Computer Networks: The Transport Layer

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St. Petersburg, Russia
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Outline

- Very quick intro to computer networking
- The *transport layer*
  - reliability
  - congestion control
  - brief intro to TCP

Application

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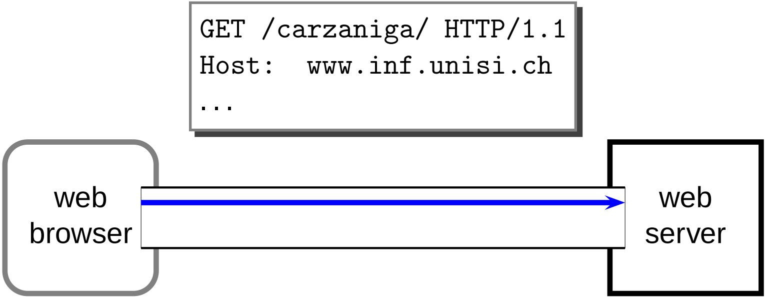

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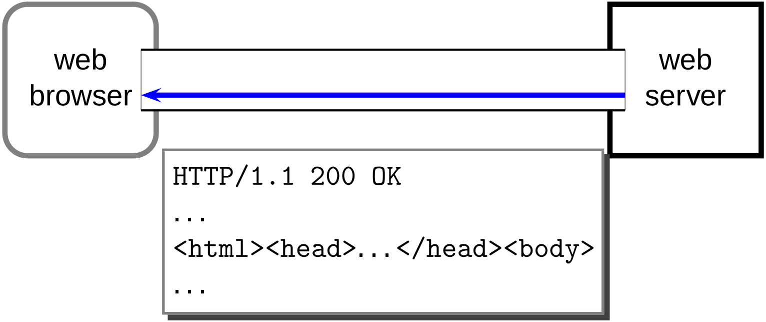

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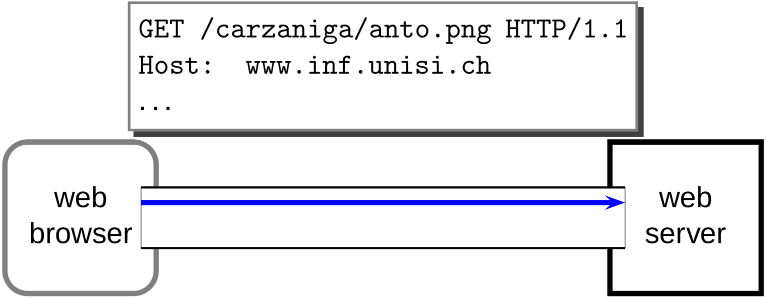

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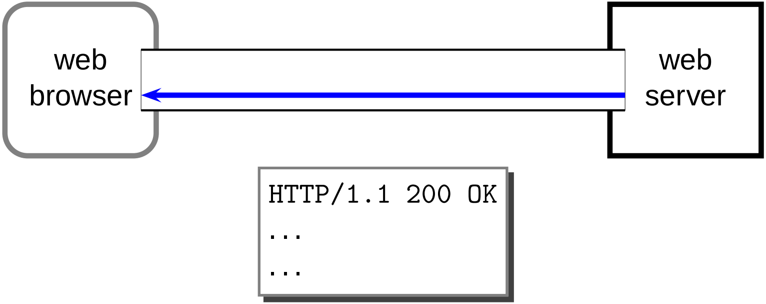

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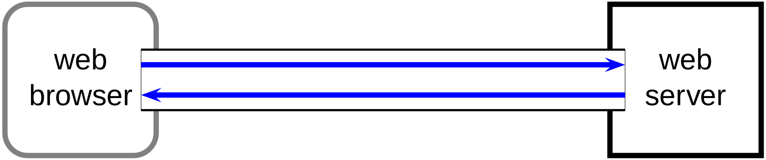

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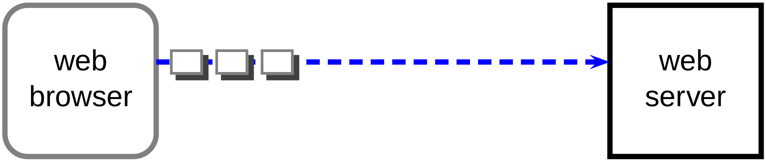

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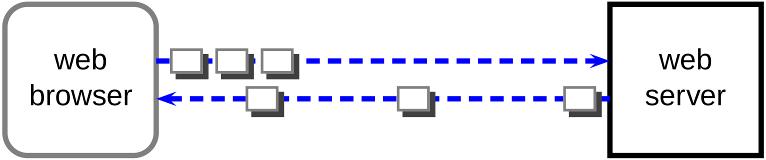

Network

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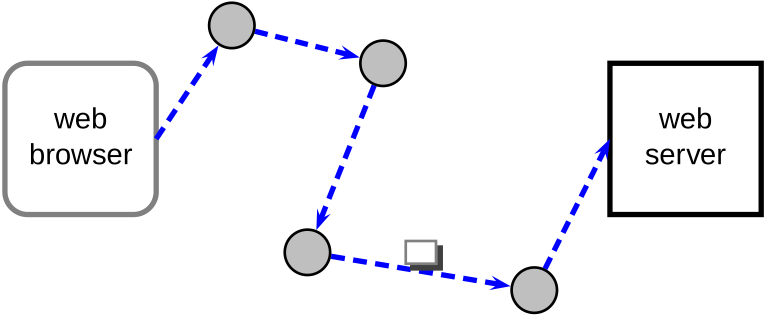

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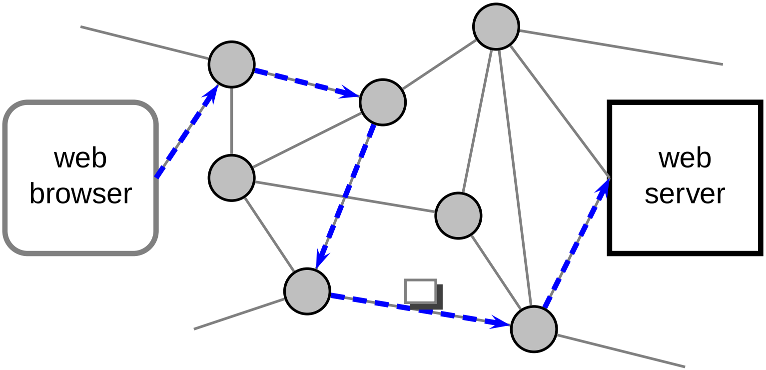

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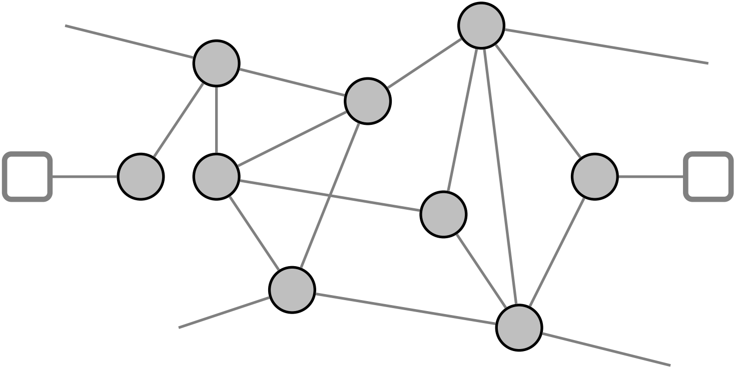

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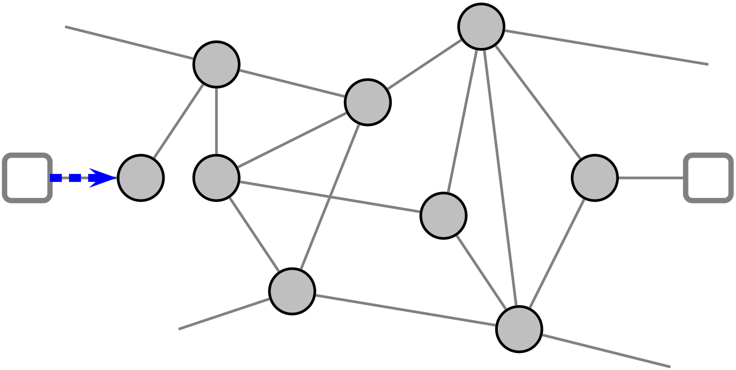

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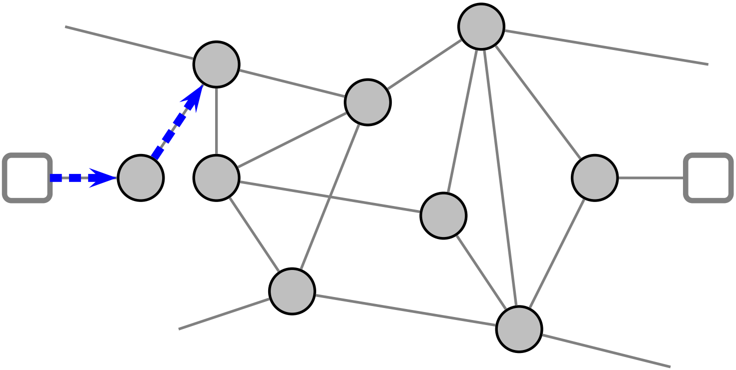

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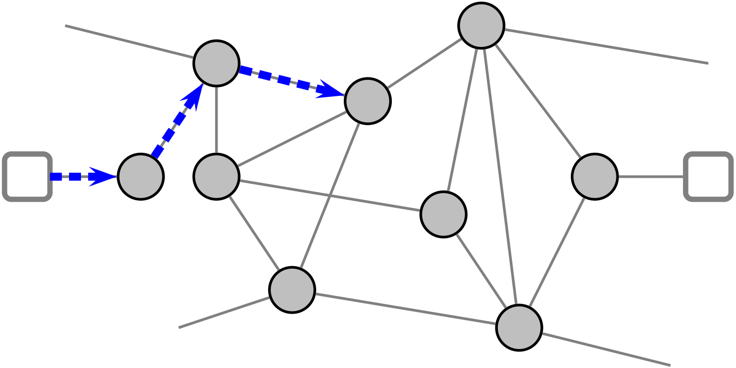

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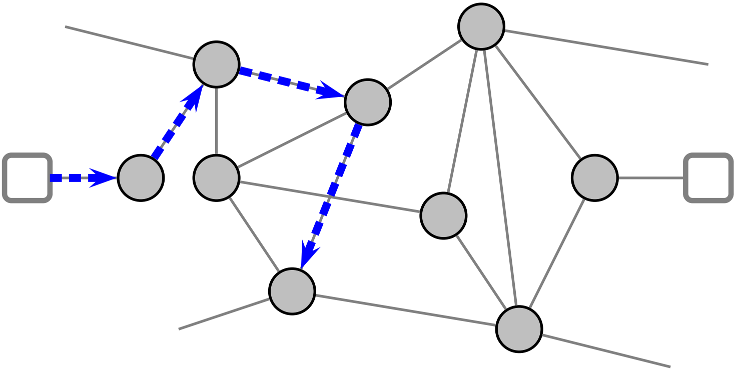

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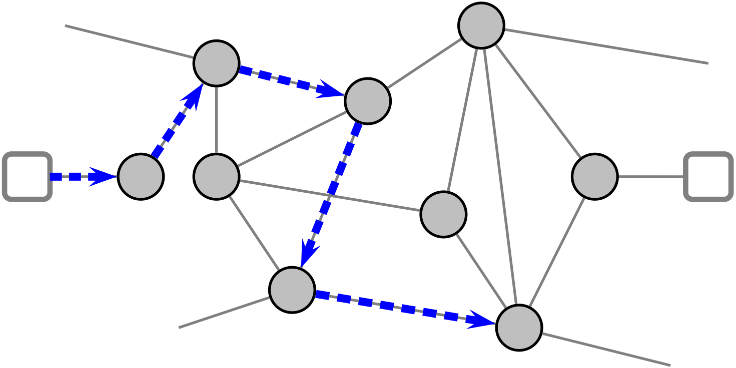

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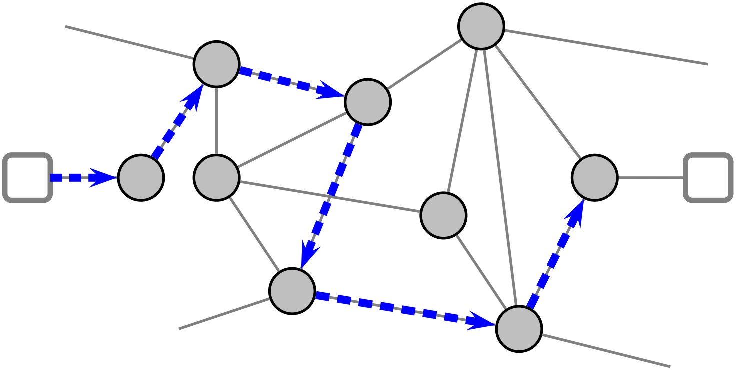

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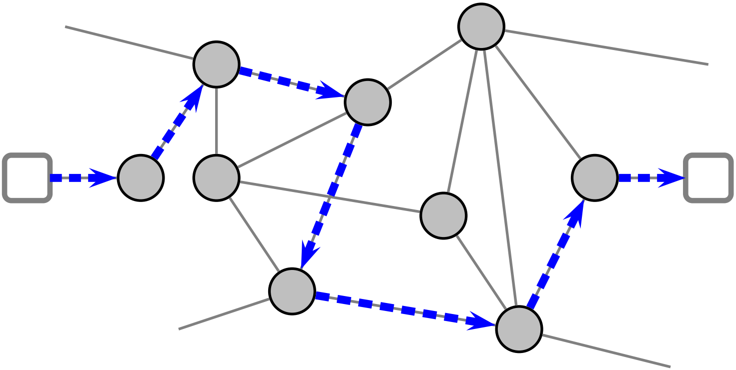

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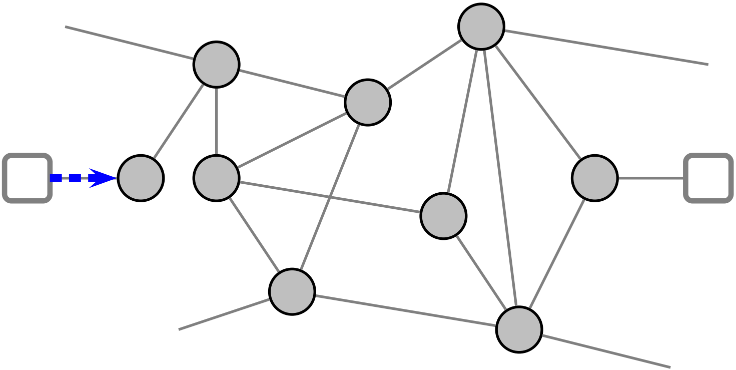

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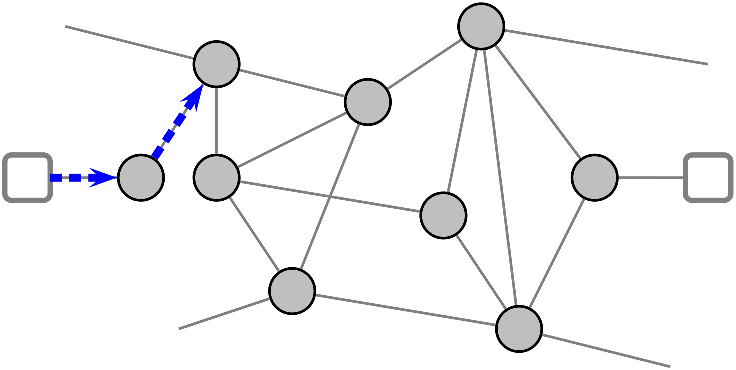

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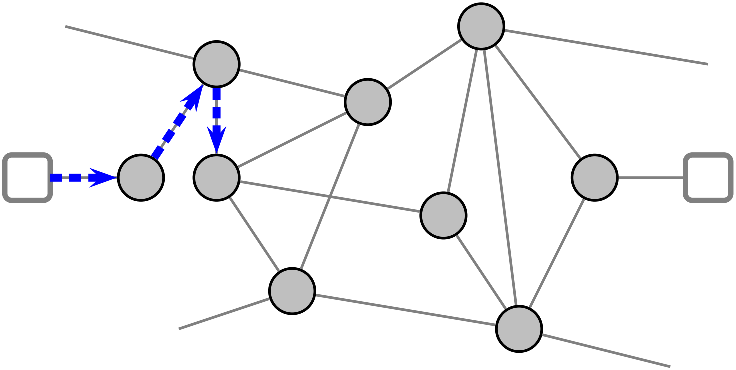

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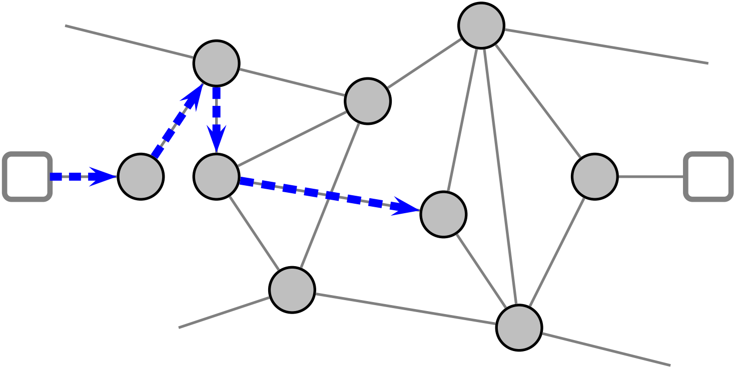

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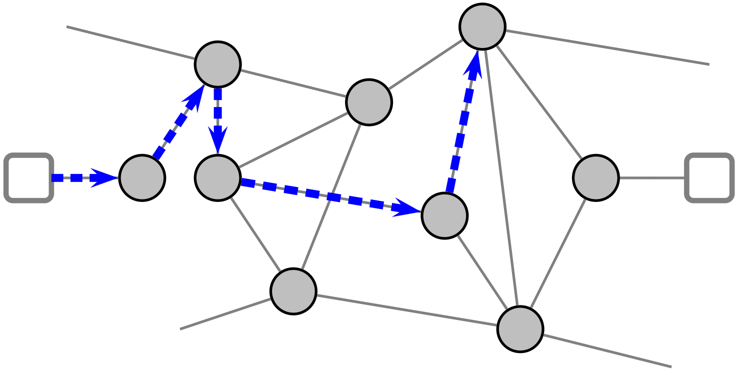

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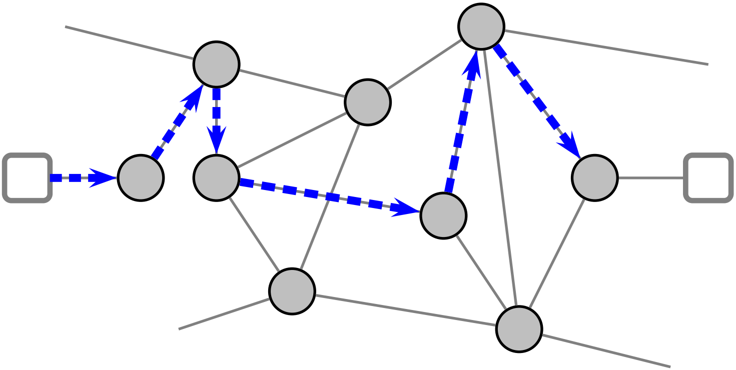

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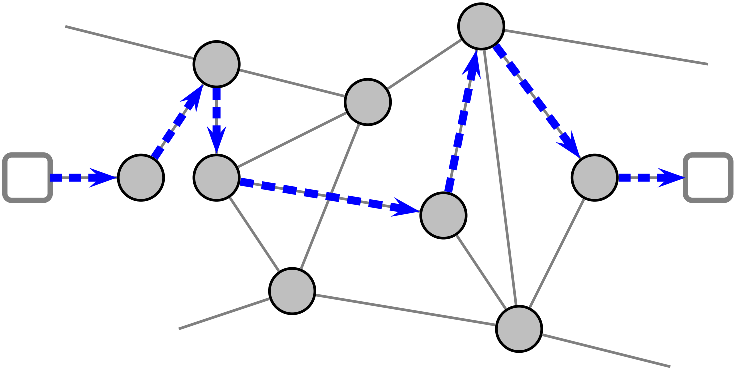

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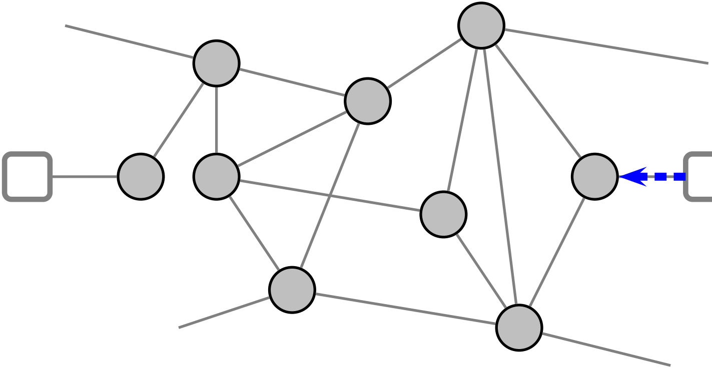

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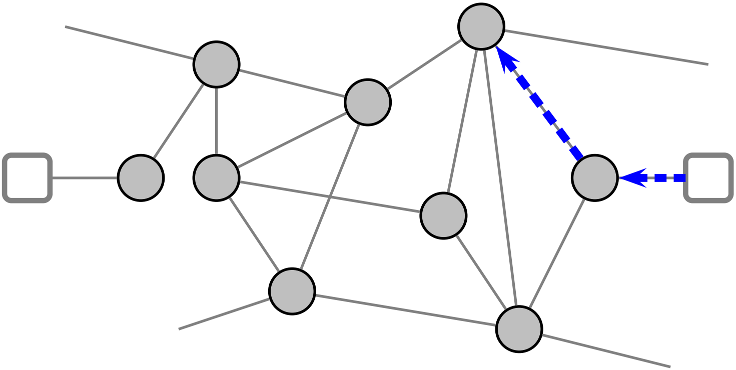

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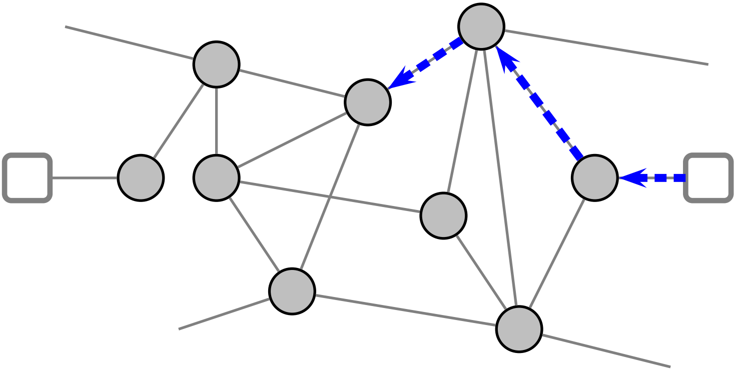

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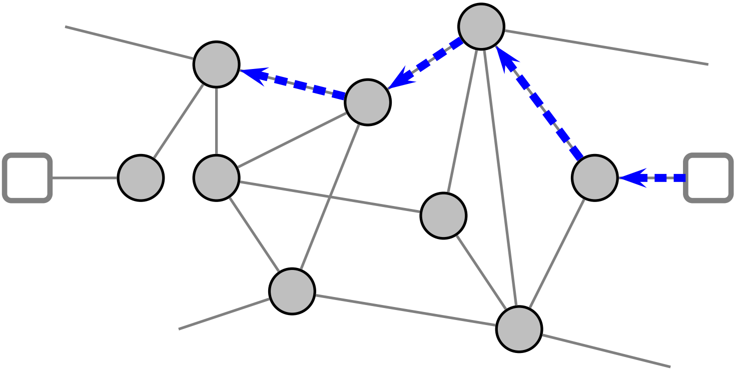

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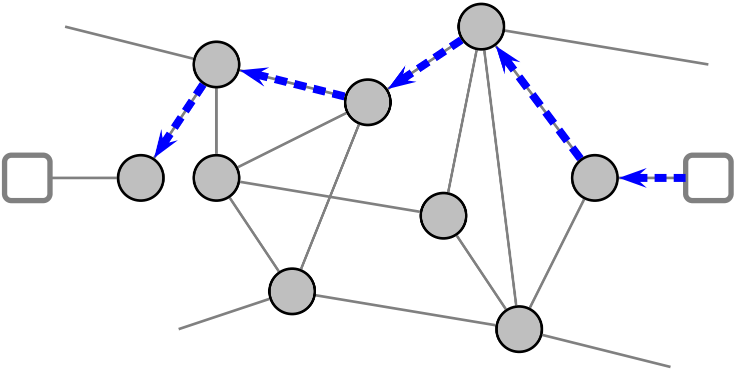

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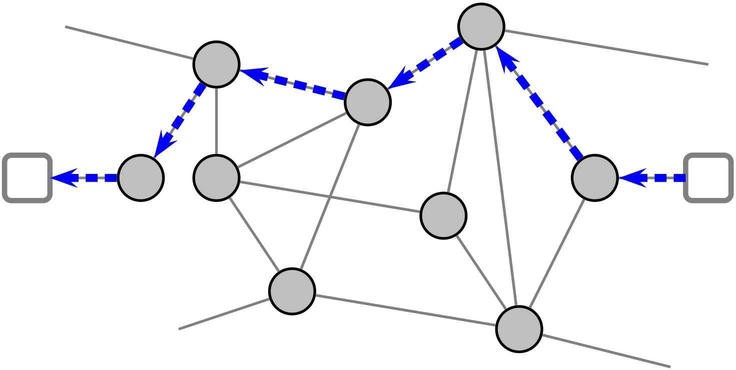

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- *Congestion control*
  - i.e., end-to-end traffic (admission) control so as to avoid destructive congestions within the network

Transport

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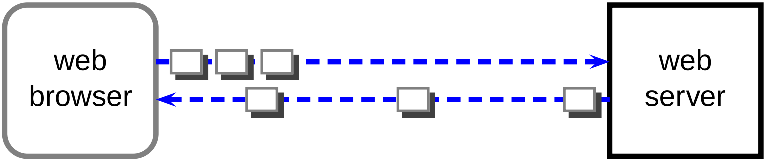

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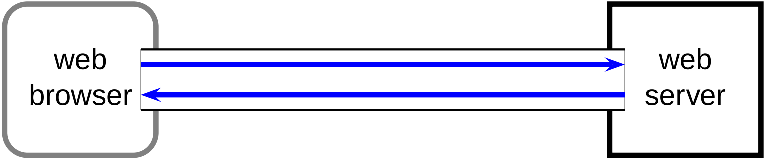

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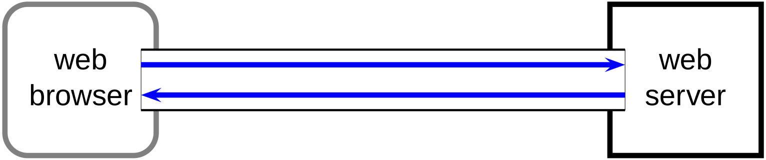

unreliable, datagram $\Longrightarrow$ *reliable “stream”*

Part I

Reliable Streams on Unreliable Networks

Finite-State Machines

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- Very useful to specify and implement network protocols
- Ubiquitous in computer science
  - theory of formal languages
  - compiler design
  - theory of computation
  - text processing
  - behavior specification
  - …

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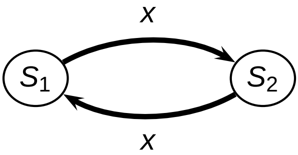

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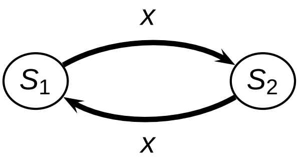

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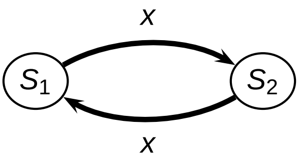

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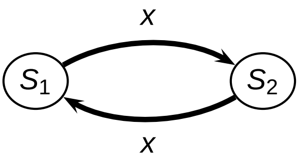

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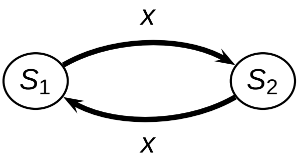

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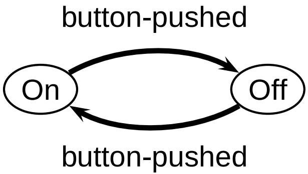

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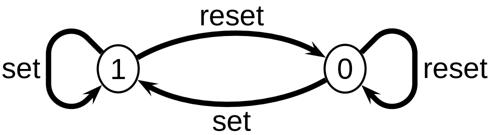

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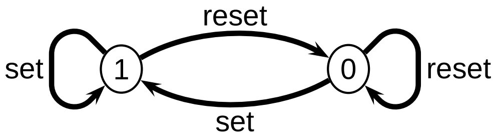

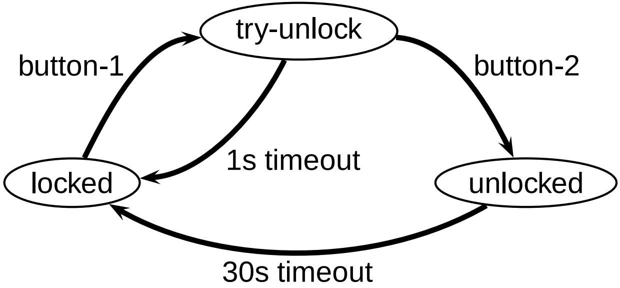

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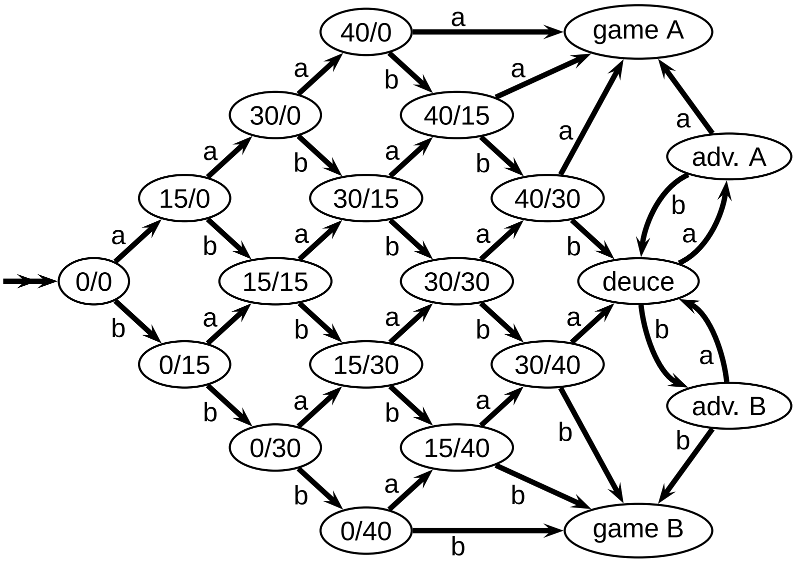

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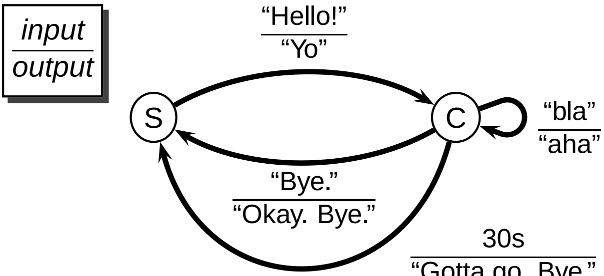
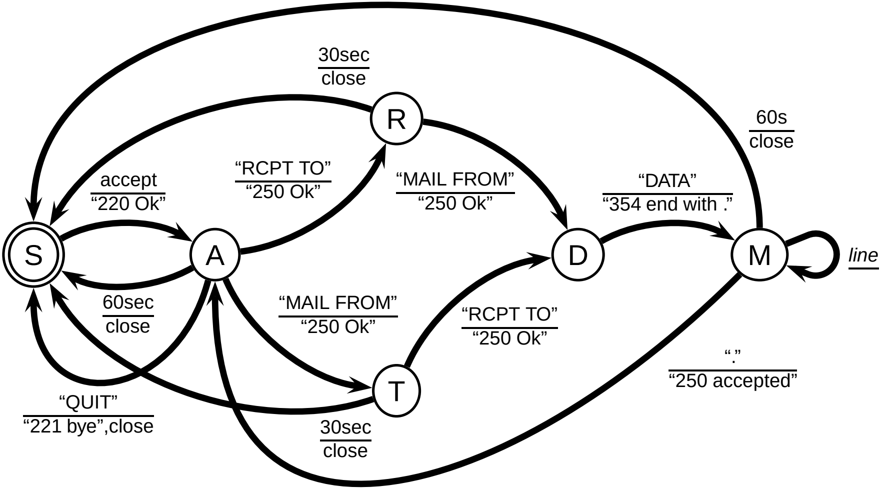
- E.g., here's a specification of a "simple conversation protocol"



Example

E.g., a subset of a server-side, SMTP-like protocol



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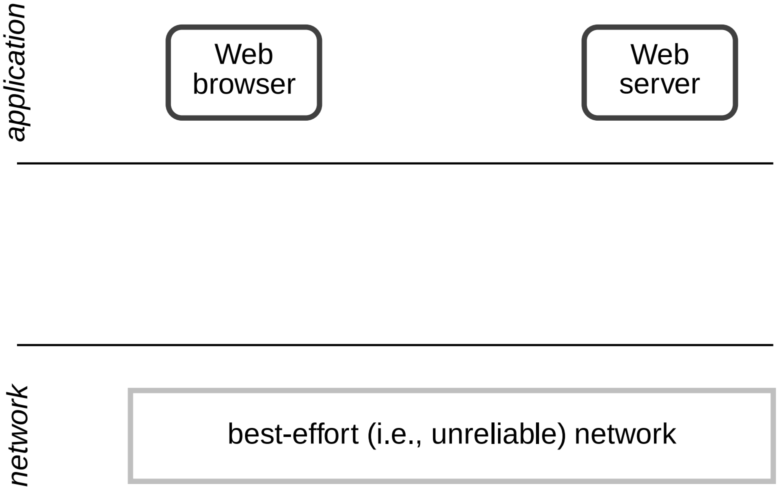

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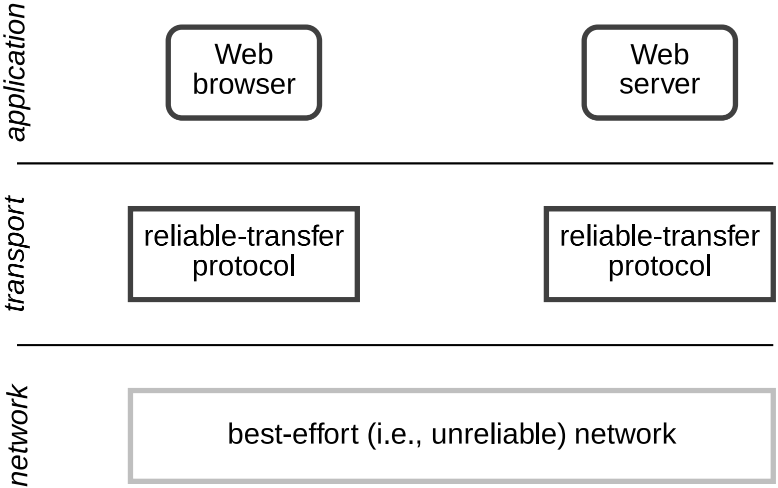

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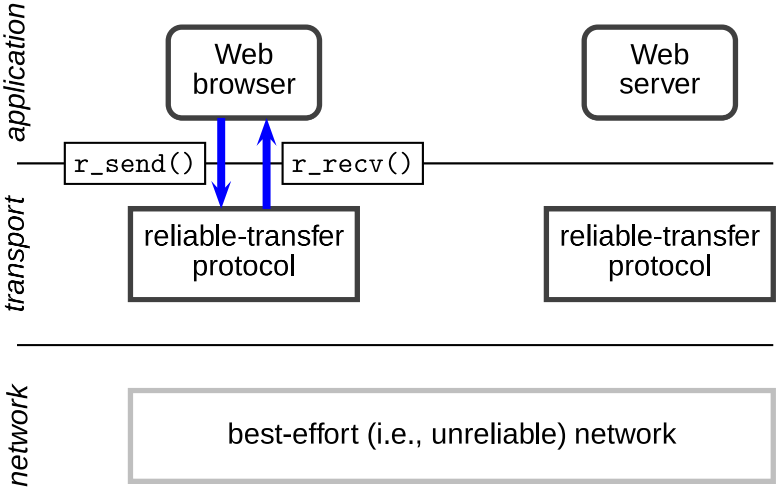

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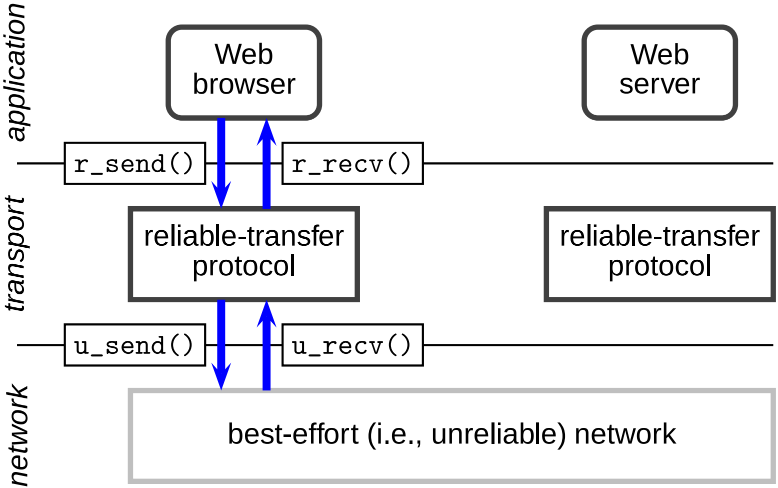

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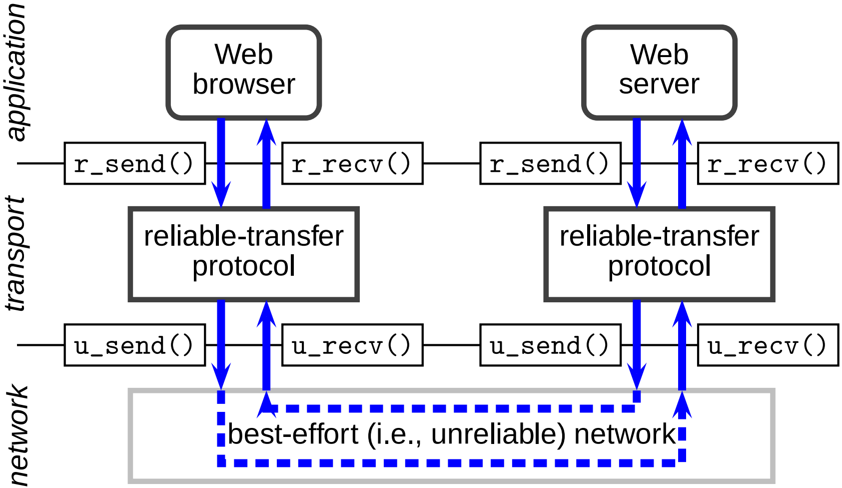

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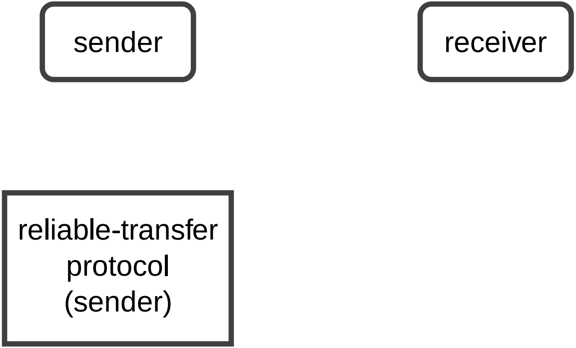

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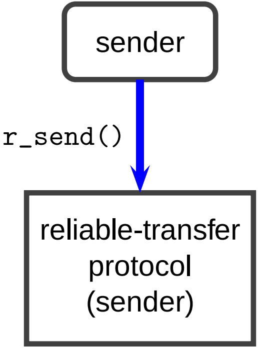

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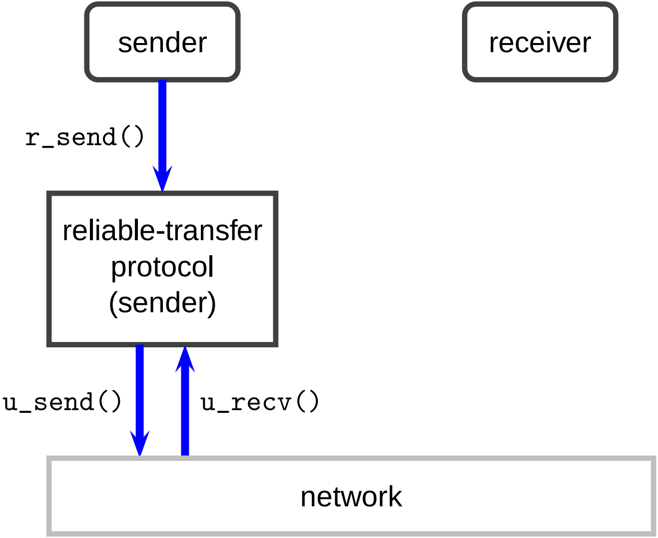

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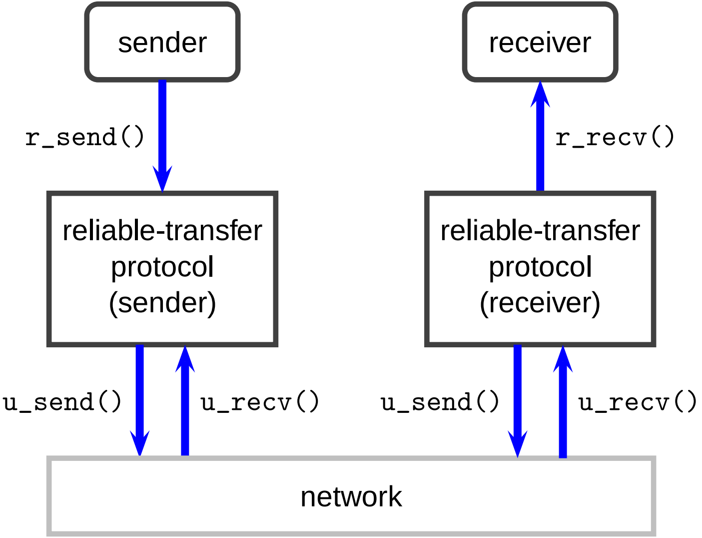
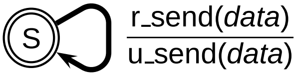


Baseline Protocol

- Reliable transport protocol that uses a reliable network (obviously a contrived example)

sender



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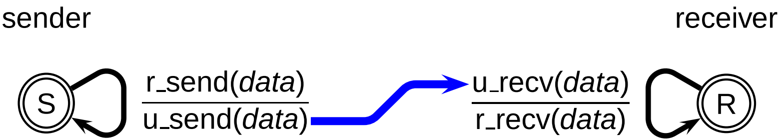

Noisy Channel

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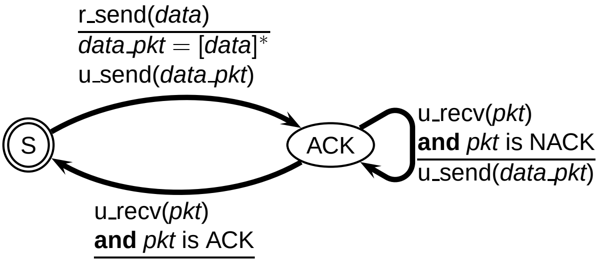

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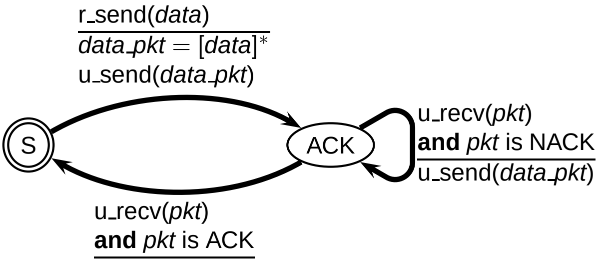

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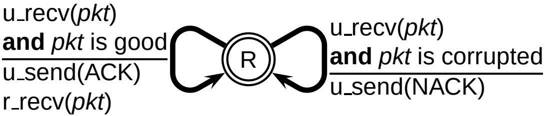

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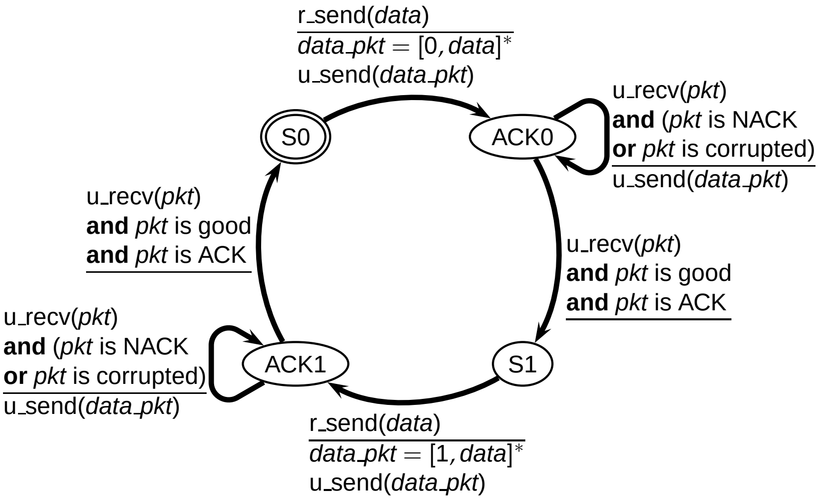

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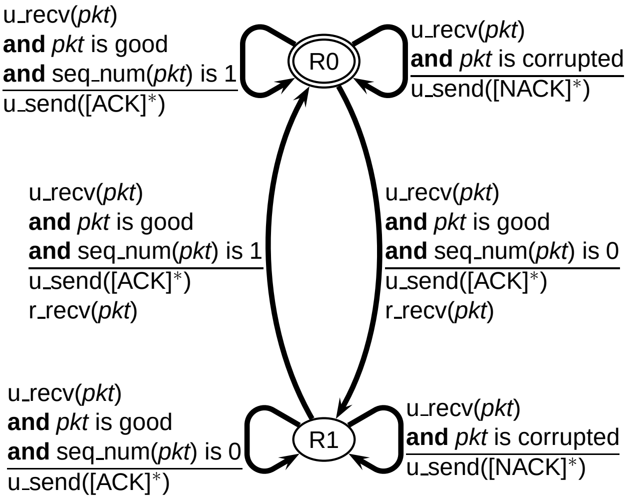

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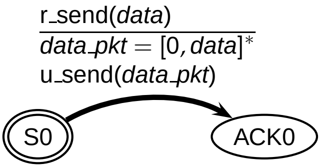

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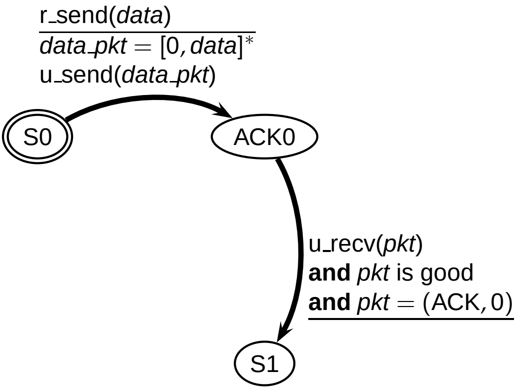

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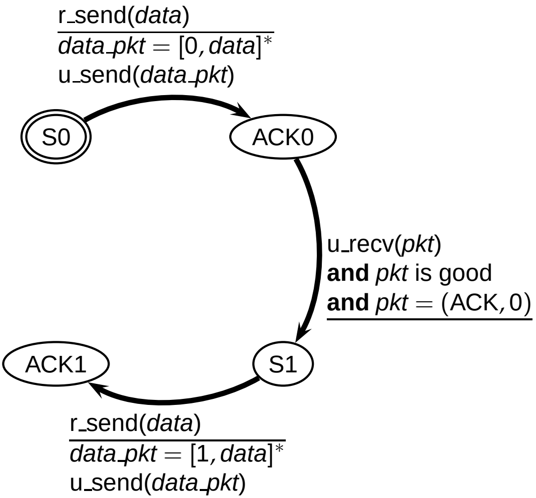

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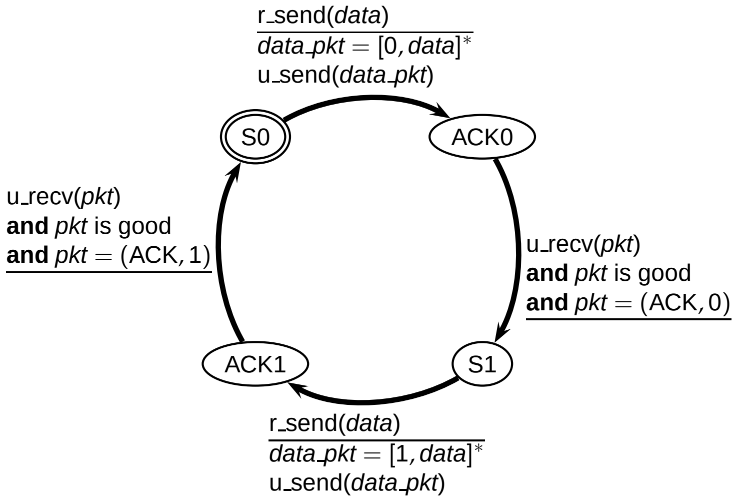

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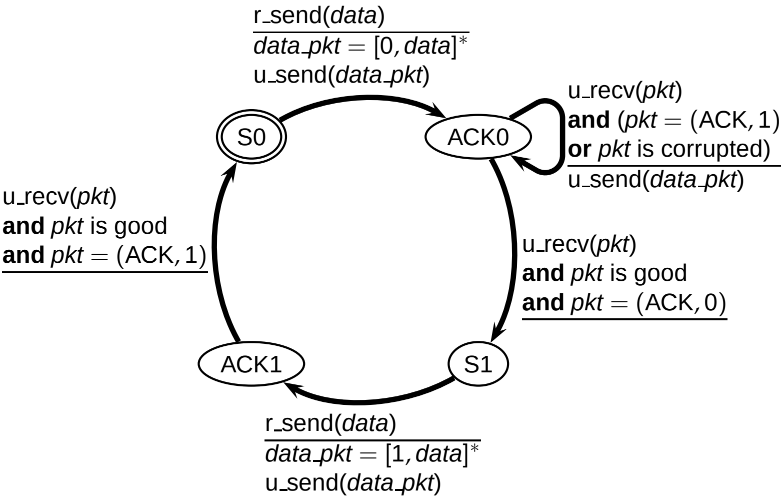

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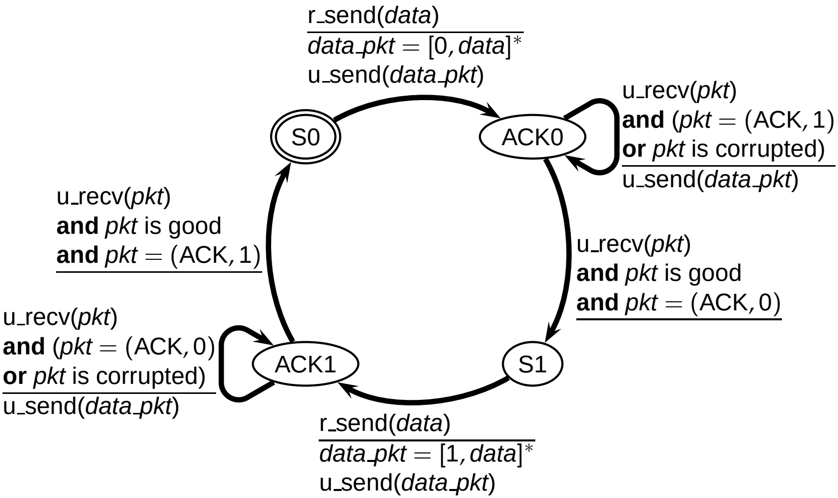

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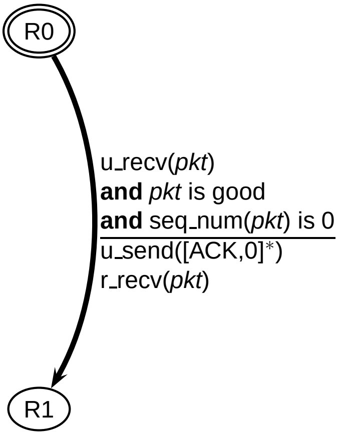

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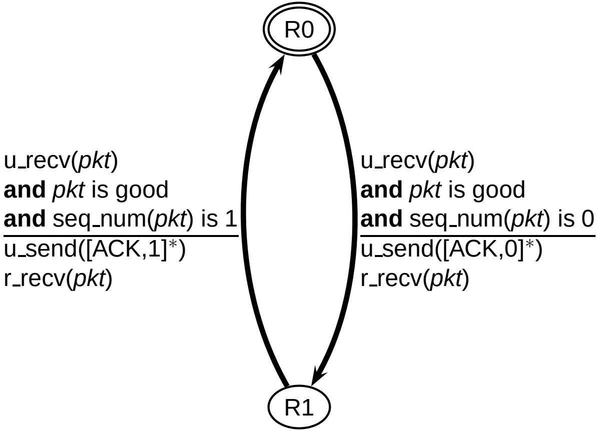

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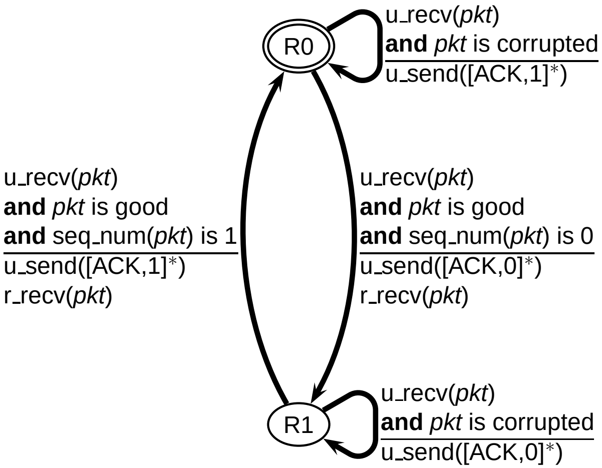

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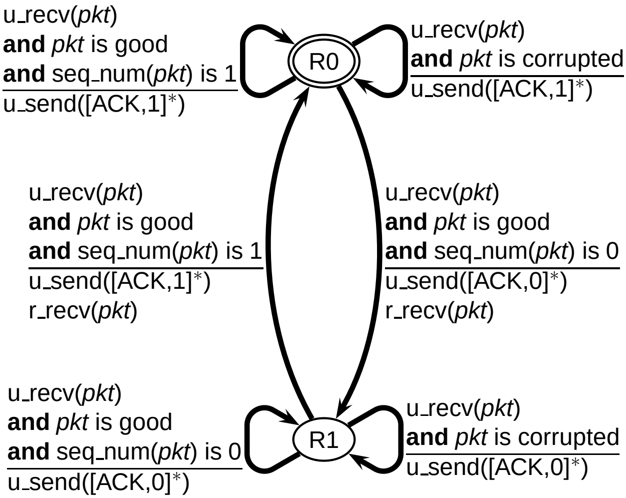

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  (Think of radio transmissions over a noisy and shared medium.
  Also, think about what we just did for noisy channels)

- *Detection:* the receiver and/or the sender must be able to determine that a packet was lost (how?)

- *ACKs, retransmission, and sequence numbers:* lost packets can be easily treated as corrupted packets

Sender Using Timeouts

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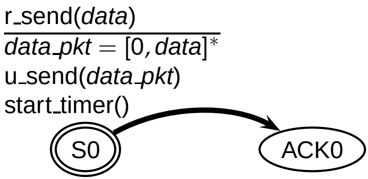

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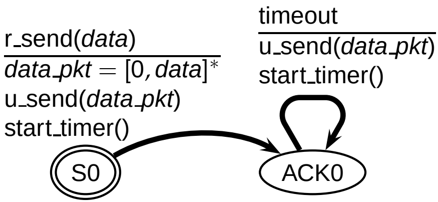

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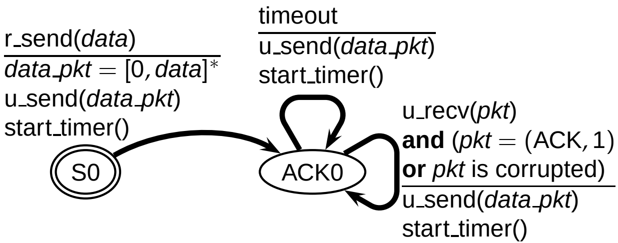

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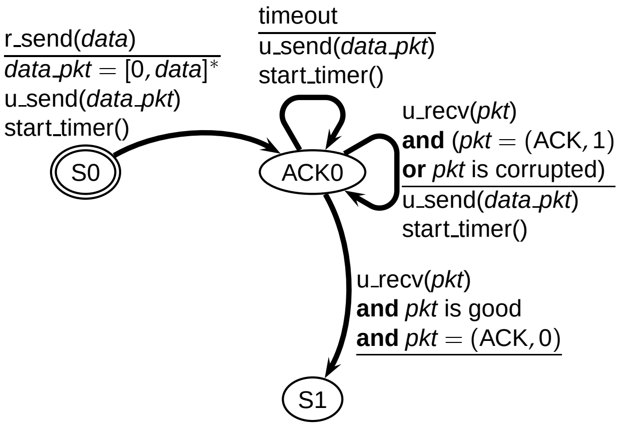

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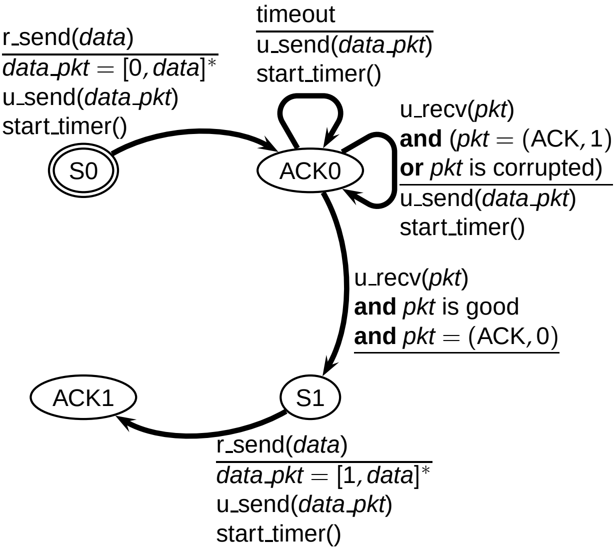

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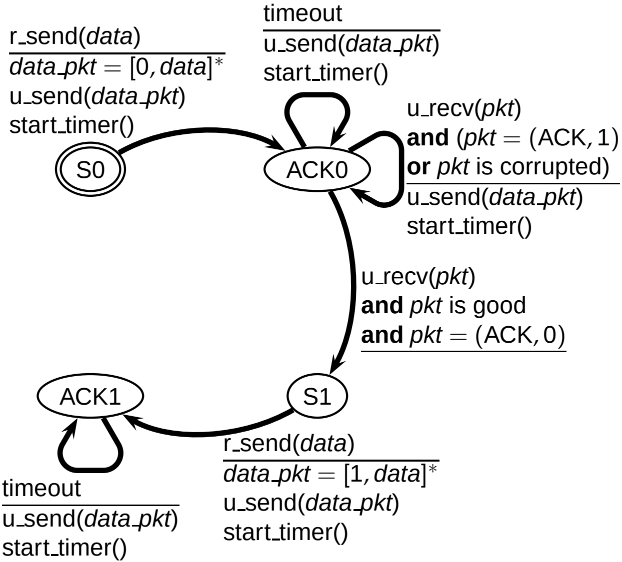

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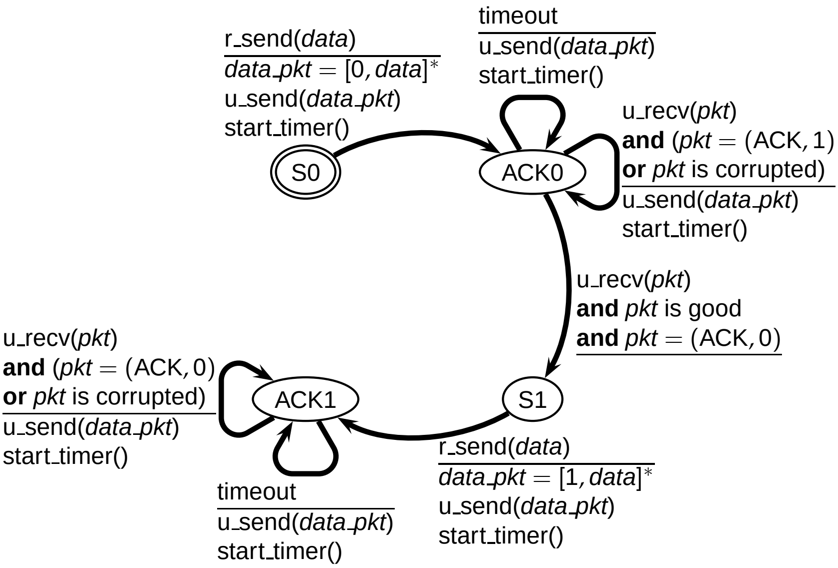

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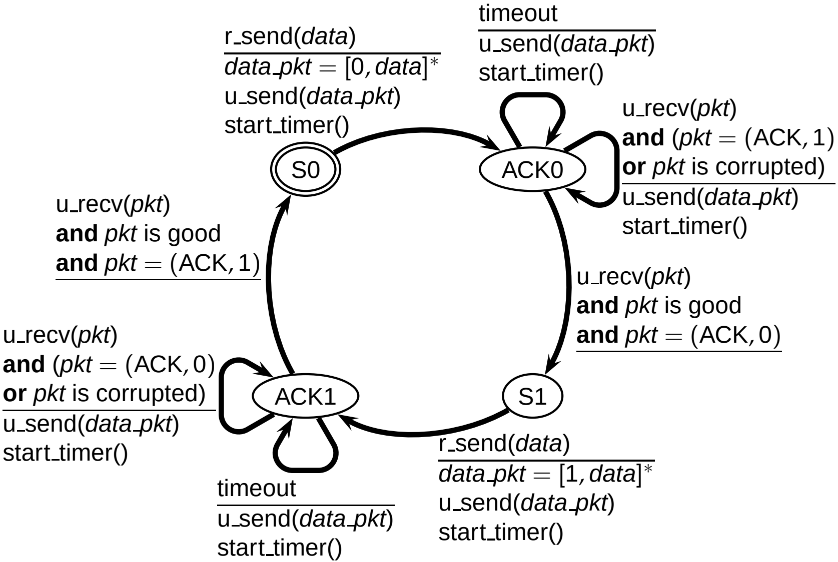

Part II

Efficient and Reliable Streams

Quantifying Data Transfer

- How do we measure the “speed” and “capacity” of a network connection?

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Quantifying Data Transfer

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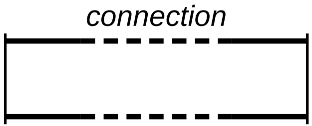
- *Latency*
  - the time it takes for *one bit* to go through the connection (from one end to the other)
- *Throughput*
  - the amount of information that can get into (or out of) the connection in a time unit
  - at “steady-state” we assume zero accumulation of traffic, therefore the input throughput is the same as the output throughput

Latency and Throughput



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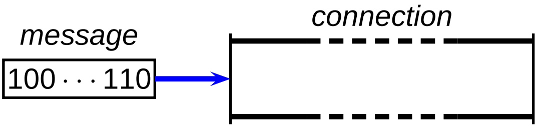

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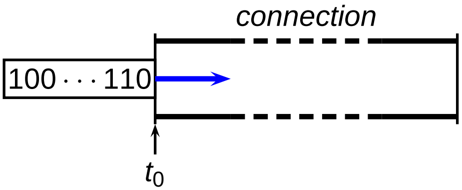

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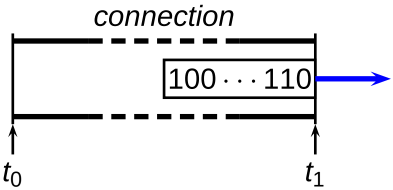

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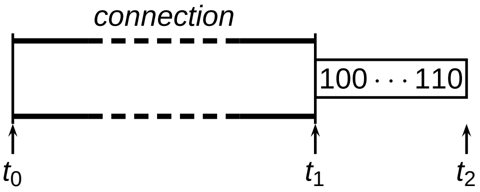

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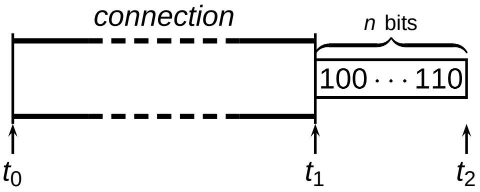

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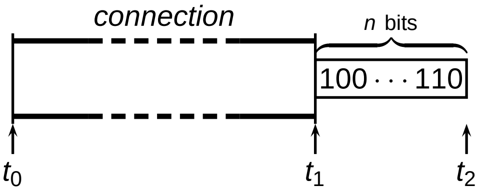
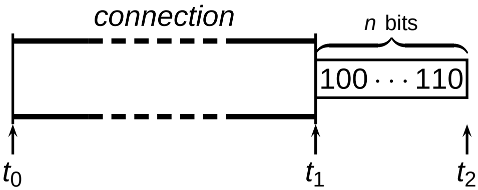


Latency $\quad L = t_1 - t_0 \quad$ sec

Latency and Throughput



Latency $L = t_1 - t_0$ sec

Throughput $T = \frac{n}{t_2 - t_1}$ bits/sec

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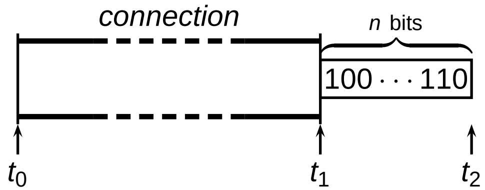

Latency	$L = t_1 - t_0$	sec
Throughput	$T = \dfrac{n}{t_2 - t_1}$	bits/sec
Transfer time	$\Delta = L + \dfrac{n}{T}$	sec

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  E.g., a (short) e-mail message

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$$
\begin{aligned}
S &= \text{4Kb} \\
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T &= \text{1Mb/s} \\
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$$

If you need to transfer 10 DVDs from Lugano to St. Petersburg and time is of the essence (and you have plenty of money)... then you're better off talking a plane rather than using the Internet

Back to Reliable Data Tranfer

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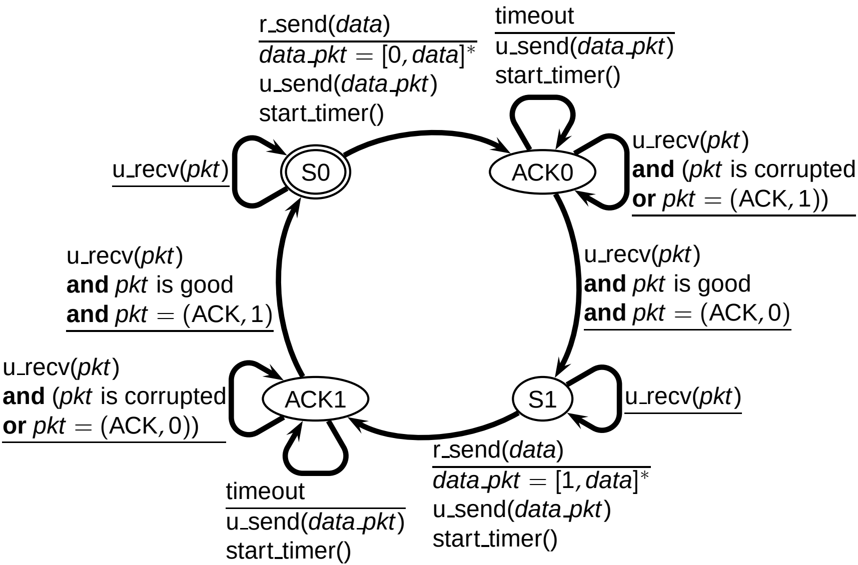

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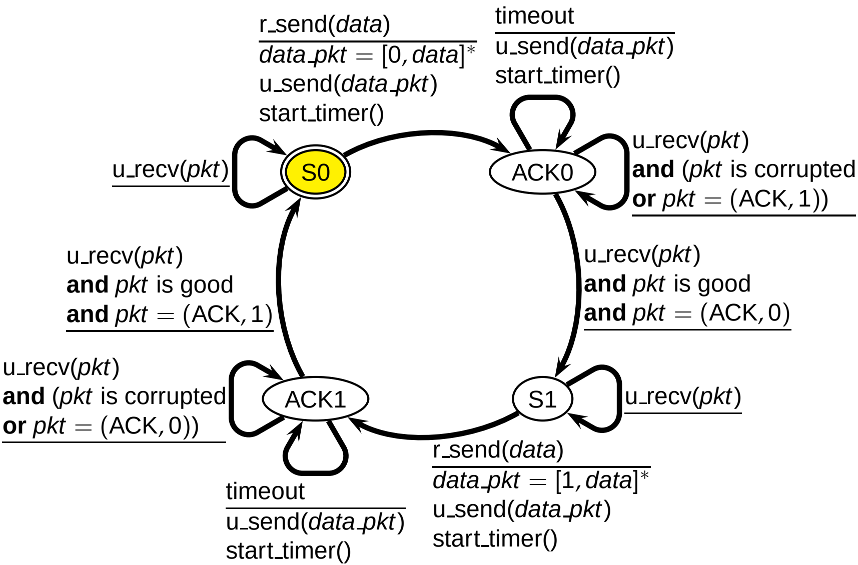

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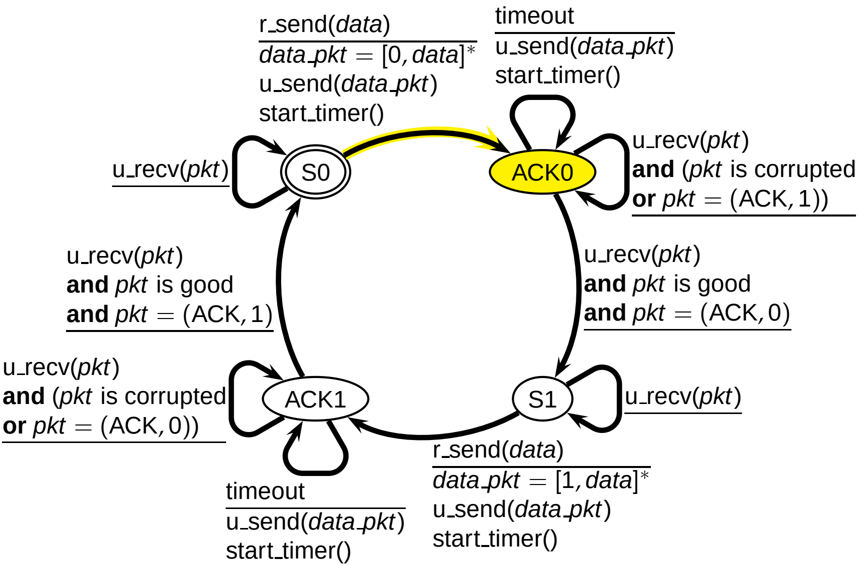

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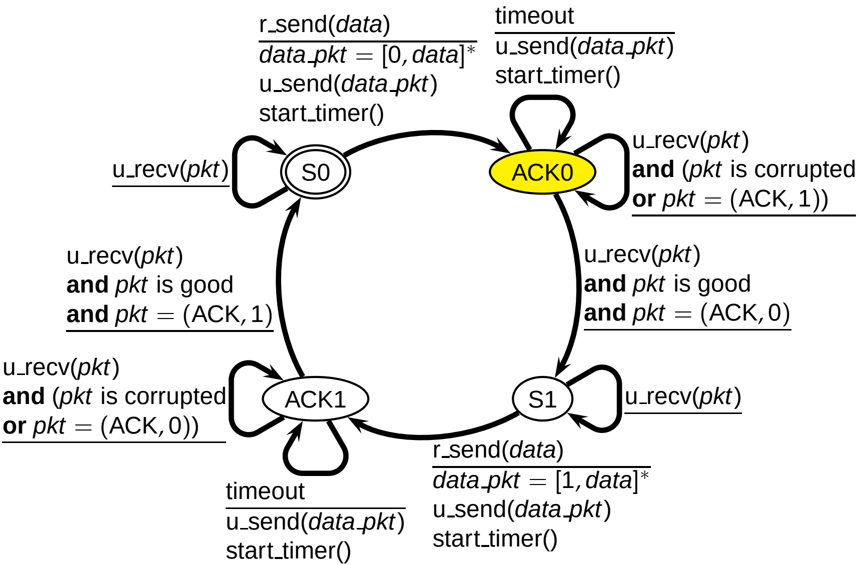

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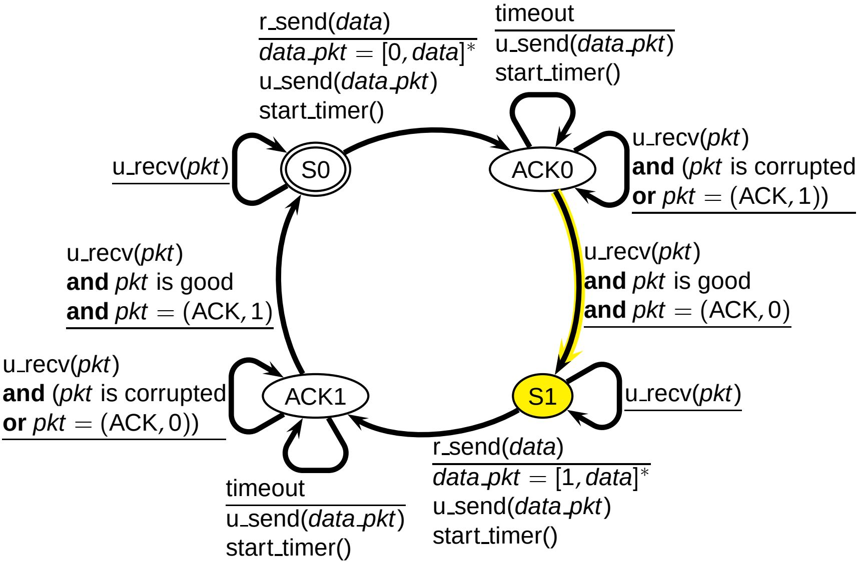

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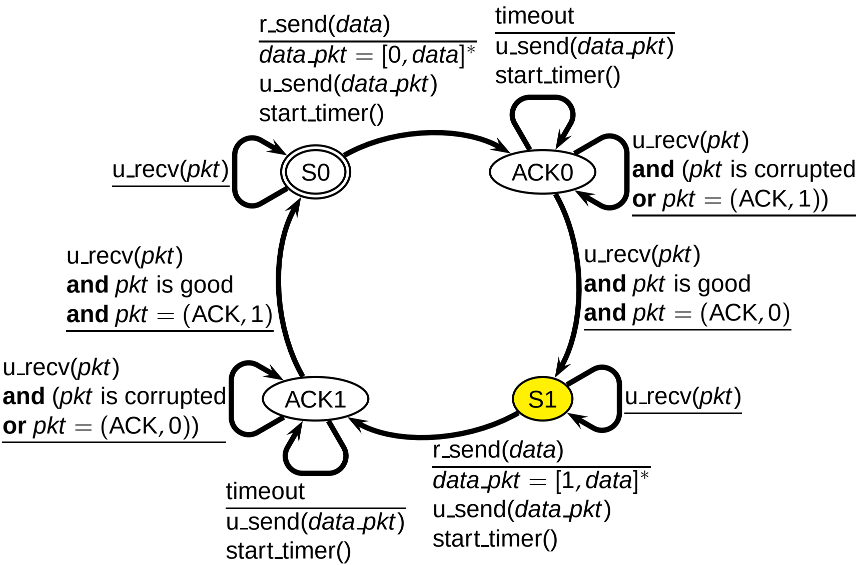

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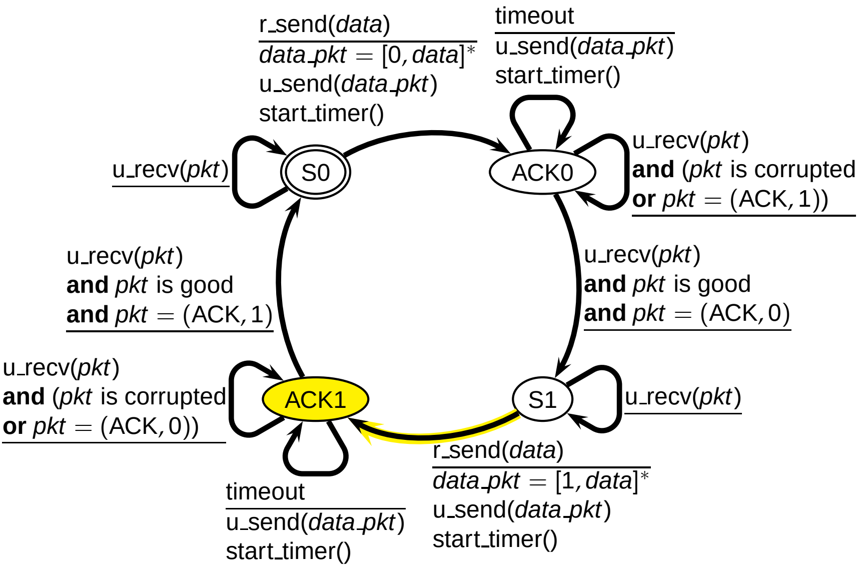

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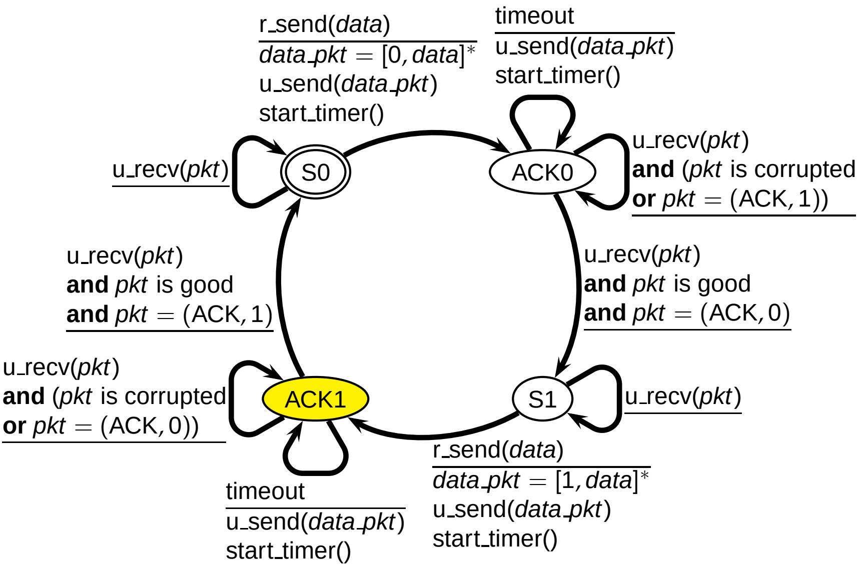

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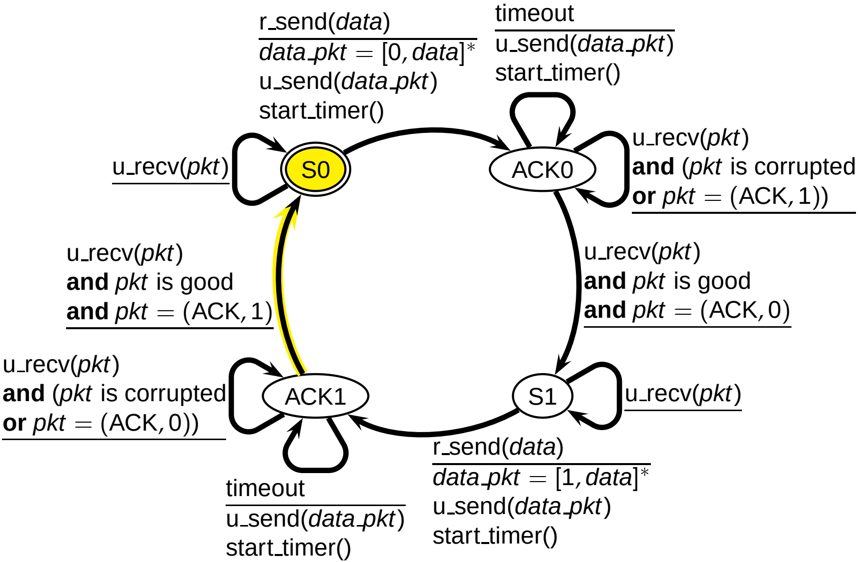

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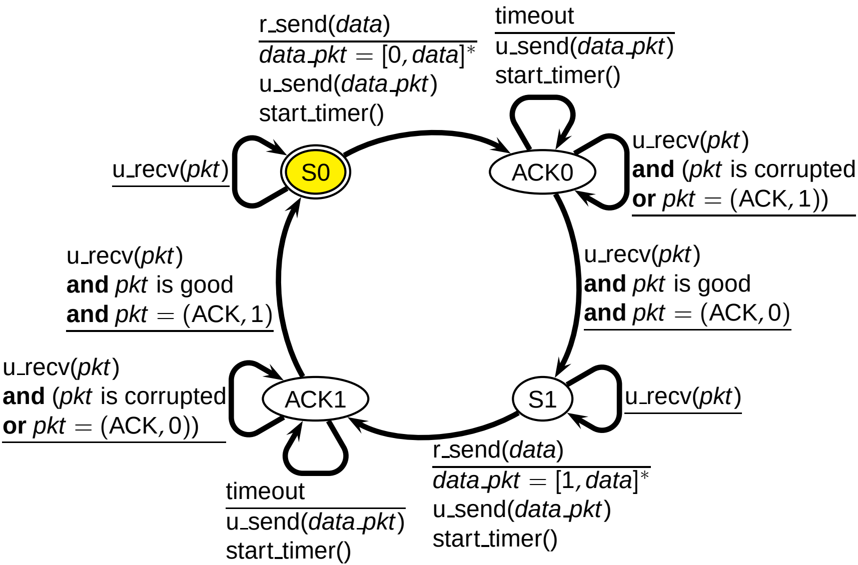
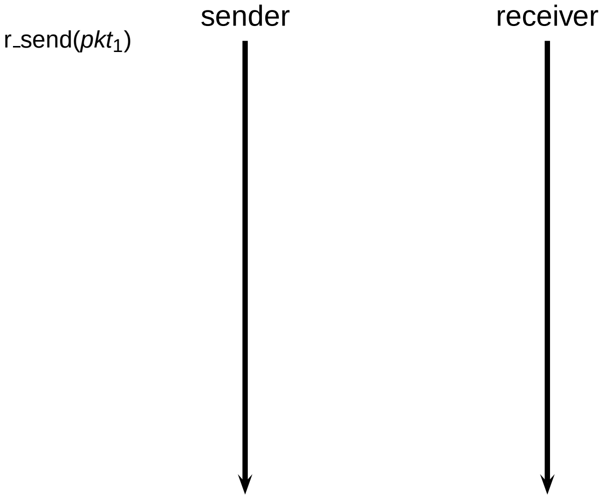


Network Usage



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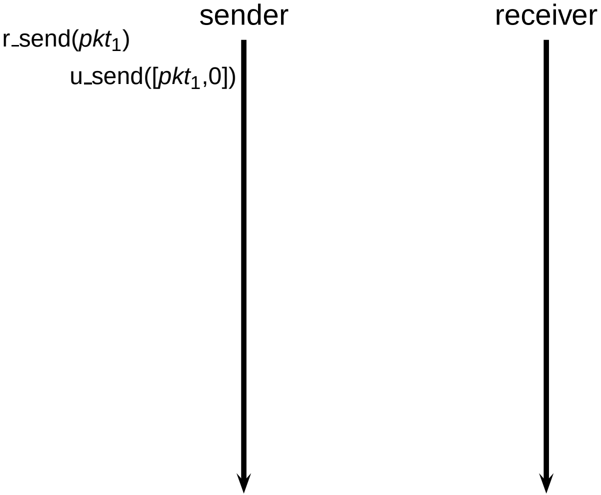

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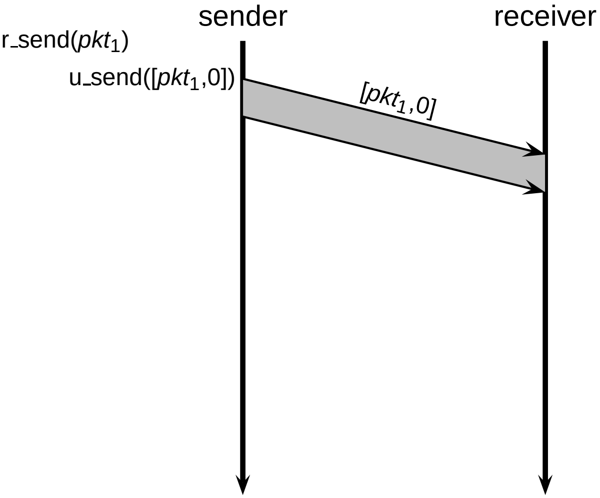

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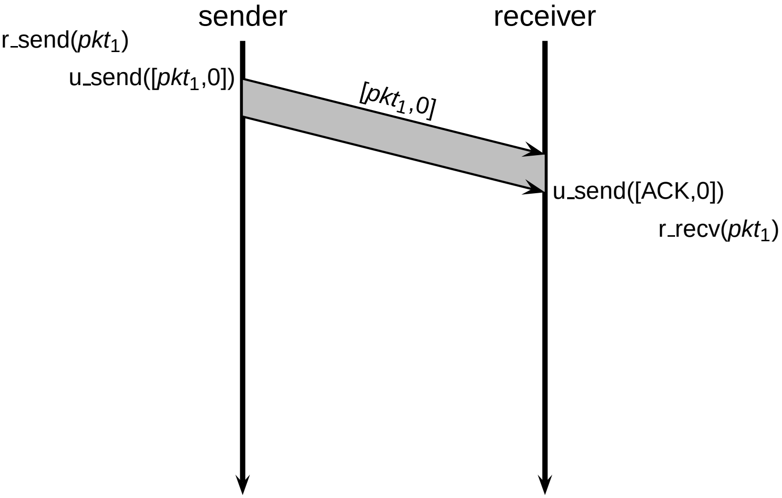

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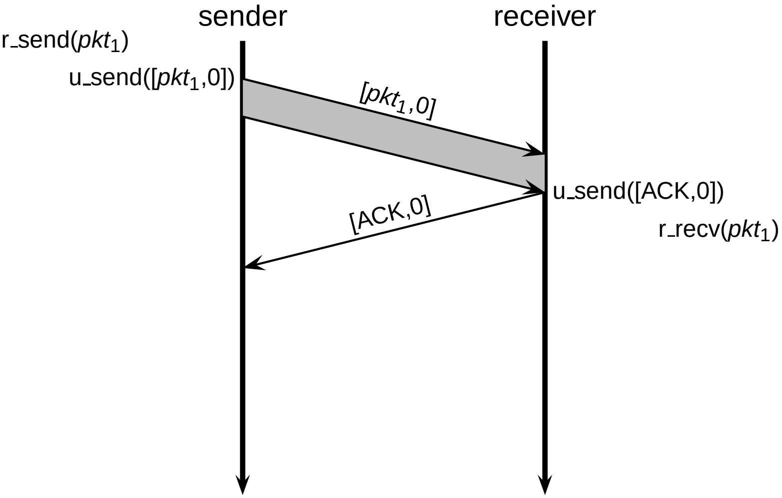

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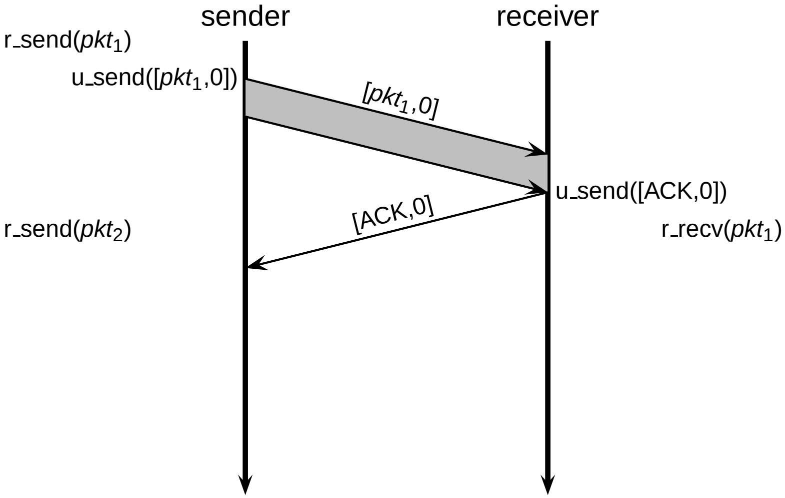

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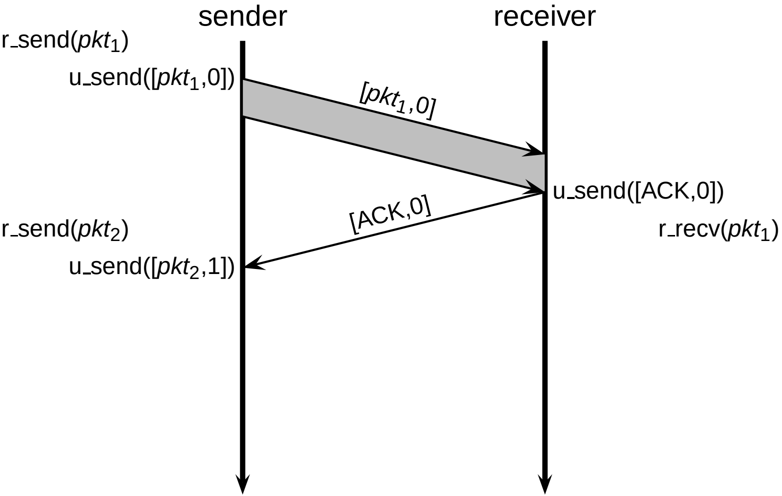

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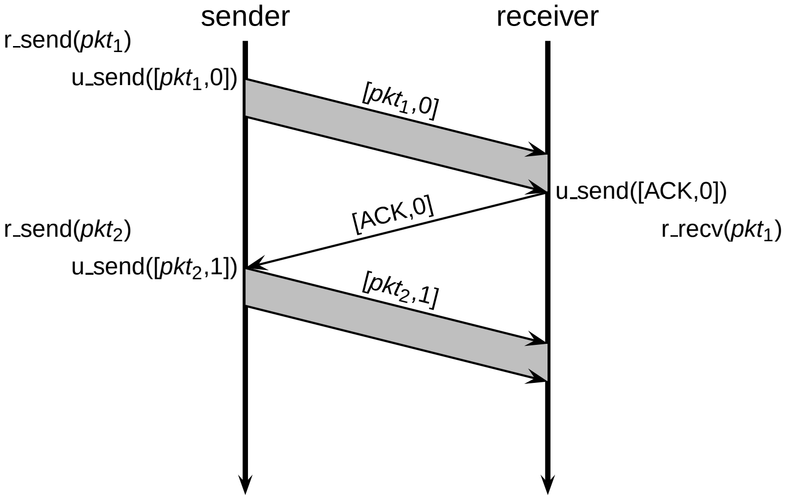

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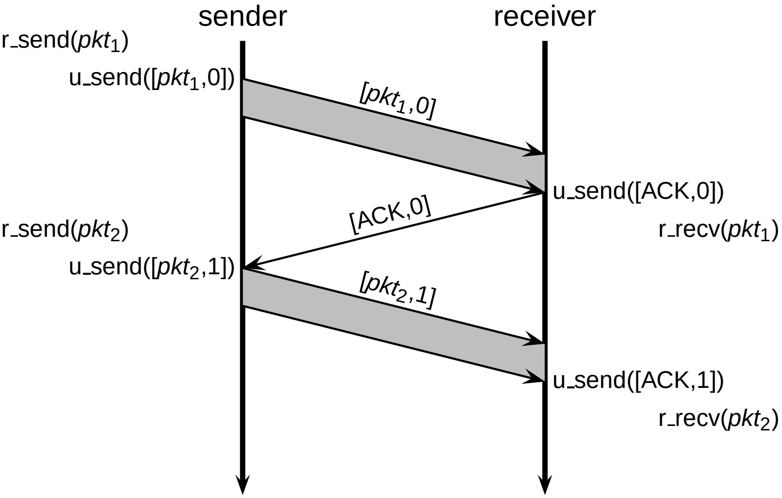

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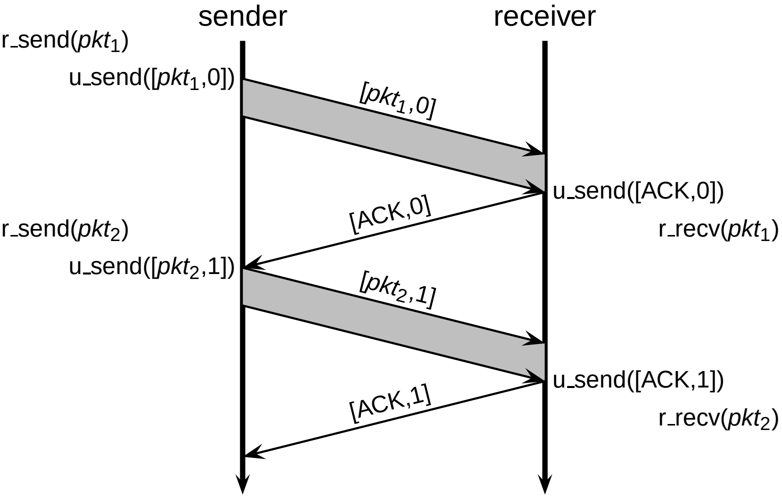

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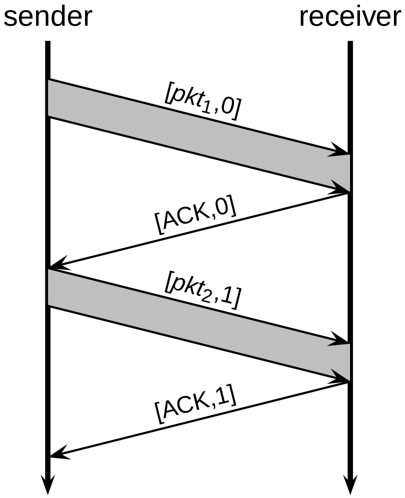

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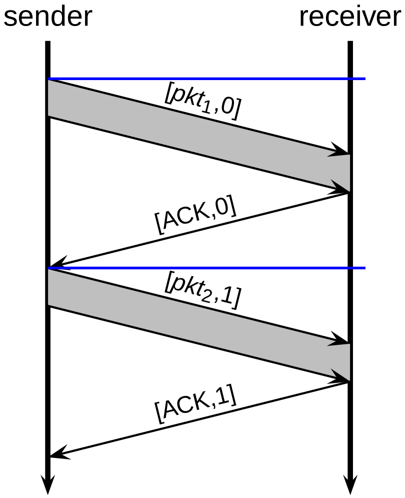

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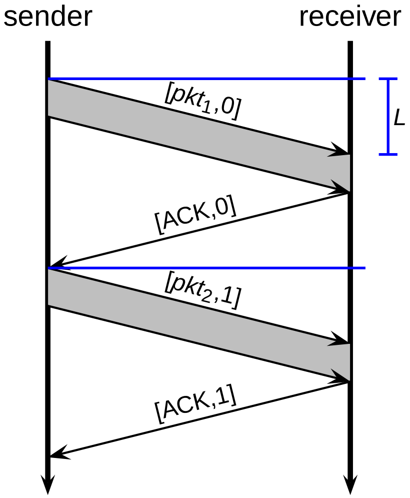

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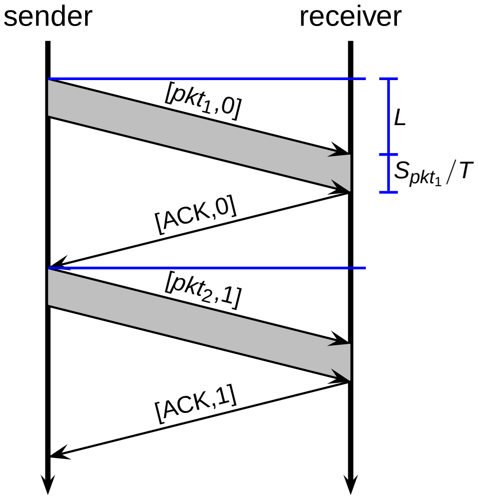

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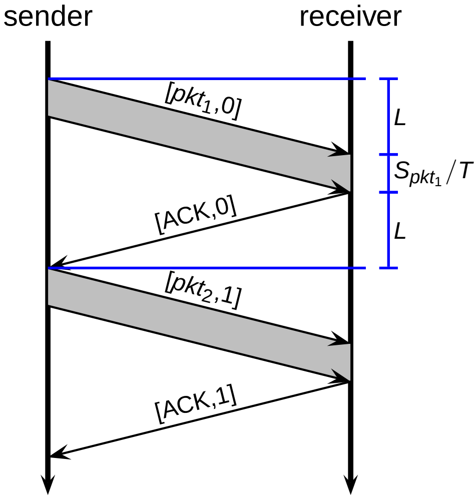
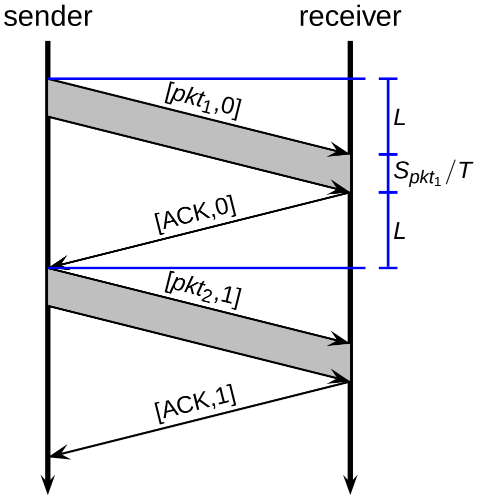


Network Usage

utilization factor

$$U = \frac{S_{pkt}/T}{2L+S_{pkt}/T}$$



Improving Network Usage

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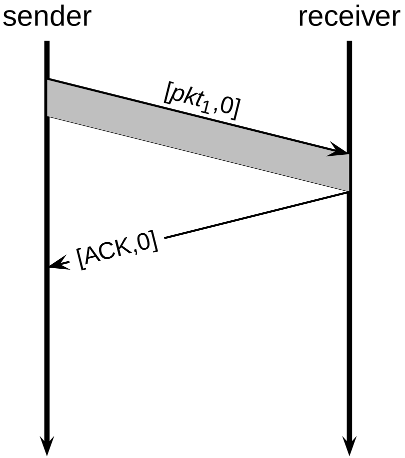

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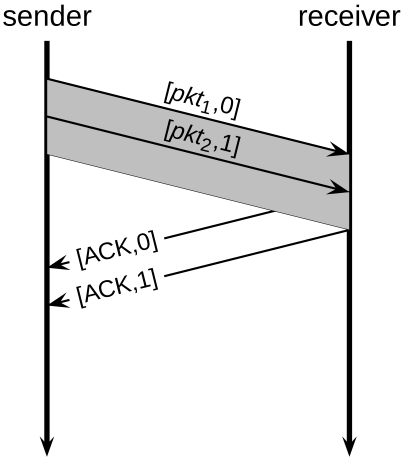

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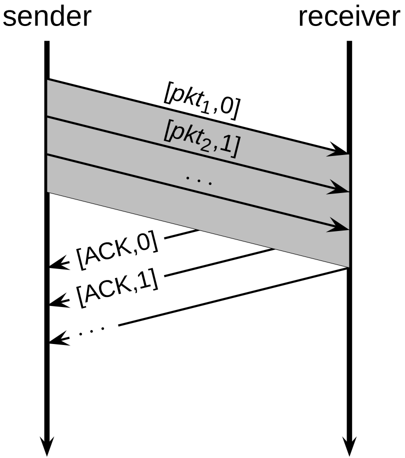

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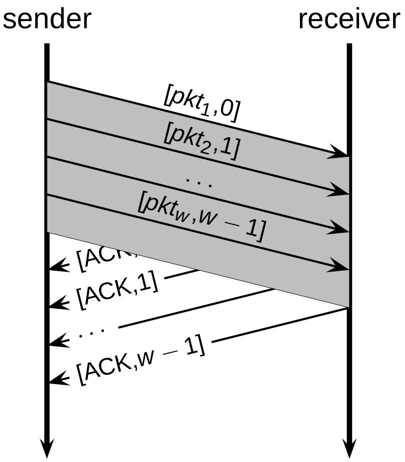

Go-Back-N

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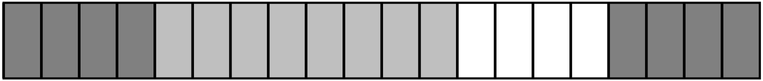

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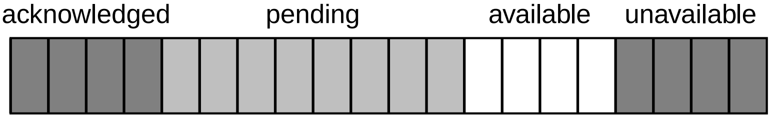

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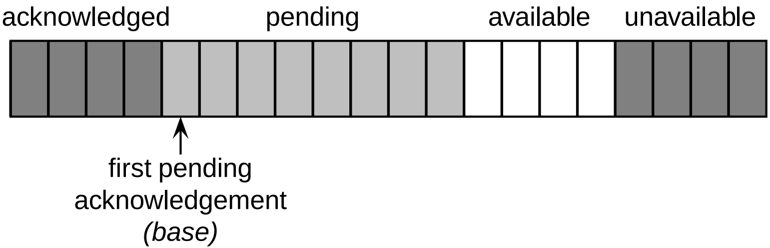

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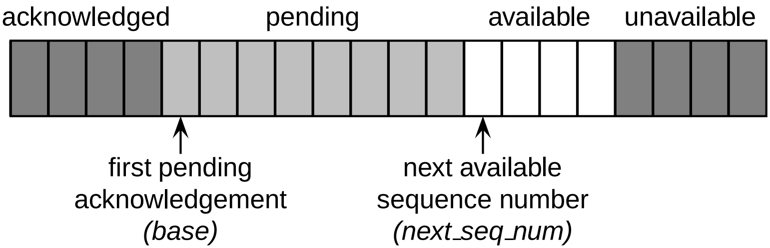

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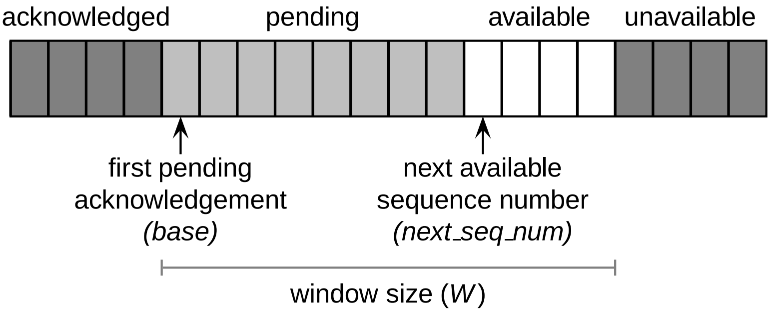
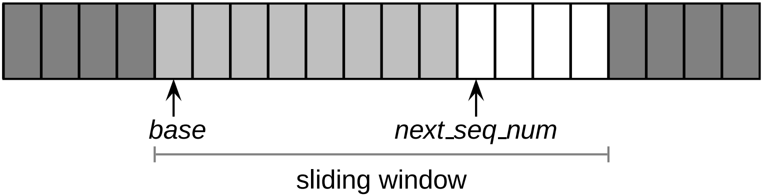


Sliding Window Protocol: Sender



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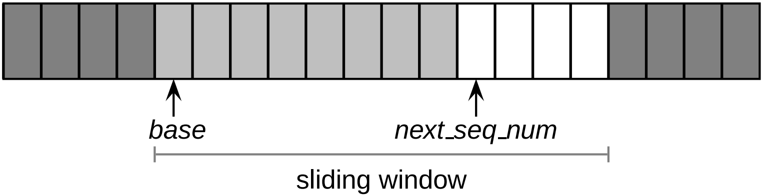

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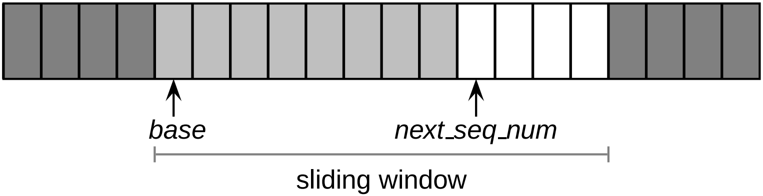

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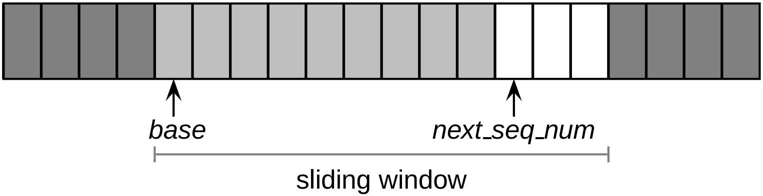

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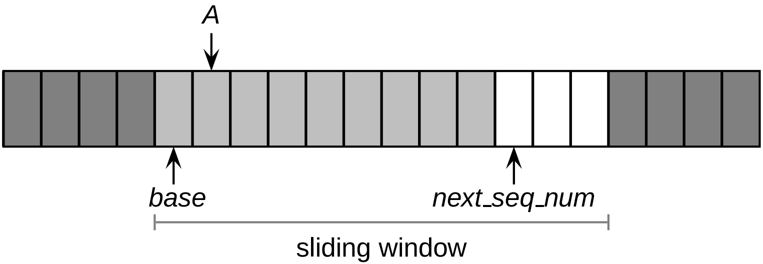

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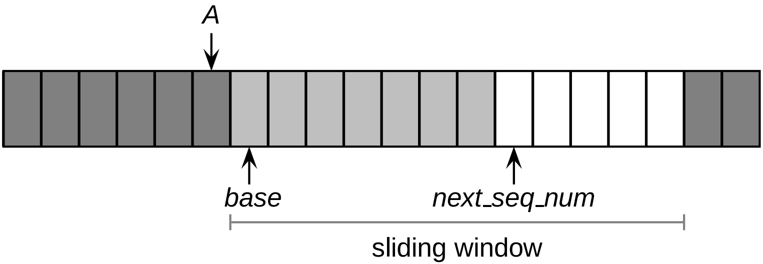

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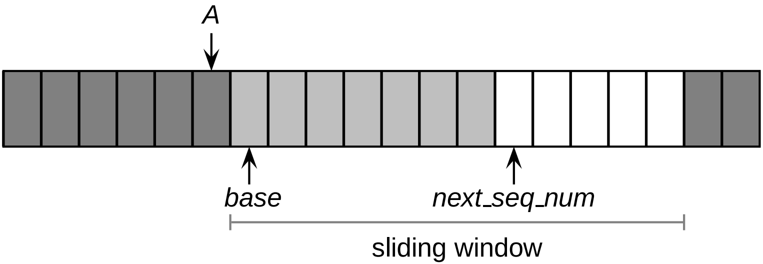

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  - notice that acknewledgements are "cumulative"

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  - or the highest acknowledged sequence number
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- The sender responds to three types of events

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  - *r_send():* invocation from the application layer: send more data if a sequence number is available
  - *ACK:* receipt of an acknowledgement: shift the window (it's a "cumulative" ACK)
  - *timeout:* "Go-Back-N." I.e., resend all the packets that have been sent but not acknowledged

Sliding Window Protocol: Sender

- $\dfrac{\textit{init}}{\begin{array}{l}\textit{base} \leftarrow 1 \\ \textit{next\_seq\_num} \leftarrow 1\end{array}}$

Sliding Window Protocol: Sender

- *init*

  $base \leftarrow 1$
  $next\_seq\_num \leftarrow 1$

- r_send(*data*)

  if ($next\_seq\_num < base + W$) {
     $pkt[next\_seq\_num] \leftarrow [next\_seq\_num, data]^*$
     u_send($pkt[next\_seq\_num]$)
     if ($next\_seq\_num = base$) {
        start_timer()
     }
     $next\_seq\_num \leftarrow next\_seq\_num + 1$
  } **else** {
     refuse_data(data)   *// block the sender*
  }

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---

base $\leftarrow$ *ack_num* $+ 1$ *// resume the sender*
if (*next_seq_num* $=$ *base*) $\{$
  stop_timer()
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Sliding Window Protocol: Sender

- u_recv(*pkt*) **and** *pkt* is corrupted
- u_recv(ACK,*ack_num*)

  base ← *ack_num* + 1 *// resume the sender*
  if (*next_seq_num* = *base*) {
     stop_timer()
  } **else** {
     start_timer()
  }
- timeout

  start_timer()
  foreach *i* **in** *base* . . . *next_seq_num* − 1 {
     u_send(*pkt*[*i*])
  }

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  - acknowledges the expected sequence number
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  - *sequence numbers*

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  - the receiver may buffer out-of-order packets. . .

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- The problem may seem a bit underspecified. What is the (average) packet size?

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  - $W \times S_{pkt} \leq 2L \times T$
    - why $W \times S_{pkt} > 2L \times T$ doesn't make much sense?
  - maximum channel utilization when $W \times S_{pkt} = 2L \times T$
  - $2L \times T$ can be thought of as the *capacity* of a connection

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  - $W \times S_{pkt} = 2L \times T = 1Mb$
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- Is there a better way to deal with retransmissions?

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  - in fact, receiver maintains a buffer of out-of-order packets
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  - sender slides the window when the lowest pending sequence number is acknowledged

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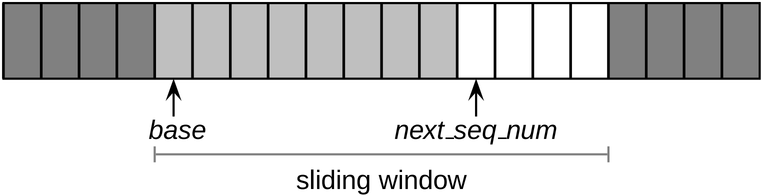

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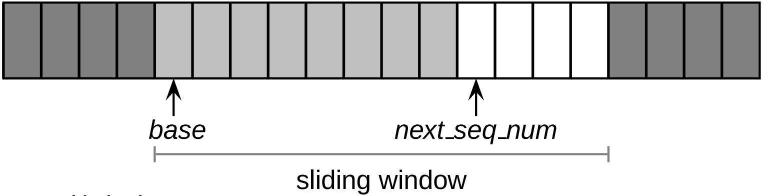

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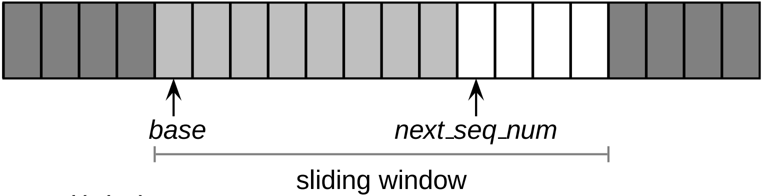

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  - u_send([pkt_1,*next_seq_num*])
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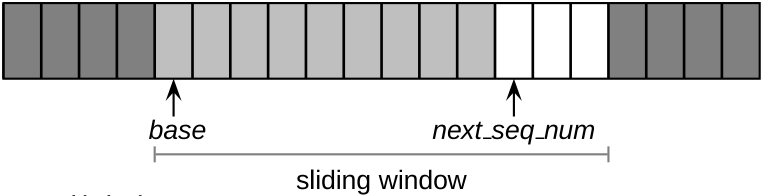

- r_send(pkt_1)
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  - start_timer($next\_seq\_num$)
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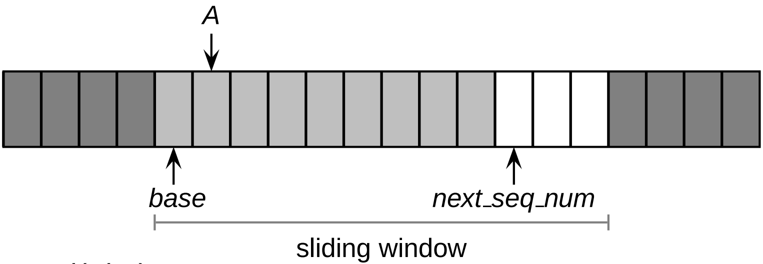

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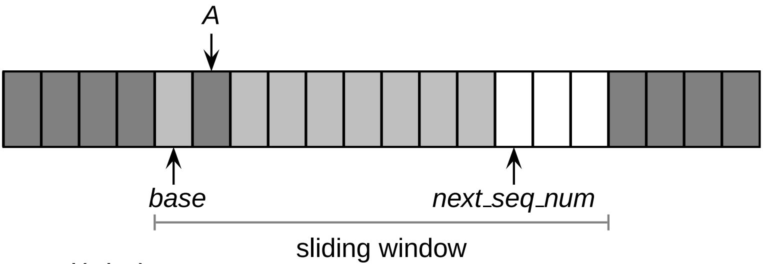

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- u_recv([ACK,A])
  - $acks[A] \leftarrow 1$ *// remember that A was ACK'd*

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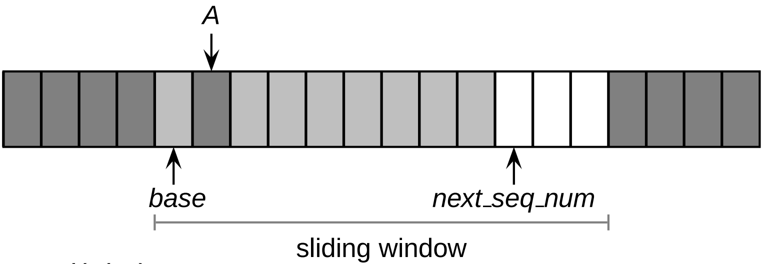

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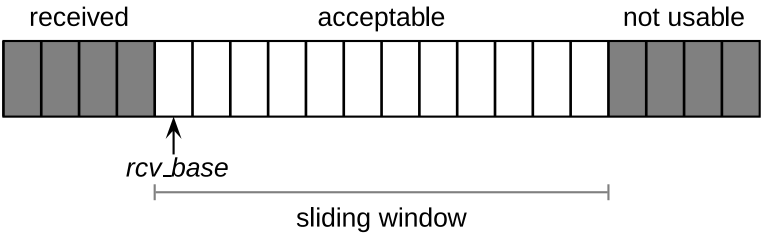

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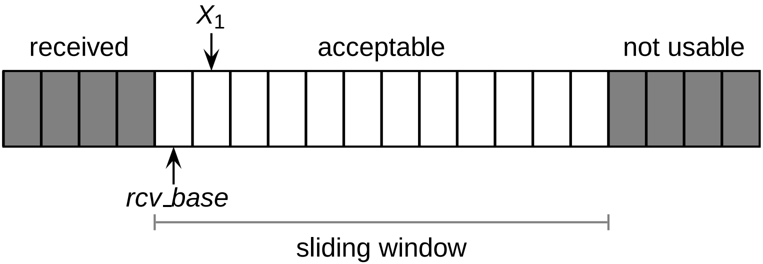
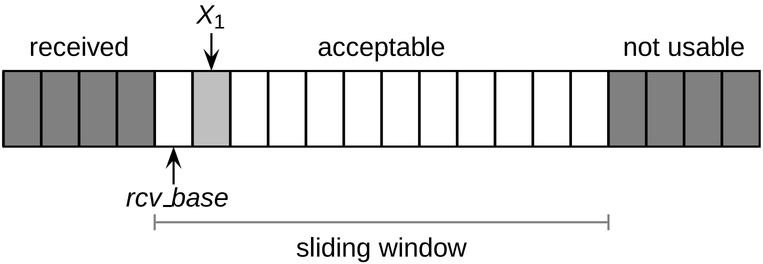


- u_recv([pkt_1,X_1]) **and** $rcv\_base \leq X_1 < rcv\_base + W$

Selective Repeat: Receiver



- u_recv([pkt_1,X_1]) **and** $rcv\_base \leq X_1 < rcv\_base + W$
  - $buffer[X_1] \leftarrow pkt_1$
  - u_send([$ACK, X_1]^*$)   *// no longer a "cumulative" ACK*

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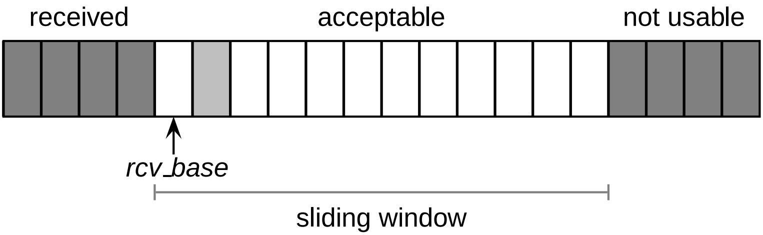

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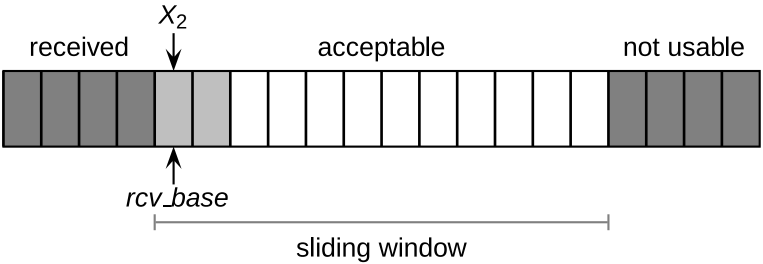
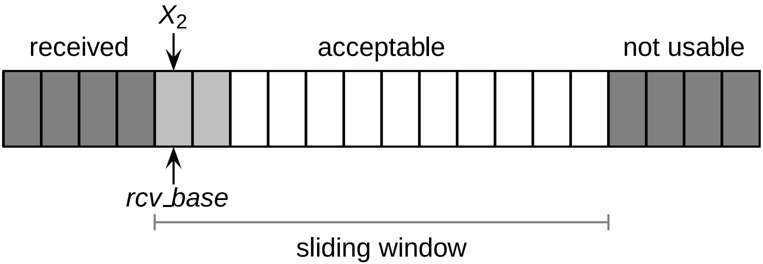


- u_recv([pkt_2,X_2]) **and** $rcv\_base \leq X_2 < rcv\_base + W$
  - $buffer[X_2] \leftarrow pkt_2$
  - u_send([ACK, X_2]*)

Selective Repeat: Receiver



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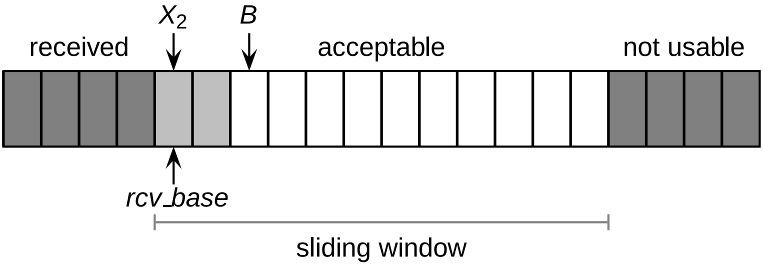

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    foreach i **in** $rcv\_base \ldots B - 1$ $\{$
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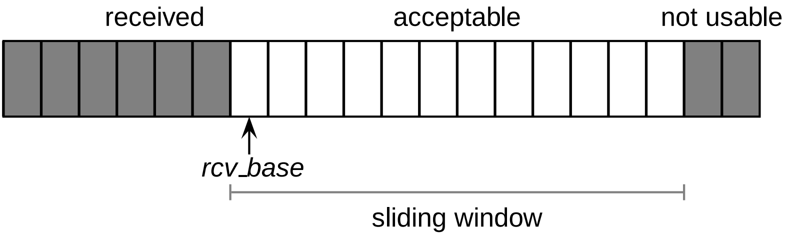

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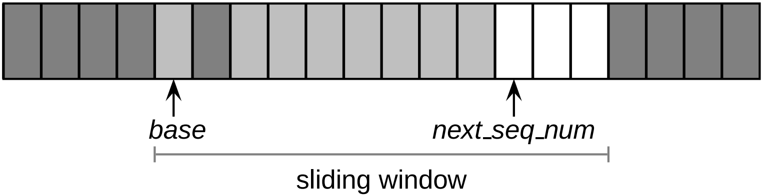

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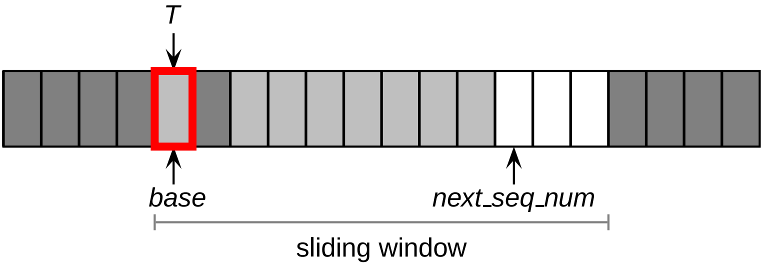

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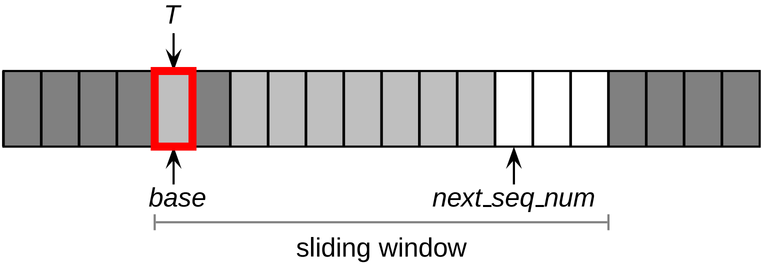

- Timeout for sequence number T
  - u_send($[pkt[T], T]^*$)

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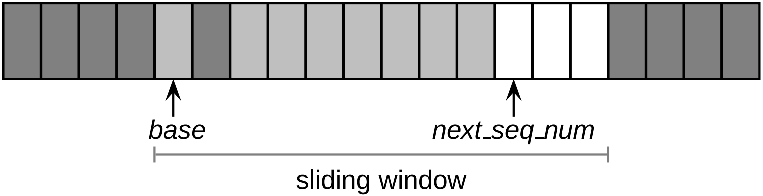

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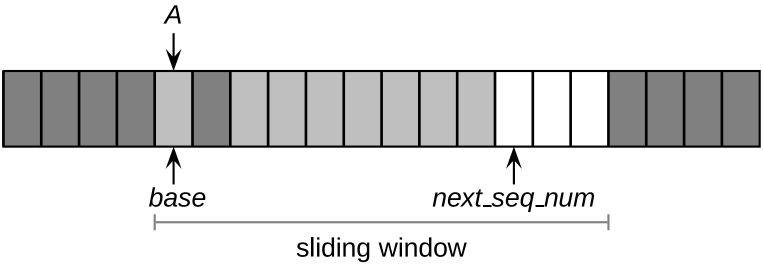

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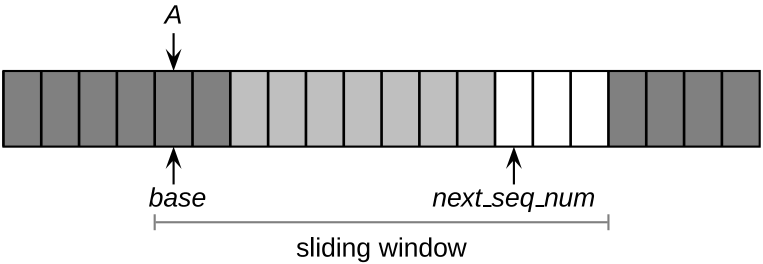

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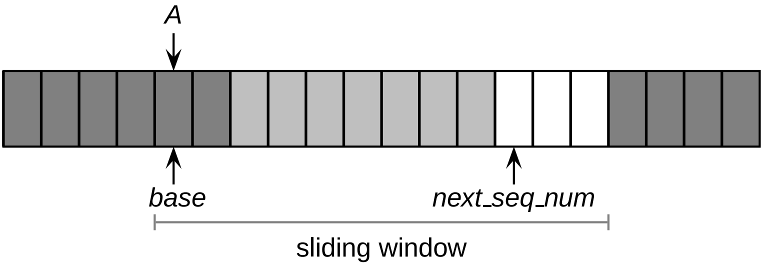

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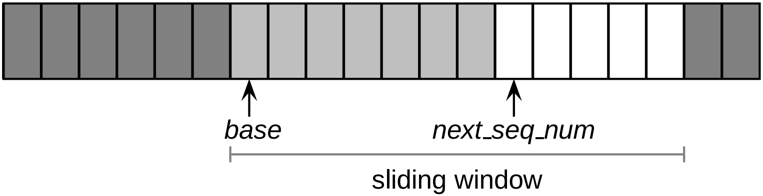

- u_recv([ACK,A])
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    $base \leftarrow first\_missing\_ack\_num()$ $\}$

Part III

Congestion Control

Understanding Congestion

- A router behaves a lot like a kitchen sink

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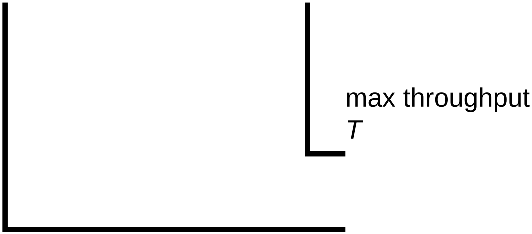

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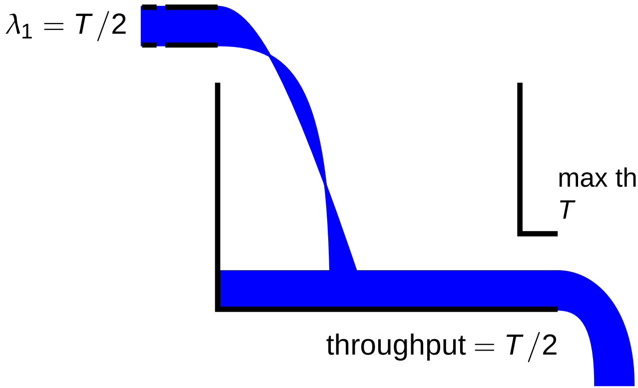

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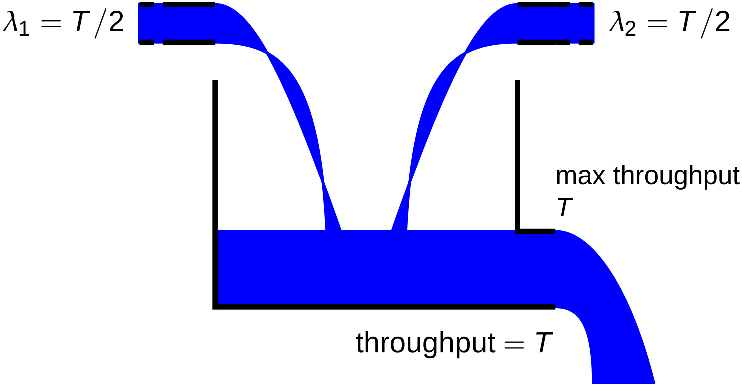

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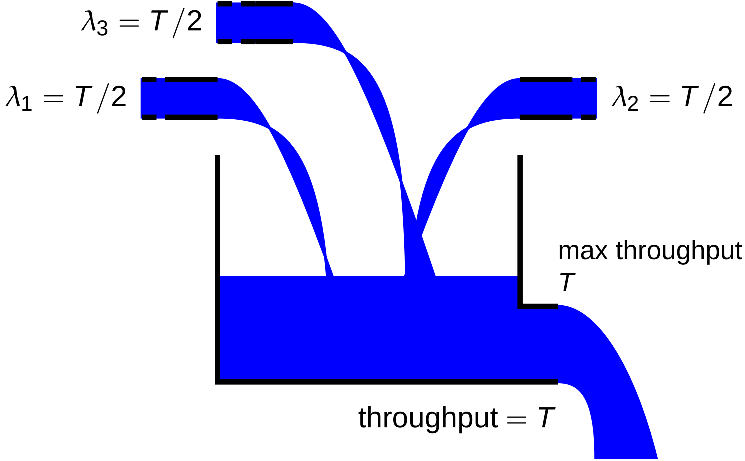

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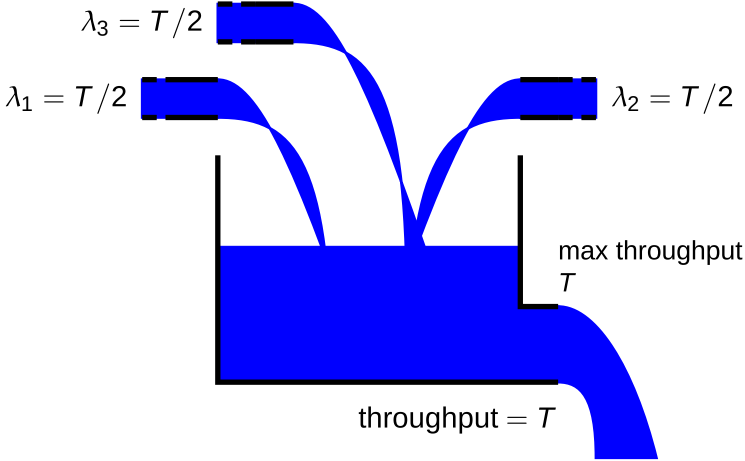

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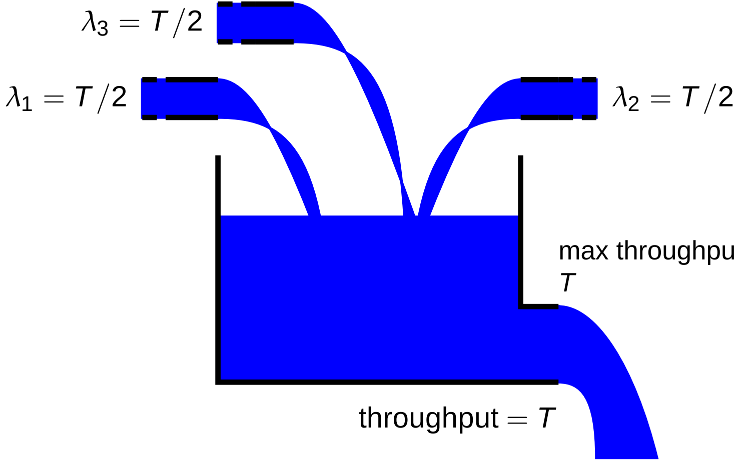

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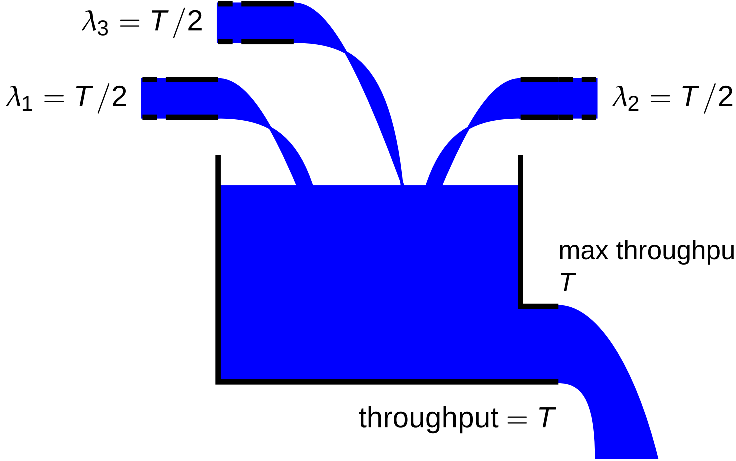

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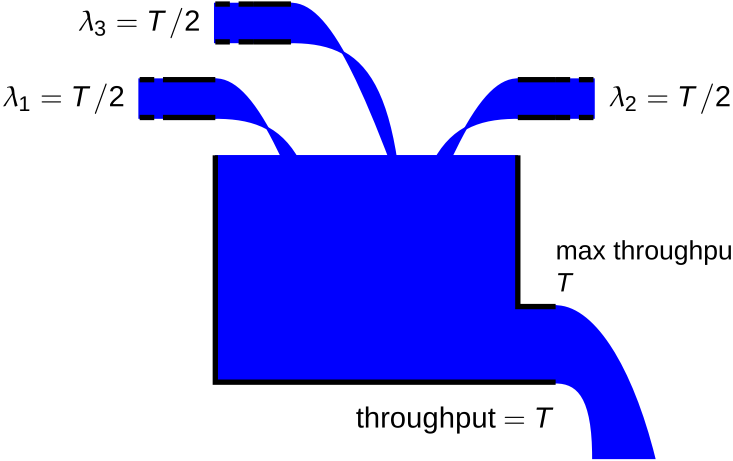

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In this case $|q| = (\lambda_{in} - T)t$ and therefore

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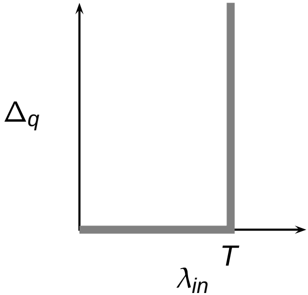

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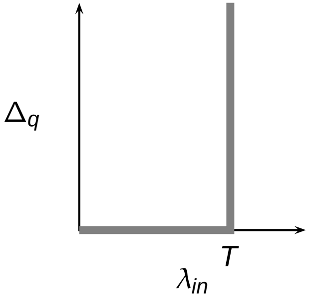

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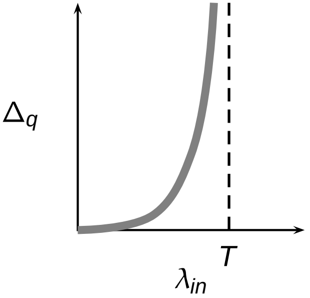

realistic input flow
λ_{in} variable

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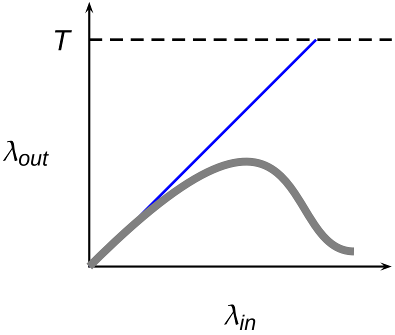

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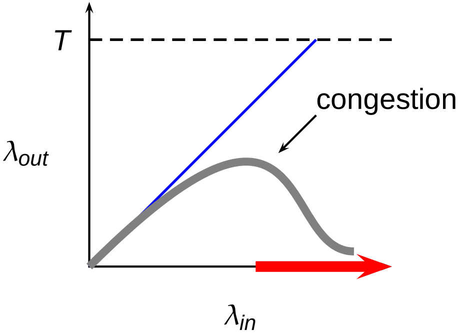

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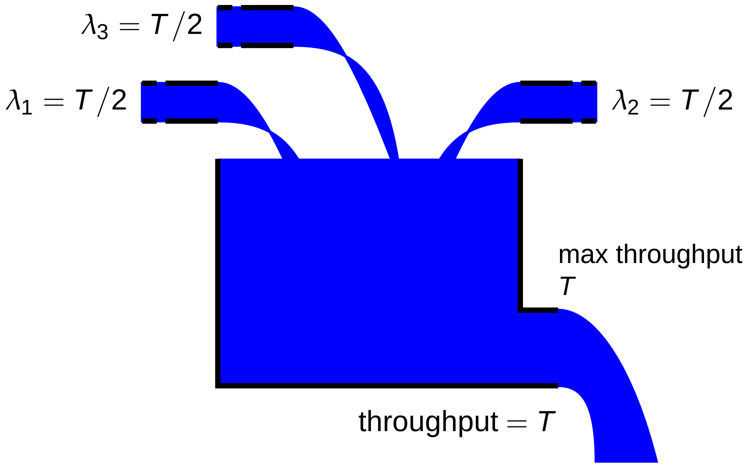

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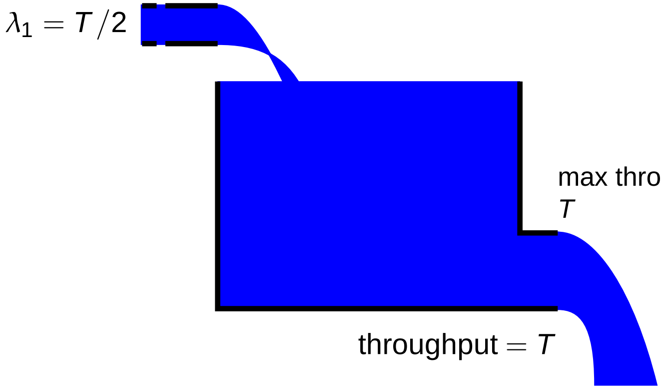

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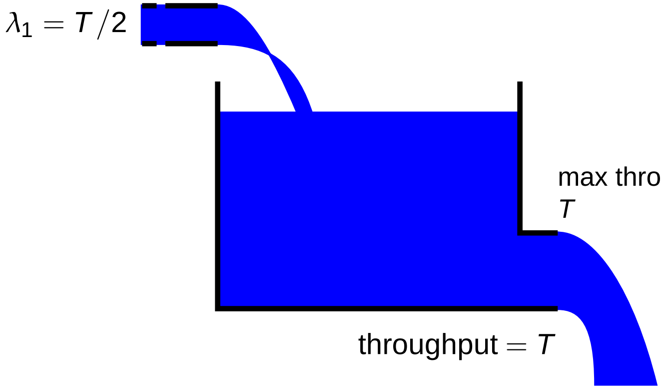

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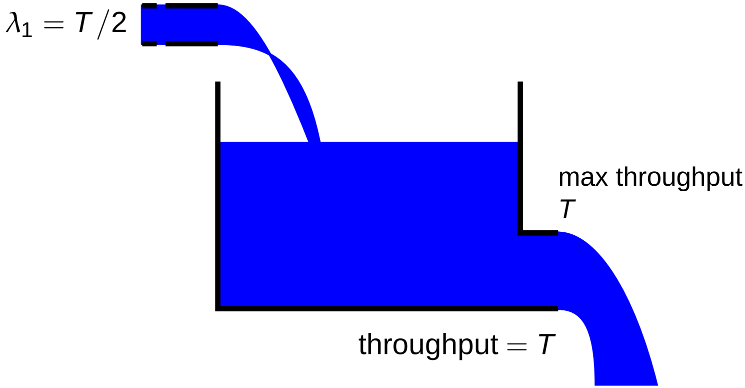

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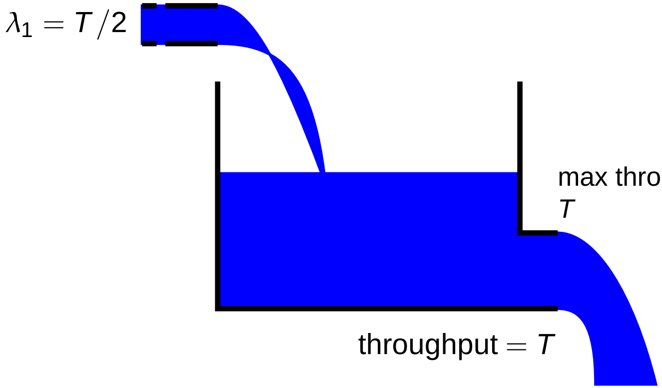

Part IV

Brief Overview of TCP

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- Full-duplex service
  - both endpoints can both send and receiver, at the same time

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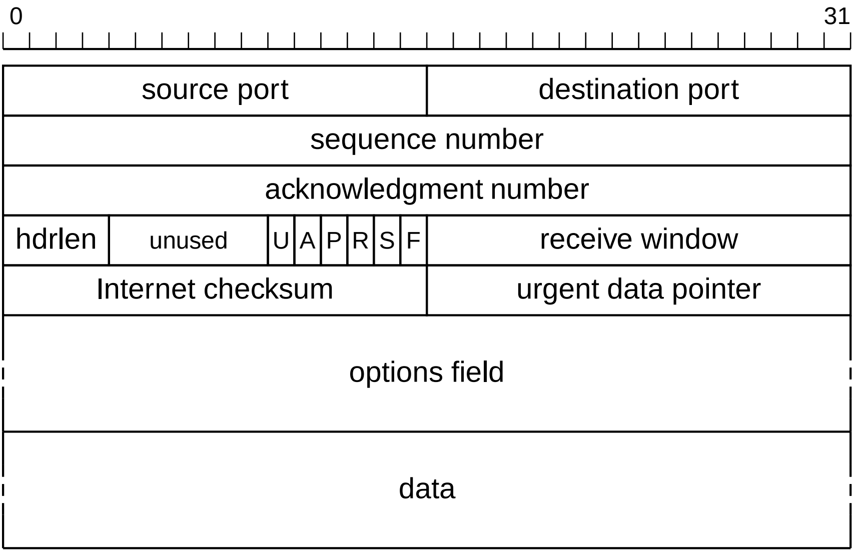
- *Maximum transmission unit (MTU):* largest link-layer frame available to the sender host
  - *path MTU:* largest link-layer frame that can be sent on all links from the sender host to the receiver host

TCP Segment Format



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- *Checksum:* (16-bit) used to detect transmission errors

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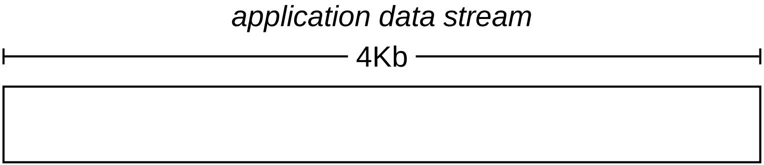

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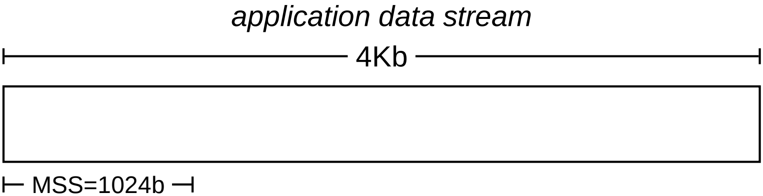

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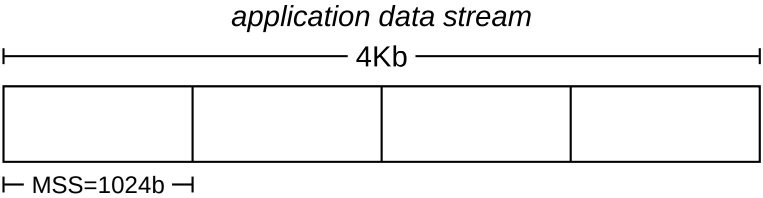

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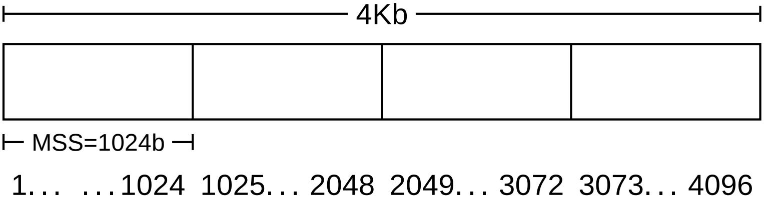

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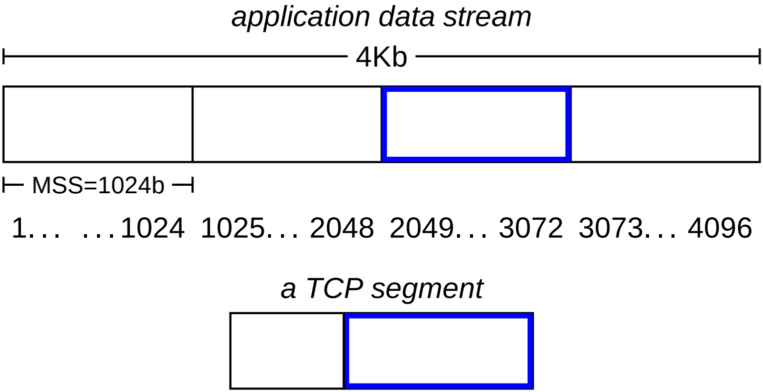

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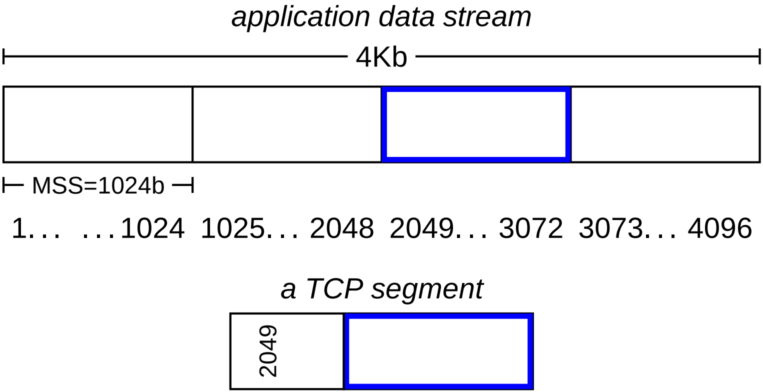

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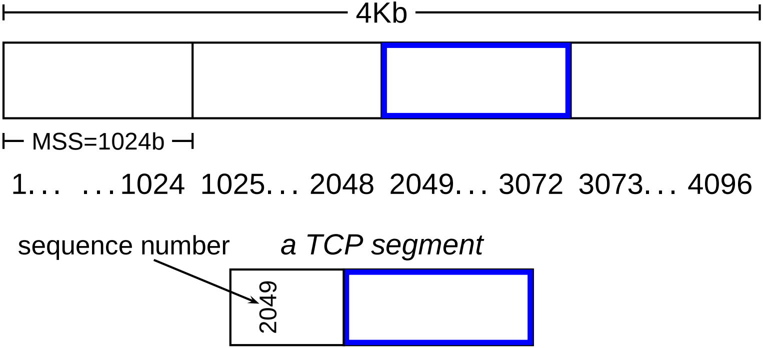

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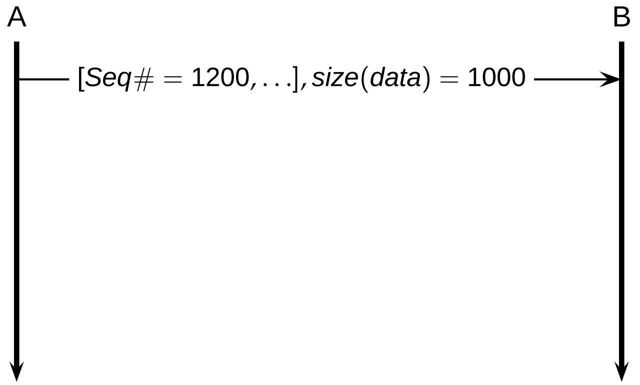

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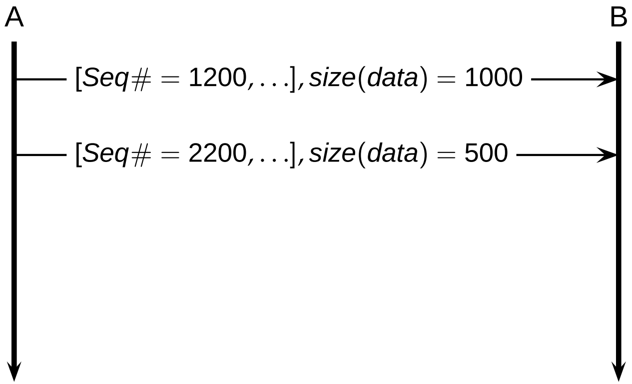

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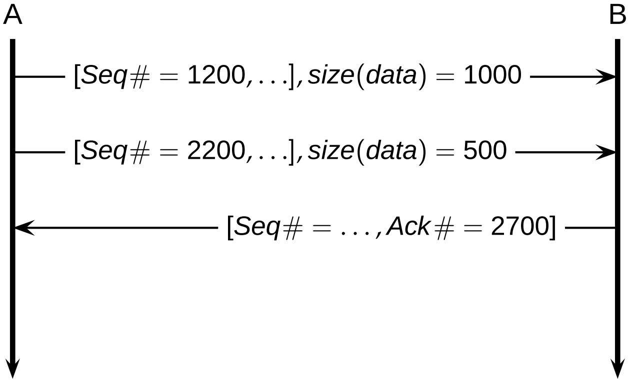

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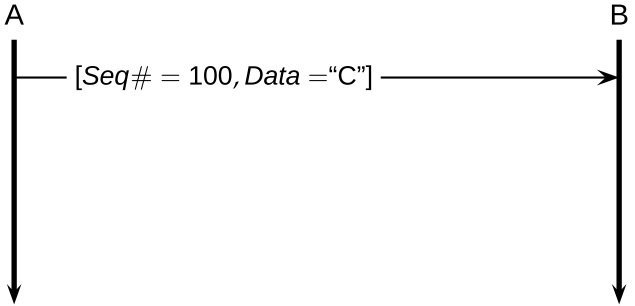

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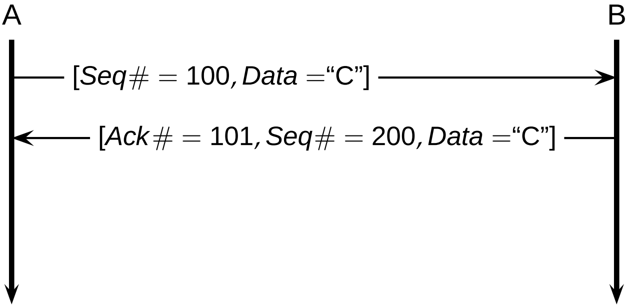

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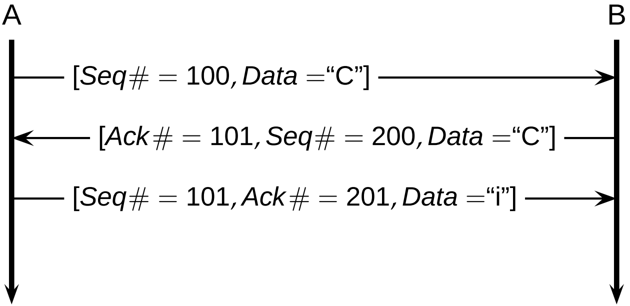

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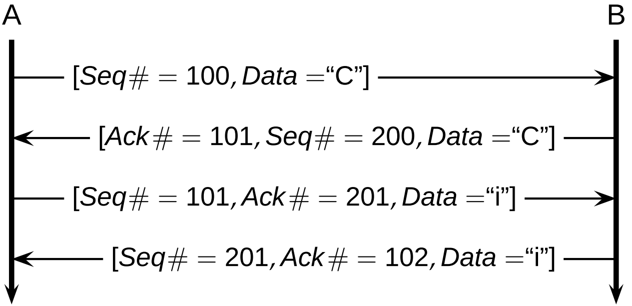

Sequence Numbers and ACK Numbers

- Notice that a TCP connection consists of is a *full-duplex* link
  - therefore, there are *two streams*
  - two different sequence numbers

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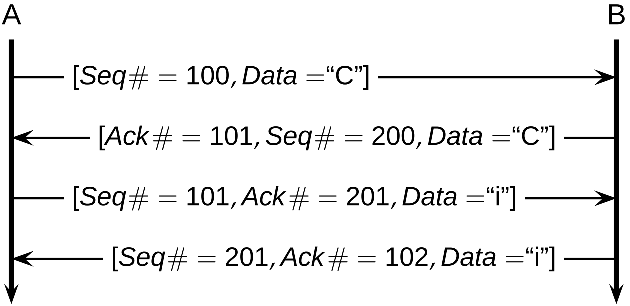

- Acknowledgments are “piggybacked” on data segments

Reliability and Timeout

- TCP provides reliable data transfer using a *timer* to detect lost segments
  - timeout without an ACK $\rightarrow$ lost packet $\rightarrow$ retransmission

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- TCP controls its timeout by continuously *estimating the current RTT*

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- Given a single sample S at any given time
- *Exponential weighted moving average (EWMA)*

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  - so as to detect (and retransmit) lost segments as quickly as possible
- TCP sets its timeouts using the estimated RTT ($\overline{RTT}$) and the variability estimate $\overline{DevRTT}$:

$$T = \overline{RTT} + 4\overline{DevRTT}$$

Reliable Data Transfer (Sender)

A simplified TCP sender

- r_send(*data*)

  ---

  if (timer not running)

      start_timer()

  u_send([*data*,*next_seq_num*])

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- u_recv([ACK,*y*])

  if ($y > base$)
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Reaction to ACKs (Sender)

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- u_recv([ACK,*y*])

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if ($y > base$)
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else
  $ack\_counter[y] \leftarrow ack\_counter[y] + 1$
  if ($ack\_counter[y] = 3$)
    u_send(segment with sequence number y)

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Three-way handshake

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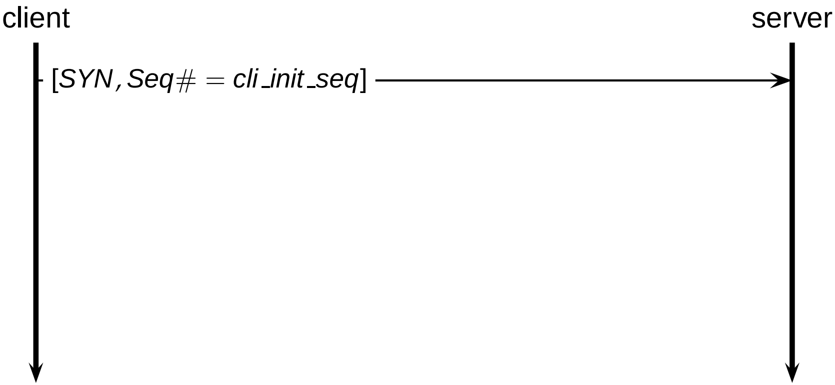

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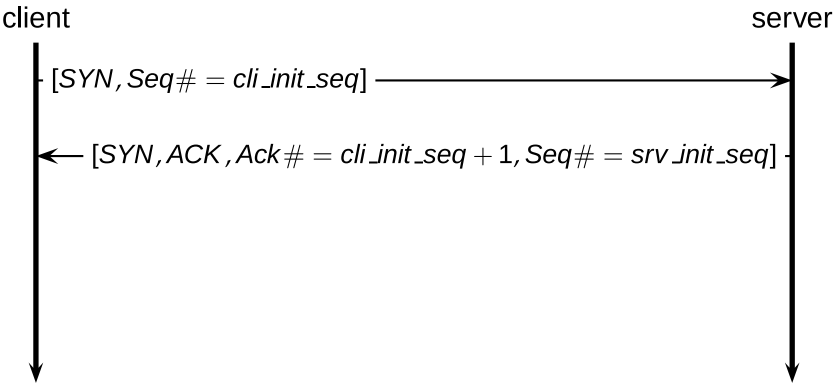

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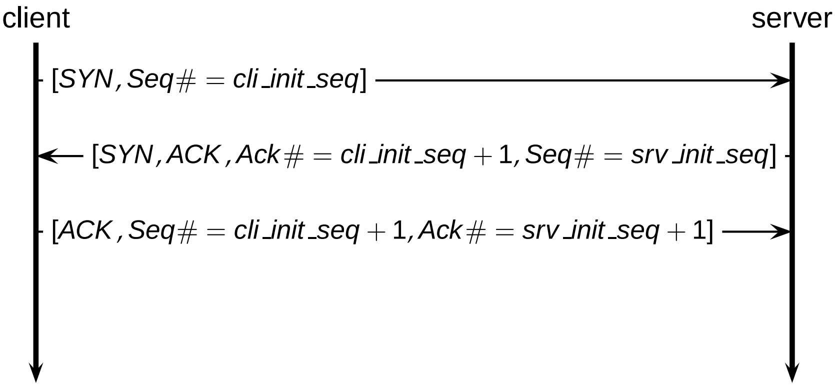

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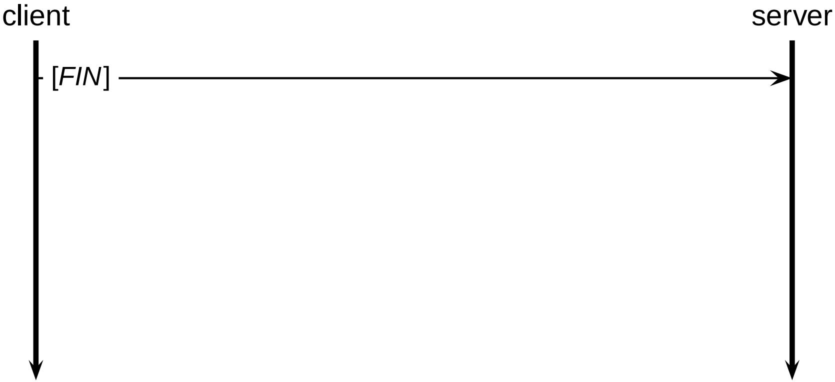

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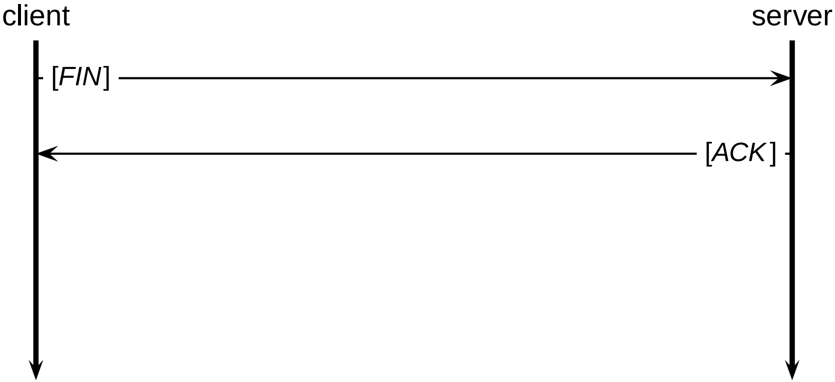

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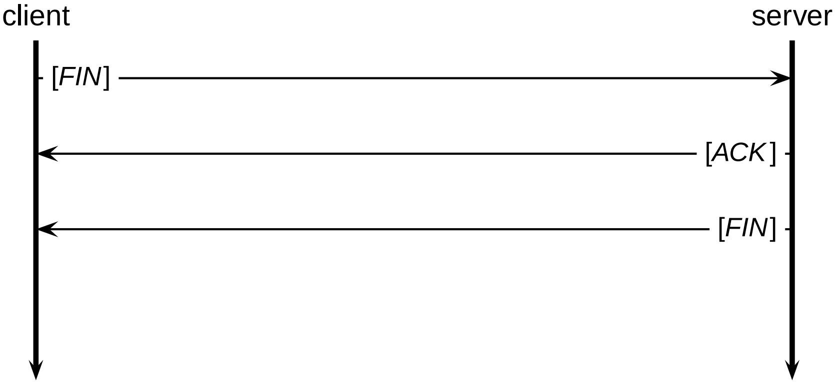

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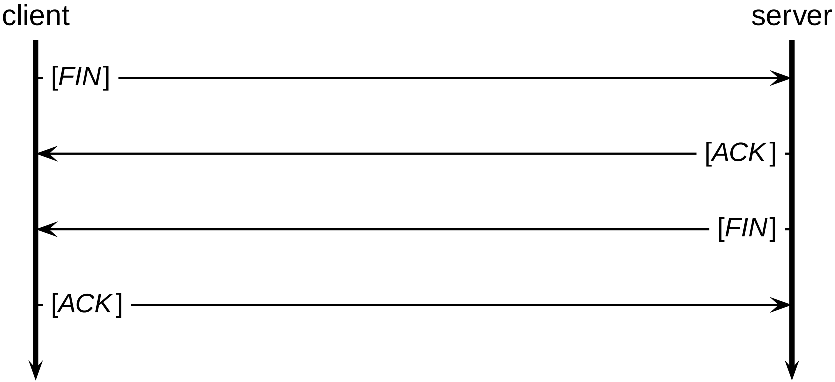

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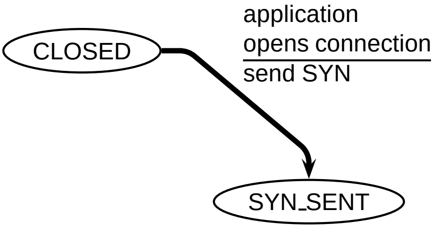

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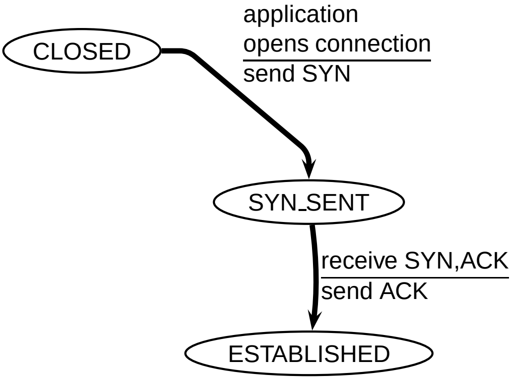

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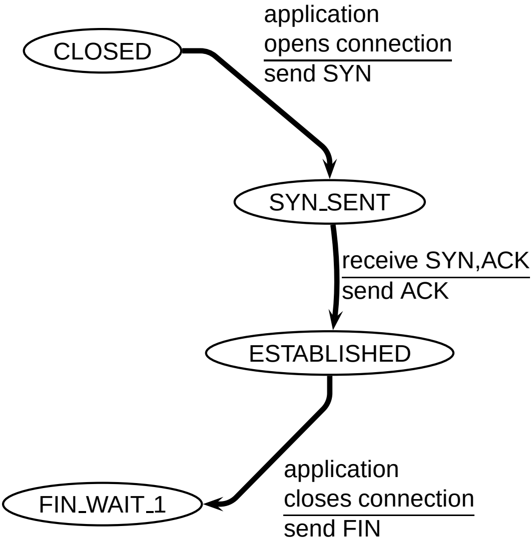

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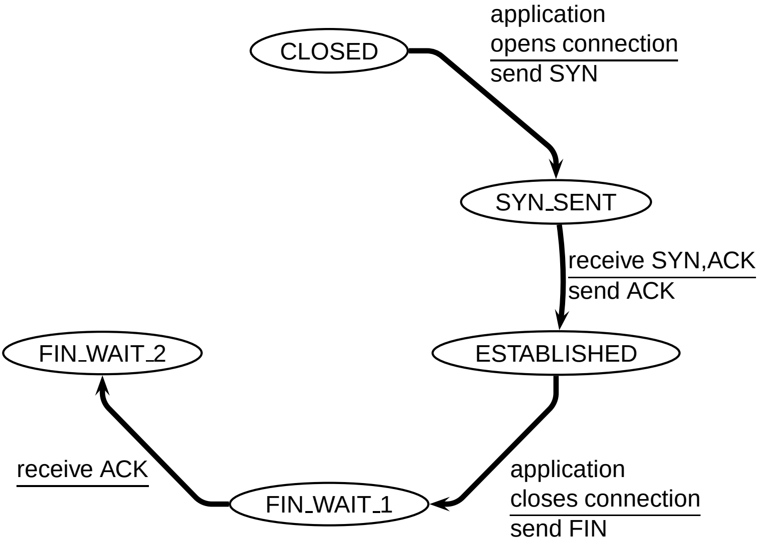

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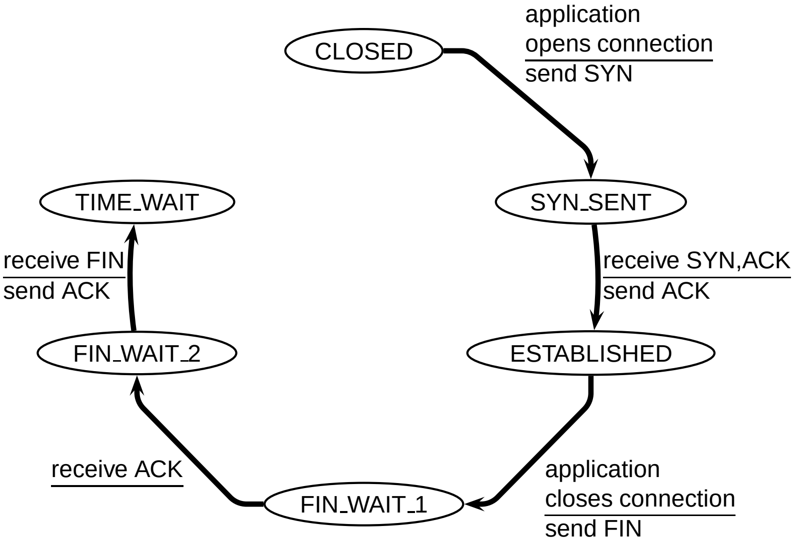

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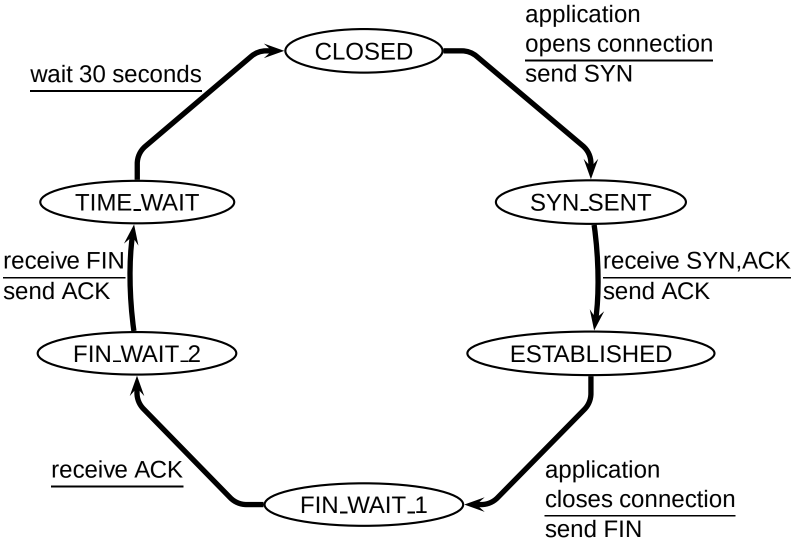

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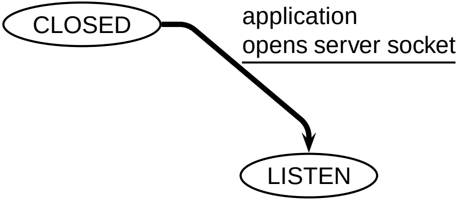

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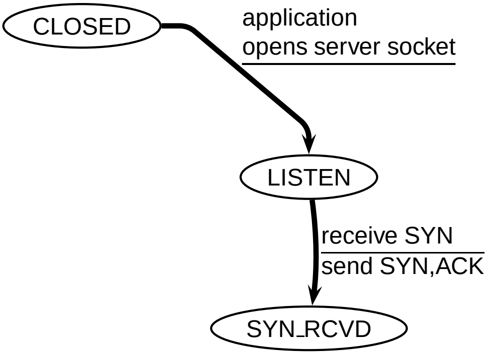

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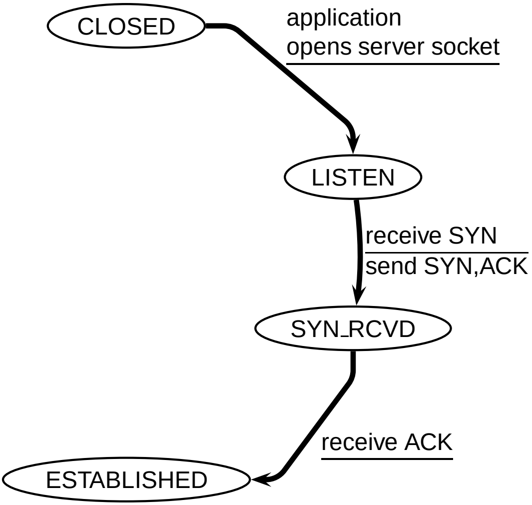

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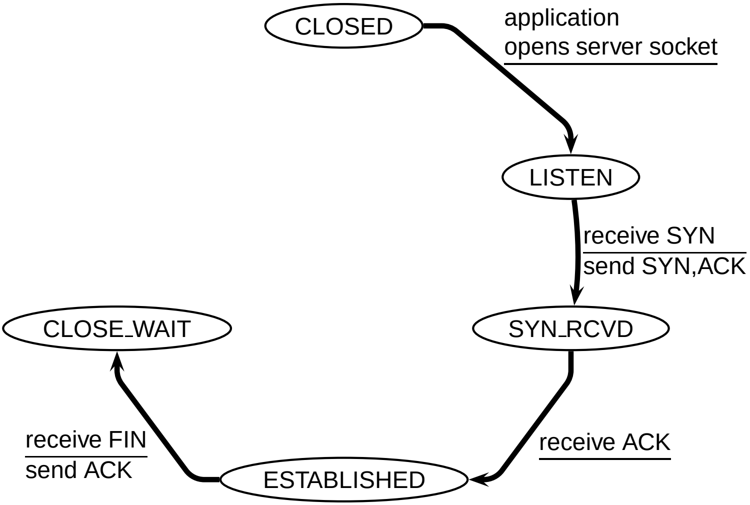

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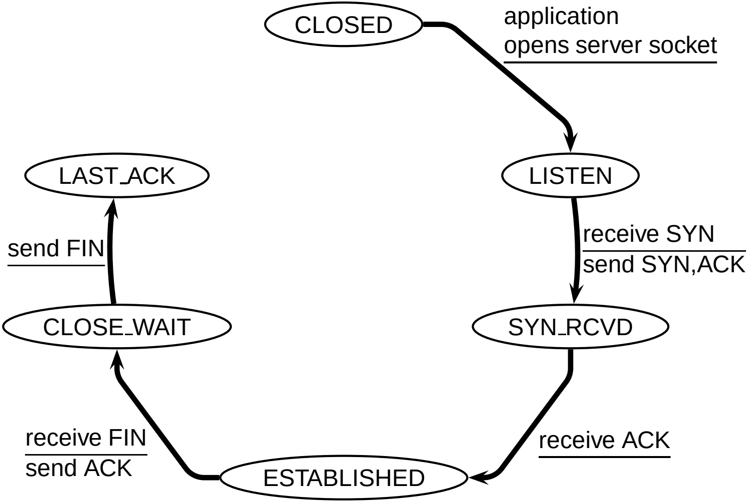

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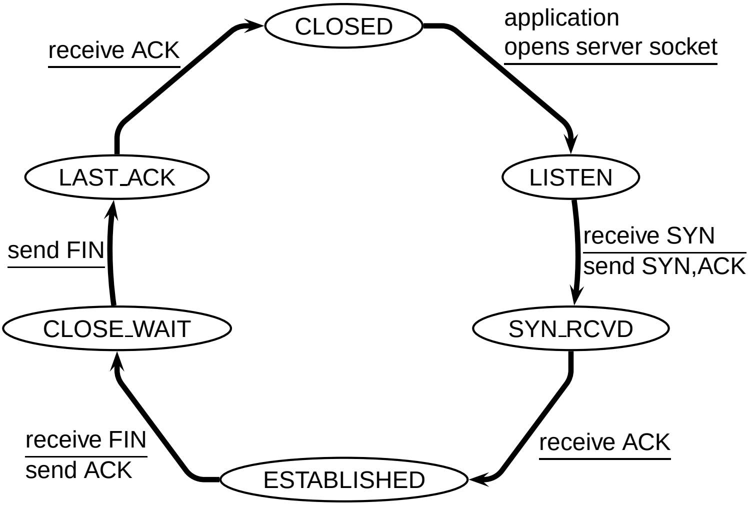

Part V

Congestion Control in TCP

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    - i.e., how does the sender detect congestion?
  - how does the sender effectively limit its output rate?
  - how should the sender "modulate" its output rate?
    - i.e., what algorithm should the sender use to decrease or increase its output rate?

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- If all traffic is correctly acknowledged, then the sender assumes (quite correctly) that there is no congestion
- Congestion means that queue overflow in one or more routers between the sender and the receiver
  - the visible effect is that some segments are dropped
- Therefore the server assumes that the network is congested when it detects a segment loss
  - time out (i.e., no ACK)
  - multiple acknowledgements (i.e., NACK)

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- The resulting maximum output rate is roughly

$$\lambda = \frac{W}{2L}$$

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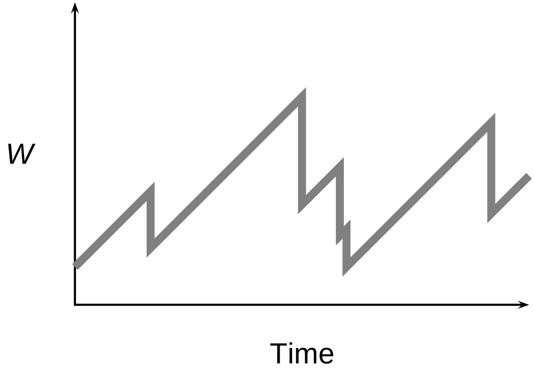
Additive-Increase/Multiplicative-Decrease

- Window size W over time



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- This process is called *slow start*, because of the small initial value of W

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- So, TCP reacts differently to a timeout and to a triple duplicate ACKs

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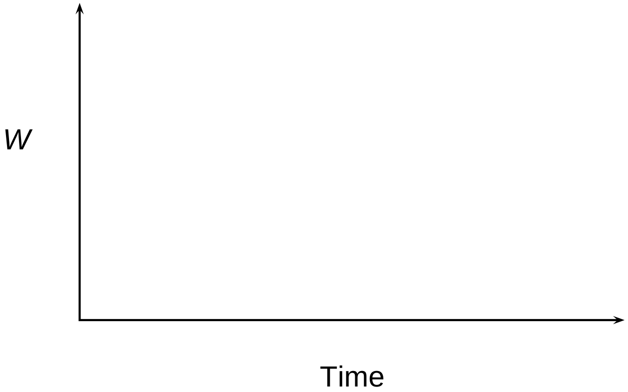
- *NACK*
  - cut W in half: $W = \overline{W}/2$
  - run *congestion avoidance*, ramping up W linearly
  - This is called *fast recovery*

Sender Behavior



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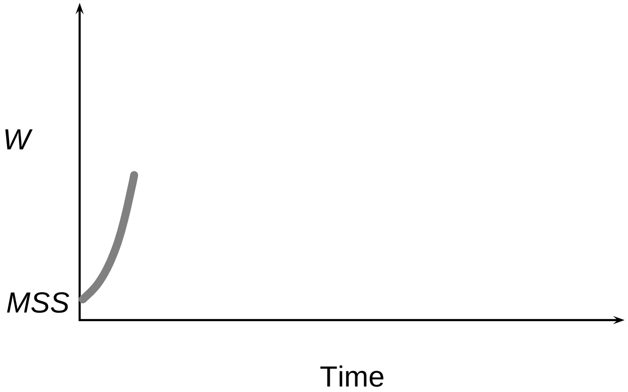

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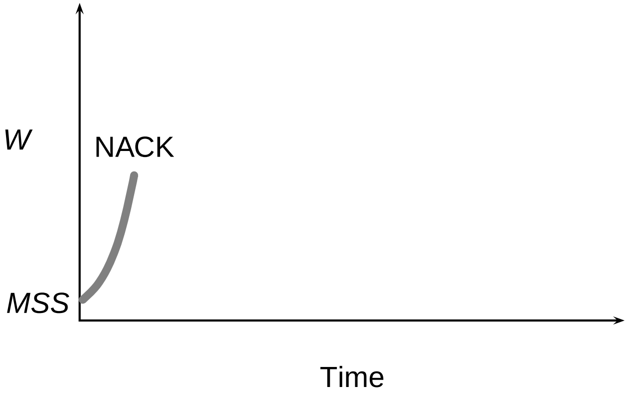

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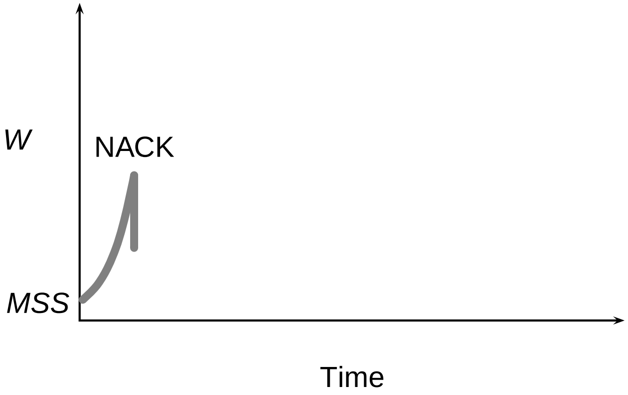

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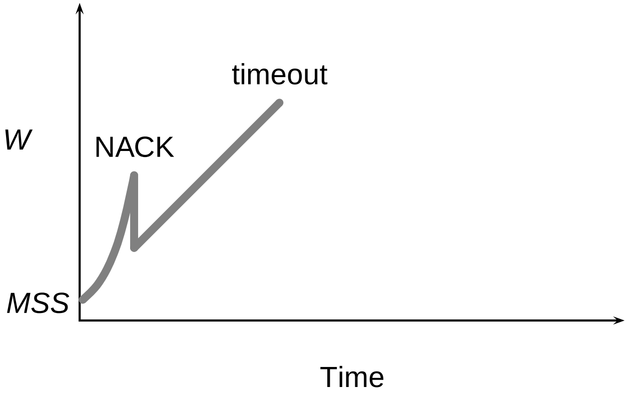

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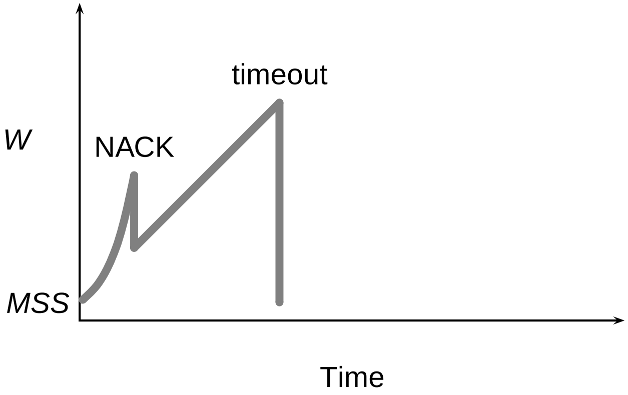
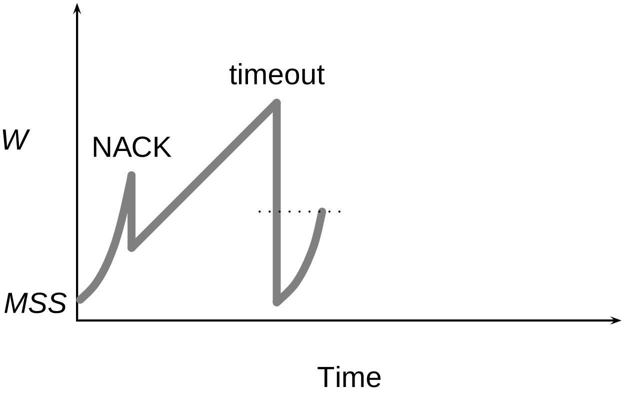
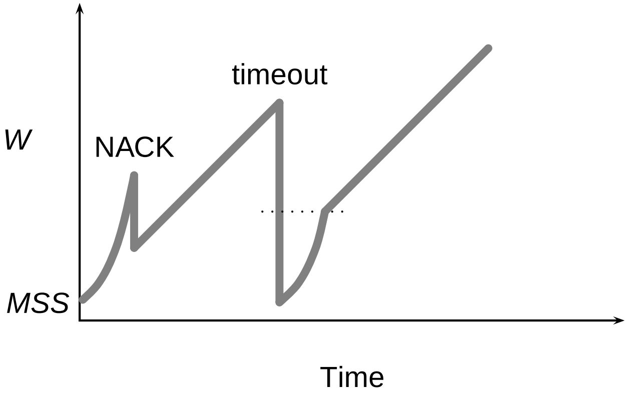


Sender Behavior



Sender Behavior



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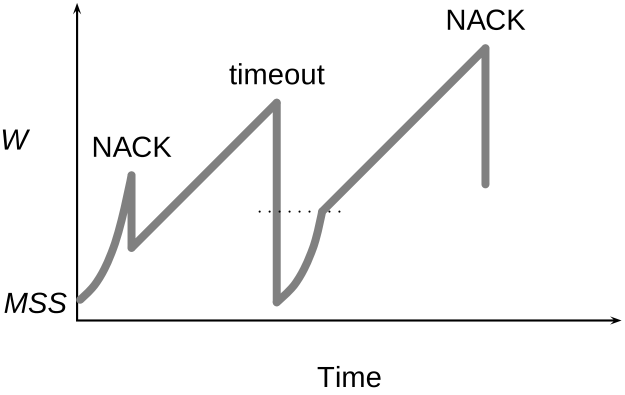
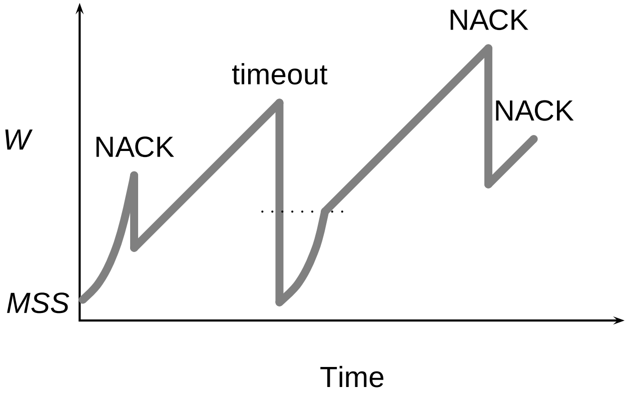


Sender Behavior



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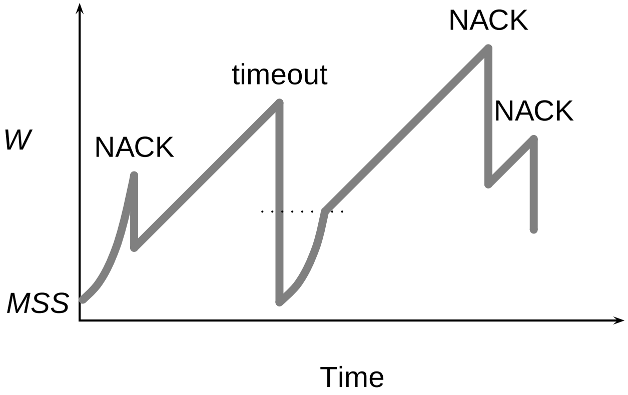
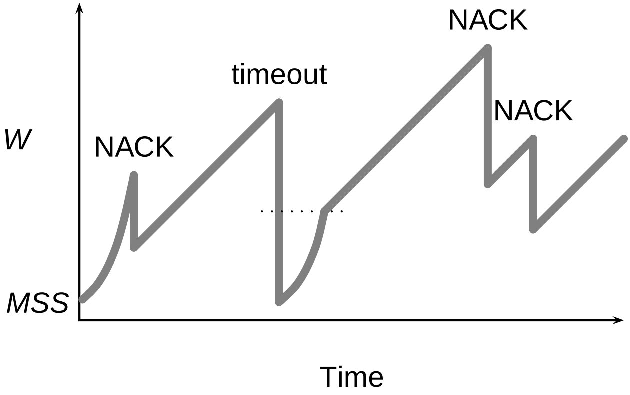


Sender Behavior



Sender Behavior

SS=*slow start* CA=*congestion avoidance*