Advanced Networking

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(help with projects & Seminars)

Dipartimento di Ingegneria e Scienza dell'Informazione
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What do you find on the web site

- Exam Rules
- Exam Details ... should be on ESSE3, but ...
- Generic (useful) information
- Teaching Material: normally posted at least the day before the lesson
- Additional Material and links
- News, Bulletin, How to find and meet me, etc.
- ...

The web site is work in progress and updated frequently, so please drop by frequently and don't blame ME if you did't read the last news ☺

Program

- **Course Perspective**
  - what do we learn and what we do not
  - are there other "networks"

- **Reharsal of basics**
  - Internet and TCP/IP
  - THE network? or YetAnother network
  - IP
  - UDP/TCP

Program

- IP and routing
  - OSPF and link-state protocols
    - Intra AS routing
    - performance driven routing
  - BGP and policy-based protocols
    - External routing
    - Cost (economical!) based routing
  - Global routing and Internet topology
    - How things look and works end-to-end

Program

- **Multicast**
  - **Abstract multicasting**
  - **Multicast groups and addresses**
  - **Internet and multicast: IGMP**
  - **Multicast routing**
  - **Application level multicast**
    - **why it's absurd ...**
    - **... why it works!!!**

Program

- **Network congestion**
  - Network load and stability
  - Call Admission Control
  - Reactive congestion control
    - Closed-loop systems
    - Implicit/Explicit
    - Forward
    - Backward
  - TCP
    - How it really works
  - TCP stabilization methods: mith and reality
    - RED, RIO, ...

Program

- **Internet multimedia communications**
  - **Voice and Video services on packet-based networks**
  - **Transport: RTP/RTCP**
  - **SIP standard**
  - **H.323 standard**
  - **Skype and P2P approaches**

  - **IP TV**
    - VoD/Broadcast/Live
    - Traditional approach
    - P2P systems

- **Recalling known topics:**

  - Internet
  - IP
  - UDP/TCP

Acknowledment:
The following slides are based on the slides developed by
J.Kurose and K.Ross to accompany their book “Computer Networks:
A Top Down Approach Featuring the Internet” by Wiley edts.

Internet

What we see:

- Services
- Applications we use
- Some "application level" protocols
- Throughput
- Losses
- Delay (sometimes)
- Delay Jitter (if we're really skilled!)

What is it:

- A collection of protocols
- Mainly centered around two centerpieces:
  - **IP** (network layer)
  - **UDP/TCP** (transport layer)
- Does not mandate a physical medium or format
- Does not mandate or limit the services/applications above (integrates services)

IP: The Network Layer

Goals:

- recall principles behind network layer services:
  - routing (path selection)
  - dealing with scale
  - how a router works
- instantiation and implementation in the Internet

Overview:

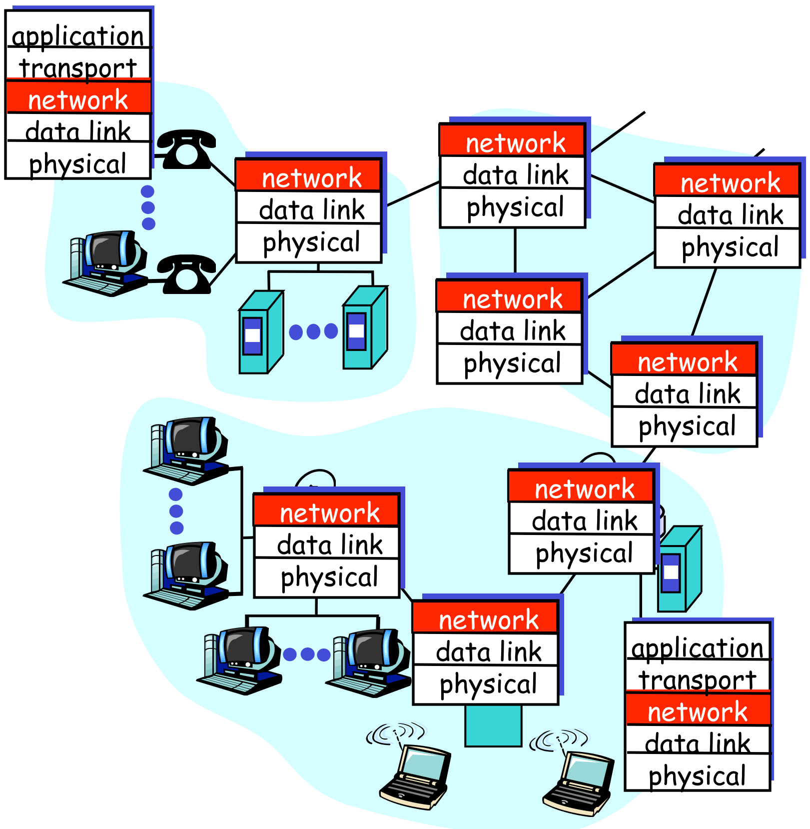
- network layer services
- routing principle: path selection
- IP
- Internet routing protocols reliable transfer
  - intra-domain
  - inter-domain
- what's inside a router?

Network layer functions

- transport packet from sending to receiving hosts
- network layer protocols in *every* host, router

three important functions:

- *path determination:* route taken by packets from source to dest. *Routing algorithms*
- *switching:* move packets from router's input to appropriate router output
- *call setup:* some network architectures require router call setup along path before data flows



Network service model

Q: What *service model* for "channel" transporting packets from sender to receiver?

service abstraction

- guaranteed bandwidth?
- preservation of inter-packet timing (no jitter)?
- loss-free delivery?
- in-order delivery?
- congestion feedback to sender?

The most important abstraction provided by network layer:

virtual circuit
or
datagram?

Virtual circuits

"source-to-dest path behaves much like telephone circuit"

- performance-wise
- network actions along source-to-dest path

- call setup, teardown for each call *before* data can flow
- each packet carries VC identifier (not destination host OD)
- *every* router on source-dest path s maintain "state" for each passing connection
  - transport-layer connection only involved two end systems
- link, router resources (bandwidth, buffers) may be *allocated* to VC
  - to get circuit-like perf.

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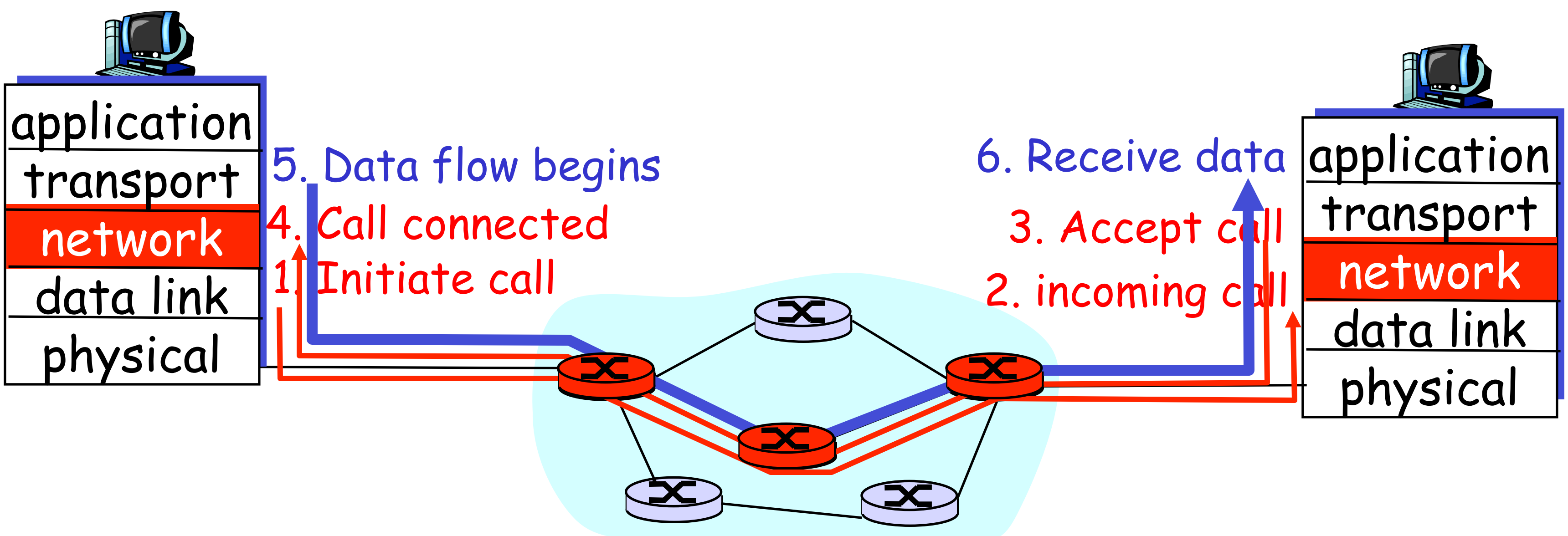
Virtual circuits: signaling protocols

- used to setup, maintain teardown VC
- used in ATM, frame-relay, X.25
- not used in today's Internet



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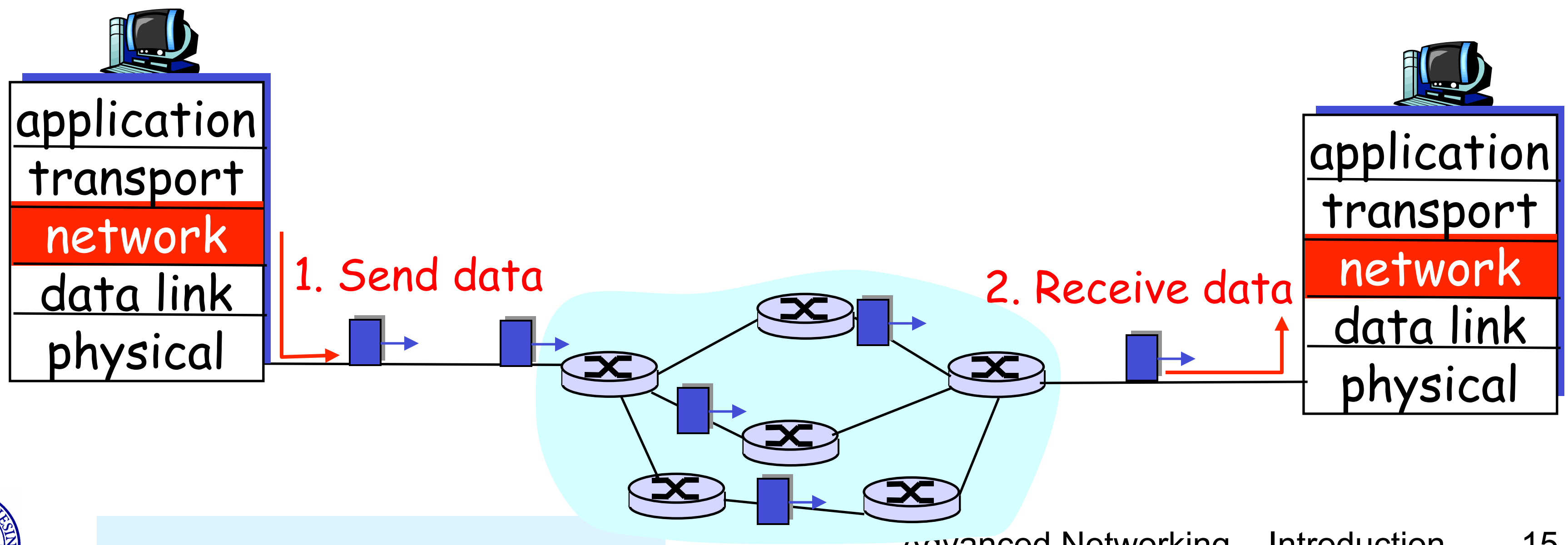
Datagram networks: the Internet model

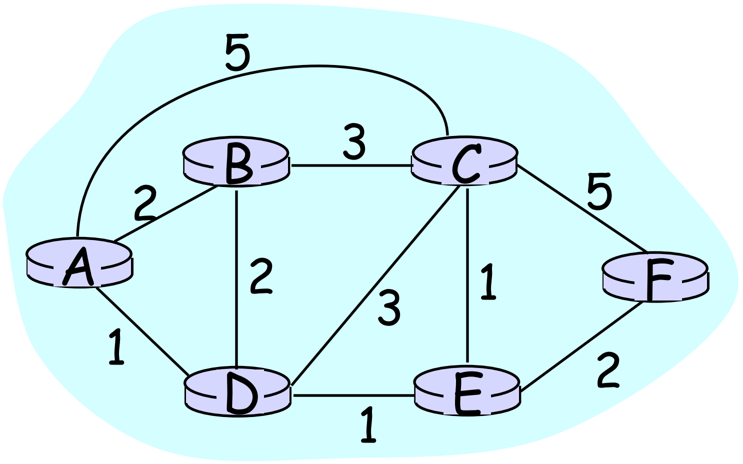
- no call setup at network layer
- routers: no state about end-to-end connections
  - no network-level concept of "connection"
- packets typically routed using destination host ID
  - packets between same source-dest pair may take different paths



Routing

Routing protocol

Goal: determine "good" path (sequence of routers) thru network from source to dest.



Graph abstraction for routing algorithms:

- graph nodes are routers
- graph edges are physical links
  - link cost: delay, $ cost, or congestion level

- "good" path:
  - typically means minimum cost path
  - other def's possible

Routing Algorithm classification

Global or decentralized information?

Global:

- all routers have complete topology, link cost info
- "link state" algorithms

Decentralized:

- router knows physically-connected neighbors, link costs to neighbors
- iterative process of computation, exchange of info with neighbors
- "distance vector" algorithms

Static or dynamic?

Static:

- routes change slowly over time

Dynamic:

- routes change more quickly
  - periodic update
  - in response to link cost changes

A Link-State Routing Algorithm

Dijkstra's algorithm

- net topology, link costs known to all nodes
  - accomplished via "link state broadcast"
  - all nodes have same info
- computes least cost paths from one node ('source") to all other nodes
  - gives routing table for that node
- iterative: after k iterations, know least cost path to k dest.'s

Notation:

- c(i,j): link cost from node i to j. cost infinite if not direct neighbors
- D(v): current value of cost of path from source to dest. V
- p(v): predecessor node along path from source to v, that is next v
- N: set of nodes whose least cost path definitively known

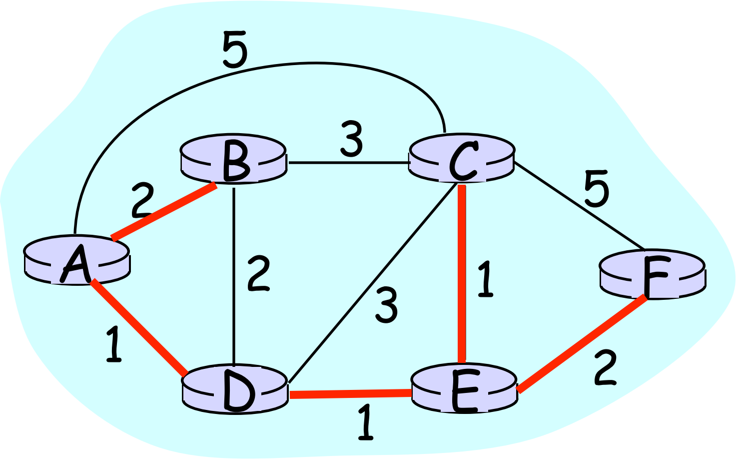
Dijsktra's Algorithm

```
Initialization:
  N = {A}
  for all nodes v
    if v adjacent to A
      then D(v) = c(A,v)
      else D(v) = infty

 Loop
   find w not in N such that D(w) is a minimum
   add w to N
   update D(v) for all v adjacent to w and not in N:
      D(v) = min( D(v), D(w) + c(w,v) )
   /* new cost to v is either old cost to v or known
    shortest path cost to w plus cost from w to v */
 until all nodes in N
```

Dijkstra's algorithm: example

Step	start N	D(B),p(B)	D(C),p(C)	D(D),p(D)	D(E),p(E)	D(F),p(F)
0	A	2,A	5,A	1,A	infinity	infinity
1	AD	2,A	4,D		2,D	infinity
2	ADE	2,A	3,E			4,E
3	ADEB		3,E			4,E
4	ADEBC					4,E
5	ADEBCF					



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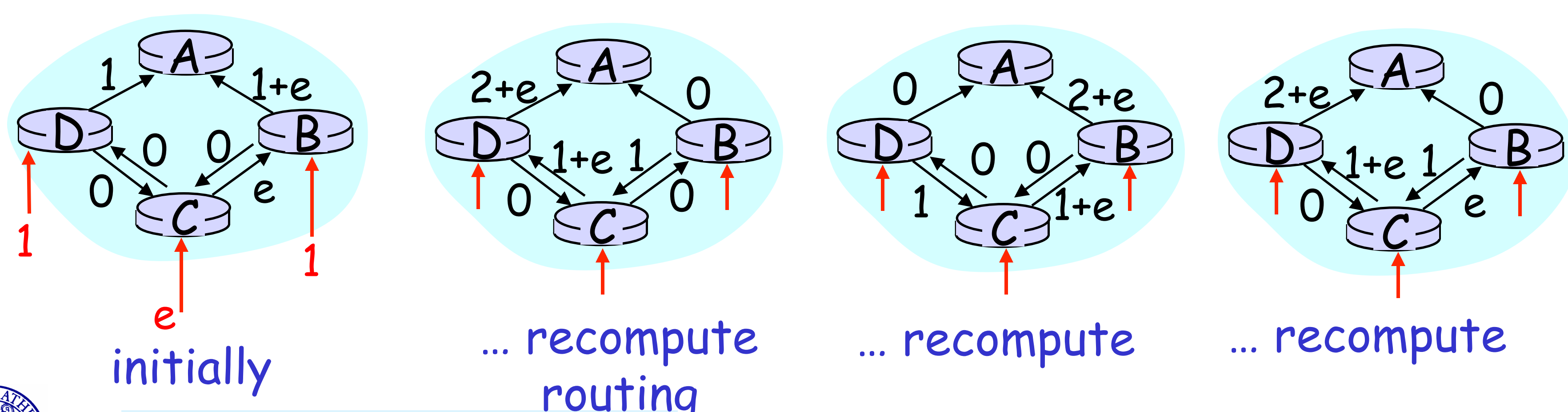
Dijkstra's algorithm, discussion

Algorithm complexity: n nodes

- each iteration: need to check all nodes, w, not in N
- n*(n+1)/2 comparisons: O(n**2)
- more efficient implementations possible: O(nlogn)

Oscillations possible:

- e.g., link cost = amount of carried traffic



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Distance Vector Routing Algorithm

iterative:

- continues until no nodes exchange info.
- *self-terminating*: no "signal" to stop

asynchronous:

- nodes need *not* exchange info/iterate in lock step!

distributed:

- each node communicates *only* with directly-attached neighbors

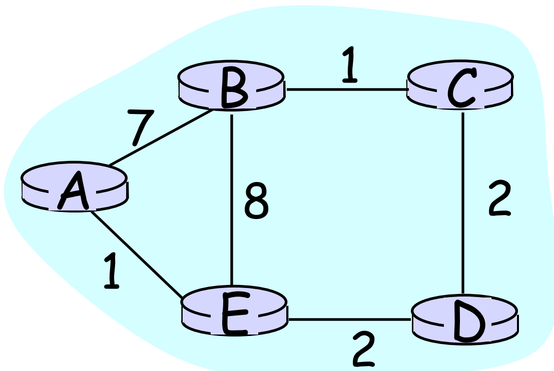
Distance Table data structure

- each node has its own
- row for each possible destination
- column for each directly-attached neighbor to node
- example: in node X, for dest. Y via neighbor Z:

$D^X(Y,Z)$ = distance *from* X *to* Y, *via* Z as next hop

$$= c(X,Z) + \min_w \{D^Z(Y,w)\}$$

Distance Table: example



$$D^E(C,D) = c(E,D) + \min_w \{D^D(C,w)\} = 2+2 = 4$$

$$D^E(A,D) = c(E,D) + \min_w \{D^D(A,w)\} = 2+3 = 5$$

loop!

$$D^E(A,B) = c(E,B) + \min_w \{D^B(A,w)\} = 8+6 = 14$$

loop!

cost to destination via

$D^E()$ (destination)	A	B	D
A	1	14	5
B	7	8	5
C	6	9	4
D	4	11	2

Distance table gives routing table

cost to destination via

$D^E()$ (destination)	A	B	D
A	1	14	5
B	7	8	5
C	6	9	4
D	4	11	2

destination	Outgoing link to use, cost
A	A,1
B	D,5
C	D,4
D	D,4

Distance table → Routing table

Distance Vector Routing: overview

Iterative, asynchronous:

each local iteration caused by:

- local link cost change
- message from neighbor: its least cost path change from neighbor

Distributed:

- each node notifies neighbors *only* when its least cost path to any destination changes
  - neighbors then notify their neighbors if necessary

Each node:

wait for (change in local link cost of msg from neighbor)

↓

recompute distance table

↓

if least cost path to any dest has changed, *notify* neighbors

Distance Vector Algorithm:

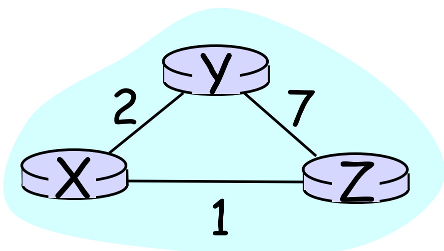
At all nodes, X:

Initialization:
 for all adjacent nodes v:
   $D^X(*,v)$ = infty   /* the * operator means "for all rows" */
   $D^X(v,v) = c(X,v)$
 for all destinations, y
   send $\min_w D^X(y,w)$ to each neighbor /* w over all X's neighbors */

Distance Vector Algorithm (cont.):

```
loop
  wait (until I see a link cost change to neighbor V
        or until I receive update from neighbor V)

   if (c(X,V) changes by d)
     /* change cost to all dest's via neighbor v by d */
     /* note: d could be positive or negative */
     for all destinations y:  D^X(y,V) =  D^X(y,V) + d

   else if (update received from V wrt destination Y)
     /* shortest path from V to some Y has changed  */
     /* V has sent a new value for its  min_w  DV(Y,w) */
     /* call this received new value is "newval"     */
     for the single destination y: D^X(Y,V) = c(X,V) + newval

   if we have a new min_w  D^X(Y,w) for any destination Y
      send new value of min_w D^X(Y,w) to all neighbors

 forever
```

Distance Vector Algorithm: example



D^X (dest)	cost via Y	cost via Z
Y	2	∞
Z	∞	7

D^Y (dest)	cost via X	cost via Z
X	2	∞
Z	∞	1

D^Z (dest)	cost via X	cost via Y
X	7	∞
Y	∞	1

D^X (dest)	cost via Y	cost via Z
Y	2	8
Z	3	7

D^Y (dest)	cost via X	cost via Z
X	2	8
Z	9	1

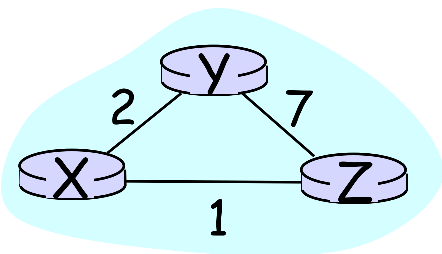
D^Z (dest)	cost via X	cost via Y
X	7	3
Y	9	1

D^X (dest)	cost via Y	cost via Z
Y		
Z		

D^Y (dest)	cost via X	cost via Z
X		
Z		

D^Z (dest)	cost via X	cost via Y
X		
Y		

Distance Vector Algorithm: example



D^X (cost via)

dest	Y	Z
Y	2	∞
Z	∞	7

D^Y (cost via)

dest	X	Z
X	2	∞
Z	∞	1

D^Z (cost via)

dest	X	Y
X	7	∞
Y	∞	1

D^X (cost via)

dest	Y	Z
Y	2	8
Z	3	7

$$D^X(Y,Z) = c(X,Z) + \min_w\{D^Z(Y,w)\}$$
$$= 7+1 = 8$$

$$D^X(Z,Y) = c(X,Y) + \min_w\{D^Y(Z,w)\}$$
$$= 2+1 = 3$$

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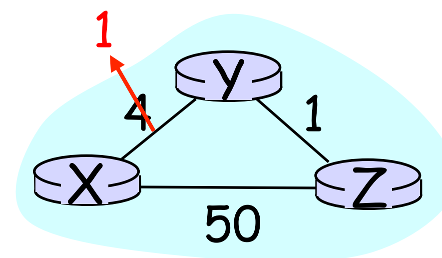
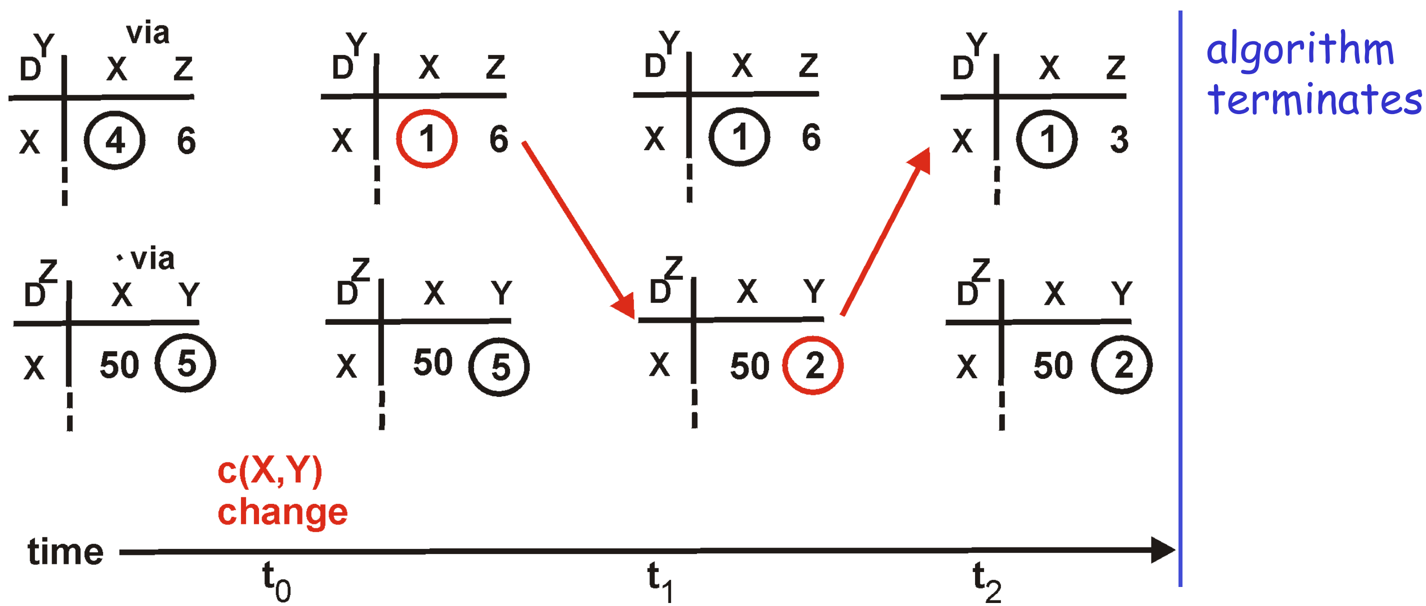
Distance Vector: link cost changes

Link cost changes:

- node detects local link cost change
- updates distance table (line 15)
- if cost change in least cost path, notify neighbors (lines 23,24)



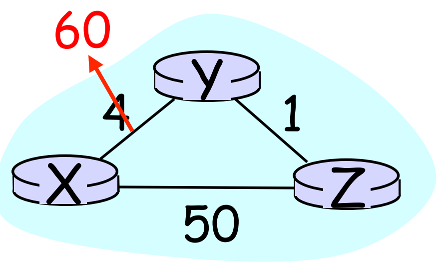
"good news travels fast"

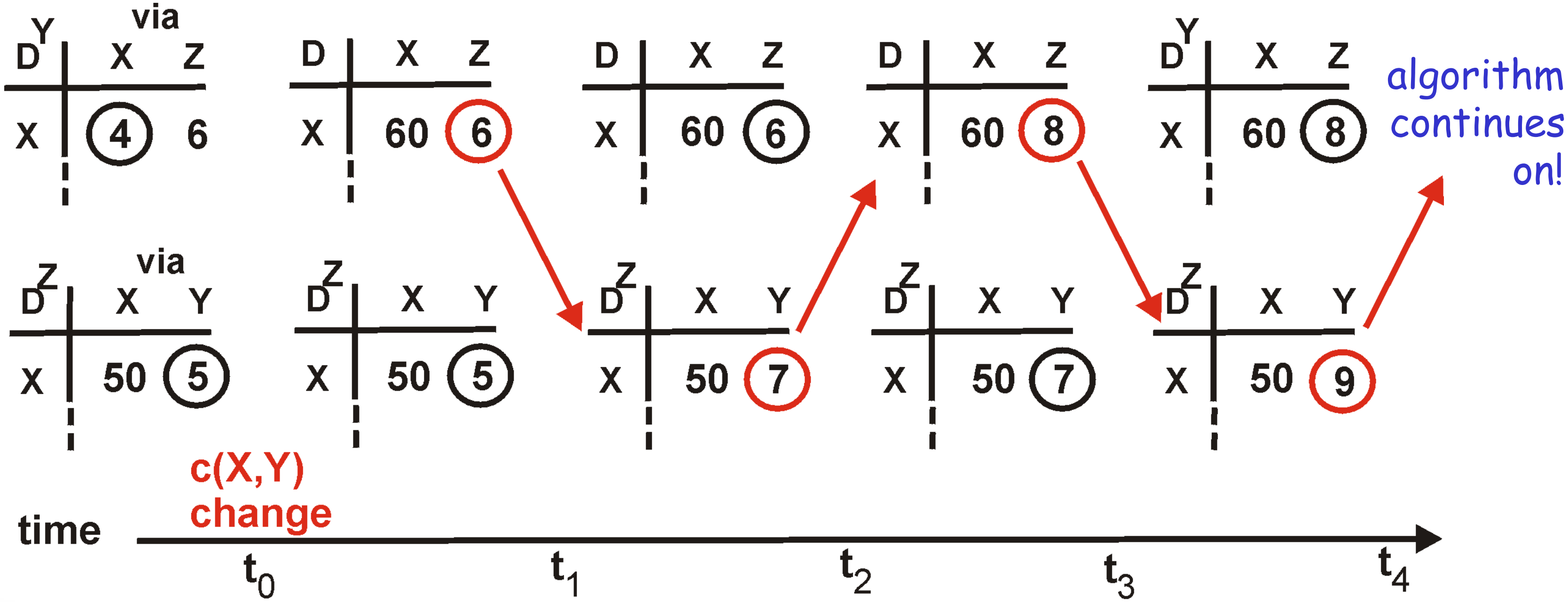


Distance Vector: link cost changes

Link cost changes:

- good news travels fast
- bad news travels slow - "count to infinity" problem!





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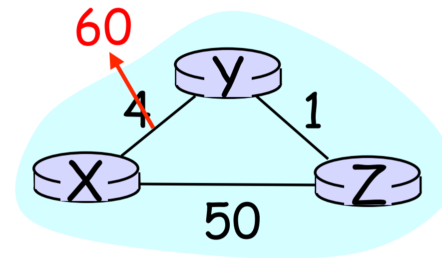
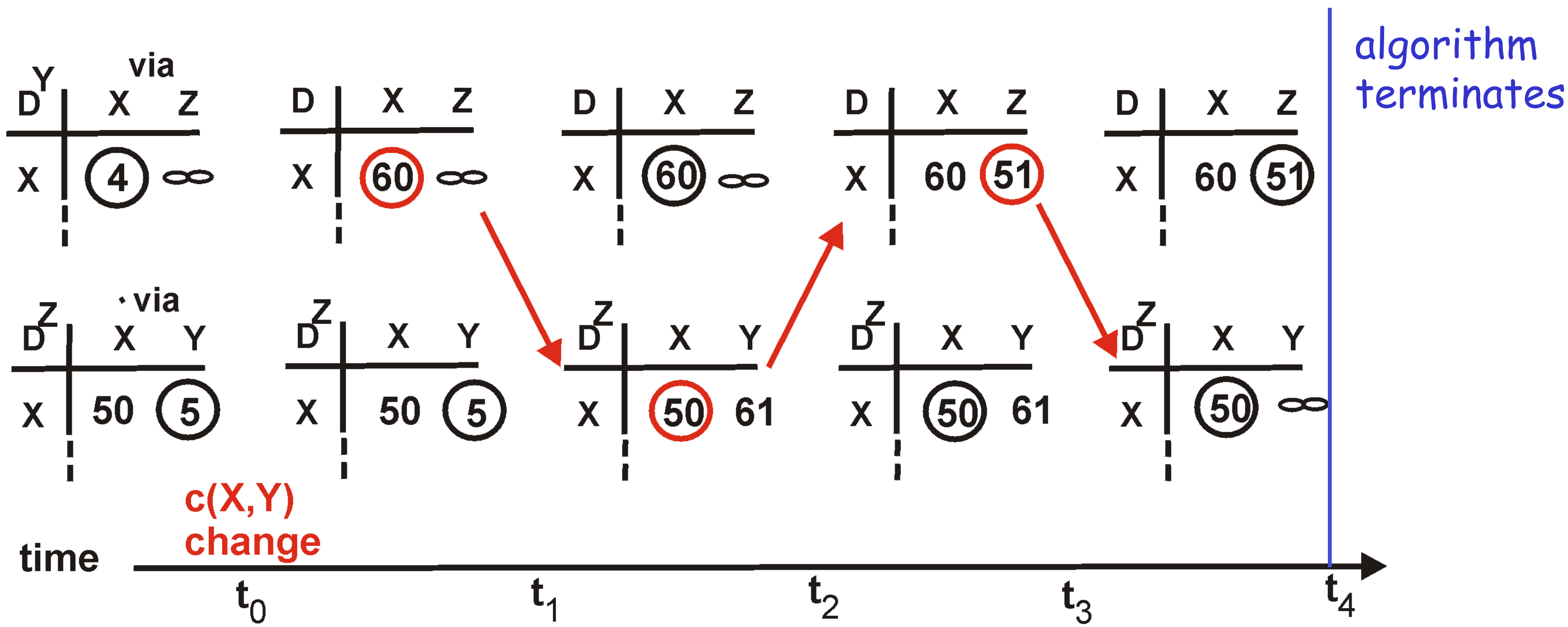
Distance Vector: poisoned reverse

If Z routes through Y to get to X :

- Z tells Y its (Z' s) distance to X is infinite (so Y won' t route to X via Z)
- will this completely solve count to infinity problem?





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Comparison of LS and DV algorithms

Message complexity

- LS: with n nodes, E links, O(nE) msgs sent each
- DV: exchange between neighbors only
  - convergence time varies

Speed of Convergence

- LS: O(n**2) algorithm requires O(nE) msgs
  - may have oscillations
- DV: convergence time varies
  - may be routing loops
  - count-to-infinity problem

Robustness: what happens if router malfunctions?

LS:

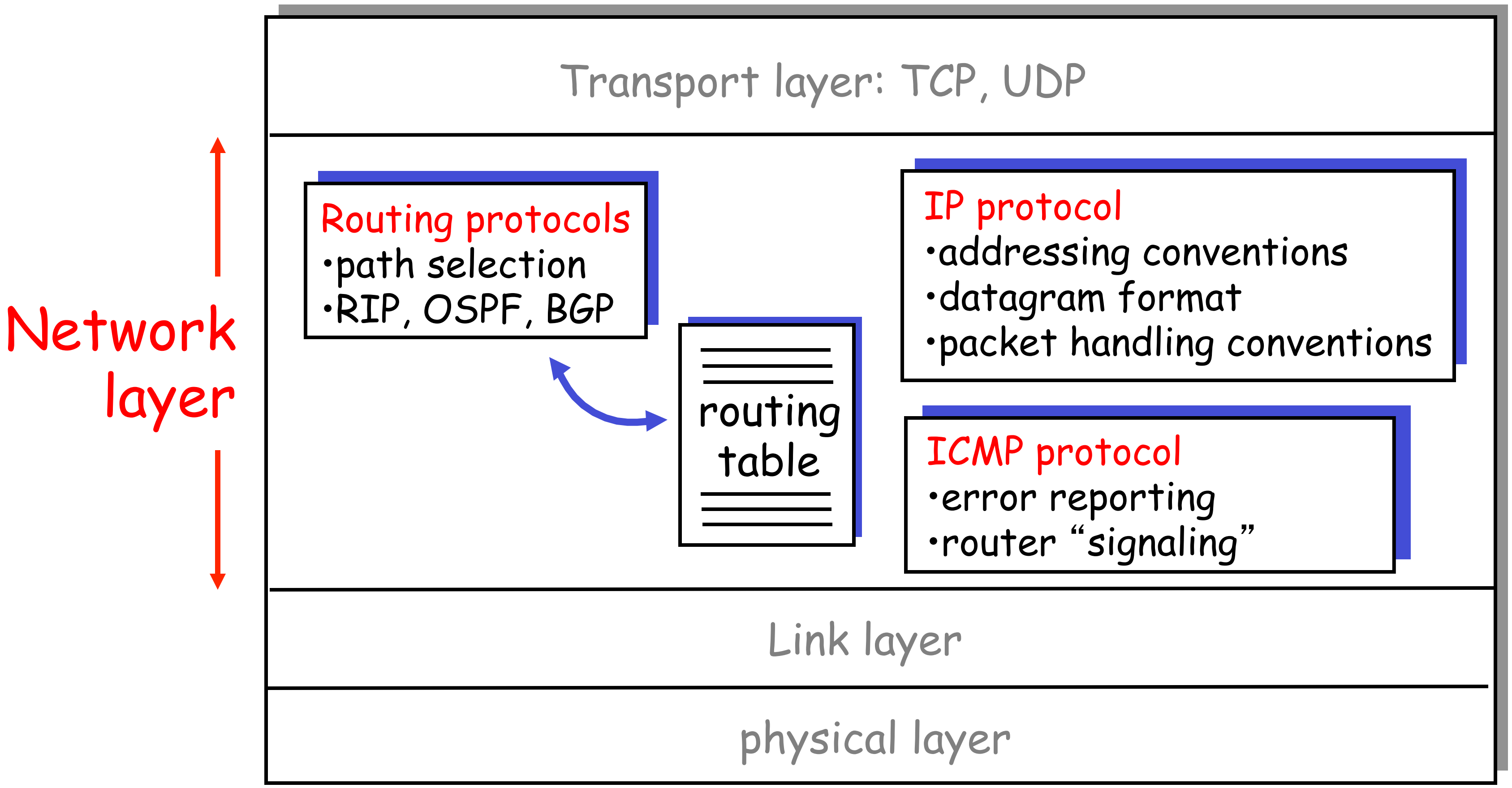
- node can advertise incorrect *link* cost
- each node computes only its *own* table

DV:

- DV node can advertise incorrect *path* cost
- each node's table used by others
  - error propagate thru network

The Internet Network layer

Host, router network layer functions:



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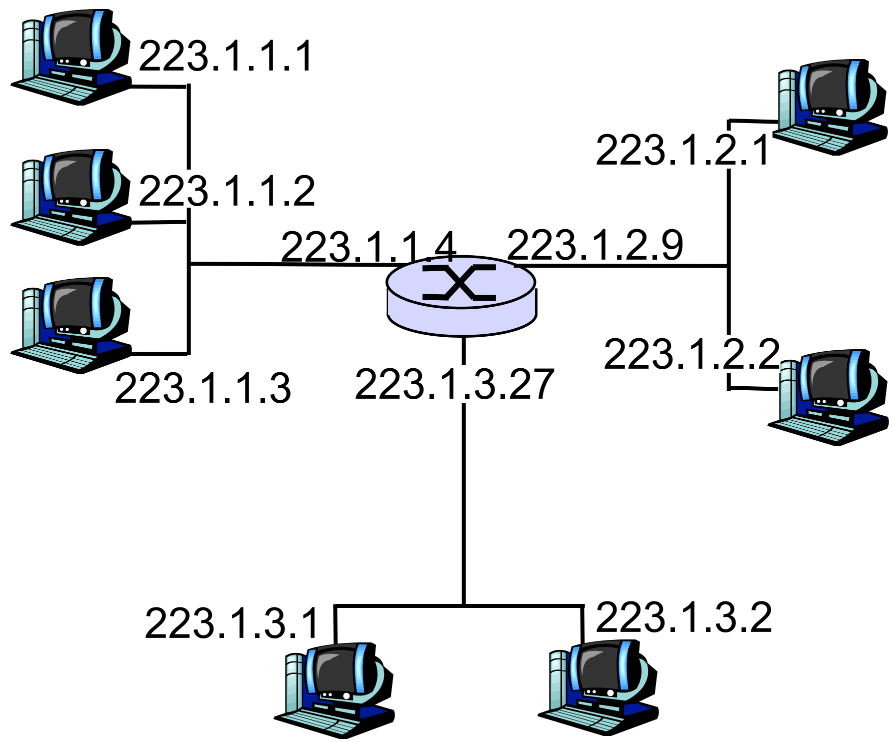
Why different Intra- and Inter-AS routing ?

- **Policy**: Inter is concerned with policies (which provider we must select/avoid, etc). Intra is contained in a single organization, so, no policy decisions necessary
- **Scale**: Inter provides an extra level of routing table size and routing update traffic reduction above the Intra layer
- **Performance**: Intra is focused on performance metrics; needs to keep costs low. In Inter it is difficult to propagate performance metrics efficiently (latency, privacy etc). Besides, policy related information is more meaningful.

We need **BOTH**!

IP Addressing

- IP address: 32-bit identifier for host, router *interface*
- *interface:* connection between host, router and physical link
  - router's typically have multiple interfaces
  - host may have multiple interfaces
  - IP addresses associated with interface, not host, router, …
- Address mng & resolution + DNS must be known well we do not repeat it

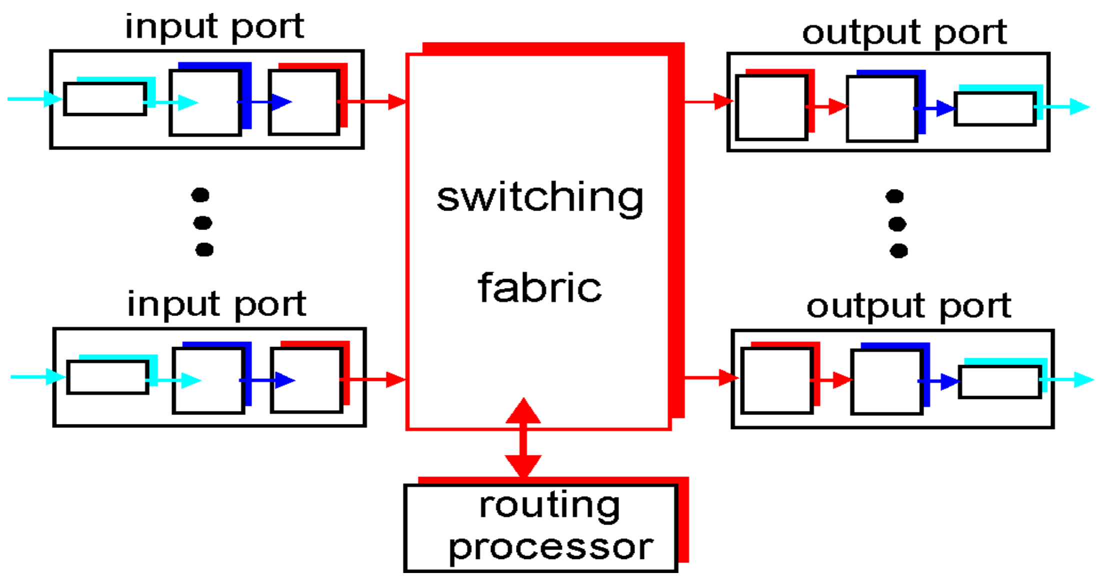


223.1.1.1 = 11011111 00000001 00000001 00000001

223 1 1 1

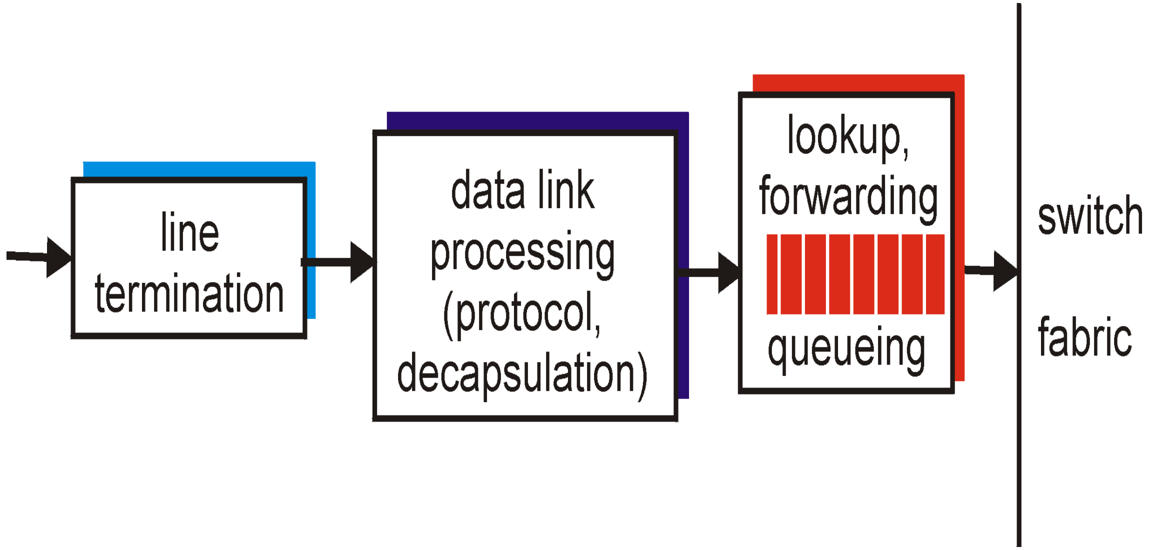
Router Architecture Overview

- Router main functions: *routing* algorithms and protocols processing, *switching* datagrams from an incoming link to an outgoing link



Router Components

Input Ports

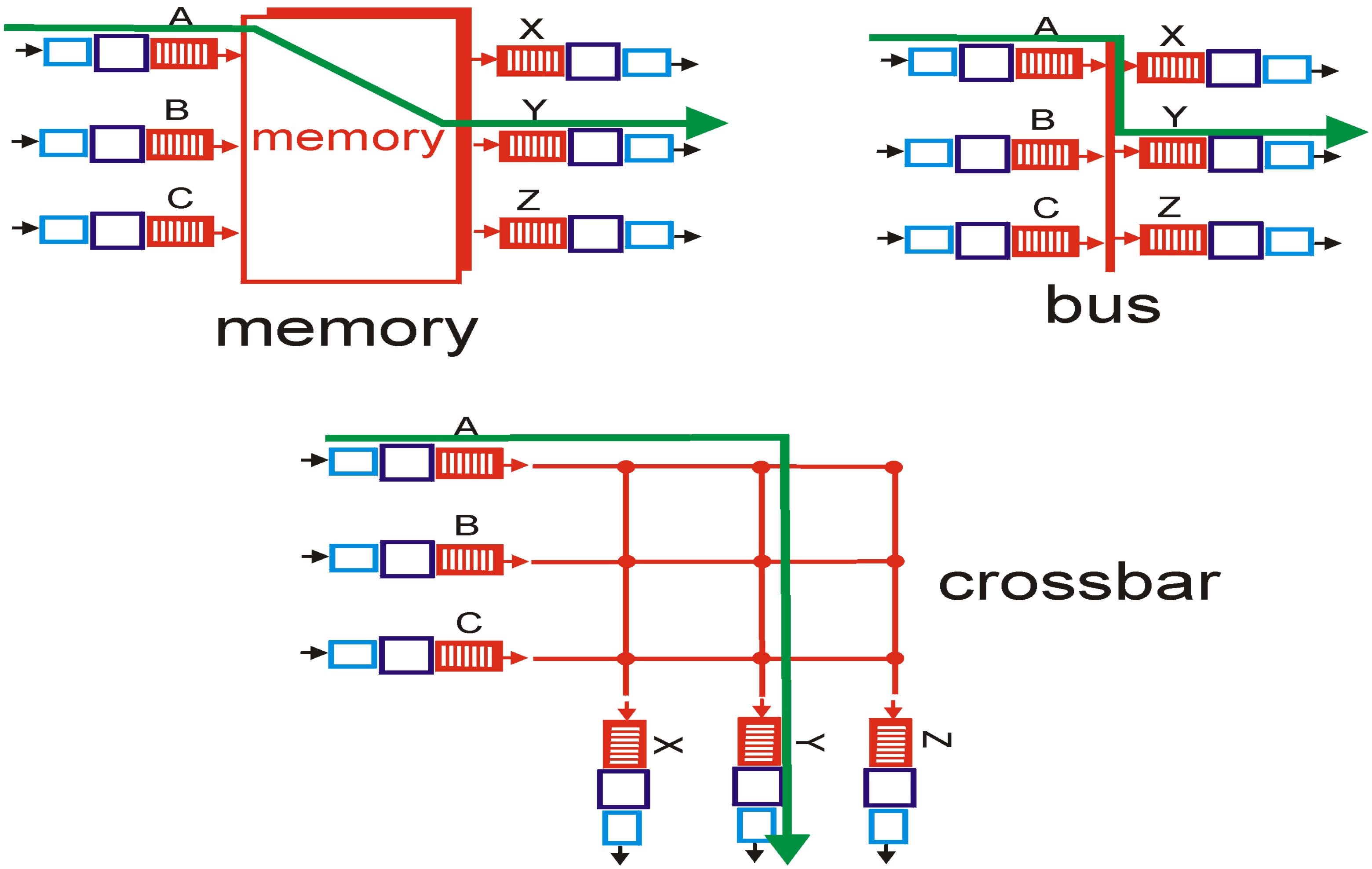


- **Decentralized switching**: perform routing table lookup using a copy of the node routing table stored in the port memory
- Goal is to complete input port processing at 'line speed', ie processing time =< frame reception time (eg, with 2.5 Gbps line, 256 bytes long frame, router must perform about 1 million routing table lookups in a second)
- Queuing occurs if datagrams arrive at rate higher than can be forwarded on switching fabric

Speeding Up Routing Table Lookup

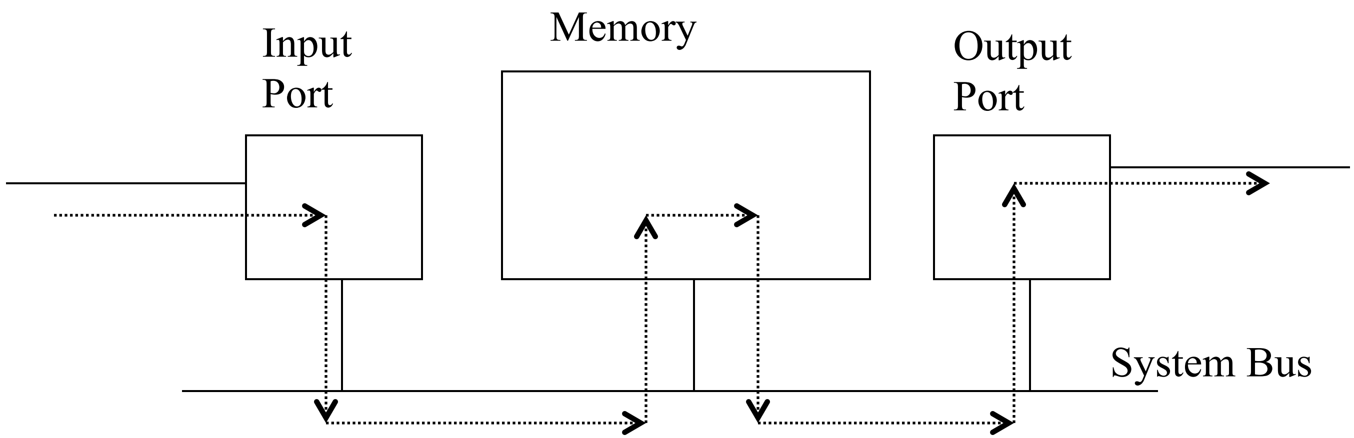
- Table is stored in a tree structure to facilitate binary search
- Content Addressable Memory (associative memory), eg Cisco 8500 series routers
- Caching of recently looked-up addresses
- Compression of routing tables

Switching Fabric



Switching Via Memory

- *First generation routers*: packet is copied under system's (single) CPU control; speed limited by Memory bandwidth. For Memory speed of B packet/sec or pps, throughput is B/2 pps



- *Modern routers*: input ports with CPUs that implement output port lookup, and store packets in appropriate locations (= switch) in a shared Memory; eg Cisco Catalyst 8500 switches

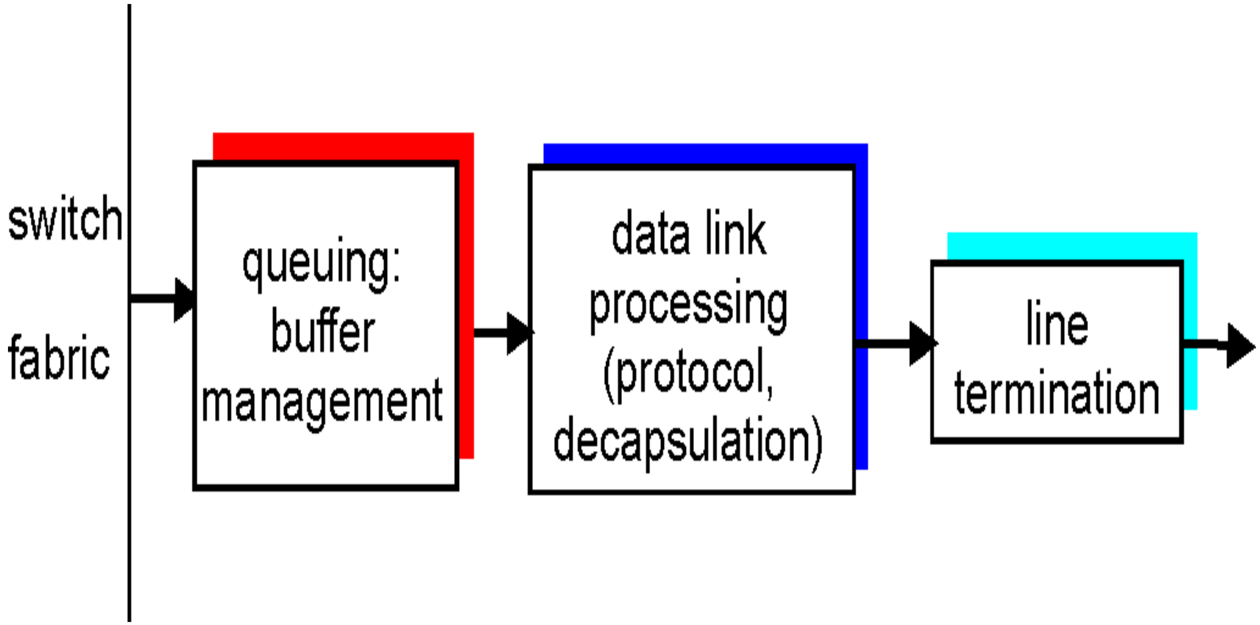
Switching Via Bus

- Input port processors transfer a datagram from input port memory to output port memory via a shared bus
- Main resource contention is over the bus; switching is limited by bus speed
- Sufficient speed for access and enterprise routers (not regional or backbone routers) is provided by a Gbps bus; eg Cisco 1900 which has a 1 Gbps bus

Switching Via An Interconnection Network

- Used to overcome bus bandwidth limitations
- Banyan networks and other interconnection networks were initially developed to connect processors in a multiprocessor computer system; used in Cisco 12000 switches provide up to 60 Gbps through the interconnection network
- Advanced design incorporates fragmenting a datagram into fixed length cells and switch the cells through the fabric; + better sharing of the switching fabric resulting in higher switching speed

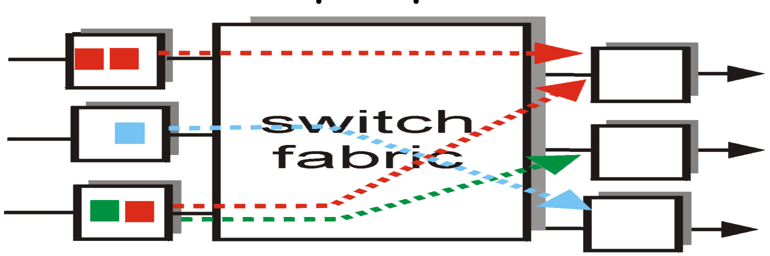
Output Ports



Buffering is required to hold datagrams whenever they arrive from the switching fabric at a rate faster than the transmission rate

Queuing At Input and Output Ports

- Queues build up whenever there is a rate mismatch or blocking. Consider the following scenarios:
  - Fabric speed is faster than all input ports combined; more datagrams are destined to an output port than other output ports; queuing occurs at output port
  - Fabric bandwidth is not as fast as all input ports combined; queuing may occur at input queues;
  - HOL blocking: fabric can deliver datagrams from input ports in parallel, except if datagrams are destined to same output port; in this case datagrams are queued at input queues; there may be queued datagrams that are held behind HOL conflict, even when their output port is available



output port contention at time t - only one red packet can be transferred

green packet experiences HOL blocking

Transport Layer: UDP & TCP

Goals:

- Recall principles behind transport layer services:
  - multiplexing/ demultiplexing
  - reliable data transfer
  - flow control
  - congestion control
- instantiation and implementation in the Internet

Overview:

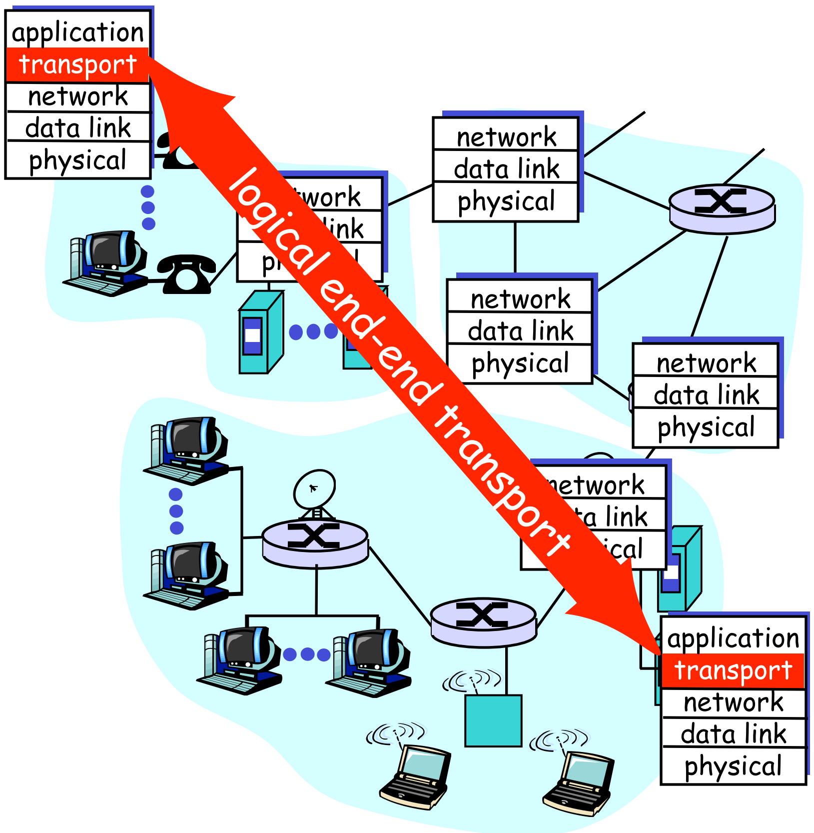
- transport layer services
- multiplexing/demultiplexing
- connectionless transport: UDP
- principles of reliable data transfer
- connection-oriented transport: TCP
  - reliable transfer
  - flow control
  - connection management

Transport services and protocols

- provide *logical communication* between app' processes running on different hosts
- transport protocols run in end systems (primarily)

transport vs network layer services:

- *network layer:* data transfer between end systems
- *transport layer:* data transfer between processes
  - relies on, enhances, network layer services



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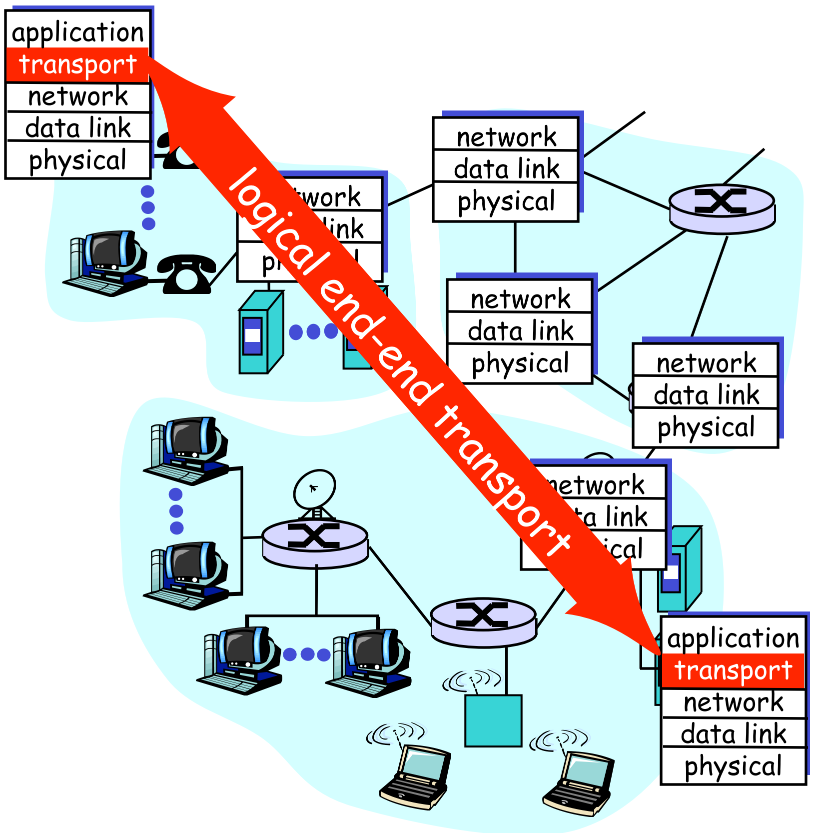
Transport-layer protocols

Internet transport services:

- reliable, in-order unicast delivery (TCP)
  - congestion
  - flow control
  - connection setup
- unreliable ("best-effort"), unordered unicast or multicast delivery: UDP
- services not available:
  - real-time
  - bandwidth guarantees
  - reliable multicast

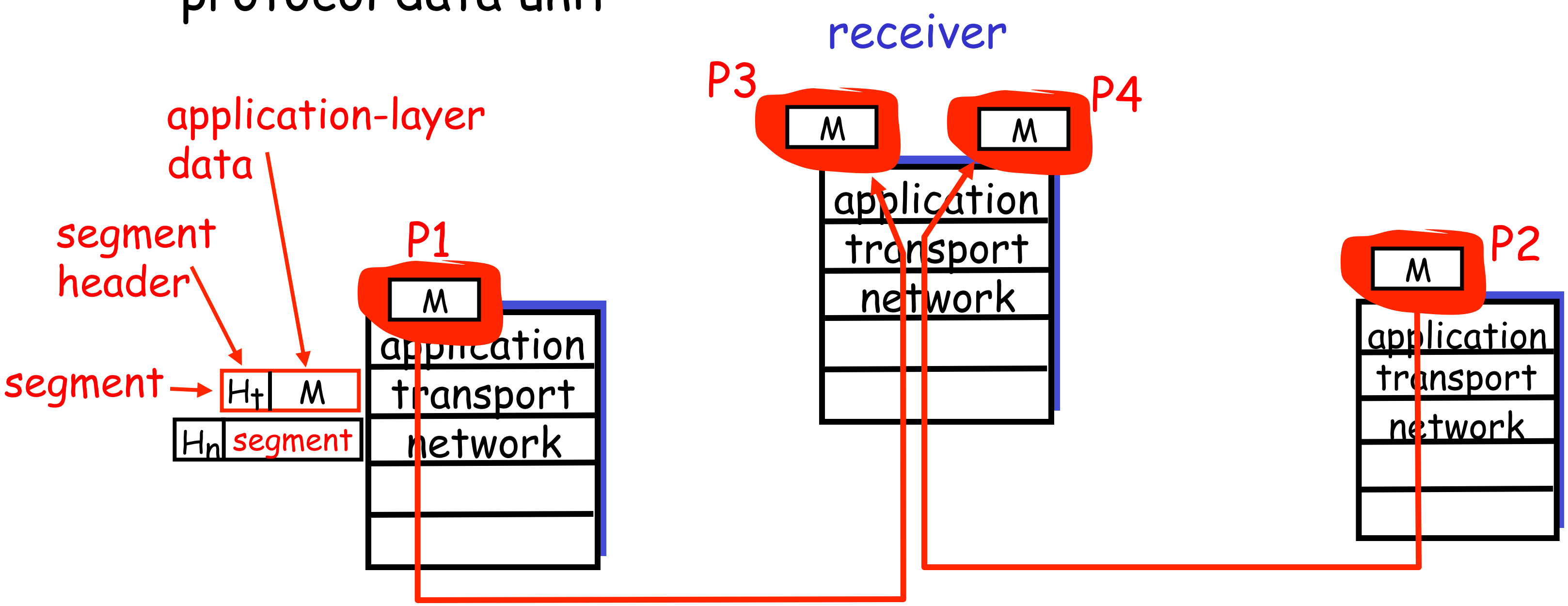


Multiplexing/demultiplexing

Recall: *segment* - unit of data exchanged between transport layer entities

- aka TPDU: transport protocol data unit

Demultiplexing: delivering received segments (TPDUs)to correct app layer processes

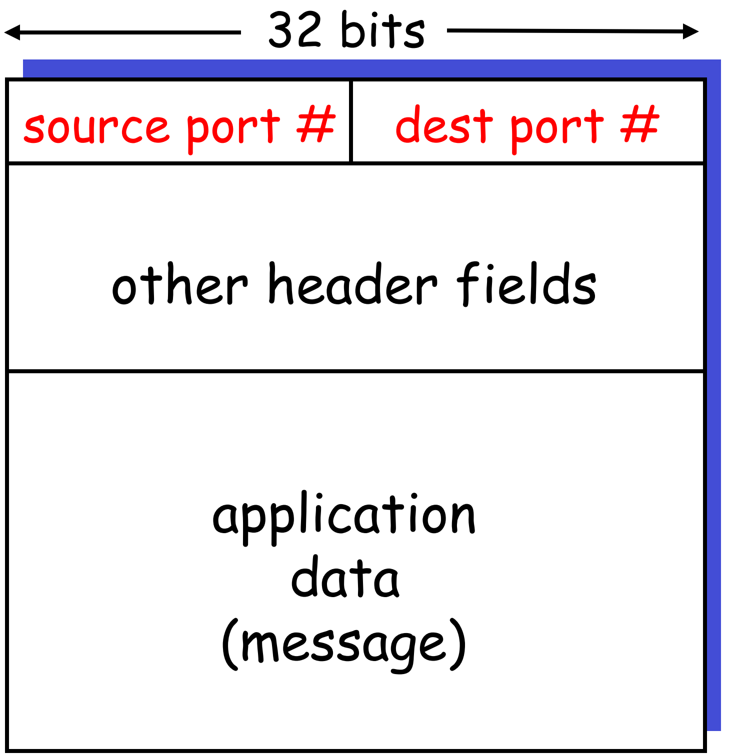


Multiplexing/demultiplexing

Multiplexing:
gathering data from multiple app processes, enveloping data with header (later used for demultiplexing)

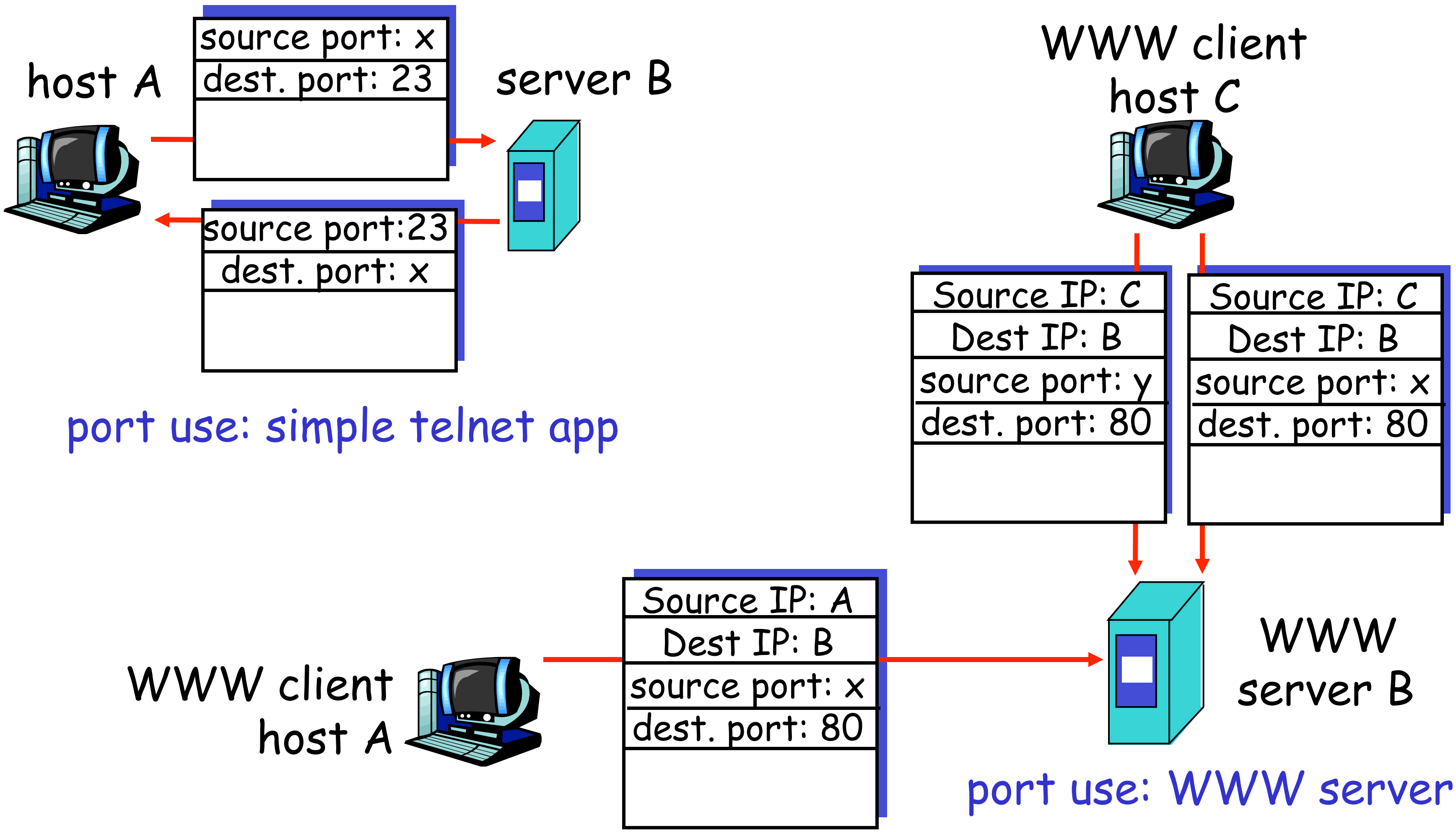
multiplexing/demultiplexing:

- based on sender, receiver port numbers, IP addresses
  - source, dest port #s in each segment
  - recall: well-known port numbers for specific applications



TCP/UDP segment format

Multiplexing/demultiplexing: examples



UDP: User Datagram Protocol [RFC 768]

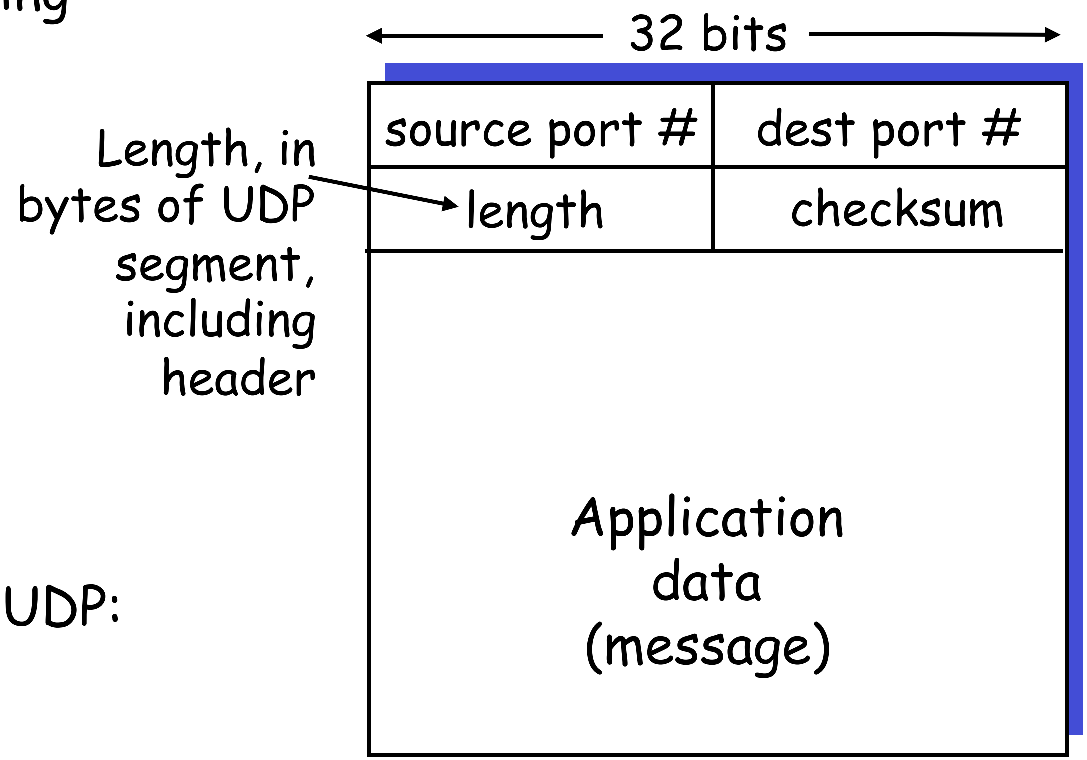
- "no frills," "bare bones" Internet transport protocol
- "best effort" service, UDP segments may be:
  - lost
  - delivered out of order to app
- *connectionless:*
  - no handshaking between UDP sender, receiver
  - each UDP segment handled independently of others

Why is there a UDP?

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

UDP: more

- often used for streaming multimedia apps
  - loss tolerant
  - rate sensitive
- other UDP uses (why?):
  - DNS
  - SNMP
- reliable transfer over UDP: add reliability at application layer
  - application-specific error recover!



UDP segment format

UDP checksum

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

Sender:

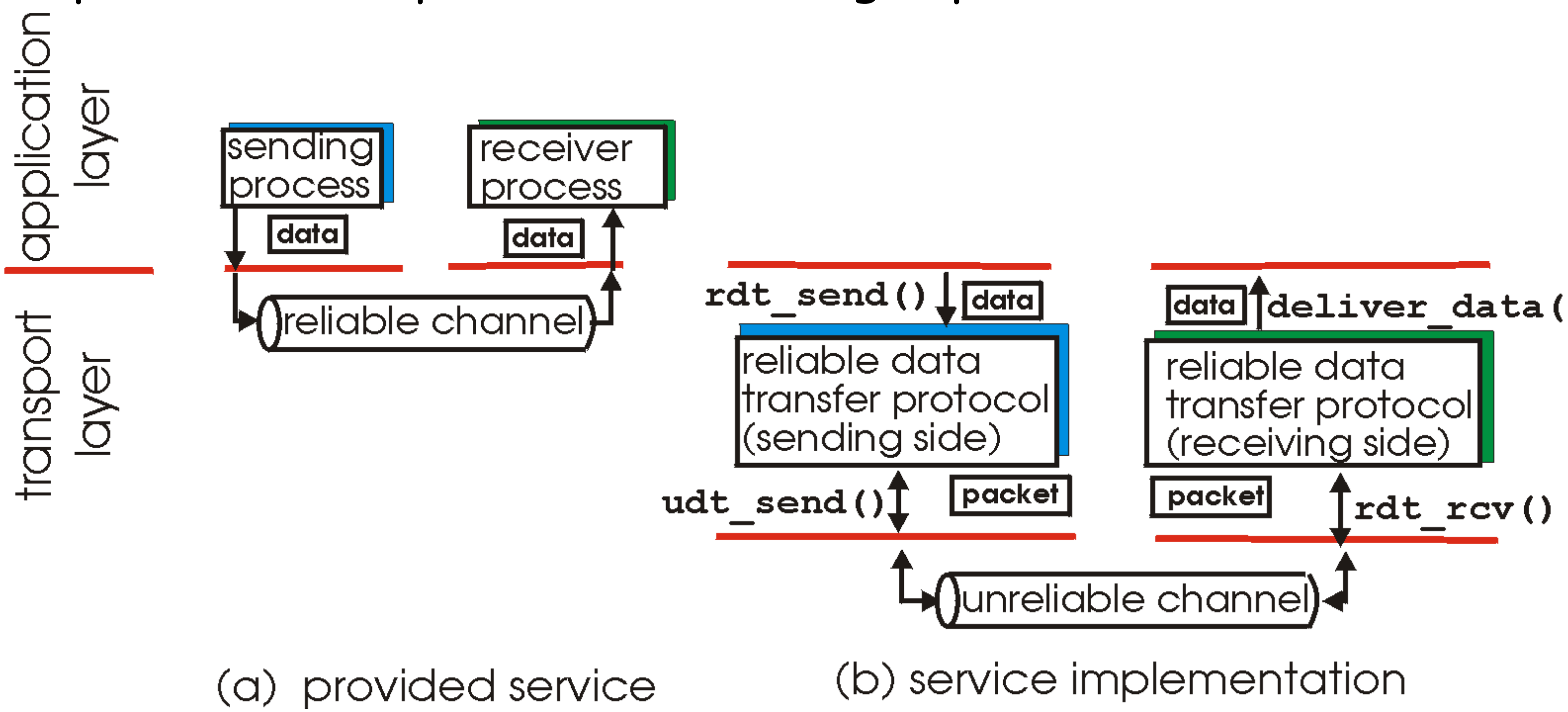
- treat segment contents as sequence of 16-bit integers
- checksum: addition (1's complement sum) of segment contents
- sender puts checksum value into UDP checksum field

Receiver:

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

Principles of Reliable data transfer

- important in app., transport, link layers
- top-10 list of important networking topics!



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

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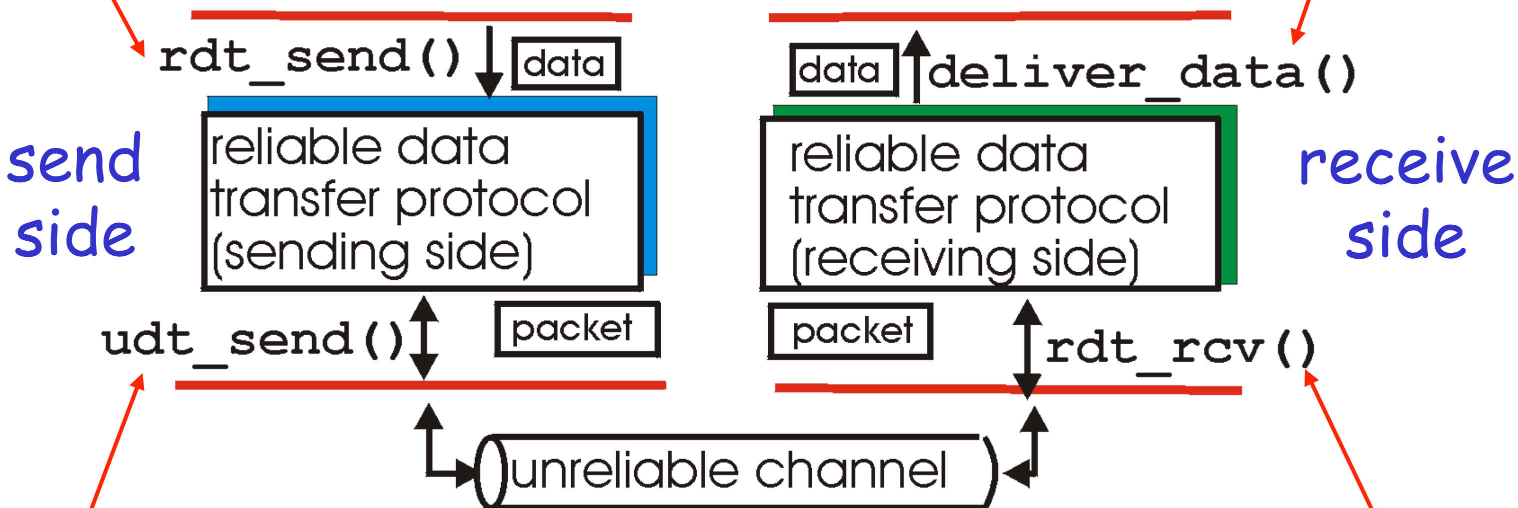
Reliable data transfer: getting started

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



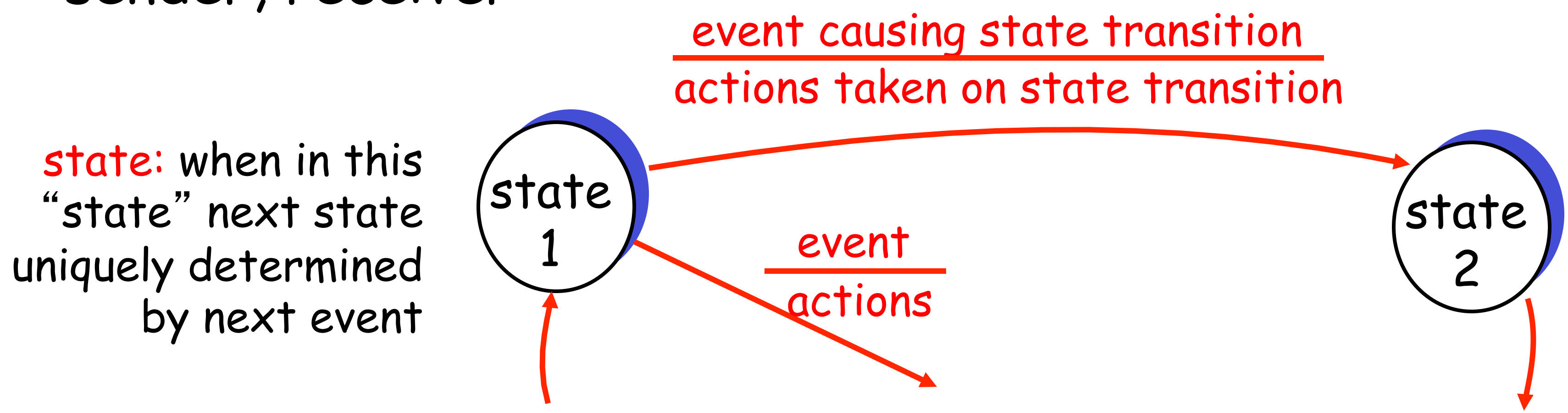
udt_send(): called by rdt, to transfer packet over unreliable channel to receiver

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



rdt: channels with errors *and* loss

Assumption: underlying channel can lose packets (data or ACKs)

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

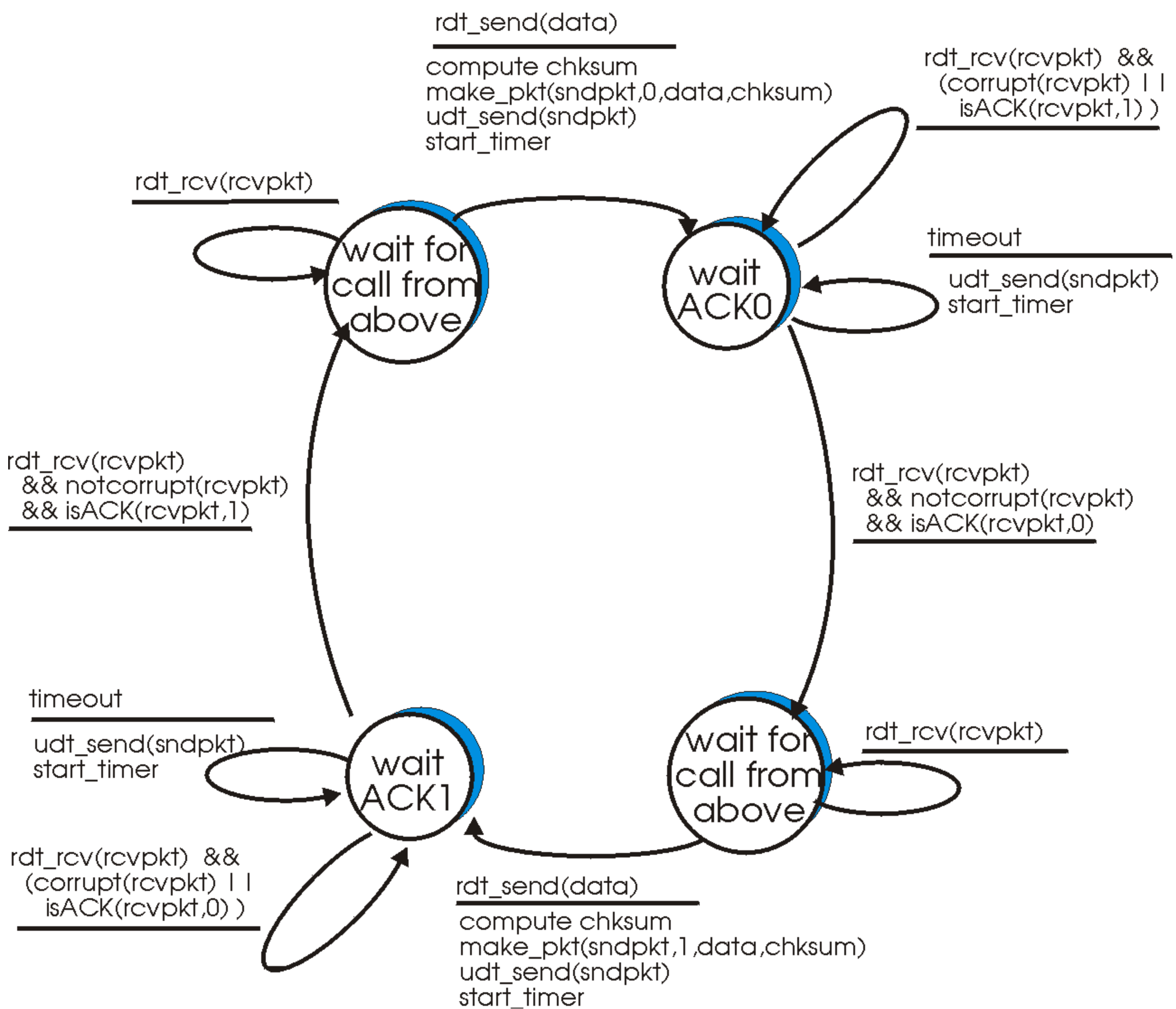
Q: how to deal with loss?

- sender waits until certain data or ACK lost, then retransmits
- yuck: drawbacks?

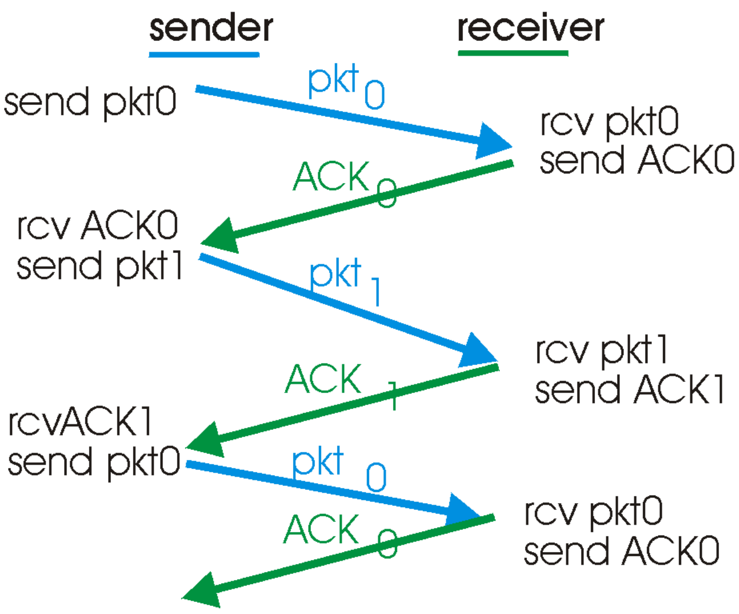
Approach: sender waits "reasonable" amount of time for ACK

- retransmits if no ACK received in this time
- if pkt (or ACK) just delayed (not lost):
  - retransmission will be duplicate, but use of seq. #'s already handles this
  - receiver must specify seq # of pkt being ACKed
- requires countdown timer

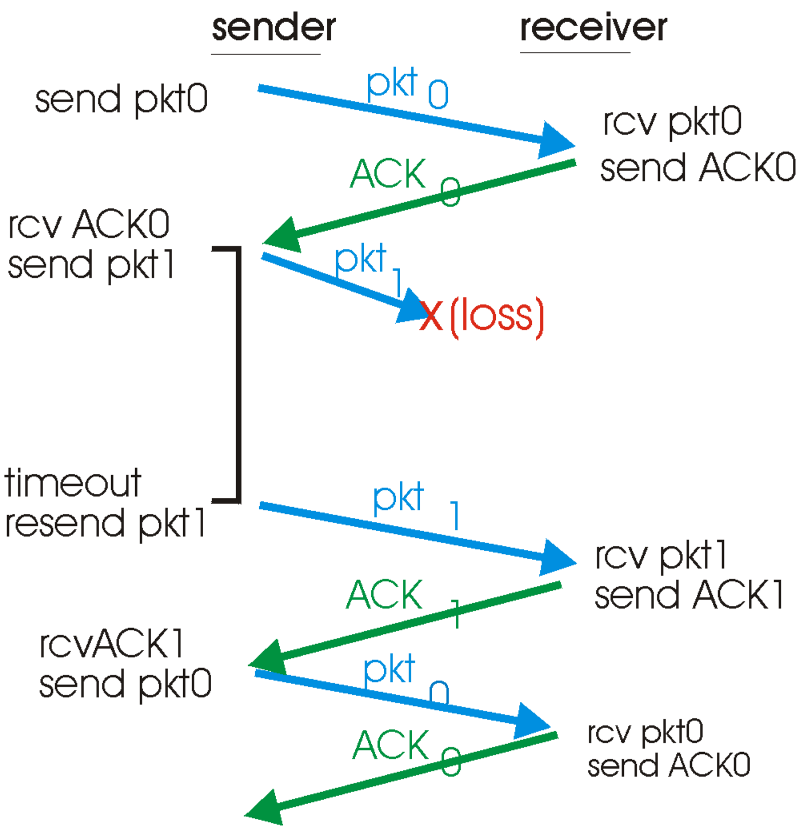
rdt: sender


rdt_send(data)
compute chksum
make_pkt(sndpkt,0,data,chksum)
udt_send(sndpkt)
start_timer
rdt_rcv(rcvpkt) && (corrupt(rcvpkt) | | isACK(rcvpkt,1))
rdt_rcv(rcvpkt)
wait for call from above
wait ACK0
timeout
udt_send(sndpkt)
start_timer
rdt_rcv(rcvpkt) && notcorrupt(rcvpkt) && isACK(rcvpkt,1)
rdt_rcv(rcvpkt) && notcorrupt(rcvpkt) && isACK(rcvpkt,0)
timeout
udt_send(sndpkt)
start_timer
wait ACK1
wait for call from above
rdt_rcv(rcvpkt)
rdt_rcv(rcvpkt) && (corrupt(rcvpkt) | | isACK(rcvpkt,0))
rdt_send(data)
compute chksum
make_pkt(sndpkt,1,data,chksum)
udt_send(sndpkt)
start_timer

rdt in action

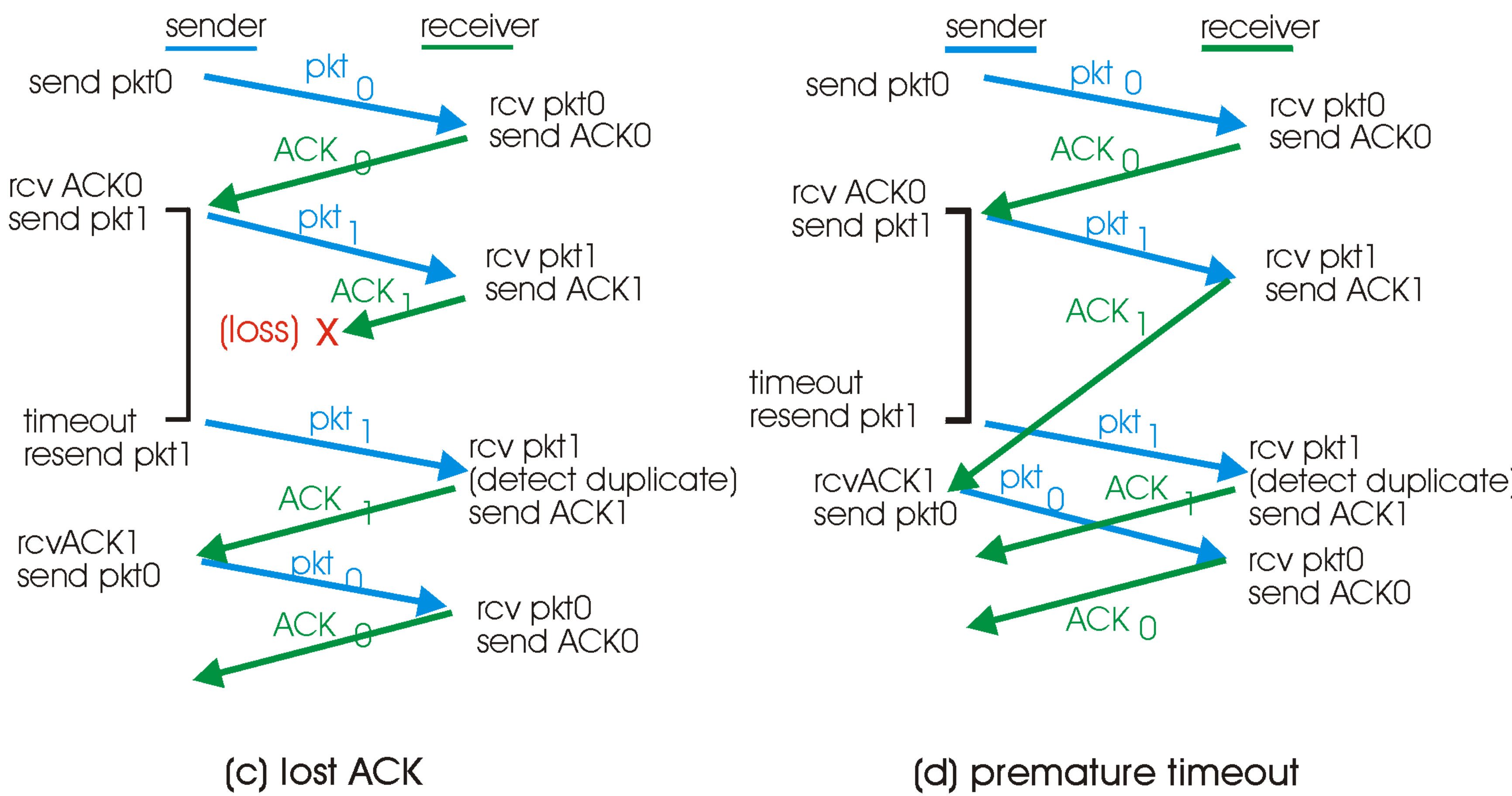


(a) operation with no loss



(b) lost packet

rdt in action



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Performance of rdt

- rdt works, but performance stinks
- example: 1 Gbps link, 15 ms e-e prop. delay, 1KB packet:

$$T_{transmit} = \frac{8kb/pkt}{10^{**}9 \ b/sec} = 8 \text{ microsec}$$

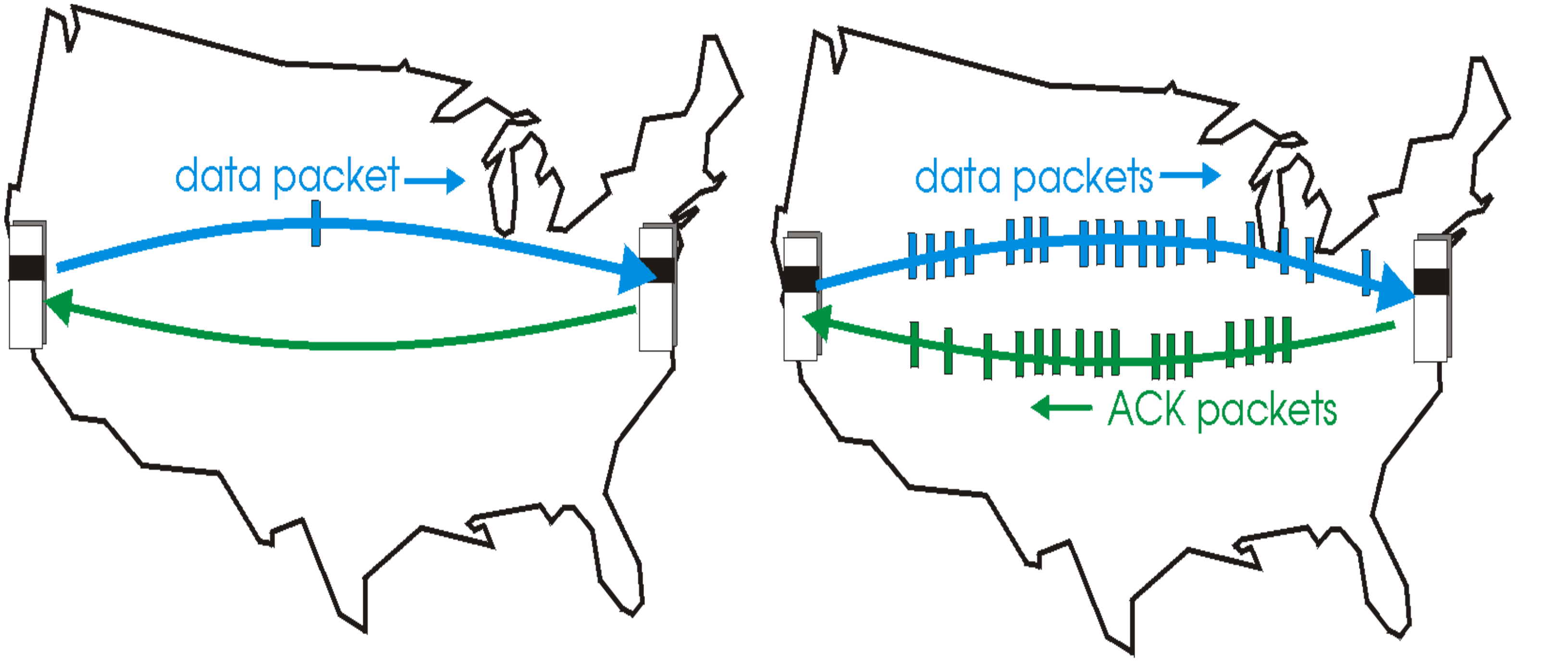
$$\text{Utilization} = U = \frac{\text{fraction of time}}{\text{sender busy sending}} = \frac{8 \text{ microsec}}{30.016 \text{ msec}} = 0.00015$$

- 1KB pkt every 30 msec -> 33kB/sec thruput over 1 Gbps link
- network protocol limits use of physical resources!

Pipelined Protocols

- Channel utilization under a Stop&Wait protocol is not high when the propagation time is long relative to the transmission time
- Solution: pipelined protocols, where more than one packet can be sent without waiting for feedback, thus filling the 'pipeline'
- Two major versions (and lots of variations on the theme):
  - Go-Back-N
  - Selective Repeat
- New requirements:
  - Buffering more than one packet at sender, and possibly at receiver too
  - Larger sequence numbers for identifying packets in transit

Filling the Pipeline



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

(b) a pipelined protocol in operation

Stop&Wait Efficiency

$$U = \frac{T_{datatrans}}{T_{datatrans} + 2 * T_{prop} + T_{proc} + T_{acktrans}}$$

For relatively small T_{proc} and $T_{acktrans}$

$$U \approx \frac{T_{datatrans}}{T_{datatrans} + 2 * T_{prop}}, \text{ or}$$

$$U \approx \frac{1}{1 + 2 * a}, \text{ where } a = \frac{T_{prop}}{T_{datatrans}}$$

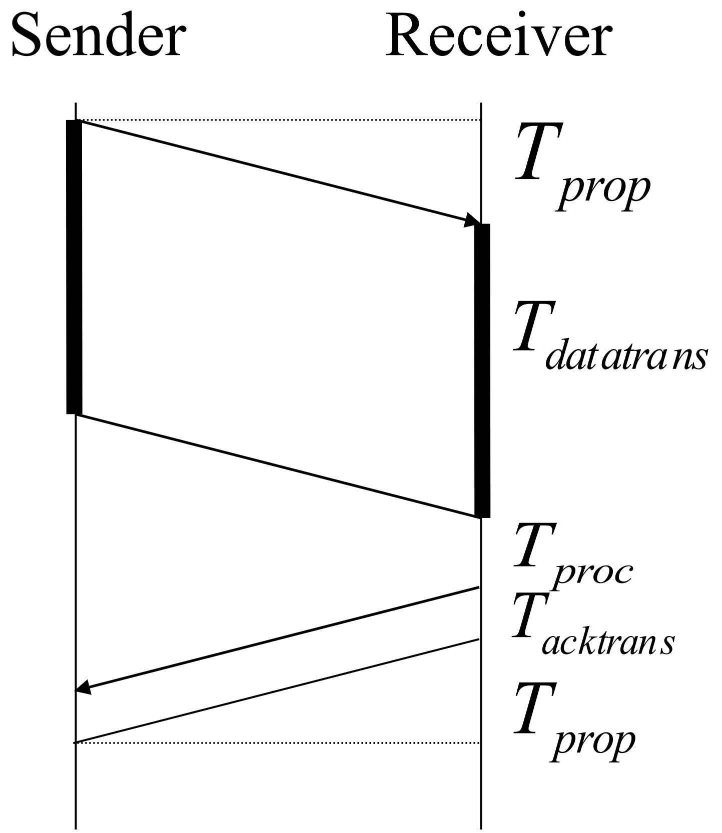
$$T_{datatrans} = \frac{L}{C}, \text{ where L is the Packet}$$

length and C is the Transmission Speed.

For one bit of data, $T_{datatrans} = 1/C$;

in this case $a = CT_{prop}$, which is

called the "Bandwidth - Delay" product

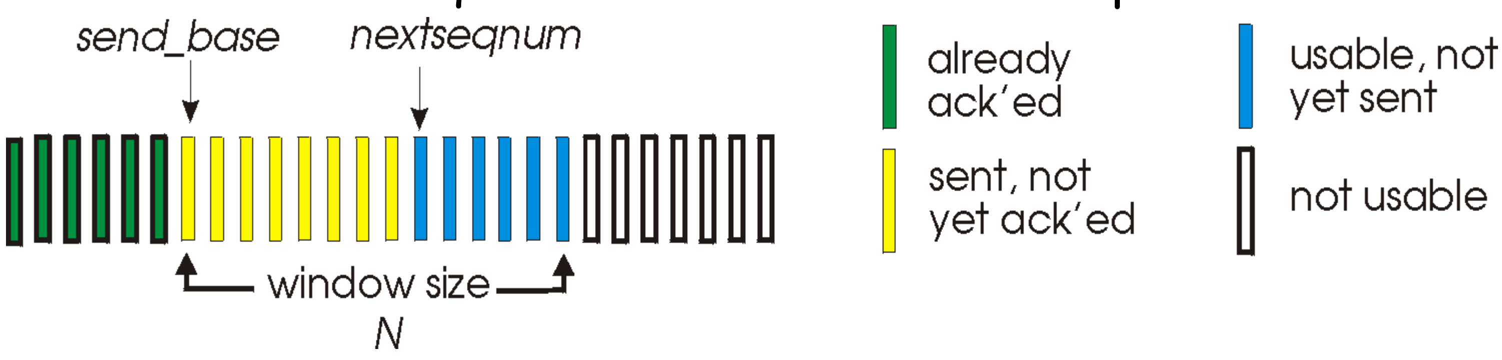


Go-Back-N

- Sender can go ahead and transmit packets without waiting for feedback up to some number of packets (for flow control reasons, details later)
- Definitions:

  N: maximum allowable number of transmission without feedback

  Base: lowest sequence number of unacked packets



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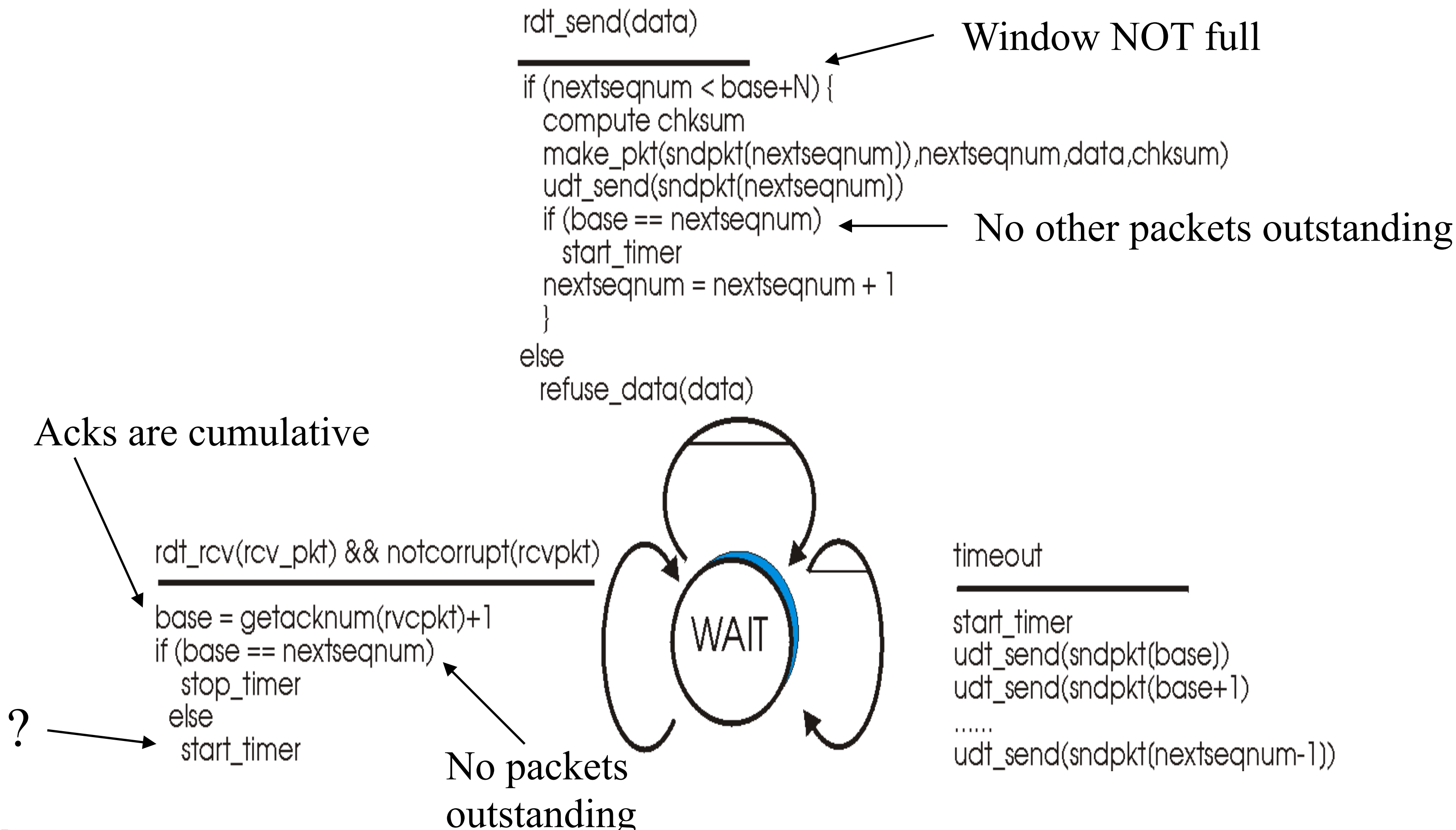
Go-Back-N Window

- From definitions and figure above:
  - *[0, base-1]* transmitted and acked
  - *[base, nextseqnum-1]* transmitted and waiting for feedback, or 'outstanding'
  - *[nextseqnum, base+N-1]* numbers that can be used when packets are provided by higher layer for transmission
  - *[base+N, maxseqnum]* numbers that cannot be used until more packets are acked

Go-Back-N Window (Cont.)

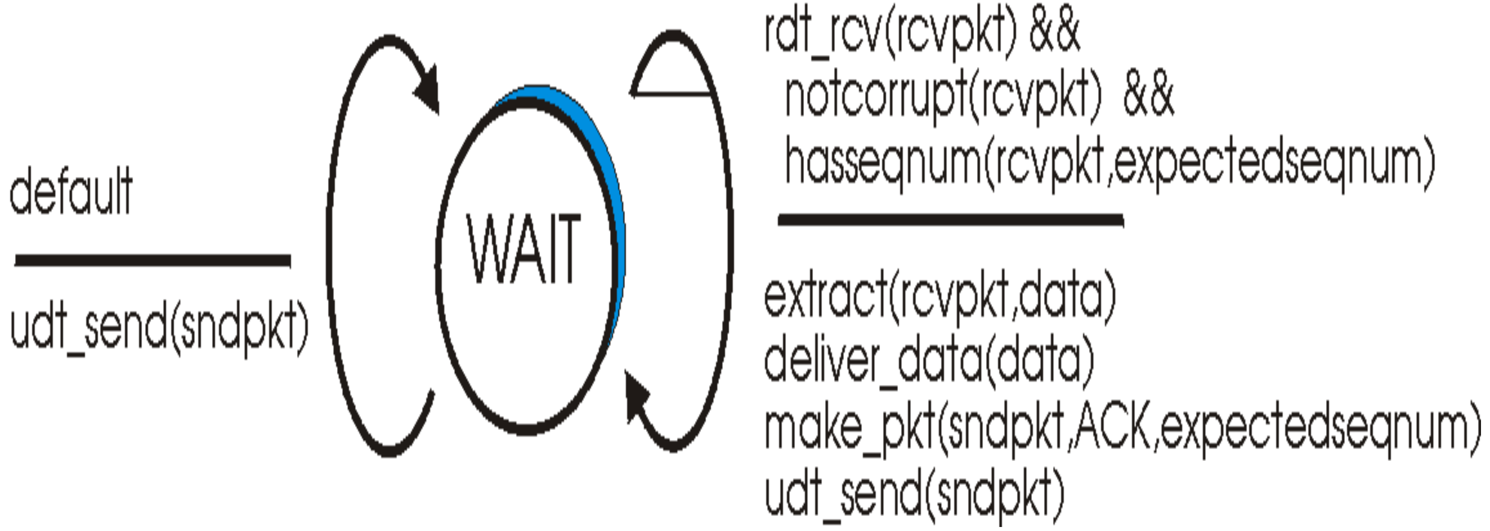
- Because of the window metaphor, these protocols are also referred to as *sliding window protocols*
- Stop&Wait can be viewed as a sliding window protocol, with window size N = 1, and sequence <u>space</u> = [0,1]
- Sequence number is carried in a fixed length field in the packet header; with k bits in the Sequence number field, the sequence space is
- Since sequence numbers must wrap around, all sequence number arithmetic is modulo

Go-Back-N Sender

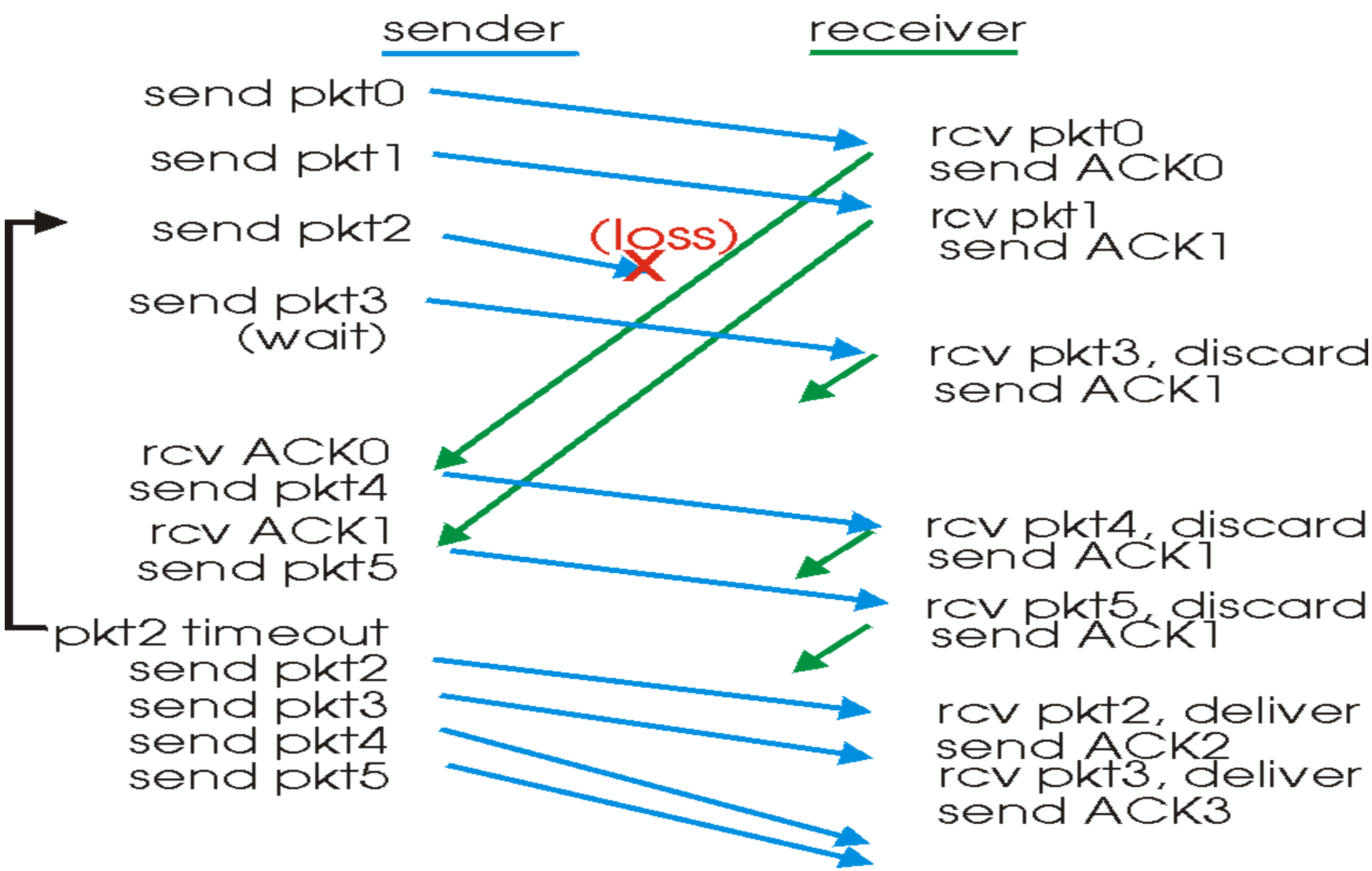


Go-Back-N Receiver

• Receiver accepts packets in order only! out-of-order packets are simply dropped



Go-Back-N Example (N=4)



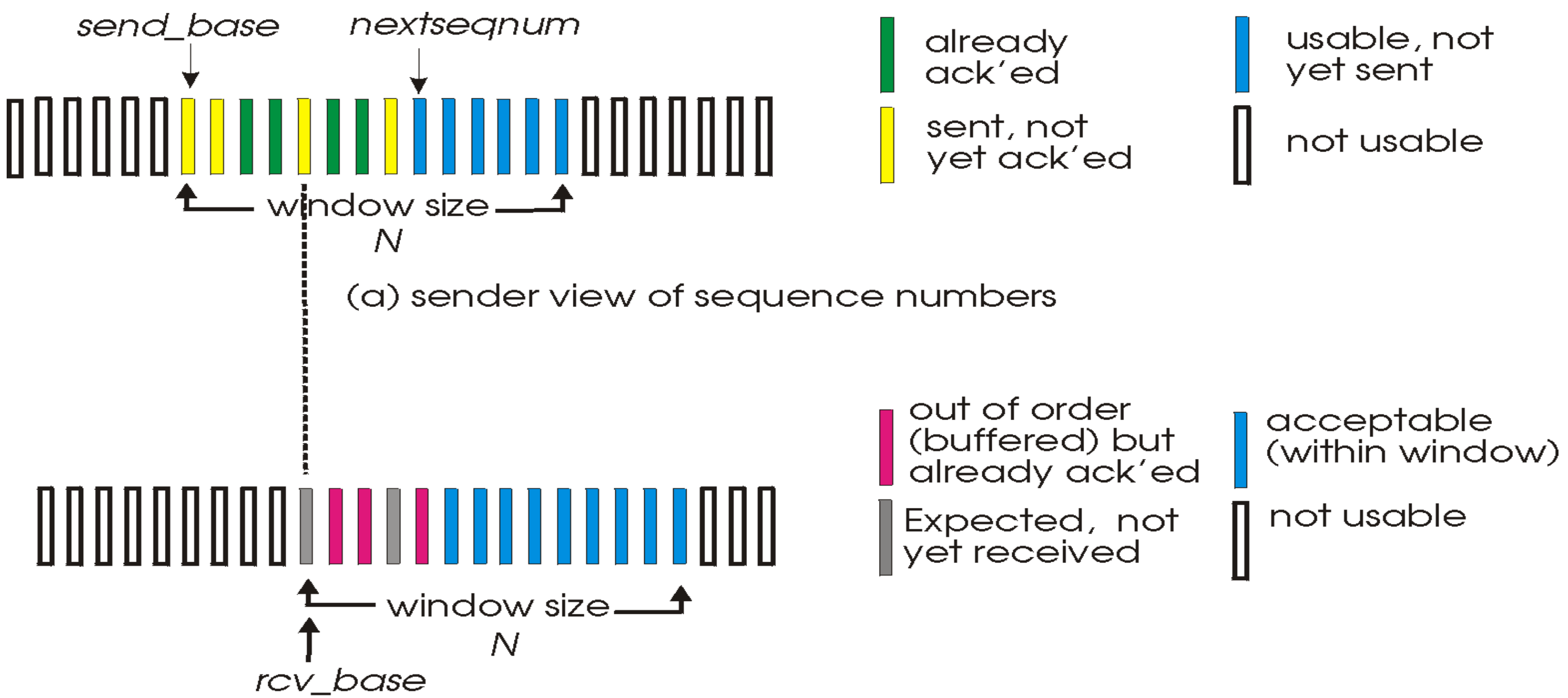
Go-Back-N Performance

- *Bandwidth-Delay Product* (ie "pipeline size") is defined as the product of the channel transmission speed and the propagation delay
- As transmission speed or propagation delay increases, more packets can be transmitted to "fill the pipeline"
- For channels with high Bandwidth-Delay product, Go-Back-N performance may deteriorate: the number of outstanding packets may be large and all these packets will be unnecessarily retransmitted when an error occurs

Selective Repeat

- Selective Repeat addresses the performance limitation of Go-back-N mentioned above
- Receiver indicates to sender which packet needs to be retransmitted; sender retransmits only that packet
- Receiver accepts and buffers packets received out of order within a limit imposed by a *receiver window*
- Groups of packets with consecutive sequence numbers (or completed sequences) are delivered to the higher layer at the sender
- A timer must be associated with each packet (but we can use one hardware timer to implement multiple logical timers)

Selective Repeat Windows



(a) sender view of sequence numbers

(b) receiver view of sequence numbers

Selective Repeat Sender Event-Driven Algorithms

- Higher layer calls to transmit data:

  if there are unused sequence numbers

  then packetize and transmit;

  else reject the data;

- Timeout occurs:

  transmit the (single) packet which timed out;

- Ack is received:

  mark packet acked;

  if base can be moved

  then move it to the unacked packet with the lowest sequence number;

Selective Repeat Receiver Event-Driven Algorithms

- Packet received, not corrupted, within current receive window:

  Ack the received packet;

  if not previously received

  then buffer the packet;

  deliver consectively sequenced received packets to higher layer;

  move window forward;

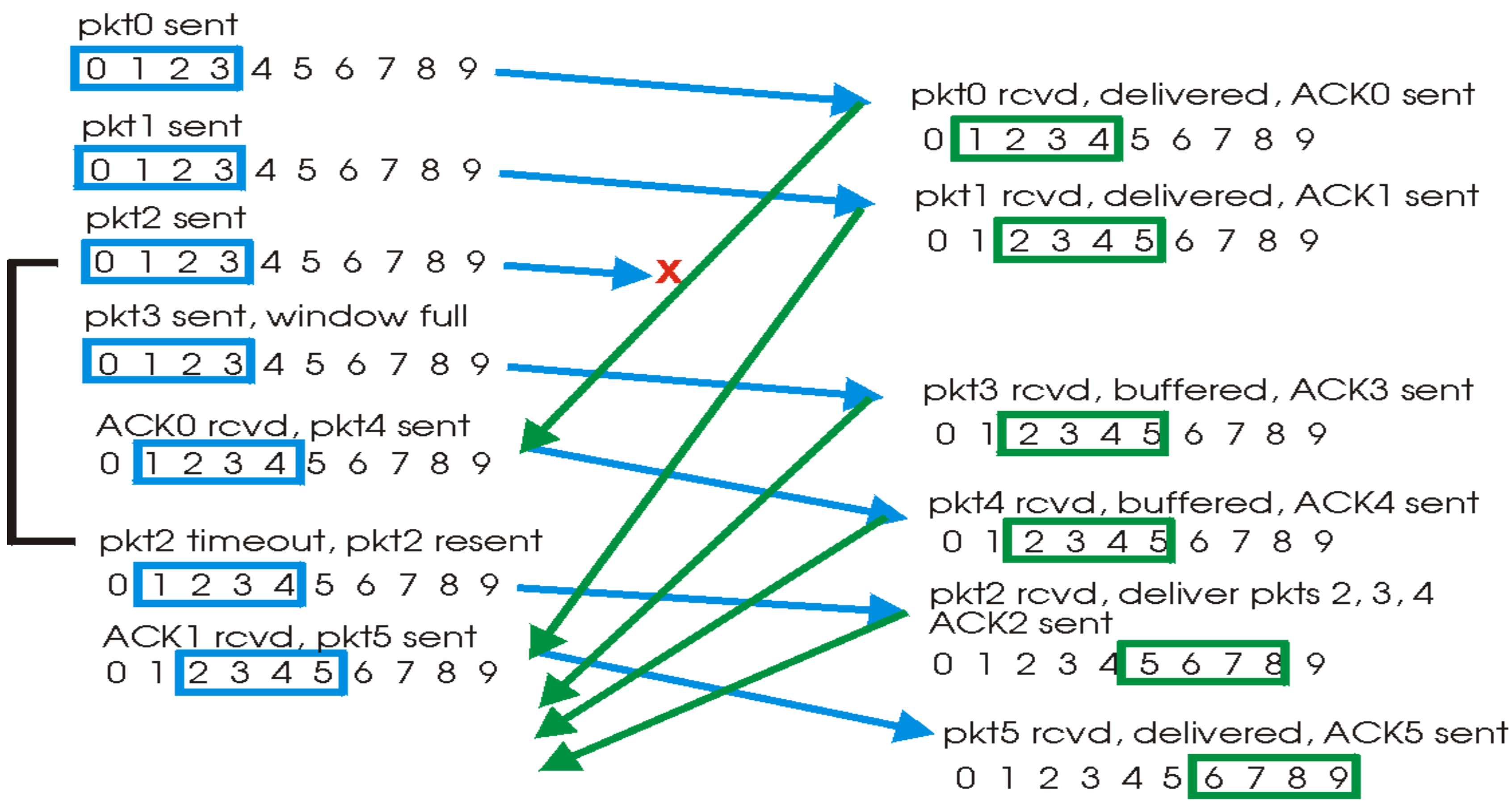
- Packet received, not corrupt, sequence number below window base:

  Ack the received packet; /* packet previously acked and already delivered to higher layer*/

- Packet received, corrupt, or sequence number beyond window:

  Ignore the packet

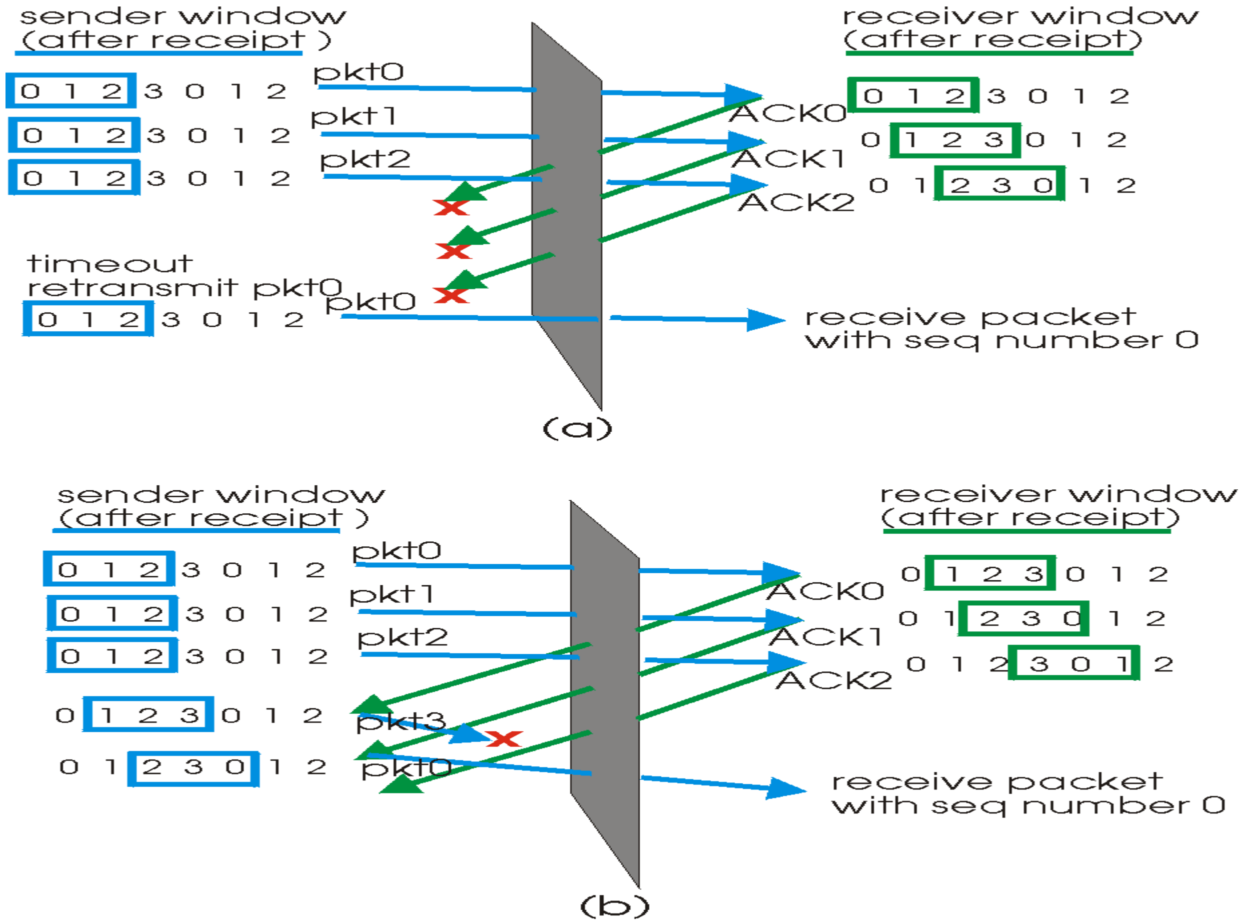
Selective Repeat Example



Setting The Window Size

- The window size N is an important parameter
- N should be large enough to allow filling the pipeline, thus making better utilization of the channel
- On the other hand, N is limited by the protocols (ensure receiver correctly identifies packets)
- It was found that N cannot be larger than half the sequence space length

Misidentification Example



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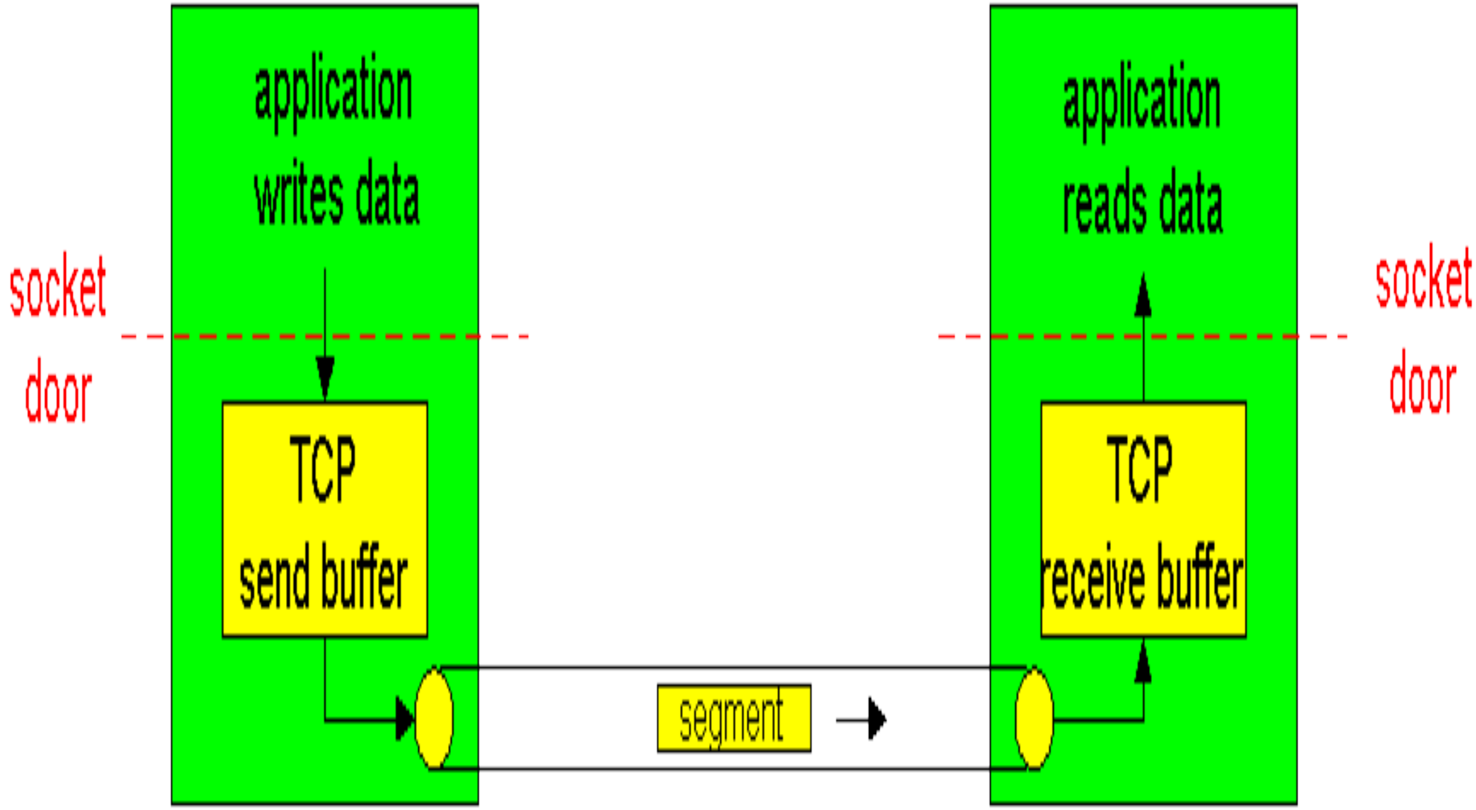
Reliable Transport Layer: TCP

- Full-duplex
- End-to-end protocol, transparent to network and lower layers in routers
- Connection-oriented, connection established through “three way handshake” protocol
- Byte Stream transfer, stream is divided into segments with a *maximum segment size* (MSS)
- Reliability through an ARQ type protocol
- Flow Control: receiver controls the amount of bytes a sender is allowed to send
- Point-to-point connection, no multicasting with TCP

TCP Connection Model



Flow/Congestion Control

- Flow Control (strict definition): regulate TCP flow so as to prevent receive buffer overflow at destination
- Flow Control (more general definition): regulate TCP flow so as to prevent buffer overflow anywhere along the path
- Congestion Control: regulate TCP flow(s) so as to avoid congestion in the entire network and to achieve efficient, fair sharing of resources.
- Key TCP flow/congestion mechanism: adjustable sender window

TCP Connection Management

- TCP connection is set up using the *three way handshake* protocol
- Special segments (SYN segment, SYNACK segment) exchange initial client and server sequence numbers and allocate buffers
- Three Way Handshake protocol allows to detect and eliminate "old" connection requests (more robust than two separate handshakes)
- Another Three Way Handshake (with FIN flag turned on) is used to close the connection, releasing all resources