Lecture 11: Transport Layer
Reliable Data Transfer and TCP

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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

1. Announcements
   - homework 5 posted
     - extension until Thursday at 11:59p
2. Recap
   - reliable data transport: channels with errors and loss
3. Pipelined protocols
   - go-back-N
   - selective repeat
   - sequence numbers in practice
4. TCP
   - overview
   - reliable data transfer

Reliable Data Transport

CHANNELS WITH ERROR AND LOSS

rdt3.0: channels with errors and loss

Problems

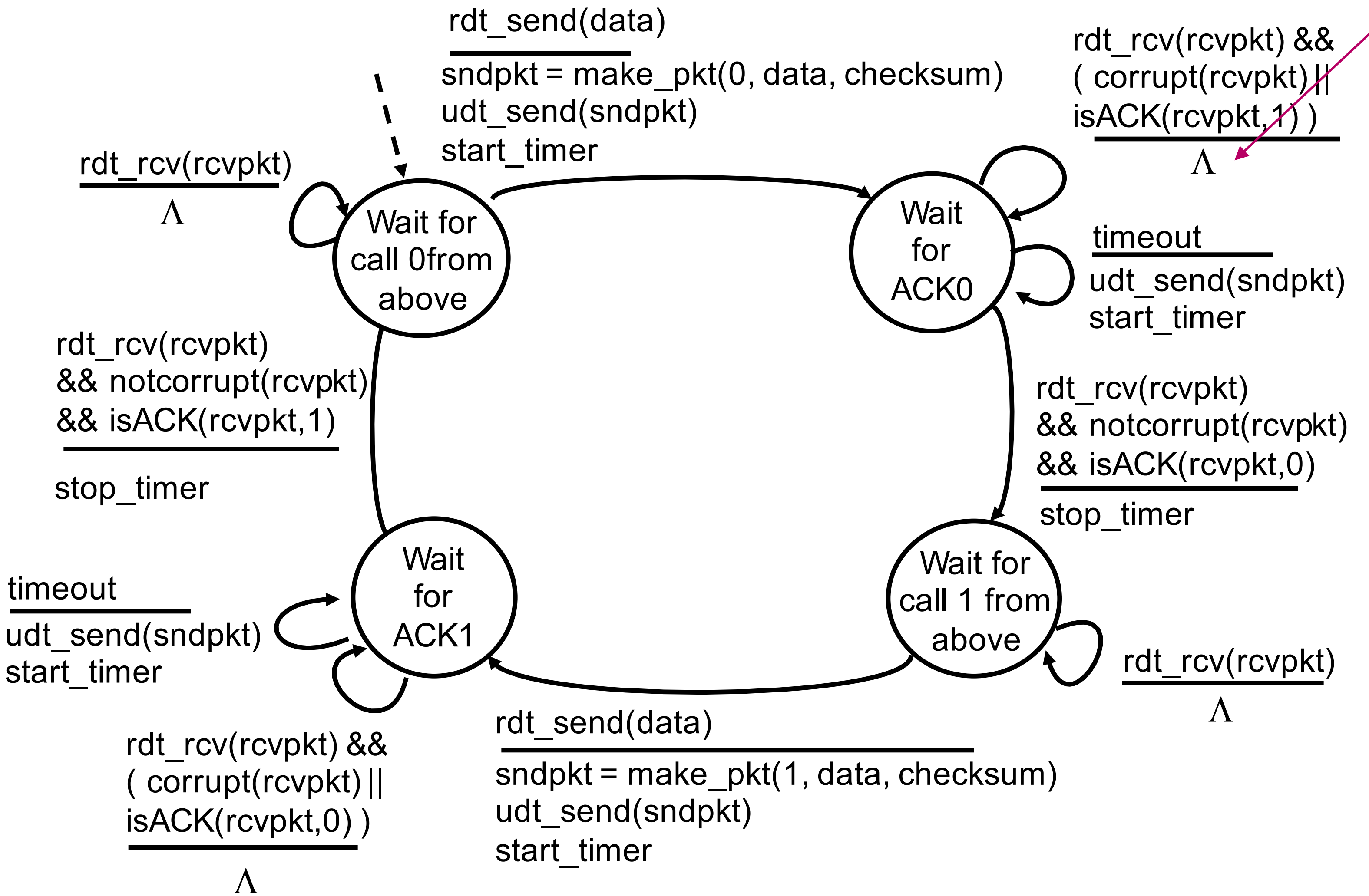
- underlying channel may flip bits in packet
  - both data and ACKs may be garbled
- underlying channel can also lose packets
  - both data and ACKs
- checksum, seq. #, ACKs, retransmissions will be of help
  - … but not enough

Solution: add countdown timer

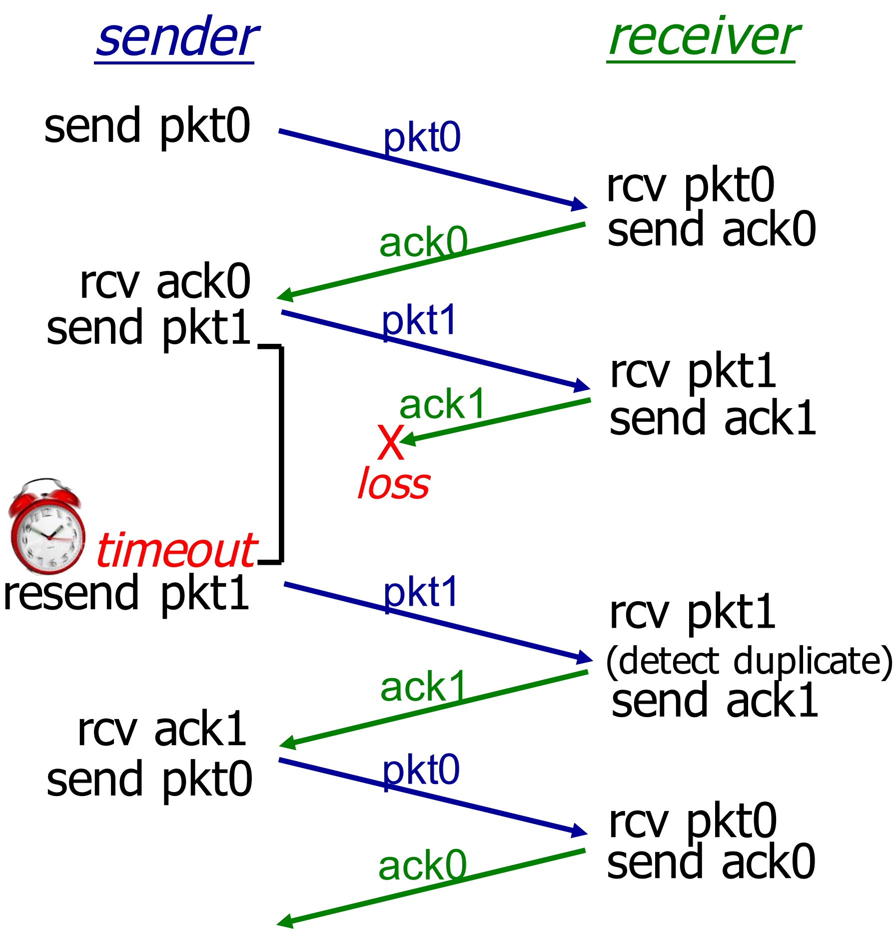
- sender waits "reasonable" amount of time for ACK
  - retransmits if no ACK received in this time
- if pkt (or ACK) just delayed (not lost)
  - retransmission will be duplicate, but seq #'s already handles this
- receiver must specify seq # of pkt being ACKed

rdt3.0 sender

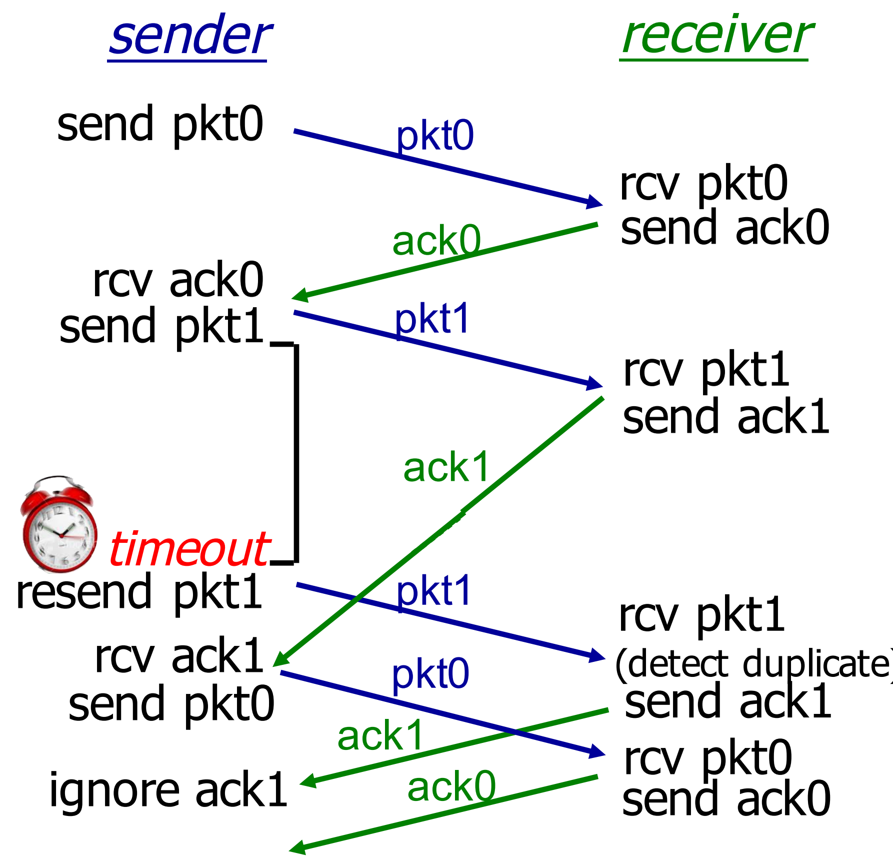
Why do nothing ? Why not resend pkt0? Because sender doesn't know whether ack1 means pkt 0 garbled or pkt 1 duplicate received
By not resending pkt 0, sender doesn't introduce potentially unnecessary (even if valid) traffic: saves bandwidth



rdt3.0 in action



ACK loss

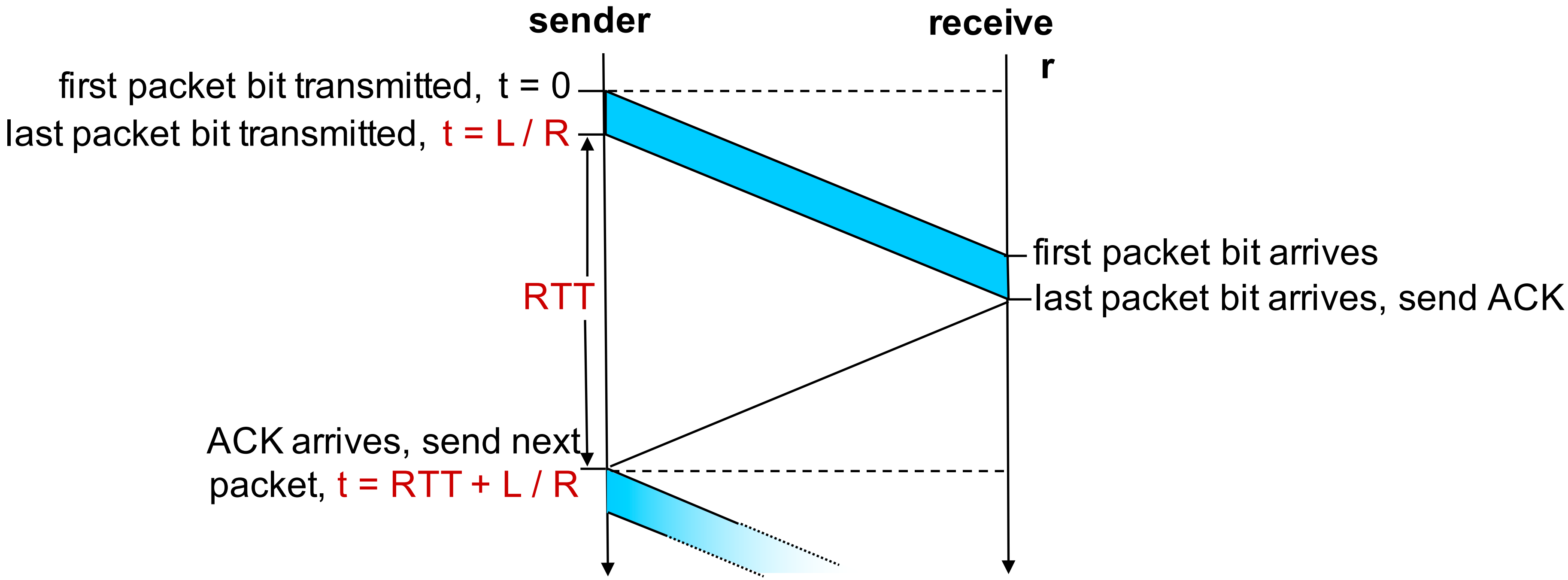


Premature timeout/delayed ACK

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 we're considering

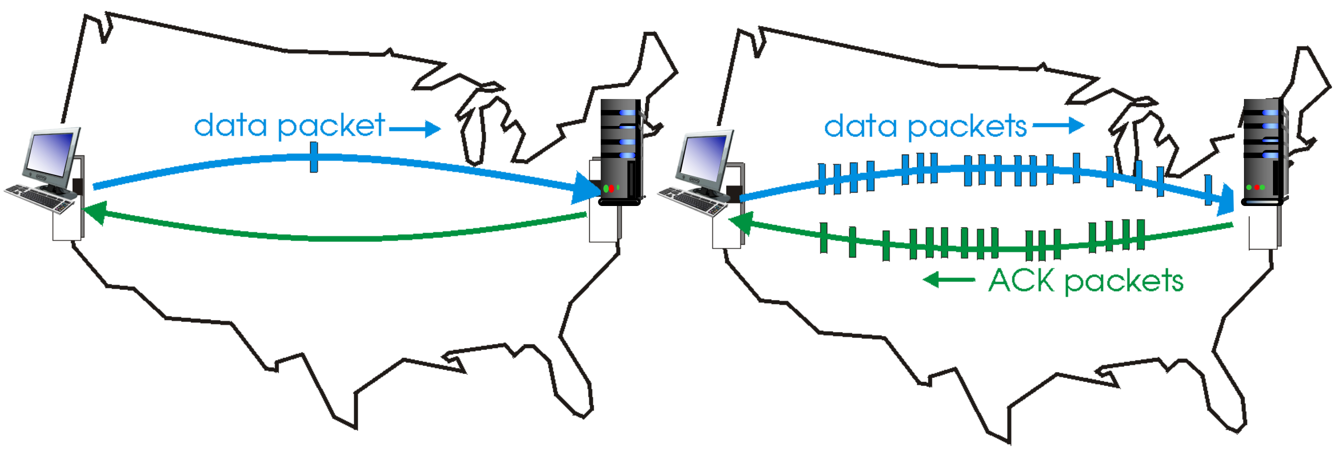
Problem: maintaining high link utilization

Creating a more efficient protocol

How? get rid of stop-and-wait

Instead: pipelining (also called sliding-window protocols)

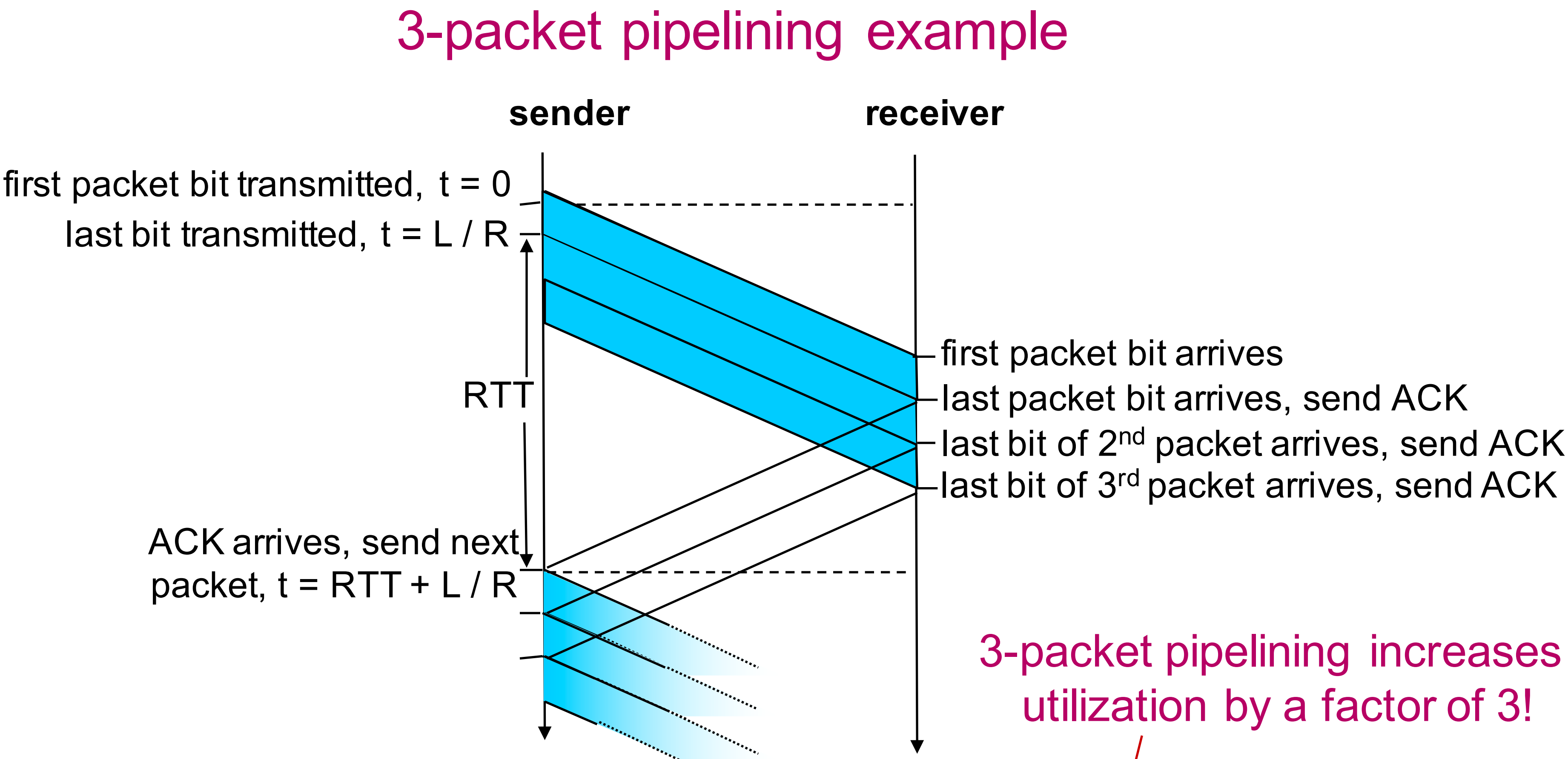
- sender allows multiple, in-flight, yet-to-be-acknowledged pkts
  - send up to N packets at a time: N packets in flight, unacked
  - range of seq #s must be increased
  - sender needs more memory to buffer outstanding unacked packets



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

Achieves higher link utilization than stop-and-wait

Pipelining: increased utilization



3-packet pipelining increases utilization by a factor of 3!

Time spent sending stuff

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

Total time we're considering

Pipelined protocols

Q: Sent N packets without receiving ACKs.
How does receiver ACK packets 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

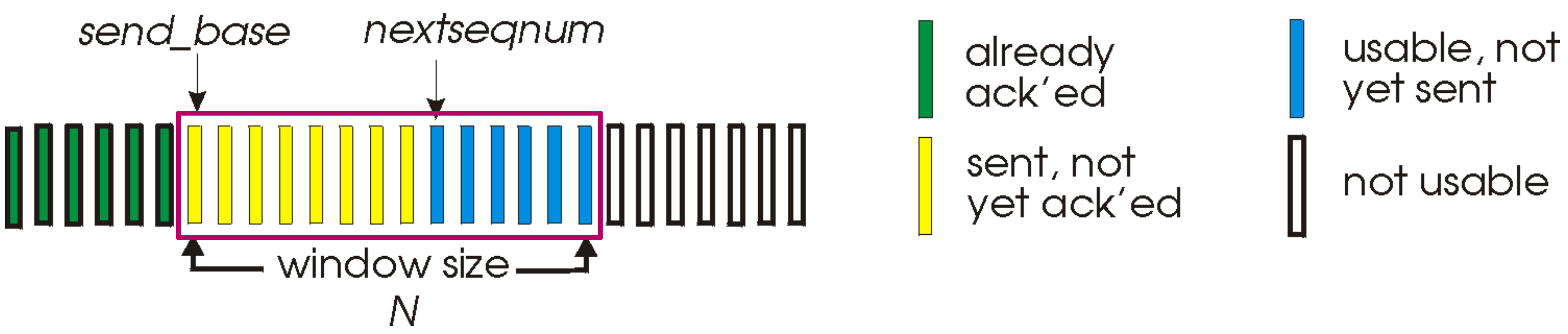
Receiver

- sends individual ack for each pkt

How pipelining/sliding window protocols work

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

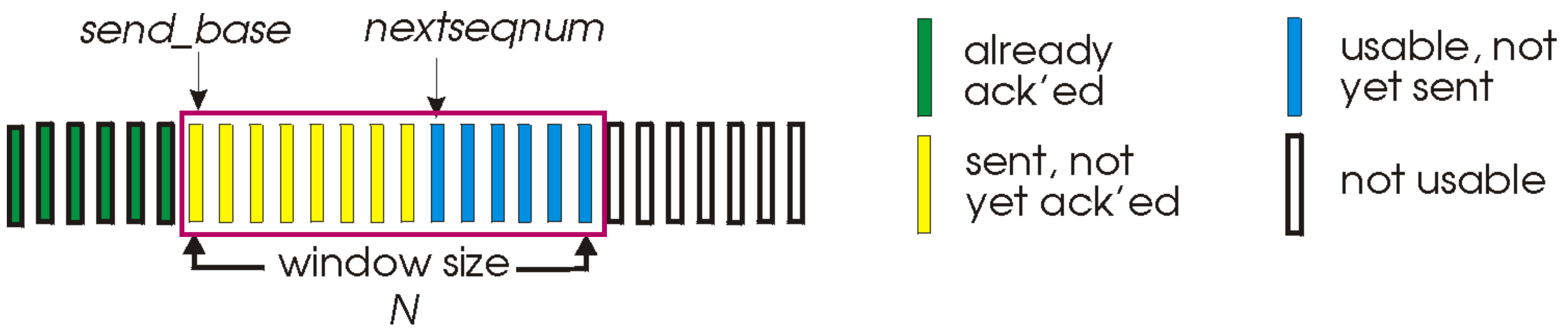
Pipelined Protocols

GO-BACK-N

Go-Back-N: sender

k-bit seq # in pkt header

- window of up to N, consecutive unack'ed 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 extended FSM

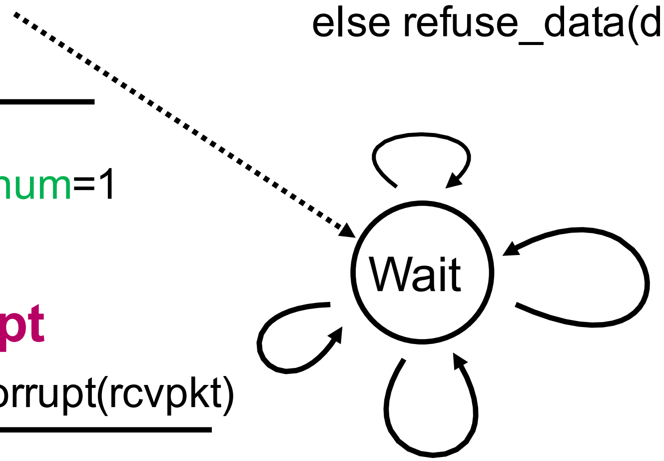
Send as long as pkt within window

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)

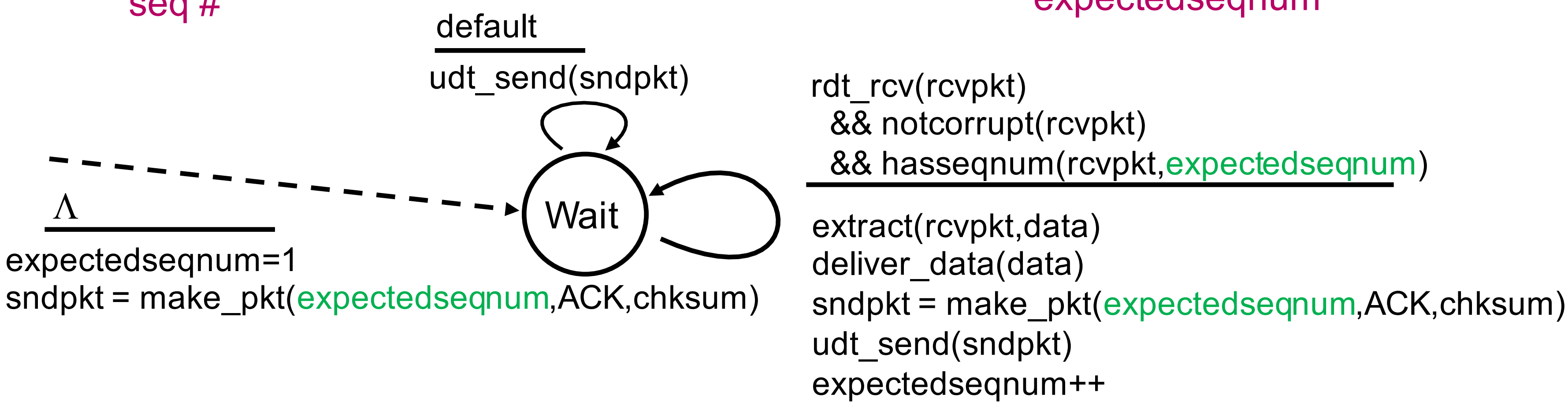
```
base = getacknum(rcvpkt)+1
If (base == nextseqnum)
    stop_timer
  else
    start_timer
```

Cumulative ack: move base to ack# + 1

Go-Back-N: receiver extended FSM

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

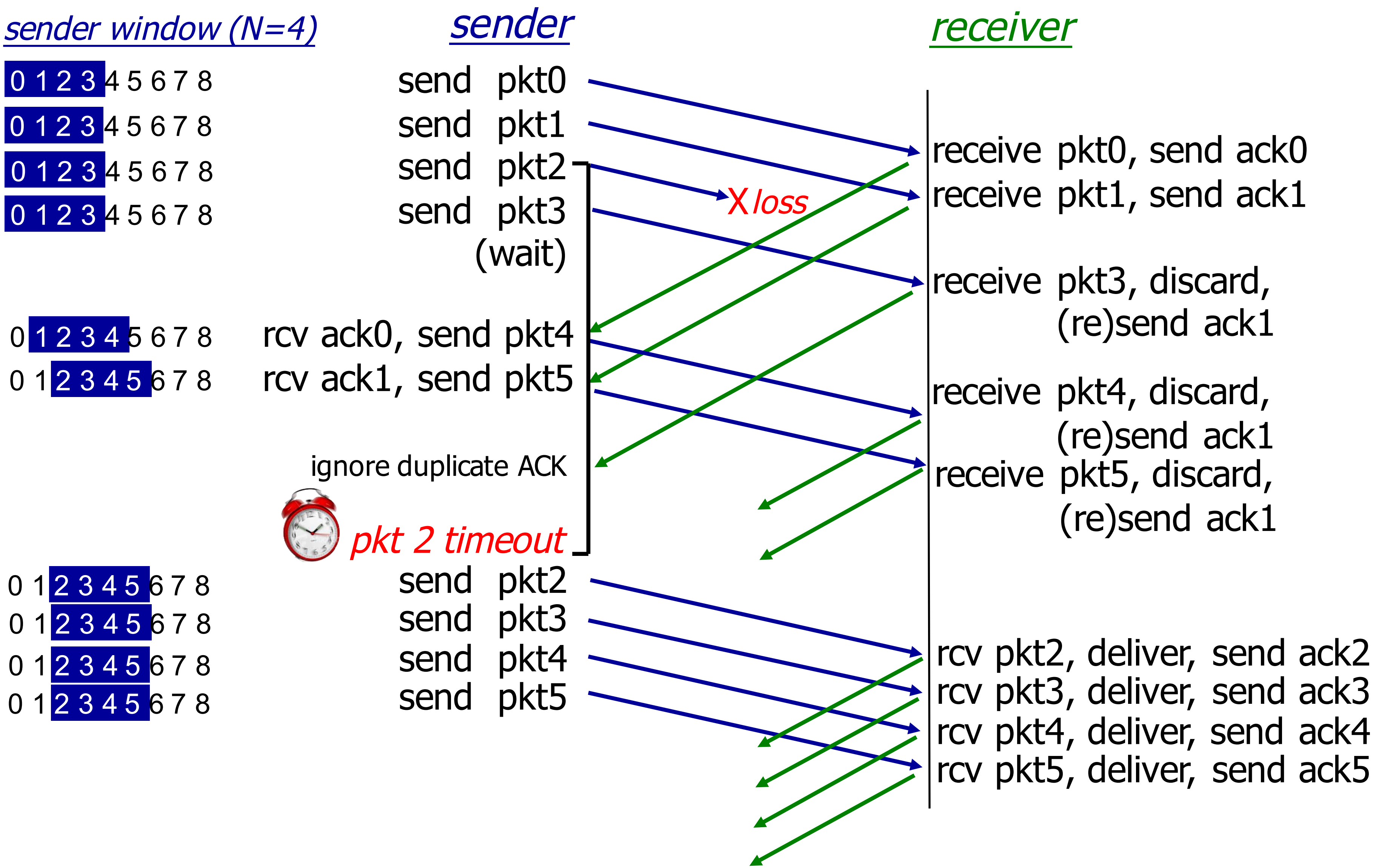
Correct pkt with highest in-order seq #
- send ACK, may be duplicate ACK
- need only remember expectedseqnum



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

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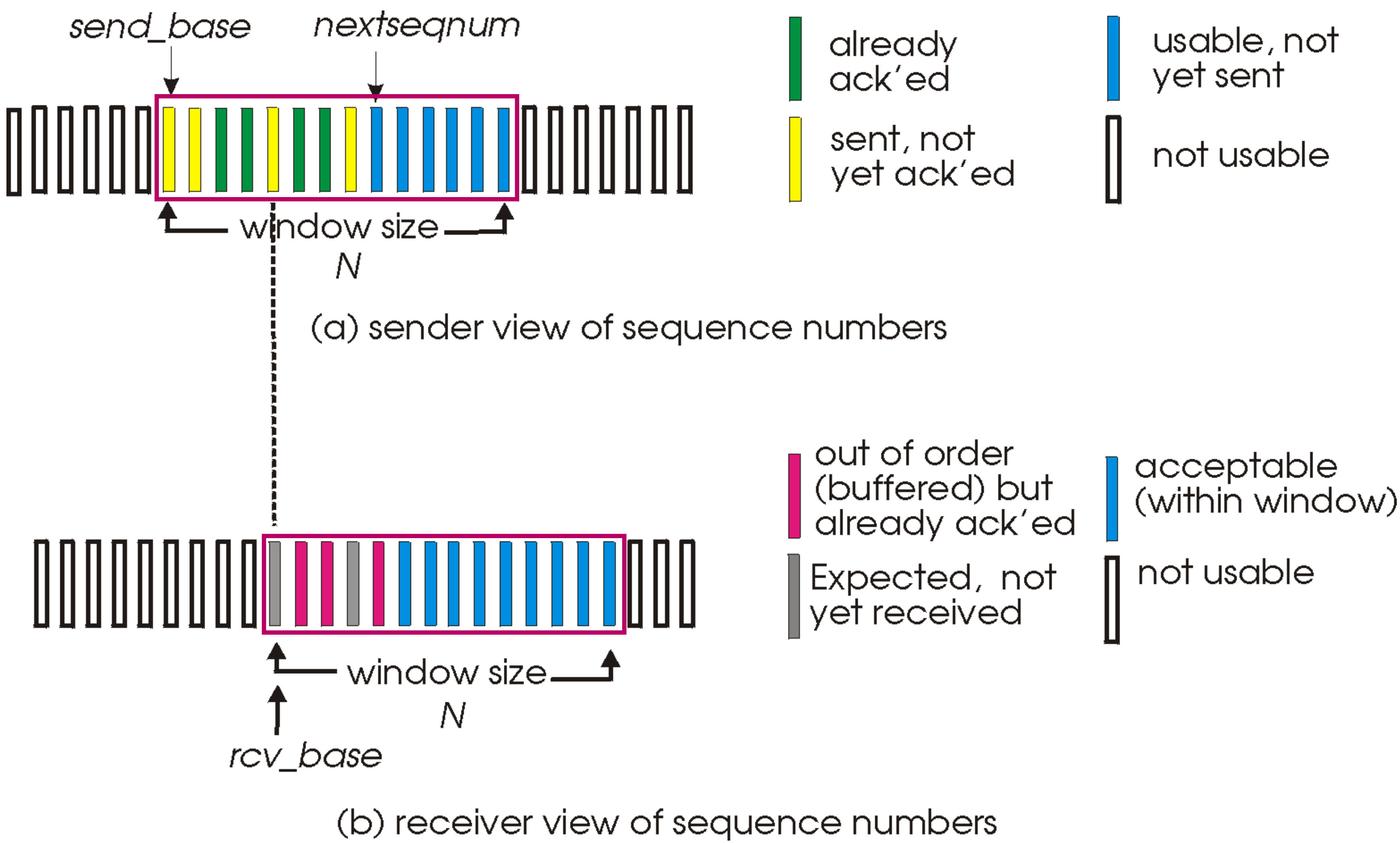
Selective repeat: sender, receiver windows



Selective repeat

sender

Data from above

- if next available seq # in window, send pkt

timeout(n)

- resend pkt n, restart timer

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

- mark pkt n as received
- if n is smallest unACKed pkt,
  - advance window base to next unACKed seq #

receiver

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

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

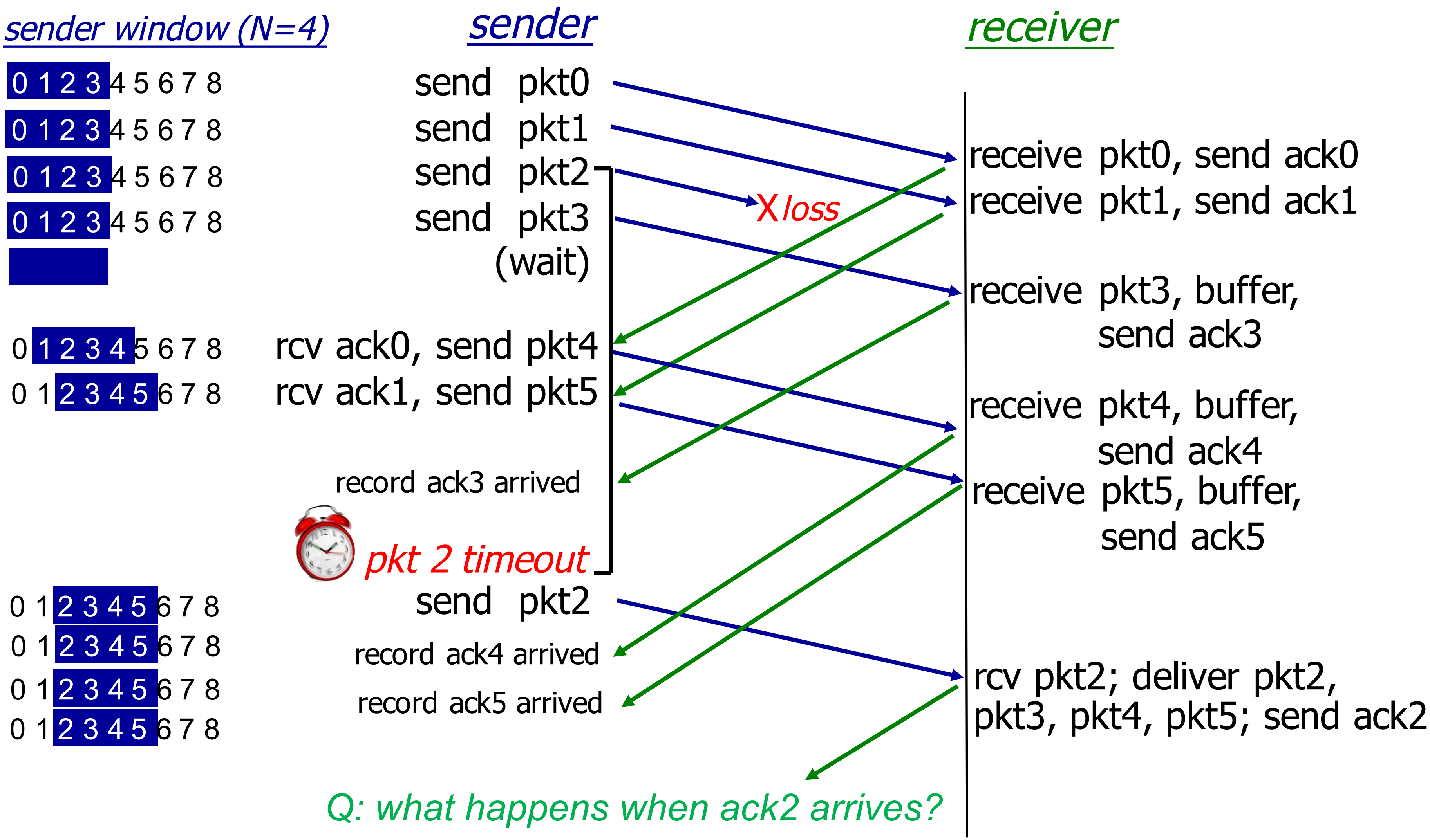
pkt n in [rcvbase-N,rcvbase-1]

- ACK(n)

otherwise

- ignore

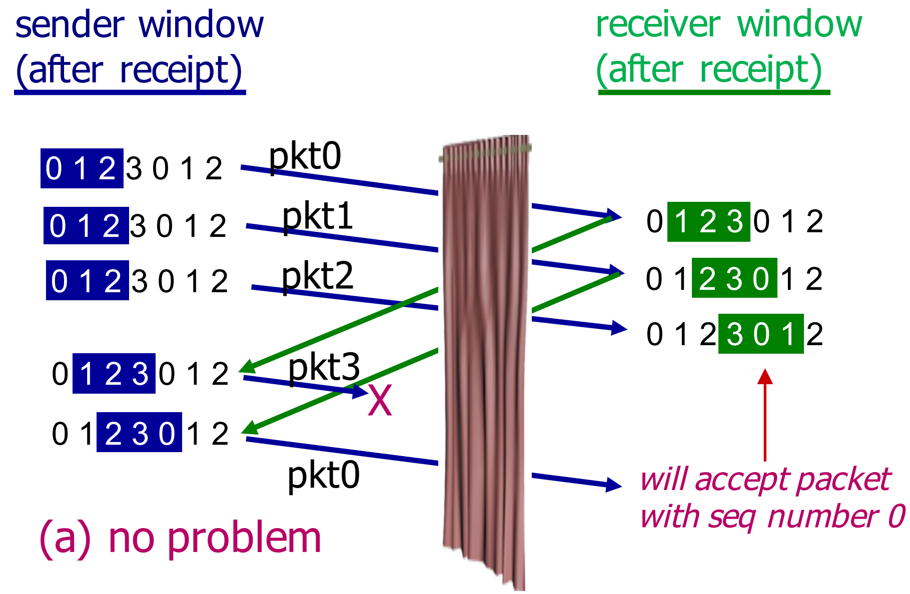
Selective repeat in action



Selective repeat: dilemma

Example

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

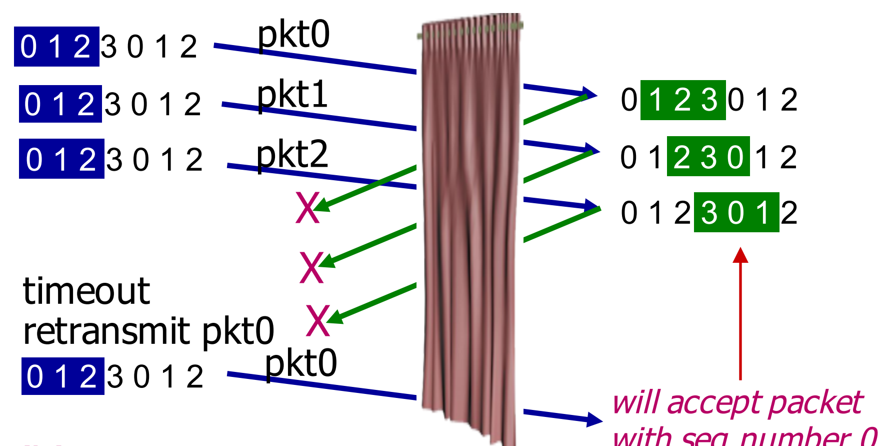


(a) no problem

Problem: duplicate data accepted as new in (b)

- receiver sees no difference in two scenarios!

receiver can't see sender side.
receiver behavior identical in both cases!
Something is (very) wrong!



(b) oops!

Q: what 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

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 OSes set differently: can fingerprint machines

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

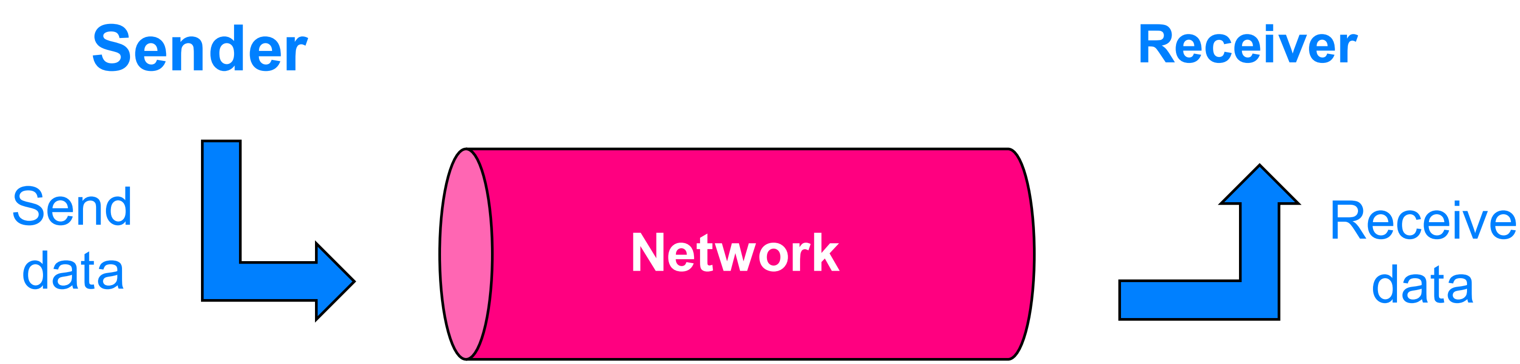
TCP
OVERVIEW

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

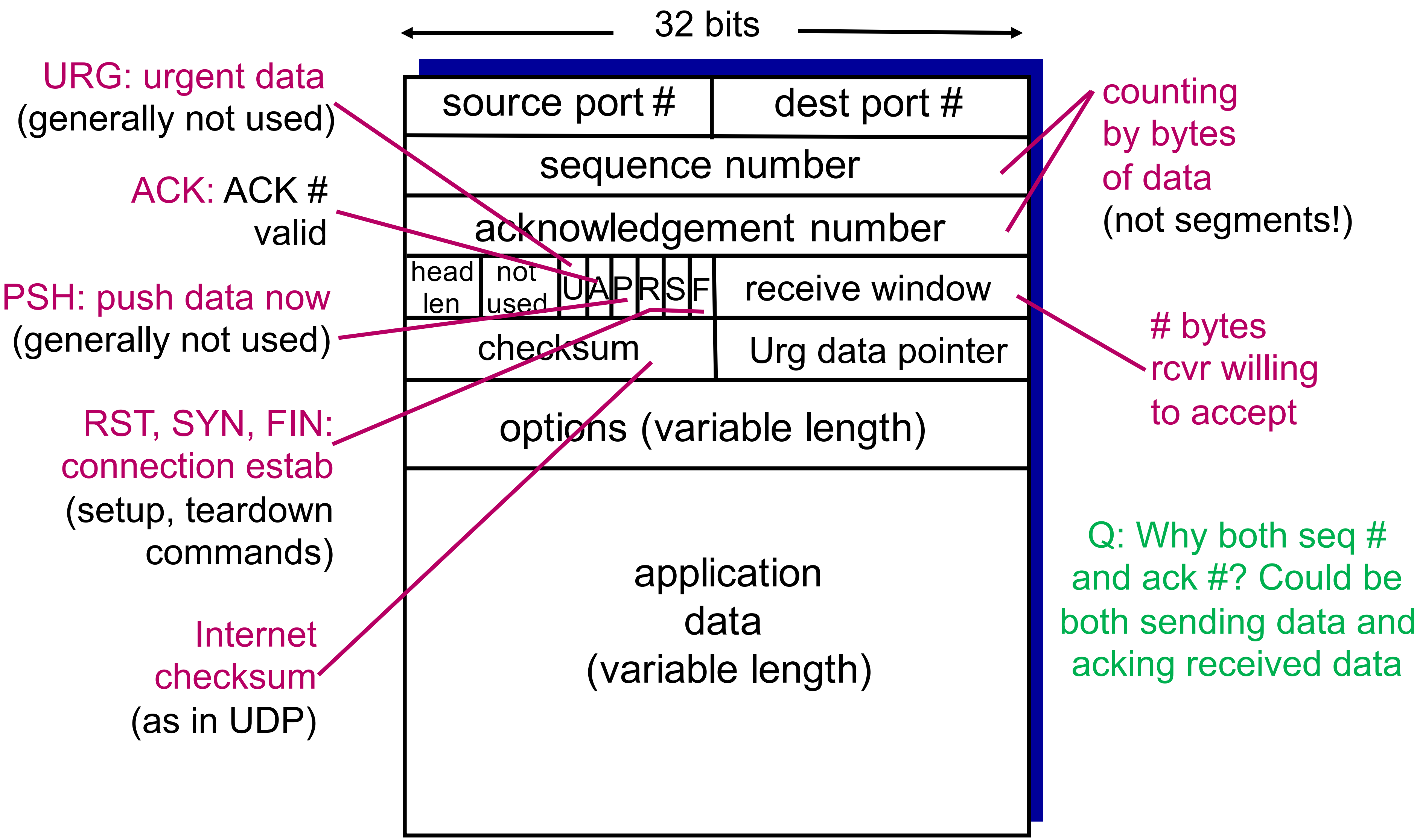
- congestion and flow control determine window size
- seq #s are byte offsets

Cumulative ACKs

- but does not drop out-of-order packets
- fast retransmit
  - duplicate ACKs (3 of them) trigger early retransmit
- only one retransmission timer
  - intuitively, associate with oldest unACKed packet
- timeout period: estimated

TCP is not perfect but works pretty well!

TCP segment structure



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                                              ..
```

TCP seq. numbers, ACKs

Sequence #s

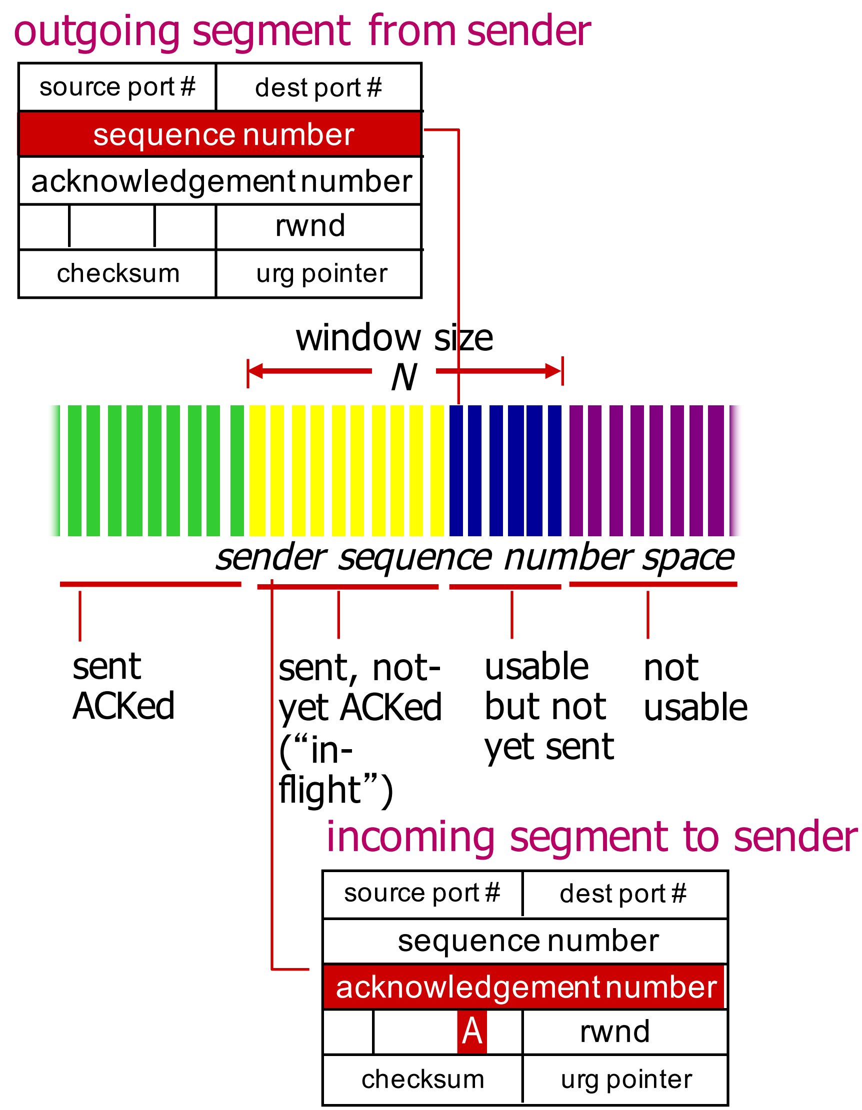
- byte stream # of first byte in segment's data

Acknowledgements

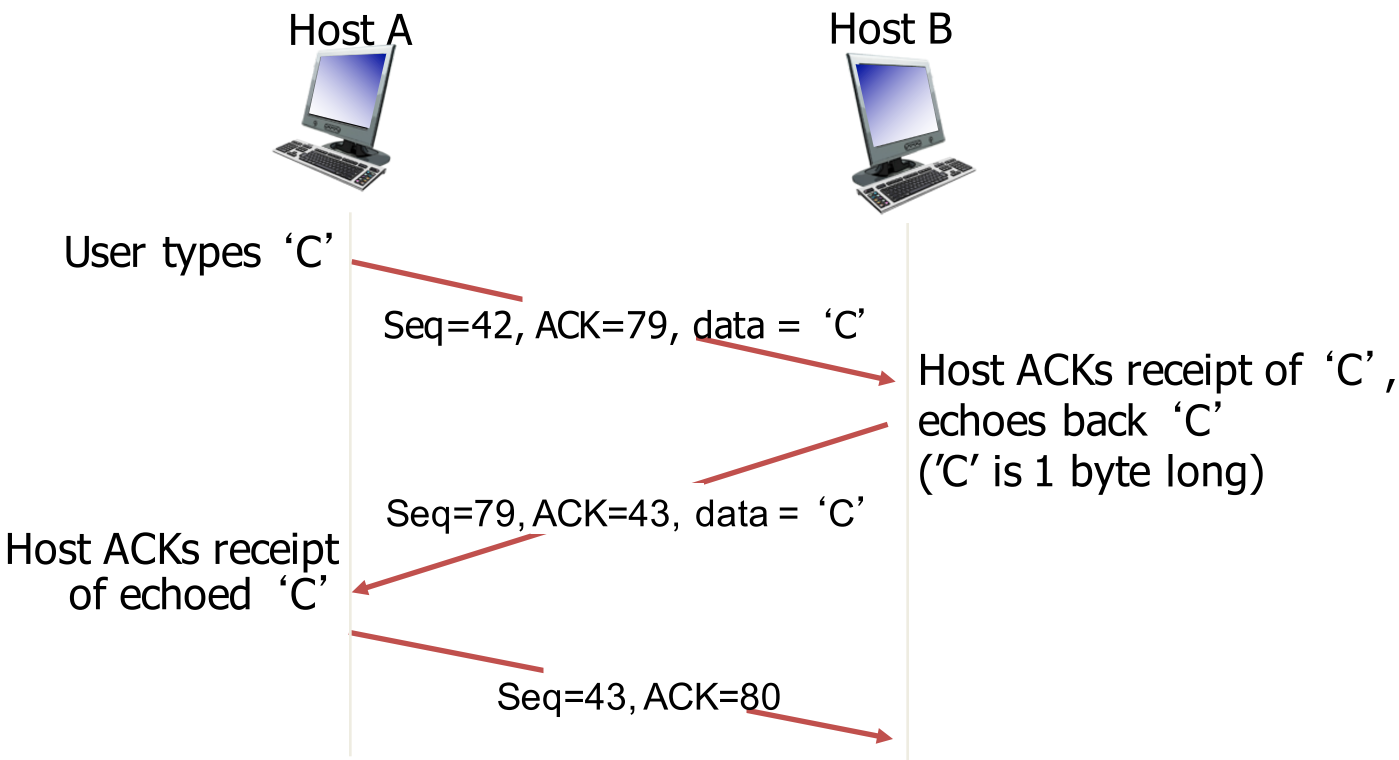
- seq # of next byte expected from other side
- cumulative ACK

Q: how receiver handles out-of-order segments

- TCP spec doesn't say
- up to implementer



TCP seq. numbers, ACKs



Simple nc scenario