Ordering & Flow Control

Lecture 15

http://www.cs.rutgers.edu/~sn624/352-F24

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Review: Reliability

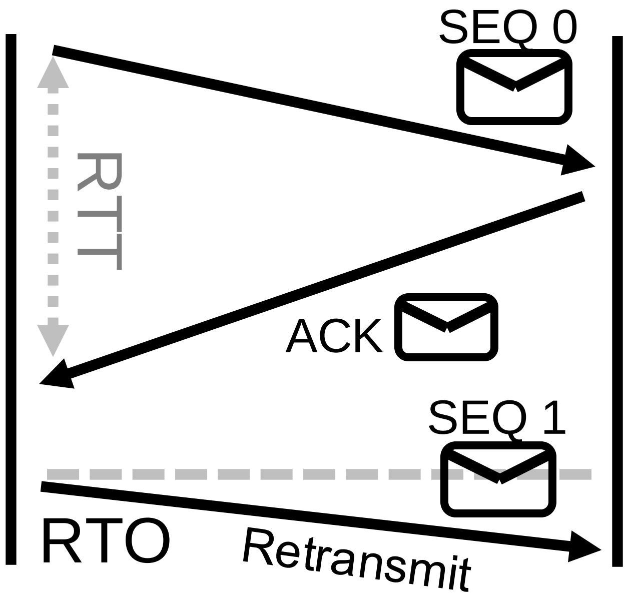
ACK pkts after a drop?

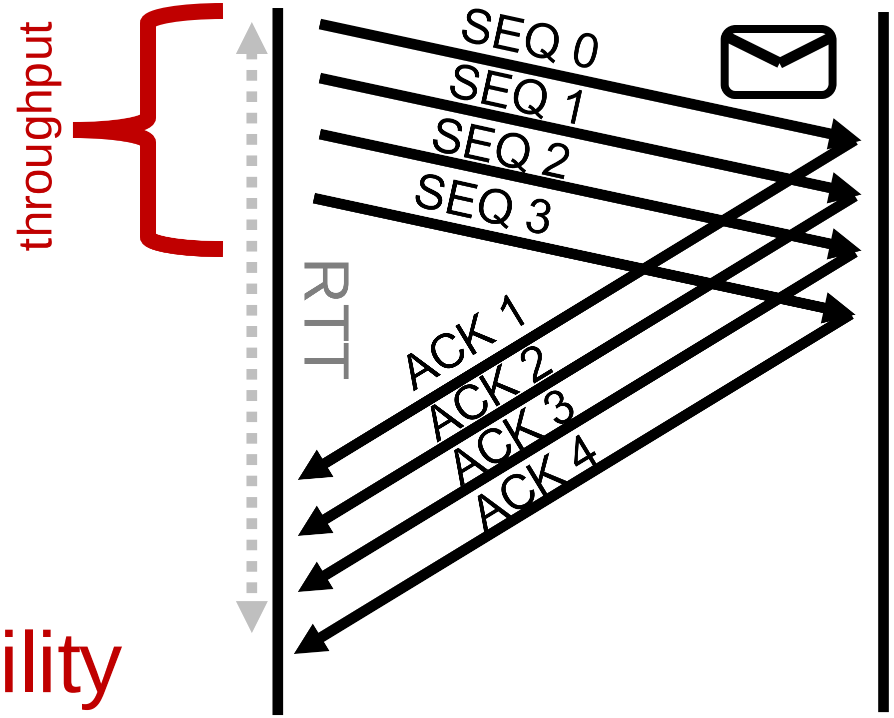
No — Go-back-N

Yes — Selective repeat

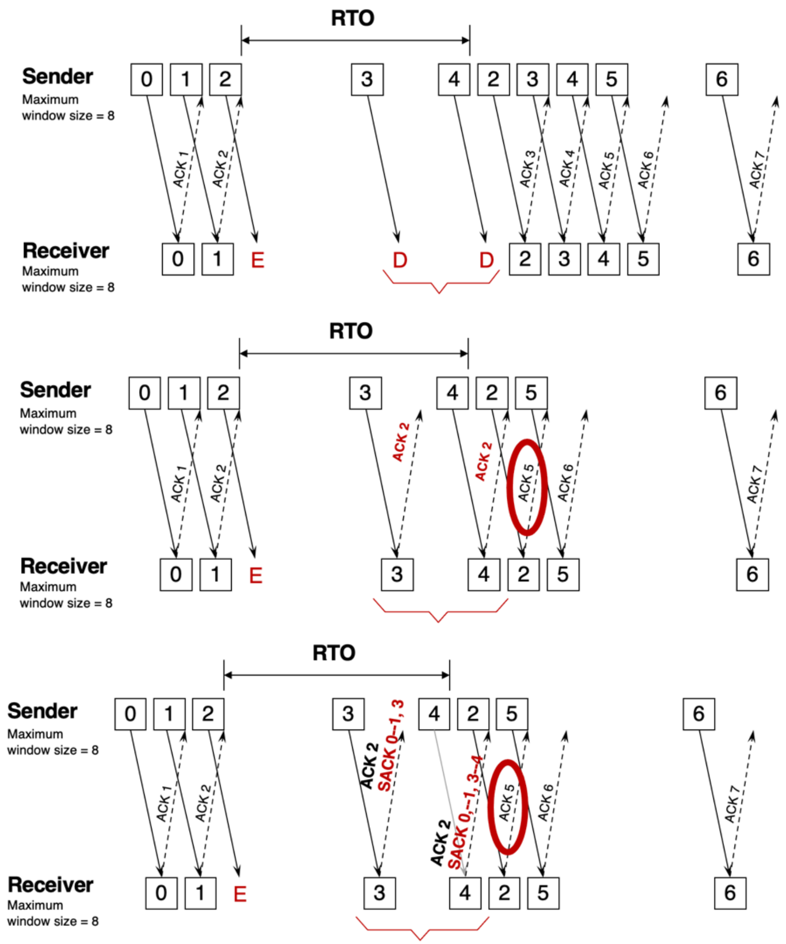
Selective repeat: Cumulative ACK / Selective ACK

Stop and Wait





Pipelined Reliability



TCP reliability metadata

Where are reliability metadata (seq and ack numbers) stored?

TCP header structure

Source port, destination port (connection demultiplexing)

Size of the TCP header (in 32-bit words)

Basic error detection through checksums (similar to UDP)

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 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
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|                        Sequence Number                        |
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|                    Acknowledgment Number                      |
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|  Data |           |U|A|P|R|S|F|                               |
| Offset| Reserved  |R|C|S|S|Y|I|            Window             |
|       |           |G|K|H|T|N|N|                               |
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|           Checksum            |         Urgent Pointer        |
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|                    Options                    |    Padding    |
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|                             data                              |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+

                       TCP Header Format

      Note that one tick mark represents one bit position.
```

TCP header structure

Identifies data in the packet from the application stream

TCP uses byte seq #s

TCP acks the next seq # that the receiver expects.

(cumulative ACK)

Selective ACKs are written into the options field

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
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|          Source Port          |       Destination Port        |
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| Offset| Reserved  |R|C|S|S|Y|I|            Window             |
|       |           |G|K|H|T|N|N|                               |
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|                             data                              |
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                       TCP Header Format

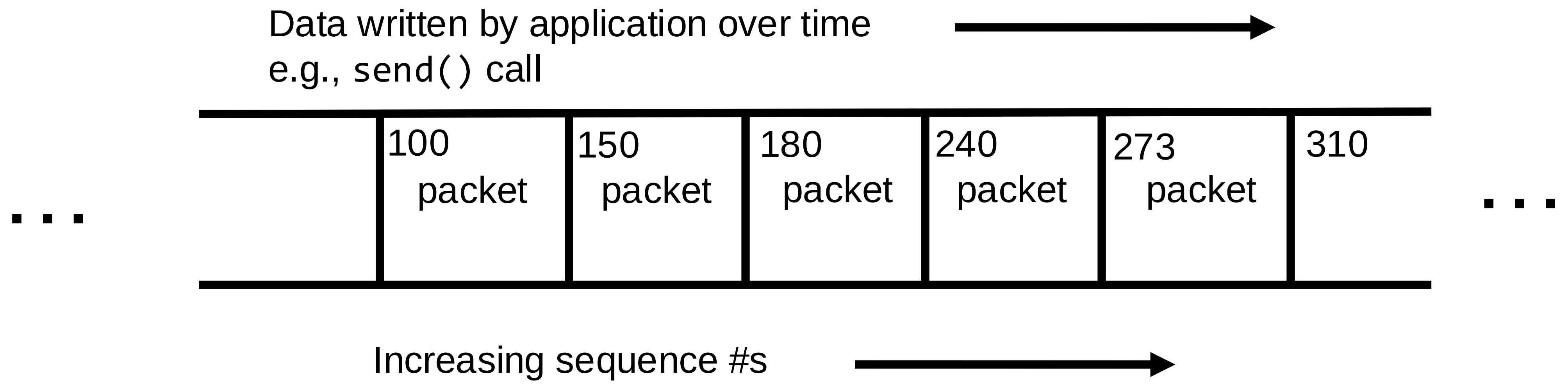
      Note that one tick mark represents one bit position.
```

Observing a TCP exchange

- `sudo tcpdump -i eno1 tcp portrange 56000-56010`
- `curl --local-port 56000-56010 https://www.google.com > output.html`
- Bonus: Try crafting TCP packets with `scapy`!

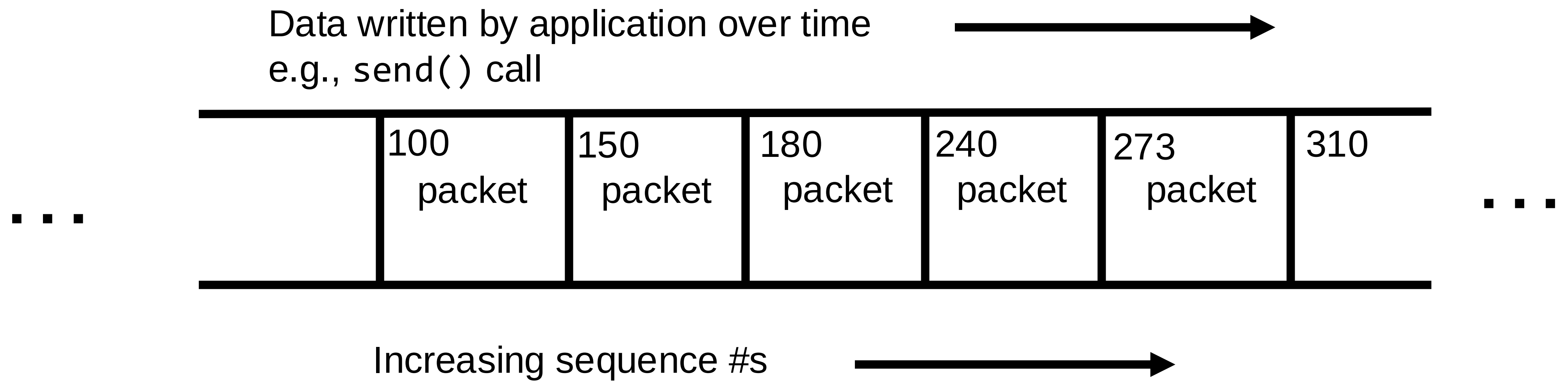
TCP Stream-Oriented Data Transfer

Sequence numbers in the app's stream



TCP uses byte sequence numbers

Sequence numbers in the app's stream

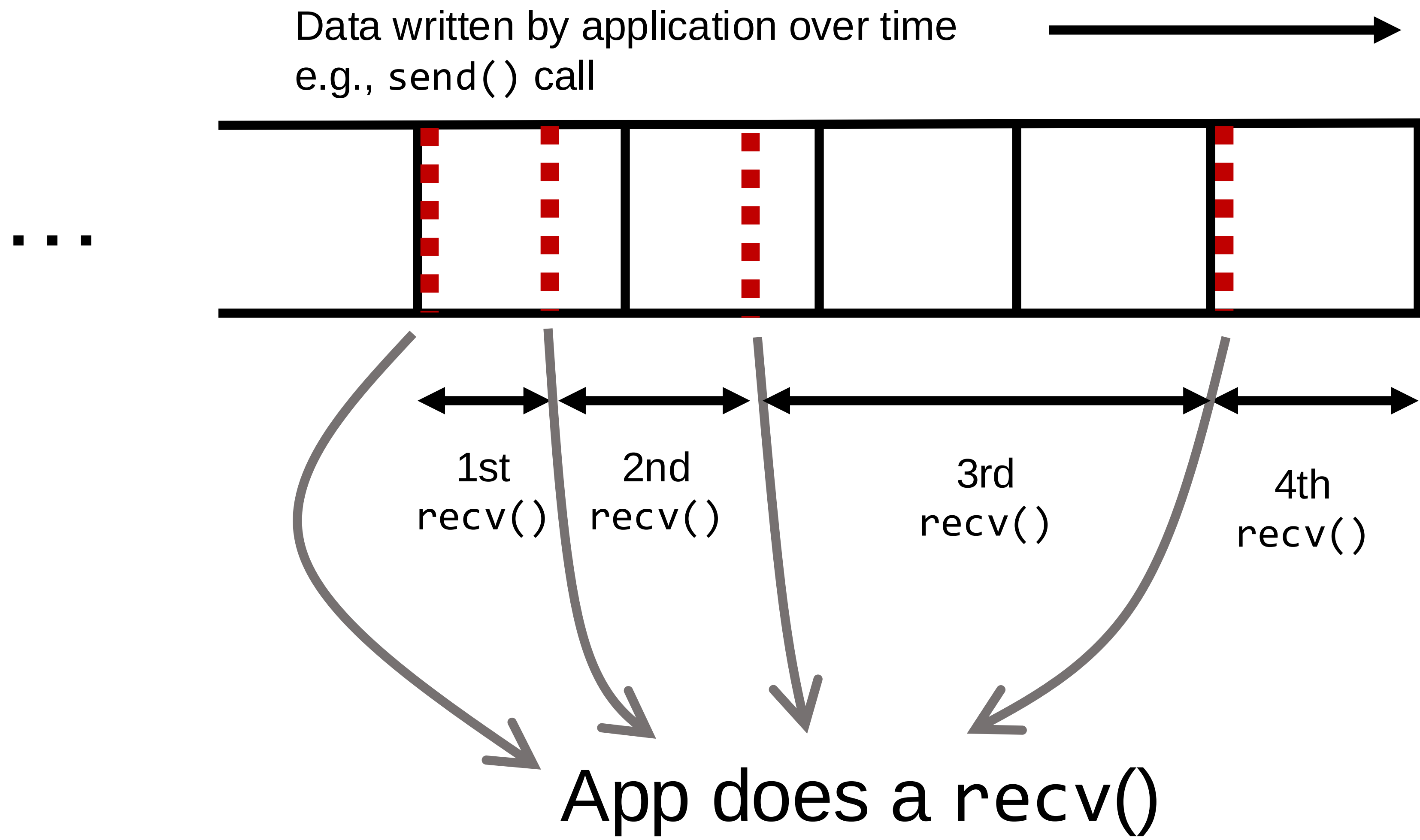


Packet boundaries aren't important for TCP software

TCP is a stream-oriented protocol

(We use `SOCK_STREAM` when creating sockets)

Sequence numbers in the app's stream



A `recv()` call may return a part of a packet, a full packet, or parts of multiple packets (in order).

Buffering and Ordering in TCP

Memory Buffers at the Transport Layer

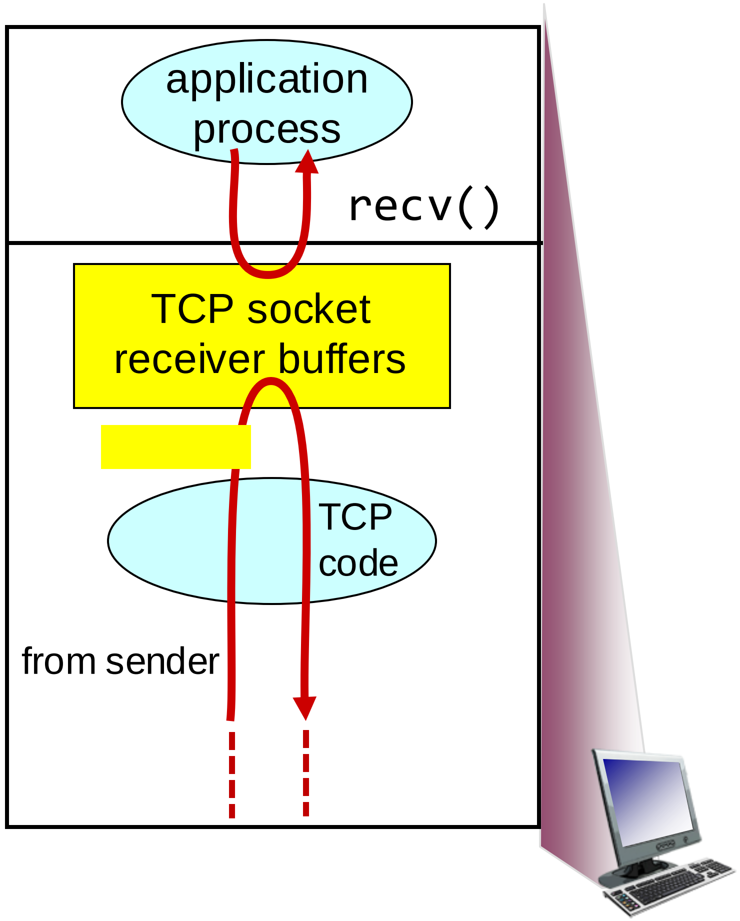
Sockets need receive-side memory buffers

- Since TCP uses selective repeat, the receiver must buffer data that is received after loss:
  - e.g., hold packets so that only the “holes” (due to loss) need to be filled in later, without having to retransmit packets that were received successfully
- Apps read from the receive-side socket buffer when you do a `recv()` call.
- Even if data is always reliably received, applications may not always read the data immediately
  - What if you invoked `recv()` in your program infrequently (or never)?
  - For the same reason, UDP sockets also have receive-side buffers

Receiver app's interaction with TCP

- Upon reception of data, the receiver's TCP stack deposits the data in the receive-side socket buffer

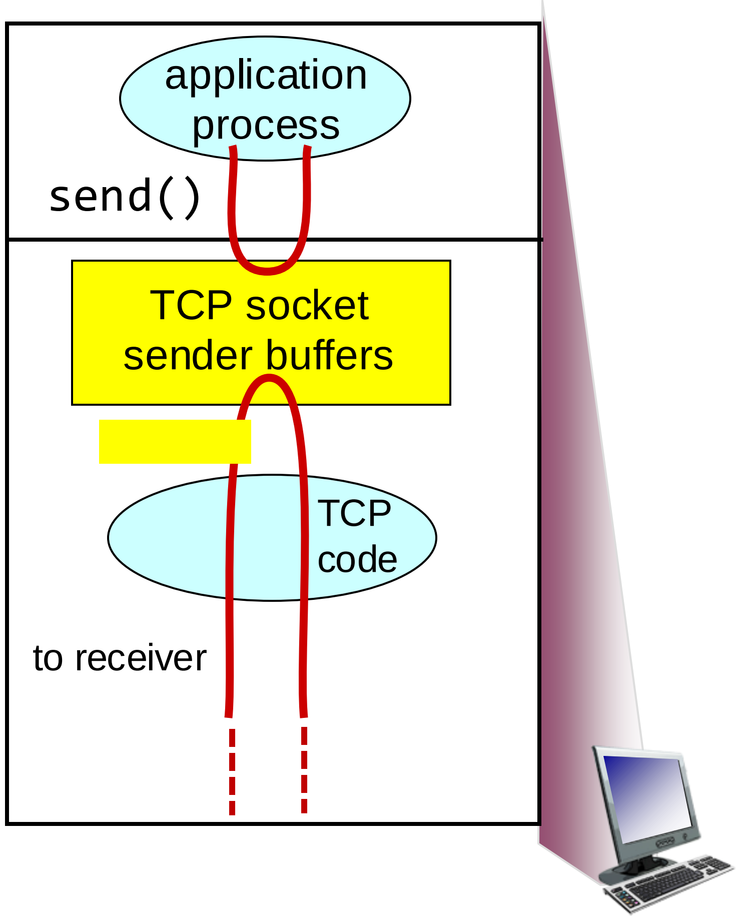
- An app with a TCP socket reads from the TCP receive socket buffer
  - e.g., when you do `data = sock.recv()`



receiver TCP interaction

Sockets need send-side memory buffers

- The possibility of packet retransmission in the future means that data can't be immediately discarded from the sender once transmitted.
- App has issued `send()` and moved on; TCP stack must buffer this data
- Transport layer must wait for ACK of a piece of data before reclaiming (freeing) the memory for that data.



sender TCP interaction

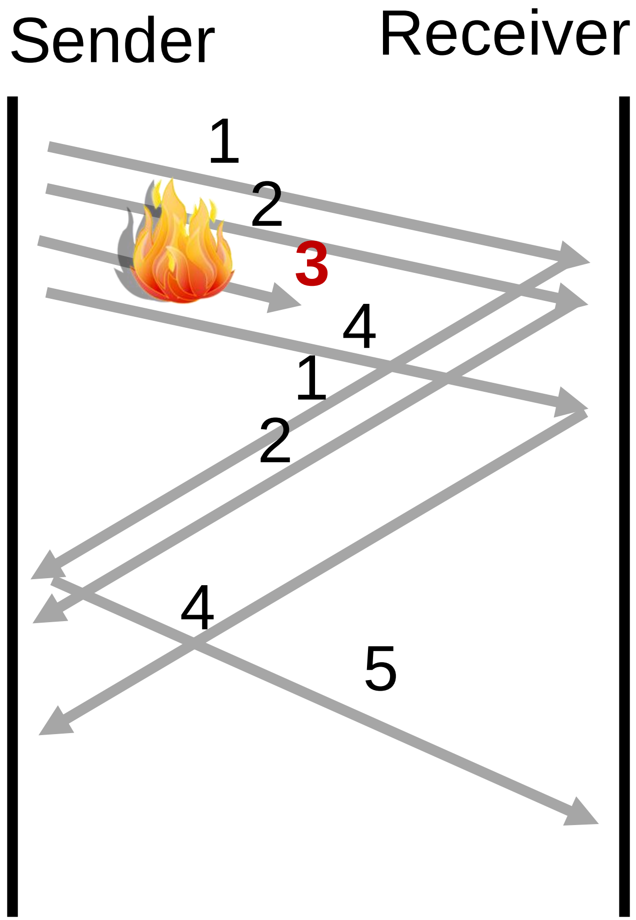
Ordered Delivery

Reordering packets at the receiver side

- Let's suppose receiver gets packets 1, 2, and 4, but not 3 (dropped)

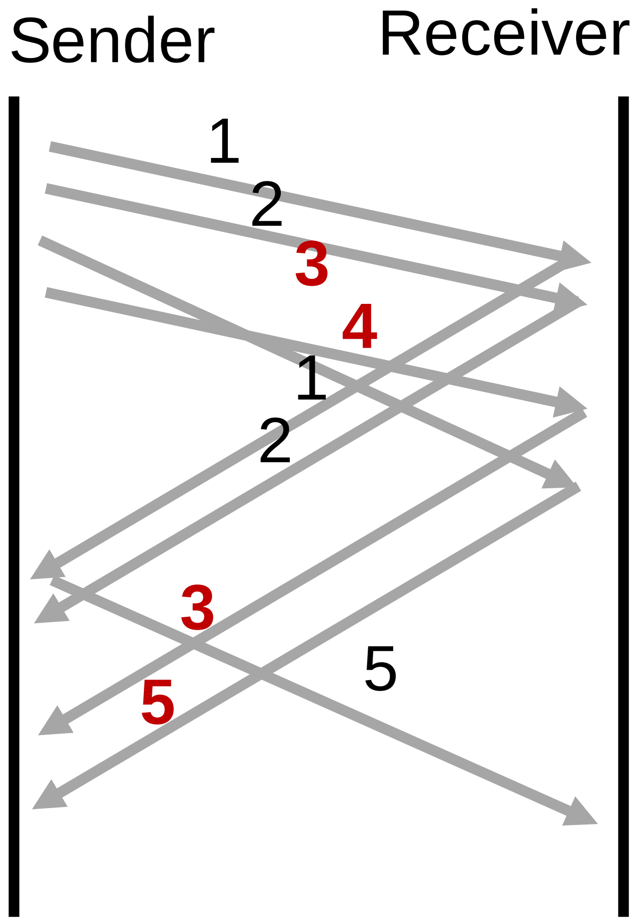
- Suppose you're trying to download a document containing a report

- What would happen if transport at the receiver directly presents packets 1, 2, and 4 to the application (i.e., receiving 1,2,4 through the `recv()` call)?



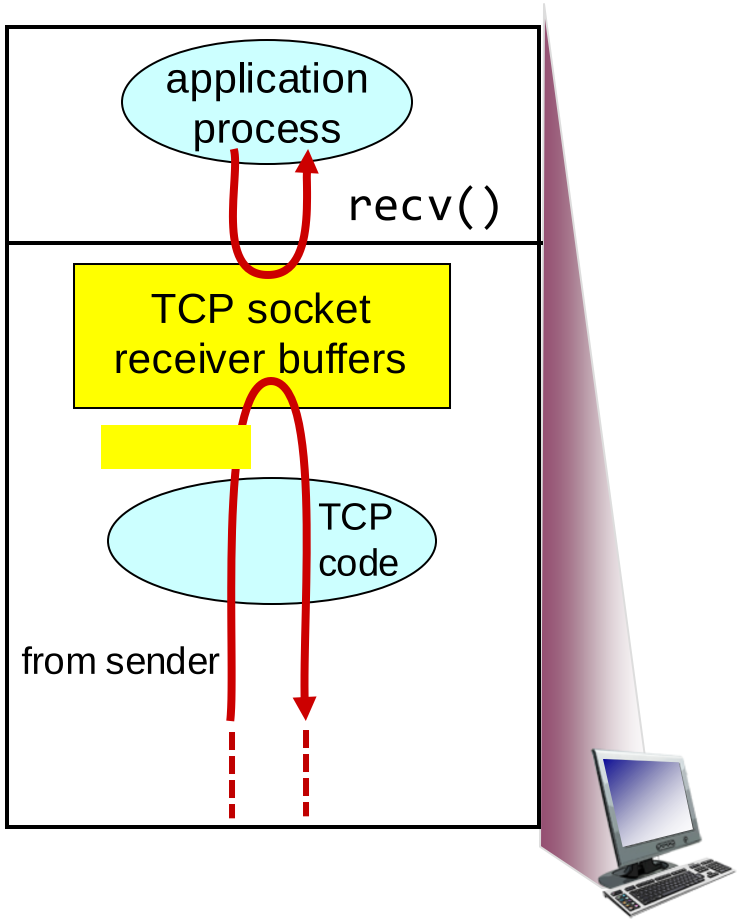
Reordering packets at the receiver side

- Reordering can happen for a few reasons:
  - Drops
  - Packets taking different paths through a network
- Receiver needs a general strategy to ensure that data is presented to the application in the same order that the sender pushed it. Ideas?
- To implement ordered delivery, the receiver uses
  - Sequence numbers
  - Receiver socket buffer
- We’ve already seen the use of these for reliability; but they can be used to order too!



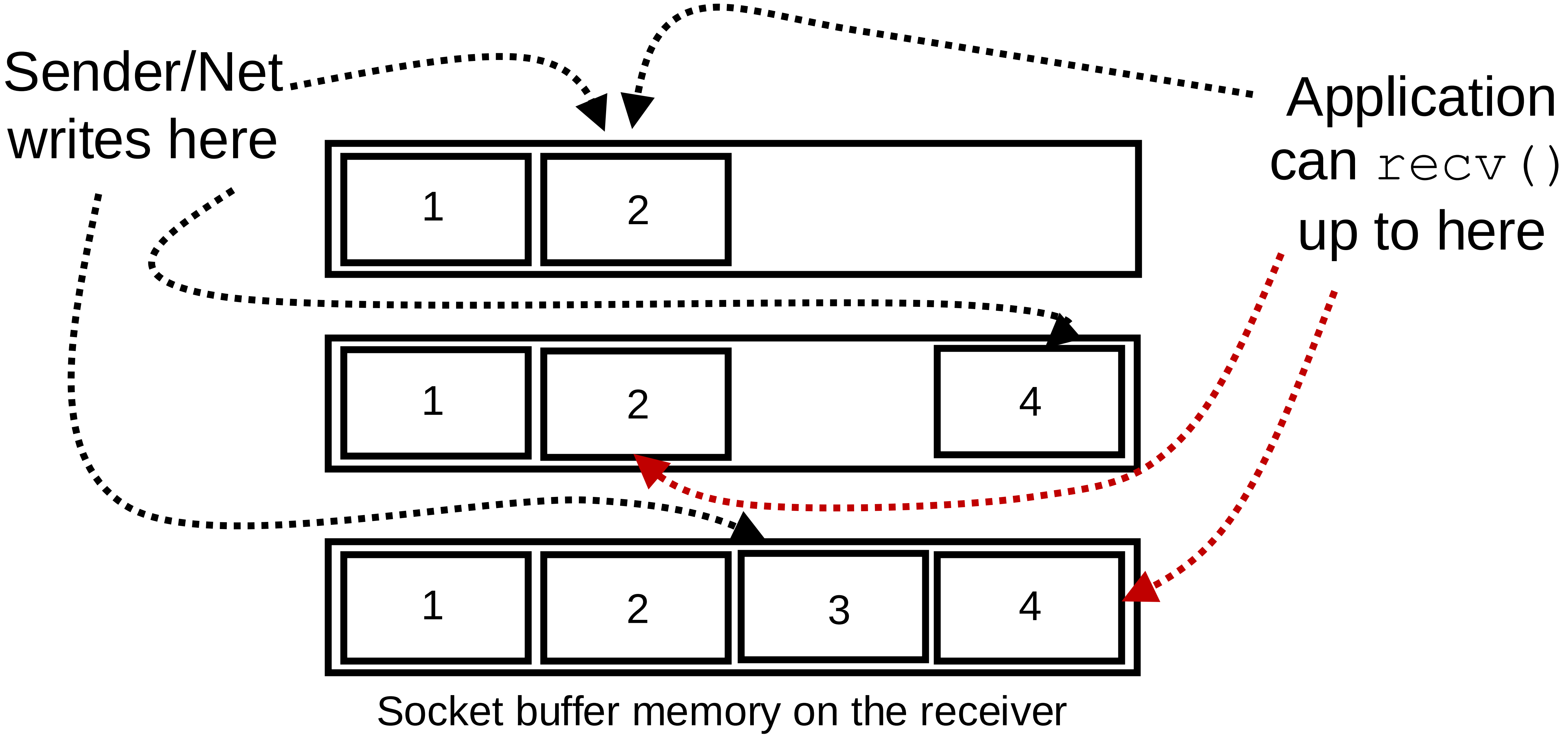
Receive-side app and TCP

- TCP receiver software only releases the data from the receive-side socket buffer to the application if:
  - the data is in order relative to all other data already read by the application
- This process is called TCP reassembly



receiver protocol stack

TCP Reassembly



Implications of ordered delivery

- Packets cannot be delivered to the application if there is an in-order packet missing from the receiver's buffer
  - The receiver can only buffer so much out-of-order data
  - Subsequent out-of-order packets dropped
  - It won't matter that those packets successfully arrive at the receiver from the sender over the network

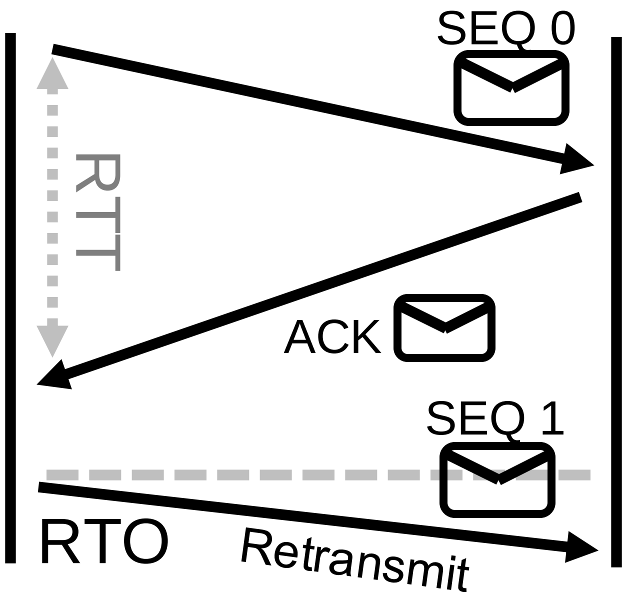
- TCP application-level throughput will suffer if there is too much packet reordering in the network
  - Data may have reached the receiver, but won't be delivered to apps upon a `recv()` `(...`or may not even be buffered!)

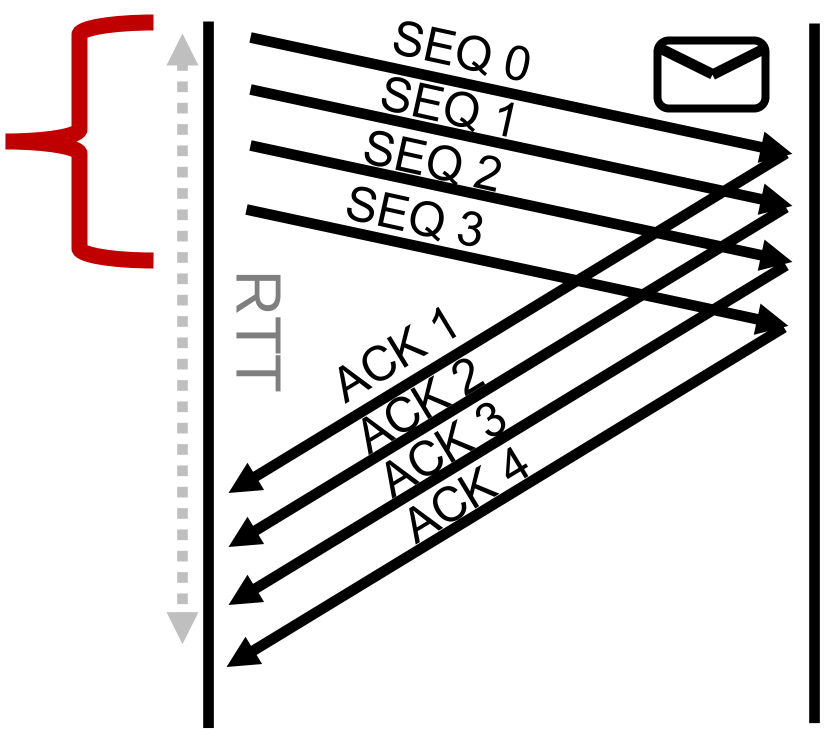
= window size

Proportional to throughput

How much data to keep in flight?

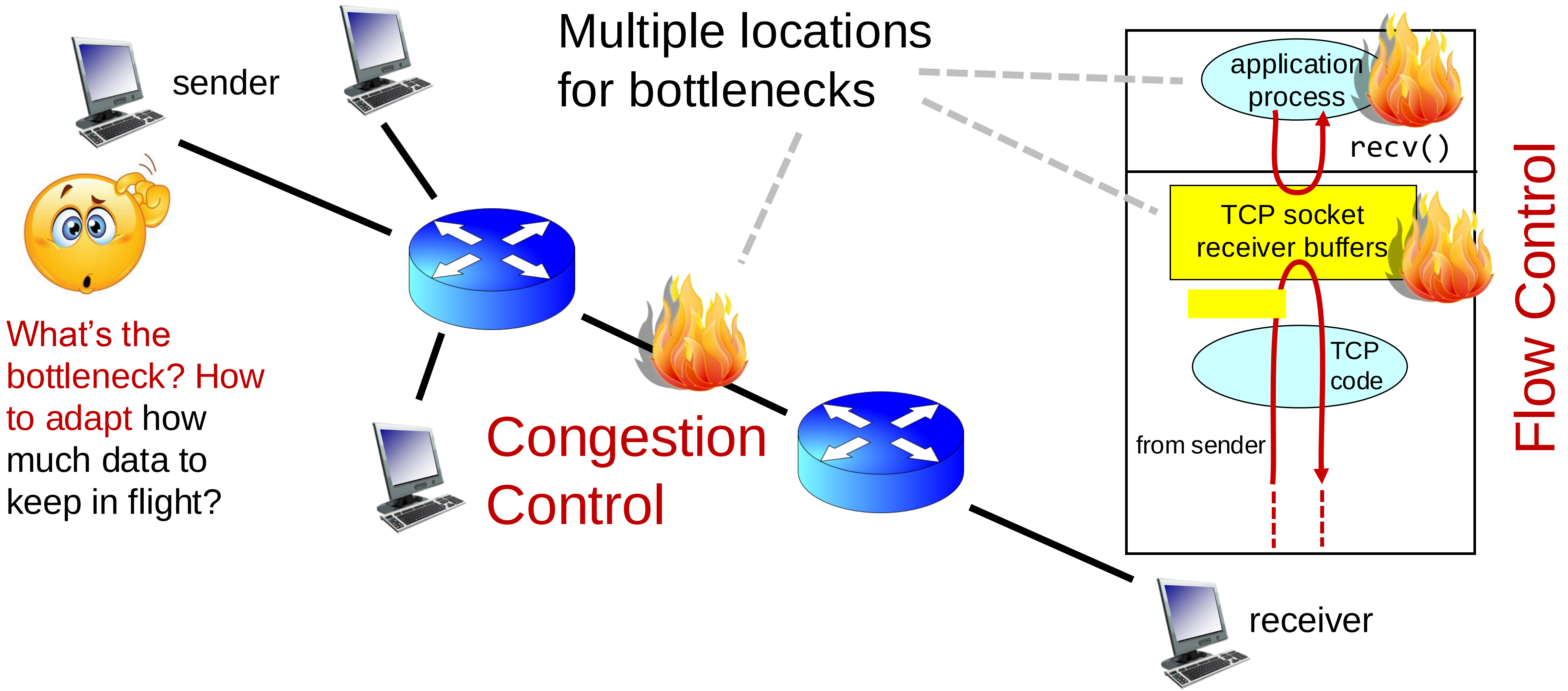
Stop and Wait





Pipelined Reliability

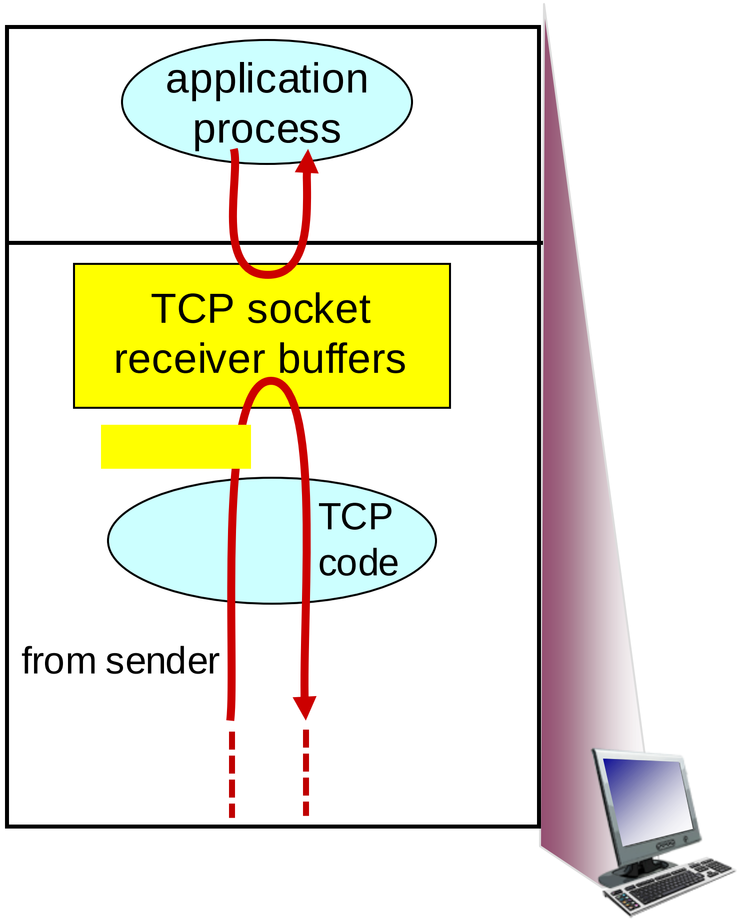
We want to increase throughput, but …



Flow Control

Socket buffers can become full

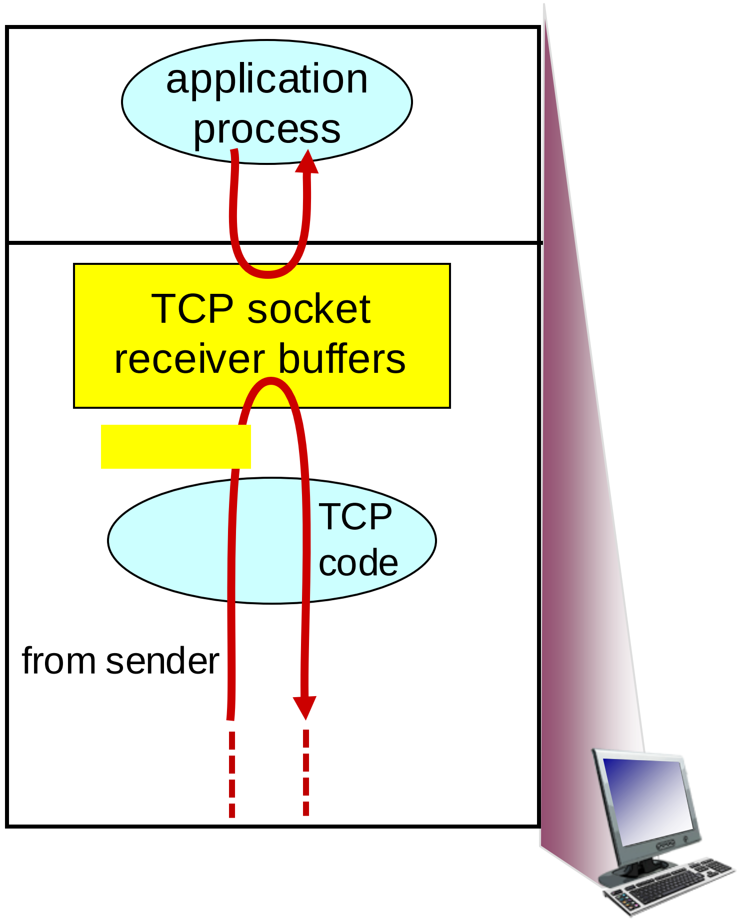
- Applications may read data slower than the sender is pushing data in
  - Example: what if an app infrequently or never calls `recv()`?
- There may be too much reordering or packet loss in the network
  - What if the first few bytes of a window are lost or delayed?
- Receivers can only buffer so much before dropping subsequent data



TCP receiver

Goal: avoid drops due to buffer fill

- Have a TCP sender only send as much as the free buffer space available at the receiver.
- *Amount of free buffer varies over time!*
- TCP implements flow control
- Receiver's ACK contains the amount of data the sender can transmit without running out the receiver's socket buffer
- This number is called the advertised window size



receiver protocol stack

Flow control in TCP headers

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
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|          Source Port          |       Destination Port        |
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|                        Sequence Number                        |
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|                    Acknowledgment Number                      |
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|  Data |           |U|A|P|R|S|F|                               |
| Offset| Reserved  |R|C|S|S|Y|I|            Window             |
|       |           |G|K|H|T|N|N|                               |
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|           Checksum            |         Urgent Pointer        |
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|                             data                              |
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                      TCP Header Format

        Note that one tick mark represents one bit position.
```

TCP flow control

- Receiver advertises to sender (in the ACK) how much free buffer is available

```
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
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|          Source Port          |       Destination Port        |
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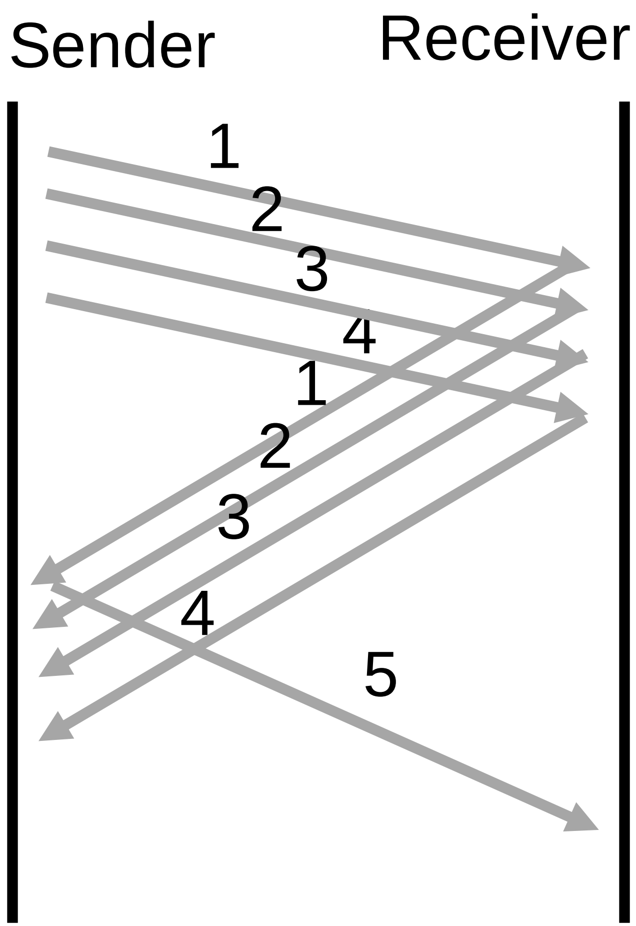
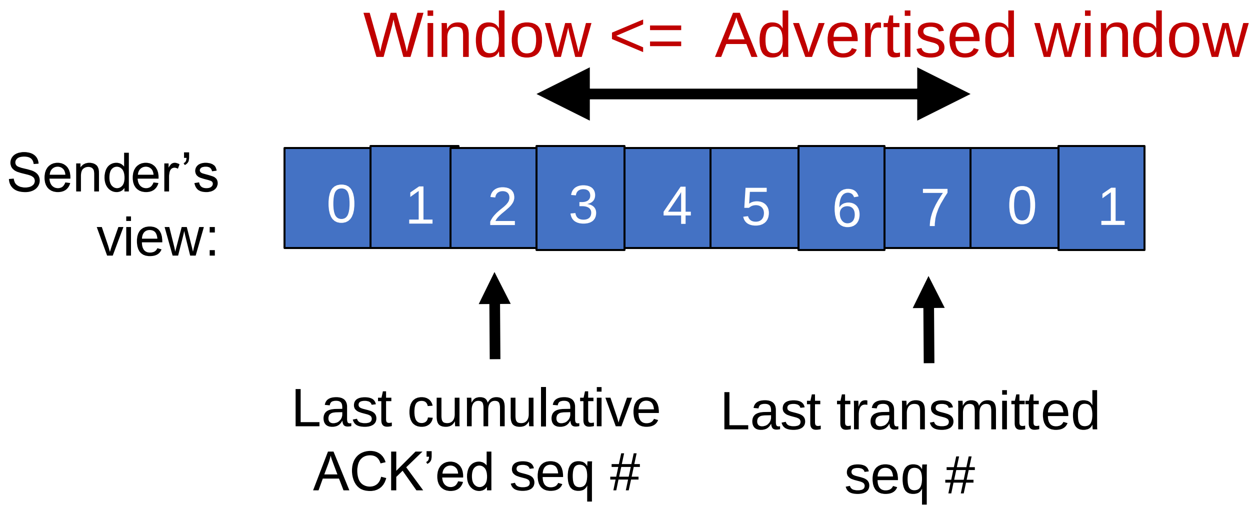
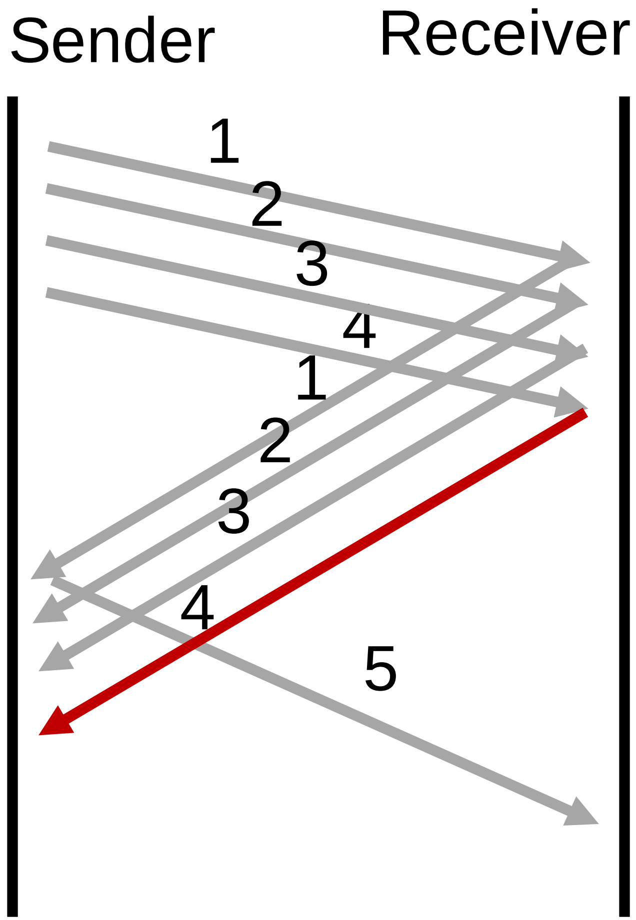


TCP flow control

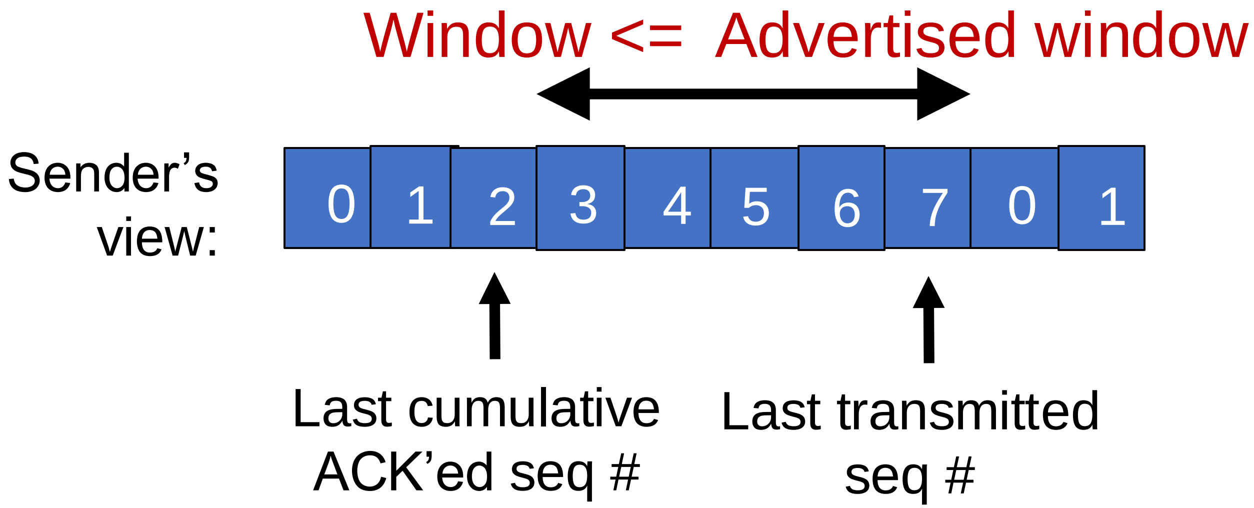
- Subsequently, the sender's sliding window cannot be larger than this value
- Restriction on new sequence numbers that can be transmitted
- == restriction on sending rate

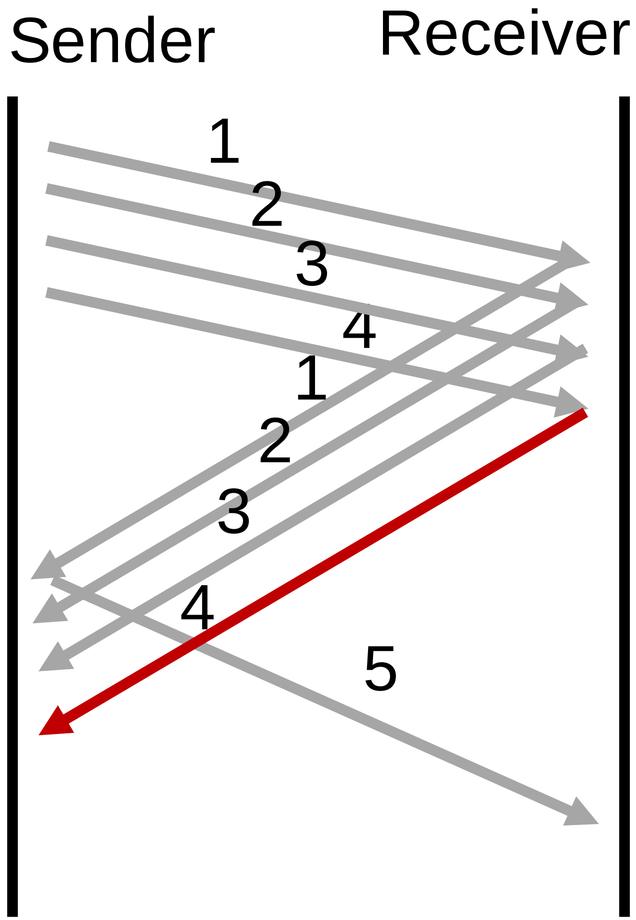




TCP flow control

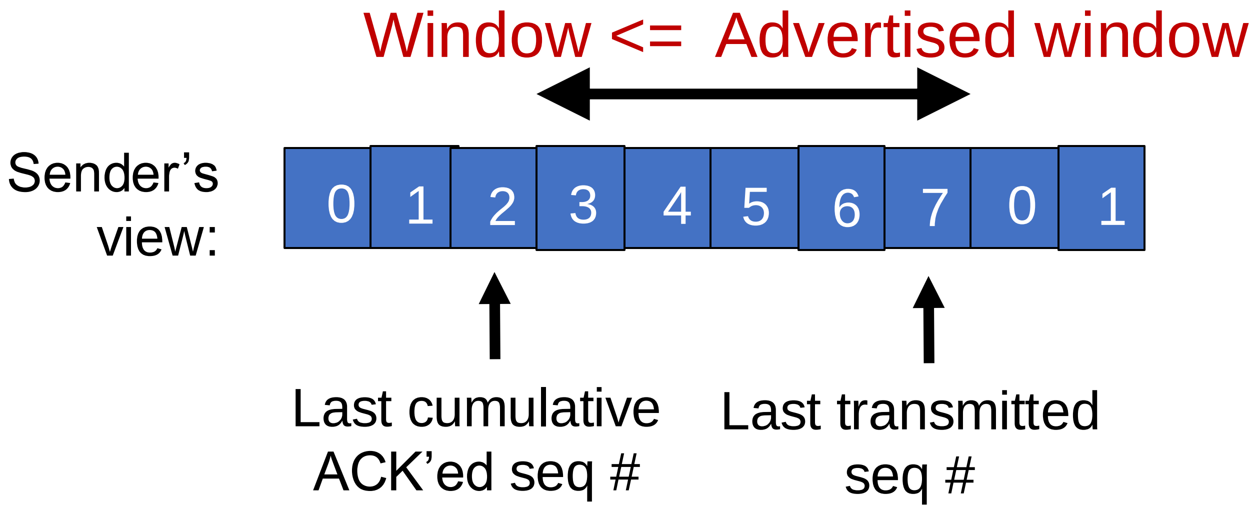
- If receiver app is too slow reading data:
  - receiver socket buffer fills up
  - => advertised window shrinks
  - => sender’s window (sending rate) reduces
  - => sender’s socket buffer fills up
  - => sender process put to sleep upon send()

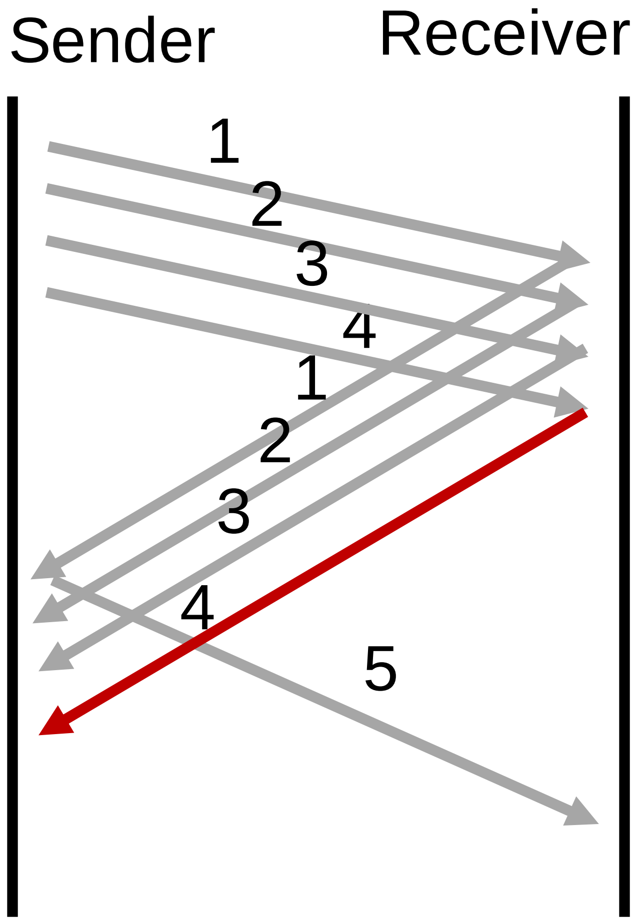




TCP flow control

Flow control matches the sending process's write speed to the receiving process's read speed.





Sizing the receiver’s socket buffer

- Operating systems have a default receiver socket buffer size
  - Listed among `sysctl -a | grep net.inet.tcp` on MAC
  - Listed among `sysctl -a | grep net.ipv4.tcp` on Linux
- If socket buffer is too small, sender can’t keep too many packets in flight ➔ lower throughput
- If socket buffer is too large, too much memory consumed per socket
- How big should the receiver socket buffer be?

Sizing the receiver’s socket buffer

- Case 1: Suppose the receiving app is reading data too slowly:
  - no amount of receiver buffer can prevent low sender throughput if the connection is long-lived!

Sizing the receiver’s socket buffer

- Case 2: Suppose the receiving app reads sufficiently fast *on average* to match the sender’s writing speed.
  - Assume the sender has a window of size W.
  - The receiver must use a buffer of size at least W. Why?
- Captures two cases:
- (1) When the first sequence #s in the window are dropped
  - *Selective repeat*: data in window buffered until the “hole” within the window can be filled by the sender. Advertised window reduces sender’s window
- (2) When the sender sends a burst of data of size W
  - The receiver may not keep up with the *instantaneous* rate of the sender
- Set receiver socket buffer > desired window size

Summary of flow control

- Keep memory buffers available at the receiver whenever the sender transmits data
- Buffers needed to hold for selective repeat and reassemble data in order
- Inform the sender on an on-going basis (each ACK)
- Function: match sender speed to receiver speed

- Correct socket buffer sizing is important for TCP throughput

Info on (tuning) TCP stack parameters

- https://www.ibm.com/support/knowledgecenter/linuxonibm/liaag/wkvm/wkvm_c_tune_tcpip.htm

- https://cloud.google.com/solutions/tcp-optimization-for-network-performance-in-gcp-and-hybrid