Chapter 3
Transport Layer

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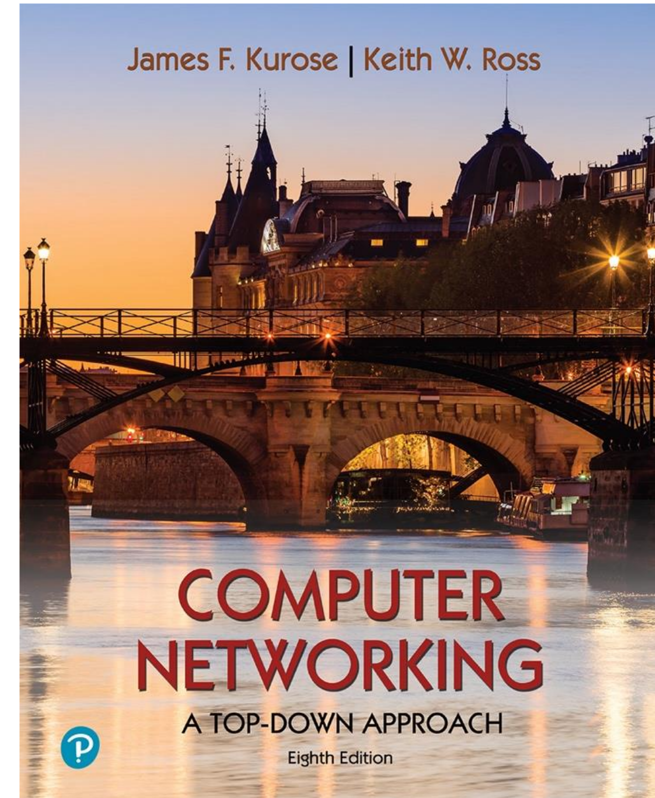
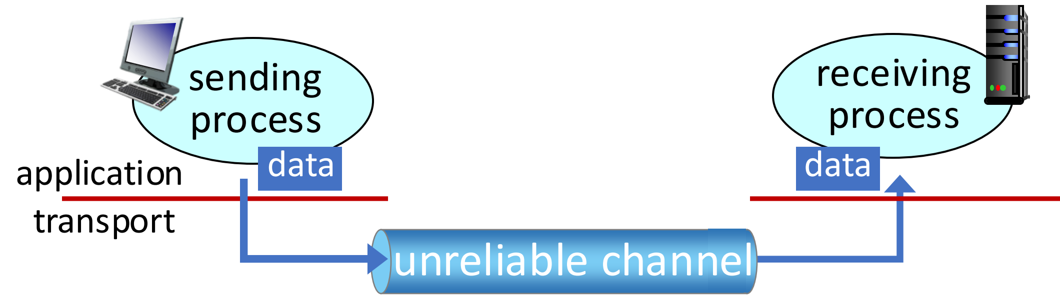
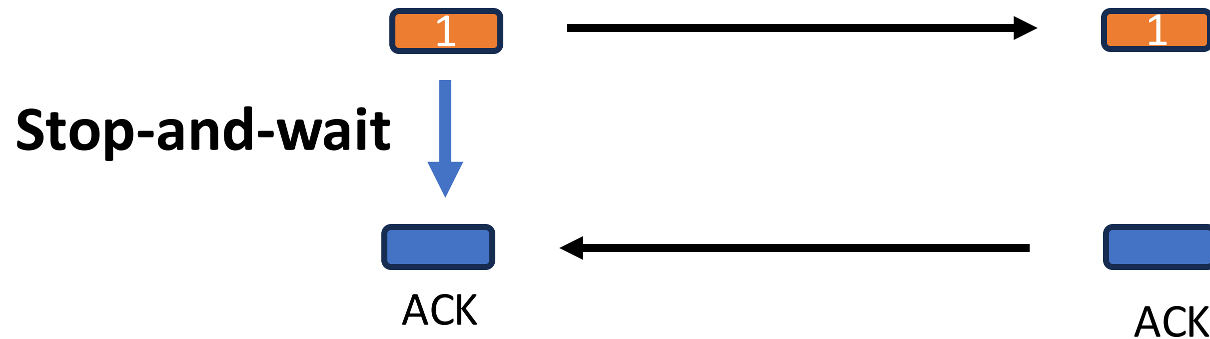
Adapted from the slides of the book's authors



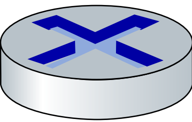
Computer Networking: A Top-Down Approach
8th edition
Jim Kurose, Keith Ross
Pearson, 2020

Stop-and-wait operation





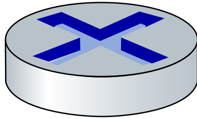
Packet transmission takes time



Source

Router

Packet transmission takes time



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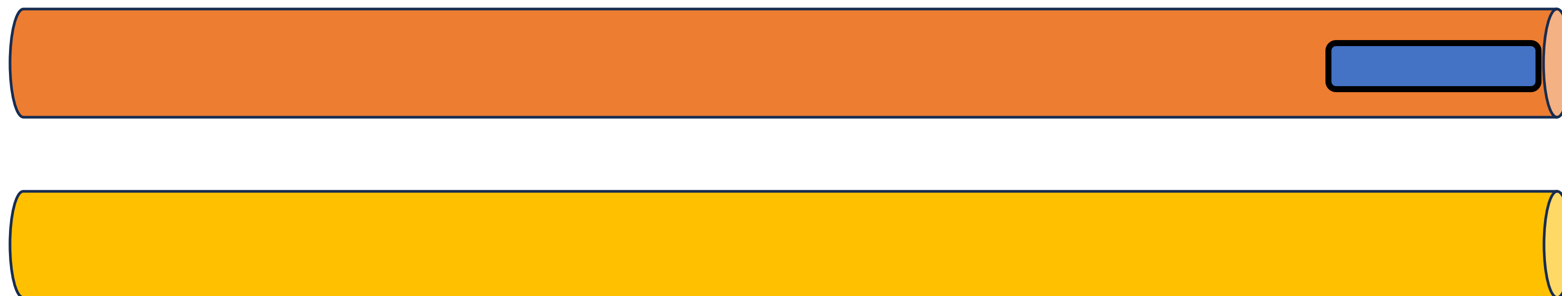

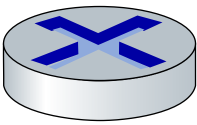

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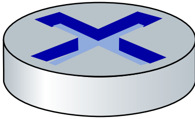

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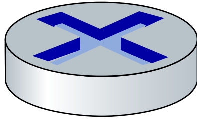

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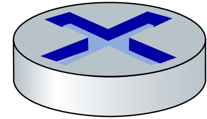
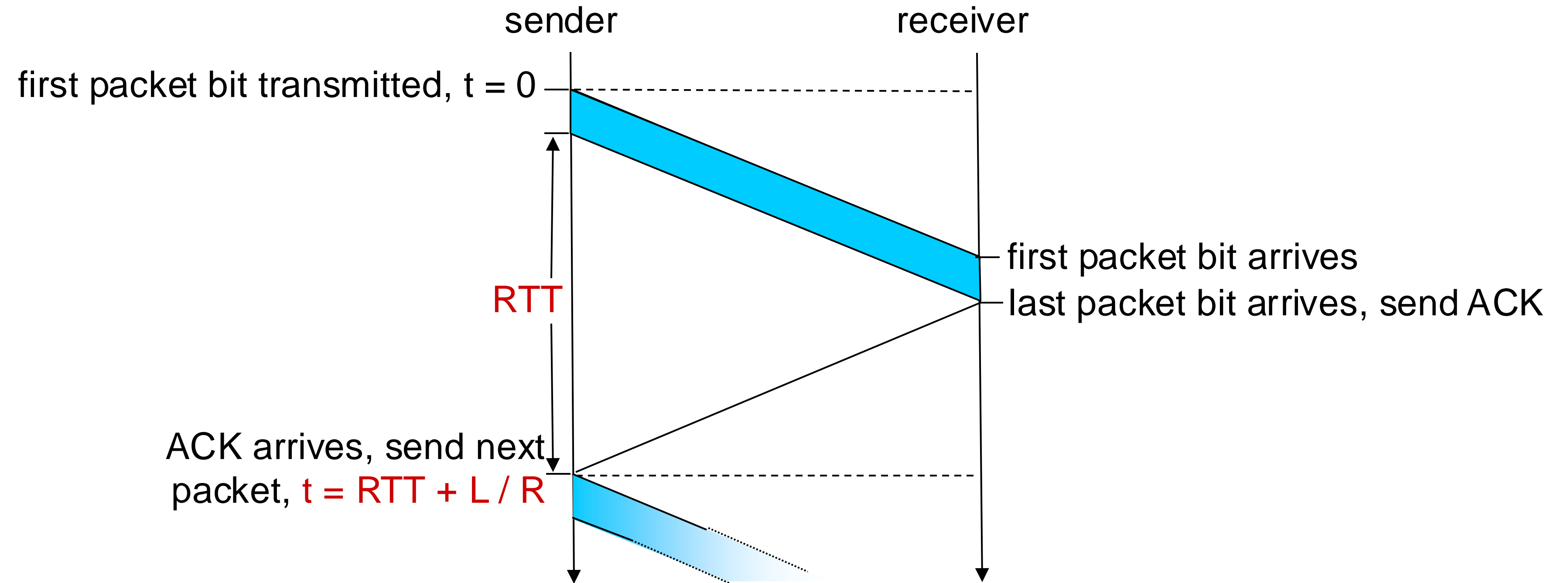


Router

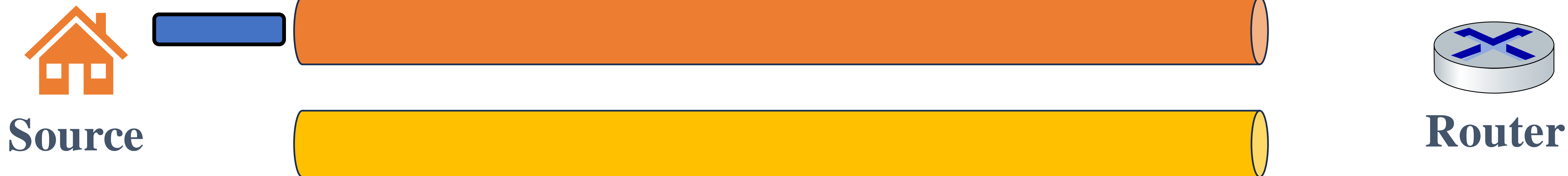
Packet transmission takes time

Stop-and-wait operation



Solution: Pipelined protocols

pipelining: sender allows multiple, "in-flight", yet-to-be-acknowledged packets



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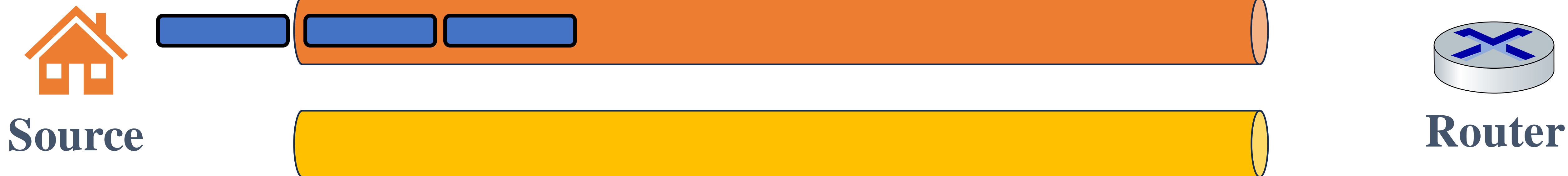

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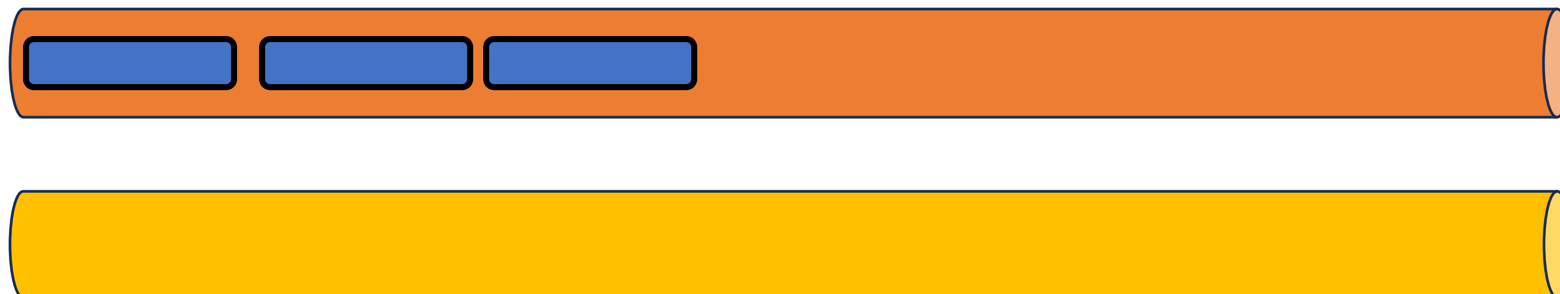

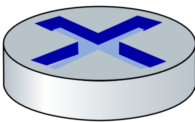

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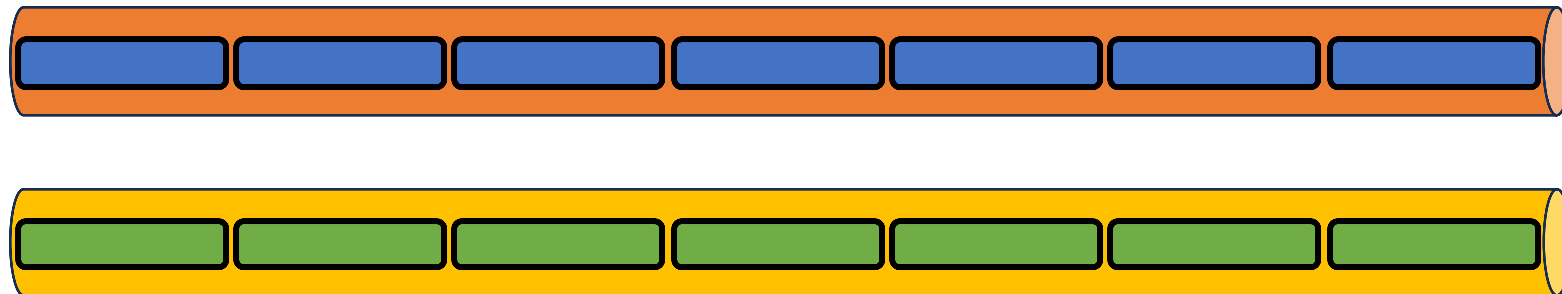
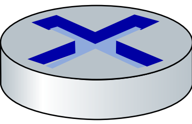
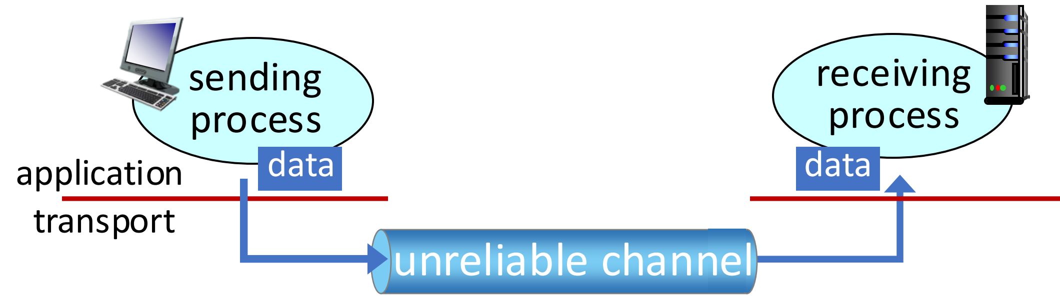




Pipelining: design question: when to stop

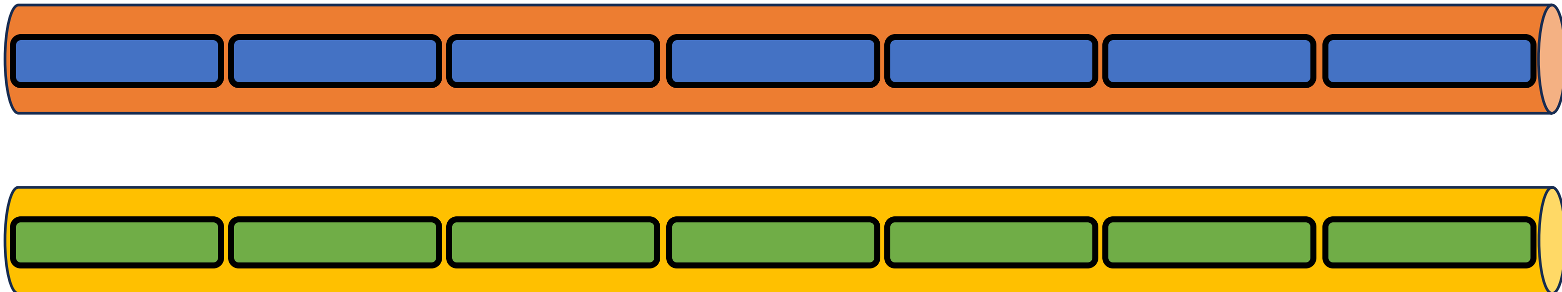


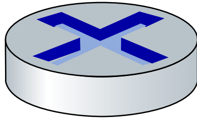
1 2 3 4 5 6 7 8 ......

Should we keep sending as many packets as possible?

Pipelining: design question: when to stop

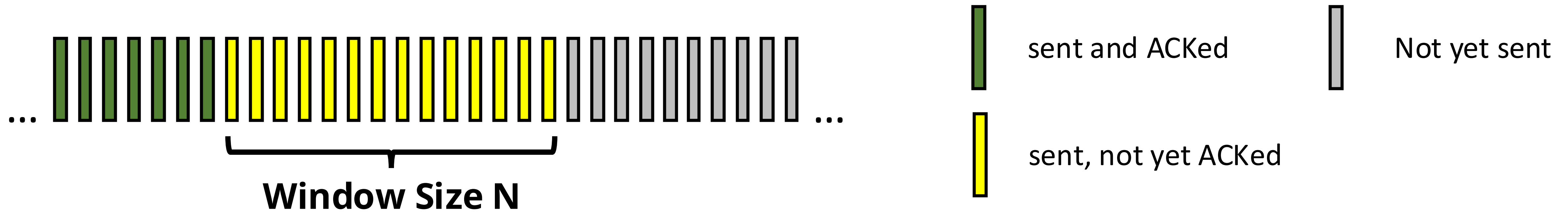
1 2 3 4 5 6 7 8 ……





We should stop when the network is full!

Sliding Window



Sliding Window

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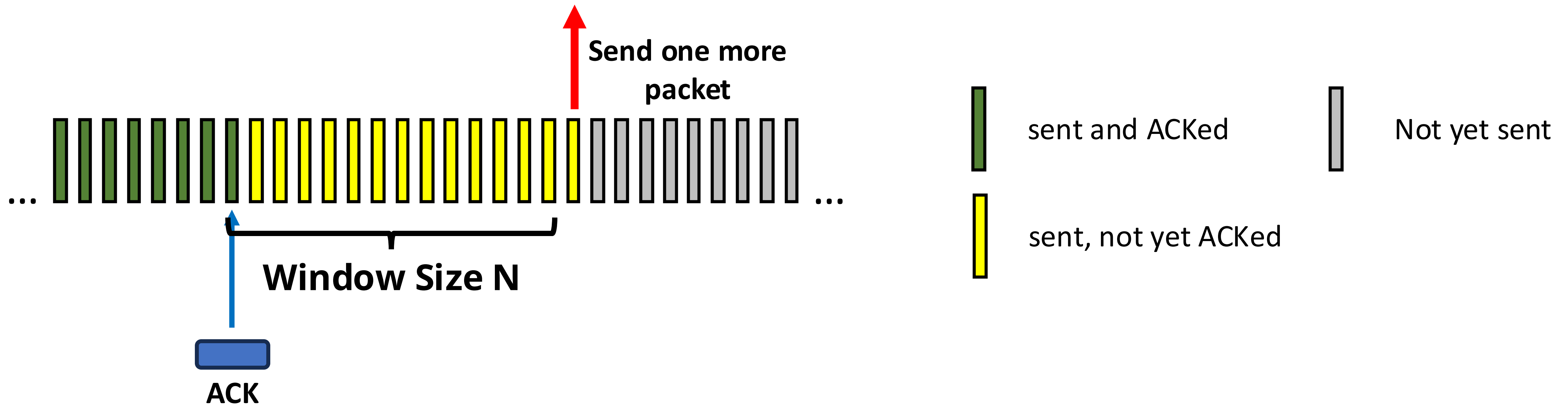

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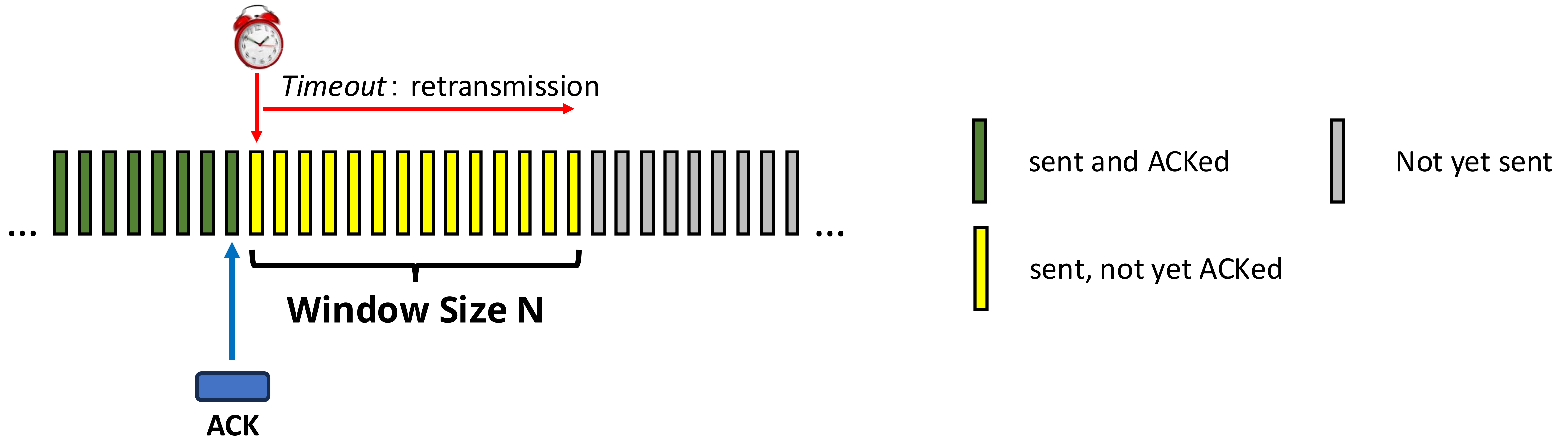
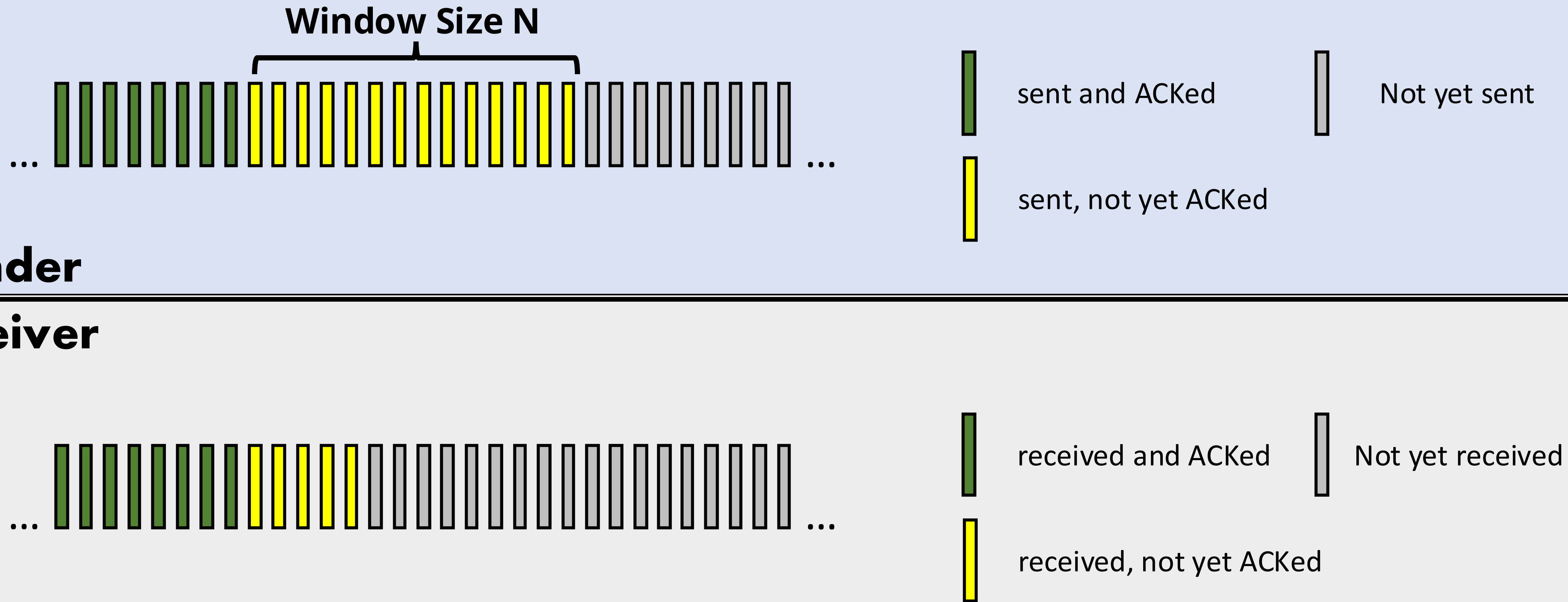


- Timer for oldest in-flight packet
- *Timeout(n):* retransmit packet n and all higher seq # packets in window

Sliding Window + cumulative ACK



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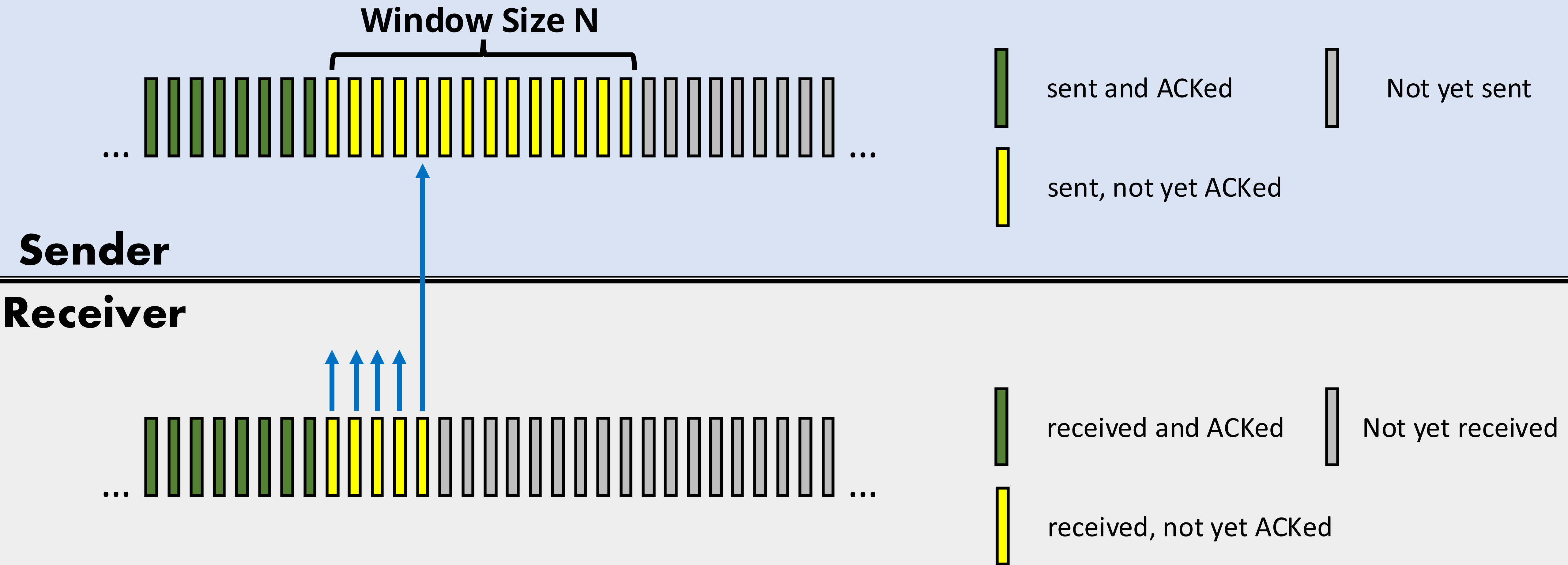

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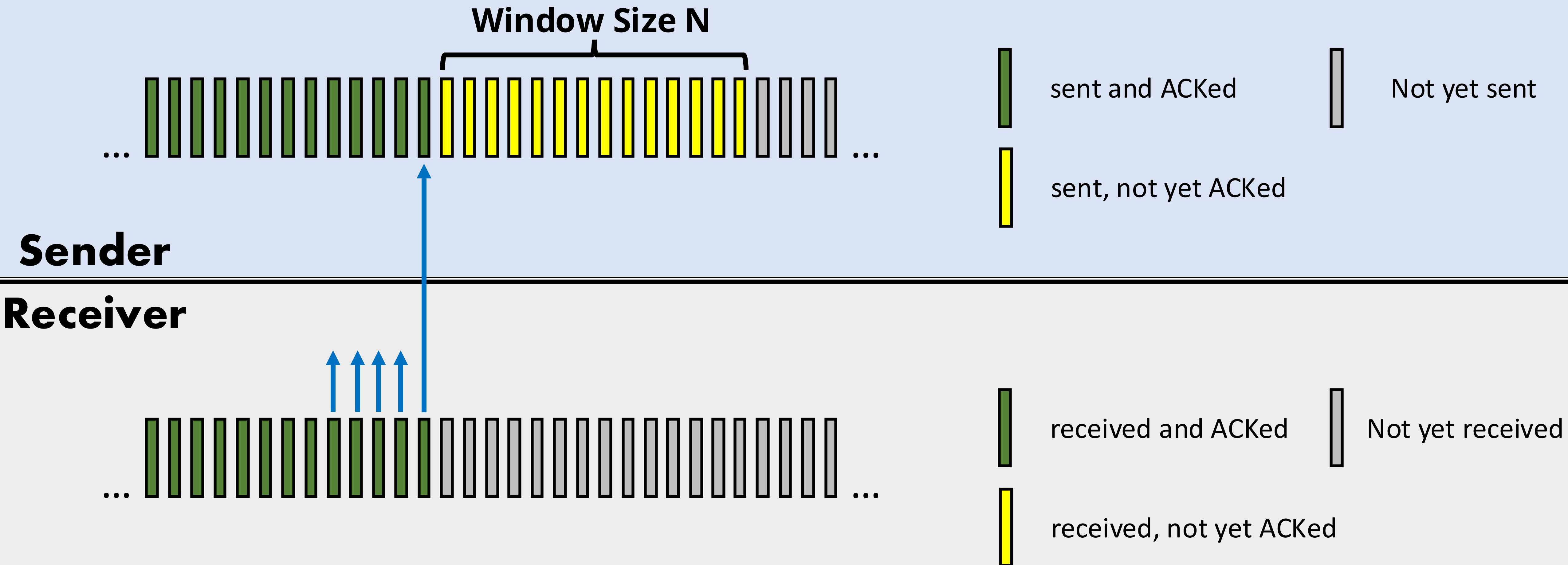


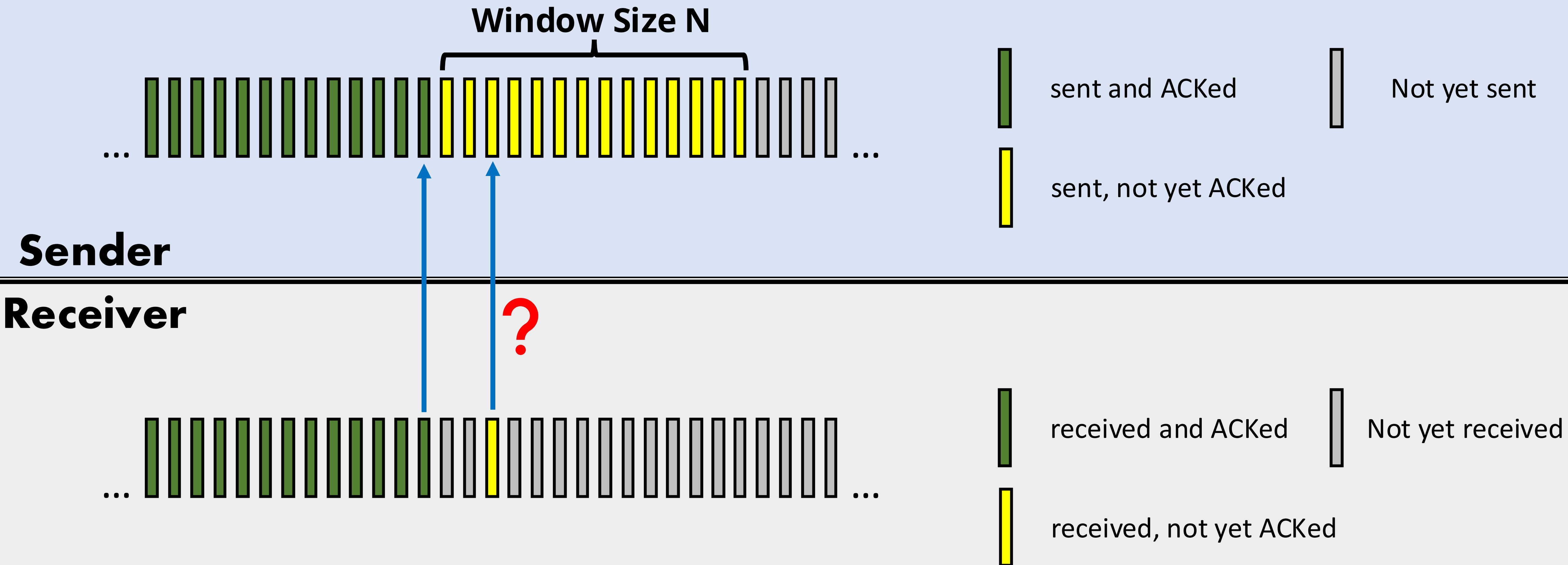
- *cumulative ACK:* ACK(*n*): ACKs all packets up to, including seq # *n*
  - on receiving ACK(*n*): move window forward to begin at *n+1*

Sliding Window + cumulative ACK: out-of-order

Two Question:

1. do we need to send ACK when we receive an out-of-order packet? If yes, what kind of ACK?

Sliding Window + cumulative ACK: out-of-order



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2. how shall we deal with the out-of-order packets we received?

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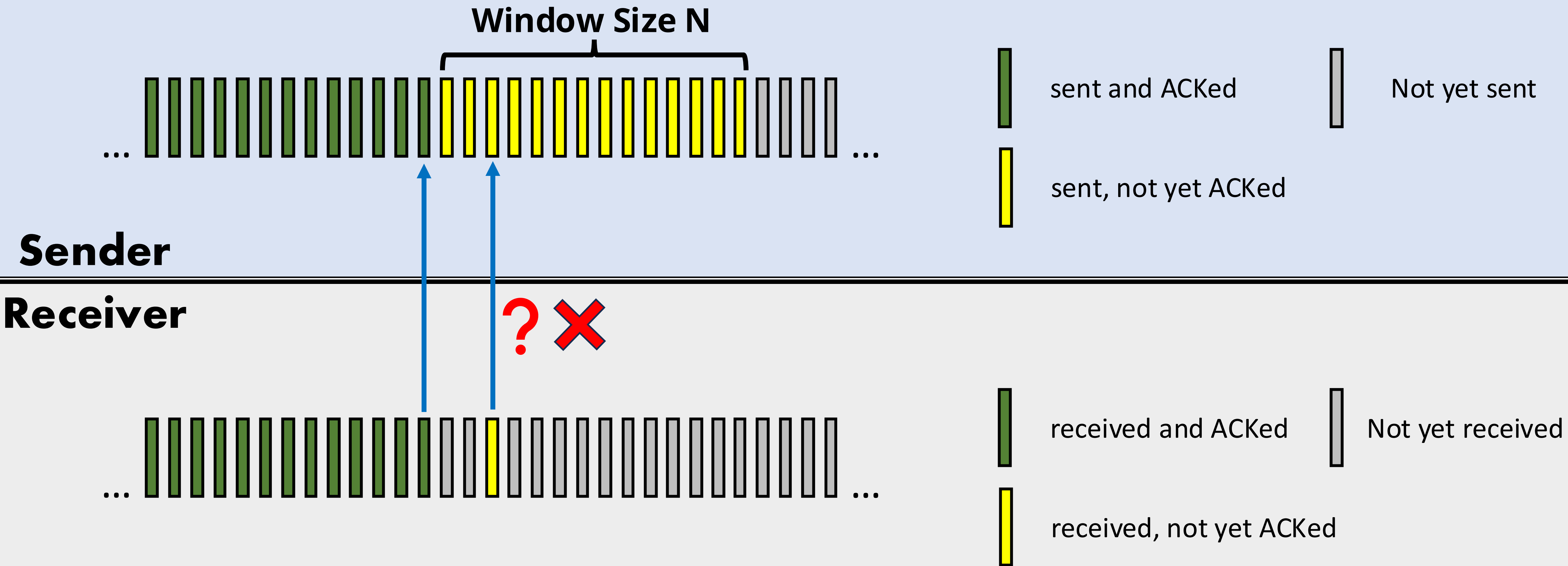

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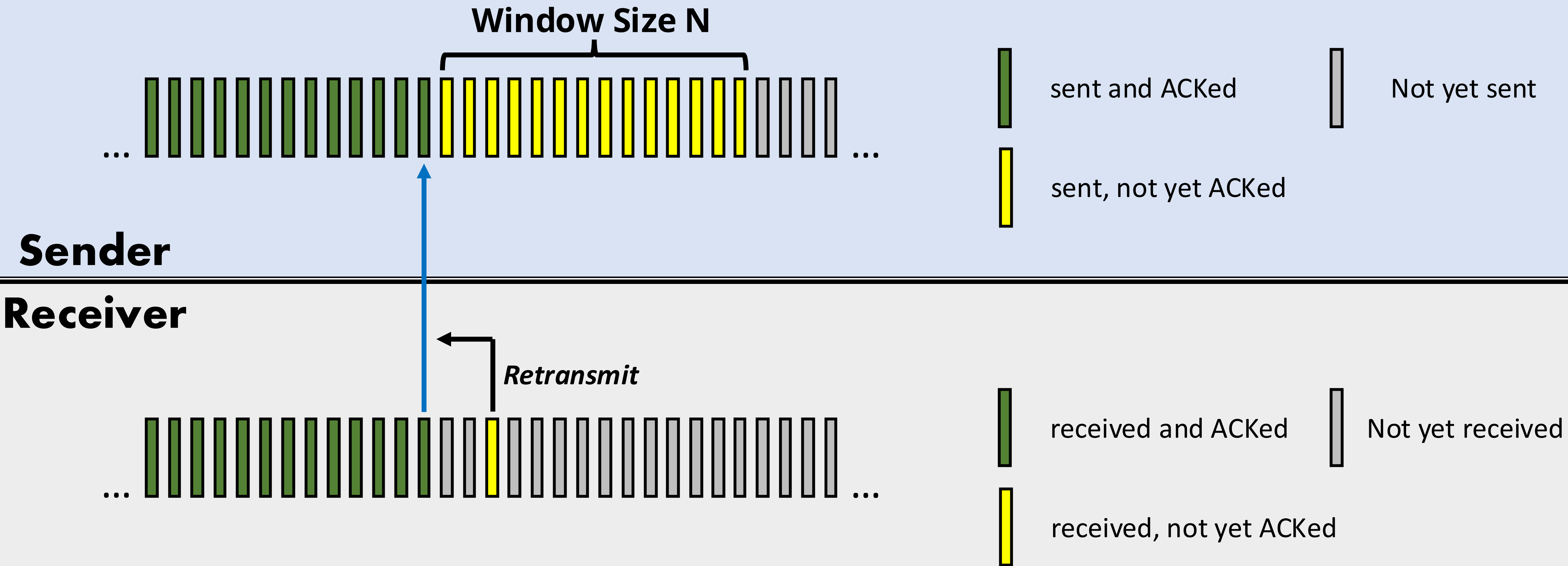
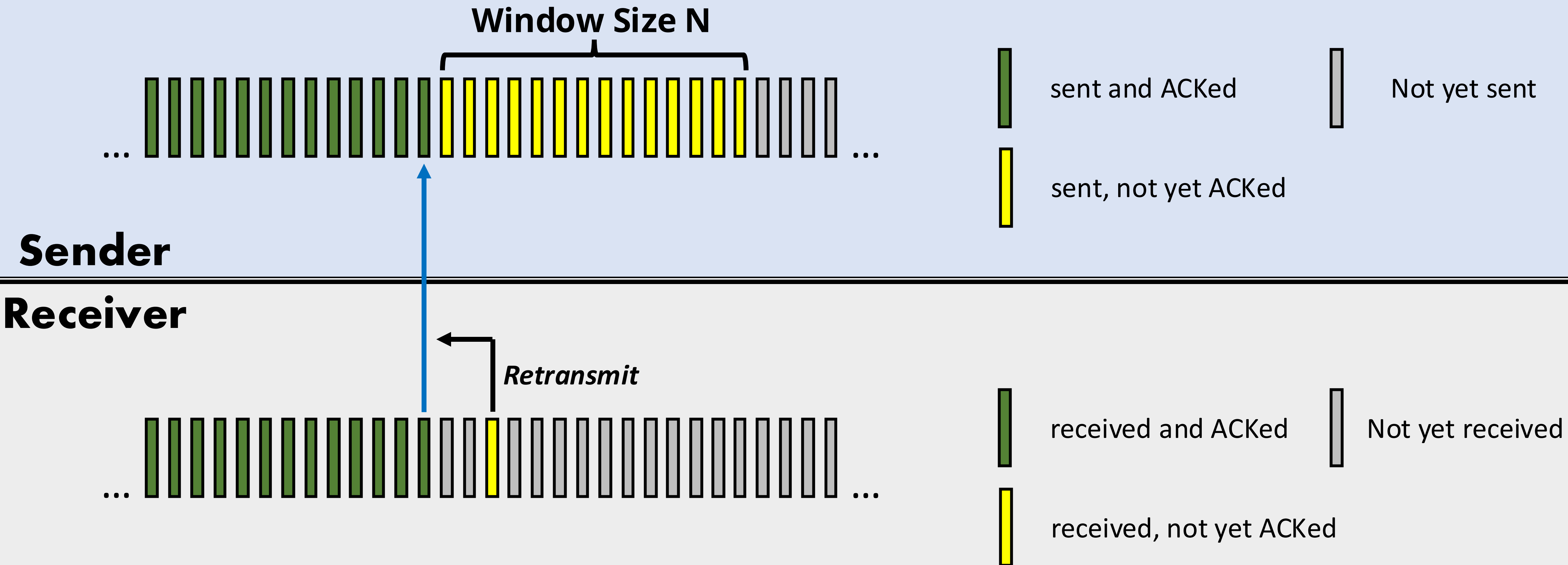


- ACK-only: always send ACK for correctly-received packet so far, with highest *in-order* seq #
  - may generate duplicate ACKs

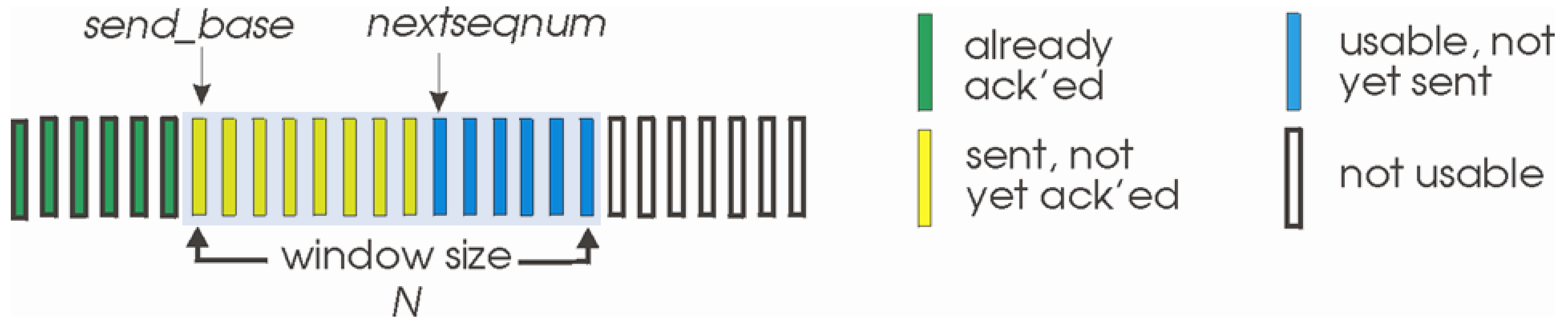
Sliding Window + cumulative ACK: out-of-order



- on receipt of out-of-order packet:
  - can discard (don't buffer) or buffer: an implementation decision
  - re-ACK pkt with highest in-order seq #

Go-Back-N: sender

- sender: "window" of up to N, consecutive transmitted but unACKed pkts
  - k-bit seq # in pkt header



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  - on receiving ACK(*n*): move window forward to begin at *n+1*
- timer for oldest in-flight packet
- *timeout(n):* retransmit packet n and all higher seq # packets in window

Go-Back-N: receiver

- ACK-only: always send ACK for correctly-received packet so far, with highest *in-order* seq #
  - may generate duplicate ACKs
  - need only remember `rcv_base`
- on receipt of out-of-order packet:
  - can discard (don't buffer) or buffer: an implementation decision
  - re-ACK pkt with highest in-order seq #

Go-Back-N in action

sender window (N=4)

0 1 2 3 4 5 6 7 8
0 1 2 3 4 5 6 7 8
0 1 2 3 4 5 6 7 8
0 1 2 3 4 5 6 7 8

0 1 2 3 4 5 6 7 8
0 1 2 3 4 5 6 7 8

0 1 2 3 4 5 6 7 8
0 1 2 3 4 5 6 7 8
0 1 2 3 4 5 6 7 8
0 1 2 3 4 5 6 7 8

sender

send pkt0
send pkt1
send pkt2
send pkt3
(wait)

rcv ack0, send pkt4
rcv ack1, send pkt5

ignore duplicate ACK

pkt 2 timeout

send pkt2
send pkt3
send pkt4
send pkt5

X *loss*

receiver

receive pkt0, send ack0
receive pkt1, send ack1

receive pkt3, discard, (re)send ack1

receive pkt4, discard, (re)send ack1
receive pkt5, discard, (re)send ack1

rcv pkt2, deliver, send ack2
rcv pkt3, deliver, send ack3
rcv pkt4, deliver, send ack4
rcv pkt5, deliver, send ack5

Sliding Window + selective repeat

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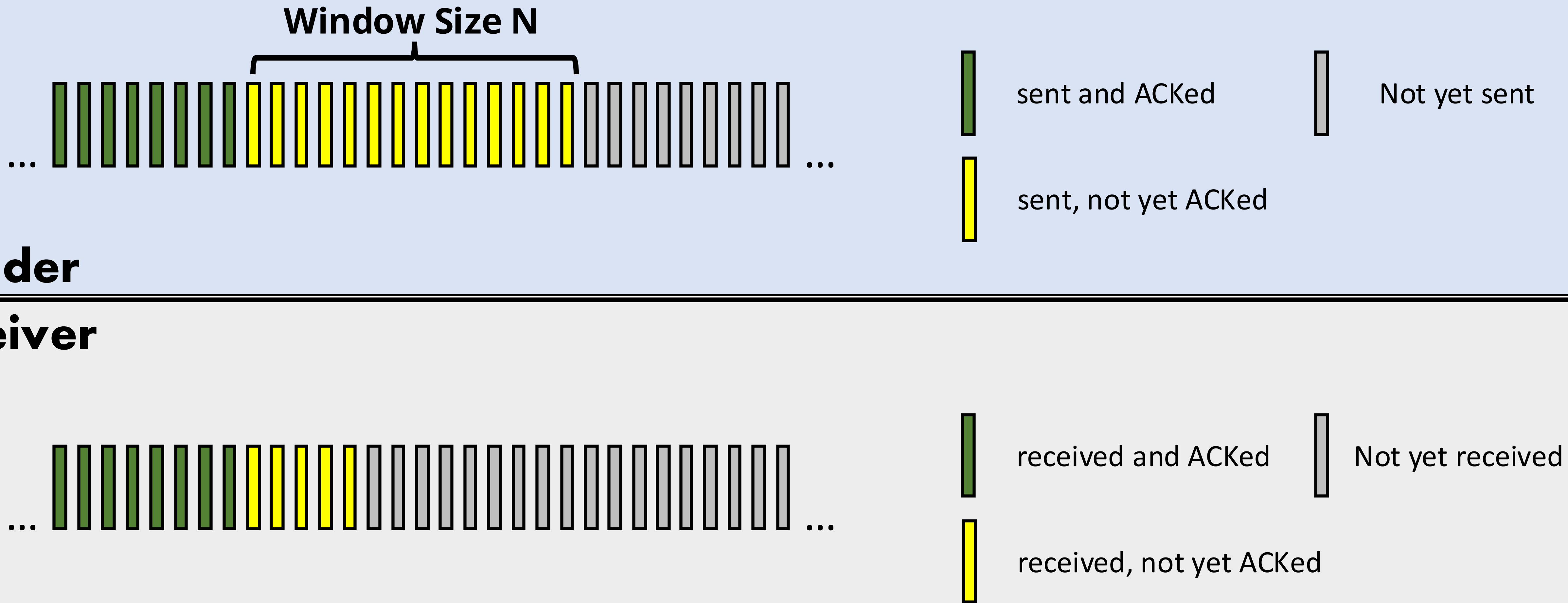

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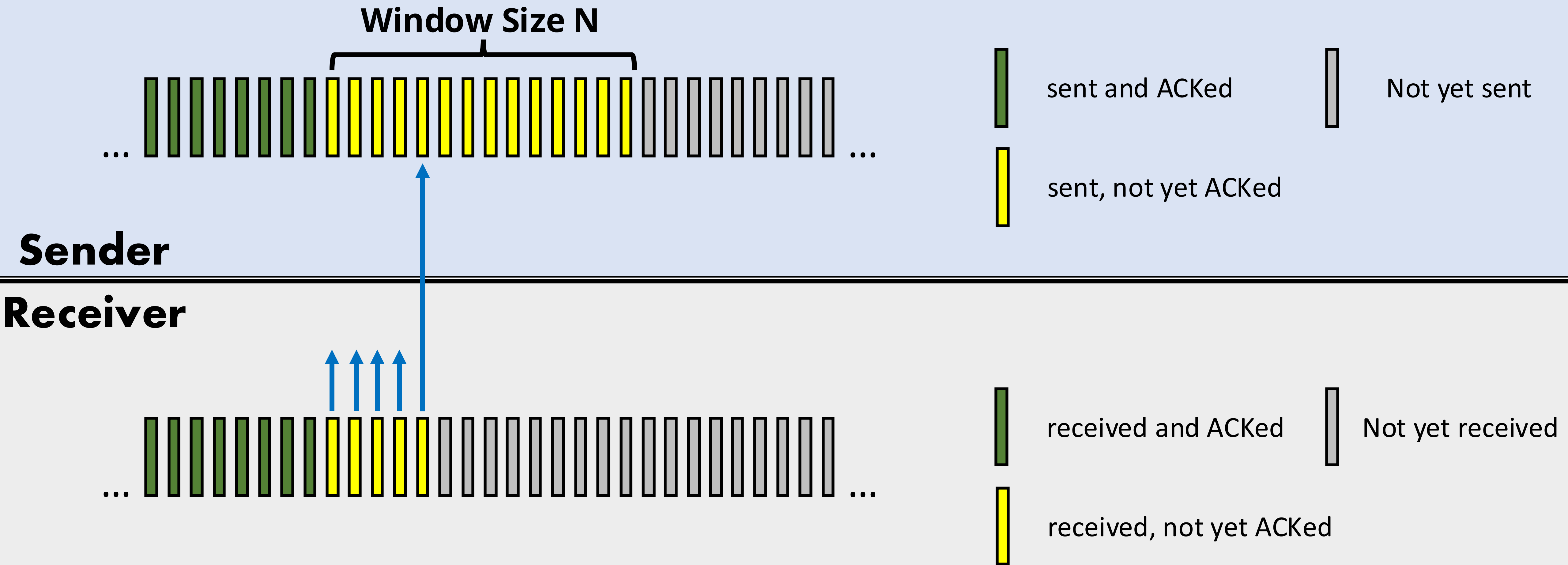

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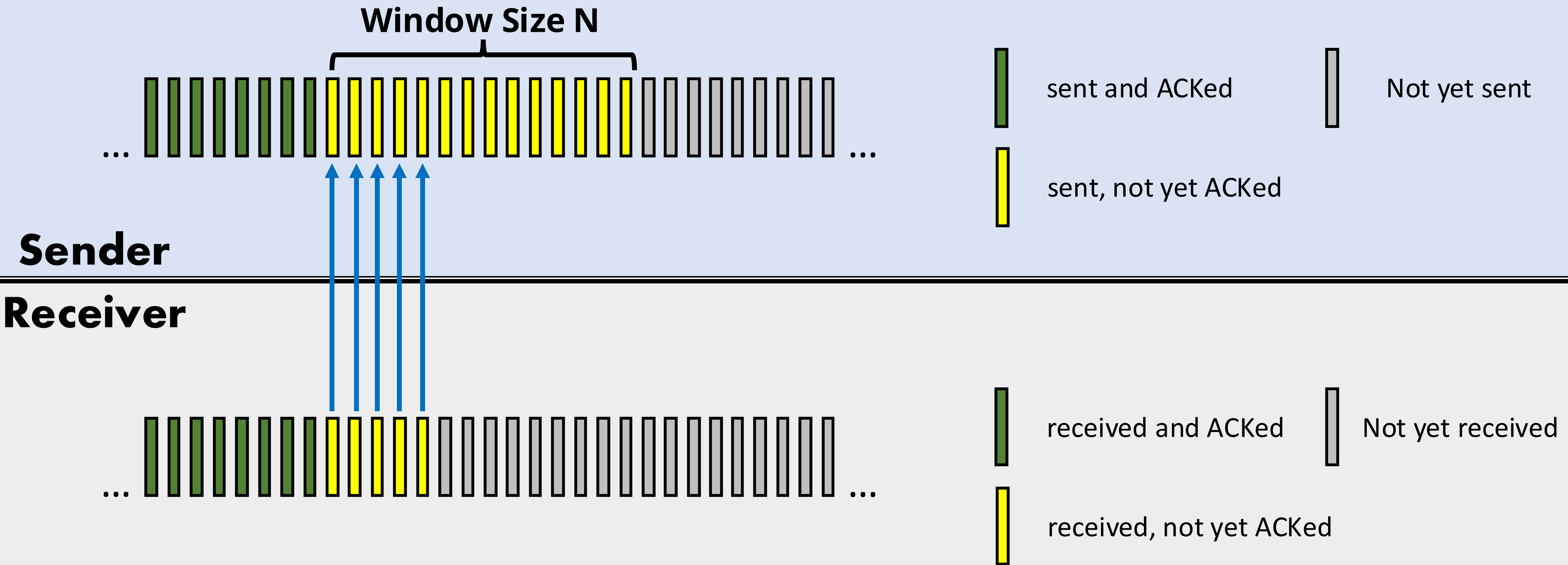

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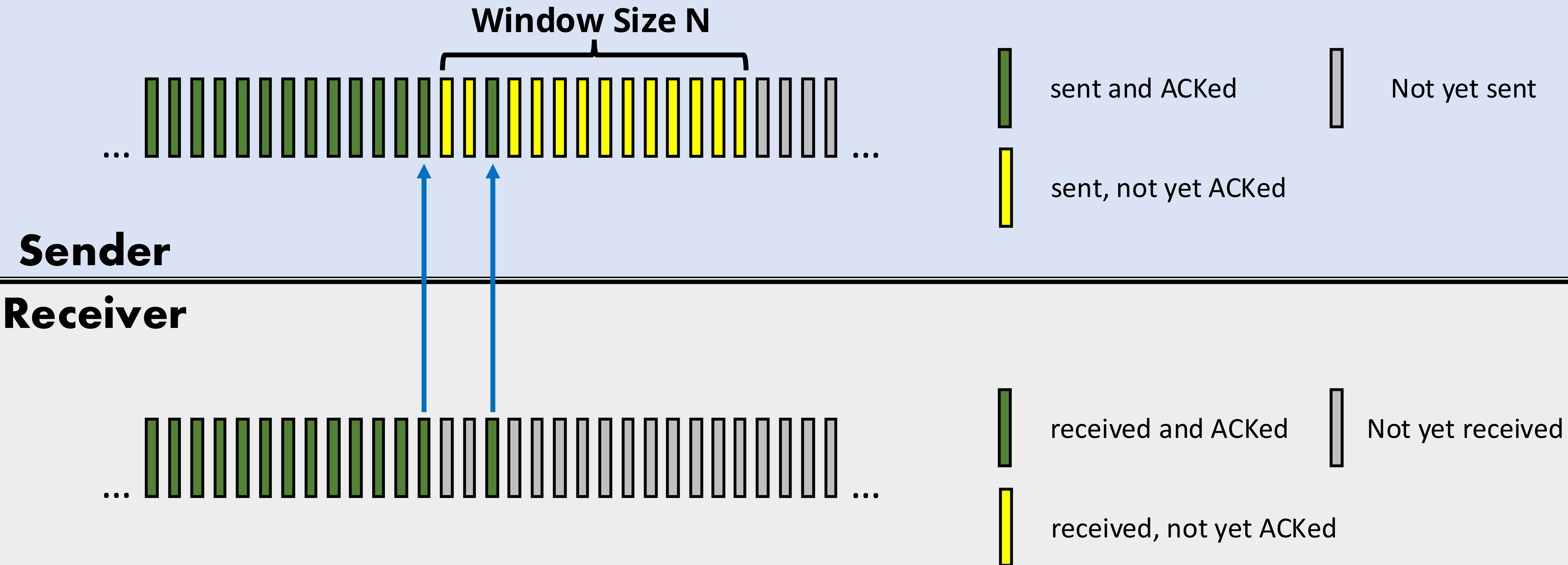
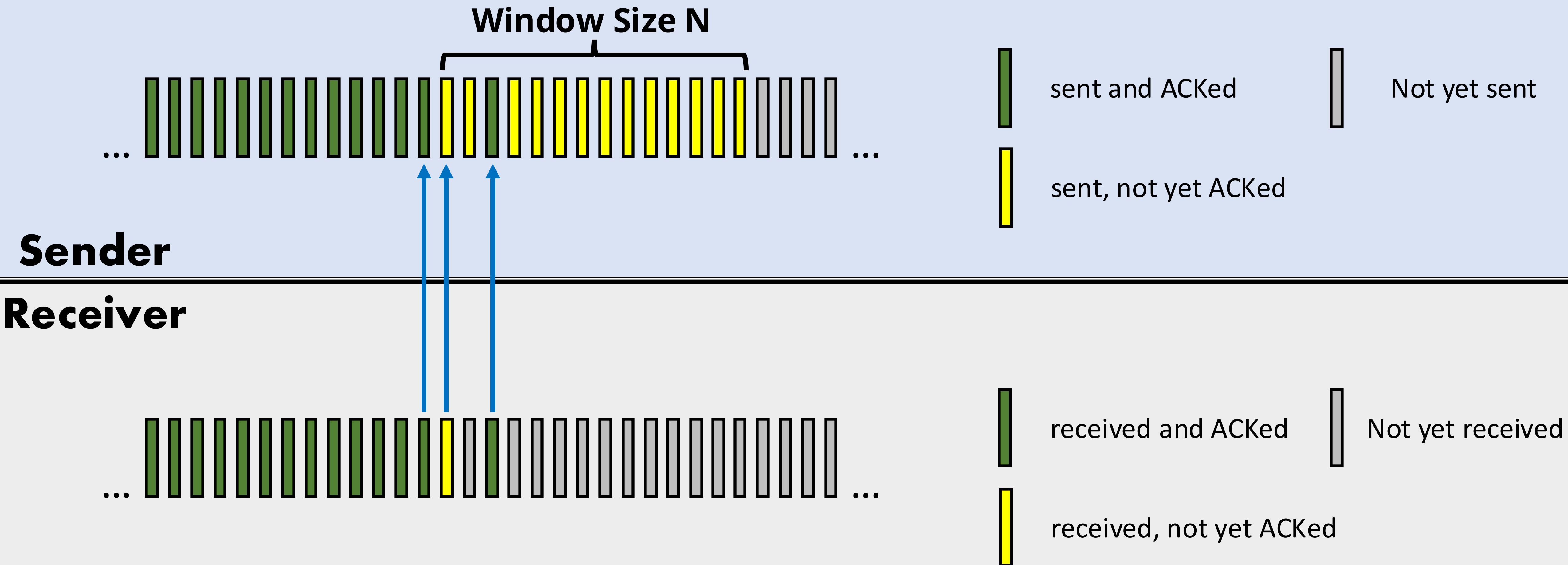


- *receiver individually ACKs* all correctly received packets
  - buffers packets, as needed, for in-order delivery to upper layer

Sliding Window + selective repeat: out-of-order



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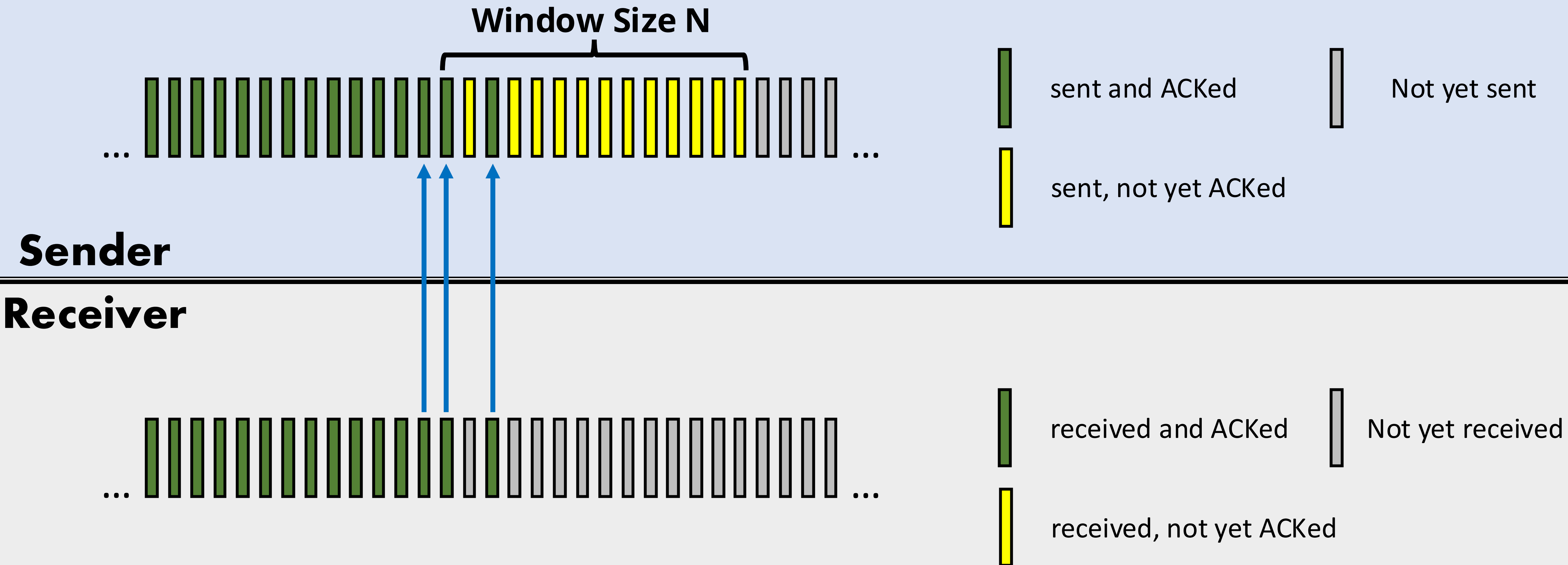

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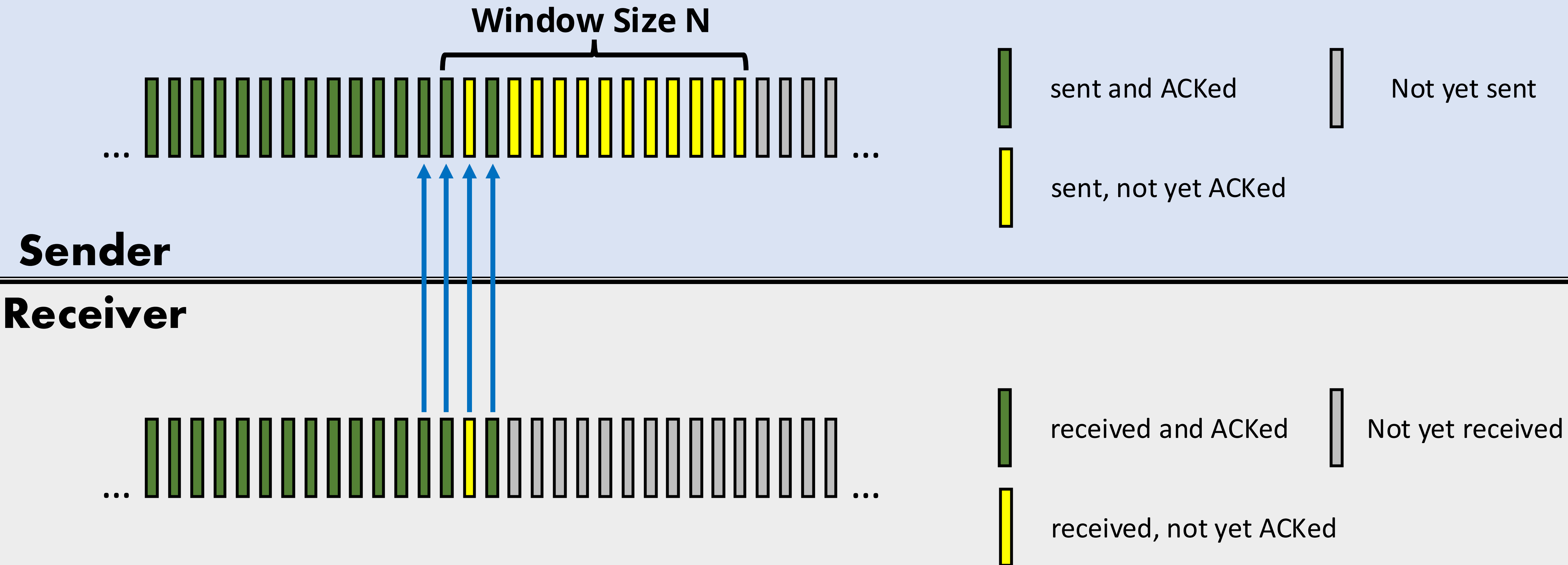

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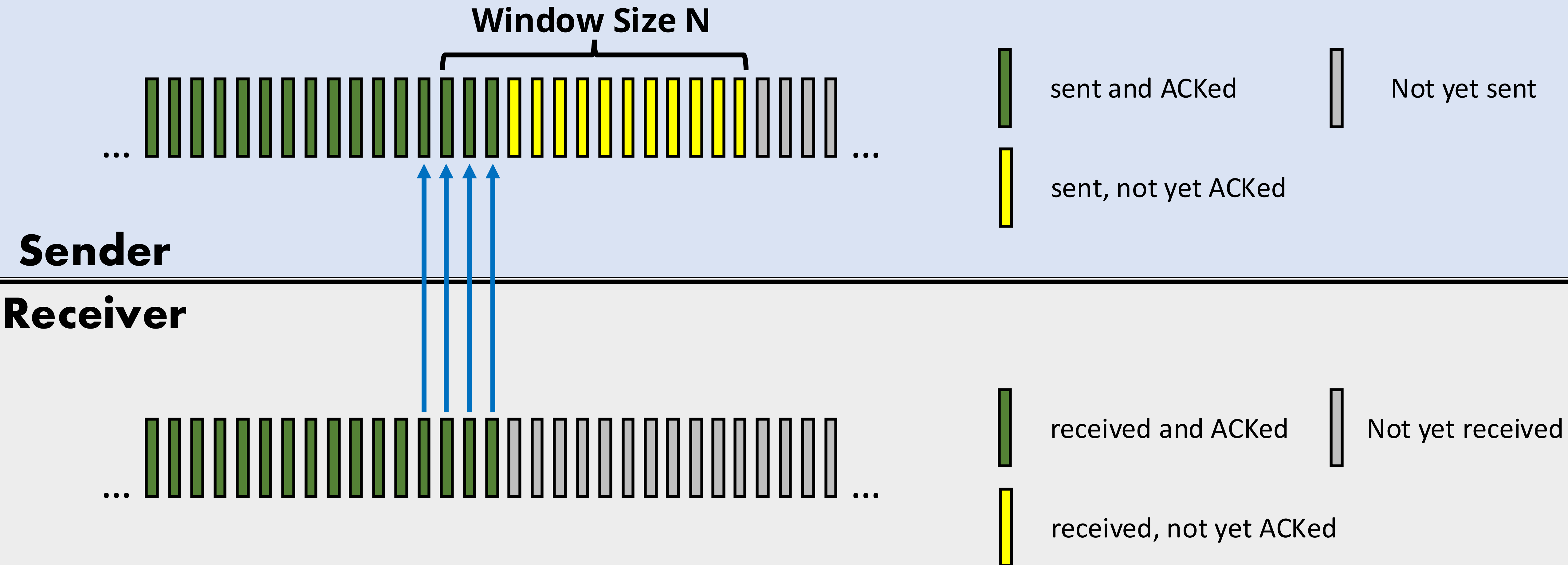

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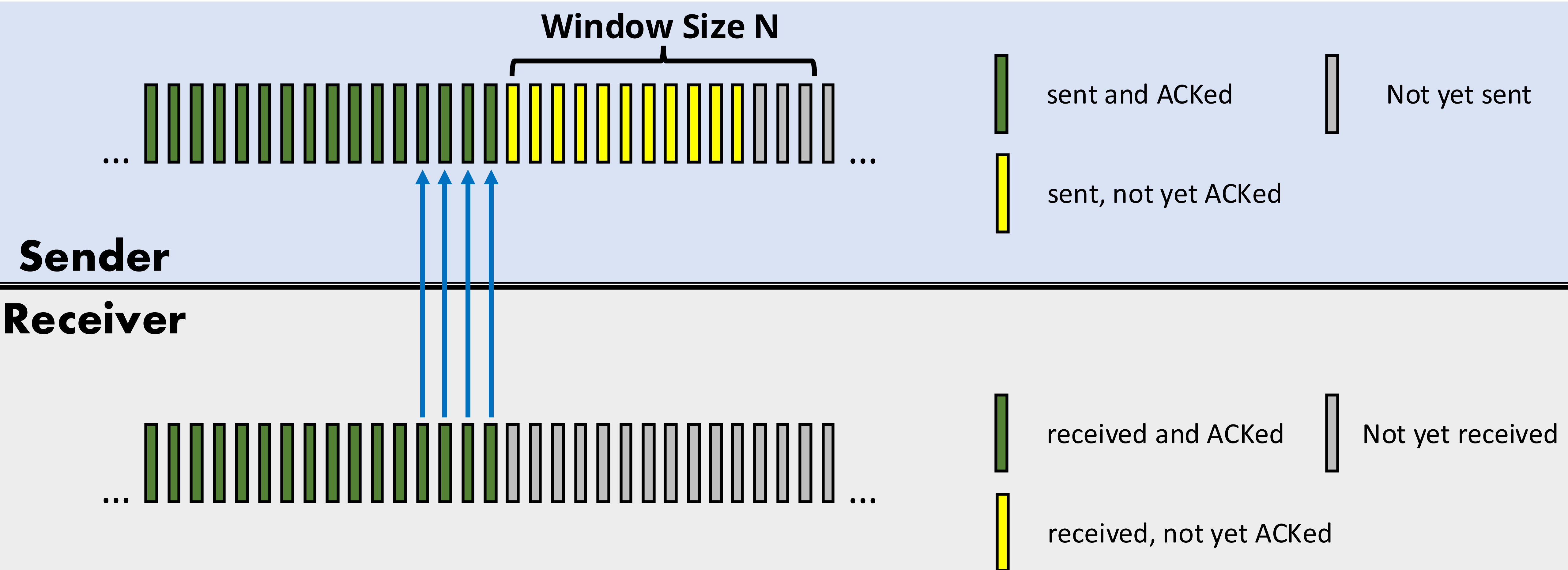

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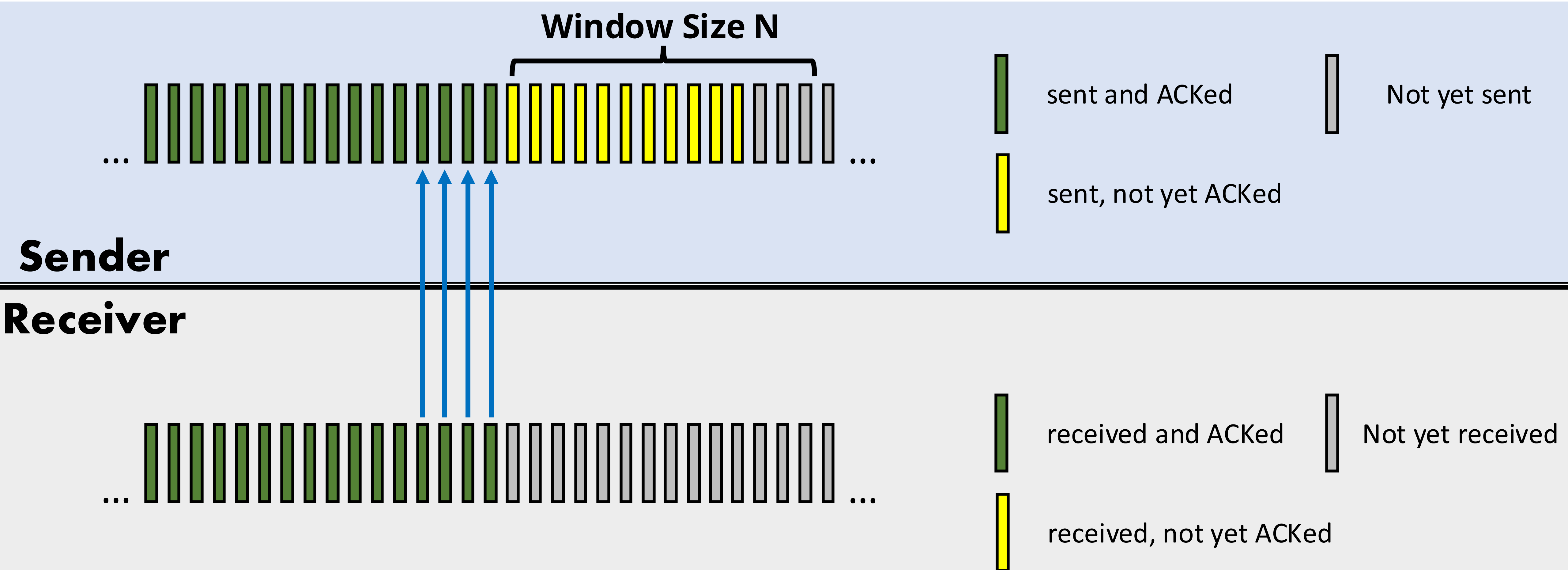

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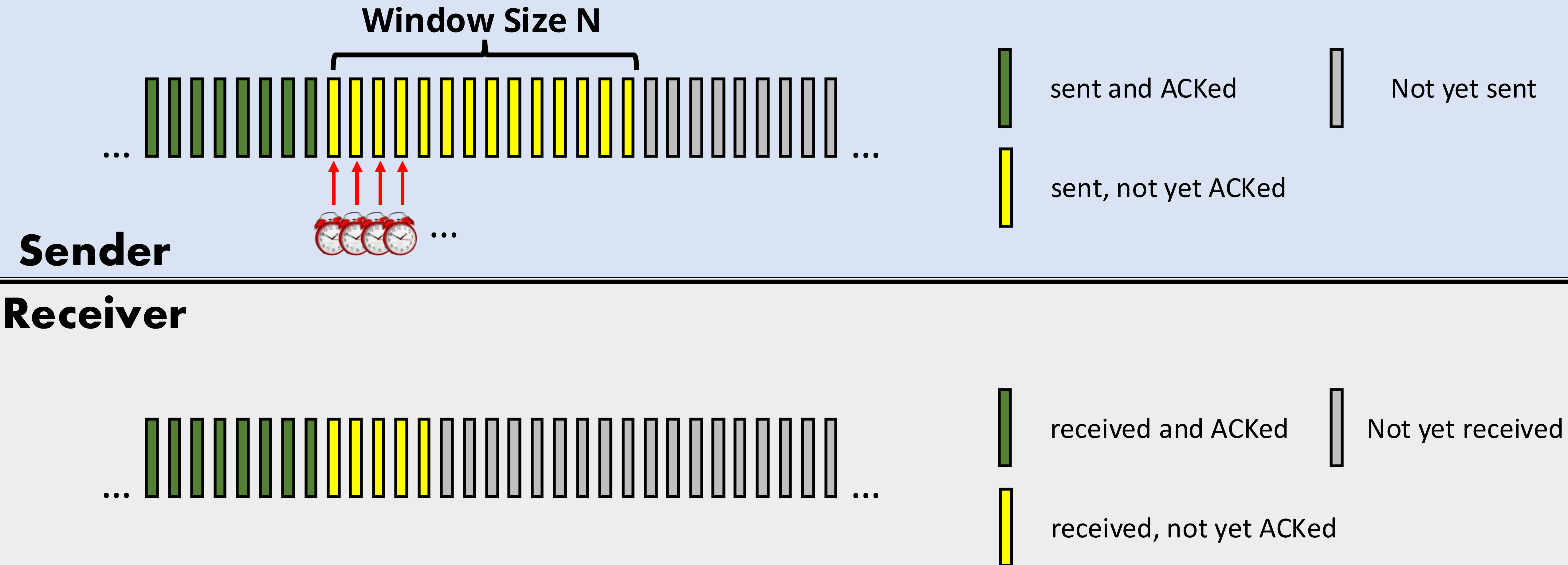
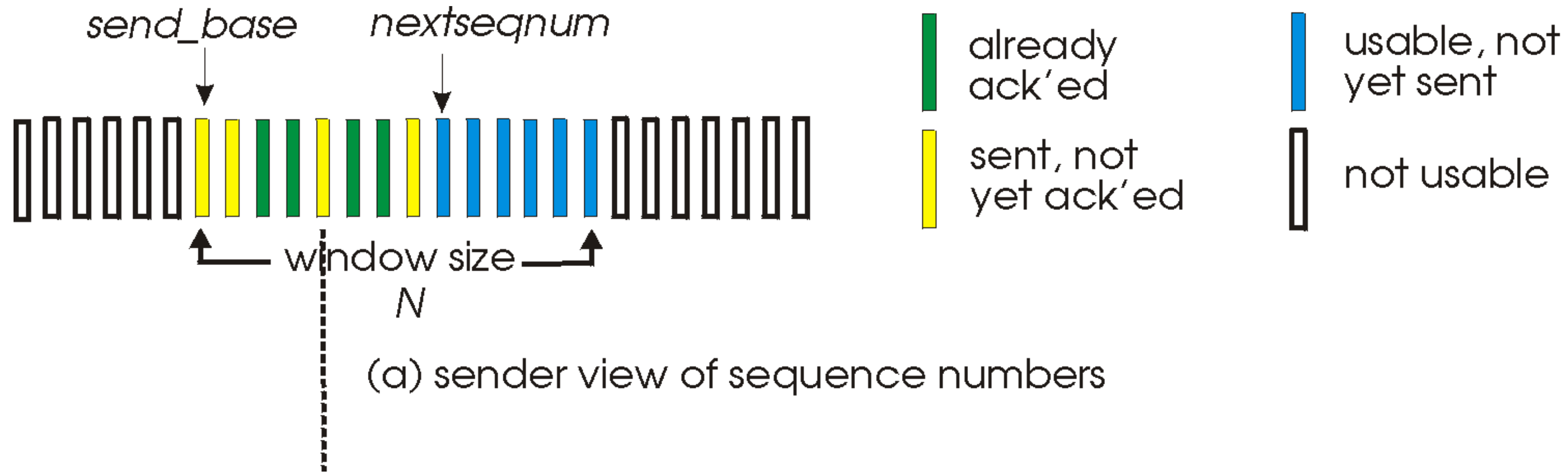


- Maintains (conceptually) a timer for each unACKed pkt
  - timeout: retransmits single unACKed packet associated with timeout

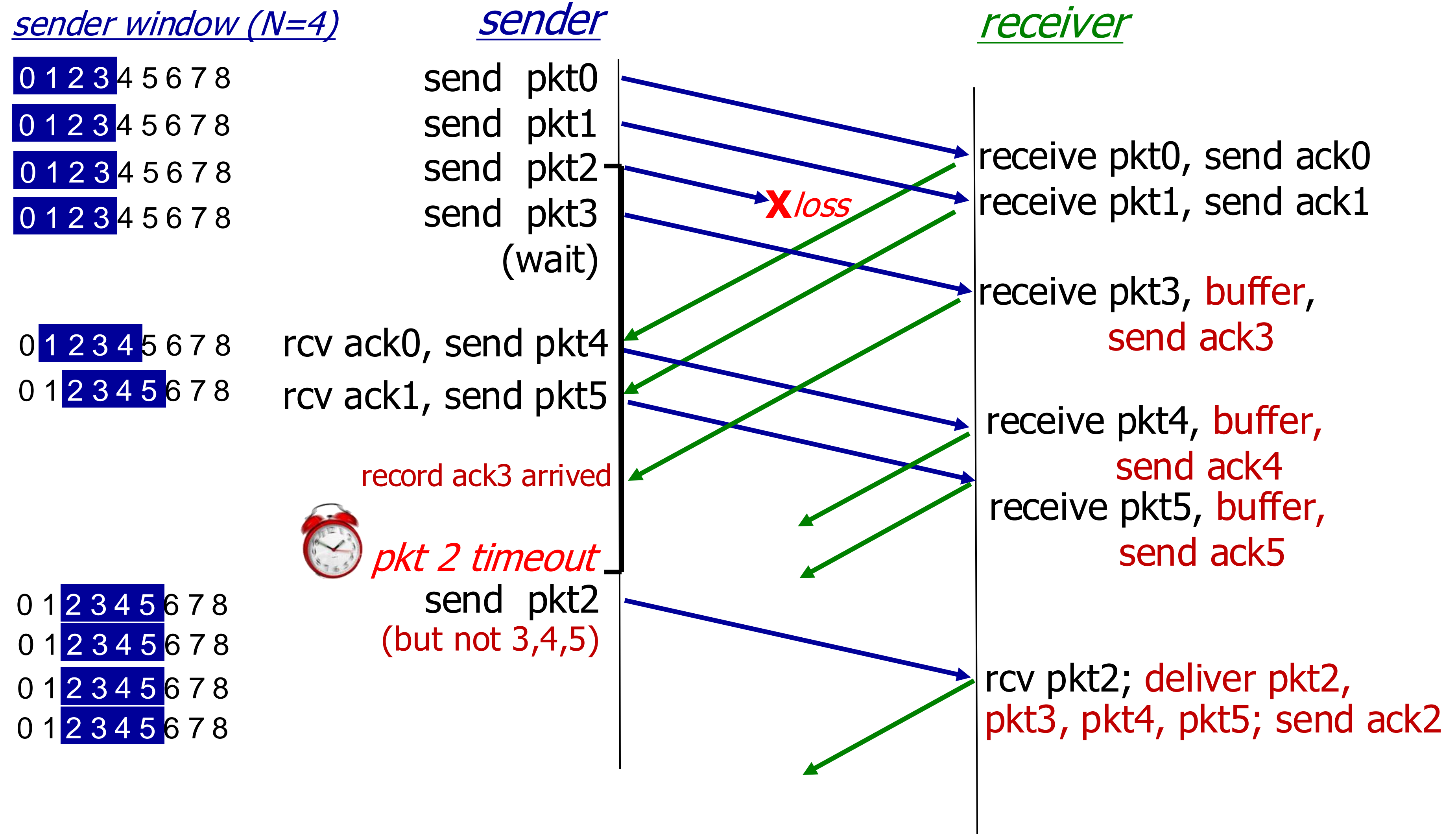
Selective repeat: the approach

- *pipelining*: *multiple* packets in flight
- *receiver individually ACKs* all correctly received packets
  - buffers packets, as needed, for in-order delivery to upper layer
- sender:
  - maintains (conceptually) a timer for each unACKed pkt
    - timeout: retransmits single unACKed packet associated with timeout
  - maintains (conceptually) "window" over *N* consecutive seq #s
    - limits pipelined, "in flight" packets to be within this window

Selective repeat: sender, receiver windows



Selective Repeat in action



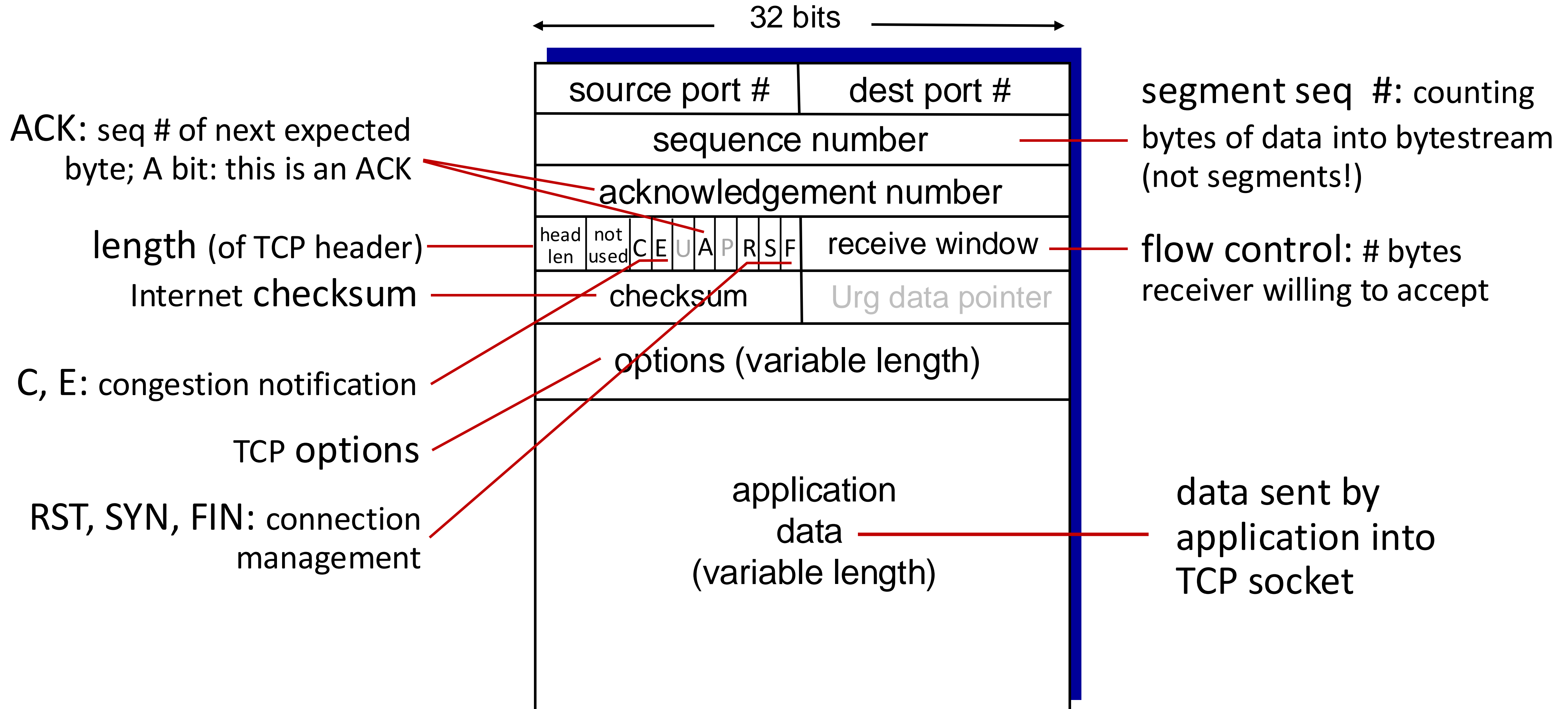
Chapter 3: roadmap

- Transport-layer services
- Multiplexing and demultiplexing
- Connectionless transport: UDP
- Principles of reliable data transfer
- Connection-oriented transport: TCP
  - segment structure
  - reliable data transfer
  - flow control
  - connection management
- Principles of congestion control
- TCP congestion control

TCP: overview RFCs: 793,1122, 2018, 5681, 7323

- point-to-point:
  - one sender, one receiver
- reliable, in-order *byte steam:*
  - no “message boundaries"
- full duplex data:
  - bi-directional data flow in same connection
  - MSS: maximum segment size
- cumulative ACKs
- pipelining:
  - TCP congestion and flow control set window size
- connection-oriented:
  - handshaking (exchange of control messages) initializes sender, receiver state before data exchange
- flow controlled:
  - sender will not overwhelm receiver

TCP segment structure



TCP sequence numbers, ACKs

Sequence numbers:

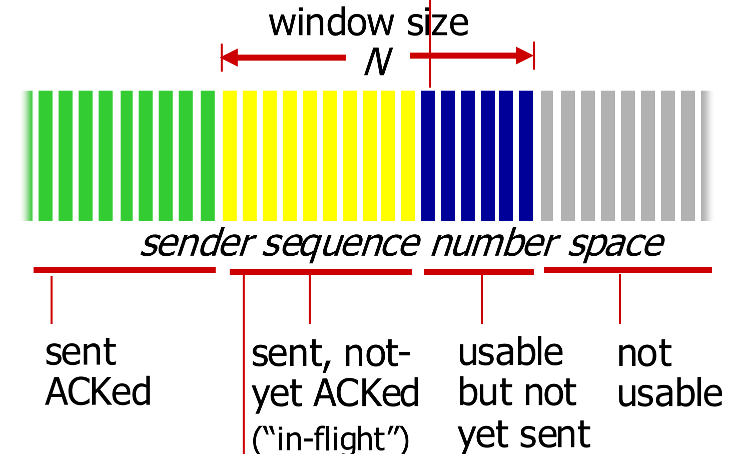
- byte stream "number" of first byte in segment's data

Acknowledgements:

- seq # of next byte expected from other side
- cumulative ACK

Q: how receiver handles out-of-order segments

- *A:* TCP spec doesn't say, - up to implementor



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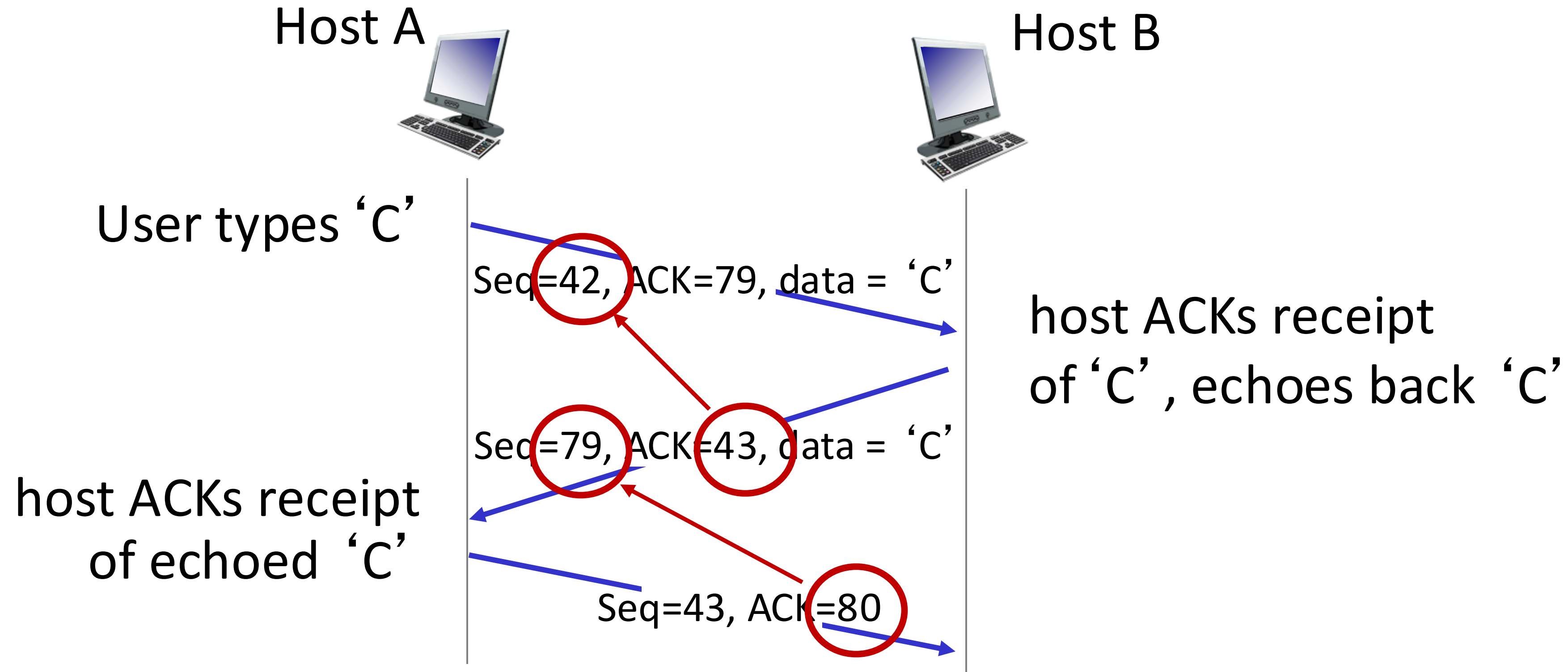


simple telnet scenario

TCP round trip time, timeout

Q: how to set TCP timeout value?

- longer than RTT, but RTT varies!
- *too short:* premature timeout, unnecessary retransmissions
- *too long:* slow reaction to segment loss

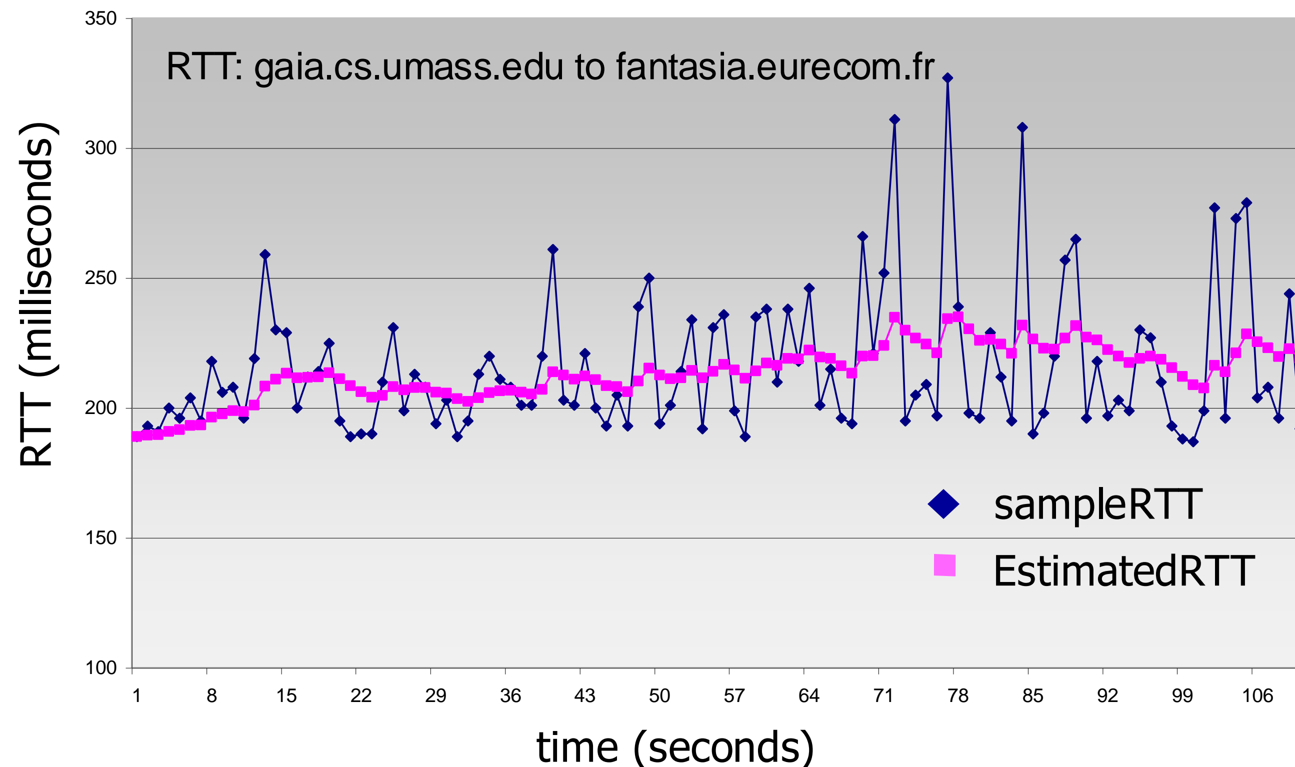
Q: how to estimate RTT?

- `SampleRTT`: measured time from segment transmission until ACK receipt
  - ignore retransmissions
- `SampleRTT` will vary, want estimated RTT "smoother"
  - average several *recent* measurements, not just current `SampleRTT`

TCP round trip time, timeout

```
EstimatedRTT = (1- α)*EstimatedRTT + α*SampleRTT
```

- exponential weighted moving average (EWMA)
- influence of past sample decreases exponentially fast
- typical value: α = 0.125



TCP round trip time, timeout

- timeout interval: **EstimatedRTT** plus "safety margin"
  - large variation in **EstimatedRTT**: want a larger safety margin

```
TimeoutInterval = EstimatedRTT + 4*DevRTT
```

estimated RTT (EstimatedRTT) — "safety margin" (4*DevRTT)

- **DevRTT**: EWMA of **SampleRTT** deviation from **EstimatedRTT**:

```
DevRTT = (1-β)*DevRTT + β*|SampleRTT-EstimatedRTT|
```

(typically, β = 0.25)

* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive/

TCP Sender (simplified)

event: data received from application

- create segment with seq #
- seq # is byte-stream number of first data byte in segment
- start timer if not already running
  - think of timer as for oldest unACKed segment
  - expiration interval: **`TimeOutInterval`**

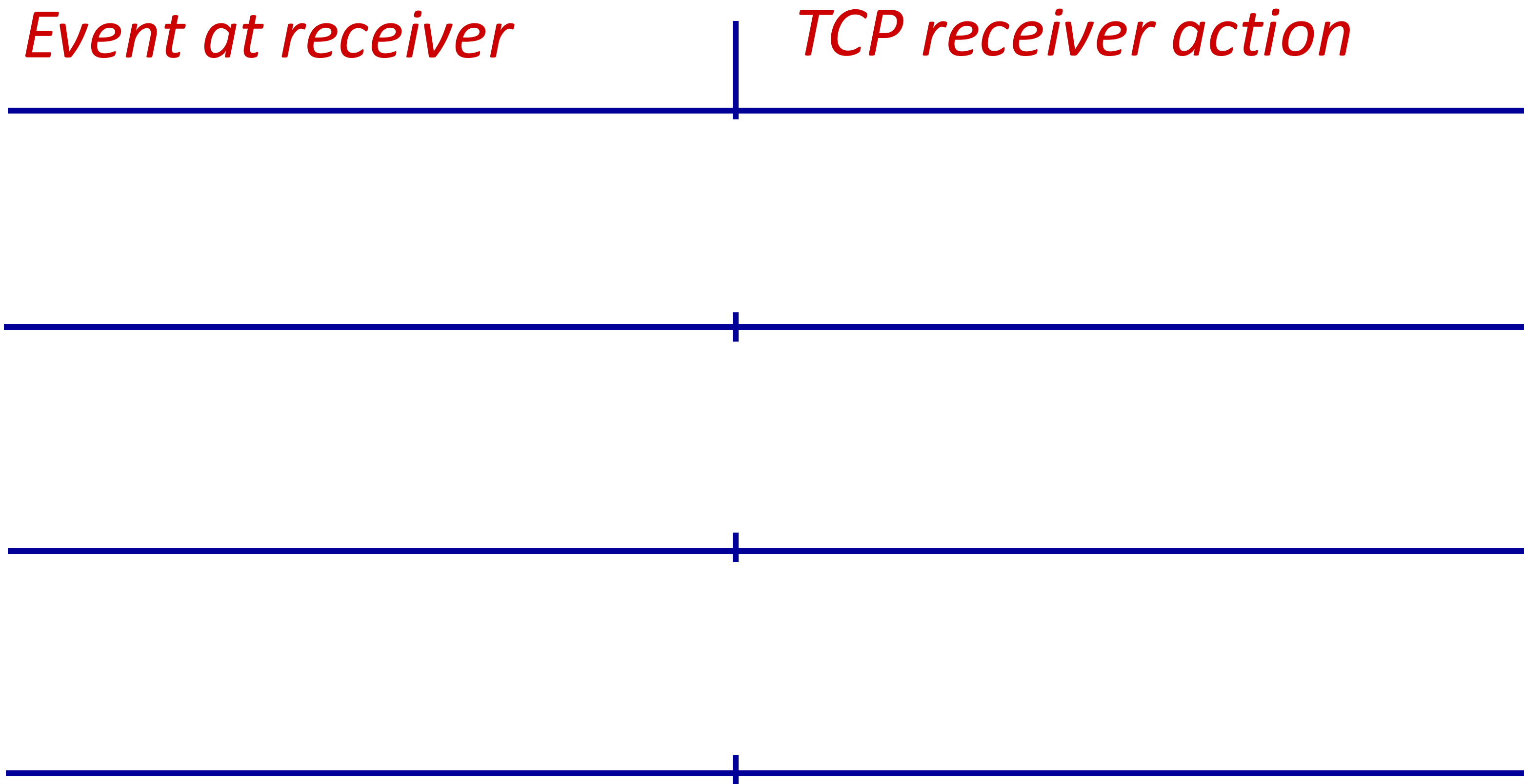
event: timeout

- retransmit segment that caused timeout
- restart timer

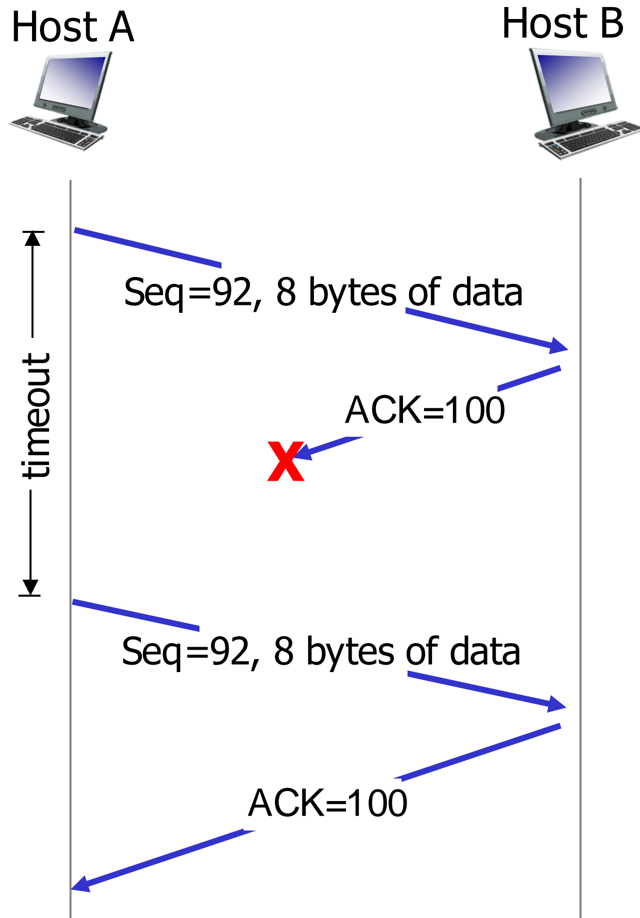
event: ACK received

- if ACK acknowledges previously unACKed segments
  - update what is known to be ACKed
  - start timer if there are still unACKed segments

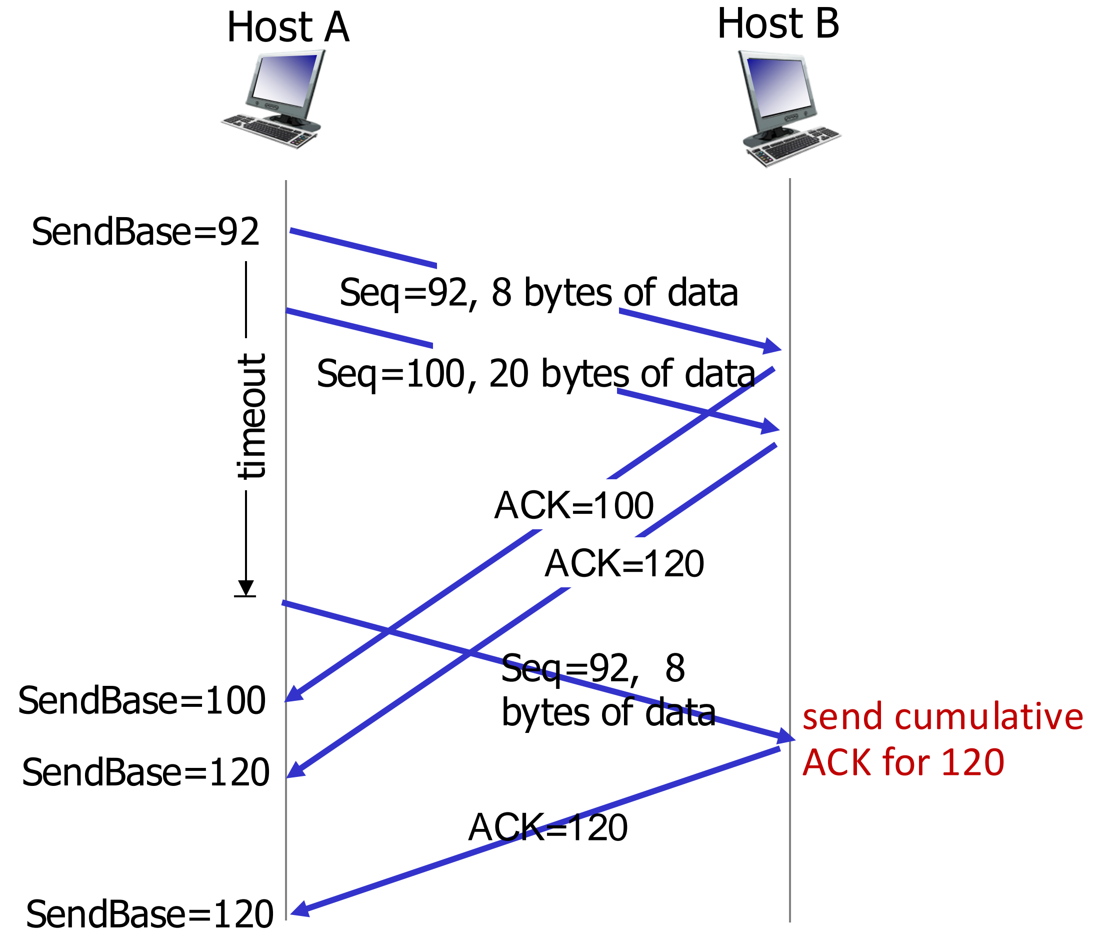
TCP Receiver: ACK generation [RFC 5681]



TCP: retransmission scenarios

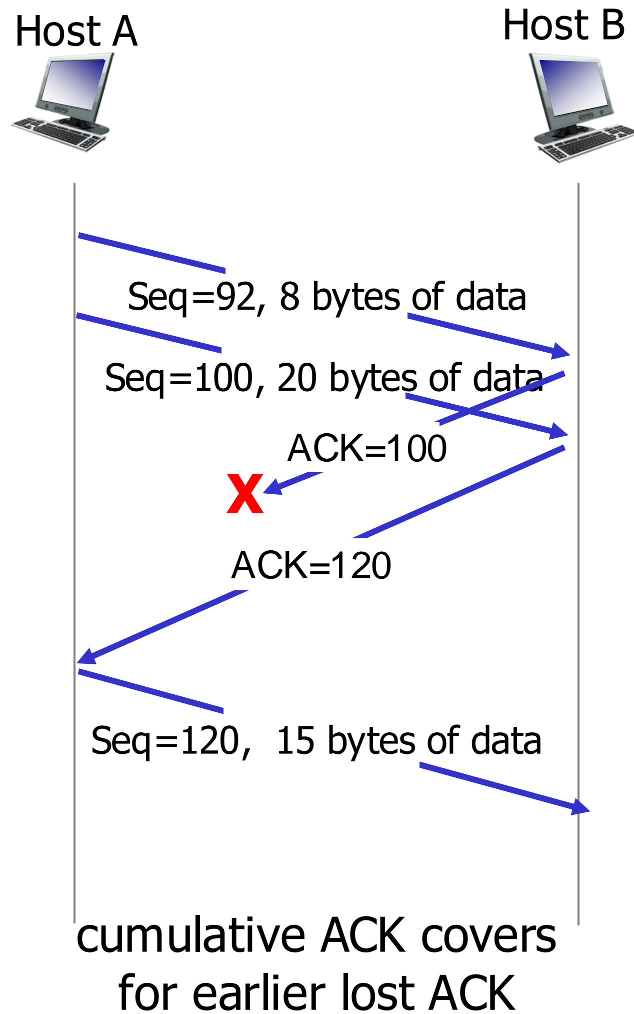


lost ACK scenario



premature timeout

TCP: retransmission scenarios

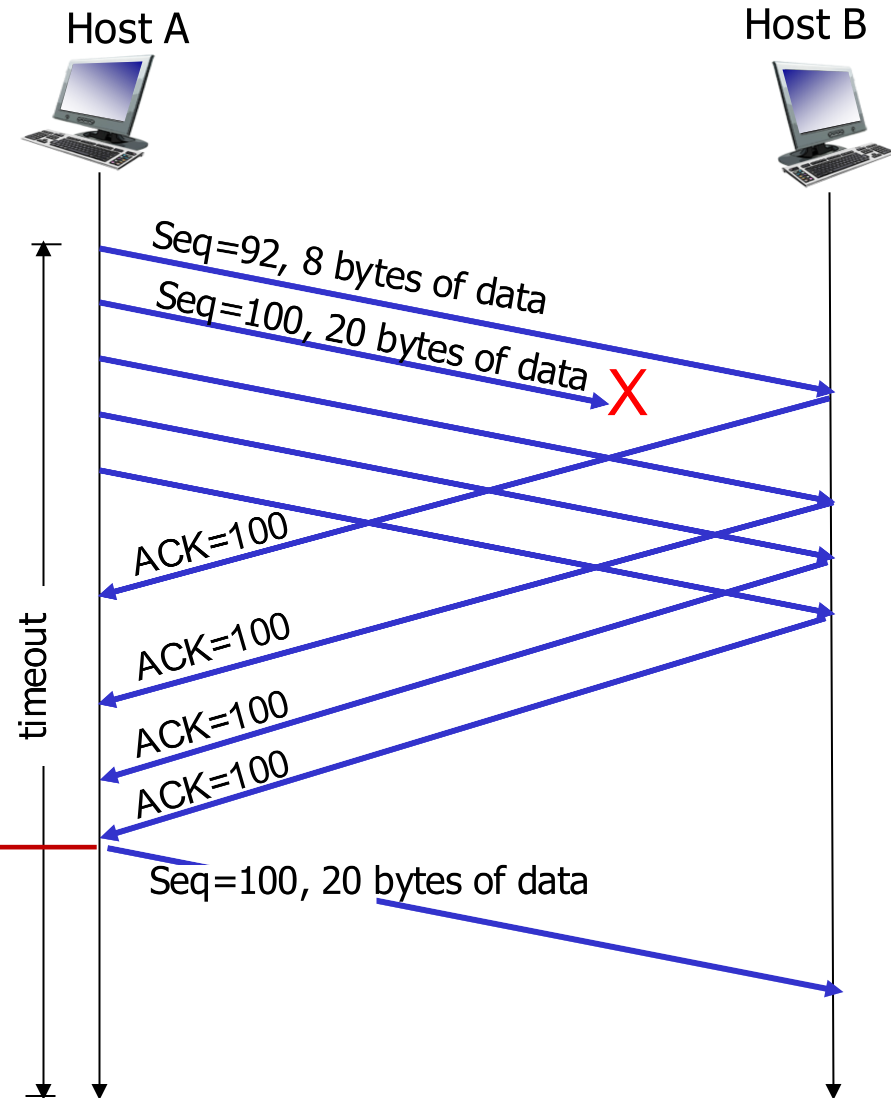


TCP fast retransmit

TCP fast retransmit

if sender receives 3 additional ACKs for same data ("triple duplicate ACKs"), resend unACKed segment with smallest seq #

- likely that unACKed segment lost, so don't wait for timeout



Receipt of three duplicate ACKs indicates 3 segments received after a missing segment – lost segment is likely. So retransmit!