Wrapping up the IP header
&
Reliability Concepts

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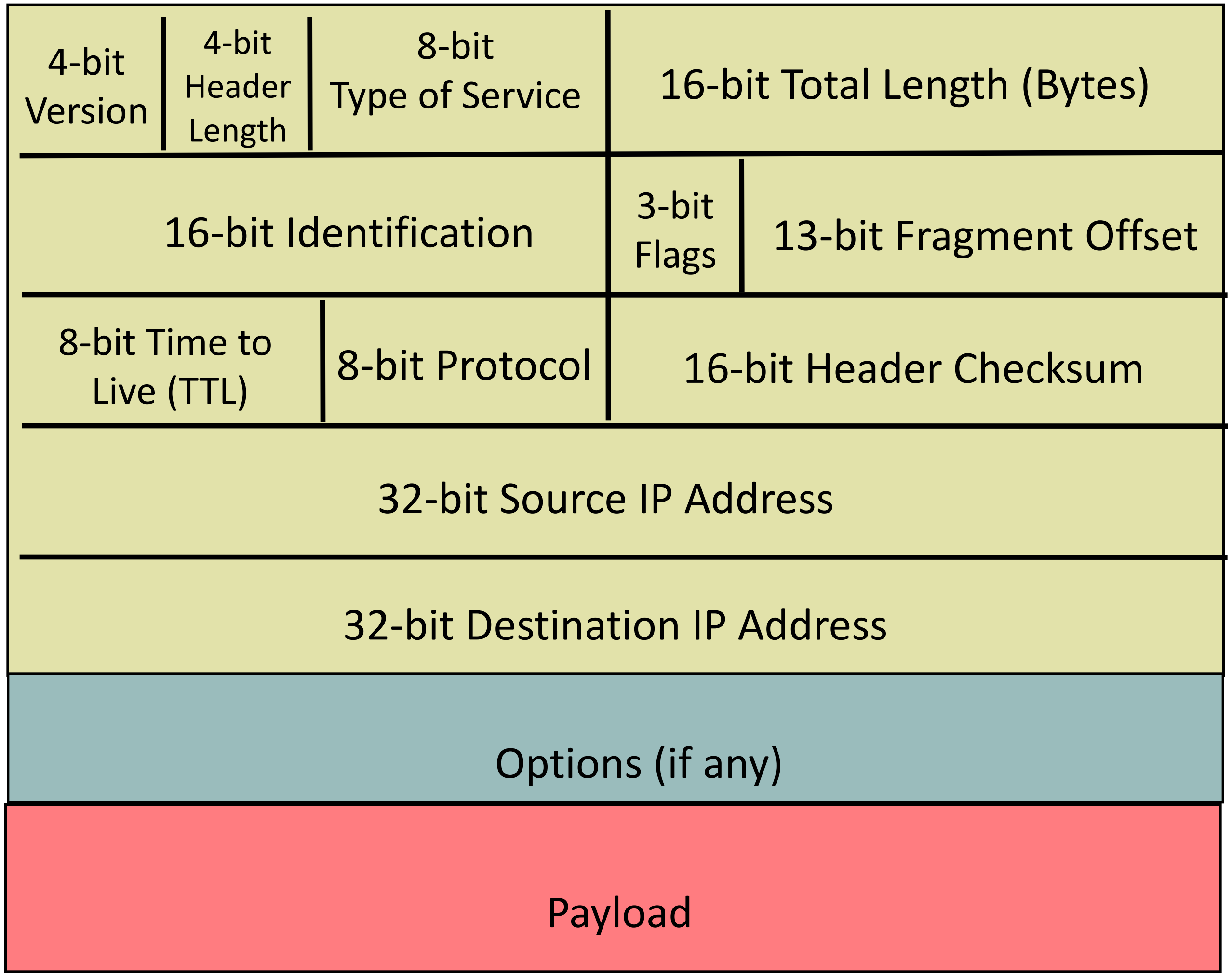
Designing IP: two remaining topics

- IPv4 → IPv6
- Security implications of the IP header

IPv6

- Motivated by address exhaustion
  - 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?

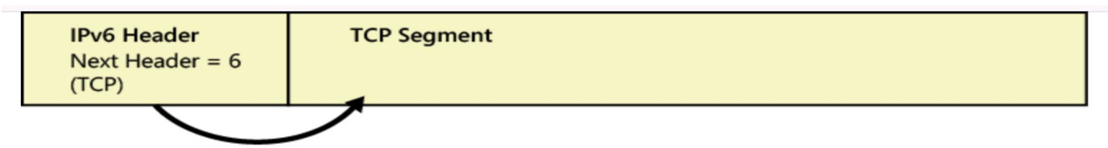


Summary of Changes

- Expanded addresses
- Eliminated checksum
- Eliminated fragmentation
- New options mechanism → “next header”

Options

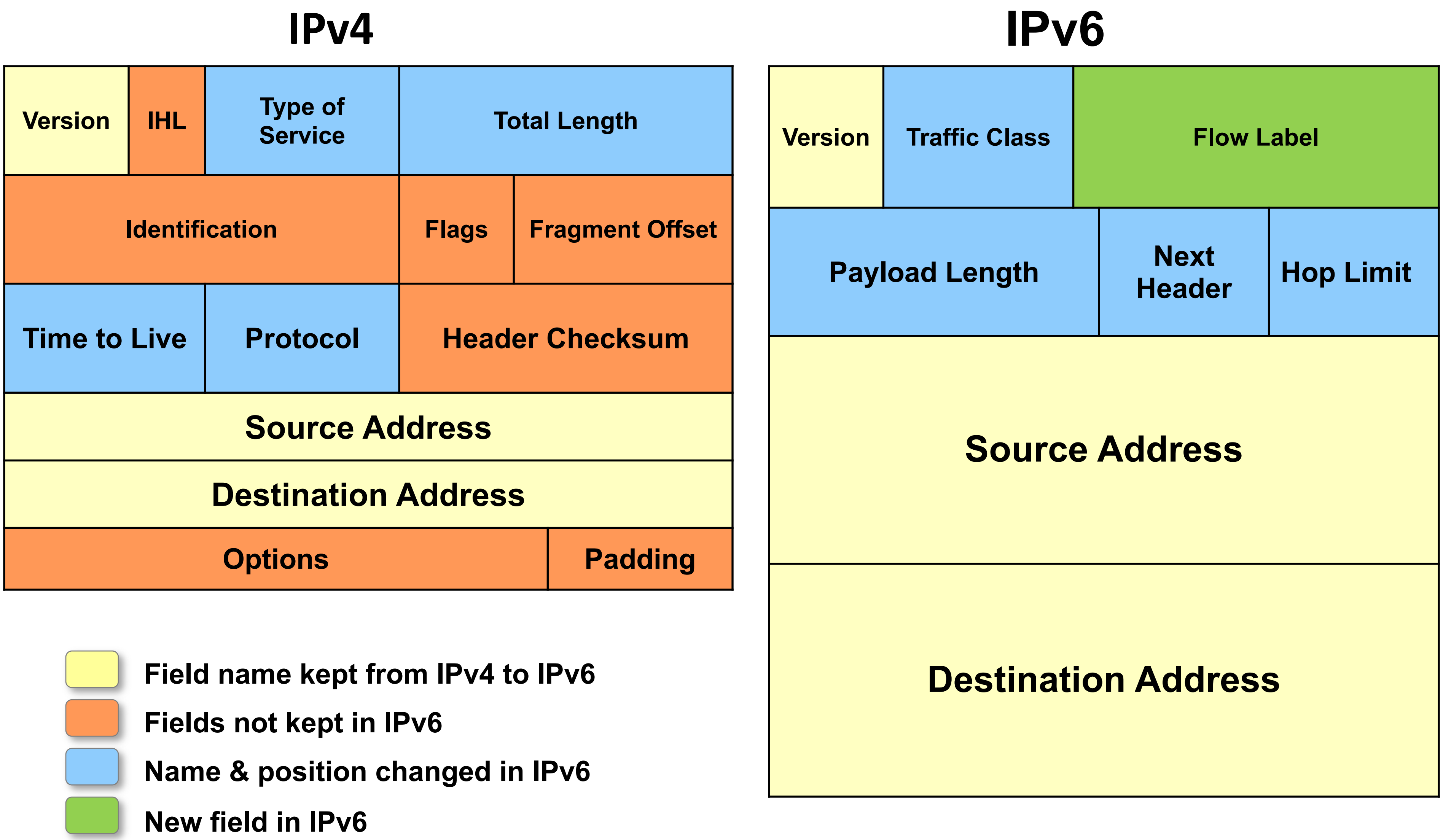
- Recall idea: options specify advanced techniques that the router should implement for this packet
  - Example: “follow this route” (source routing)
- Problem: leads to variable IP header lengths
- IPv6 approach: encode options in a separate header



Summary of Changes

- Expanded addresses
- Eliminated checksum
- Eliminated fragmentation
- New options mechanism → "next header"
- Eliminated header length
- Added Flow Label
  - *Explicit* mechanism to denote related streams of packets

IPv4 and IPv6 Header Comparison



Philosophy of Changes

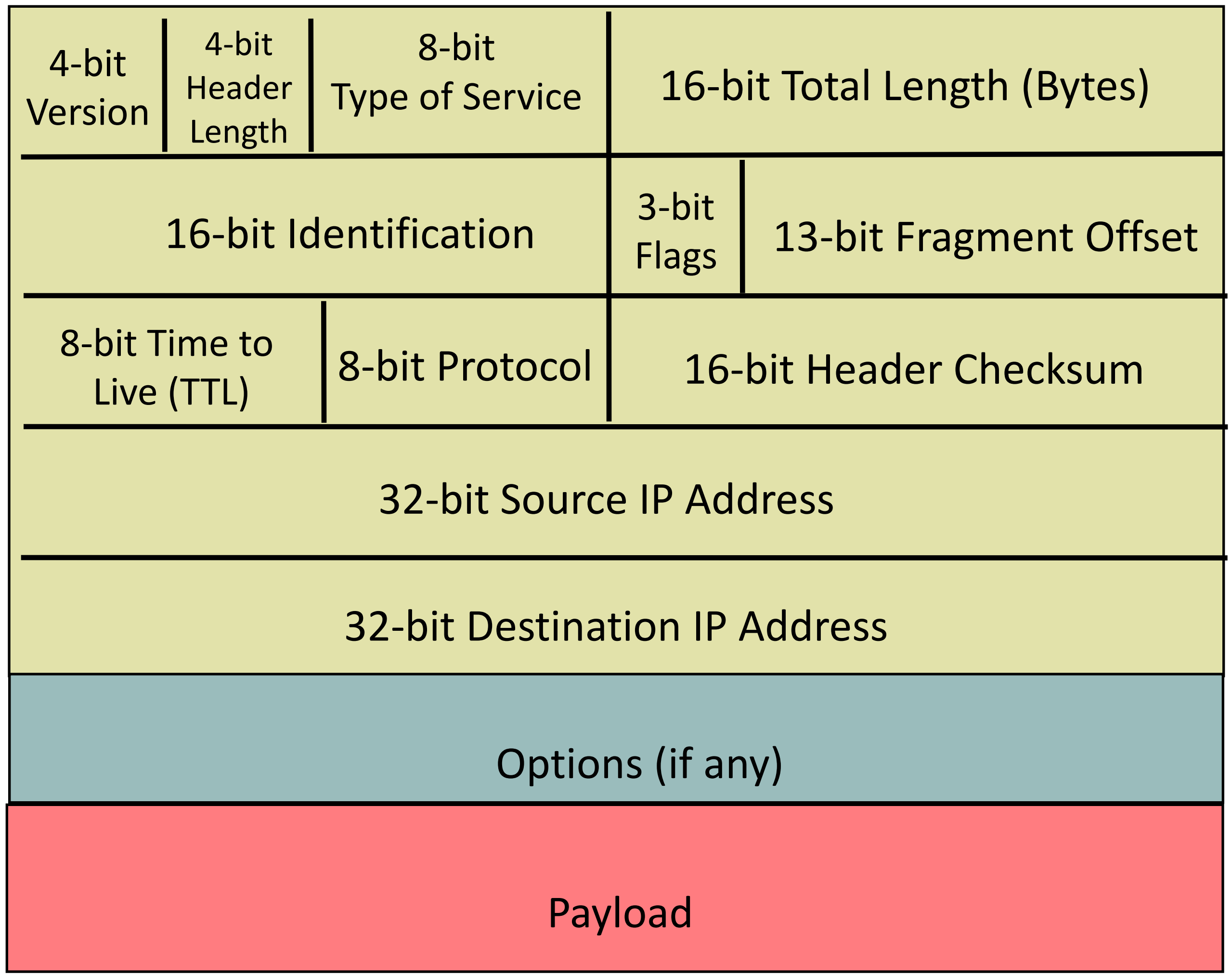
- Don’t deal with problems: leave to ends
  - Eliminated fragmentation
  - Eliminated checksum
  - Why retain TTL?
- Simplify:
  - Got rid of options
  - Got rid of IP header length
- While still allowing extensibility
  - general next-header approach
  - general flow label for packet

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

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

Implications of IP Address Integrity

- Why would someone use a bogus source address?

- Attack the destination
  - Send excessive packets, overload network path to destination
  - But: victim can identify/filter you by the source address
  - Hence, evade detection by putting different source addresses in the packets you send ("spoofing")

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

Security Implications of TOS?

- Attacker sets TOS priority for their traffic?
  - Network *prefers* attack traffic
- What if the network charges for TOS traffic …
  - … and attacker spoofs the victim's source address?
- Today, mostly set/used by operators, not end-hosts

Security Implications of Fragmentation?

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

More Security Implications

- 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

Security Implications of TTL? (8 bits)

- 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

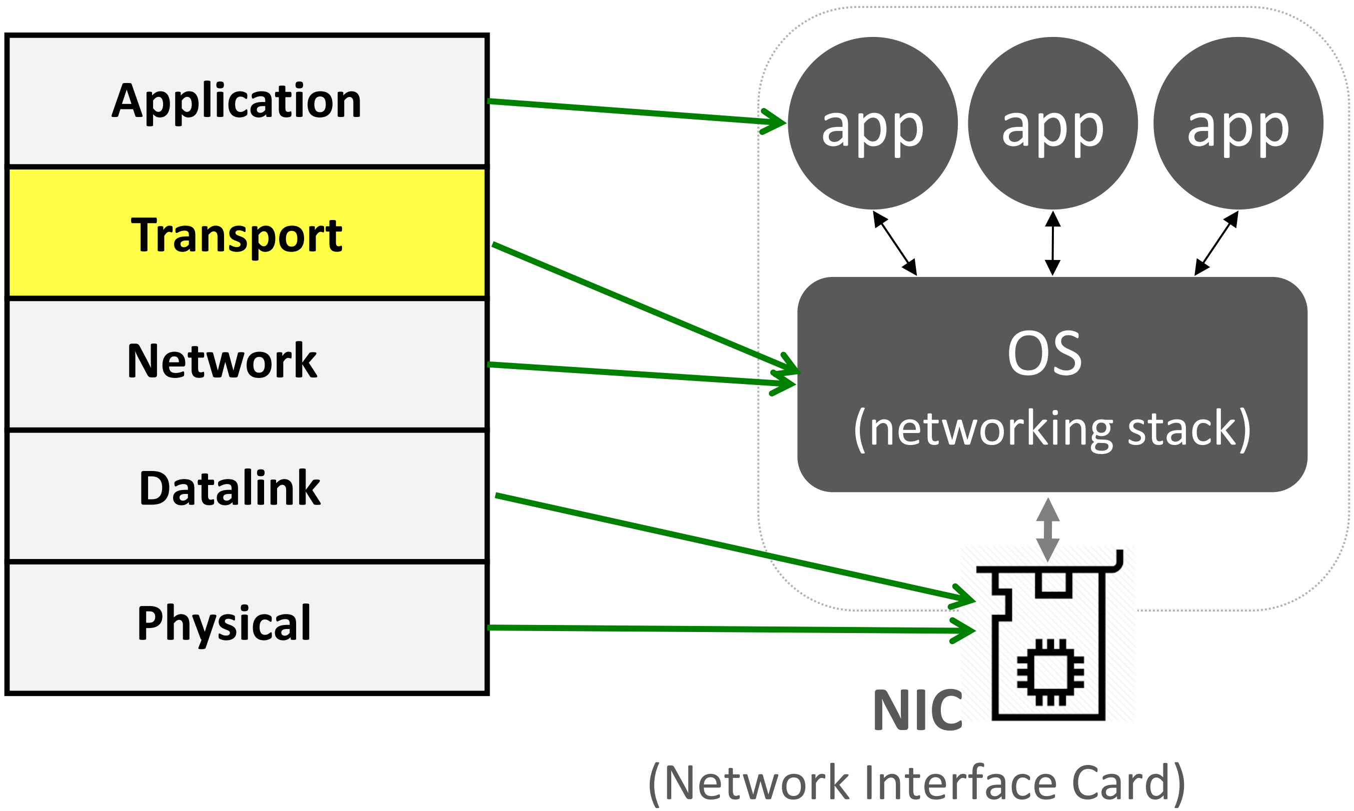
- More nuanced than it first seems!
- Must juggle multiple goals
  - Efficient implementation
  - Security
  - Future needs

Questions?

Next Topic: Transport Layer

(and the design of TCP)

Transport in our layered architecture



Role of Transport Layer

- Bridging the gap between
  - The abstractions application designers want
  - The abstractions networks can easily support
- Having a common implementation simplifies app development

Role of Transport Layer?

- Application layer
  - Communication for specific applications
  - E.g., File Transfer Protocol (FTP), Network Time Protocol (NTP), HyperText Transfer Protocol (HTTP)
- **Transport layer**
  - **What do we need here?**
- Network layer
  - Best-effort global packet delivery
  - IP

What functions does the transport layer implement?

- **Reliability** (today)
- **Demultiplexing** between processes/apps (next lecture)
- **Translate** between packets & app-level abstractions (next lecture)
- **Flow control**: avoid overloading the receiver (next lecture)
- **Congestion control**: avoid overloading the network (next week)

Will first discuss each topic in general, and then how TCP implements it.

Reliable Transport

Reliable Delivery Is Necessary

- Many app semantics involve reliable delivery
  - E.g., file transfer
- Challenge: building a reliable service on top of unreliable packet delivery

A recurring theme in systems

- **How to build reliable services over unreliable components**
  - Reliable storage from inexpensive disks (RAID)
  - Reliable computing over unreliable servers

Recall: Architectural Principles

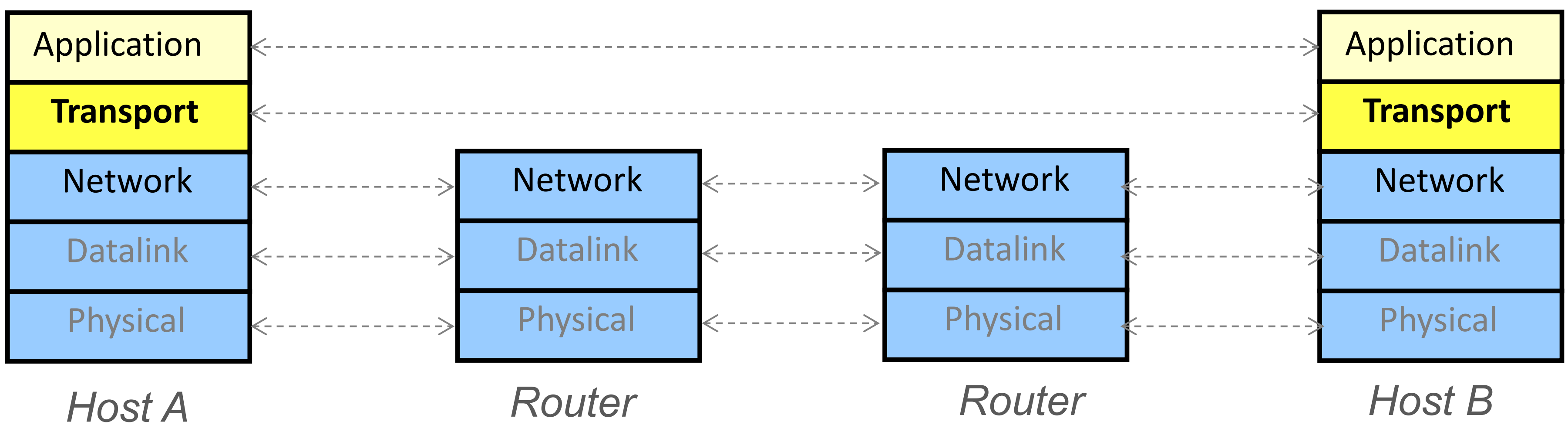
- How to break system into modules
  - **Dictated by Layering**
- Where modules are implemented
  - **Dictated by End-to-End Principle**
- Where state is stored
  - **Dictated by Fate-Sharing**

Applied to Reliable Delivery

- **The end-to-end principle tells us:**
  - Put reliability in the end hosts, not in the network
  - With reliability state in end hosts (“fate sharing”)
- **Layering dictates putting reliability in L4**
  - Above the networking layer L3
  - Below the application layer L7

Semantics of correct delivery

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



Goals For Reliable Transfer
(at the Transport Layer)

- **Correctness**
  - 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

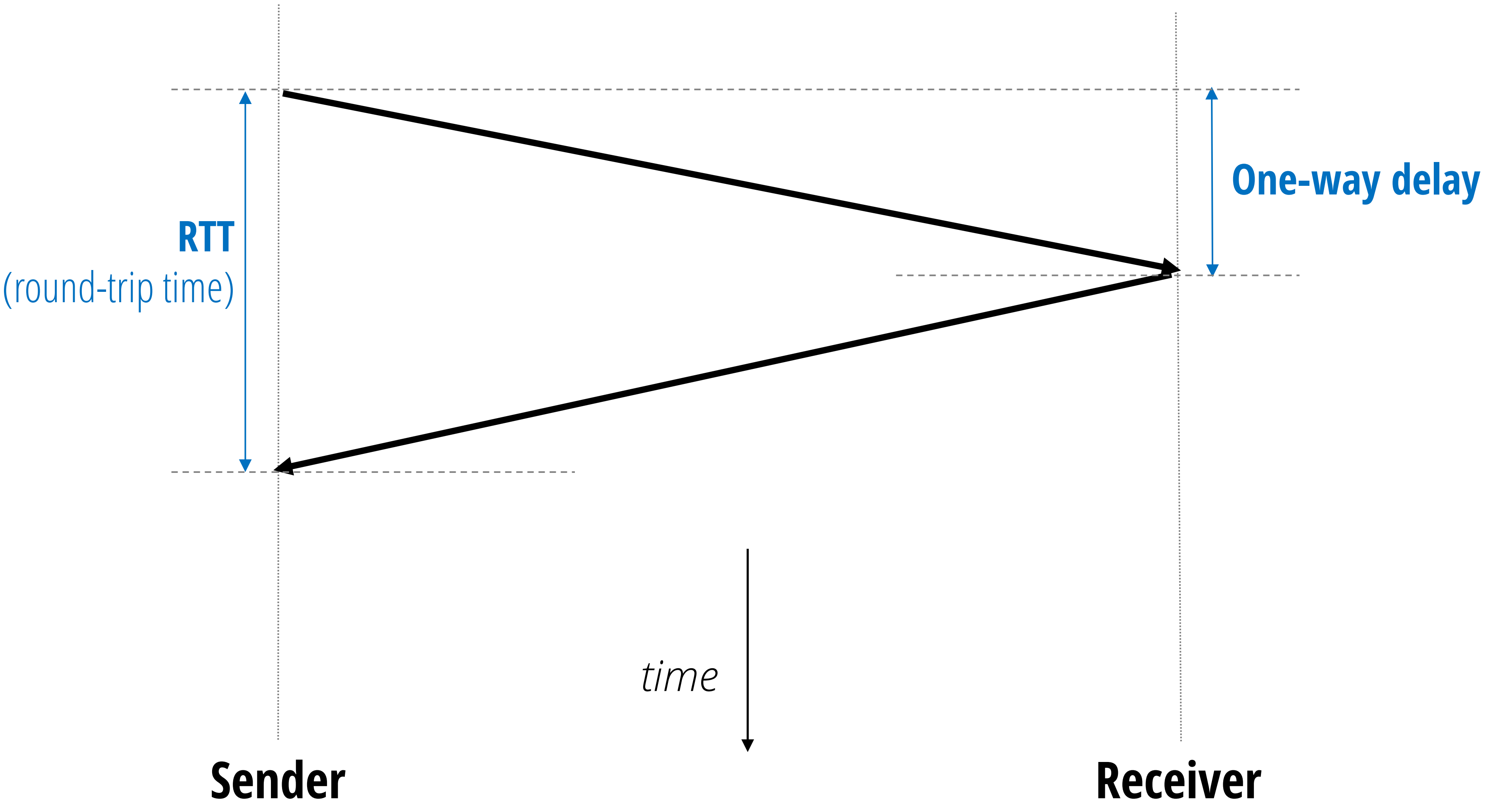
Note!

- 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

A best-effort network

- Packets can be lost (i.e., dropped)
- Packets can be corrupted
- Packets can be reordered
- Packets can be delayed
- Packets can be duplicated

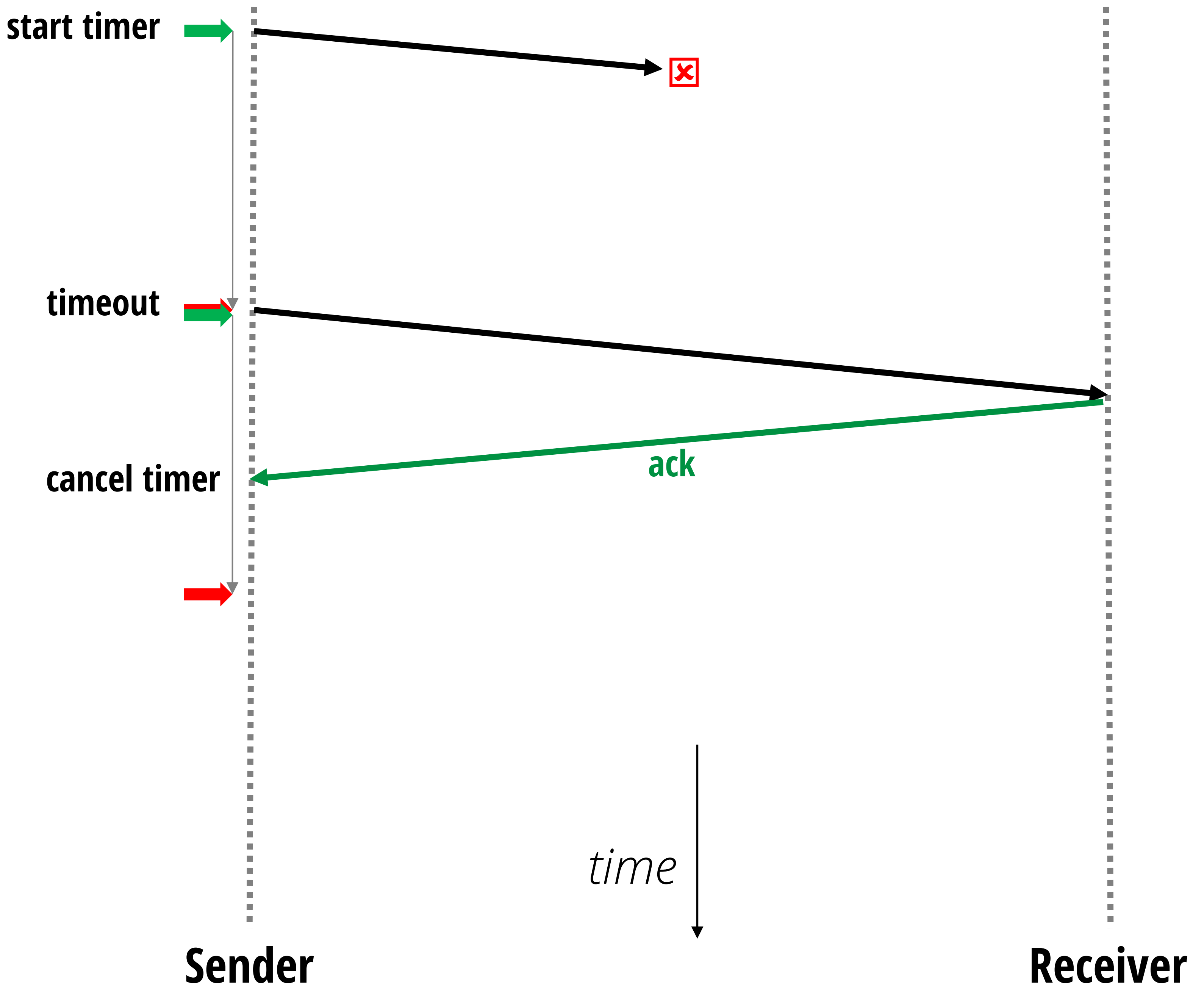
Quick reminder

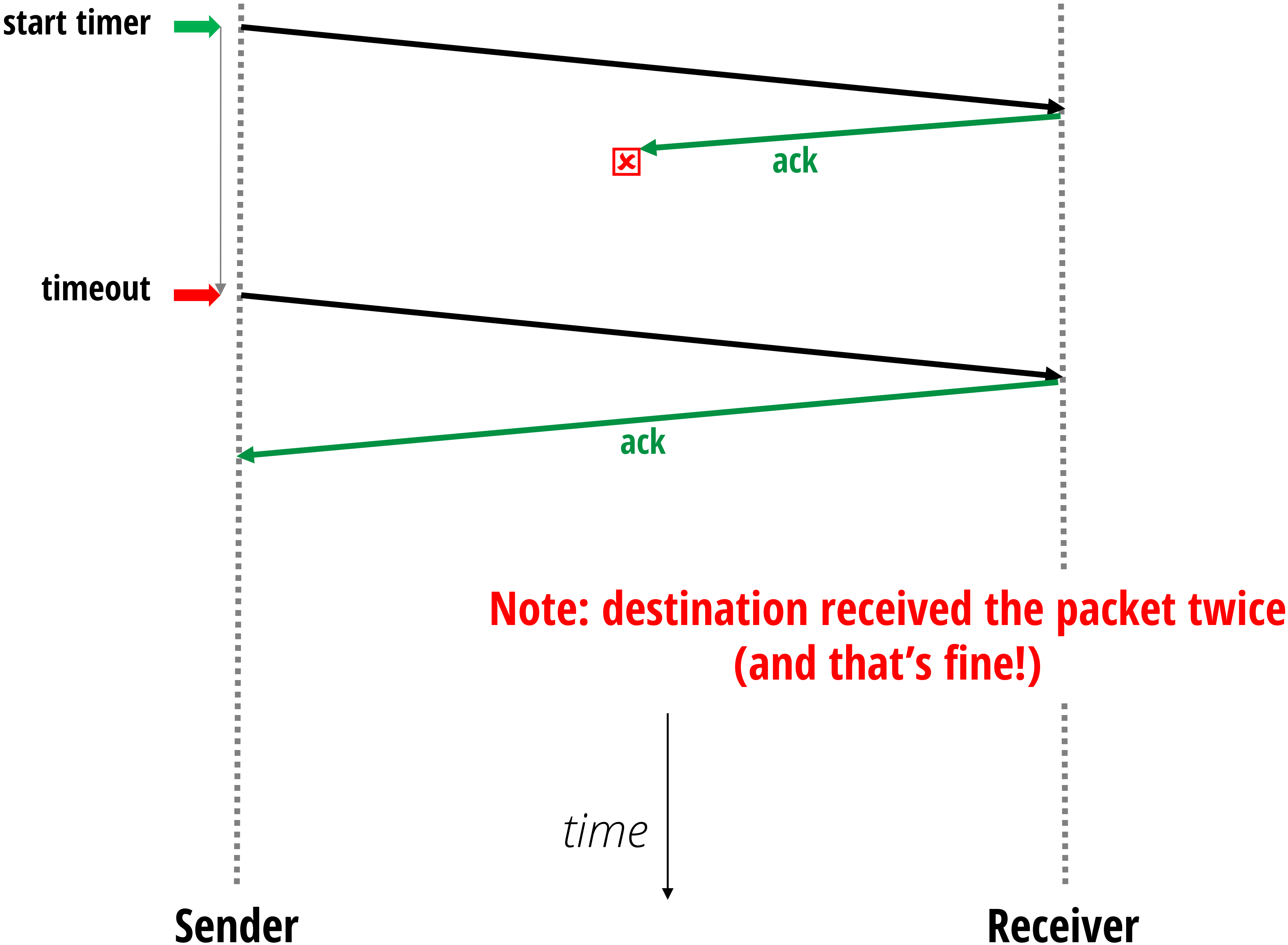


Designing a reliability protocol

- Let’s start with the single packet case

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


start timer
timeout
ack
cancel timer
time
Sender
Receiver


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

How to set timers?

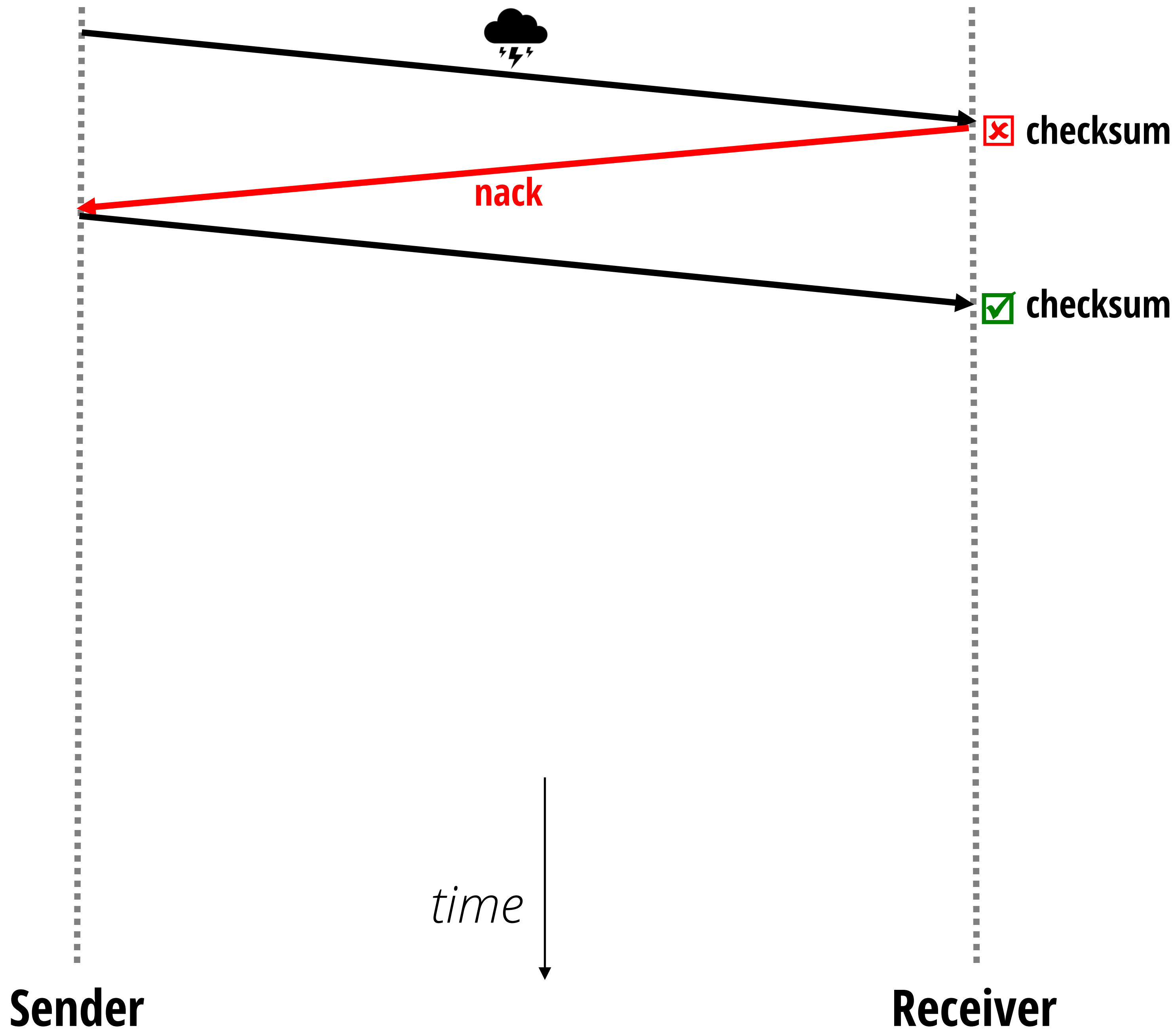
- Too long: will delay delivery
- Too short: unnecessary retransmissions

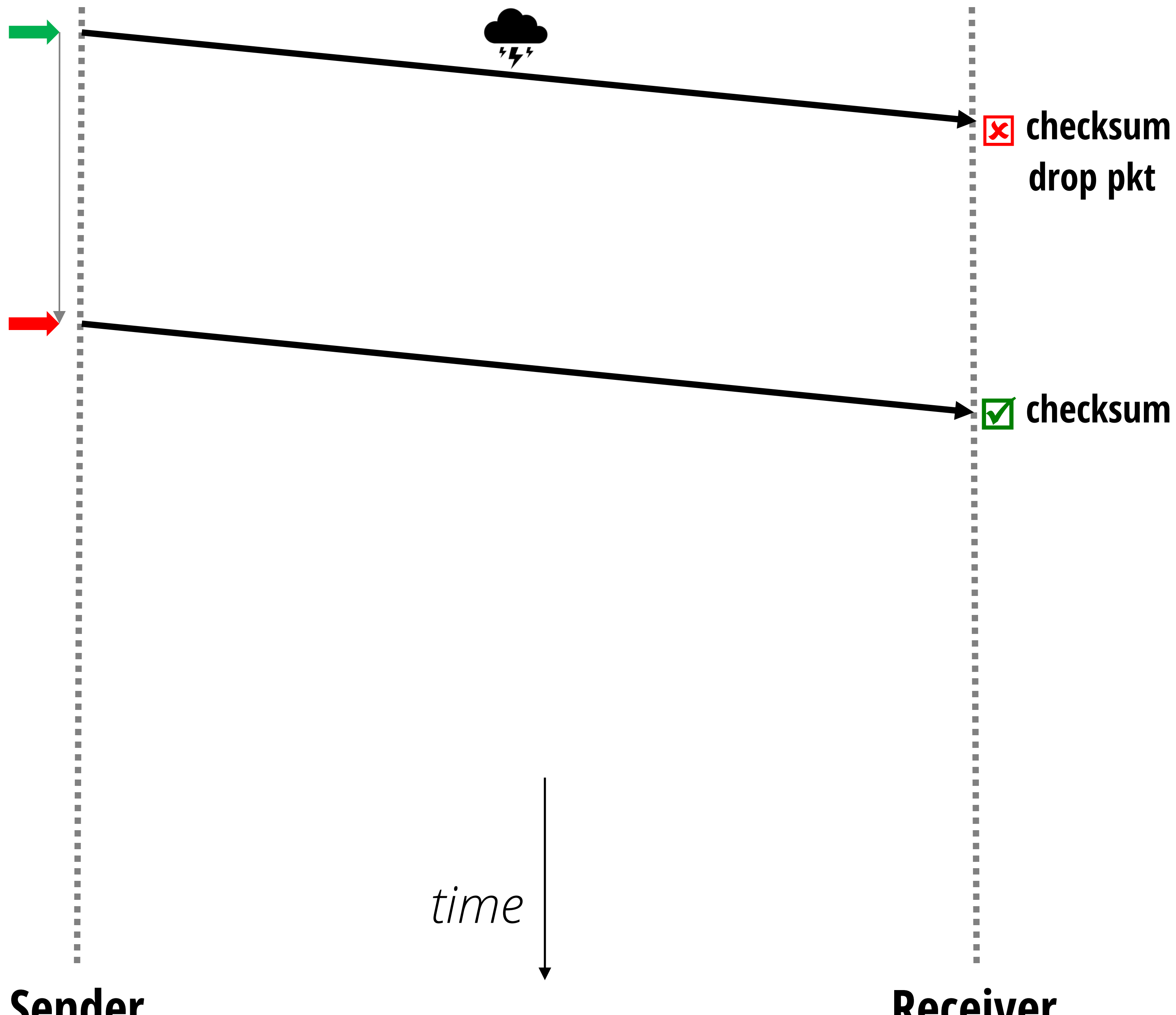
- Ideally, proportional to the RTT (next lecture)

- Non-trivial to get right in practice
  - RTTs vary across paths (10µs to 100s ms)
  - RTT of a fixed path varies over time (load, congestion)

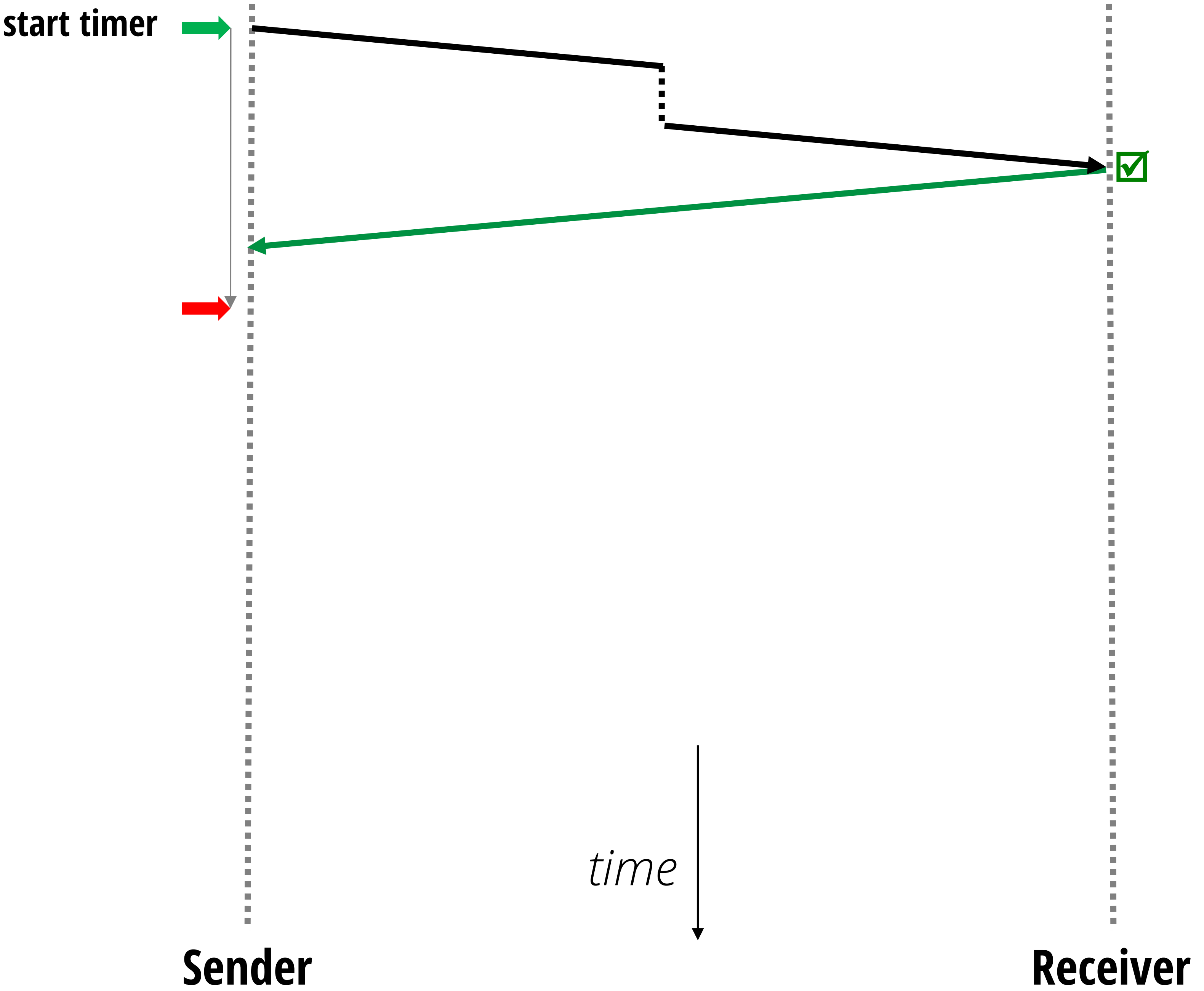
- Hence, often used as last resort

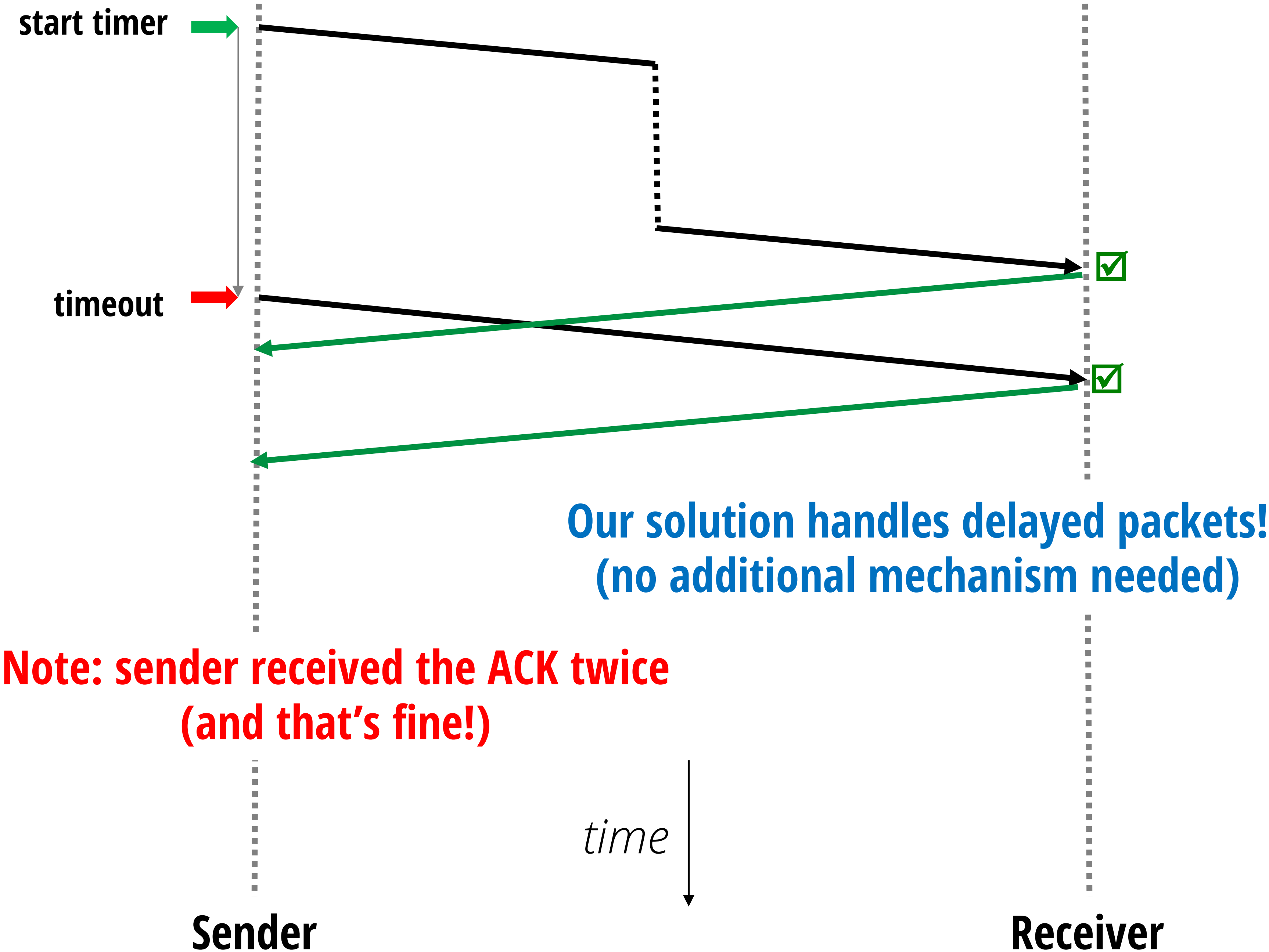
- We said
  - Packets can be lost (data or ACKs) 👍
  - Packets can be corrupted
  - Packets can be delayed
  - Packets can be duplicated
  - Packets can be reordered


checksum
nack
checksum
time
Sender
Receiver

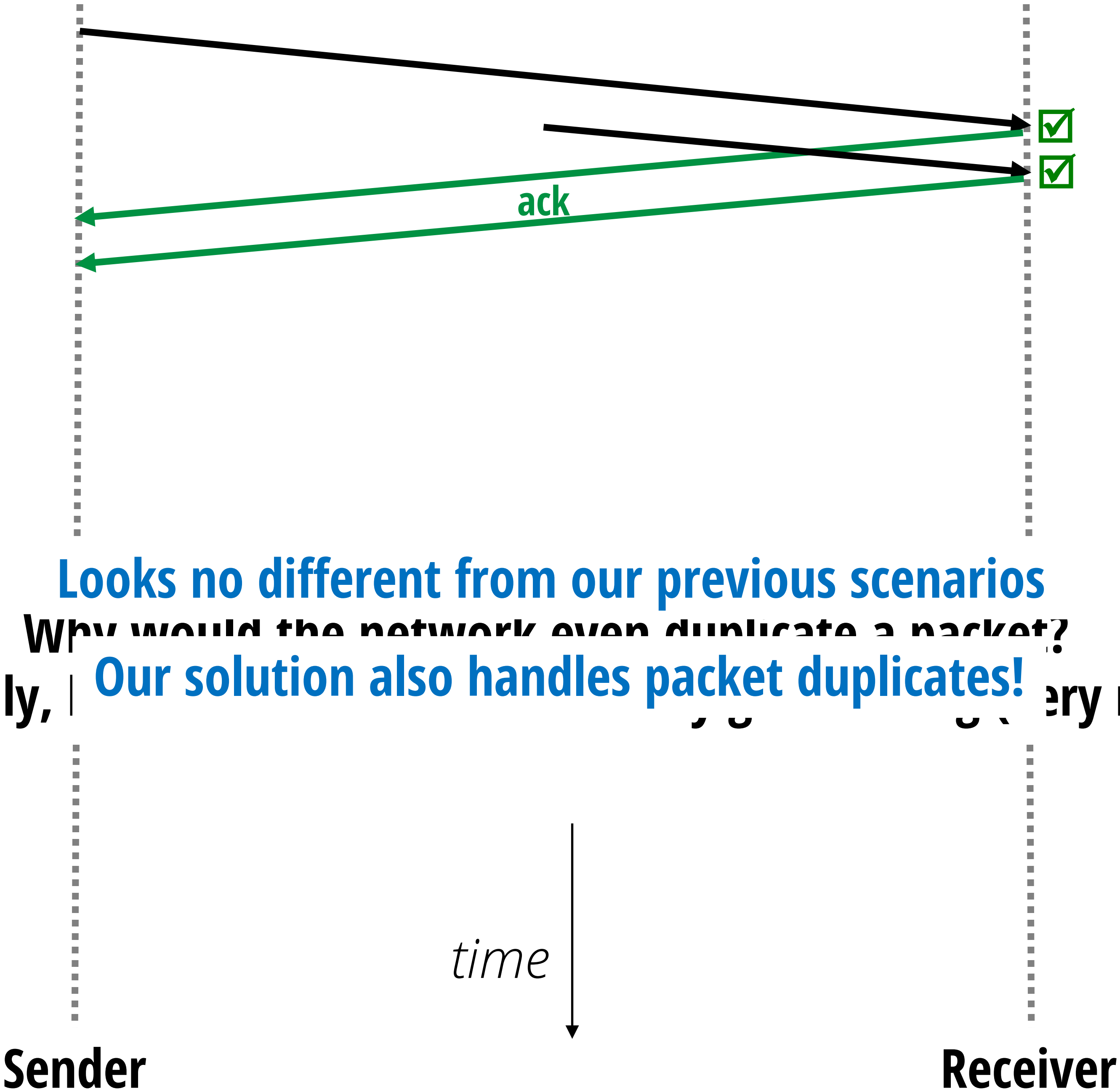

checksum
drop pkt
checksum
time
Sender
Receiver

- 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


start timer
time
Sender
Receiver


start timer
timeout
Our solution handles delayed packets!
(no additional mechanism needed)
Note: sender received the ACK twice
(and that's fine!)
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



Looks no different from our previous scenarios

Why would the network even duplicate a packet?

Our solution also handles packet duplicates!

Usually, ery rare)

- 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

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?

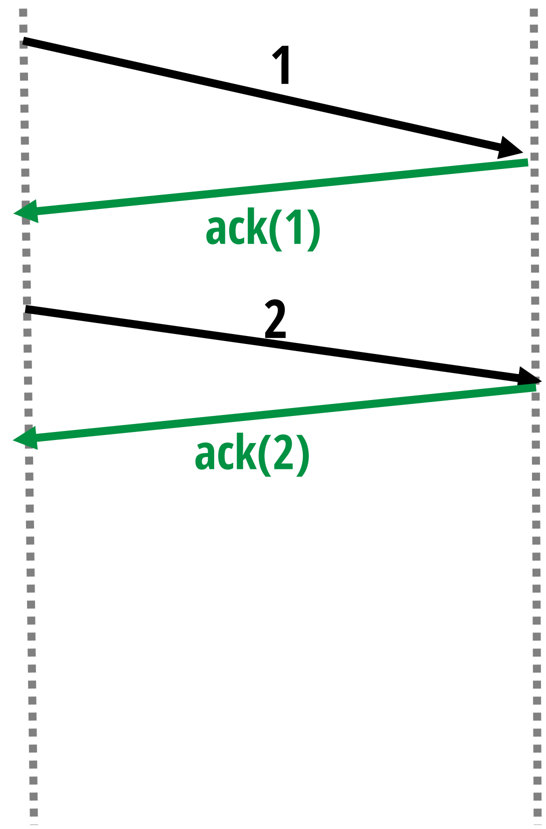
- Building blocks for a solution
  - **Checksums**: to detect corruption
  - **Feedback** from receiver: positive/negative (ack/nack)
  - **Retransmissions**: sender resends packets
  - **Timeouts**: when to resend a packet

- 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

- Will need +1 design component: sequence numbers!



Data packets carry sequence numbers;

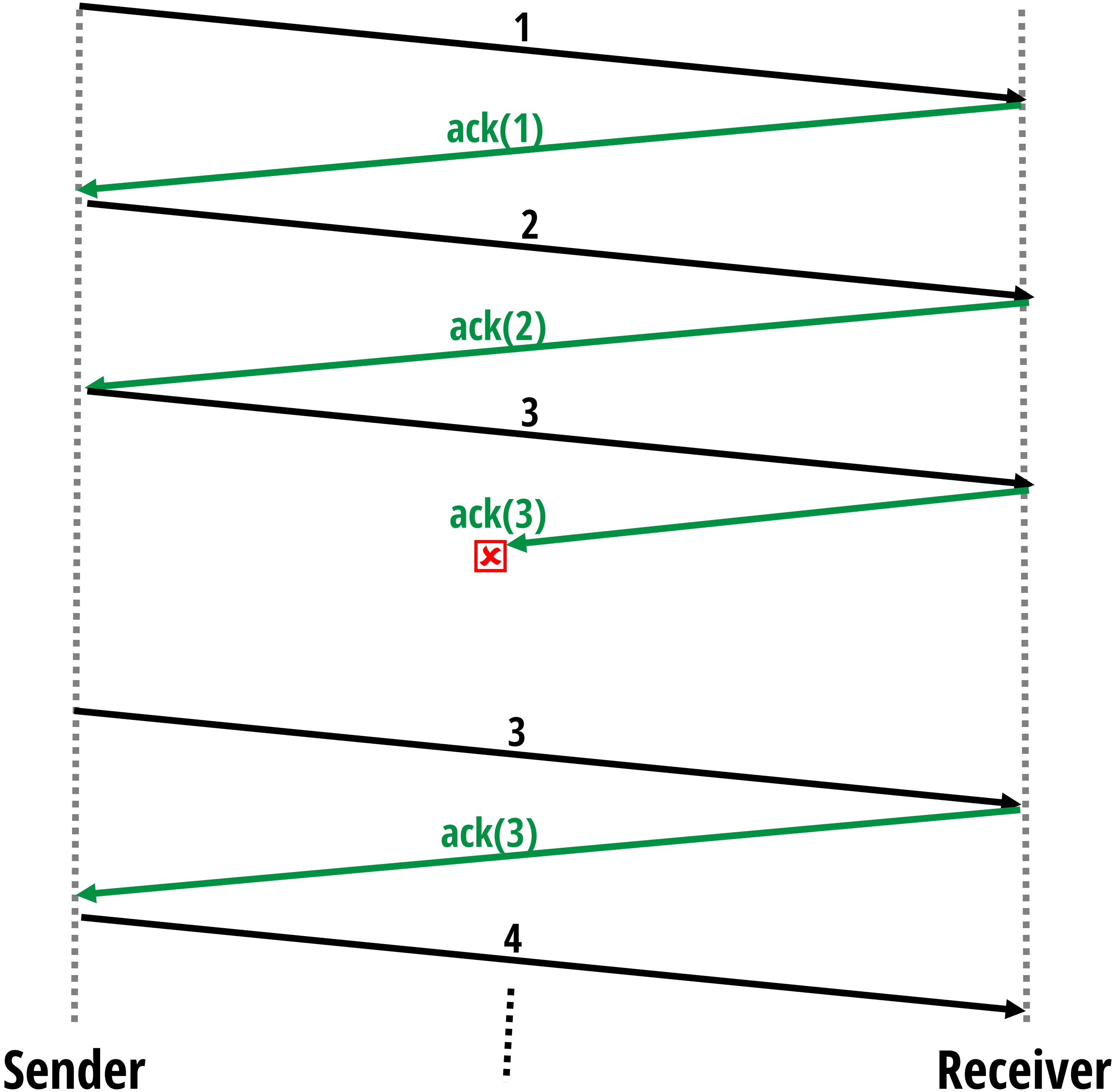
and ACKs indicate what sequence numbers have been received

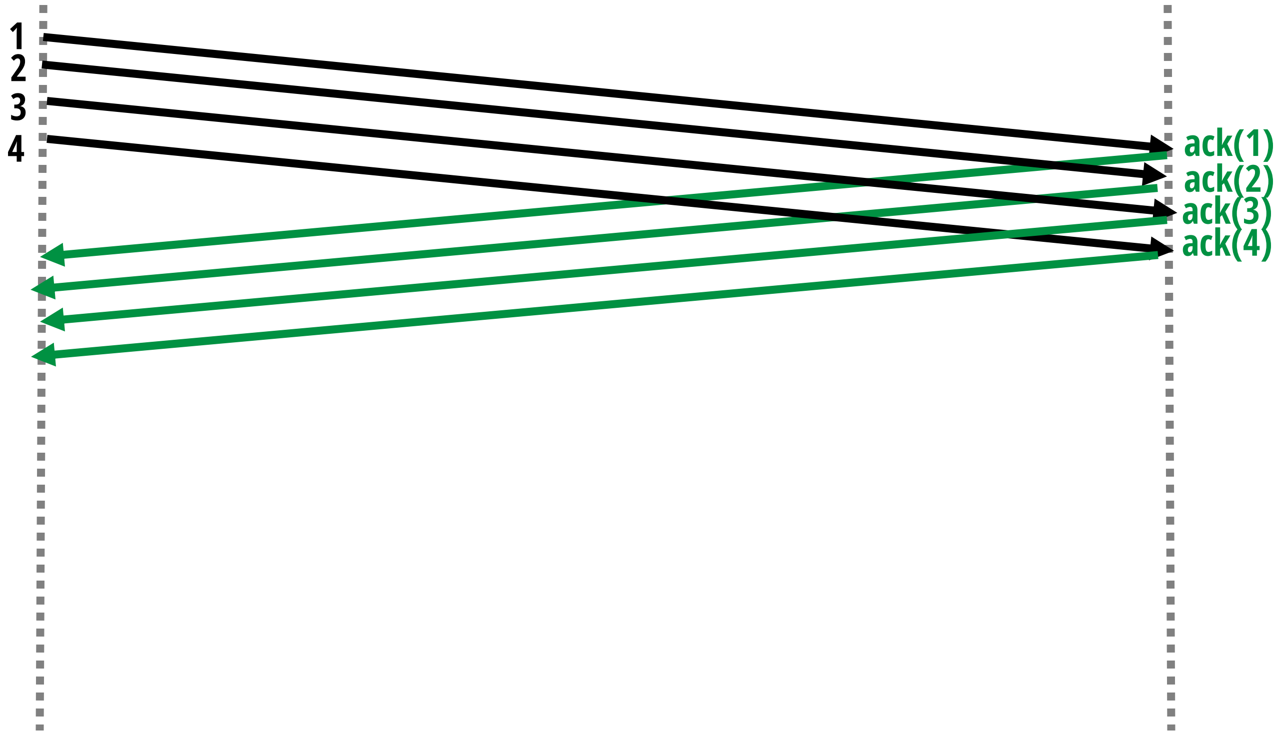
Next: reliably send multiple packets

- 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
  - 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



Idea: have multiple packets "in flight"

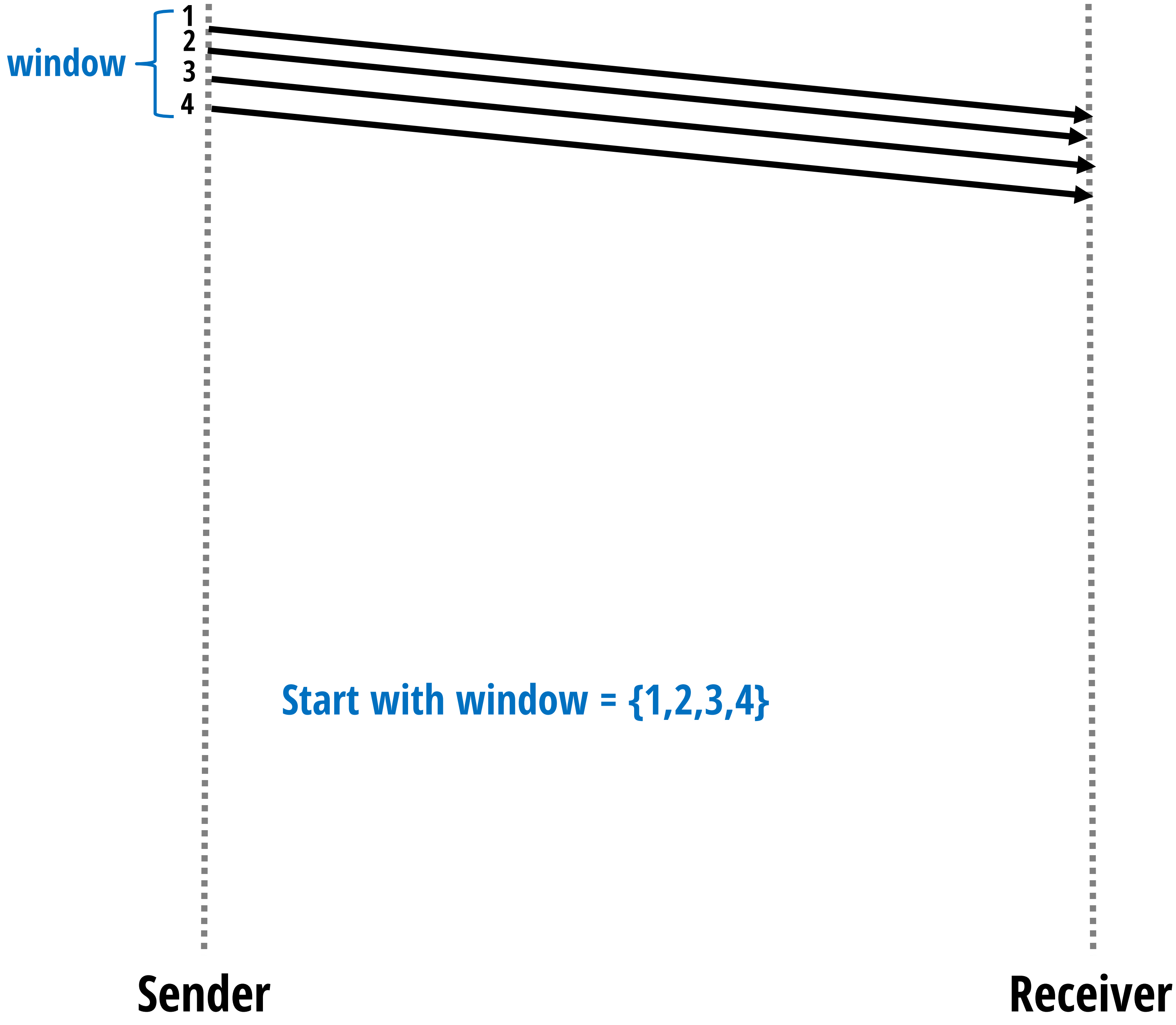
(send additional packets while waiting for ACKs to come in)

Sender **Receiver**

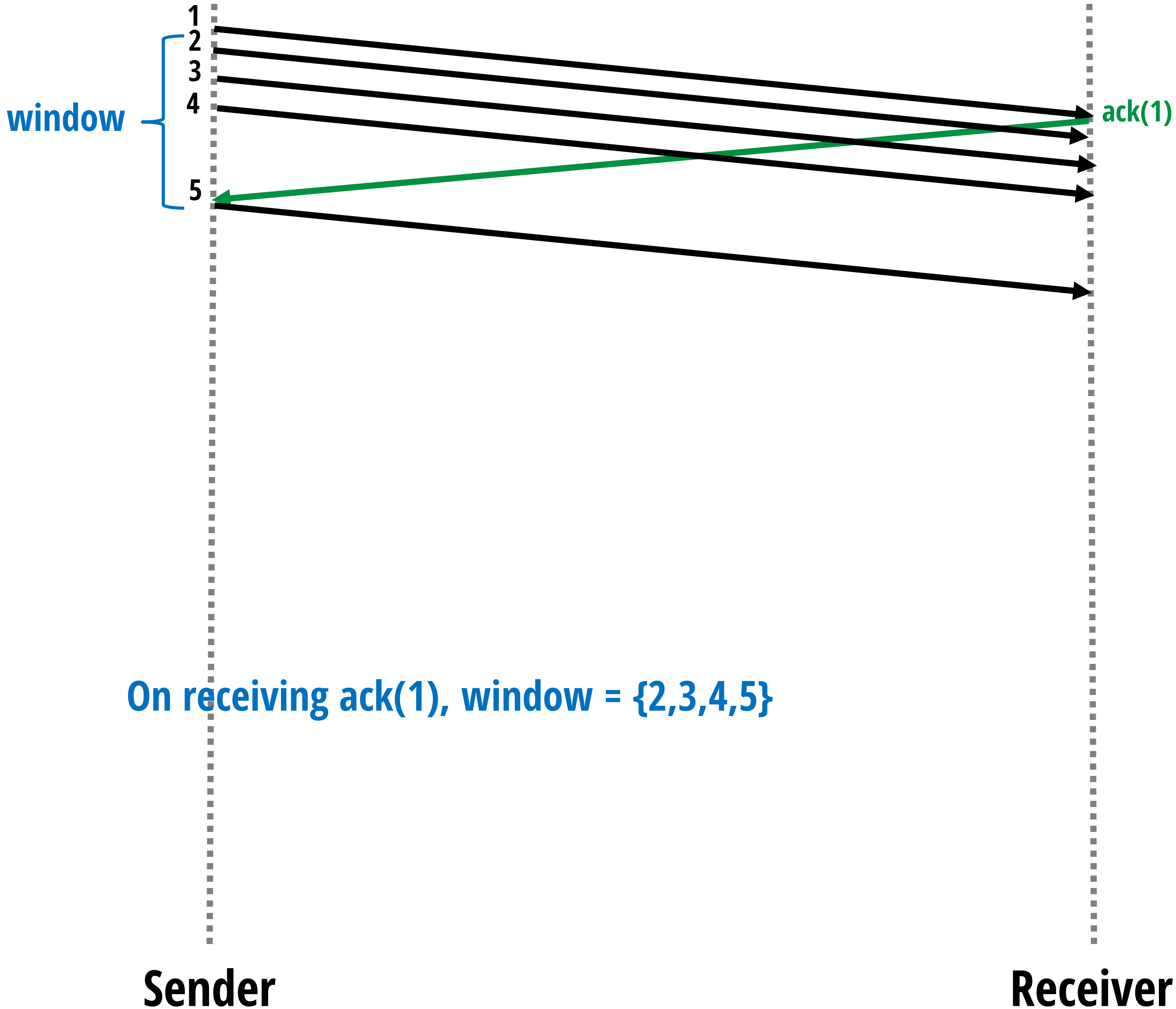
Window-based Algorithms

- 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 another packet

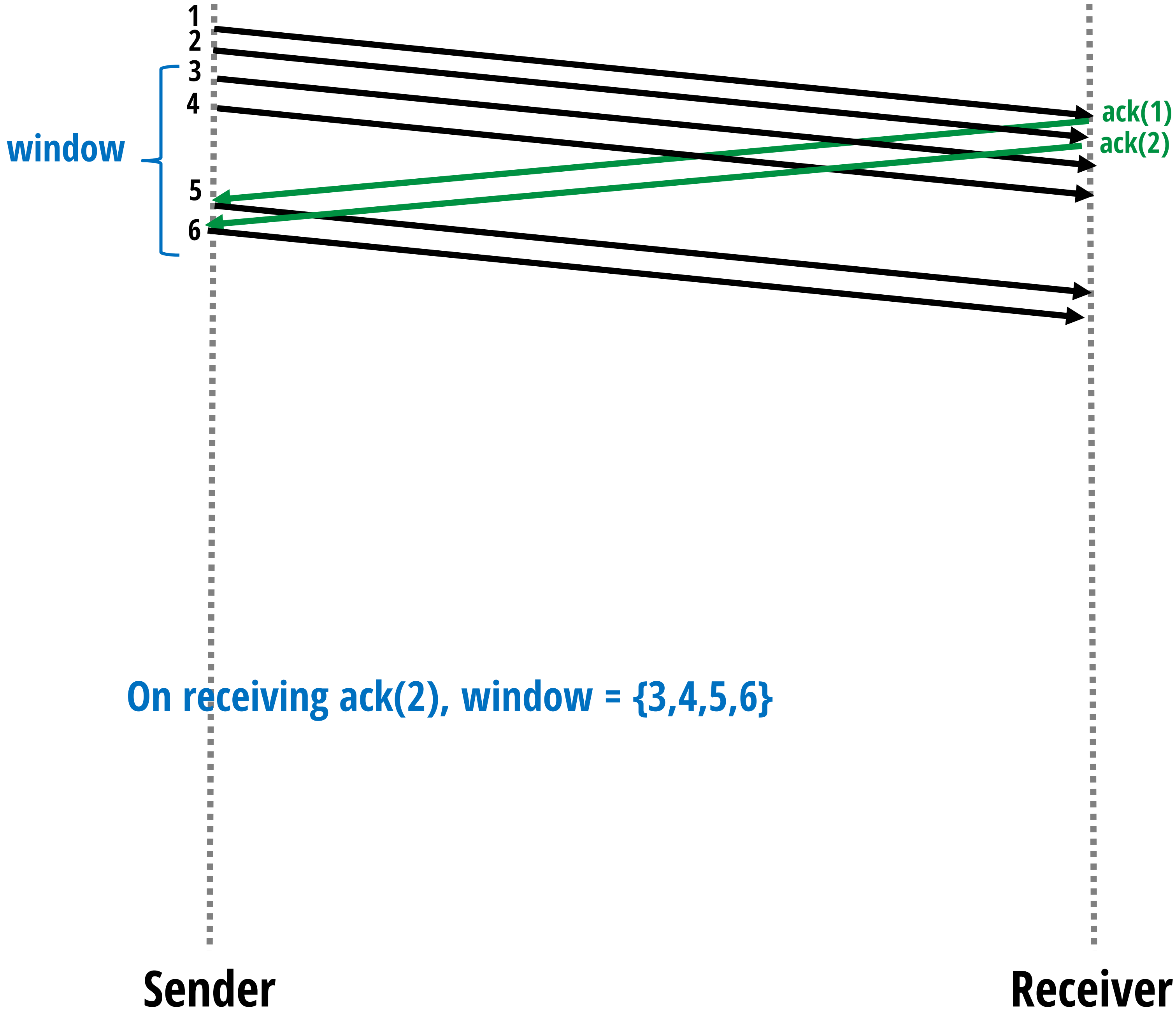
Example with W=4



Example with W=4



Example with W=4



On receiving ack(2), window = {3,4,5,6}

Reliably sending many packets

- Will need +1 design component: sequence numbers!
- We now have all the *necessary* building blocks
- Plus one more, for **efficiency (performance)**
  - Window

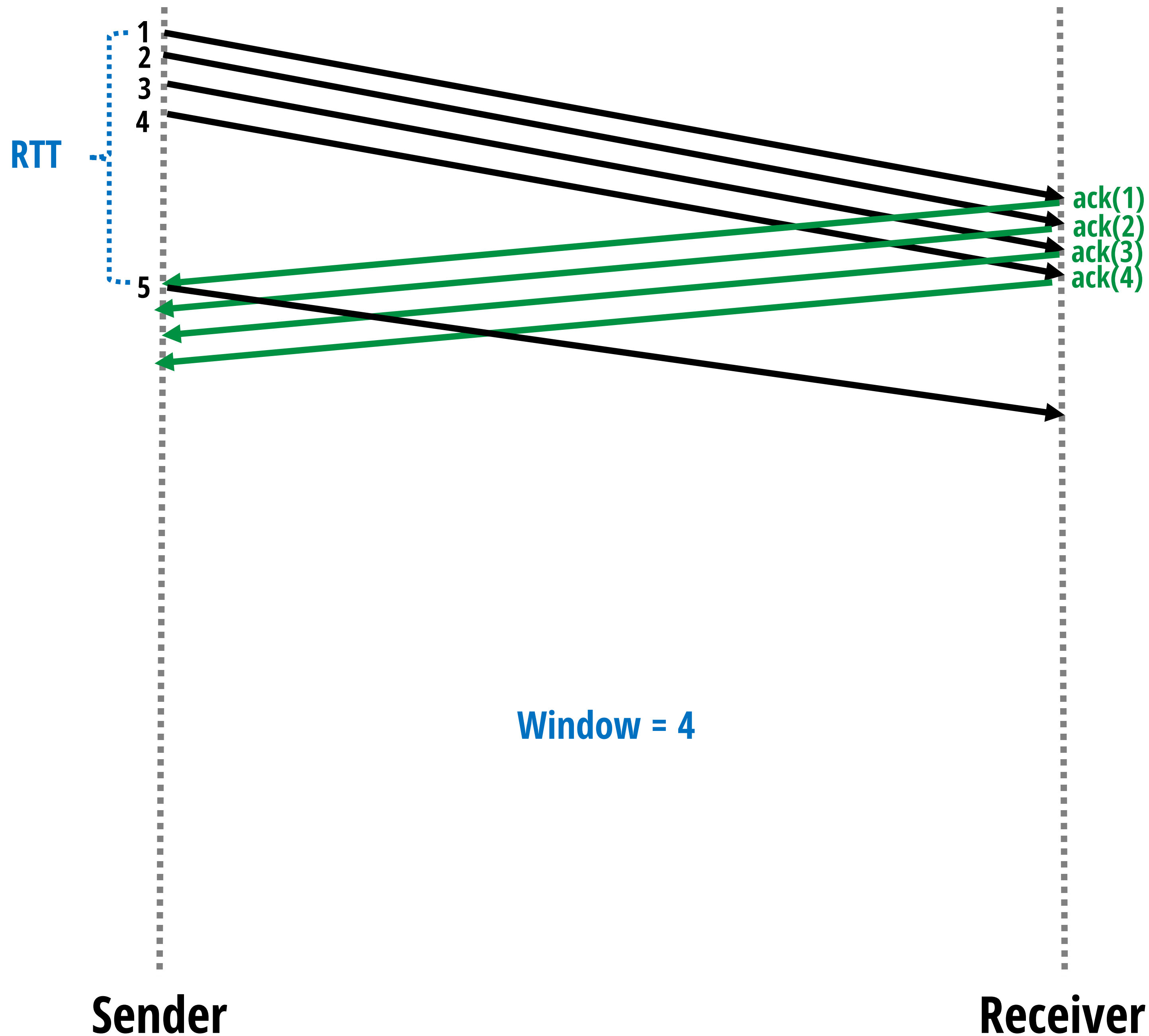
New Design Considerations

- 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?
- How is the window managed?

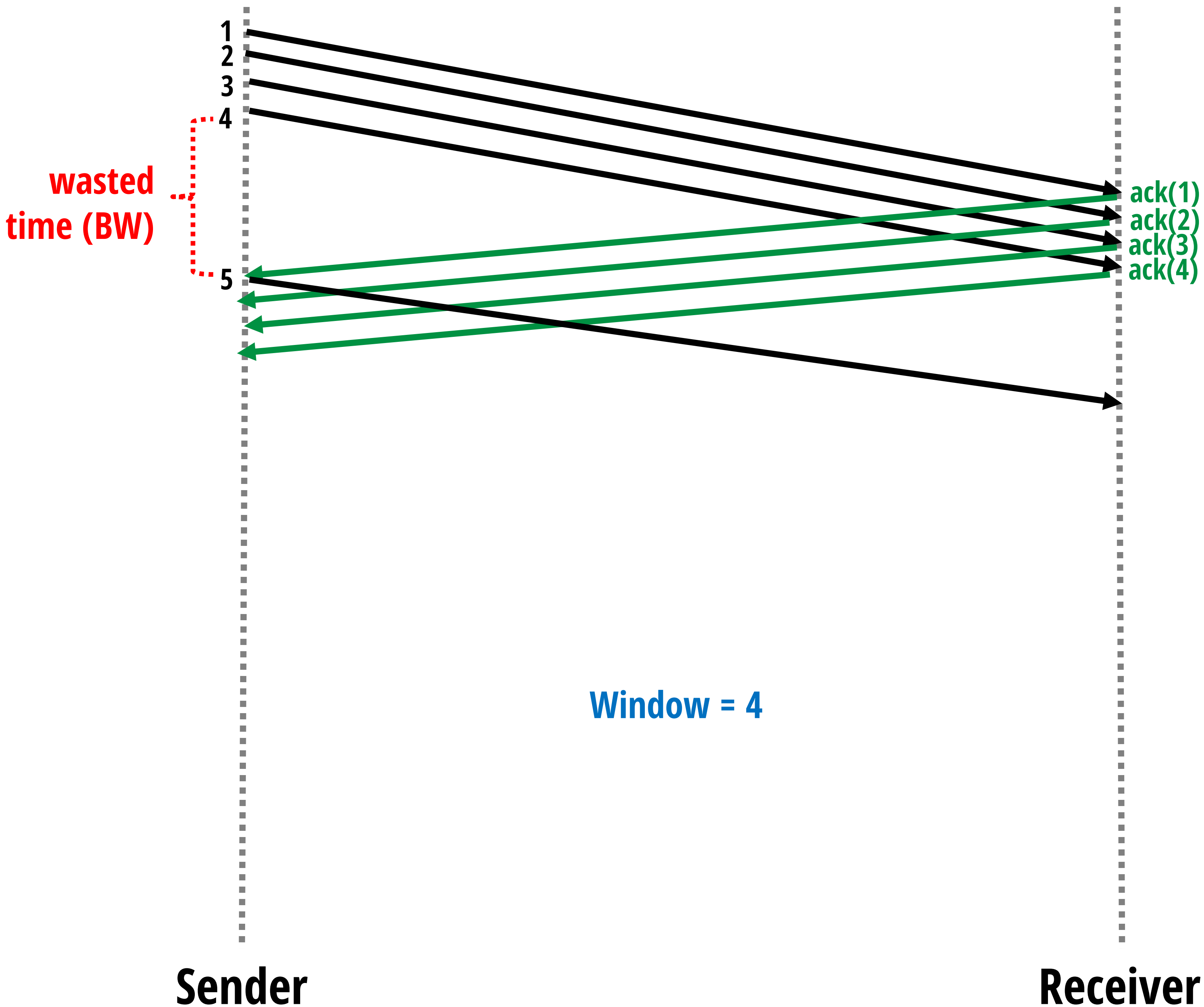
How big should the window be?

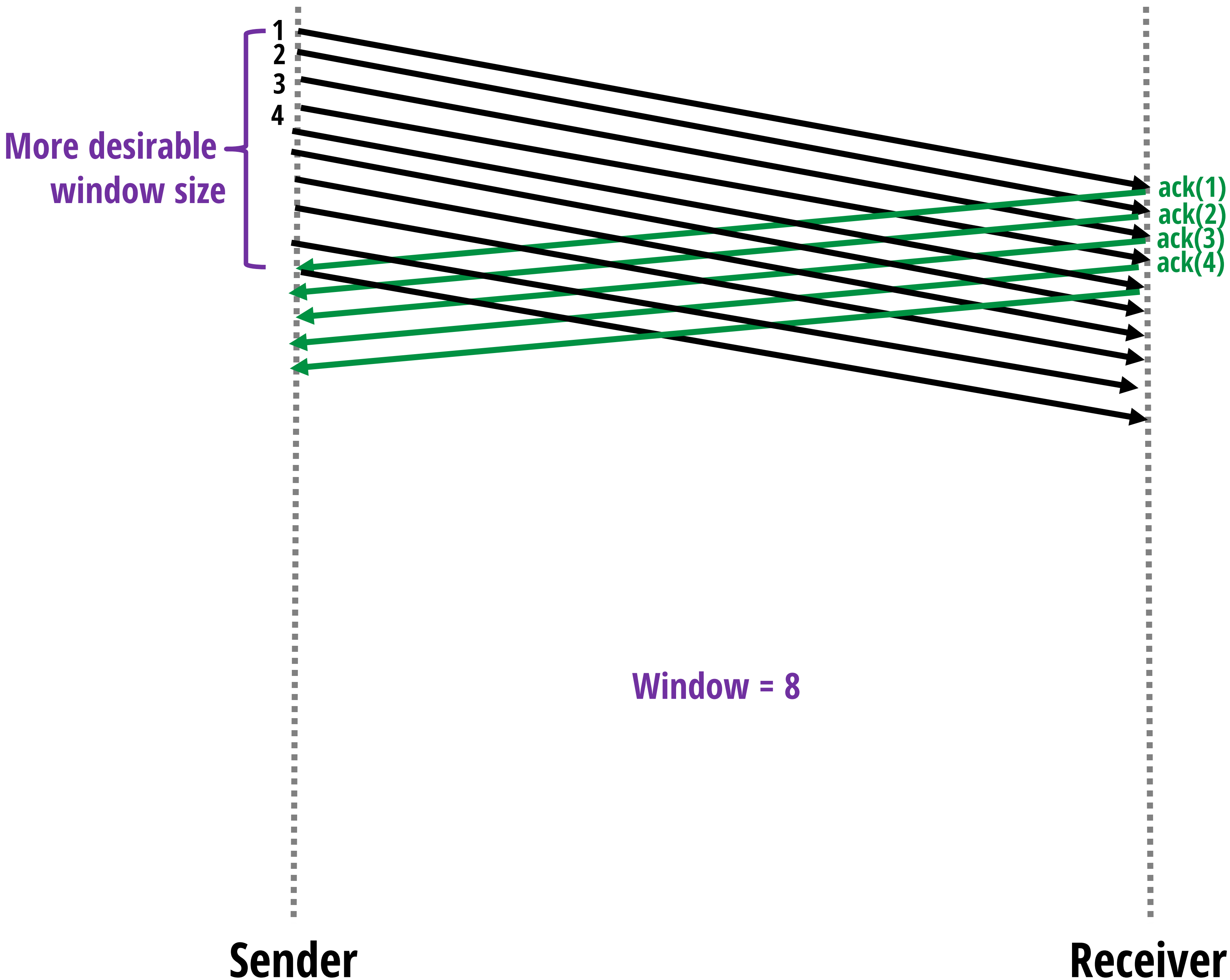
- Pick window size **W** to balance three goals
  - Take advantage of network capacity (“fill the pipe”)
  - But don’t overload links (congestion control)
  - And don’t overload the receiver (flow control)

- 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



RTT
1
2
3
4
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

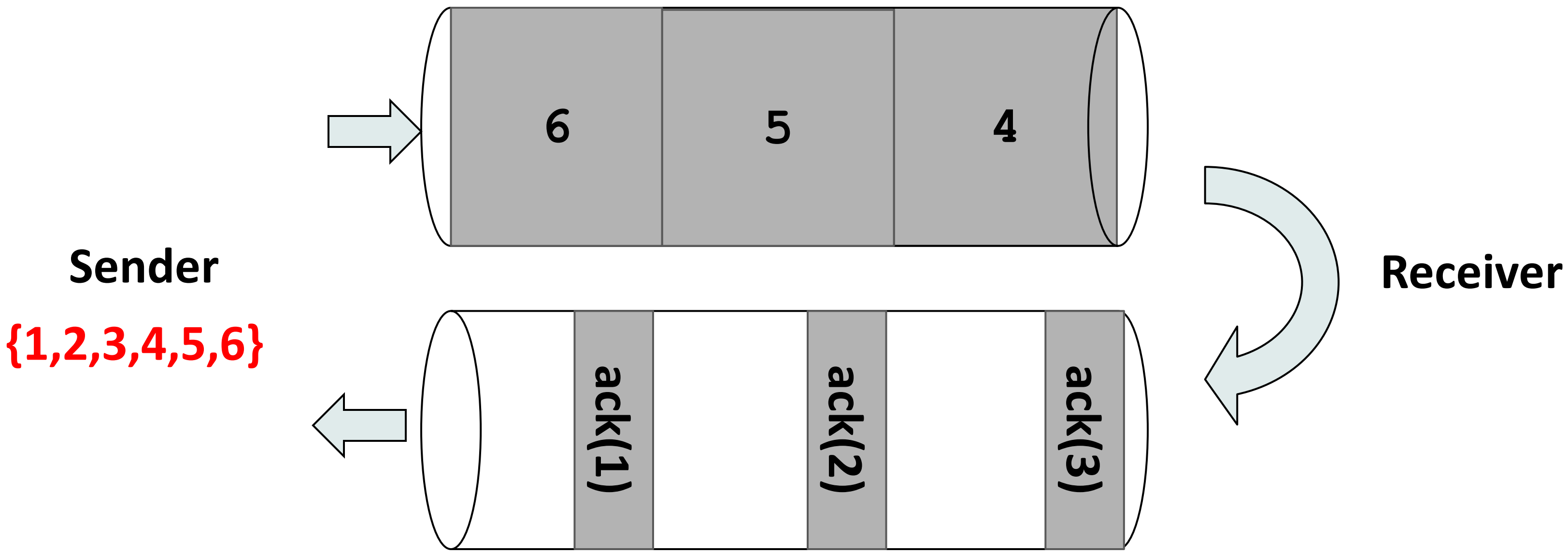


1
2
3
4
More desirable window size
ack(1)
ack(2)
ack(3)
ack(4)
Window = 8
Sender
Receiver

What Does This Mean?

- 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)
- 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



New Design Considerations

- Window size
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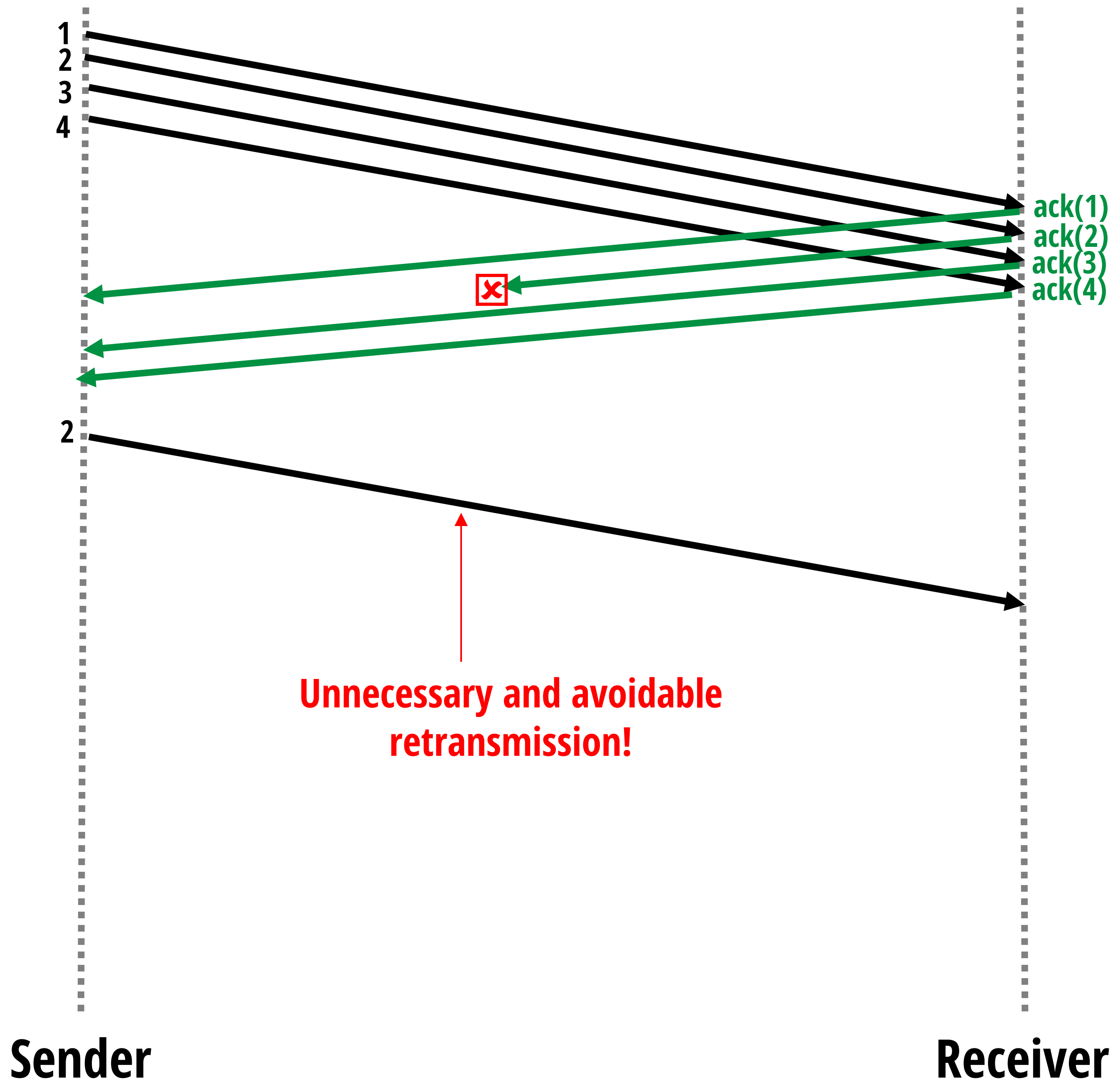
- Detection of loss
  - Can we do better than waiting for timeouts?
- Response to loss
  - Which packet should sender resend?
- How is the window managed?

ACKs: design options

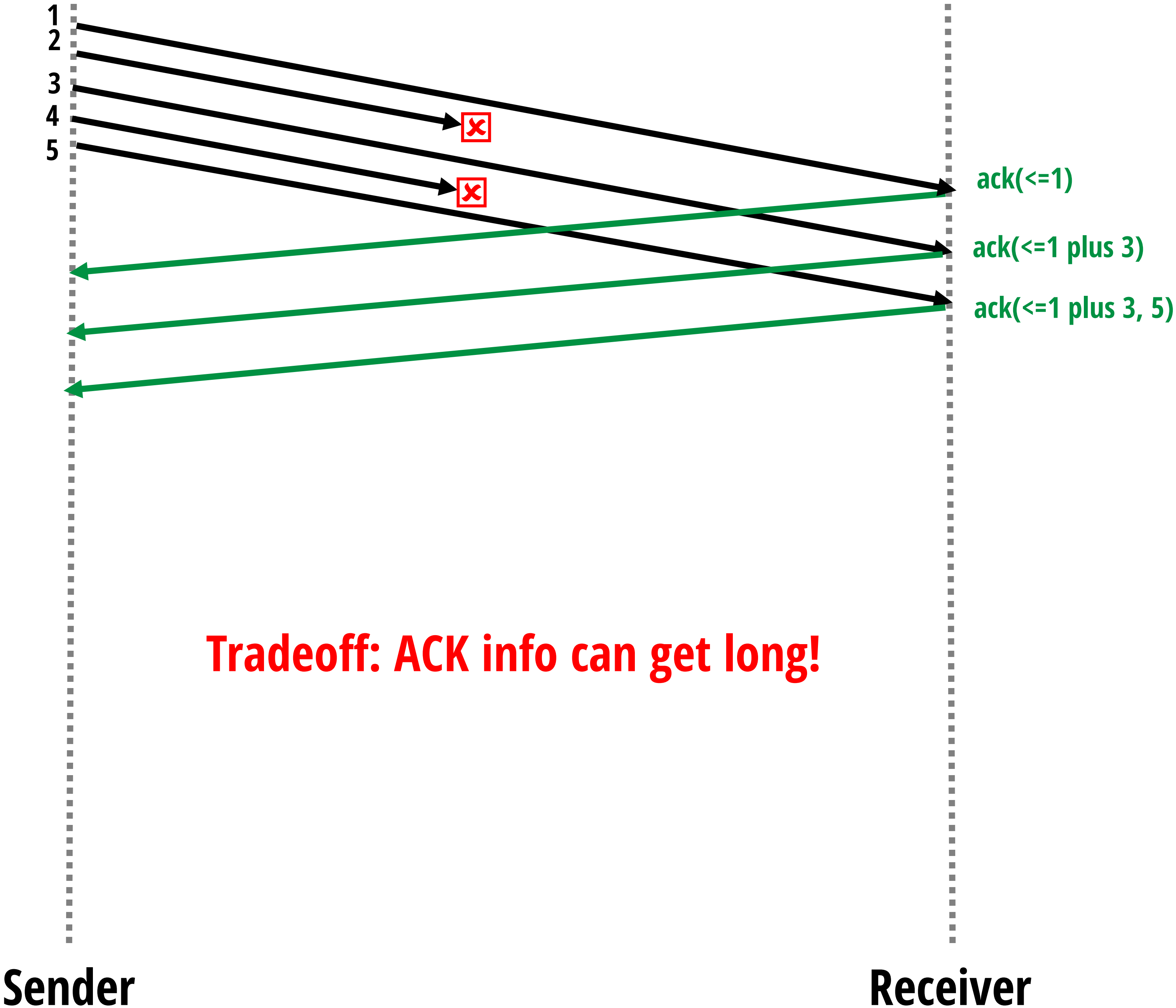
- **Individual packet ACKs (our design so far)**
  - On receiving packet `i`, send ack(`i`)


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

ACKs: design options

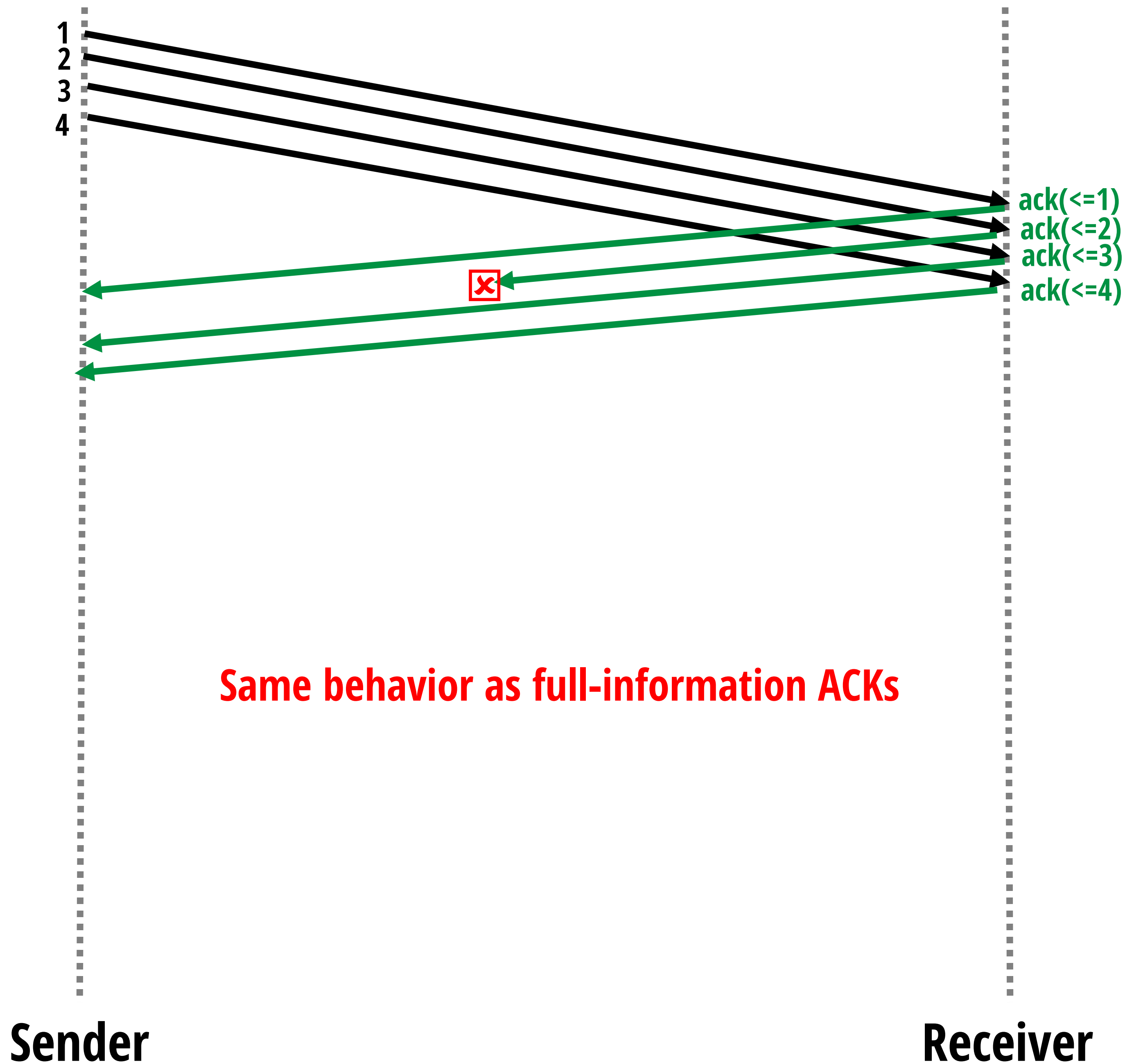
- **Individual packet ACKs (our design so far)**
  - On receiving packet `i`, send ack(`i`)
- **Full Information ACKs**
  - Give highest cumulative ACK plus any additional packets received (“*everything up to #12 and #14, #15*”)

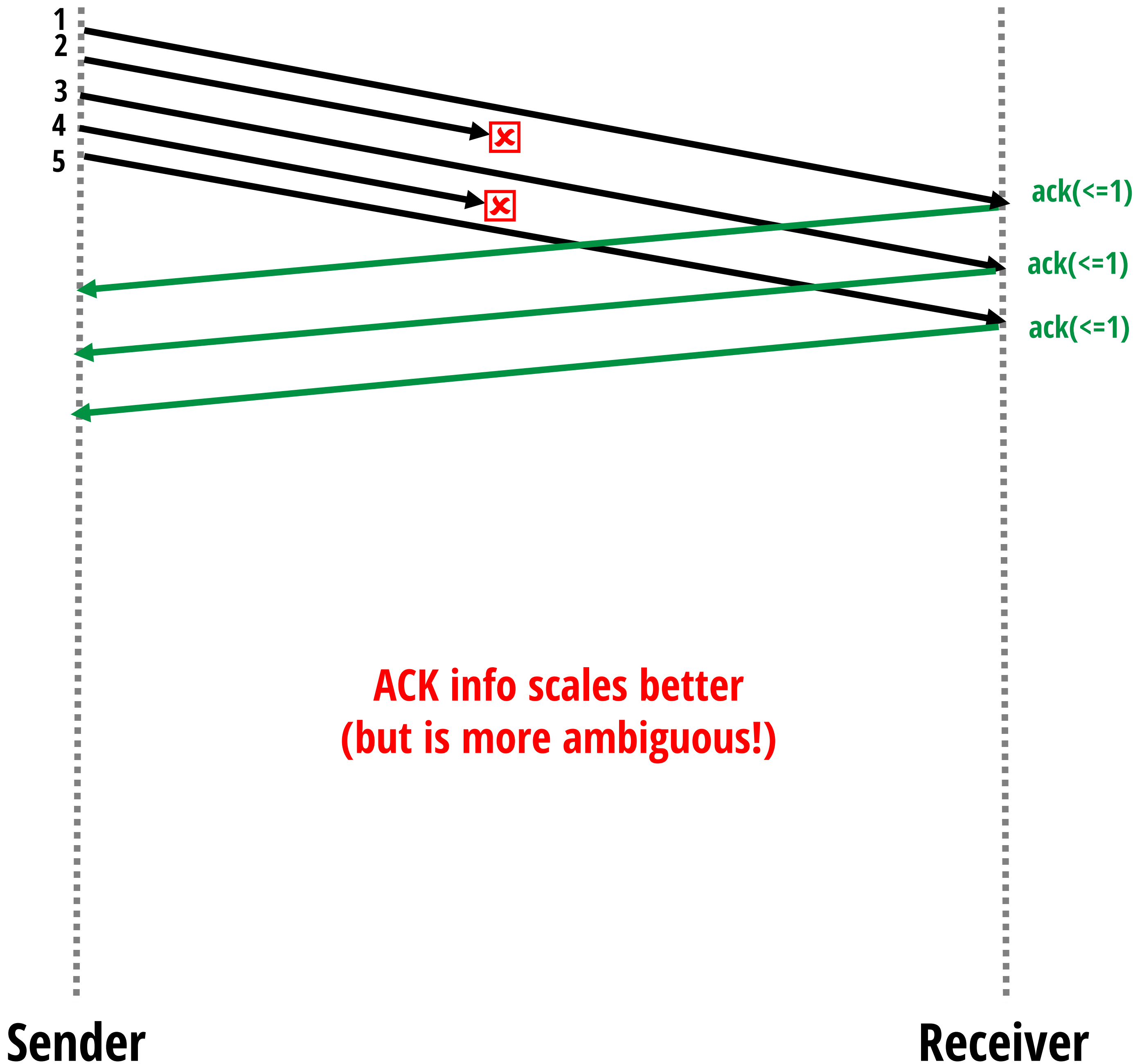
Sender learns #2 was received when it receives the 3rd and 4th ACK


1
2
3
4
5
ack(<=1)
ack(<=1 plus 3)
ack(<=1 plus 3, 5)
Tradeoff: ACK info can get long!
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"*)
- **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)
Same behavior as full-information ACKs
Sender
Receiver



ACK info scales better
(but is more ambiguous!)

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
- **Hybrids**
  - E.g., Selective ACK (SACK): cumulative + finite length full ACKs

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?
- How is the window managed?

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

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

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

Loss with full information

- Same story, except that the “hole” is explicit in each ACK
- Stream of ACKs will be:
  - Up to 1
  - Up to 2
  - Up to 3
  - Up to 4
  - Up to 4, plus 6
  - Up to 4, plus 6,7
  - Up to 4, plus 6,7,8

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

Loss with cumulative ACKs

- Assume packet 5 is lost, but no others
- Stream of ACKs will be:
  - Up to 1
  - Up to 2
  - Up to 3
  - Up to 4
  - Up to 4 (sent when packet 6 arrives)
  - Up to 4 (sent when packet 7 arrives)
  - Up to 4 (sent when packet 8 arrives)

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?
- How is the window managed?

Response to loss

- On timeout, always retransmit corresponding packet

- 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

- ACK 4 arrives

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 9

- ACK 4 arrives → send 9

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 9

- ACK 4 arrives → send 9
- ACK 6 arrives

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 9 10

- ACK 4 arrives → send 9
- ACK 6 arrives → send 10

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 9 10

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

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 9 10 11

- ACK 4 arrives → send 9
- ACK 6 arrives → send 10
- ACK 7 arrives → **resend 3**, send 11

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 9 10 11

- ACK 4 arrives → send 9
- ACK 6 arrives → send 10
- ACK 7 arrives → **resend 3**, send 11
- ACK 8 arrives

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 9 10 11 12

- 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
  - 3-8 are "in flight"

1 2 3 4 5 6 7 8

#duplicate ACKs = 1

- (for packet 4) ACK 2

Response with cumulative 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 9

#duplicate ACKs = 1

- (for packet 4) ACK 2 → send 9

Response with cumulative 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 9

#duplicate ACKs = 2

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

Response with cumulative 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 9 10

#duplicate ACKs = 2

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

Response with cumulative 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 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
  - Packets 1,2 have been ACKed
  - 3-8 are "in flight"

1 2 3 4 5 6 7 8 9 10 11

#duplicate ACKs = 3

- (for packet 4) ACK 2 → send 9
- (for packet 6) ACK 2 → send 10
- (for packet 7) ACK 2 → resend 3, send 11

Response with cumulative 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 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!

Cumulative ACKs

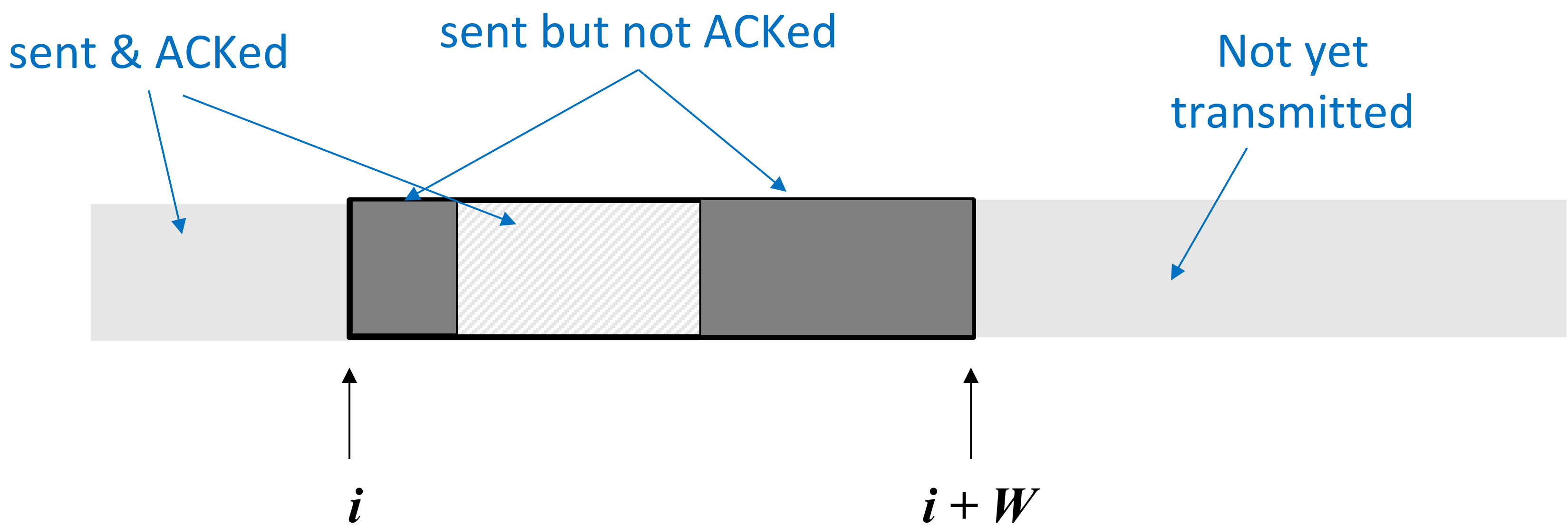
- A few benefits
  - ACKs are smaller and simpler than with full-information
  - More resilient than Individual ACKs
- But ambiguity in feedback leads to problems
  - #dupACKs tell us *how many* packets we can (re)send but not *which* ones
- Makes retransmission and window management ad-hoc
- Will see this again when we come to TCP …

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?
- How is the window managed?

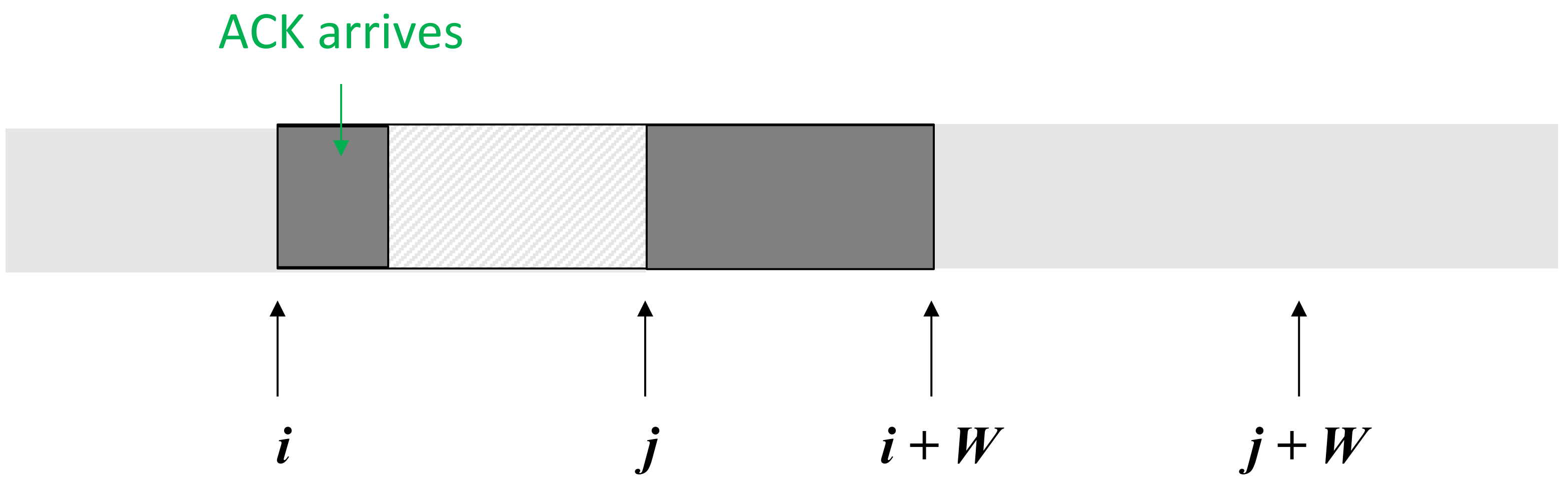
Two approaches to managing windows

- Contiguous ("sliding") window



Two approaches to managing windows

- Contiguous ("sliding") window



Two approaches to managing windows

- Contiguous ("sliding") window
  - Packets in flight must lie between i and $i{+}W$ where i the first unacknowledged packet

- Scattered windows
  - Sender can have any W packets in flight

Taking Stock...

- We've identified our design building blocks
  - Checksums
  - ACK/NACKs
  - Timeouts
  - Retransmissions
  - Sequence numbers
  - Windows

- 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

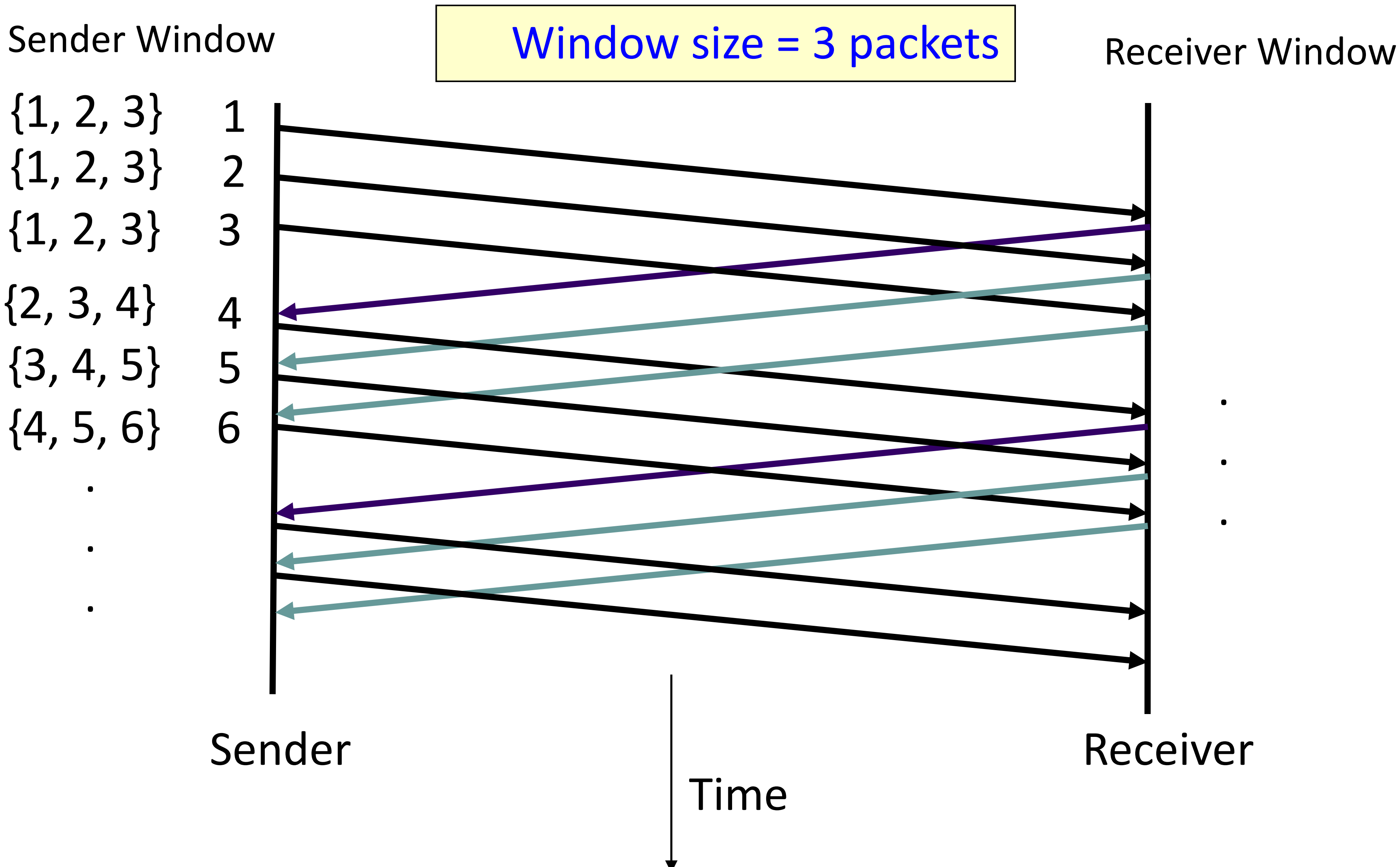
- Can put together a variety of reliability protocols from our building blocks!
  - We saw one already: Stop-and-Wait
  - Another possibility: “Go-Back-N” (coming up)
  - TCP implements yet another (this and next lectures)

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

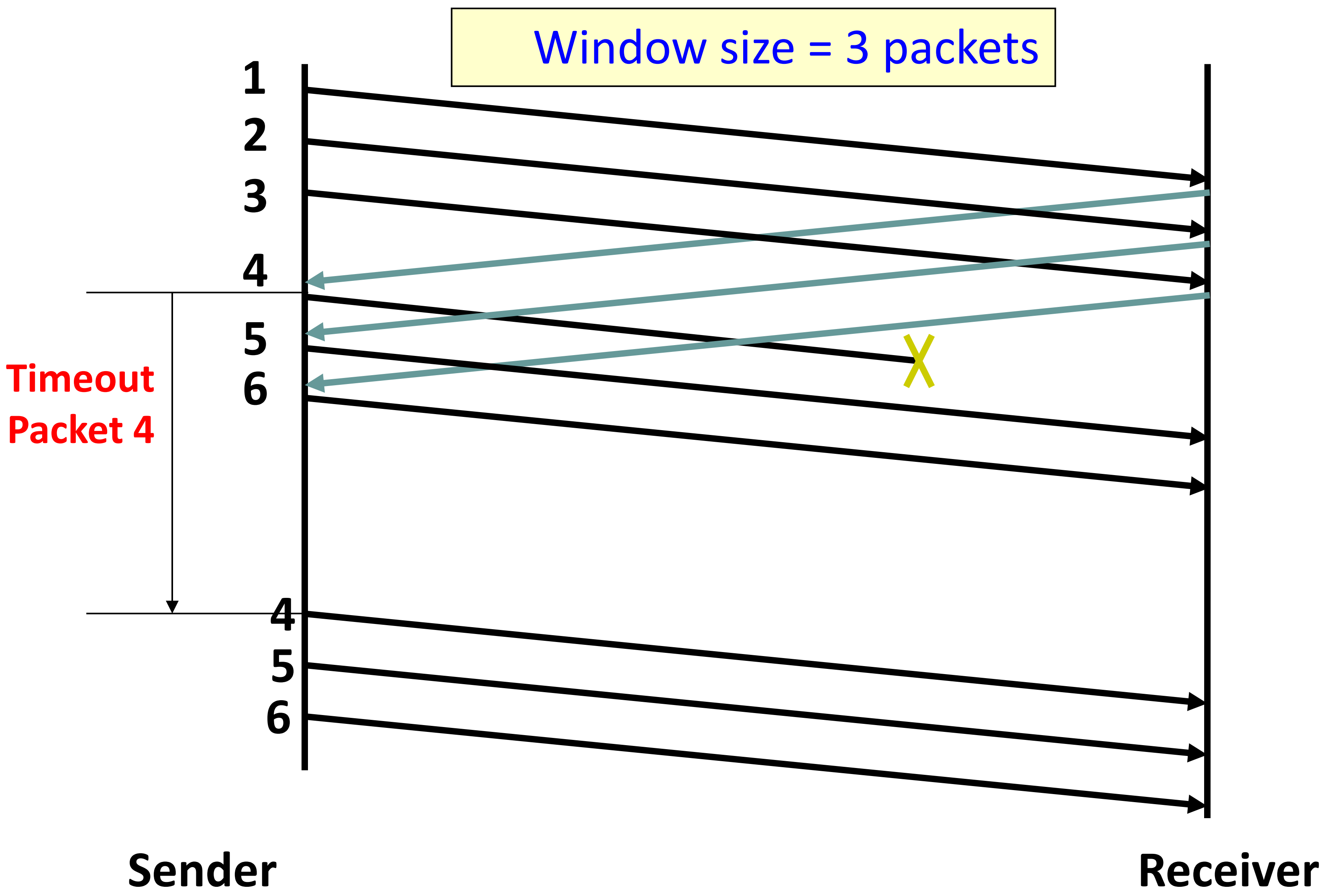
Go-Back-N

- Simple algorithm (not advisable, but simple)
- Sender’s window allows up to W **contiguous** packets to be outstanding (i.e., a sliding window)
- When a loss is detected by timeout, resend all W packets starting with loss
- Receiver discards out-of-order packets
  - And acks packets that arrive in order (individual ACK)

GBN Example w/o Errors



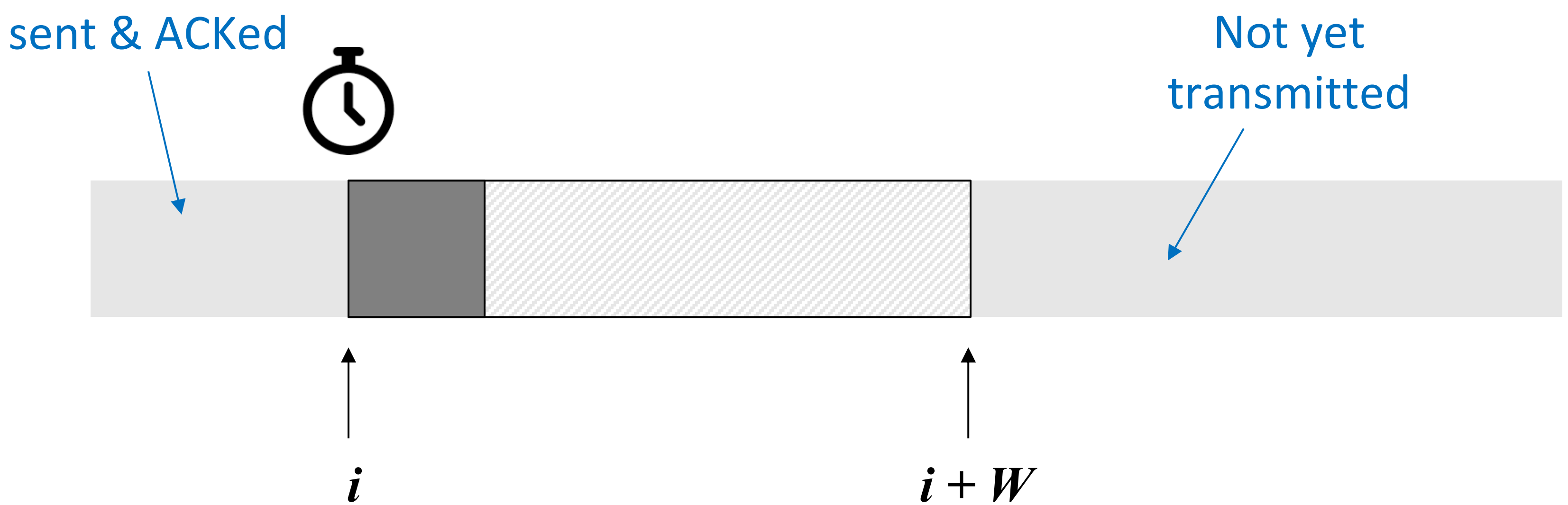
GBN Example with Errors



At a glance: 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 hybrid form of ACKs (SACK)
  - Timer (w/ timer estimation algorithm)

Reliability in TCP

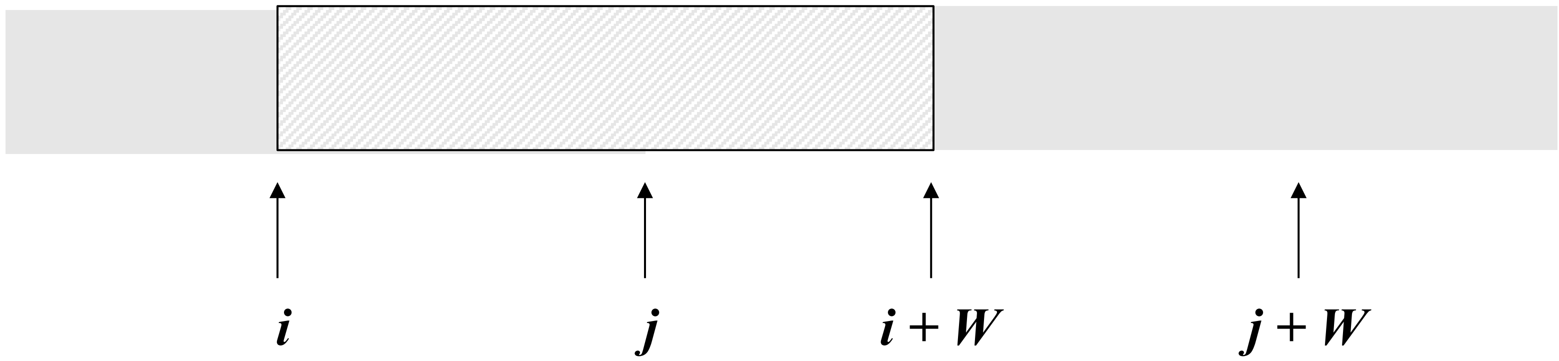


Sender maintains a **sliding** window of W **contiguous** bytes

Sender maintains a single timer, for the LHS of window

On timeout, sender retransmits the packet starting at ***i***

Reliability in TCP



Receiver sends cumulative ACKs; sender counts #dupACKs

Fast Retransmit: Sender retransmits i when #dupACKs = 3

Sender slides window on receiving an ACK for new data ($j > i$)

Questions?