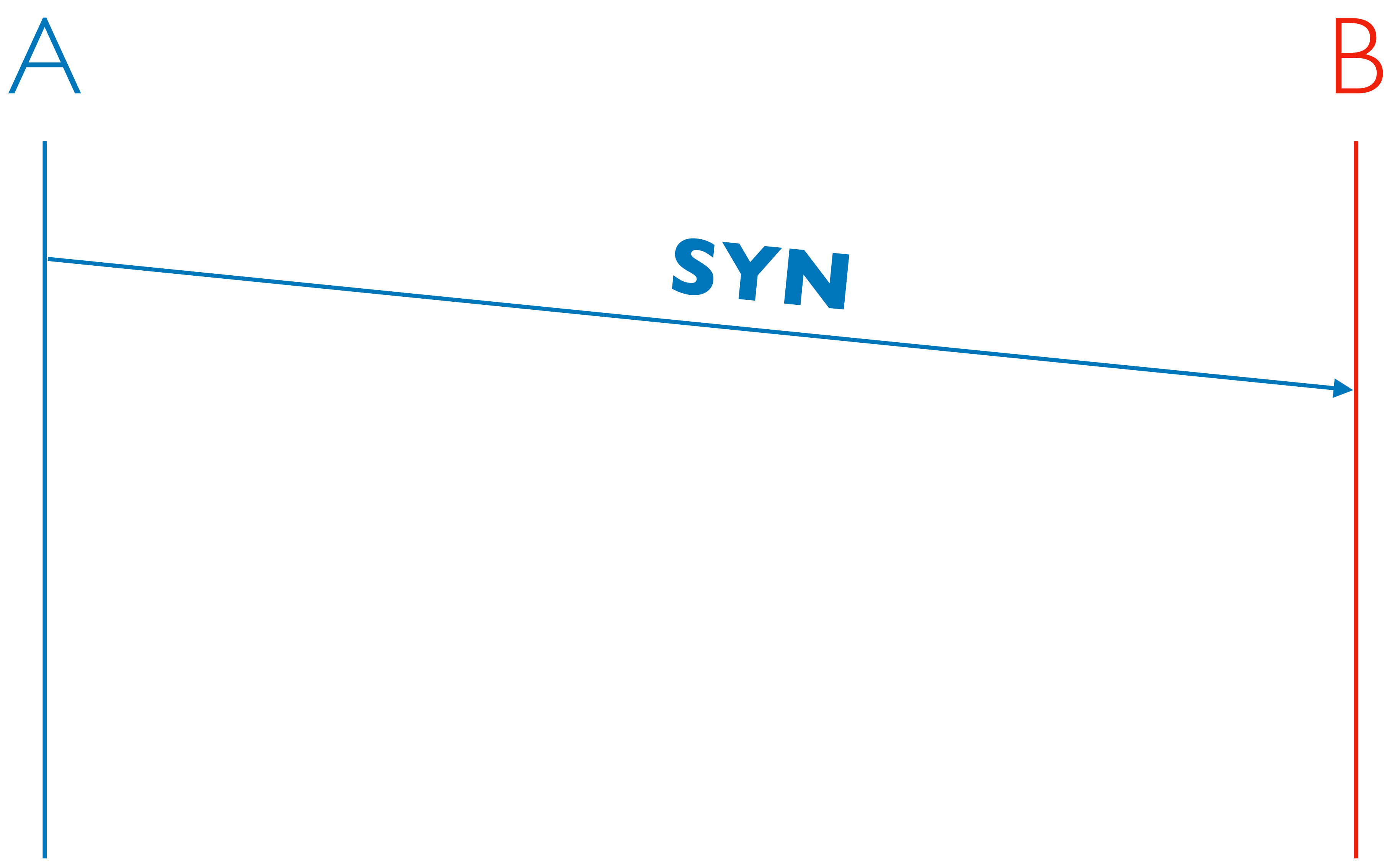
- **Three-way handshake to establish connection**

Establishing a TCP Connection



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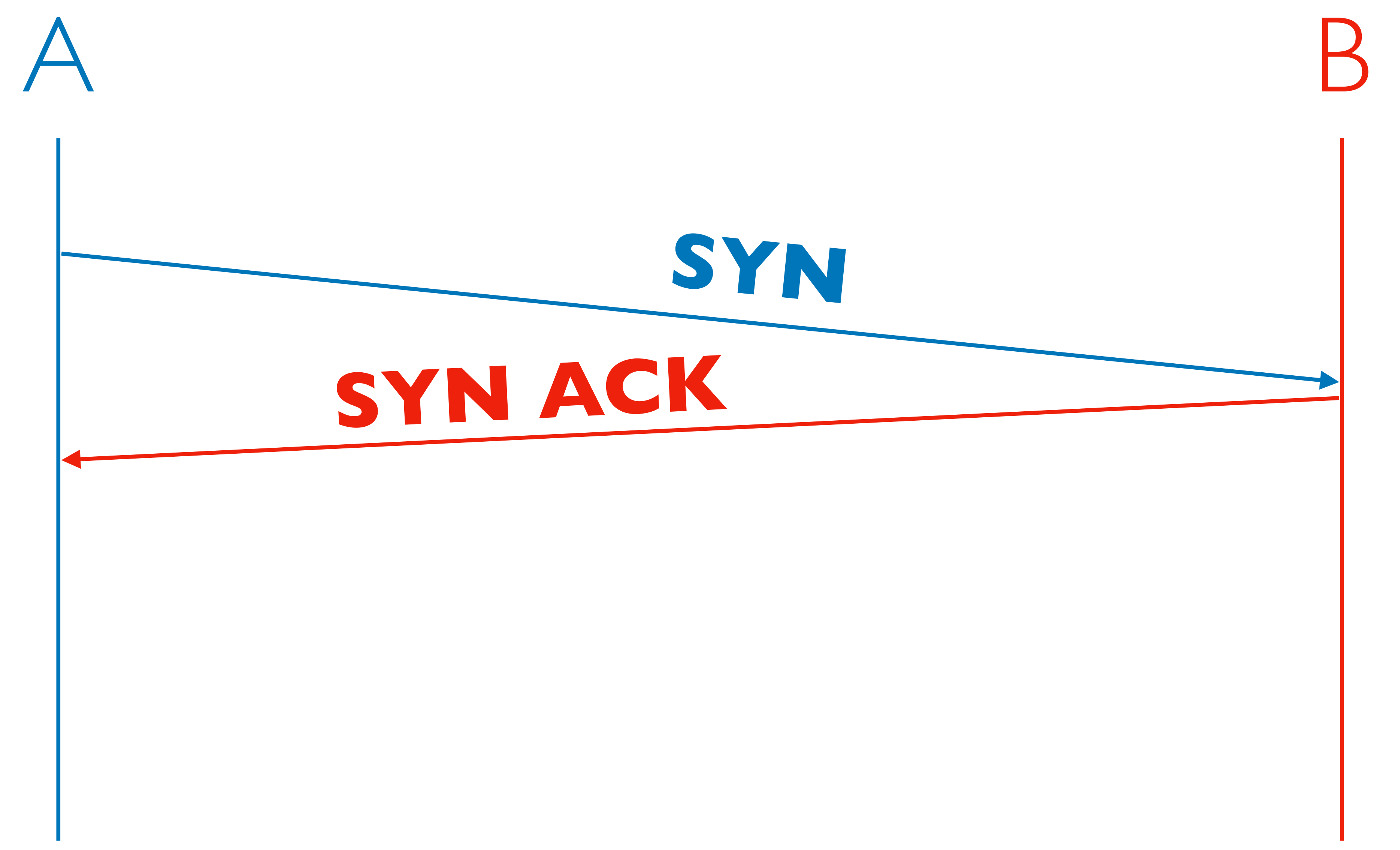

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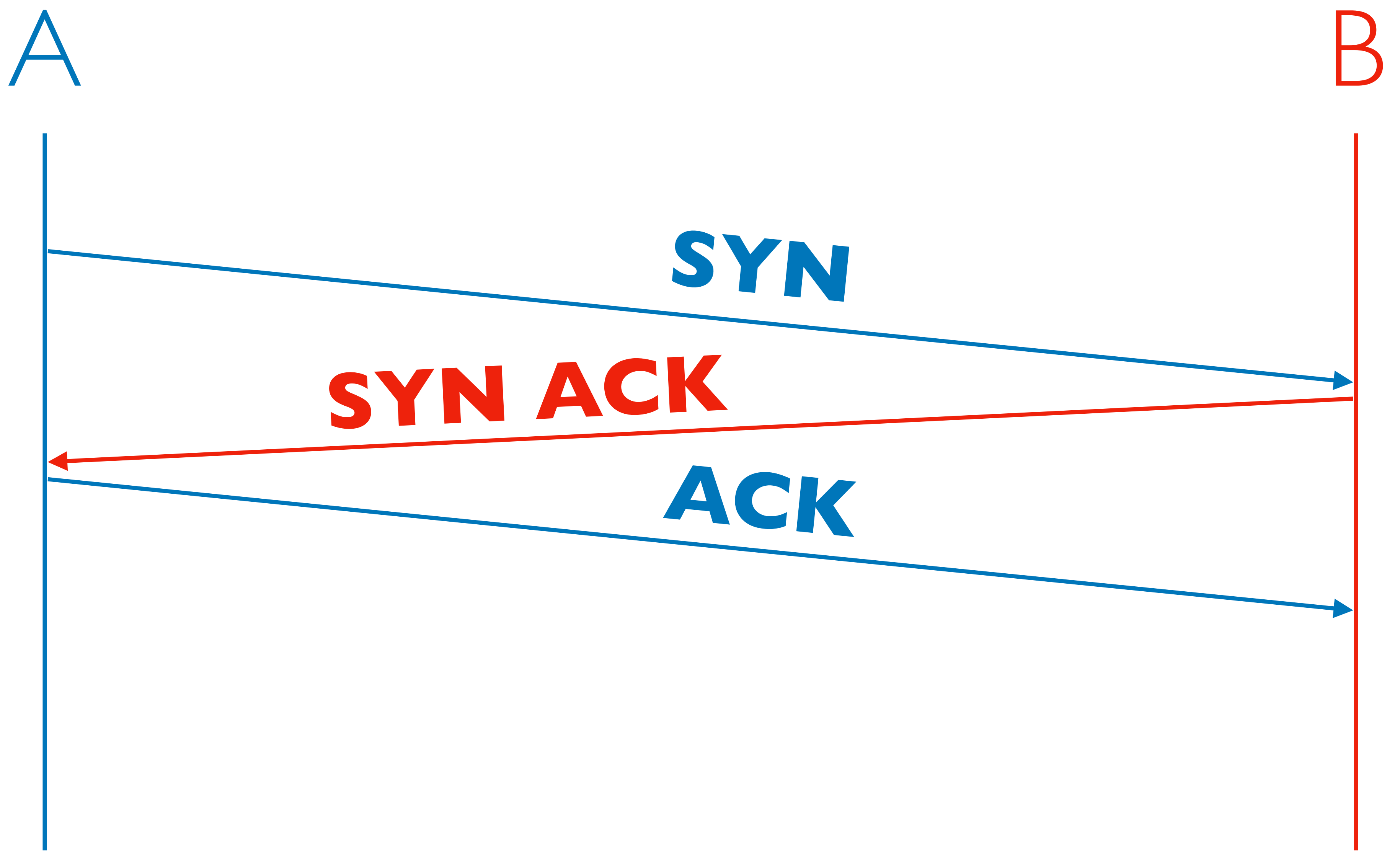

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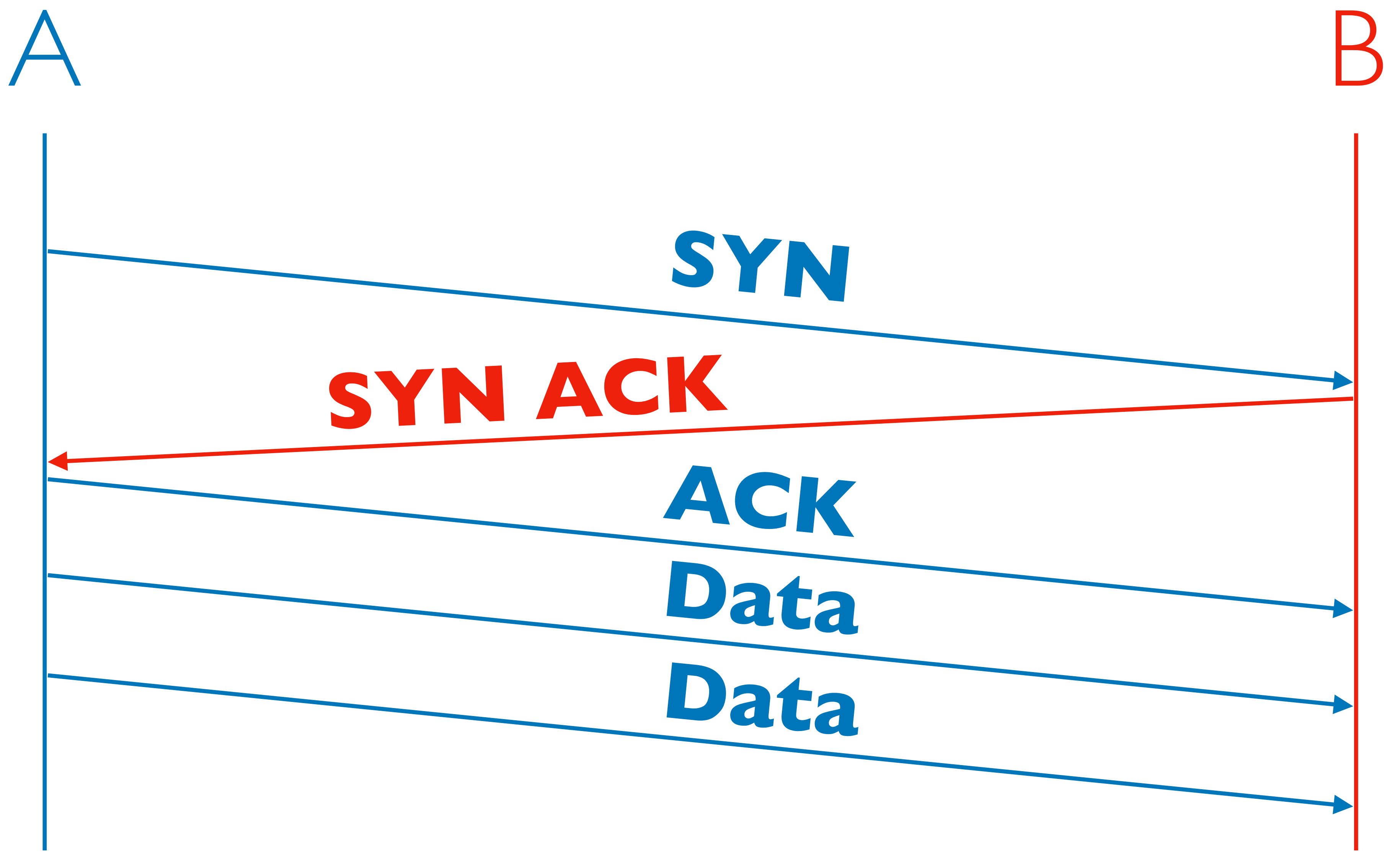

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FIN
RST
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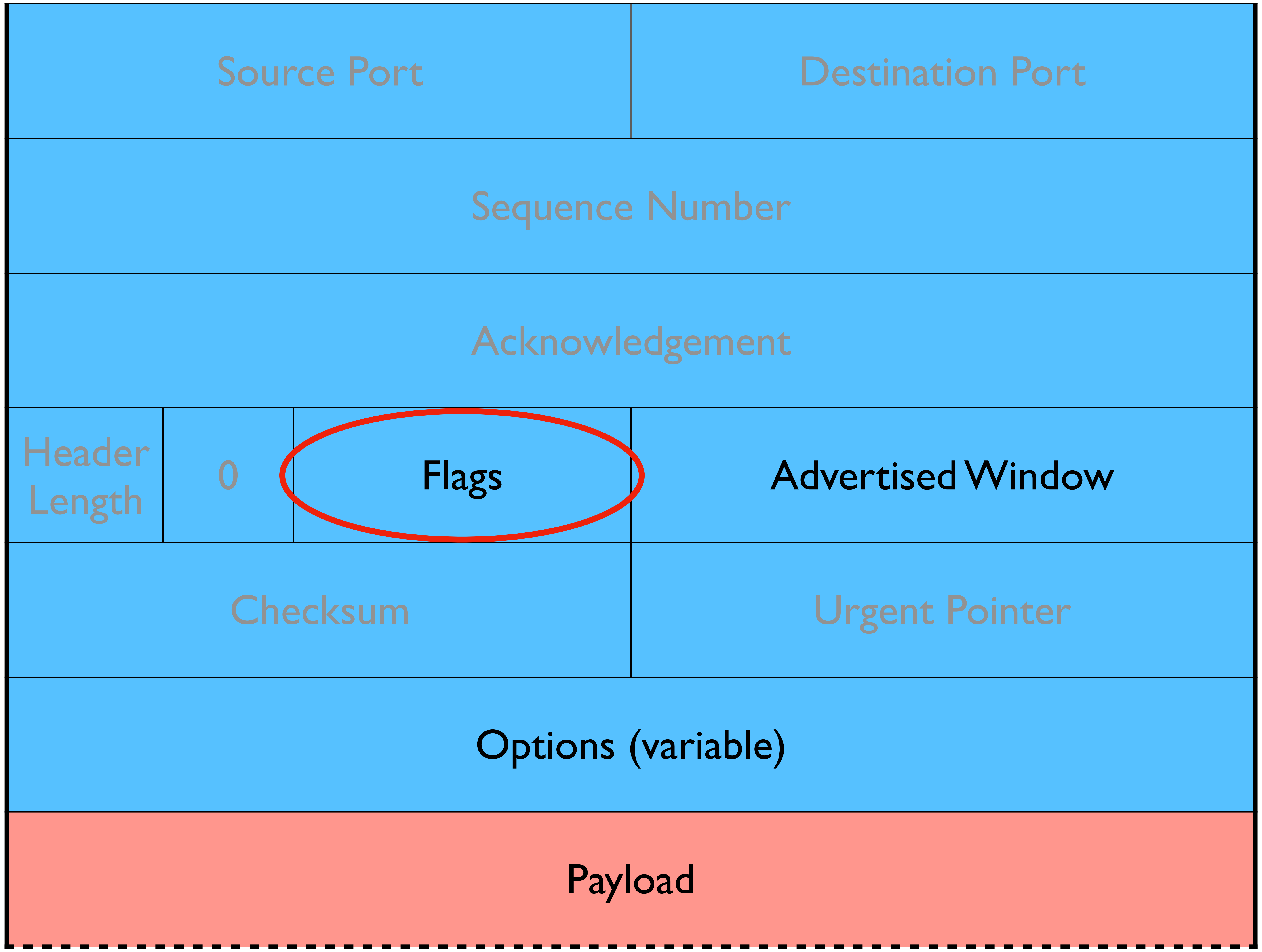
URG



Step 1: A's Initial SYN Packet

SYN
ACK
FIN
RST
PSH
URG

A's Port			**B's Port**
A's Initial Sequence Number			
(Irrelevant since ACK is not set)			
5	0	Flags	Advertised Window
Checksum			Urgent Pointer
~~**Options (variable)**~~			

Step 1: A's Initial SYN Packet

A tells B it wants to open a connection…

SYN
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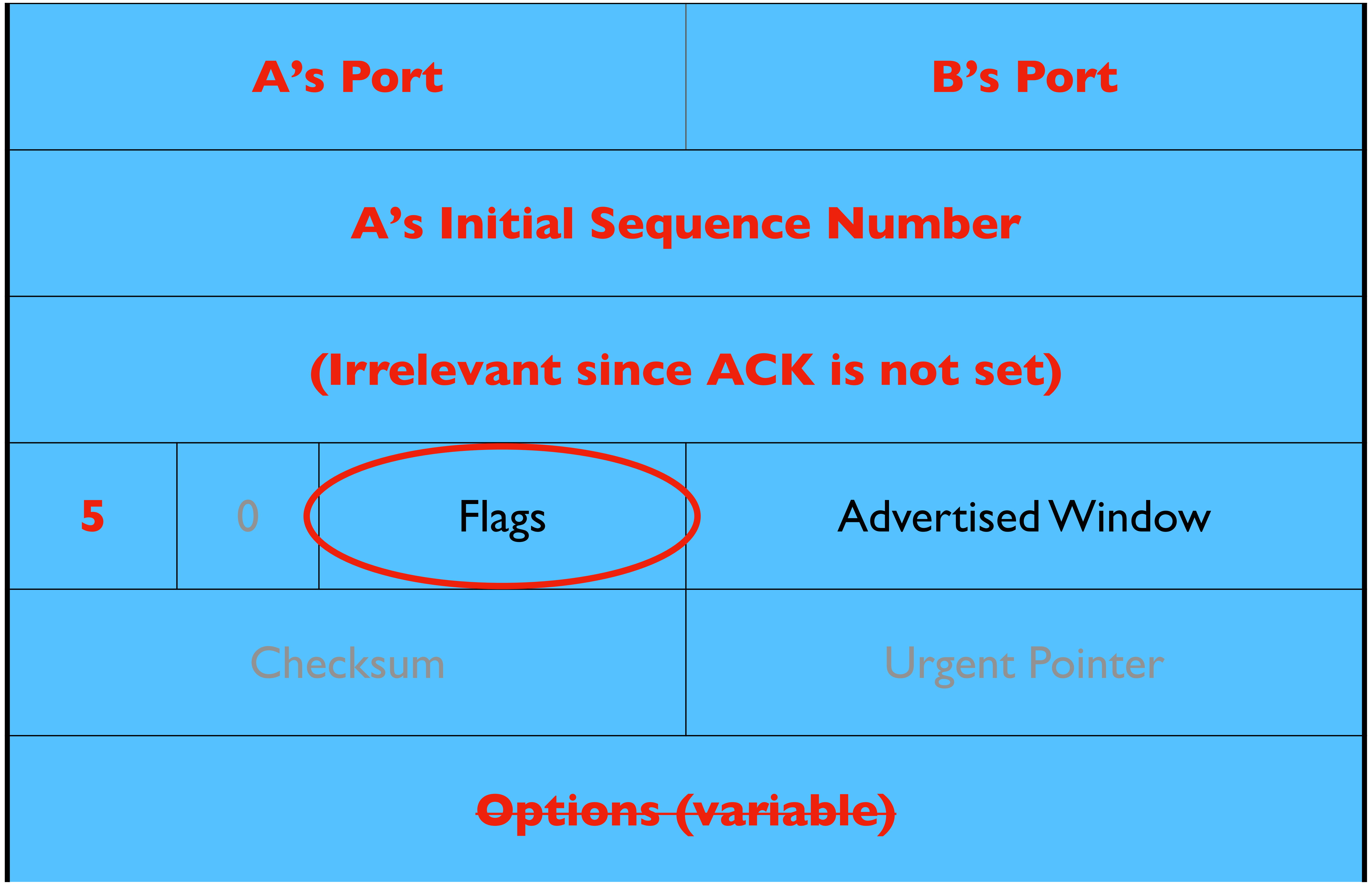
FIN
RST
PSH
URG



Step 2: B's SYN ACK Packet

SYN
ACK
FIN
RST
PSH
URG

B's Port			**A's Port**
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ACK = ISN of A plus one			
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B tells A it accepts, and is reading to hear the next byte

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… on receiving this packet, A can start sending data

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<table>
<tr><td colspan="3">A's Port</td><td>B's Port</td></tr>
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FIN
RST
PSH
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… on receiving this packet, B can start sending data

Timing Diagram: 3-way Handshaking

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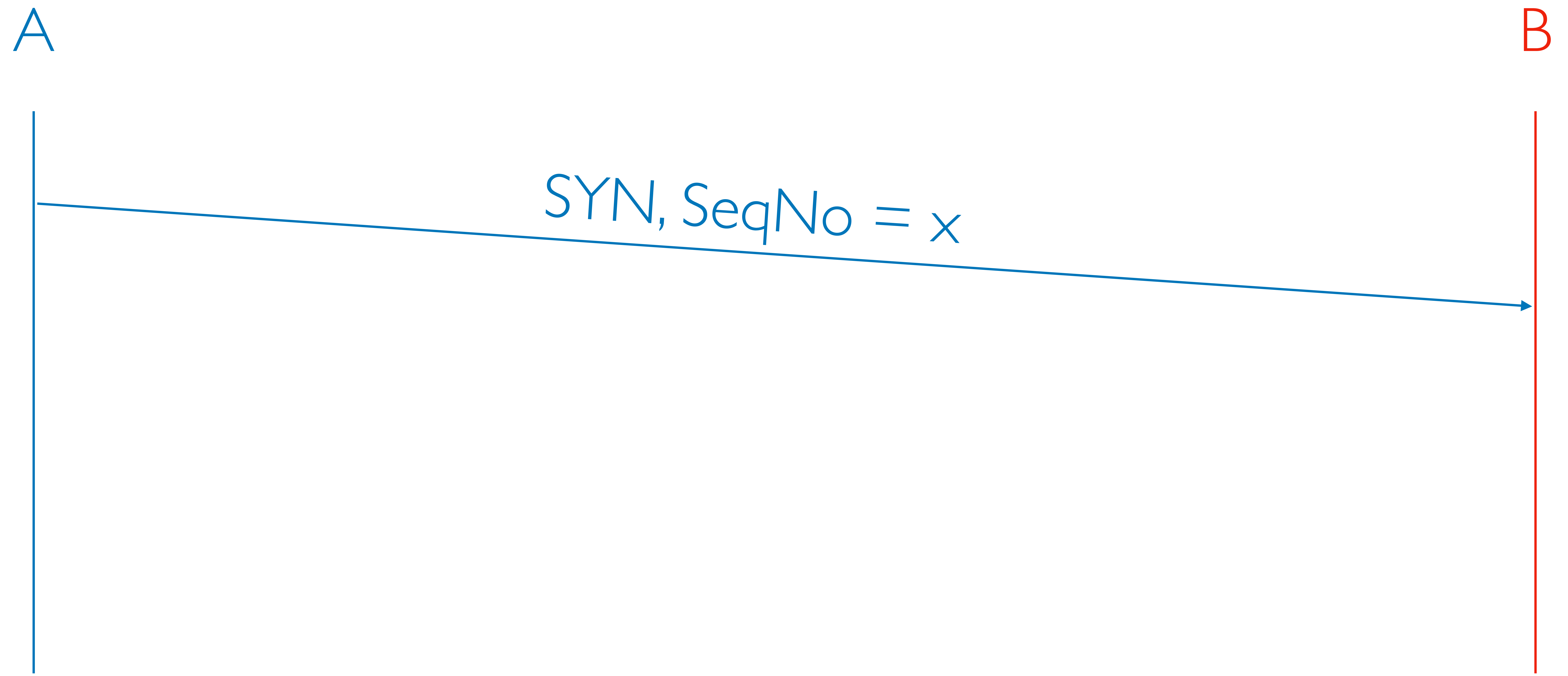

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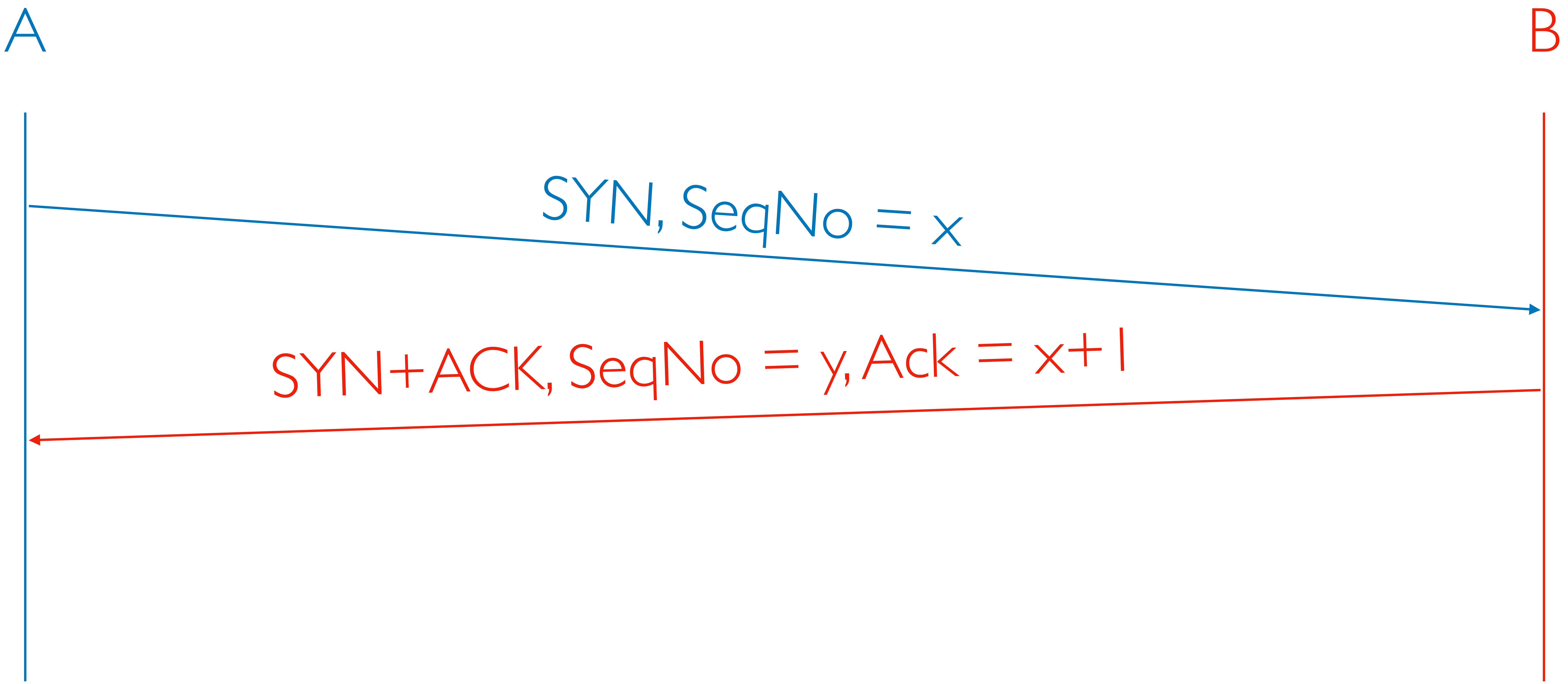

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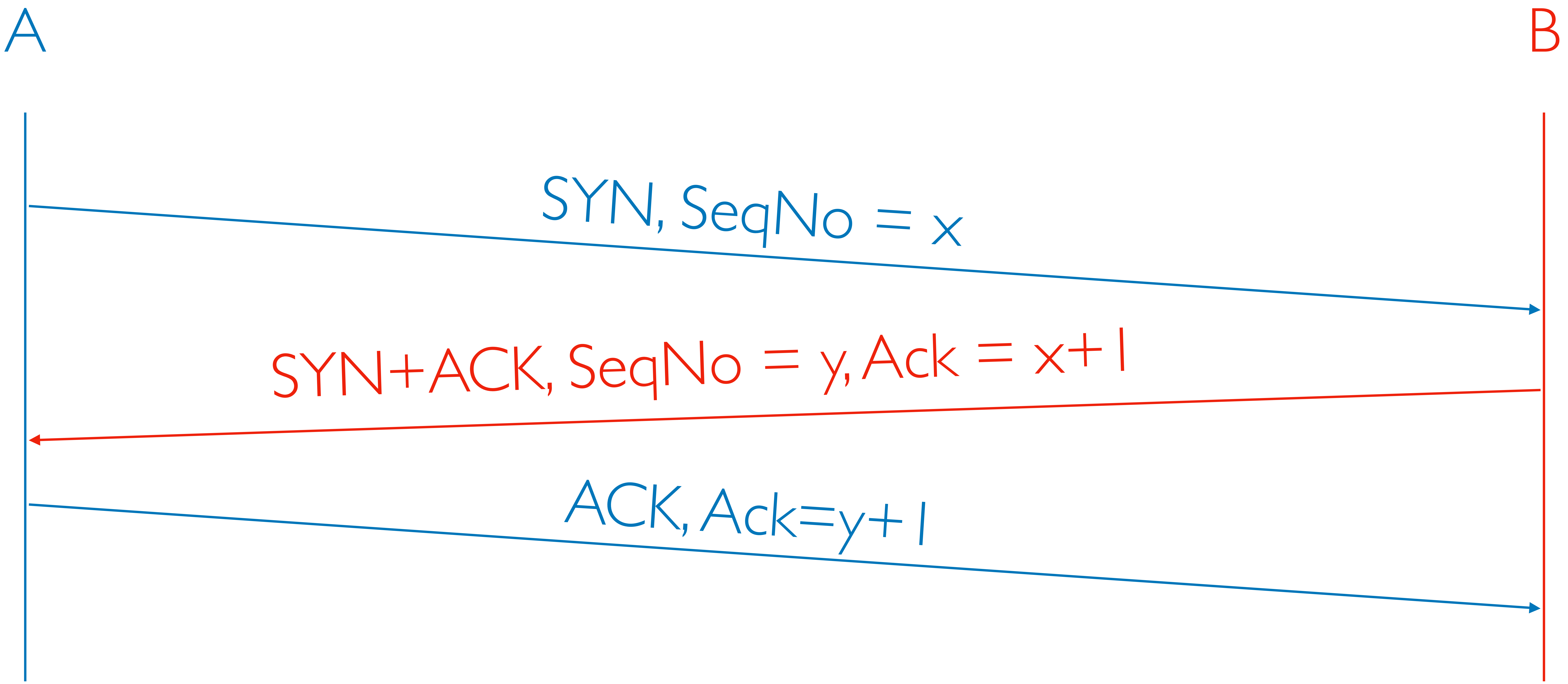

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  - Sender sets a timer and waits for the SYN ACK
  - … and retransmits the SYN if needed
- **How should the TCP sender set the timer?**
  - Sender has no idea how far away the receiver is
  - Hard to guess a reasonable length of time to wait
  - ***Should*** (RFCs 1122 & 2988) use default of 3 seconds
    - Some implementations instead use 6 seconds

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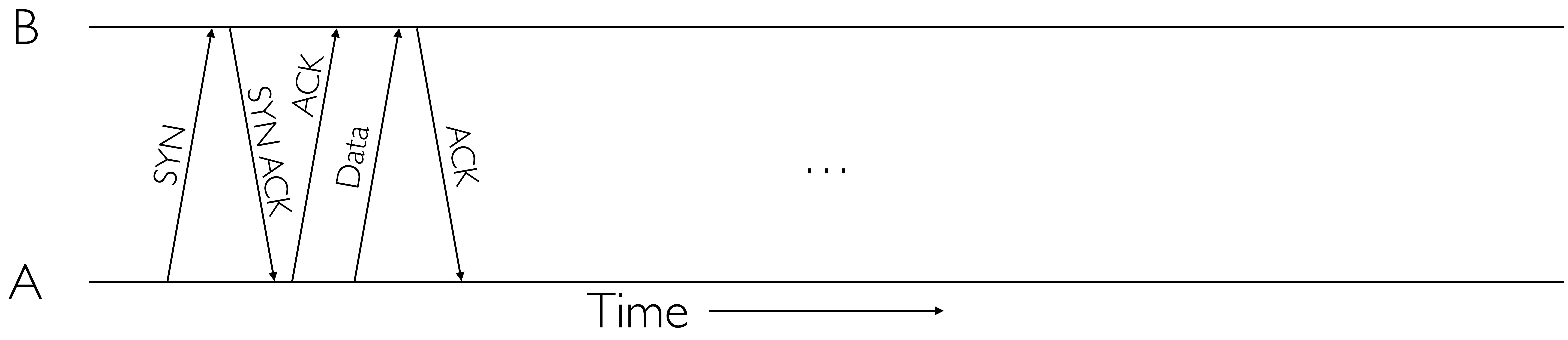
- **You inadvertently trigger an "abort" of the "connect"**
  - Browser creates a *new* socket and does another "connect"
  - Essentially, forces a faster send of a new SYN packet!
  - Sometimes very effective, and the page loads quickly

Tearing Down the Connection

Normal Termination, One Side At a Time



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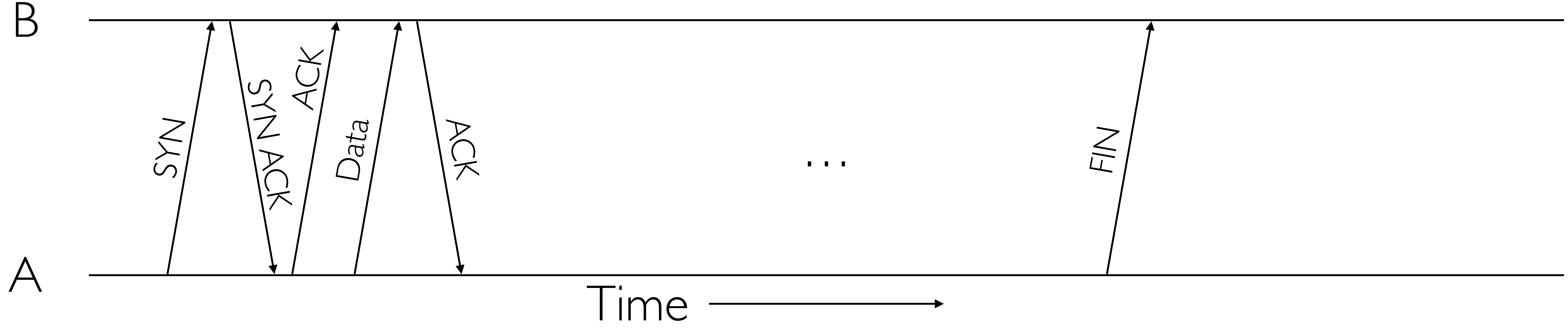

- Finish (**FIN**) to close and receive remaining bytes
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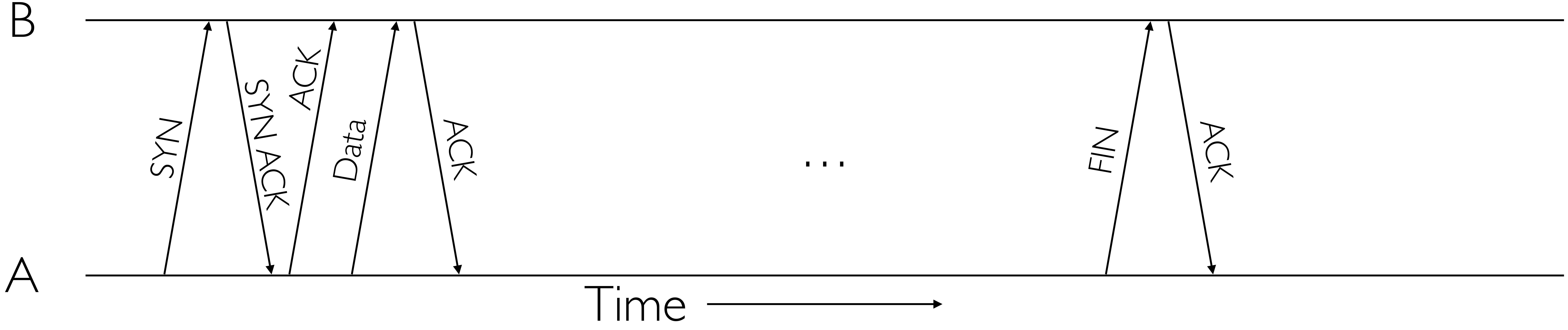

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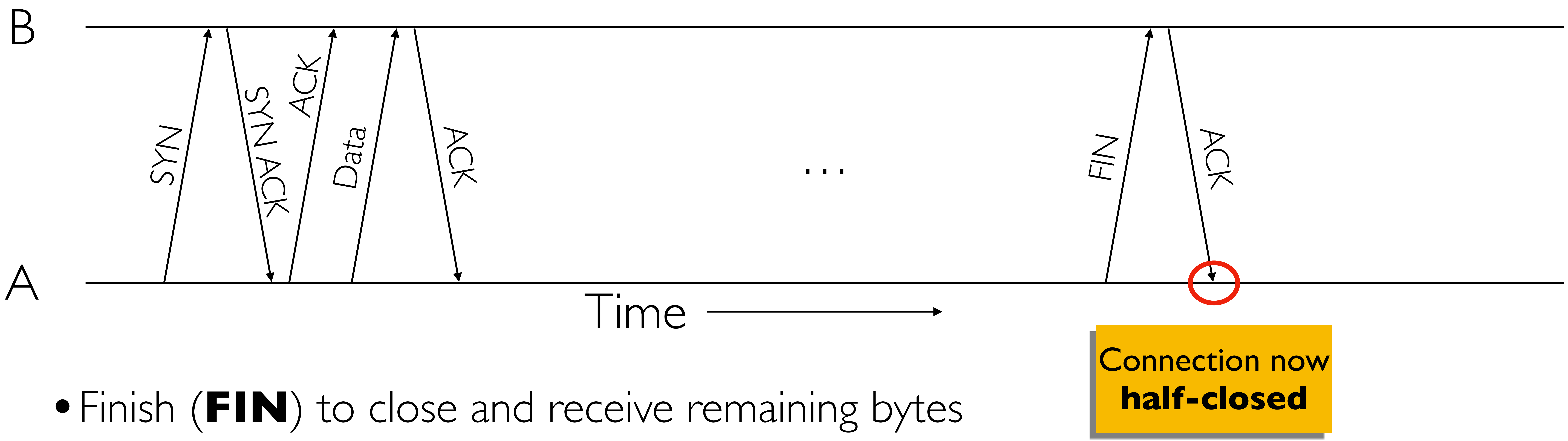

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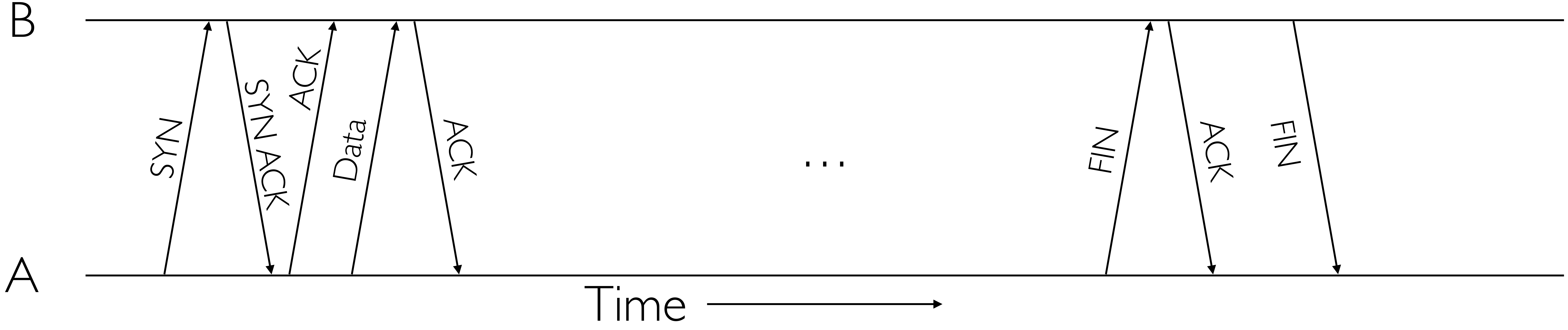

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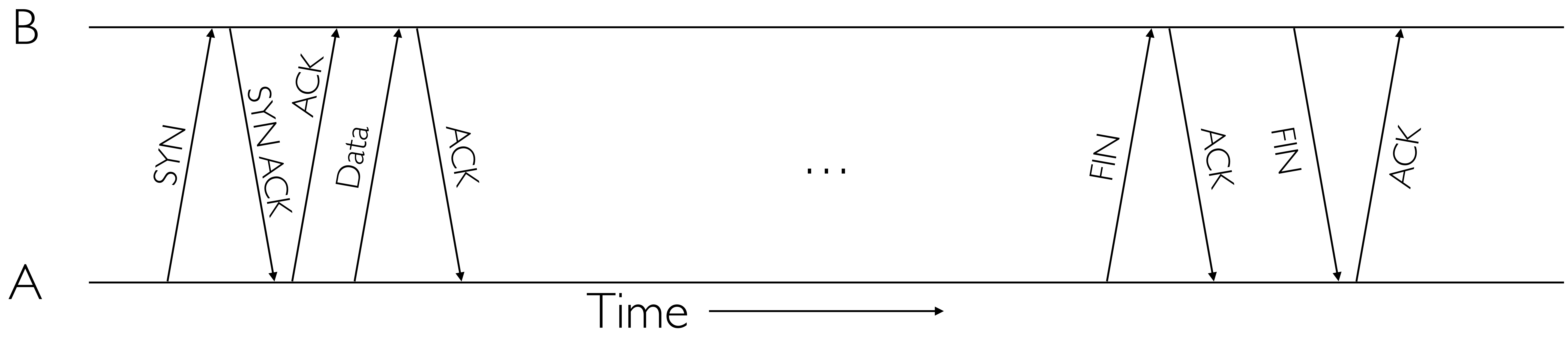

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  - Which A then ACKs

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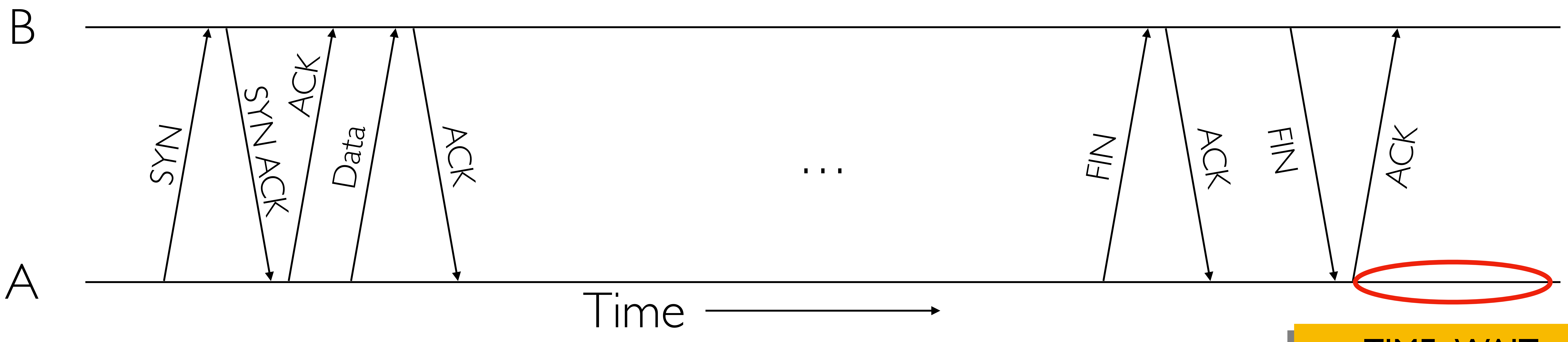

TIME_WAIT:
Avoid reincarnation;
B will retransmit FIN if
ACK is lost

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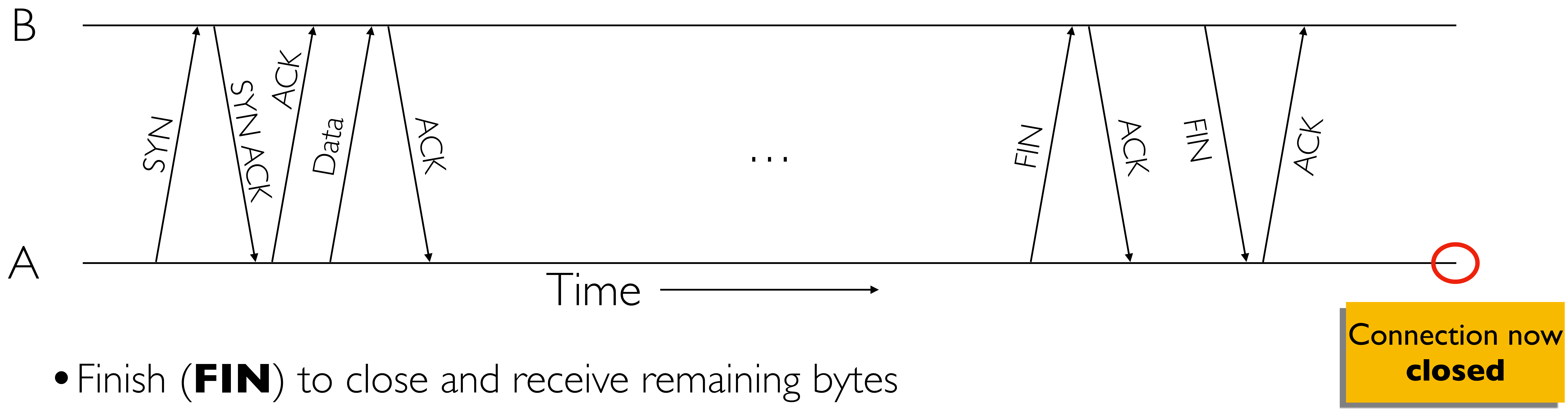

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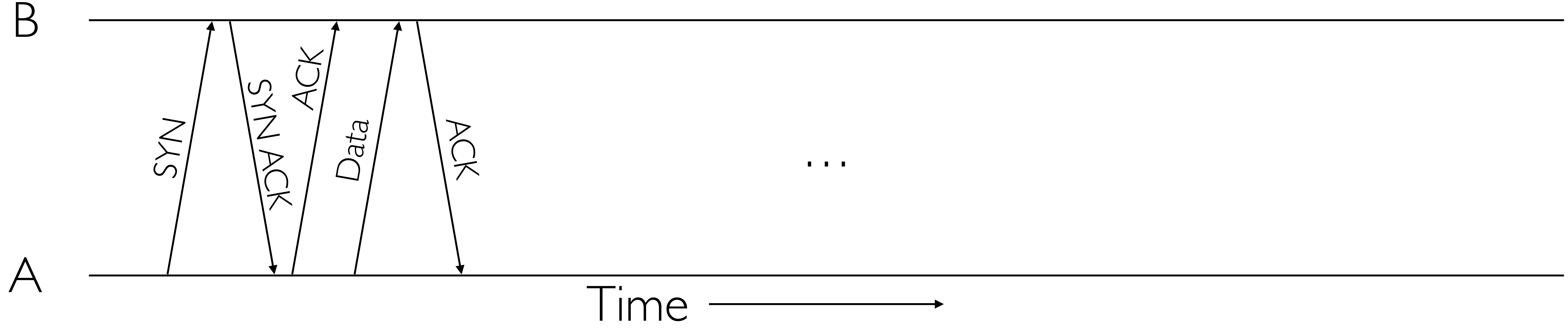

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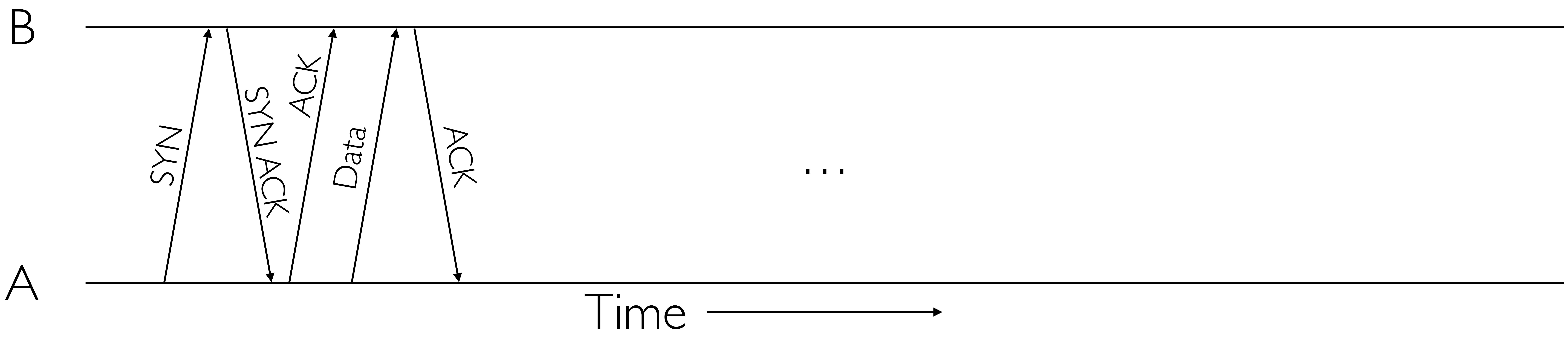

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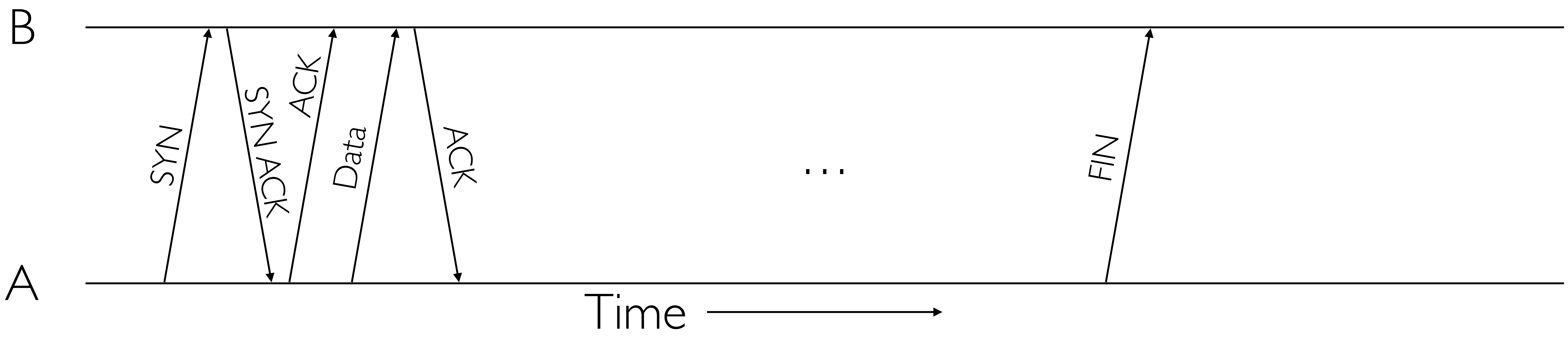

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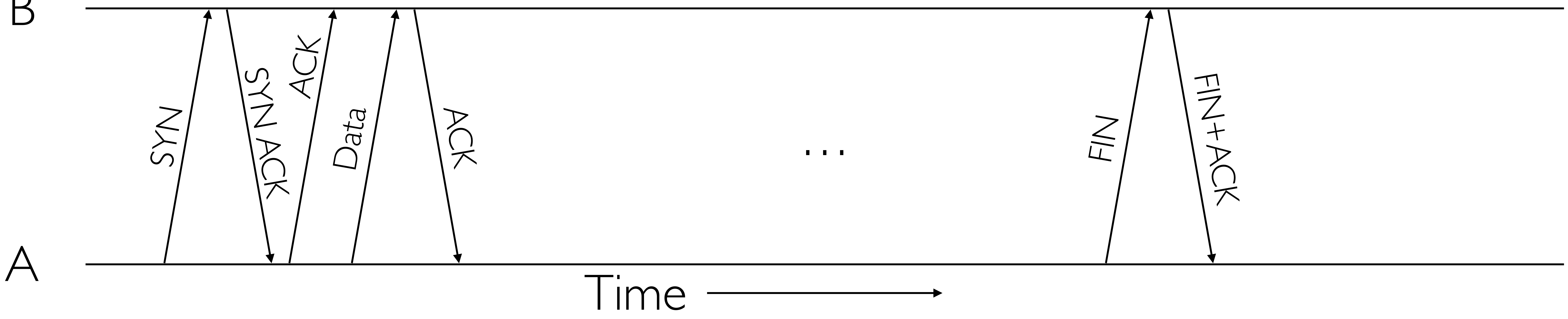

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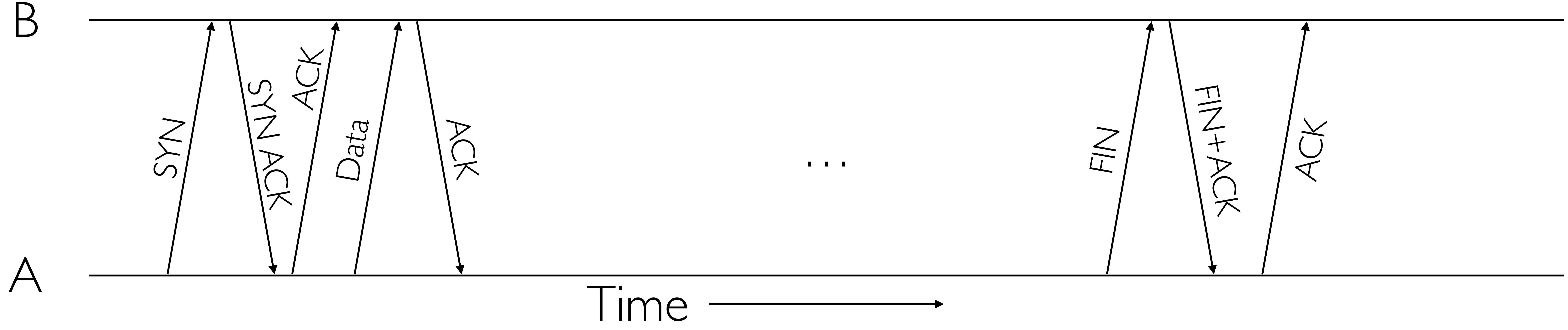

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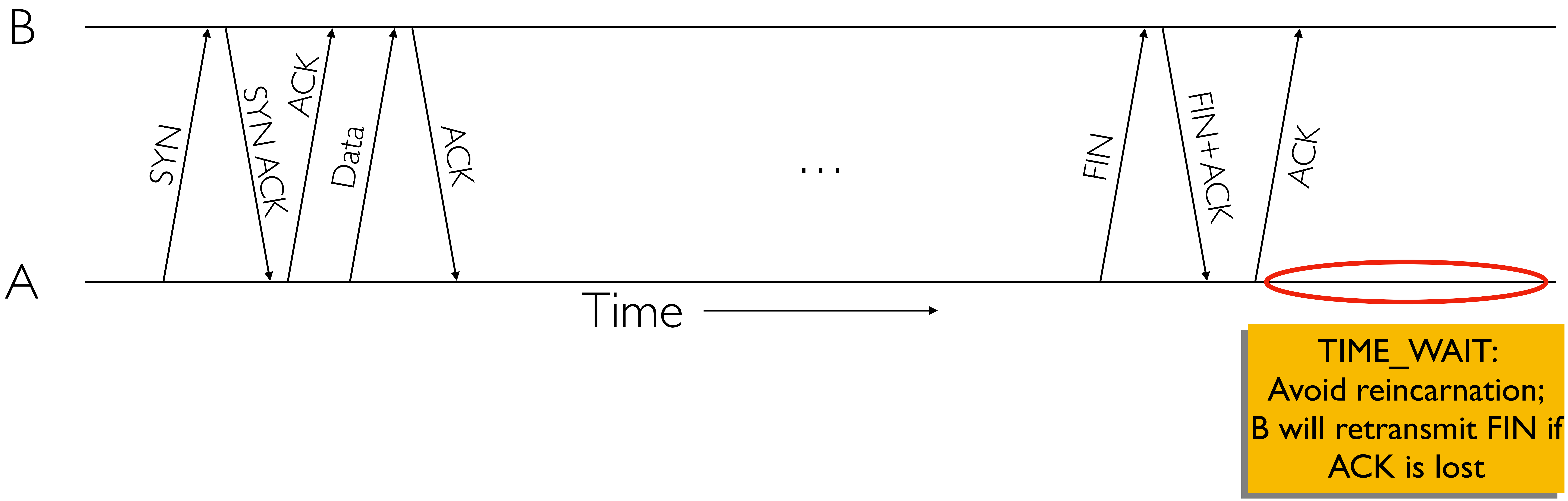

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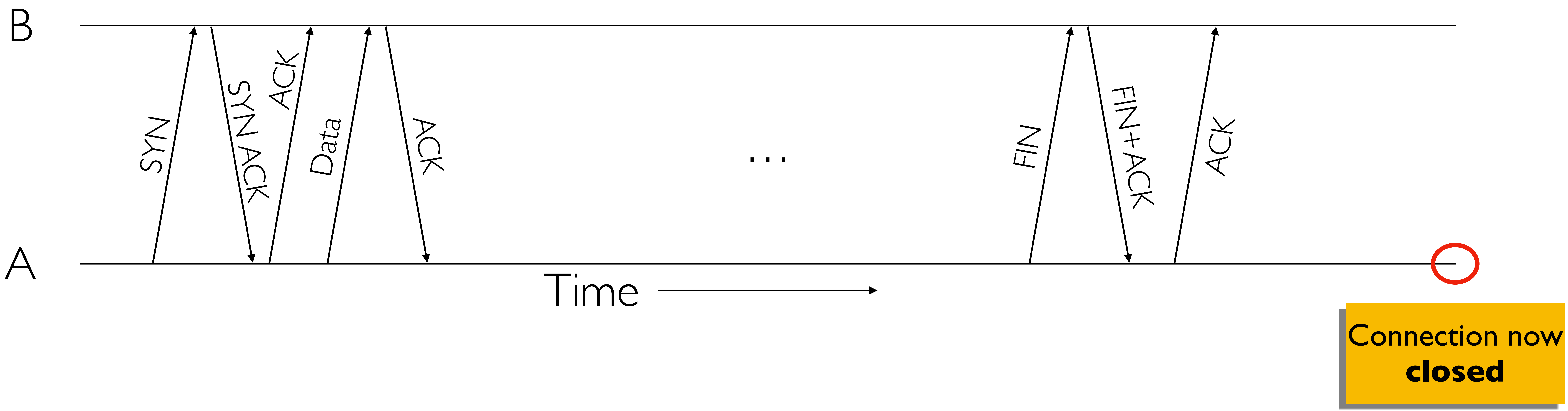

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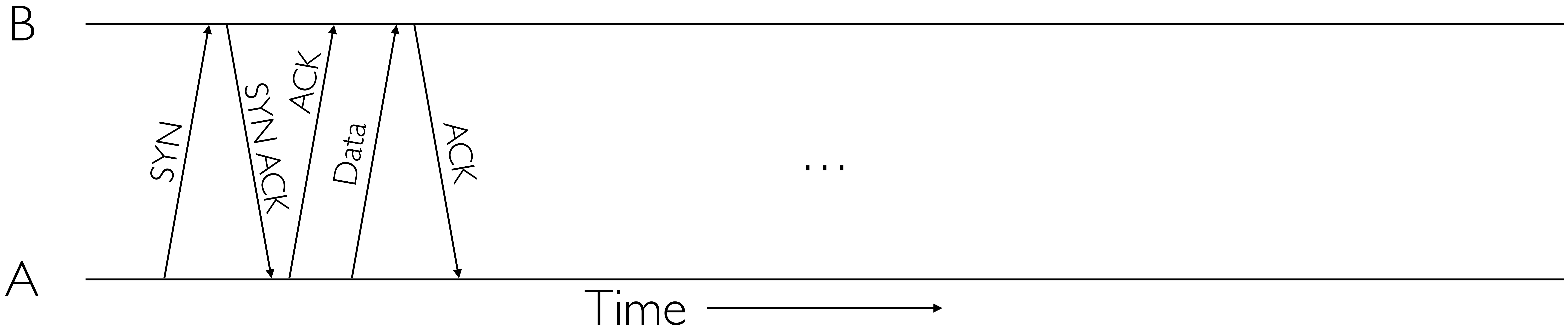

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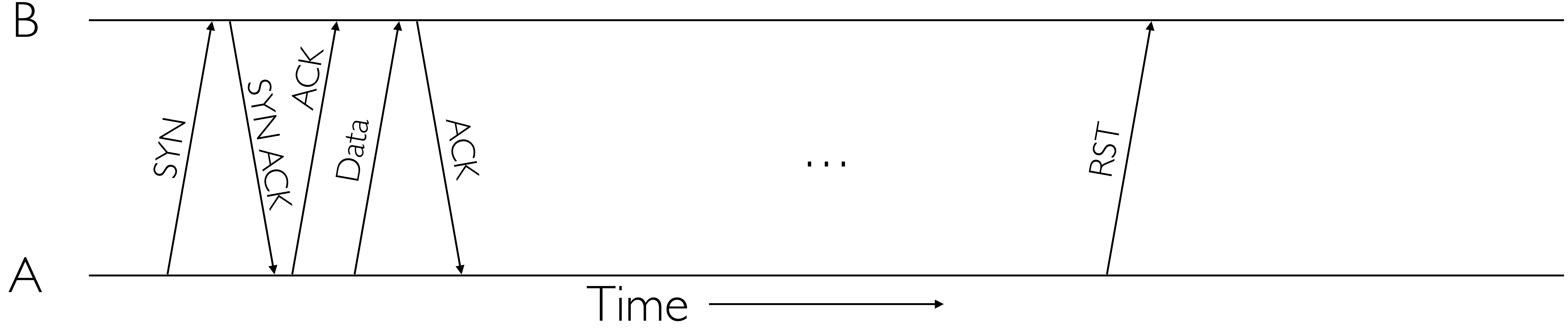

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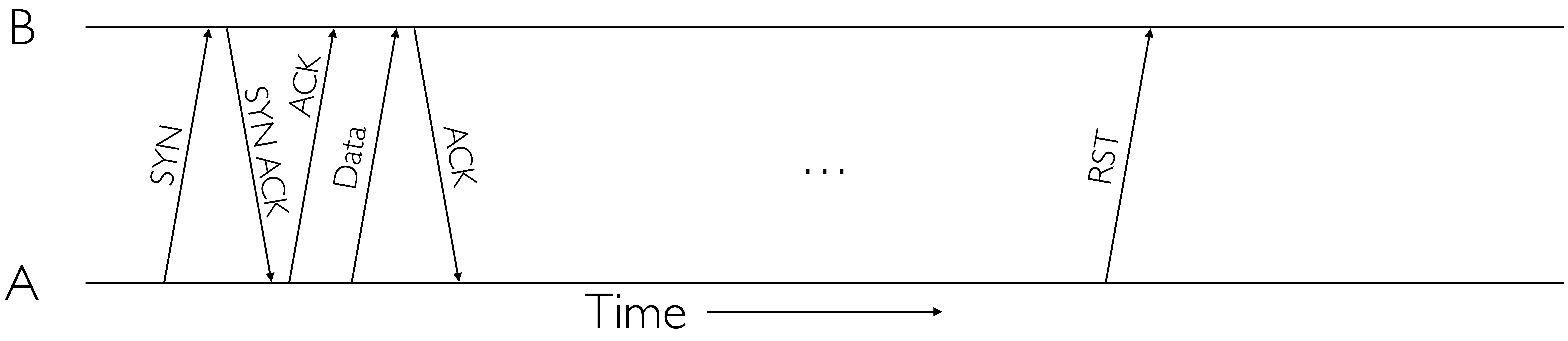

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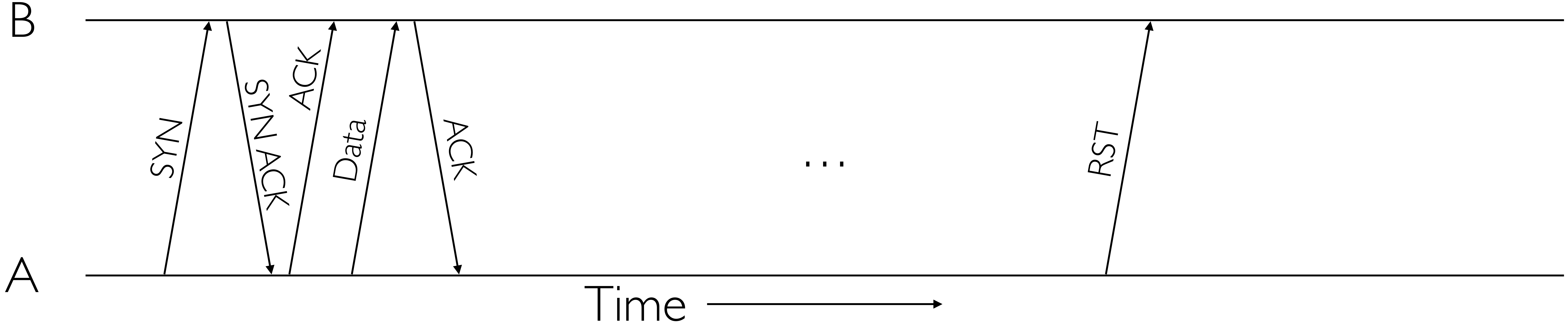

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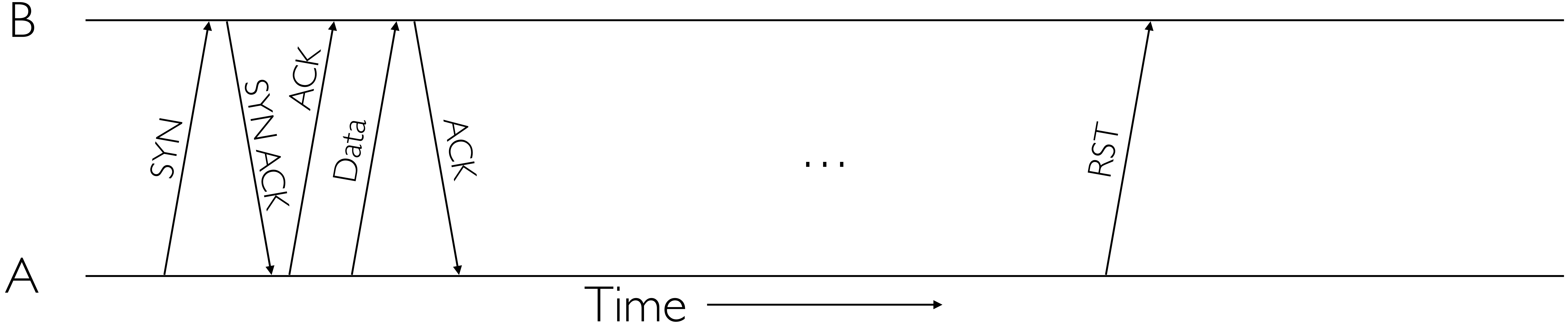

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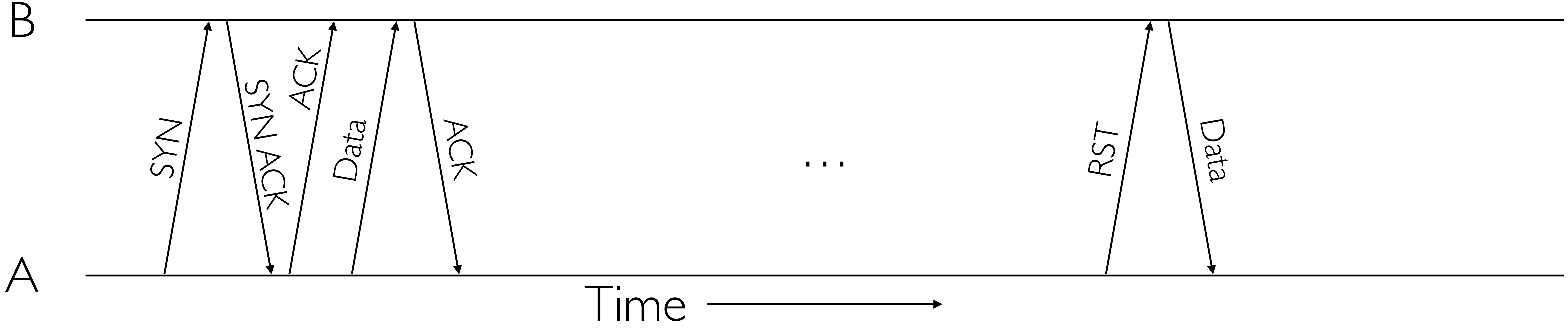

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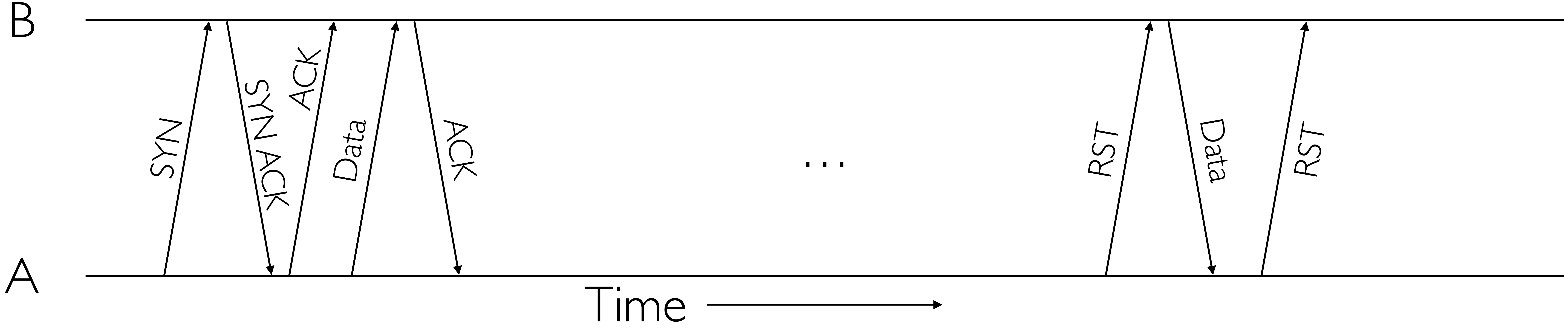

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TCP Header

SYN
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RST
PSH
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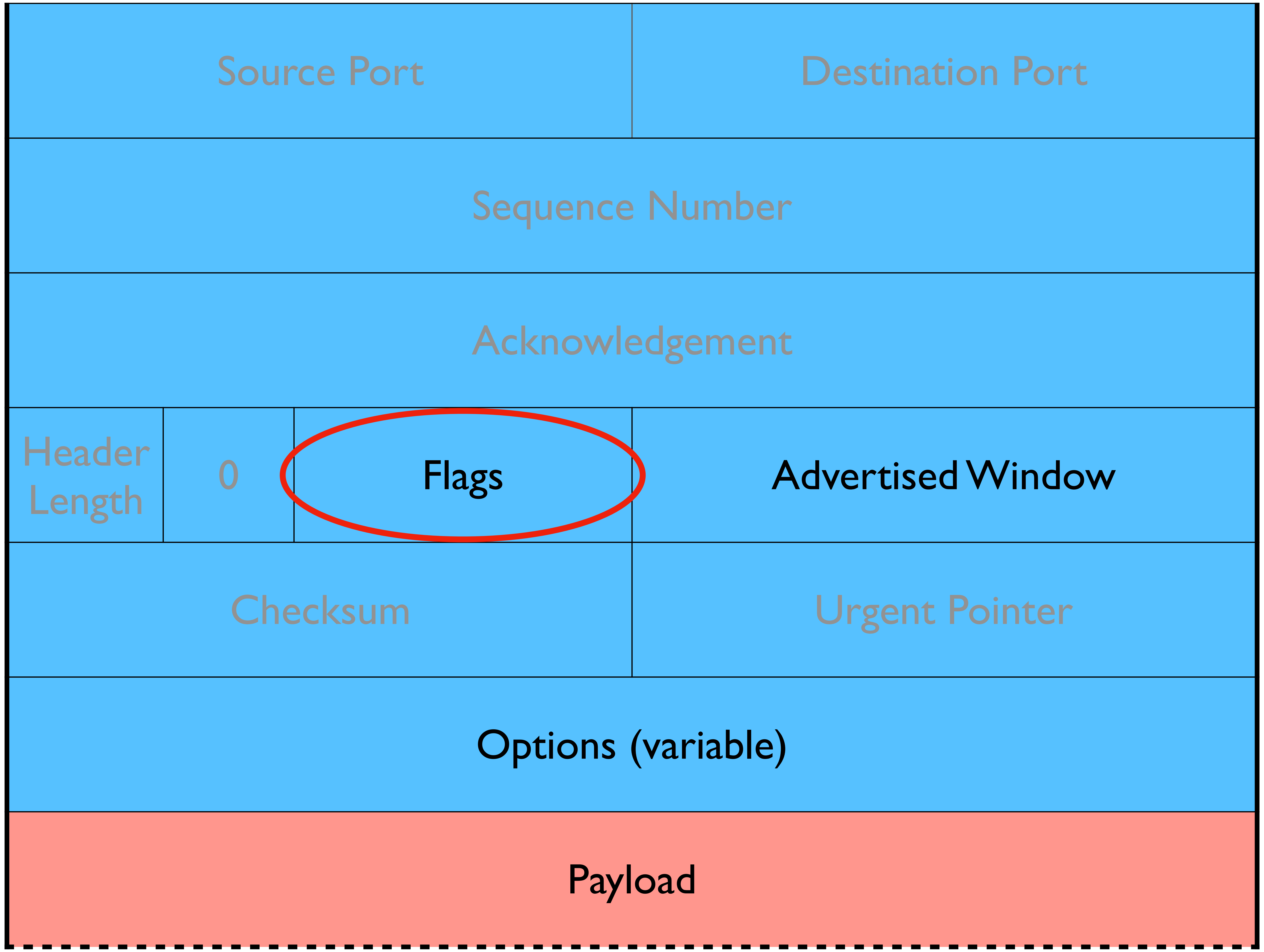
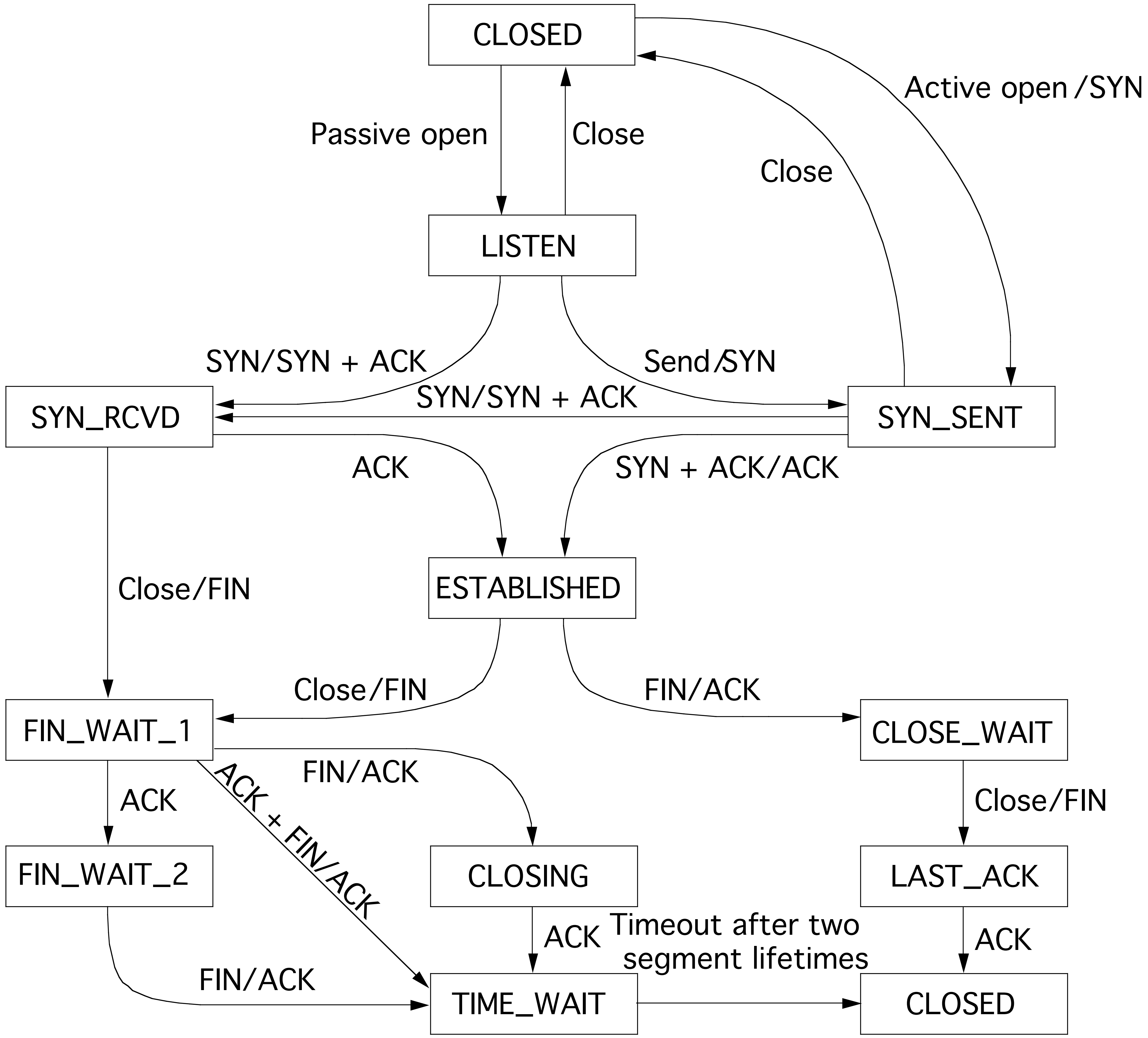


TCP State Transitions



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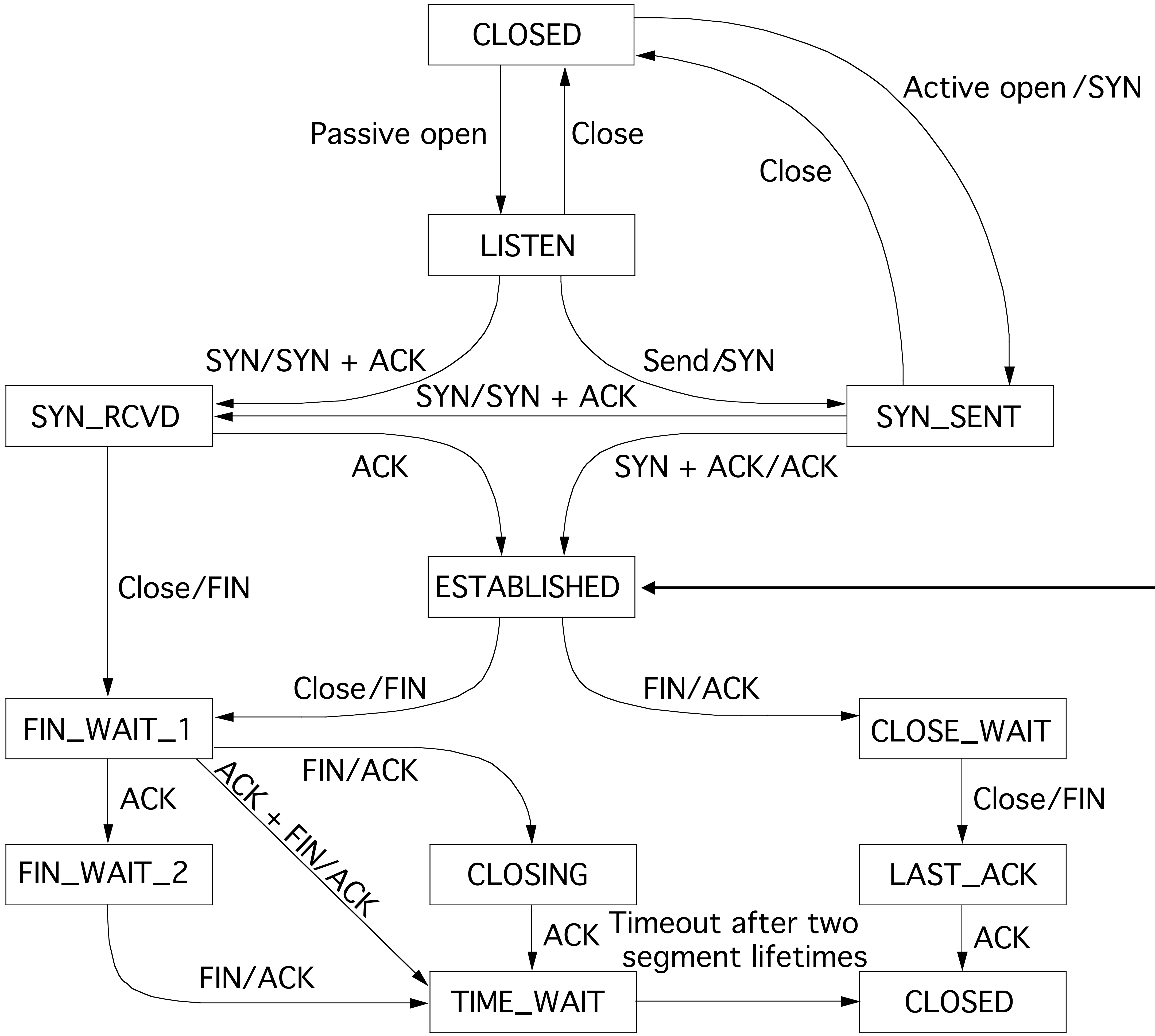
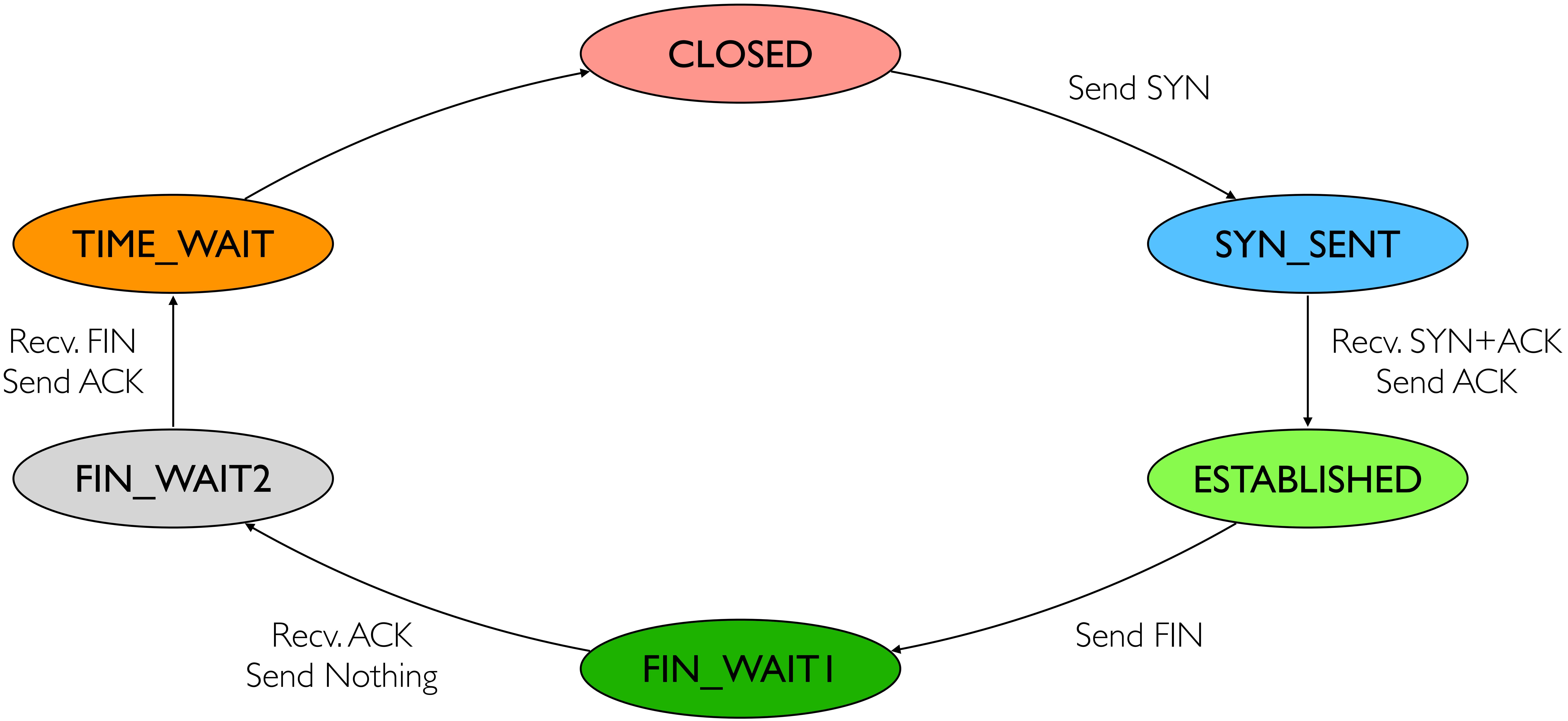


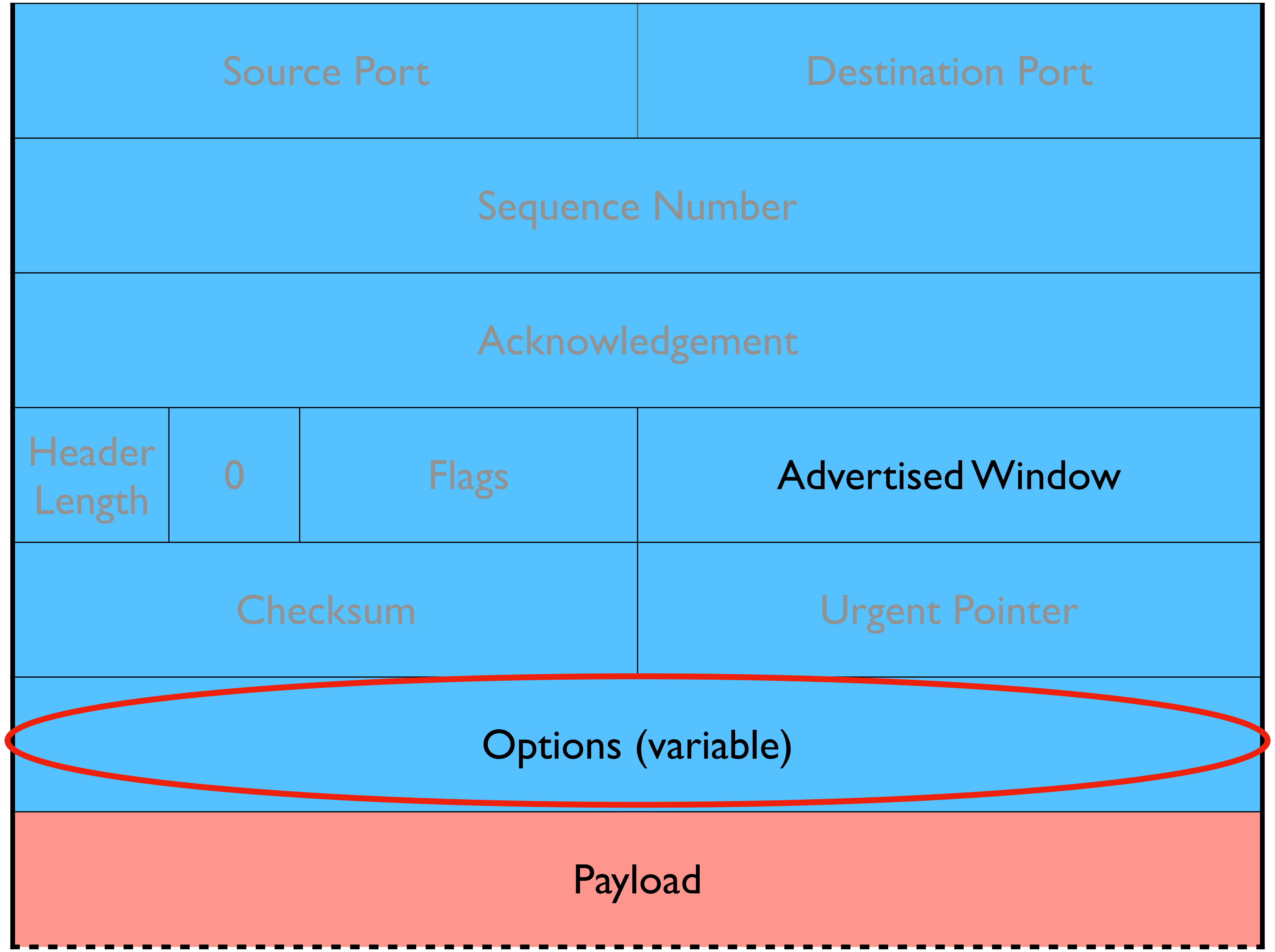
Data, ACK exchanges are in here

A Simpler View on the Client Side



TCP Header

Used to negotiate use of additional features



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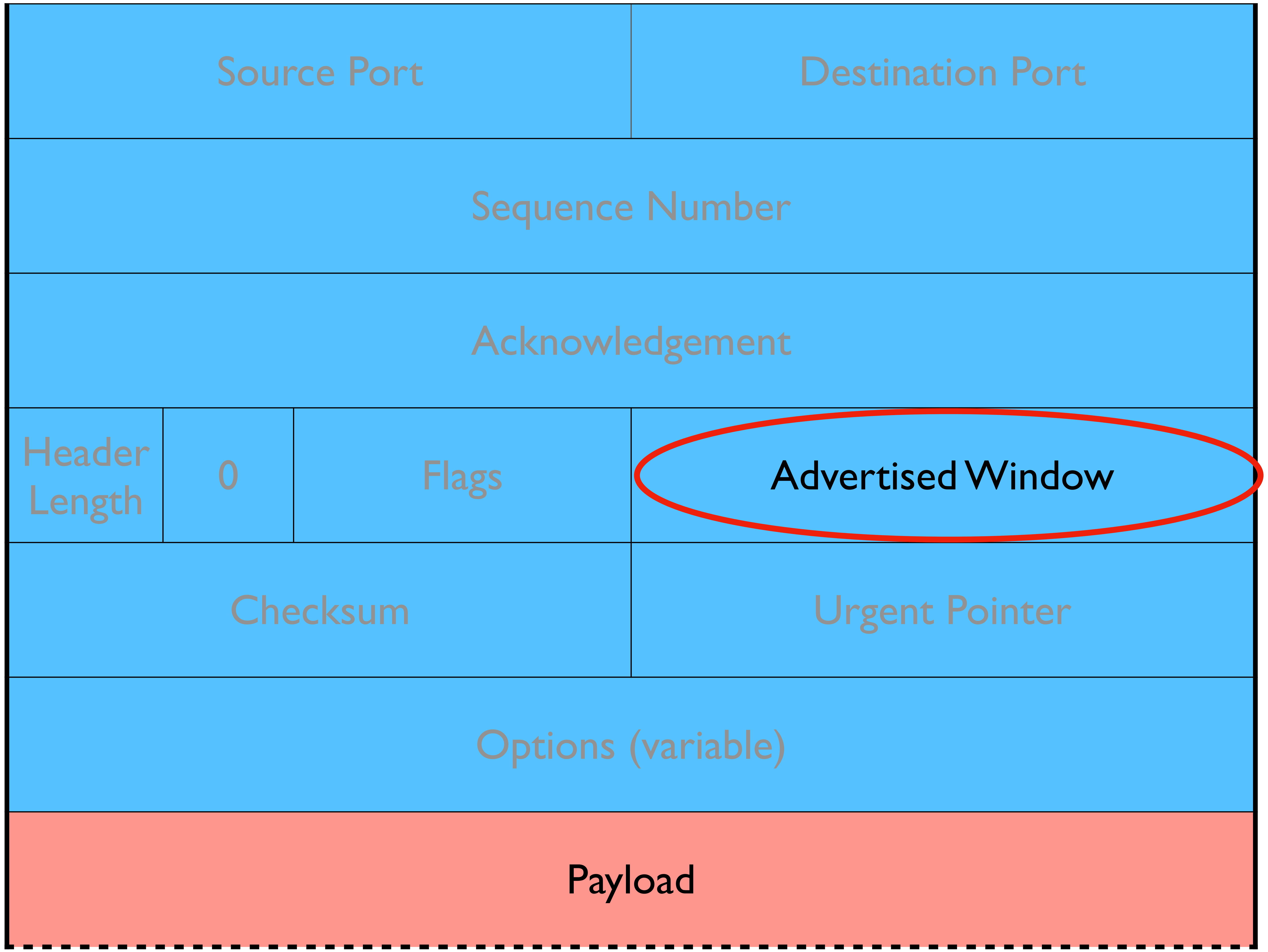
Source Port
Destination Port
Sequence Number
Acknowledgement
Header Length
0
Flags
Advertised Window
Checksum
Urgent Pointer
Options (variable)
Payload

Last Time: Sliding Window

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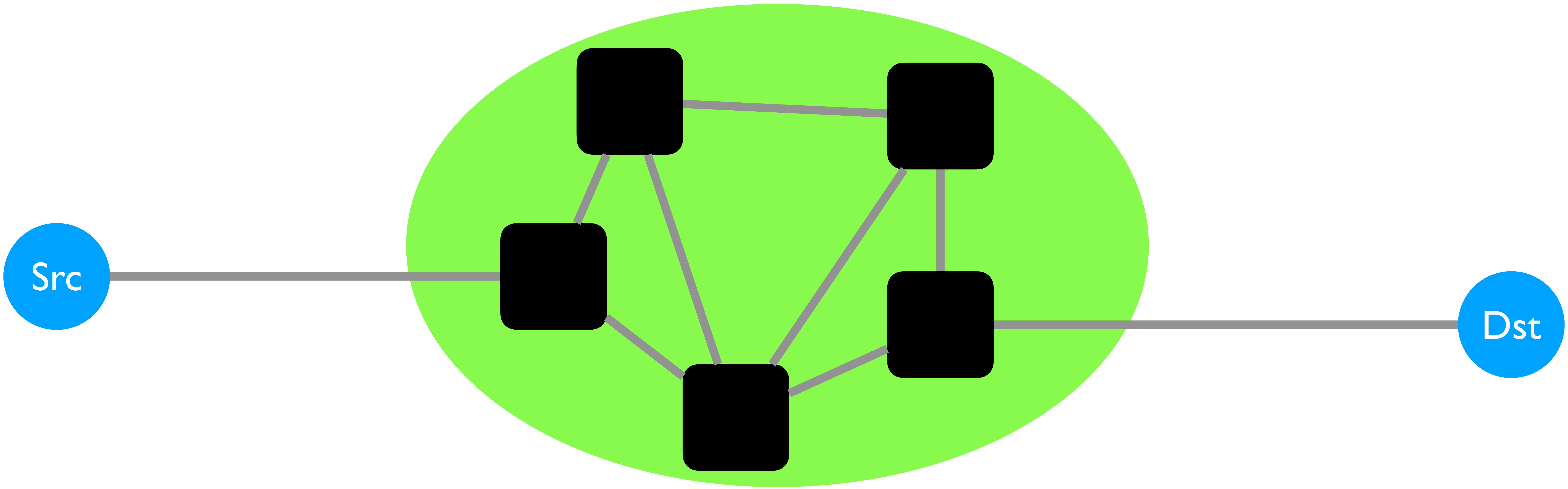
Where in the transport layer?

Only the transport layer?

Where is the buffer?



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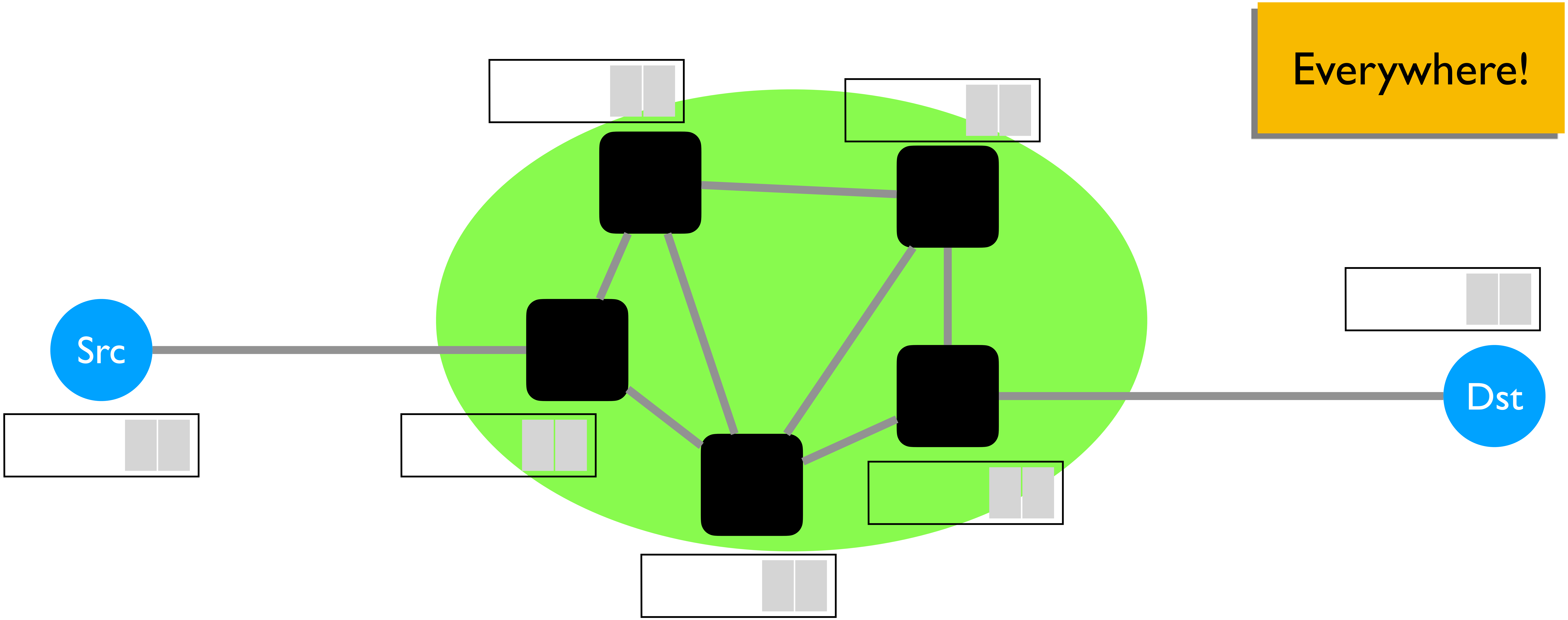

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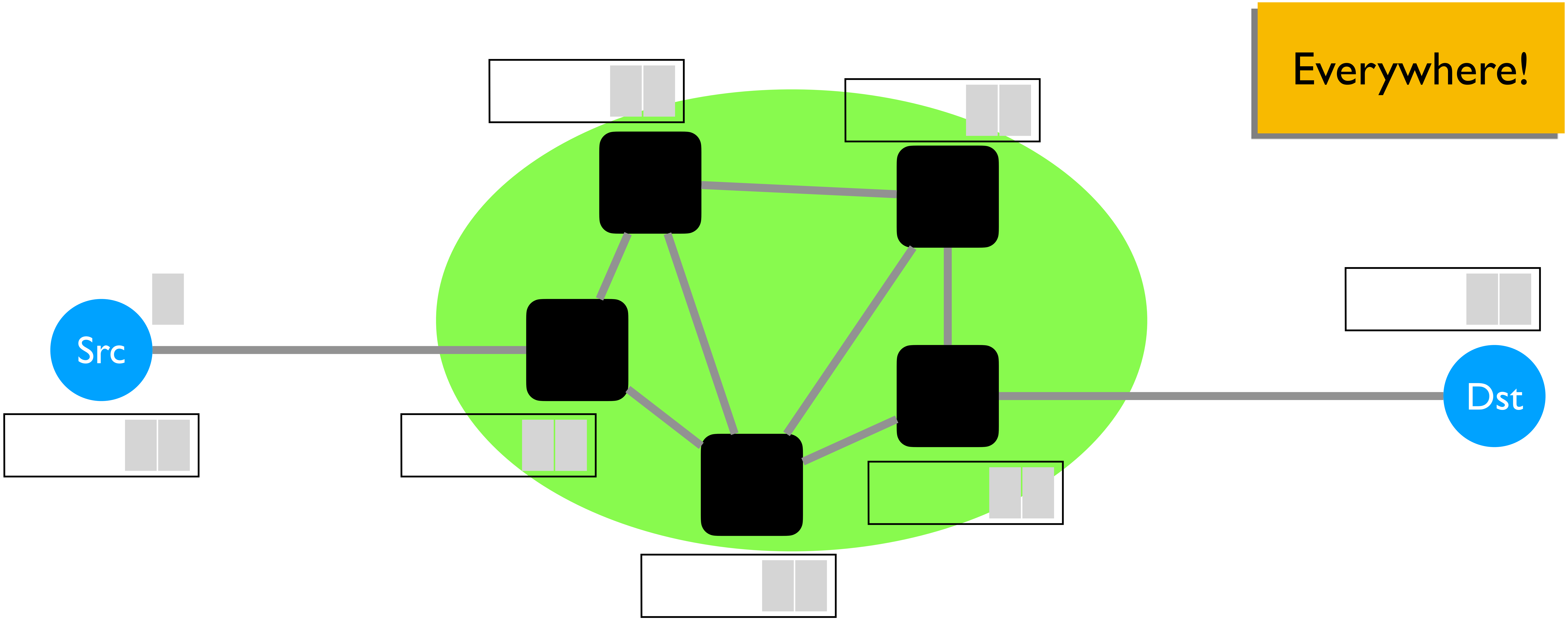

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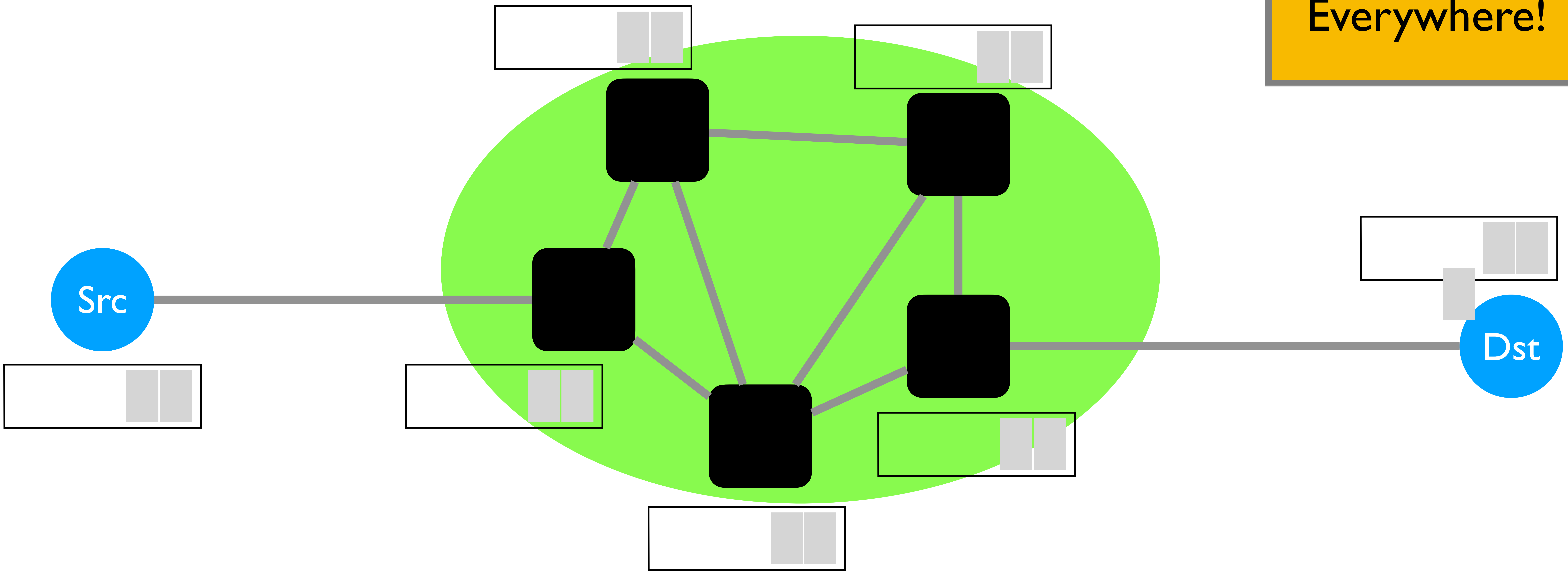

Everywhere!

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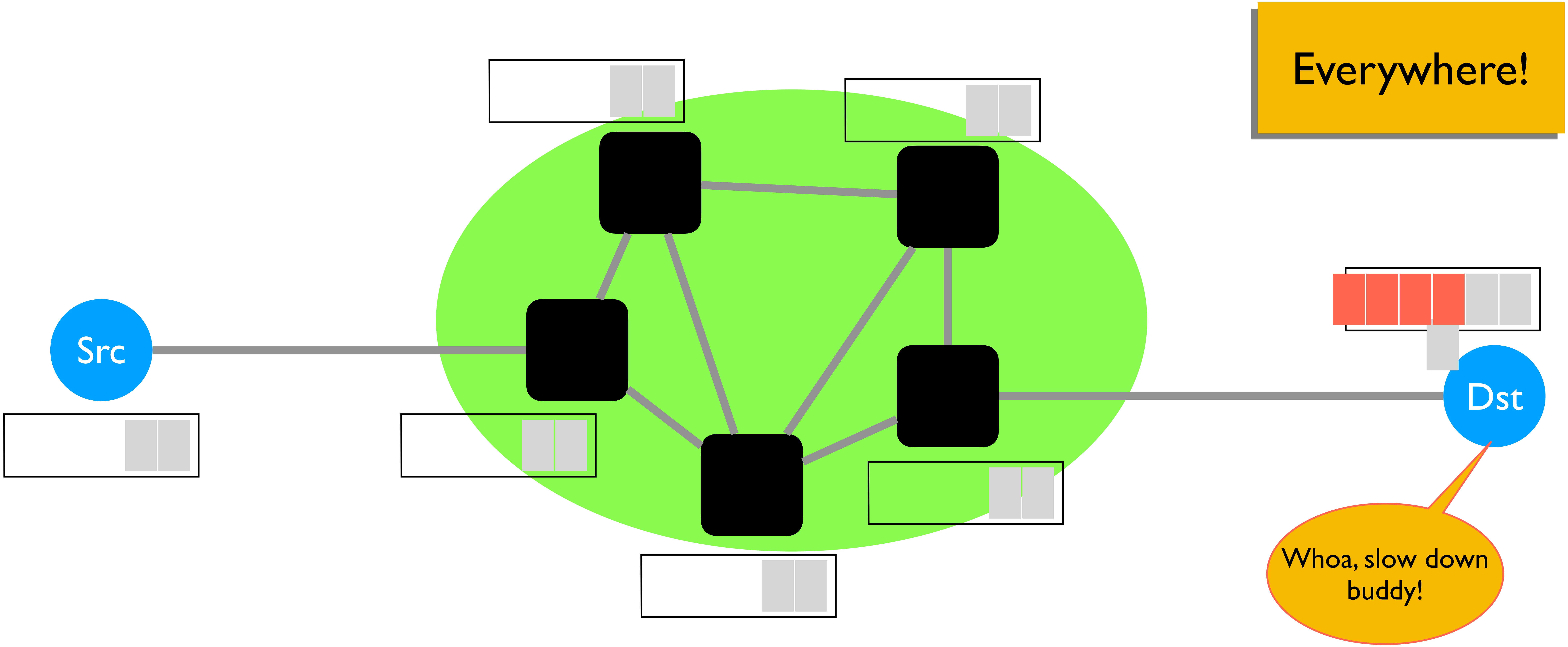

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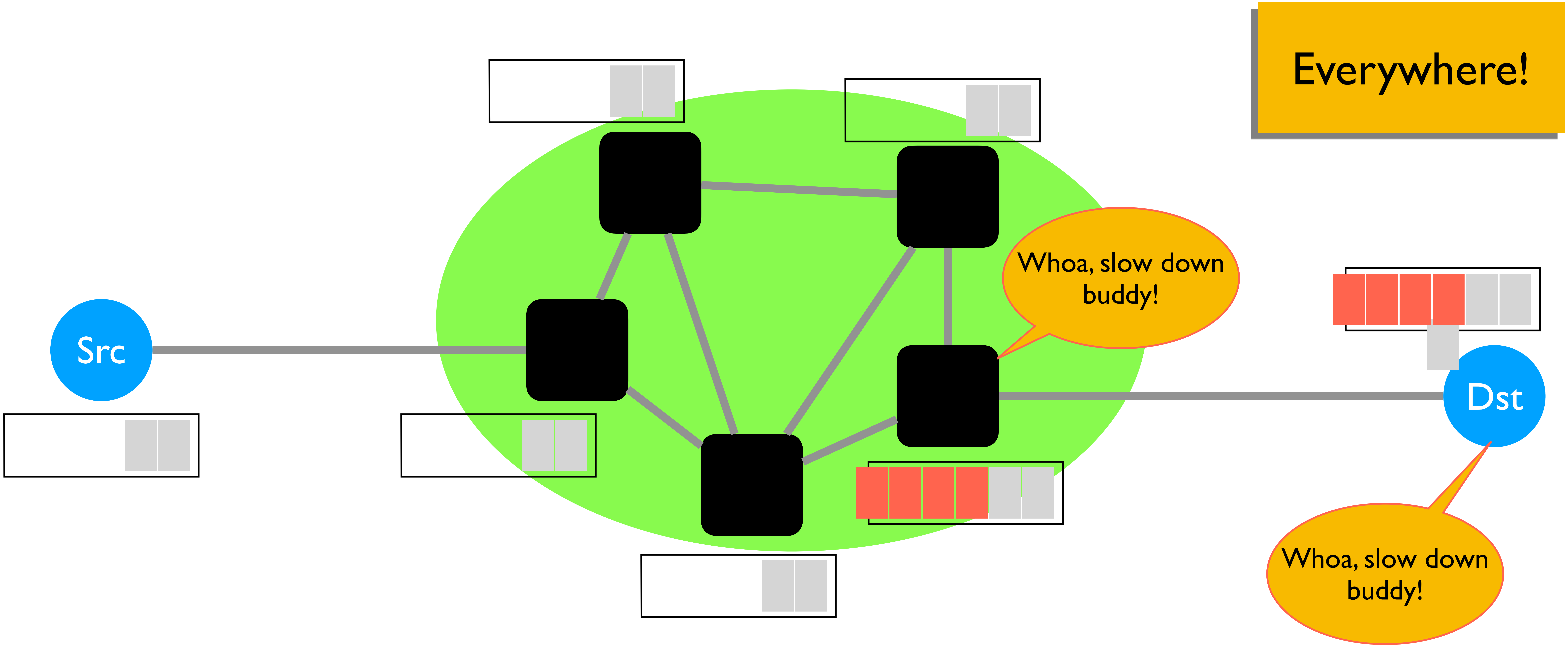
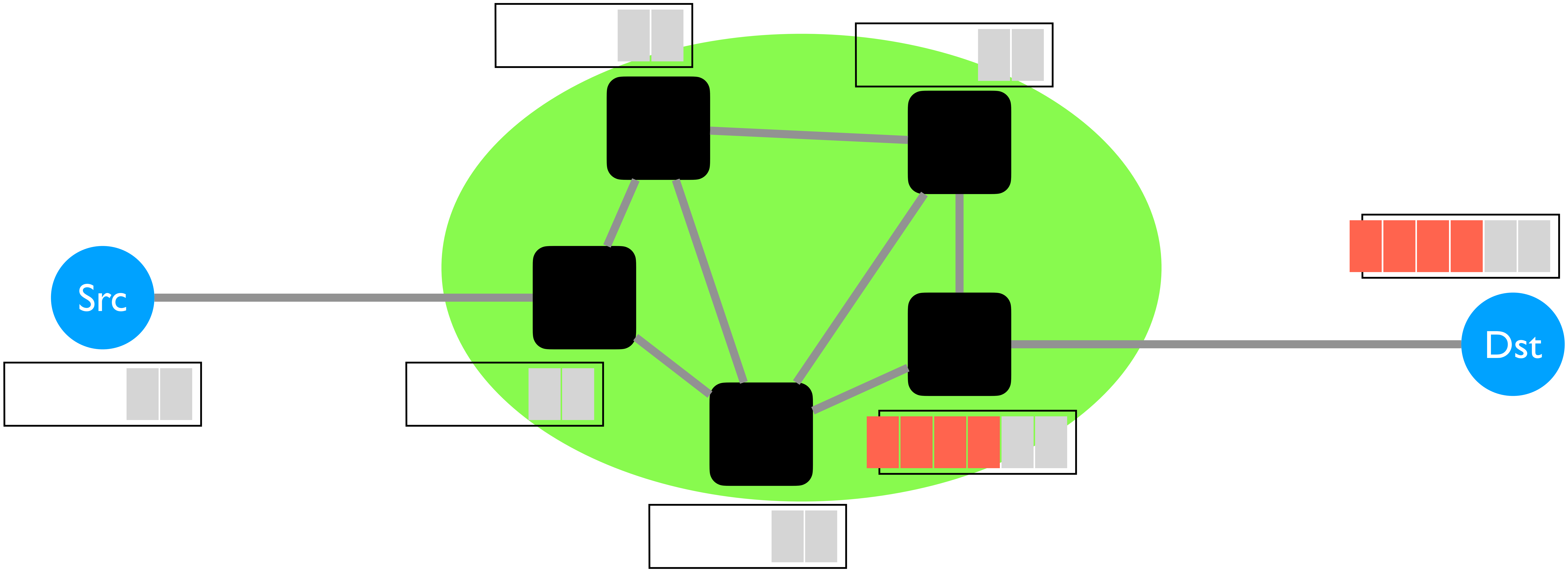


How does TCP deal with buffer limits?



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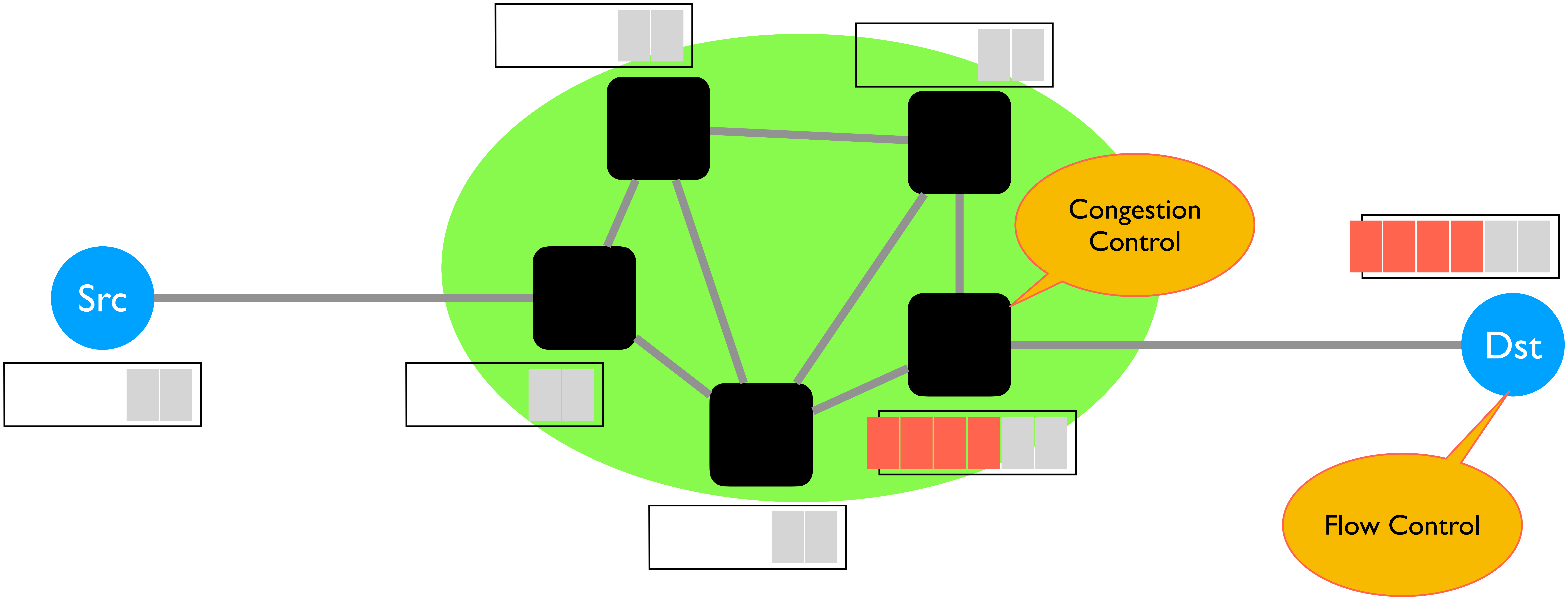

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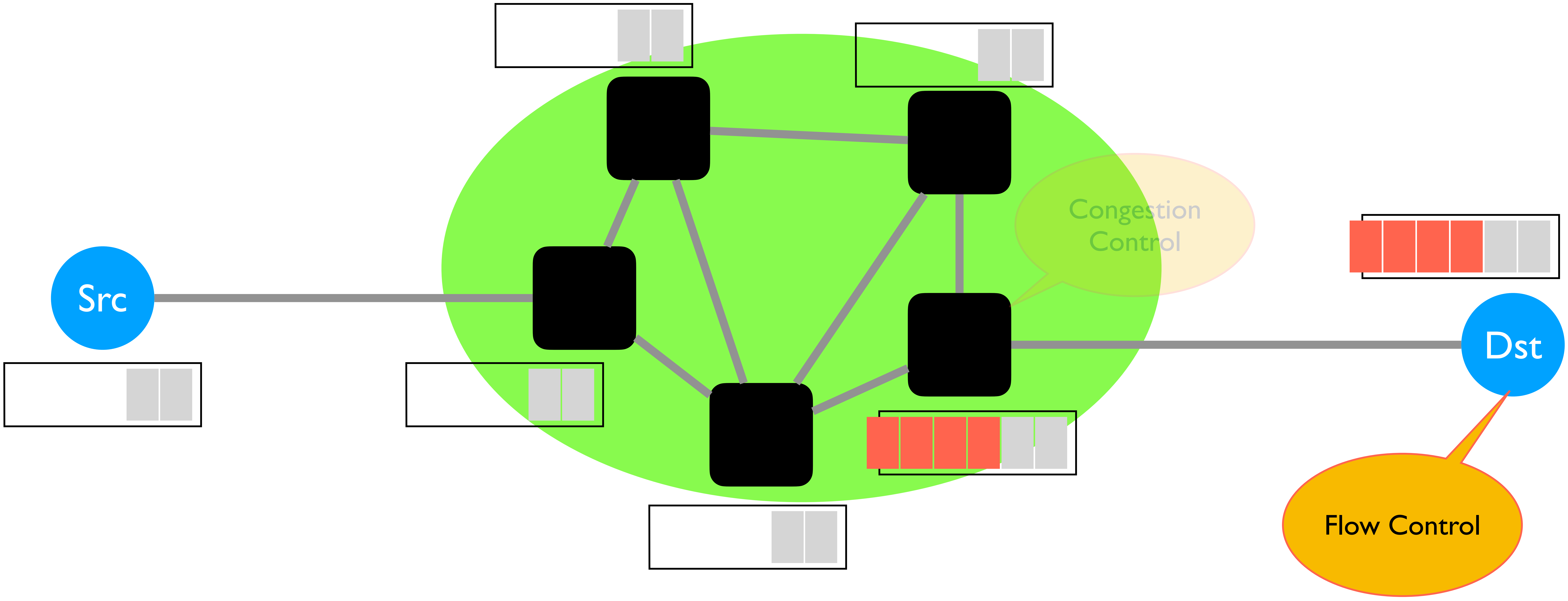
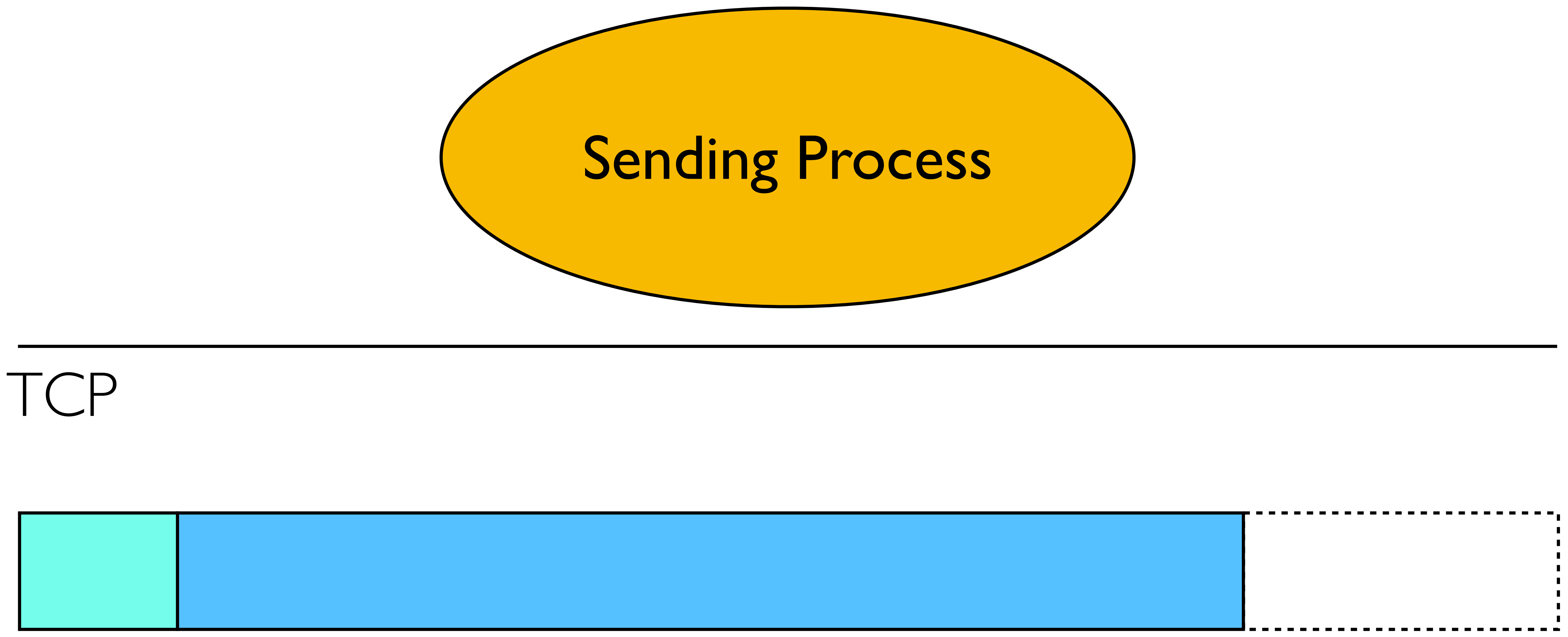


Sliding Window at Sender



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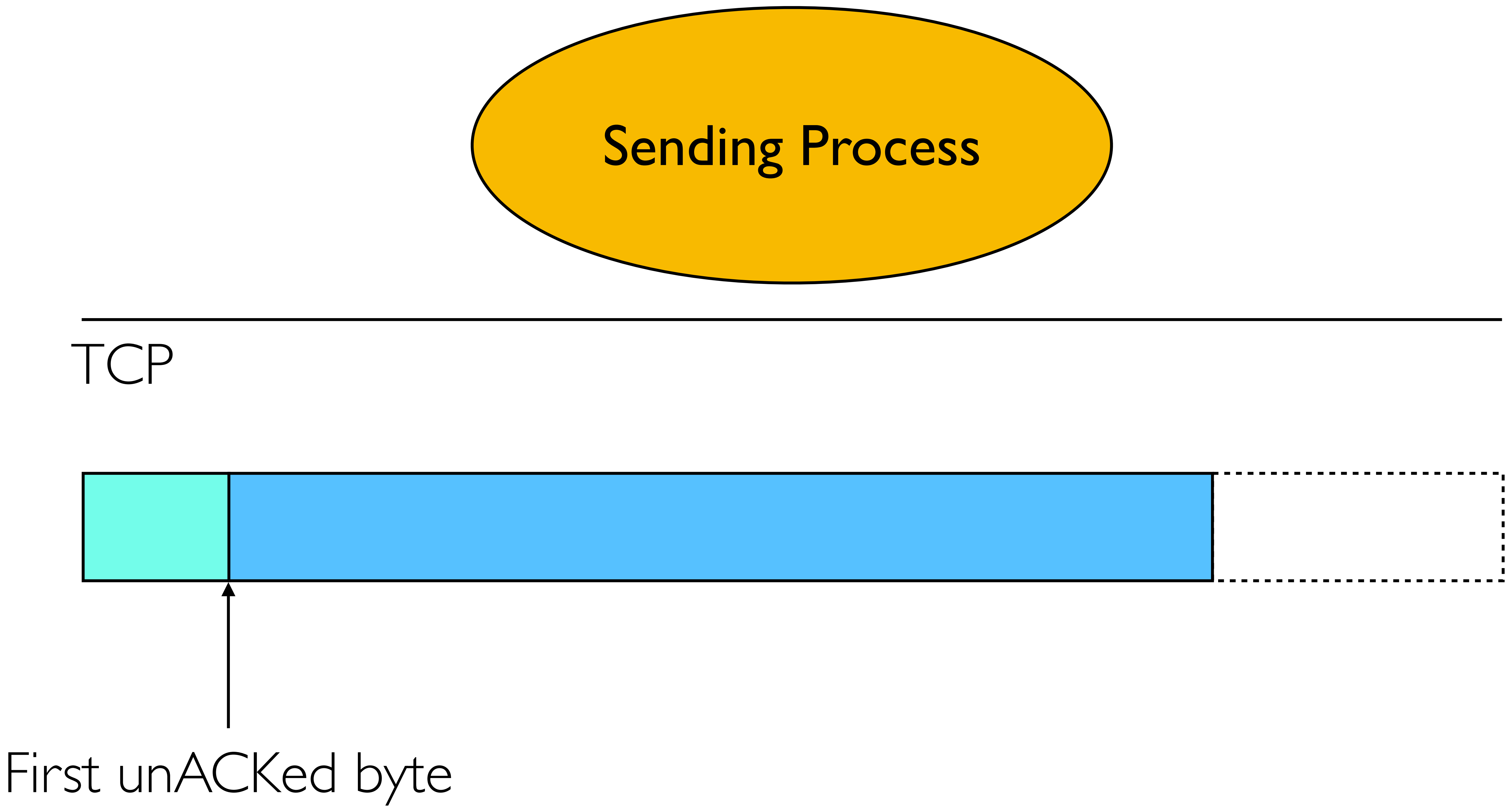

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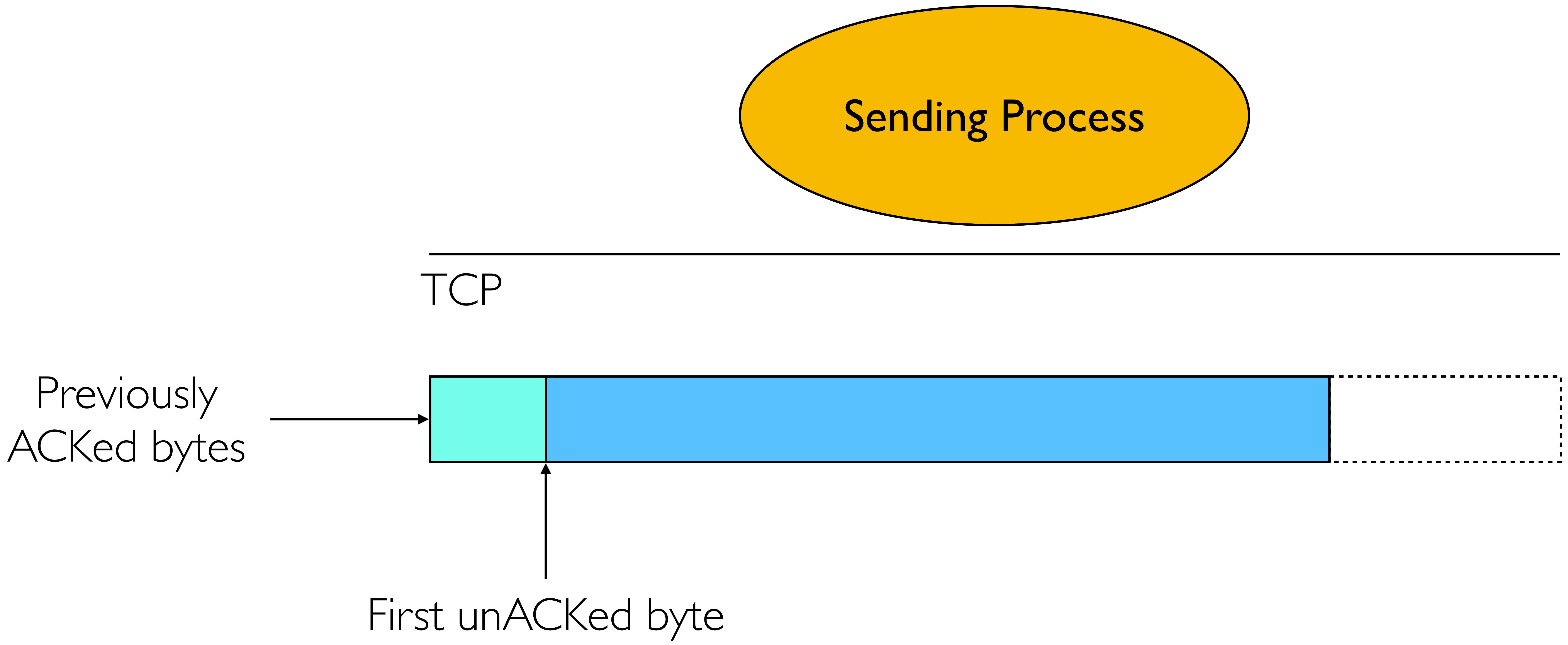
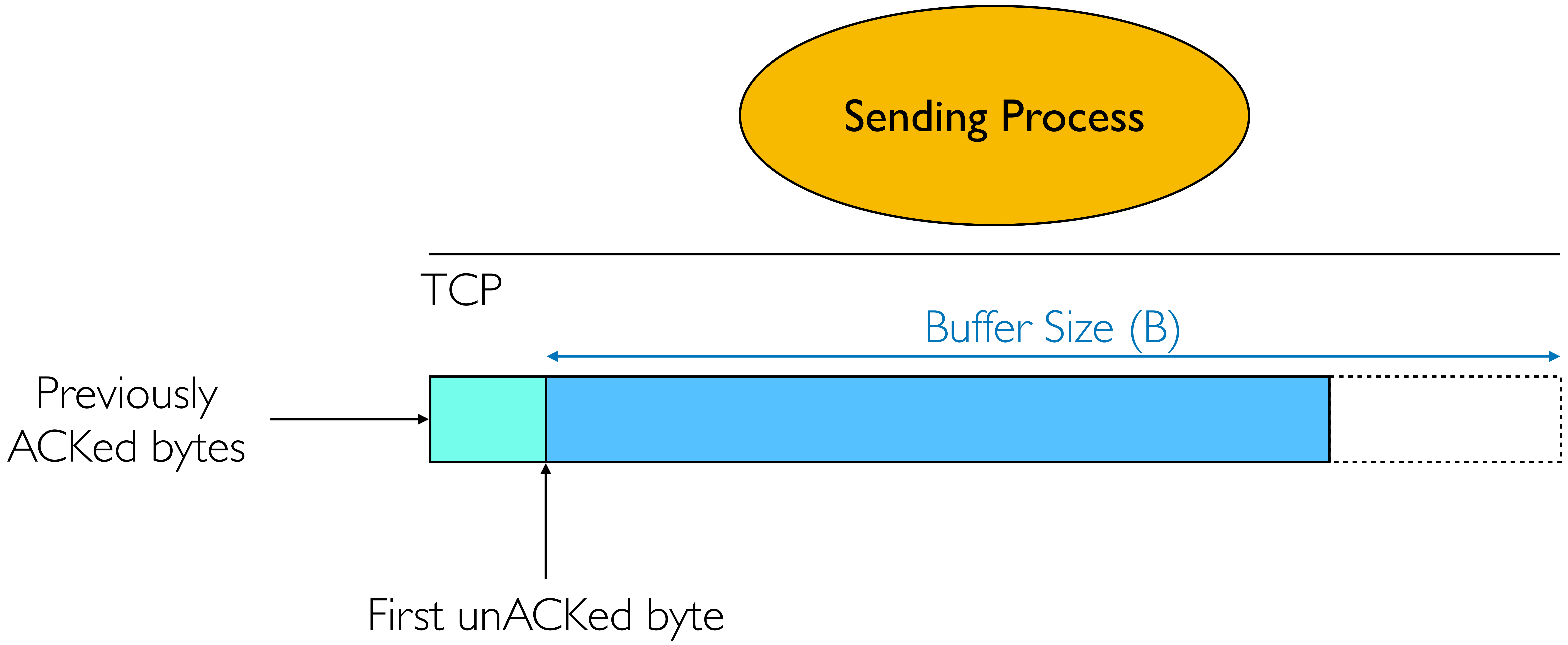
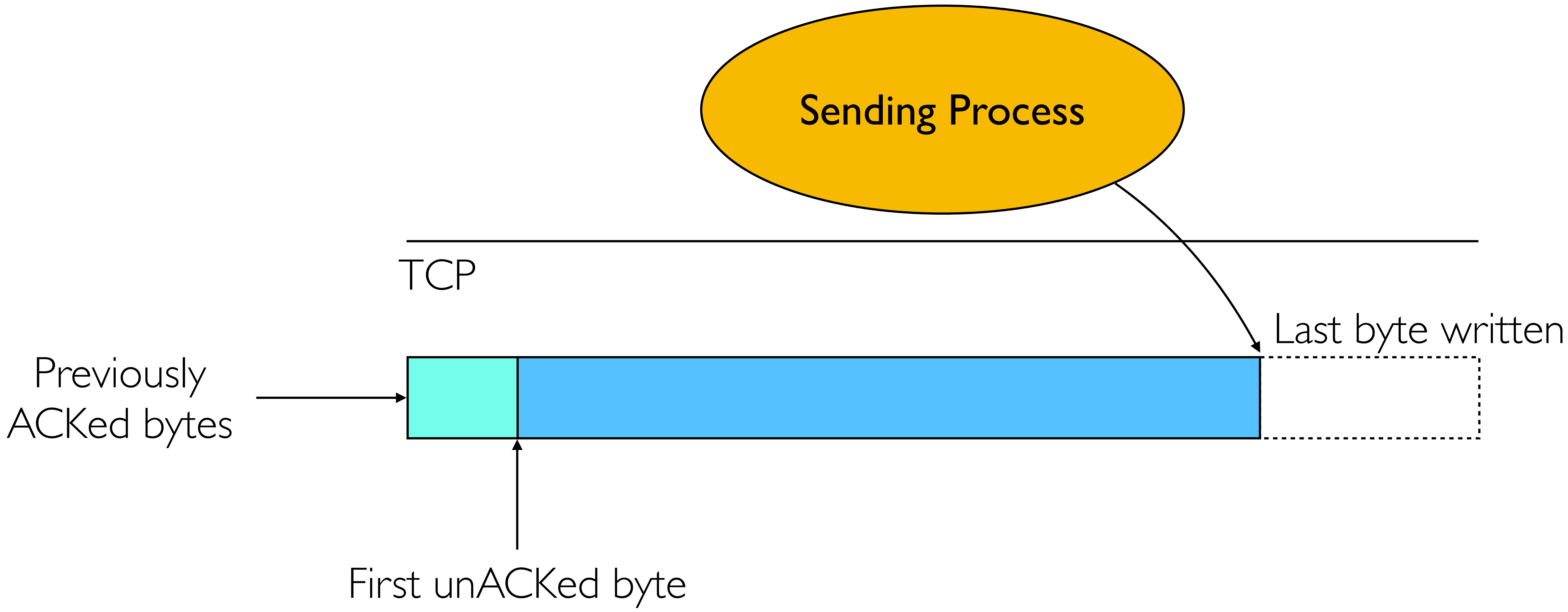


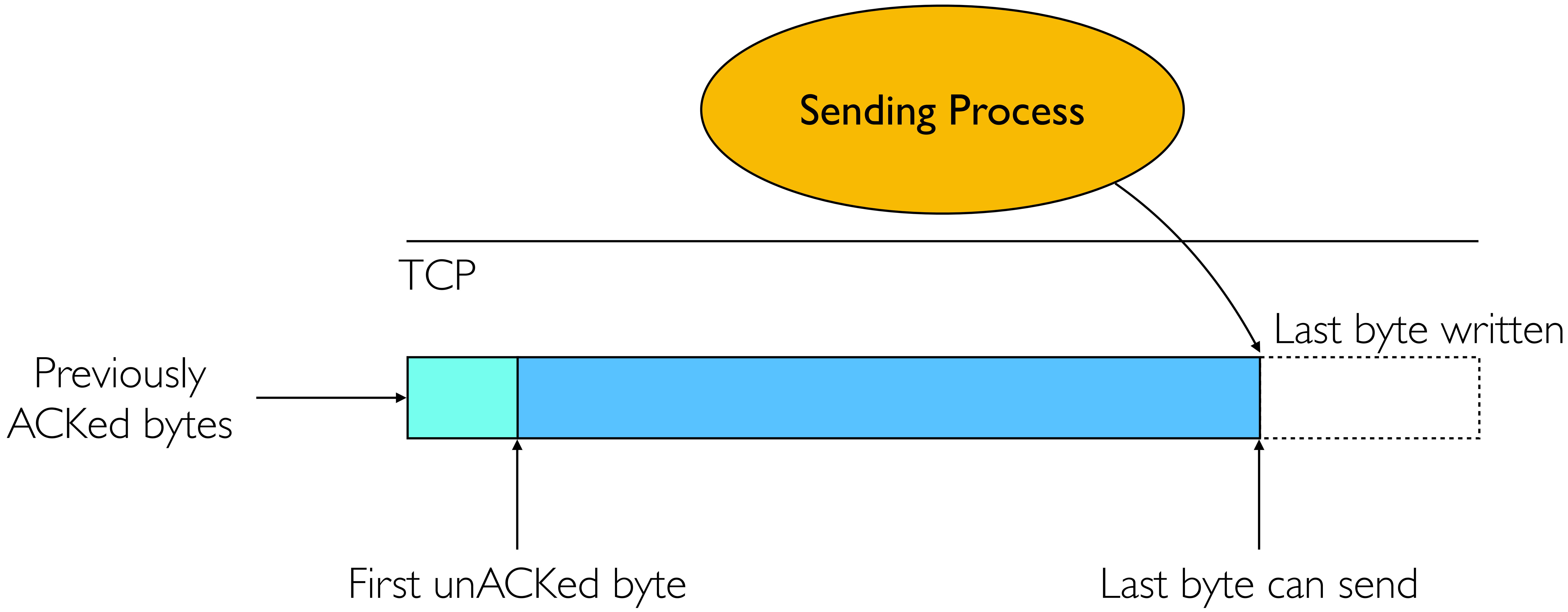
Sliding Window at Sender



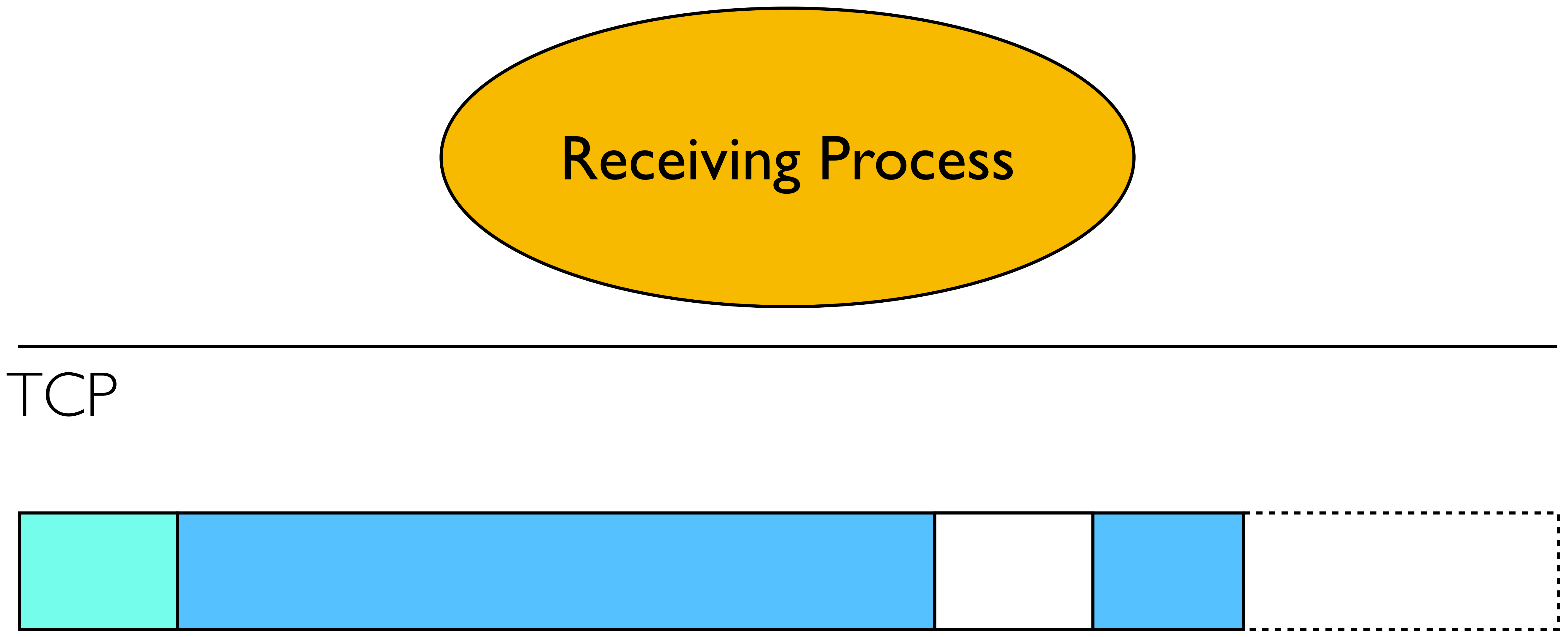
Sliding Window at Sender



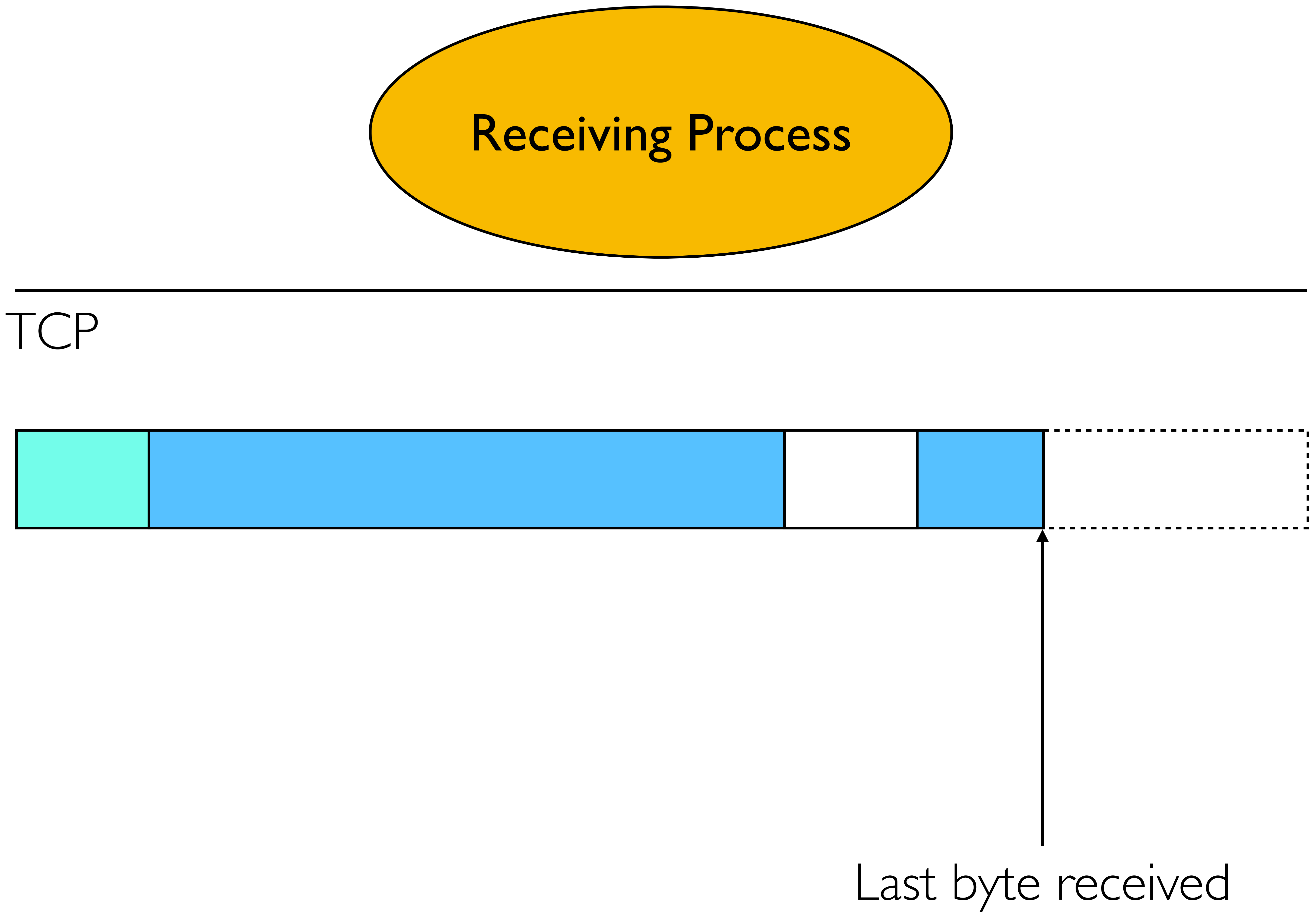
Sliding Window at Sender



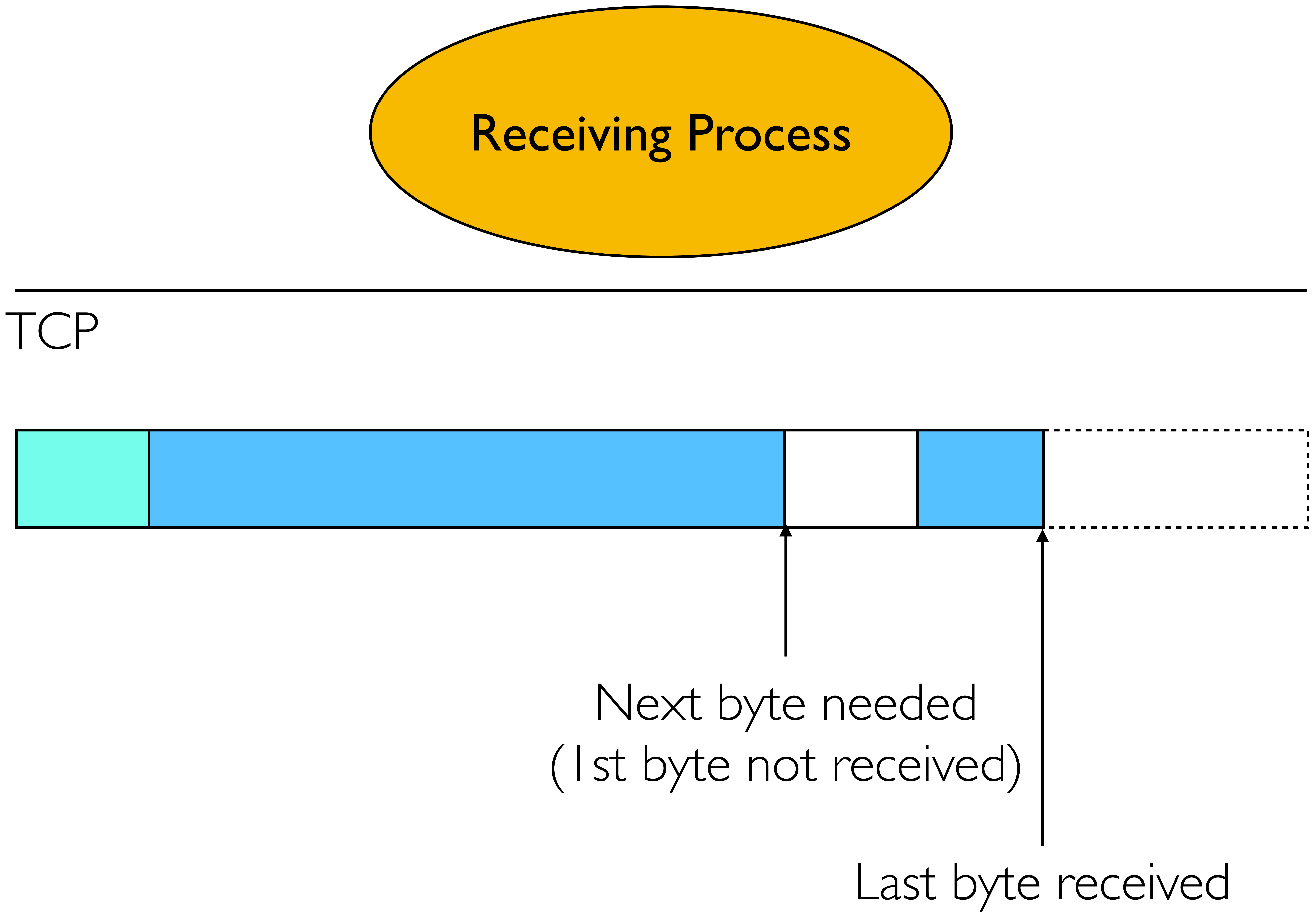
Sliding Window at Receiver



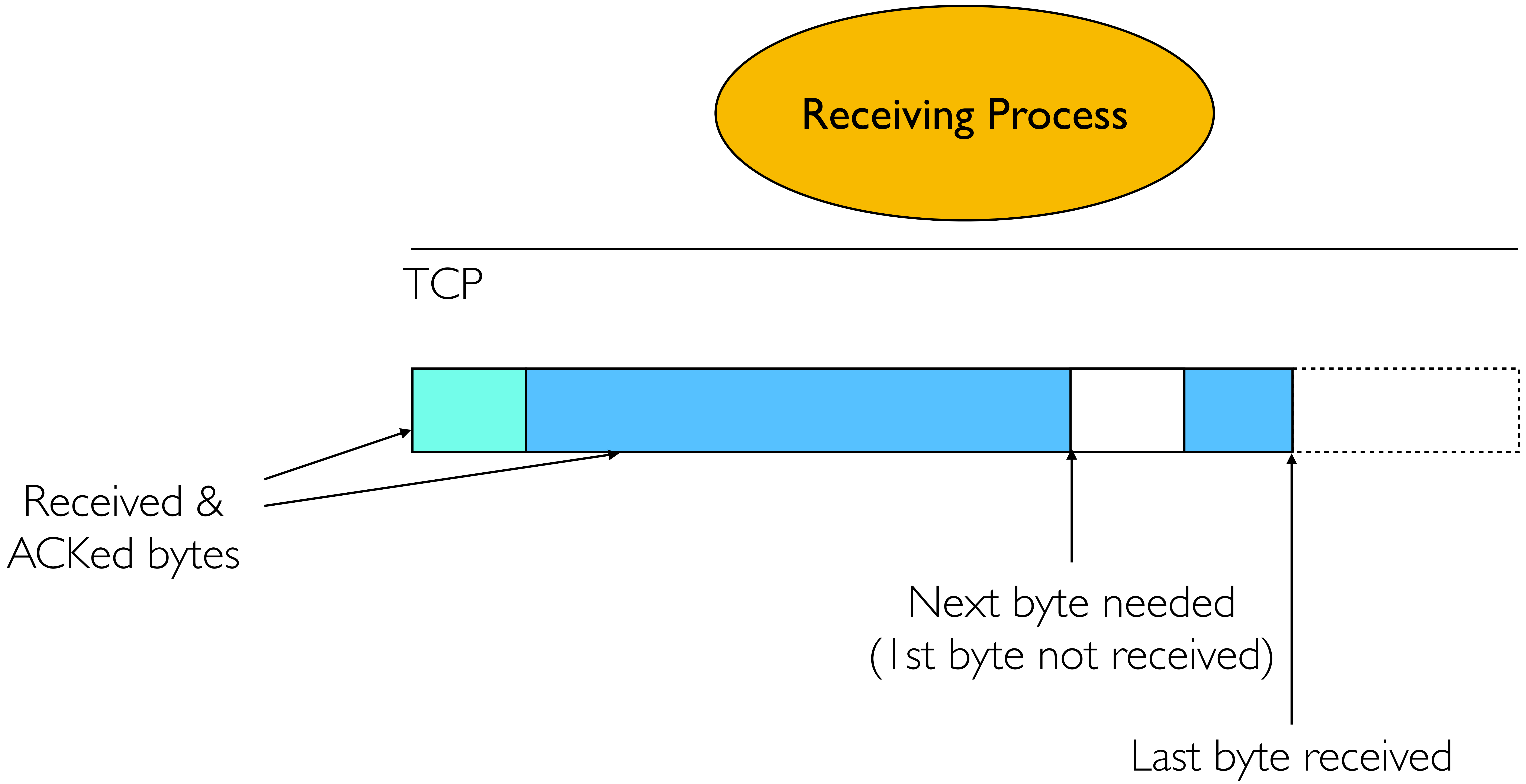
Sliding Window at Receiver



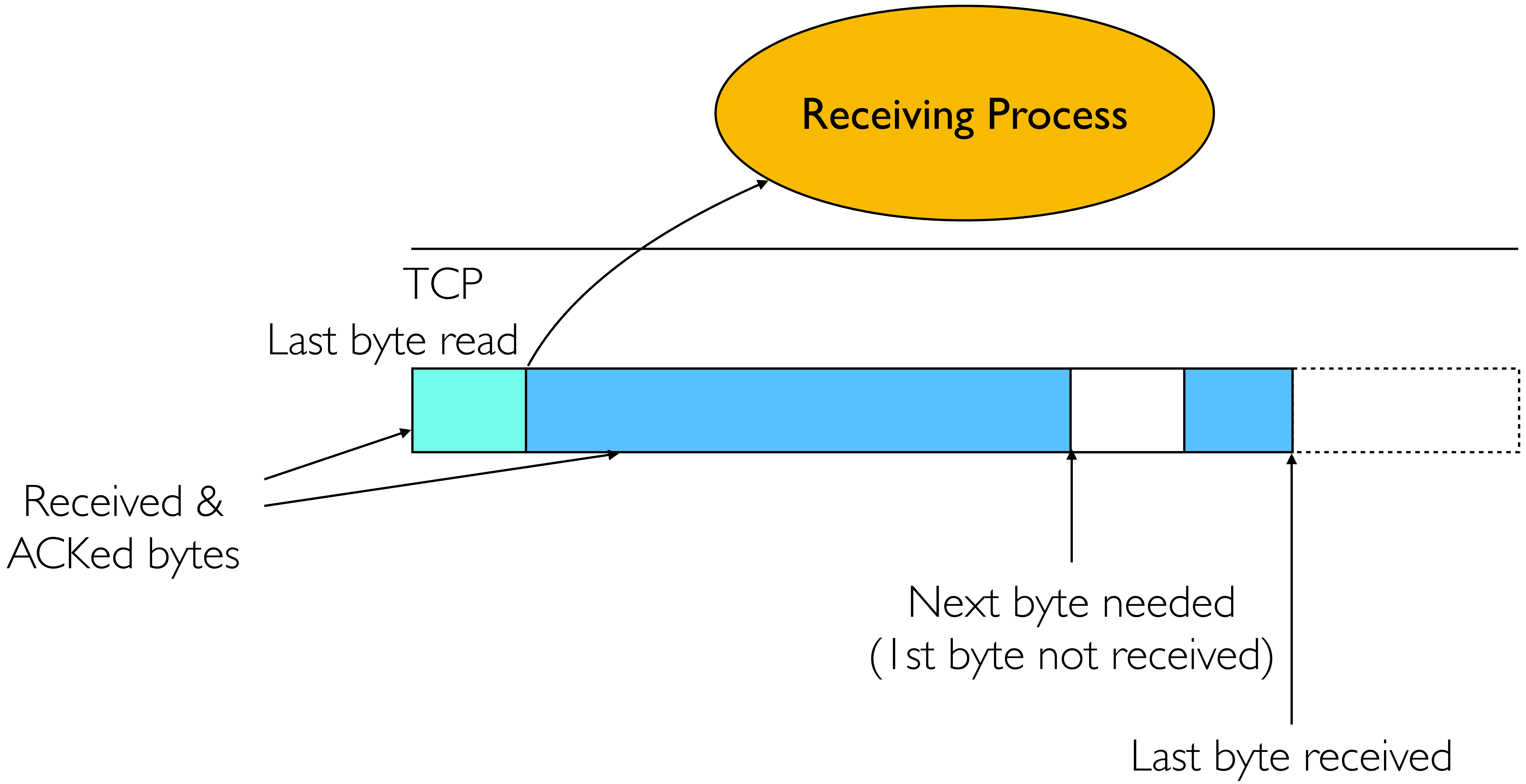
Sliding Window at Receiver



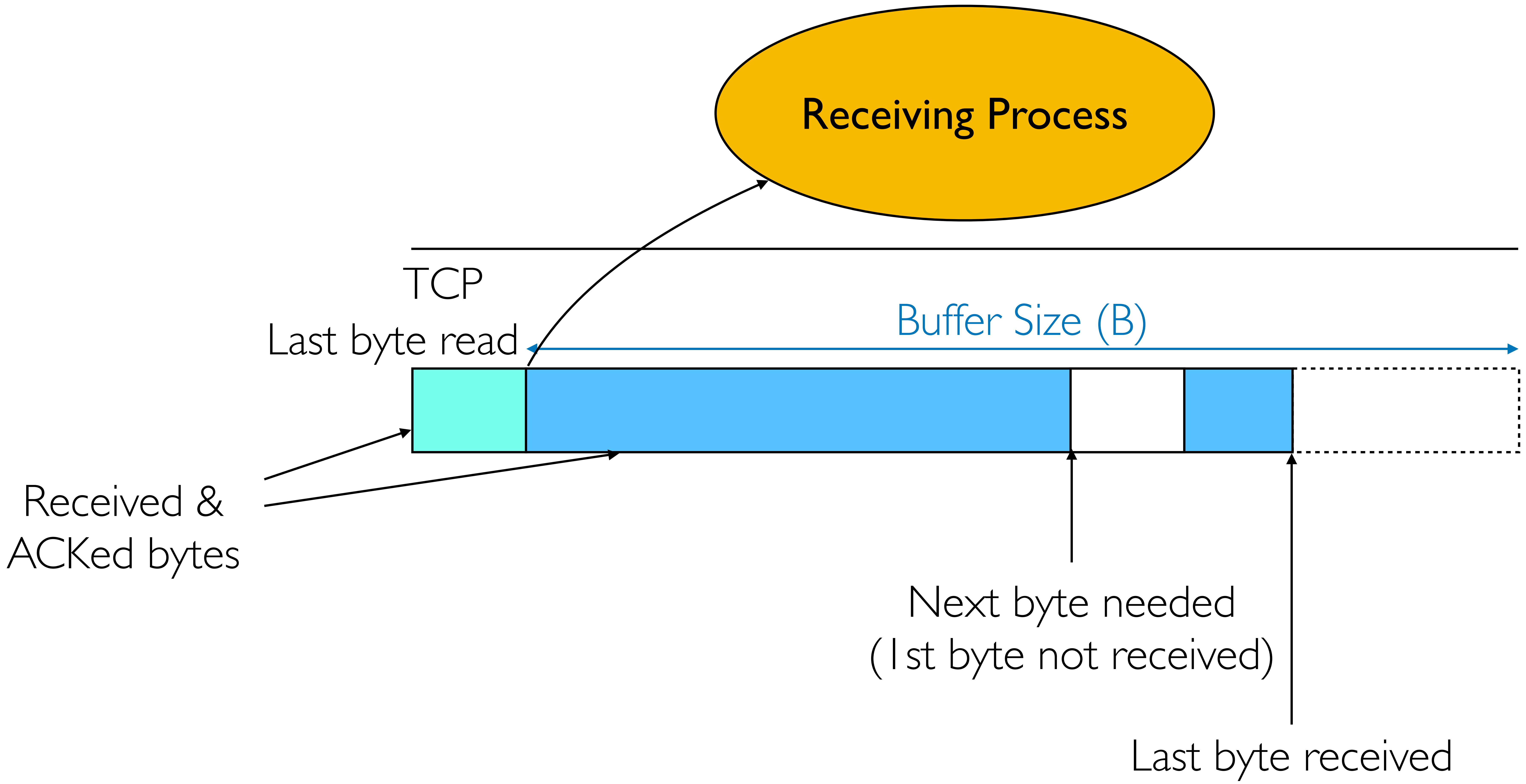
Sliding Window at Receiver



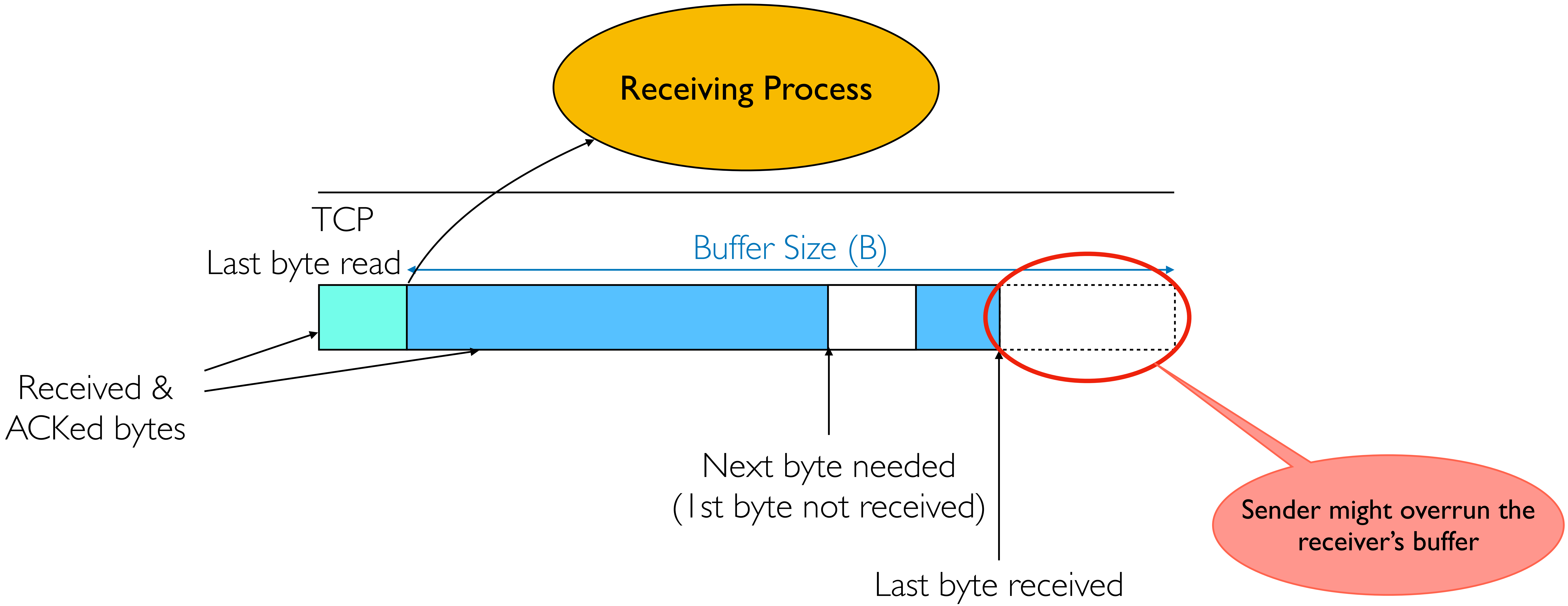
Sliding Window at Receiver



Sliding Window at Receiver



Sliding Window at Receiver

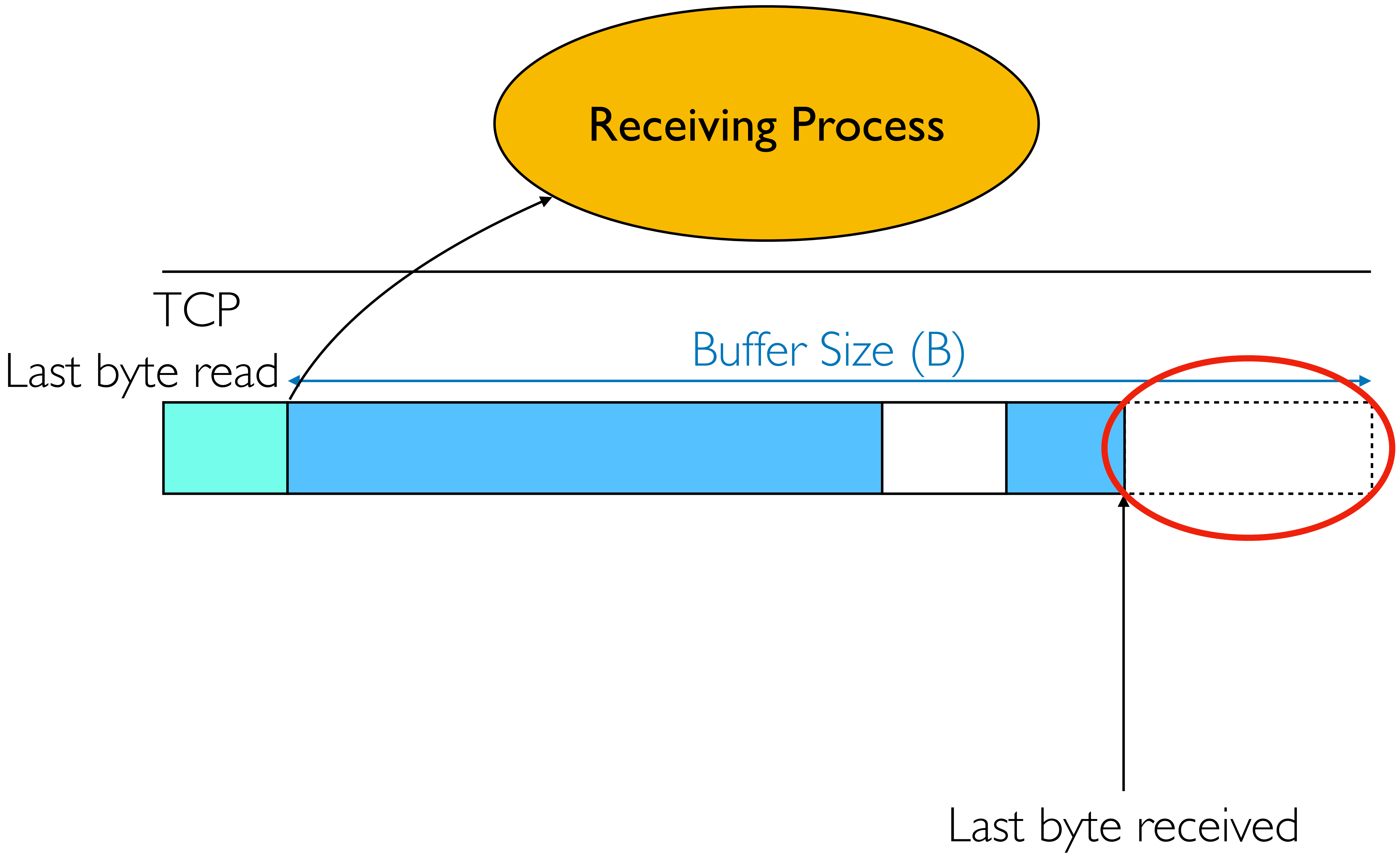


Solution: Advertised Window (Flow Control)

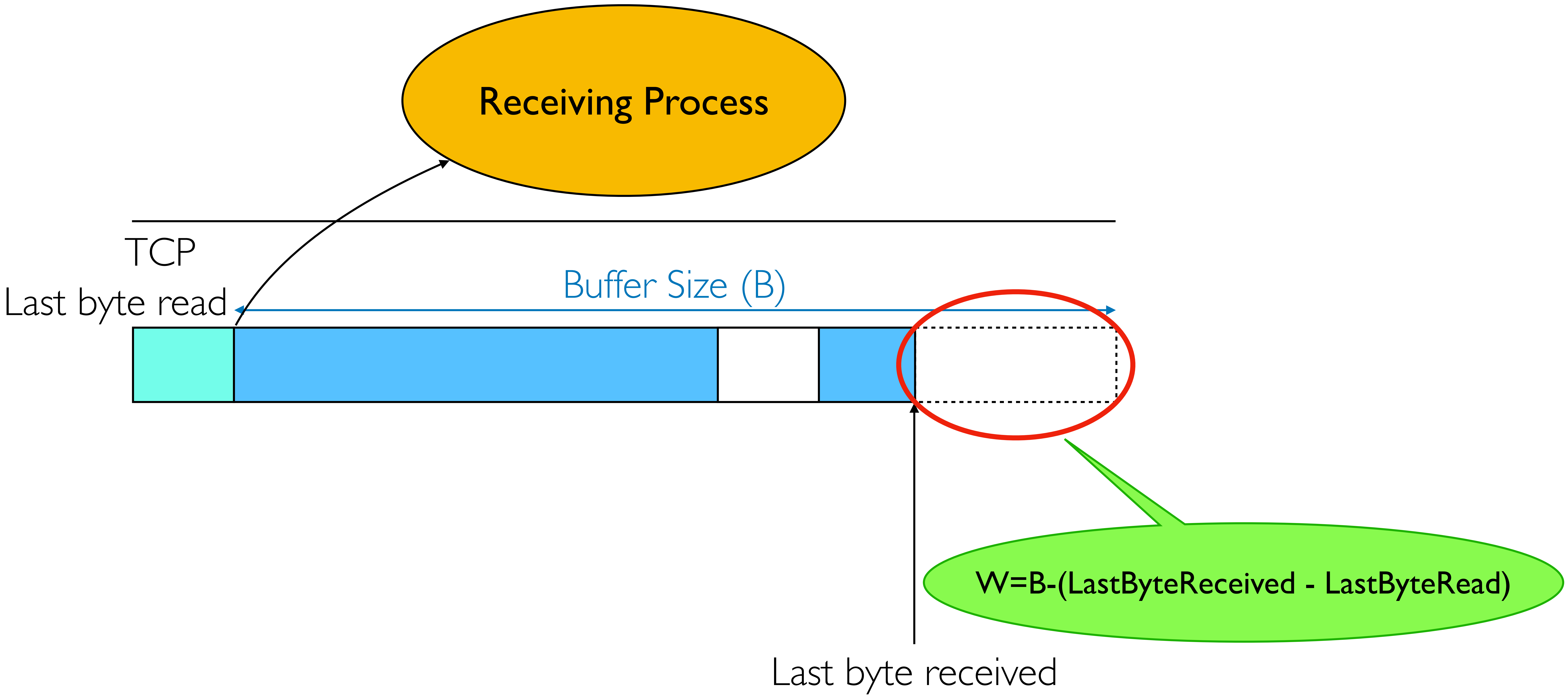
Solution: Advertised Window (Flow Control)

- **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

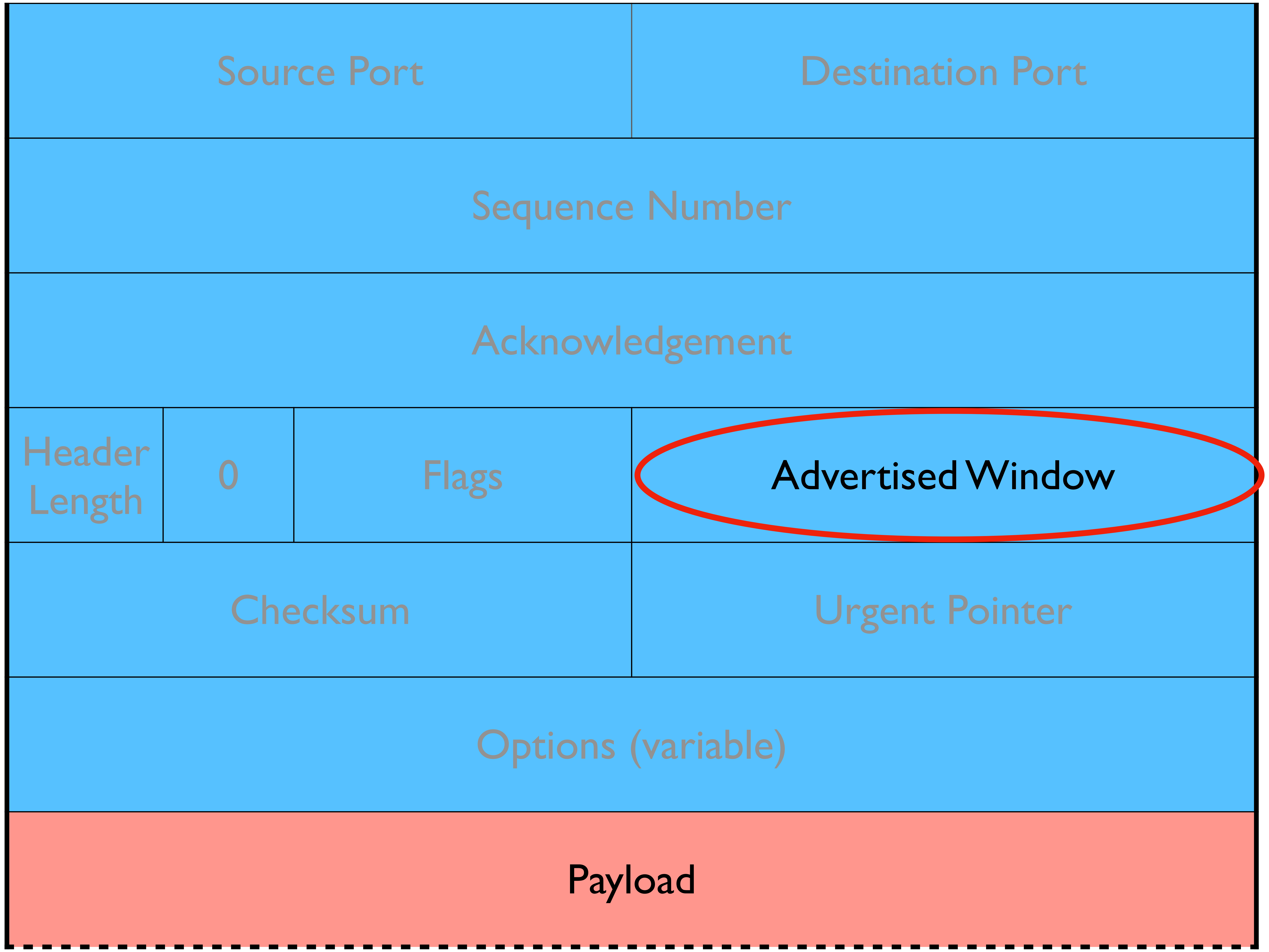
Sliding Window at Receiver



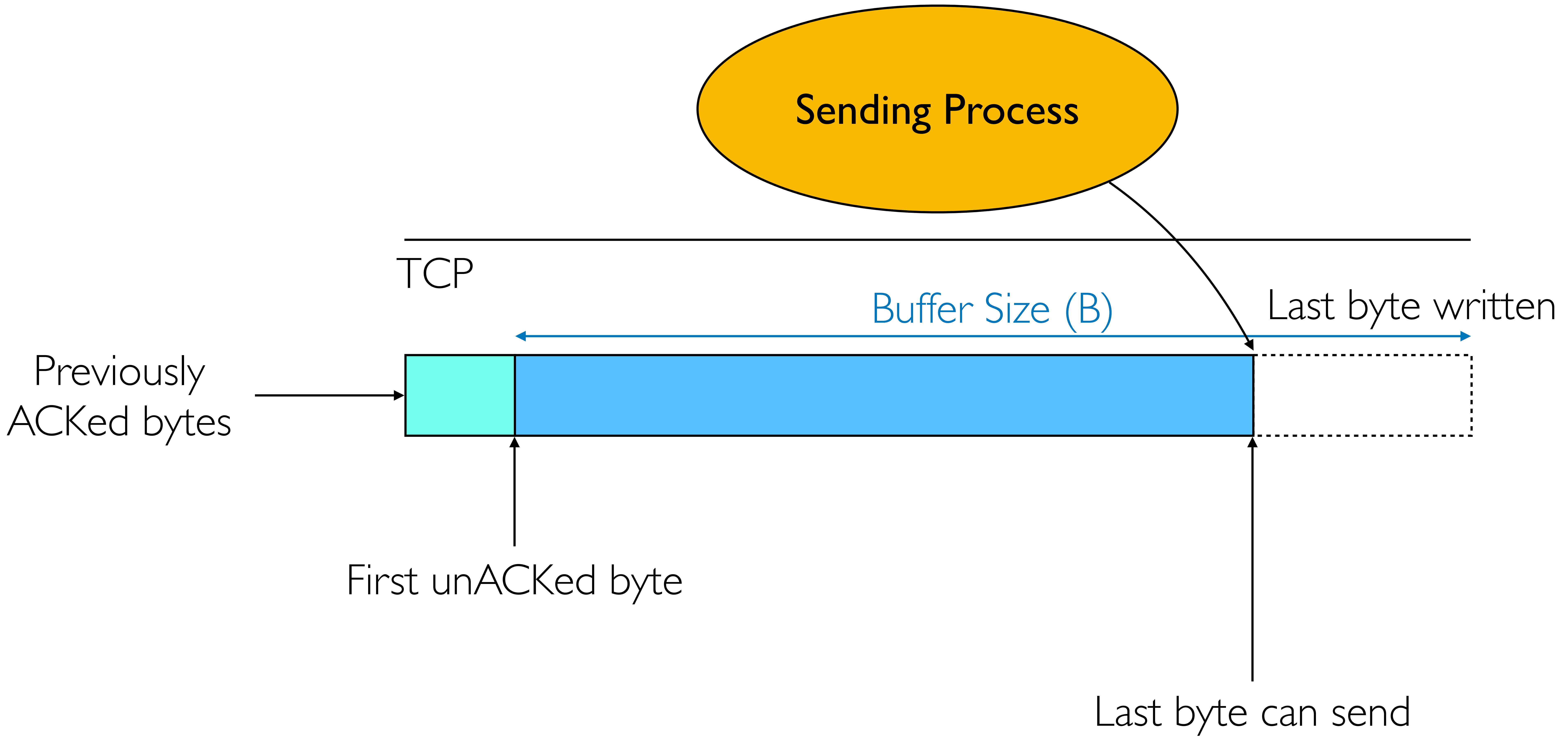
Sliding Window at Receiver



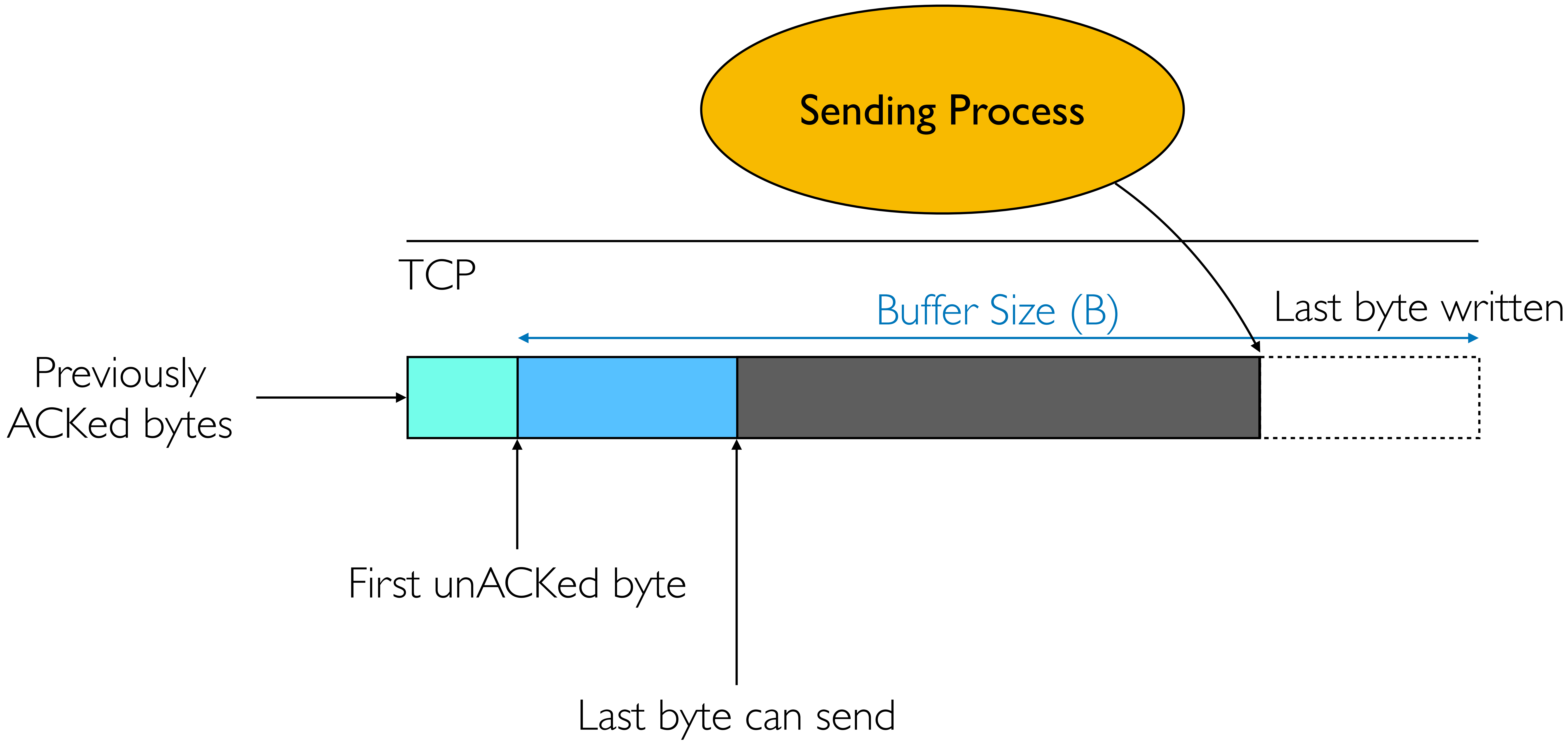
TCP Header


Source Port
Destination Port
Sequence Number
Acknowledgement
Header Length
0
Flags
Advertised Window
Checksum
Urgent Pointer
Options (variable)
Payload

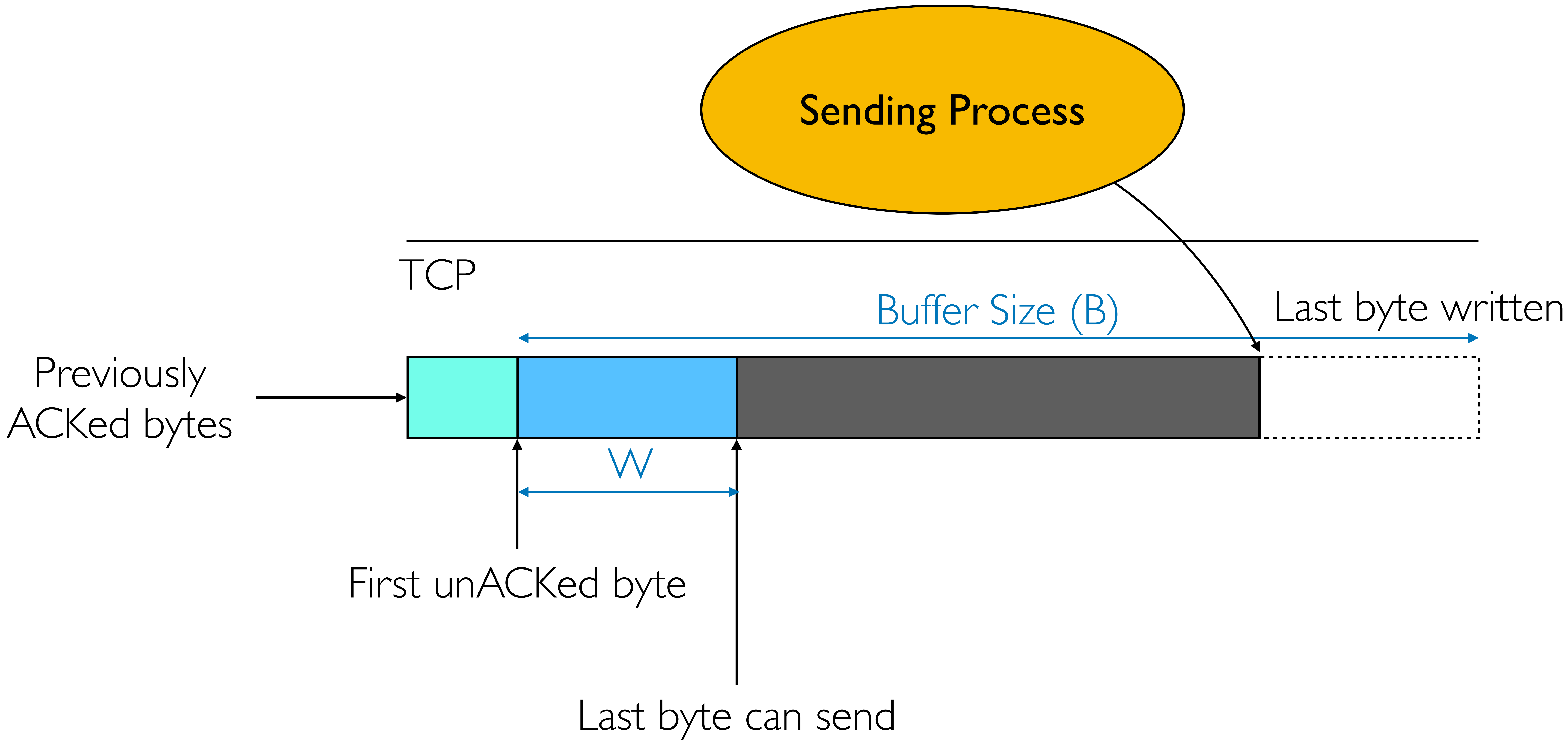
Sliding Window at Sender



Sliding Window at Sender



Sliding Window at Sender



Sending Window with Flow Control

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- **Sender:** window advances *when new data ACKed*

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- **Receiver:** window advances as *receiving process consumes data*

Sending Window with Flow Control

- **Sender:** window advances *when new data ACKed*
- **Receiver:** window advances as *receiving process consumes data*
- Receiver *advertises* to sender where receiver window currently ends ("right hand edge")
  - Sender agrees not to exceed this amount

Advertised Window Limits Rate

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- Sender can send no faster than W/RTT bytes/sec

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Advertised Window Limits Rate

- Sender can send no faster than W/RTT bytes/sec
- Receiver only advertises more space when it has consumed old arriving data
- In original TCP design, that was the **sole** protocol mechanism controlling the sender's rate
- What was missing?

Taking Stock

- The concepts underlying TCP are simple
  - Acknowledgements
  - Timers
  - Sliding Windows
  - Buffer Management
  - Sequence Numbers

Taking Stock

- The concepts underlying TCP are simple
- But tricky in the details
  - How do we set timers
  - What is the seqno for an ACK only packet
  - What happens if the advertised window = 0
  - What if the advertised window is 1/2 an MSS
  - Should receiver acknowledge packets right away
  - What if the application generates data in units of 0.1 MSS
  - What happens if I get a duplicate SYN? Or an RST while I'm in FIN_WAIT?
  - *etc., etc., etc.*

Taking Stock

- The concepts underlying TCP are simple
- But tricky in the details
- Do the details matter?

Sizing Windows for Congestion Control

- What are the problems?
- How might we address them?