Lecture 12: Transport Layer
Reliable Data Transfer and Seq #s

COMP 332, Spring 2023

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Acknowledgements: materials adapted from Computer Networking: A Top Down Approach 7th edition: ©1996-2016, J.F Kurose and K.W. Ross, All Rights Reserved as well as from slides by Abraham Matta at Boston University, and some material from Computer Networks by Tannenbaum and Wetherall.

Today

Announcements

- homework 5 Friday at 11:59p
  - but can be turned over the break if need be
- today's lecture will help with question 2
- Wed nights: I will do zoom help session

Recap

- reliable data transport over channels with errors and loss

Pipelined protocols

- go-back-N
- selective repeat
- sequence numbers in practice

TCP overview

Reliable Data Transport

REVIEW

Reliable data transport versions

rdt1.0: underlying channel is perfectly reliable

– Sender and receiver send/read data from channel

These are Stop-and-wait protocols: sender does not send new packet until sure receiver has current packet

rdt2.0: channel with bit errors on packets

– Checksum on packets to detect error
– ACK/NAK to tell sender packet received ok/not ok

rdt2.1: channel with bit errors on packets and ACKs/NAKs

– Checksum on packets and ACKs/NAKs to detect error
– ACK/NAK to tell sender packet received ok/not ok
– Sender retransmits current packet if ACK/NAK corrupted
  - Sender adds sequence # to each packet so receiver can distinguish new packets from retransmissions
  - Receiver discards duplicates that may arise due to retransmissions

Reliable data transport versions

rdt2.2: channel with bit errors on packets and ACKs

- ACK last packet correctly received
- Duplicate ACKs at sender: interpreted as NAK
- Receiver must specify sequence # of packet being ACKed

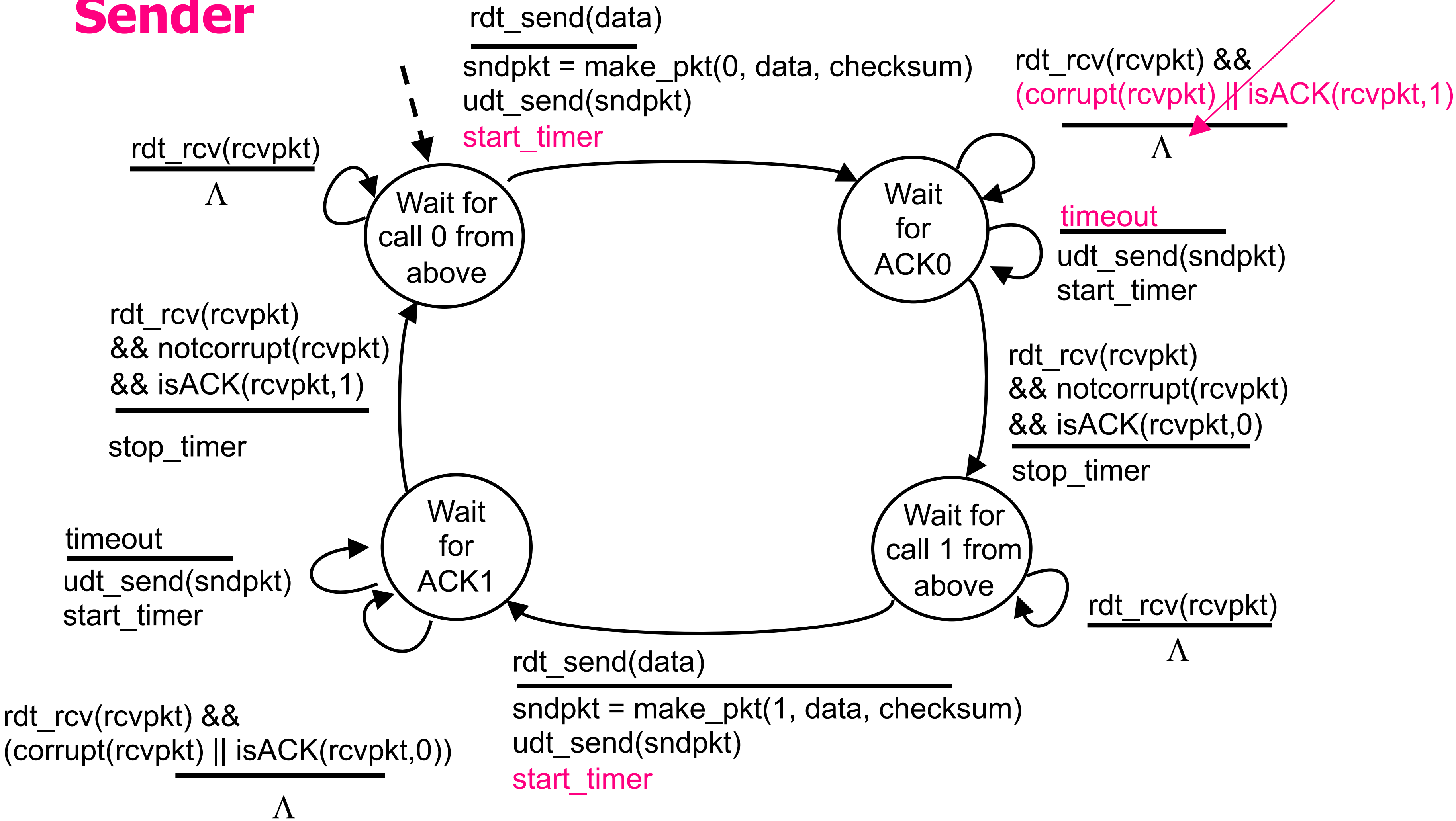
rdt3.0: channel with bit errors, loss

- Sender starts timer when packet sent
  - retransmits if expires without having received ACK
- If packet (or ACK) just delayed (not lost)
  - retransmission will be duplicate, but seq #'s already handles this

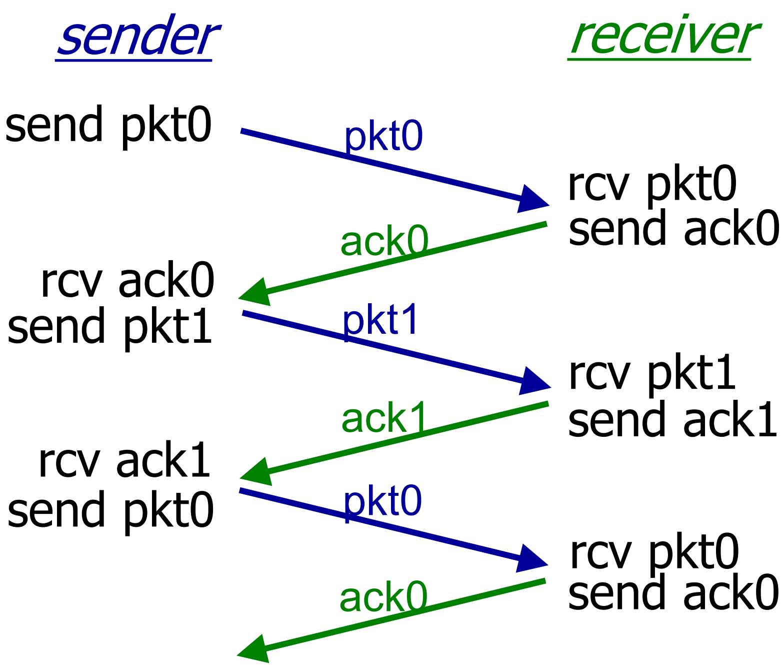
rdt3.0 sender

Why do nothing ? Why not resend pkt0? Because sender doesn't know whether ack1 means pkt 0 garbled or pkt 1 duplicate received
By not resending pkt 0, sender doesn't introduce potentially unnecessary (even if valid) traffic: saves bandwidth

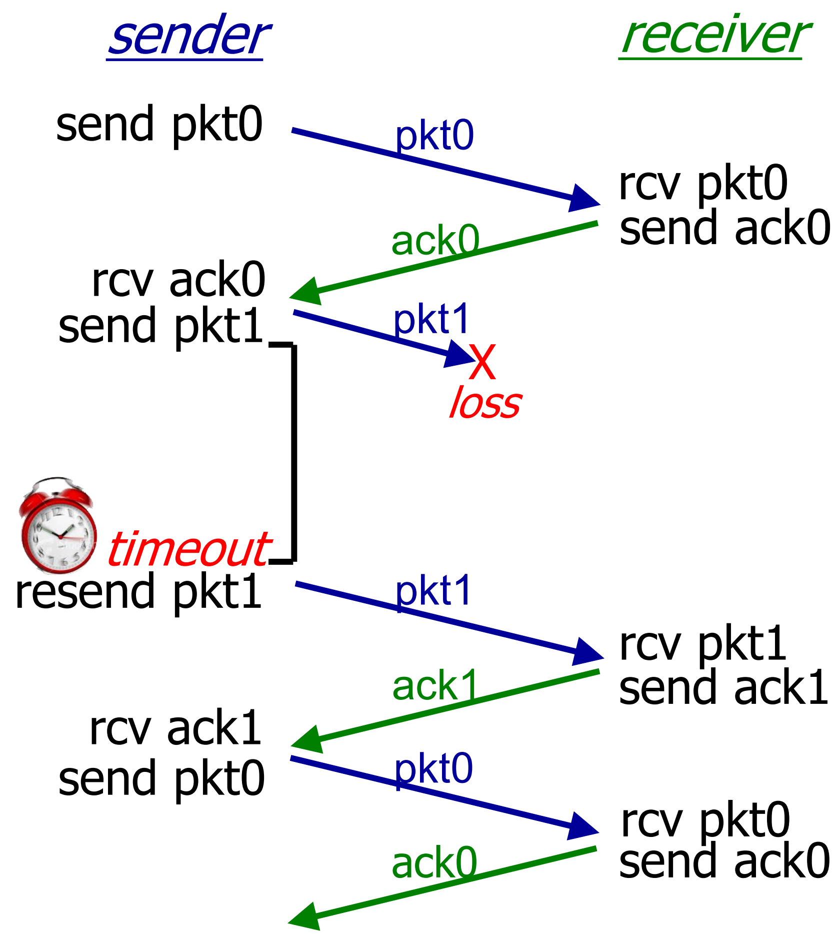
Sender



rdt3.0 in action

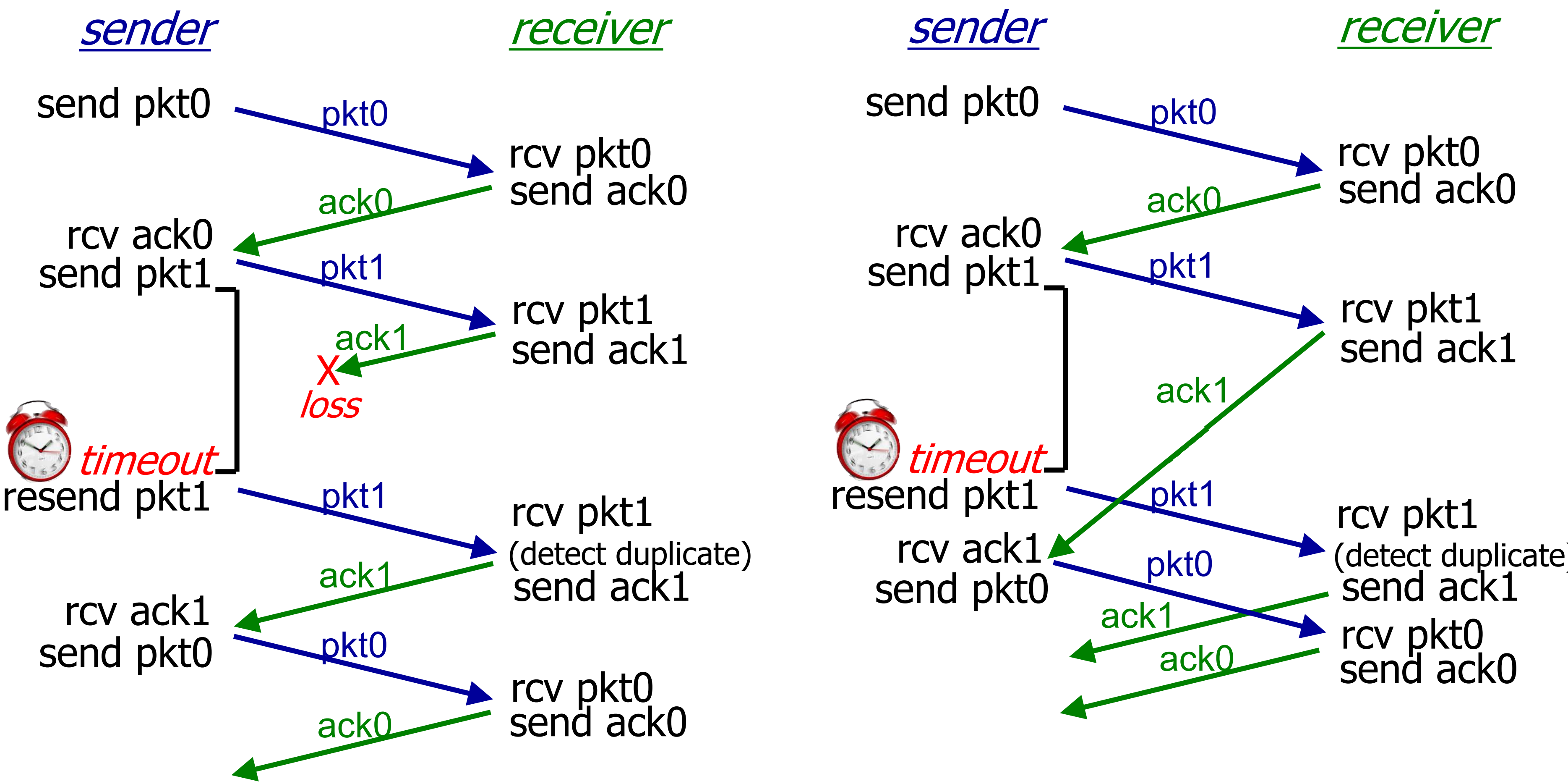


(a) no loss



(b) packet loss

rdt3.0 in action



(c) ACK loss

(d) premature timeout/ delayed ACK

Summary of techniques and uses

Channel problems | **Protocol solutions**

Corrupted packets → Checksum, Acknowledgements, Sequence #s, Retransmissions and buffering

Duplicate packets → Seq #s

Reordered packets → Seq #s

(haven't talked about reordering yet)

Delayed packets → Timeouts and timers, Acknowledgements, Retransmissions and buffering

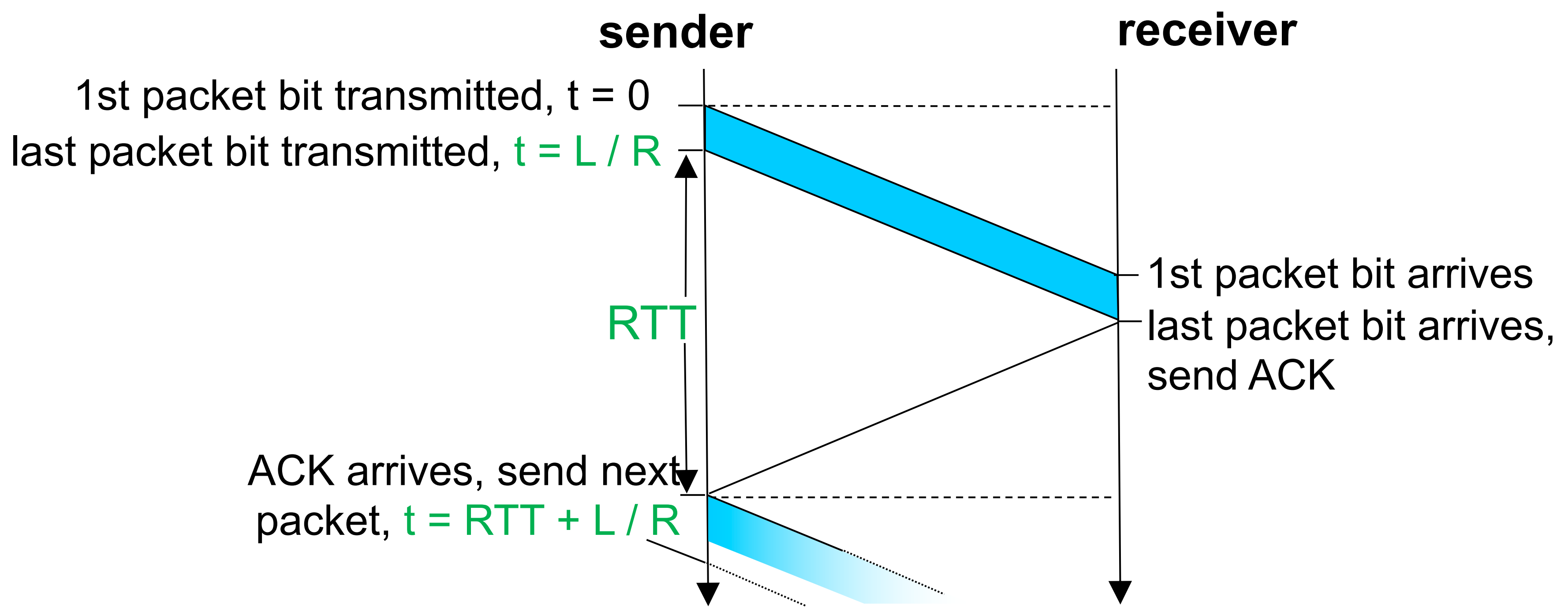
Dropped packets → Timeouts and timers, Acknowledgements, Retransmissions and buffering

Will see: # of seq #s must be > 2x window size if reordering

Reliable Data Transport

PIPELINED PROTOCOLS

rdt3.0: stop-and-wait operation



Time spent sending stuff

$$U_{sender} = \frac{L / R}{RTT + L / R} = \frac{.008}{30.008} = 0.00027$$

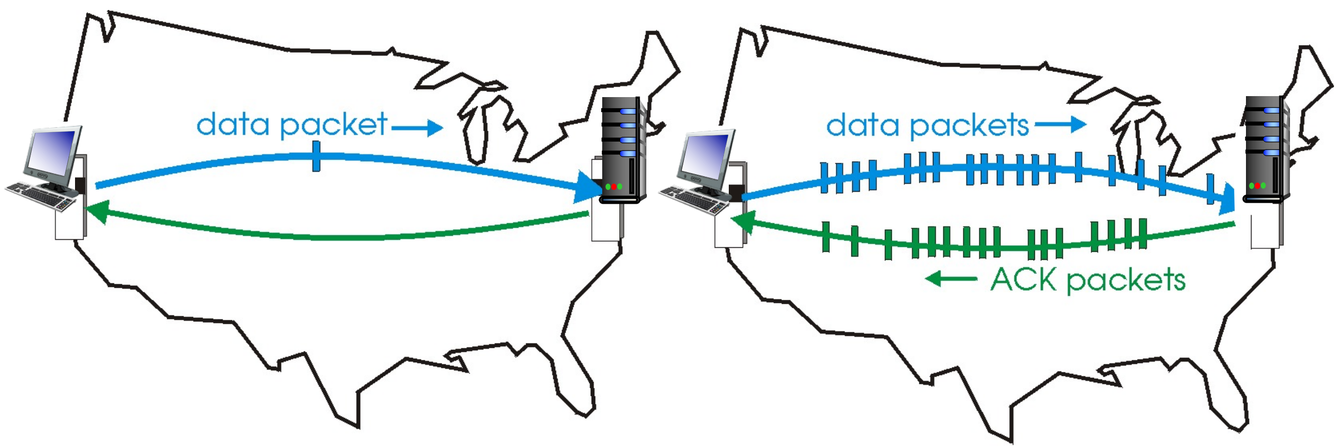
Total time

Problem: how to maintain high link utilization?

Get rid of stop-and wait

Use pipelining (aka sliding-window protocols), like in HTTP

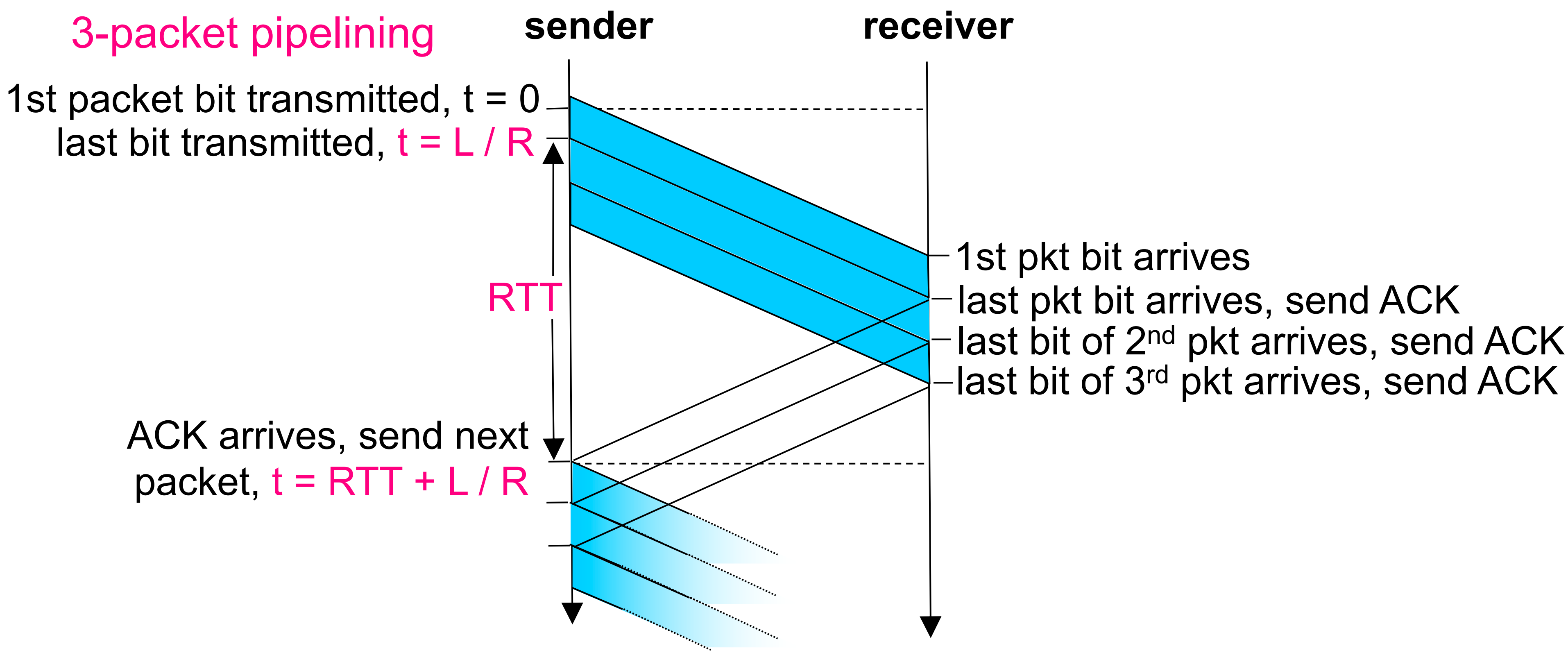
- sender allows multiple, in-flight, yet-to-be-acknowledged pkts
  - send up to N packets at a time, unacked
  - range of seq #s must be increased
  - sender needs more memory to buffer outstanding unacked packets



Stop and wait **Pipelined**

Achieves higher link utilization than stop-and-wait!

Increased utilization with pipelining



Time spent sending stuff

$$U_{sender} = \frac{3L / R}{RTT + L / R} = \frac{.0024}{30.008} = 0.00081$$

Total time

3-packet pipelining increases utilization by factor of 3!

Pipelined protocols

Send N packets without receiving ACKs. How to ACK now?

Cumulative ACKs: Go-Back-N protocol

- **sender**
  - has timer for oldest unacked pkt
  - when timer expires: retransmit all unacked pkts
  - pkts received correctly may be retransmitted
- **receiver** only sends cumulative ack, doesn't ack pkt if gap

Selective ACKs: Selective Repeat protocol

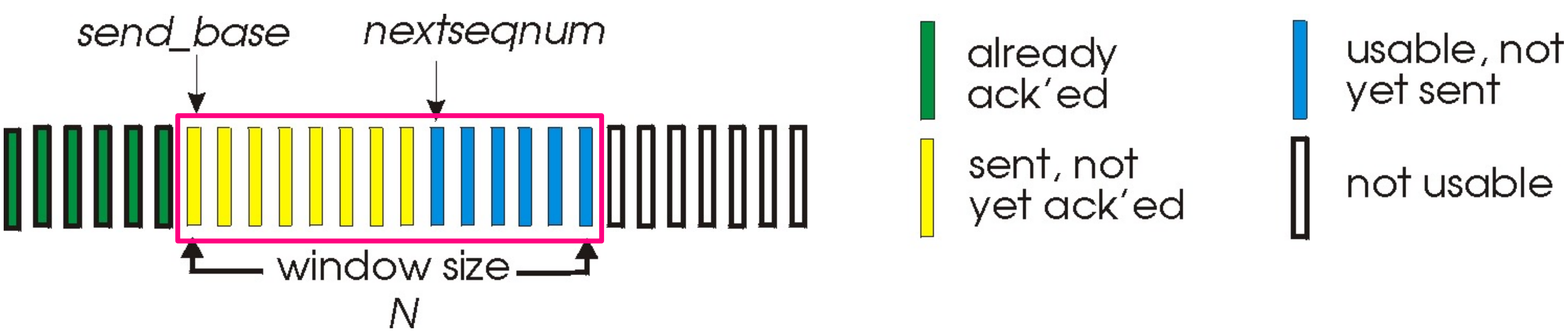
- **sender**
  - has timer for each unacked pkt
  - when timer expires, retransmit only unacked pkt
  - only corrupted/lost pkts are retransmitted
- **receiver** sends individual ack for each pkt

How pipelining protocols work

What is window size on stop and wait protocol?

Use sliding window

- how sender keeps track of what it can send
- window: set of N adjacent seq #s
  - only send packets in window



If window large enough, will fully utilize link

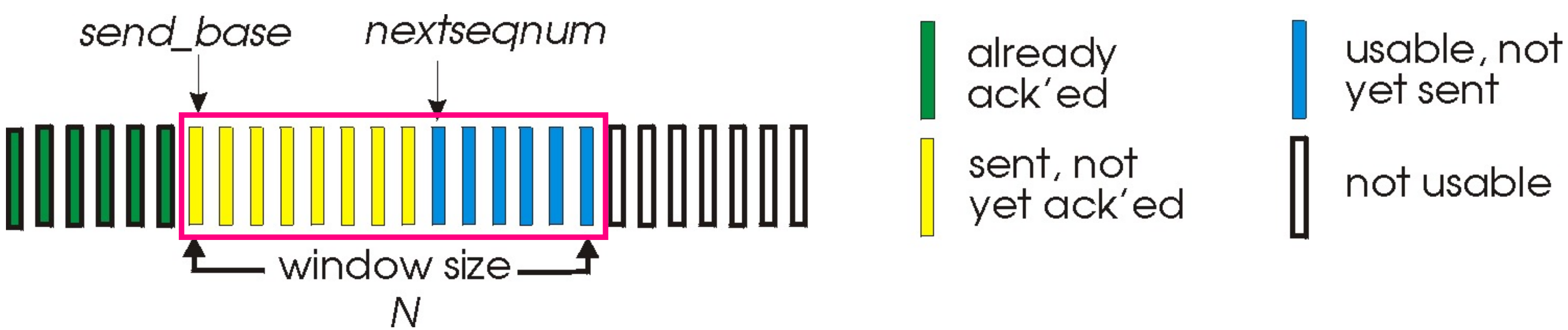
Pipelined Protocols

GO-BACK-N

Go-Back-N: sender

Window of up to N consecutive unacked pkts allowed

- ACK(n) is cumulative ACK
  - ACKs all pkts up to, including seq # n
  - may receive duplicate ACKs (see receiver)
- timer for oldest in-flight pkt
  - timeout(n): retransmit packet n and all higher seq # pkts in window

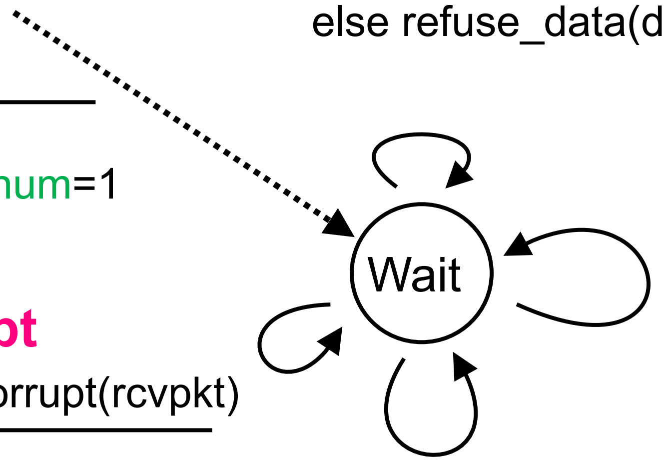


Go-Back-N: sender FSM

Send as long as pkt within window

rdt_send(data)
___
```
if (nextseqnum < base+N) {
    sndpkt[nextseqnum] = make_pkt(nextseqnum,data,chksum)
    udt_send(sndpkt[nextseqnum])
    if (base == nextseqnum)
      start_timer
    nextseqnum++
}
else refuse_data(data)
```

Λ
___
base=1
nextseqnum=1



Resend up to nextseqnum on timeout

timeout
___
```
start_timer
udt_send(sndpkt[base])
udt_send(sndpkt[base+1])
…
udt_send(sndpkt[nextseqnum-1])
```

Ignore corrupt

rdt_rcv(rcvpkt) && corrupt(rcvpkt)
___
Λ

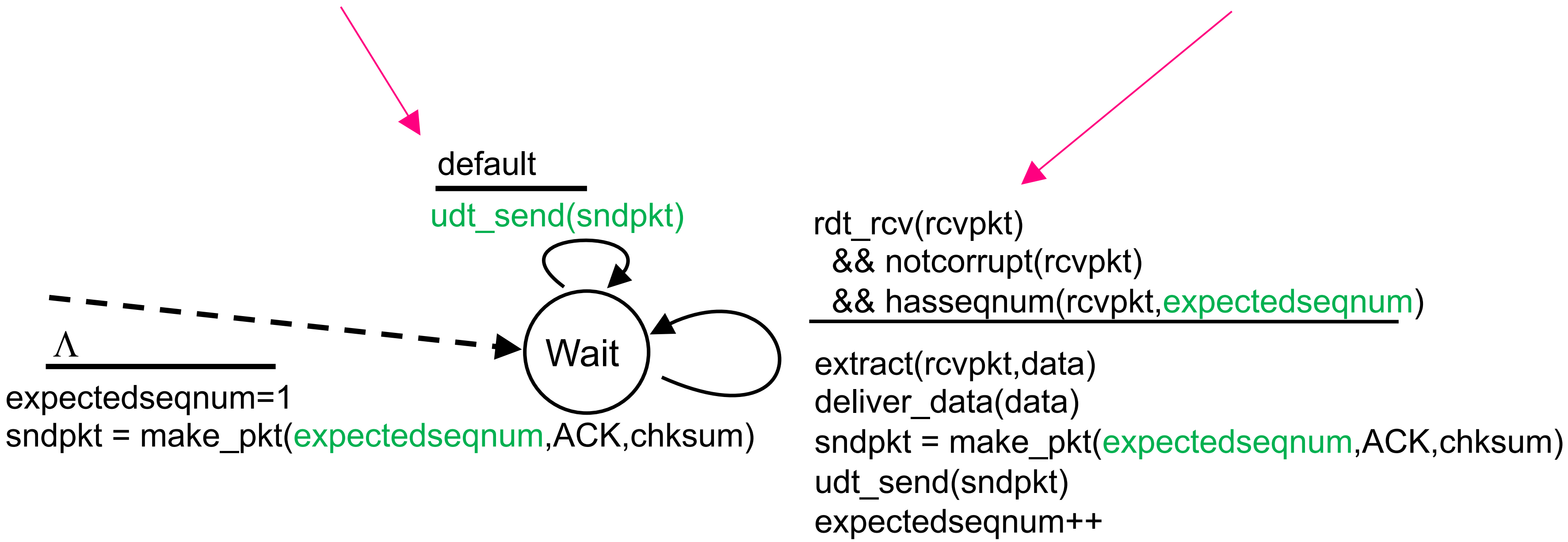
rdt_rcv(rcvpkt) &&
notcorrupt(rcvpkt)
___
```
base = getacknum(rcvpkt)+1
If (base == nextseqnum)
   stop_timer
 else
   start_timer
```

Cumulative ack: move base to ack# + 1

Go-Back-N: receiver FSM

Out-of-order pkt and all other cases
- discard: no receiver buffering!
- re-ACK pkt with highest in-order seq #

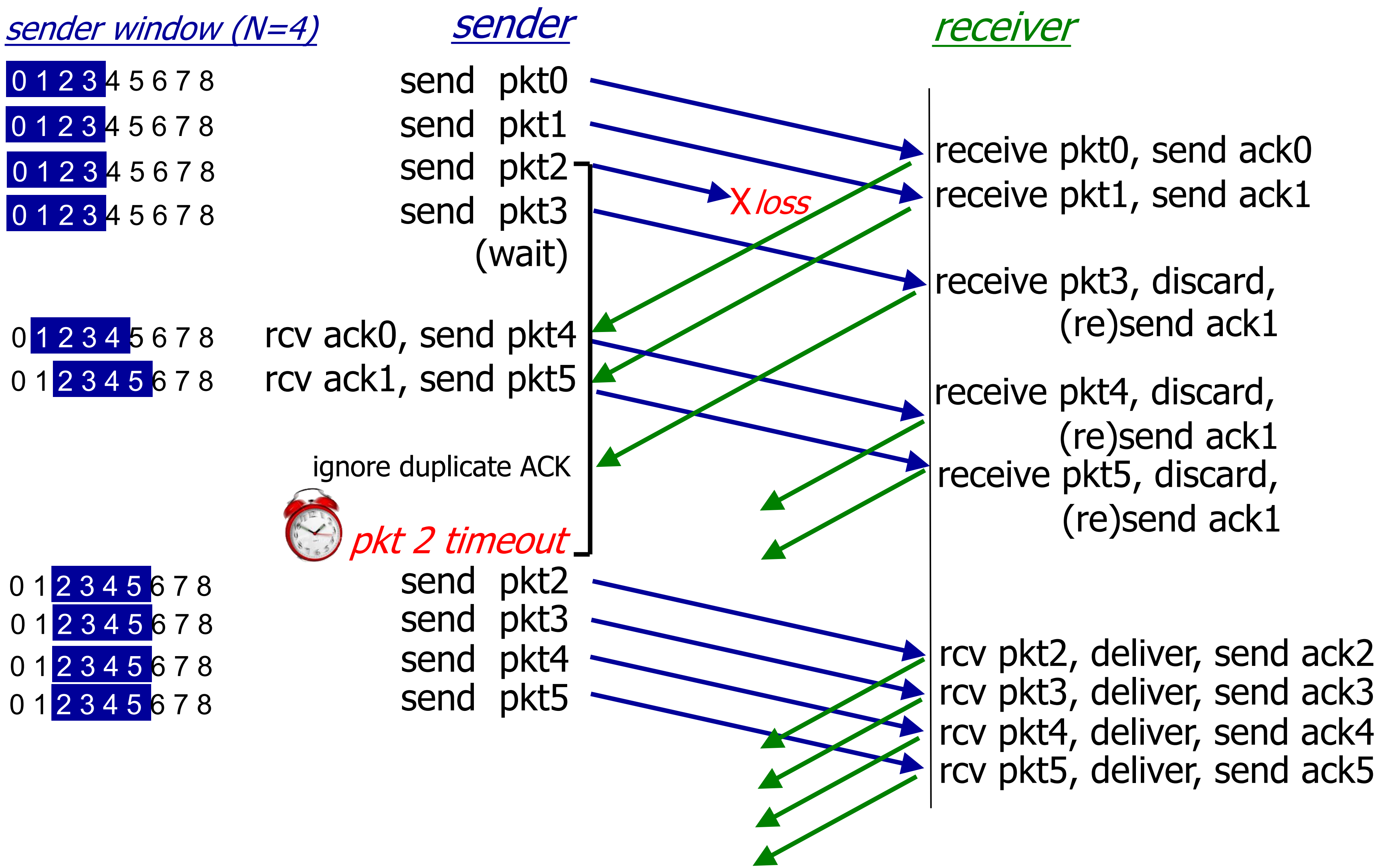
Correct pkt with highest in-order seq #
- send ACK, may be duplicate ACK
- need only remember expectedseqnum



Retransmit windowsize worth of packets for 1 error

large window size ⇒ large delays

Go-Back-N in action



Go-Back-N summary

Pros

- no receiver buffering
  - saves resources by requiring packets to arrive in-order
  - avoids large bursts of packet delivery to higher layers
- simpler buffering & protocol processing
  - can easily detect duplicates if out-of-sequence packet is received

Cons

- wastes capacity
  - on timeout for packet N sender retransmits from N all over again (all outstanding packets) including potentially correctly received packets

Tradeoff: buffering/processing complexity vs. capacity (time vs. space)

Pipelined Protocols

SELECTIVE REPEAT

Selective repeat

Rather than ACK cumulatively, ACKs selectively

Receiver

- individually ACKs all correctly received pkts
- buffers pkts, as needed, for eventual in-order delivery to upper layer

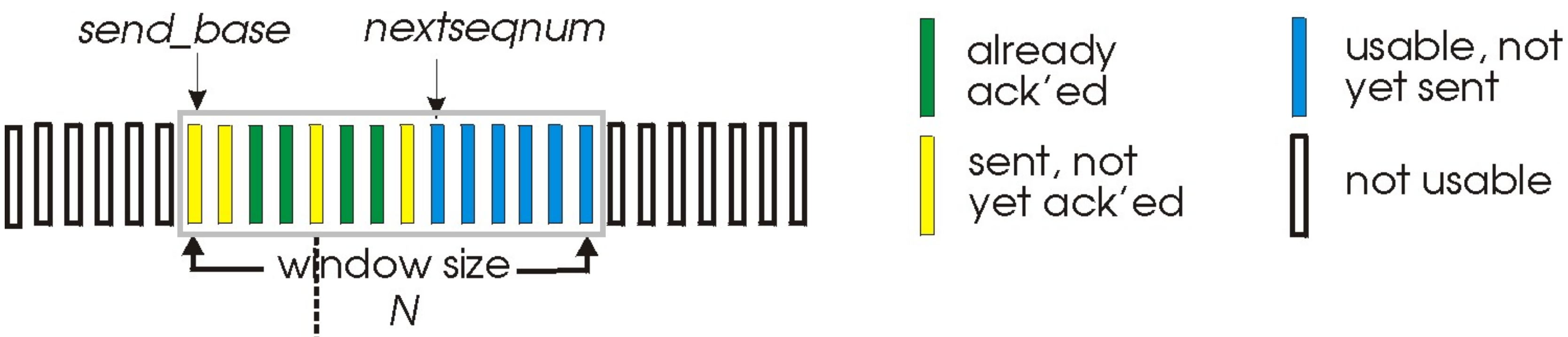
Sender

- only resends pkts for which ACK not received
- sender timer for each unACKed pkt

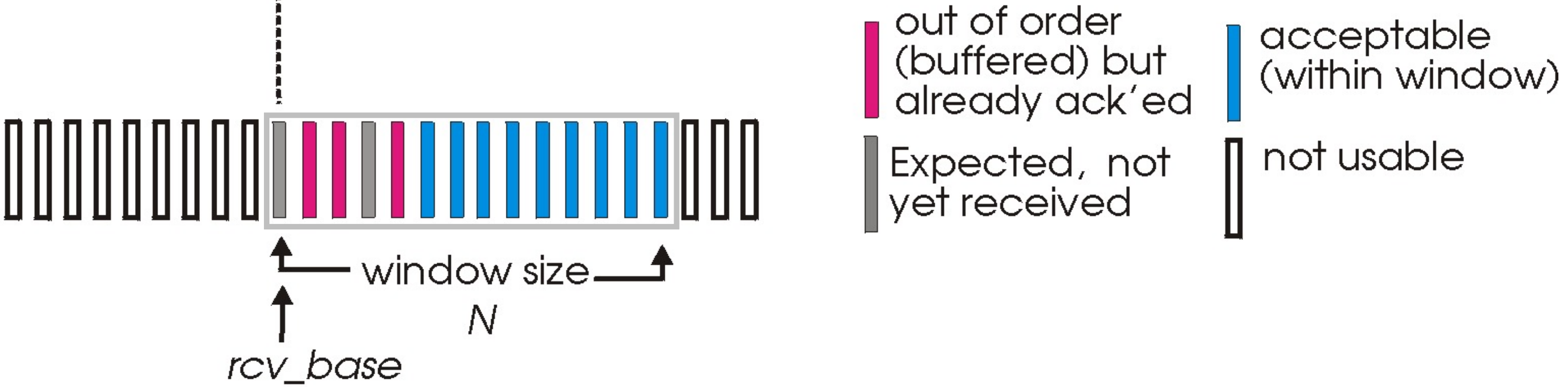
Sender window

- N consecutive seq #s
- limits seq #s of sent, unACKed pkts

Selective repeat: sender, receiver windows



Sender view of seq #s



Receiver view of seq #s

Selective repeat sender

Event: data from above

- **action:** if has next available seq # in window, send packet, start timer

Event: timeout(n)

- **action:** resend packet n, restart timer

Event: ACK(n) in [sendbase, sendbase + N]

- **action**
  - mark packet n as received
  - if n is smallest unACKed packet
    - advance window base to next unACKed seq #

Selective repeat receiver

Event: pkt n in [rcvbase, rcvbase+N-1]

- **action:**
  - send ACK(n)
  - out-of-order
    - buffer
  - in-order
    - deliver (also deliver buffered, in-order pkts)
    - advance window to next not-yet-received pkt

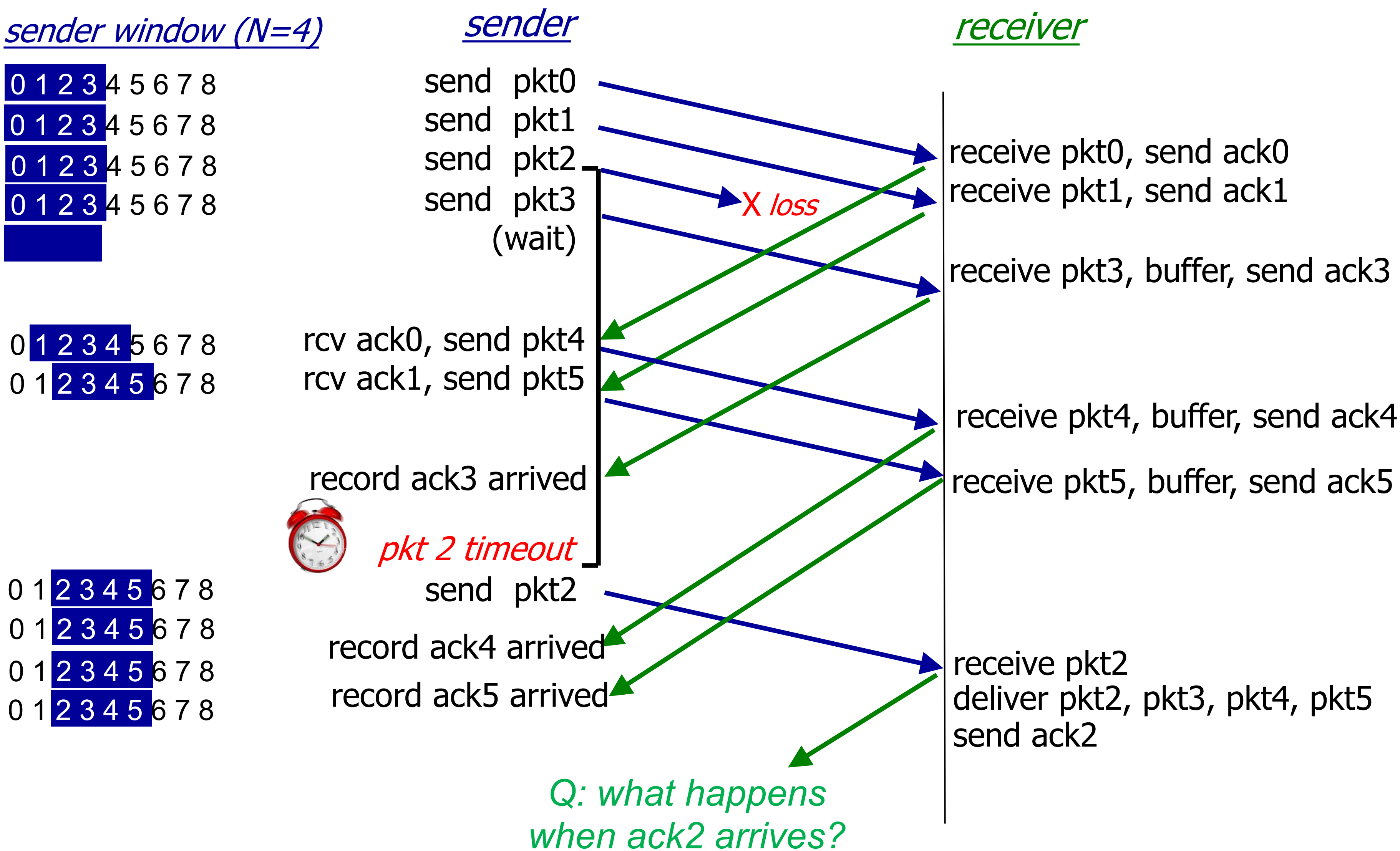
Event: pkt n in [rcvbase-N, rcvbase-1]

- **action:** send ACK(n)

Event: otherwise

- **action:** ignore

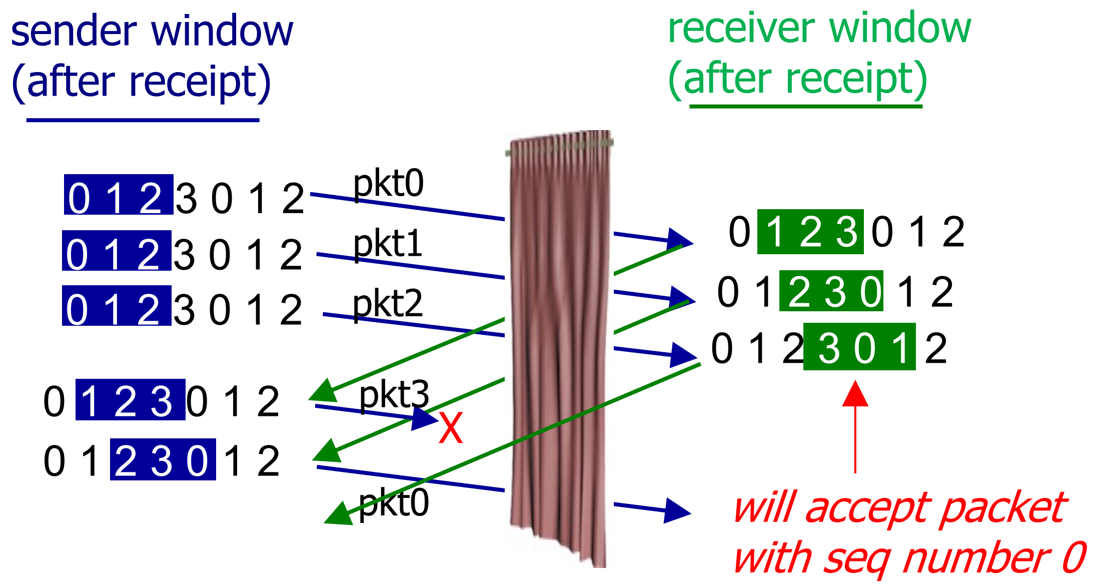
Selective repeat in action



Selective repeat: dilemma

Example

- seq #'s: 0, 1, 2, 3 and window size=3

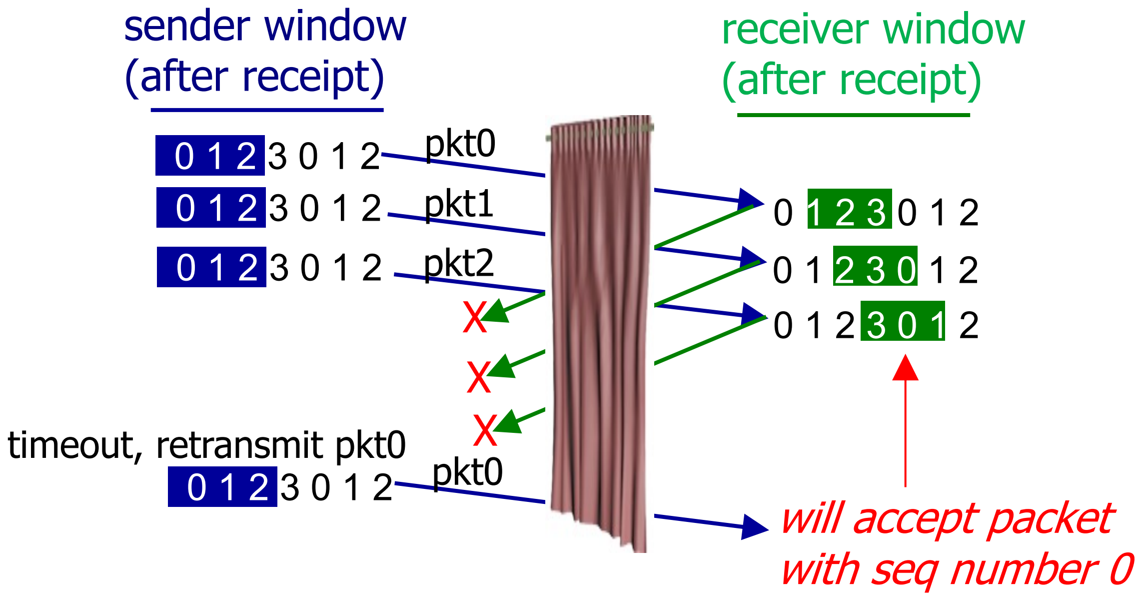


No problem…

Selective repeat: dilemma

Example

– seq #'s: 0, 1, 2, 3 and window size=3



Problem: duplicate data accepted as new:
receiver sees no difference in two scenarios!

Q: what is relationship between seq # size and window size to avoid problem in (b)?

Selective repeat summary

Q: When is selective repeat useful?

When channel generates errors frequently

Pros

- more efficient capacity use
  - only retransmit missing packets

Cons

- receiver buffering
  - to store out-of-order packets
- more complicated buffering & protocol processing
  - to keep track of missing out-of-order packets

Tradeoff again between buffering/processing complexity and capacity

Sequence numbers

HOW USED IN PRACTICE

Sequence #s in practice

How large must seq # space be?

– depends on window size

Example

– seq # space = [0, 2^4-1]
– window size = 8

Window

Sender: [0 1 2 3 4 5 6 7] 0 1 2 3 4 5 6 7

Acks not received, times out and retransmits seq #0-7

Receiver: 0 1 2 3 4 5 6 7 [0 1 2 3 4 5 6 7]

Acks sent

Receiver willing to accept seq #0-7
Sender sending seq# 0-7 but different packets!

Solution: seq # space must be large enough to cover both sender + receiver windows. I.e., >= 2x window size

Sequence #s in practice

What are they counting?

- bytes, not packets
  - sending packets but counting bytes
  - so seq #s do not increase incrementally

Sequence # space

- finite
  - e.g., 32 bits so 0 to 2^{32}-1 values
  - must wrap around to 0 when hit max seq #
- TCP initial seq # is randomly chosen from space of values
  - security (harder to spoof)
  - to prevent confusing segments from different connections
  - different operating systems set differently: can fingerprint machines

TCP
OVERVIEW

Transmission Control Protocol (TCP)

RFCs: 793,1122,1323, 2018, 2581

Main transport protocol used in Internet, provides

- mux/dmux: which packets go where
- connection-oriented, point-to-point
  - 2 hosts set up connection before exchanging data, tear down after
  - bidirectional data flow (full duplex)
- flow control: don't overwhelm receiver
- congestion control: don't overwhelm network
- reliable: resends lost packets, checks for and corrects errors
- in-order: buffers data until sequential chunk to pass up
- byte stream: no msg boundaries, data treated as stream

How does TCP provide these services?

Using many techniques we already talked about

Sliding window

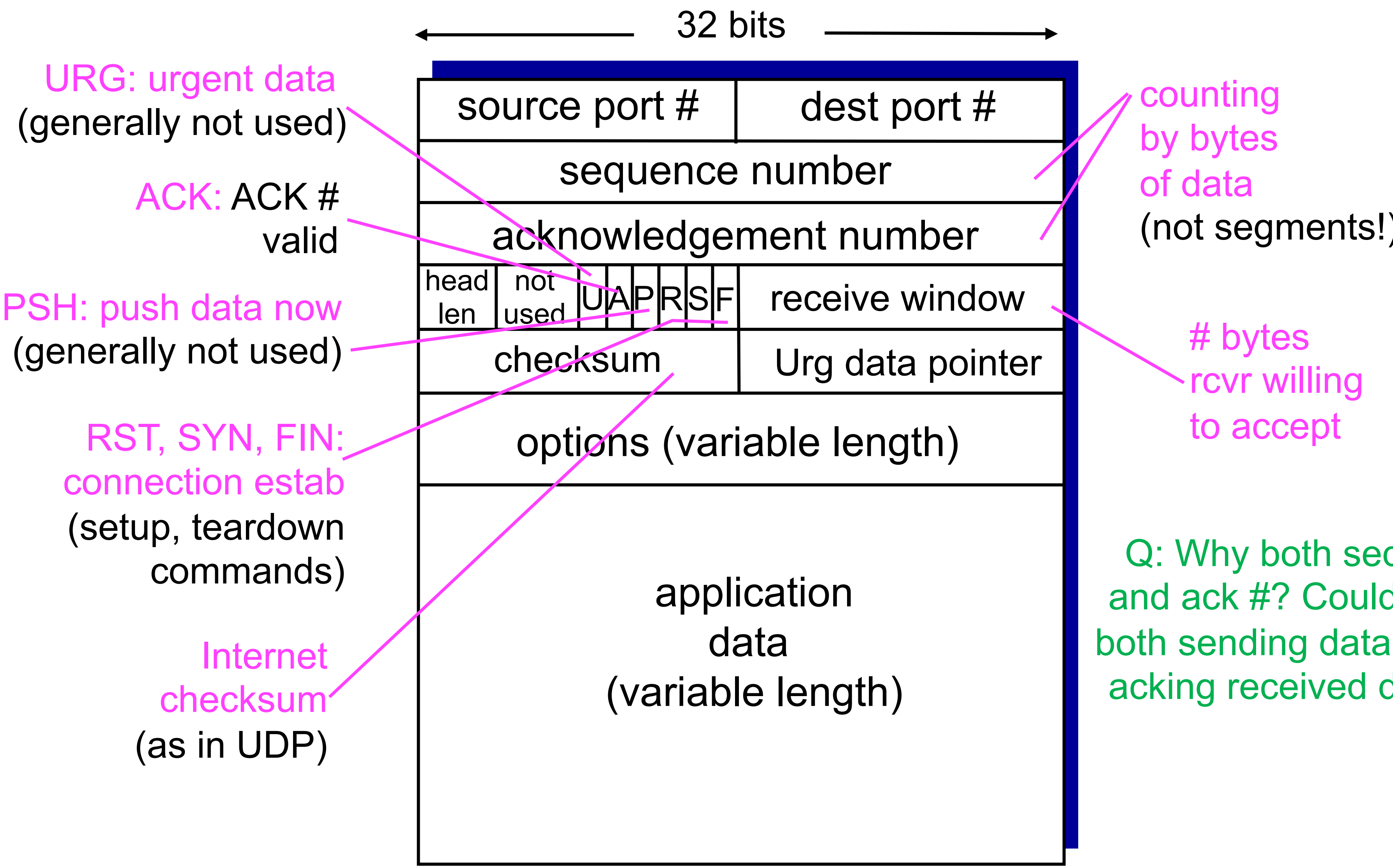
- congestion and flow control determine window size
- seq #s are byte offsets

Cumulative ACKs but does not drop out-of-order packets

- **only one retransmission timer**
  - intuitively, associate with oldest unACKed packet
- **timeout period**
  - estimated from observations
- **fast retransmit**
  - 3 duplicate ACKs trigger early retransmit

TCP is not perfect but works pretty well!

TCP segment structure



Q: Why both seq # and ack #? Could be both sending data and acking received data

No.	Time	Source	Destination
42	4.878920	172.217.11.10	vmanfredismbp2.wireless.wesleyan.edu
44	4.879137	outlook-namnortheast2.offi…	vmanfredismbp2.wireless.wesleyan.edu
46	4.879346	vmanfredismbp2.wireless.we…	outlook-namnortheast2.office365.com

```
▶ Internet Protocol Version 4, Src: outlook-namnortheast2.office365.com (40.97.120.226), Dst: v
▼ Transmission Control Protocol, Src Port: 443 (443), Dst Port: 52232 (52232), Seq: 0, Ack: 1,
    Source Port: 443
    Destination Port: 52232
    [Stream index: 0]
    [TCP Segment Len: 0]
    Sequence number: 0    (relative sequence number)
    Acknowledgment number: 1    (relative ack number)
    Header Length: 32 bytes
  ▼ Flags: 0x012 (SYN, ACK)
      000. .... .... = Reserved: Not set
      ...0 .... .... = Nonce: Not set
      .... 0... .... = Congestion Window Reduced (CWR): Not set
      .... .0.. .... = ECN-Echo: Not set
      .... ..0. .... = Urgent: Not set
      .... ...1 .... = Acknowledgment: Set
      .... .... 0... = Push: Not set
      .... .... .0.. = Reset: Not set
    ▶ .... .... ..1. = Syn: Set
      .... .... ...0 = Fin: Not set
      [TCP Flags: *******A**S*]
    Window size value: 8190
    [Calculated window size: 8190]
  ▶ Checksum: 0xcb80 [validation disabled]
    Urgent pointer: 0
  ▶ Options: (12 bytes), Maximum segment size, No-Operation (NOP), Window scale, No-Operation
  ▶ [SEQ/ACK analysis]
```

```
0000  78 4f 43 73 43 26 3c 8a  b0 1e 18 01 08 00 45 20   xOCsC&<. ......E
0010  00 34 32 41 40 00 eb 06  7e eb 28 61 78 e2 81 85   .42A@... ~.(ax...
0020  bb ae 01 bb cc 08 a9 a2  4d d9 59 5a 86 d8 80 12   ........ M.YZ....
0030  1f fe cb 80 00 00 02 04  05 50 01 03 03 04 01 01   ........ .P......
0040  04 02                                              ..
```