The Transport Layer

CPSC 433/533, Spring 2021

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Administrivia

- **HW1 grades posted, HW2 out!**
  - Any issues with HW1 grading (e.g., regrade request), email Ramla, cc-me
- Hopefully Project#1 is going well — **due next Tue!**
  - **No class next Tue though (break day)…**
- **Periodic check-in:**
  - Are you keeping up with the course fine? If not, reach out! Email, come to OH…

Taking Stock: Network Layer

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- ***Best-effort global delivery of packets***

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- **Control Plane:** Routing

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- ***Best-effort global delivery of packets***
- **Control Plane:** Routing
- **Data Plane:** Forwarding
- **Key enabler of scalability:** Addressing

Addressing: Hierarchical for Scalability

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- **Hierarchical address structure**

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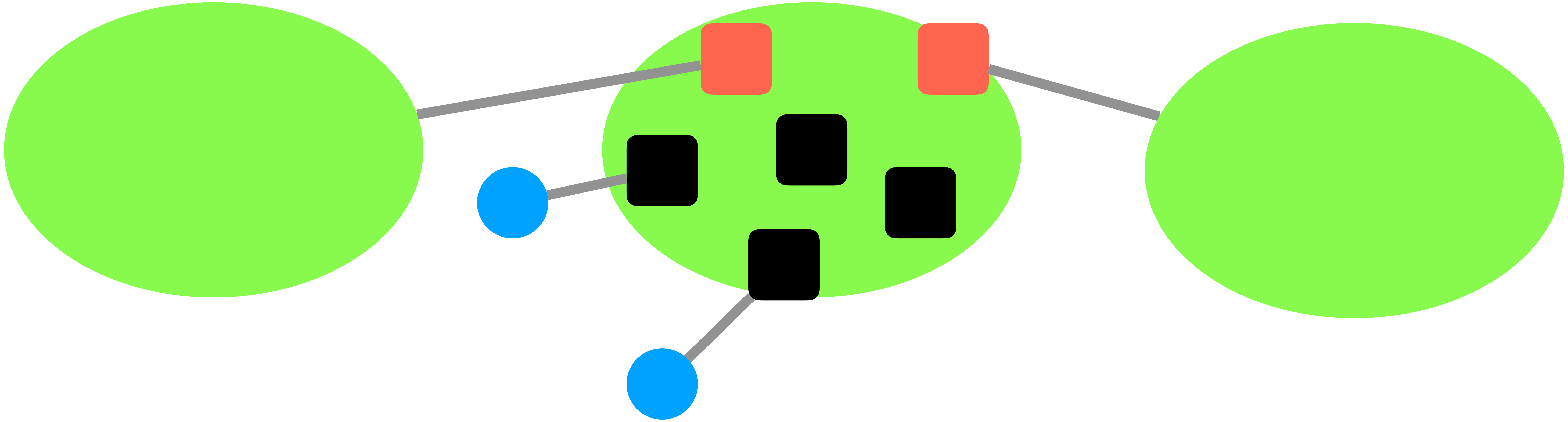
Addressing: Hierarchical for Scalability

- **Hierarchical address structure**
- **Hierarchical address allocation**
- **Hierarchical addresses and routing scalability**

Control Plane: **Routing**



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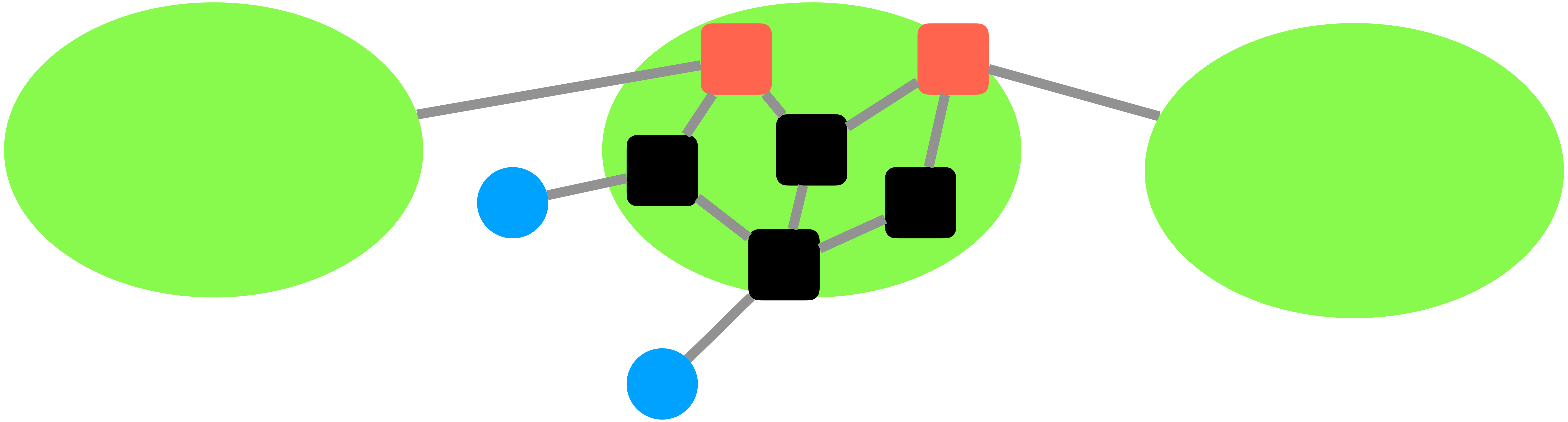

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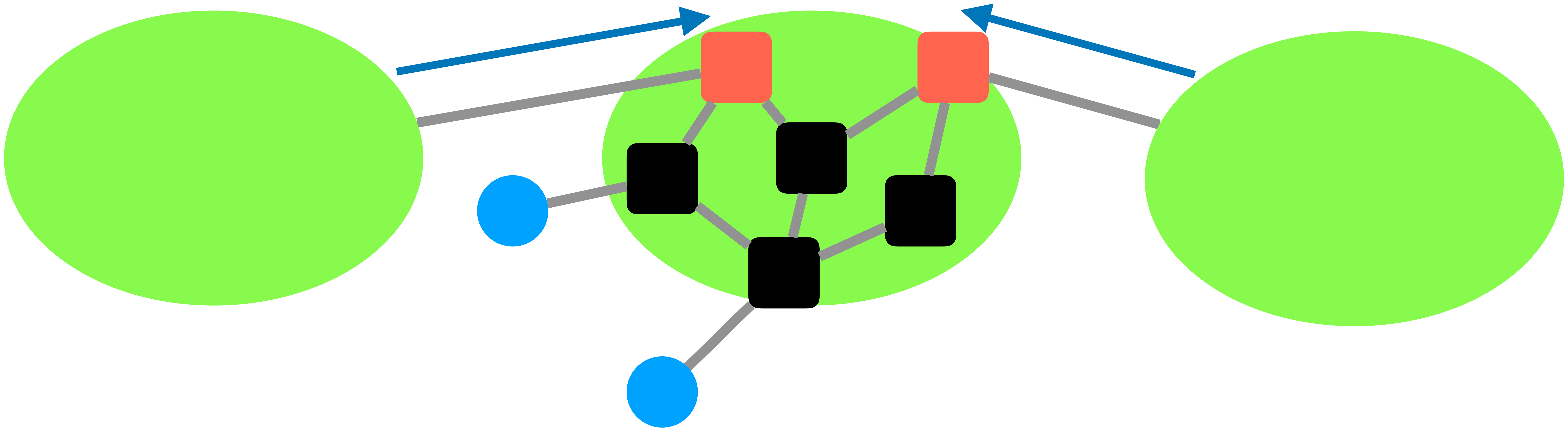

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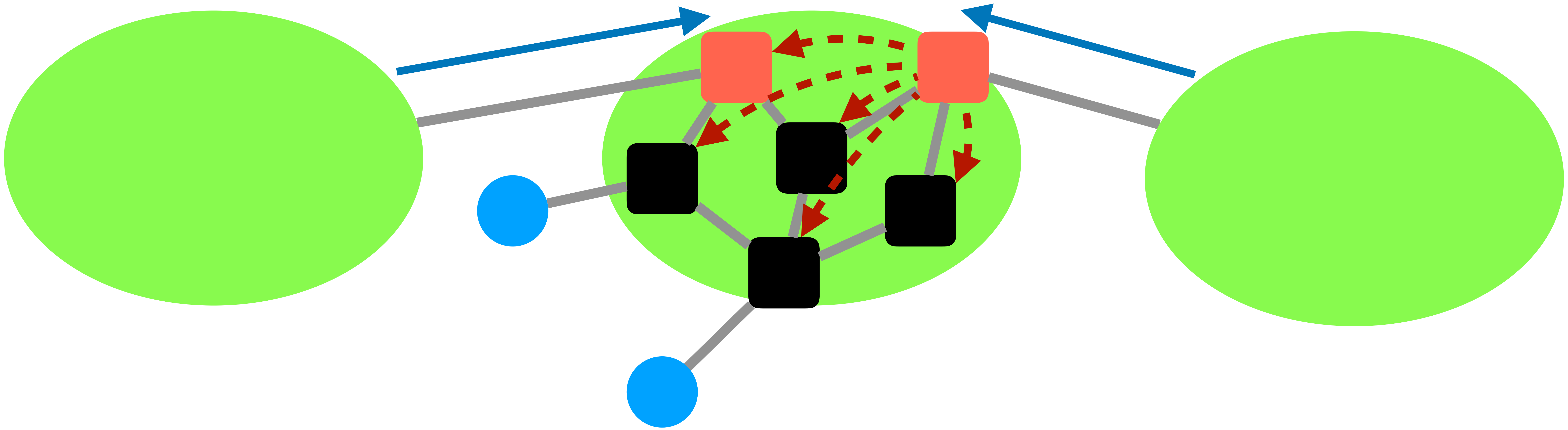

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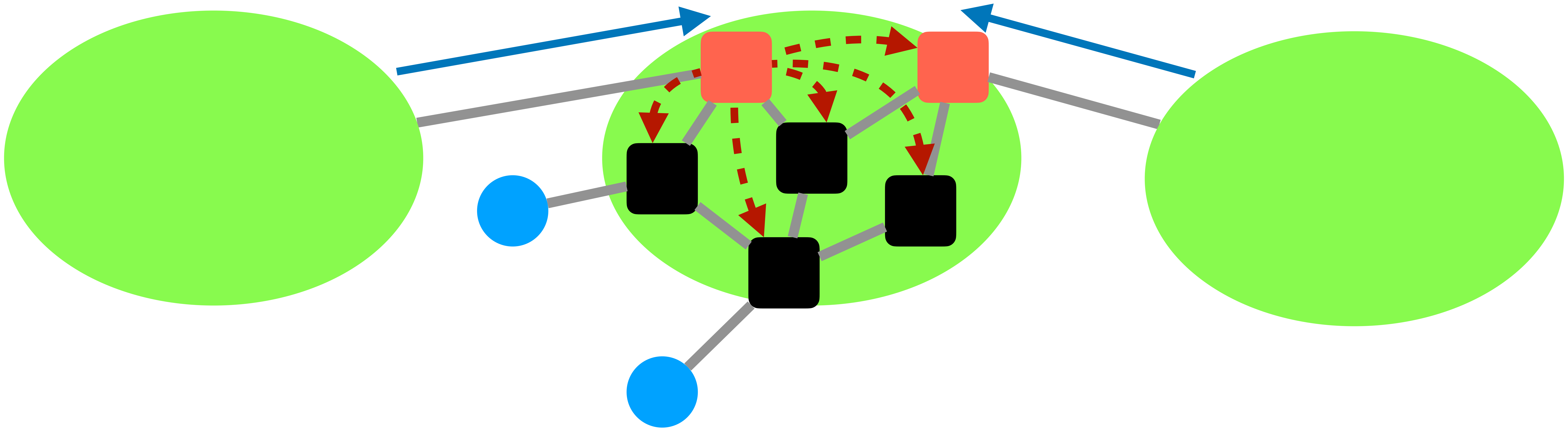

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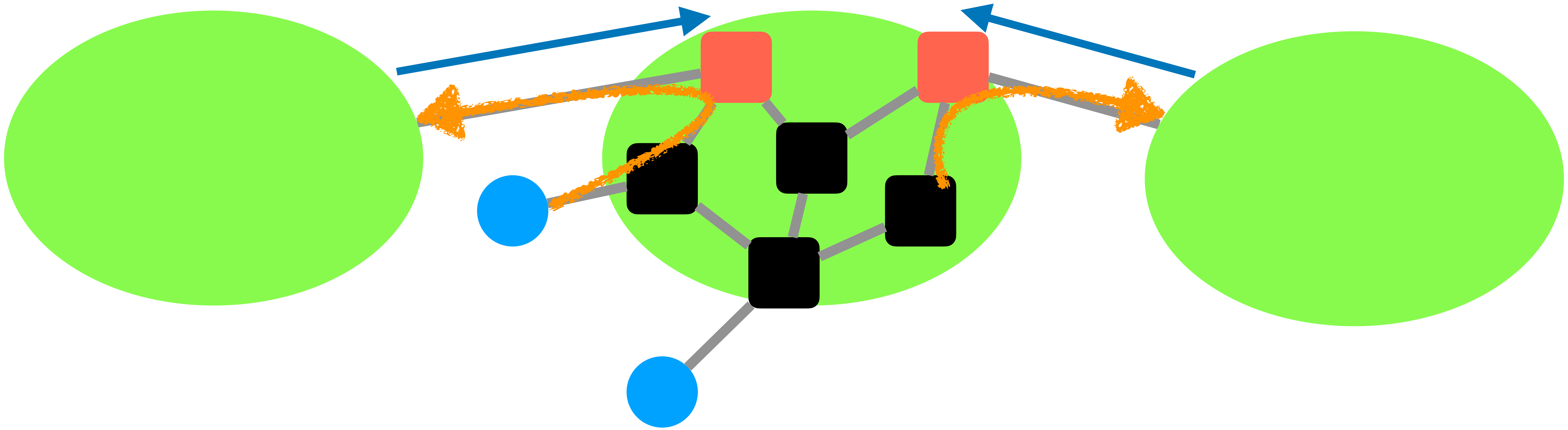

1. Provide internal reachability (**IGP**)
2. Learn routes to external destinations (**eBGP**)
3. Distribute externally learned routes internally (**iBGP**)
4. Travel shortest path to egress (**IGP**)

Data Plane: **Forwarding**

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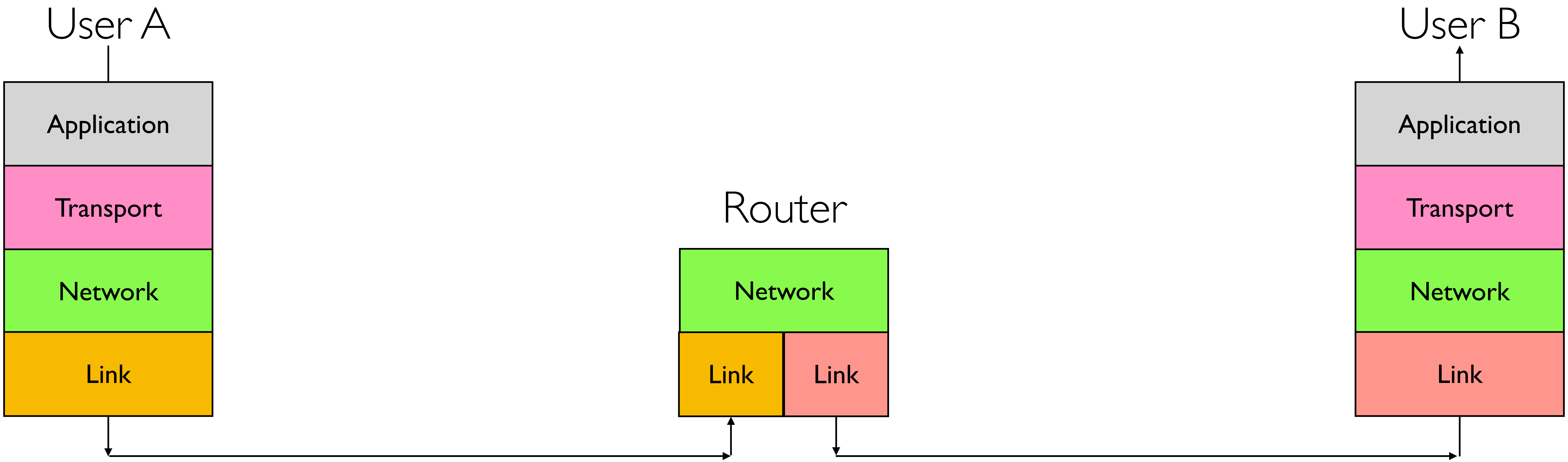

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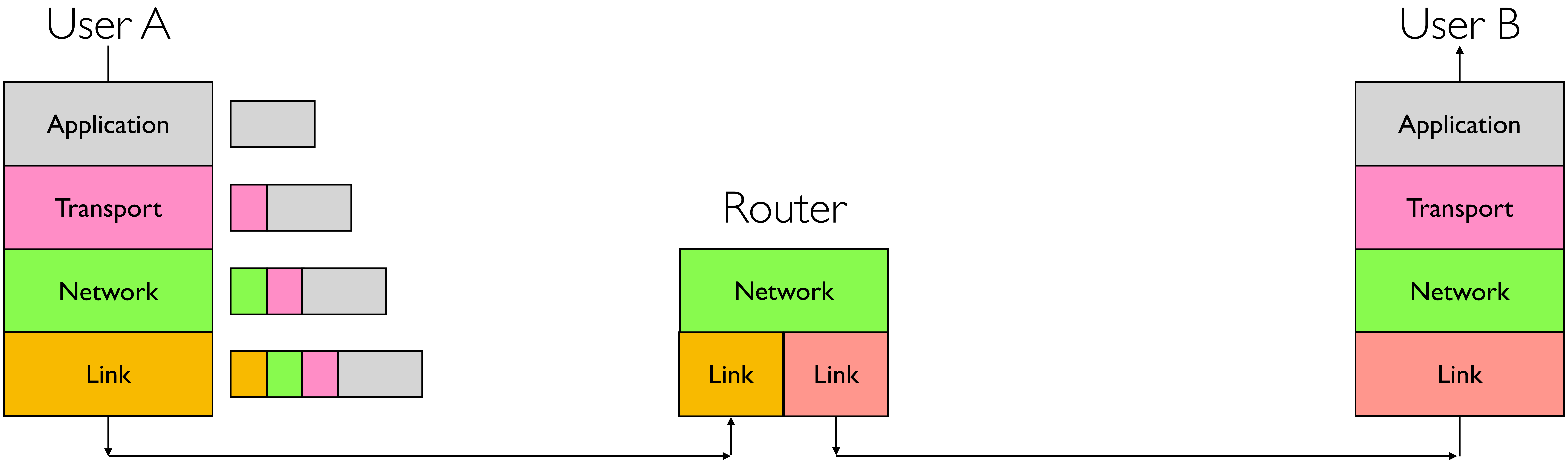

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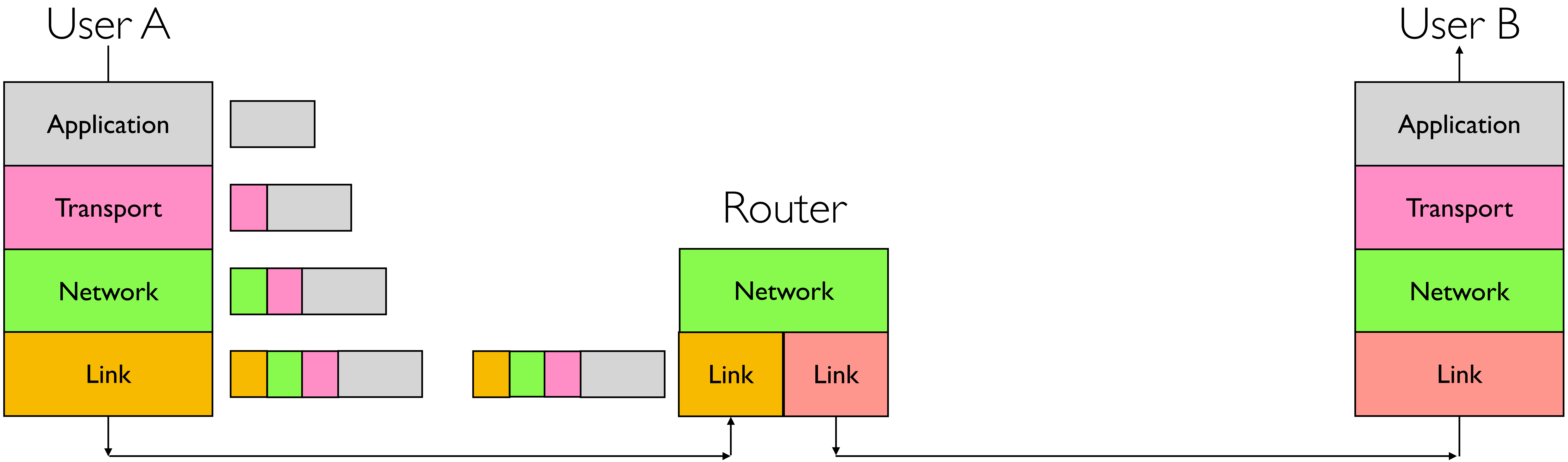

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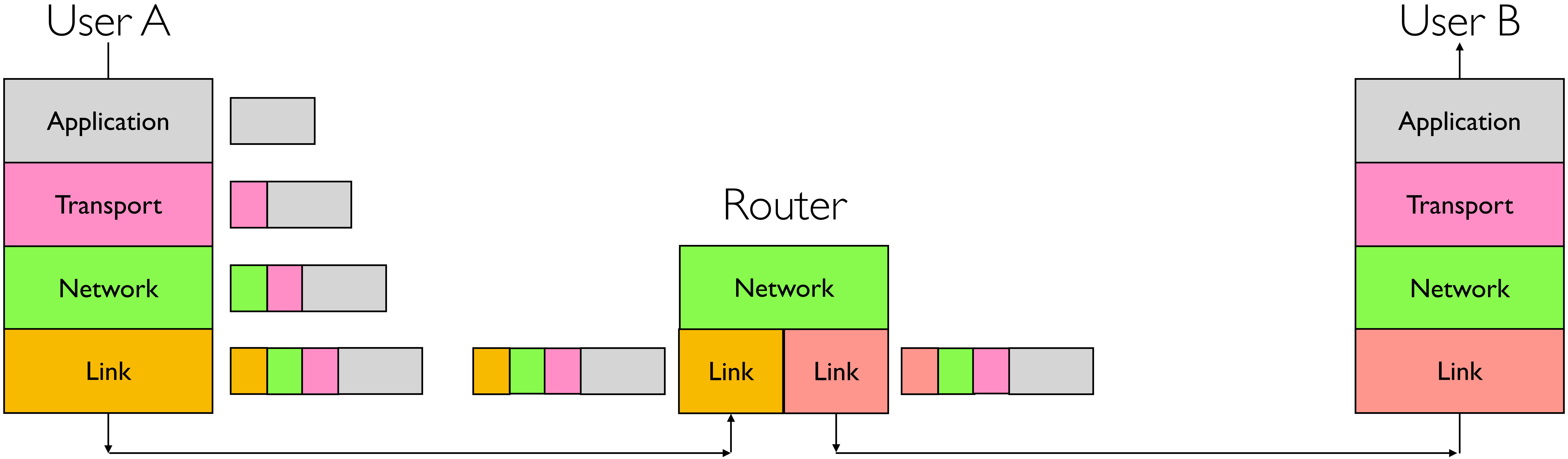

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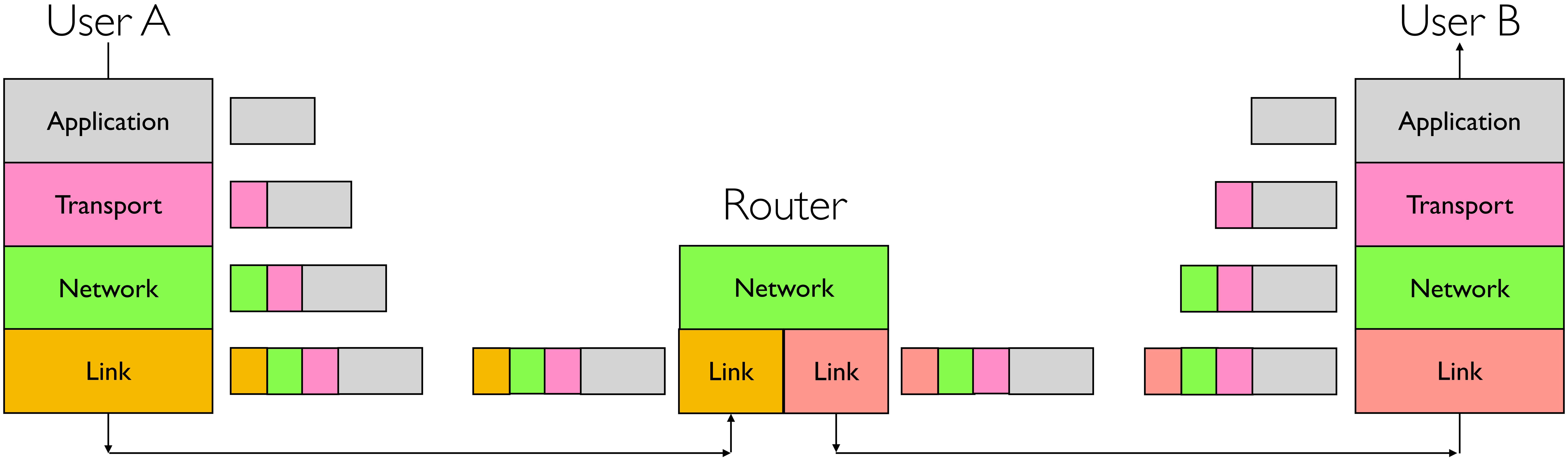

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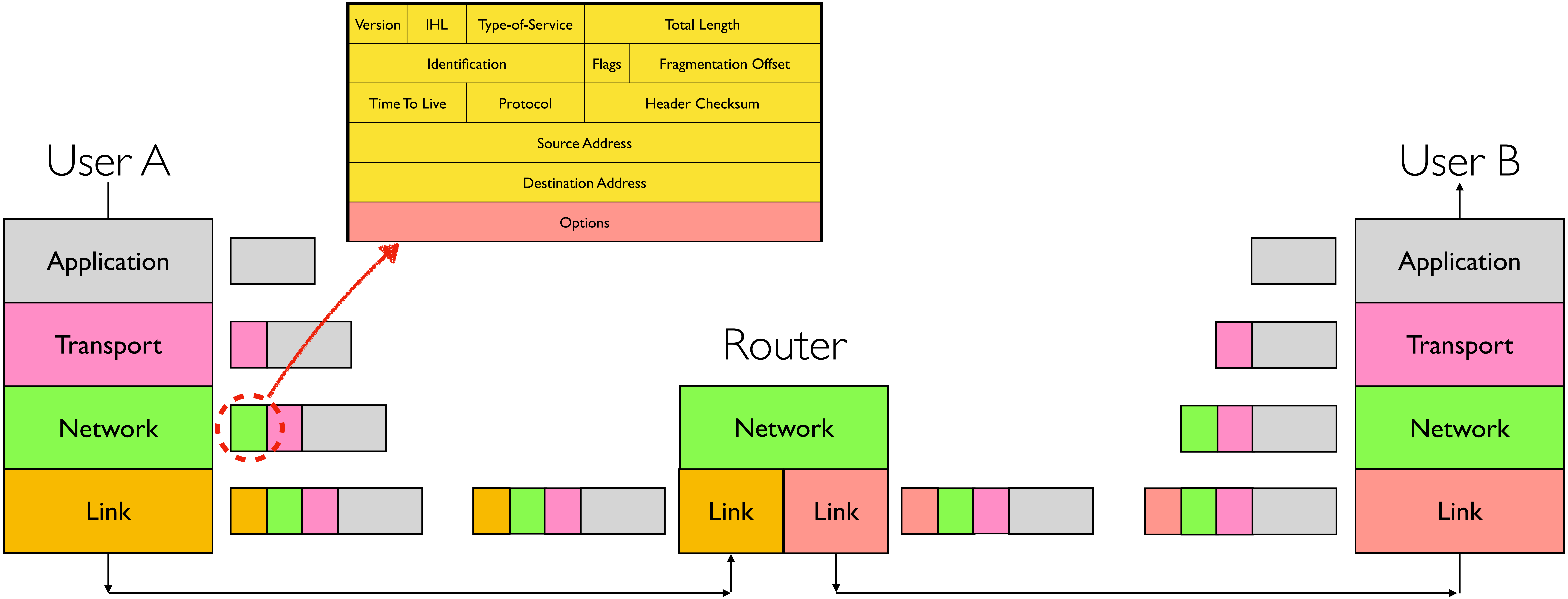

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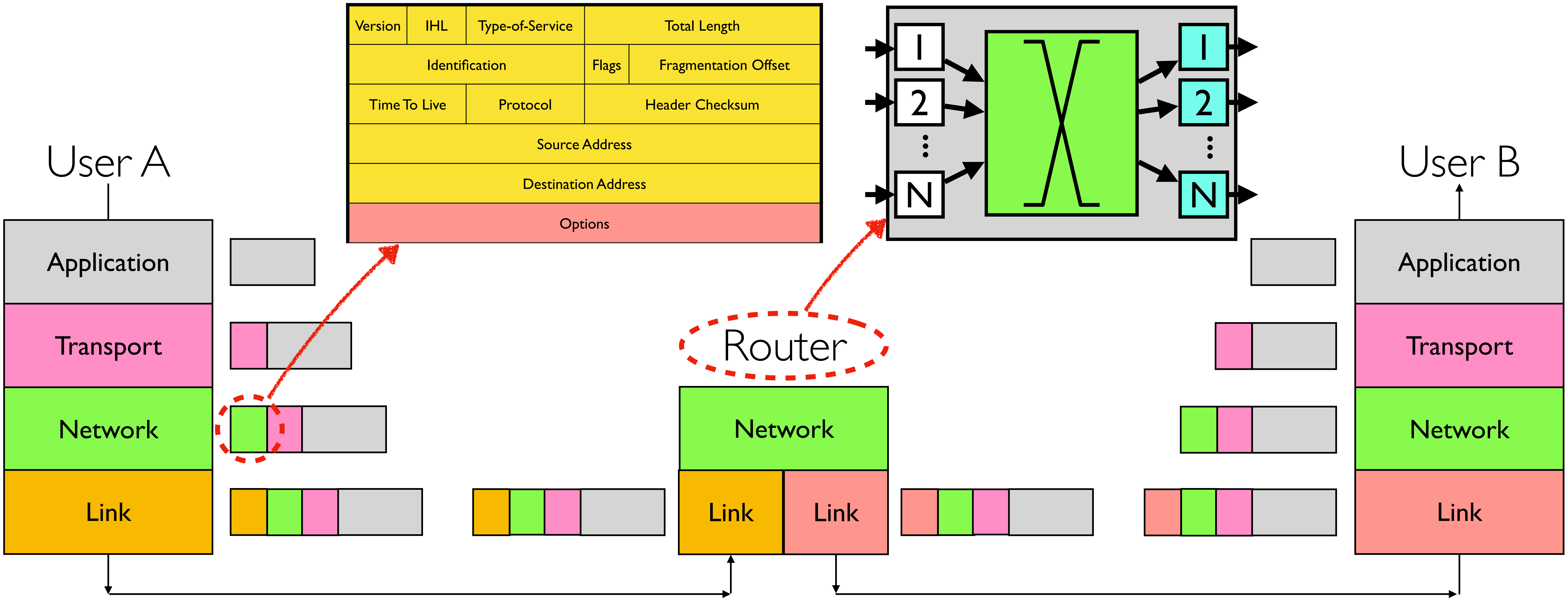
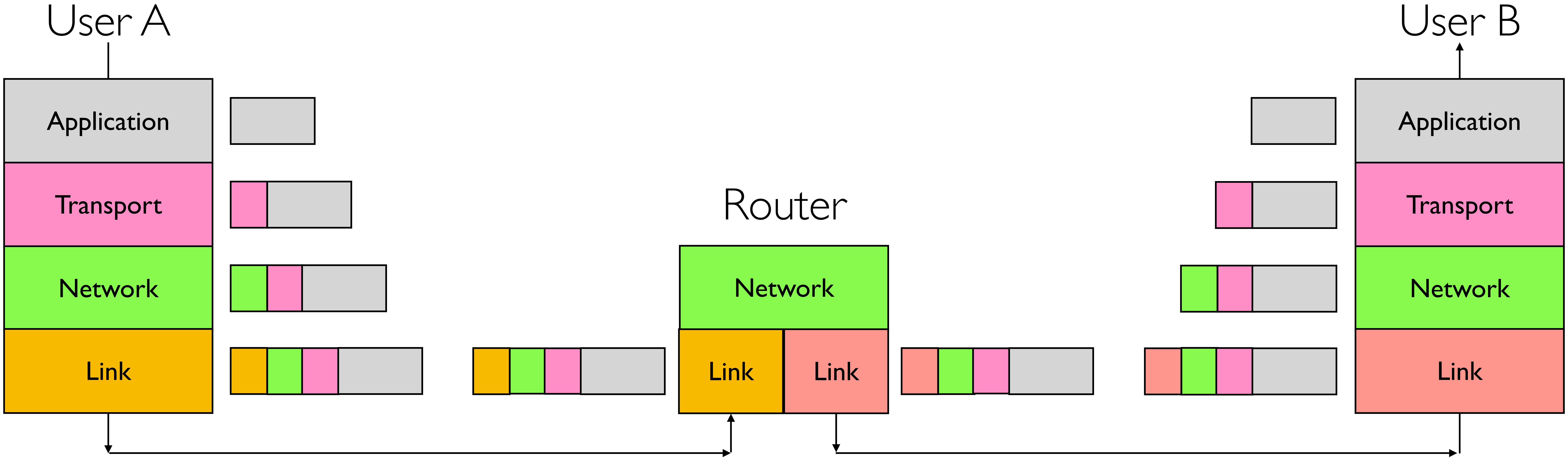


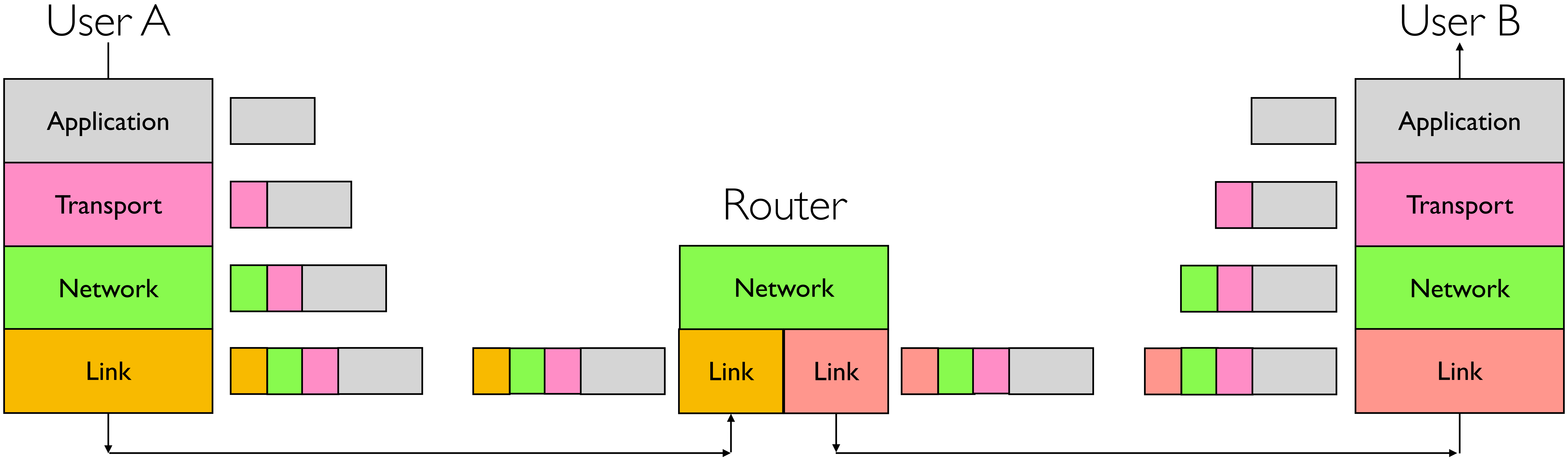
Up Next…



User A
User B
Application
Transport
Network
Link
Router
Network
Link
Link
Application
Transport
Network
Link

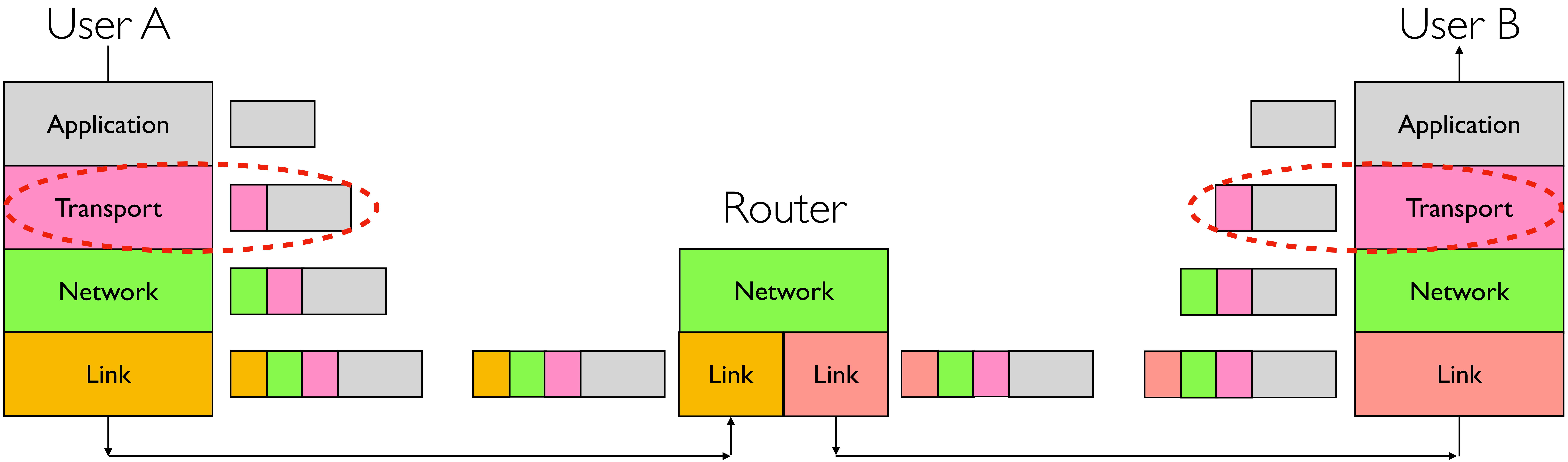
Up Next…

- **So far: Network Layer,** *Best-effort global delivery of packets*



Up Next…

- **So far: Network Layer,** *Best-effort global delivery of packets*
- **Next: Transport Layer,** *Reliable (or unreliable) delivery of data*
  - *Layer at* ***end-hosts,*** *between the application and network layers*



Why a Transport Layer?

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- **Transport layer and application both on host**

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- **Why not combine the two?**

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- **Transport layer and application both on host**
- **Why not combine the two?**
- **And what should that code do anyway?**

Why a Transport Layer?

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1. **De-multiplex packets between many applications**

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1. **De-multiplex packets between many applications**
2. **Additional (optional) services on top of IP**

Why a Transport Layer: Demultiplexing

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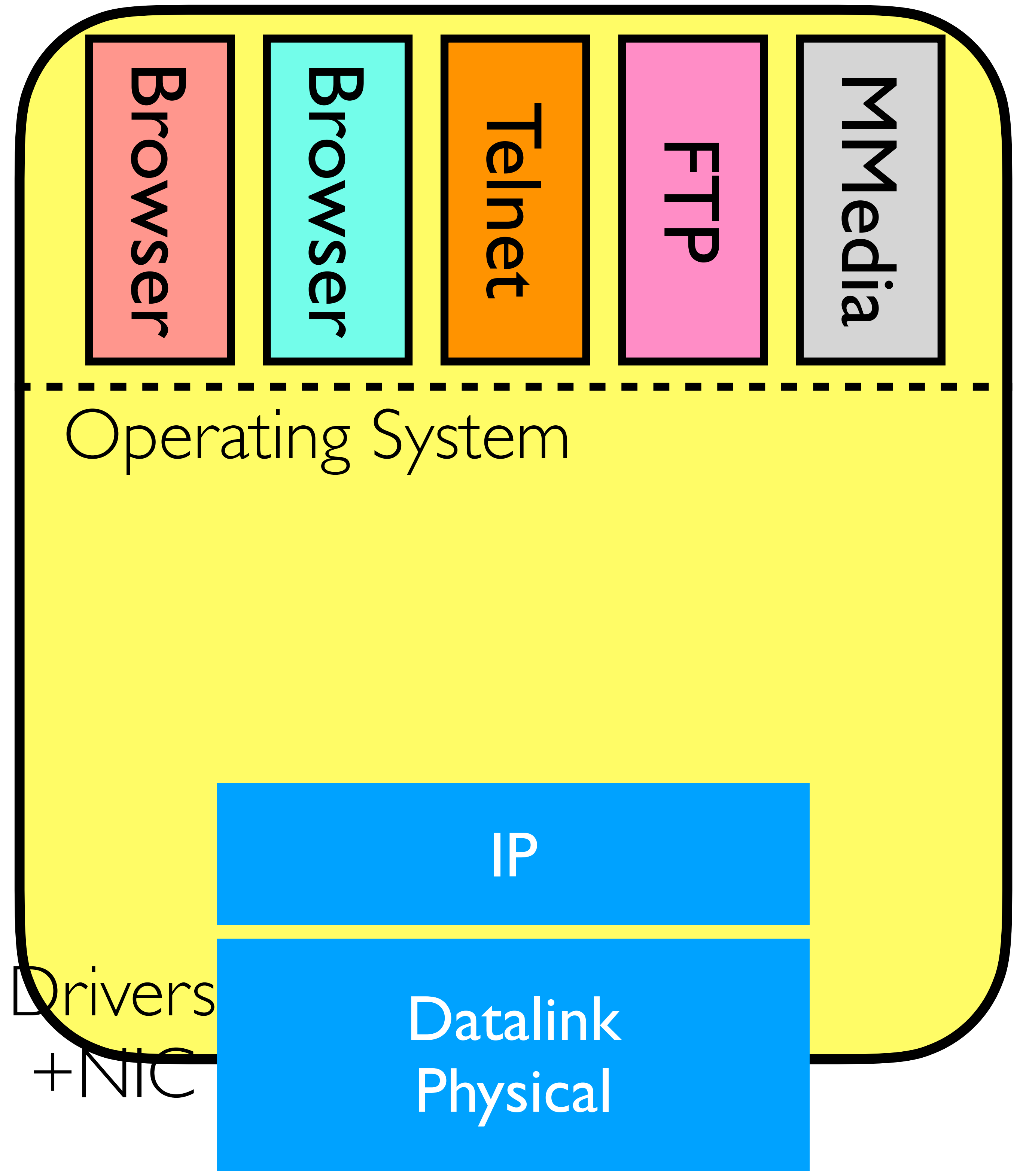
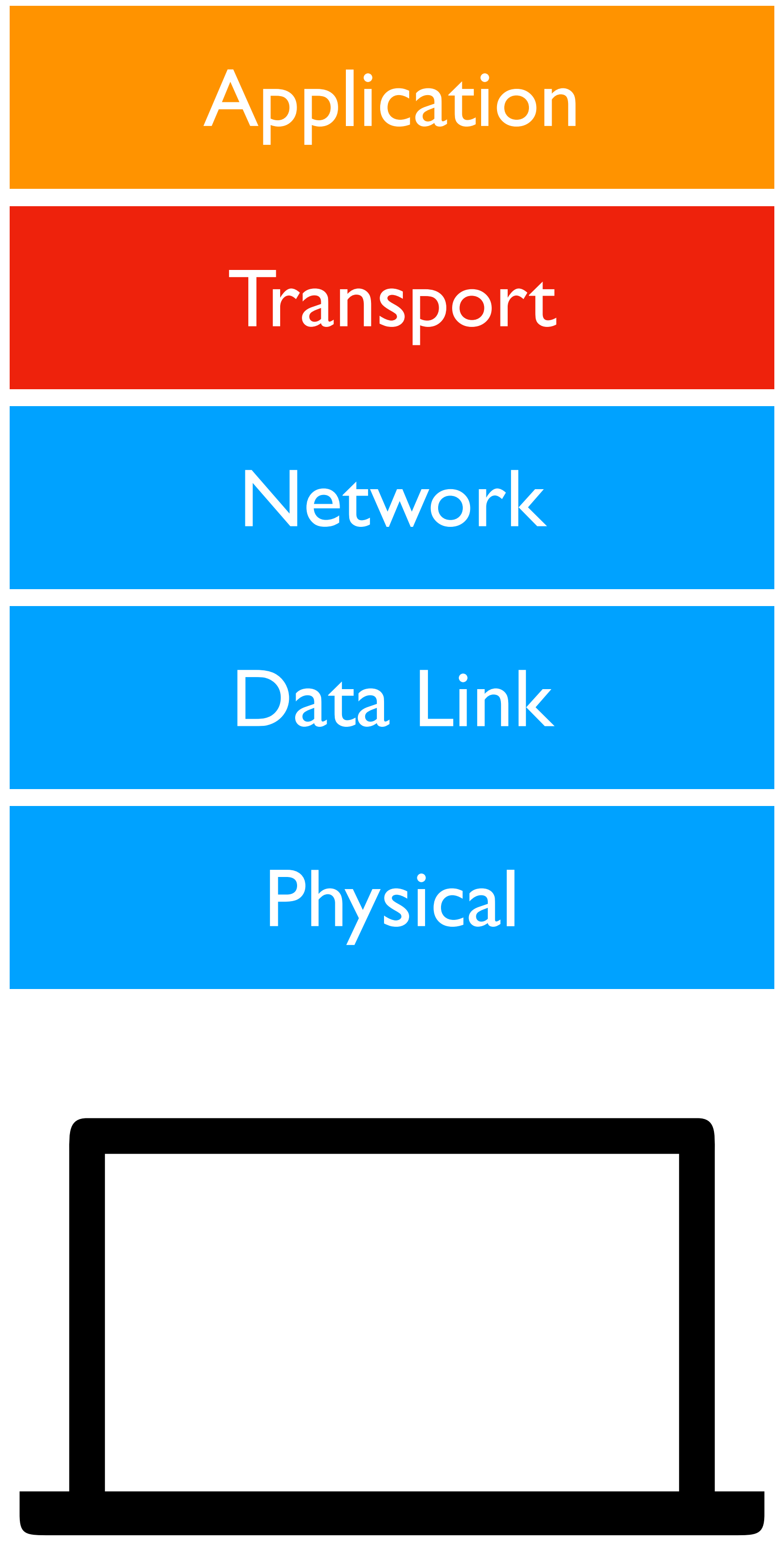
- **IP packets are addressed to a host, but end-to-end communication is between application processes at hosts**
  - Need a way to decide which packets go to which applications (*multiplexing/ demultiplexing*)

Why a Transport Layer: Demultiplexing

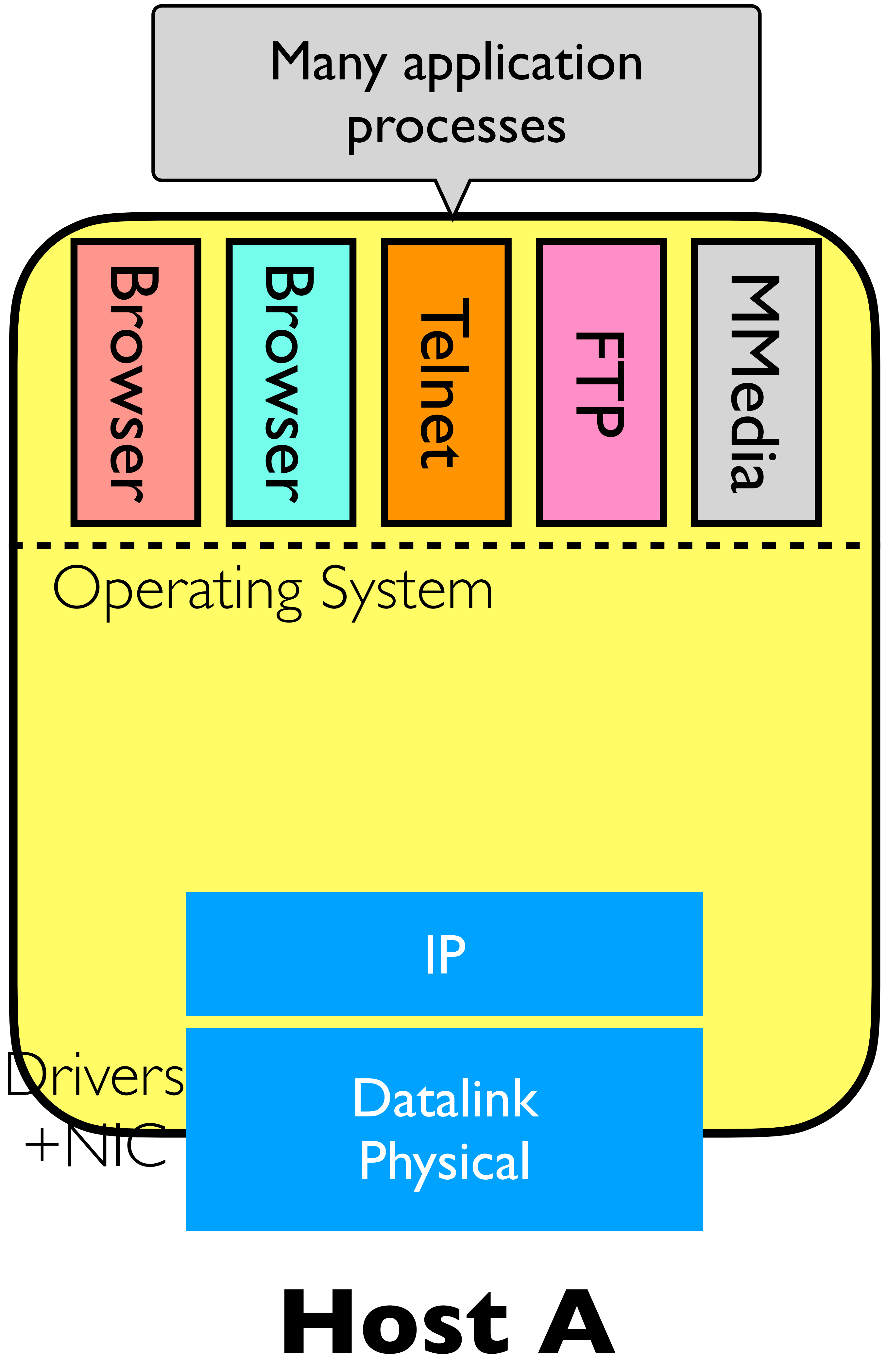


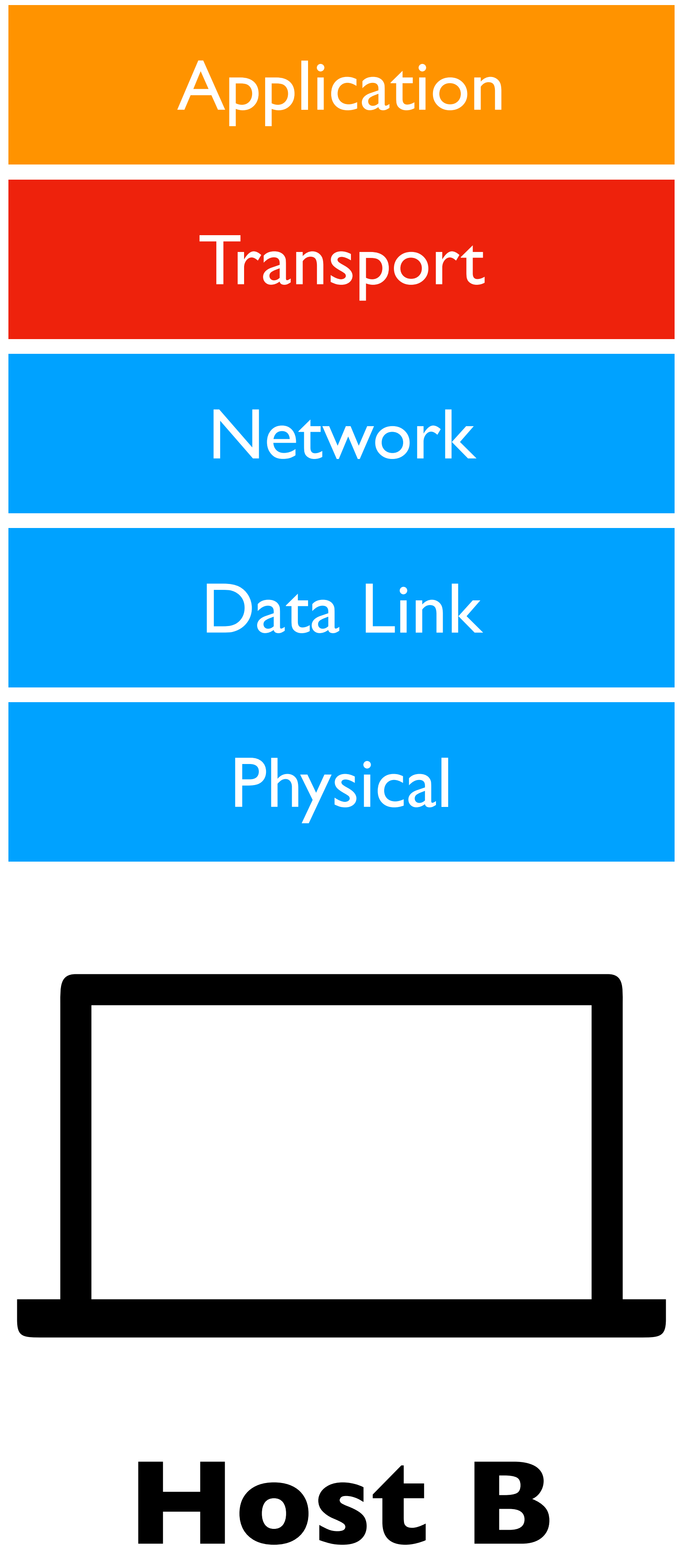
Host A



Host B

Why a Transport Layer: Demultiplexing





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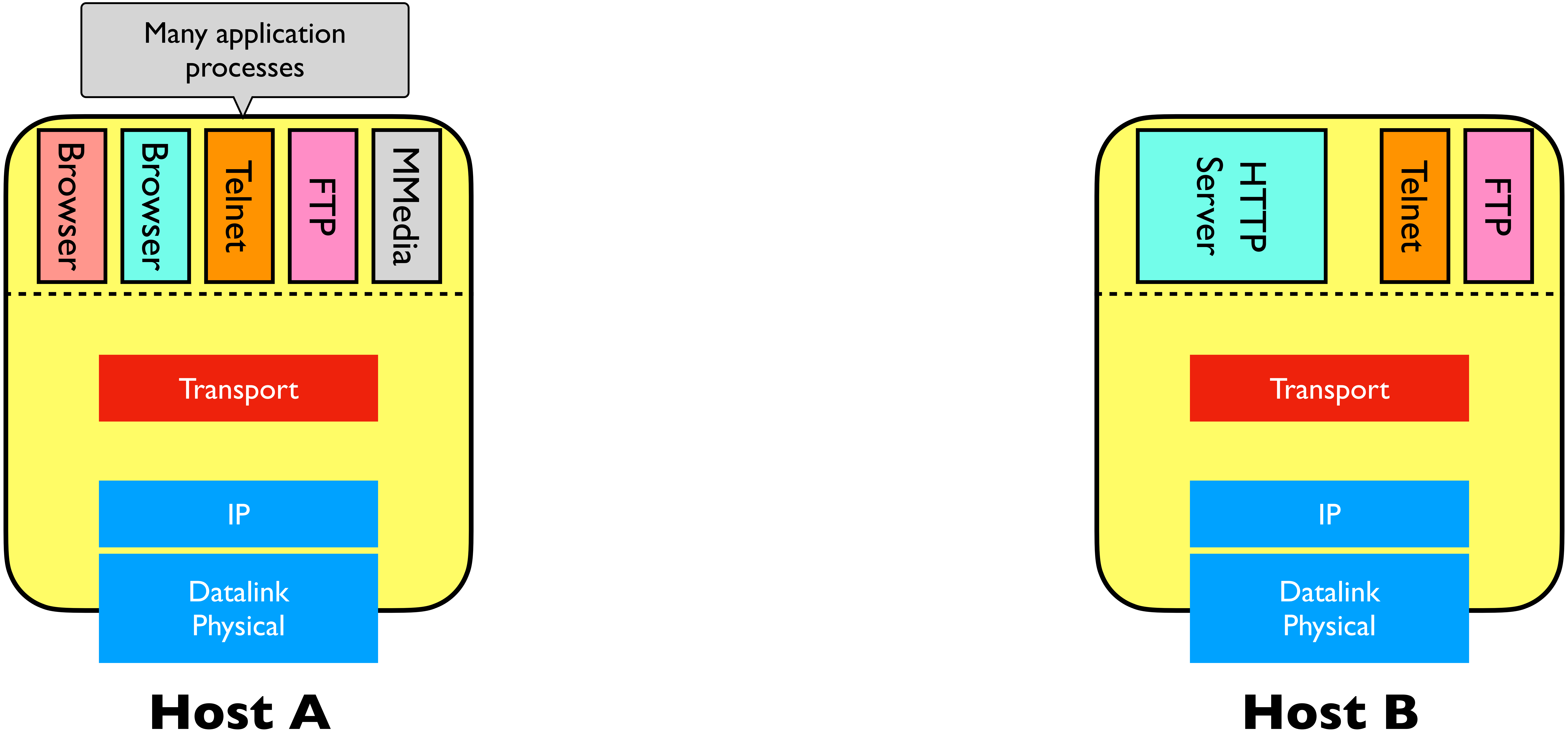

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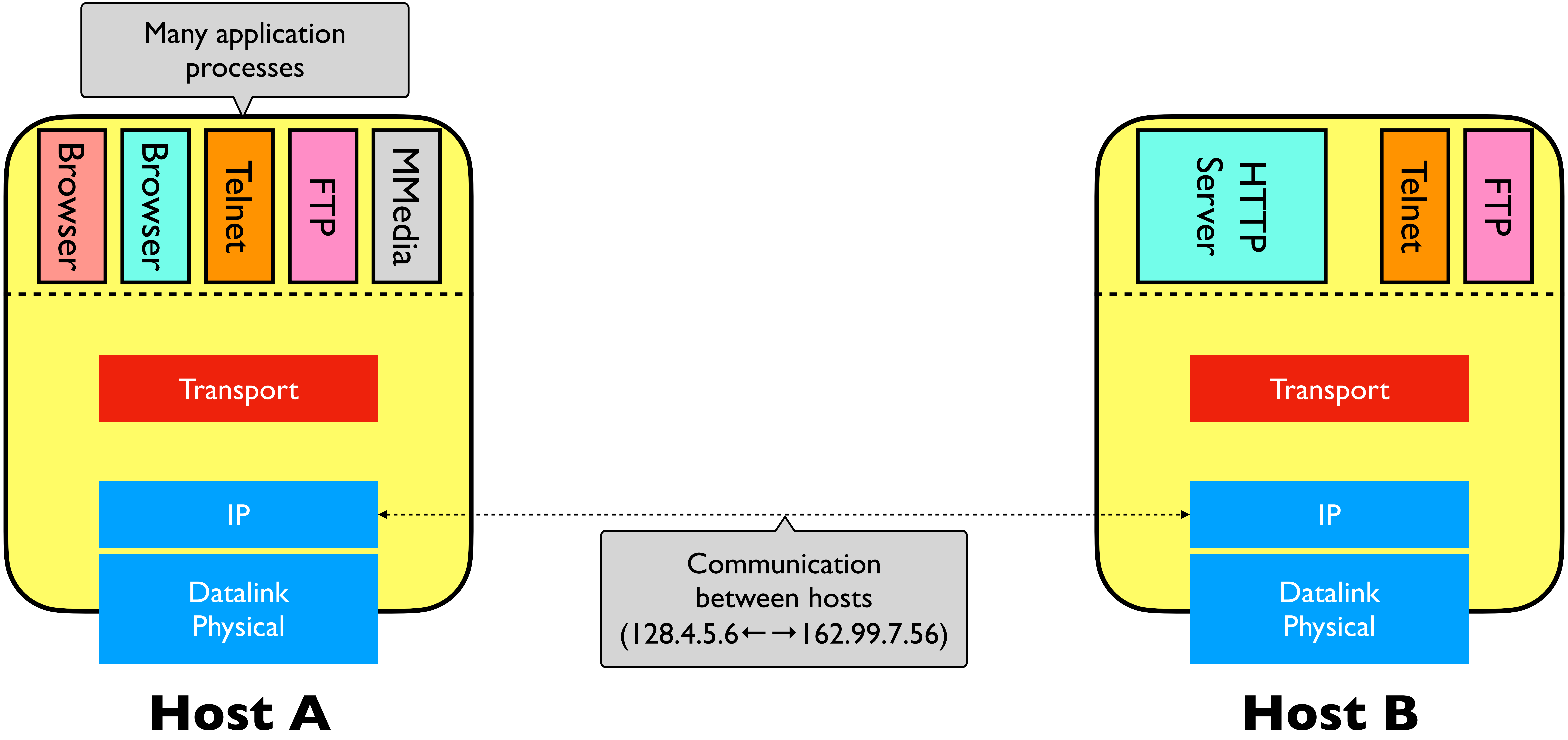

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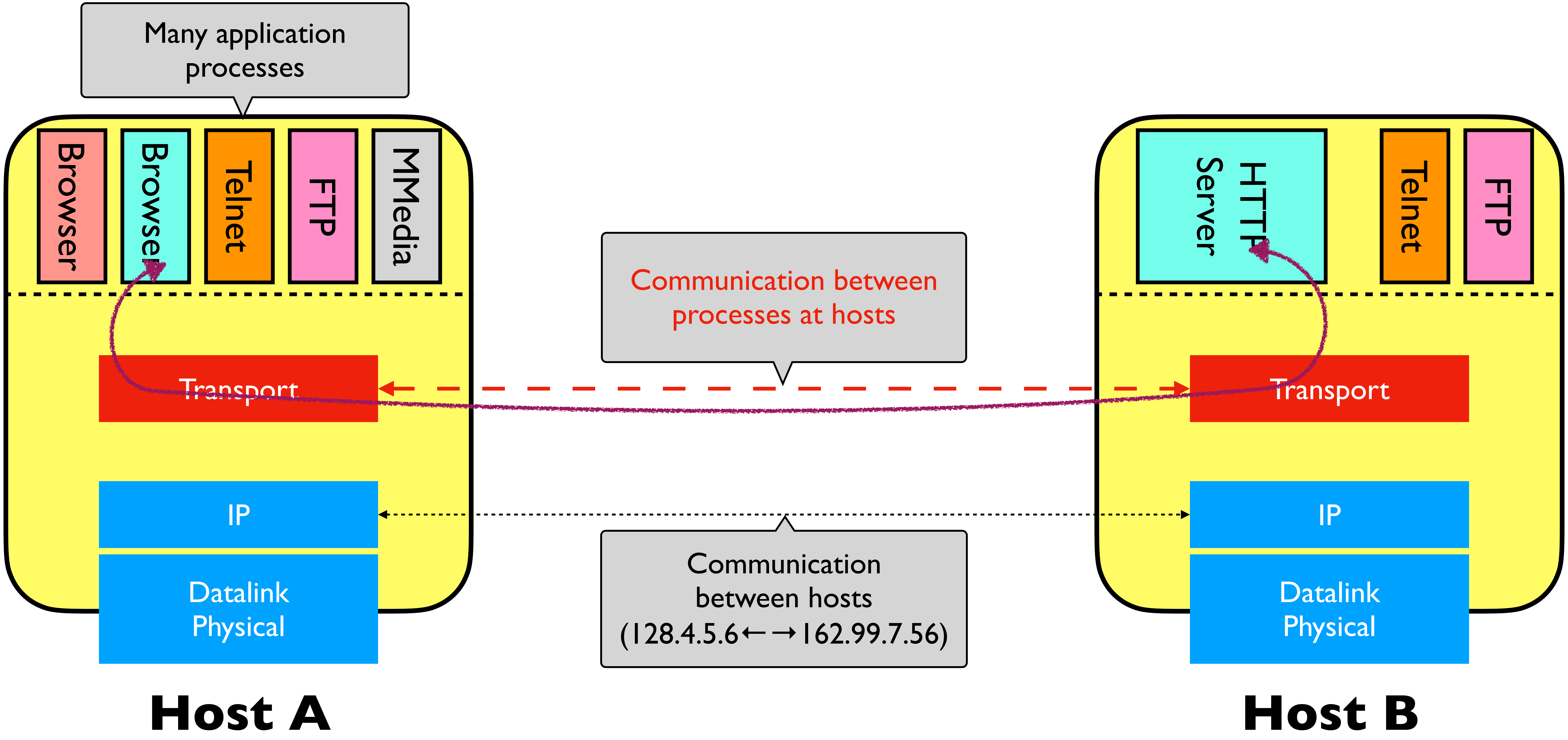

Why a Transport Layer: Improved Service Model

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- **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

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- **Communication between application processes**
  - Multiplex and demultiplex from/to application processes
  - Implemented using ***ports*** (not the same as router ports!)

Role of the Transport Layer

- **Communication between application processes**

- **Provide common end-to-end services for application layer [optional]**
  - Reliable, in-order data delivery
  - Well-placed data delivery
    - Too fast may overwhelm the network
    - Too slow is not efficient

Role of the Transport Layer

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

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- **UDP is a minimalist, no-frills transport protocol**
  - Only provides multiplex/demultiplex capabilities

Role of the Transport Layer

- **Communication between application processes**
- **Provide common end-to-end services for application 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 applications a reliable, in-order, byte stream abstraction
  - With congestion control
  - But no performance guarantees (delay, bw, etc.)

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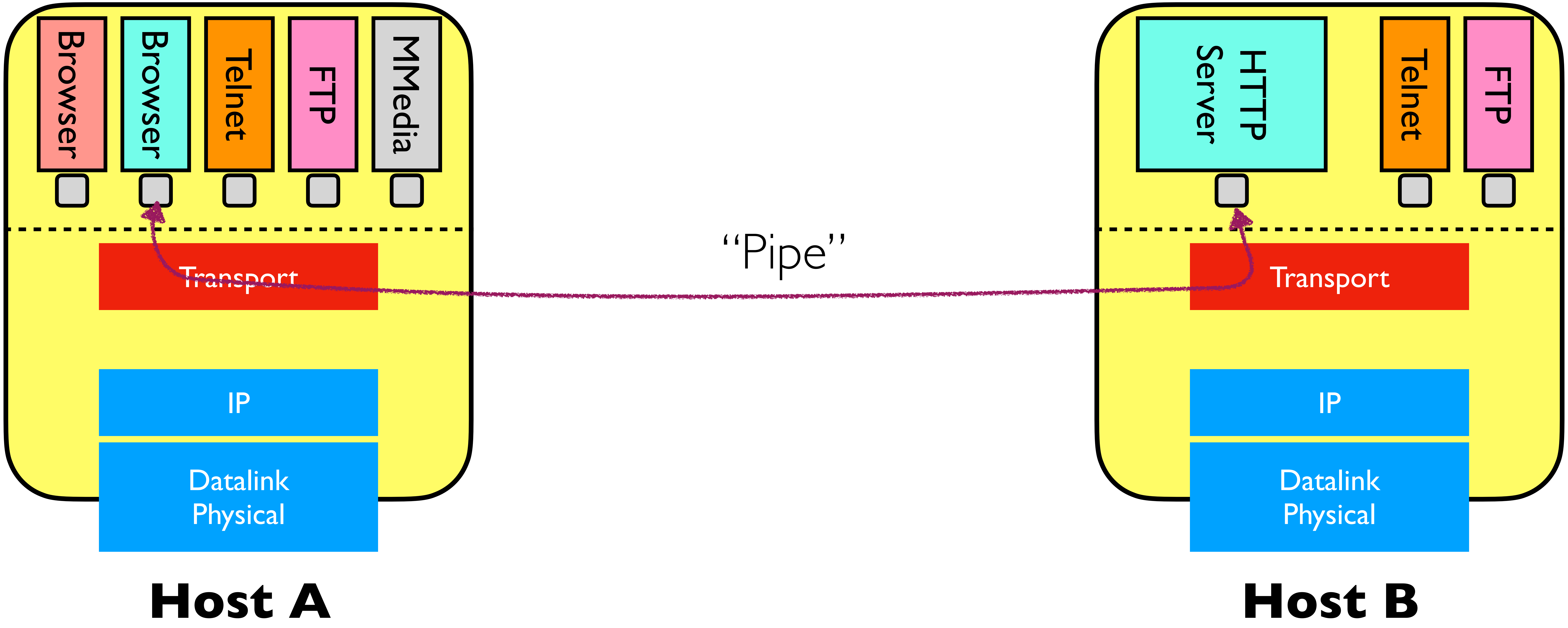

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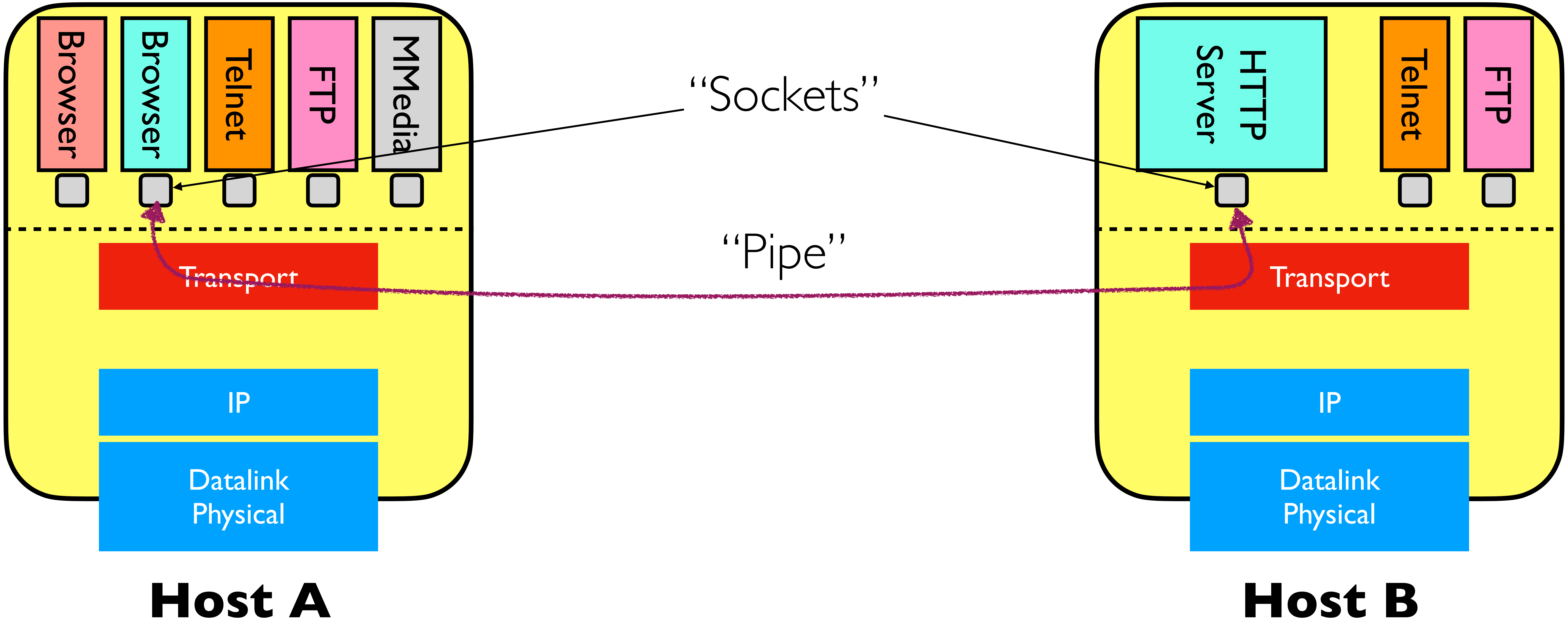

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- **Unreliable packet delivery:** User Datagram Protocol (UDP)
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- **Unreliable packet delivery:** User Datagram Protocol (UDP)
  - Messages are limited to a single packet ("datagrams")
  - Pipe is "leaky": applications need to deal with leaks (lost/corrupted datagrams)
- **Reliable byte stream:** Transmission Control Protocol (TCP)
  - Bytes inserted into pipe by sender
  - They emerge, in order, at the receiver (to the application)

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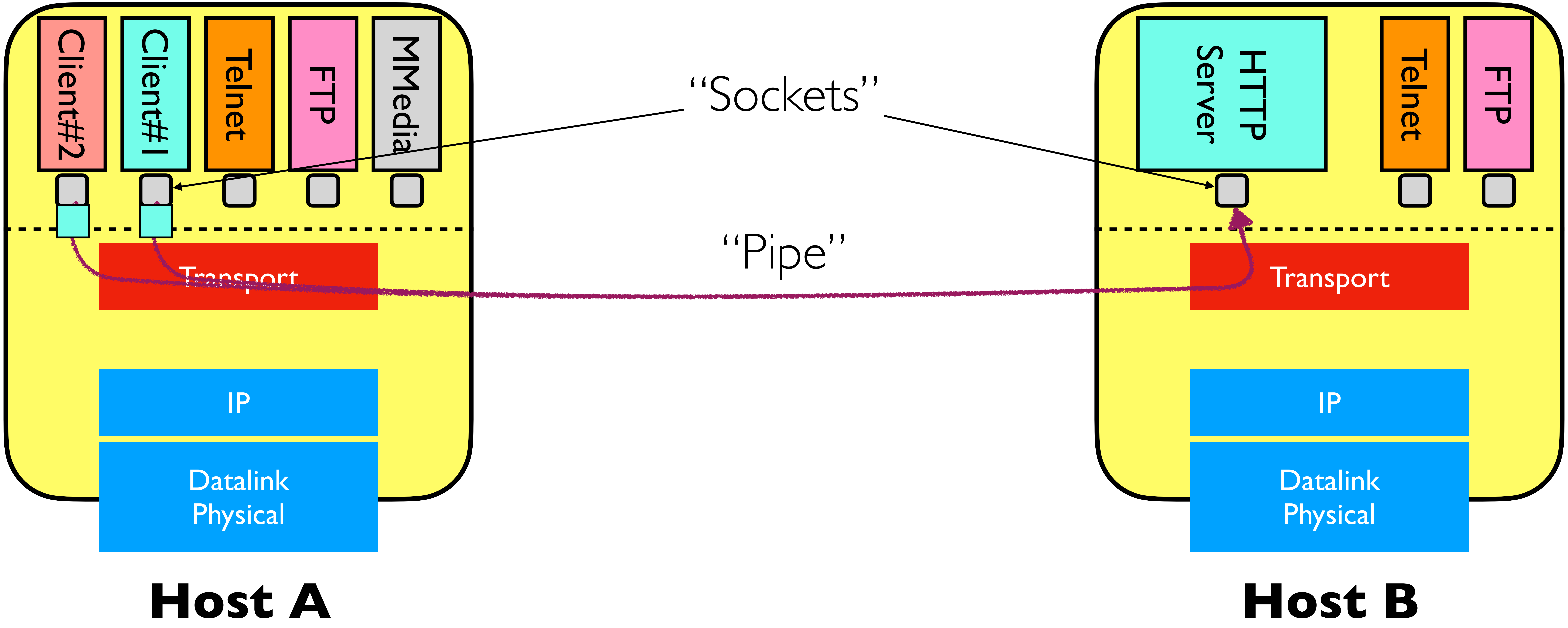

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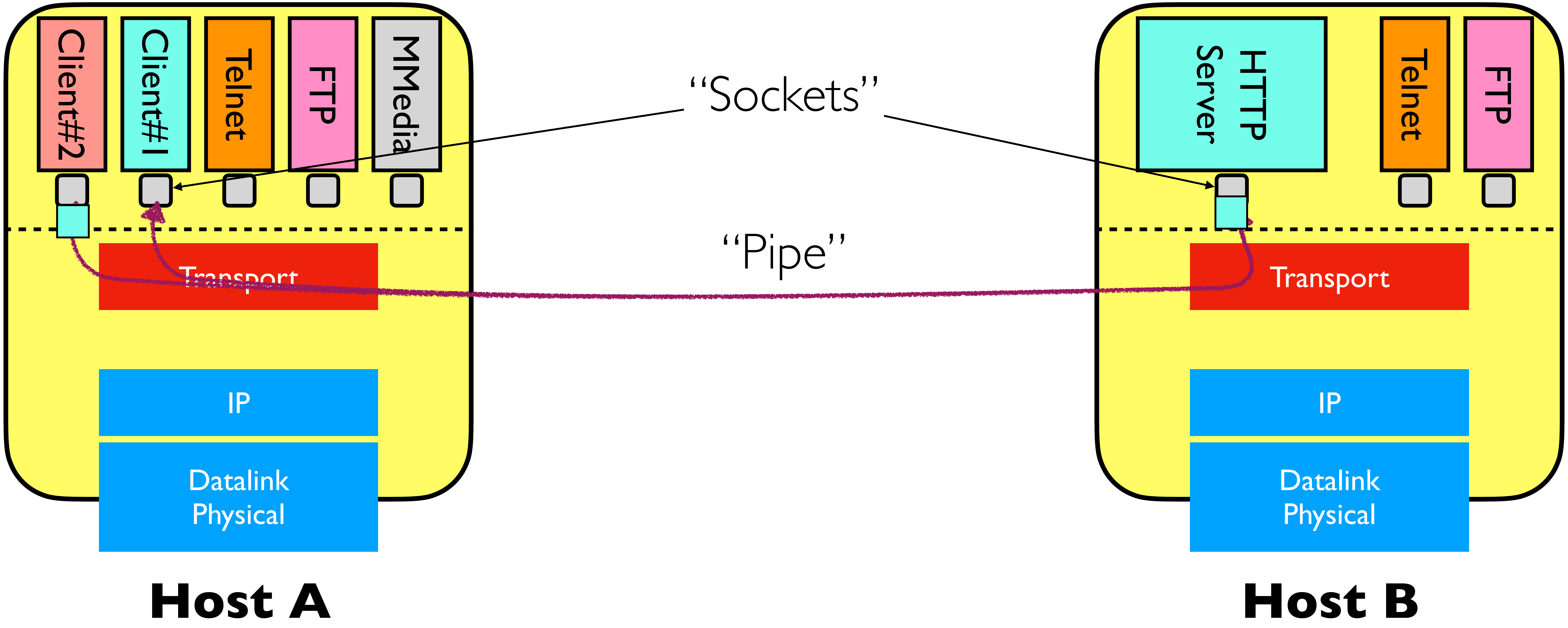

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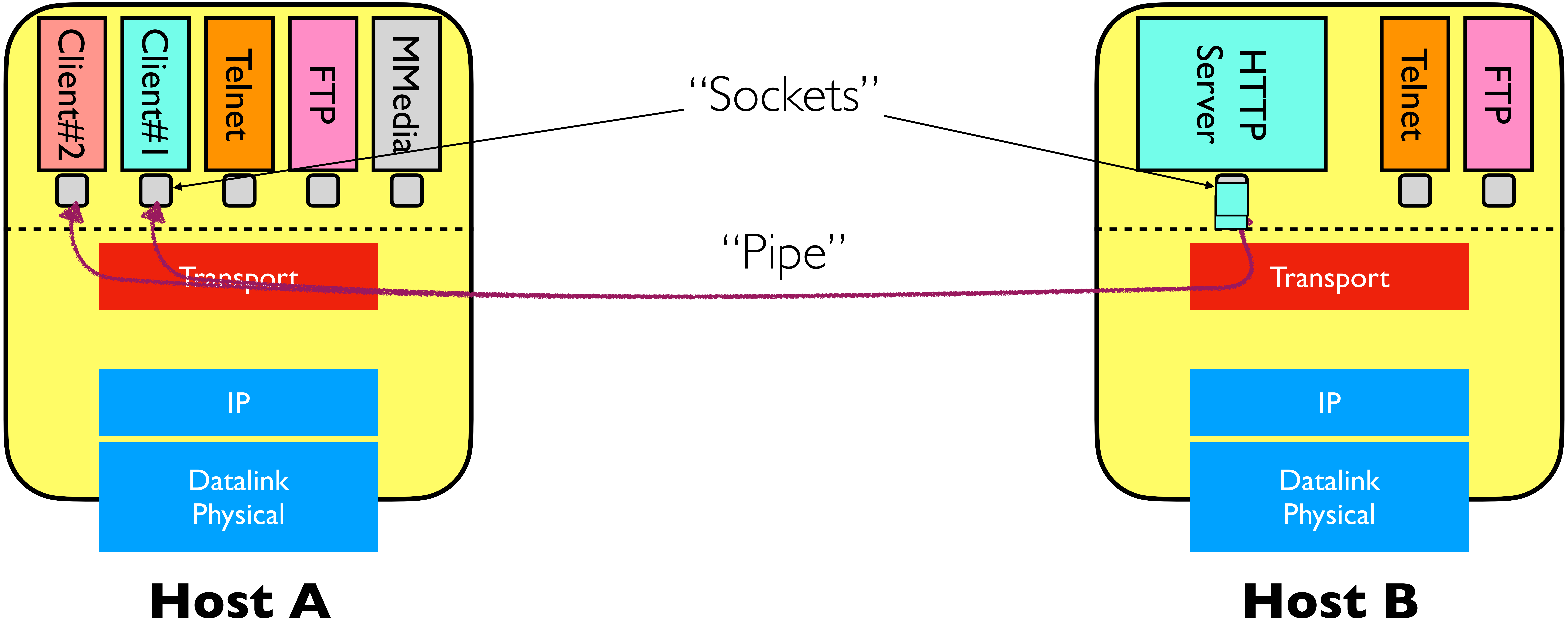

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    - Flow control (to prevent overwhelming receiver) [source]
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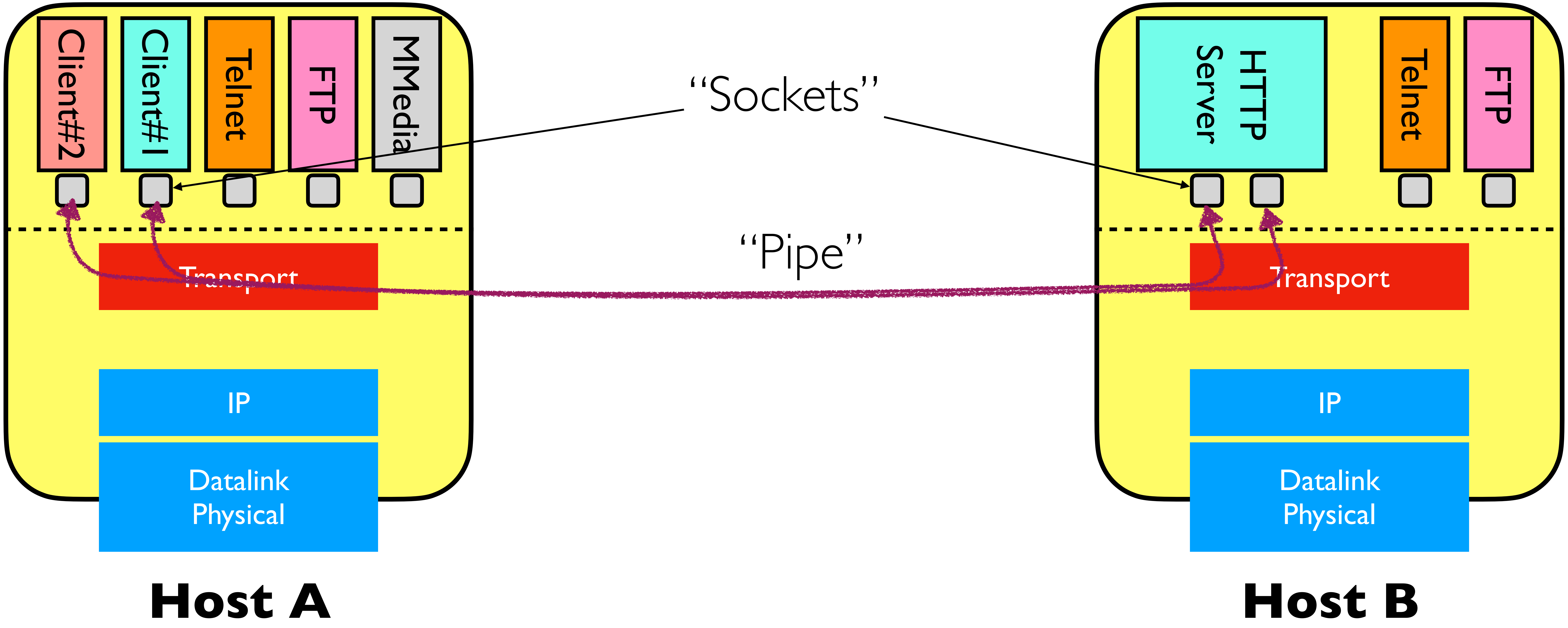
- Every source-destination pair has a dedicated stream oriented “connection” (or “session”)

Abstraction: Pipes & Sockets



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

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- **Q: Why the difference?**

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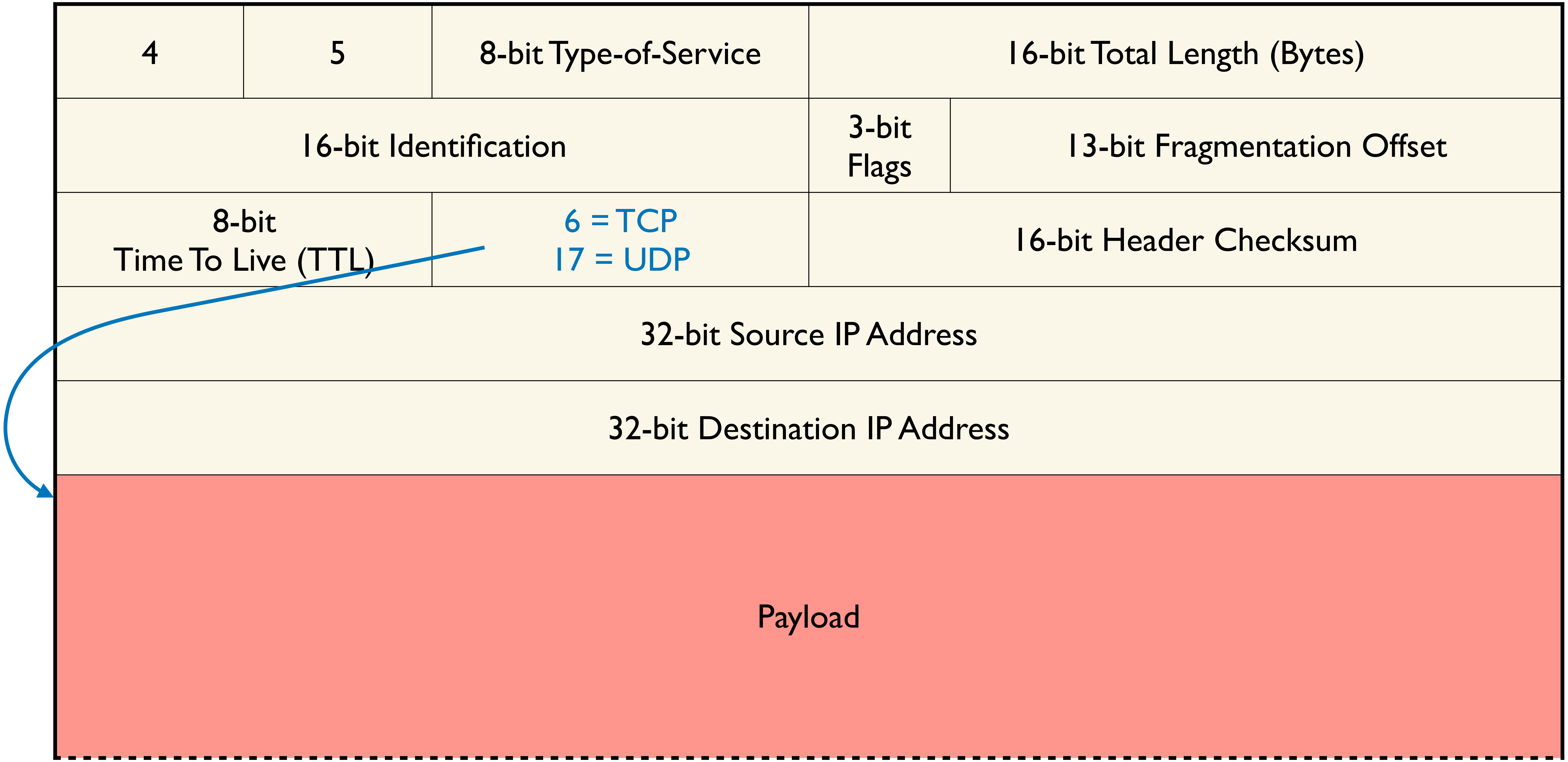
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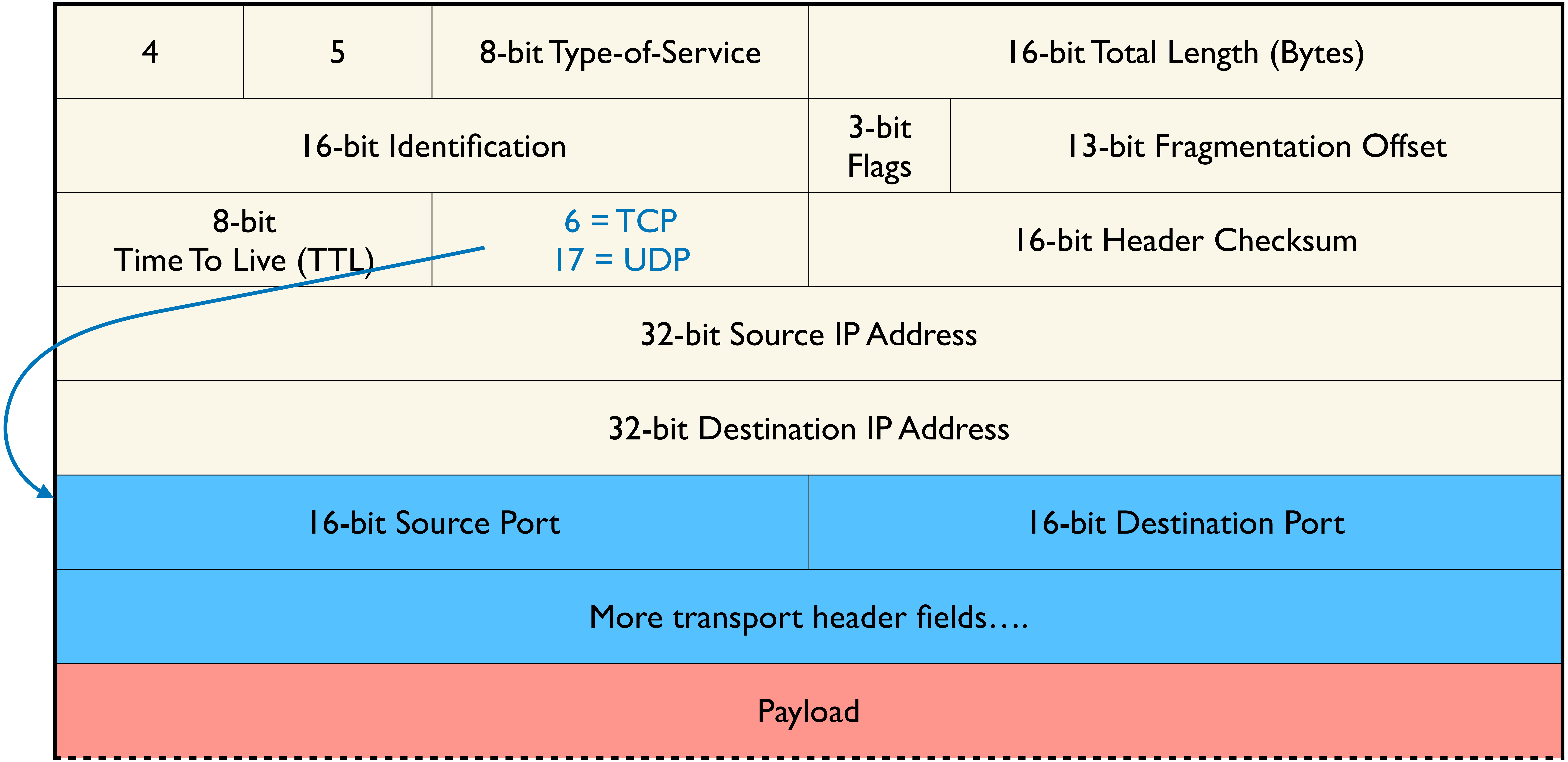
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More transport header fields….
Payload

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  - Helps client know server’s port
  - Services can listen on well-known ports

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  - e.g., ssh:22, http:80
  - Helps client know server's port
  - Services can listen on well-known ports
- **Ephemeral ports (most of 1024-65535):** given to clients

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- **Host receives IP packets**
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  - Each Transport Layer header has source and destination port number

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- **Host receives IP packets**
  - Each IP header has source and destination IP address
  - Each Transport Layer header has source and destination port number
- **Host uses IP addresses and port numbers to direct the message to appropriate socket**
  - UDP maps local destination port and address to socket
  - TCP maps address pair and port pair to socket

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*)
- **IP provides a weak service model (*best-effort*)**
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Rest of Lecture

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- **Reliable Transport**

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- **Next Lecture: Details of TCP**

Reliable Transport

- **In a perfect world, reliable transport is easy**

@Sender
- Send packets

@Receiver
- Wait for packets

Reliable Transport

- **In a perfect world, reliable transport is easy**
- **All the bad things "best-effort" can permit:**
  - A packet is corrupted (bit errors)
  - A packet is lost (*why?*)
  - A packet is delayed (*why?*)
  - Packets are reordered (*why?*)
  - A packet is duplicated (*why?*)

Reliable Transport

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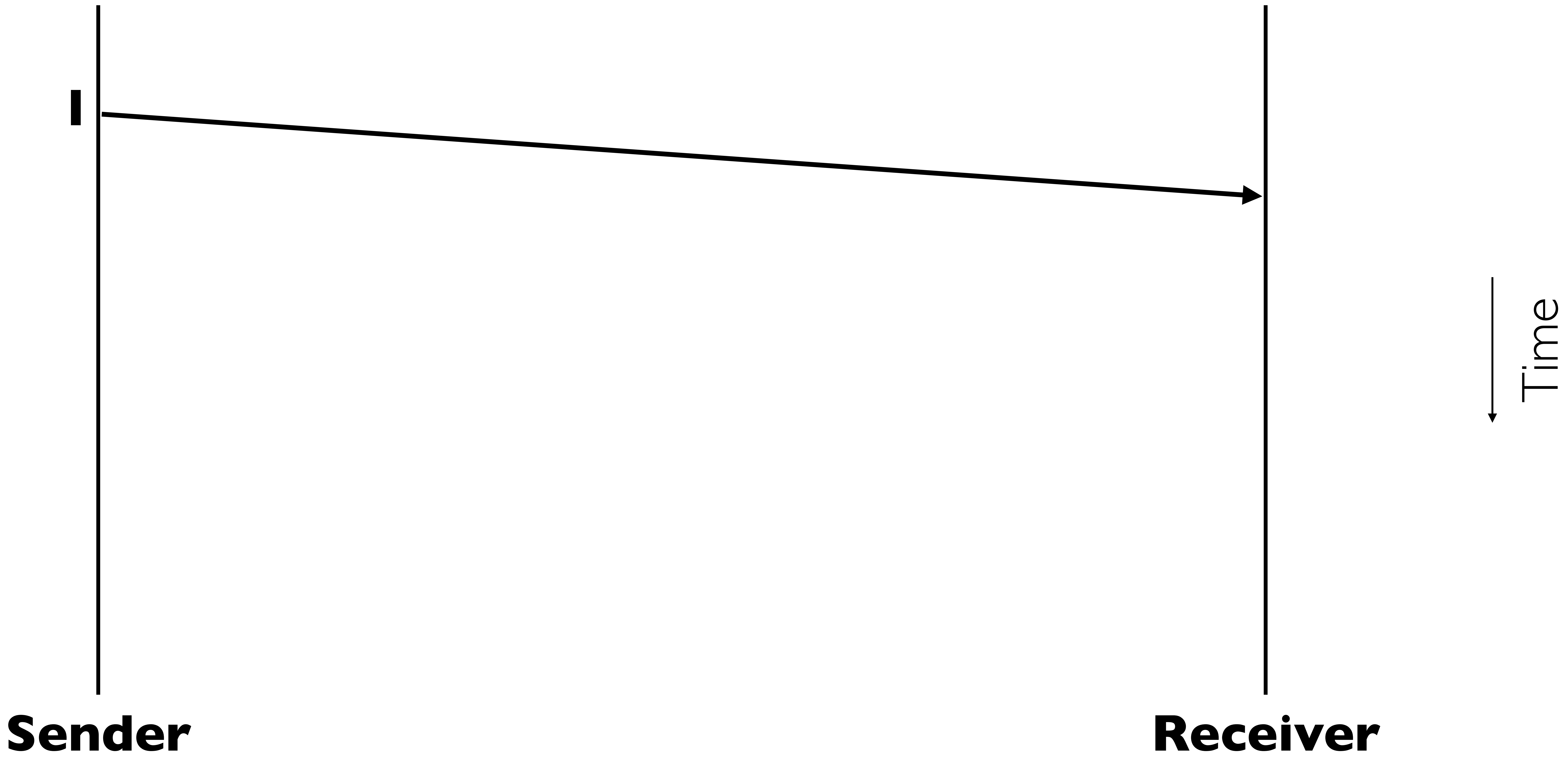

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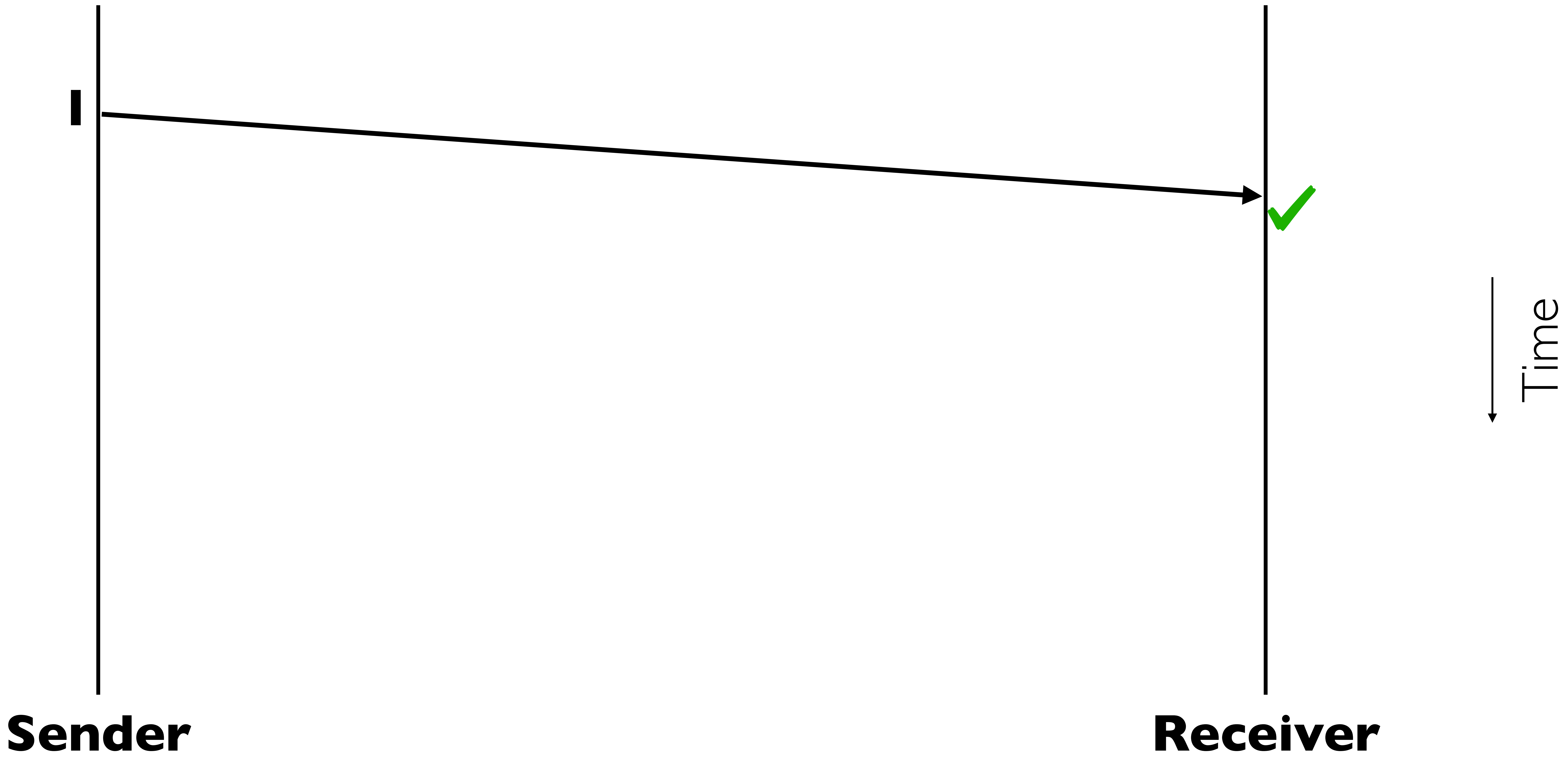

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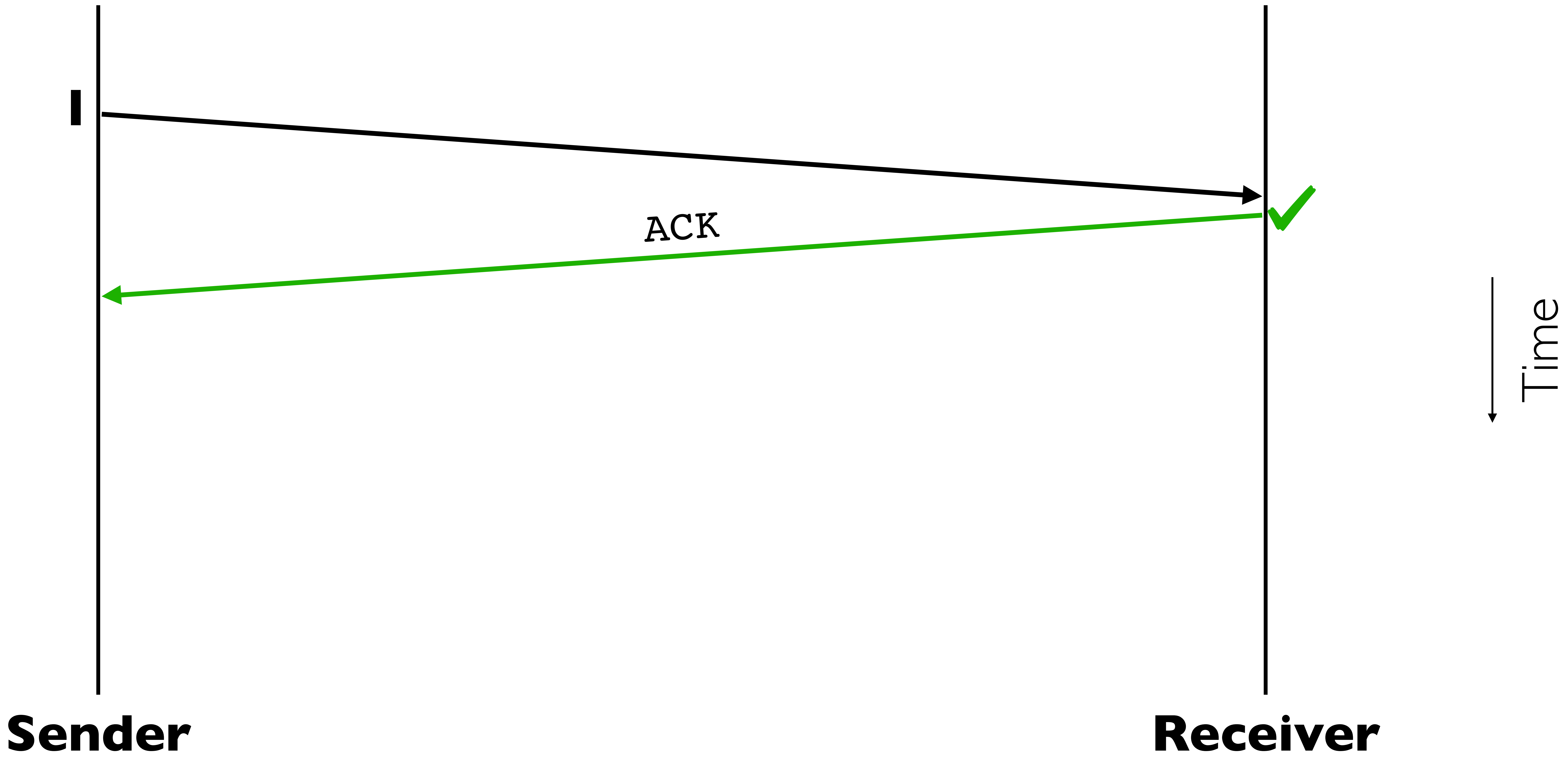

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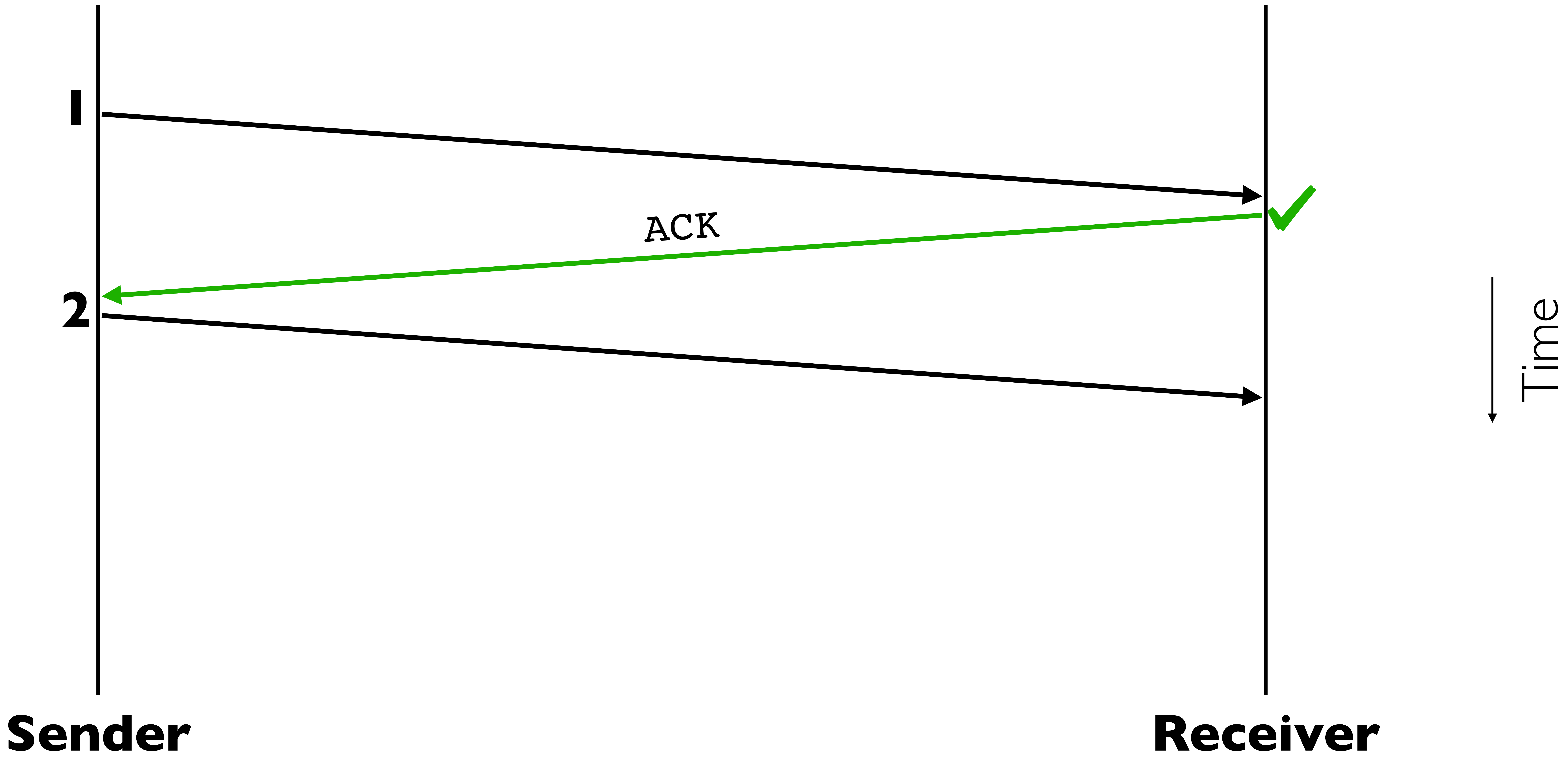

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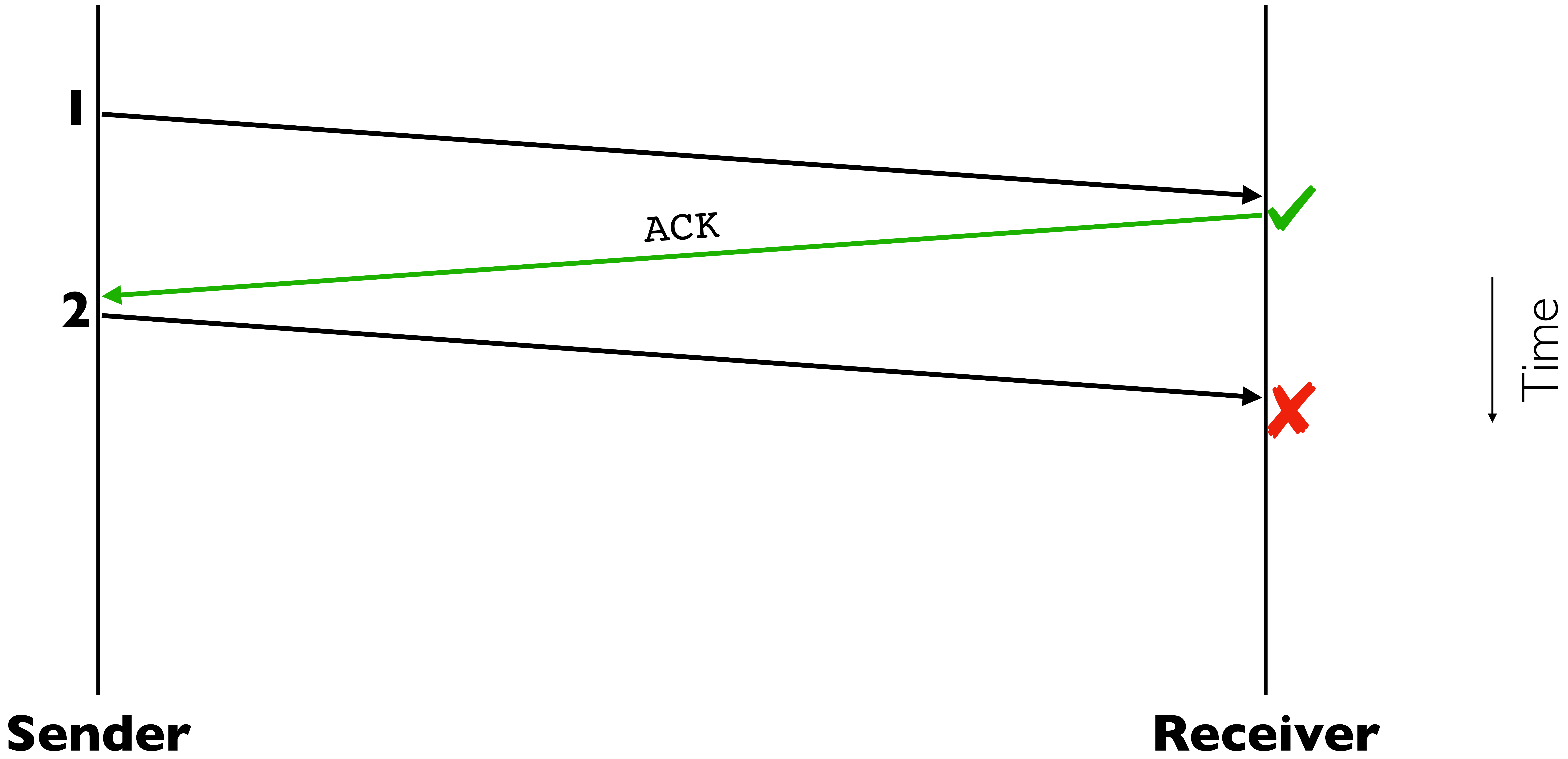

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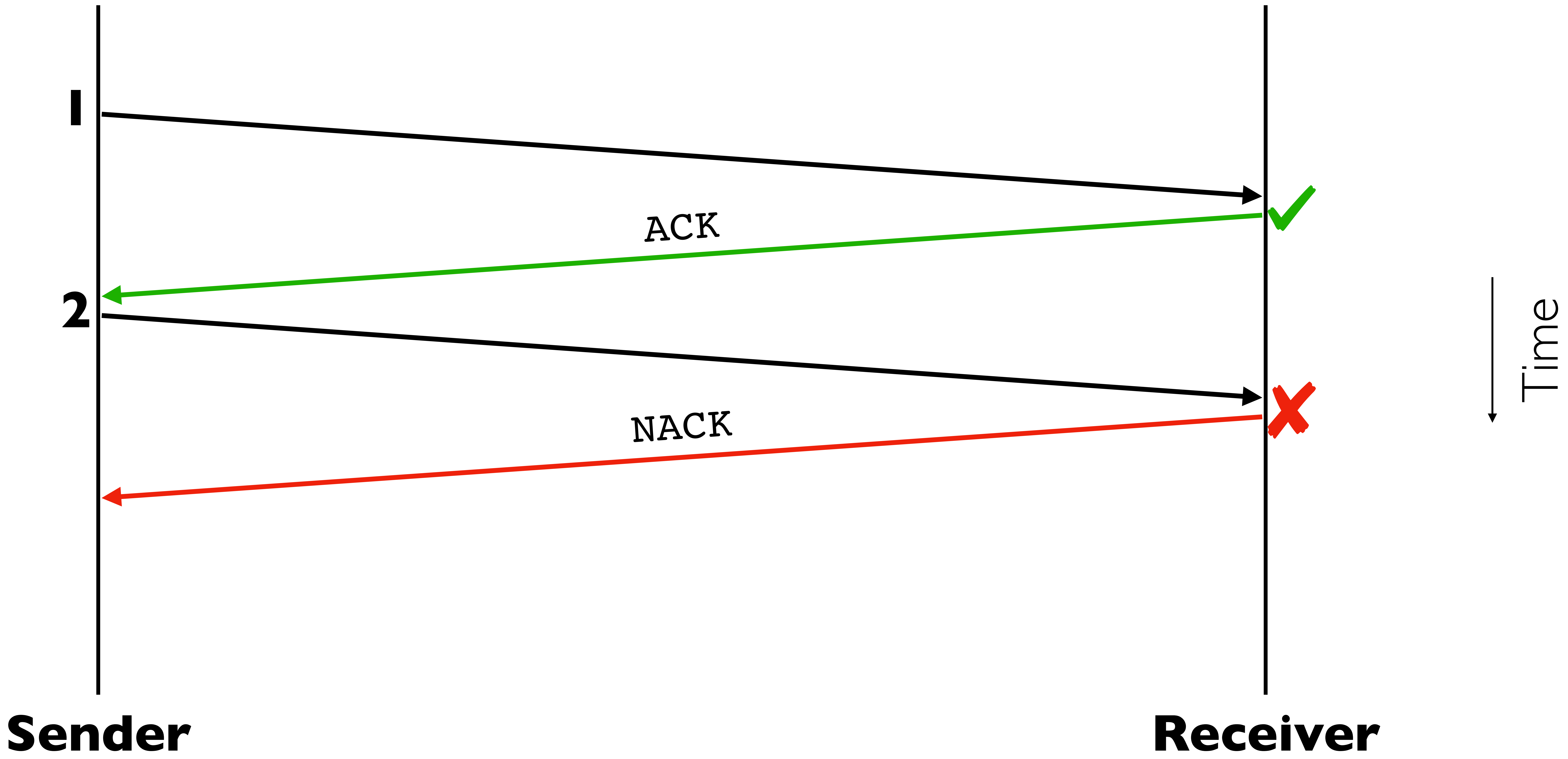

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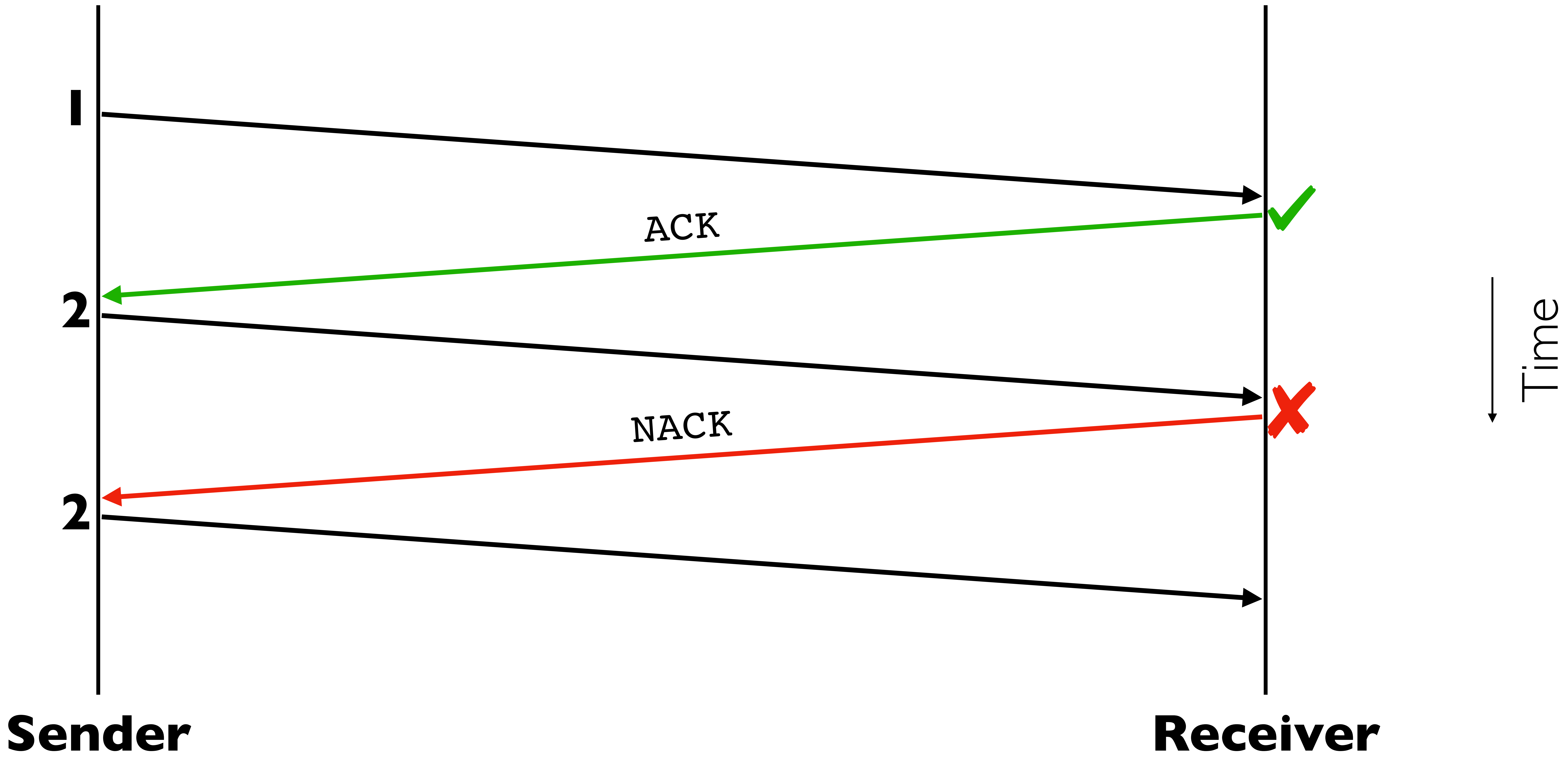

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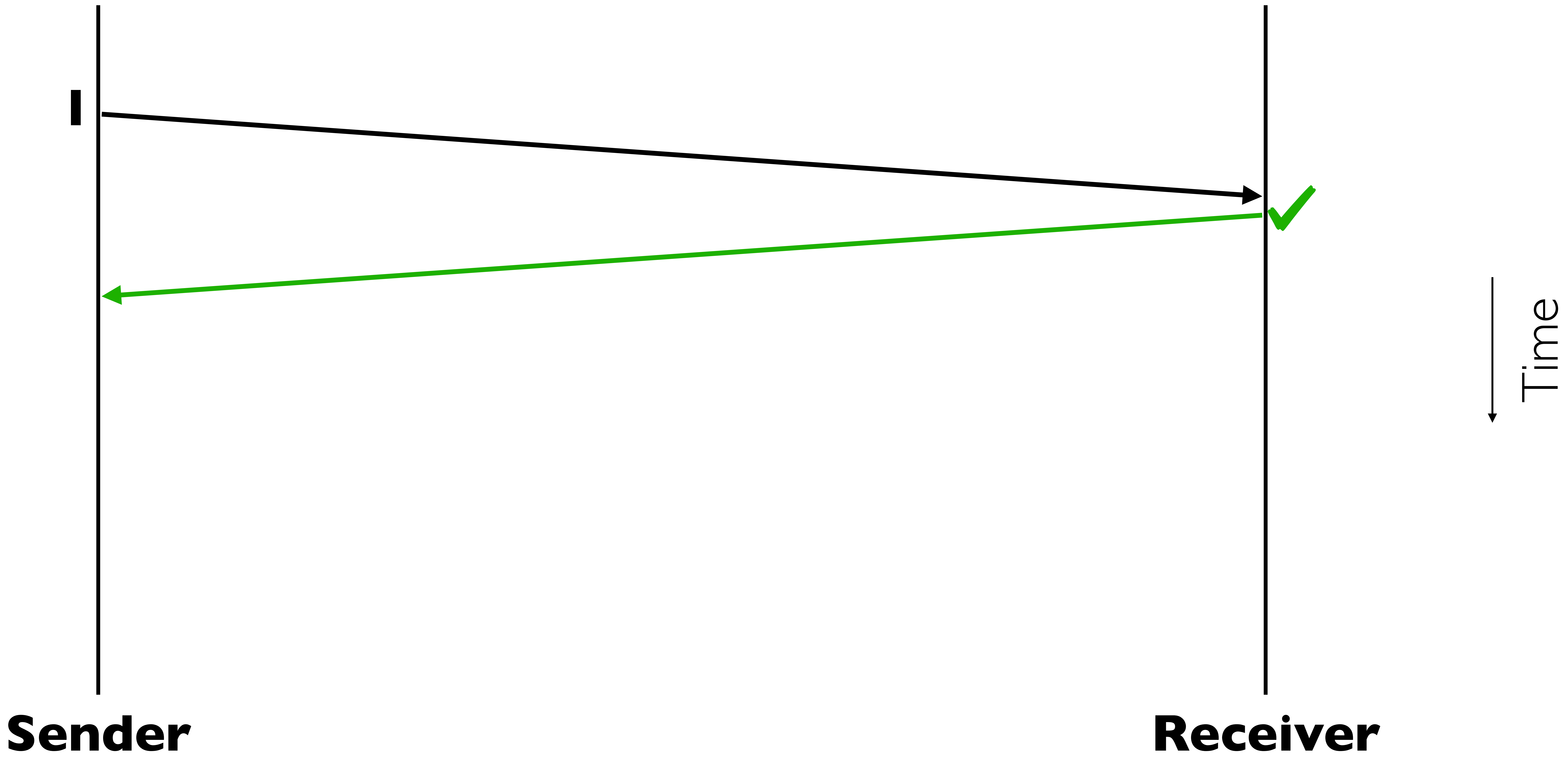

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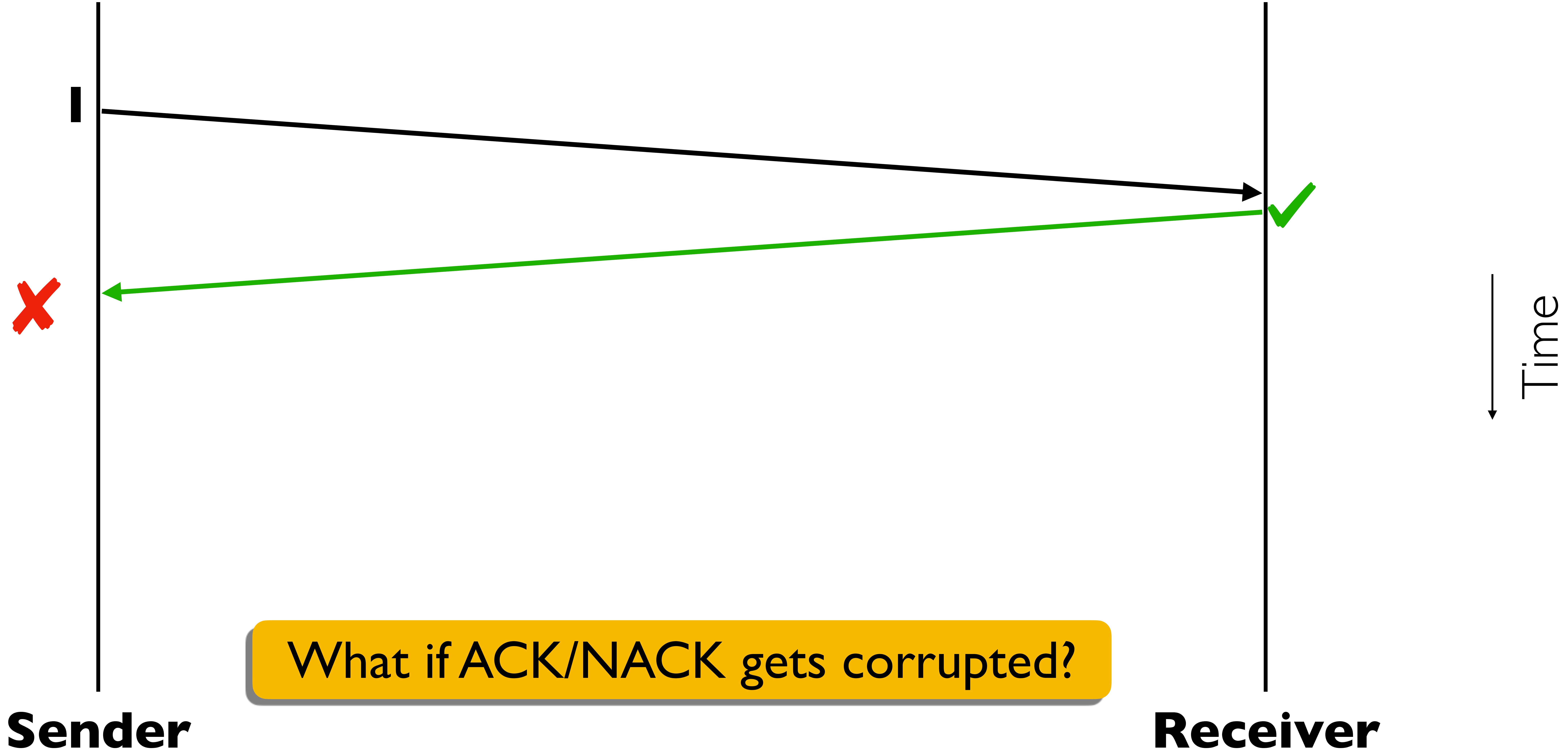

What if ACK/NACK gets corrupted?

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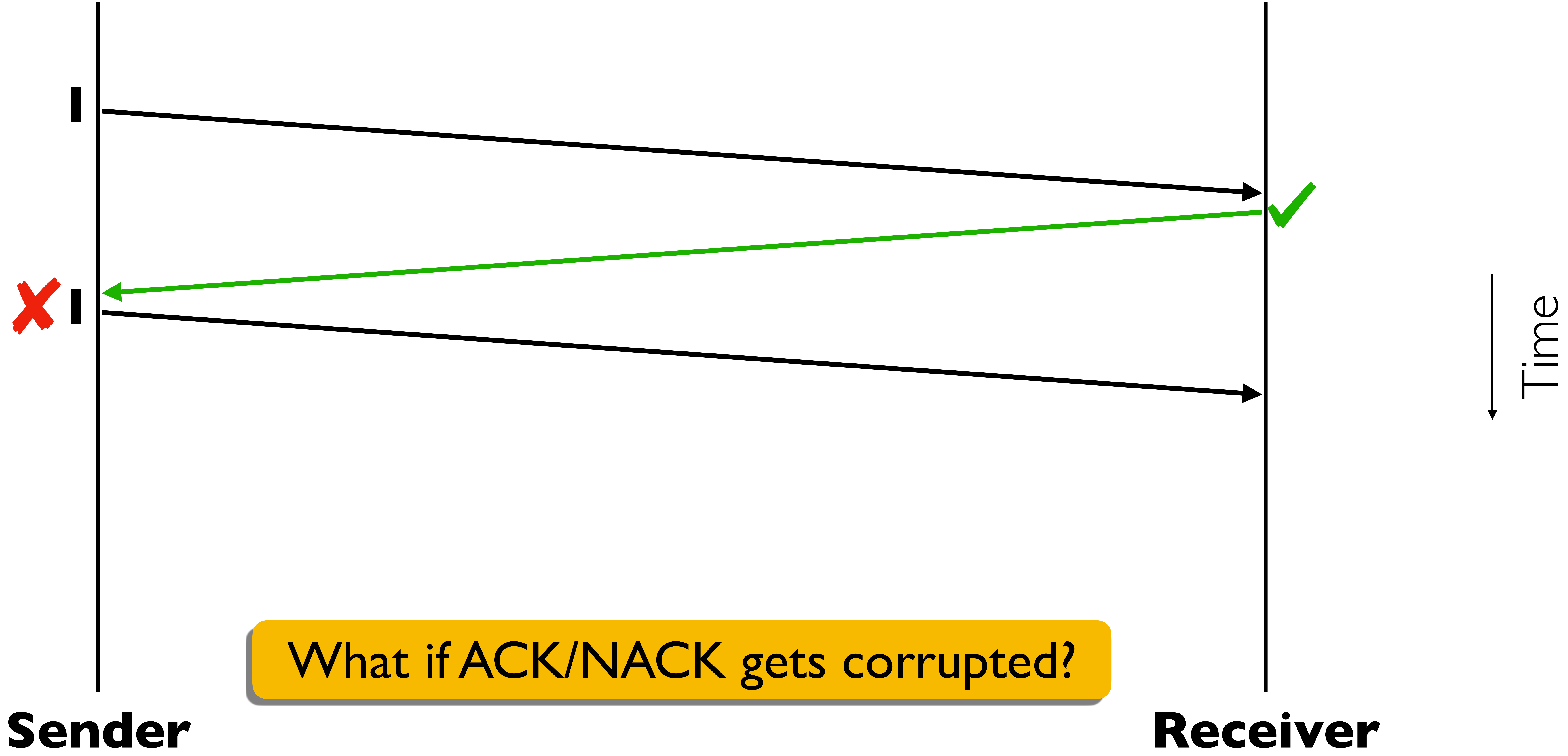

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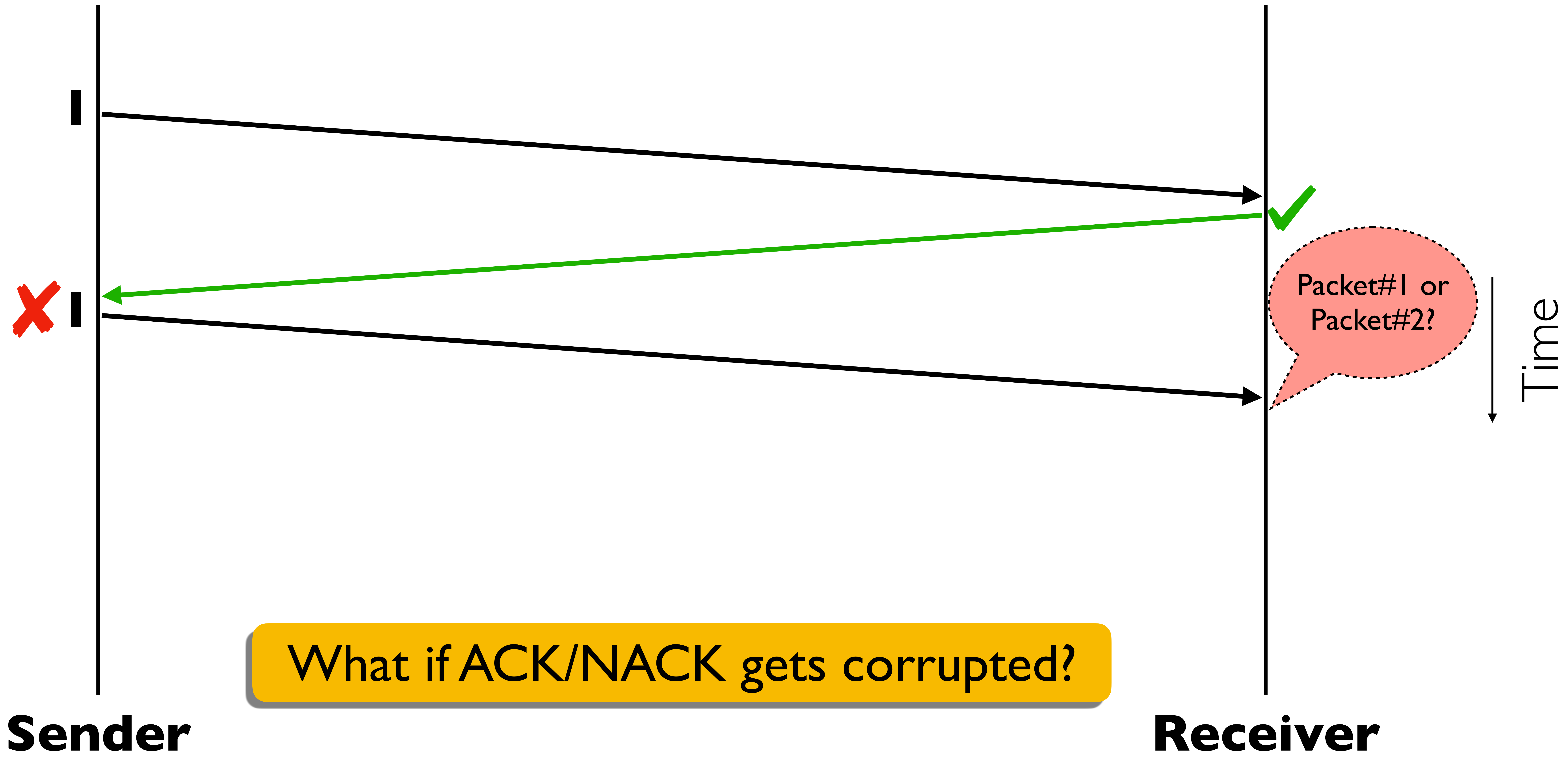

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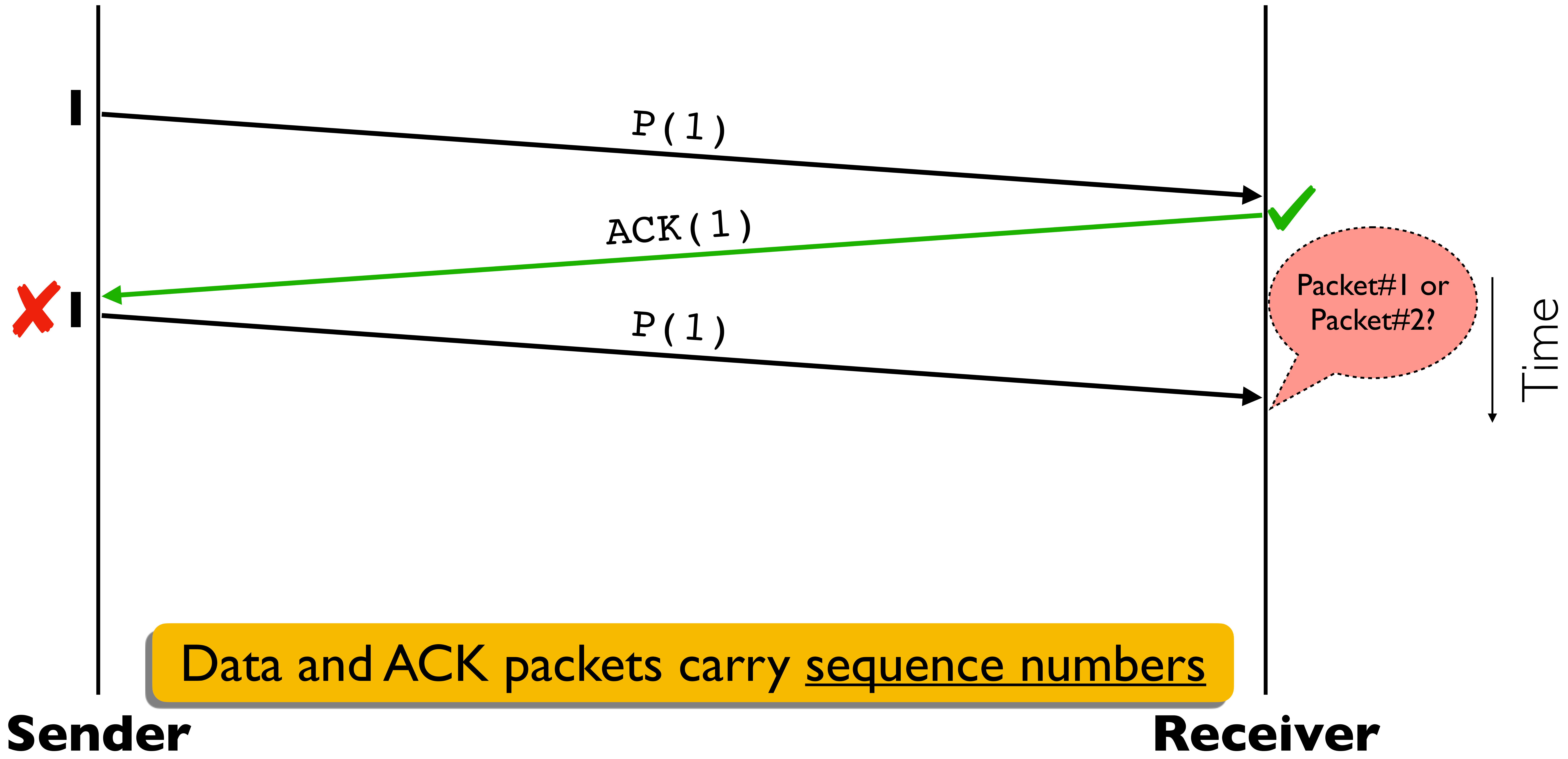

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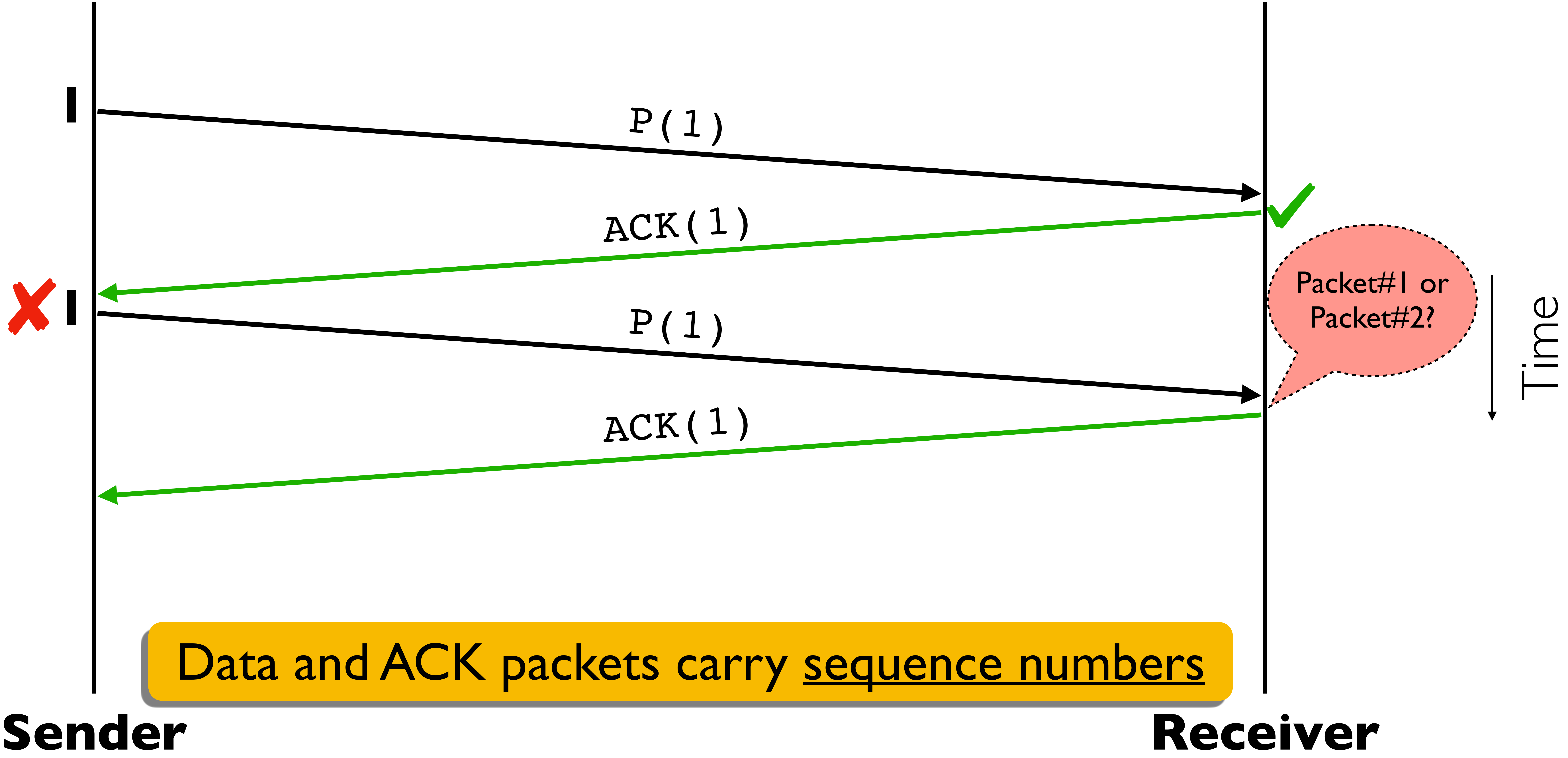
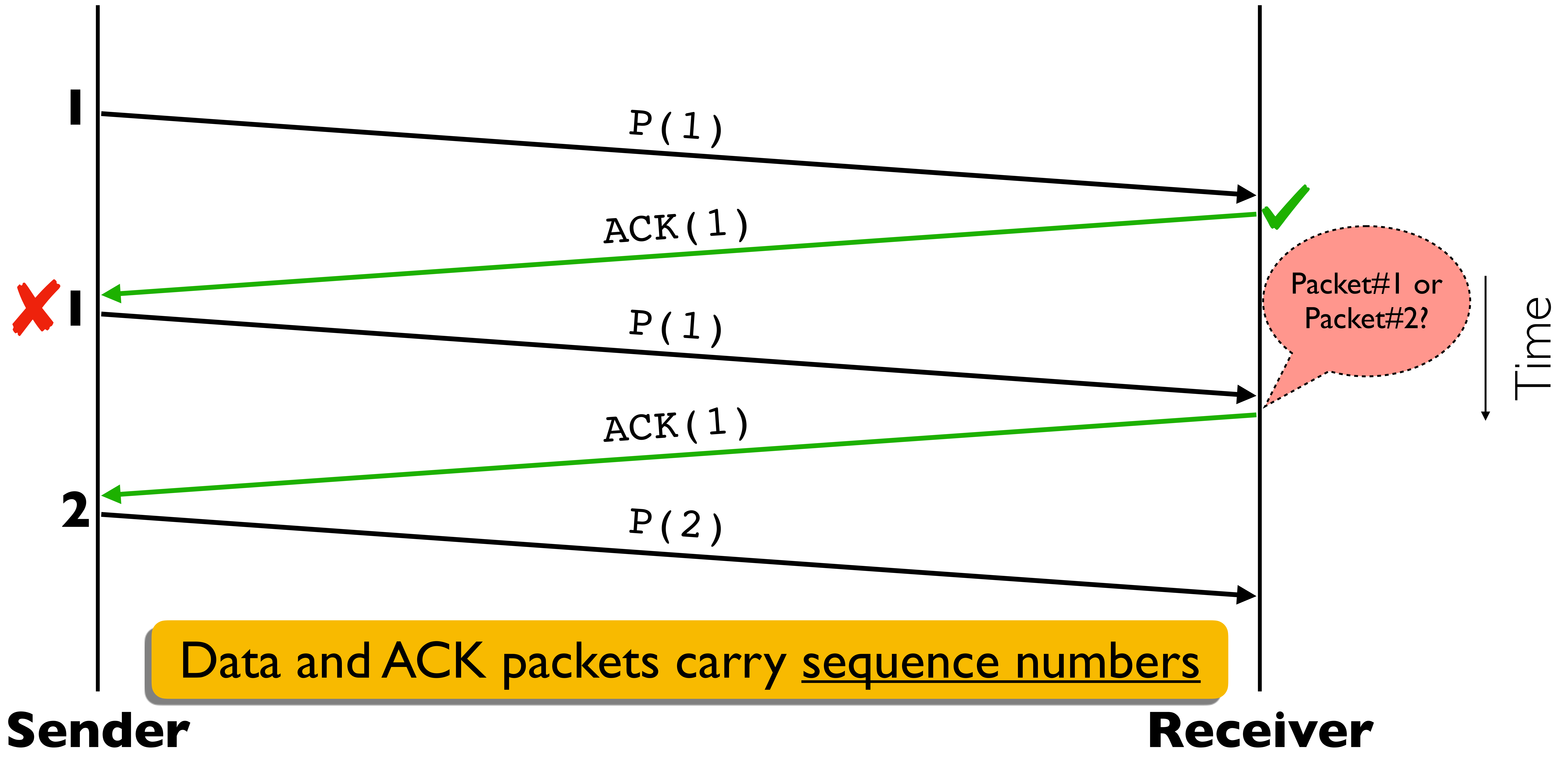


Data and ACK packets carry sequence numbers

Dealing with Packet Corruption



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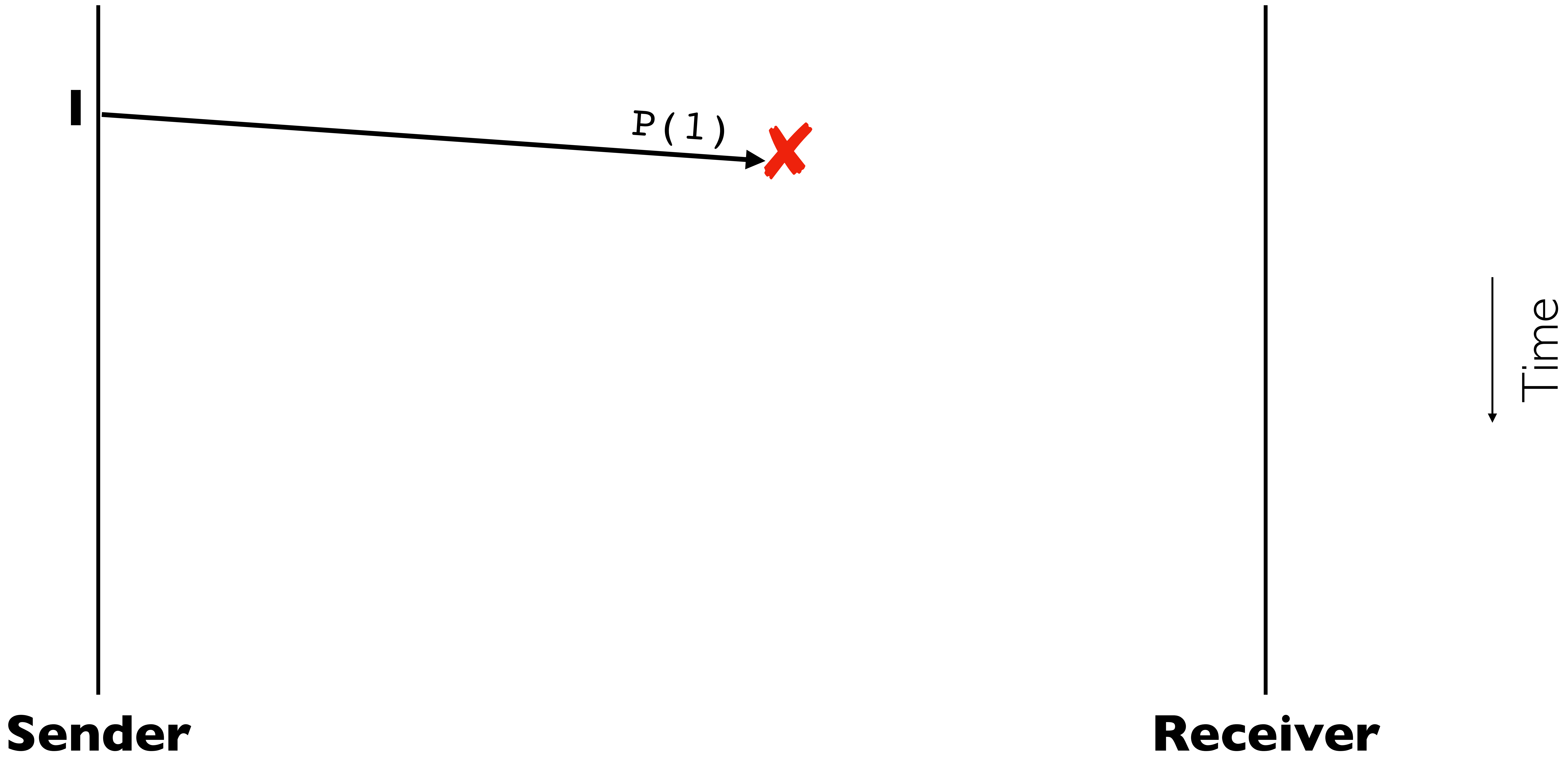

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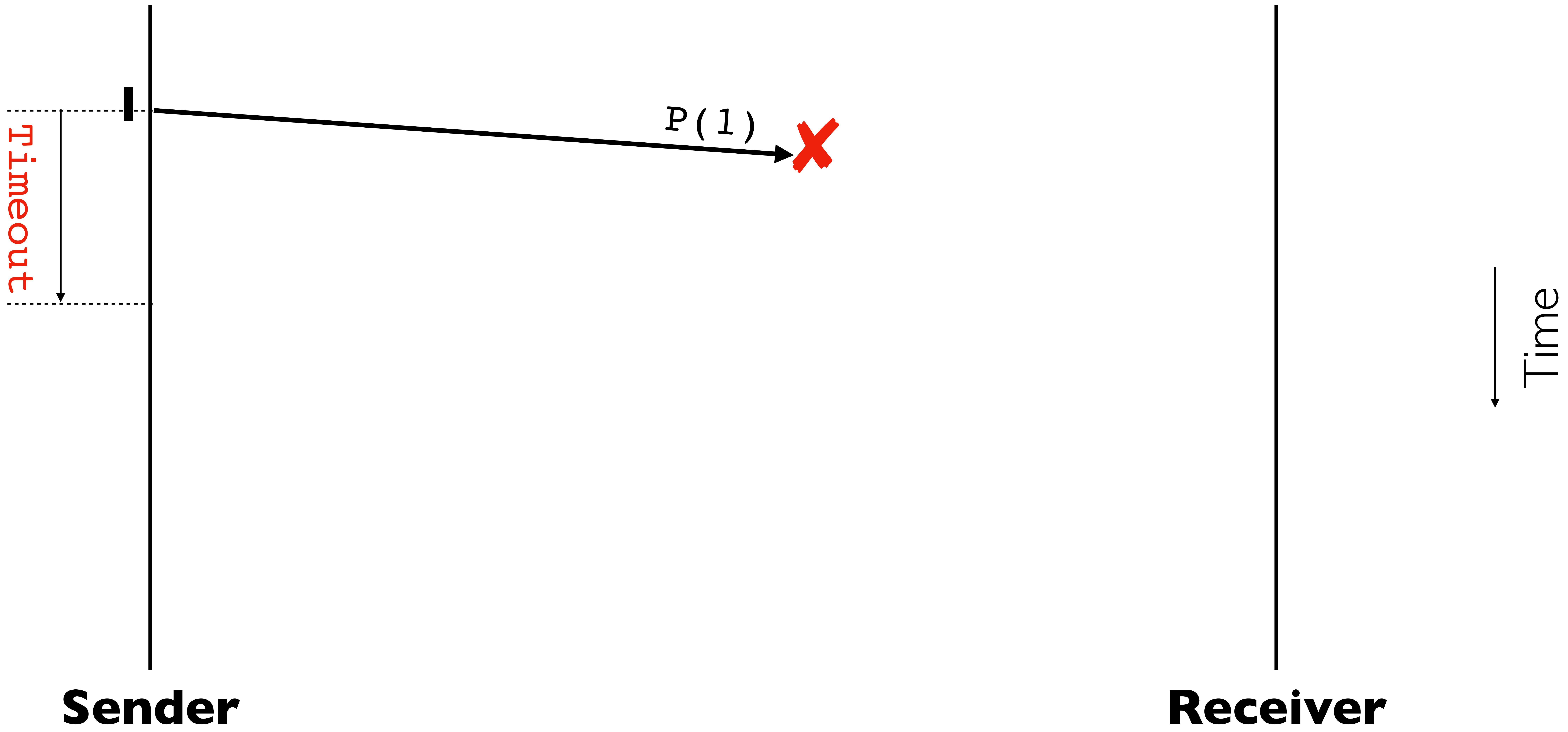

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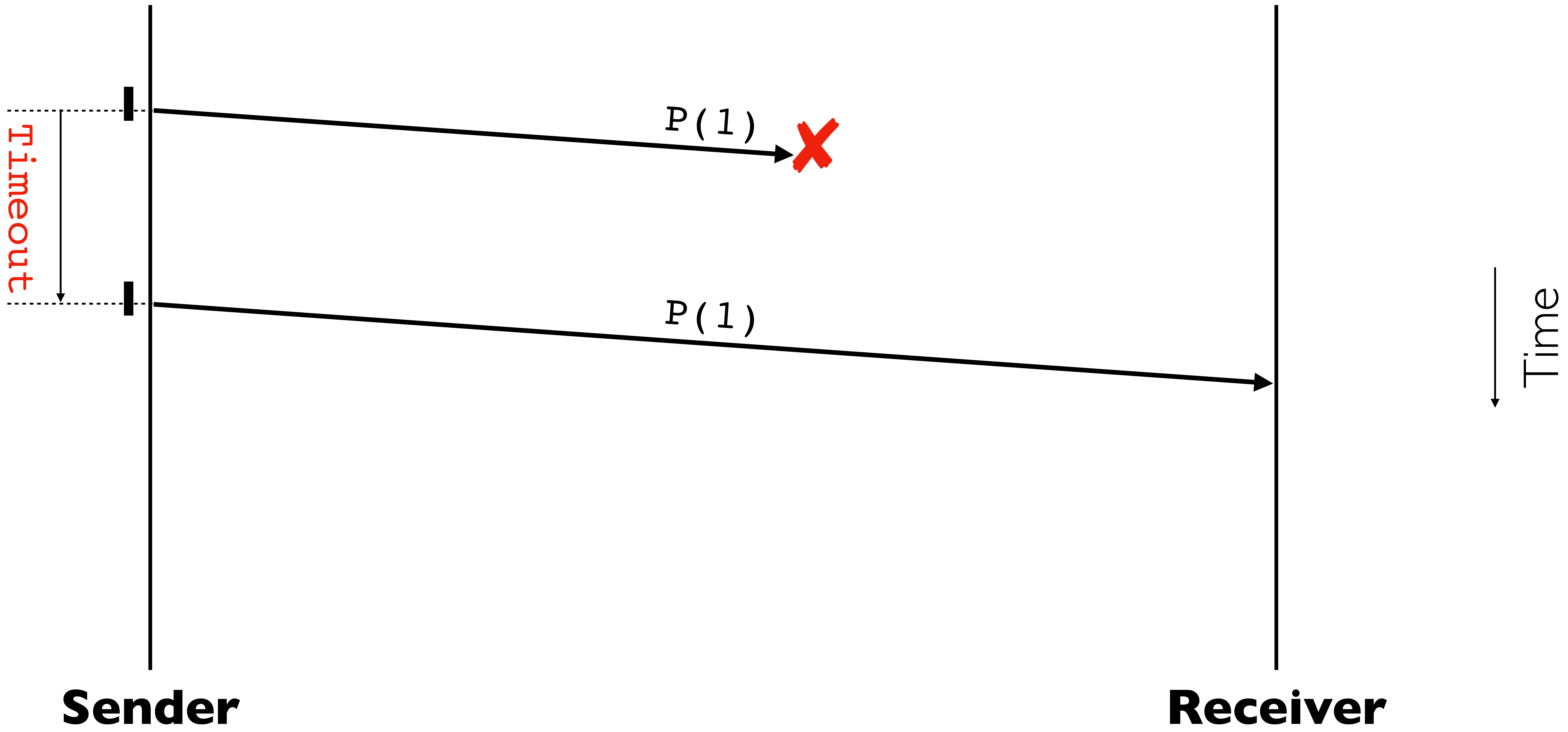

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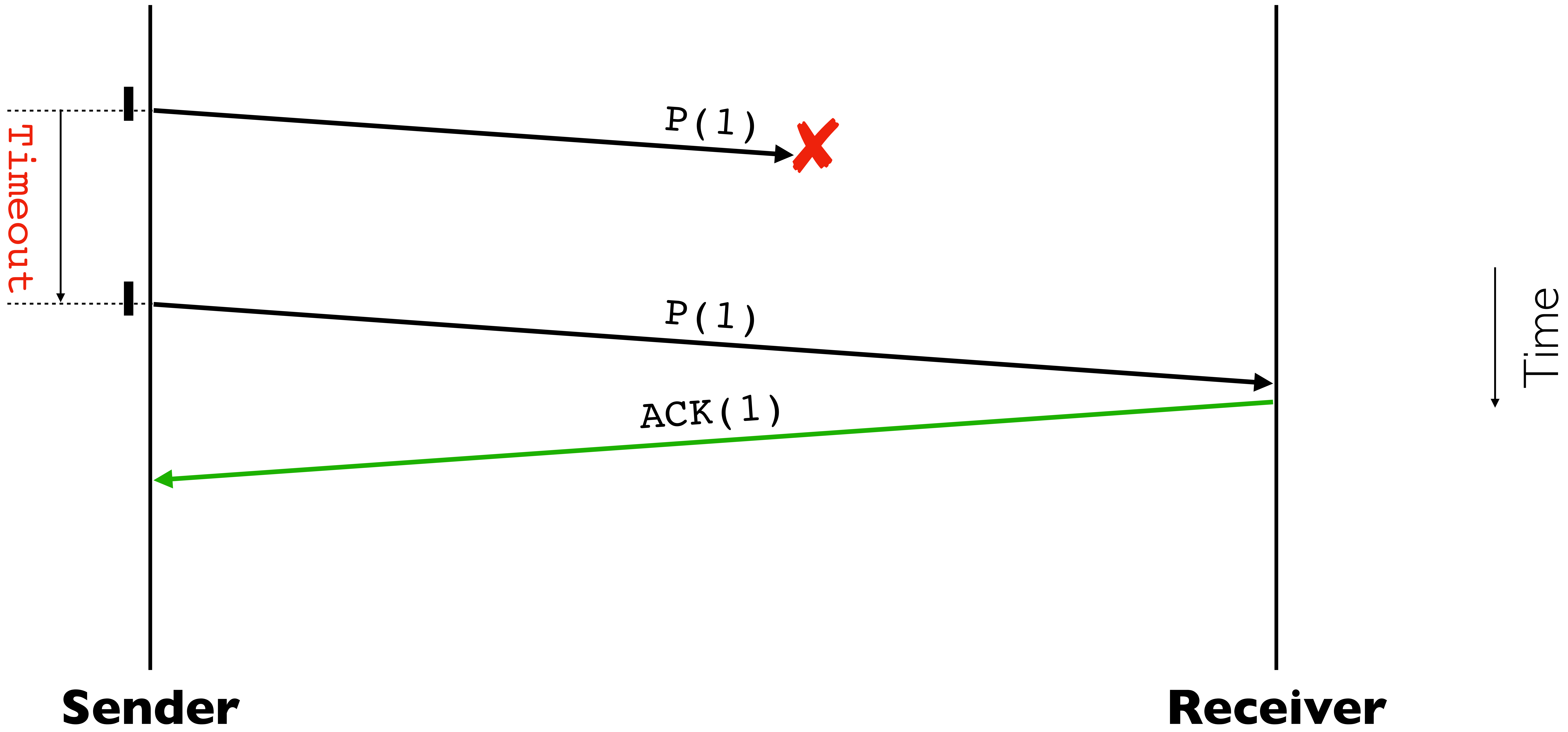

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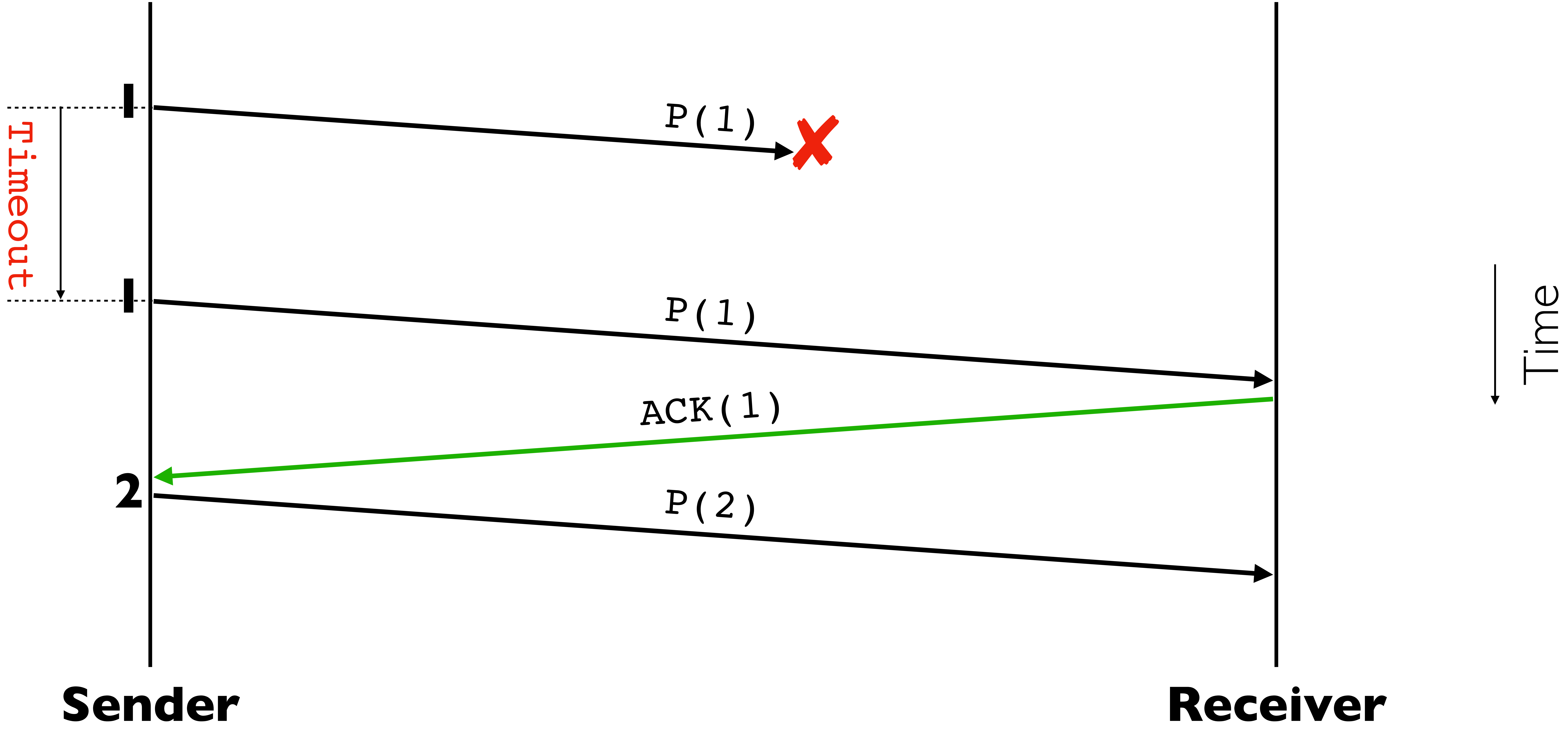

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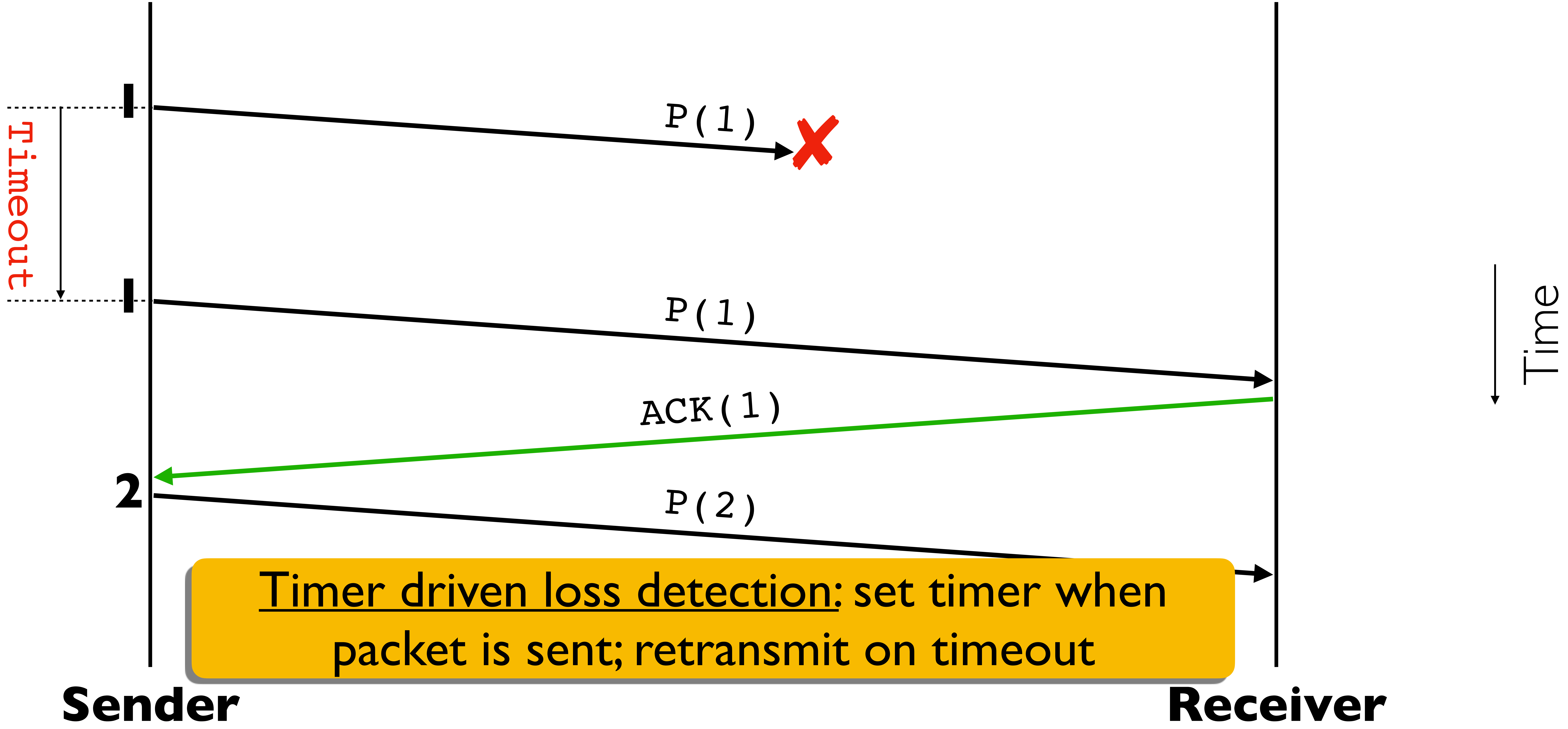
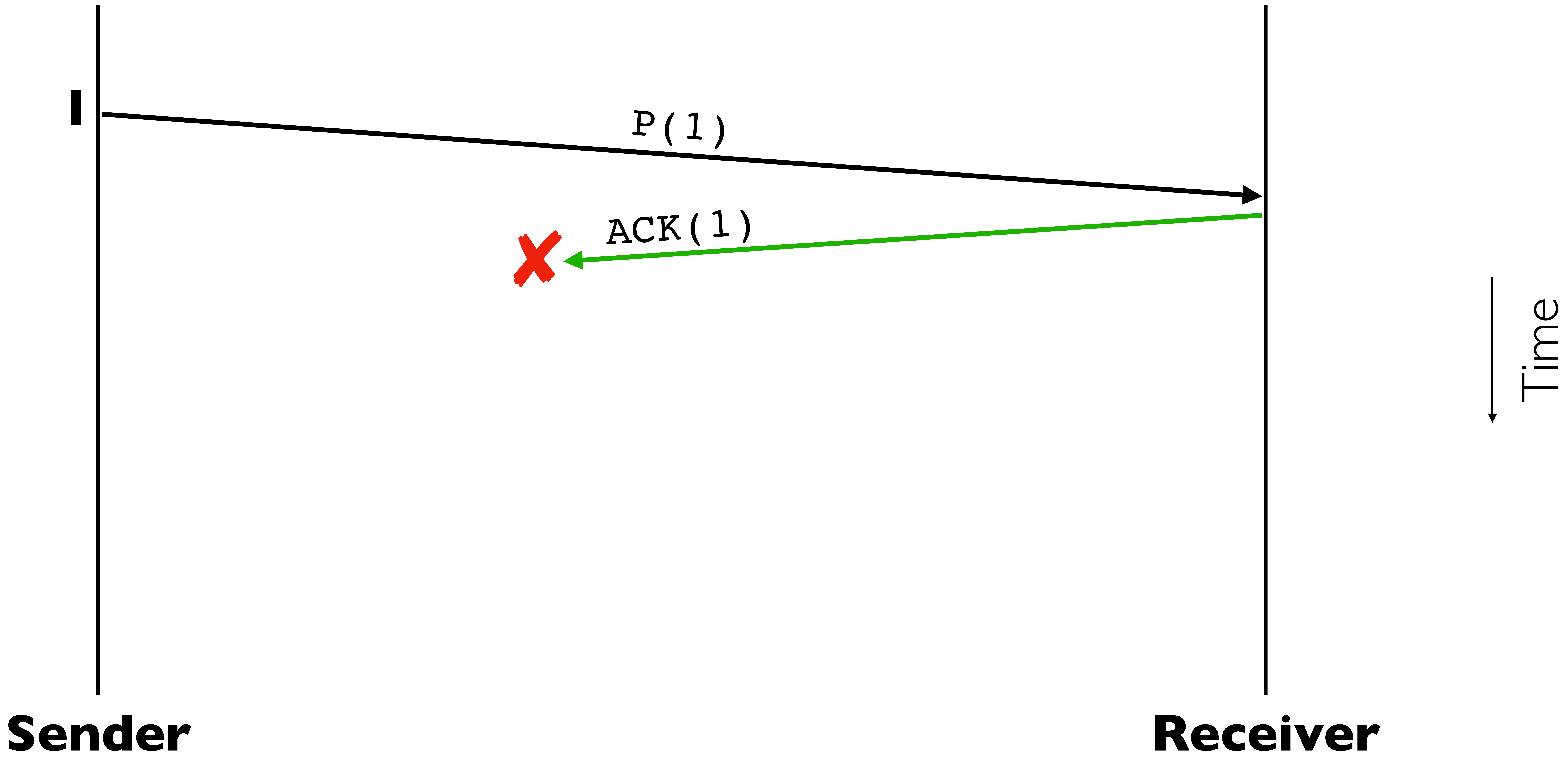


<u>Timer driven loss detection</u>: set timer when packet is sent; retransmit on timeout

Dealing with Packet Loss (of ACK)



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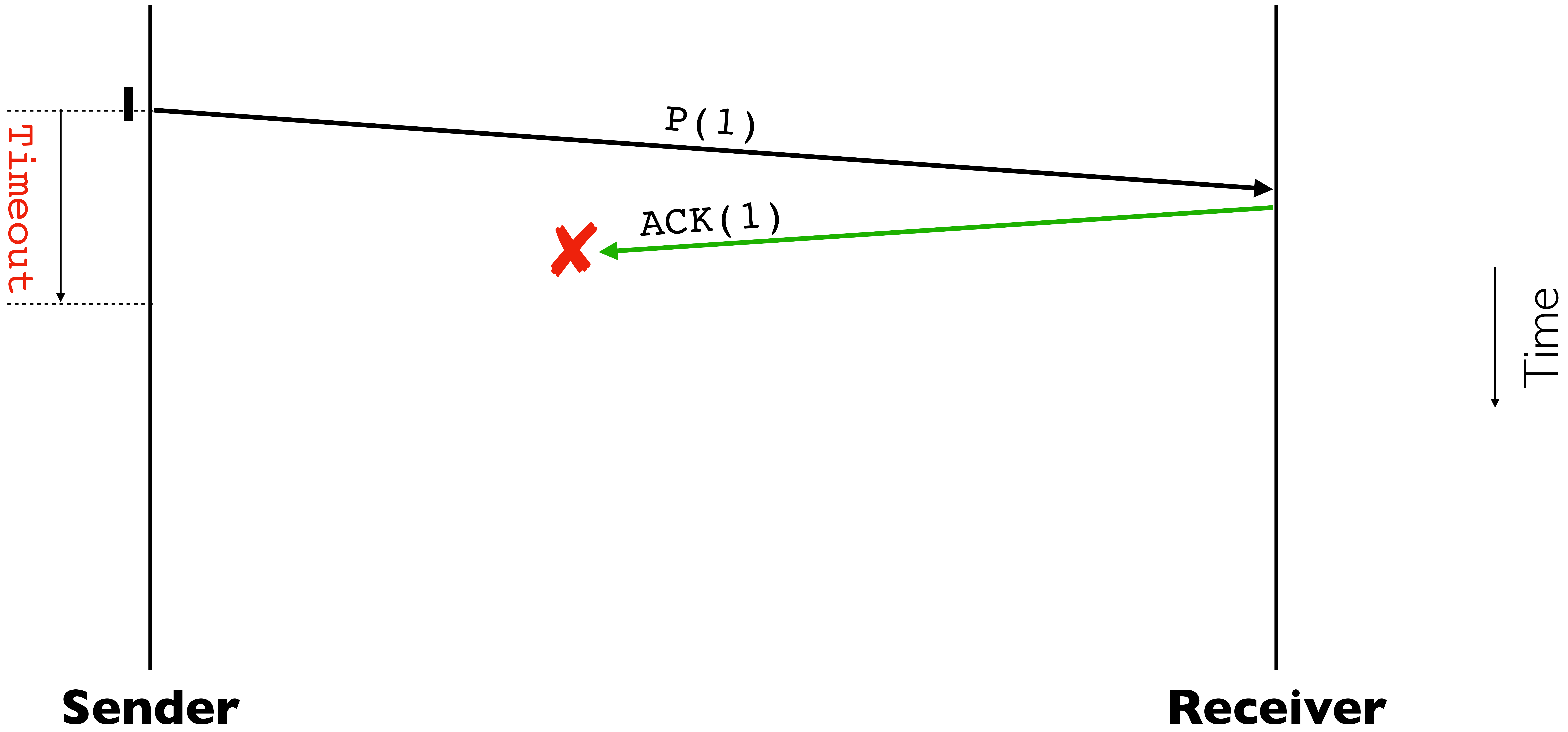

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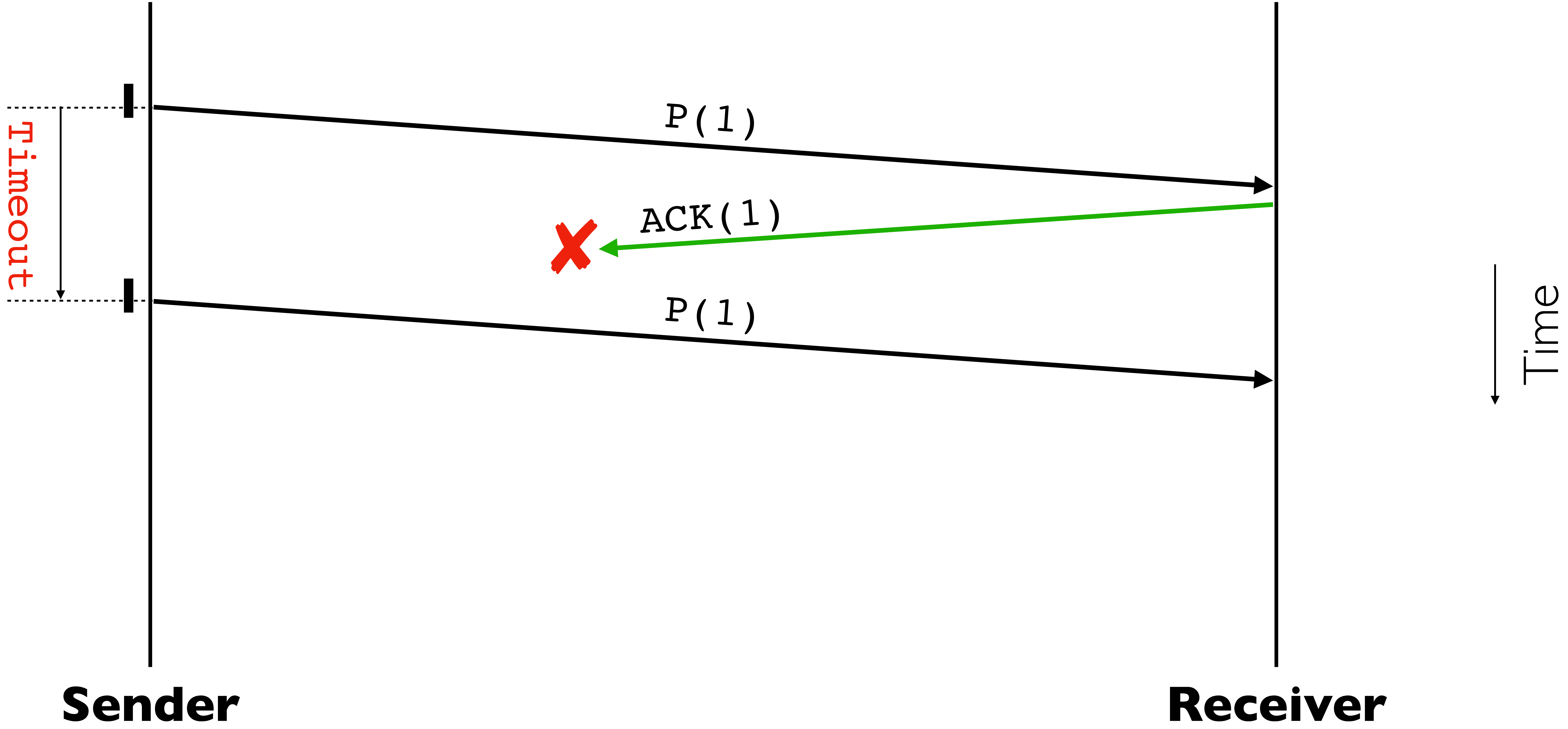

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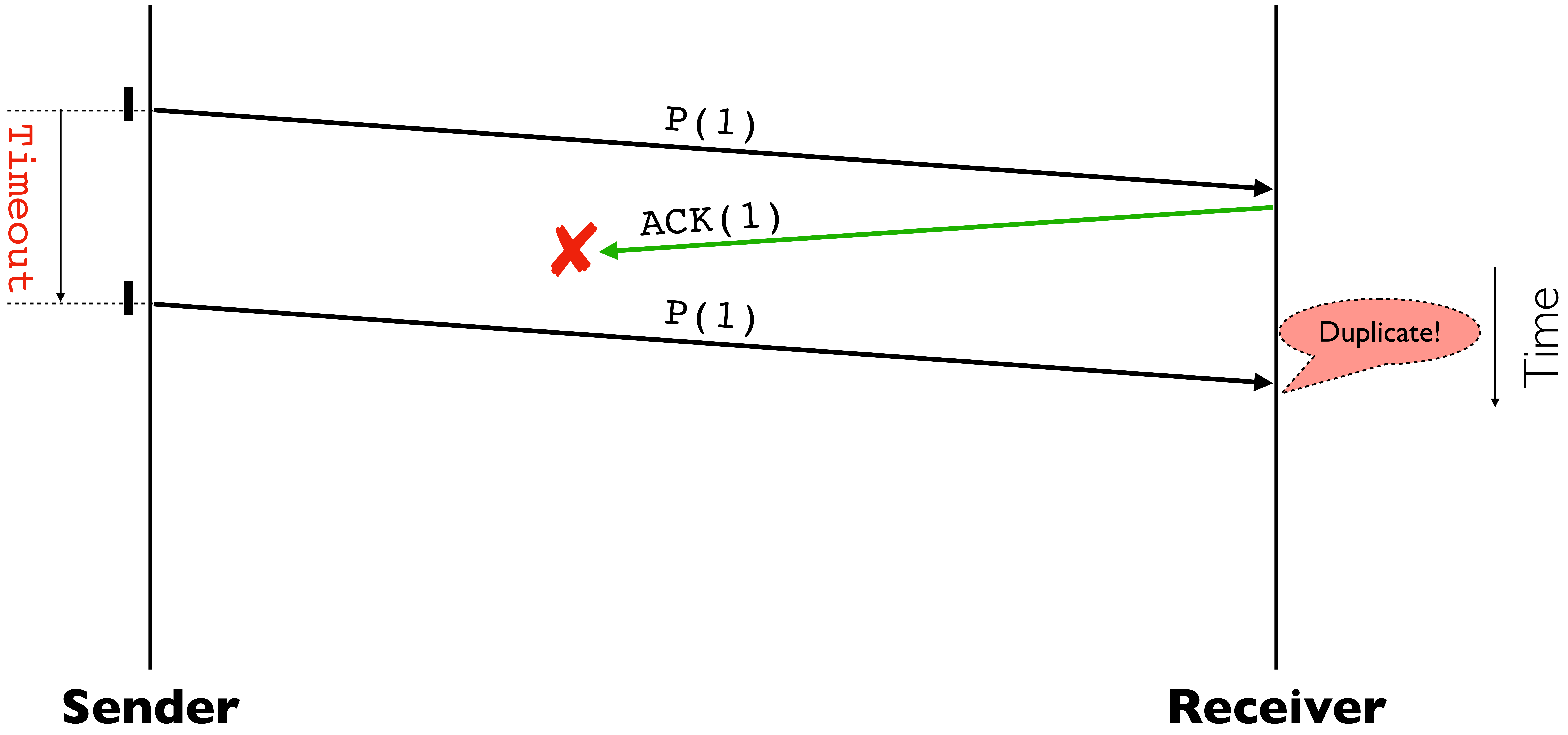

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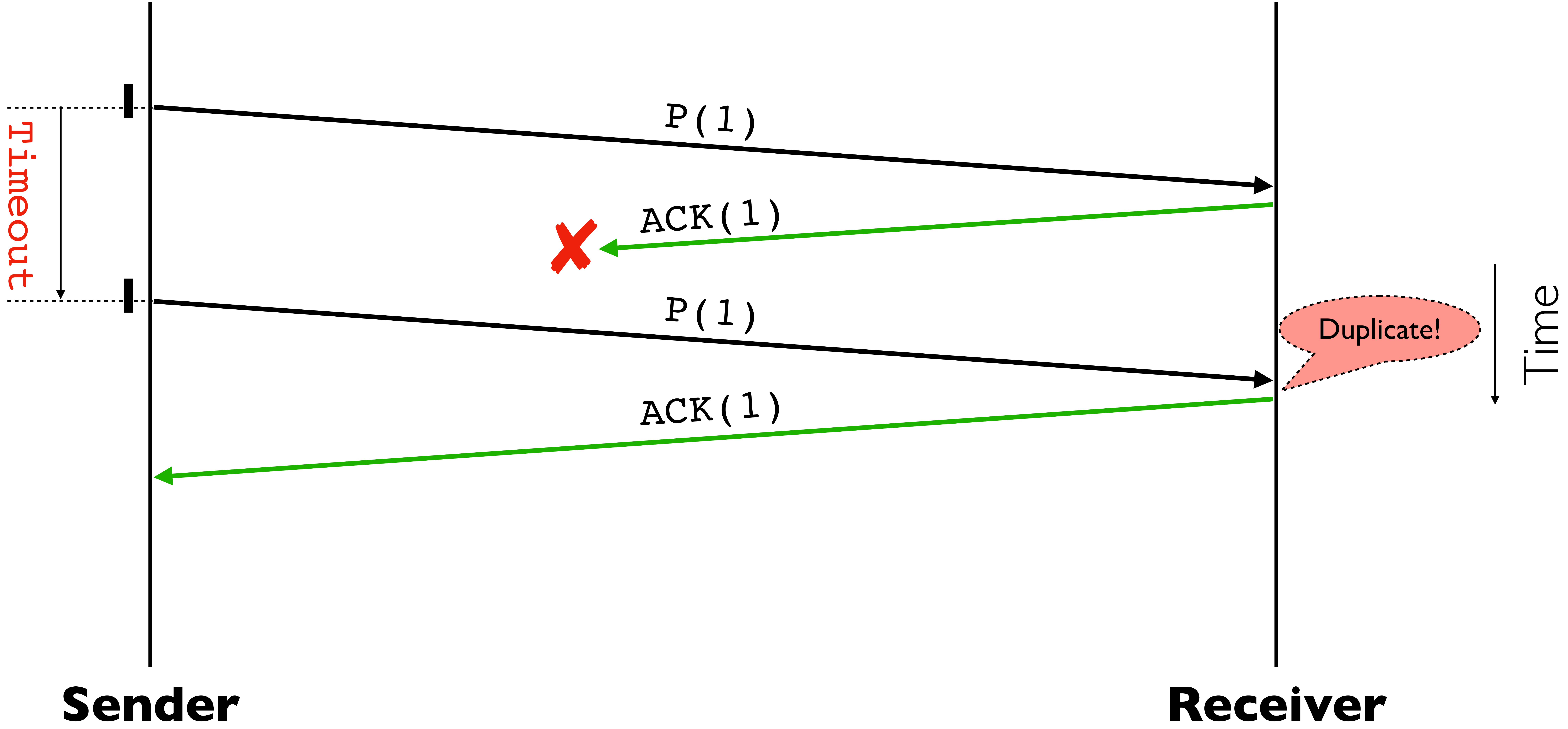

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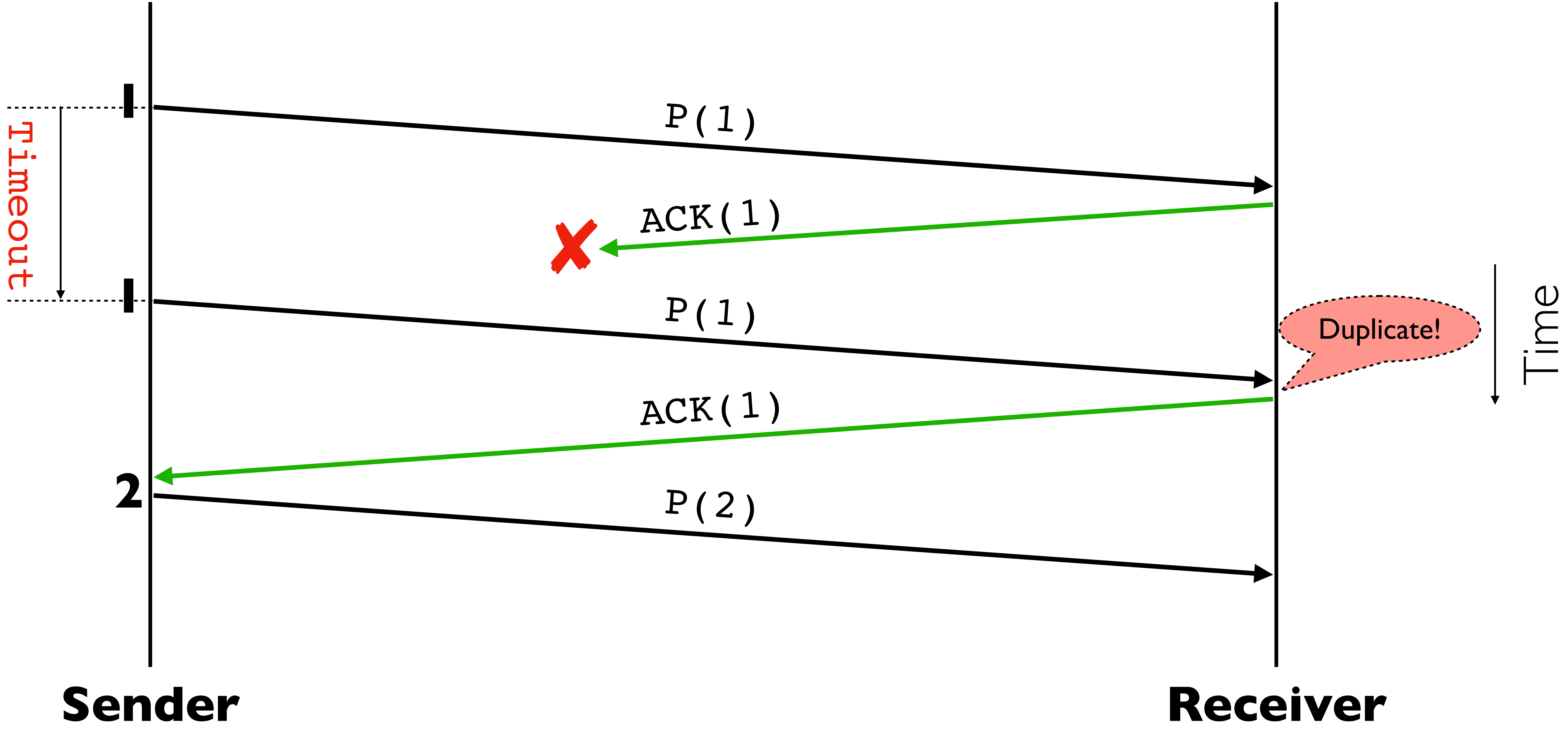

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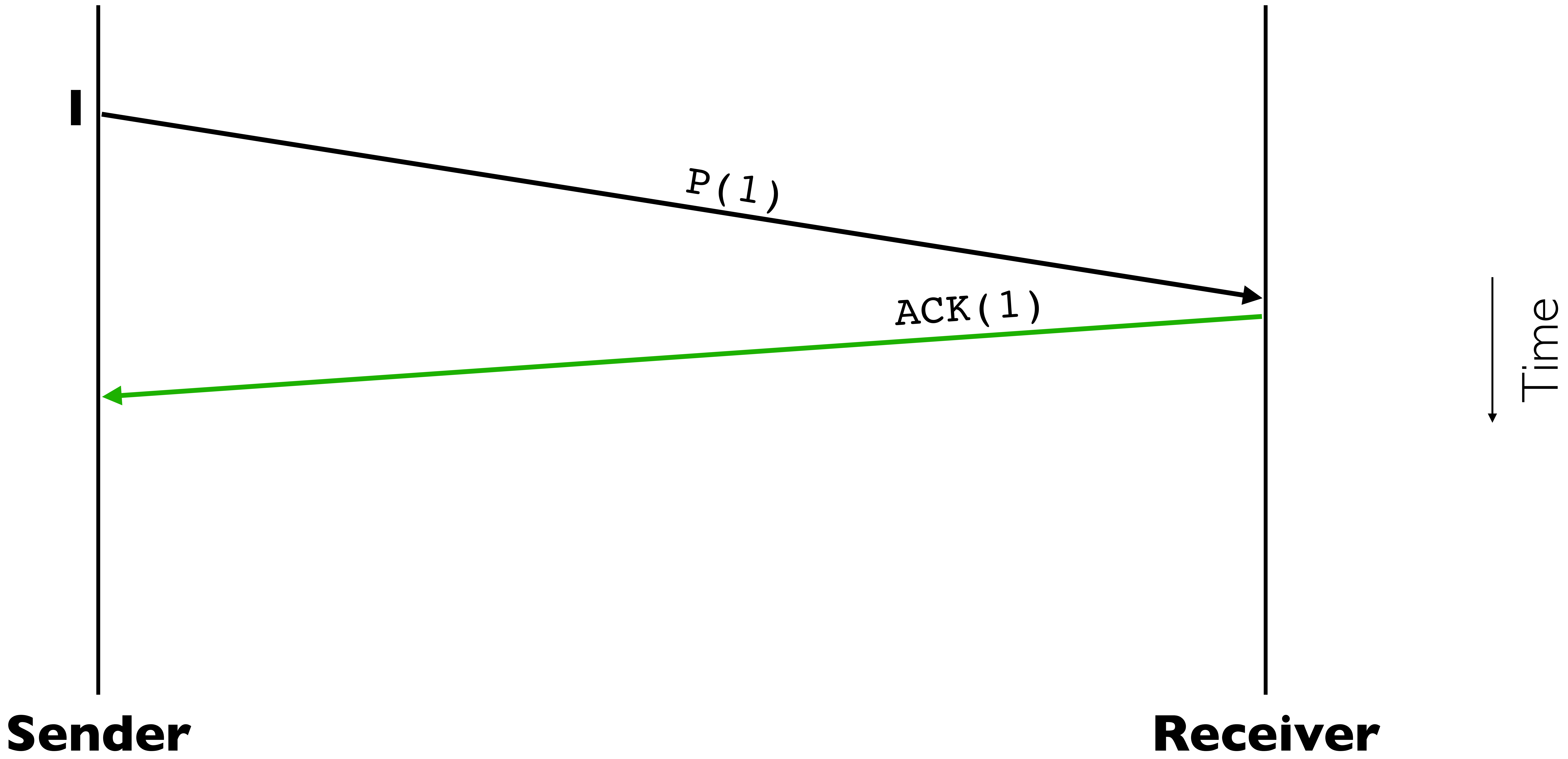

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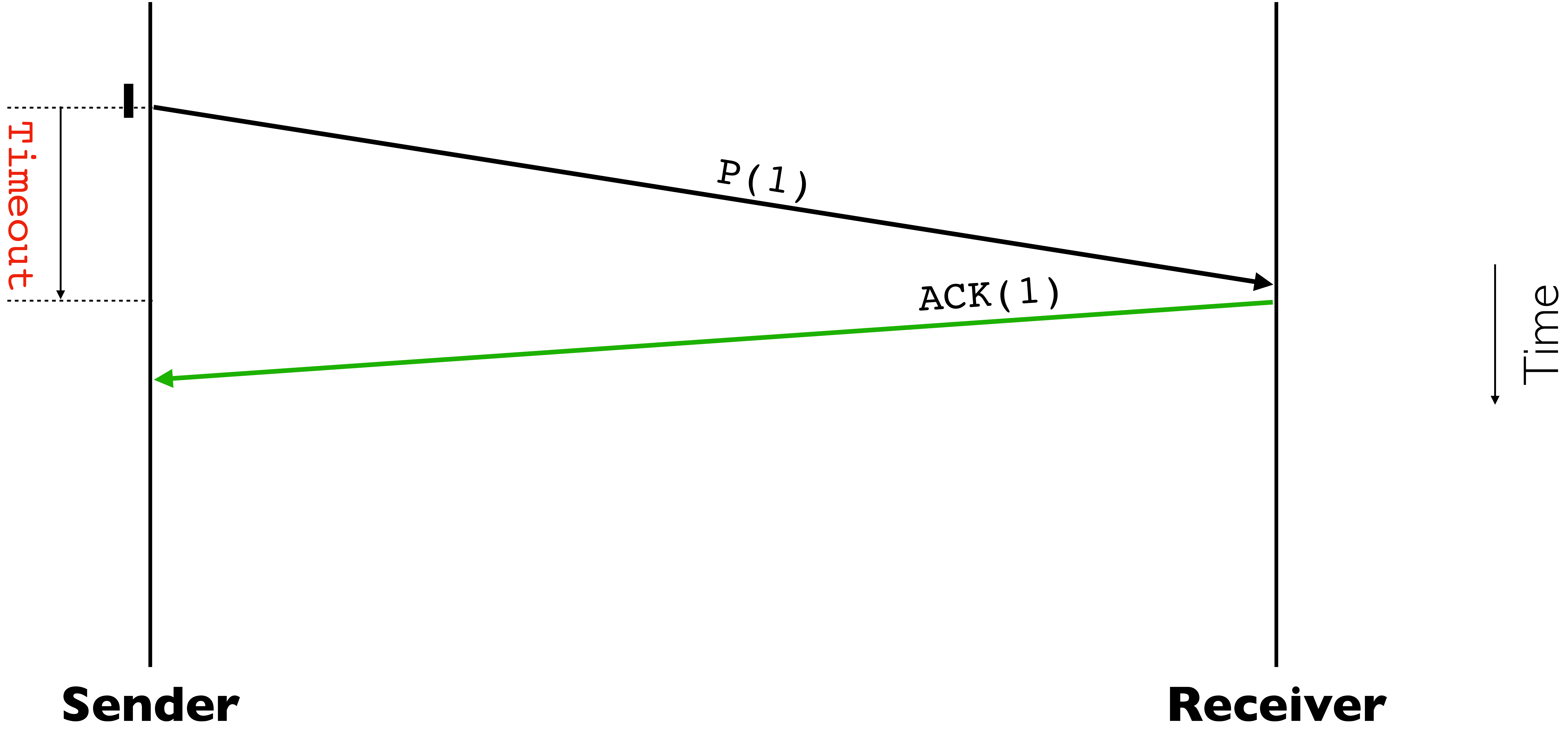

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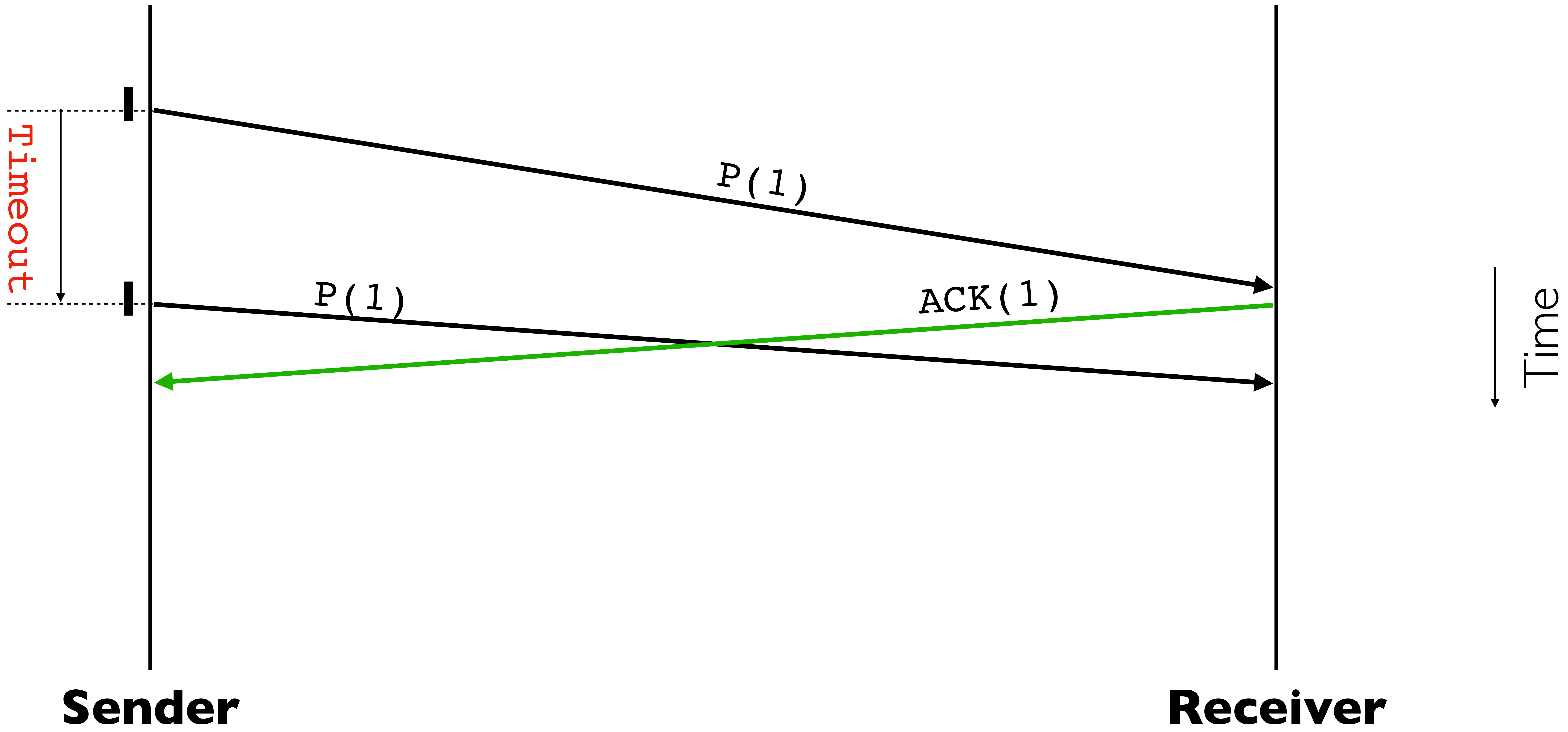

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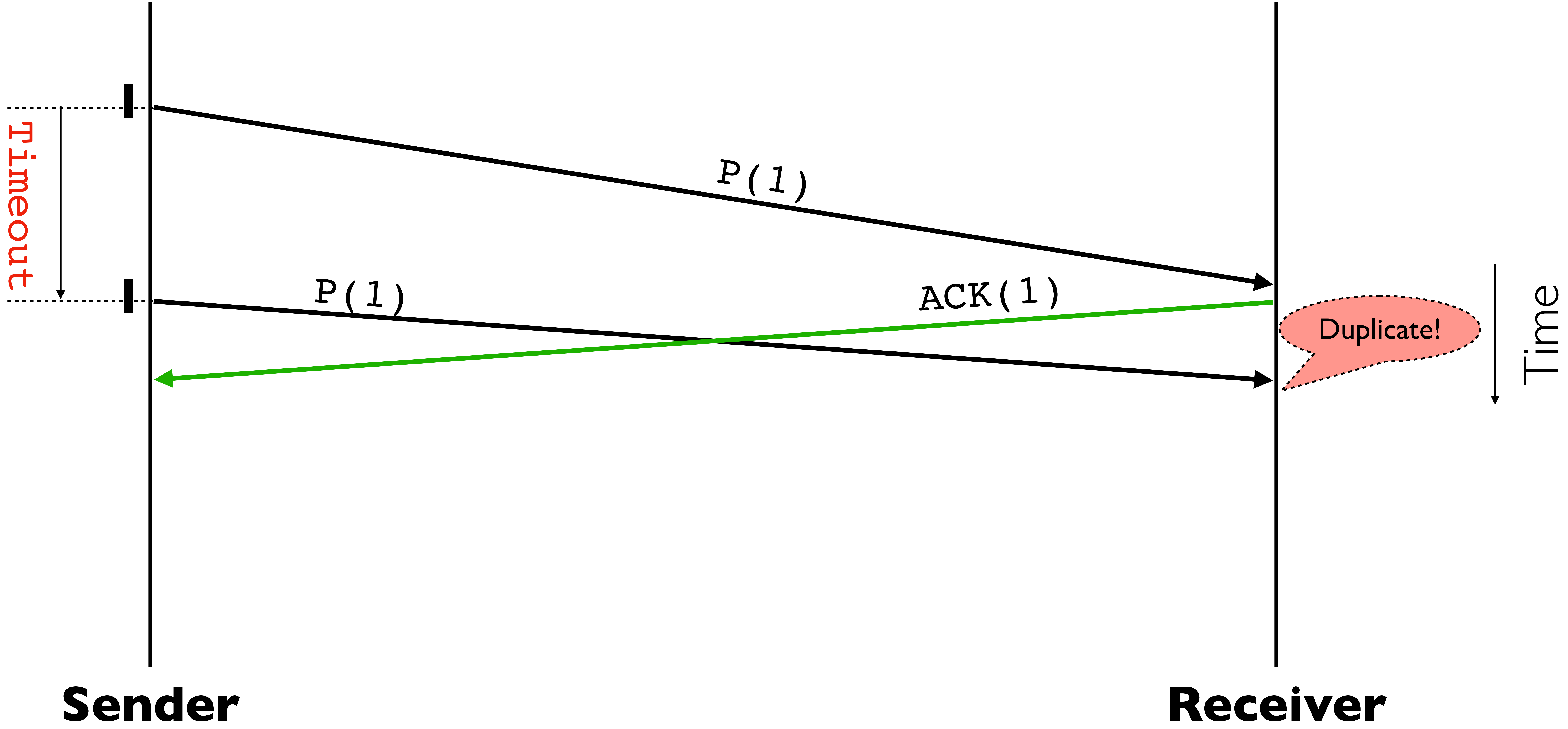

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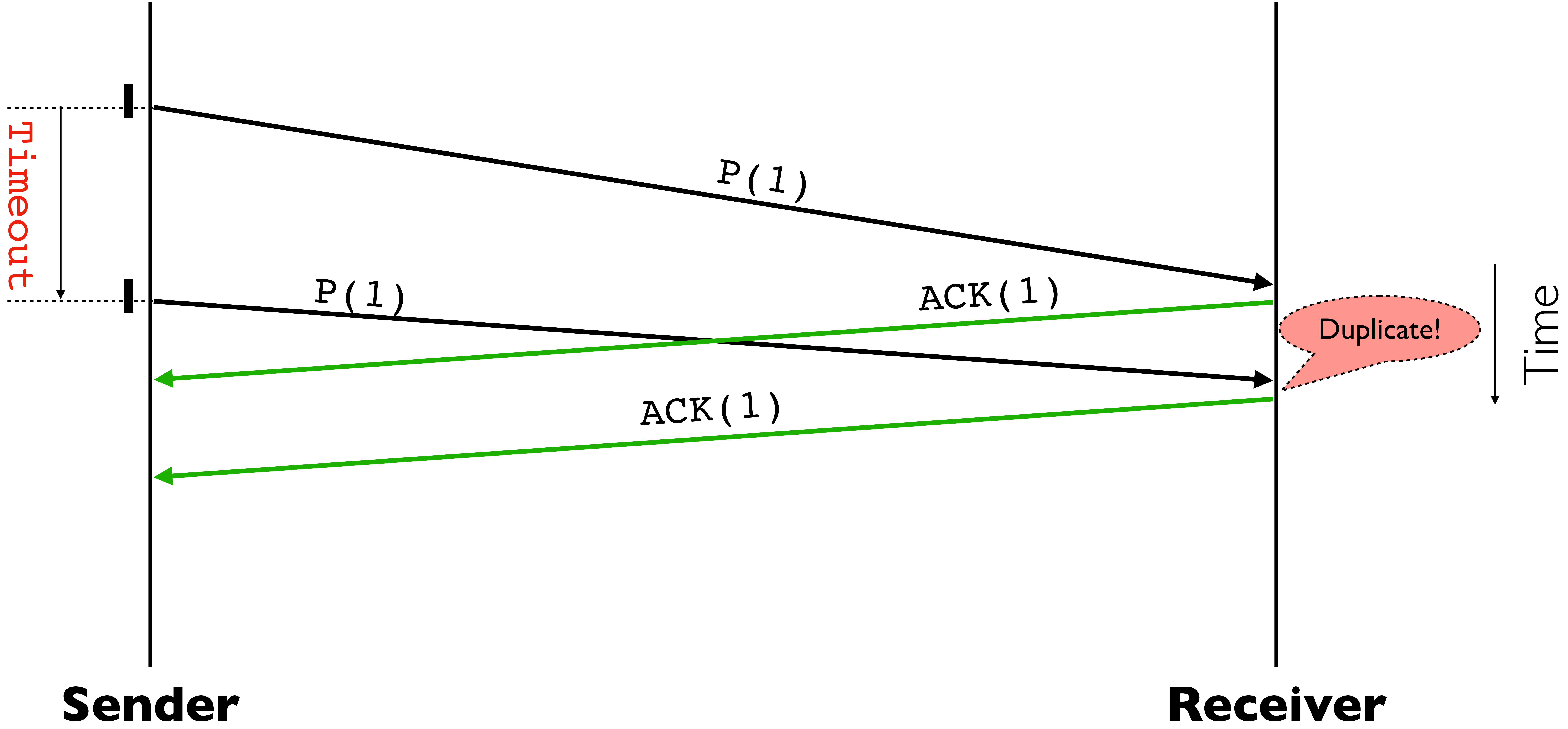

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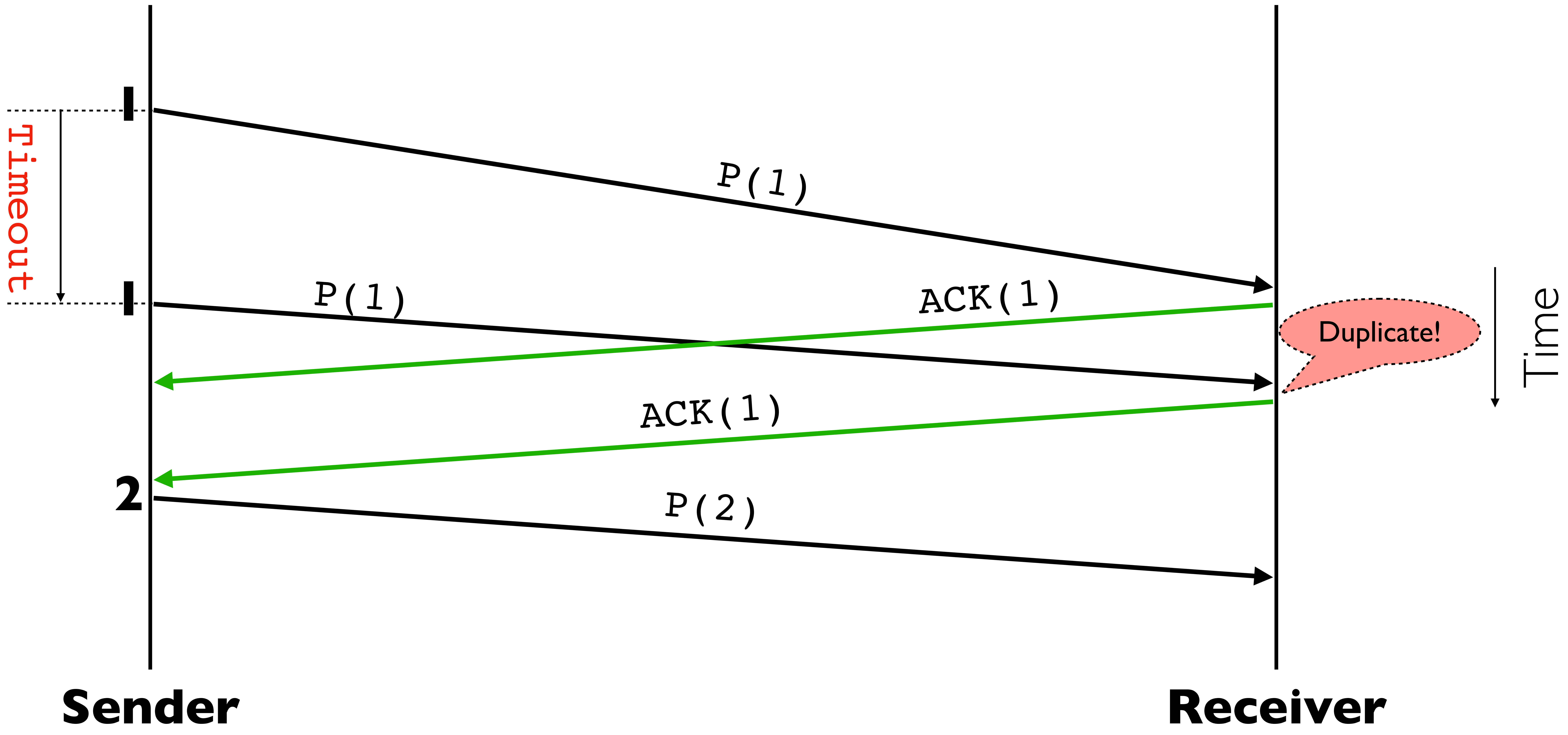

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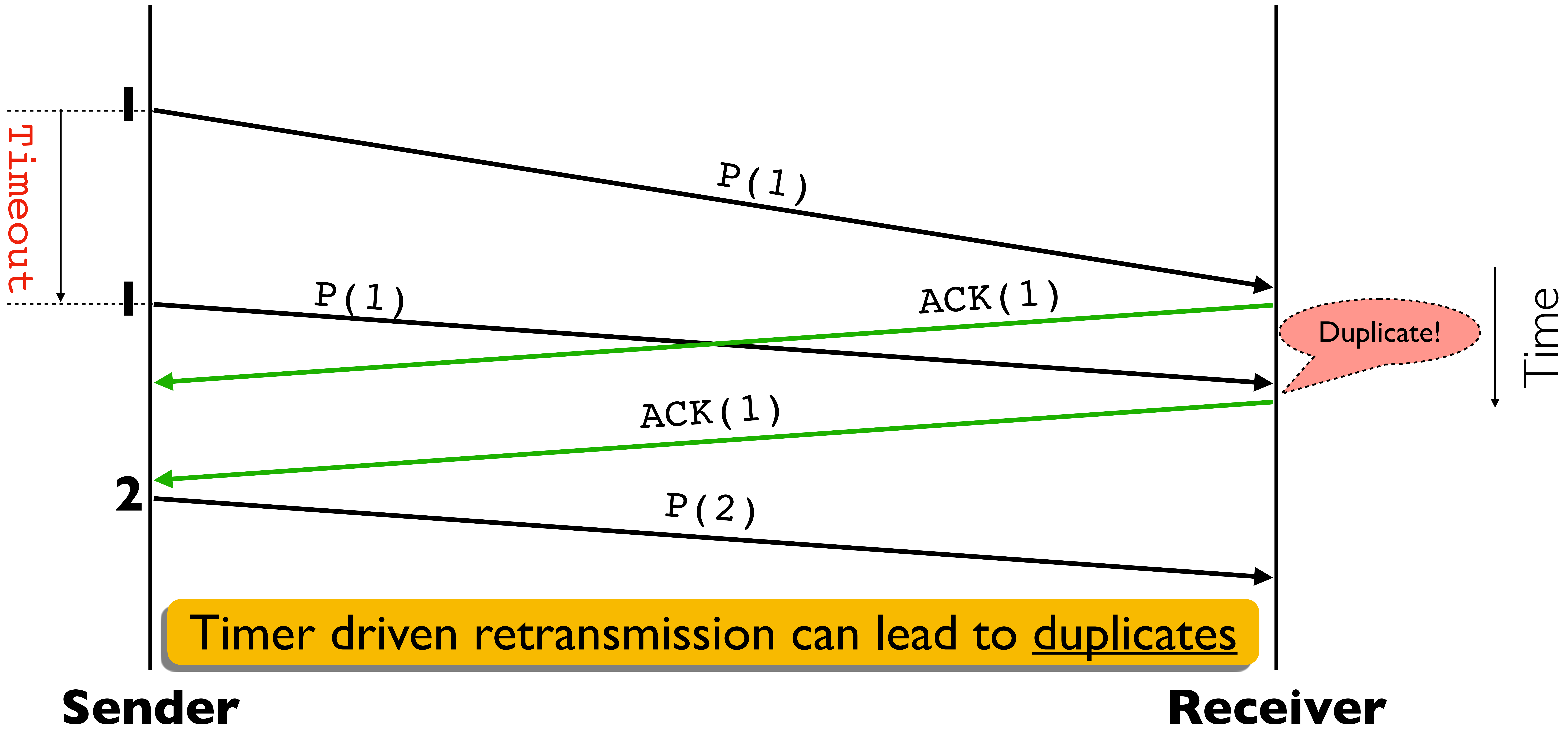

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- **But we have not put together into a coherent design…**

Designing Reliable Transport

A solution: "Stop and Wait"

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- Send packet(i); (re)set timer; wait for ack
- If (ACK)
  - i++; repeat
- If (NACK or TIMEOUT)
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- Wait for packet(i)
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- **We have a correct reliable protocol!**
- **Probably the world's most inefficient one…** ***why?***

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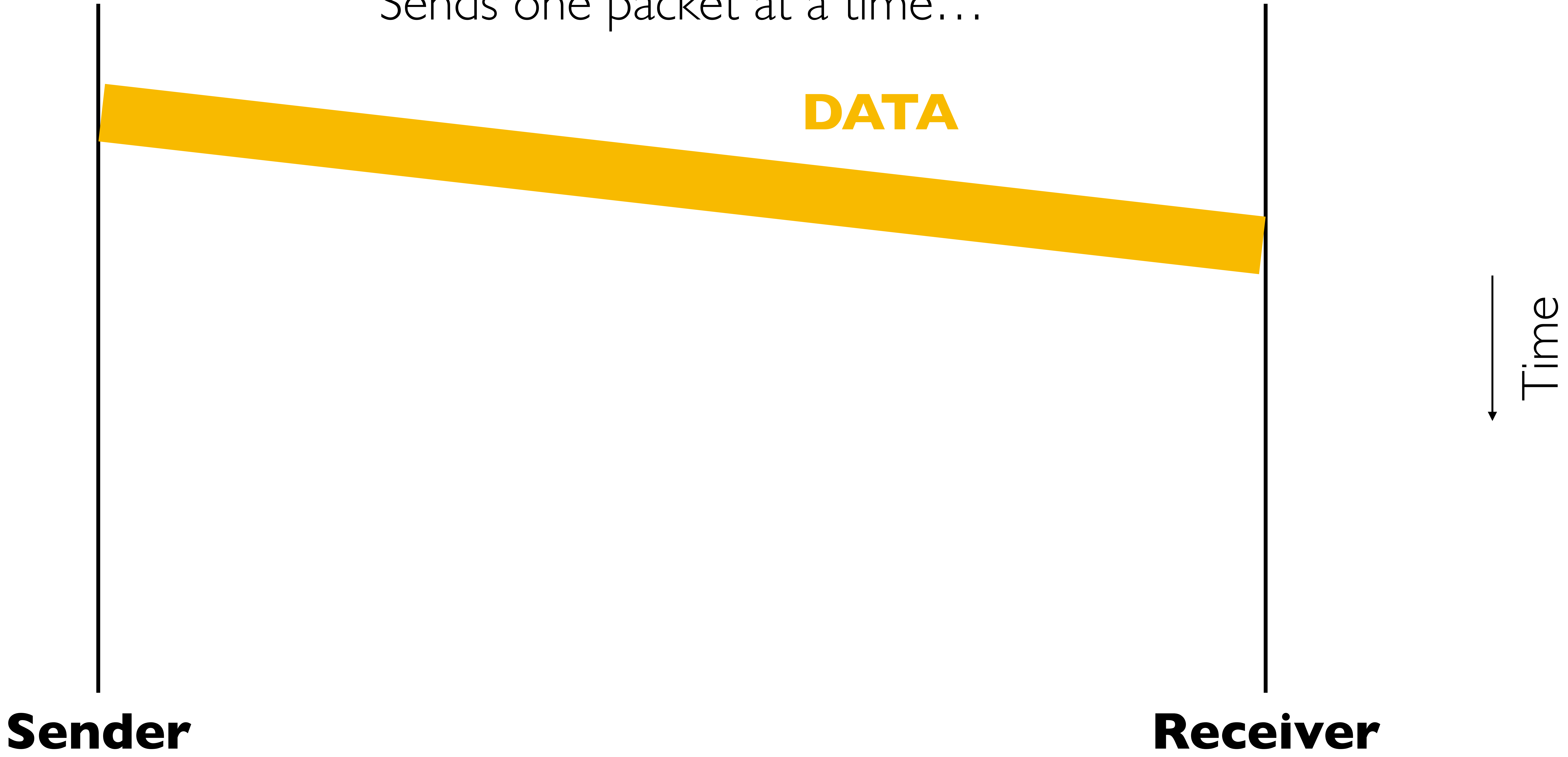

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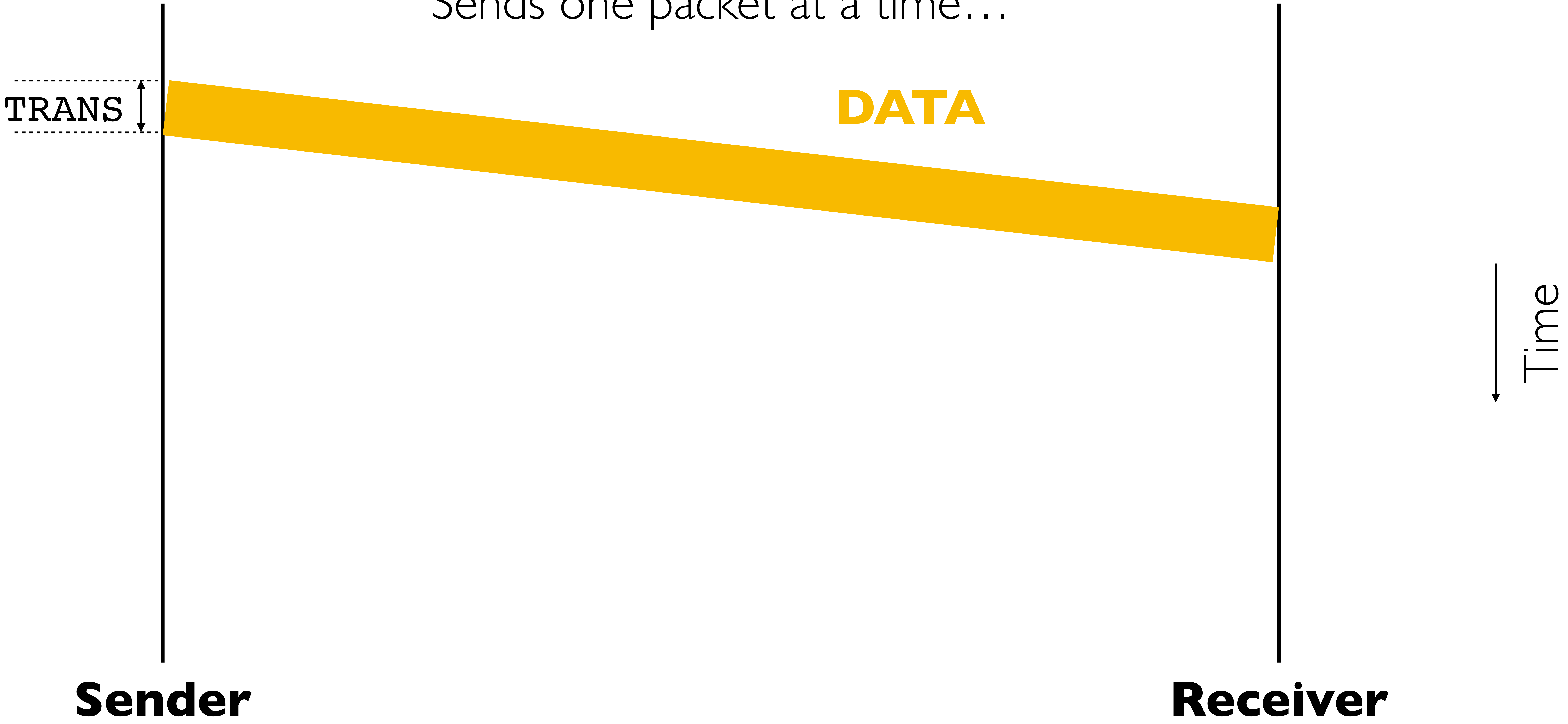

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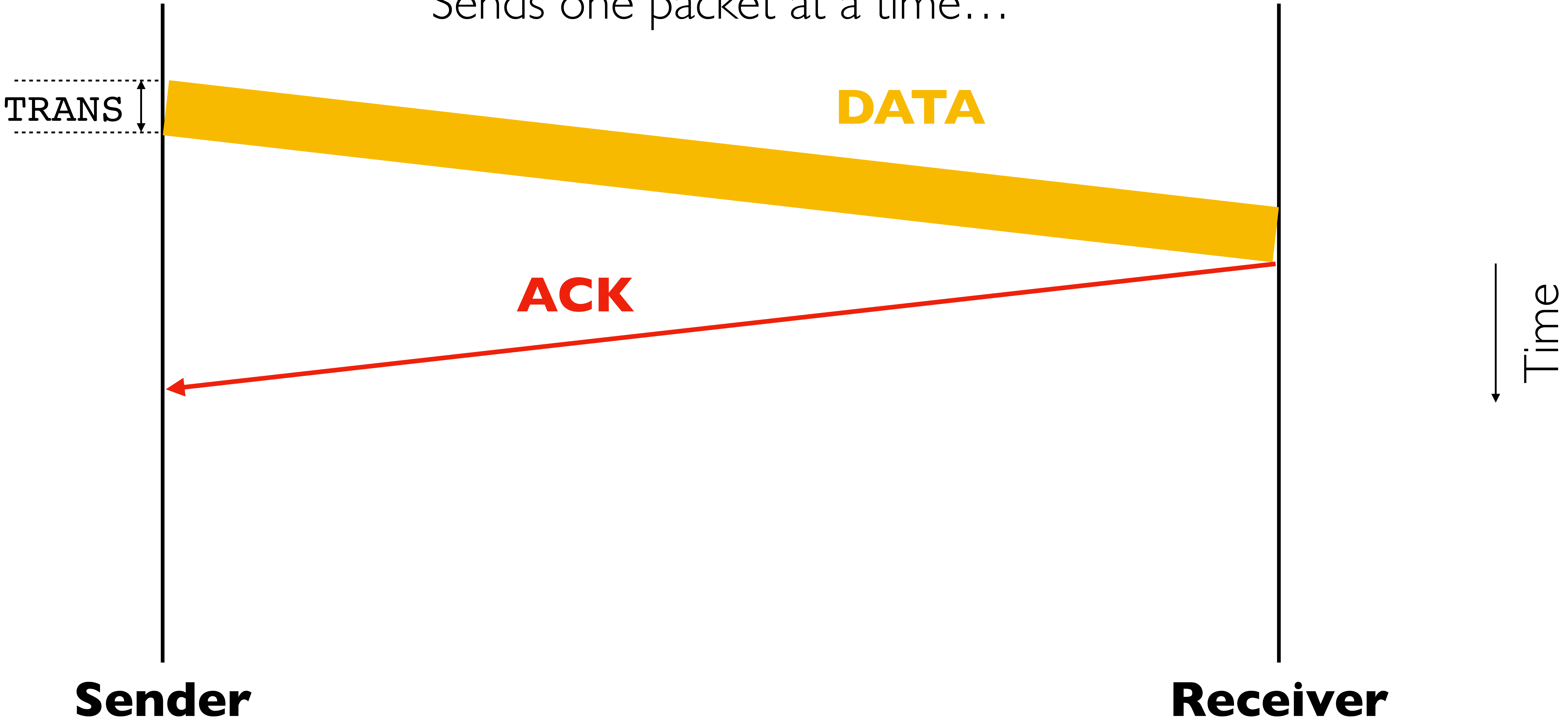

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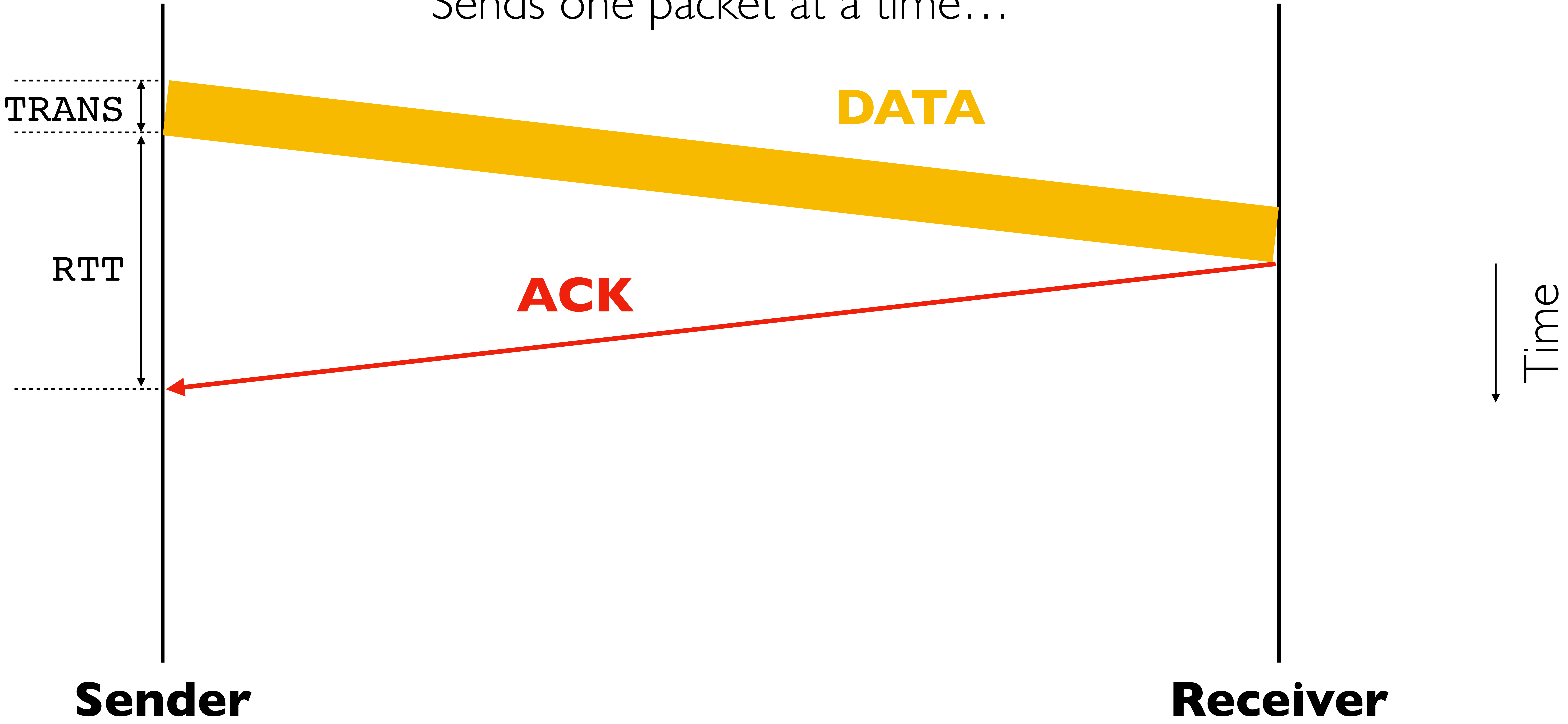

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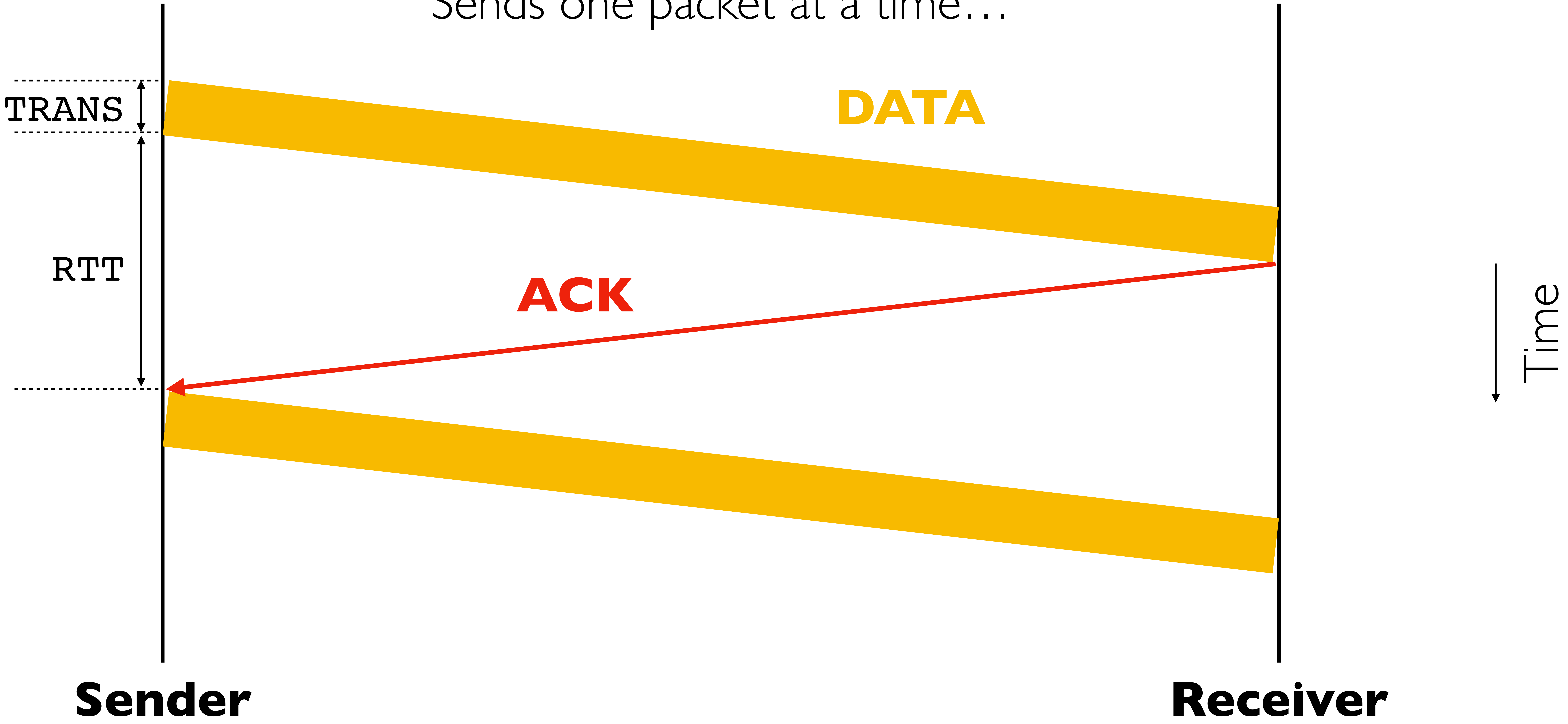

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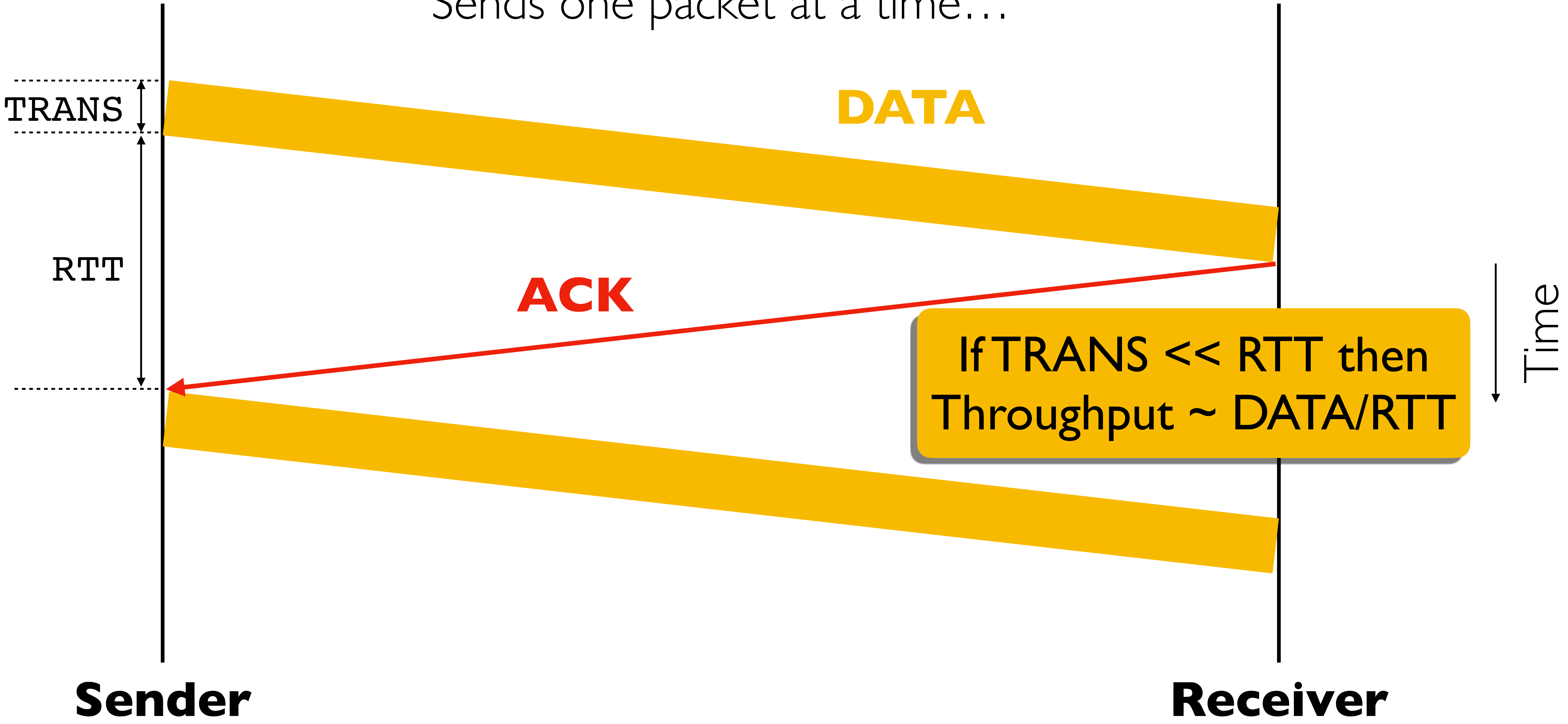

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  - 1500 byte / 10 ms = 1.5Mbps!

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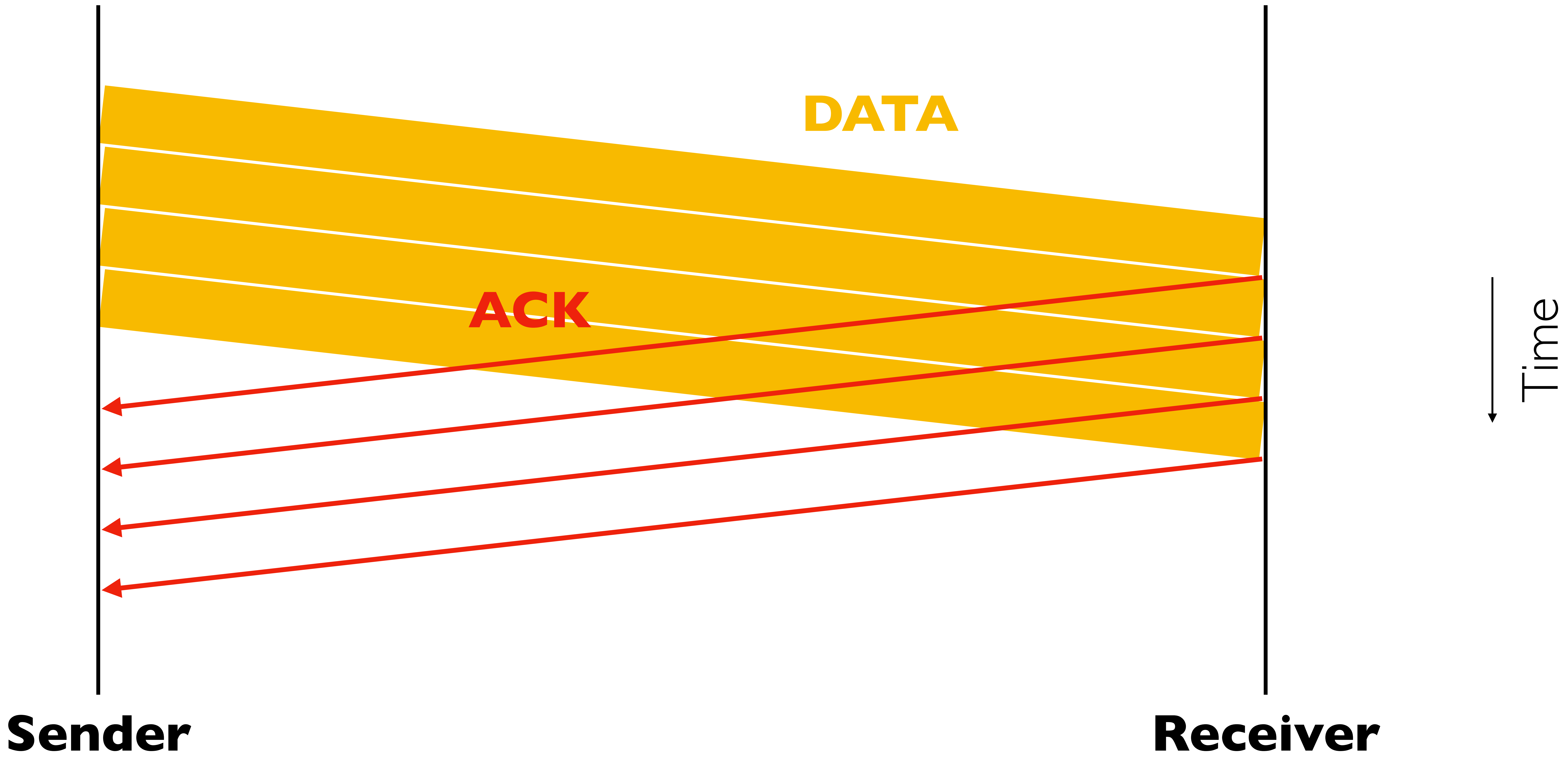

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- **Sliding window often called "packets in flight"**

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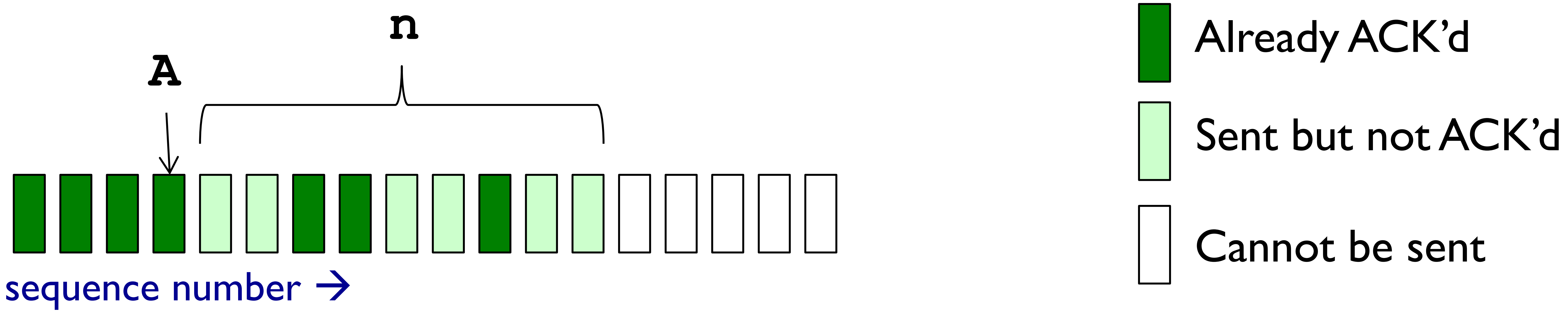
- Let A be the **last ACK'd packet of sender without gap**; then window of sender = {A+1, A+2, …, A+n}



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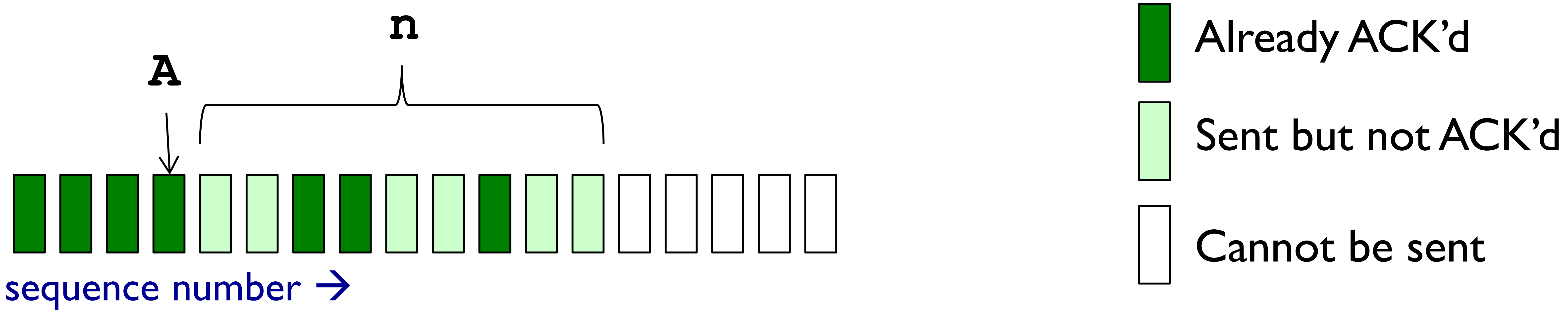

- Let B be the **last received packet without gap** by receiver; then window of receiver = {B+1, …, B+n}

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MIN[**n *** DATA/RTT, Link bandwidth]

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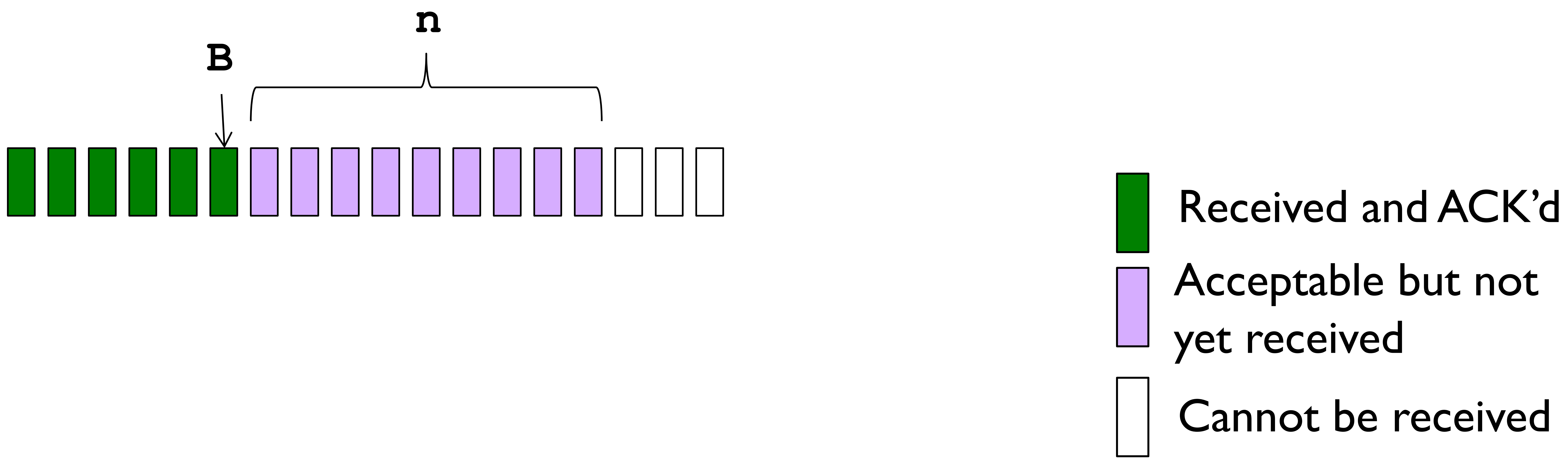
- Two questions:
    - What happens when n gets too large?
    - How do we choose n?

Acknowledgements with Sliding Window

- **Two common options**
  - **Cumulative ACKs:** ACK carries *next in-order sequence number* that the receiver expects

Cumulative Acknowledgements (1)

- At receiver



Cumulative Acknowledgements (1)

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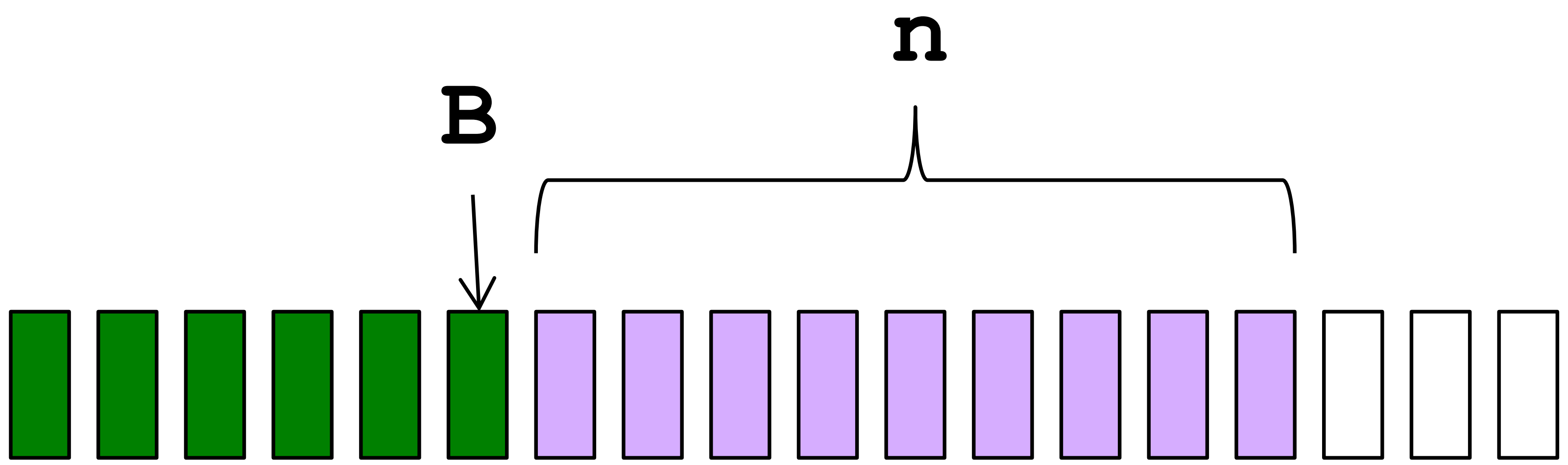
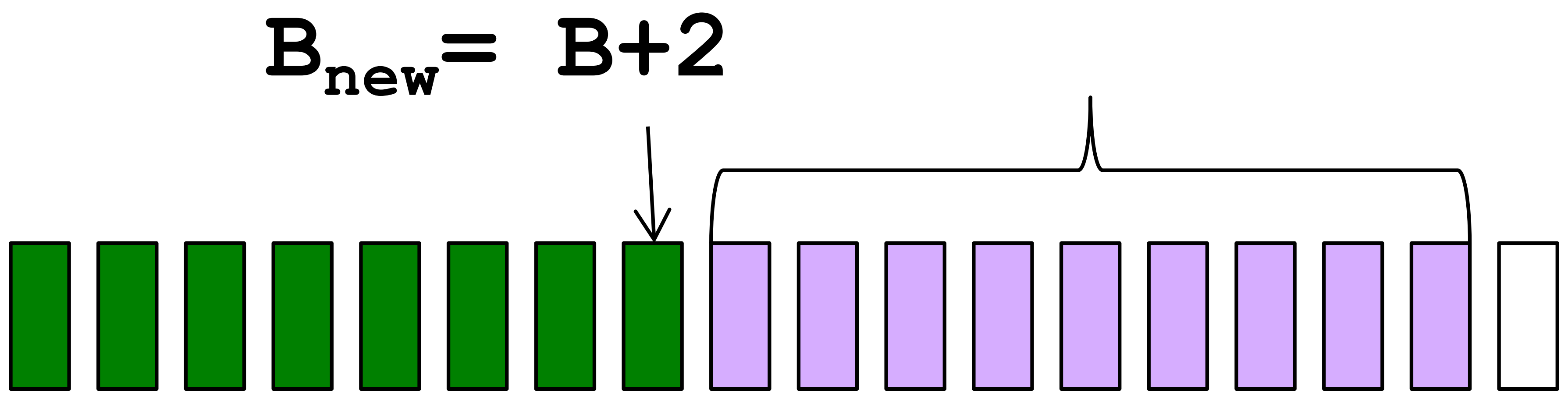
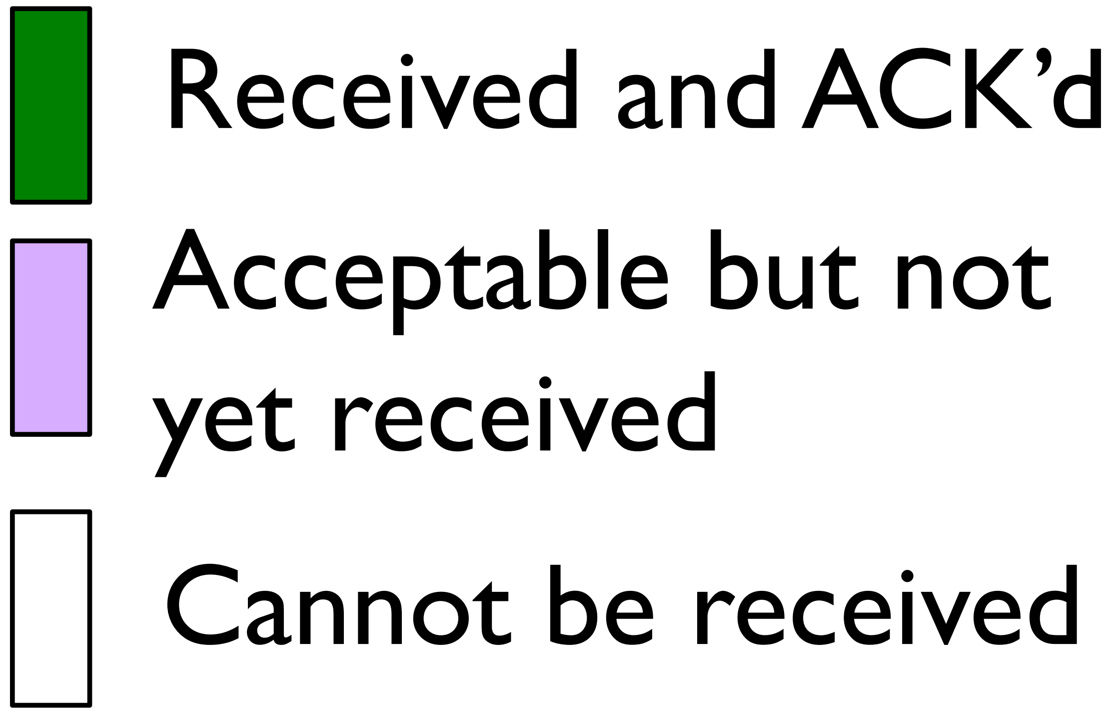


- After receiving B+1, B+2





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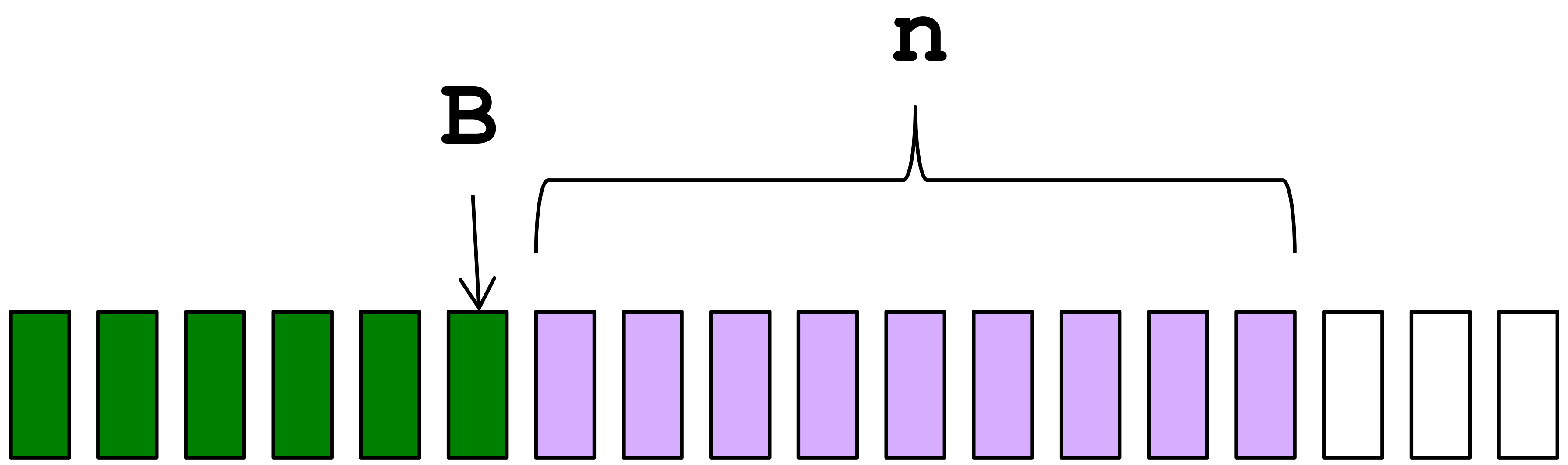

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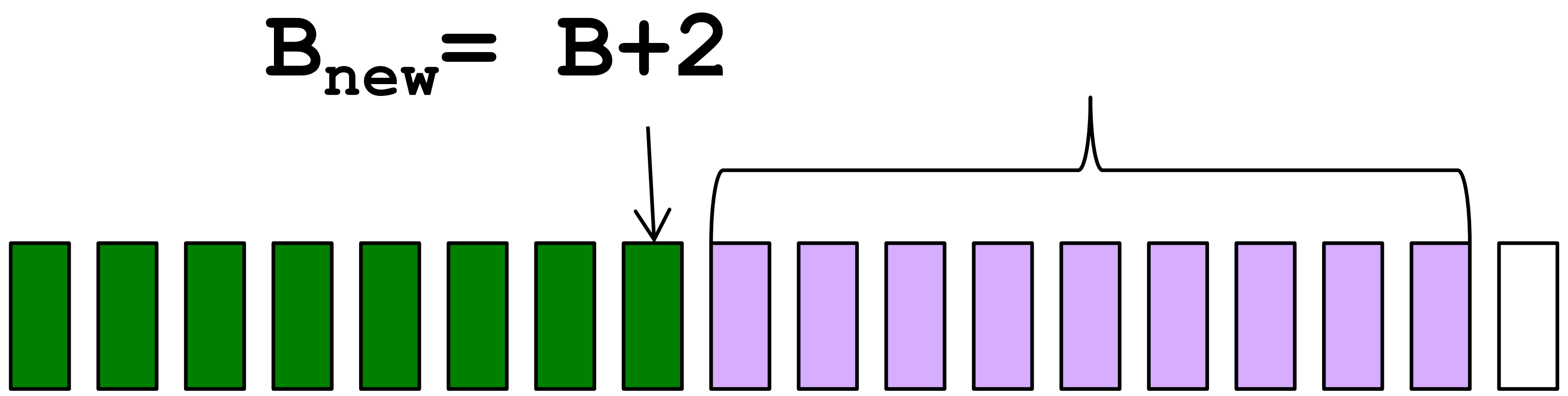
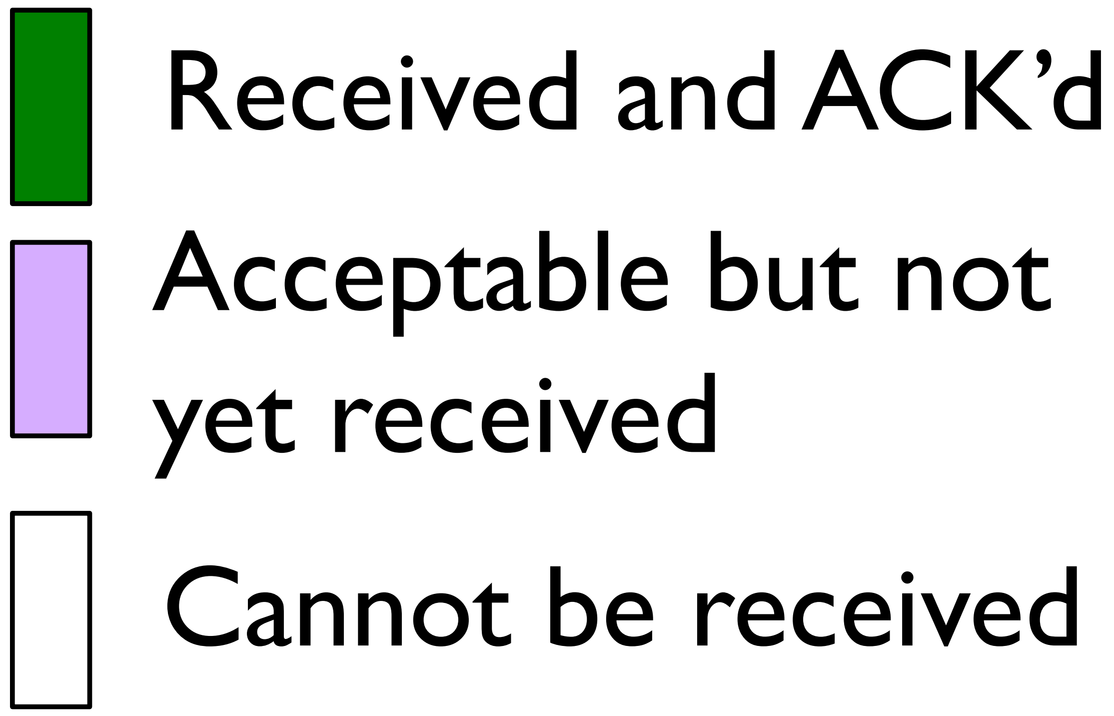
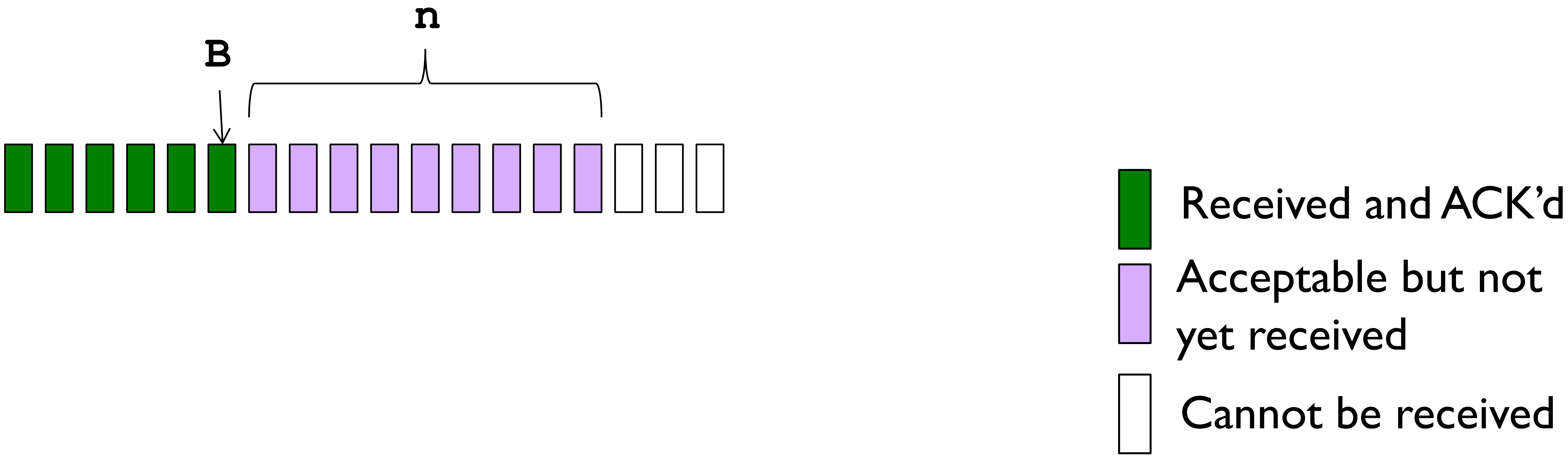




- Receiver sends **ACK(B+3) = ACK(B_{new}+1)**

Cumulative Acknowledgements (2)

- At receiver



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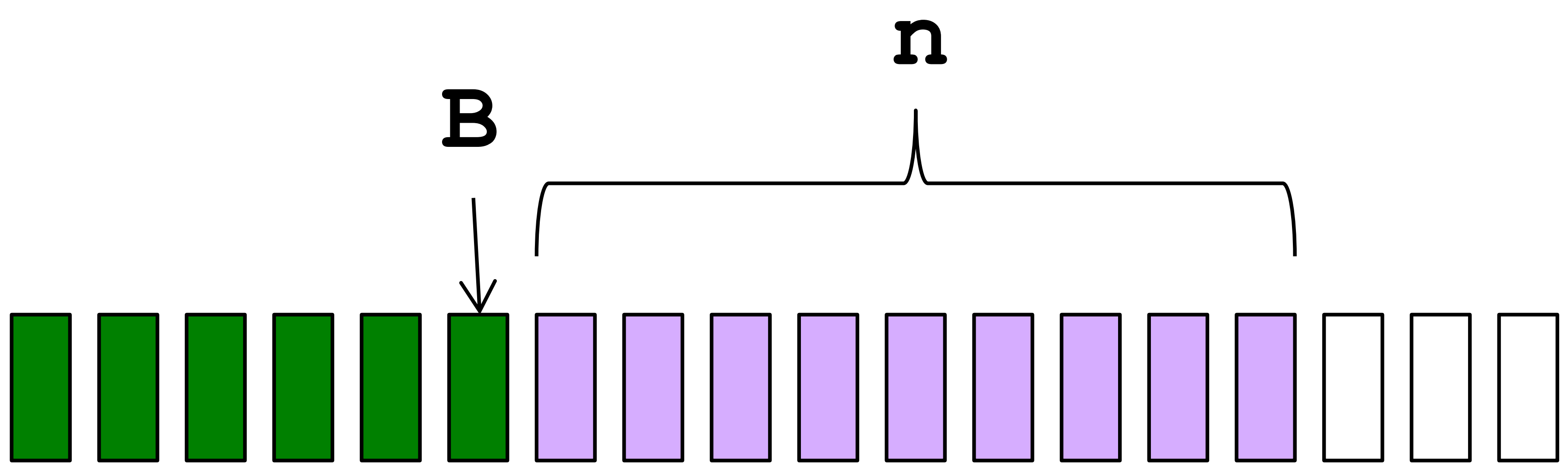
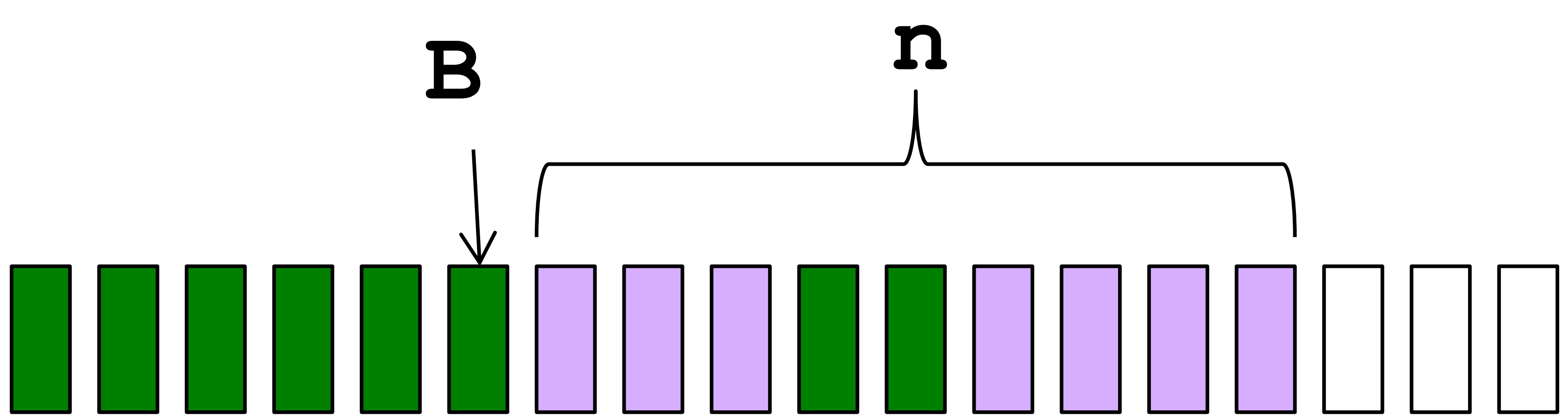
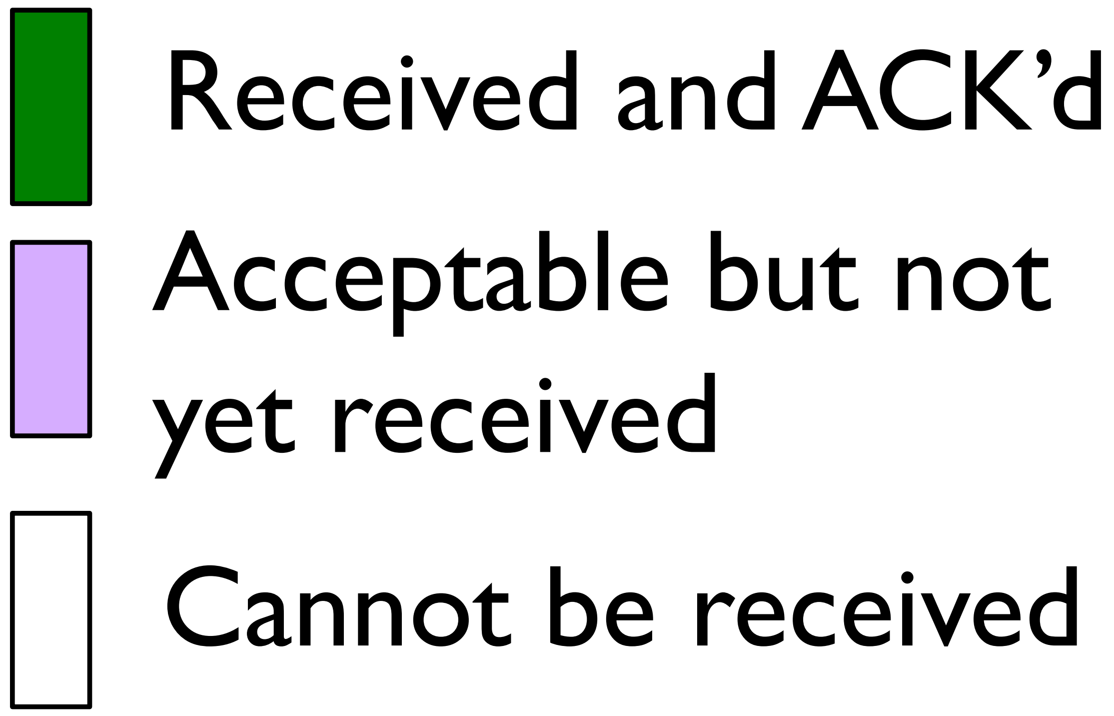


- After receiving B+4, B+5





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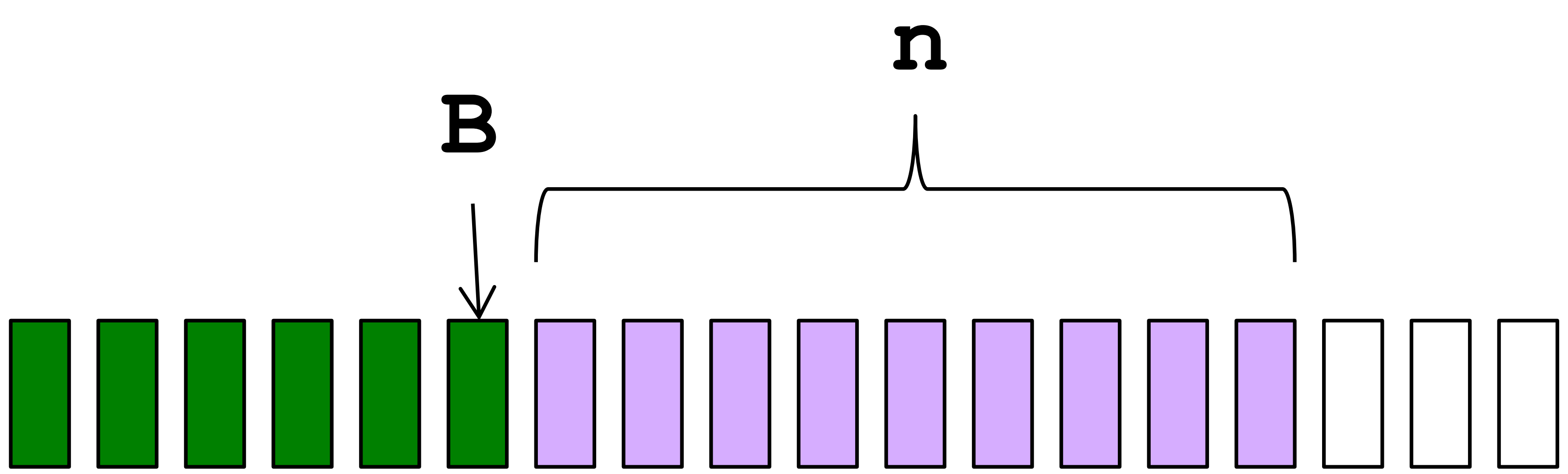

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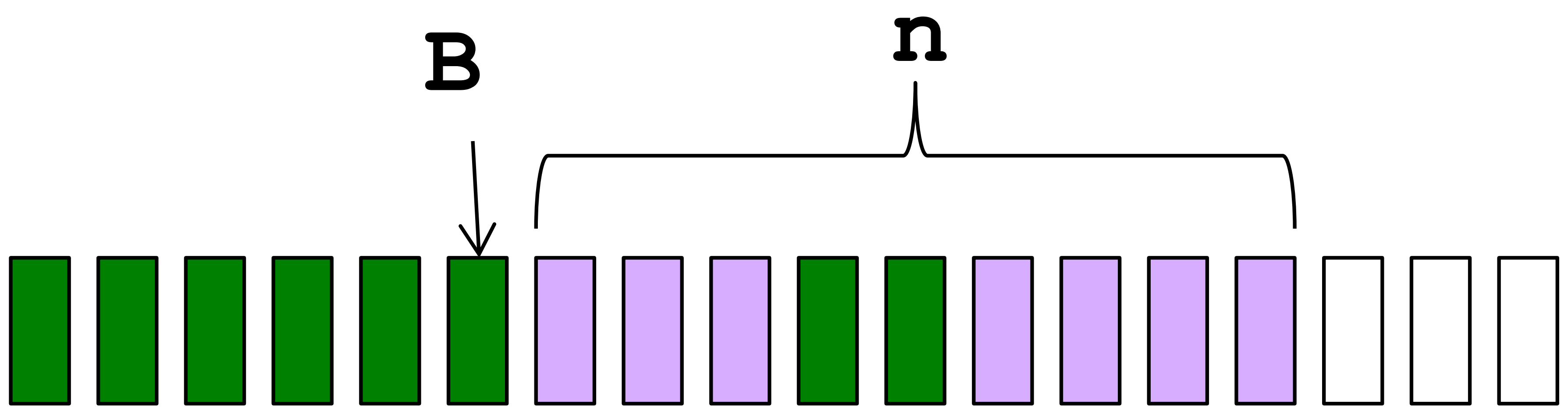

- Receiver sends **ACK(B+1)**

Received and ACK'd

Acceptable but not yet received

Cannot be received

Acknowledgements with Sliding Window

- **Two common options**
  - **Cumulative ACKs:** ACK carries *next in-order sequence number* that the receiver expects

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  - **Cumulative ACKs:** ACK carries *next in-order sequence number* that the receiver expects
  - **Selective ACKs:** ACK *individually acknowledges* correctly received packets
- Selective ACKs offer **more precise information** but require **more complicated book-keeping**

Sliding Window Protocols

- **Resending packets:** two canonical approaches
  - Go-Back-N (GBN)
  - Selective Repeat
- Many variants that differ in implementation details

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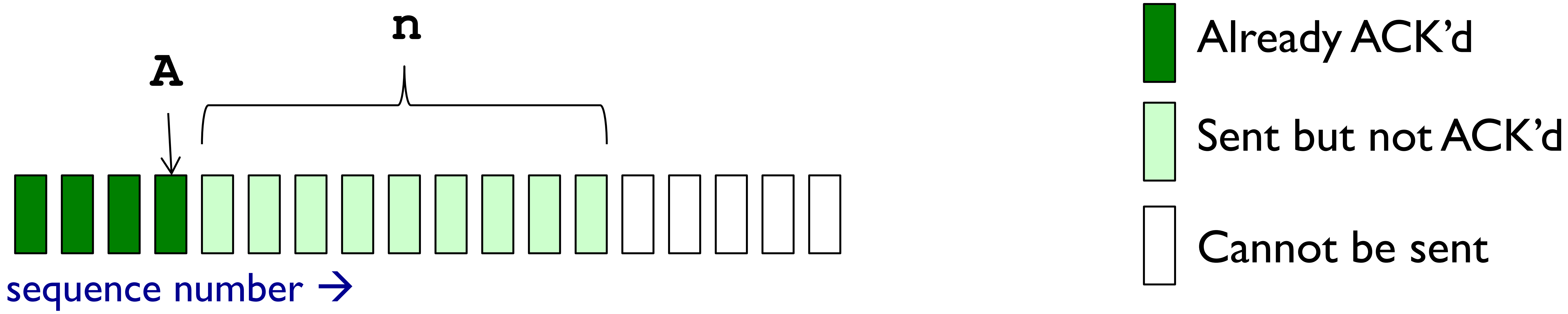
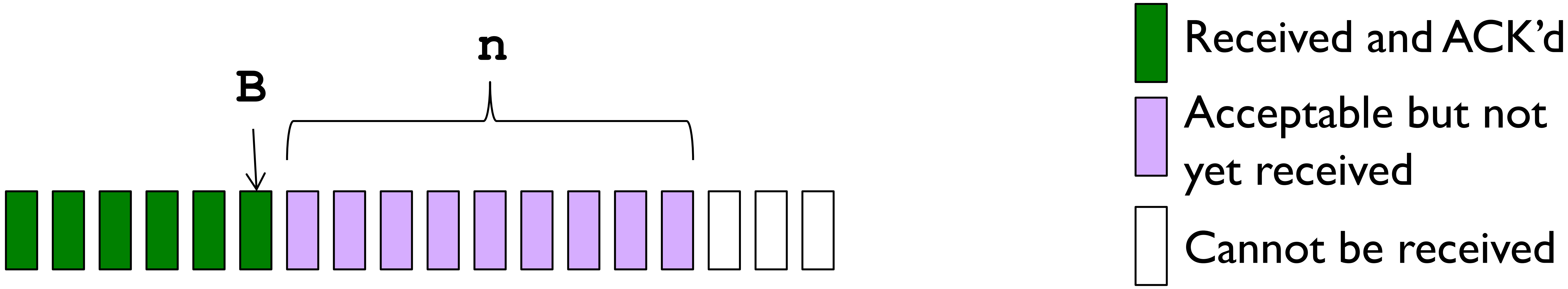
- If timeout, retransmit A+1, …, A+n

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

Sender Window

Receiver Window

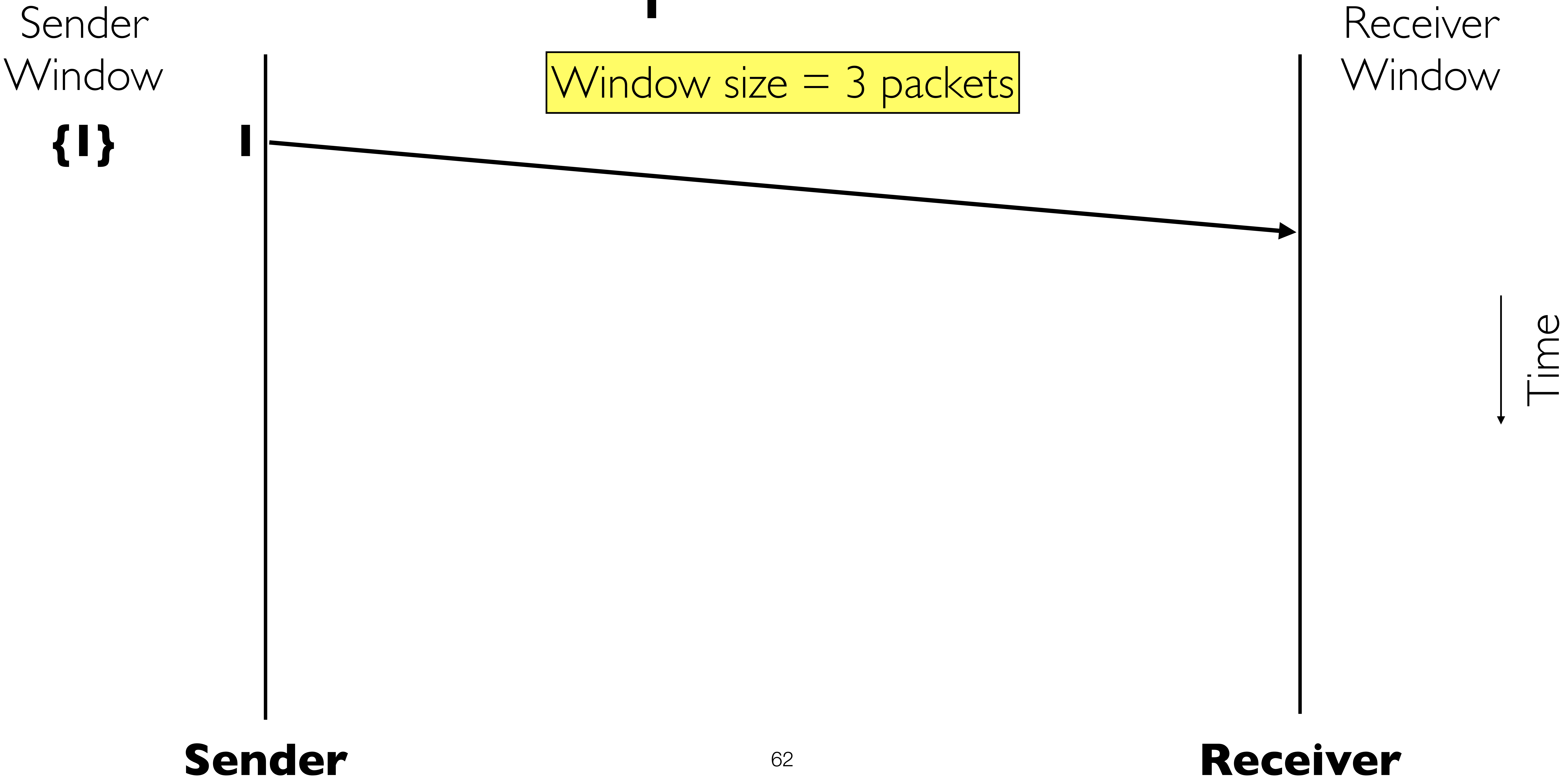
Window size = 3 packets

Time

Sender

Receiver

GBN Example without Errors



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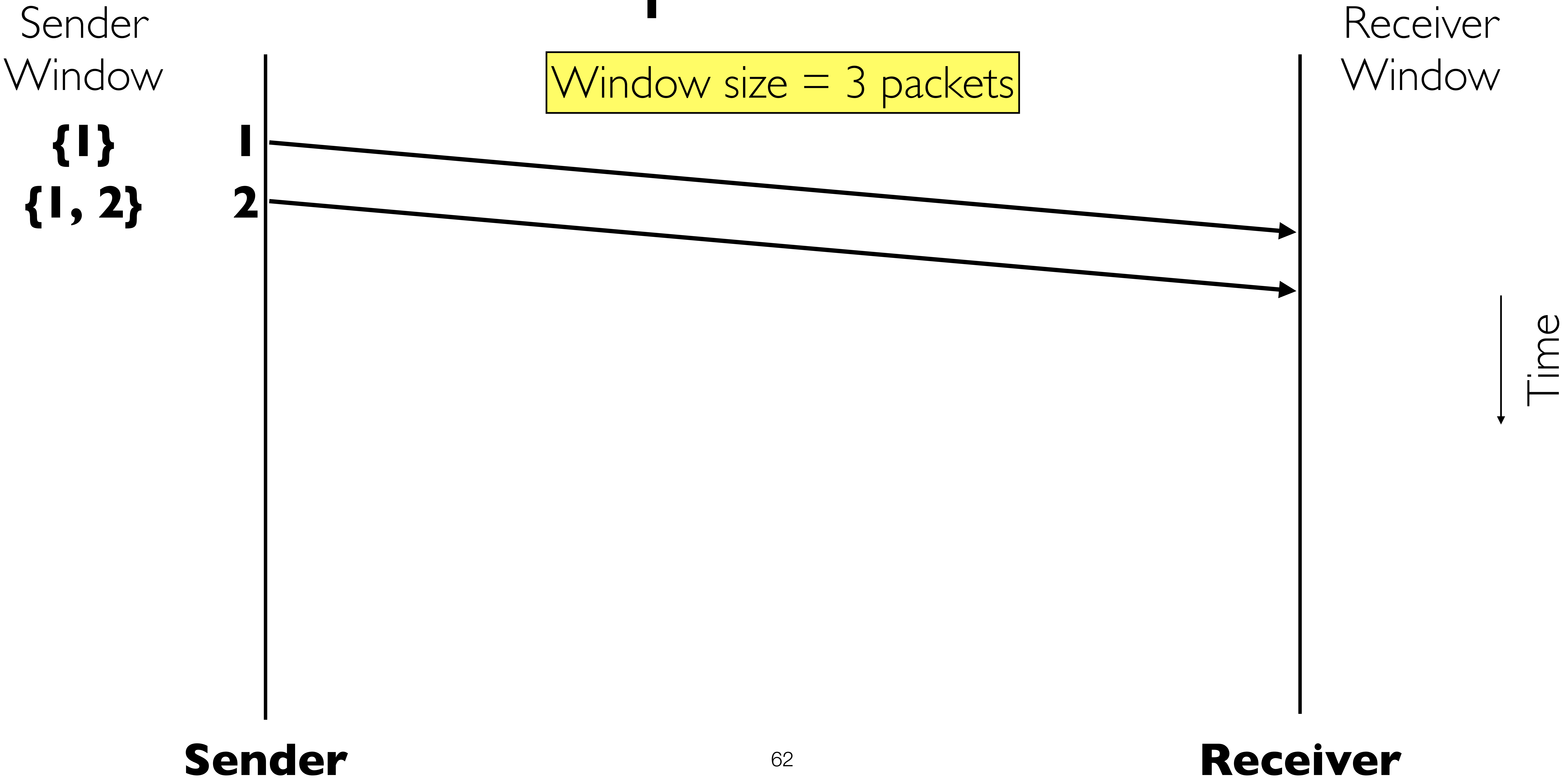

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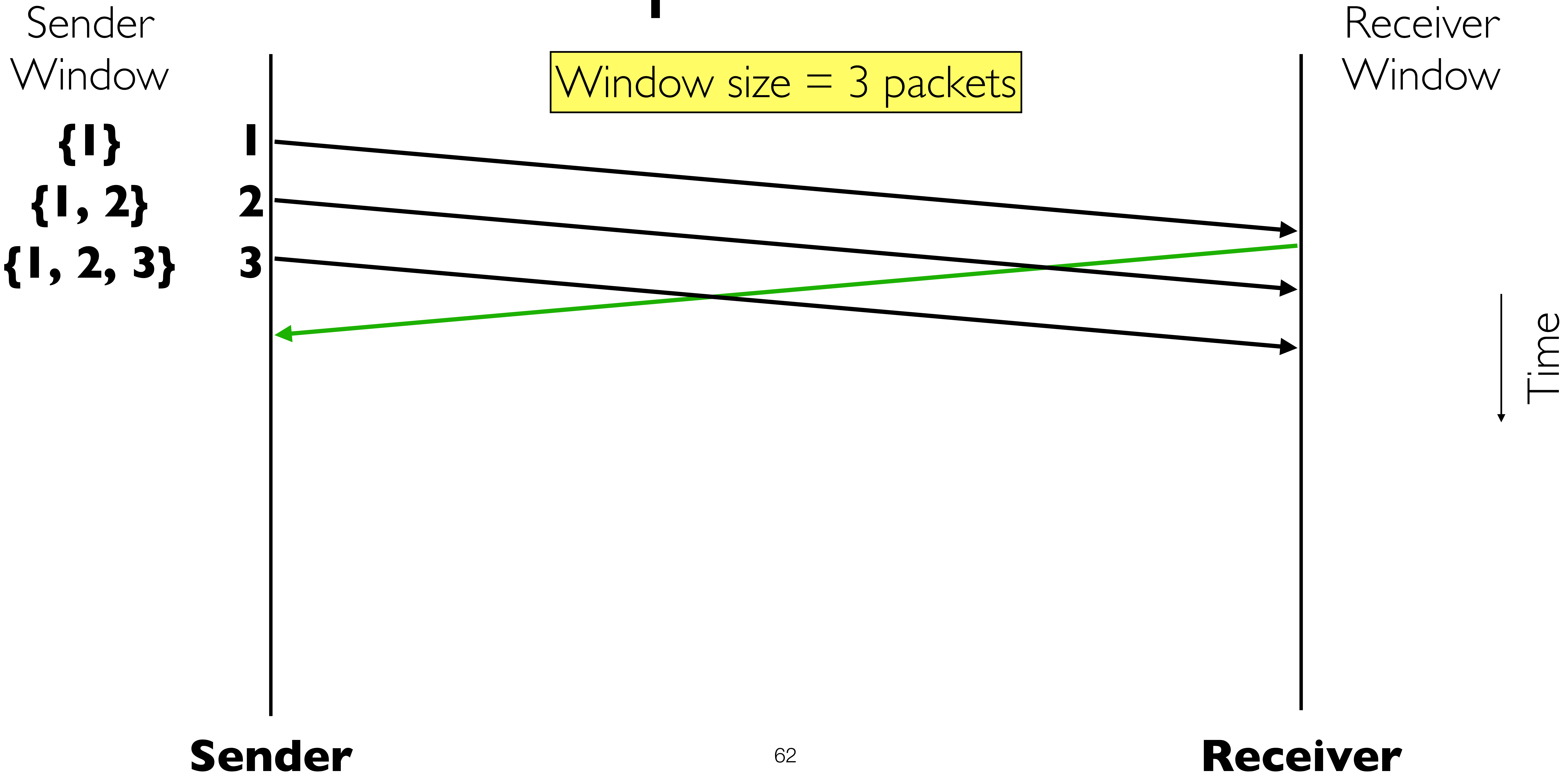

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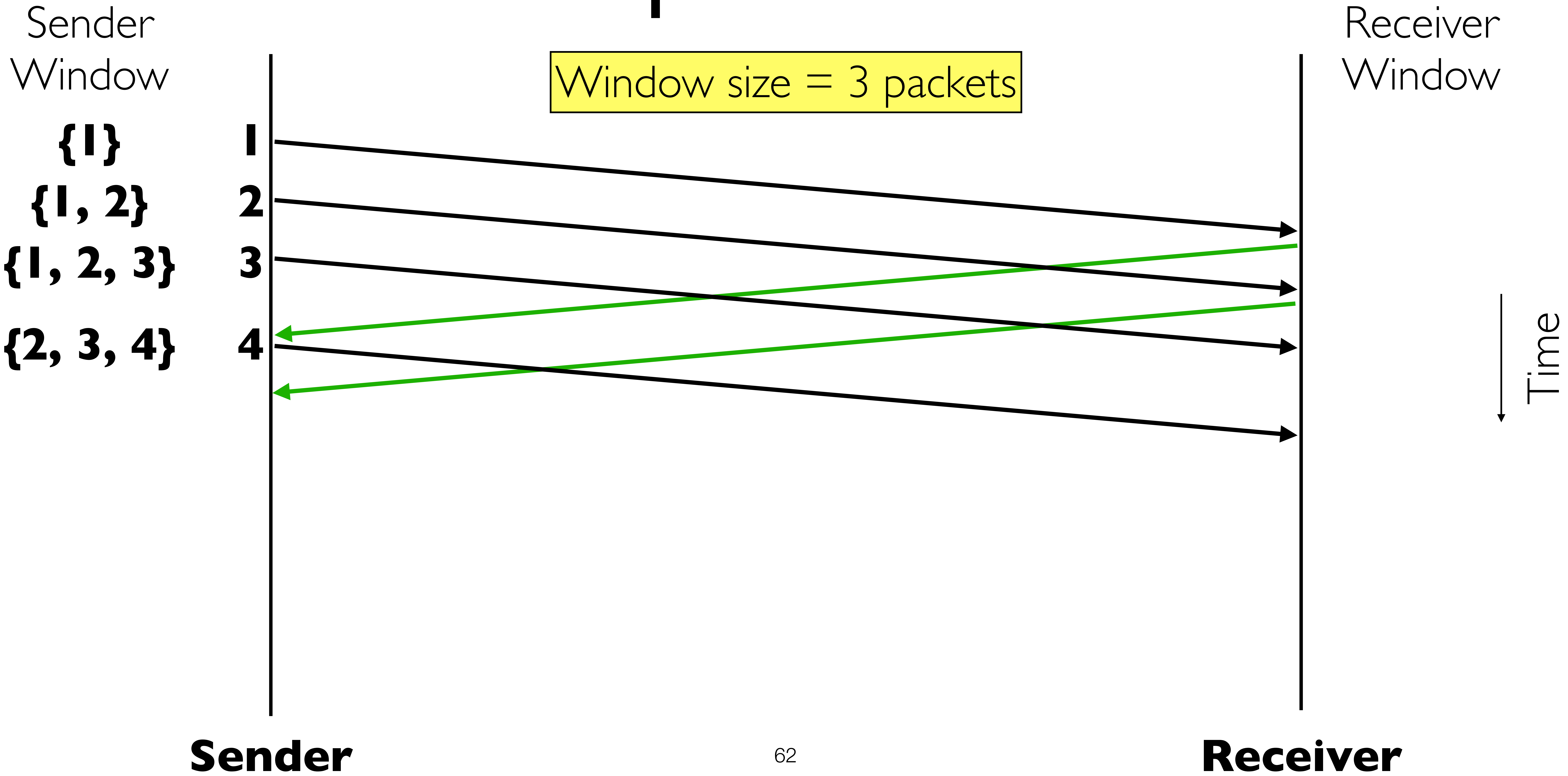

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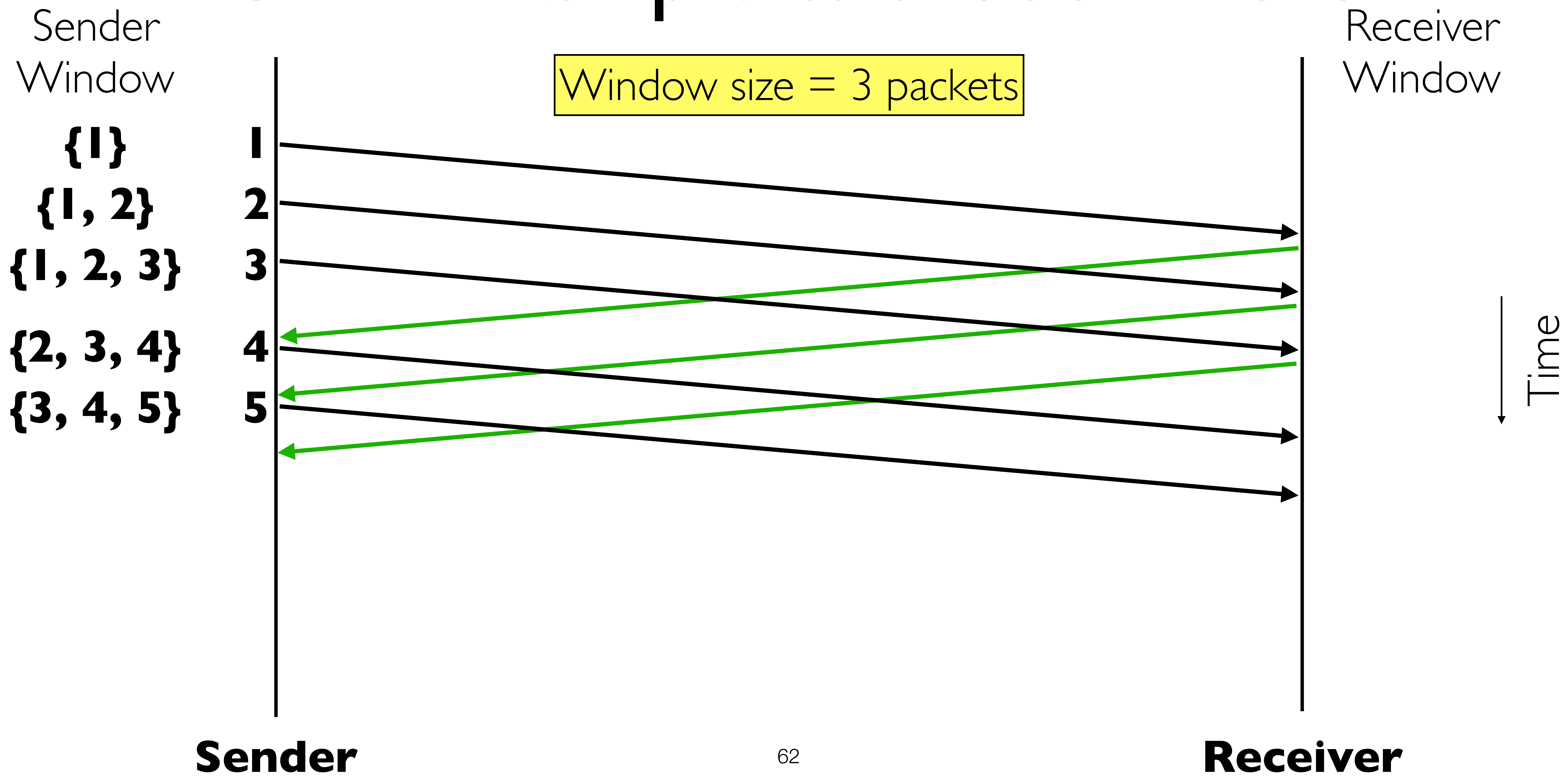

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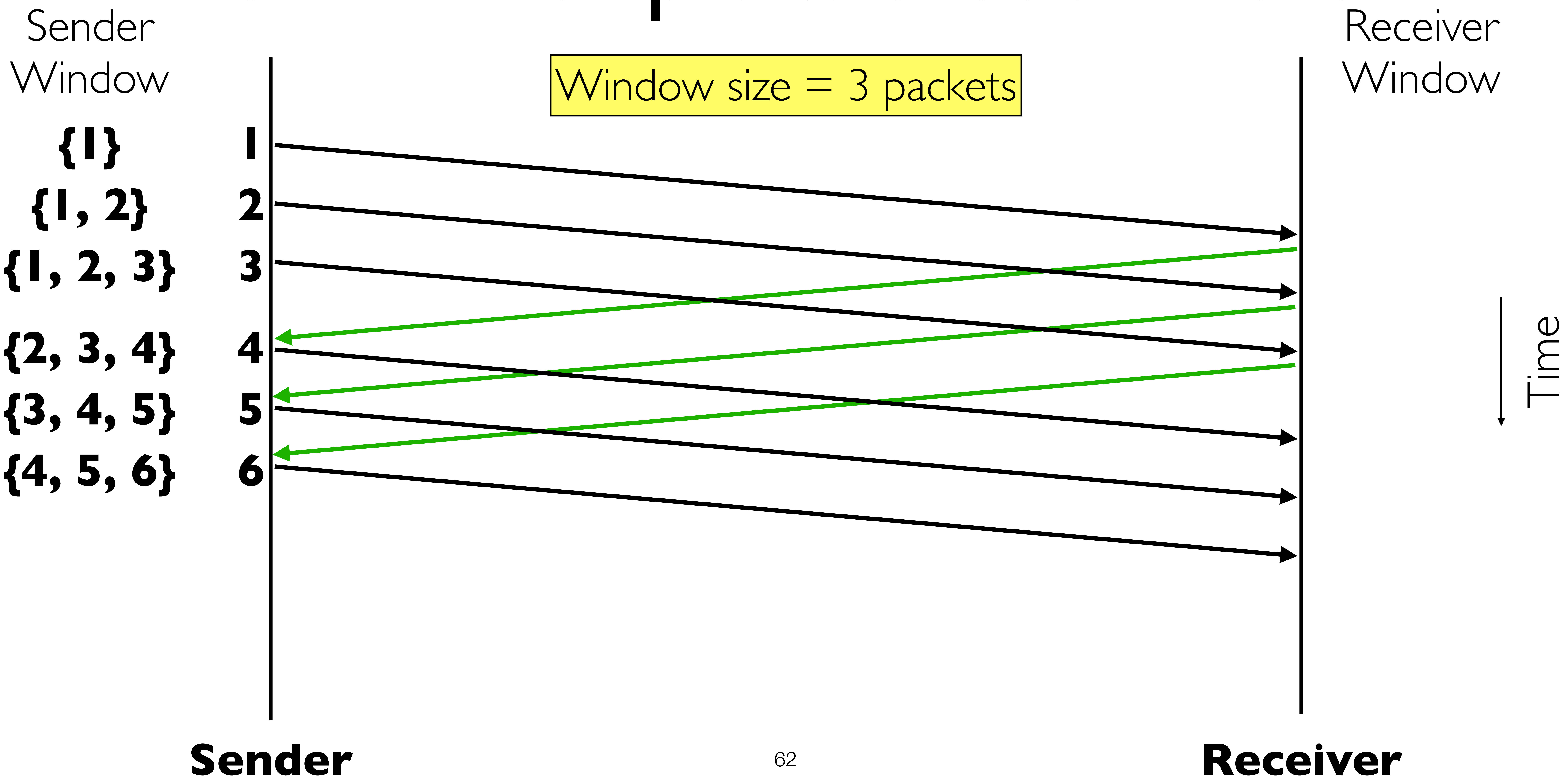

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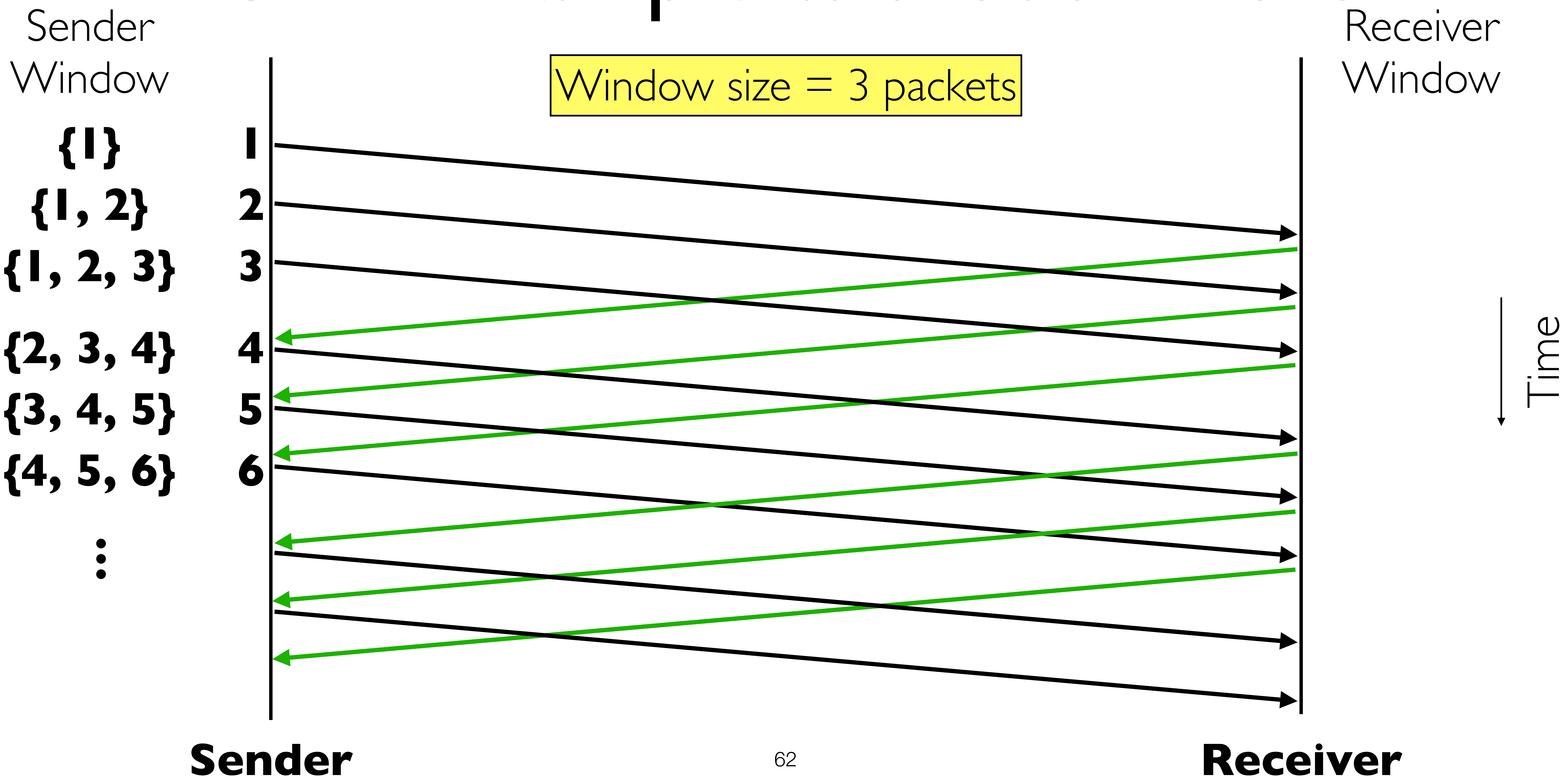

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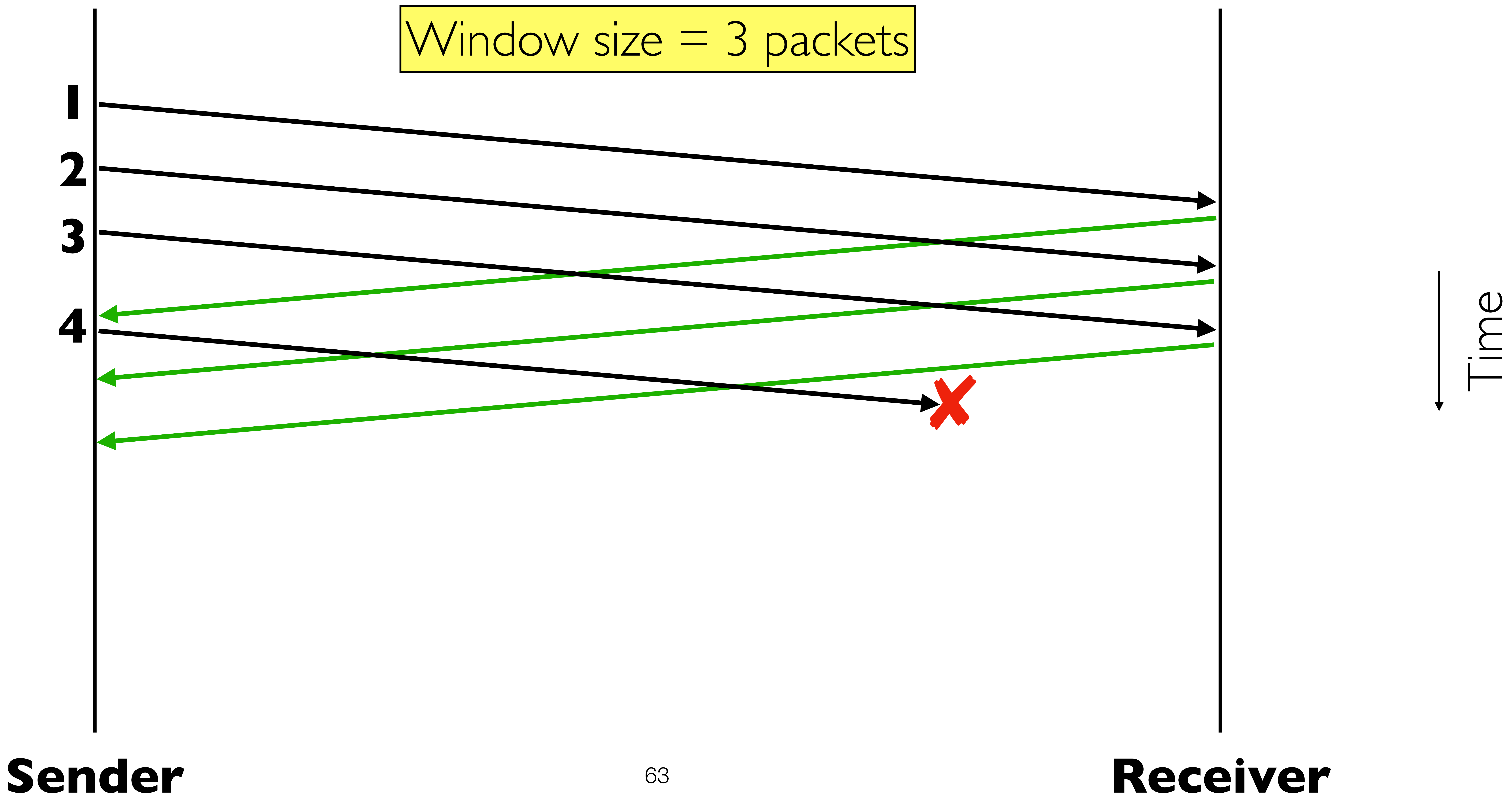

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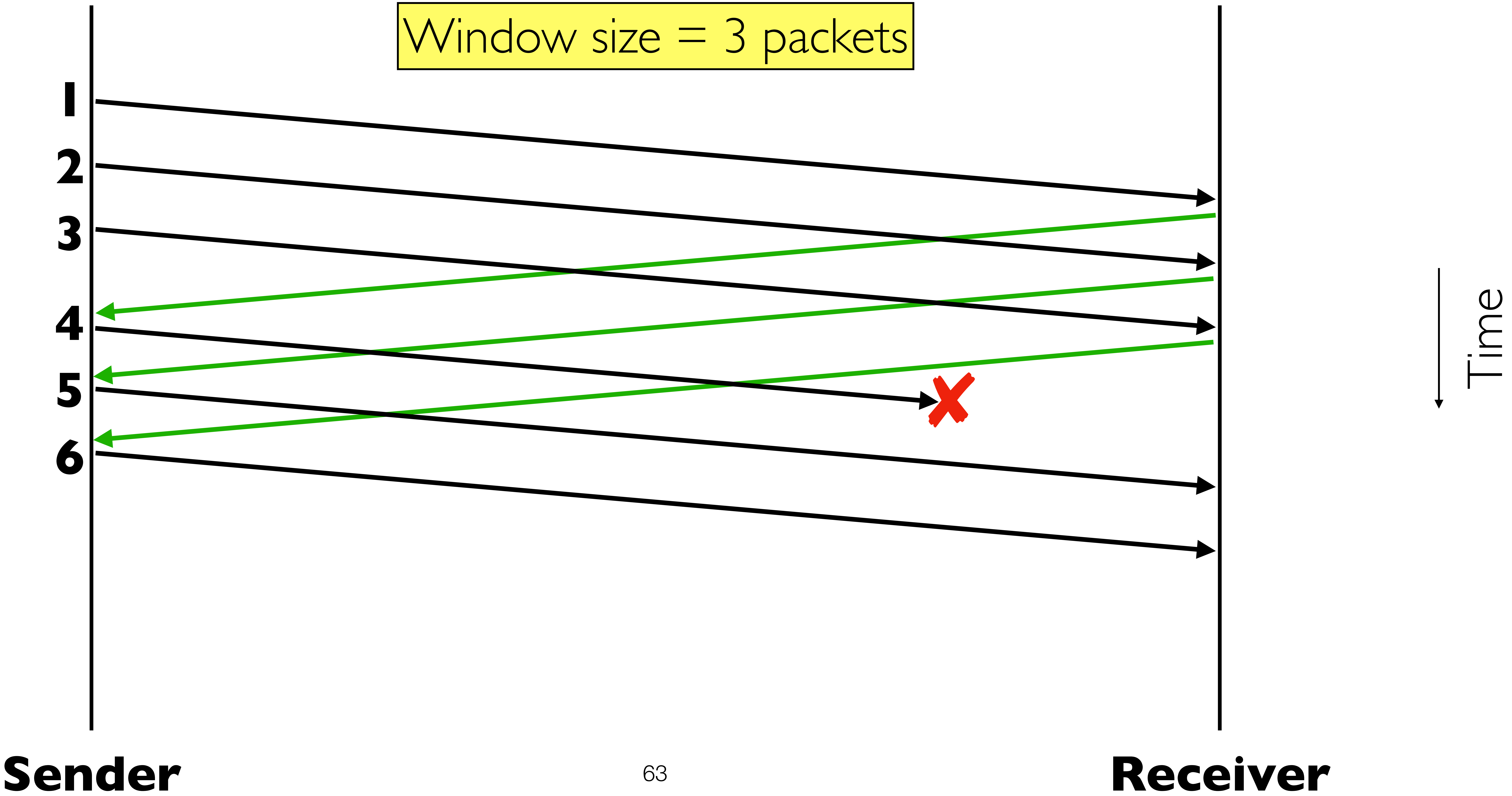

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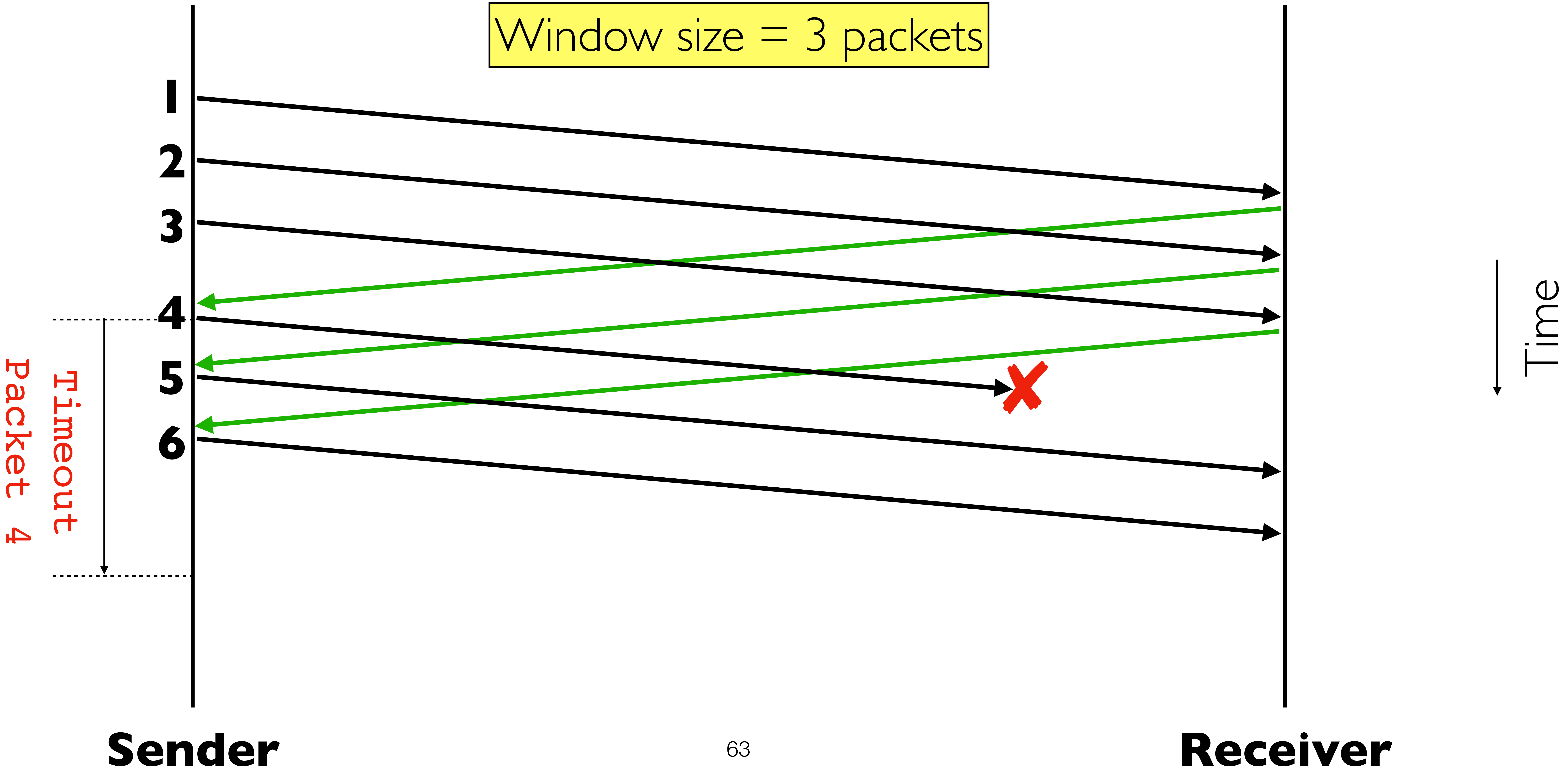

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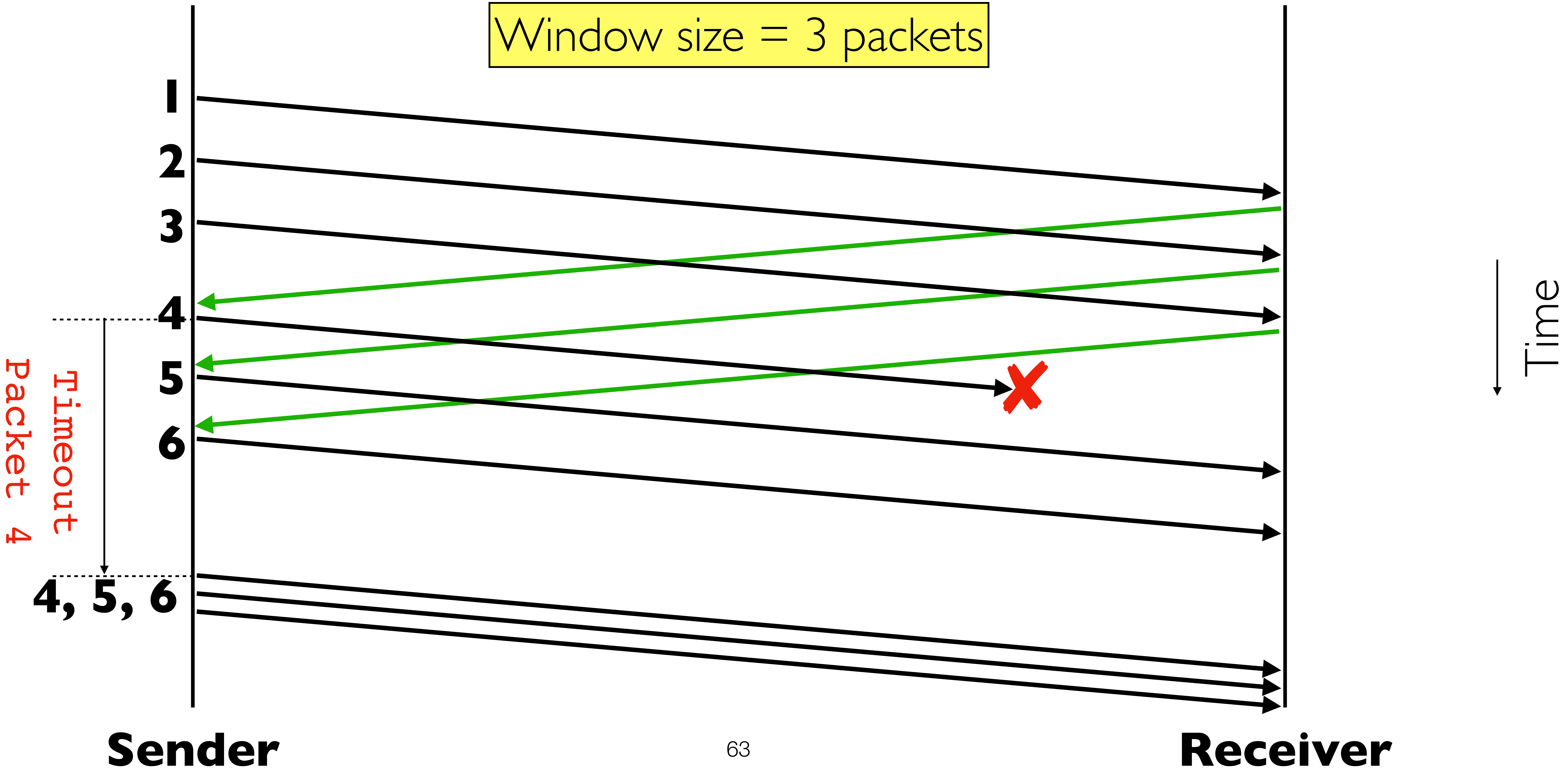

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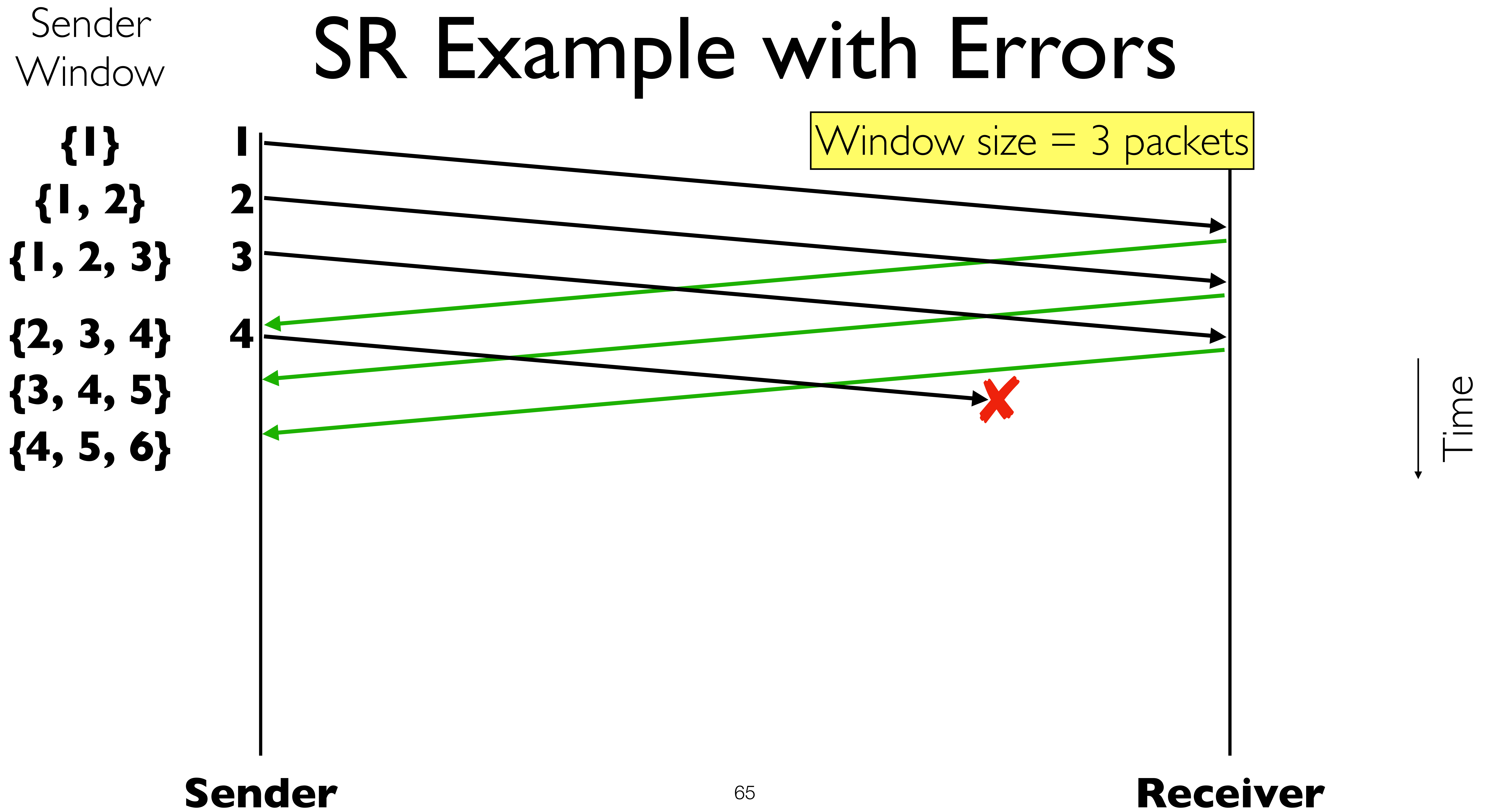
- Efficient in retransmissions but complex bookkeeping
    - Need a timer per packet!

SR Example with Errors



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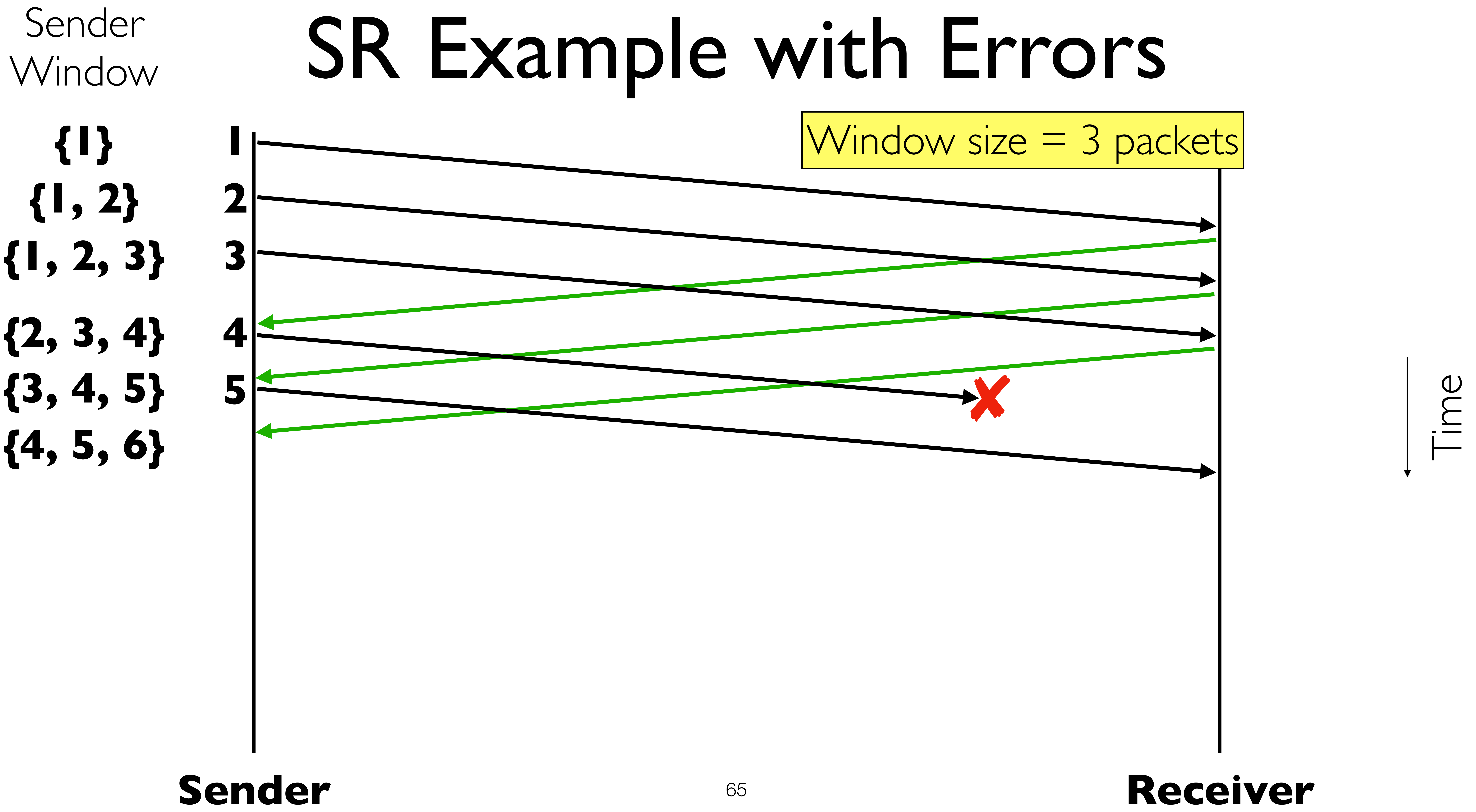

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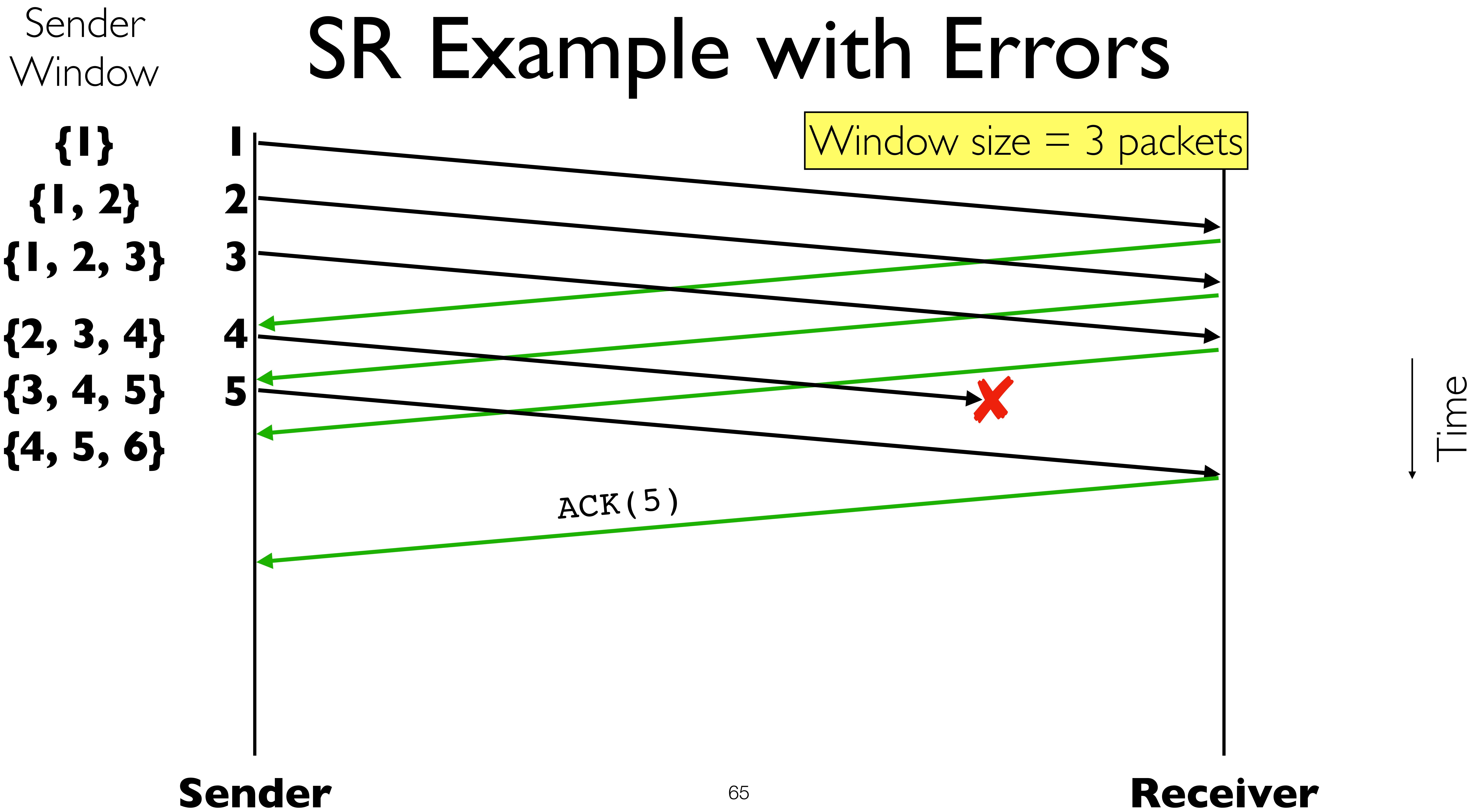

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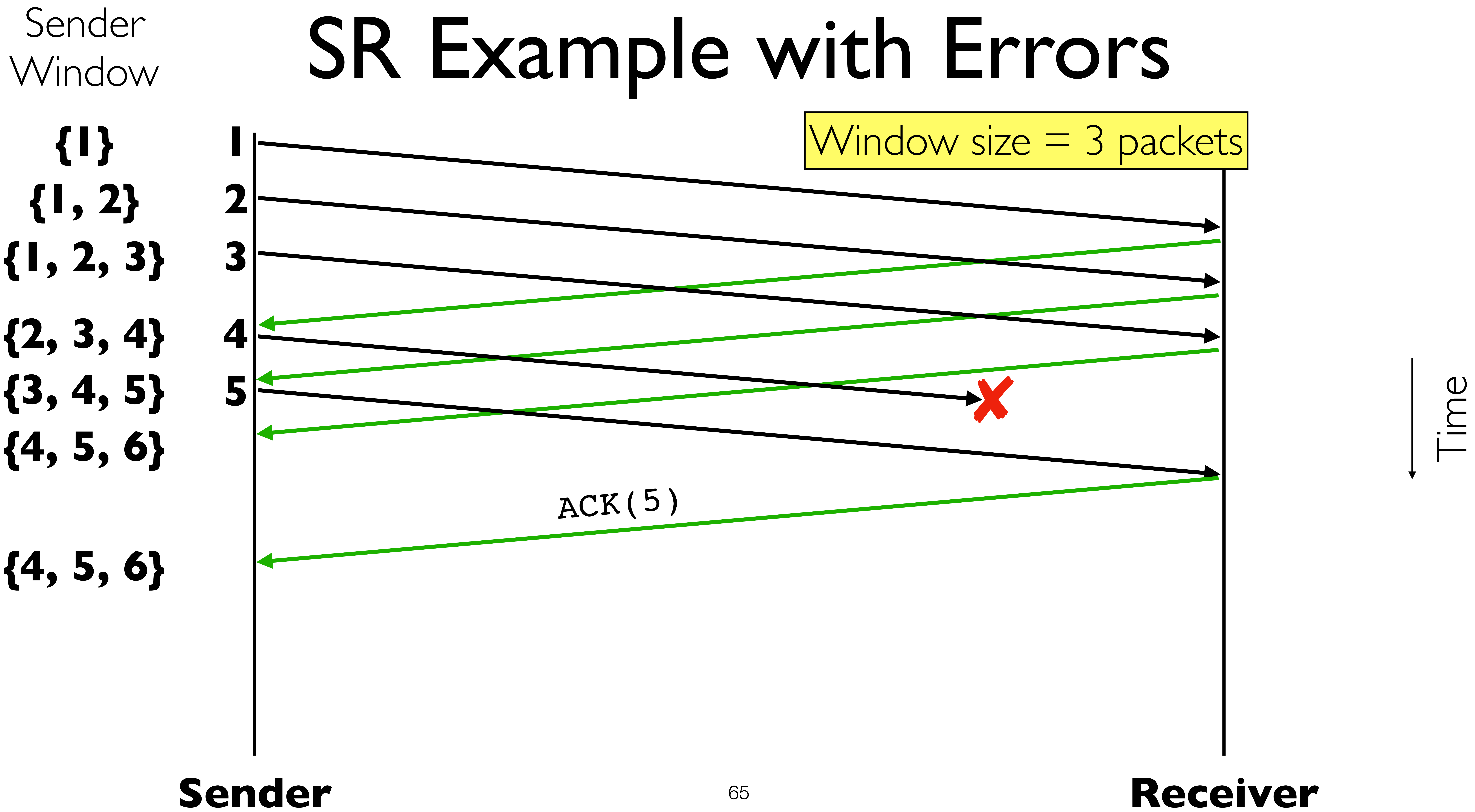

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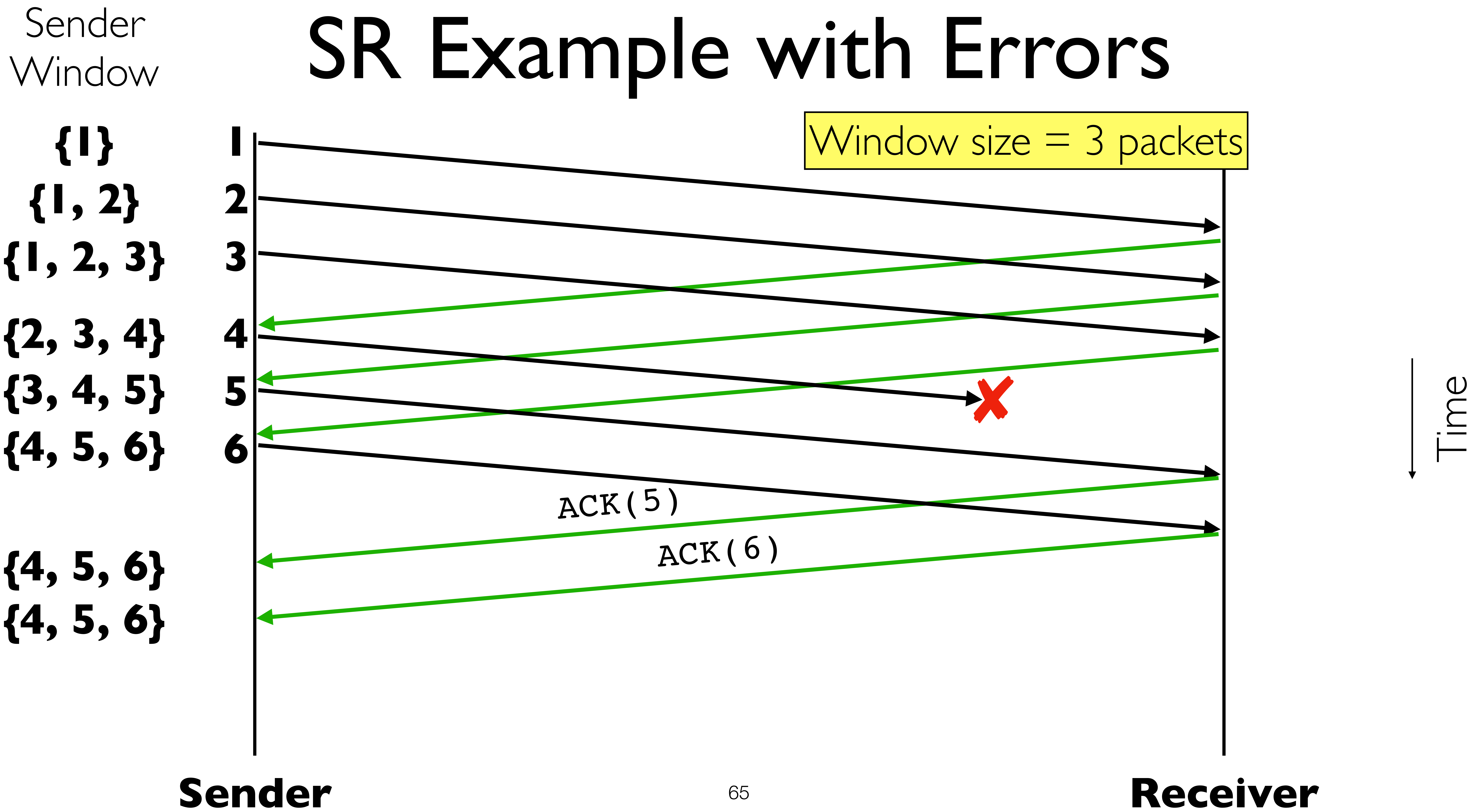

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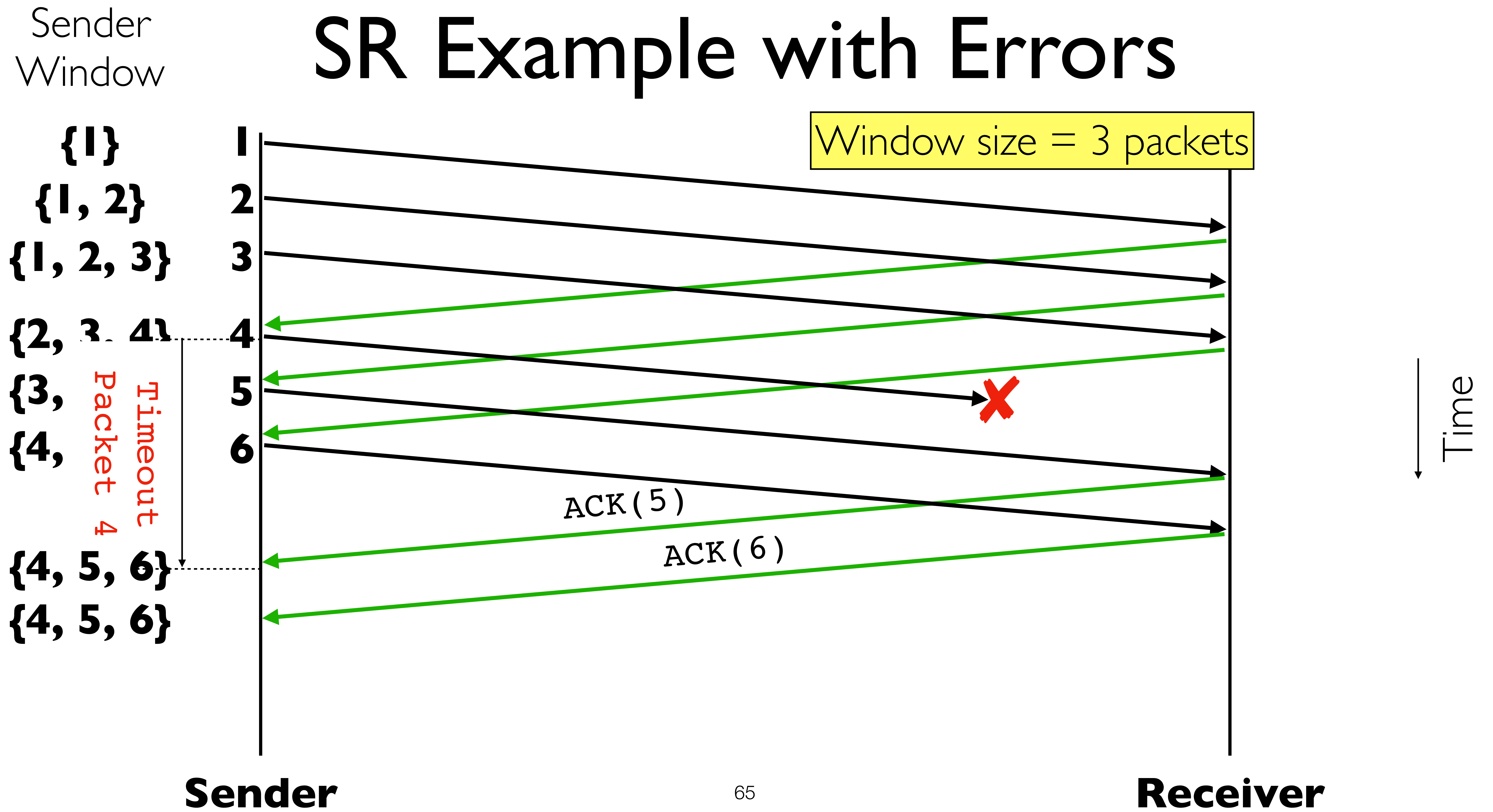

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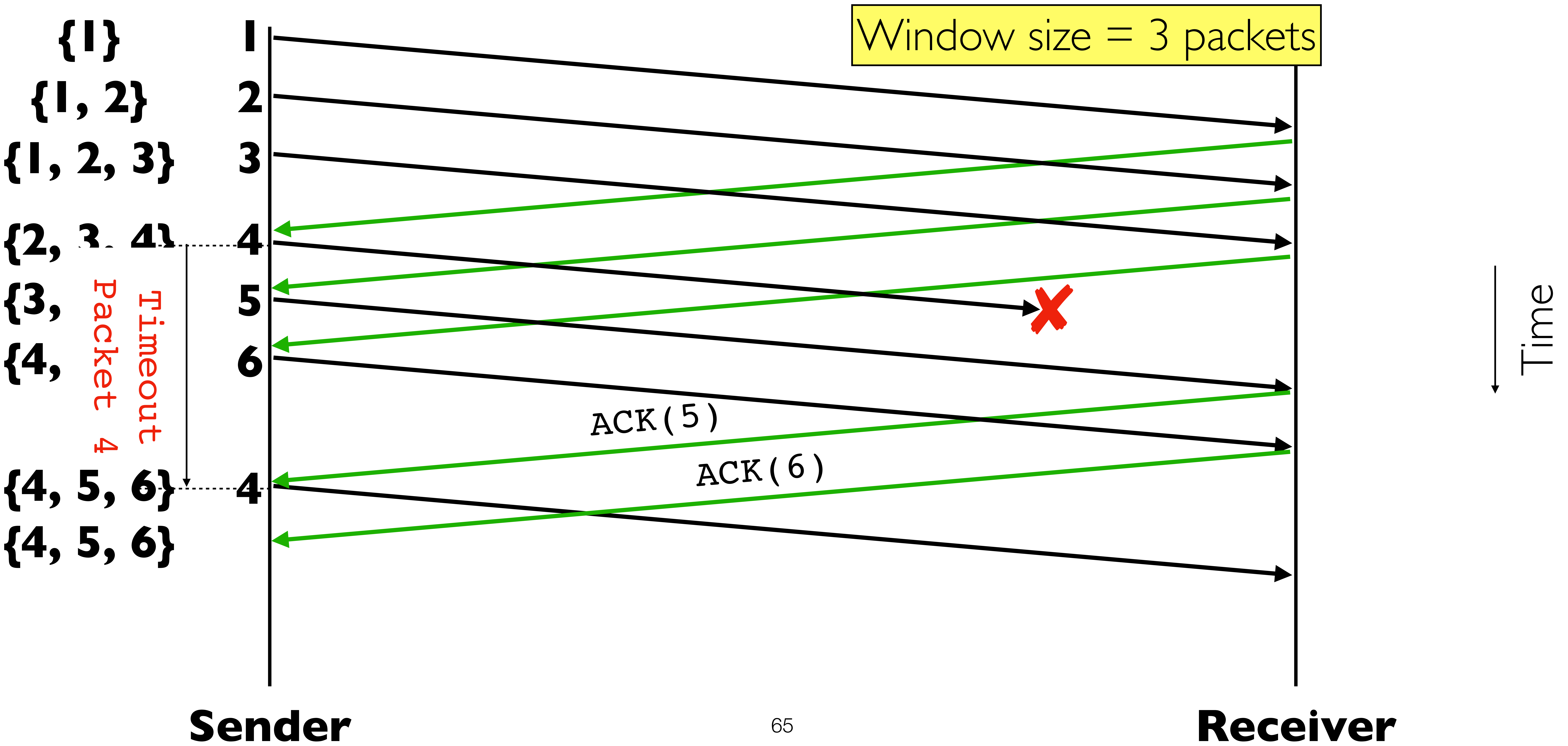

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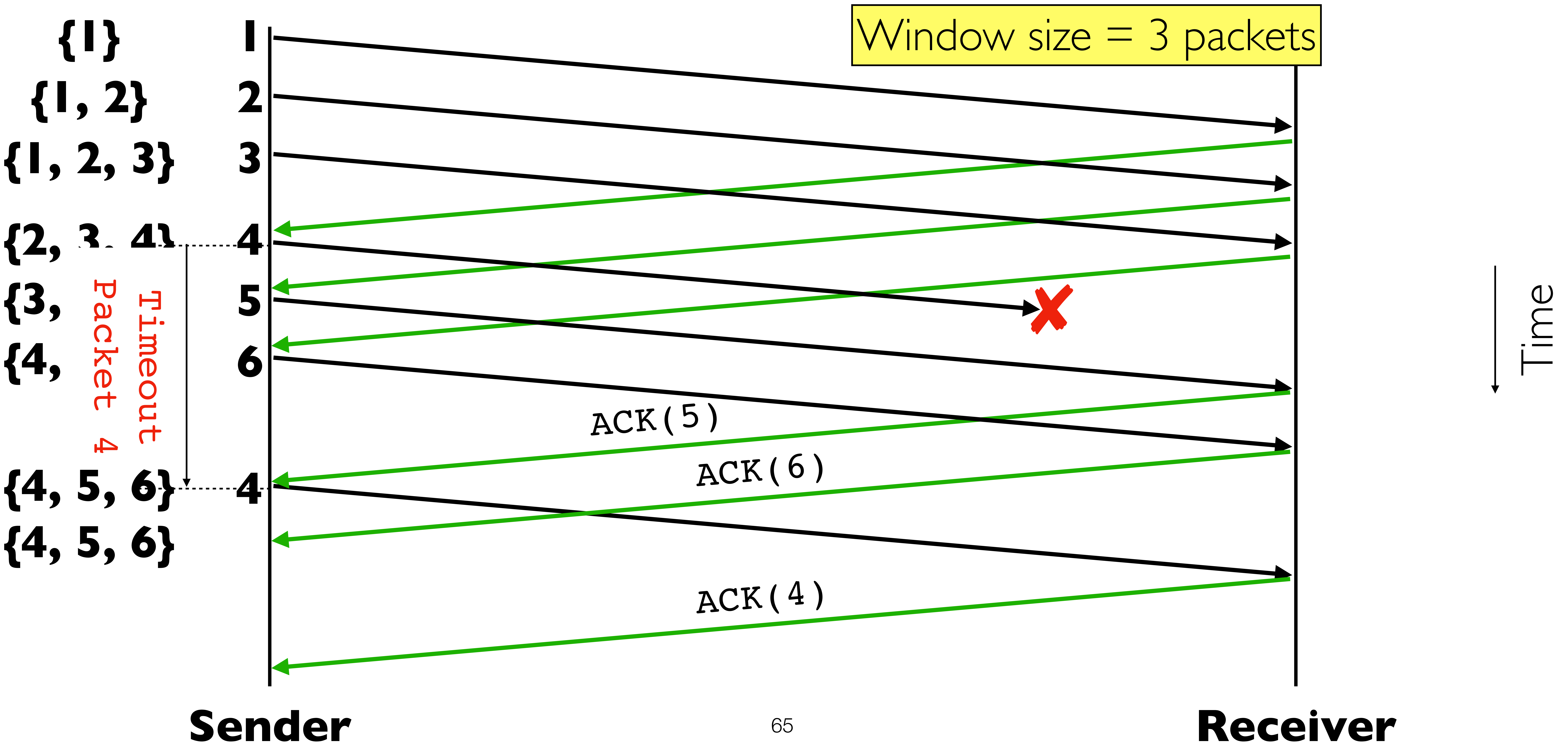

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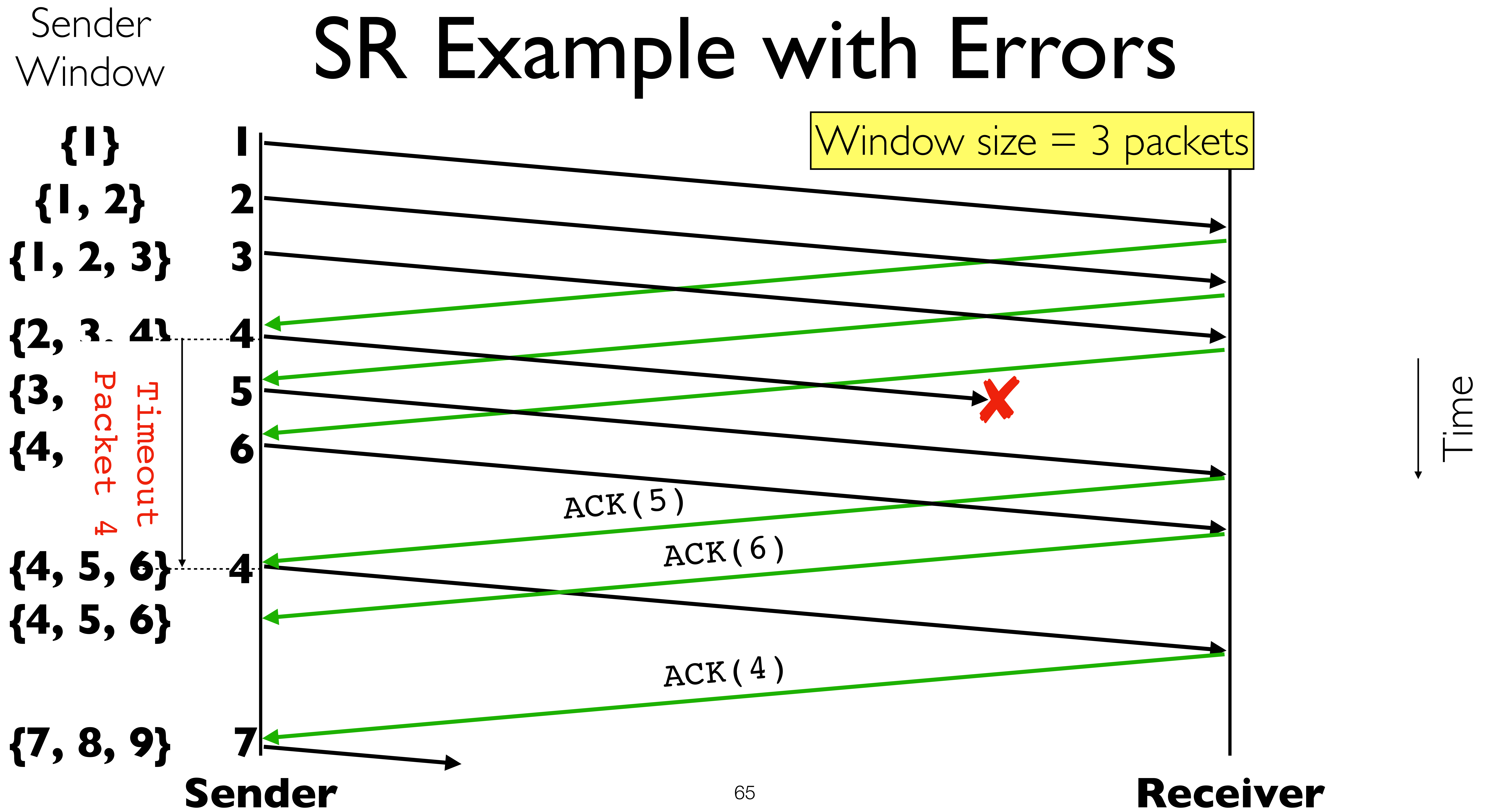

GBN vs Selective Repeat

- 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

- **Checksums:** for error detection
- **Timers:** for loss detection
- **ACKs**
  - Cumulative
  - Selective
- **Sequence numbers:** tracking duplicates, windows
- **Sliding Windows:** for efficiency

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

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  - Introduces timeout estimation algorithms (next time)

Next Time

- **TCP**
  - Reliability
  - Congestion control