# CS 352
# Reliability: Pipelined Delivery

Lecture 12

http://www.cs.rutgers.edu/~sn624/352-F22

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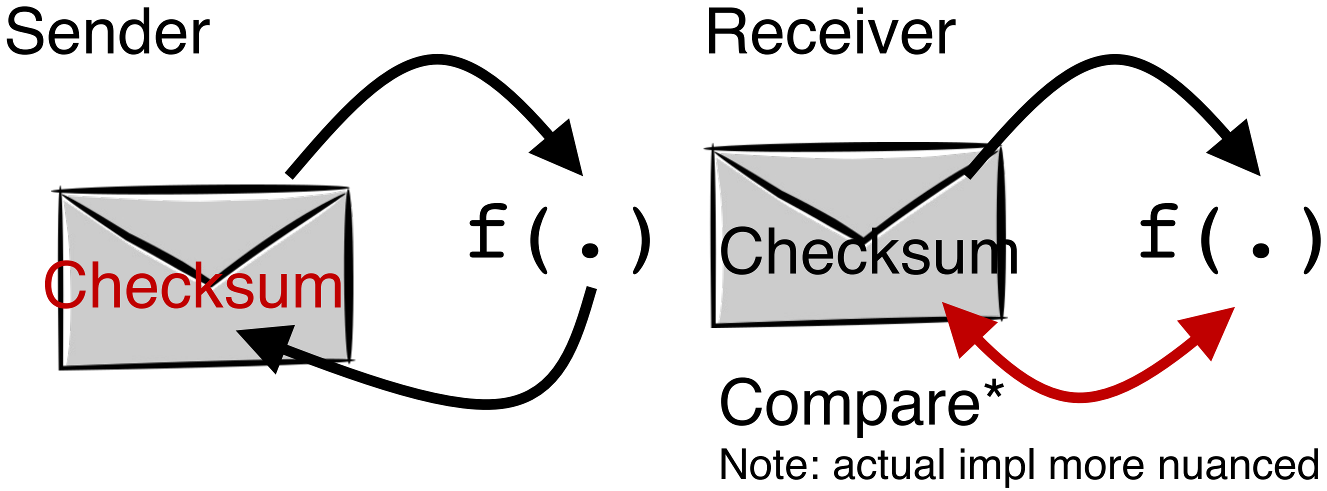
# Quick recap of concepts


## UDP
Connectionless

## TCP
Connection-oriented

Error detection




Detecting errors is insufficient.
Need to correct errors.

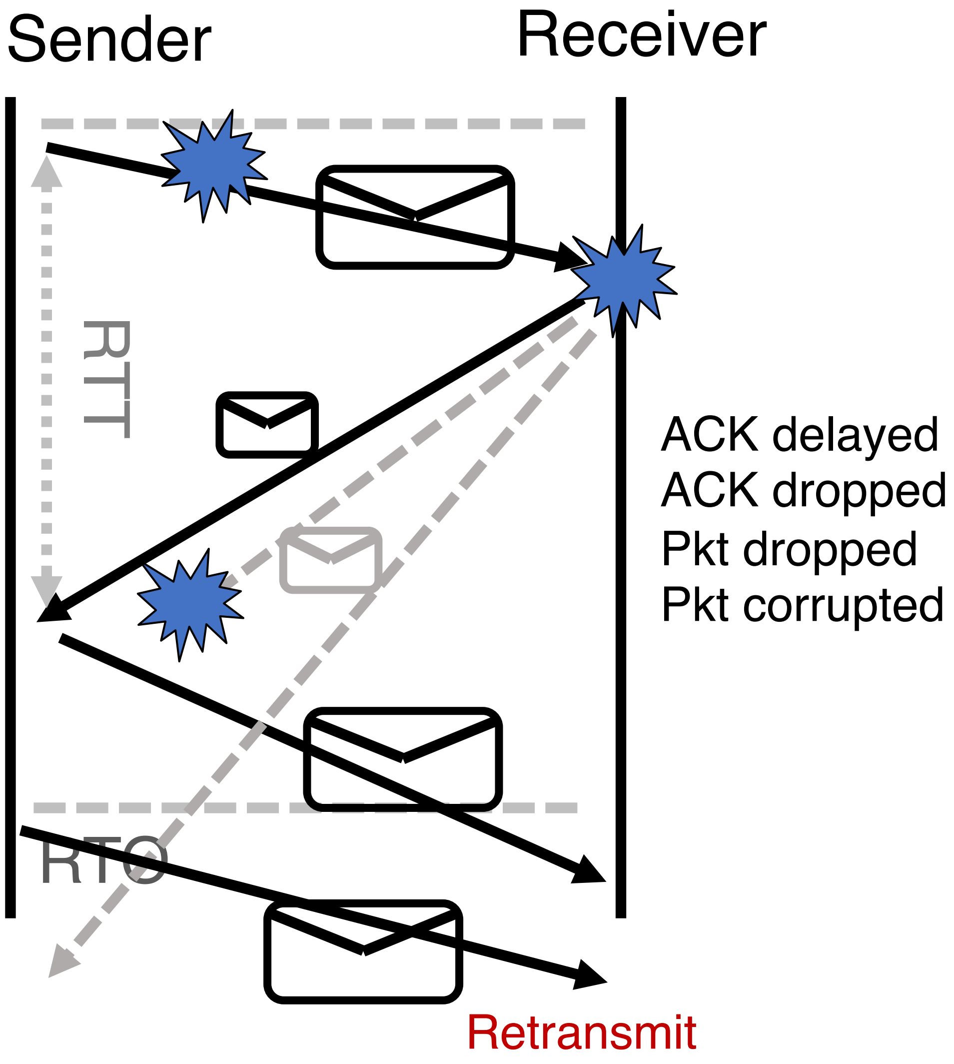
Also, data may simply be lost.
(checksum is also lost)

Need better mechanisms for reliable data delivery!

TCP uses 3 simple ideas

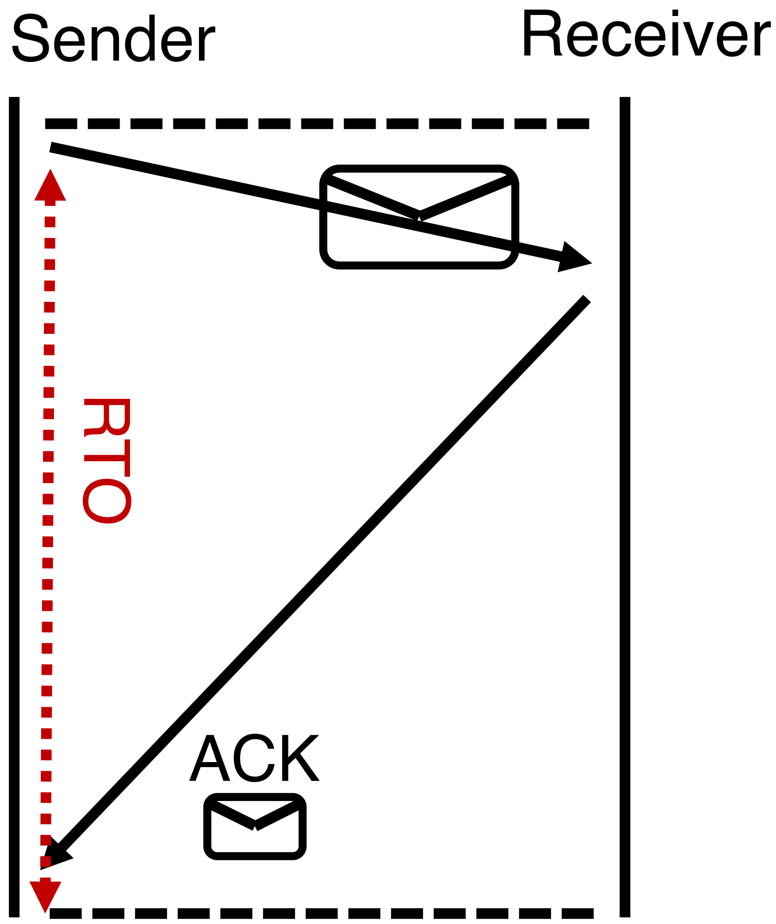
# Review:

- Sender sends a single packet, then waits for an ACK to know the packet was successfully received. Then the sender transmits the next packet.
- If ACK is not received until a timeout (RTO), sender retransmits the packet
- How to set the RTO?
  - Bad RTO: retransmit too early or too late



# How should the RTO be set?

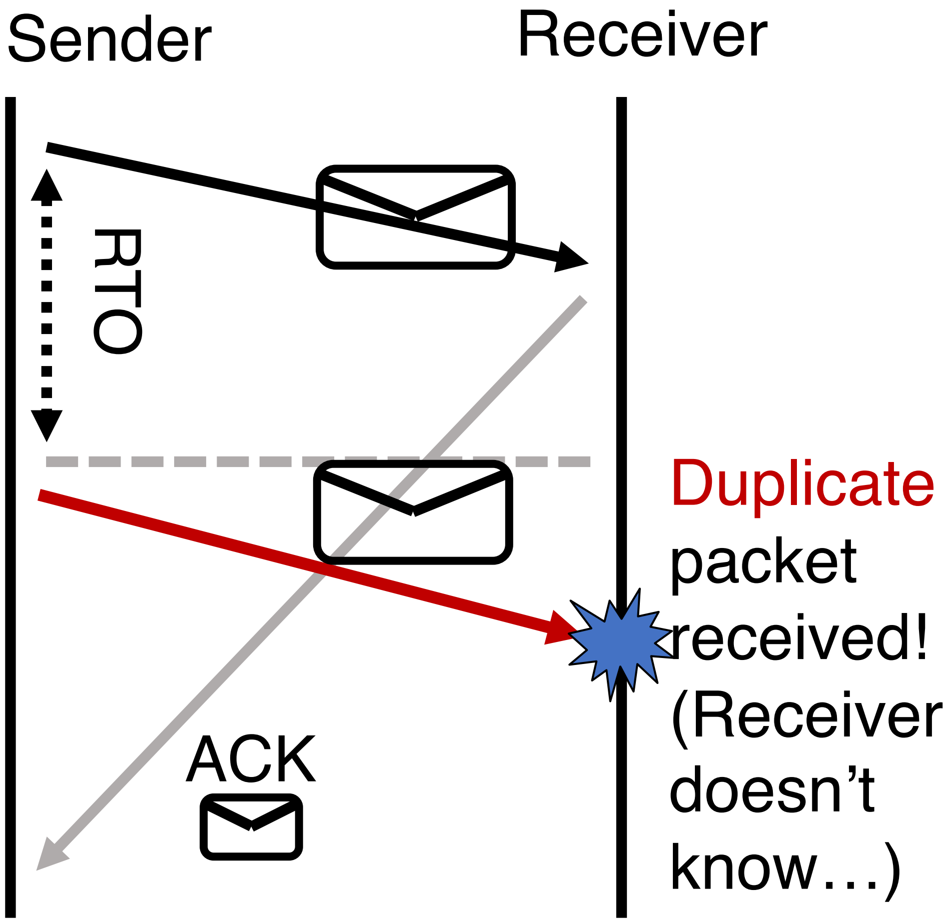
- A good RTO must predict the round-trip time (RTT) between the sender and receiver
  - RTT: the time to send a single packet and receive a (corresponding) single ACK at the sender
- Intuition: If an ACK hasn't returned, and our (best estimate of) RTT has elapsed, the packet was likely dropped.
- RTT can be measured directly at the sender. No receiver or router help needed.



# Coping with packet duplication

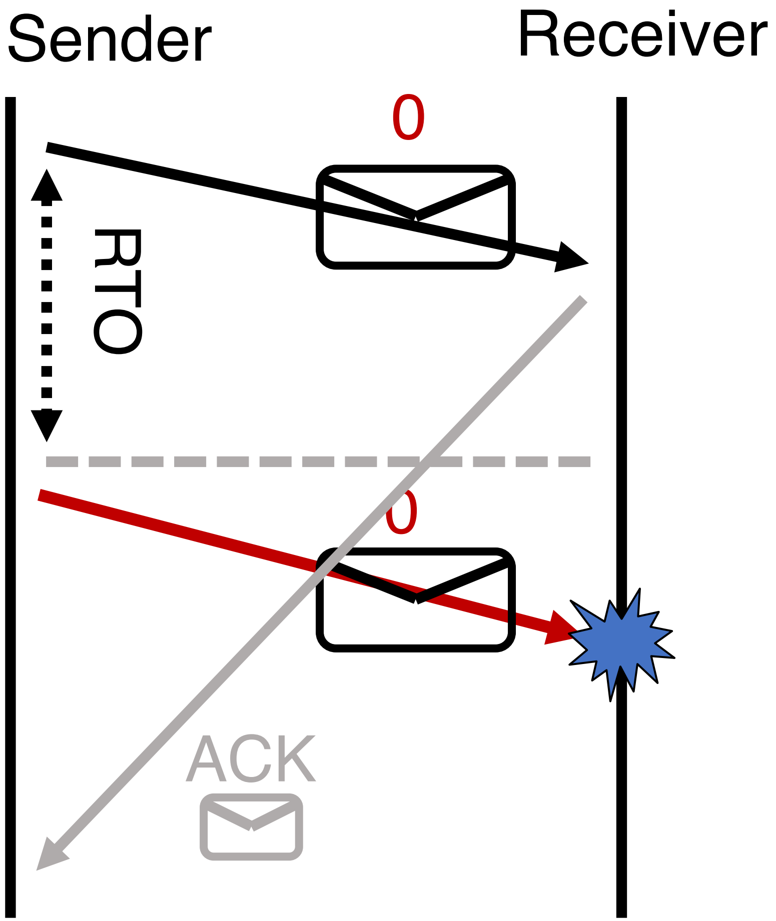
- If ACKs delayed beyond the RTO, sender may retransmit the same data
  - Receiver wouldn't know that it just received duplicate data from this retransmitted packet

- Add some identification to each packet to help distinguish between adjacent transmissions
  - This is known as the sequence number



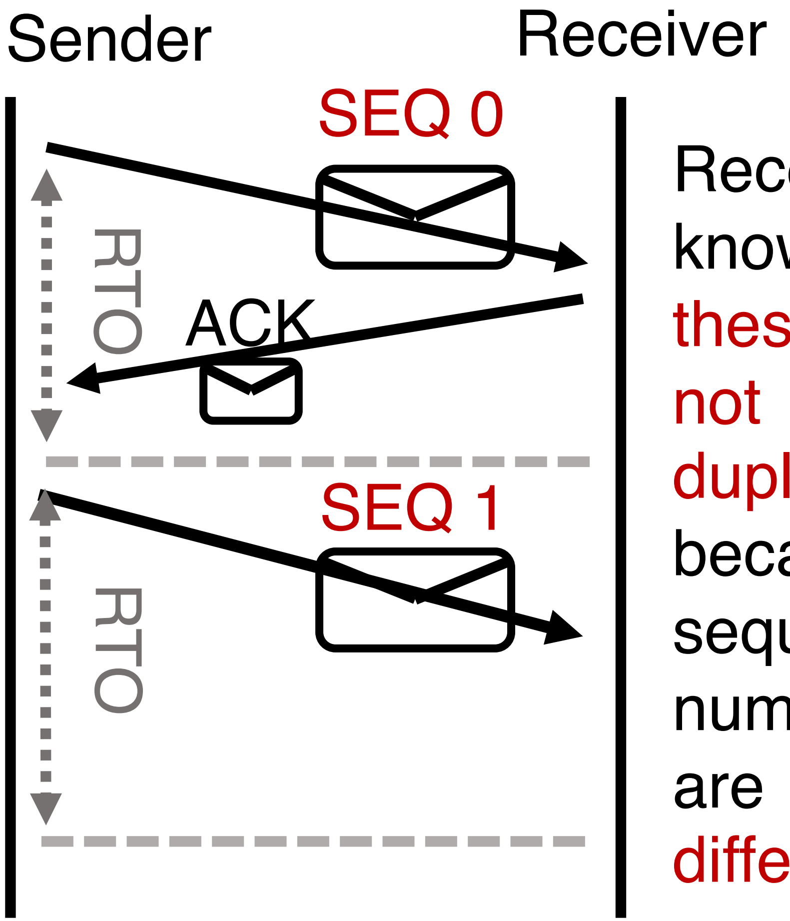
# Coping with packet loss: (3) Sequence #s

- A bad scenario: Suppose an ACK was delayed beyond the RTO; sender ended up retransmitting the packet.
- At the receiver: sequence number helps disambiguate a fresh transmission from a retransmission
  - Sequence number same as earlier: retransmission
  - Fresh sequence number: fresh data



# Coping with packet loss: (3) Sequence #s

- A good scenario: packet successfully received and ACK returned within RTO
- Sequence numbers of successively transmitted packets are different




Receiver knows these are not duplicate, because sequence numbers are different

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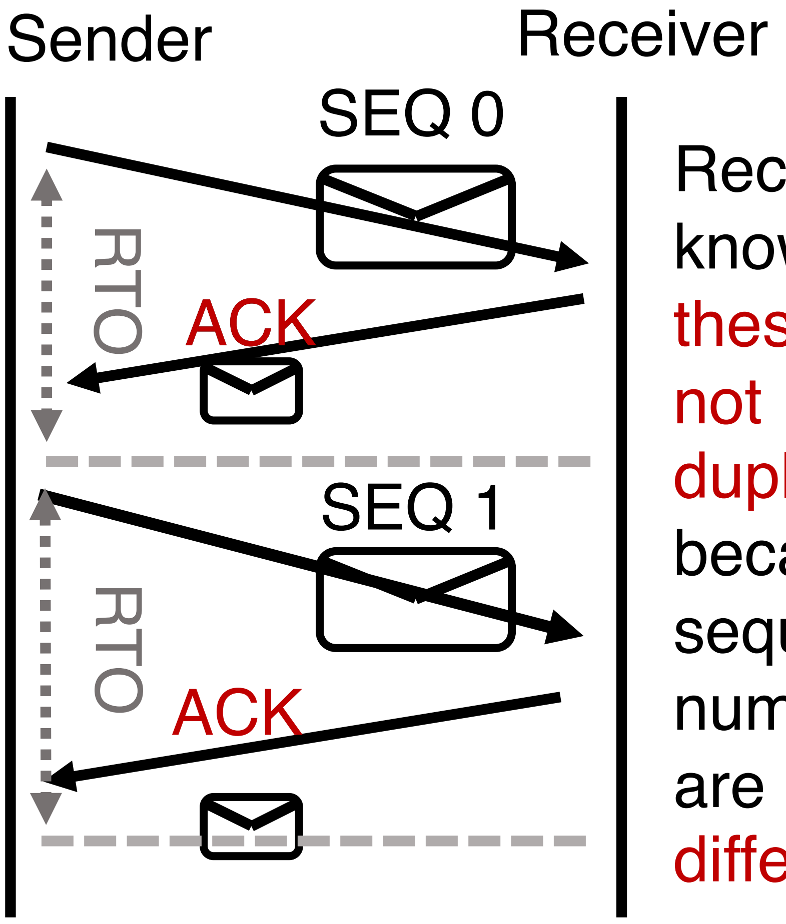
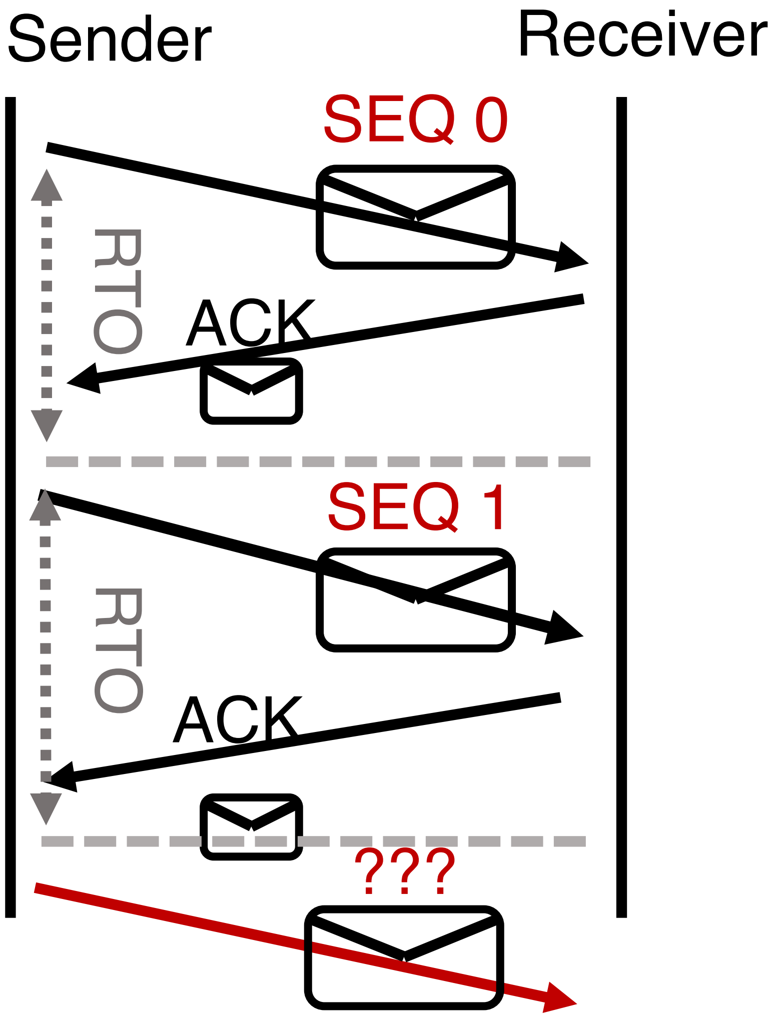



Receiver knows these are not duplicate, because sequence numbers are different

# Q: What is the seq# of third packet?

- Goal: Avoid ambiguity on which packet was received/ACK'ed from both the sender and receiver's perspective
- One option: increment seq#: 2, 3, …
- Alternative: since seq # 0 was successfully ACK'ed earlier, it is OK to reuse seq #0 for next transmission.
- Seq #s reusable if older packets with those seq #s known to be delivered

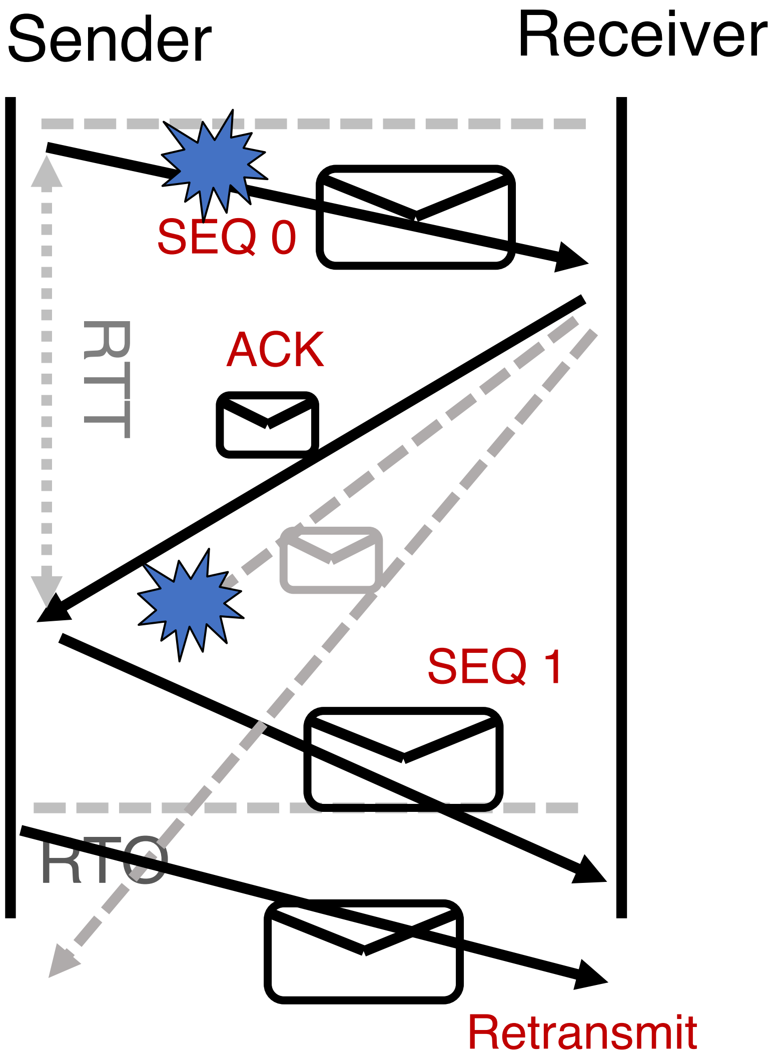


# Stop-and-Wait Reliability

- Sender sends a single packet, then waits for an ACK to know the packet was successfully received. Then the sender transmits the next packet.

- If ACK is not received until a timeout (RTO), sender retransmits the packet

- Disambiguate duplicate vs. fresh packets using sequence numbers that change on “adjacent” packets



In principle, these three ideas are sufficient to implement reliable data delivery!

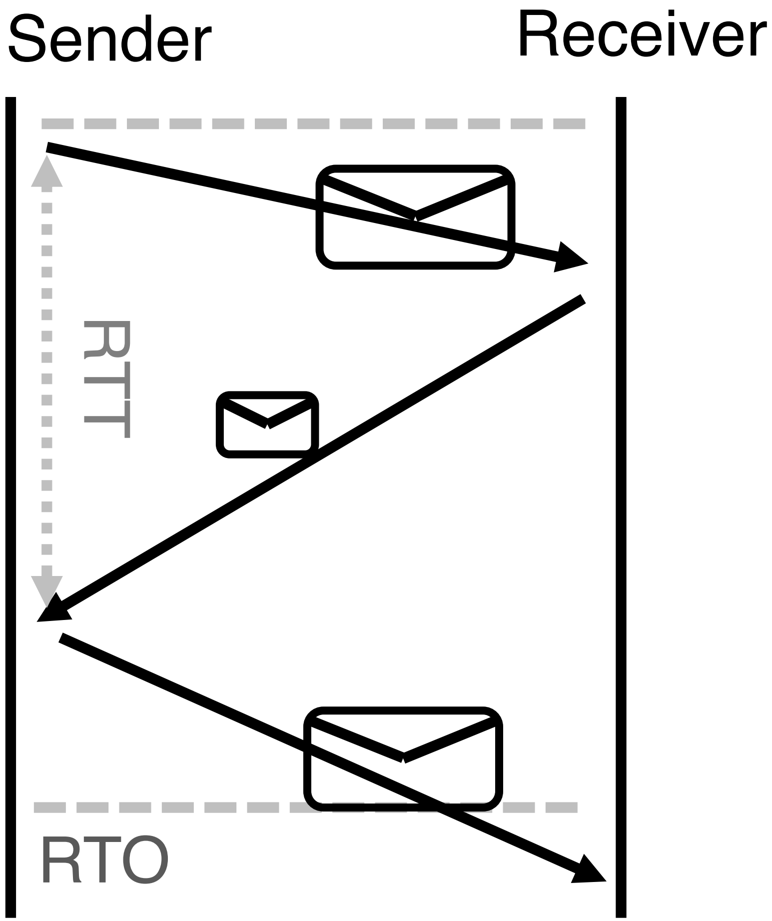
# Making reliable data transfer efficient

# Efficiency problem with stop-and-wait

- Sender sends one packet, waits for an ACK (or RTO) before transmitting next one
  - Unfortunately, too slow ☹

- Suppose RTO = RTT = 100 milliseconds
- Packet size (bytes in 1 packet) = 12,000 bits
- Bandwidth of links from sender to receiver = 12 Mbit/s (1 M = $10^6$)

- Rate of data transfer = data size / time

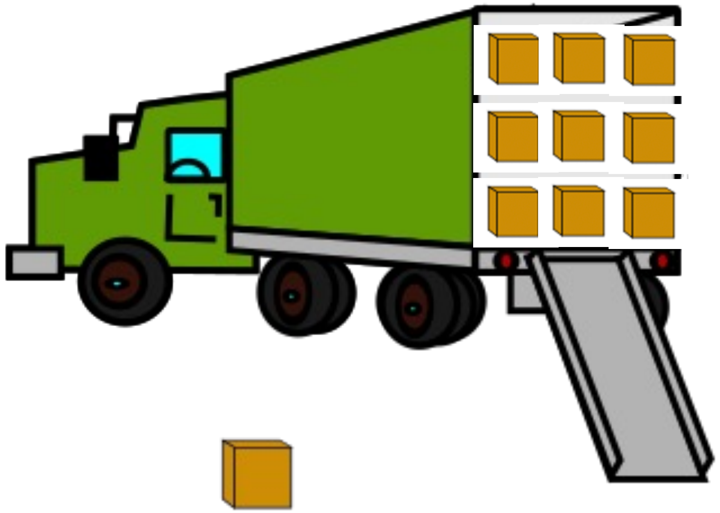



120 Kilobit/s == 1% of bw!

Sending one packet per RTT makes the data transfer rate limited by the time between the endpoints, rather than the bandwidth.

Ensure you got the (one) box safely; make N trips

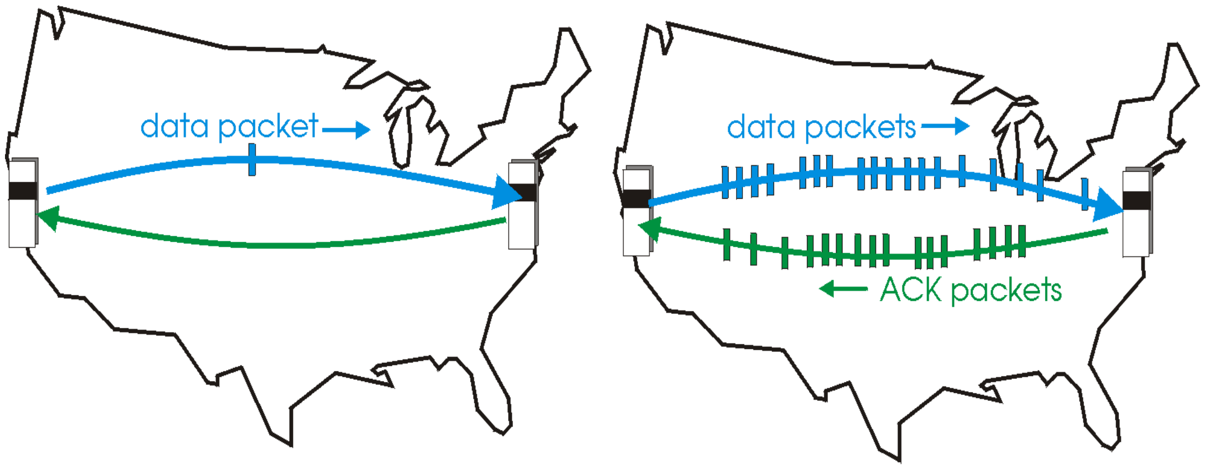
Ensure you get N boxes safely; make just 1 trip!



Keep many packets in flight

# Pipelined reliability

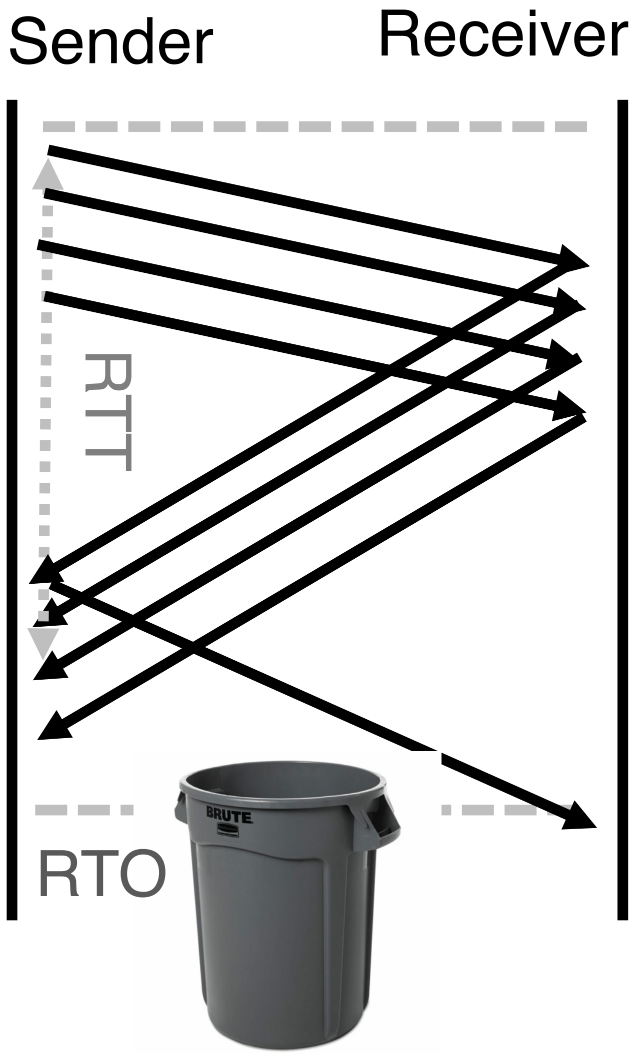
- Data in flight: data that has been sent, but sender hasn’t yet received ACKs from the receiver
    - Note: can refer to packets in flight or bytes in flight
- New packets sent at the same time as older ones still in flight
- New packets sent at the same time as ACKs are returning
- More data moving in same time!
- Improves throughput
    - Rate of data transfer




(a) a stop-and-wait protocol in operation (b) a pipelined protocol in operation

# Pipelined reliability

- Stop and wait: send 1 packet per RTT
- Pipelined: send N packets per RTT
- If there are N packets in flight, throughput improves by N times compared to stop-and-wait!



Pipelining makes reliable data transfer efficient.

However, pipelining also makes it more complex.

Which packets are currently in flight?

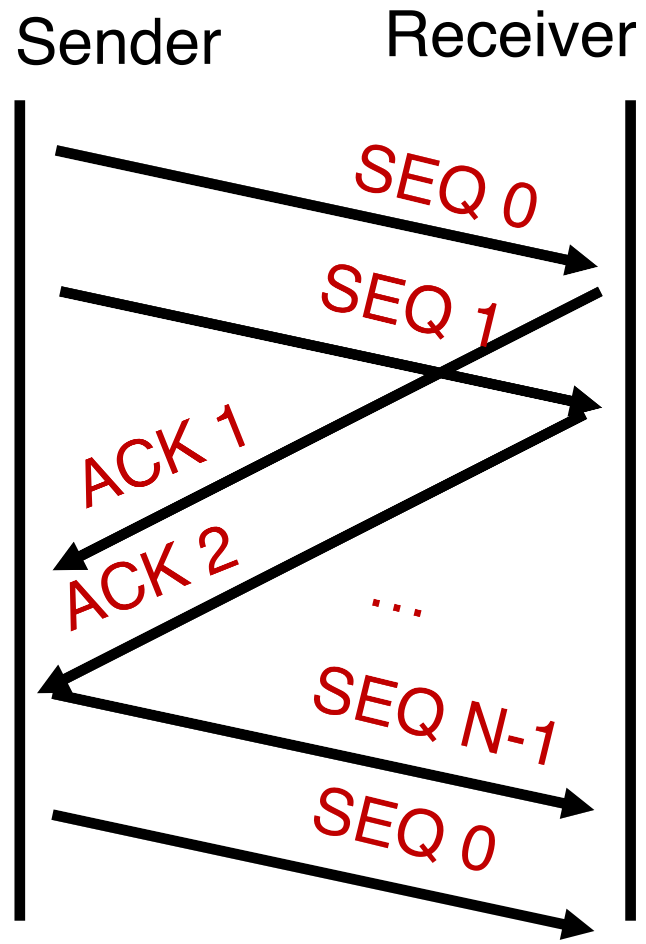
Which packets were successfully delivered?

Which packets should the sender retransmit?

# Sliding Windows

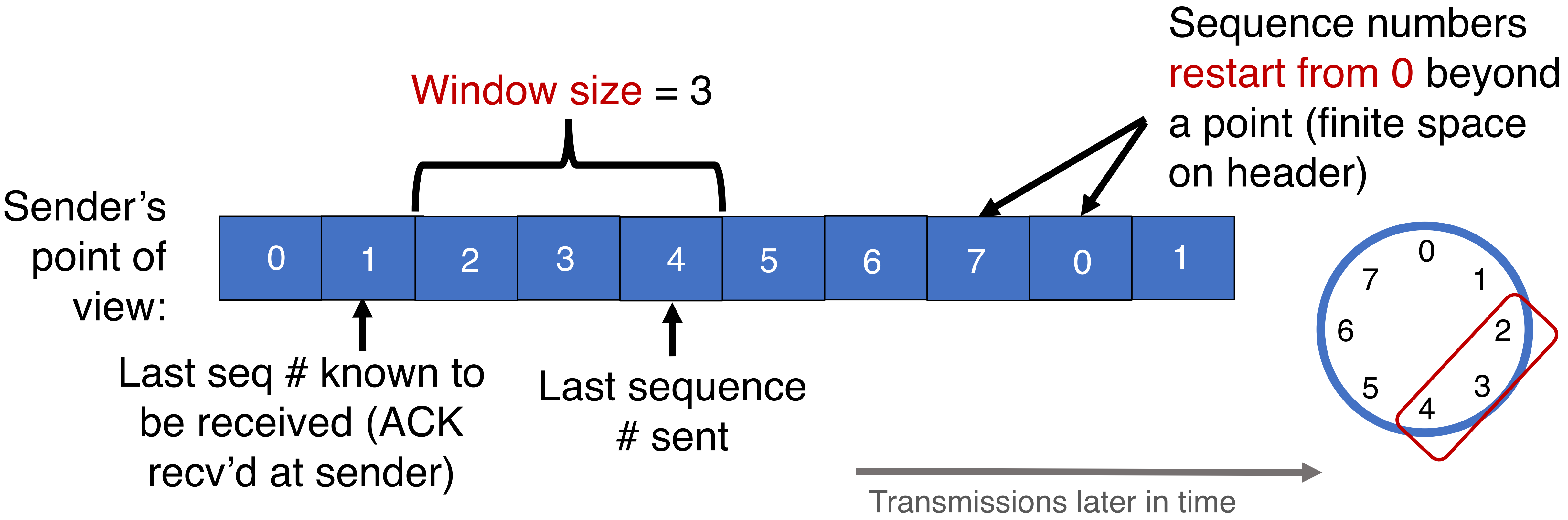
# Setup

- Assume packets are labeled by sequence numbers
  - Increasing from 0, …, N-1, then roll back to 0
- Assume ACKs indicate the sequence numbers of data that was received
  - Note: Didn't need this for stop-and-wait
- Convention: ACK#s carry the next sequence number expected
  - Used in TCP.



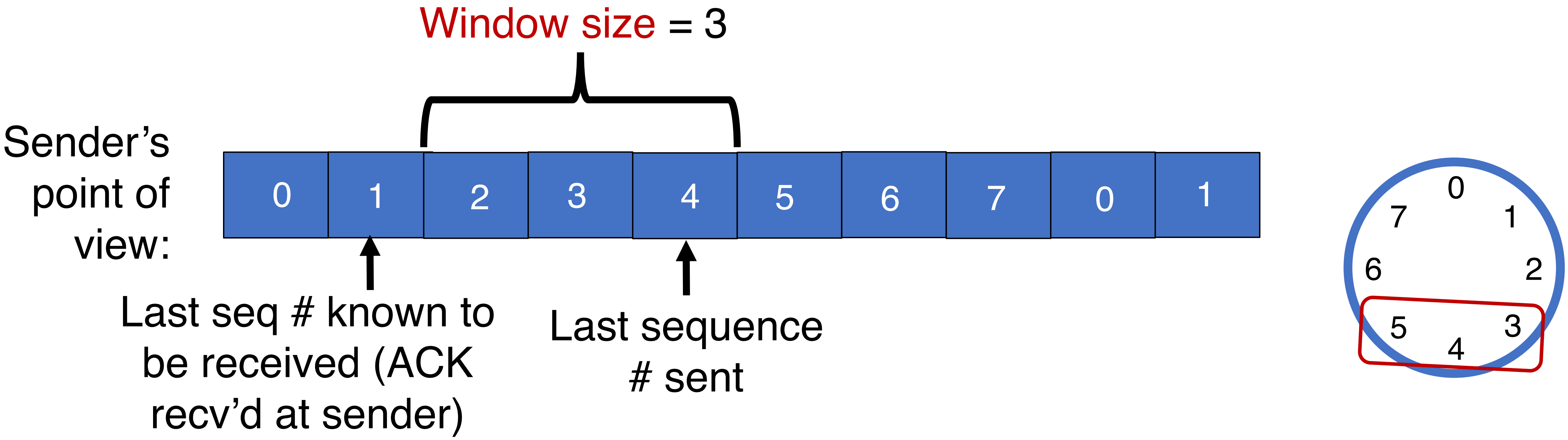
# Sliding window (sender side)

- Window: Sequence numbers of in-flight data
- Window size: The amount of in-flight data (unACKed)



# Sliding window (sender side)

- Suppose sequence number 2 is acknowledged by the receiver
  - Sender receives the ACK. Sender can transmit sequence # 5
  - The window “slides” forward



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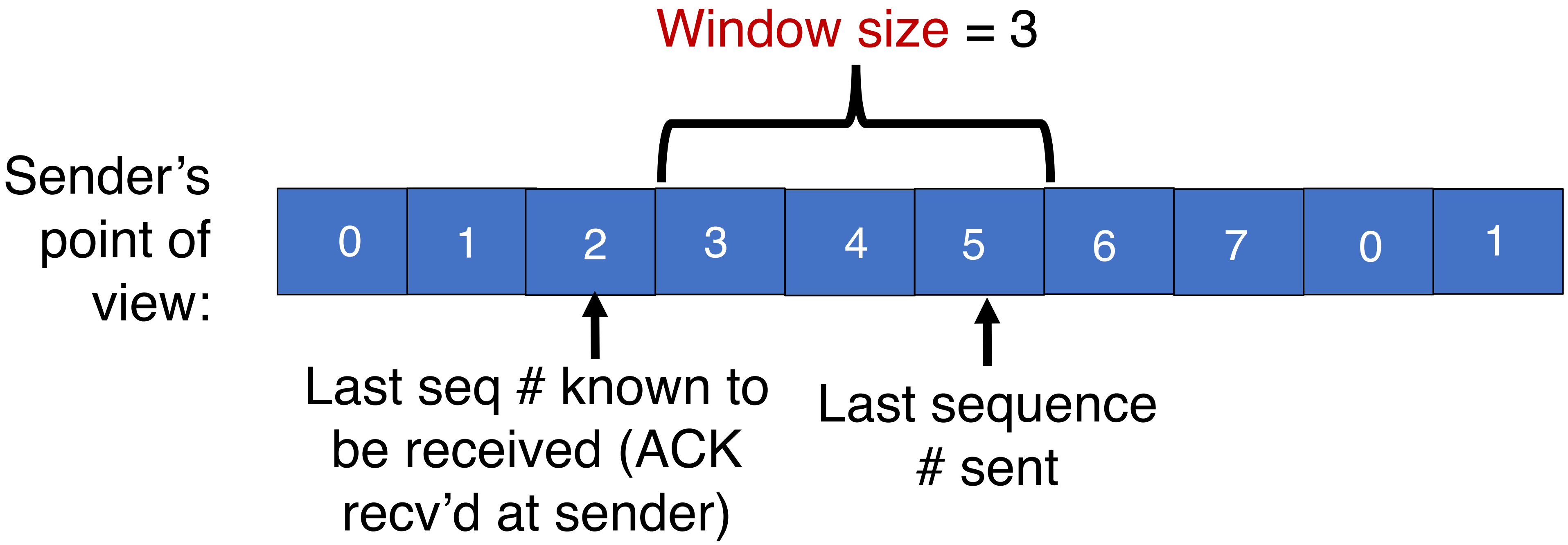
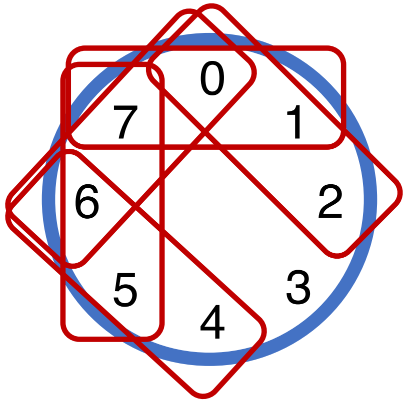
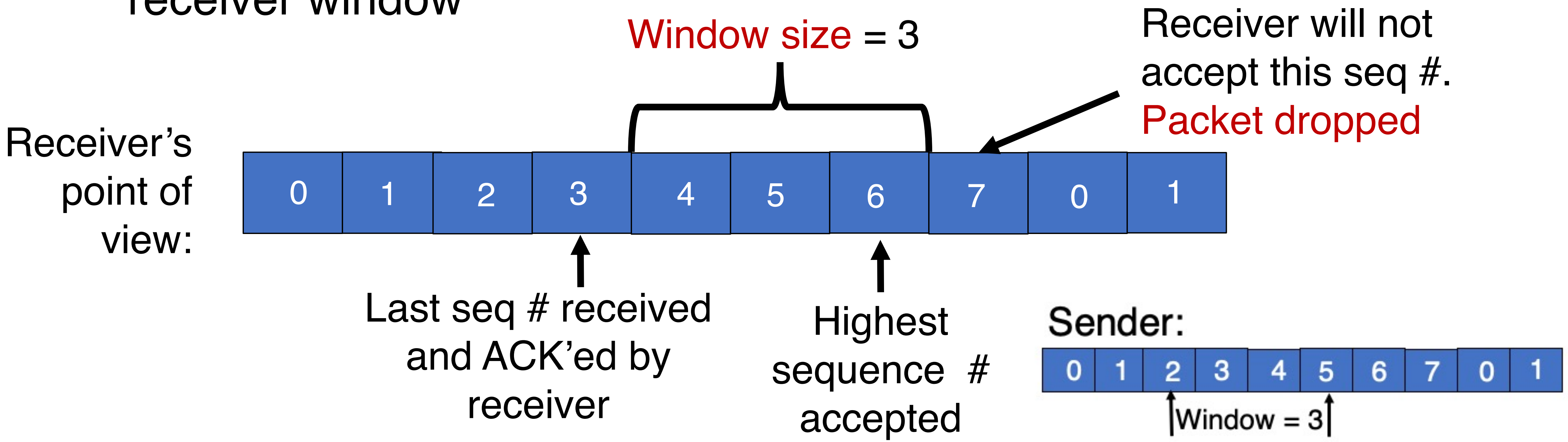


# Sliding window (receiver side)

- Window of in-flight packets can look different between sender and the receiver
- Receiver only accepts sequence #s allowed by the current receiver window



# Summary of sliding windows

- Sender and receiver can keep several packets of in-flight data
  - Book-keep the sequence numbers using the window
- Windows slide forward as packets are ACKed (at receiver) and ACKs are received (at sender)
- Common case: Improve throughput by sending and ACKing more packets in the same duration

Pipelining makes reliable data transfer efficient.

However, pipelining also makes it more complex.

Which packets are currently in flight?

Which packets were successfully delivered?

Which packets should the sender retransmit?

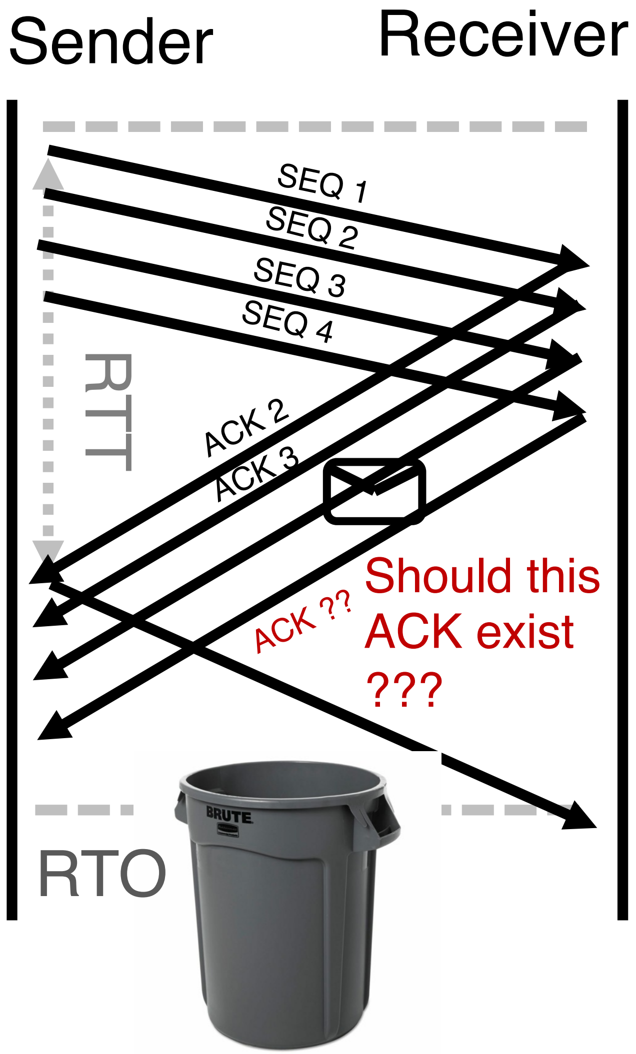
# Which packets to retransmit?

# How to identify dropped packets?

- Suppose 4 packets sent, but 1 dropped. How does sender know which one(s) dropped?

- Recall: Receiver writes sequence numbers on the ACK indicating successful reception
- Key idea: Sender can infer which data was received successfully using the ACK #s!
  - Hence, sender can know which data to retransmit

- Q1: Should receivers ACK subsequent packets upon detecting data loss?
- Q2: If so, what sequence number should receiver put on the ACK?



# Receiver strategies upon packet loss

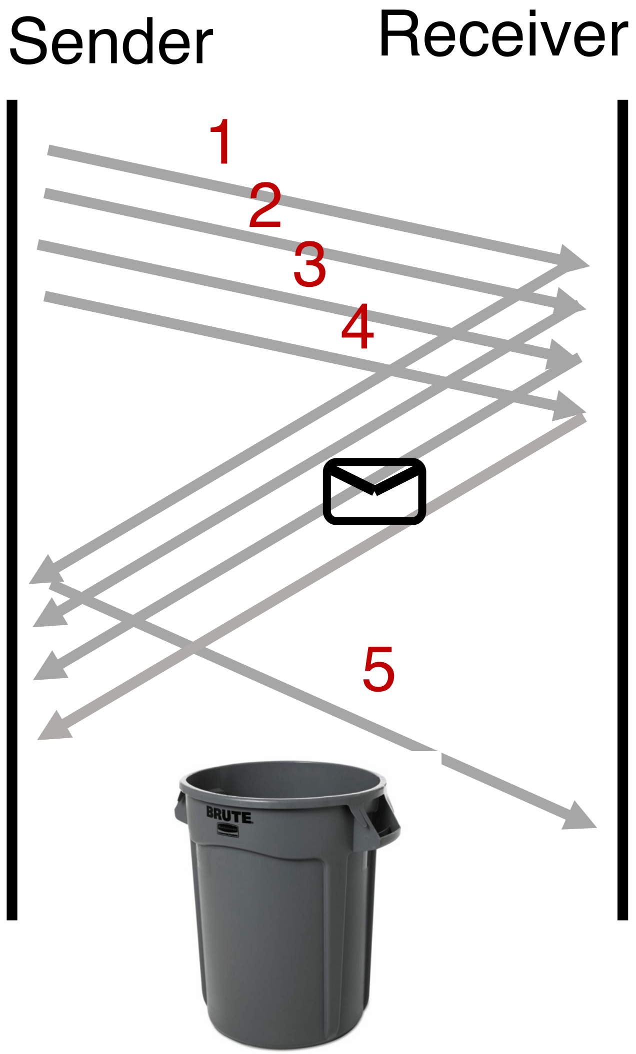
ACK pkts after a drop?

No — **Go-back-N**

Yes — **Selective Repeat**

What # on ACK?

- Last seq# in order — **Cumulative ACK**
- Seq# *ranges* received so far — **Selective ACK** (TCP's default)



# Sliding Window with Go Back N

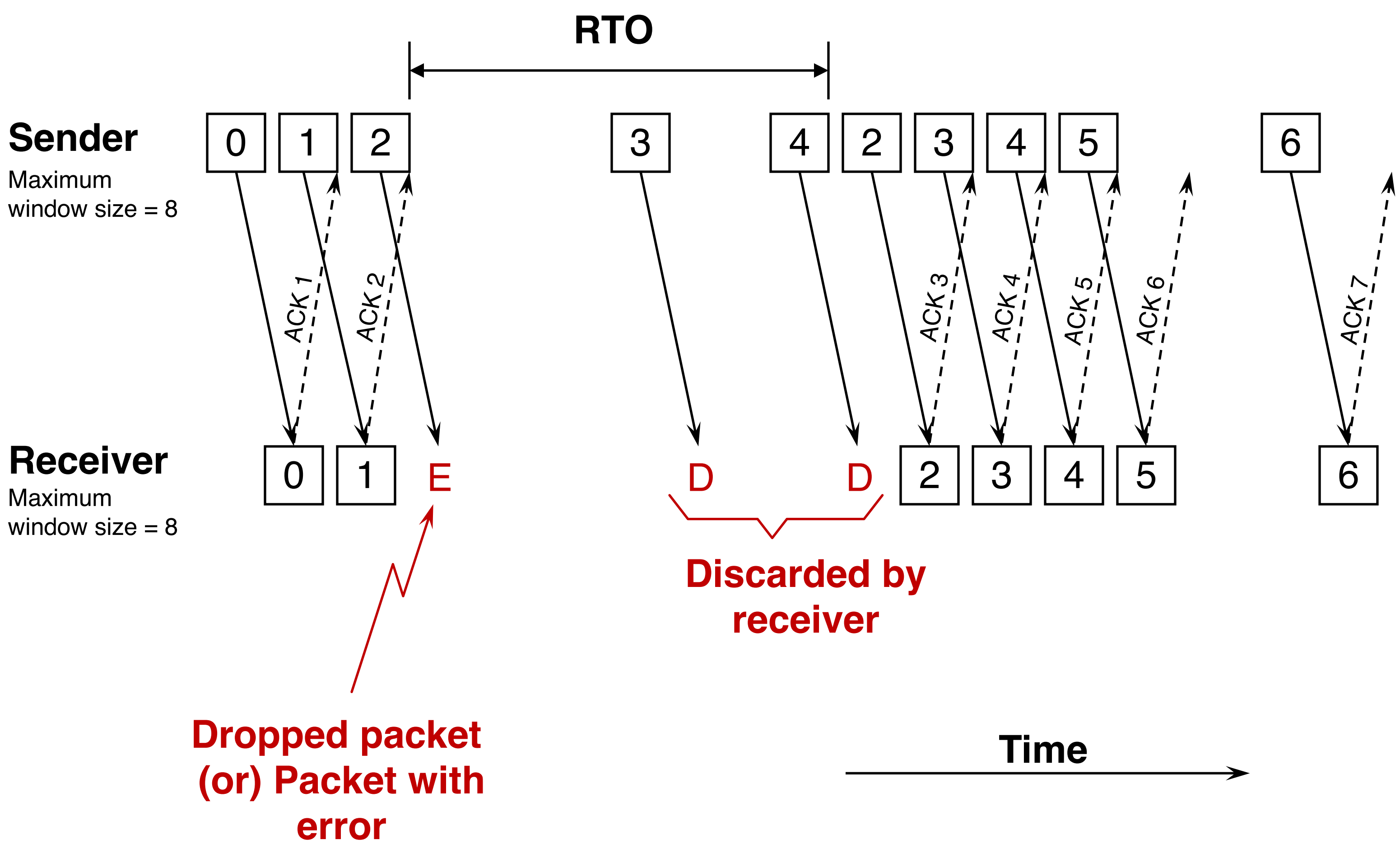
- When the receiver notices missing data:

- It simply discards all data with greater sequence numbers
    - i.e.: the receiver will send no further ACKs

- The sender will eventually time out (RTO) and retransmit all the data in its sending window

- Subtle: conceptually, separate timer per byte to infer RTO

# Go back N


RTO
Sender
Maximum
window size = 8
0
1
2
3
4
2
3
4
5
6
ACK 1
ACK 2
ACK 3
ACK 4
ACK 5
ACK 6
ACK 7
Receiver
Maximum
window size = 8
0
1
E
D
D
2
3
4
5
6
Discarded by
receiver
Dropped packet
(or) Packet with
error
Time

# Go back N

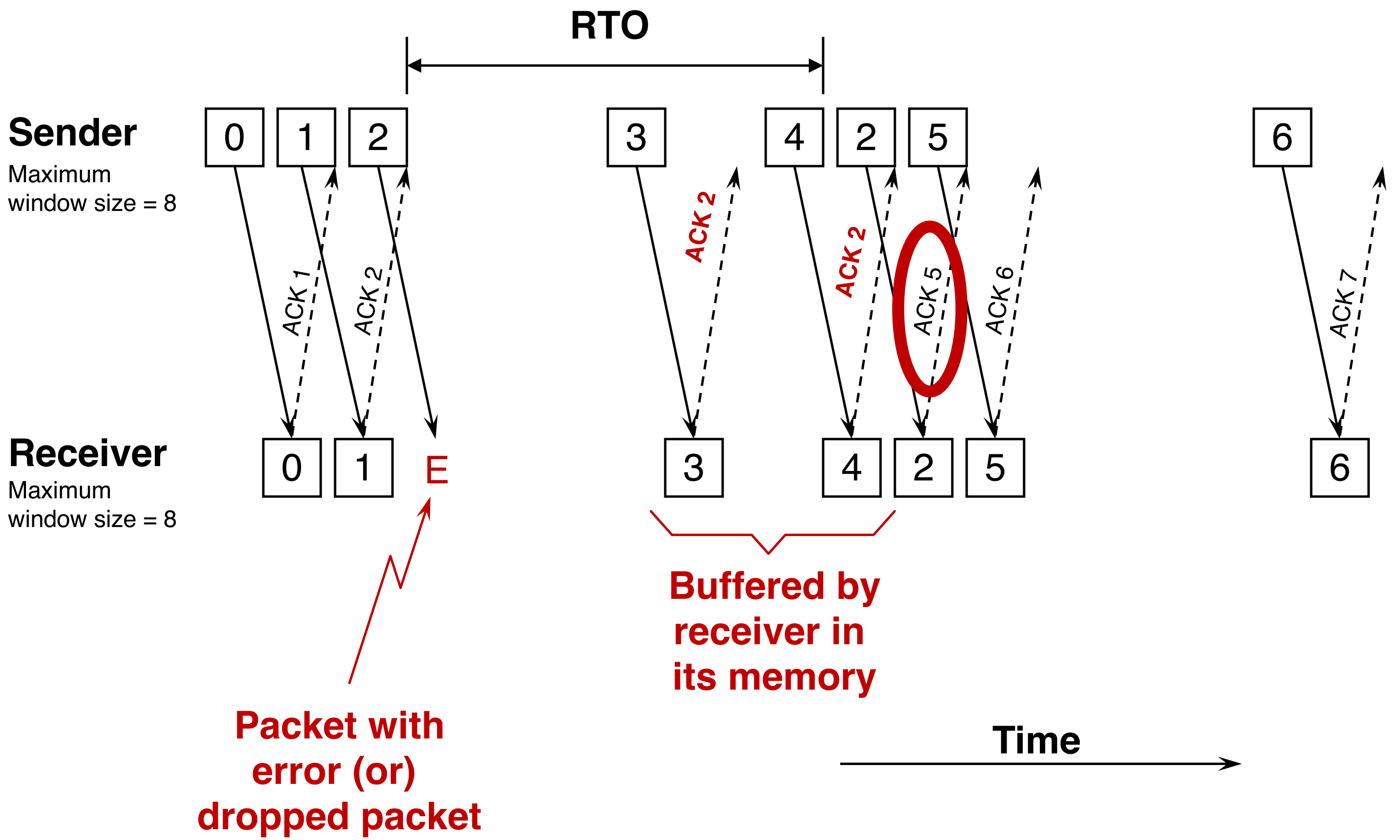
- Go Back N can recover from erroneous or missing packets.
- But it is wasteful.
- If there are errors, the sender will spend time and network bandwidth retransmitting data the receiver has already seen.

# Selective repeat with cumulative ACK

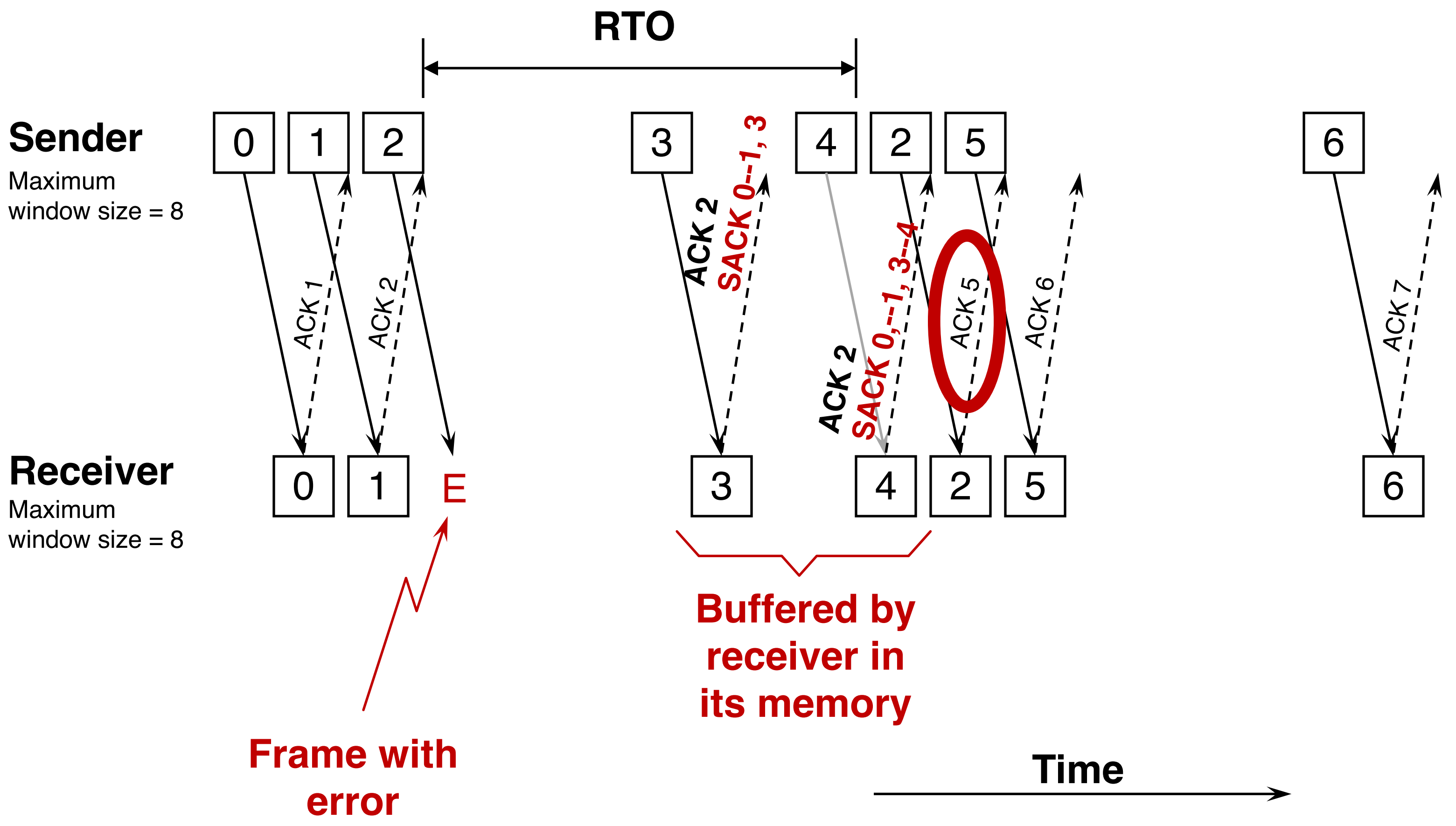
Idea: sender should only retransmit dropped/corrupted data.

- The receiver stores all the correct frames that arrive following the bad one. (Note that the receiver requires memory to hold data for each sequence number in the receiver window.)
- When the receiver notices a skipped sequence number, it keeps acknowledging the first in-order sequence number it wants to receive. This is termed cumulative ACK.
- When the sender times out waiting for an acknowledgement, it just retransmits the first unacknowledged data, not all its successors.
- Recall that RTO applies independently to each sequence #

# Selective repeat with cumulative ACK



# Selective repeat with selective ACK



# TCP: Cumulative & Selective ACKs

- Sender retransmits the seq #s it thinks aren't received successfully yet
- Pros & cons: selective vs. cumulative ACKs
  - Precision of info available to sender
  - Redundancy of retransmissions
  - Packet header space
  - Complexity (and bugs) in transport software
- On modern Linux, TCP uses selective ACKs by default