Wrapping up the IP header
&
Reliability Concepts

Spring 2024

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Designing IP: two remaining topics

- IPv4 → IPv6
- Security implications of the IP header

IPv6

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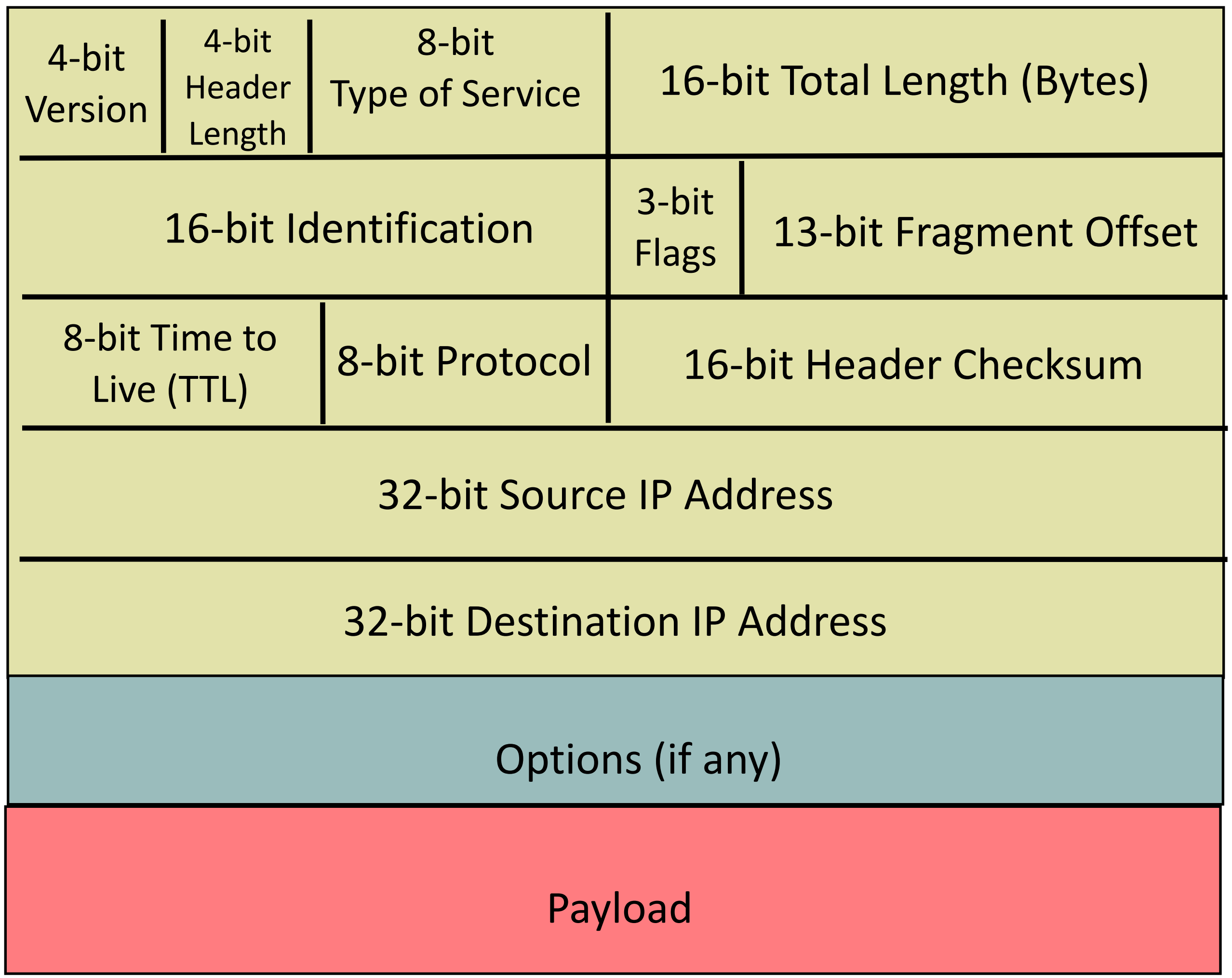
  - Addresses ***four*** times as big
- Took the opportunity to do some “spring cleaning”
  - Got rid of all fields that were not absolutely necessary
- Result is an elegant, if unambitious, protocol

What "clean up" would you do?



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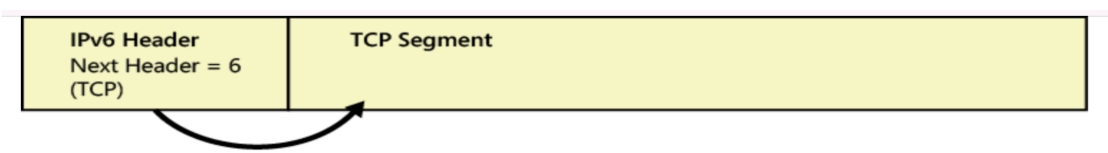

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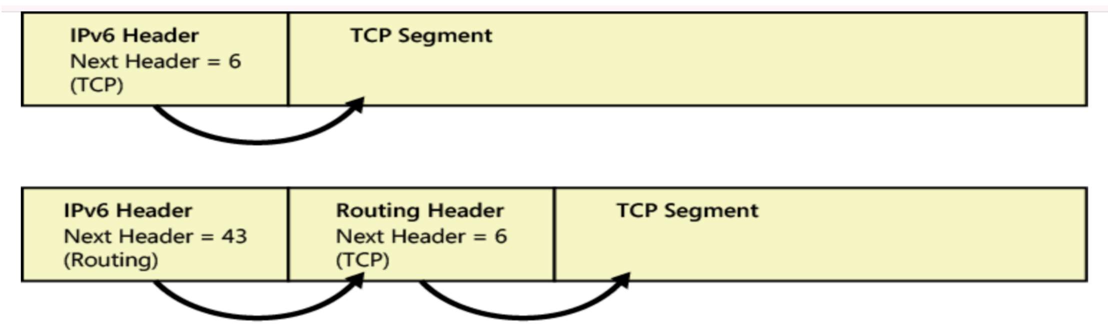

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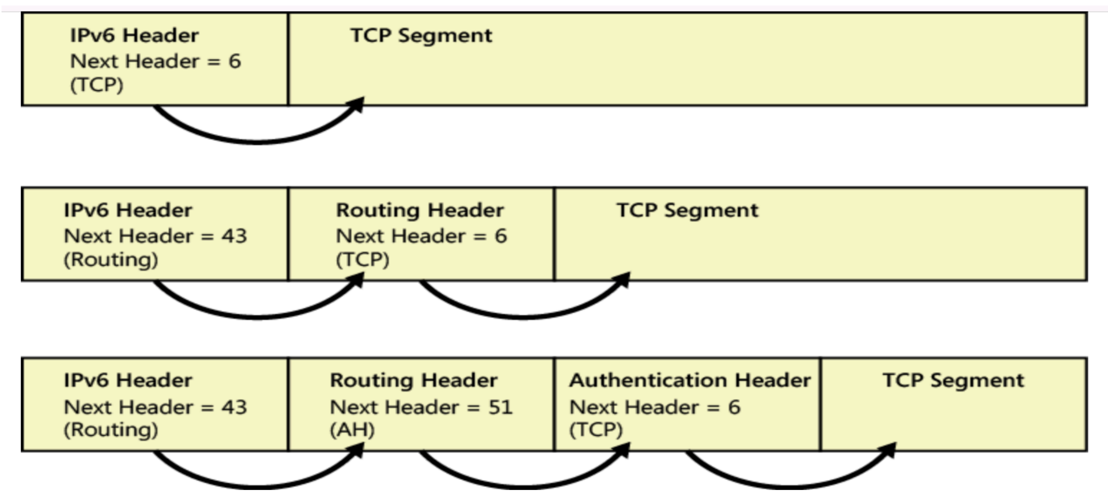

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- Added Flow Label
    - *Explicit* mechanism to denote related streams of packets

IPv4 and IPv6 Header Comparison

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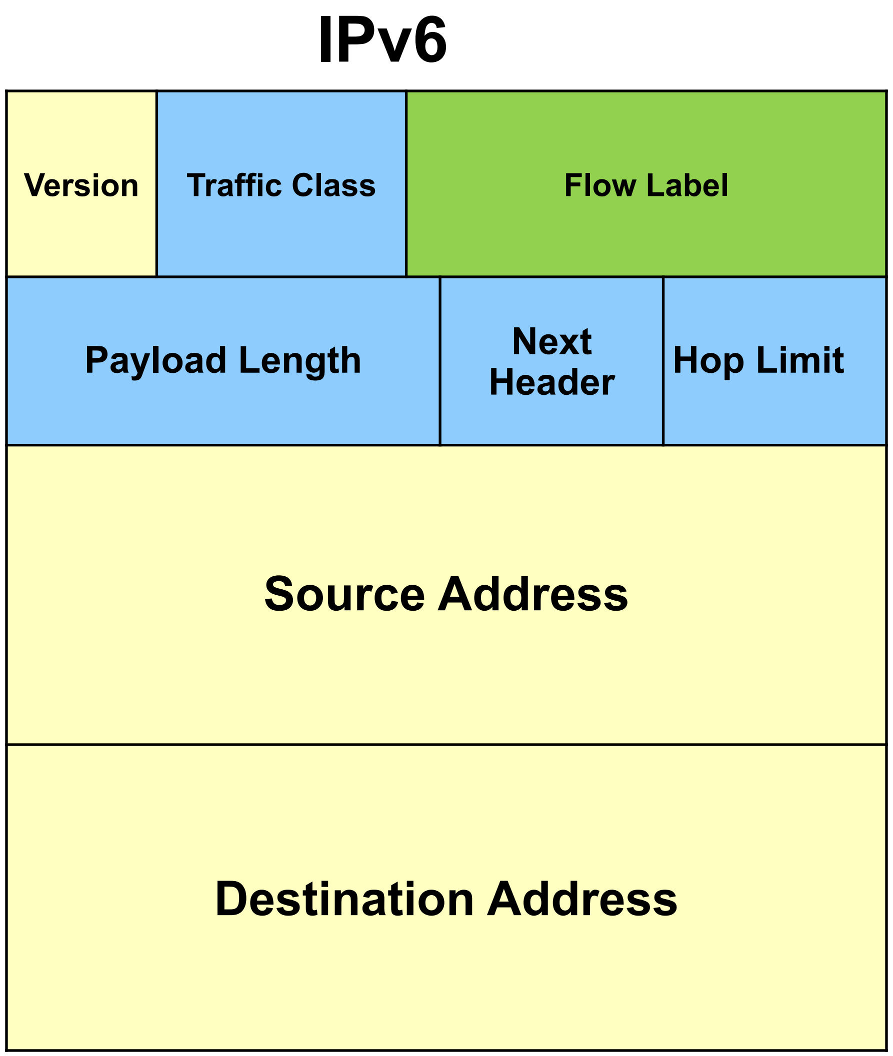

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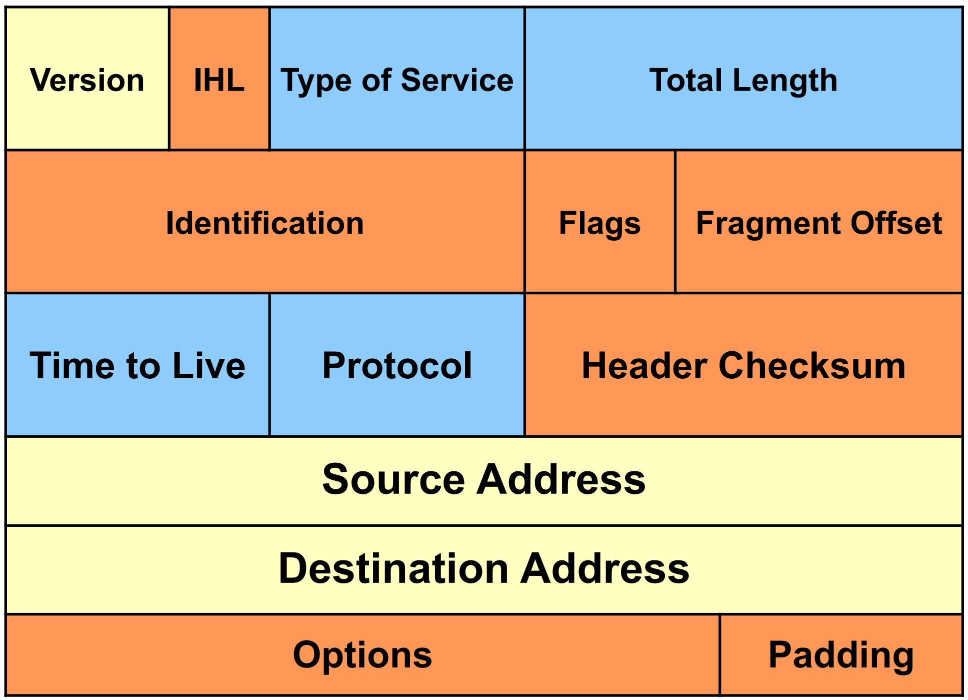
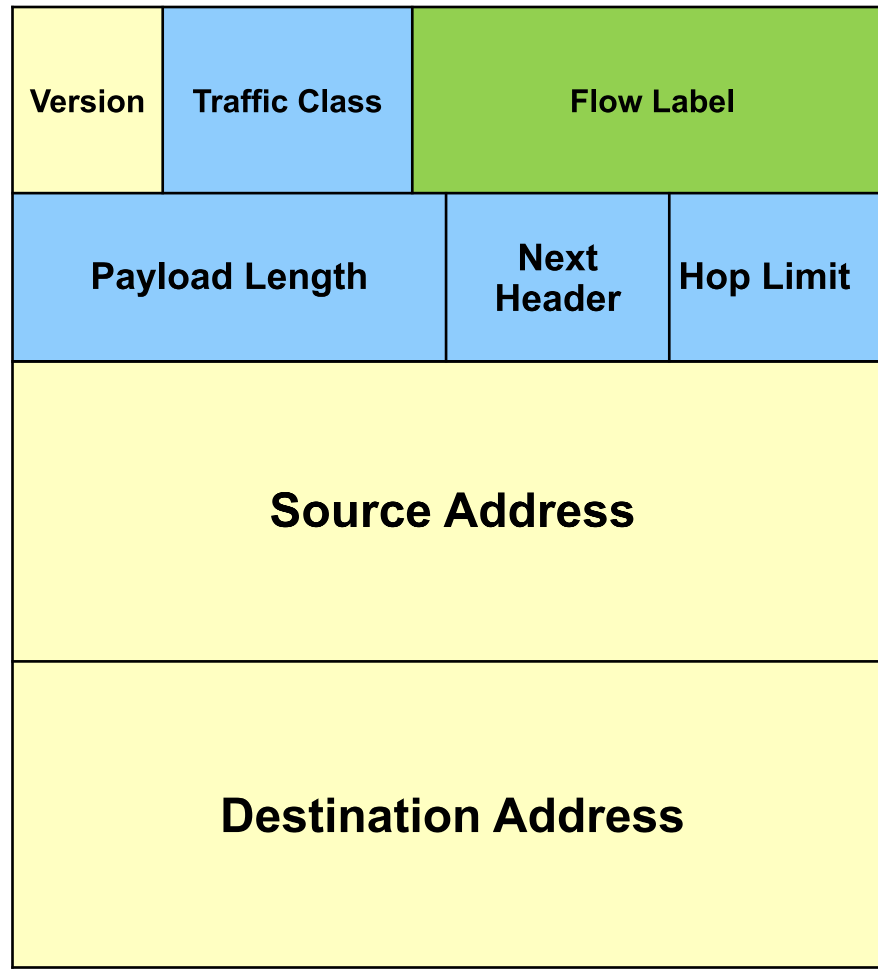


IPv6



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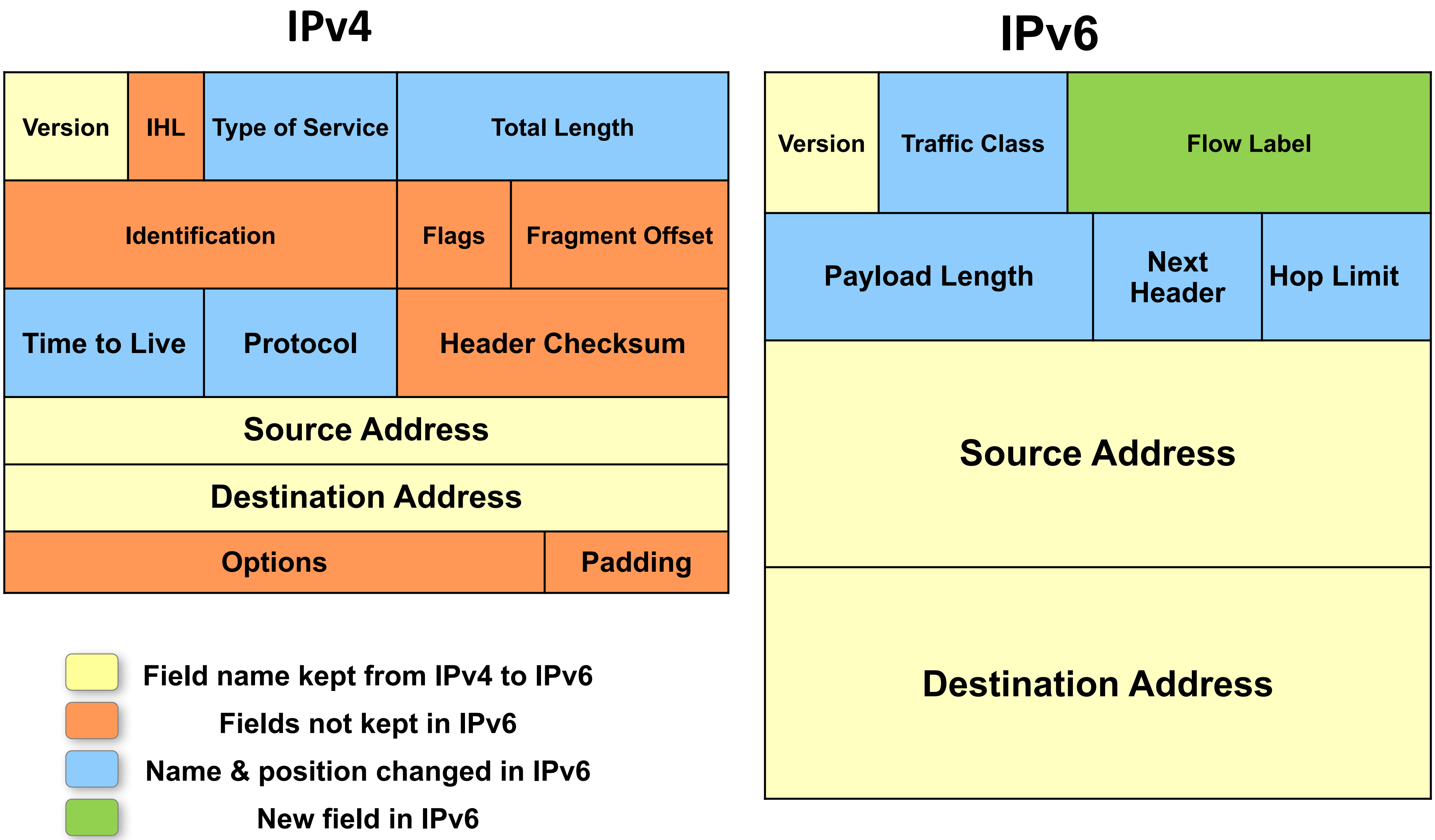

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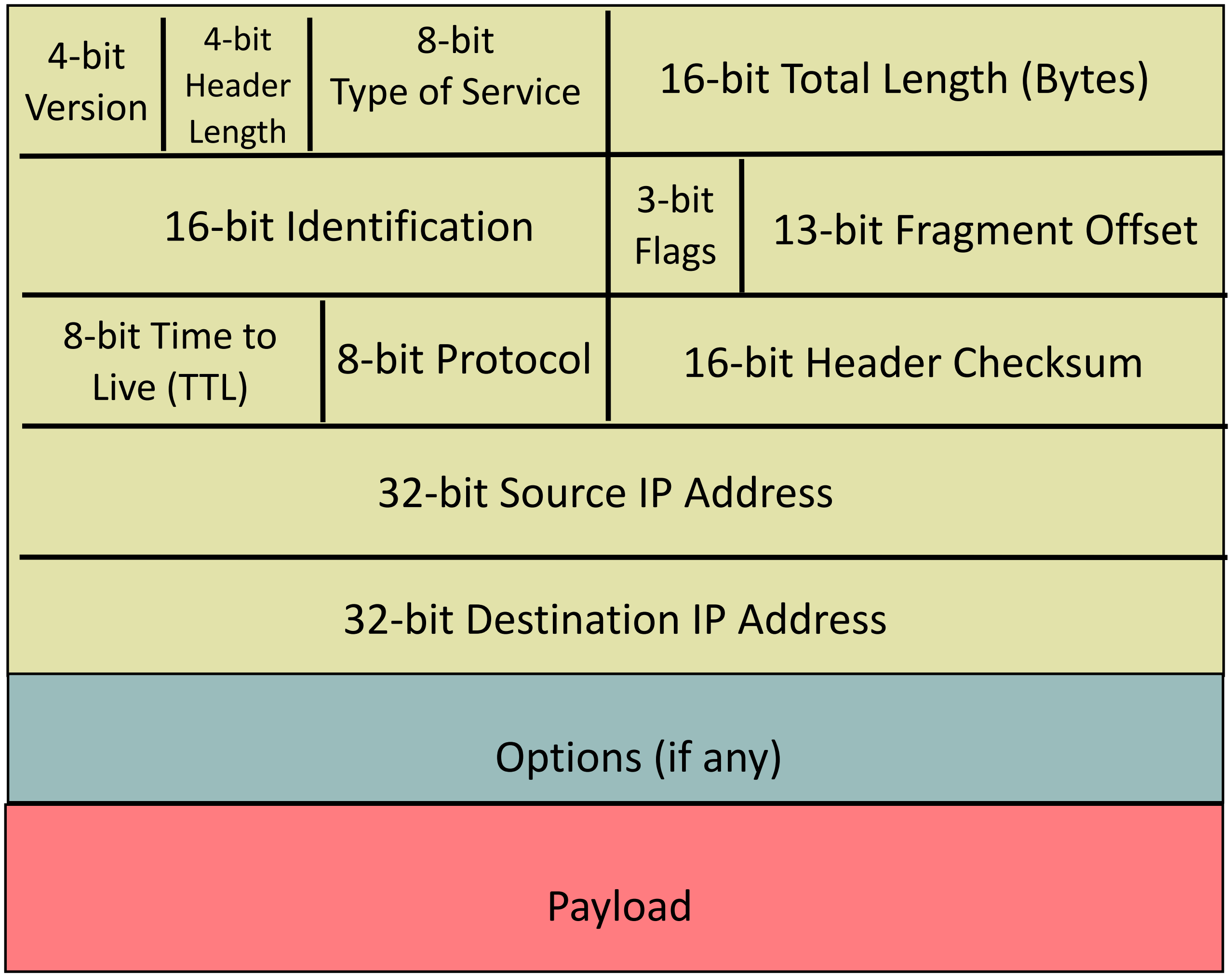
  - general next-header approach
  - general flow label for packet

Quick Security Analysis of IP Header

Focus on Sender Attacks

- Vulnerabilities a sender can exploit
- Note: not a comprehensive view of potential attacks!
  - For example, we'll ignore attackers other than the sender

IP Packet Structure



IP Address Integrity

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- Source address should be the sending host
  - But who’s checking?
  - You could send packets with any source you want

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- Or: as a way to bother the spoofed host
  - Spoofed host is wrongly blamed
  - Spoofed host may receive return traffic from the receiver(s)

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- Today, mostly set/used by operators, not end-hosts

Security Implications of Fragmentation?

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- Send packets larger than MTU → make routers do extra work
  - Can lead to resource exhaustion

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- IP options
  - Processing IP options often processed in router's control plane (i.e., slow path) → attacker can try to overload routers
- Routers often ignore options / drop packets with options

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- Allows discovery of topology (a la *traceroute*)
- Some routers do not respond with a TTL exceeded error message

Other Security Implications?

- No apparent problems with protocol field (8 bits)
  - It's just a de-muxing handle
  - If set incorrectly, next layer will find packet ill-formed
- Bad IP checksum field (16 bits) will cause packet to be discarded by the network
  - Not an effective attack…

Recap: IP header design

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- More nuanced than it first seems!
- Must juggle multiple goals
  - Efficient implementation
  - Security
  - Future needs

Questions?

Next topic: Reliable Transport

- **Today**: focus on concepts and mechanisms
- **Next lecture:** the design of TCP

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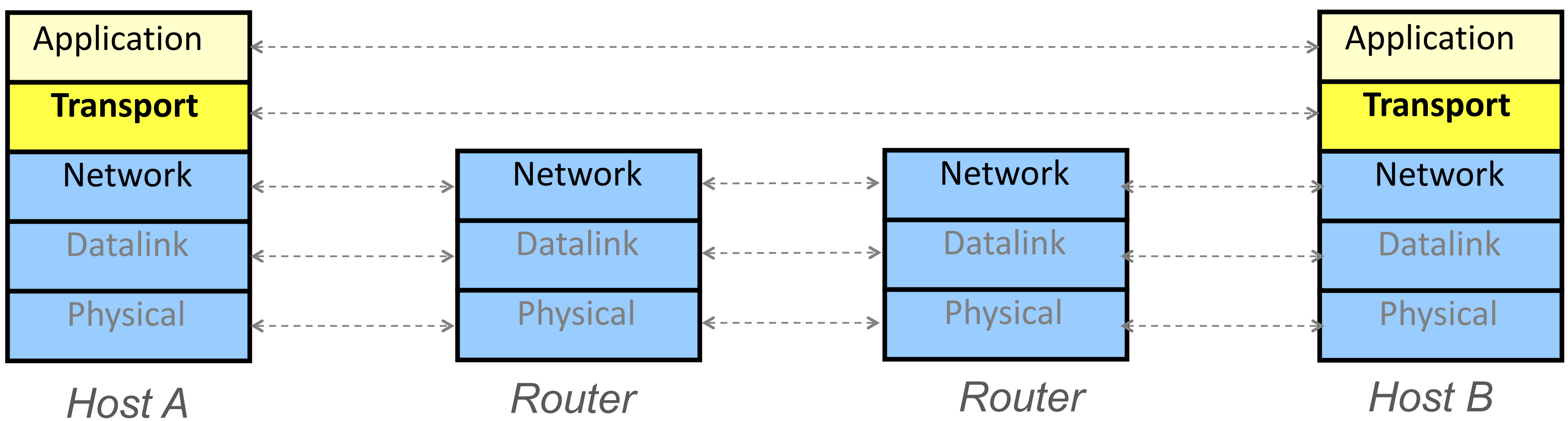
- Challenge: building a reliable service on top of unreliable packet delivery

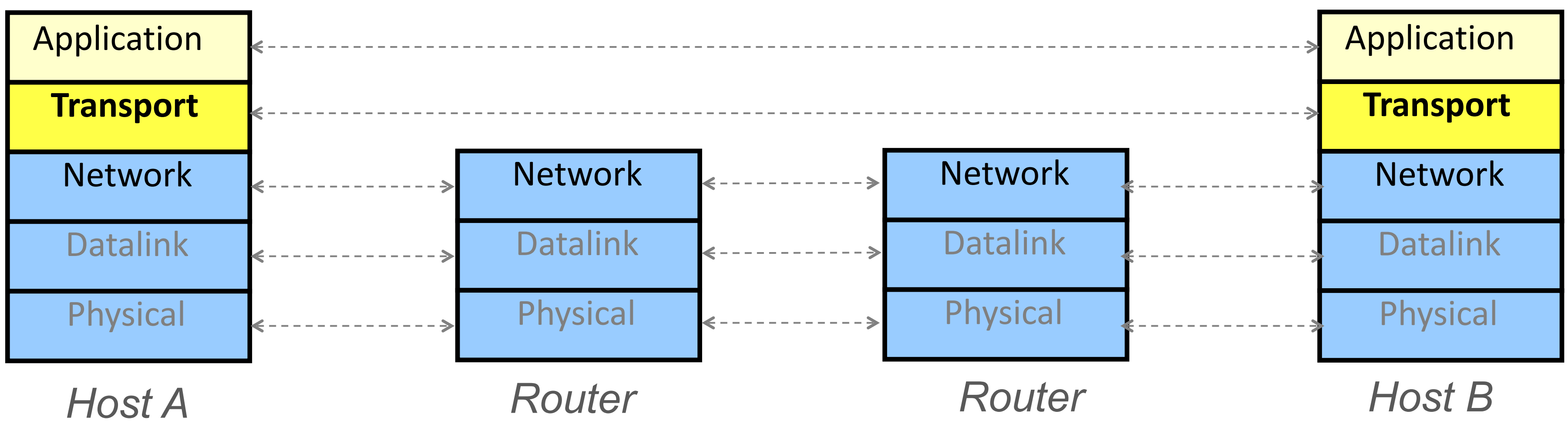
- Bridging the gap between
  - **the abstractions application designers want**
  - **the abstractions networks can easily support**

Semantics of correct delivery



Semantics of correct delivery

- At network layer: *best-effort* delivery



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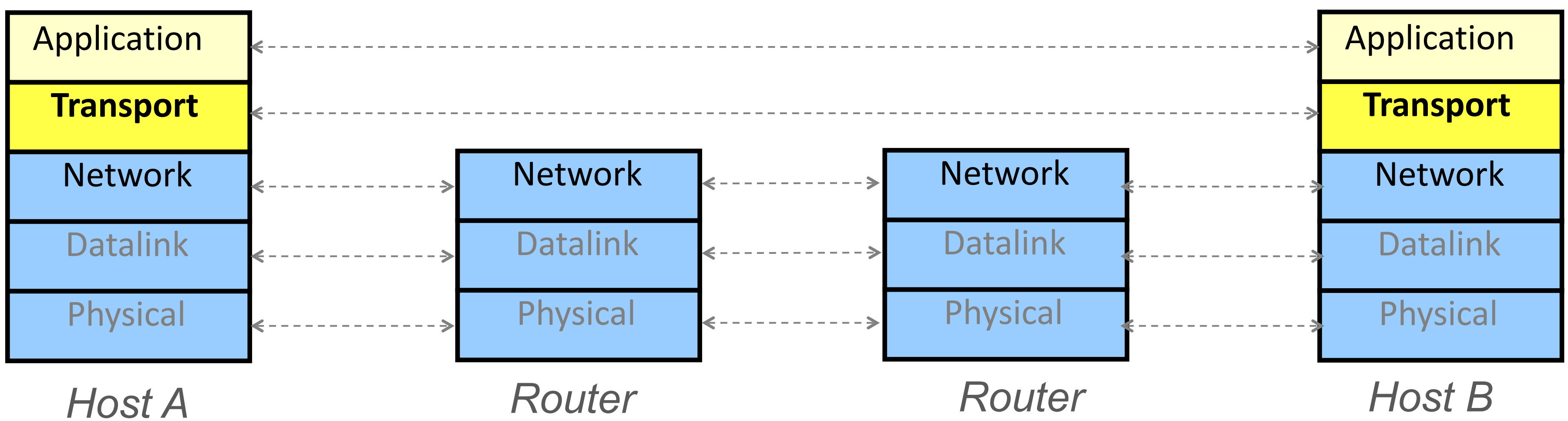

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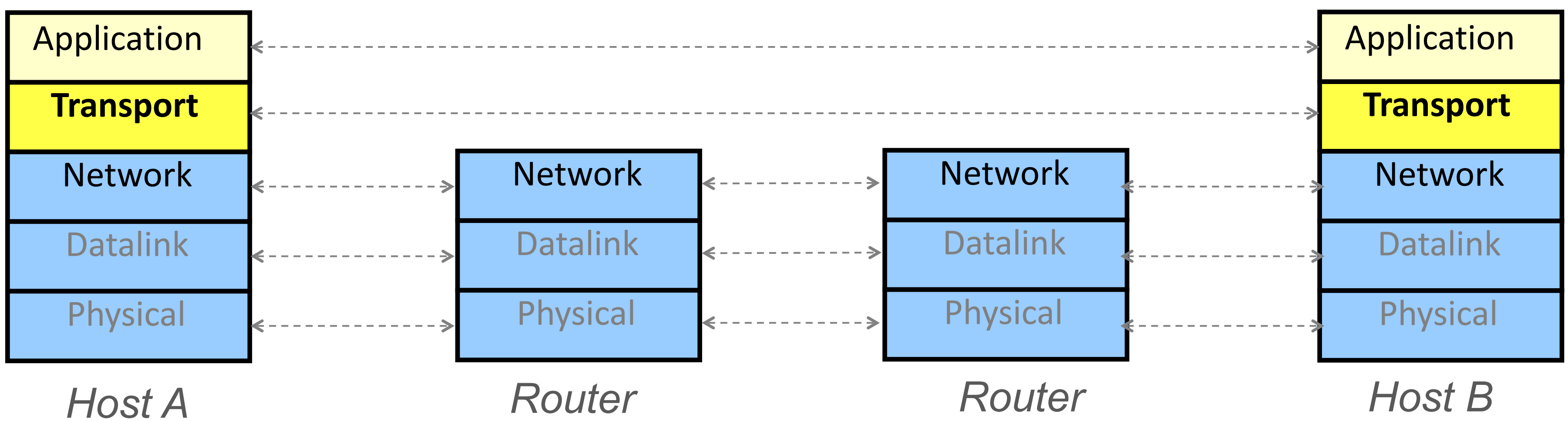
- At transport layer: *at-least-once* delivery
- At the app layer: *exactly-once* delivery



Goals For Reliable Transfer

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  - The destination receives every packet, uncorrupted, at least once
- **Timeliness**
  - Minimize time until data is transferred
- **Efficiency**
  - Would like to minimize use of bandwidth
  - i.e., avoid sending packets unnecessarily

Note!

- A reliability protocol (at the transport layer) can “give up”, but must announce this to application
  - E.g., if the network is partitioned
- But it can never falsely claim to have delivered a packet

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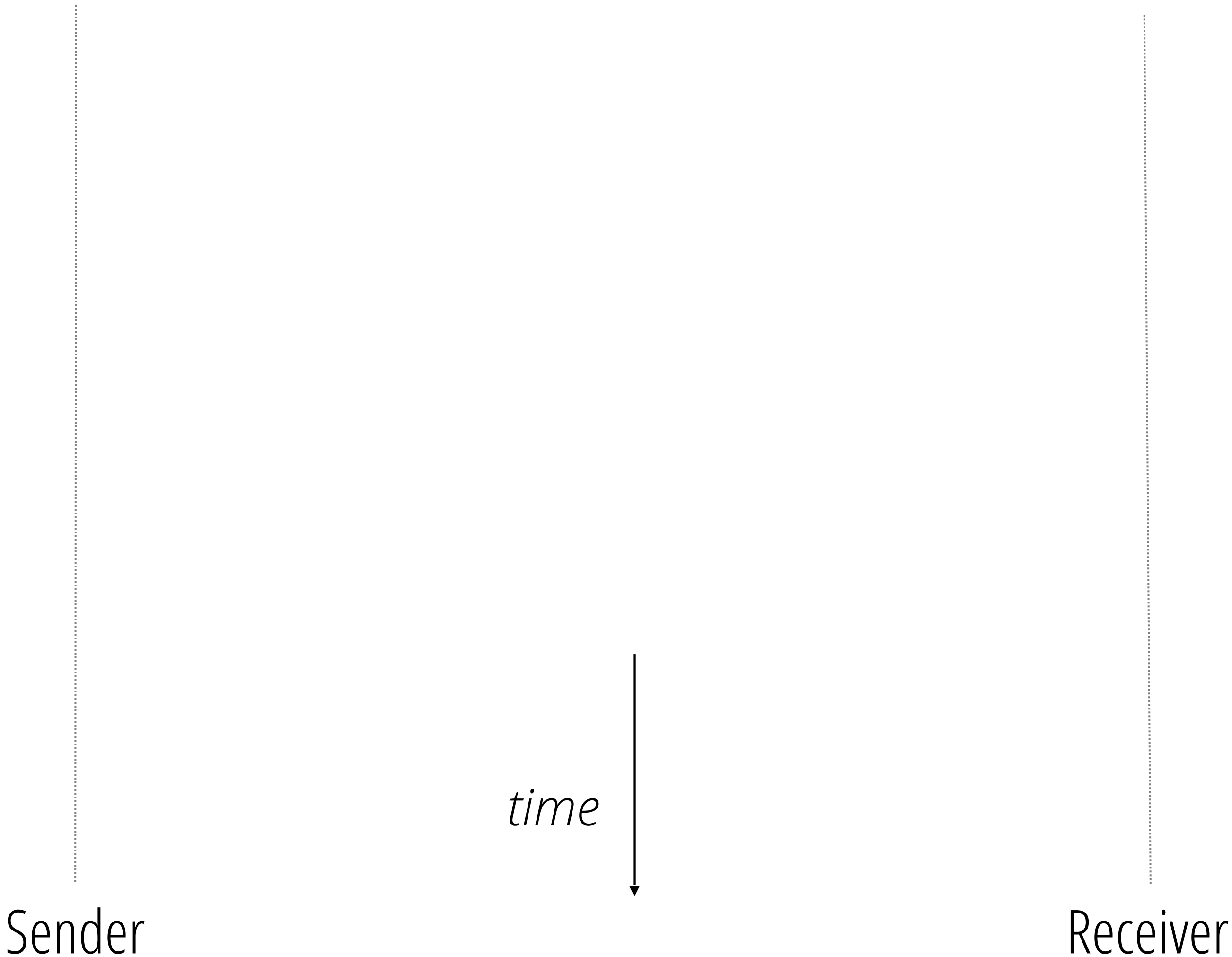

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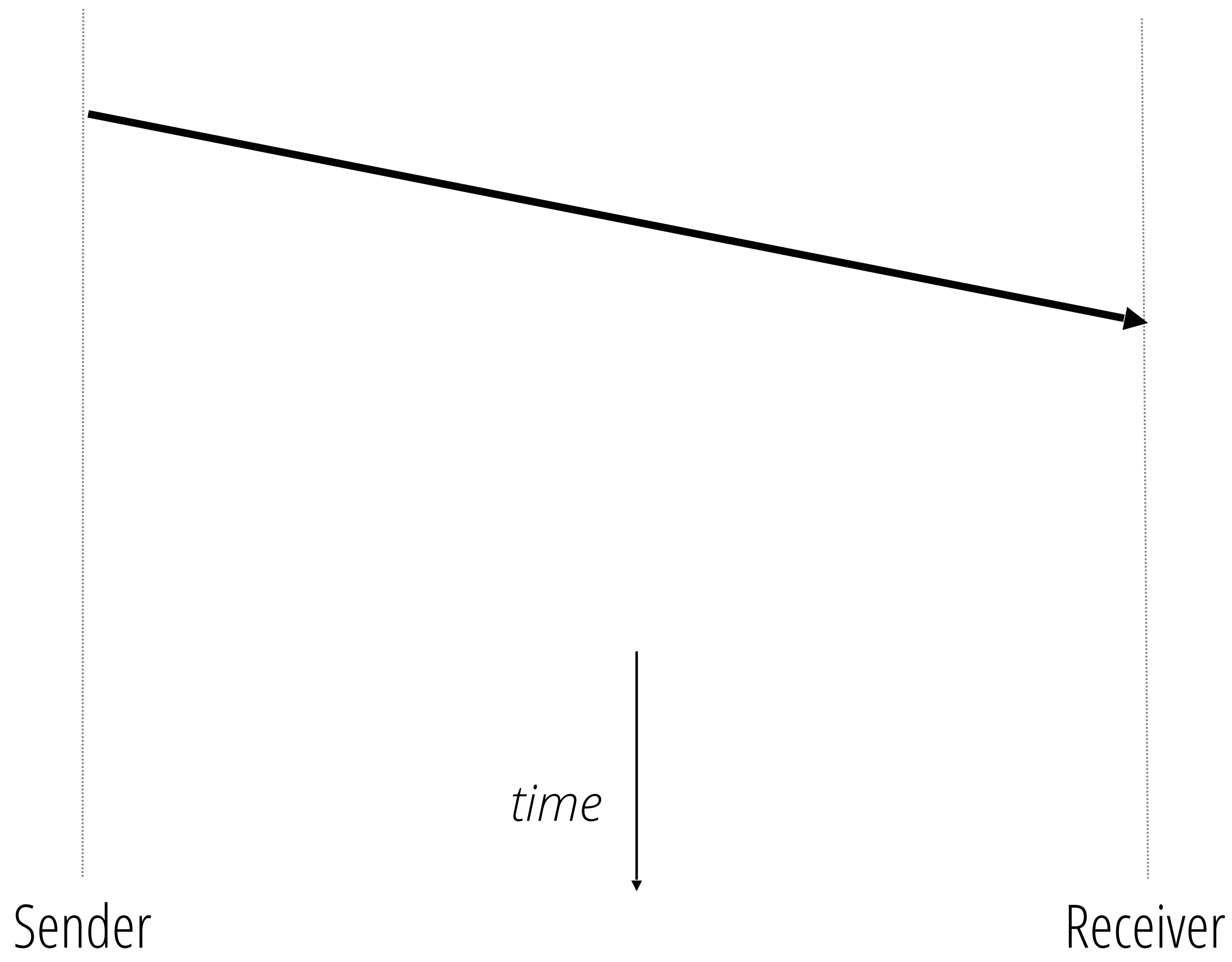

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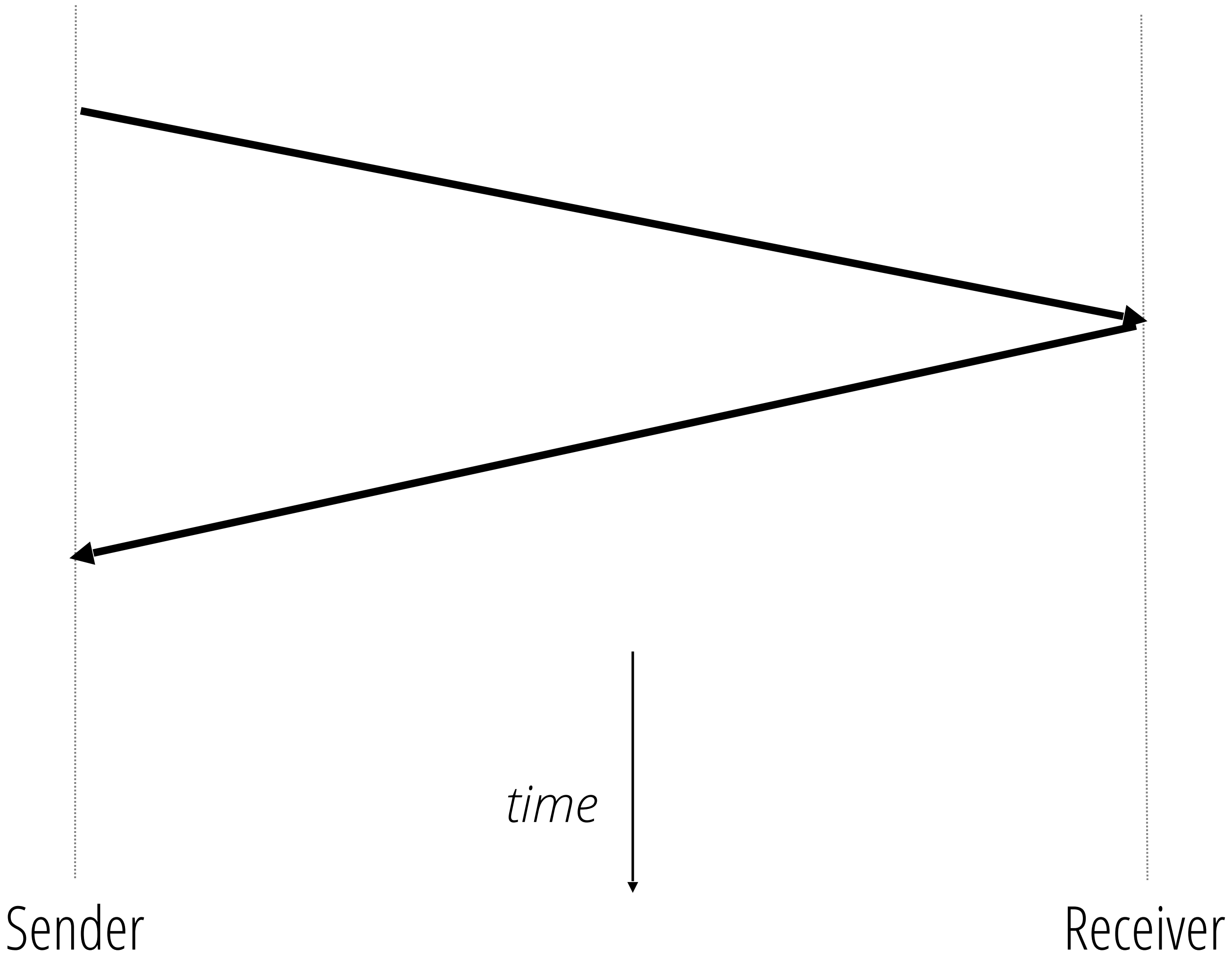

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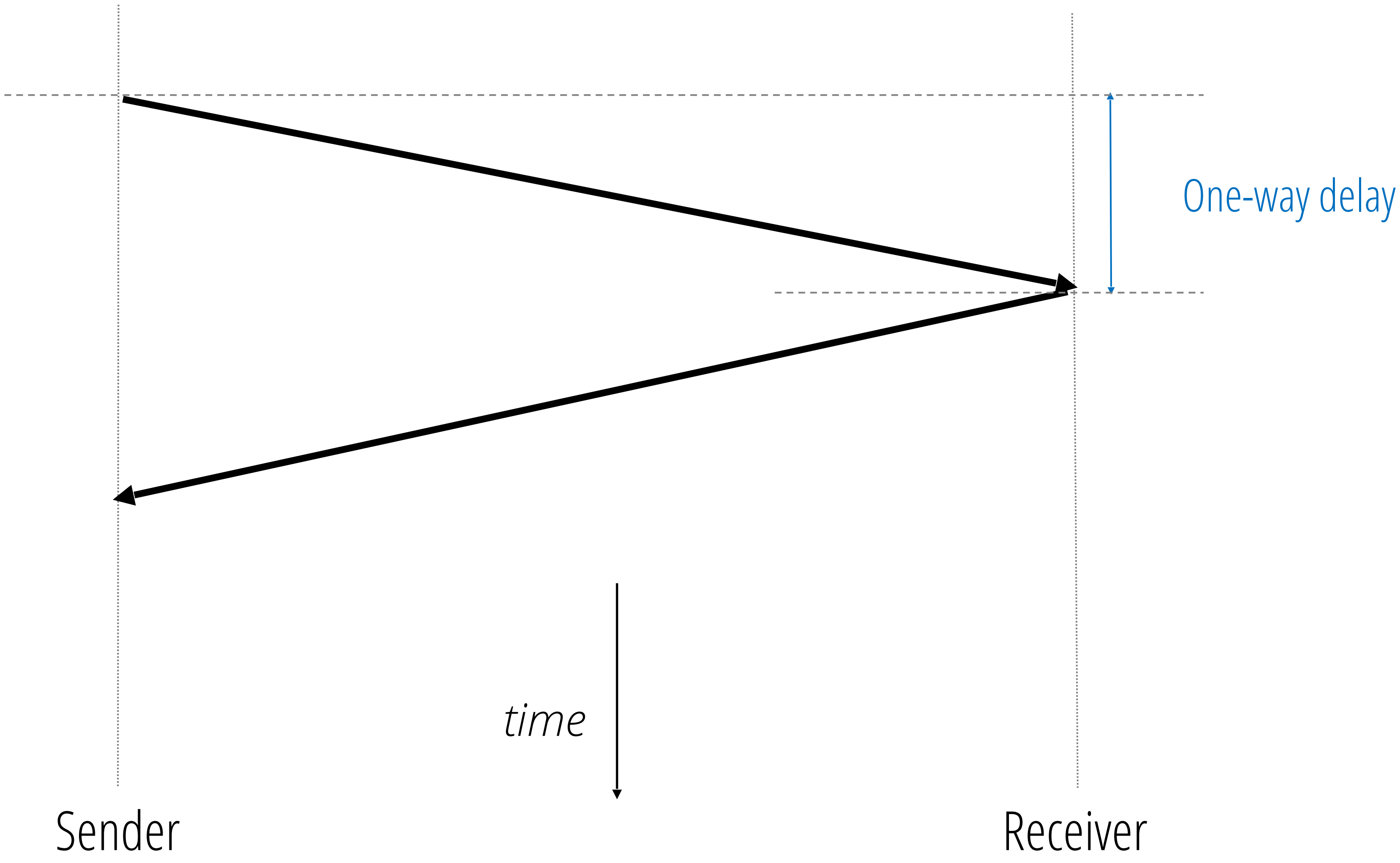

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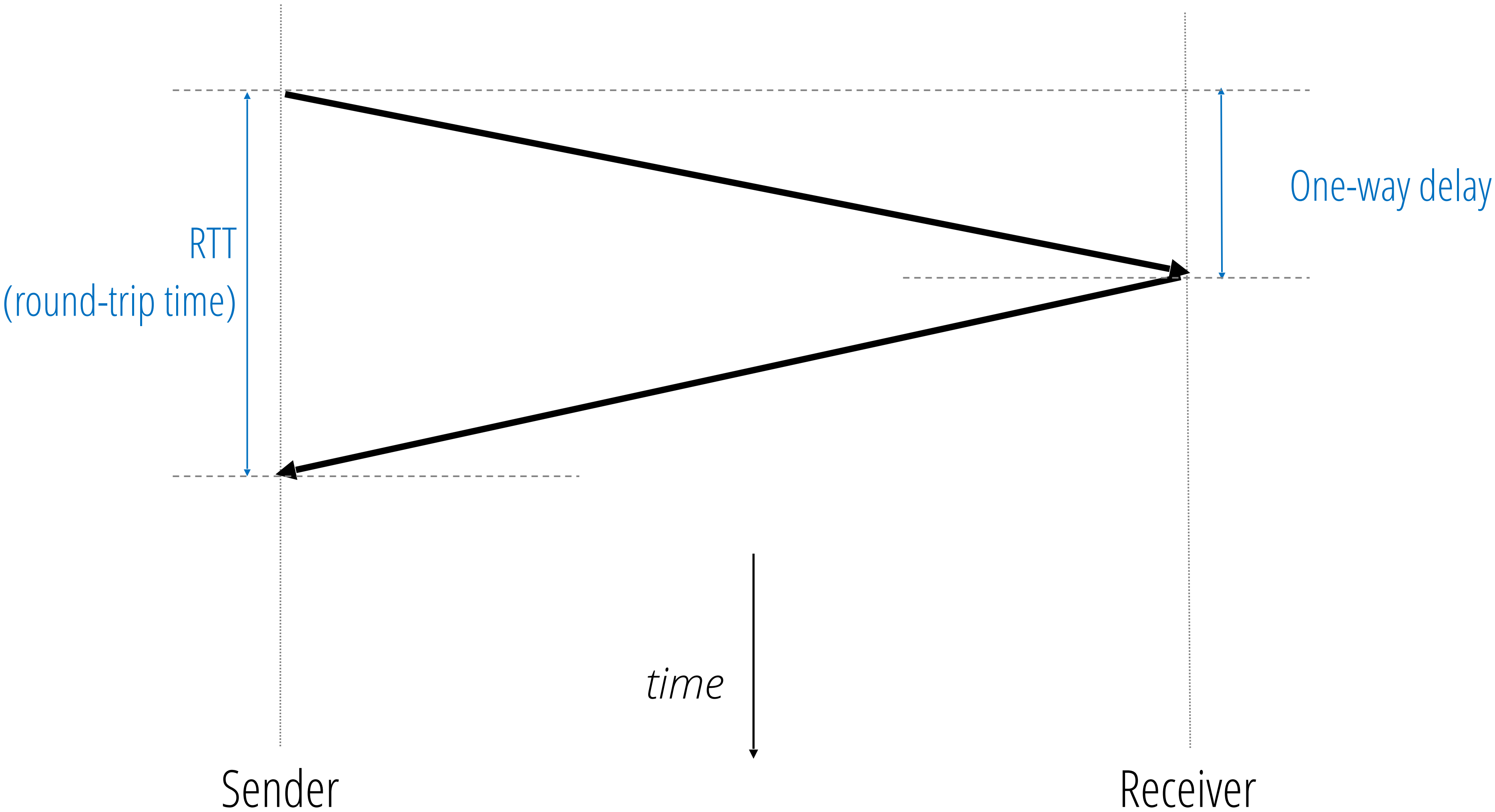

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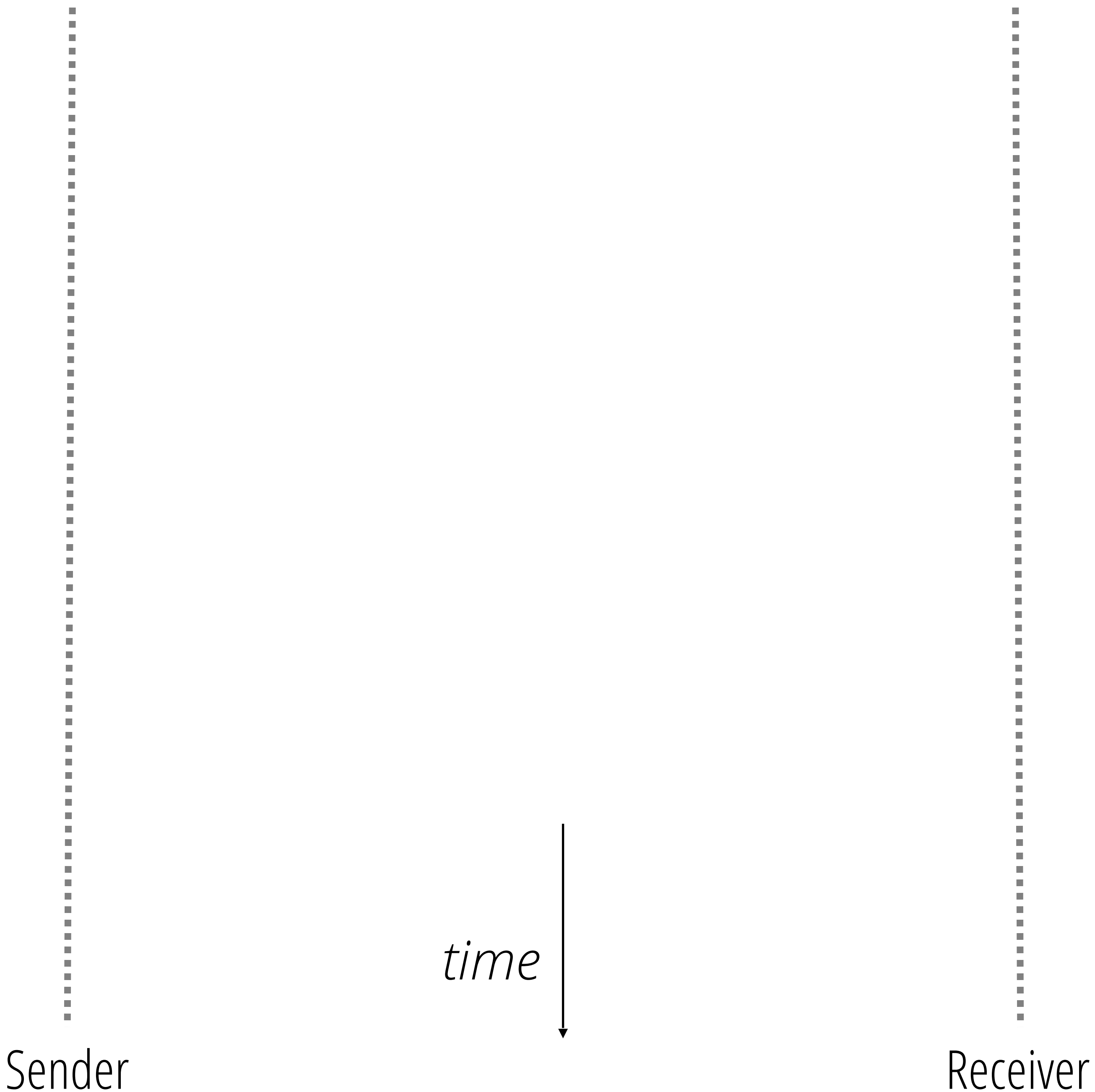
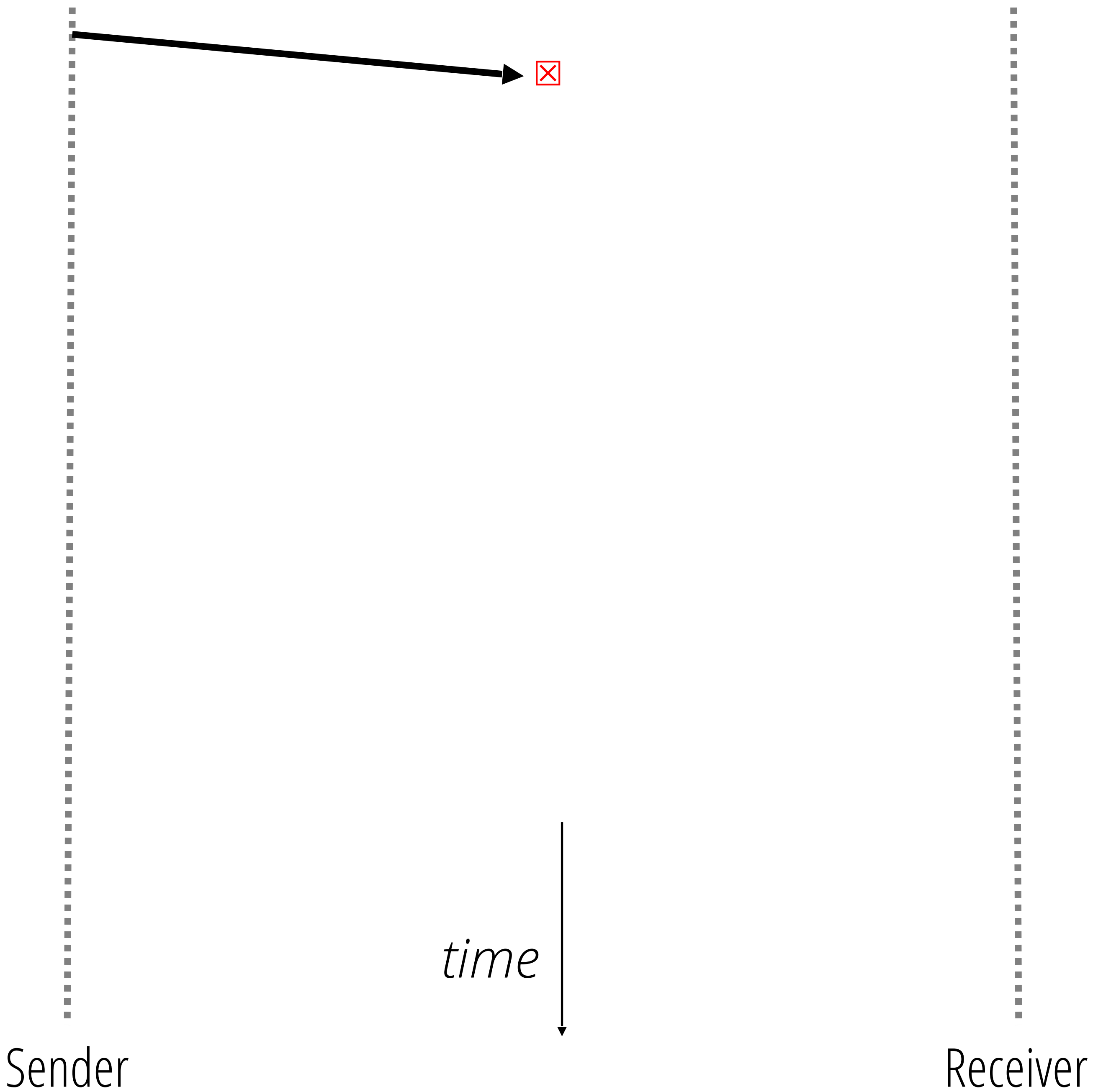
  - Packets can be corrupted
  - Packets can be reordered
  - Packets can be delayed
  - Packets can be duplicated
  - ….


time
Sender
Receiver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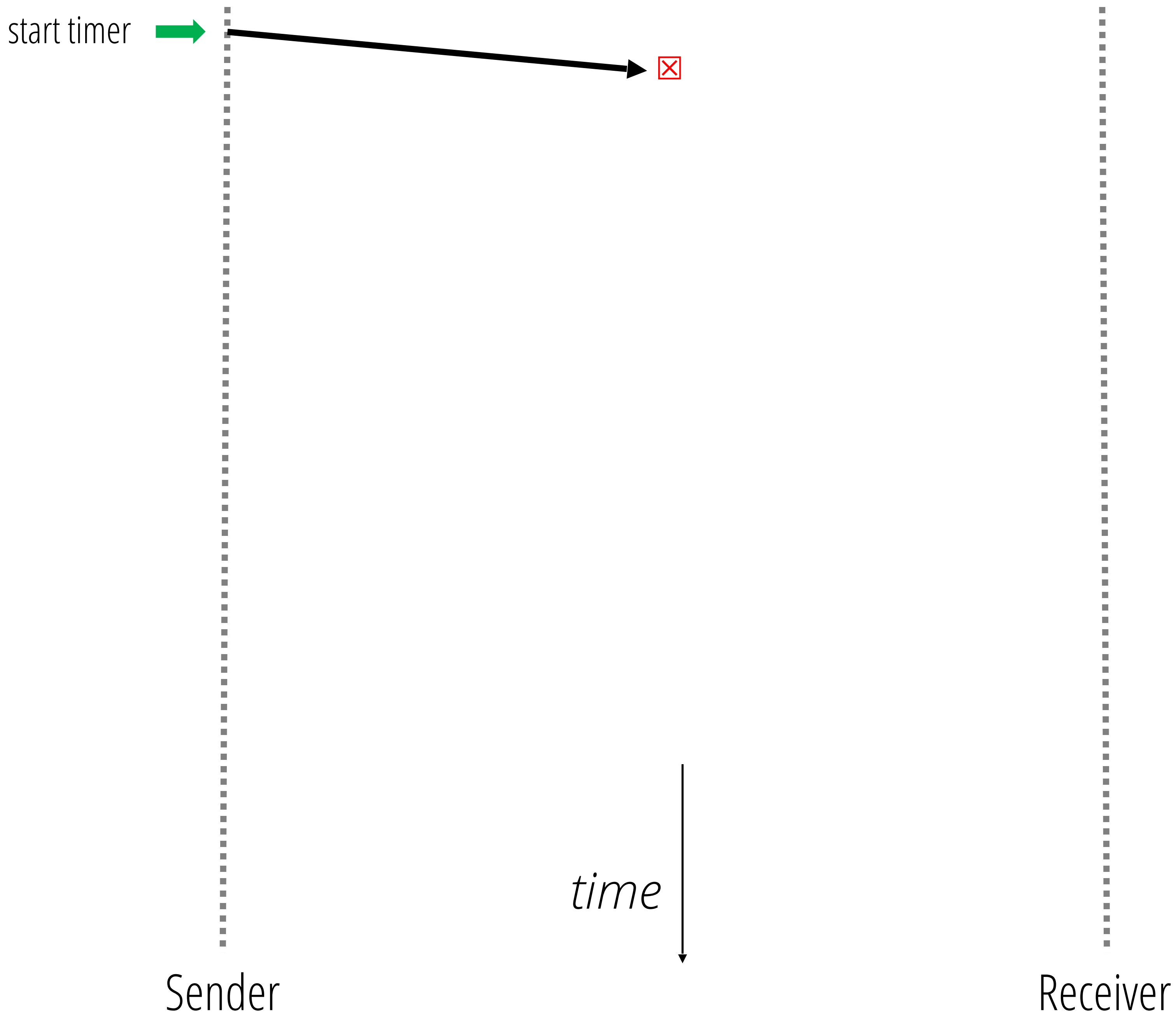
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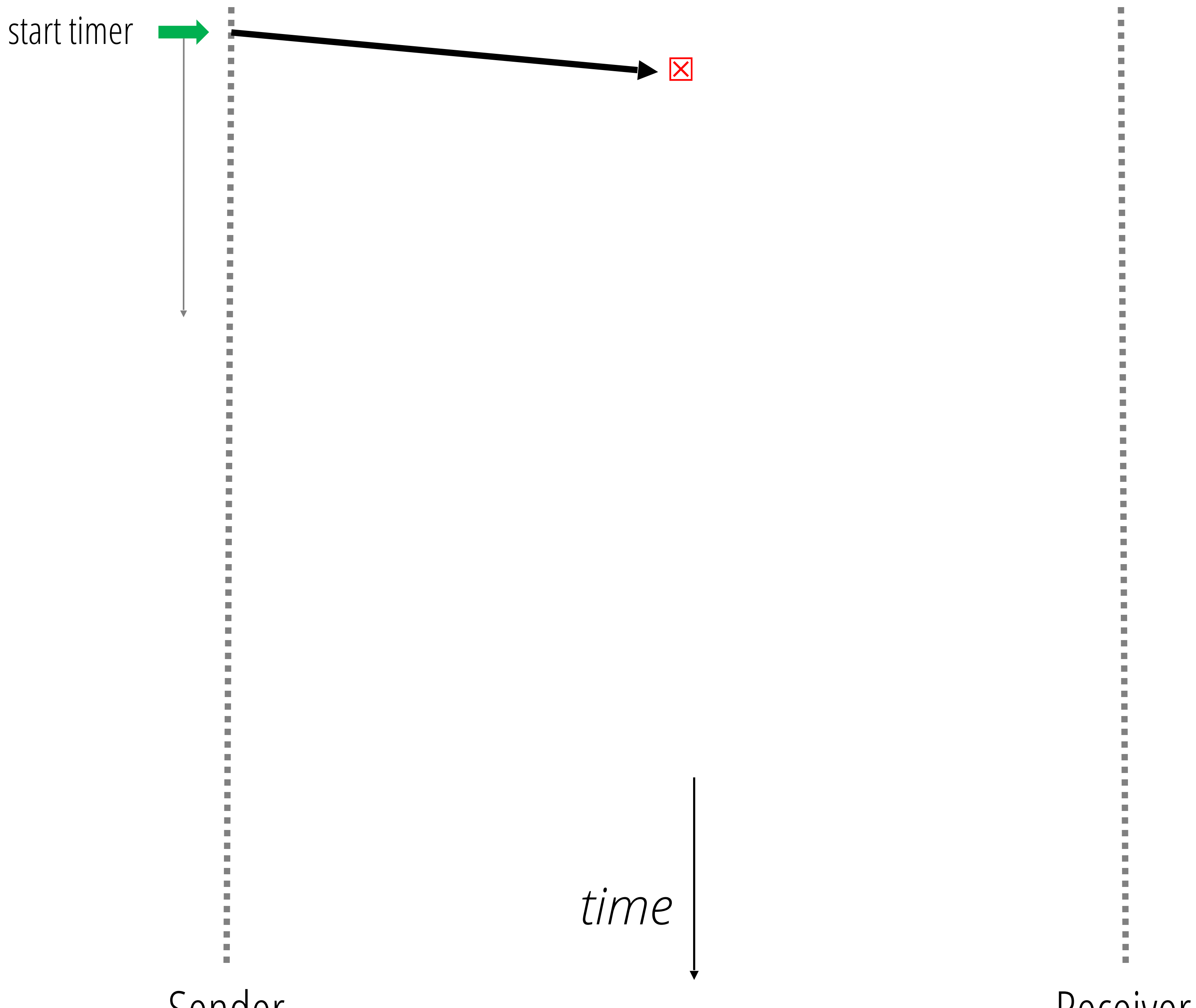
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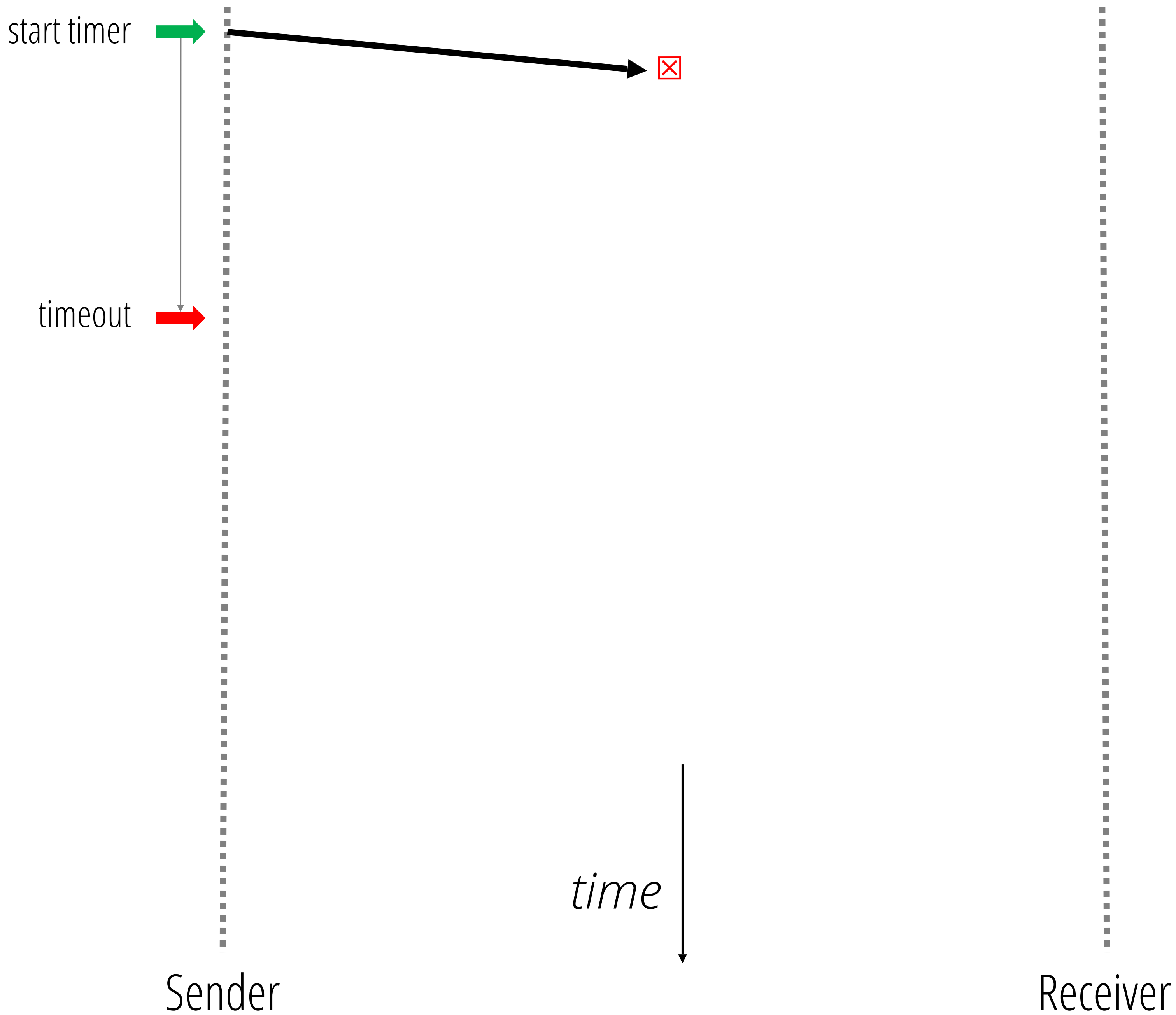
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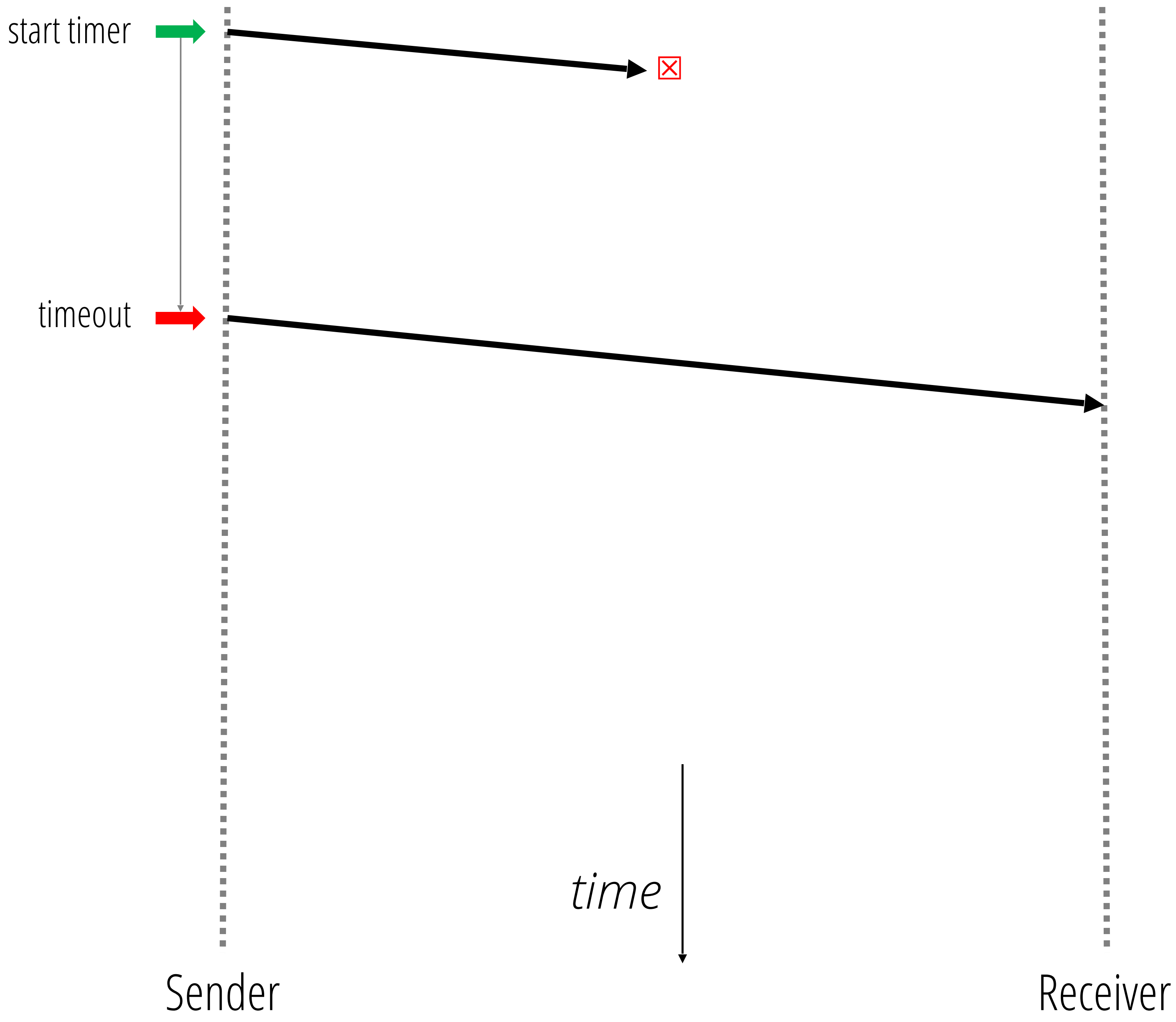
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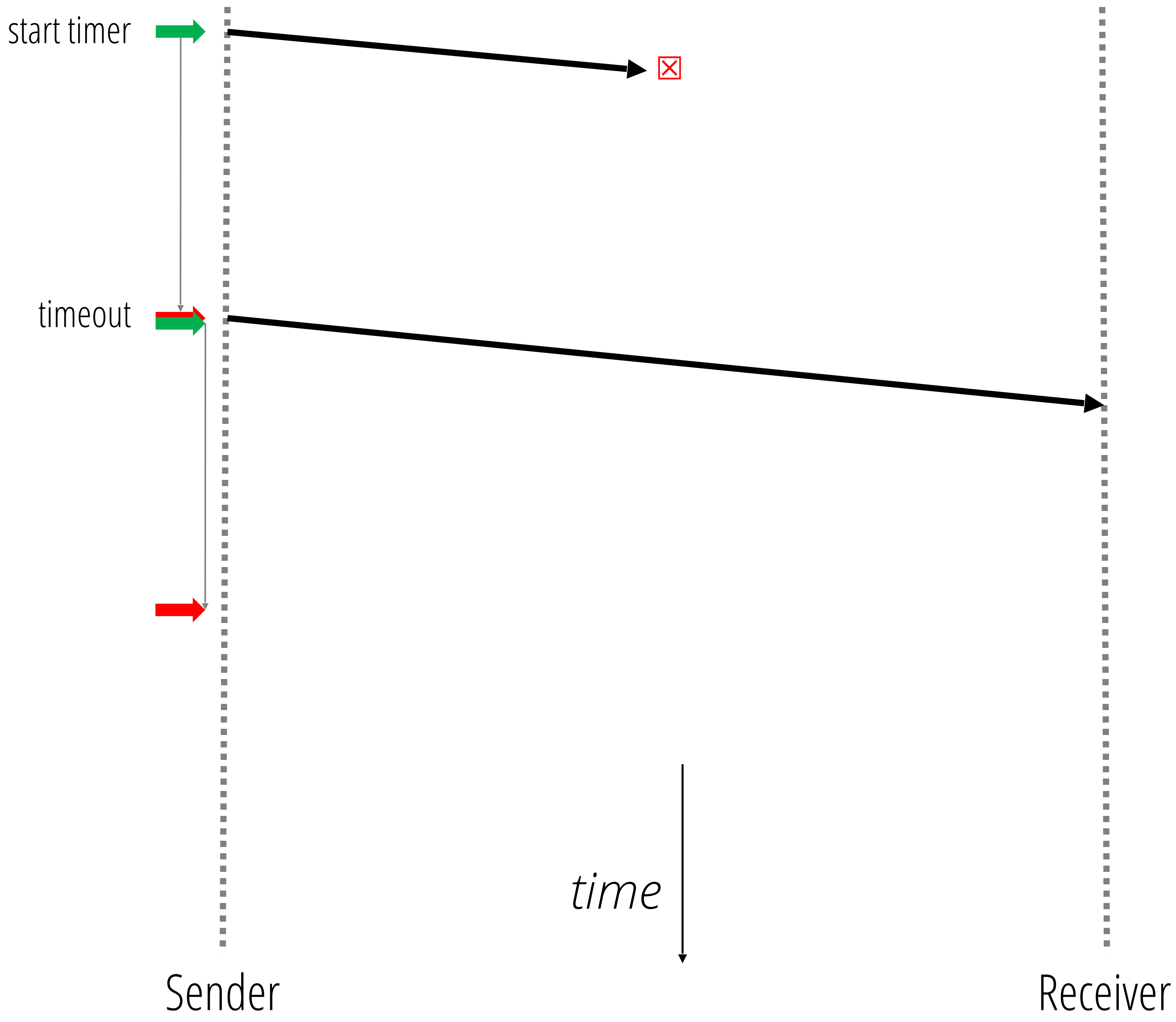

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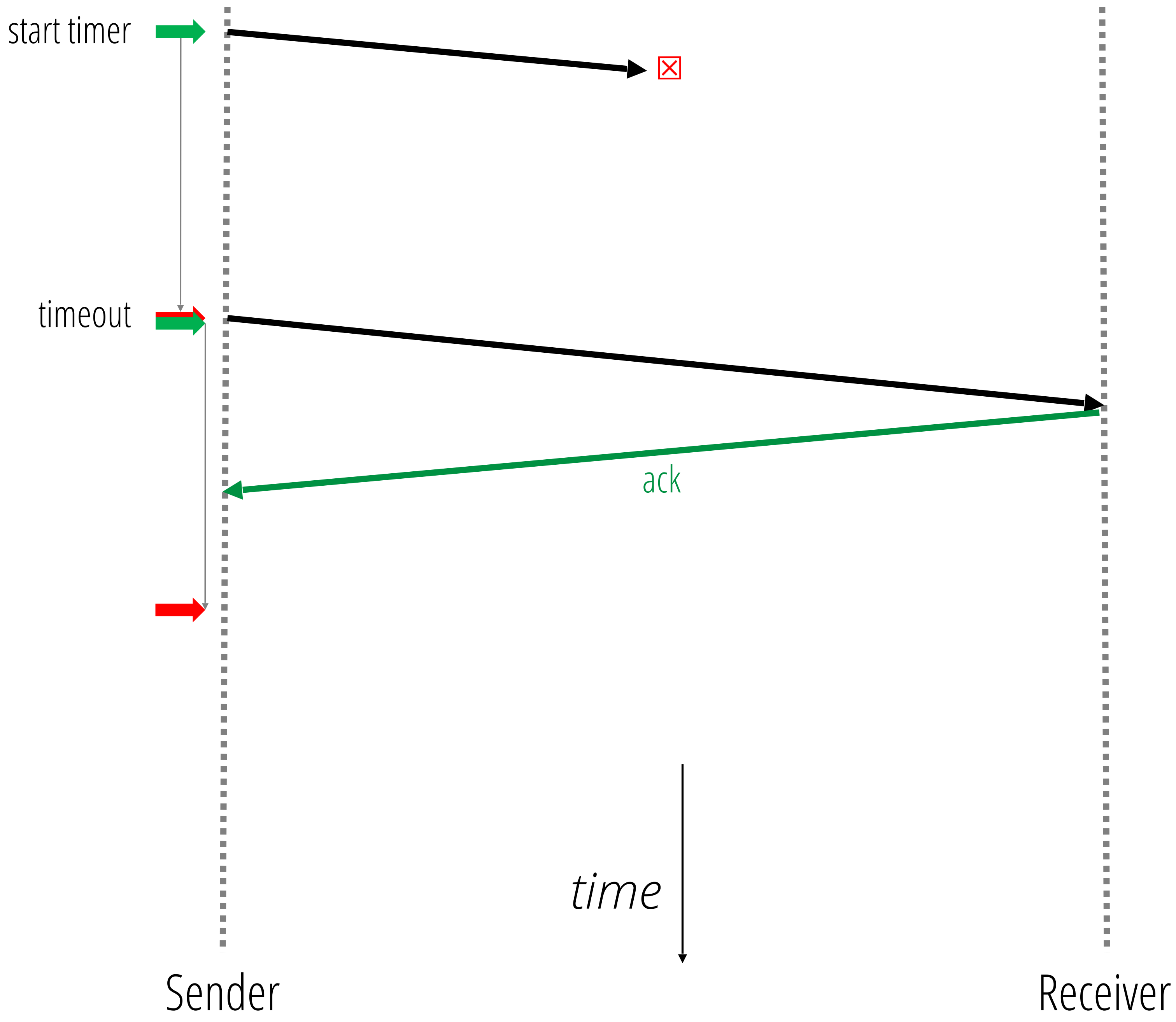
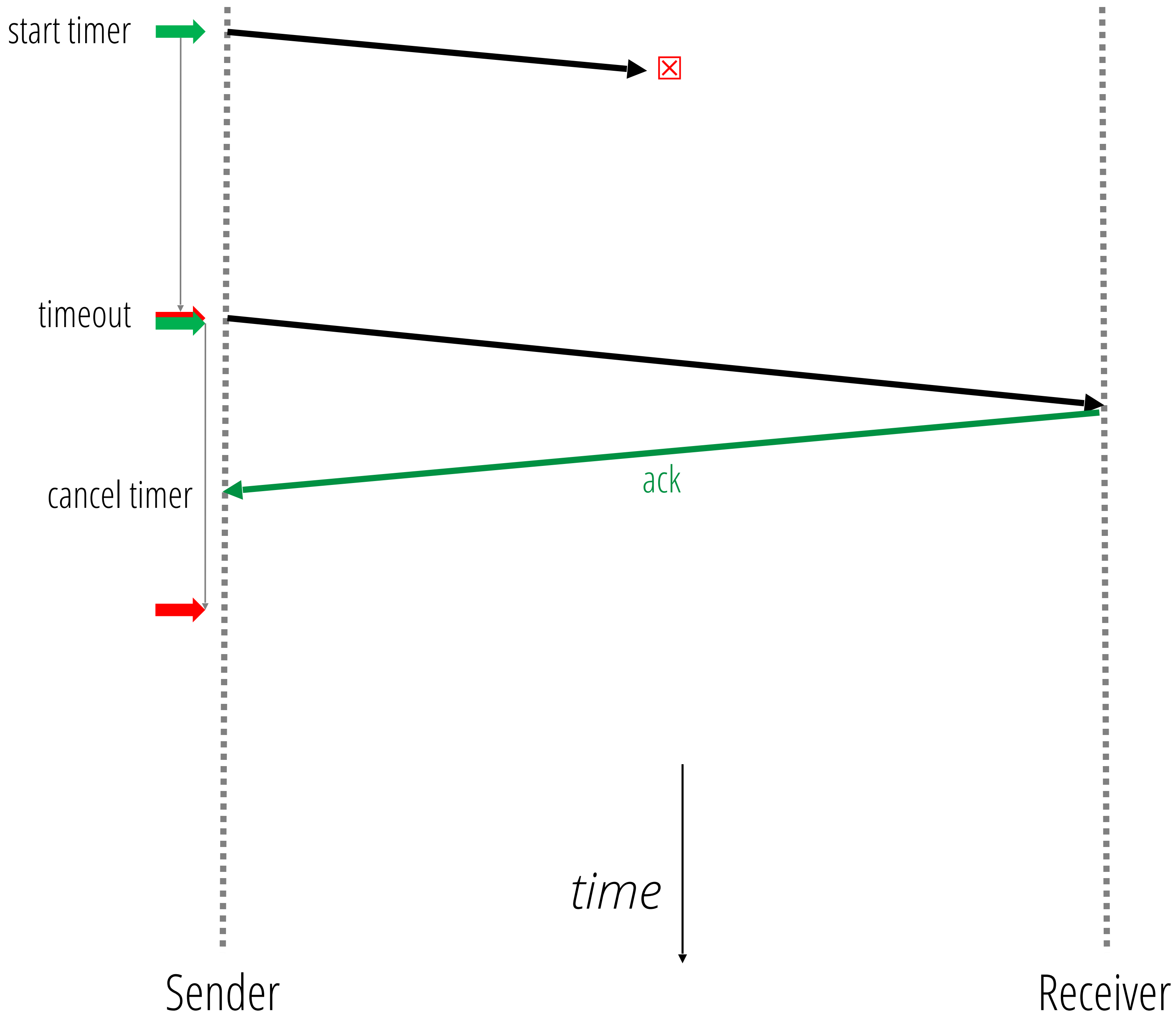
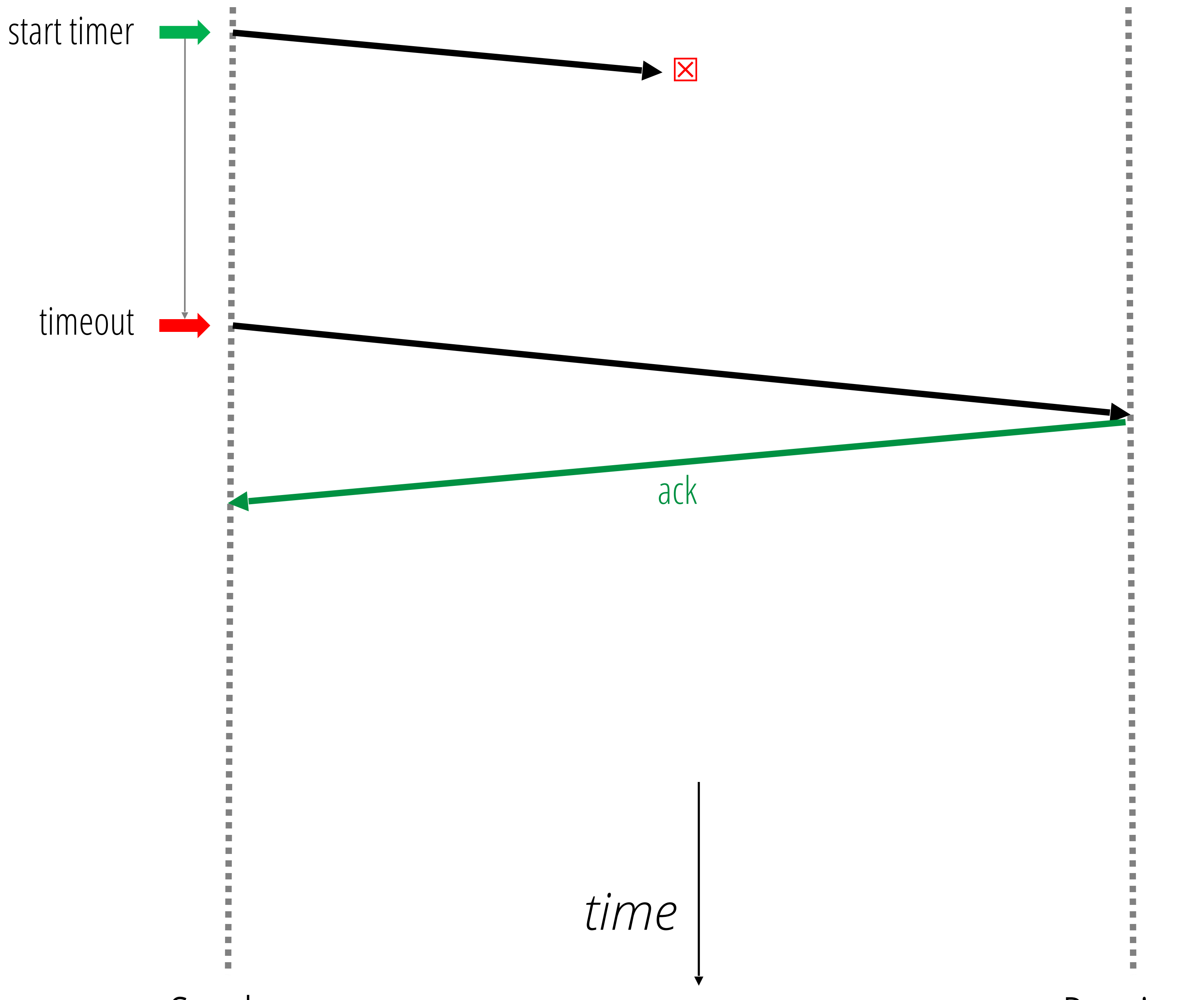

start timer
timeout
ack
time
Sender
Receiver


start timer
timeout
cancel timer
ack
time
Sender
Receiver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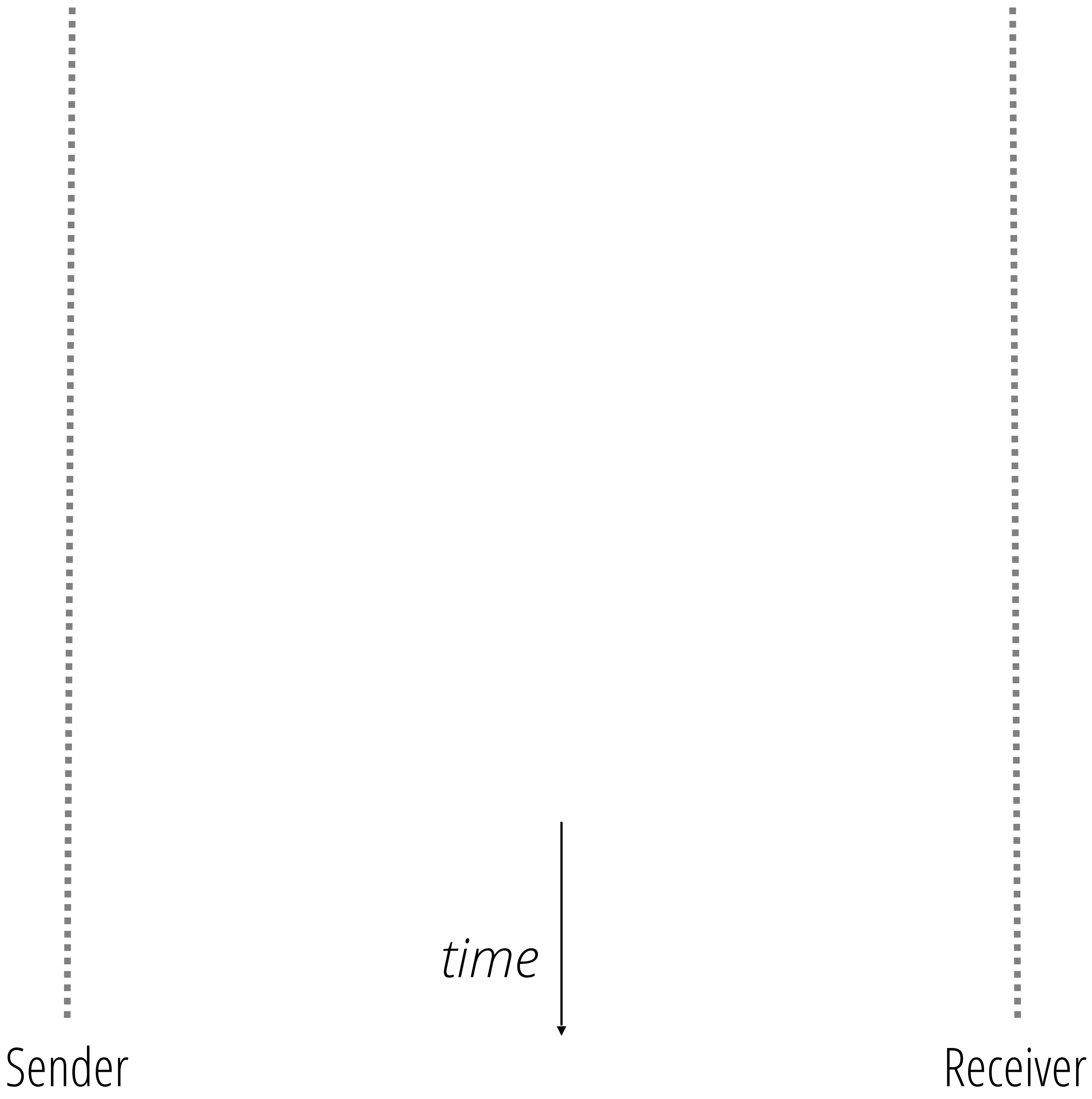
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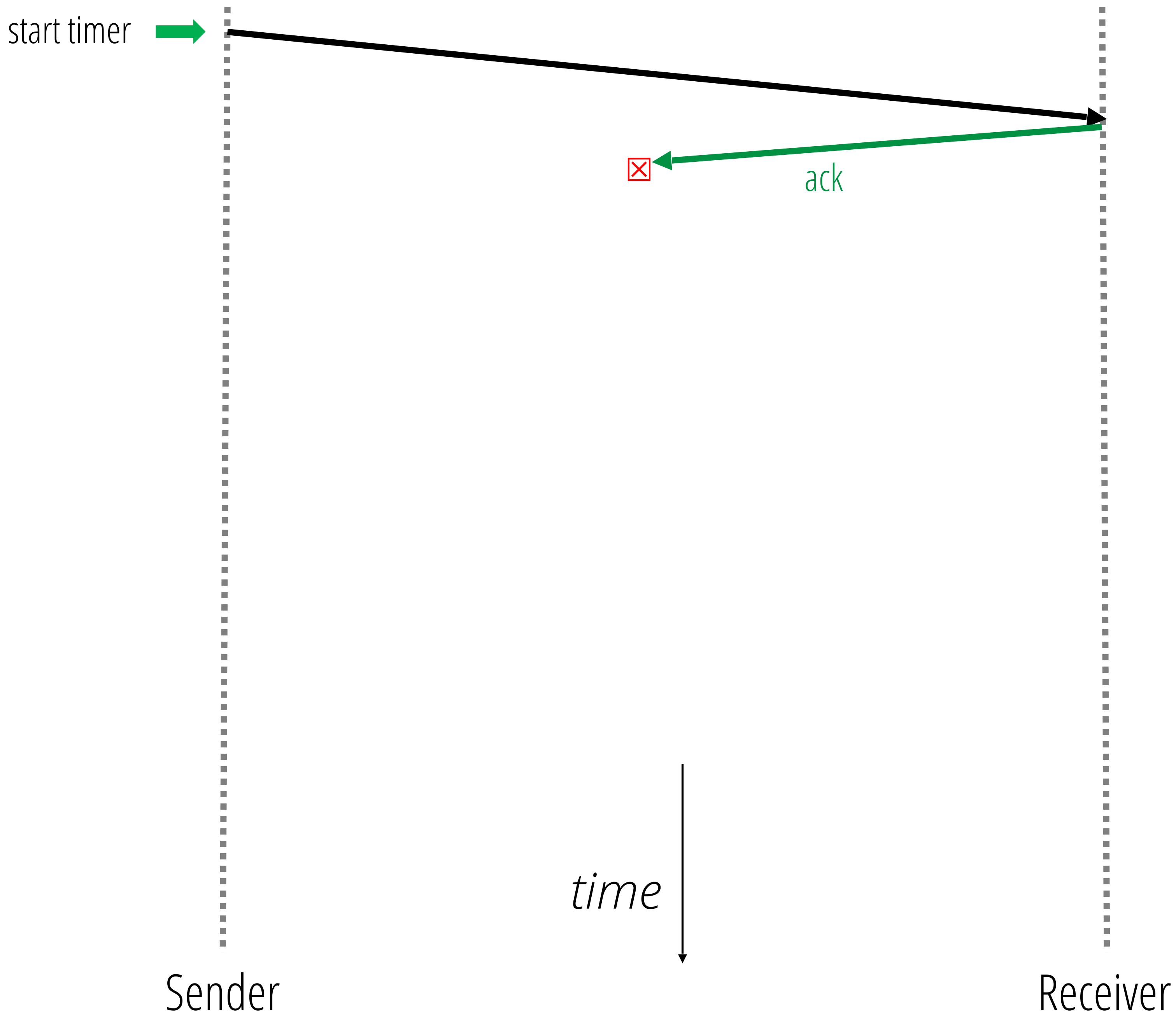

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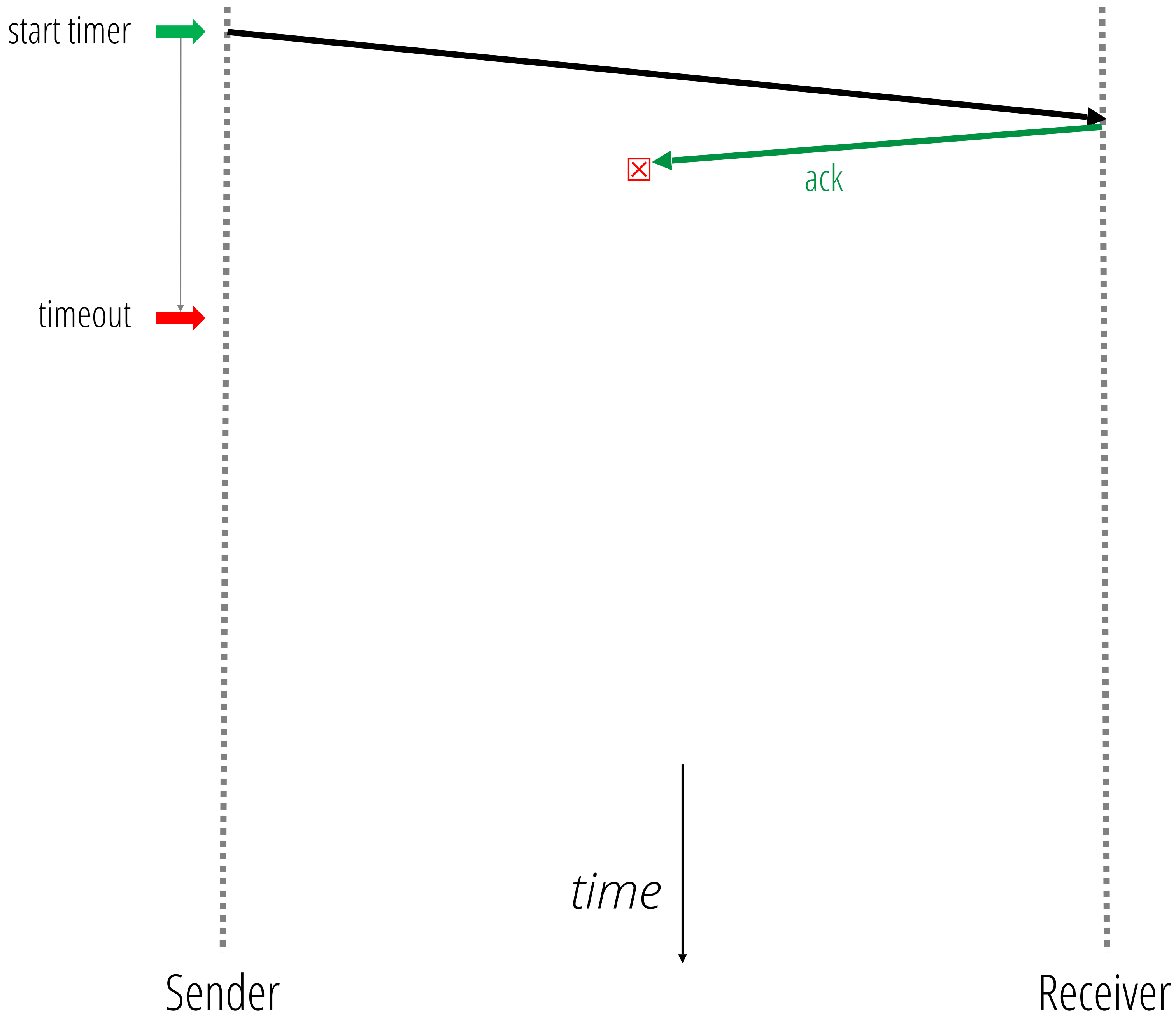
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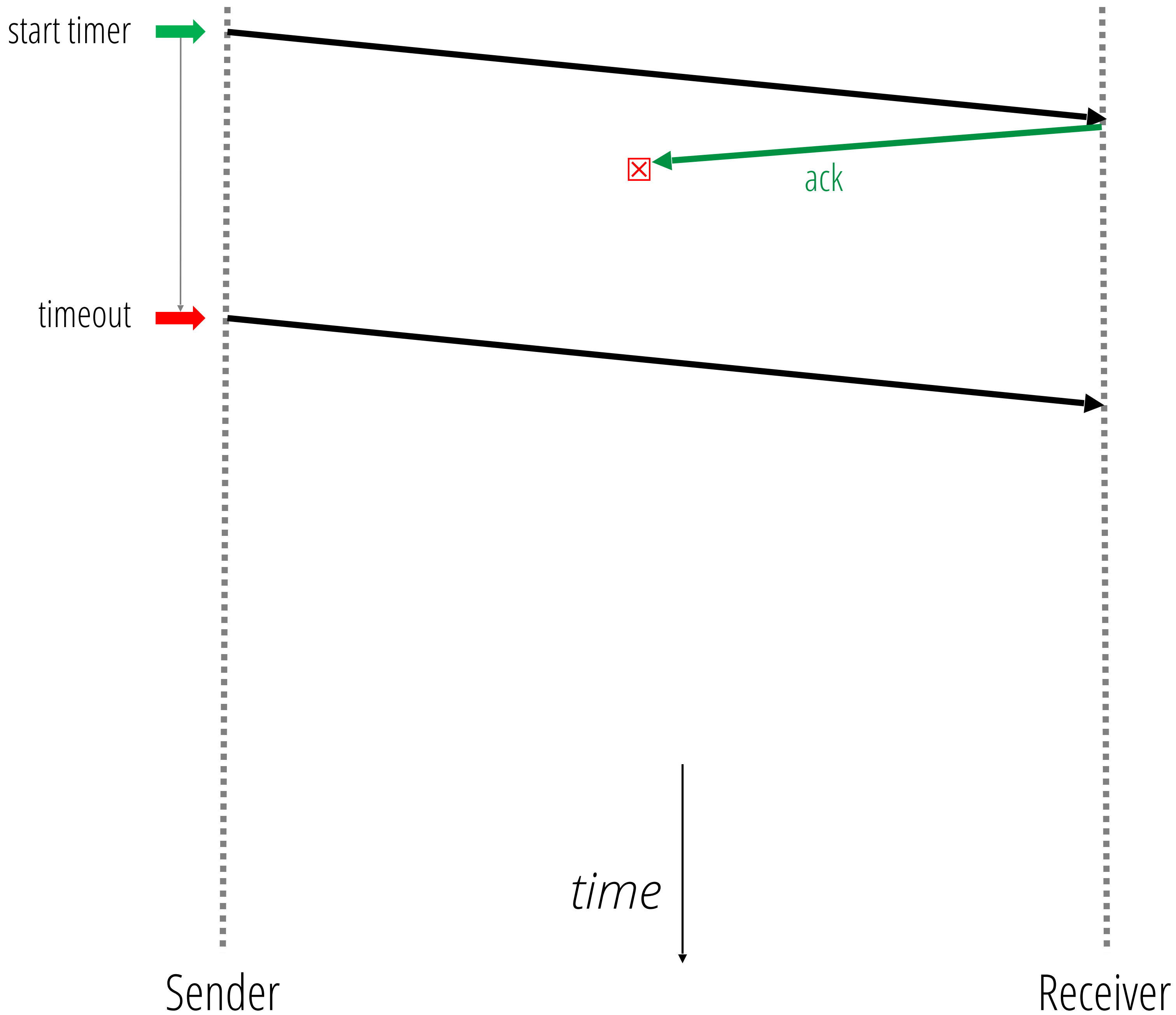
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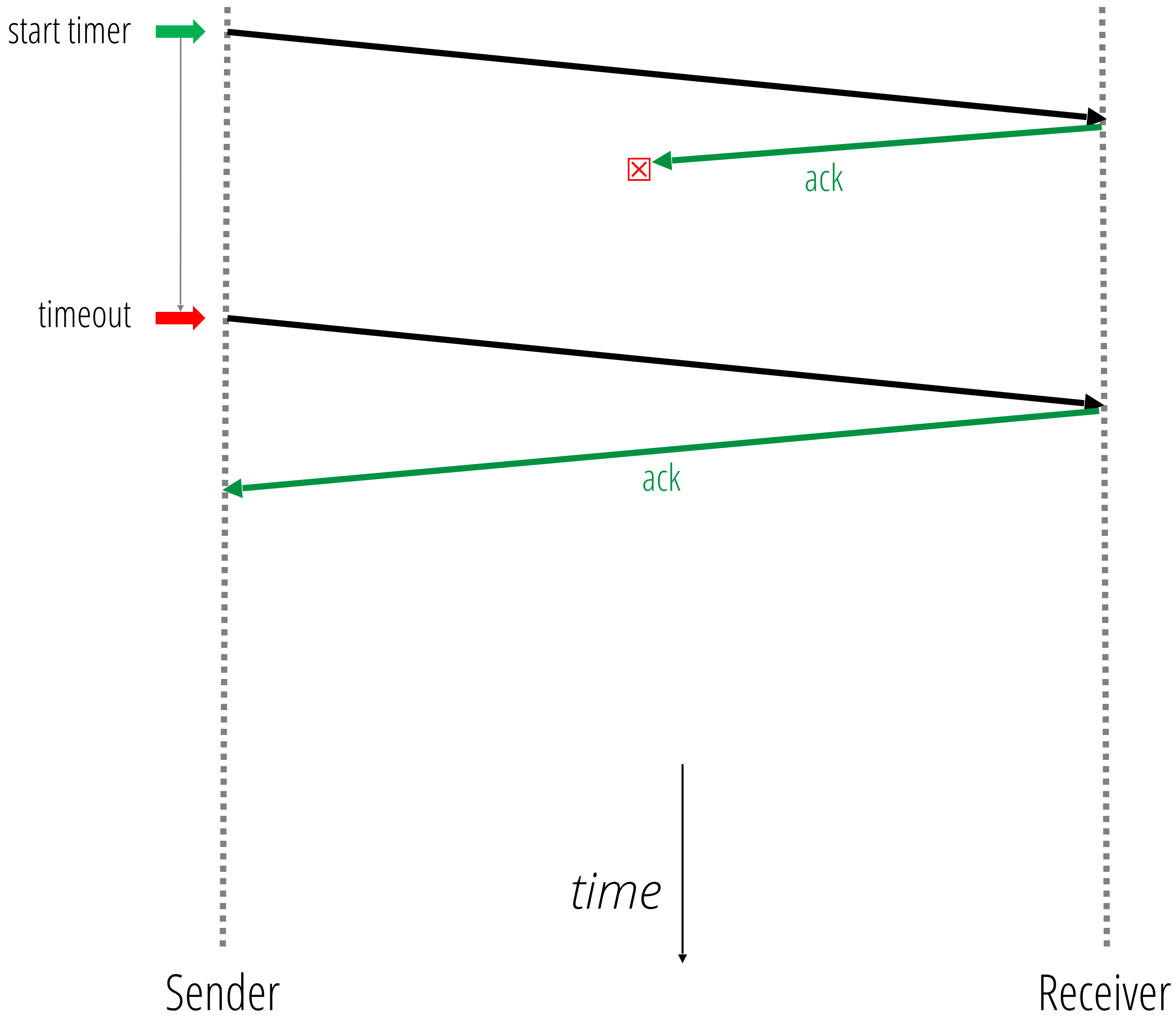
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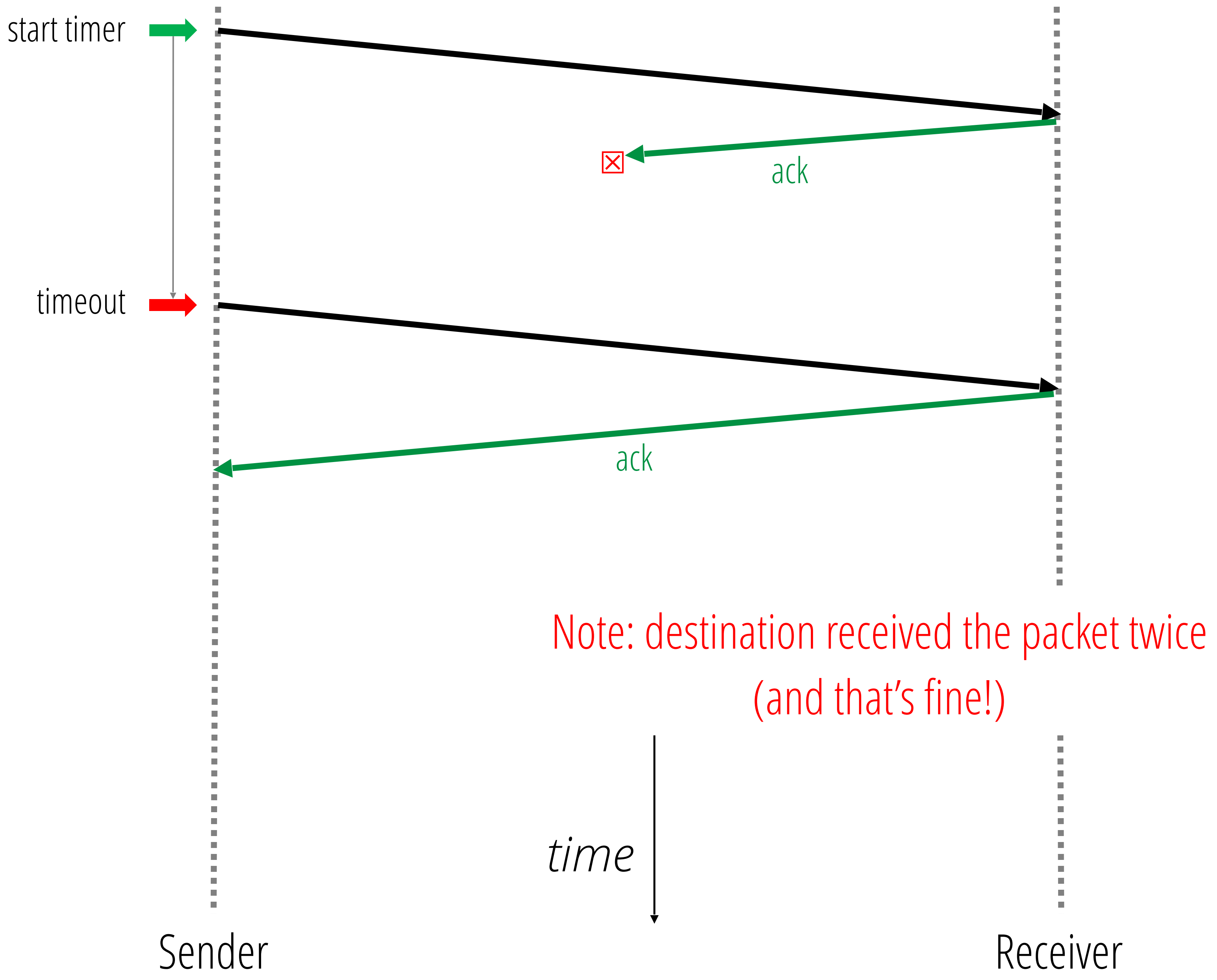
start timer
ack
timeout
ack
Note: destination received the packet twice
(and that's fine!)
time
Sender
Receiver

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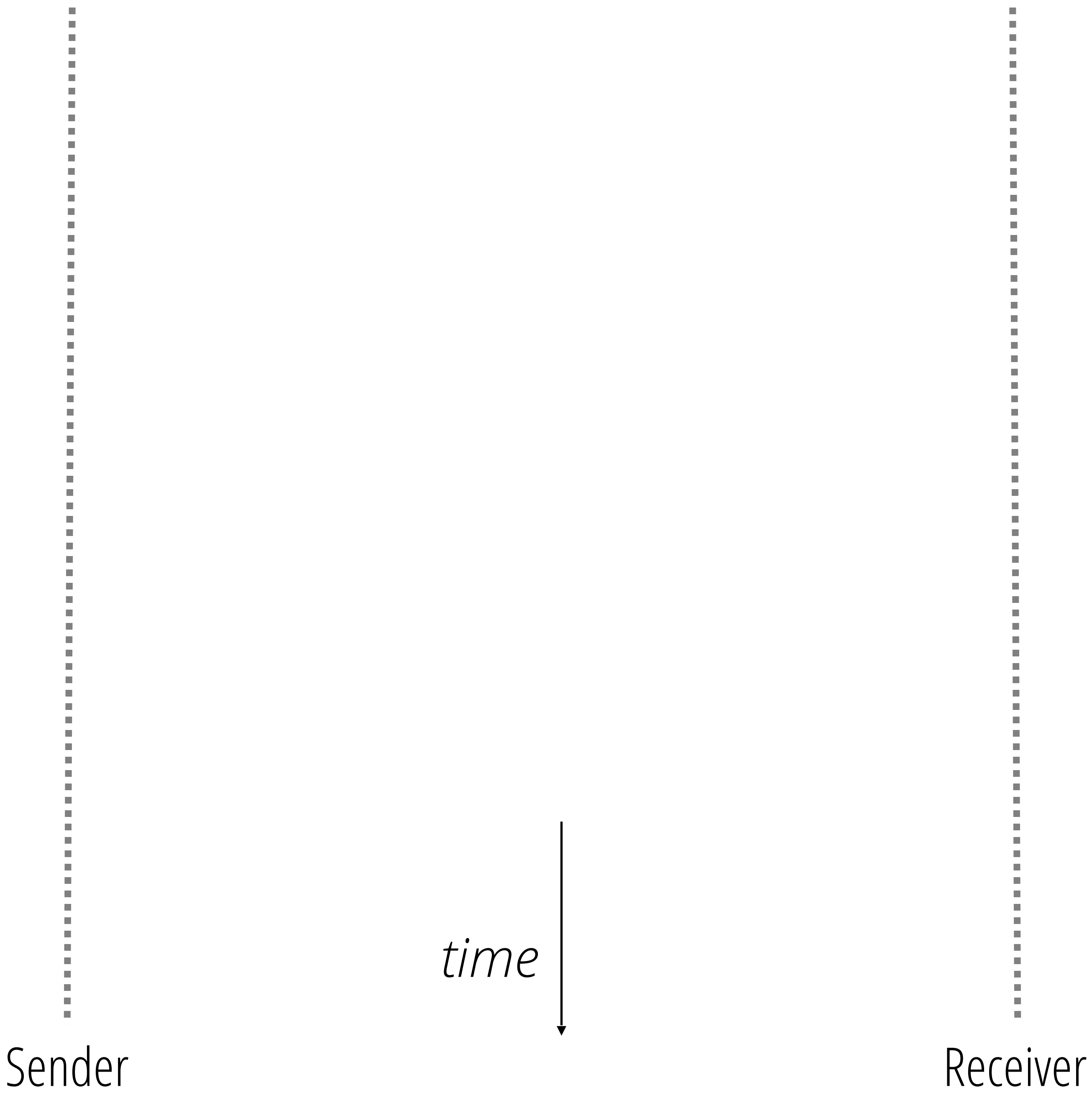
- Hence, often used as last resort

- We said
  - Packets can be lost (data or ACKs) 👍
  - Packets can be corrupted
  - Packets can be delayed
  - Packets can be duplicated
  - Packets can be reordered



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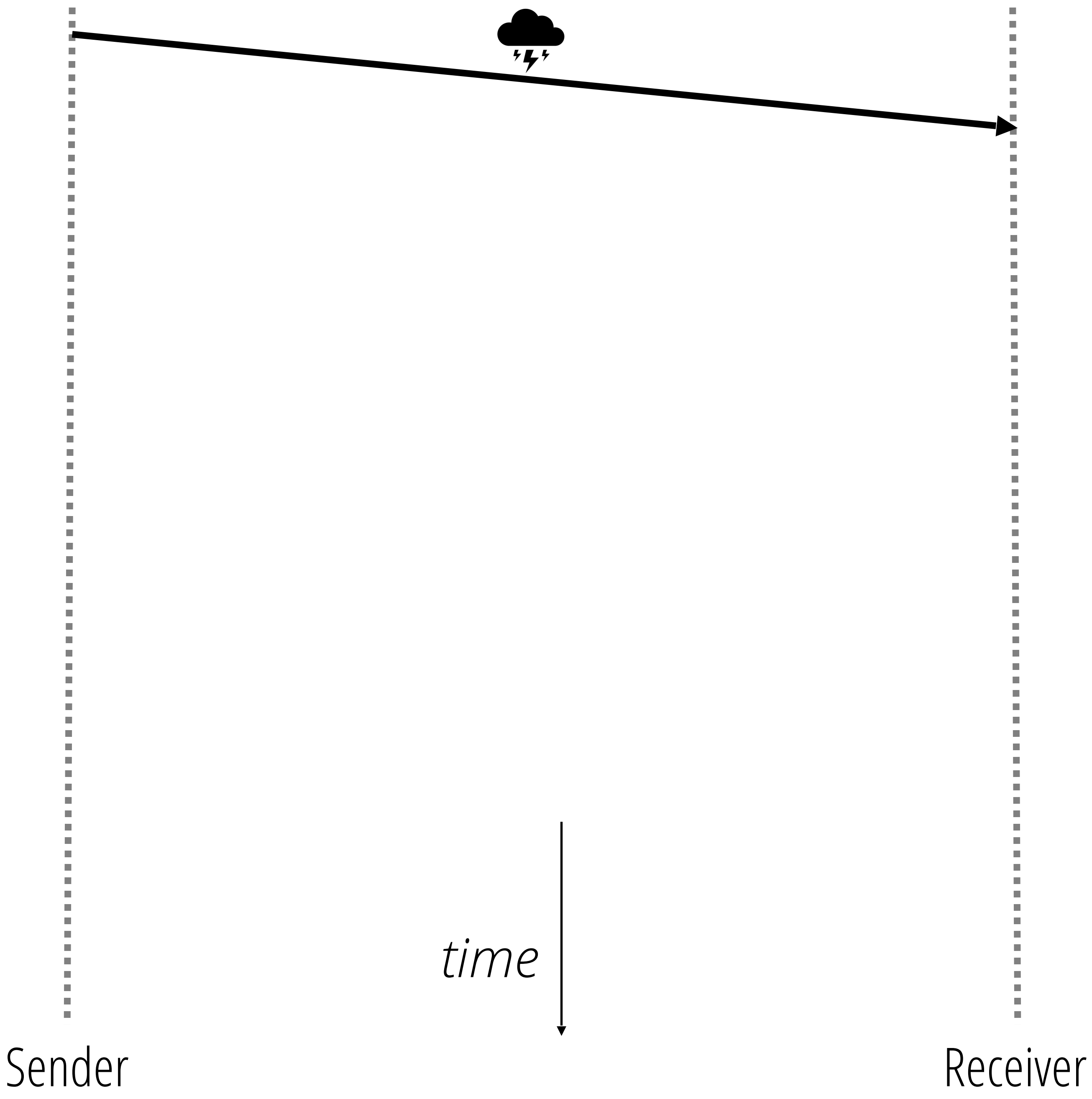
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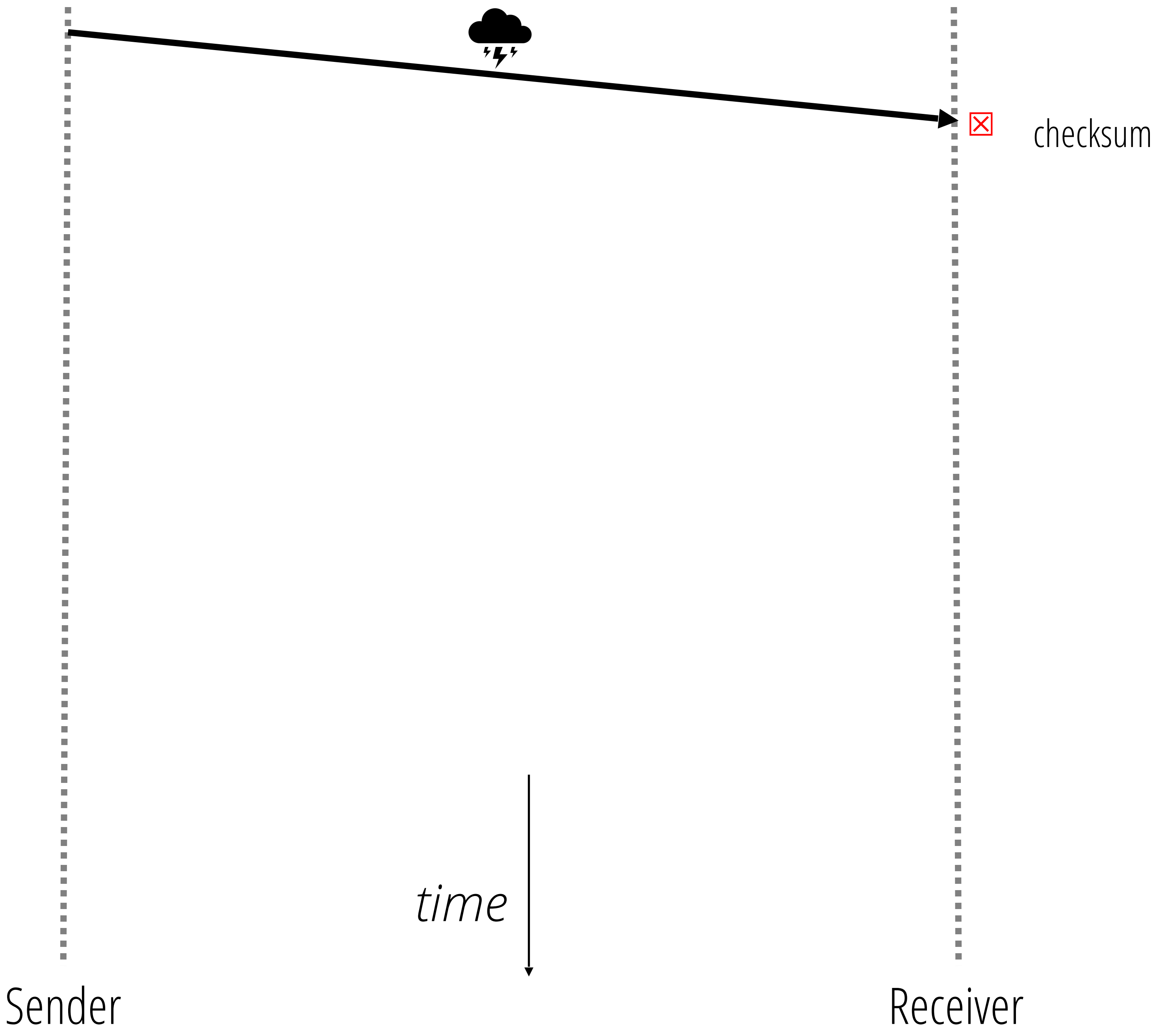
checksum
time
Sender
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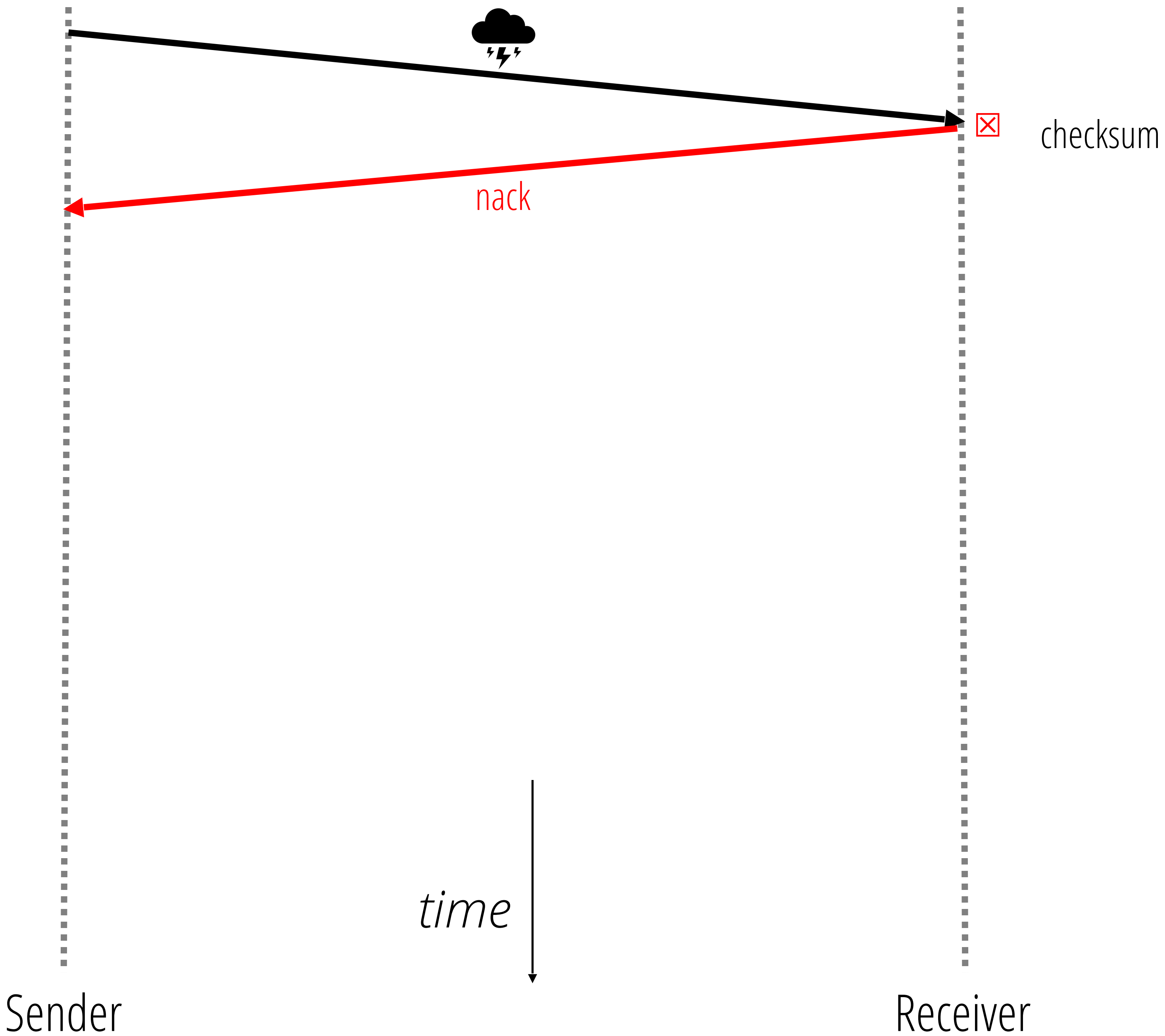
checksum
nack
time
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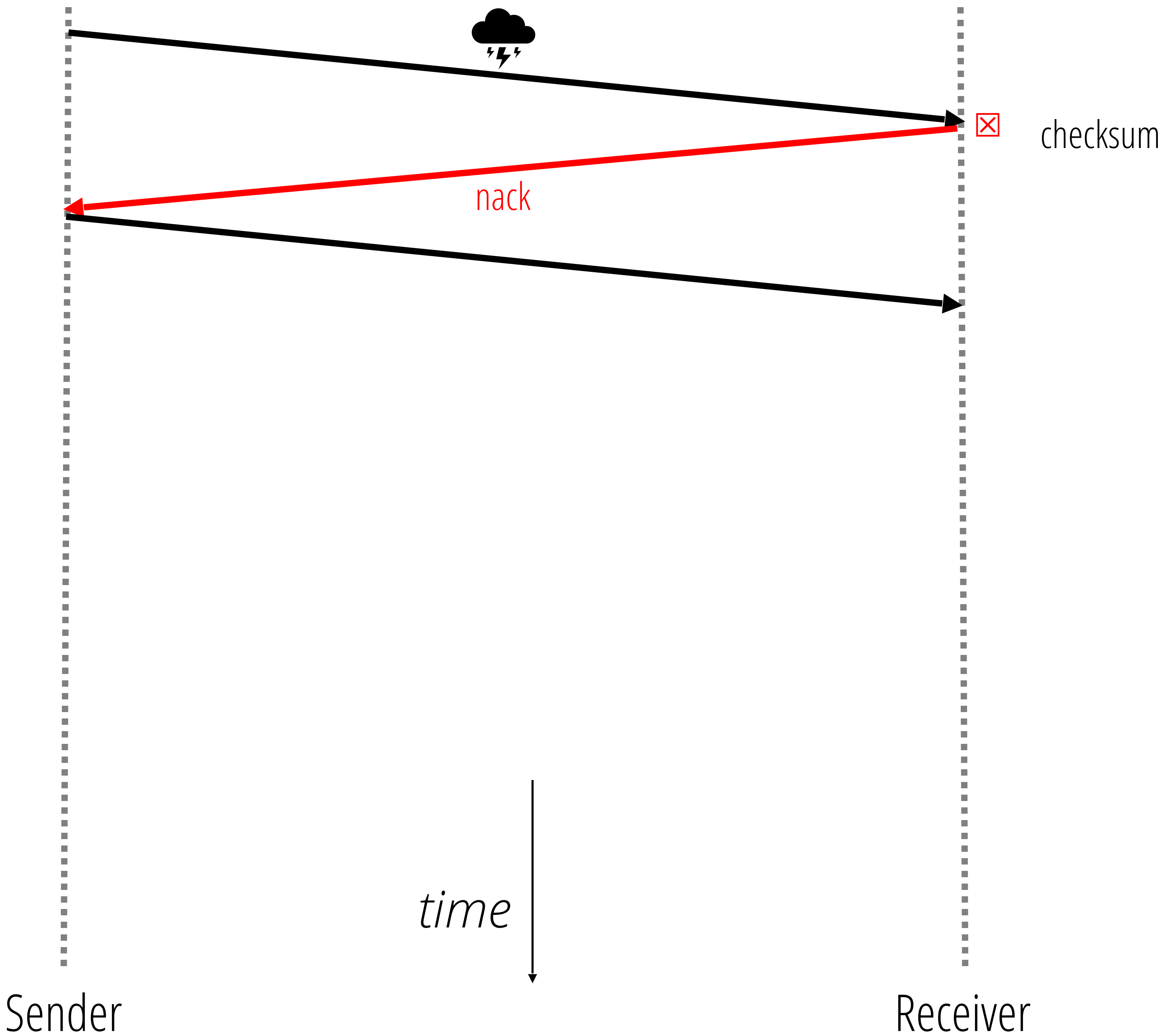
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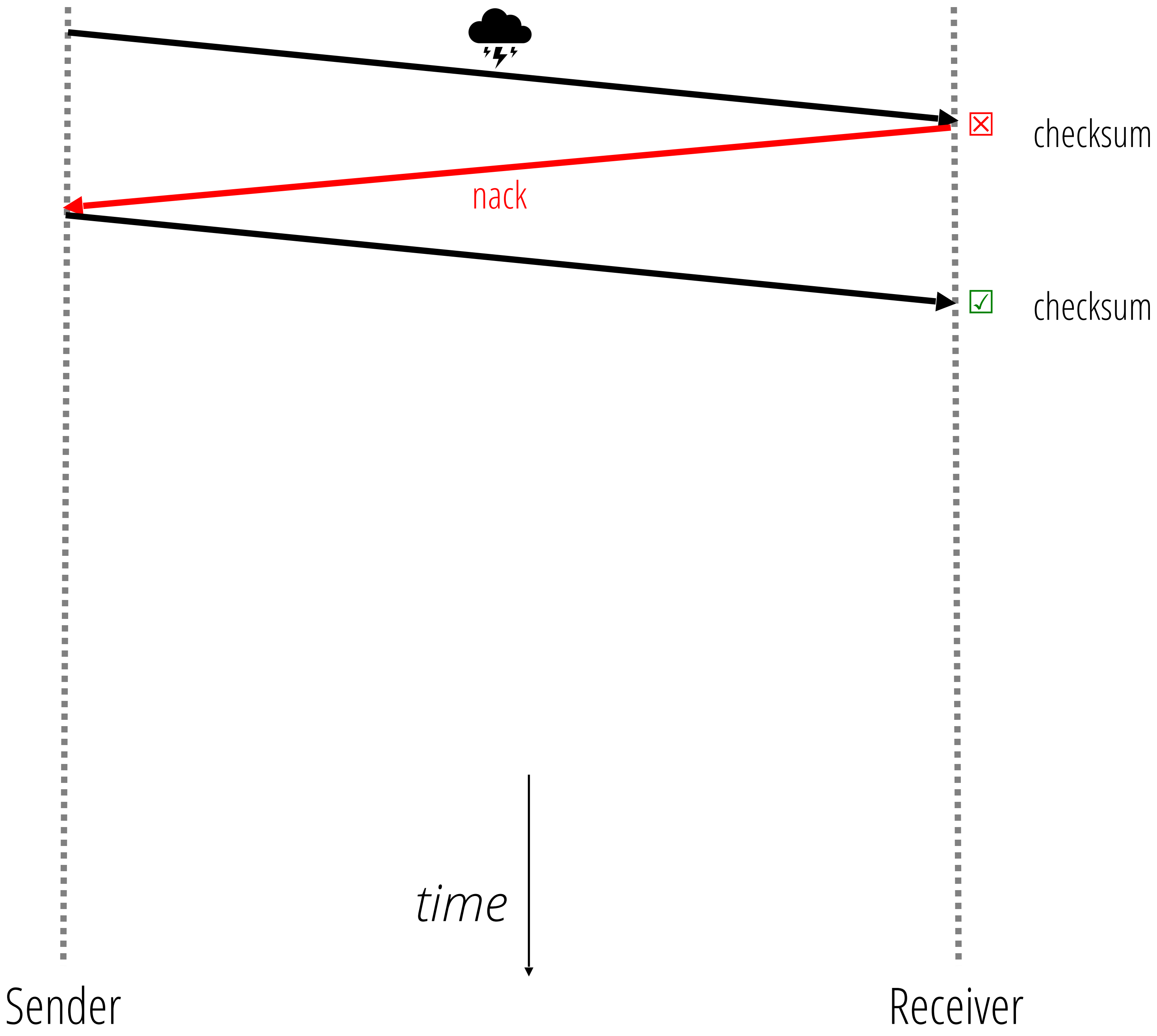
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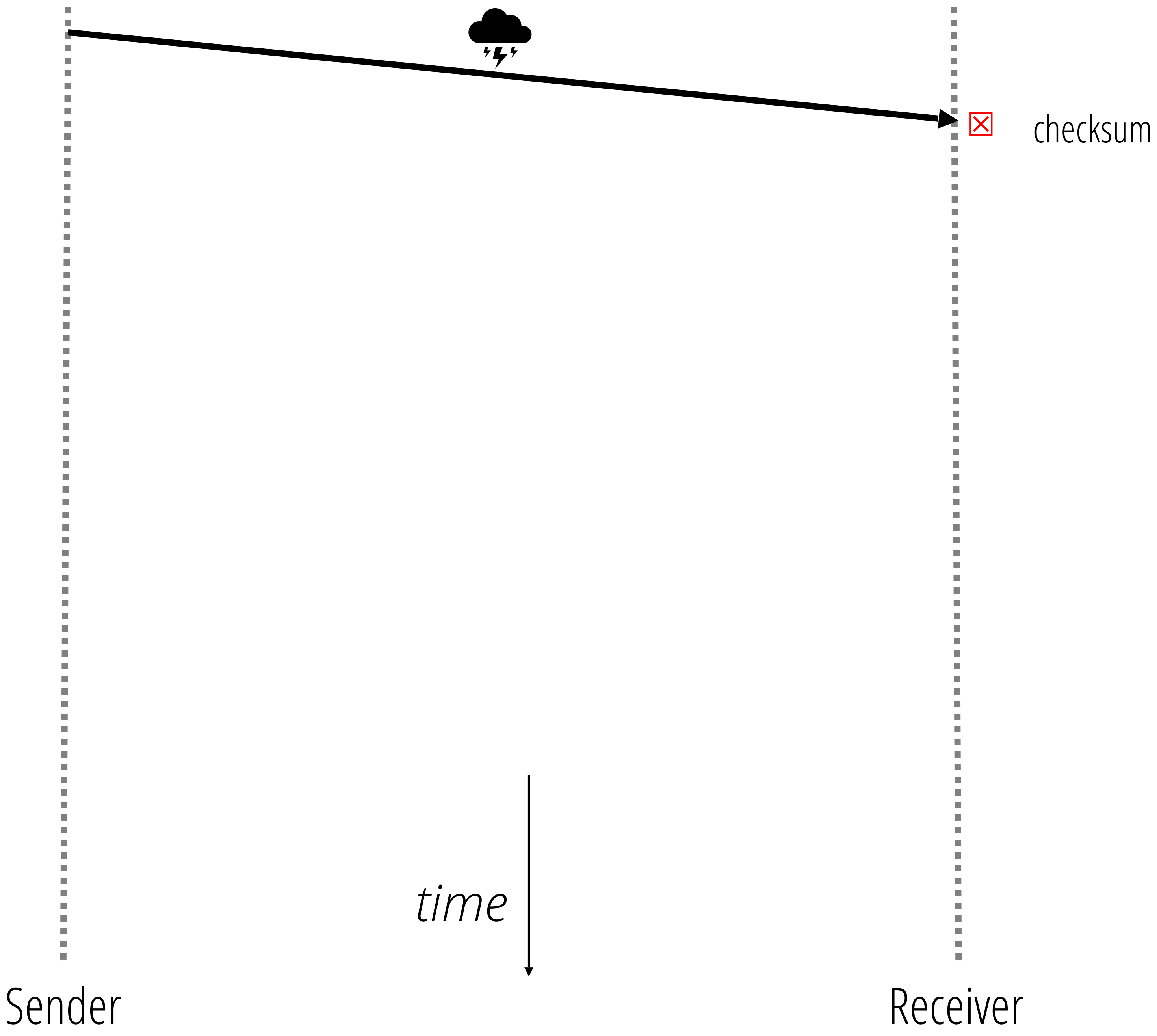
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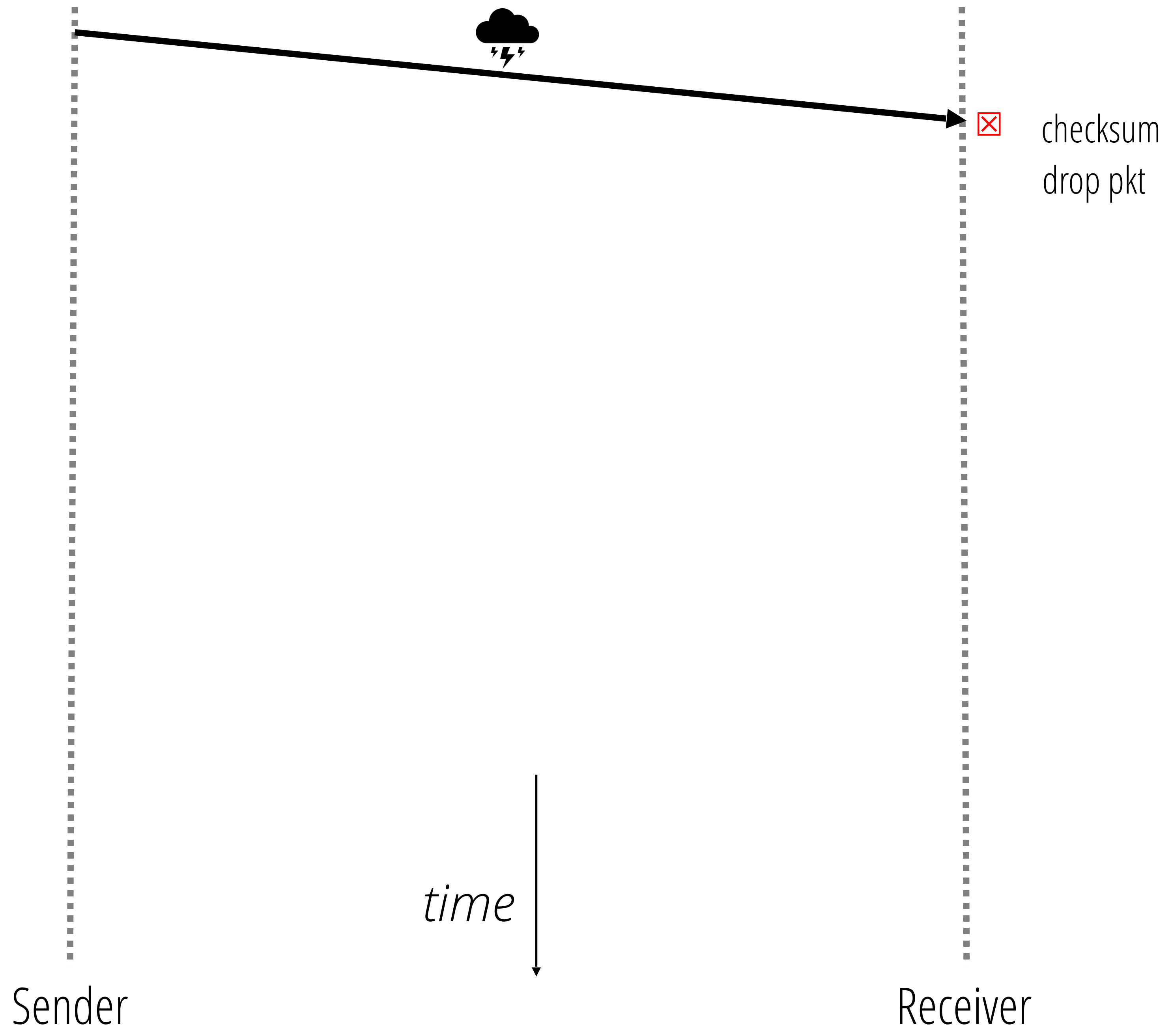
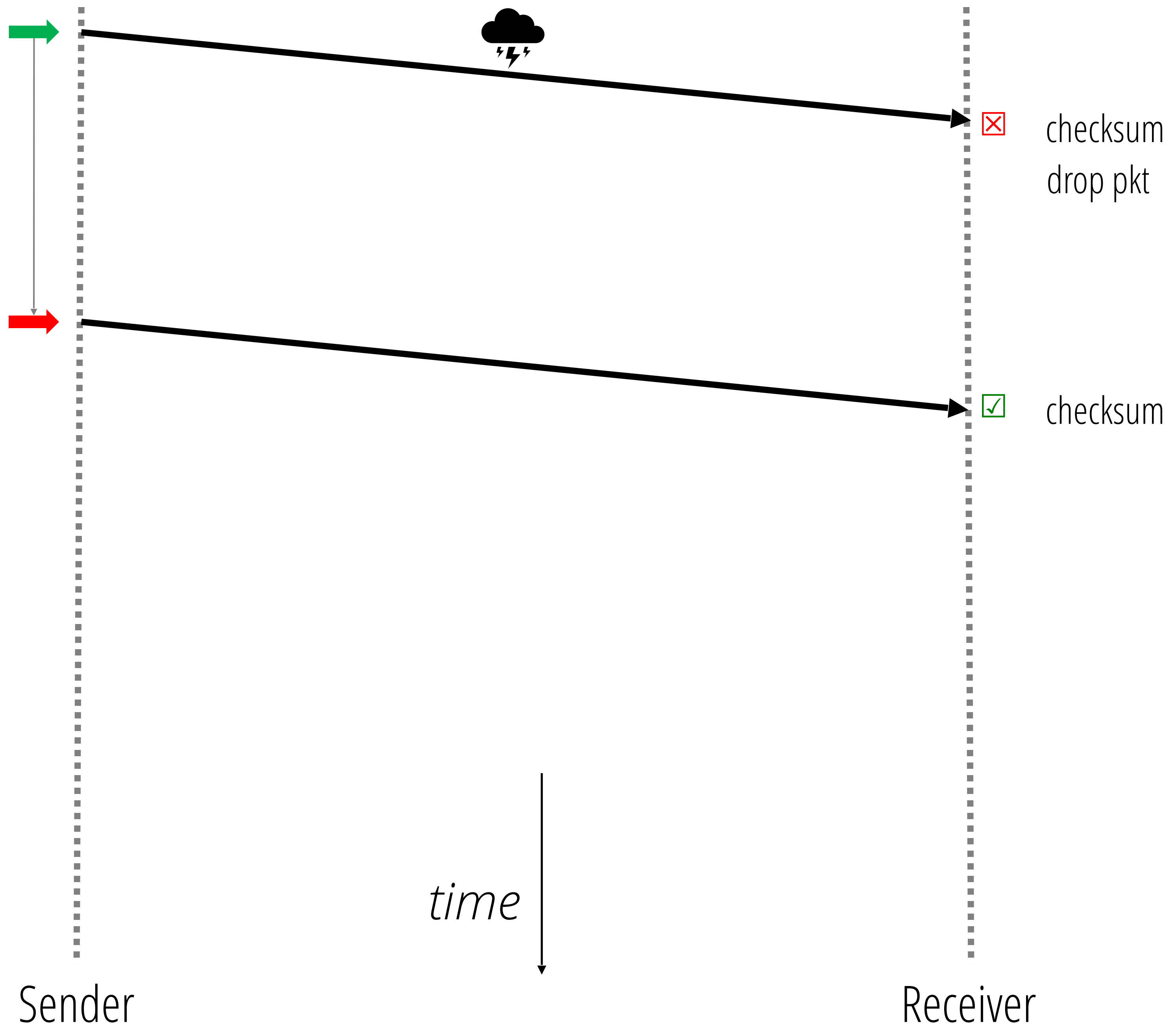
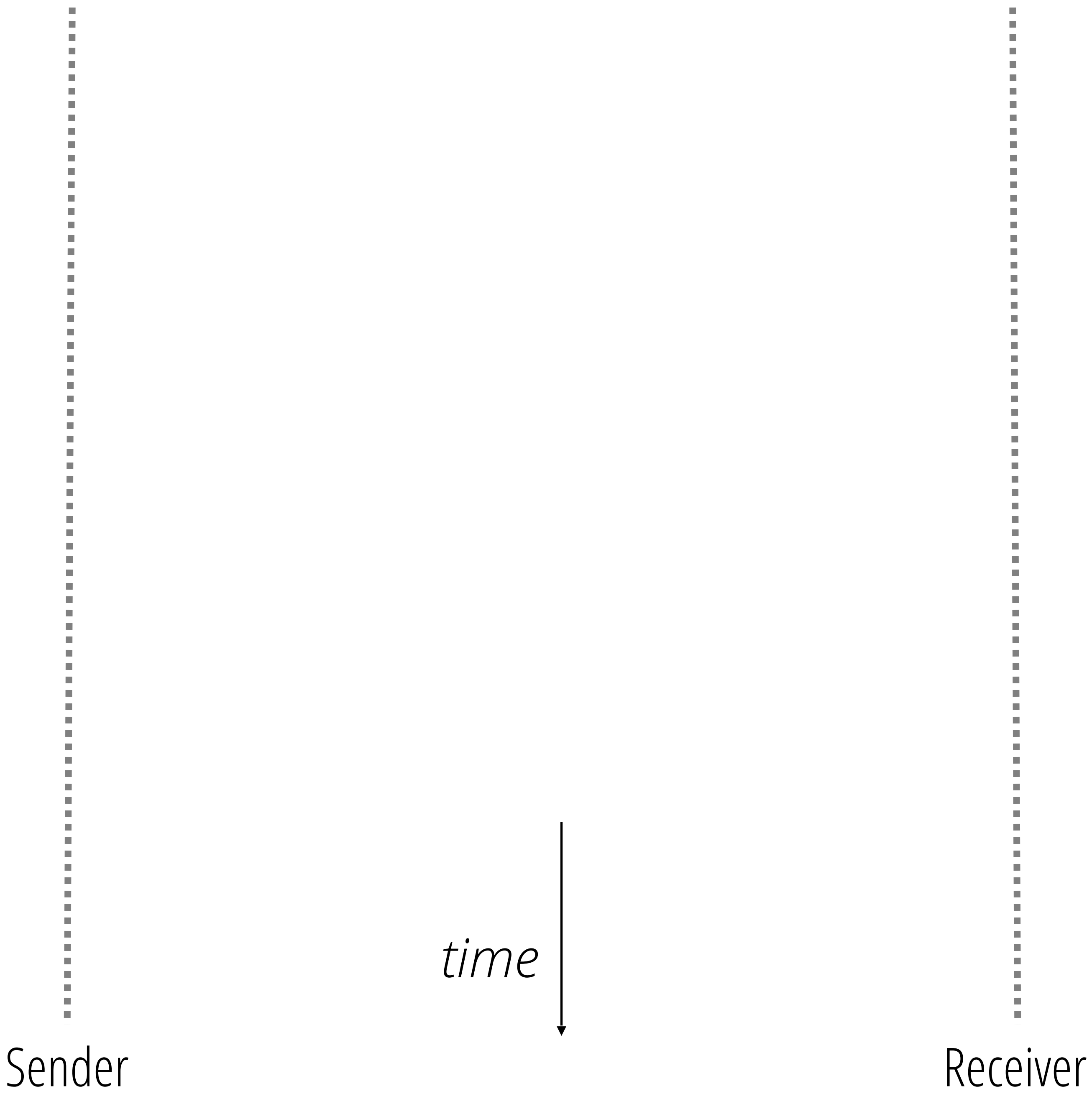
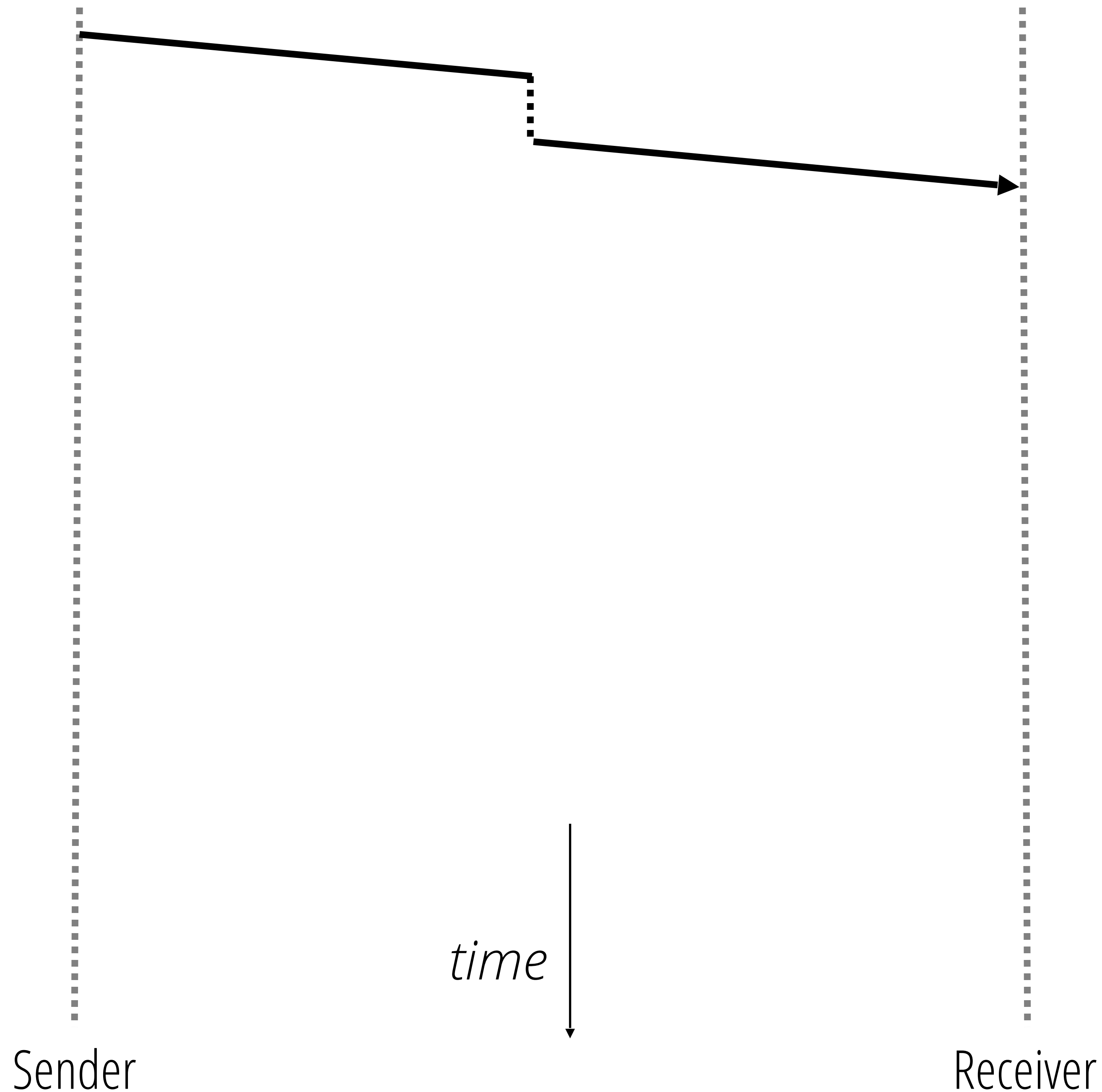
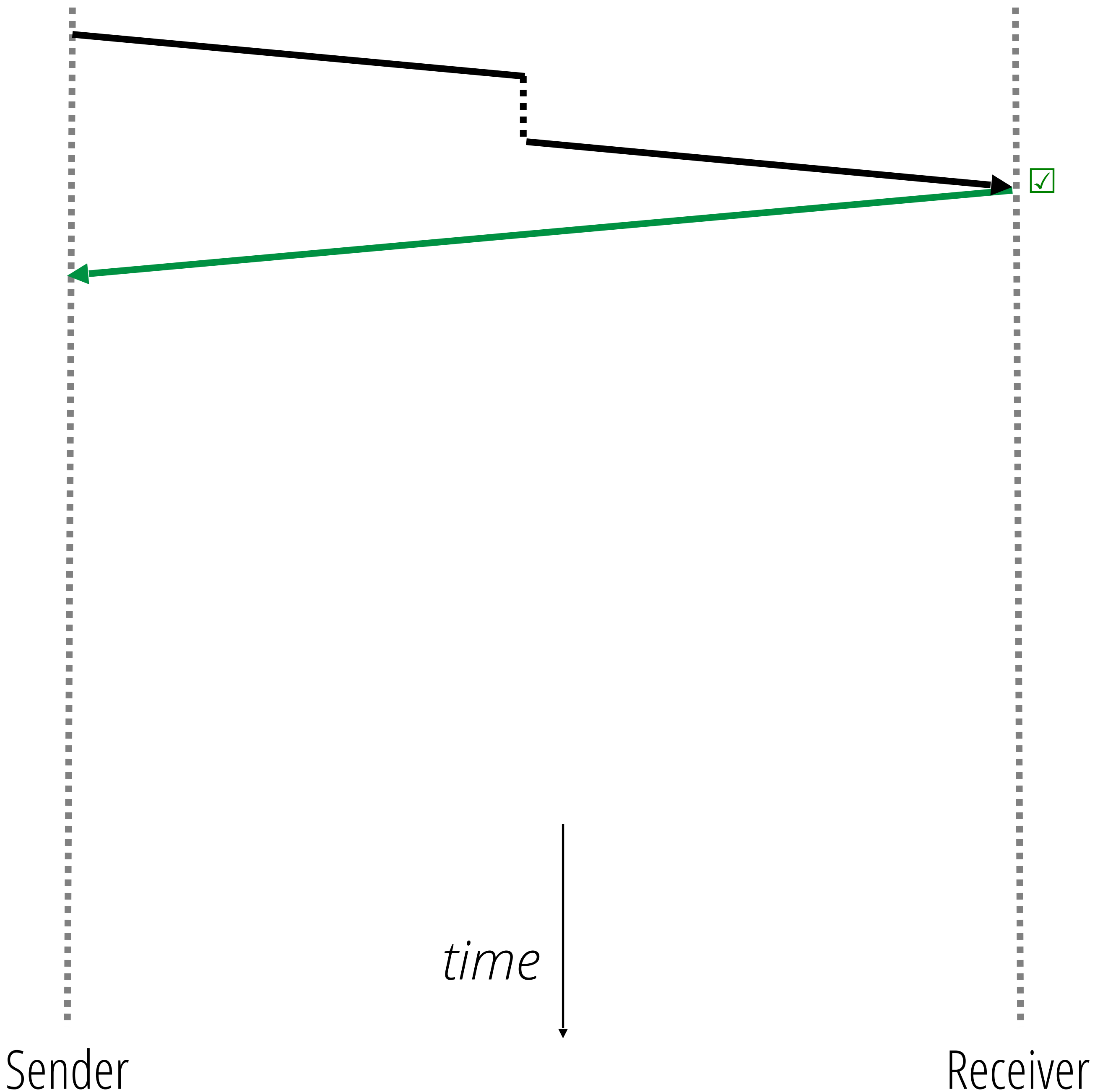

checksum
drop pkt
time
Sender
Receiver

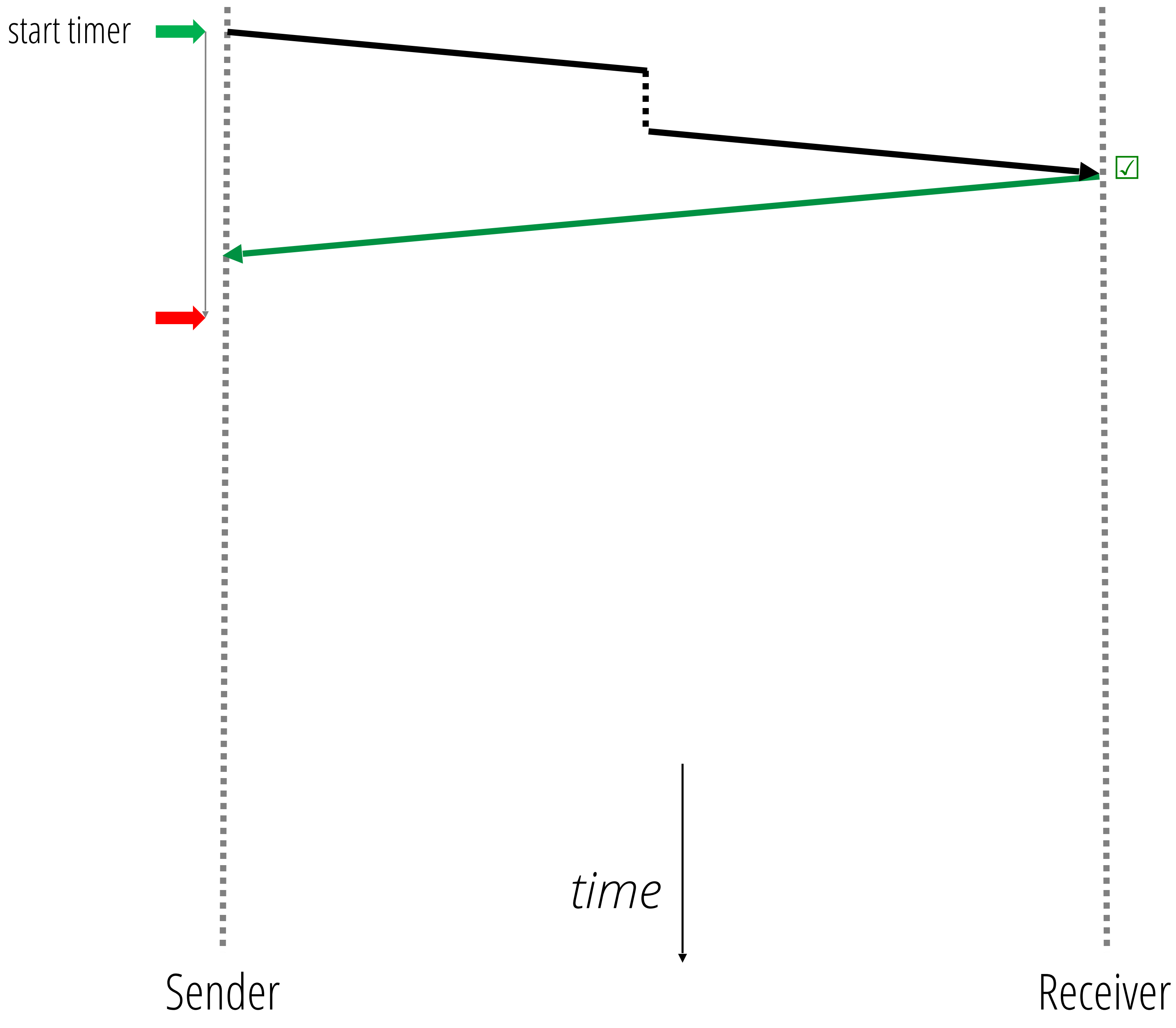

checksum
drop pkt
checksum
time
Sender
Receiver

- We said
  - Packets can be lost (data or ACKs) 👍
  - Packets can be corrupted 👍
  - Packets can be delayed
  - Packets can be duplicated
  - Packets can be reordered

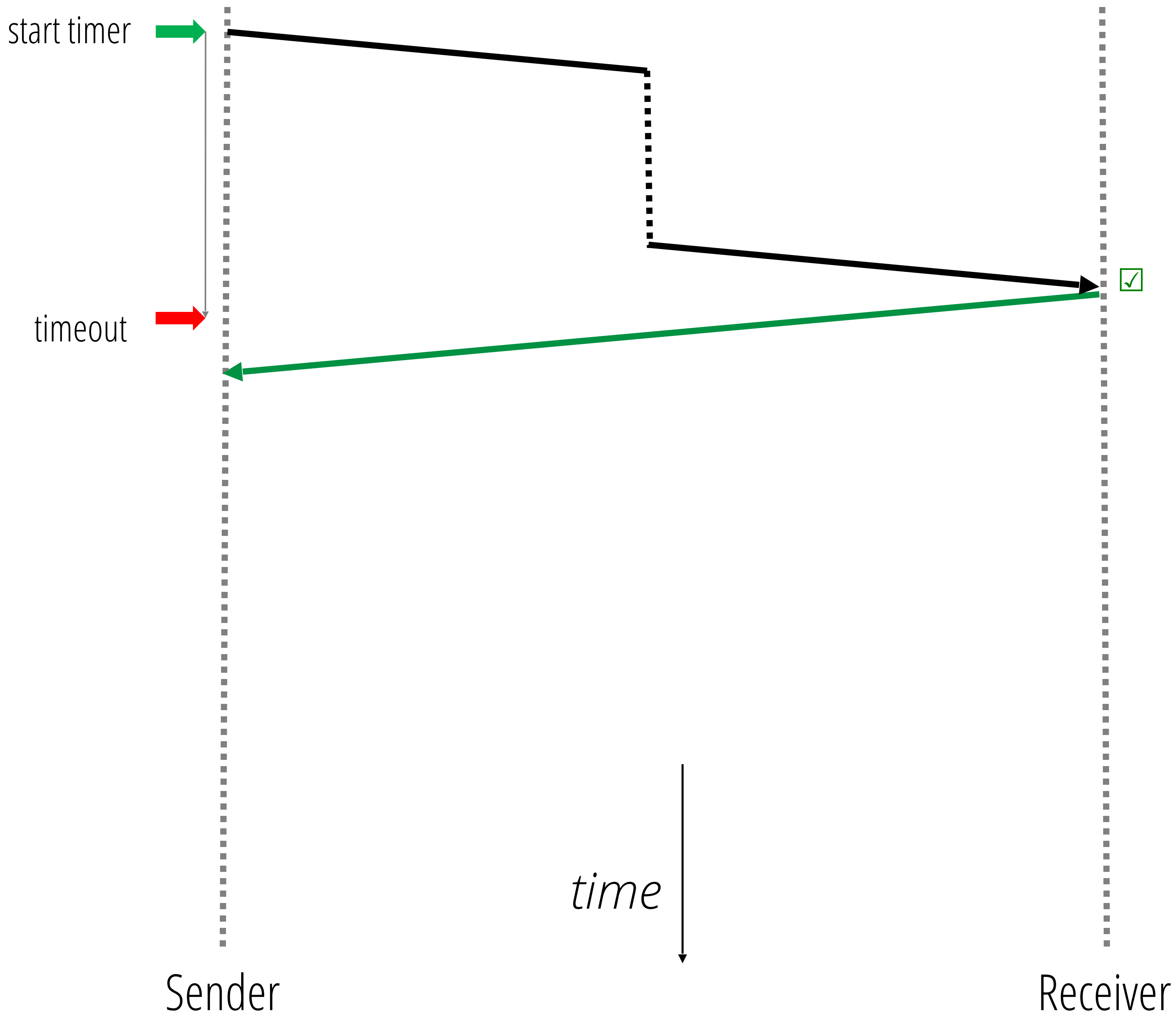

time
Sender
Receiver

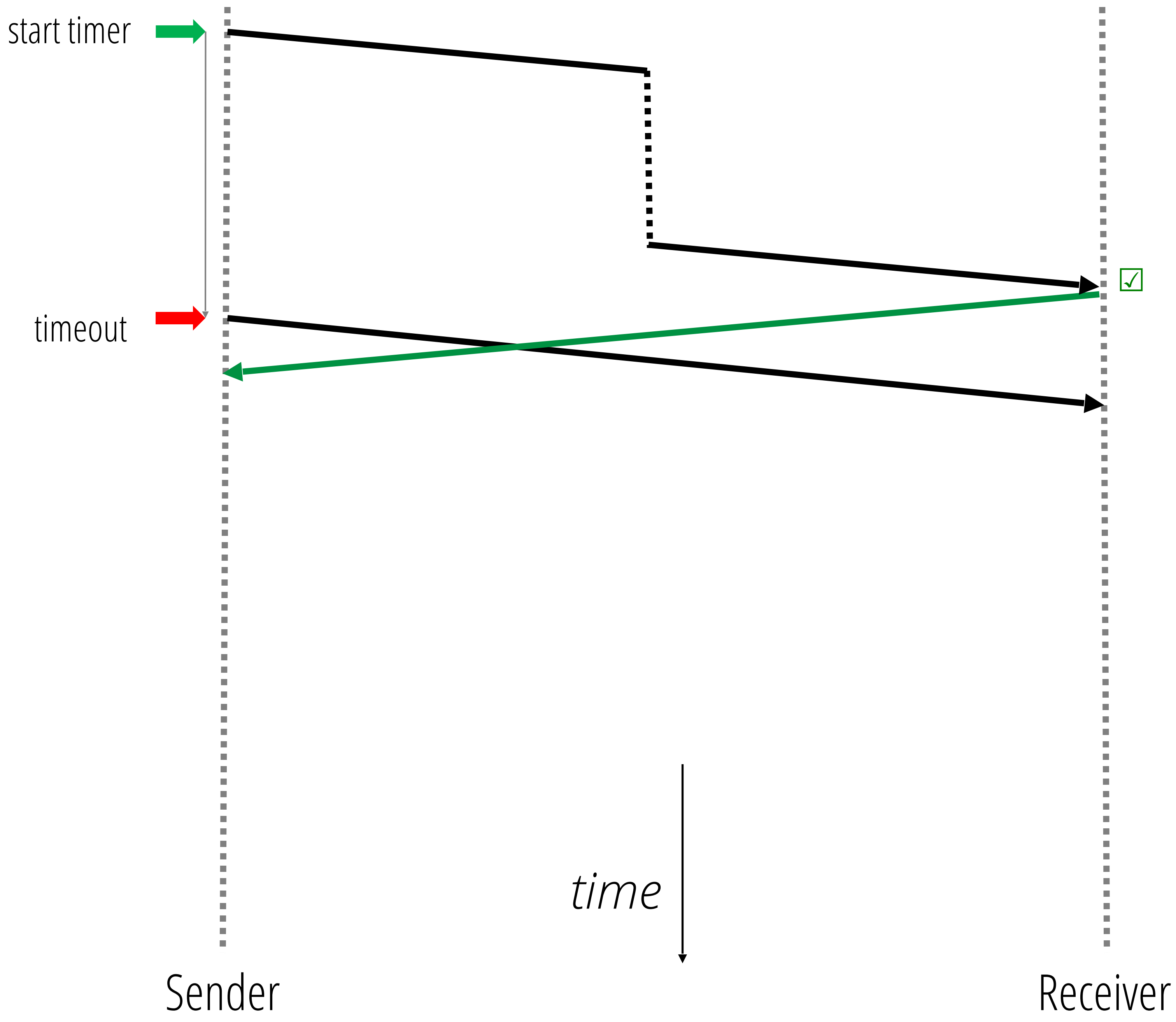

time
Sender
Receiver

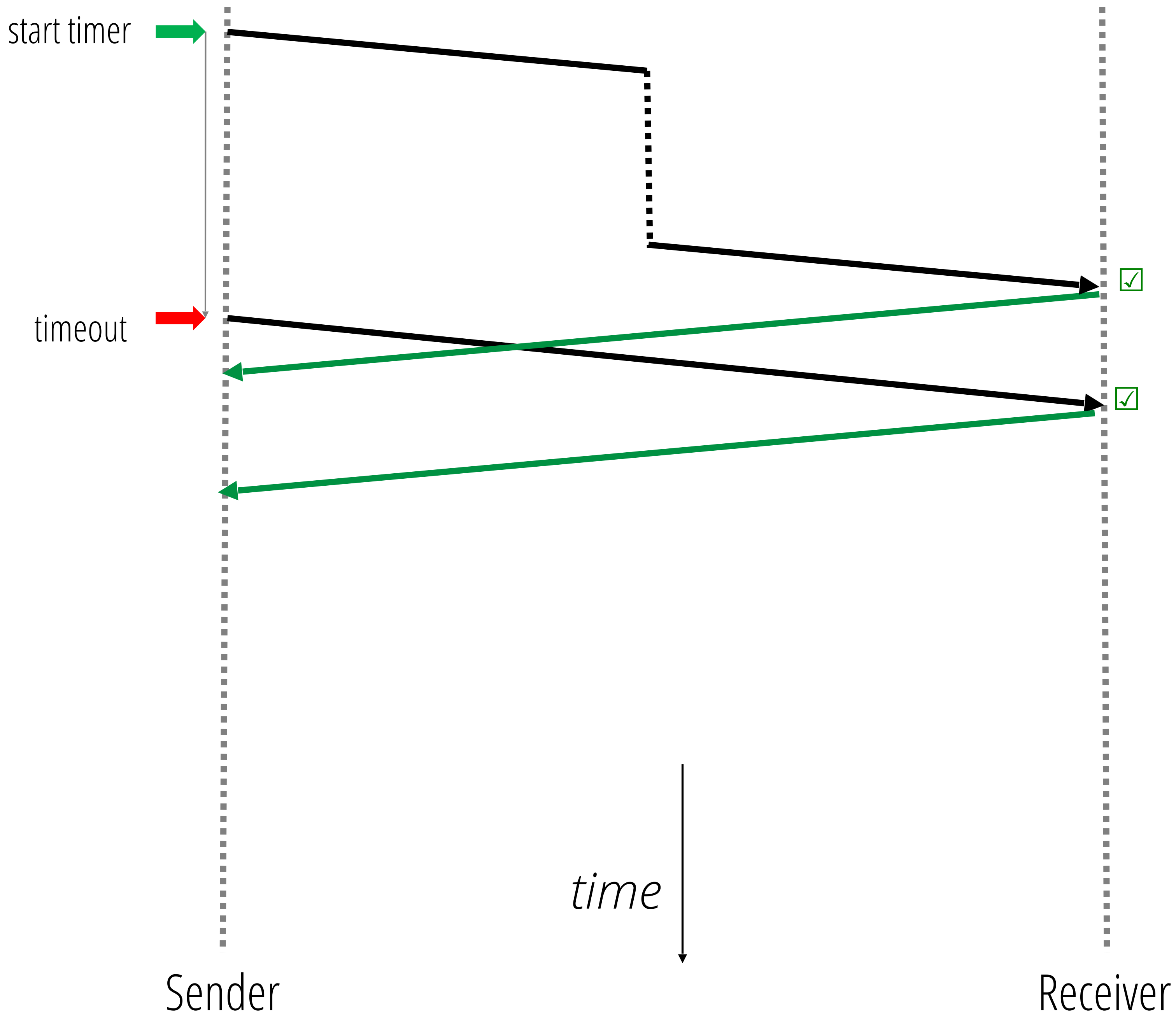

☑
time
Sender
Receiver



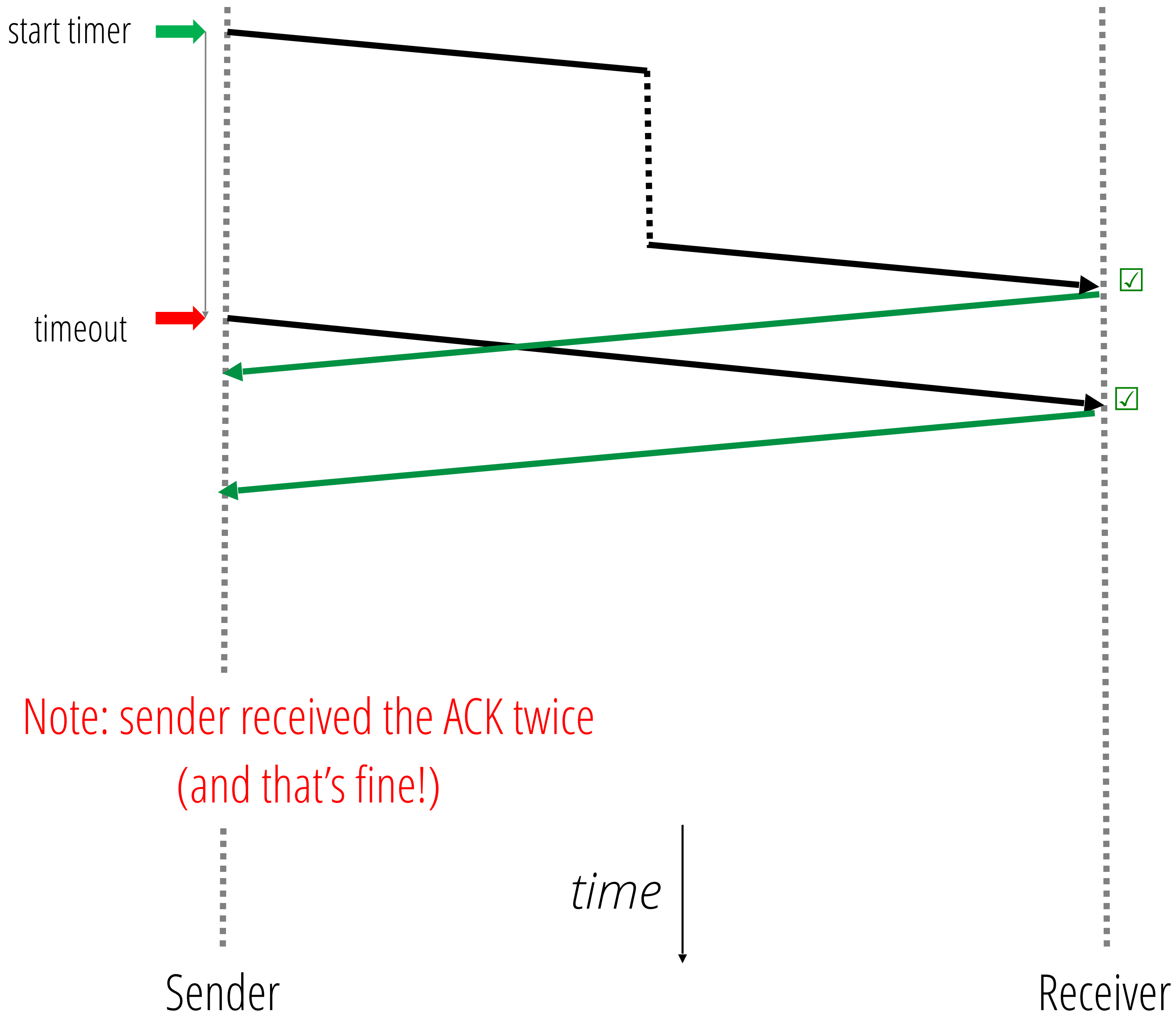
start timer
☑
time
Sender
Receiver


start timer
timeout
☑
time
Sender
Receiver


start timer
timeout
☑
time
Sender
Receiver

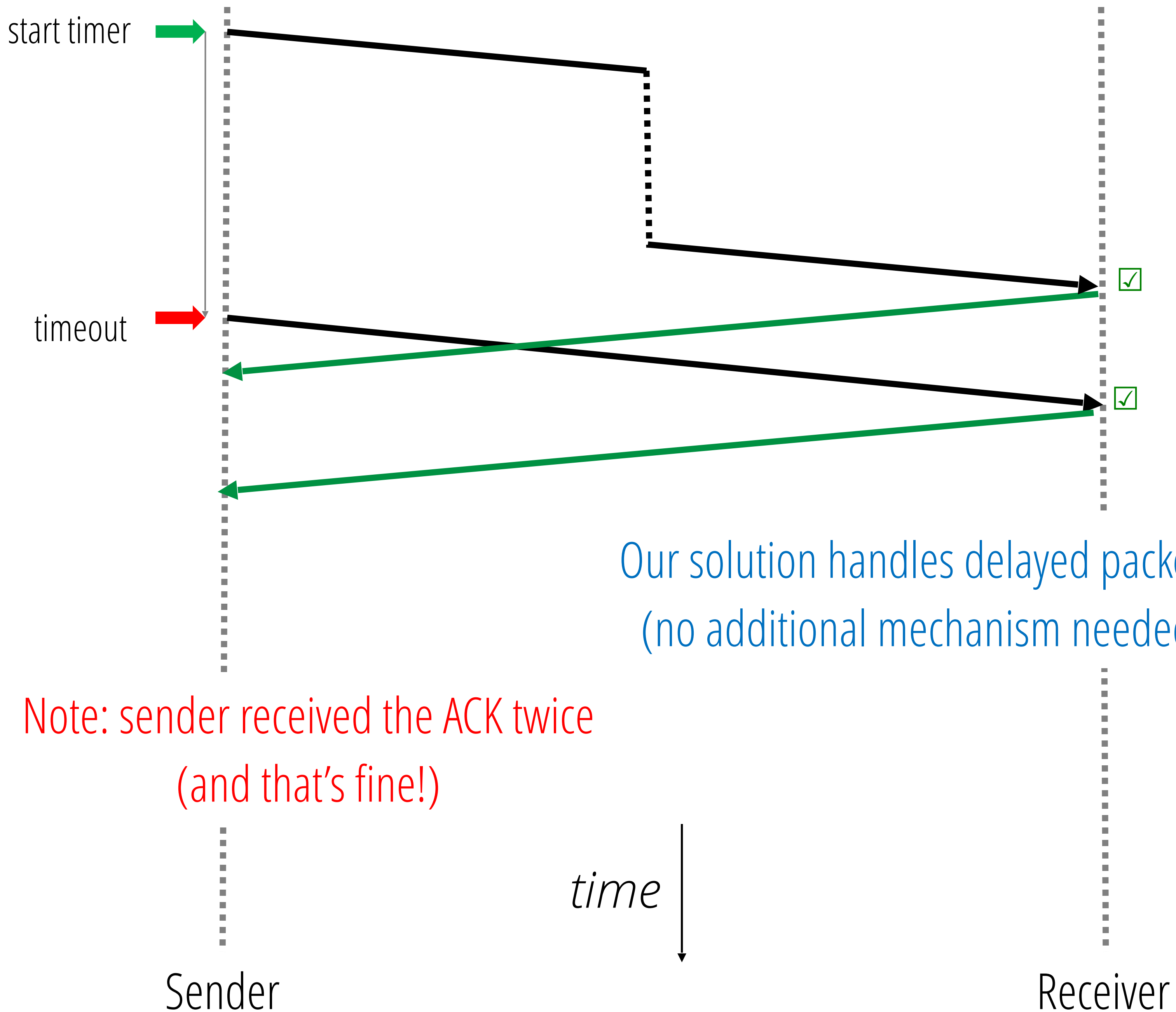


start timer
timeout
☑
☑
time
Sender
Receiver



Note: sender received the ACK twice

(and that's fine!)



Our solution handles delayed packets!
(no additional mechanism needed)

Note: sender received the ACK twice
(and that's fine!)

- We said
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  - Packets can be corrupted 👍
  - Packets can be delayed 👍
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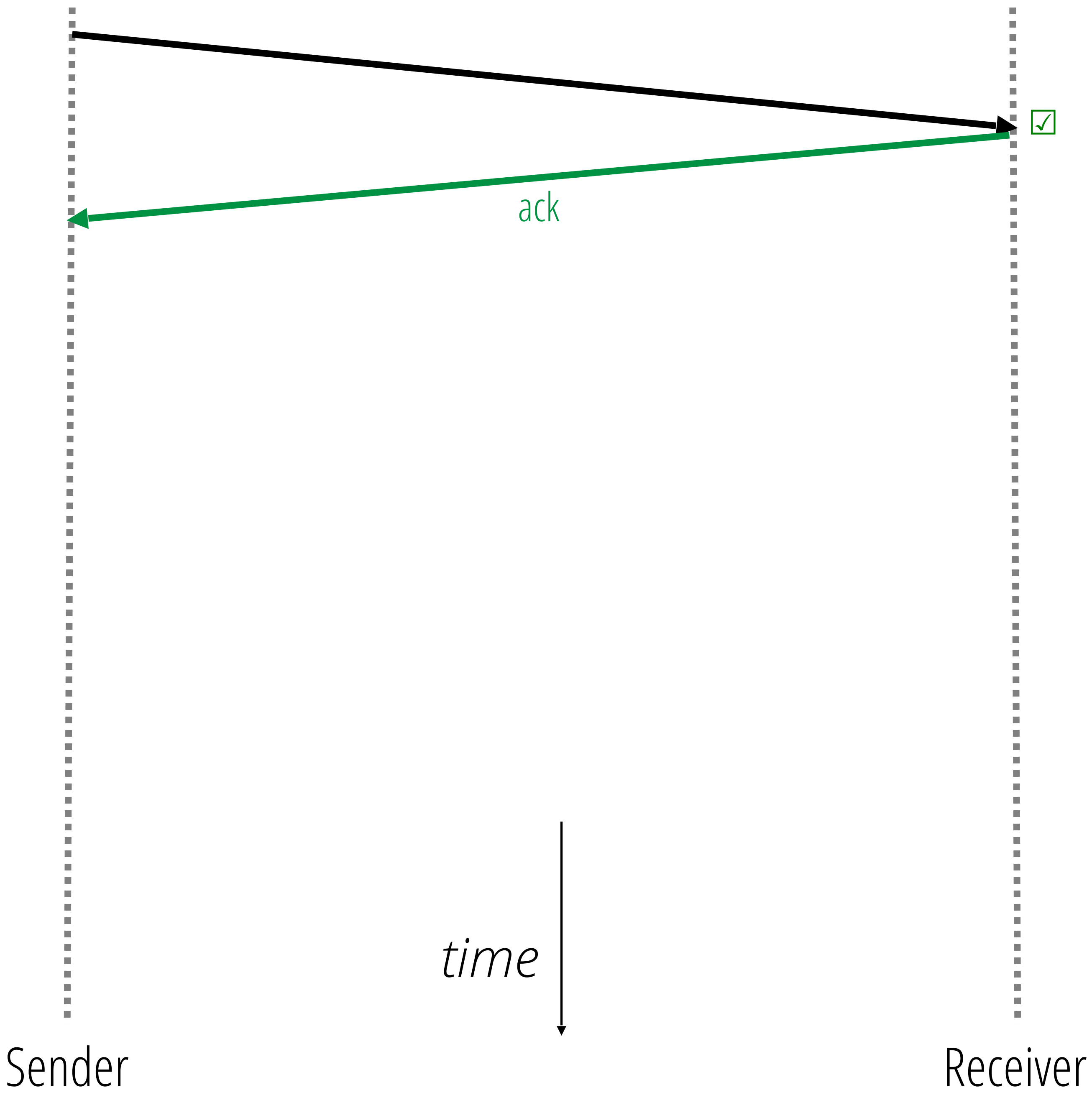
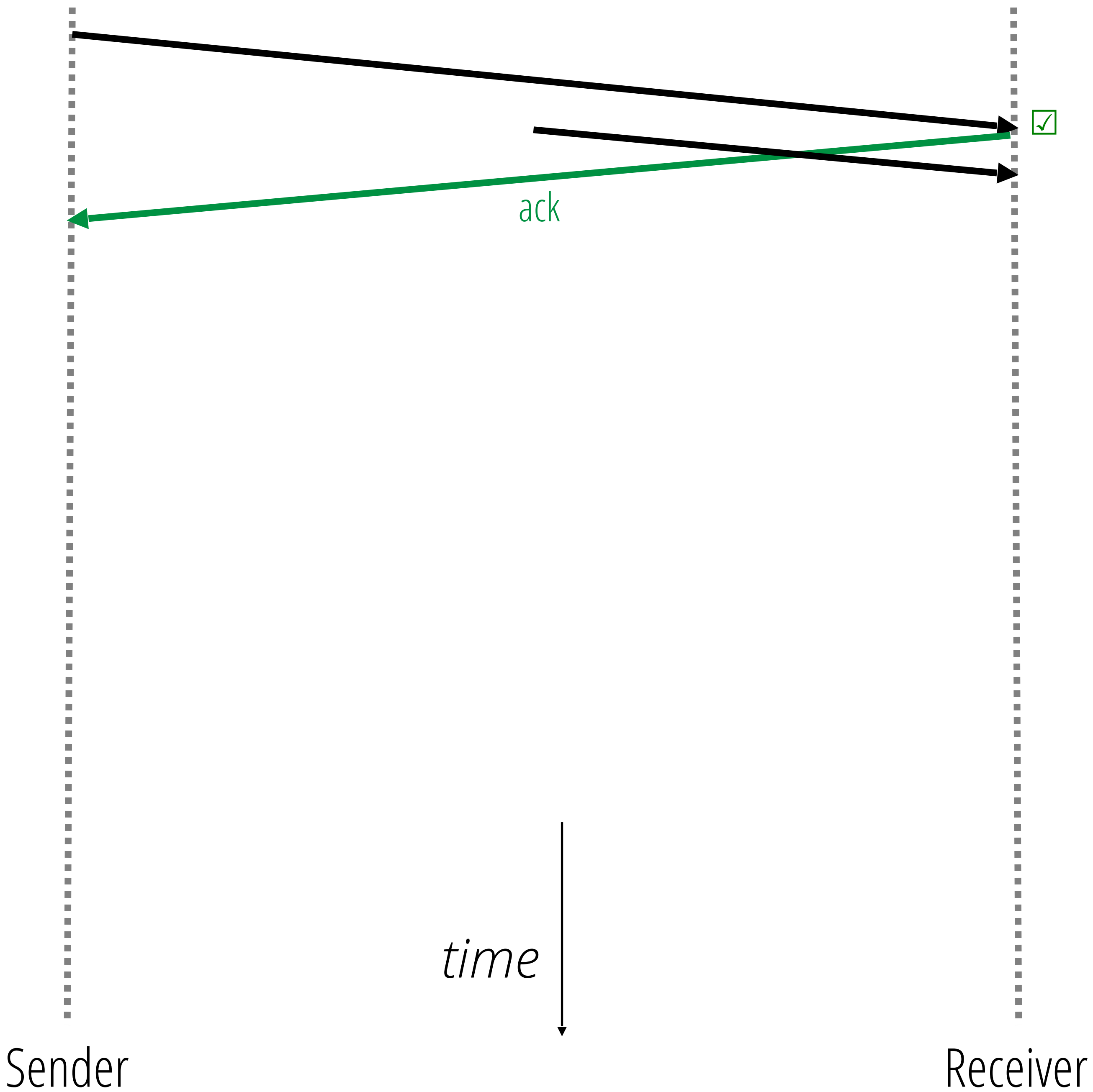
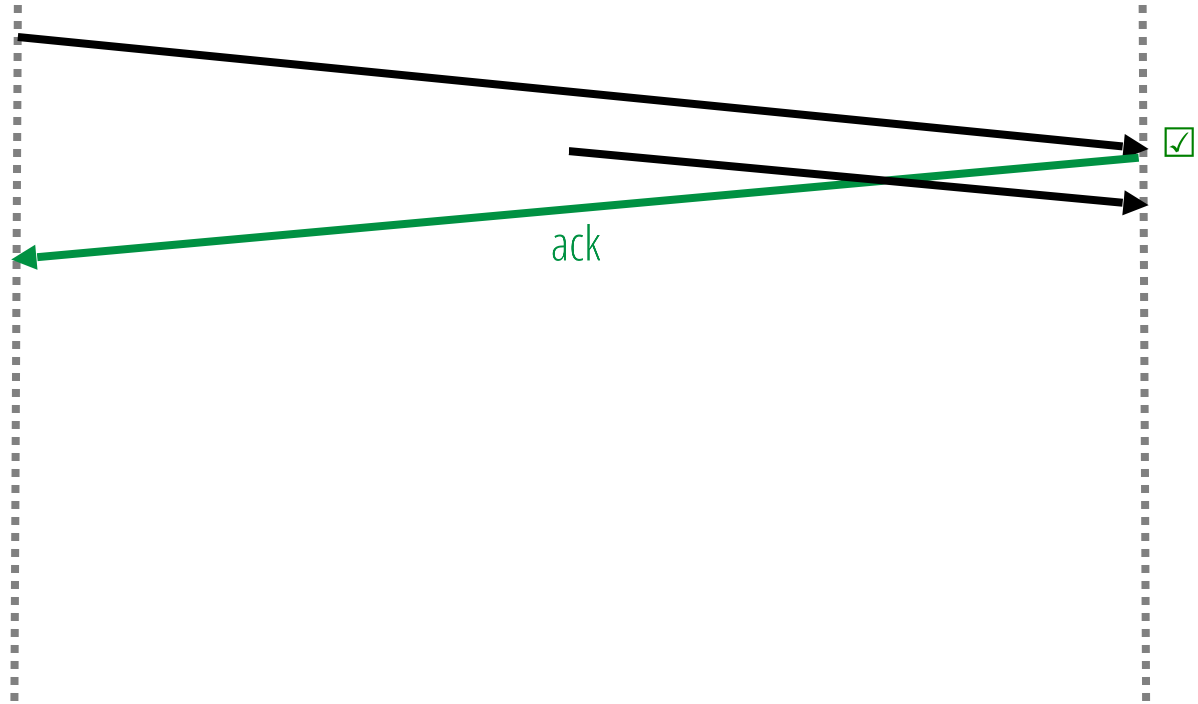
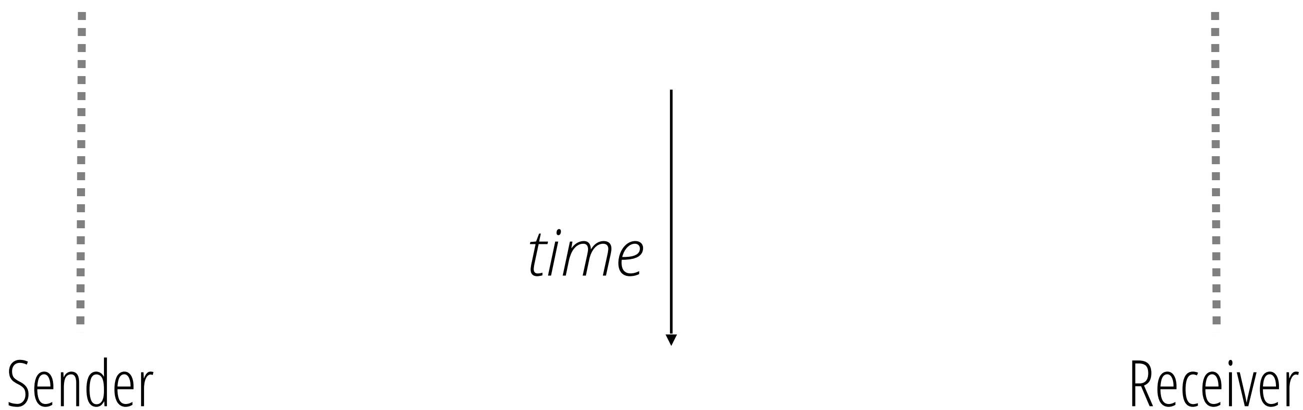

☑
ack
time
Sender
Receiver

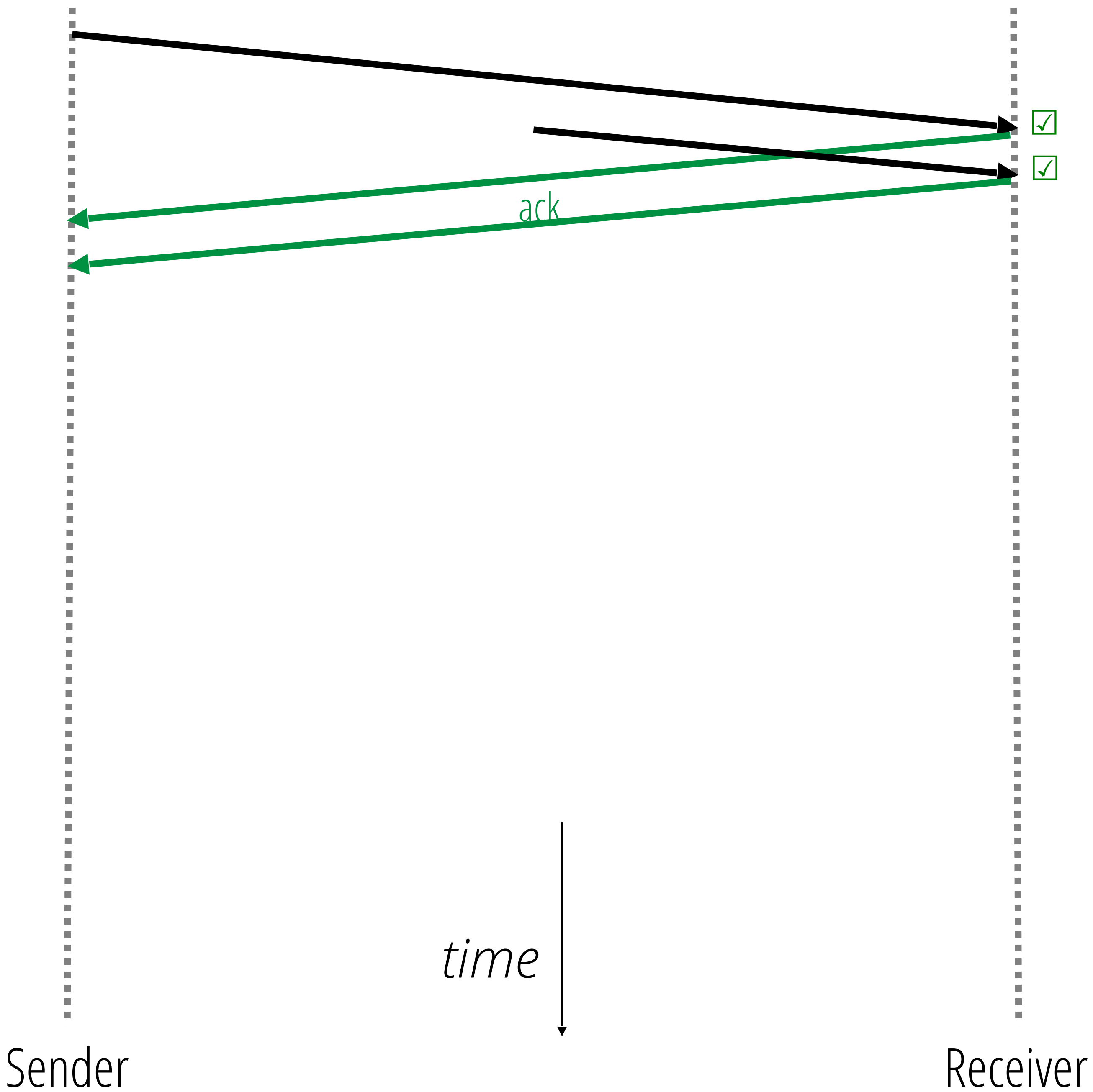

☑
ack
time
Sender
Receiver

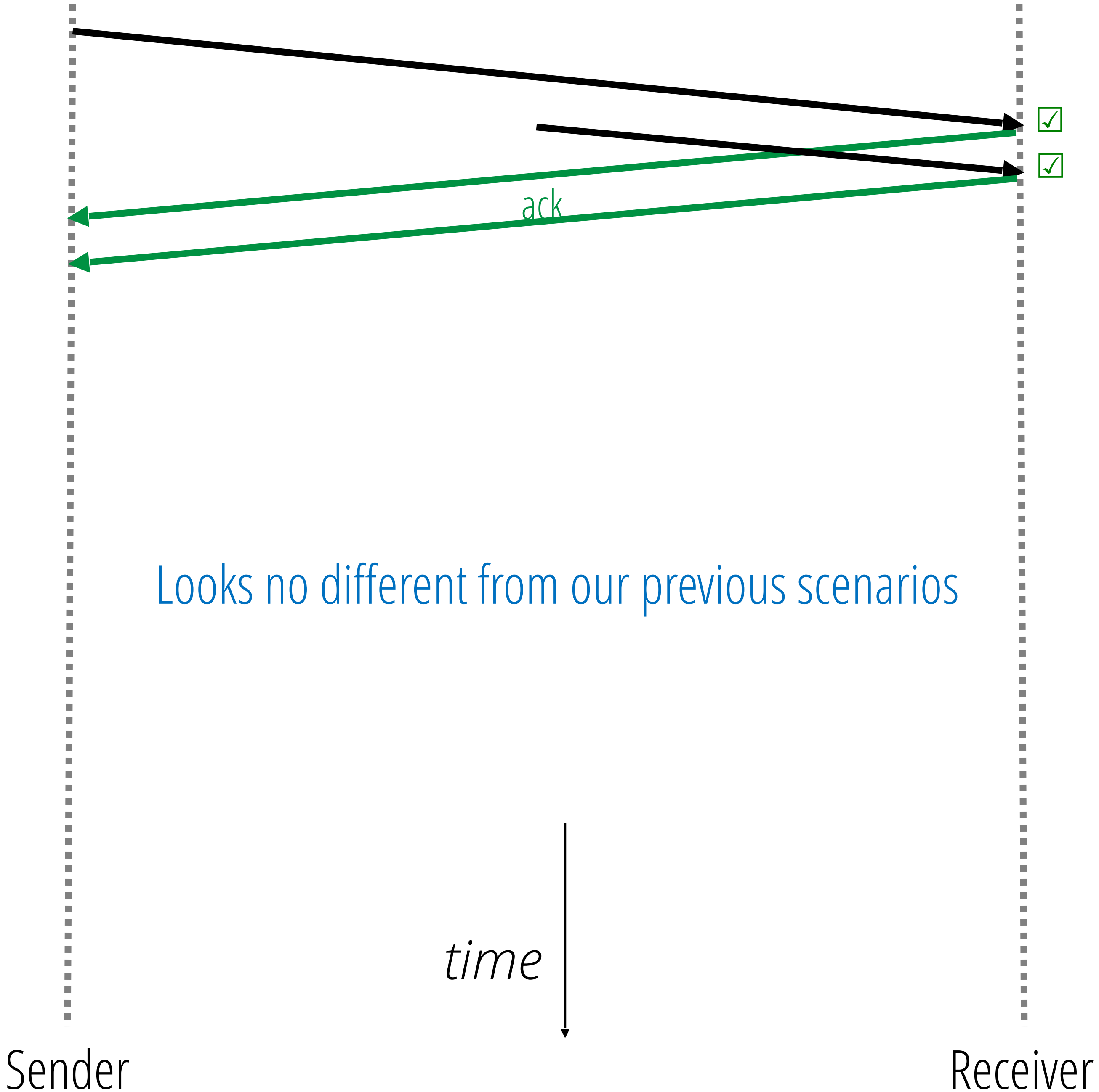


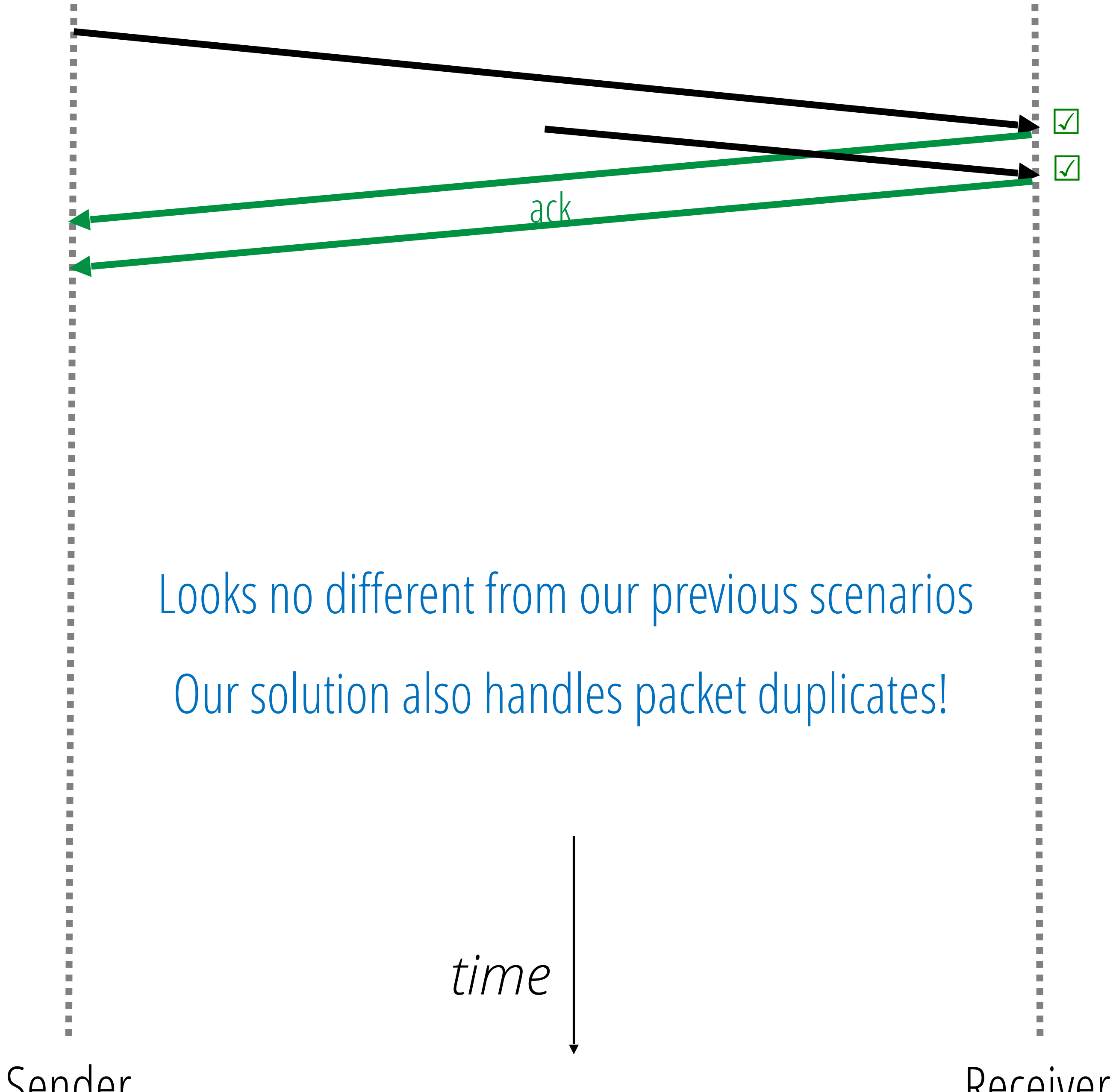
Why would the network even duplicate a packet?

Usually, because of link-level reliability gone wrong (very rare)




☑
☑
ack
time
Sender
Receiver


ack
Looks no different from our previous scenarios
time
Sender
Receiver



Looks no different from our previous scenarios

Our solution also handles packet duplicates!

- We said
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  - Packets can be delayed 👍
  - Packets can be duplicated 👍
  - Packets can be reordered

Have solved the single packet case!

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- Sender:
  - Send packet
  - Set timer
  - If no ACK arrives before the timer goes off, resend packet
    - And reset timer

Have solved the single packet case!

- Sender:
  - Send packet
  - Set timer
  - If no ACK arrives before the timer goes off, resend packet
    - And reset timer
- Receiver
  - When receiver gets packet, sends ACK

What have we learnt?

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- Building blocks for a solution
  - **Checksums**: to detect corruption
  - **Feedback** from receiver: positive/negative (ack/nack)
  - **Retransmissions**: sender resends packets
  - **Timeouts**: when to resend a packet

What have we learnt?

- Building blocks for a solution
  - **Checksums**: to detect corruption
  - **Feedback** from receiver: positive/negative (ack/nack)
  - **Retransmissions**: sender resends packets
  - **Timeouts**: when to resend a packet

- Semantics of a solution: “at least once”
  - Receiver can receive the same packet more than once
  - Sender can see the same ack/nack more than once

Questions?

Next: reliably send multiple packets

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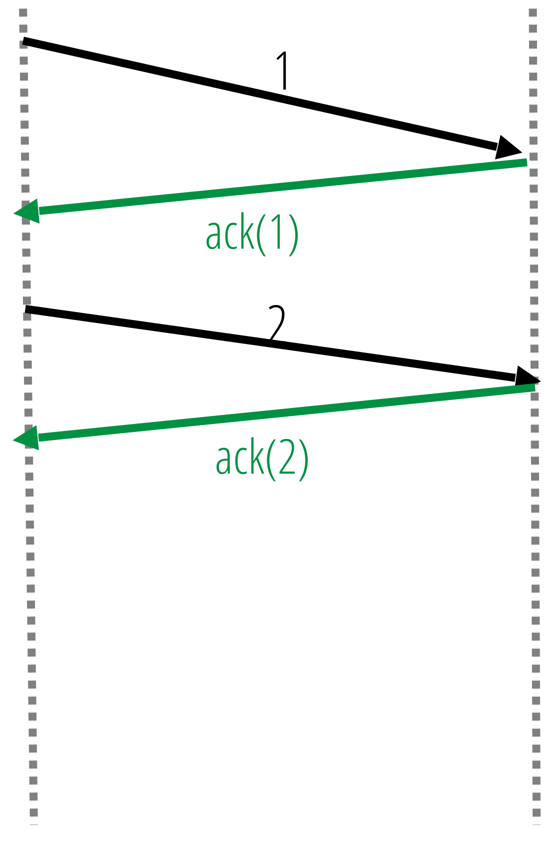
- Will need +1 design component: sequence numbers!



Data packets carry sequence numbers;
and ACKs indicate what sequence numbers have been received

Next: reliably send multiple packets

- Will need +1 design component: sequence numbers!
- We now have all the *necessary* building blocks!

The “Stop and Wait” protocol

- Use our single-packet solution repeatedly

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  - Wait for packet `i` to be acknowledged before sending `i+1`

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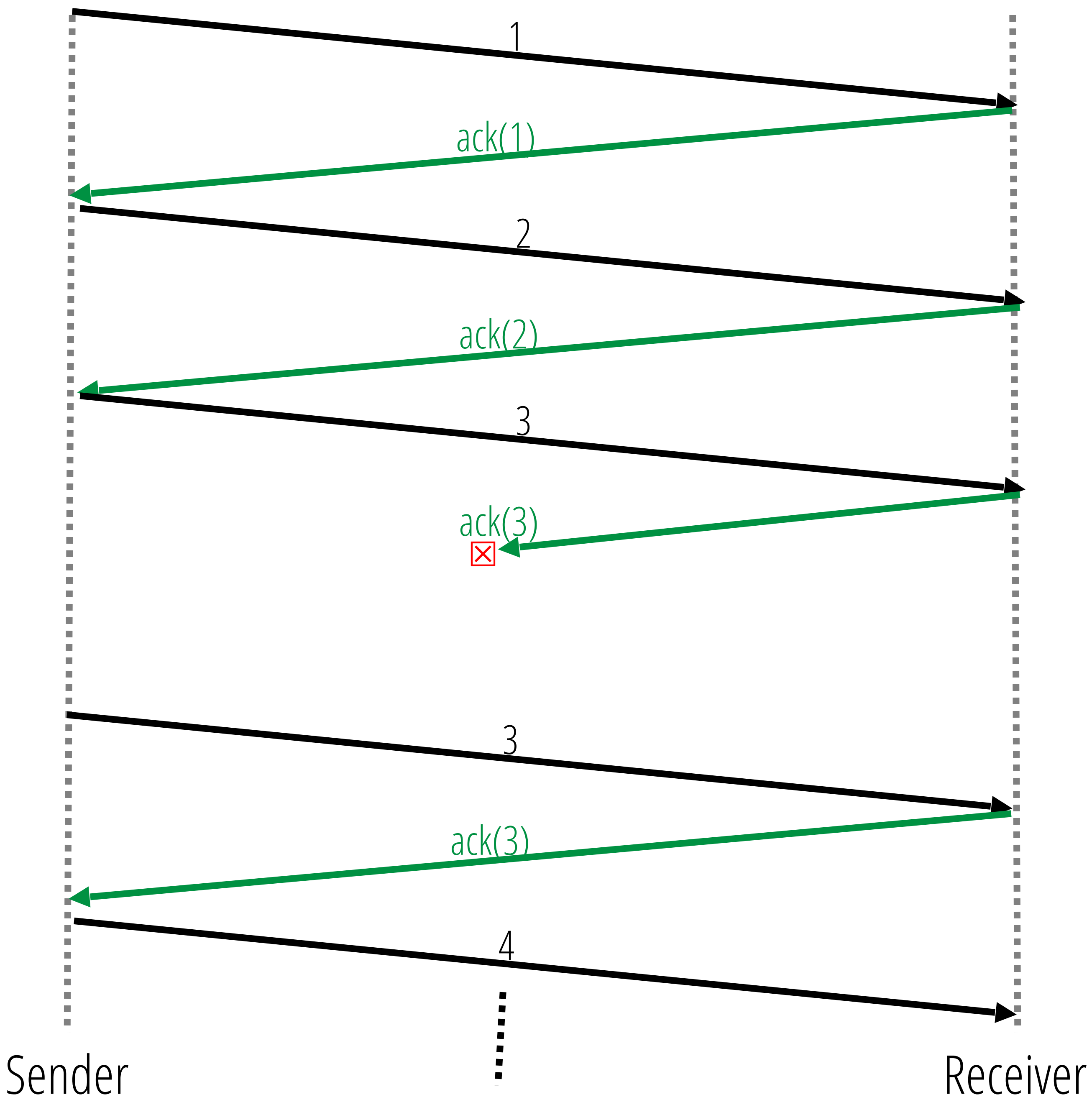
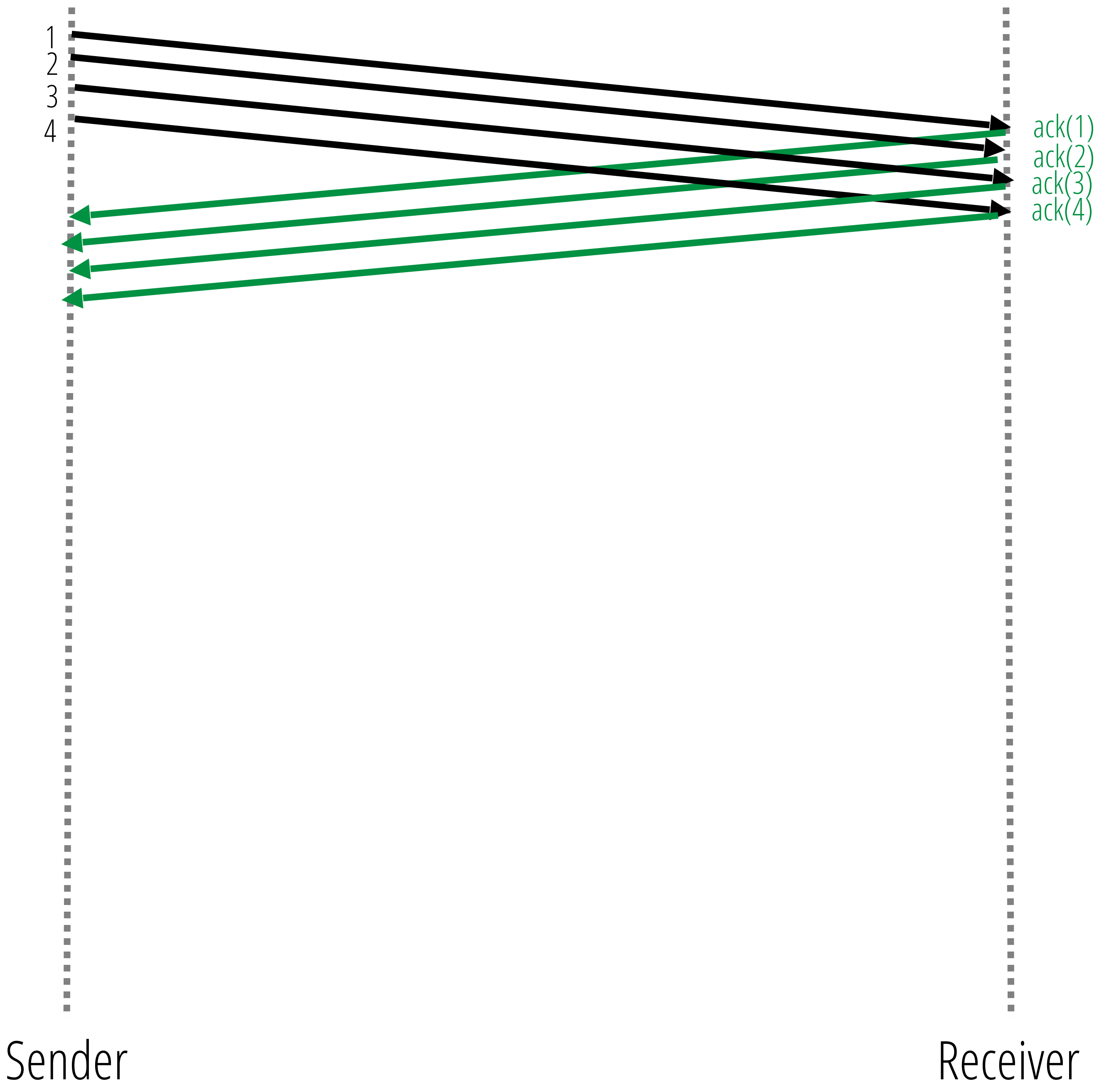
The “Stop and Wait” protocol

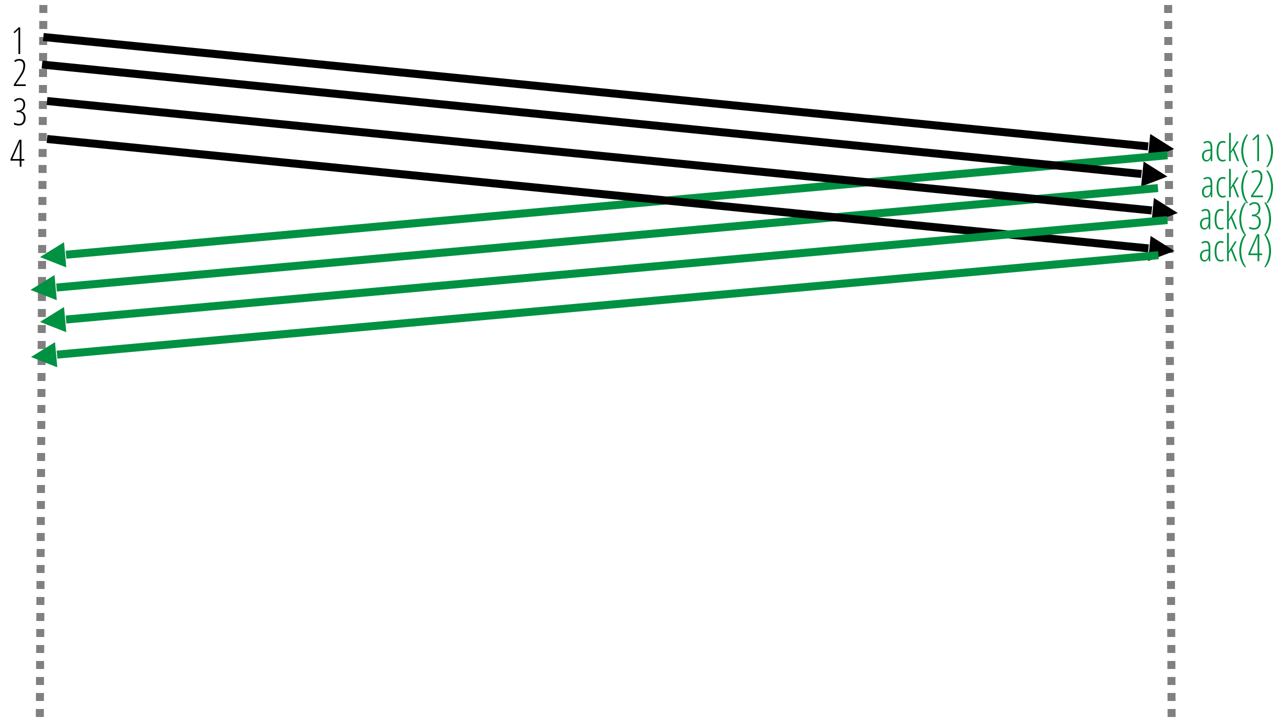
- Use our single-packet solution repeatedly
  - Wait for packet *`i`* to be acknowledged before sending *`i+1`*

- We have a correct reliable delivery protocol!

- Probably the world’s most inefficient one
  - Max throughput ~ one packet per RTT


1
ack(1)
2
ack(2)
3
ack(3)
3
ack(3)
4
Sender
Receiver


1
2
3
4
ack(1)
ack(2)
ack(3)
ack(4)
Sender
Receiver



Idea: have multiple packets "in flight"

(send additional packets while waiting for ACKs to come in)

Window-based Algorithms

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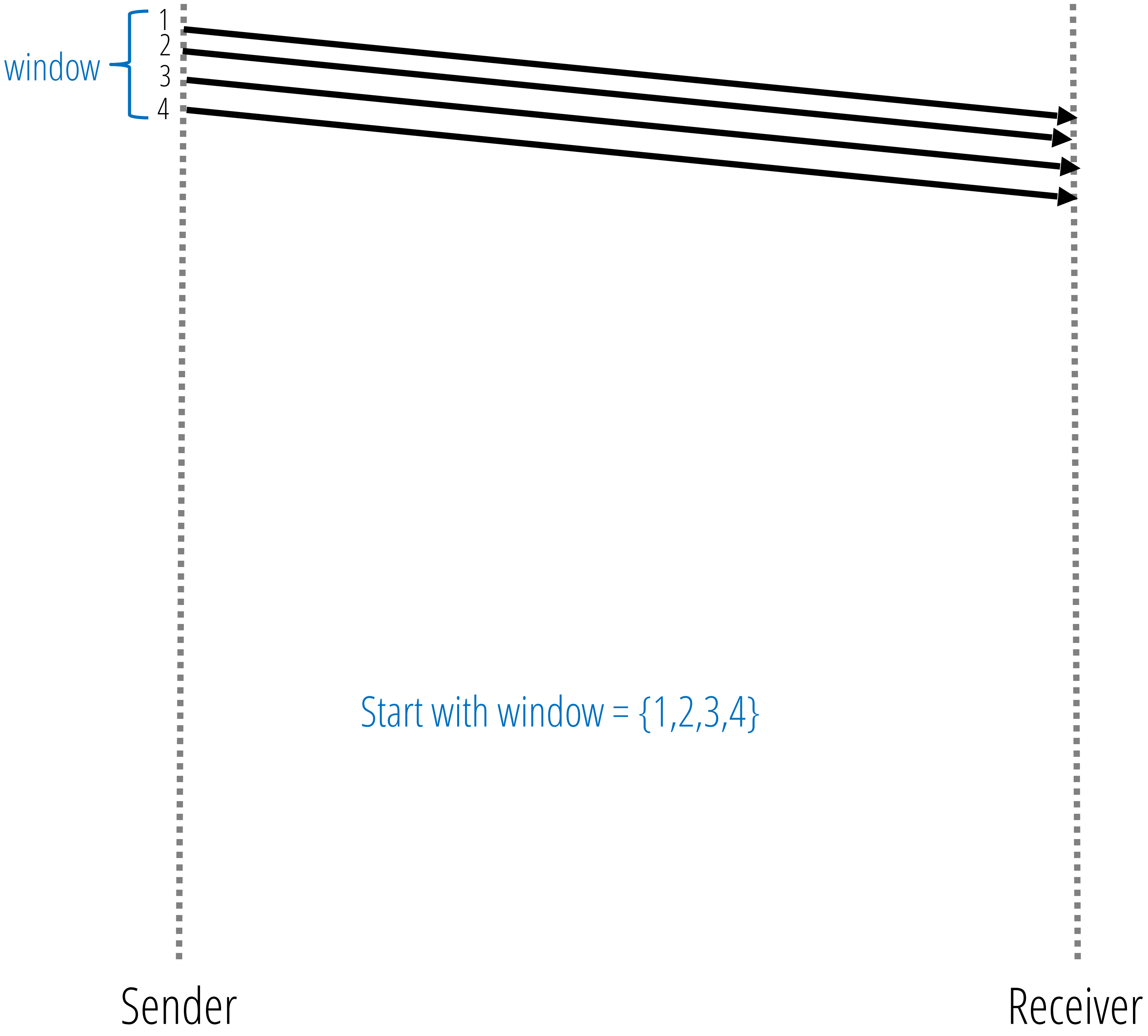
- Basic idea: allow **W** packets "in flight" at any time
  - W is the size of the window

Window-based Algorithms

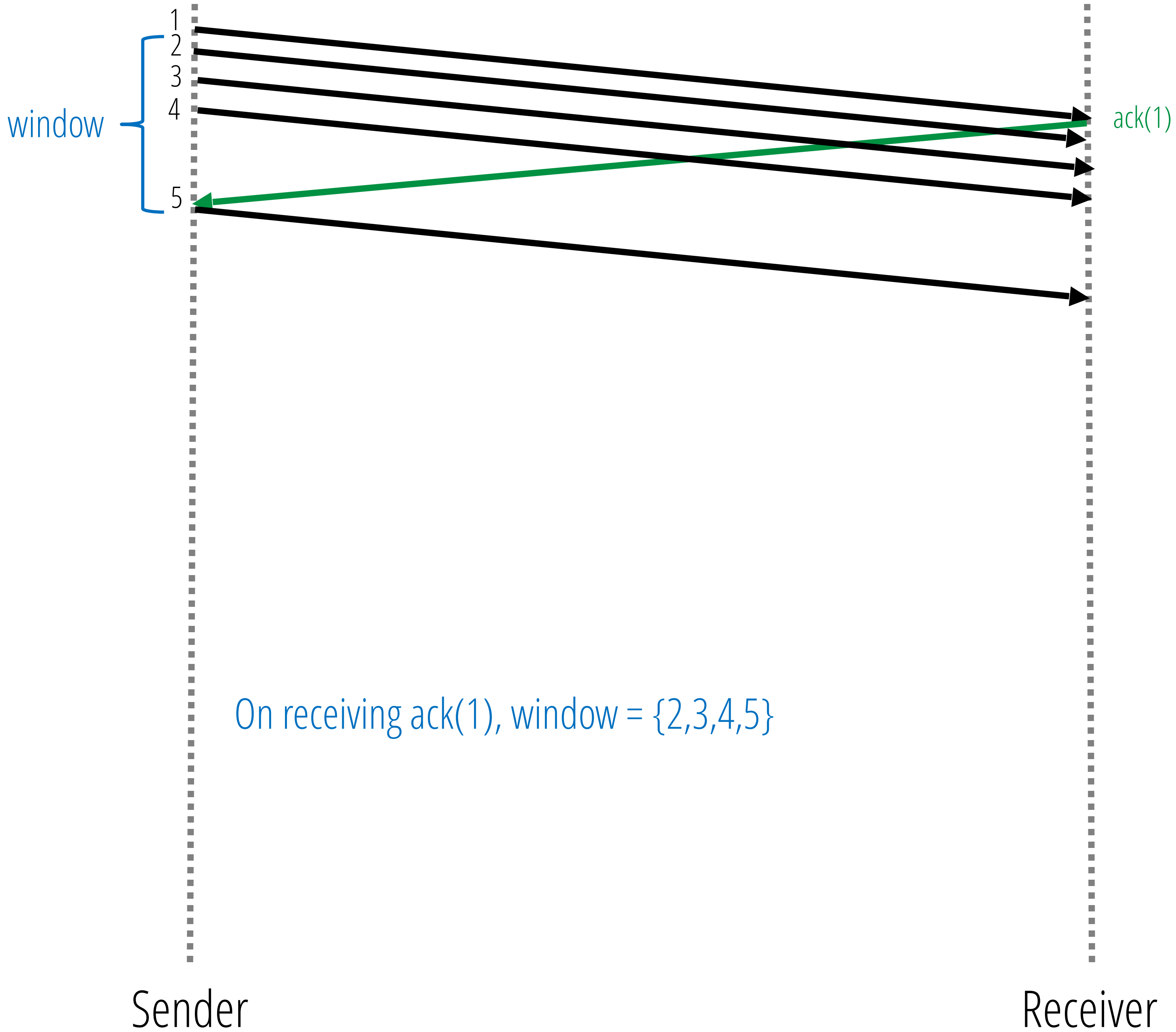
- Basic idea: allow **W** packets "in flight" at any time
  - W is the size of the window
- Hence, a simple algorithm (at sender)
  - Send W packets
  - When one gets ACK'ed, send the next packet in line

Example with W=4



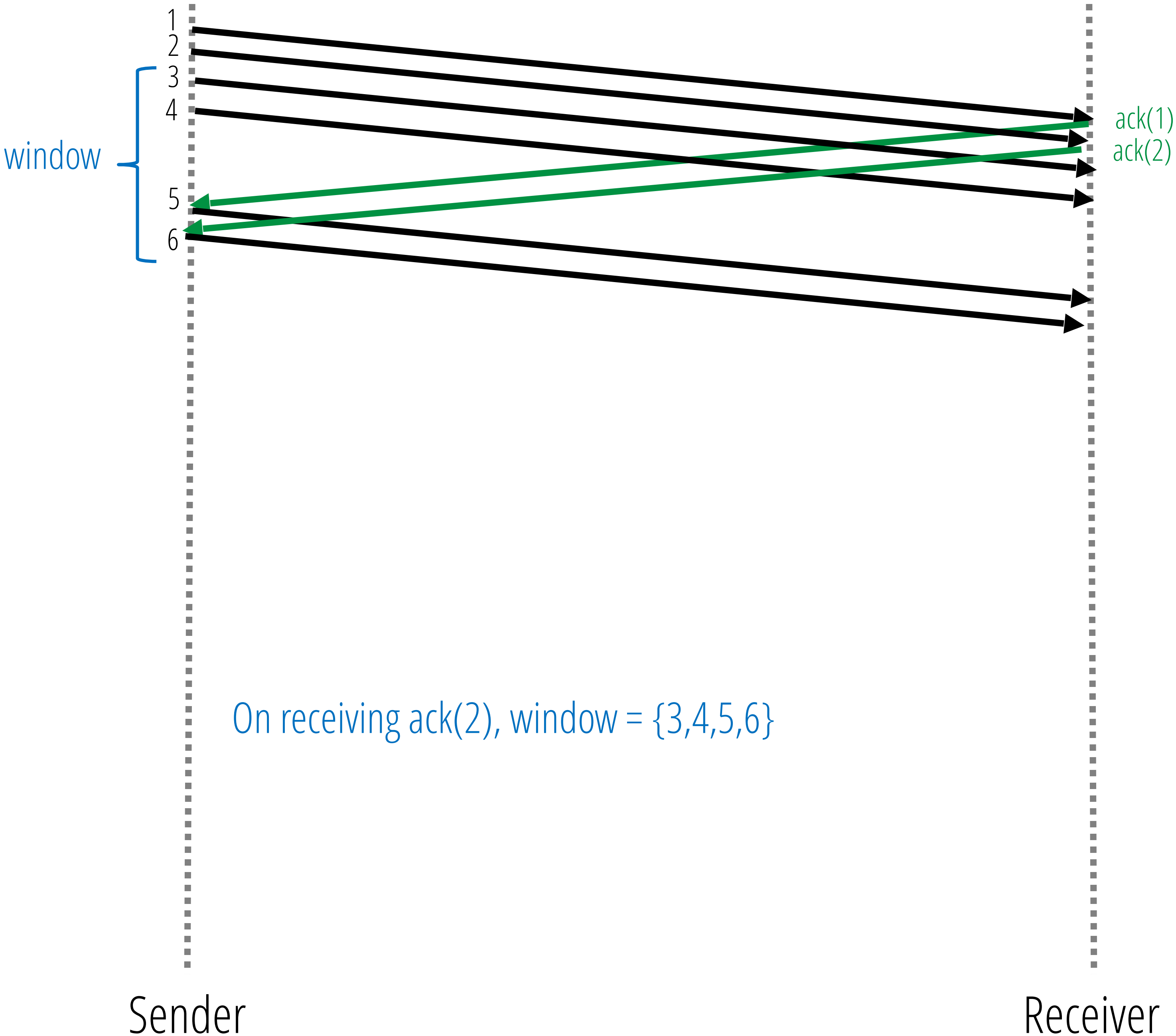
Start with window = {1,2,3,4}

Example with W=4



On receiving ack(1), window = {2,3,4,5}

Example with W=4



Reliably sending many packets

- Will need +1 design component: sequence numbers!
- We now have all the *necessary* building blocks

Reliably sending many packets

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- We now have all the *necessary* building blocks
- Plus one more, for **efficiency (performance)**
  - Window

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  - How many in-flight packets do we want?

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How big should the window be?

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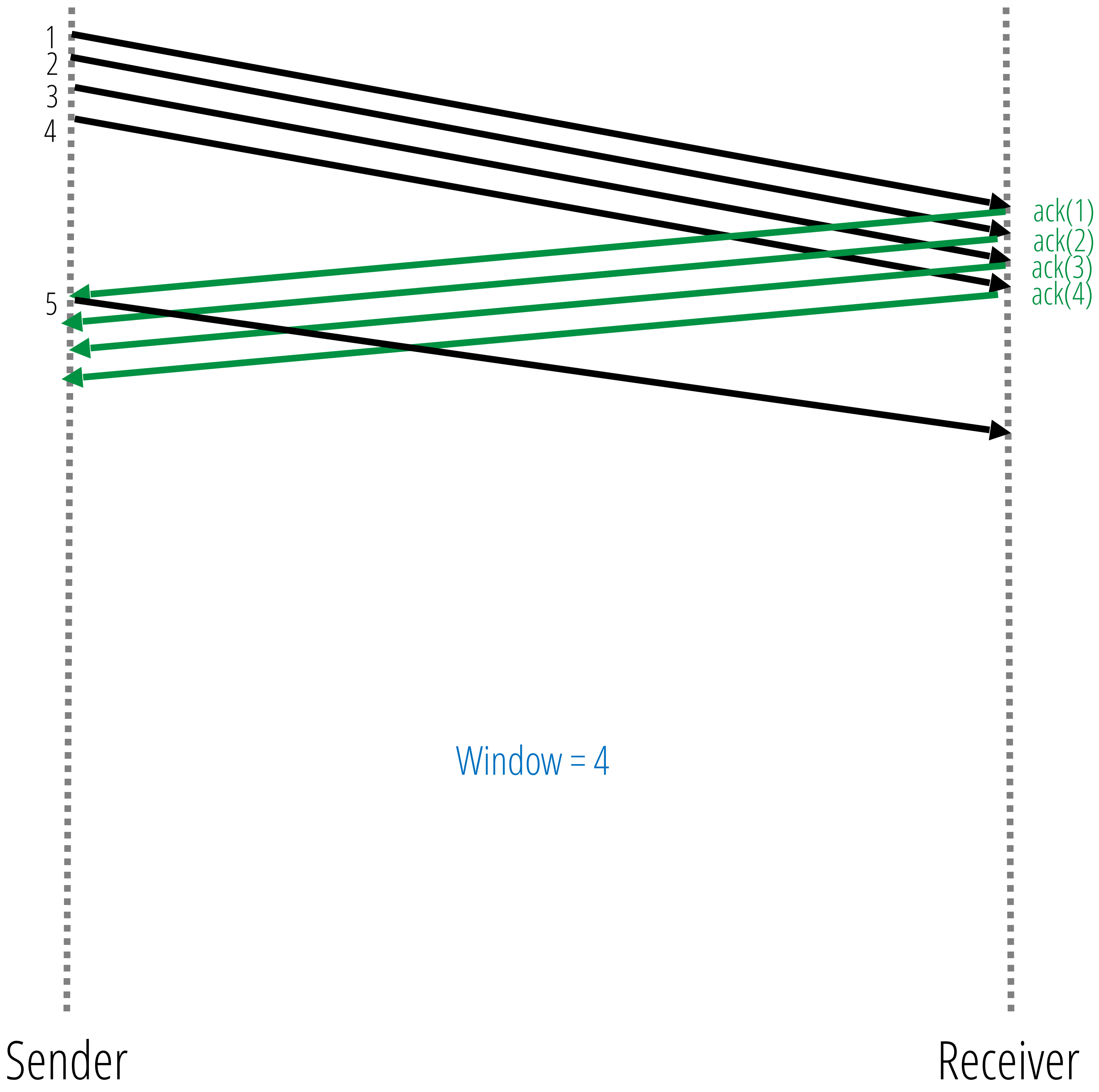
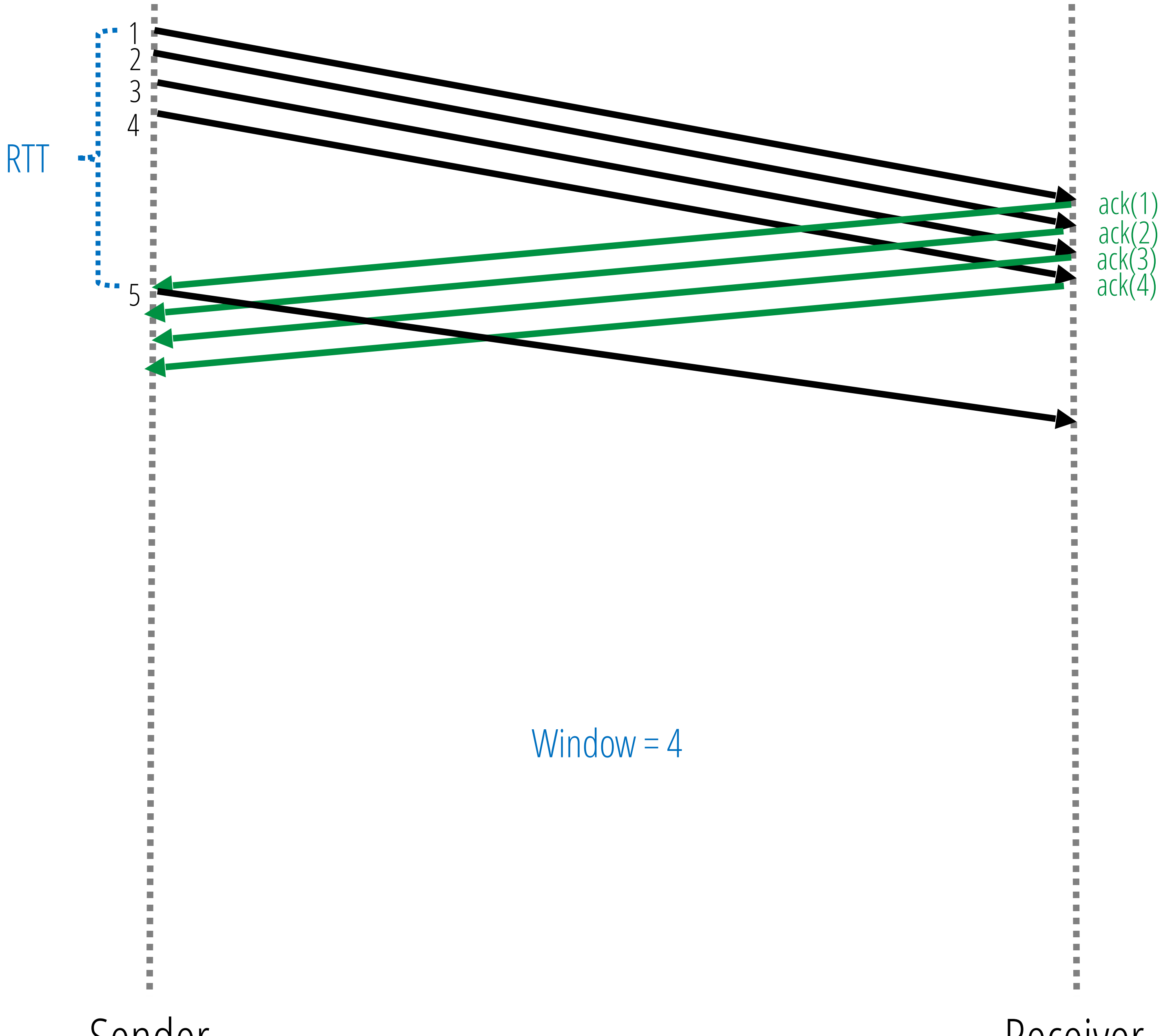
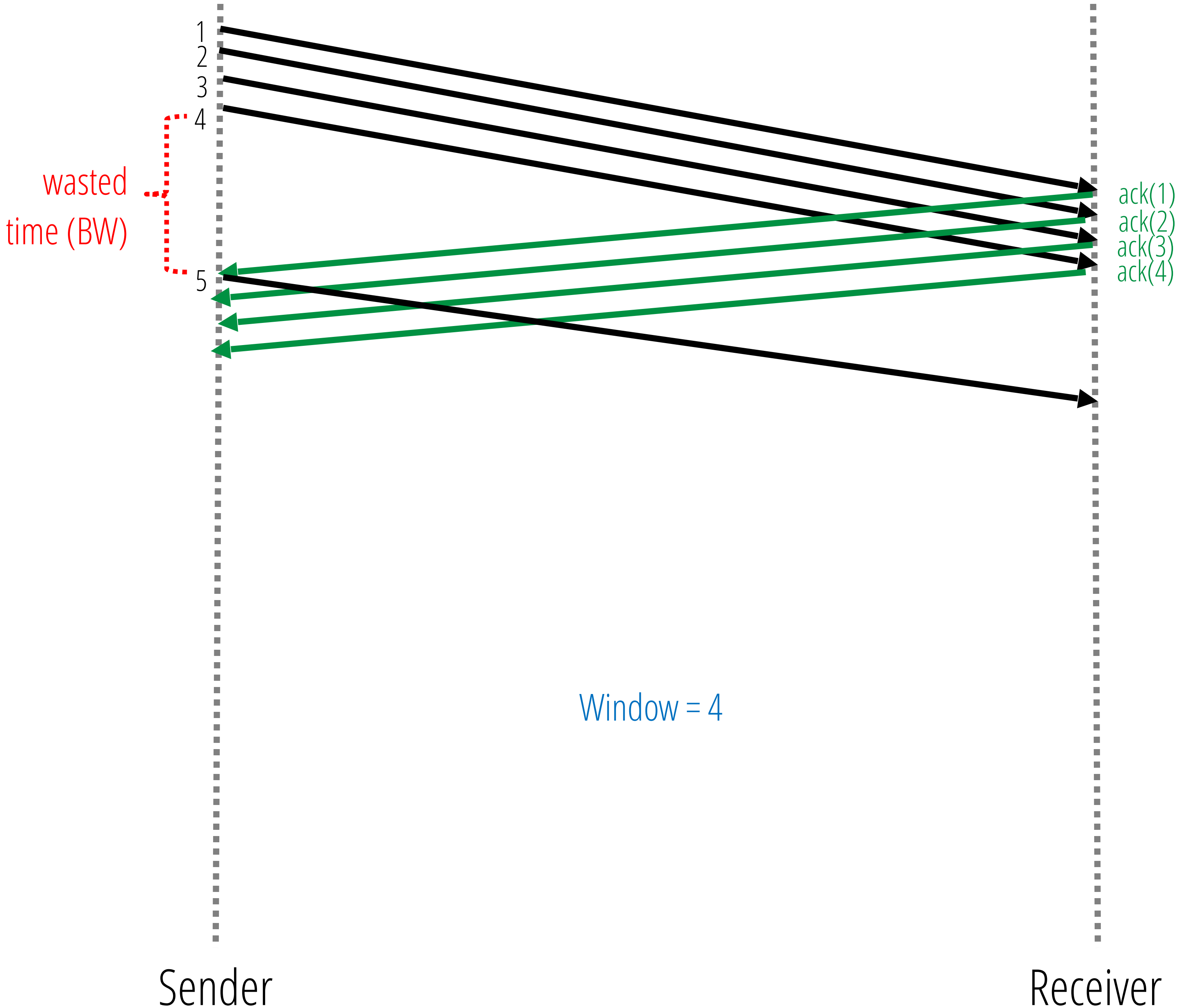
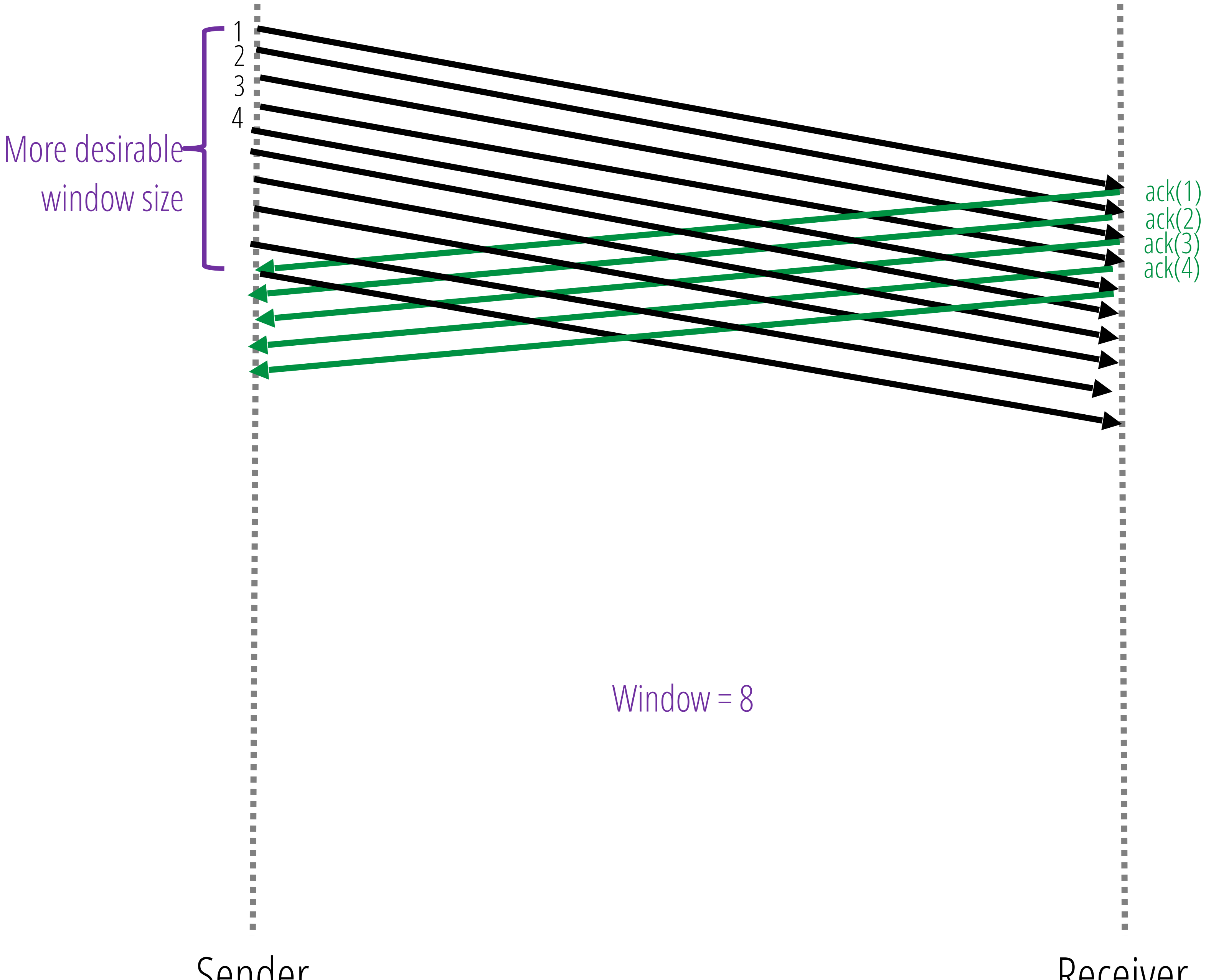
  - And don’t overload the receiver (flow control)

- If we ignore all but the first goal then we want to keep the sender always sending (ideal case)
  - W should allow sender to transmit for entire RTT
    - From sending first packet until receive first ACK


1
2
3
4
ack(1)
ack(2)
ack(3)
ack(4)
5
Window = 4
Sender
Receiver


1
2
3
4
RTT
5
ack(1)
ack(2)
ack(3)
ack(4)
Window = 4
Sender
Receiver


1
2
3
4
wasted
time (BW)
5
ack(1)
ack(2)
ack(3)
ack(4)
Window = 4
Sender
Receiver


More desirable window size
1
2
3
4
ack(1)
ack(2)
ack(3)
ack(4)
Window = 8
Sender
Receiver

What Does This Mean?

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- Let B be the minimum (“bottleneck”) link bandwidth along the path
  - Obviously shouldn’t send faster than that
  - Don’t want to send slower than that (for first goal)

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  - I.e., ACK for the first packet arrives at the sender, just as the last of W packets leaves

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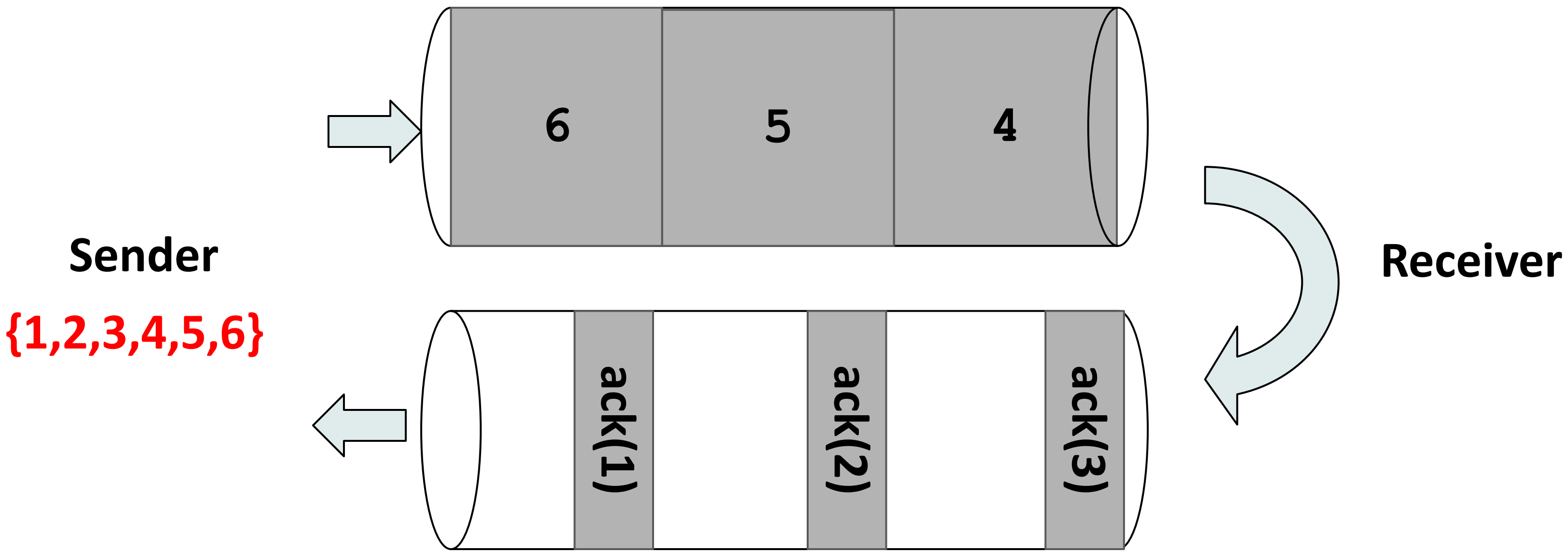
  - Obviously shouldn’t send faster than that
  - Don’t want to send slower than that (for first goal)
- Want the sender to send at rate B for the duration of RTT
  - I.e., ACK for the first packet arrives at the sender, just as the last of W packets leaves
- Hence, condition: W x Packet-Size ~ RTT x B
  - E.g., for a path with RTT=1 second and bottleneck B = 8 Mbits/second, if packet size = 100 Bytes, we want a window size W = 10,000 packets

Setting W to be one RTT of packets



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- Nature of feedback
  - Can we do better than ACKing one packet at a time?
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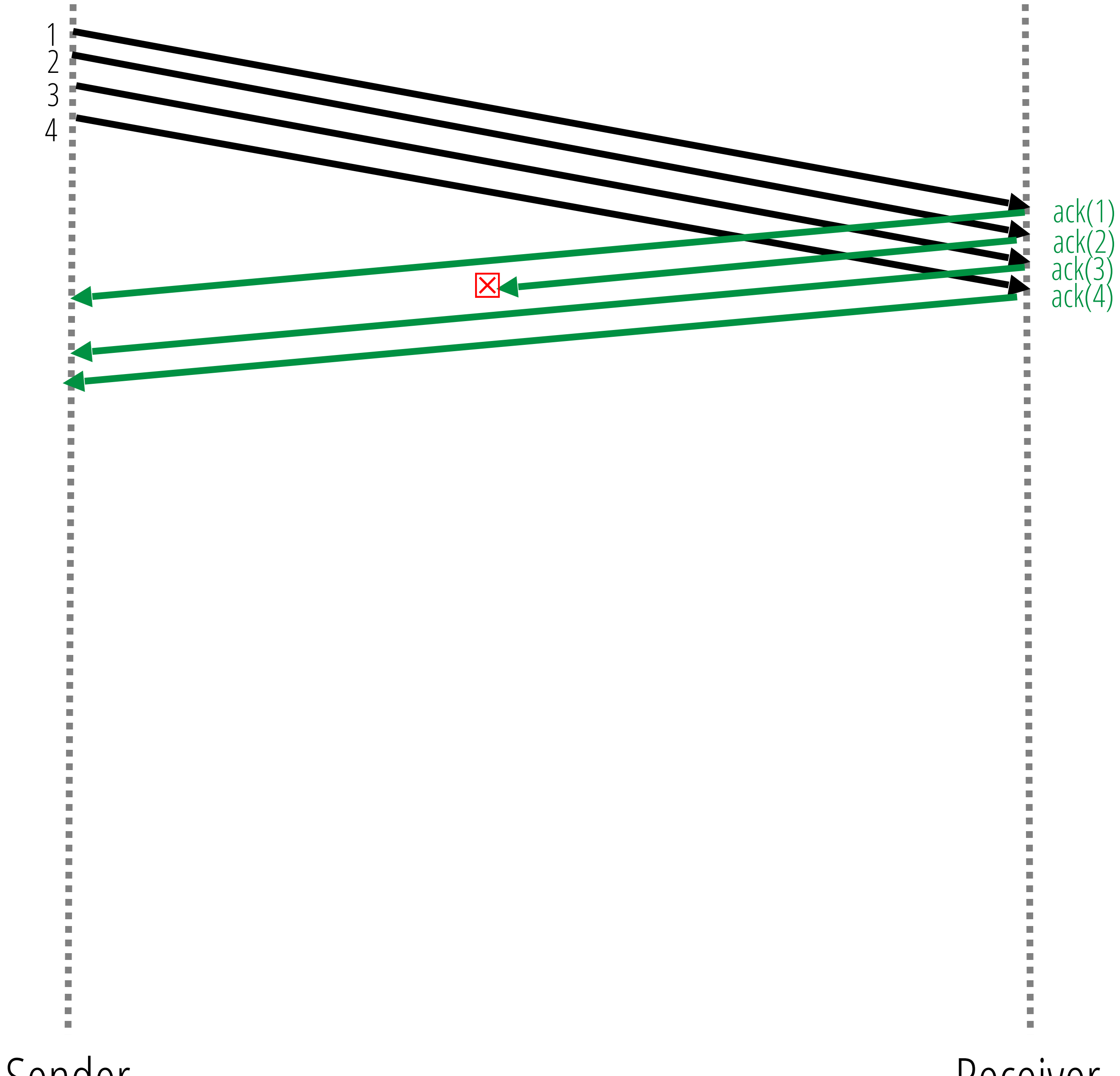
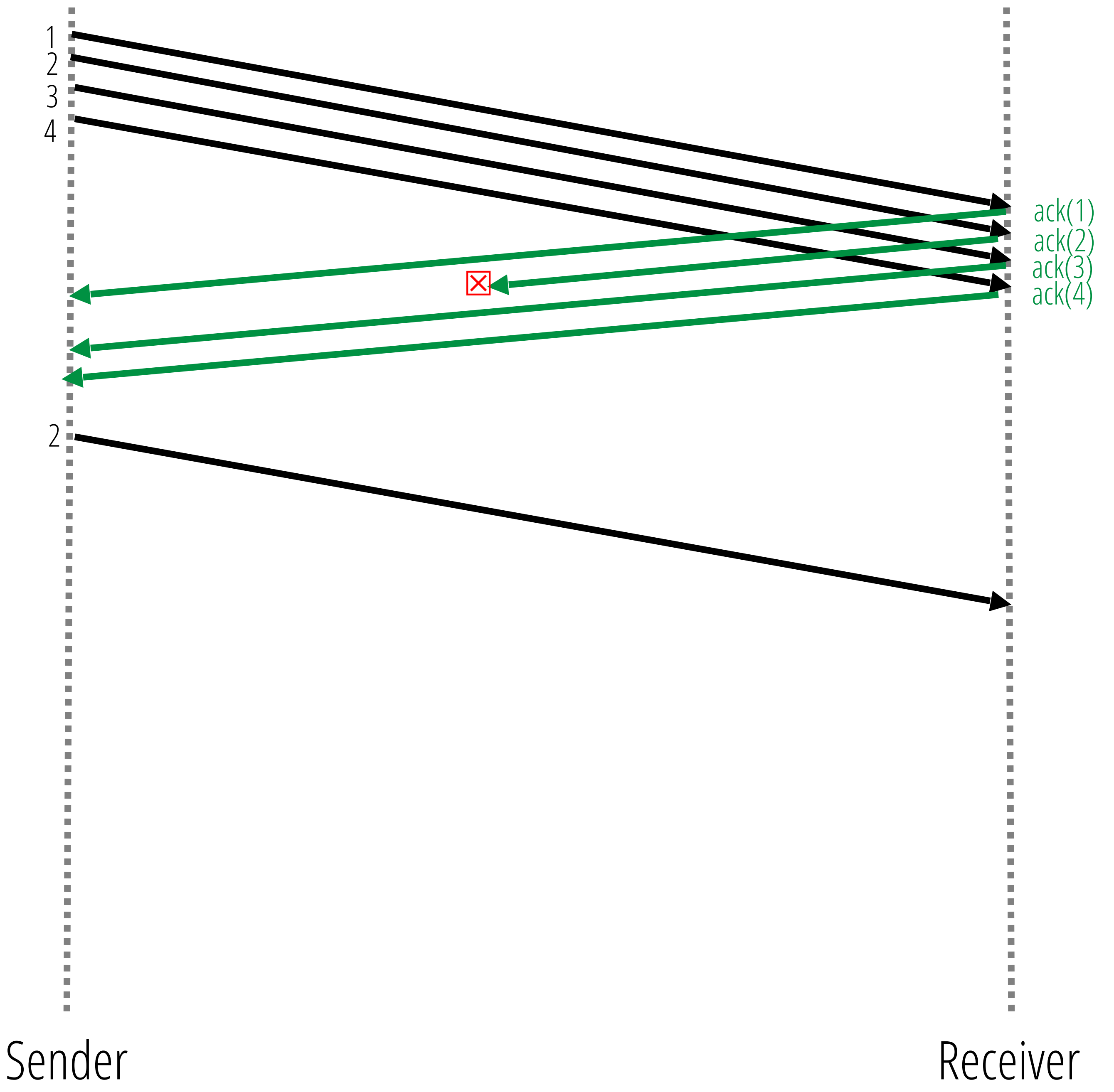
  - Can we do better than waiting for timeouts?
- Response to loss
  - Which packet should sender resend?

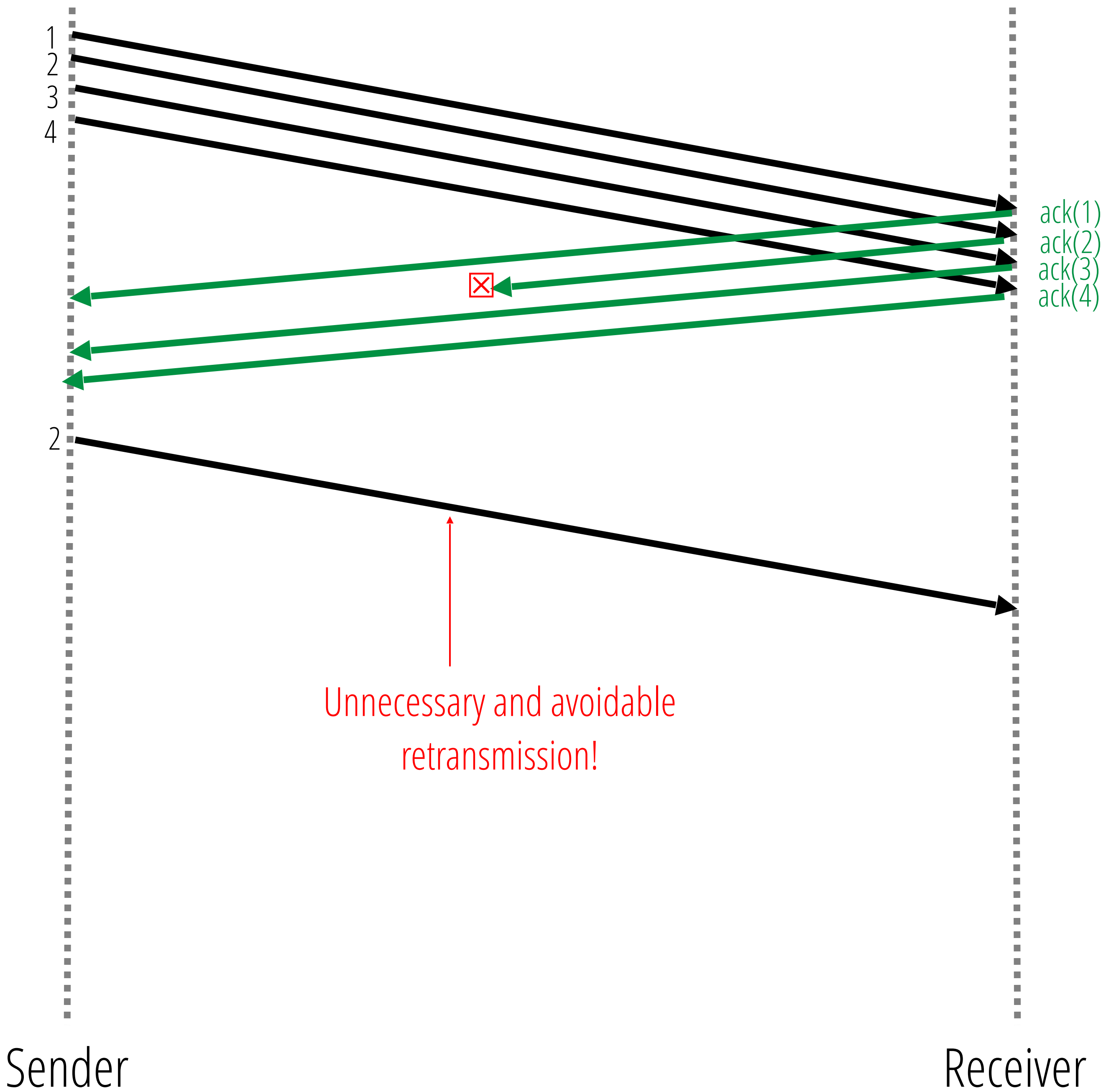
ACKs: design options

- **Individual packet ACKs (our design so far)**
  - On receiving packet i, send ack(i)


1
2
3
4
ack(1)
ack(2)
ack(3)
ack(4)
Sender
Receiver



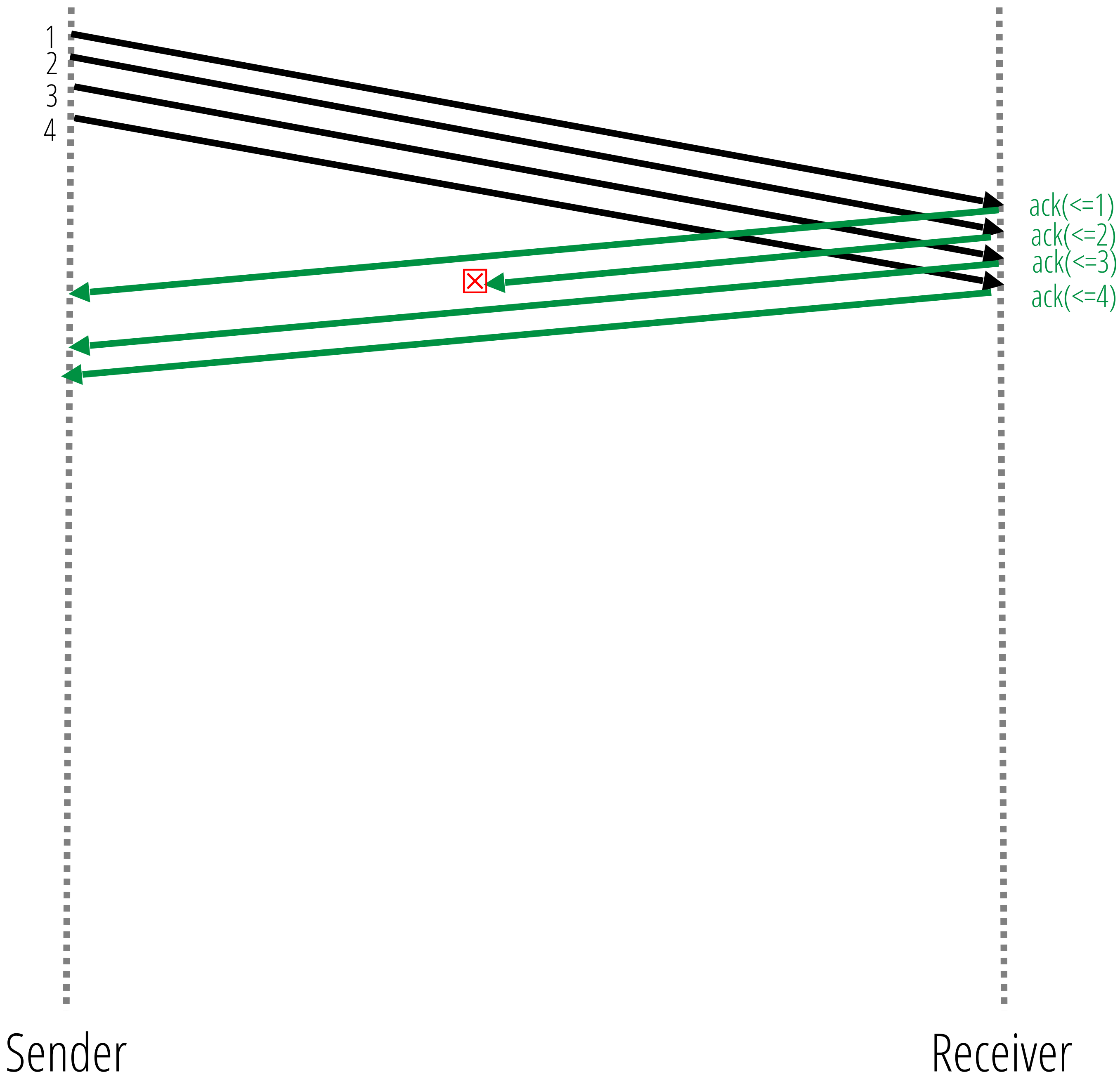
1
2
3
4
ack(1)
ack(2)
ack(3)
ack(4)
2
Sender
Receiver

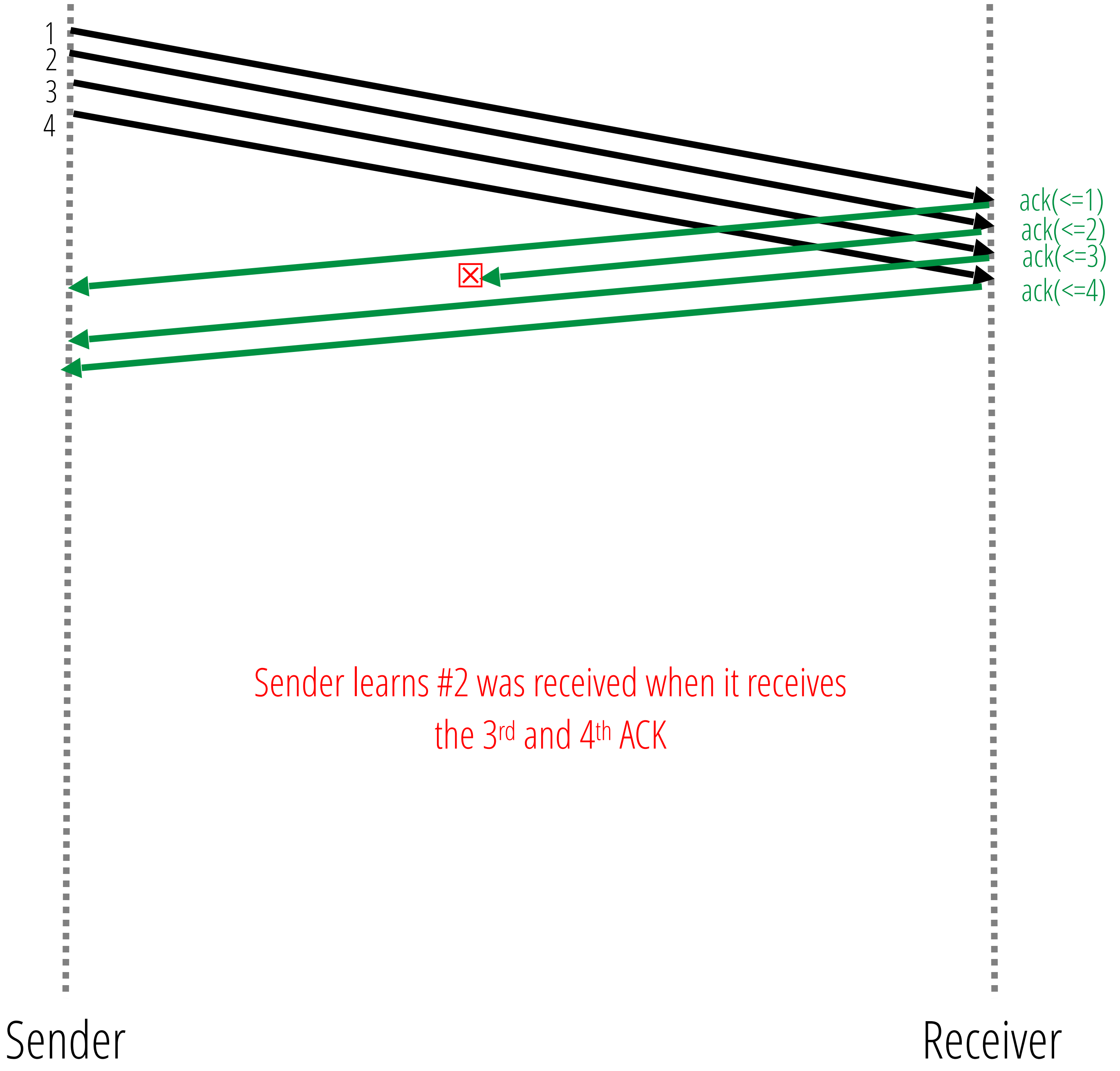


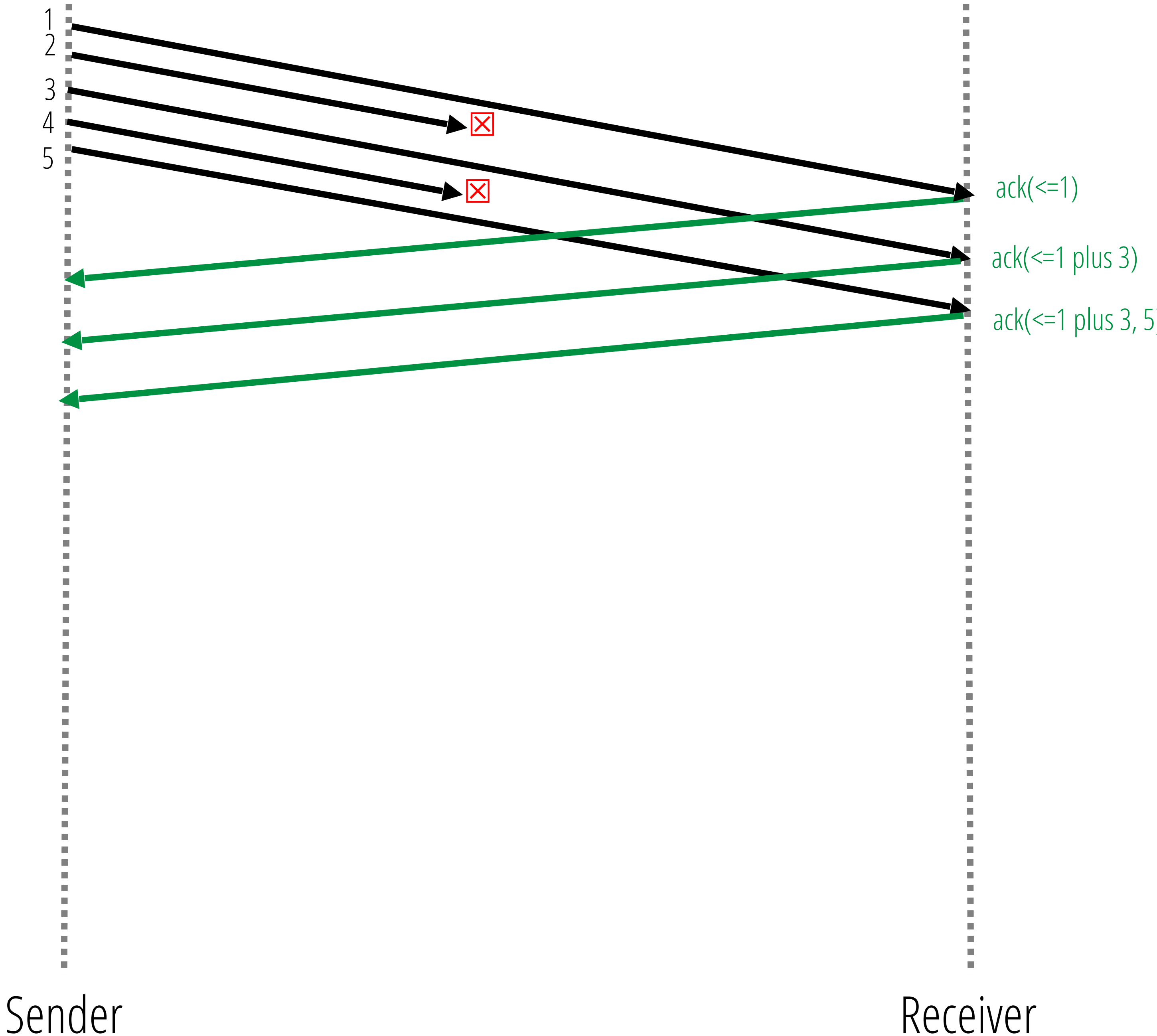
1
2
3
4
ack(1)
ack(2)
ack(3)
ack(4)
2
Unnecessary and avoidable
retransmission!
Sender
Receiver

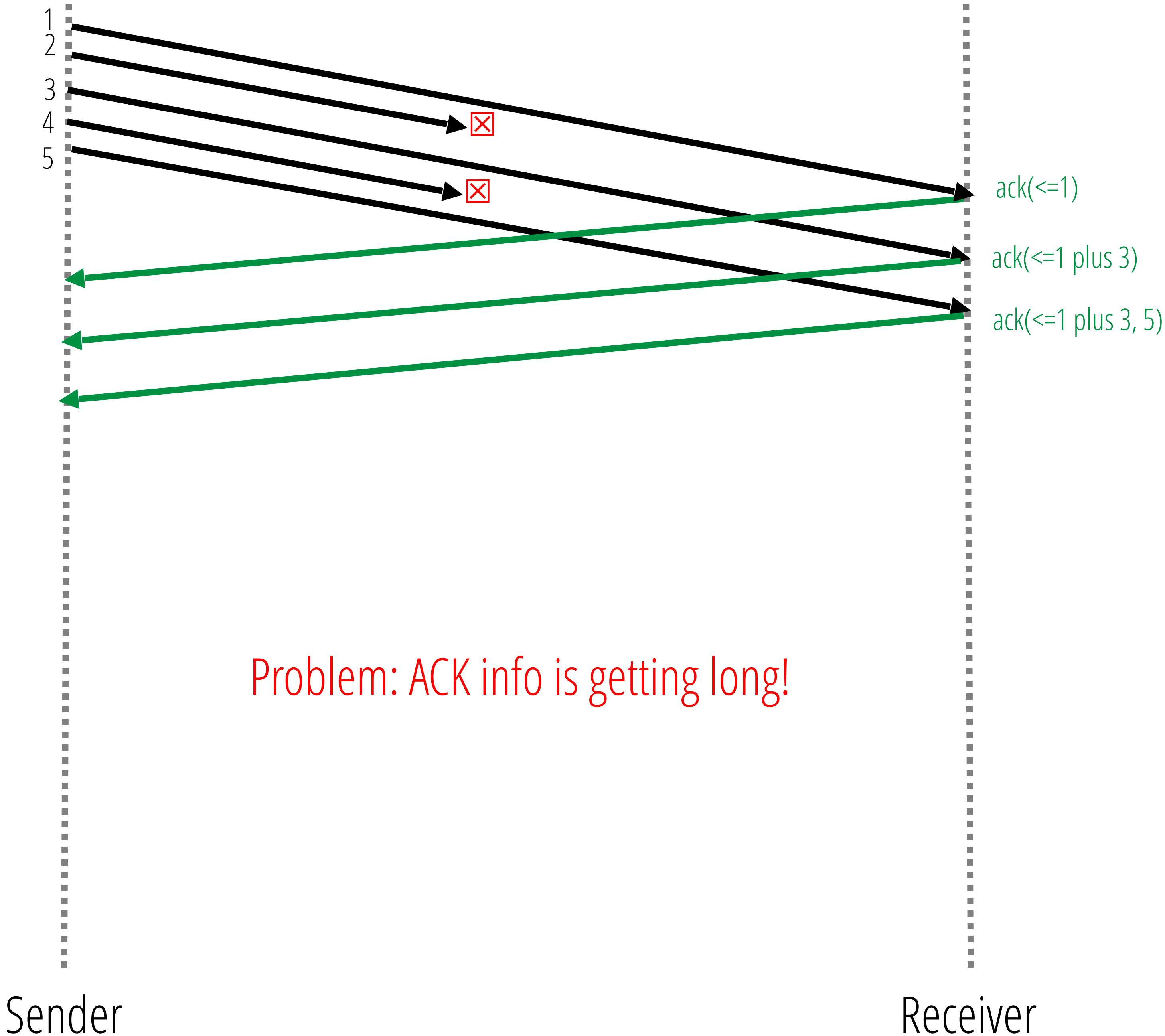
ACKs: design options

- **Individual packet ACKs (our design so far)**
  - On receiving packet i, send ack(i)
- **Full Information ACKs**
  - Give highest cumulative ACK plus any additional packets received (“*everything up to #12 and #14, #15*”)


1
2
3
4
ack(<=1)
ack(<=2)
ack(<=3)
ack(<=4)
Sender
Receiver


1
2
3
4
ack(<=1)
ack(<=2)
ack(<=3)
ack(<=4)
Sender learns #2 was received when it receives the 3rd and 4th ACK
Sender
Receiver


1
2
3
4
5
ack(<=1)
ack(<=1 plus 3)
ack(<=1 plus 3, 5)
Sender
Receiver



Problem: ACK info is getting long!

ACKs: design options

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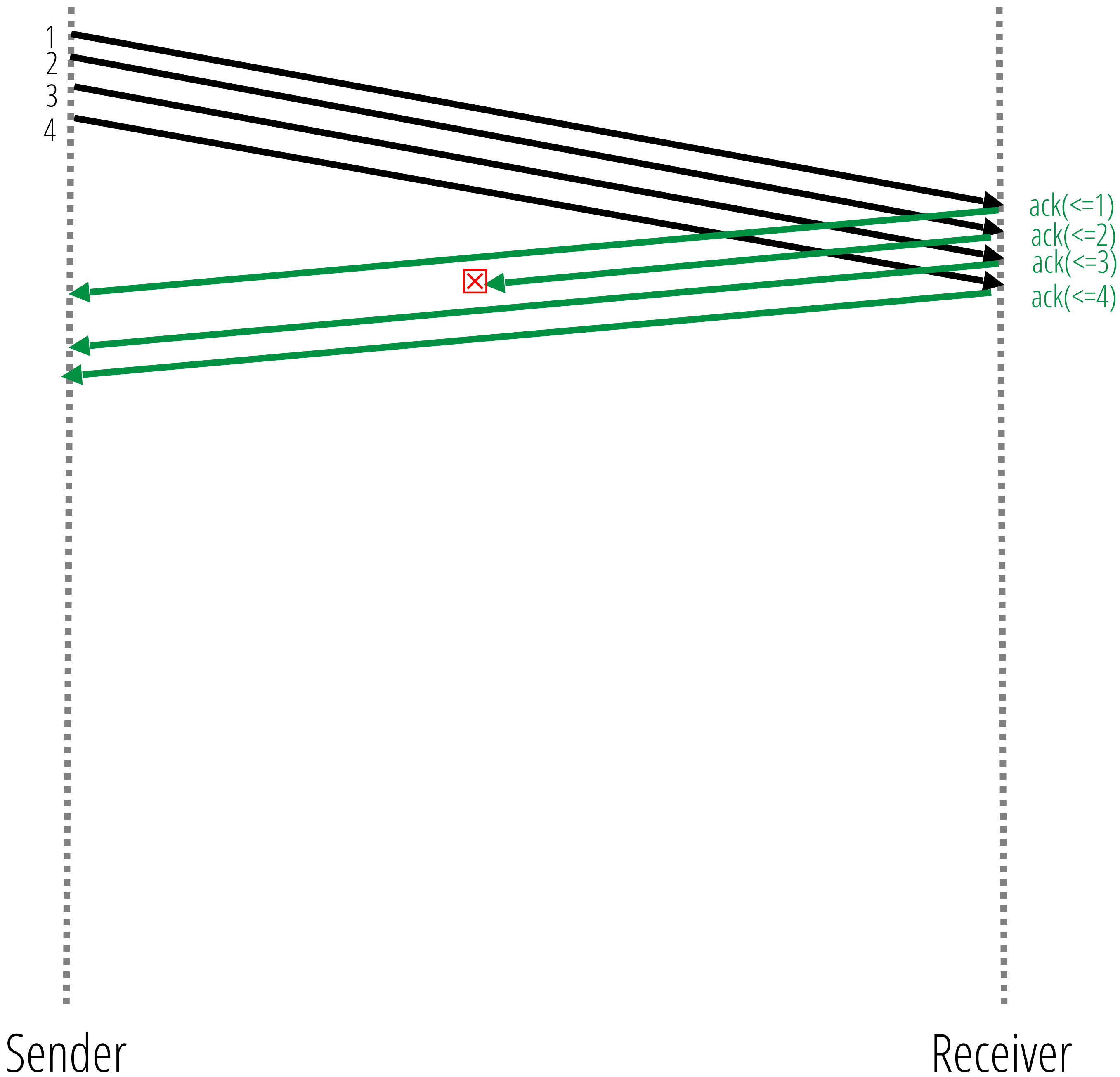
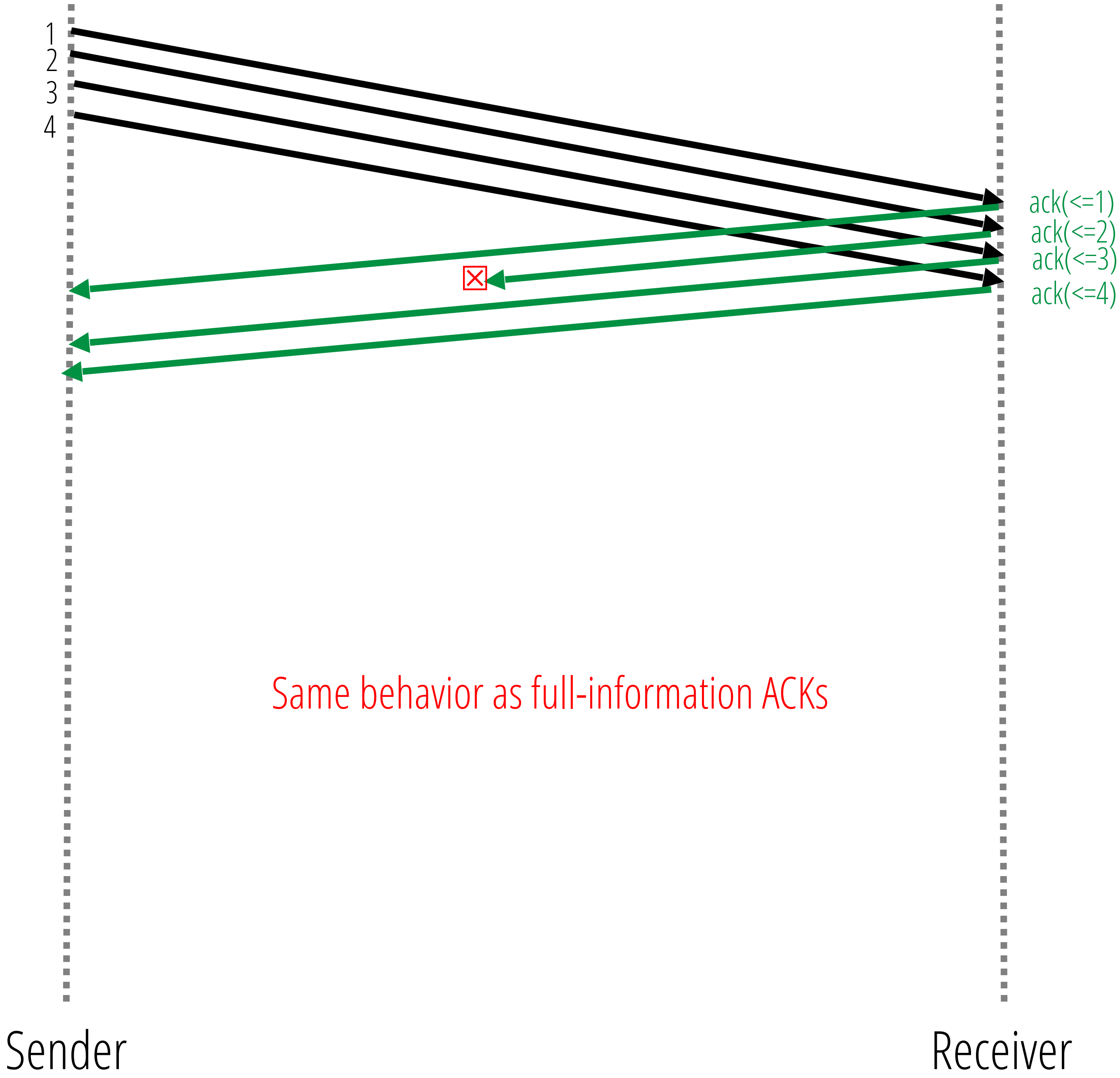
  - On receiving packet i, send ack(i)

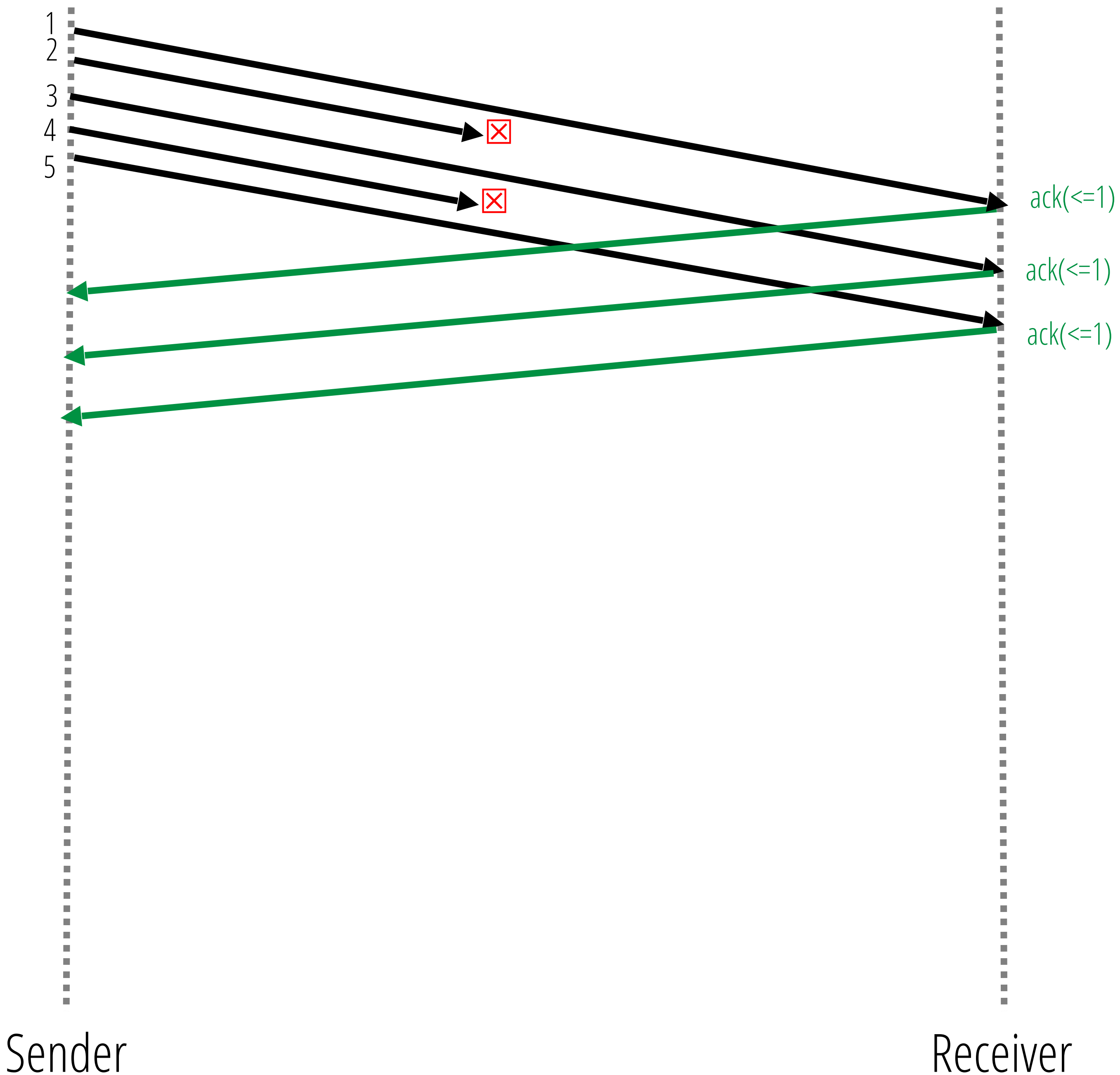
- **Full Information ACKs**
  - Give highest cumulative ACK plus any additional packets received ("*everything up to #12 and #14, #15*")

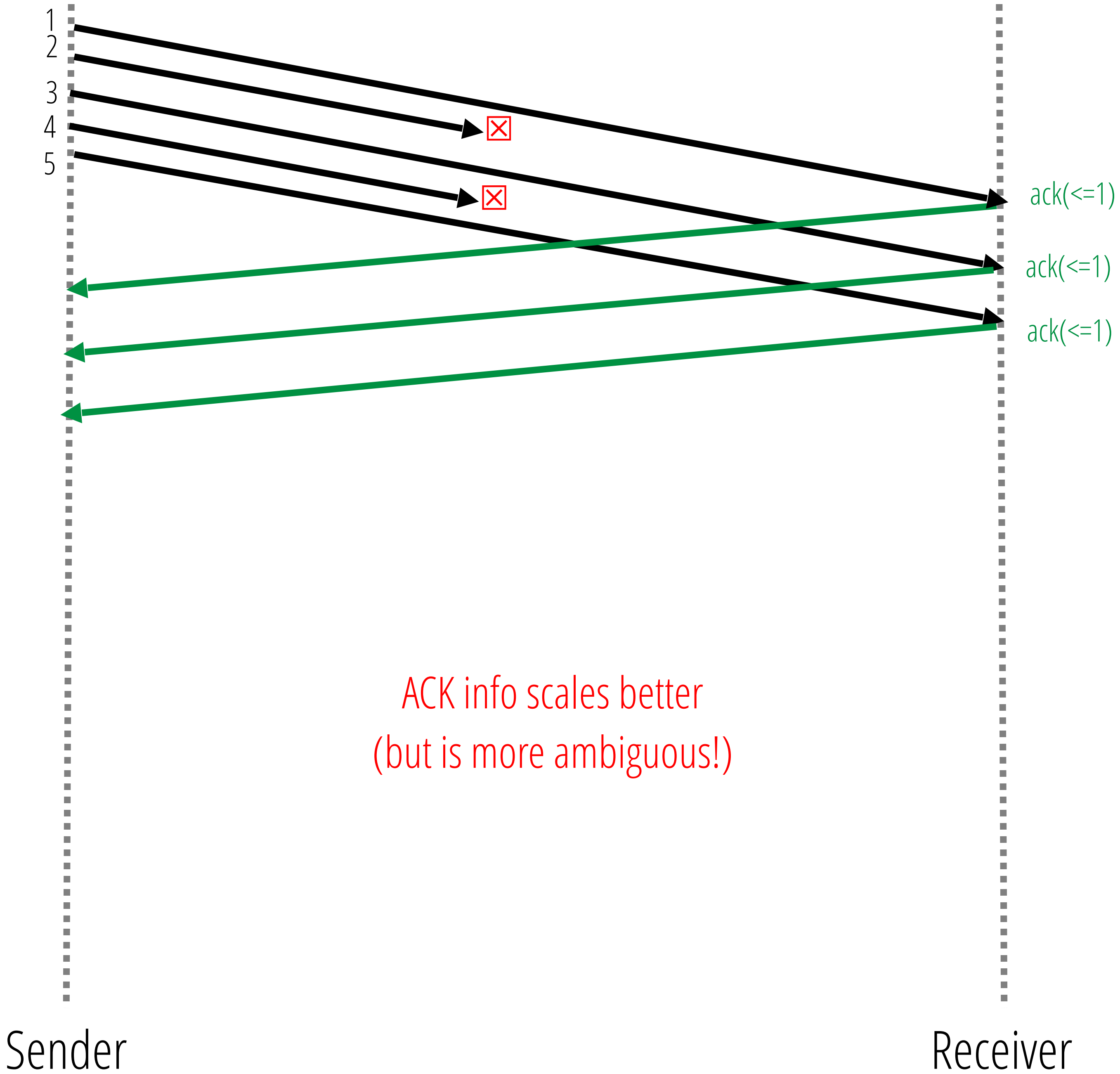
- **Cumulative ACKs**
  - ACK the highest sequence number for which all previous packets have been received


1
2
3
4
ack(<=1)
ack(<=2)
ack(<=3)
ack(<=4)
Sender
Receiver



Same behavior as full-information ACKs


1
2
3
4
5
ack(<=1)
ack(<=1)
ack(<=1)
Sender
Receiver



ACK info scales better
(but is more ambiguous!)

Recap: ACK tradeoffs

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- **Individual**
  - Pro: compact; simple
  - Con: loss of ACK packet *always* requires a retransmission

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Recap: ACK tradeoffs

- **Individual**
  - Pro: compact; simple
  - Con: loss of ACK packet *always* requires a retransmission
- **Full Information**
  - Pro: complete info on data packets; more resilient to ACK loss
  - Con: Could require sizable overhead in bad cases
- **Cumulative**
  - Pro: compact; more resilient to ACK loss (vs. individual ACKs)
  - Con: Incomplete info on which data packets arrived

New Design Considerations

- Window size
  - How many in-flight packets do we want?
- Nature of feedback
  - Can we do better than ACKing one packet at a time?
- Detection of loss
  - Can we do better than waiting for timeouts?
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Detecting Loss

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- If packet times out, assume it is lost...

- How else can you detect loss?

Detecting Loss

- If packet times out, assume it is lost...
- How else can you detect loss?
- When ACKs for k “subsequent packets” arrive
  - E.g., only packet 5 is lost, will receive ACKs for 6, 7, ...
  - E.g., if k=3, retransmit 5 after we receive ACKs for 6, 7, 8
  - Details look a little different for each ACK option (next slides)

Loss with individual ACKs

- Assume packet 5 is lost, but no others

Loss with individual ACKs

- Assume packet 5 is lost, but no others

- Stream of ACKs will be:
  - 1
  - 2
  - 3
  - 4
  - 6
  - 7
  - 8
  - ….

Loss with individual ACKs

- Assume packet 5 is lost, but no others

- Stream of ACKs will be:
  - 1
  - 2
  - 3
  - 4
  - 6
  - 7
  - 8
  - ….

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Declare packet 5 lost! (Because received k=3 subsequent ACKs)

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  - Up to 3
  - Up to 4
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  - Up to 4, plus 6,7
  - Up to 4, plus 6,7,8

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Duplicate ACKs
(dupACKs)

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Duplicate ACKs (dupACKs)

Packet 5 lost! (Received k=3 dupACKs)

New Design Considerations

- Window size
  - How many in-flight packets do we want?
- Nature of feedback
  - Can we do better than ACKing one packet at a time?
- Detection of loss
  - Can we do better than waiting for timeouts?
- Response to loss
  - Which packet should sender resend?

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- On timeout, always retransmit corresponding packet

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- What about when our ACK-based rule fires?
  - Retransmit unACKed packet, but which one?
  - Decision is clear with individual and full-info ACKs
  - Decision is clear with cumulative ACKs and a single packet loss
  - But can be ambiguous with cumulative ACKs and multiple losses

Response with individual ACKs

- Consider a sender with a window size = 6 & k=3
  - Packets 1,2 have been ACKed
  - 3-8 are “in flight”

1 2 3 4 5 6 7 8

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Response with individual ACKs

- Consider a sender with a window size = 6 & k=3
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1 2 3 4 5 6 7 8 9

- ACK 4 arrives → send 9

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- ACK 6 arrives

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- ACK 4 arrives → send 9
- ACK 6 arrives → send 10
- ACK 7 arrives (3rd ACK for subsequent packet)

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- ACK 4 arrives → send 9
- ACK 6 arrives → send 10
- ACK 7 arrives → **resend 3**, send 11
- ACK 8 arrives → **resend 5**, send 12
- ACK 9 arrives → send 13, and so on...

Response with full-info ACKs

- Similar behavior as with Individual ACKs

Response with cumulative ACKs

- Consider a sender with a window size = 6 & k=3
  - Packets 1,2 have been ACKed
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Response with cumulative ACKs

- Consider a sender with a window size = 6 & k=3
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- (for packet 4) ACK 2

Response with cumulative ACKs

- Consider a sender with a window size = 6 & k=3
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  - 3-8 are "in flight"

1 2 3 4 5 6 7 8

#duplicate ACKs = 1

- (for packet 4) ACK 2

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- Consider a sender with a window size = 6 & k=3
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Response with cumulative ACKs

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#duplicate ACKs = 2

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Response with cumulative ACKs

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Response with cumulative ACKs

- Consider a sender with a window size = 6 & k=3
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1 2 3 4 5 6 7 8 9 10

#duplicate ACKs = 3

- (for packet 4) ACK 2 → send 9
- (for packet 6) ACK 2 → send 10
- (for packet 7) ACK 2

Response with cumulative ACKs

- Consider a sender with a window size = 6 & k=3
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Response with cumulative ACKs

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1 2 3 4 5 6 7 8 9 10 11 12...

#duplicate ACKs = 4+

- (for packet 4) ACK 2 → send 9
- (for packet 6) ACK 2 → send 10
- (for packet 7) ACK 2 → resend 3, send 11
- (for packet 8,9,10) ACK 2 → unclear what packet to resend!

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- But not *which ones* to (re)send
  - Ambiguity leads to ad-hoc heuristics

- Unfortunately, TCP uses cumulative ACKs...

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  - ACK/NACKs
  - Timeouts
  - Retransmissions
  - Sequence numbers
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- And discussed tradeoffs in how to apply them
  - Individual vs. Full vs. Cumulative ACKs
  - Timeout vs. ACK-driven loss detection

From design options to design

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- Can put together a variety of reliability protocols from our building blocks!
  - We saw one already: Stop-and-Wait
  - Another possibility: “Go-Back-N” (in section)
  - TCP implements yet another (next lecture)

From design options to design

- Can put together a variety of reliability protocols from our building blocks!
  - We saw one already: Stop-and-Wait
  - Another possibility: “Go-Back-N” (in section)
  - TCP implements yet another (next lecture)

- More important that you know how to design and evaluate a reliability protocol, than that you memorize the details of any one implementation!

Preview: what does TCP do?

- Uses most of our building blocks w/ a few diffs.
  - Checksums
  - ACKs (no explicit NACKs)
  - “Sliding” Windows
  - Sequence numbers → measured in byte offsets
  - Cumulative ACKs (and counting dupACKs)
  - Option for a form of full-information ACKs (SACK)
  - Timers (w/ timer estimation algorithm)

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- Sender **encodes** the data to be resilient to loss
    - Basic idea: add some redundancy to data / packet stream
    - E.g., take k packets, encode as n (>k) packets
    - Original packets can be recovered if any k’ of n packets are received (n > k’ > k)
    - Efficiency depends on k’/k

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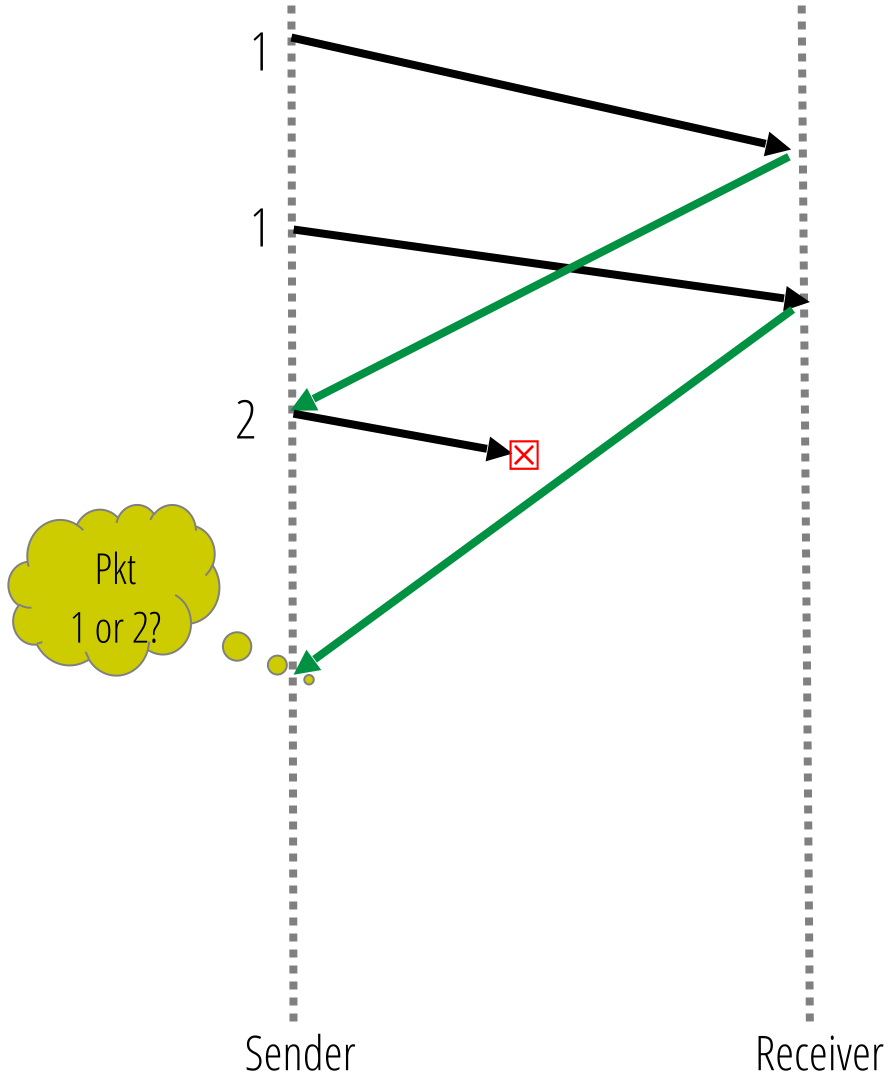
  - Efficiency depends on k'/k
- Vast literature on coding schemes
  - E.g., fountain codes, raptor codes, ...
- Historically not used very much but that could change...

Questions?



Backup#2: We need sequence numbers with stop-and-wait