

Transport Layer

our goals:

- ❖ understand principles behind transport layer services:
 - multiplexing, demultiplexing
 - reliable data transfer
 - flow control
 - congestion control
- ❖ learn about Internet transport layer protocols:
 - UDP: connectionless transport
 - TCP: connection-oriented reliable transport
 - TCP congestion control

Outline

3.1 transport-layer services

3.2 multiplexing and demultiplexing

3.3 connectionless transport: UDP

3.4 principles of reliable data transfer

3.5 connection-oriented transport: TCP

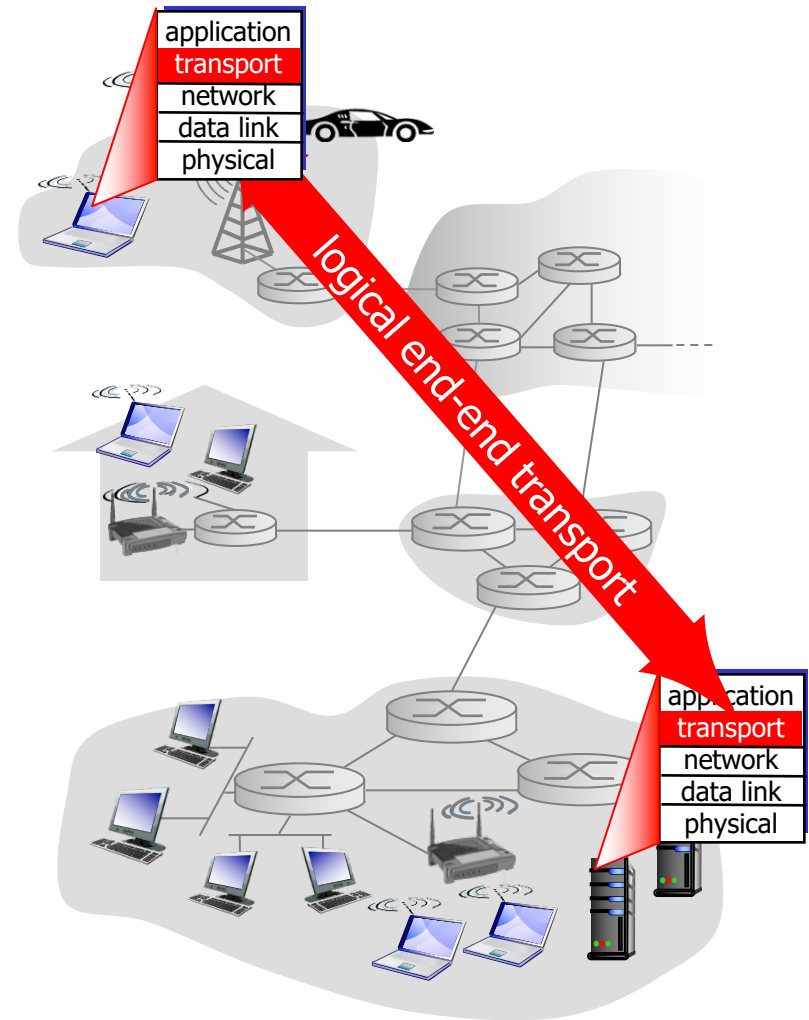
- segment structure
- reliable data transfer
- flow control
- connection management

3.6 principles of congestion control

3.7 TCP congestion control

Transport services and protocols

- ❖ provide *logical communication* between app processes running on different hosts
- ❖ transport protocols run in end systems
 - **send side:** breaks app messages into *segments*, passes to network layer
 - **rcv side:** reassembles segments into messages, passes to app layer
- ❖ more than one transport protocol available to apps
 - Internet: TCP and UDP



Transport vs. network layer

- ❖ *network layer:*
logical
communication
between hosts
- ❖ *transport layer:*
logical
communication
between processes
 - relies on, enhances,
network layer
services

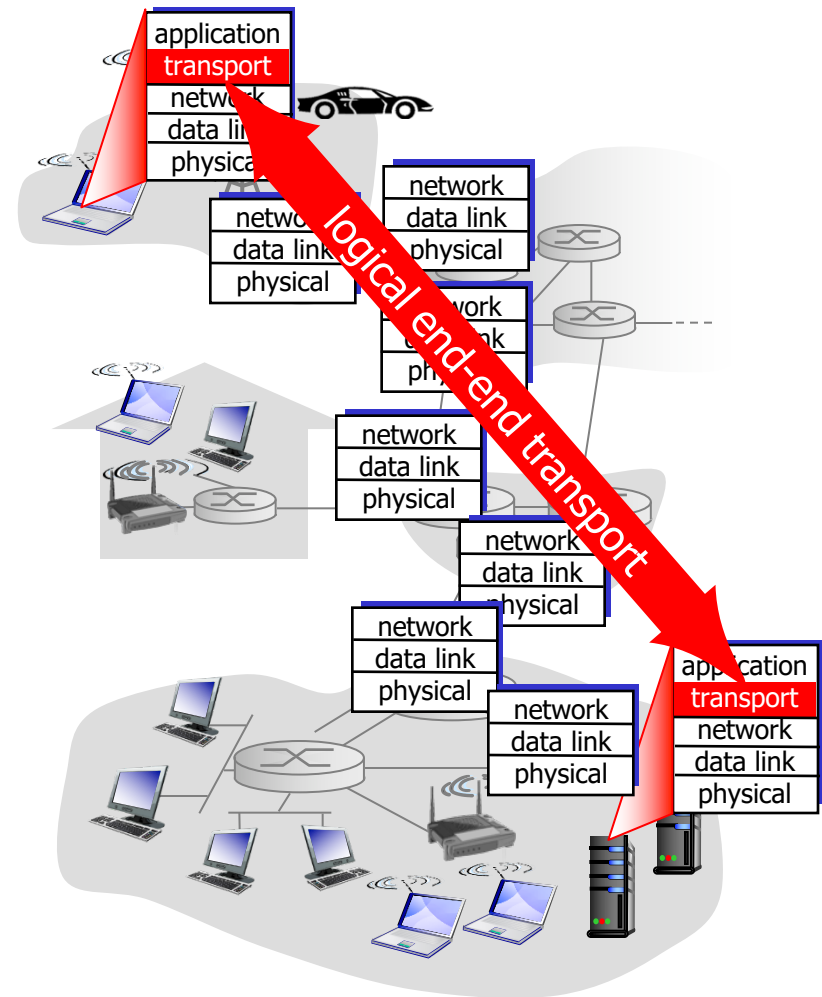
household analogy:

*12 kids in Ann's house
sending letters to 12
kids in Bill's house:*

- ❖ hosts = houses
- ❖ processes = kids
- ❖ app messages = letters
in envelopes
- ❖ transport protocol =
Ann and Bill who demux
to in-house siblings
- ❖ network-layer protocol
= postal service

Internet transport-layer protocols

- ❖ reliable, in-order delivery (TCP)
 - congestion control
 - flow control
 - connection setup
- ❖ unreliable, unordered delivery: UDP
 - no-frills extension of “best-effort” IP
- ❖ services not available:
 - delay guarantees
 - bandwidth guarantees



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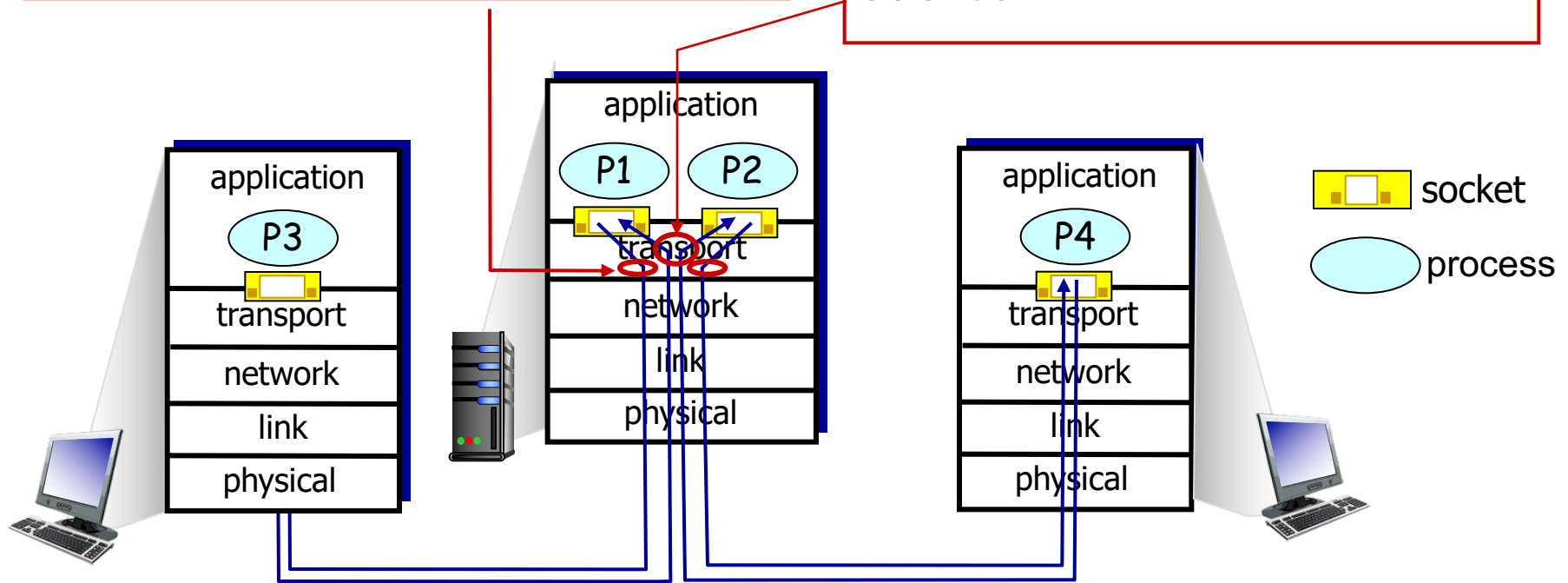
Multiplexing/demultiplexing

multiplexing at sender:

handle data from multiple sockets, add transport header (later used for demultiplexing)

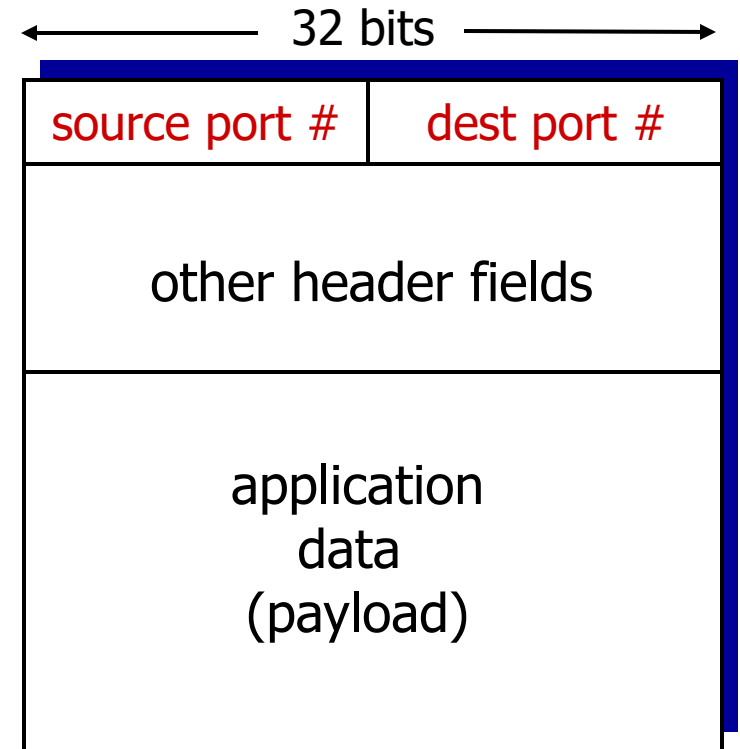
demultiplexing at receiver:

use header info to deliver received segments to correct socket



How demultiplexing works

- ❖ host receives IP datagrams
 - each datagram has source IP address, destination IP address
 - each datagram carries one transport-layer segment
 - each segment has source, destination port number
- ❖ host uses *IP addresses & port numbers* to direct segment to appropriate socket



TCP/UDP segment format

Connectionless demultiplexing

- ❖ *recall*: created socket has host-local port #:

```
DatagramSocket mySocket1  
= new DatagramSocket(12534);
```

- ❖ *recall*: when creating datagram to send into UDP socket, must specify

- destination IP address
- destination port #

- ❖ when host receives UDP segment:

- checks destination port # in segment
- directs UDP segment to socket with that port #



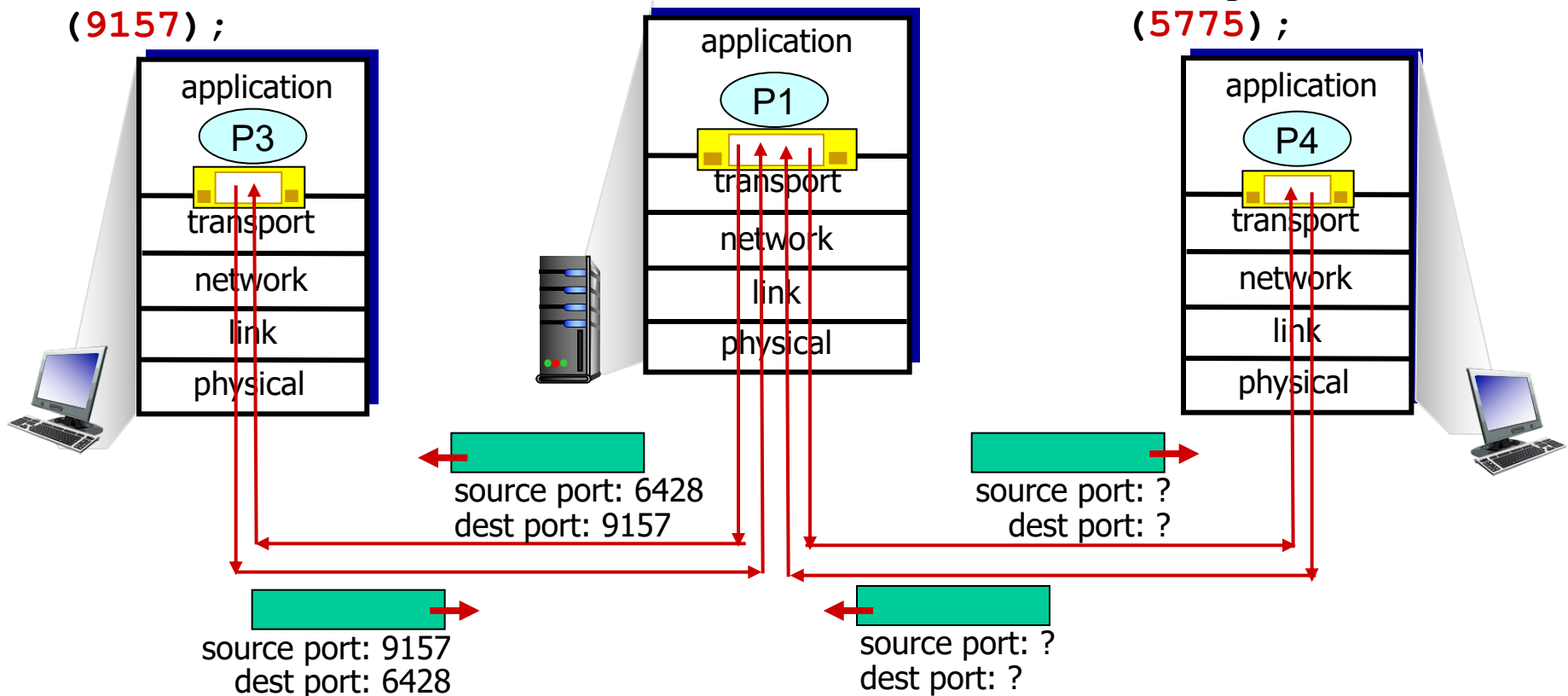
IP datagrams with *same dest. port #*, but different source IP addresses and/or source port numbers will be directed to *same socket* at dest

Connectionless demux: example

```
DatagramSocket  
mySocket2 = new  
DatagramSocket  
(9157);
```

```
DatagramSocket  
serverSocket = new  
DatagramSocket  
(6428);
```

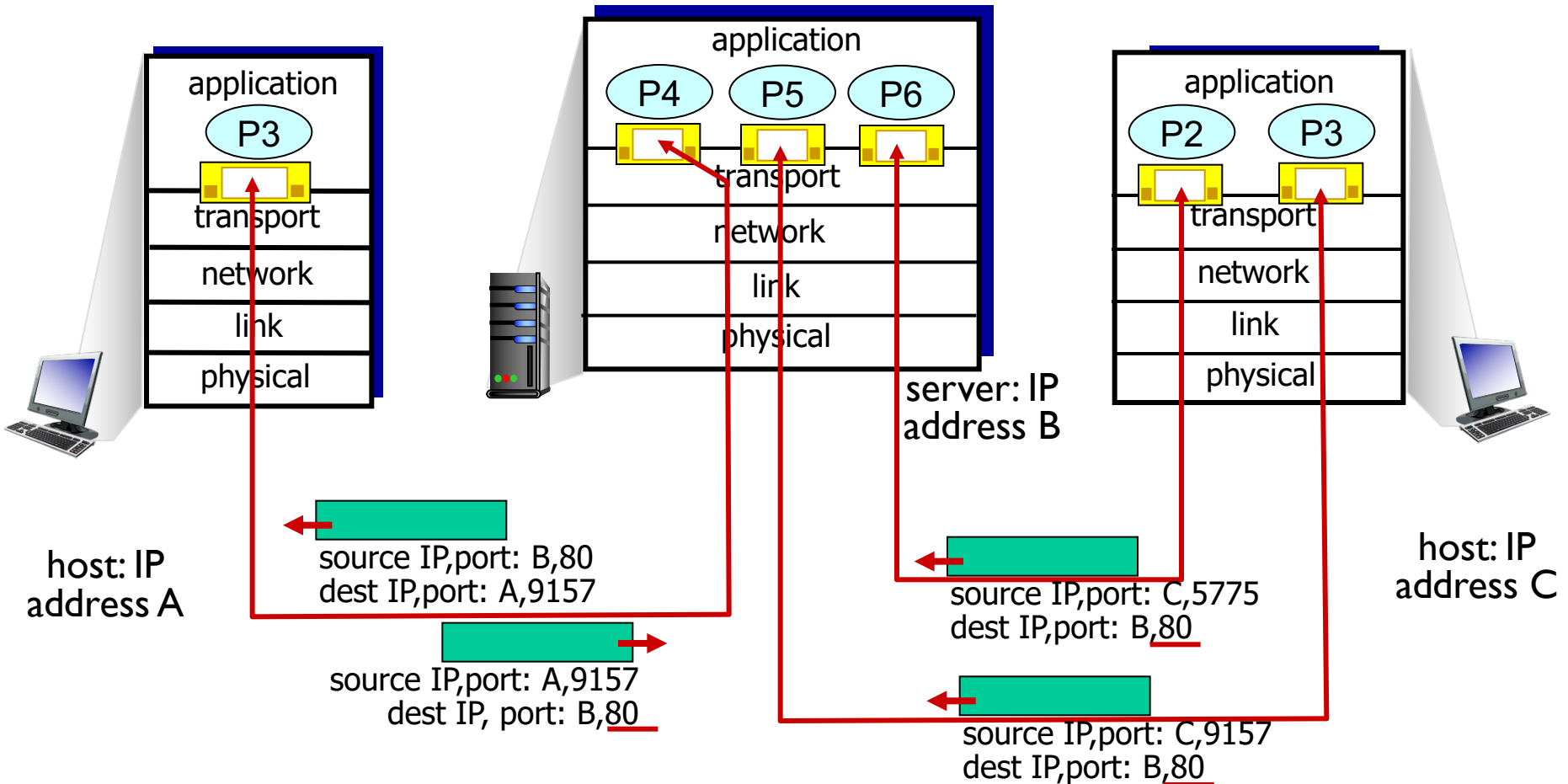
```
DatagramSocket  
mySocket1 = new  
DatagramSocket  
(5775);
```



Connection-oriented demux

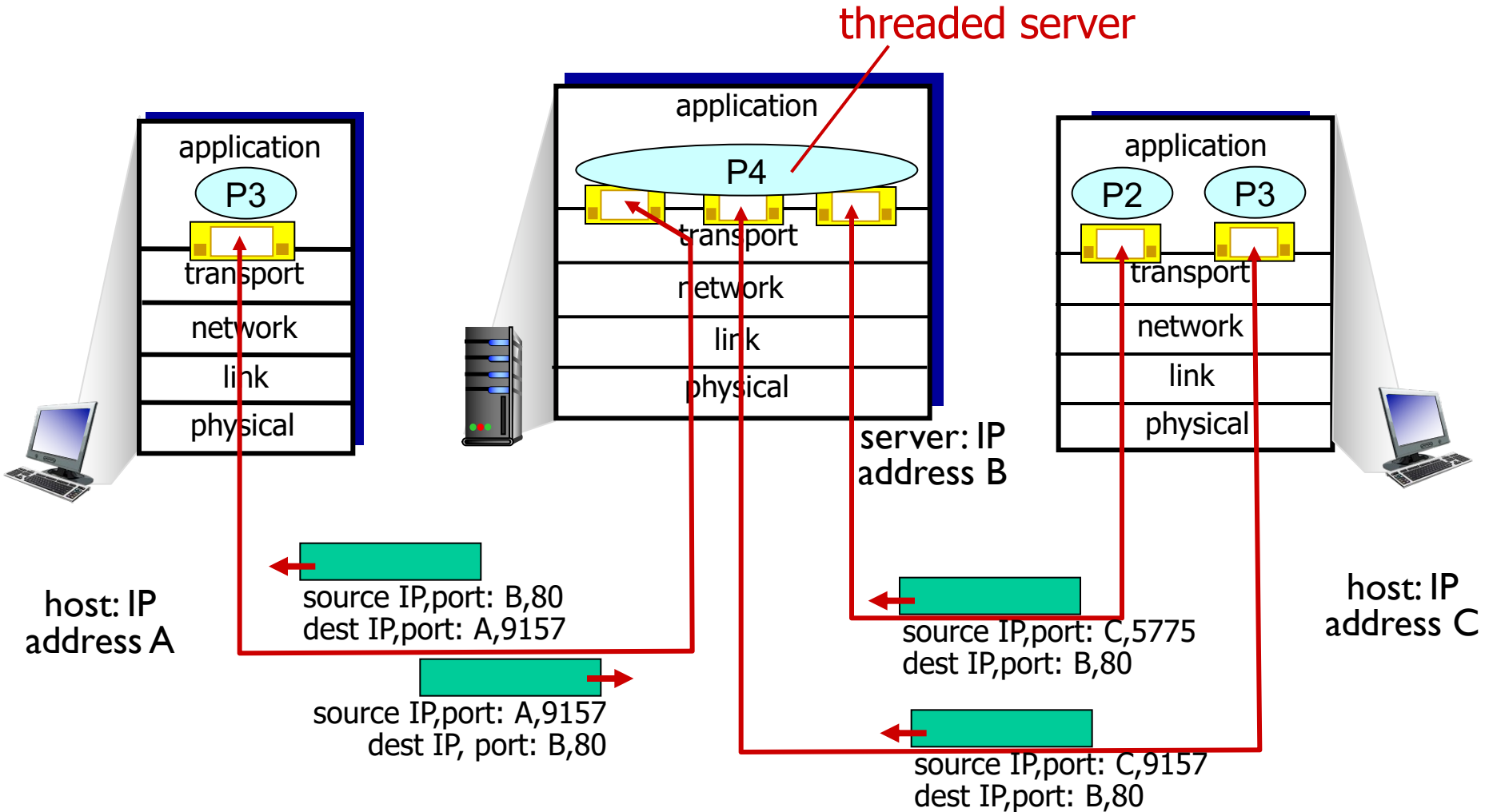
- ❖ TCP socket identified by 4-tuple:
 - source IP address
 - source port number
 - dest IP address
 - dest port number
- ❖ demux: receiver uses all four values to direct segment to appropriate socket
- ❖ server host may support many simultaneous TCP sockets:
 - each socket identified by its own 4-tuple
- ❖ web servers have different sockets for each connecting client
 - non-persistent HTTP will have different socket for each request

Connection-oriented demux: example



three segments, all destined to IP address: B,
dest port: 80 are demultiplexed to *different* sockets

Connection-oriented demux: example



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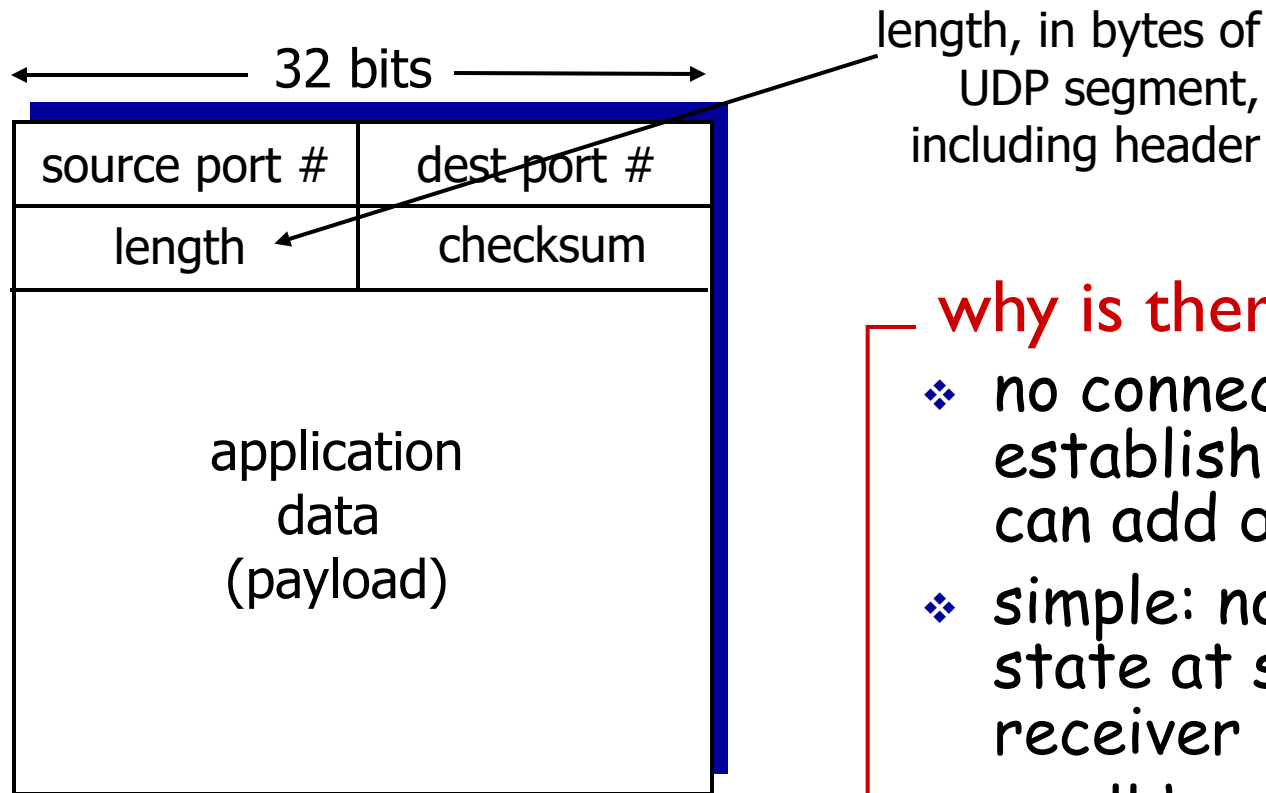
3.6 principles of congestion control

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UDP: User Datagram Protocol [RFC 768]

- ❖ “no frills,” “bare bones” Internet transport protocol
- ❖ “best effort” service, UDP segments may be:
 - lost
 - delivered out-of-order to app
- ❖ *connectionless*:
 - no handshaking between UDP sender, receiver
 - each UDP segment handled independently of others
- ❖ UDP use:
 - streaming multimedia apps (loss tolerant, rate sensitive)
 - DNS
 - SNMP
- ❖ reliable transfer over UDP:
 - add reliability at application layer
 - application-specific error recovery!

UDP: segment header



UDP segment format

why is there a UDP?

- ❖ no connection establishment (which can add delay)
- ❖ simple: no connection state at sender, receiver
- ❖ small header size
- ❖ no congestion control: UDP can blast away as fast as desired

UDP checksum

Goal: detect “errors” (e.g., flipped bits) in transmitted segment

sender:

- ❖ treat segment contents, including **header fields**, as sequence of 16-bit integers
- ❖ checksum: addition (one's complement sum) of segment contents
- ❖ sender puts checksum value into UDP checksum field

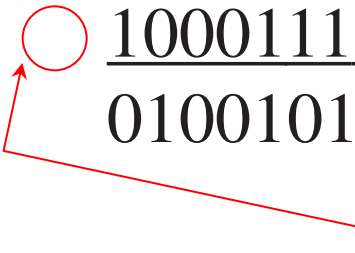
receiver:

- ❖ compute checksum of received segment
- ❖ check if computed checksum equals checksum field value:
 - NO - error detected
 - YES - no error detected. *But maybe errors nonetheless?*
More later

Internet checksum: example

example: add three 16-bit integers

0110011001100000	1011101110110101
<u>0101010101010101</u>	<u>1000111100001100</u>
1011101110110101	0100101011000010

 wraparound

sum 0 1 0 0 1 0 1 0 1 1 0 0 0 0 1 0

checksum 1 0 1 1 0 1 0 1 0 0 1 1 1 1 0 1

Note: when adding numbers, a carryout from the most significant bit needs to be added to the result

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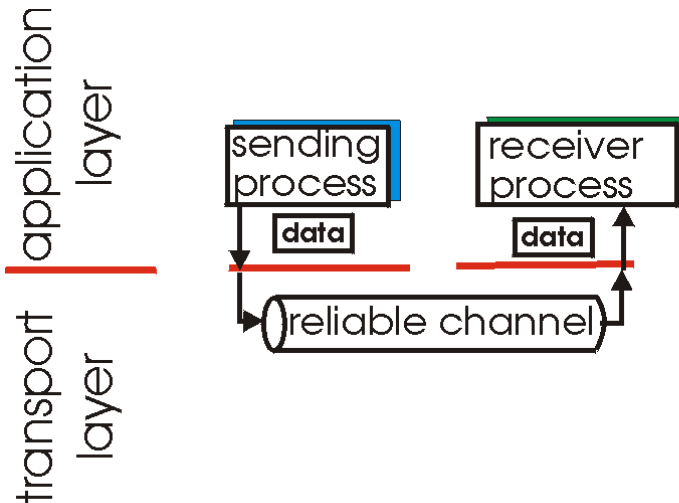
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Principles of reliable data transfer

- ❖ important in application, transport, link layers
 - top-10 list of important networking topics!



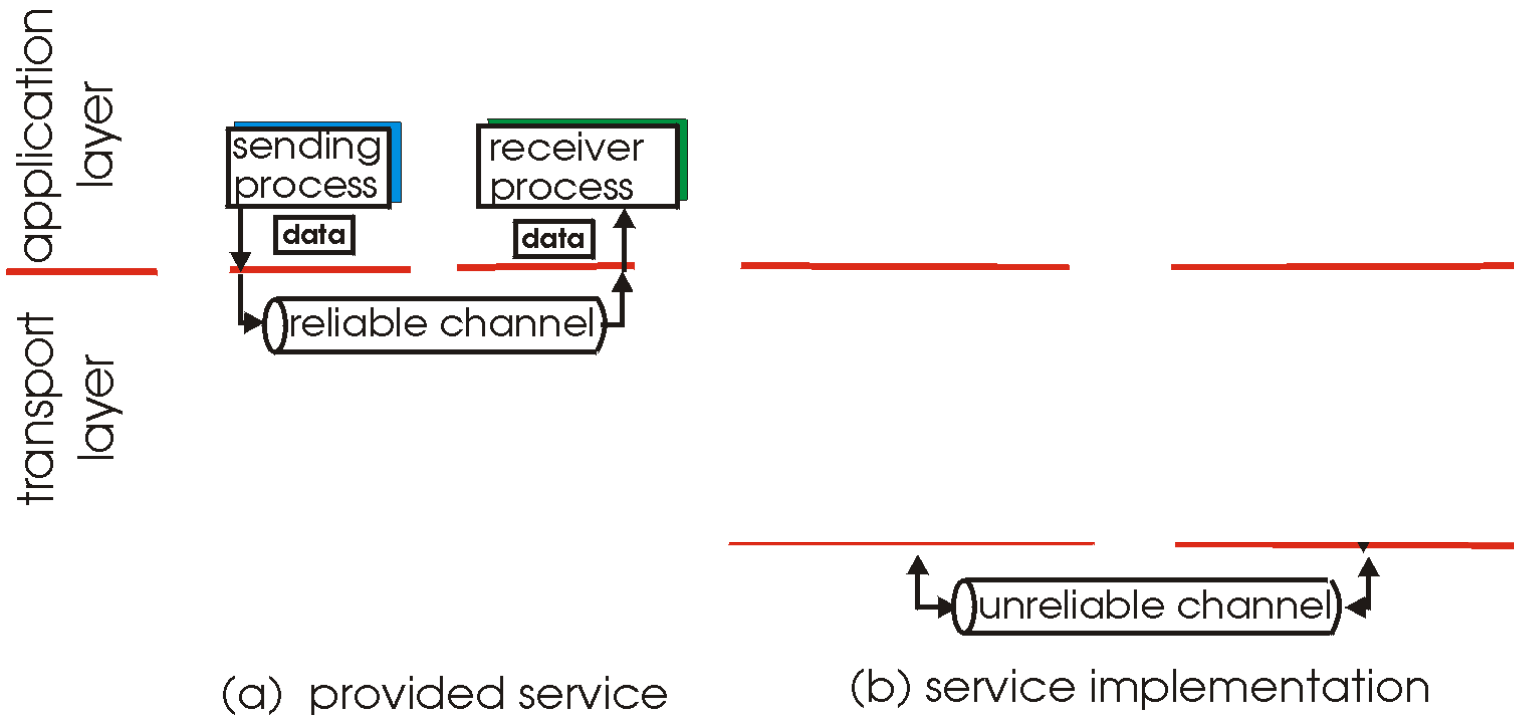
(a) provided service

(b) service implementation

- ❖ characteristics of unreliable channel will determine complexity of reliable data transfer protocol (rdt)

Principles of reliable data transfer

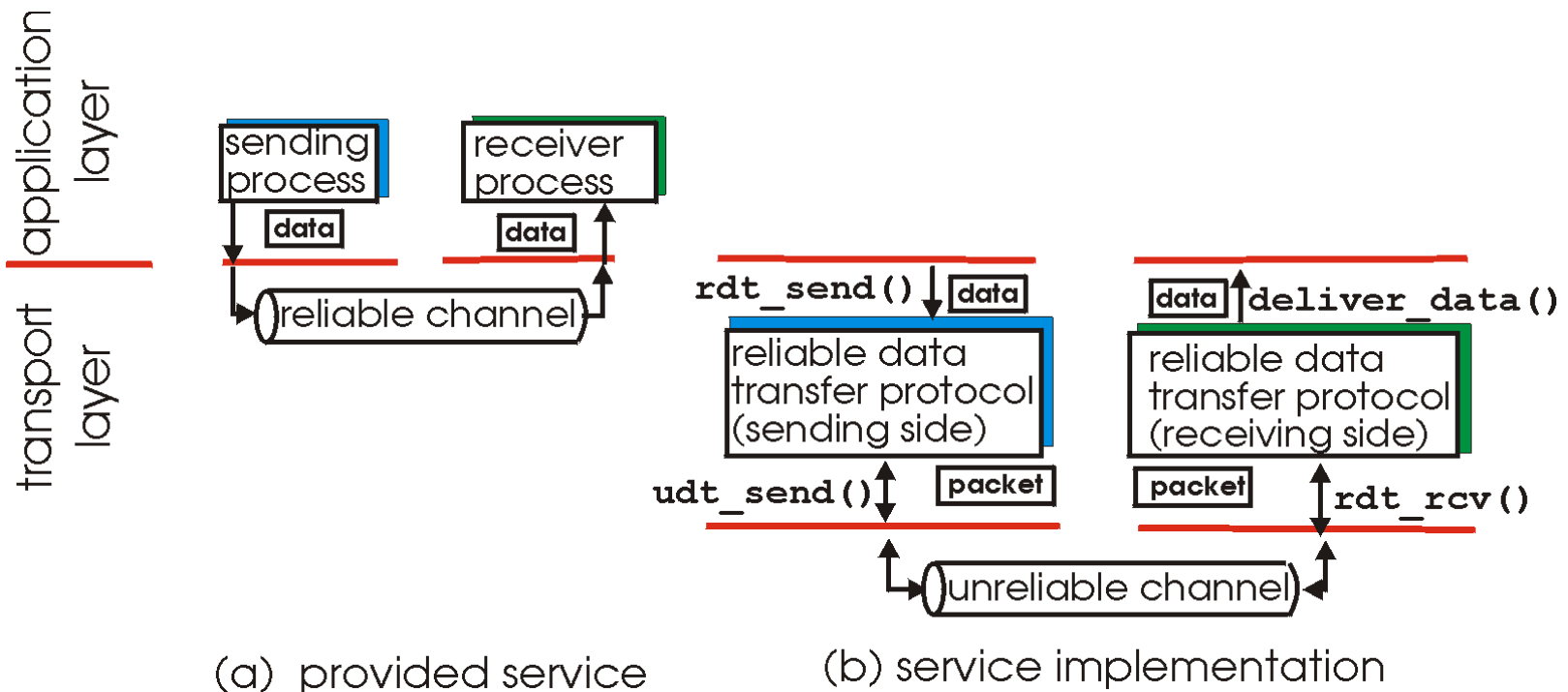
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Principles of reliable data transfer

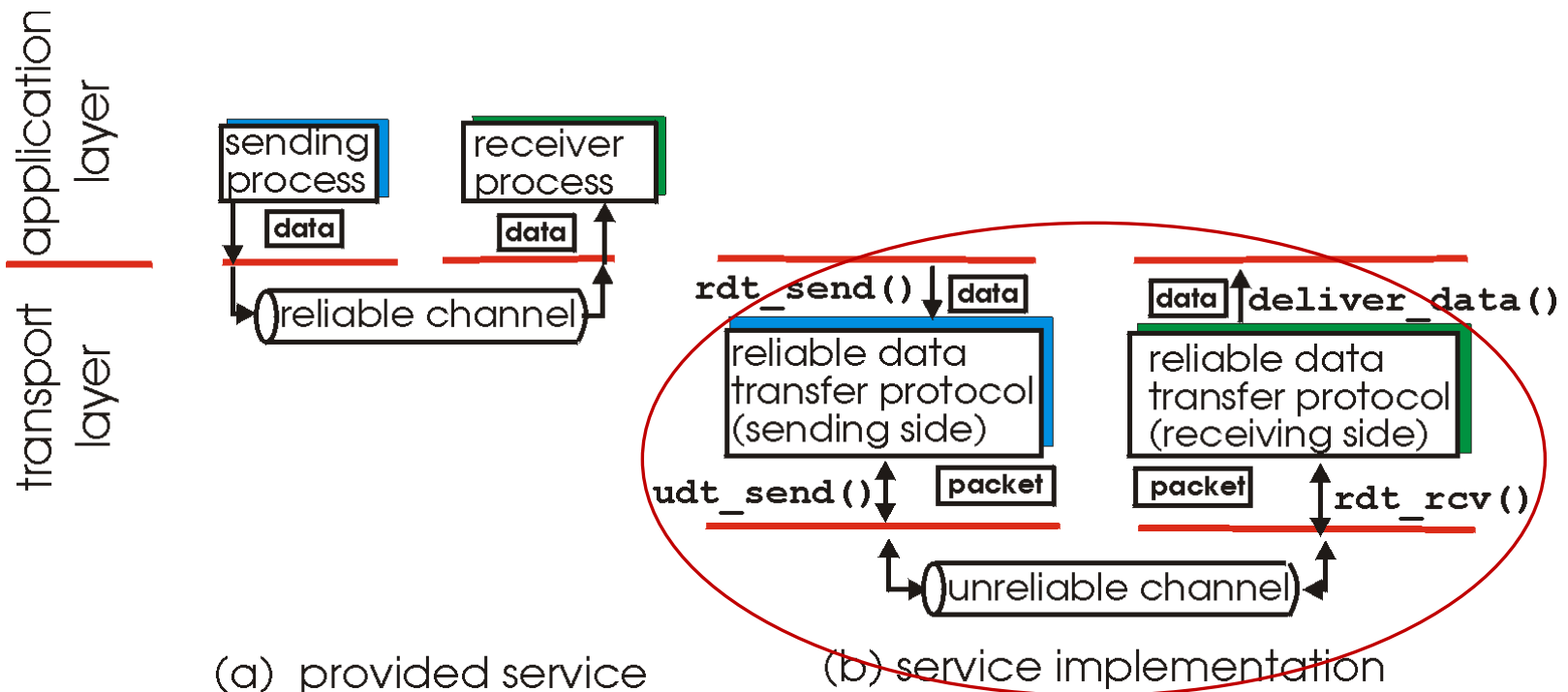
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Principles of reliable data transfer

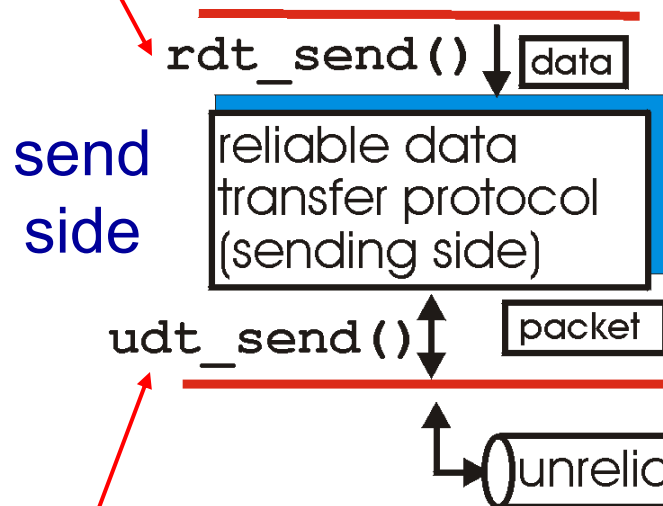
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 - top-10 list of important networking topics!



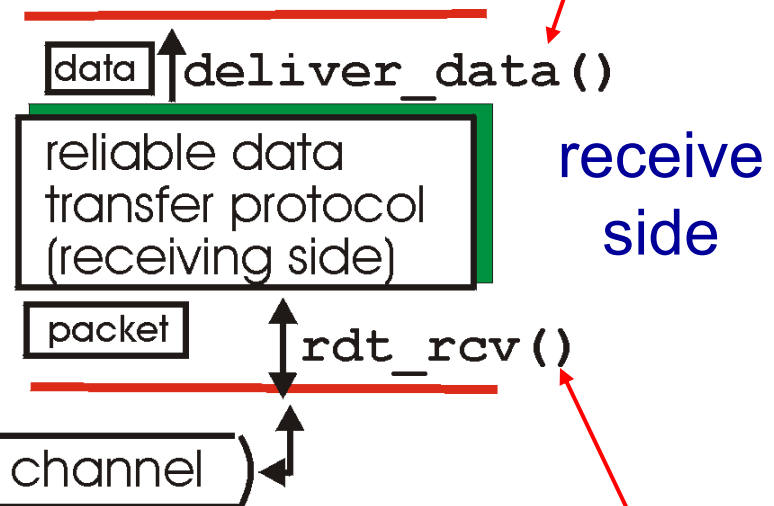
- ❖ characteristics of unreliable channel will determine complexity of reliable data transfer protocol (rdt)

Reliable data transfer: getting started

rdt_send() : called from above,
(e.g., by app.). Passed data to
deliver to receiver upper layer



deliver_data() : called by
rdt to deliver data to upper



udt_send() : called by rdt,
to transfer packet over
unreliable channel to receiver

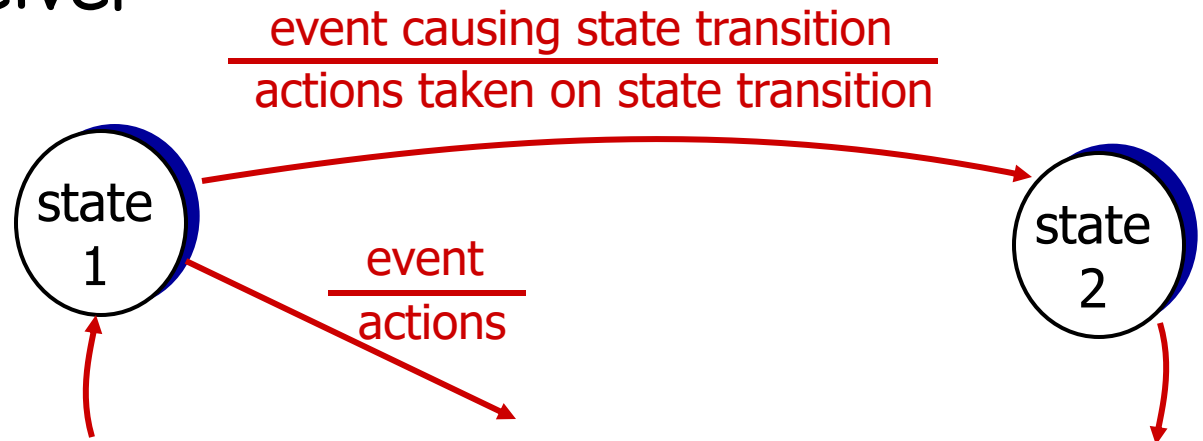
rdt_rcv() : called when packet
arrives on rcv-side of channel

Reliable data transfer: getting started

we'll:

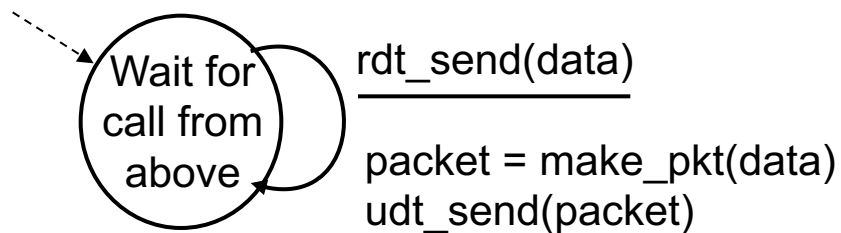
- ❖ incrementally develop sender, receiver sides of reliable data transfer protocol (rdt)
- ❖ consider only unidirectional data transfer
 - but control info will flow on both directions!
- ❖ use finite state machines (FSM) to specify sender, receiver

state: when in this “state” next state uniquely determined by next event

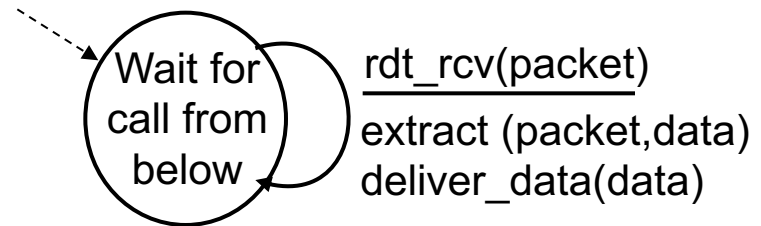


rdt1.0: reliable transfer over a reliable channel

- ❖ underlying channel perfectly reliable
 - no bit errors
 - no loss of packets
- ❖ separate FSMs for sender, receiver:
 - sender sends data into underlying channel
 - receiver reads data from underlying channel



sender



receiver

rdt2.0: channel with bit errors

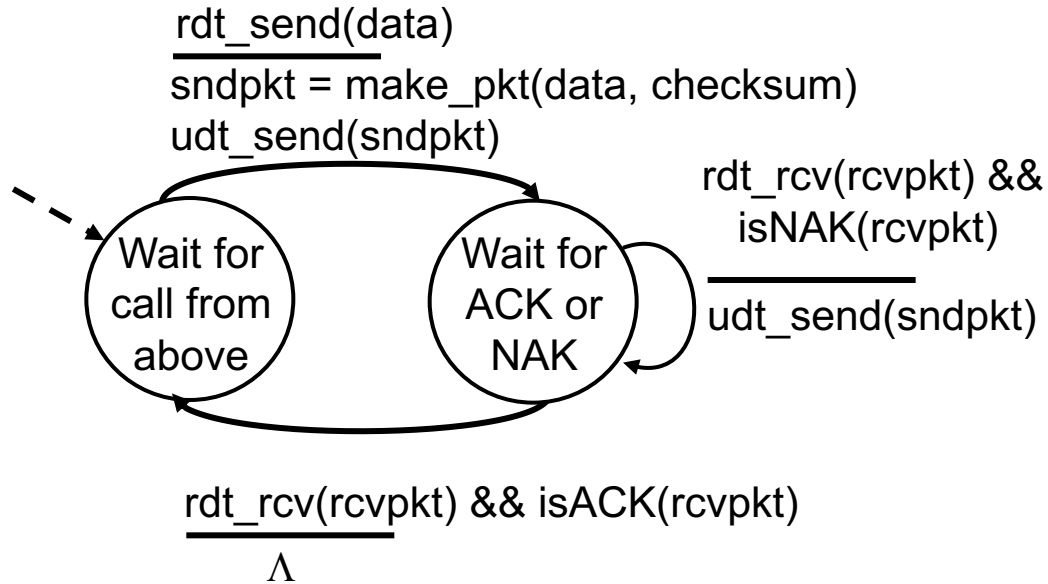
- ❖ underlying channel may flip bits in packet
 - checksum to detect bit errors
- ❖ *the question: how to recover from errors:*

*How do humans recover from “errors”
during conversation?*

rdt2.0: channel with bit errors

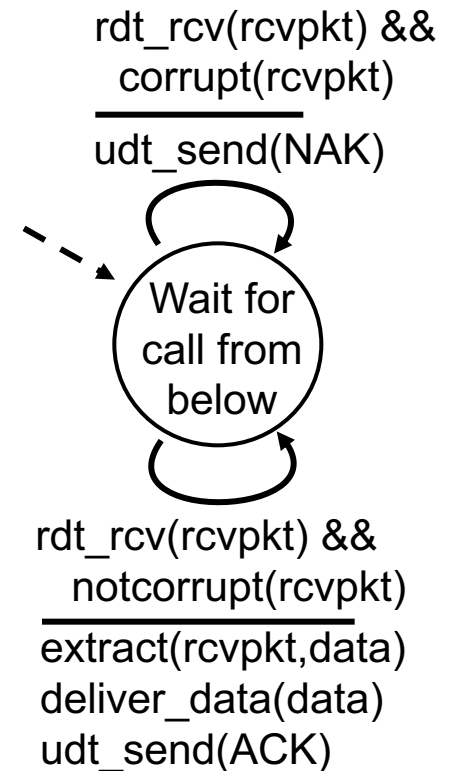
- ❖ underlying channel may flip bits in packet
 - checksum to detect bit errors
- ❖ *the question: how to recover from errors:*
 - *acknowledgements (ACKs)*: receiver explicitly tells sender that pkt received OK
 - *negative acknowledgements (NAKs)*: receiver explicitly tells sender that pkt had errors
 - sender retransmits pkt on receipt of NAK
- ❖ new mechanisms in rdt2.0 (beyond rdt1.0):
 - error detection
 - feedback: control msgs (ACK,NAK) from receiver to sender

rdt2.0: FSM specification

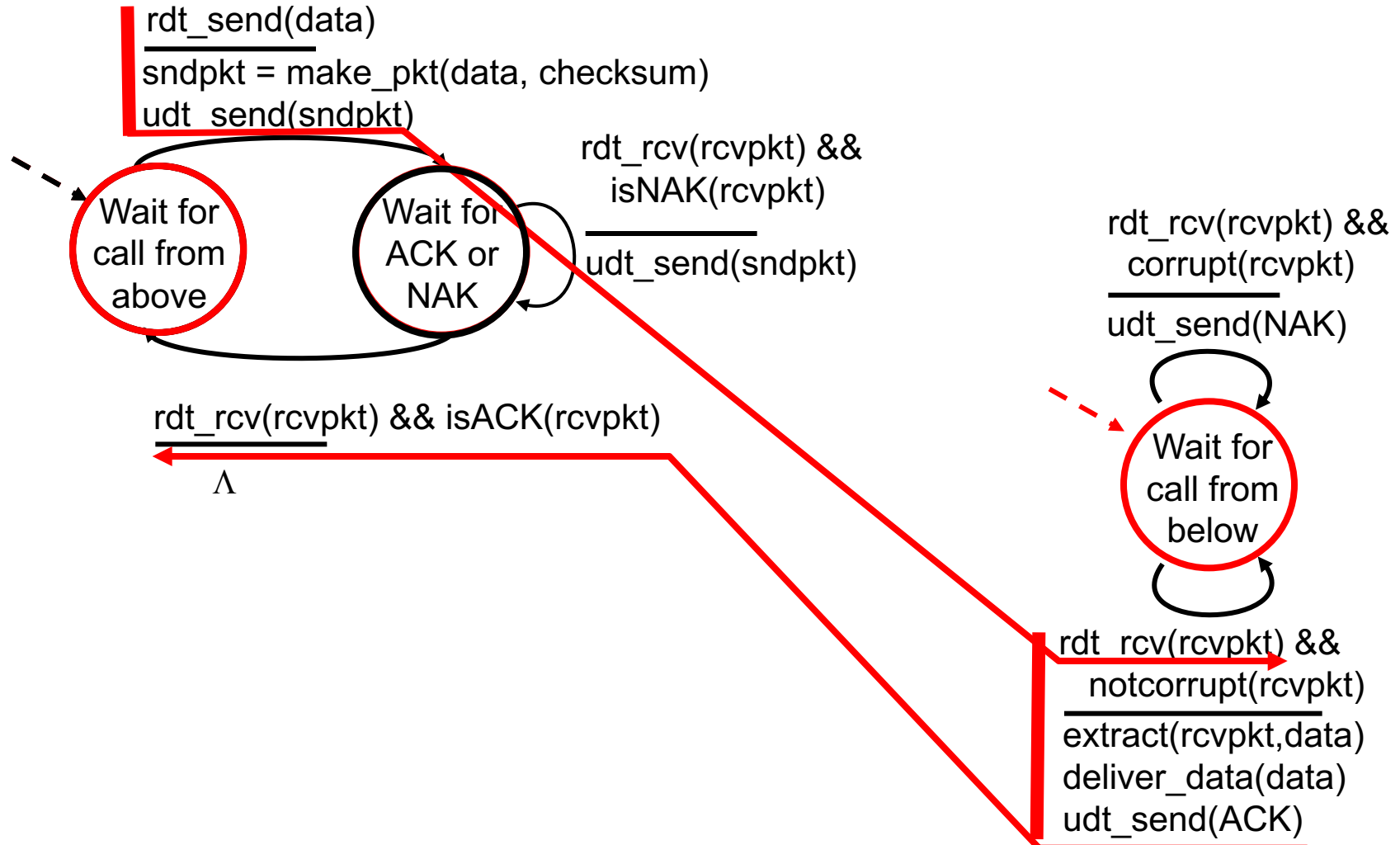


sender

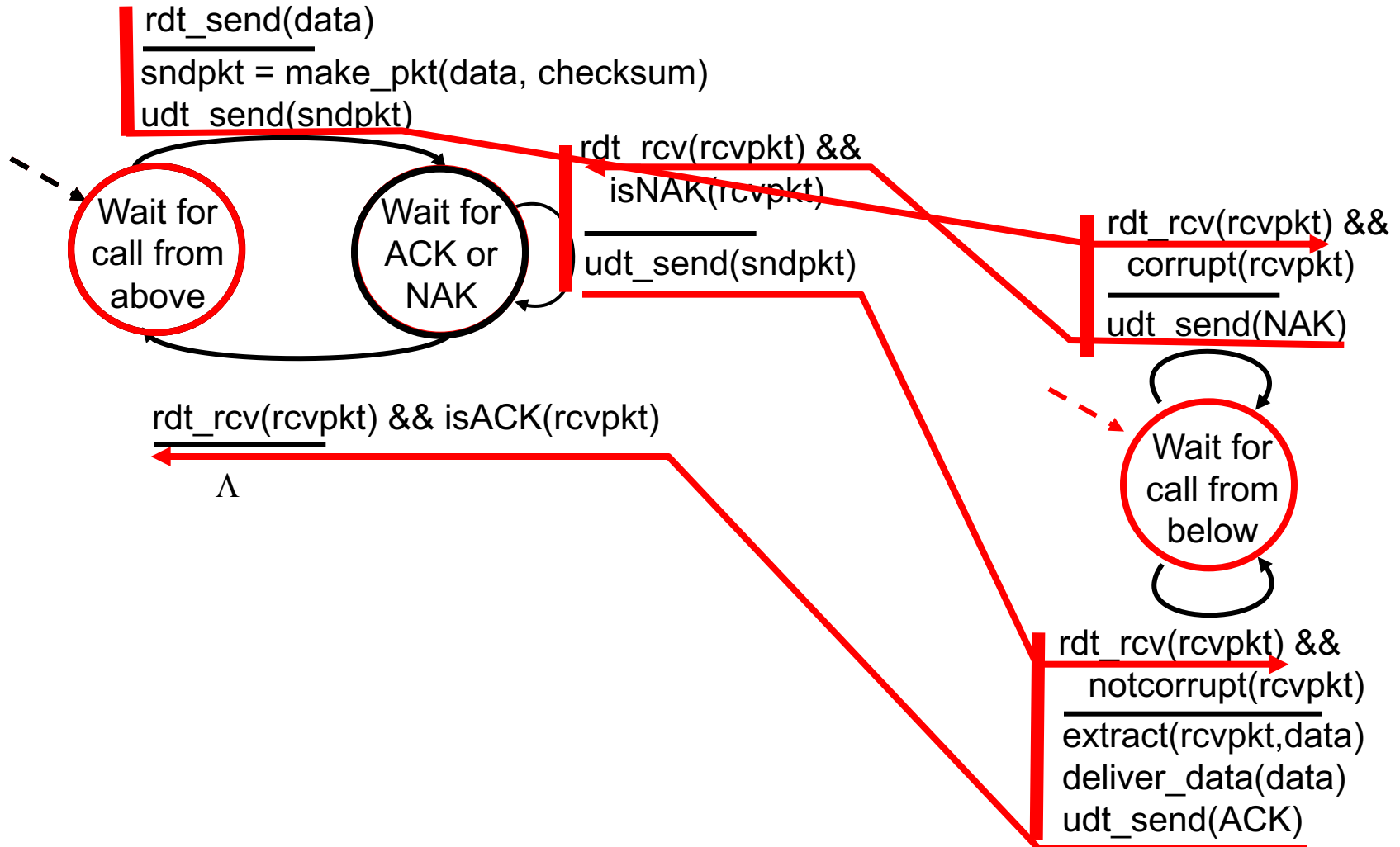
receiver



rdt2.0: operation with no errors



rdt2.0: error scenario



rdt2.0 has a fatal flaw!

what happens if
ACK/NAK
corrupted?

- ❖ sender doesn't know what happened at receiver!
- ❖ can't just retransmit: possible duplicate

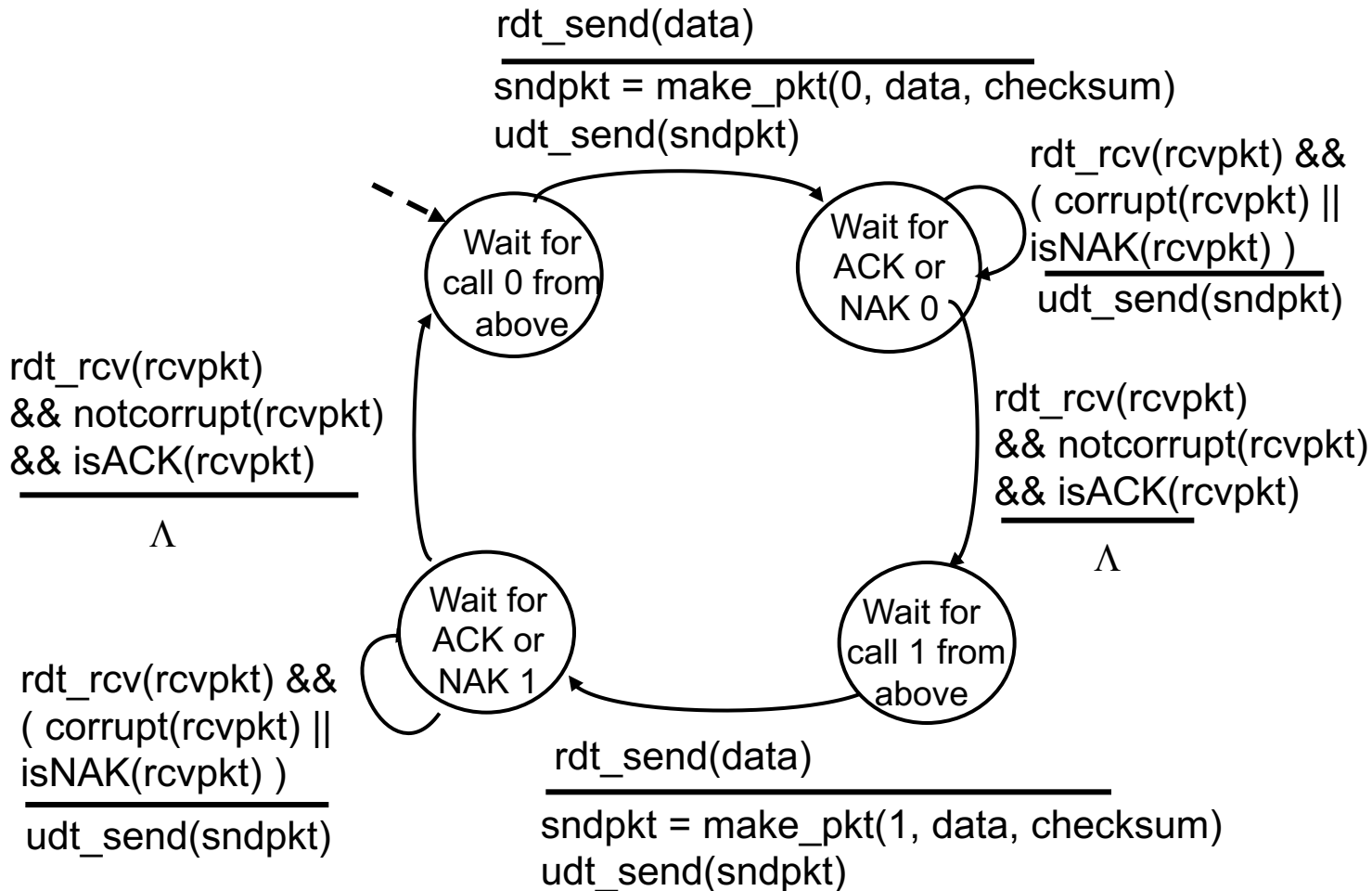
handling duplicates:

- ❖ sender retransmits current pkt if ACK/NAK corrupted
- ❖ sender adds *sequence number* to each pkt
- ❖ receiver discards (doesn't deliver up) duplicate pkt

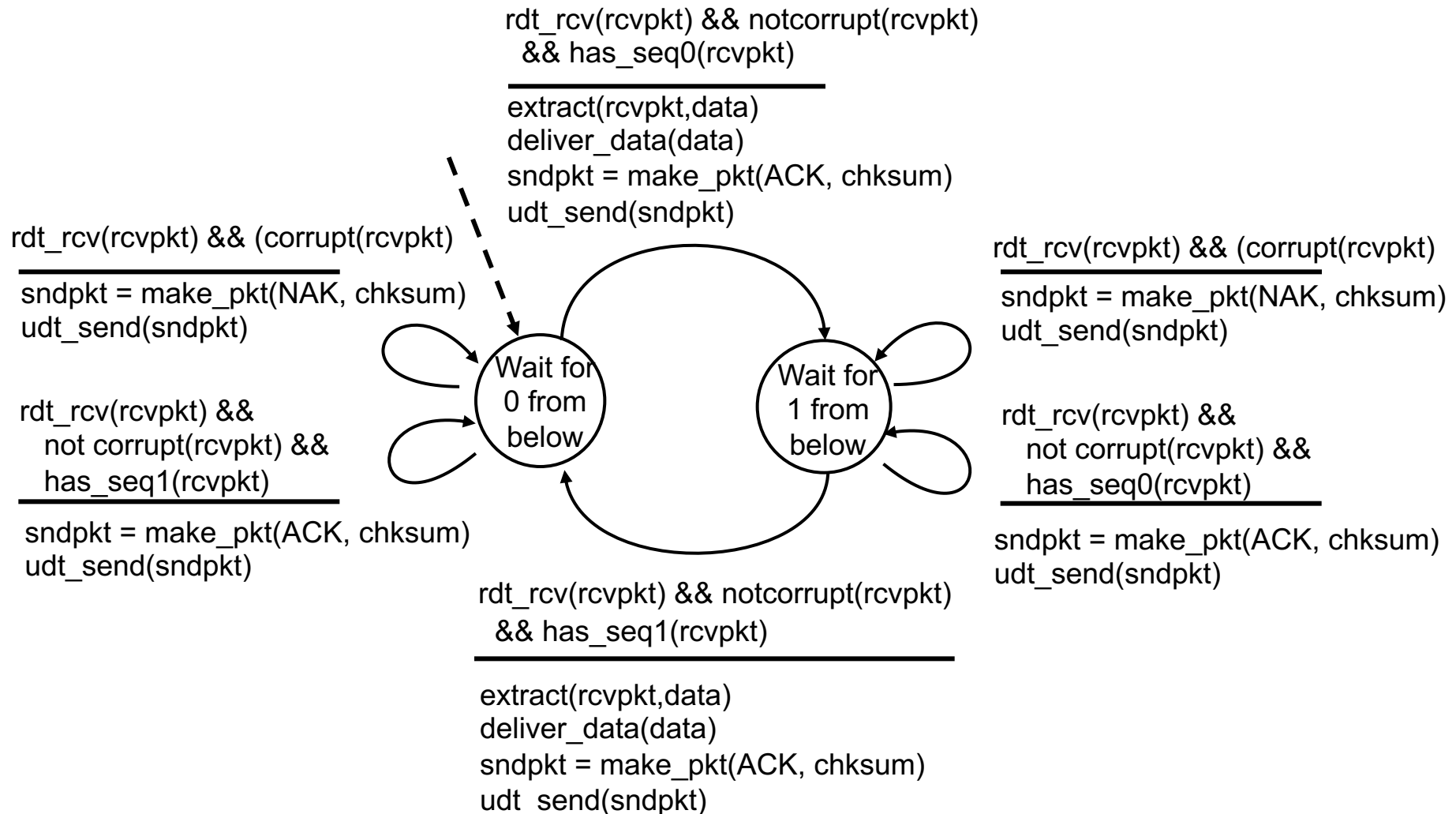
stop and wait

sender sends one packet,
then waits for receiver
response

rdt2.1: sender, handles garbled ACK/NAKs



rdt2.1: receiver, handles garbled ACK/NAKs



rdt2.1: discussion

sender:

- ❖ seq # added to pkt
- ❖ two seq. #'s (0,1) will suffice. Why?
- ❖ must check if received ACK/NAK corrupted
- ❖ twice as many states
 - state must “remember” whether “expected” pkt should have seq # of 0 or 1

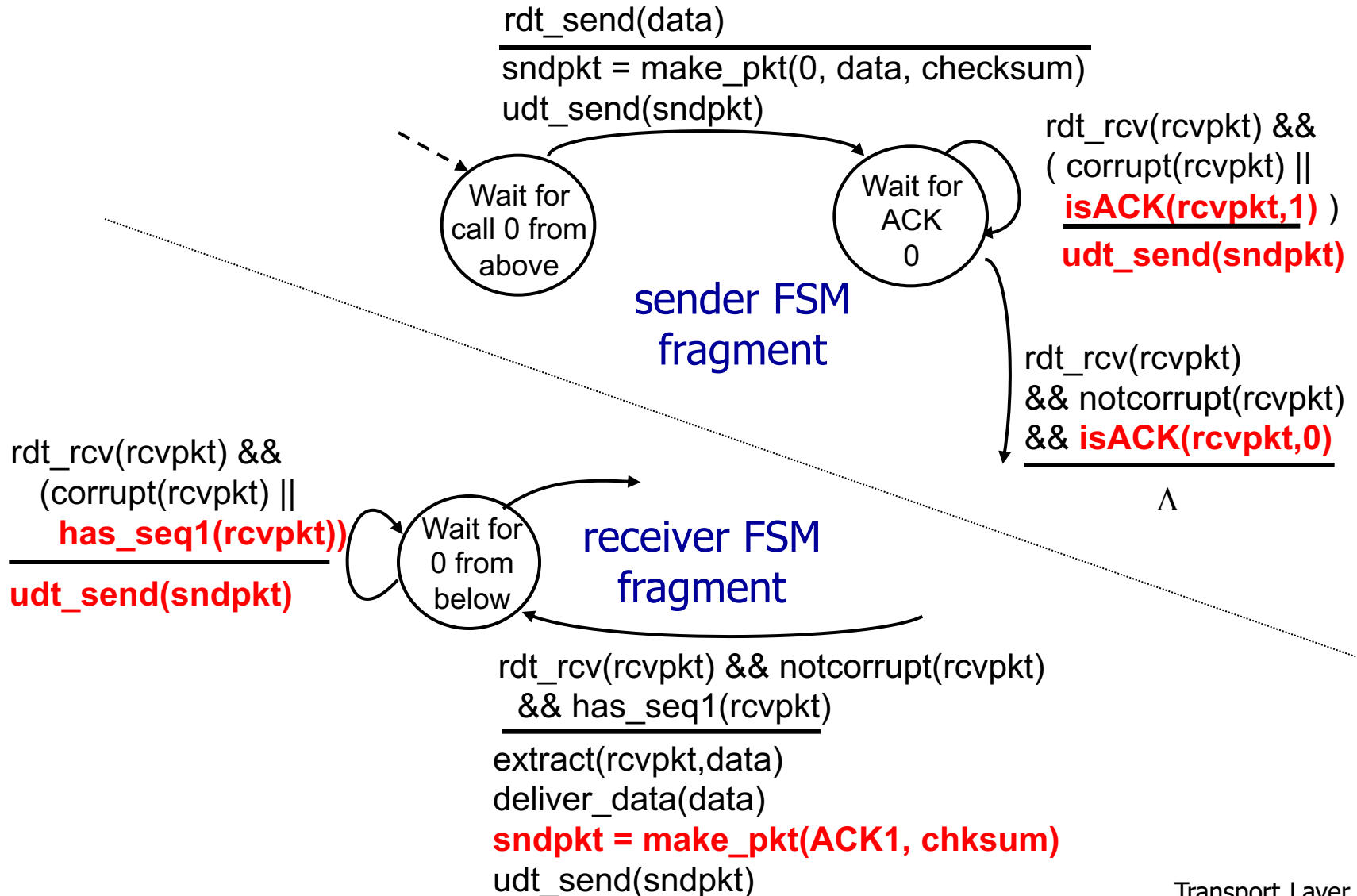
receiver:

- ❖ must check if received packet is duplicate
 - state indicates whether 0 or 1 is expected pkt seq #
- ❖ note: receiver can *not* know if its last ACK/NAK received OK at sender

rdt2.2: a NAK-free protocol

- ❖ same functionality as rdt2.1, using ACKs only
- ❖ instead of NAK, receiver sends ACK for last pkt received OK
 - receiver must *explicitly* include seq # of pkt being ACKed
- ❖ duplicate ACK at sender results in same action as NAK: *retransmit current pkt*

rdt2.2: sender, receiver fragments



rdt3.0: channels with errors *and* loss

new assumption:

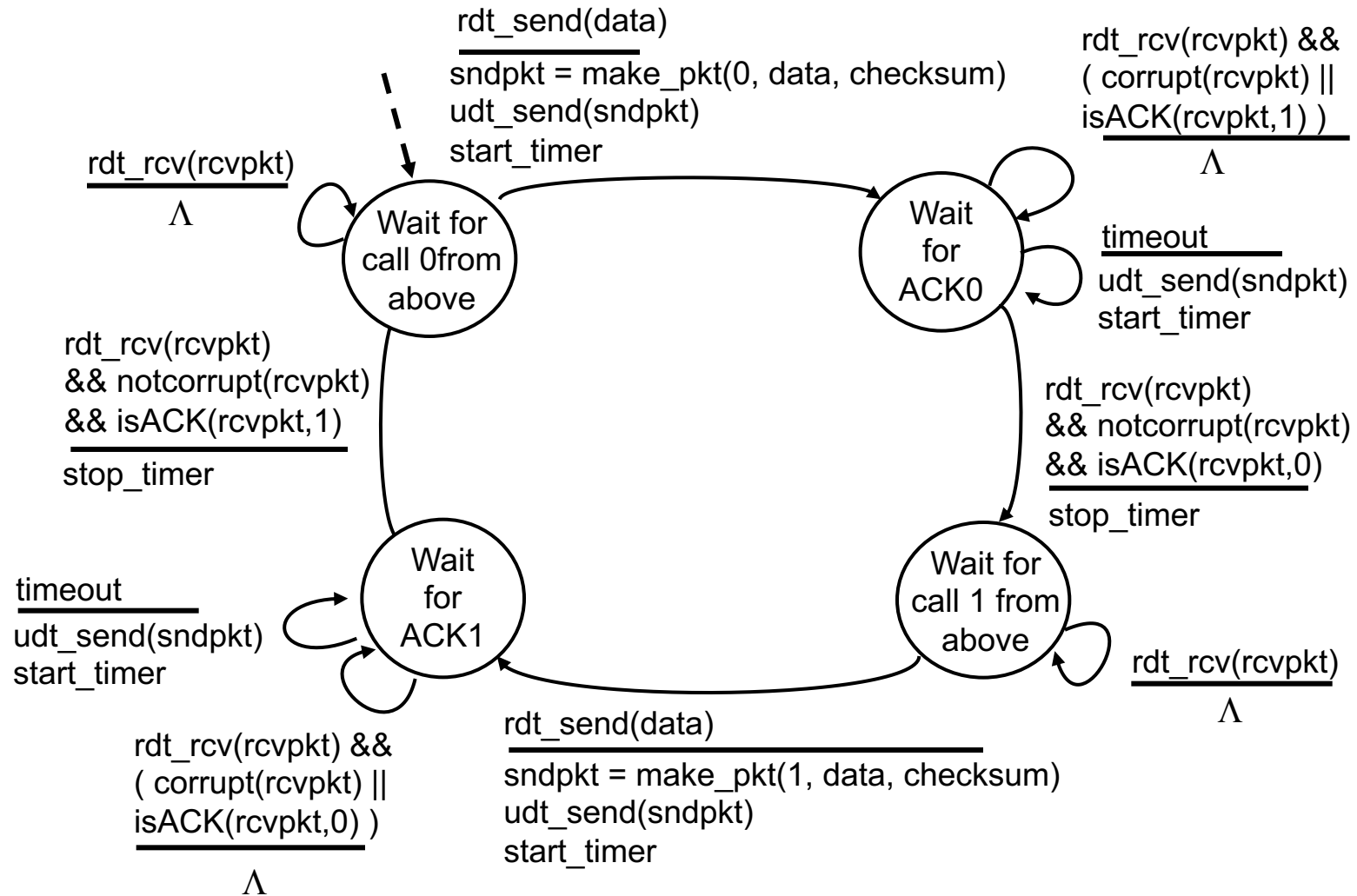
underlying channel
can also lose packets
(data, ACKs)

- checksum, seq. #,
ACKs,
retransmissions will
be of help ... but not
enough

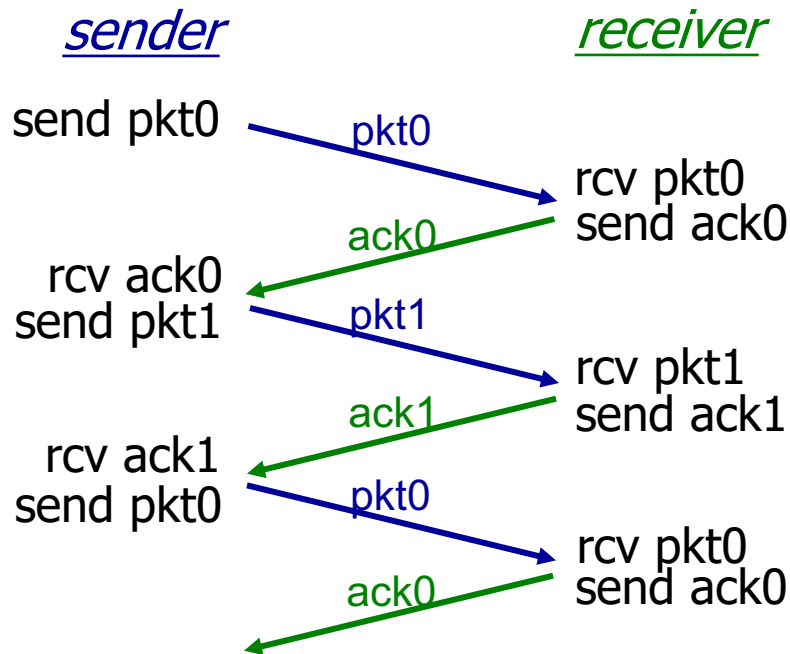
approach: sender waits
“reasonable” amount
of time for ACK

- ❖ 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
- ❖ requires countdown timer

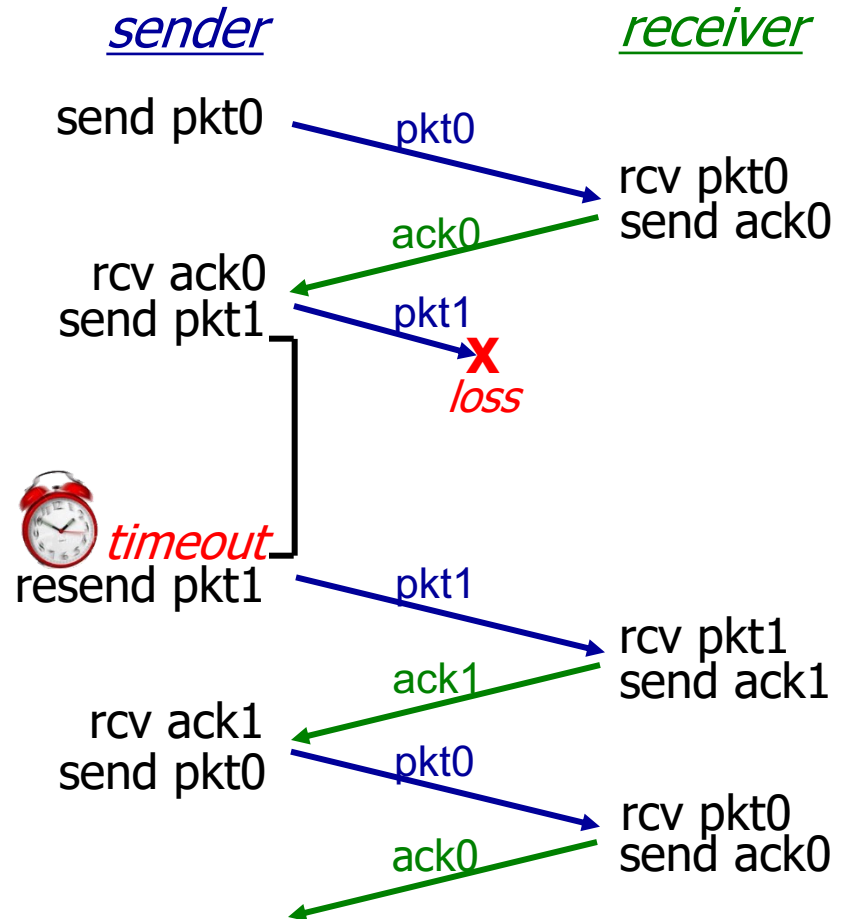
rdt3.0 sender



rdt3.0 in action

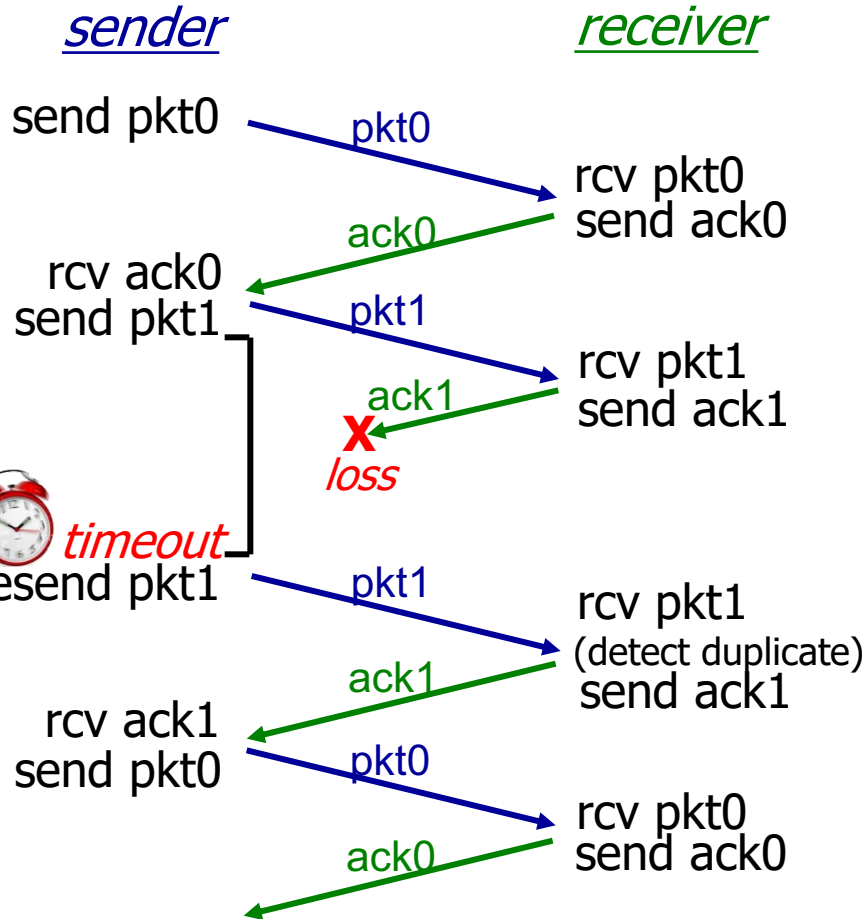


(a) no loss

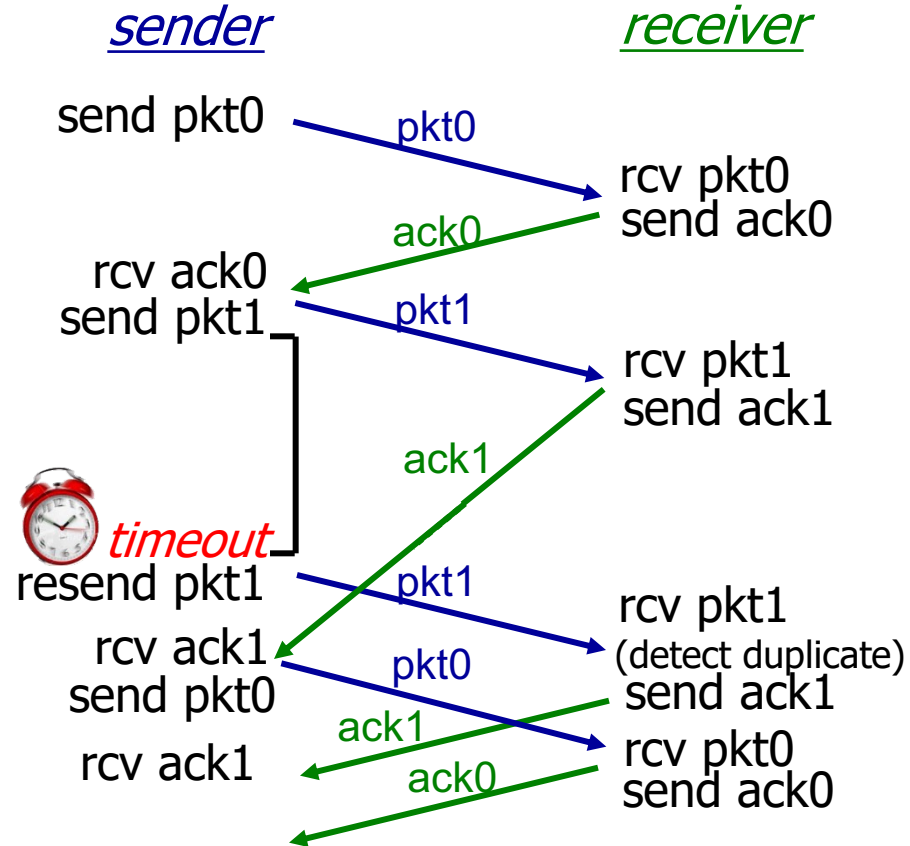


(b) packet loss

rdt3.0 in action

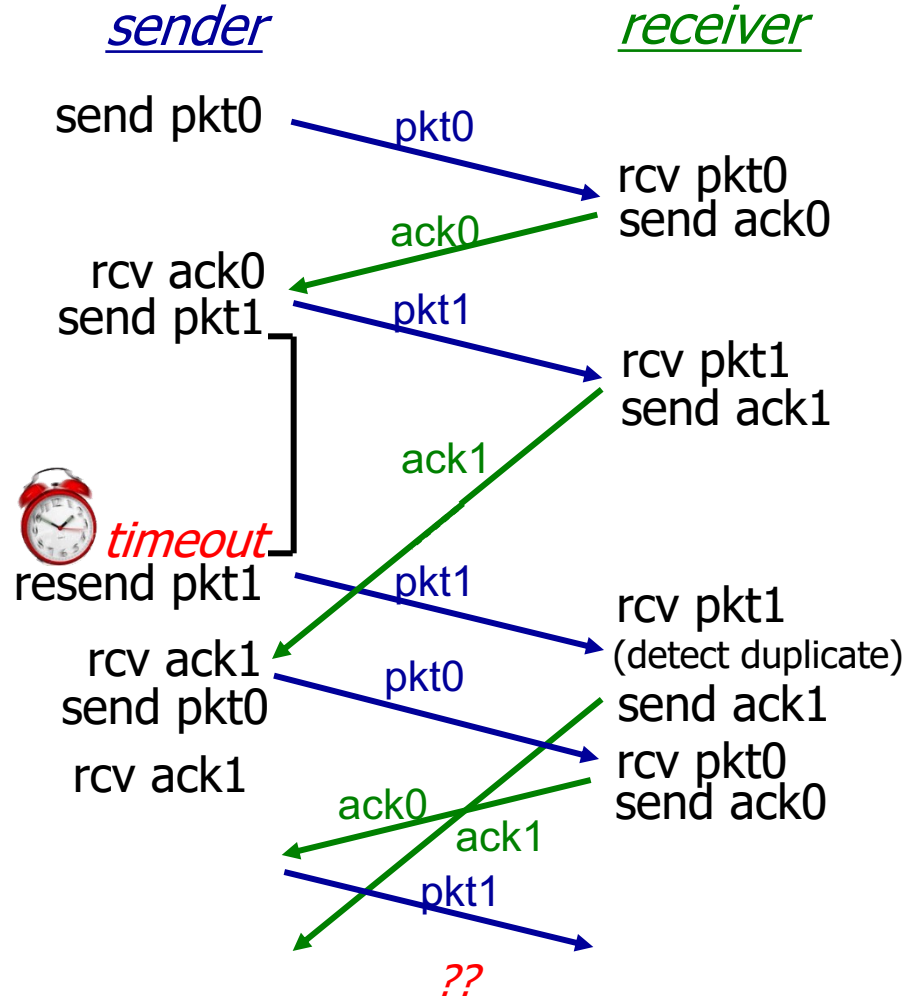


(c) ACK loss



(d) premature timeout/ delayed ACK

rdt3.0 in action



(d) disorder ACKs

Performance of rdt3.0

- ❖ rdt3.0 is correct, but performance stinks
- ❖ e.g.: 1 Gbps link, 15 ms prop. delay, 8000 bit packet:

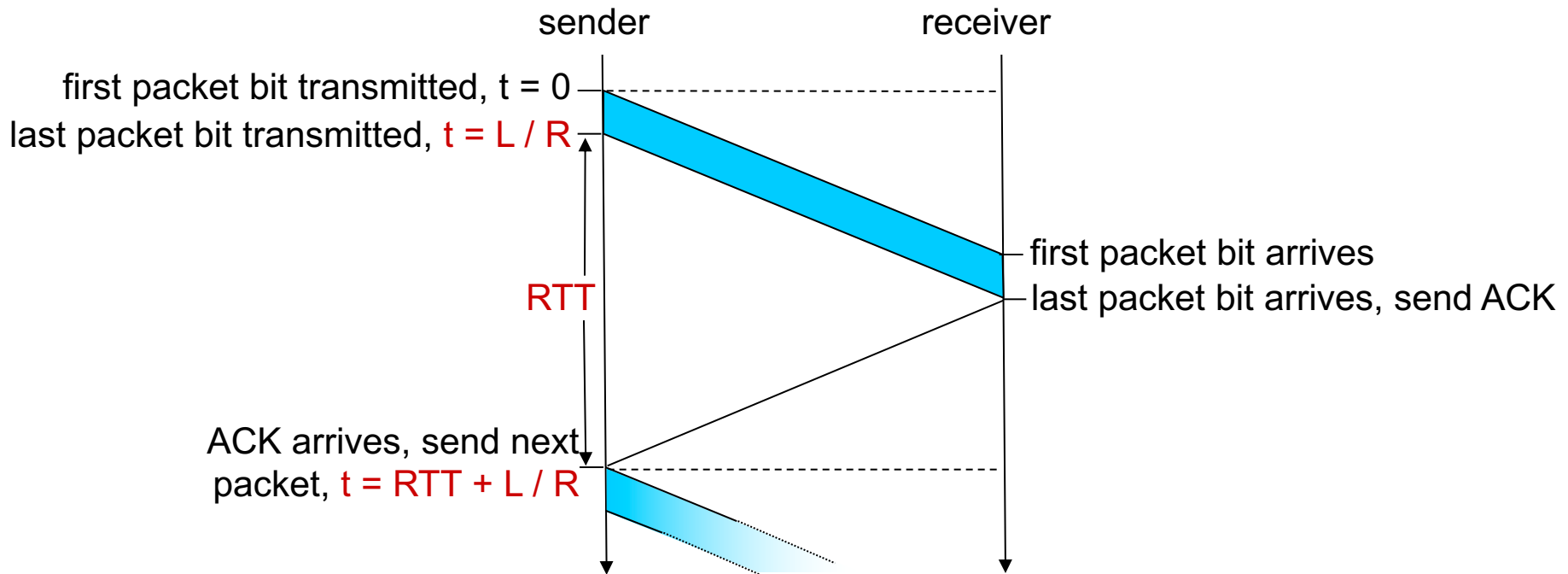
$$D_{trans} = \frac{L}{R} = \frac{8000 \text{ bits}}{10^9 \text{ bits/sec}} = 8 \text{ microseconds}$$

- U_{sender} : **utilization** = fraction of time sender busy sending

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

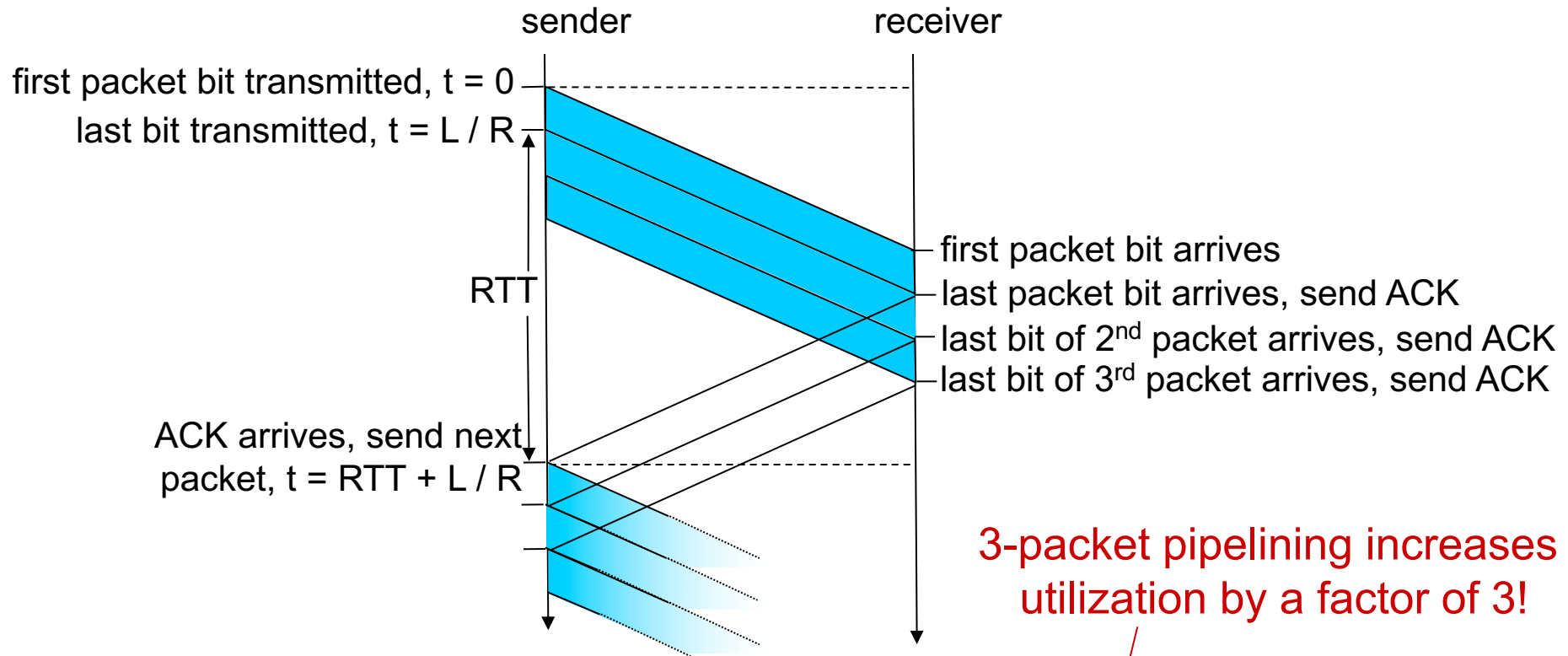
- if $RTT=30$ msec, 1KB pkt every 30 msec: 33kB/sec thruput over 1 Gbps link
- ❖ network protocol limits use of physical resources!

rdt3.0: stop-and-wait operation



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

Pipelining: increased utilization



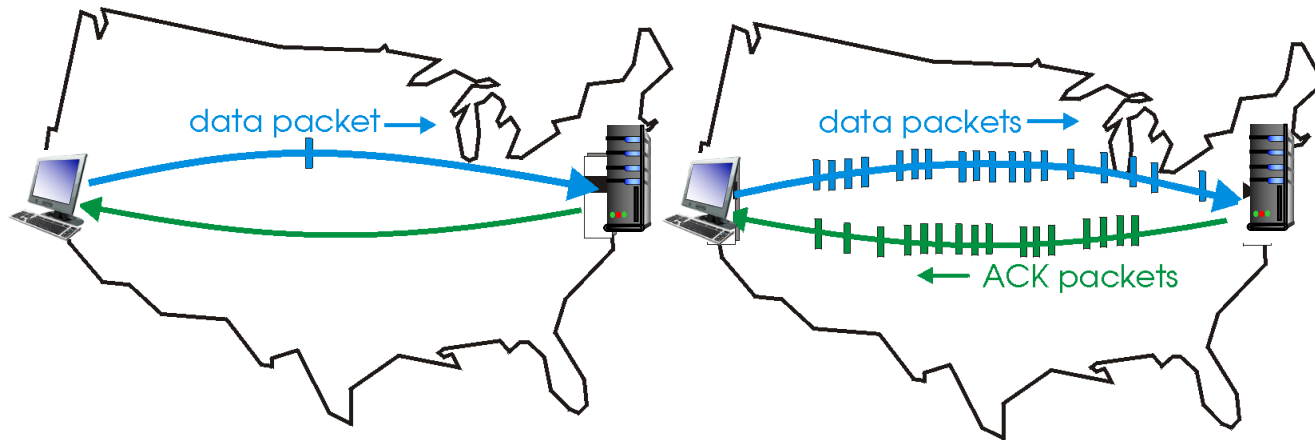
3-packet pipelining increases utilization by a factor of 3!

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

Pipelined protocols

pipelining: sender allows multiple, “in-flight”, yet-to-be-acknowledged pkts

- range of sequence numbers must be increased
- buffering at sender and/or receiver



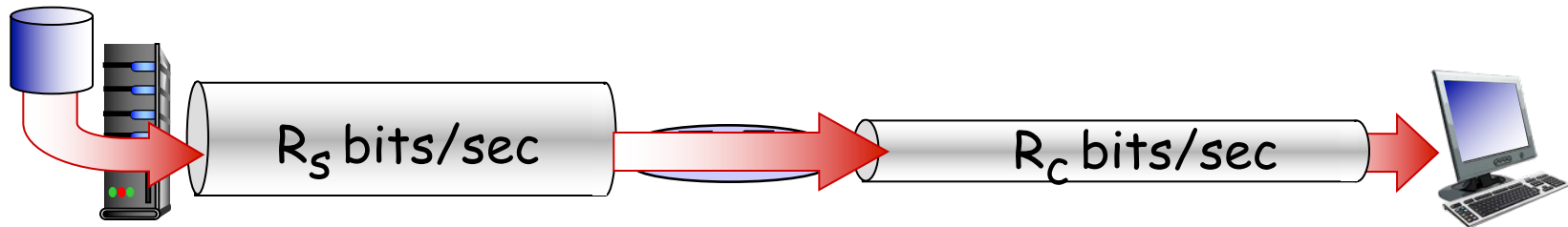
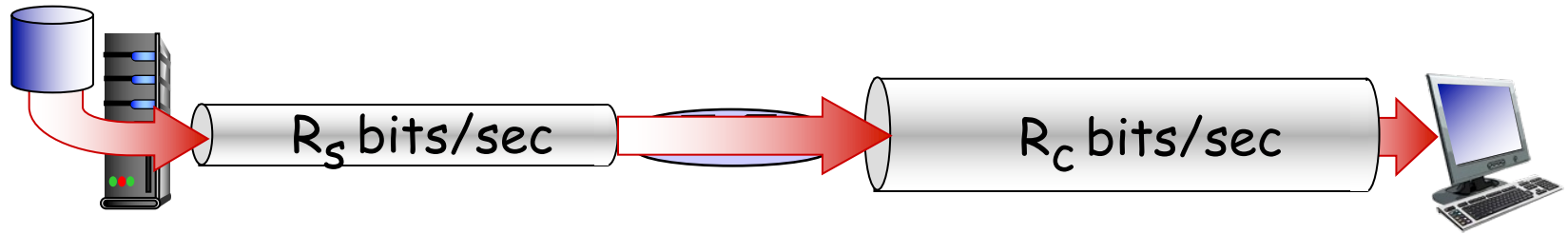
(a) a stop-and-wait protocol in operation

(b) a pipelined protocol in operation

❖ two generic forms of pipelined protocols: *go-Back-N, selective repeat*

Bandwidth Delay Product

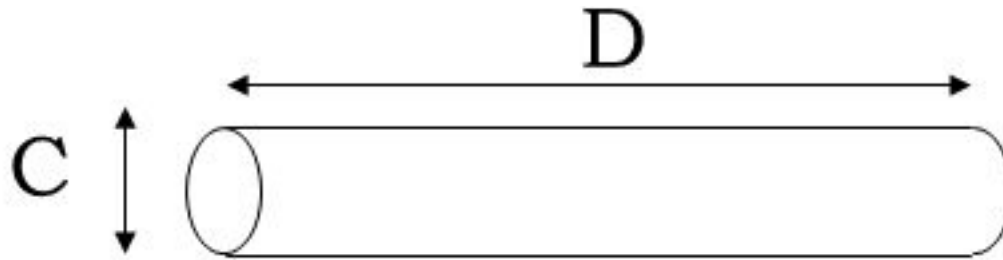
❖ What is average end-end throughput?



❖ keeping the pipe full

Bandwidth Delay Product

- ❖ $C = \min\{R_s, R_c\}$; D: Round Trip Delay, RTT



- ❖ Bandwidth Delay Product = $C[\text{bits/s}] * D[\text{s}]$
 - number of flying bits in the network

- ❖ Keeping the pipe full

IDEAL number of “in-flight” packets

Pipelined protocols: overview

Go-back-N:

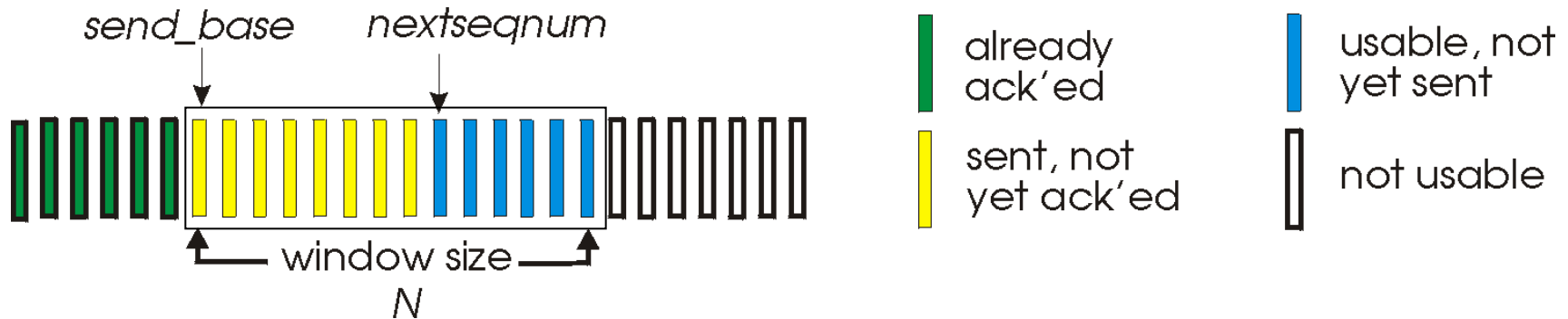
- ❖ sender can have up to N unacked packets in pipeline
- ❖ receiver only sends *cumulative ack*
 - doesn't ack packet if there's a gap
- ❖ sender has timer for oldest unacked packet
 - when timer expires, retransmit *all* unacked packets

Selective Repeat:

- ❖ sender can have up to N unack'ed packets in pipeline
- ❖ rcvr sends *individual ack* for each packet
- ❖ sender maintains timer for each unacked packet
 - when timer expires, retransmit only that unacked packet

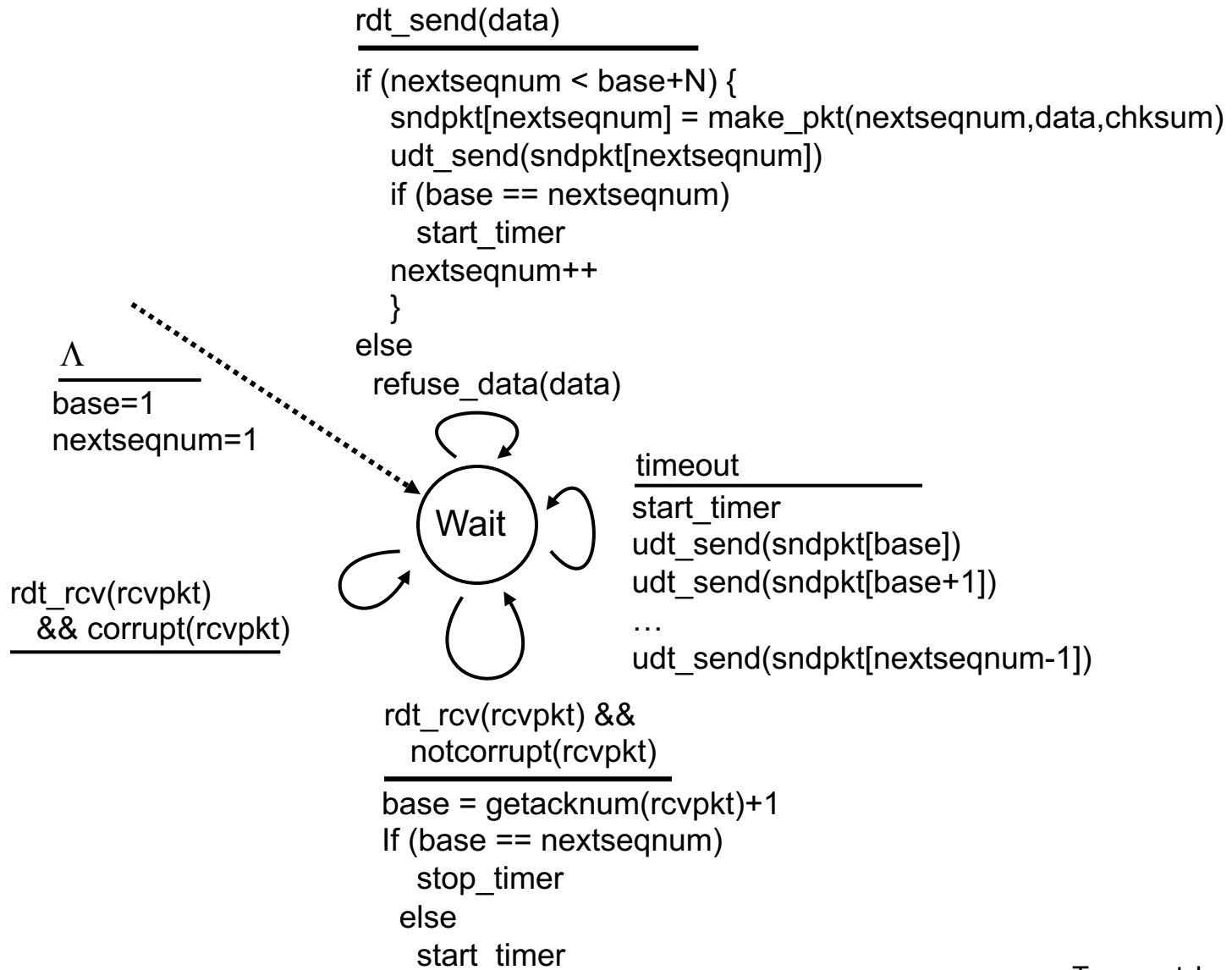
Go-Back-N: sender

- ❖ k-bit seq # in pkt header
- ❖ “window” of up to N, consecutive unack’ed pkts allowed

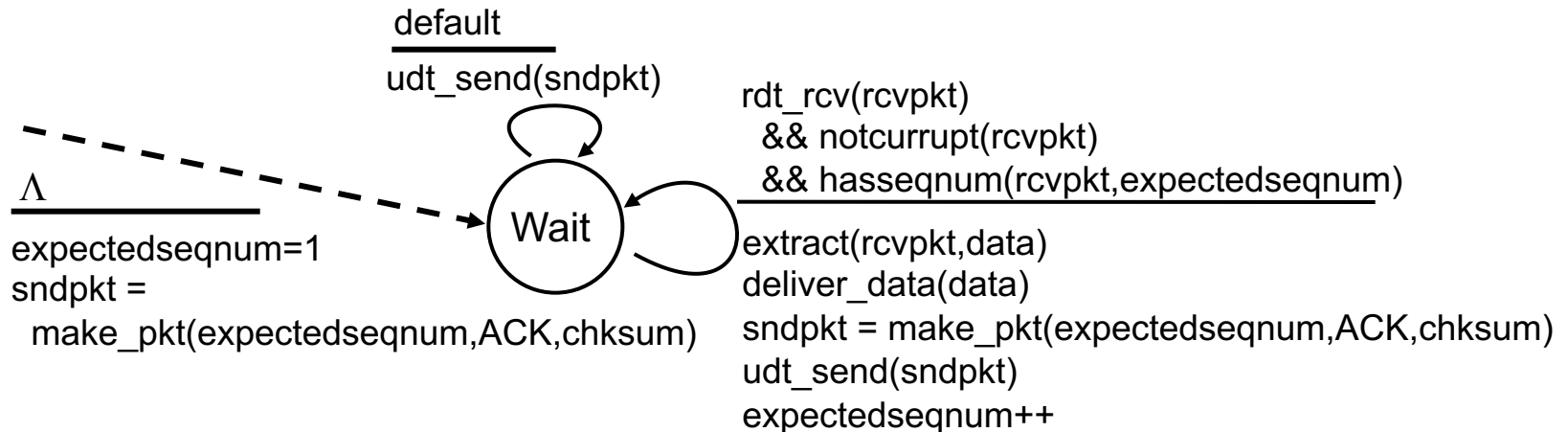


- ❖ ACK(n): ACKs all pkts up to, including seq # n - “*cumulative ACK*”
 - may receive duplicate ACKs (see receiver)
- ❖ timer for oldest in-flight pkt
- ❖ *timeout(n)*: retransmit packet n and all higher seq # pkts in window

GBN: sender extended FSM



GBN: receiver extended FSM



ACK-only: always send ACK for correctly-received pkt with highest *in-order* seq #

- may generate duplicate ACKs
- need only remember expectedseqnum

❖ out-of-order pkt:

- discard (don't buffer): *no receiver buffering!*
- re-ACK pkt with highest in-order seq #

GBN 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

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

GBN 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

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

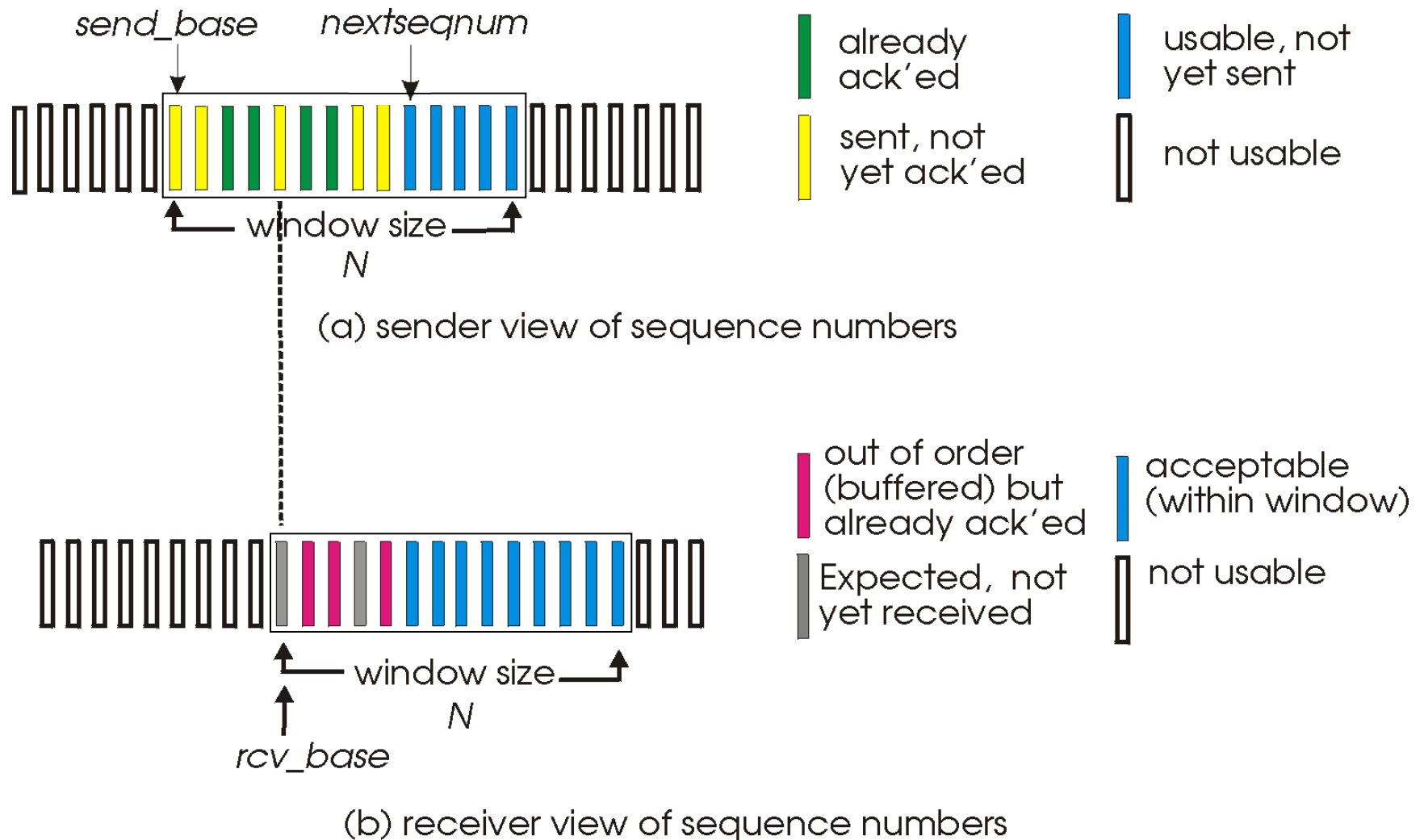
loss X

State of the window??

Selective repeat

- ❖ receiver *individually* acknowledges 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



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-1]:

- ❖ mark pkt n as received
- ❖ if n 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

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

record ack3 arrived



pkt 2 timeout

send pkt2

record ack4 arrived

record ack5 arrived

receiver

receive pkt0, send ack0

receive pkt1, send ack1

receive pkt3, buffer,
send ack3

receive pkt4, buffer,
send ack4

receive pkt5, buffer,
send ack5

rcv pkt2; deliver pkt2,
pkt3, pkt4, pkt5; send ack2

Q: what happens when ack2 arrives?

Selective repeat: dilemma

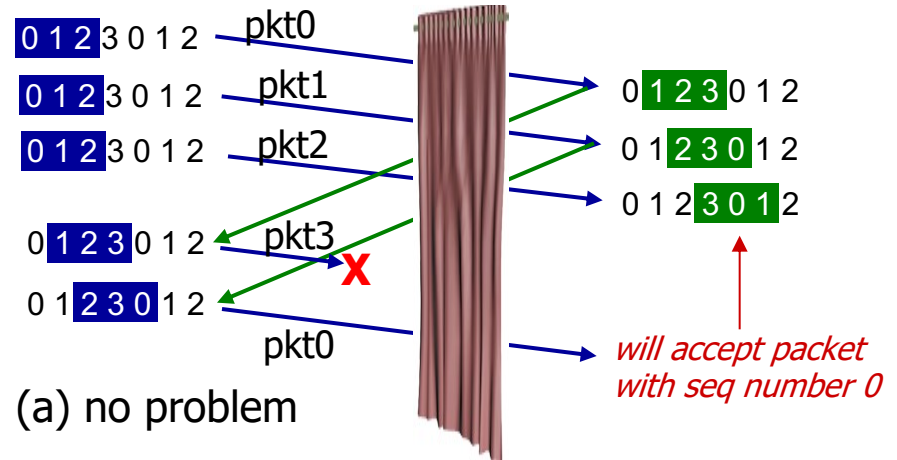
example:

- ❖ seq #'s: 0, 1, 2, 3
- ❖ window size=3
- ❖ receiver sees no difference in two scenarios!
- ❖ duplicate data accepted as new in (b)

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

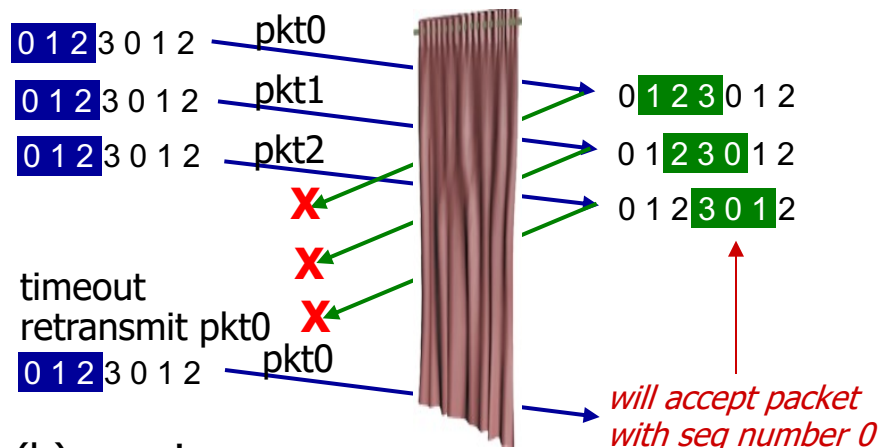
sender window (after receipt)

receiver window (after receipt)



(a) no problem

*receiver can't see sender side.
receiver behavior identical in both cases!
something's (very) wrong!*



(b) oops!

Outline

3.1 transport-layer services

3.2 multiplexing and demultiplexing

3.3 connectionless transport: UDP

3.4 principles of reliable data transfer

3.5 connection-oriented transport: TCP

- segment structure
- reliable data transfer
- flow control
- connection management

3.6 principles of congestion control

3.7 TCP congestion control