A Quick Review of Computer Networking

Architecture, Applications, Transport (TCP), Routing

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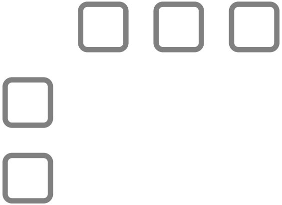
What is *Inside* the Internet?



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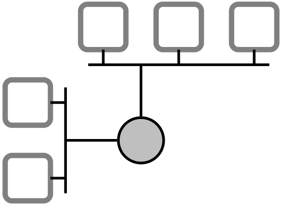

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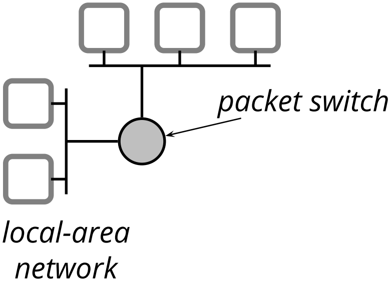

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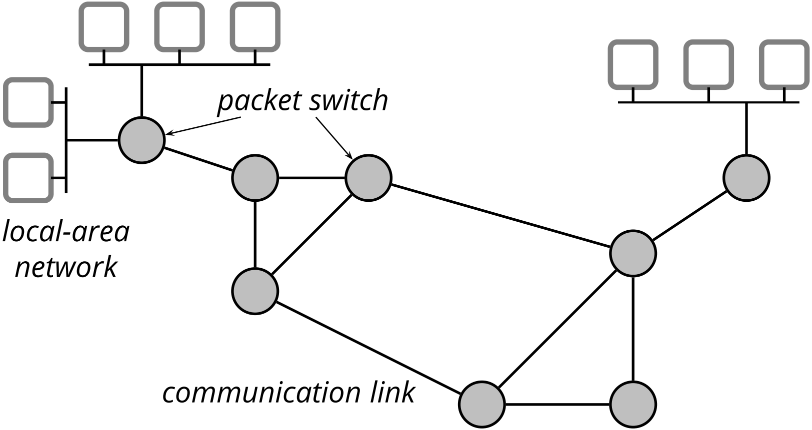

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Basic Concepts

- The Internet uses ***packet switching***
- ***Packet switch:*** a *link-layer switch* or a ***router***
- ***Communication link:*** a connection between packet switches and/or end systems
- ***Route:*** sequence of switches that a packet goes through (a.k.a. *path*)
- ***Protocol:*** control the sending and receiving of information to and from end systems and packet switches

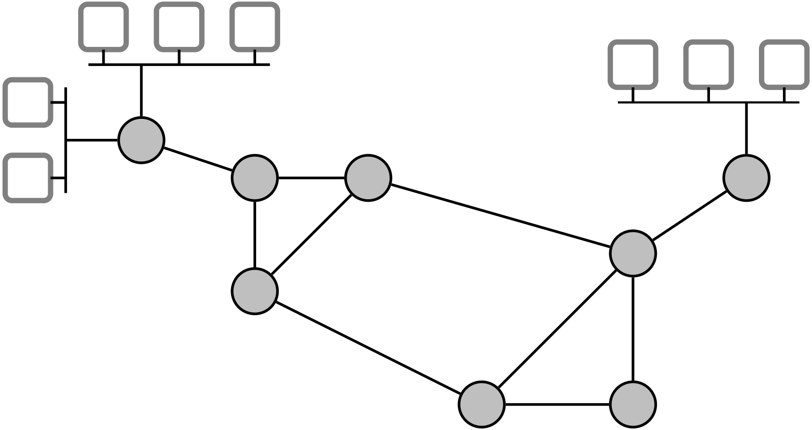
Communication Links

- Various types and forms of medium

Communication Links

- Various types and forms of medium
  - Fiber-optic cable
  - Twisted-pair copper wire
  - Coaxial cable
  - Wireless local-area links (e.g., 802.11, Bluetooth)
  - Satellite channel
  - ...

Packet Switching



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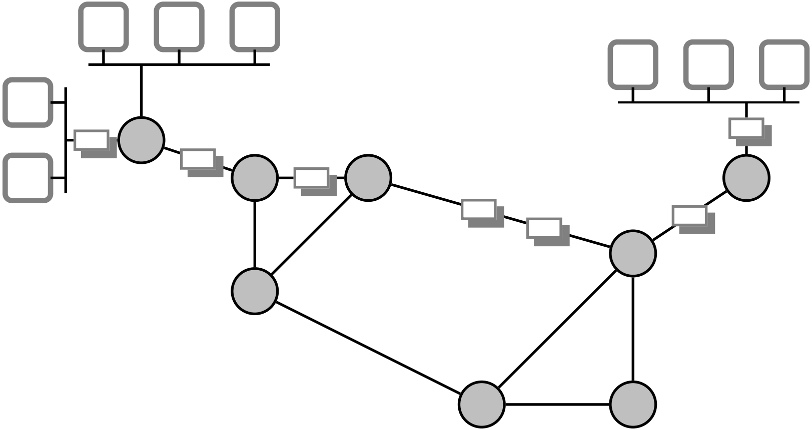

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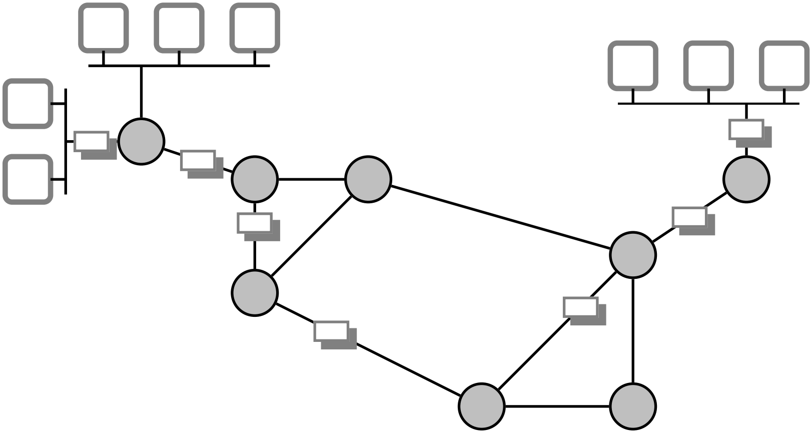

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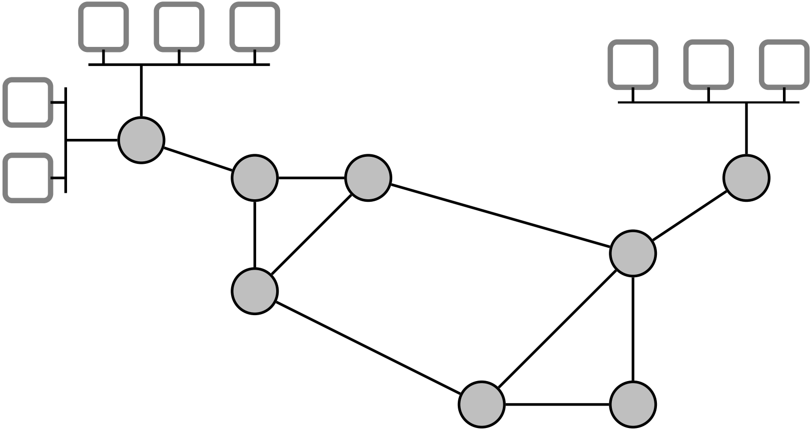
- A switch (router) receives packets and *forwards* them along to other switches or to end systems
- Every forwarding decision is taken on the basis of the information contained in the packet

Circuit Switching



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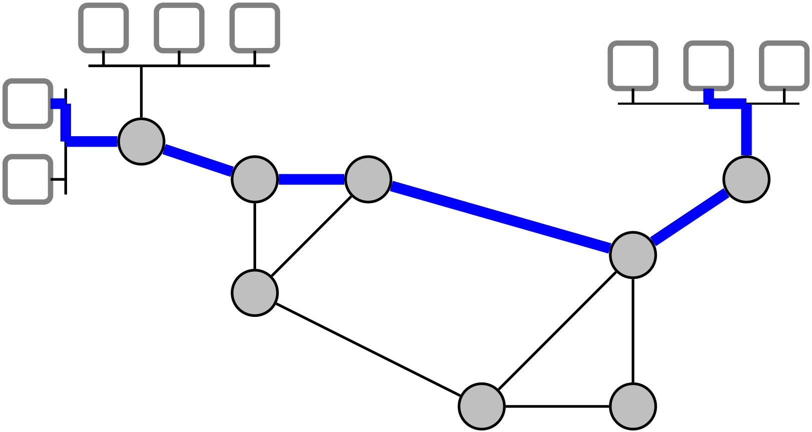

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  - not any more, really, but still…

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- After a successful setup, the communicating systems are connected by ***a set of links dedicated to the connection*** for the entire duration of their conversation

- When the conversation ends, the network tears down the connection, freeing the corresponding resources (links, buffers, etc.) for other connections

Circuit vs. Packet Switching

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  - however, once the connection is established, little or no processing is required

- Packet switching does not incur any setup cost
  - however, it always incurs a significant processing and space overhead, on a per-packet basis
    - *processing cost* for forwarding
    - *space overhead* because every packet must be self-contained

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- Circuit switching admits a straightforward implementation of quality-of-service guarantees
  - network resources are reserved at connection setup time
- Guaranteeing any quality of service with packet switching is very difficult
  - no concept of a “connection”
  - and again, processing, space overhead, etc.

- Circuit switching allows only a limited sharing of communication resources
  - once a connection is established, the resources are blocked even though there might be long silence periods
  - i.e., circuit switching is an inefficient way to use the network

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- Circuit switching allows only a limited sharing of communication resources
  - once a connection is established, the resources are blocked even though there might be long silence periods
  - i.e., circuit switching is an inefficient way to use the network
- Packet switching achieves a much better utilization of network resources
  - it is designed specifically to share links
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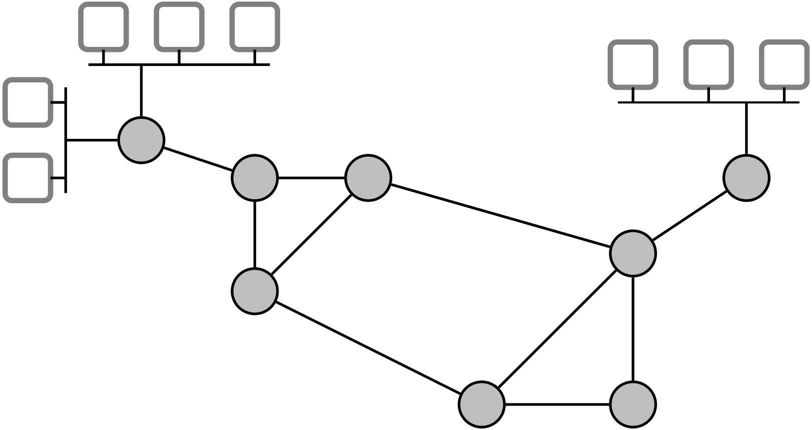
- The connection does not create a physical circuit, but rather a “virtual circuit”
- Information is sent in packets, so links can be shared more effectively
- Packets carry a *virtual circuit identifier* instead of the destination address
  - *Important observation:* at any given time there are much fewer *connections* than *destinations*
    - much faster per-packet processing (forwarding)
    - lower per-packet space overhead

Virtual Circuit



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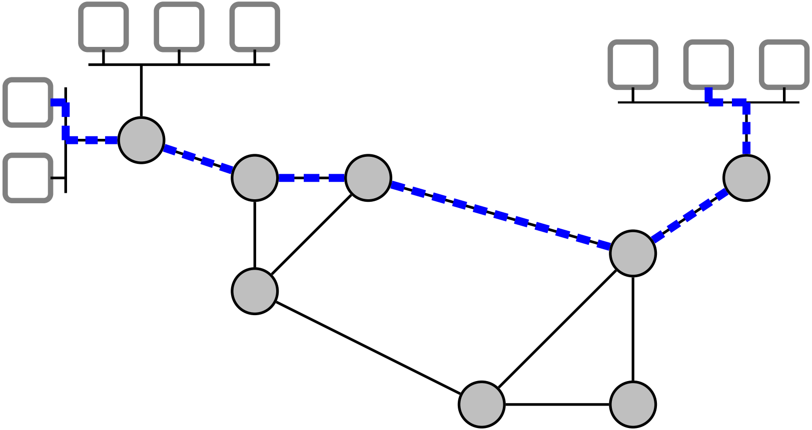

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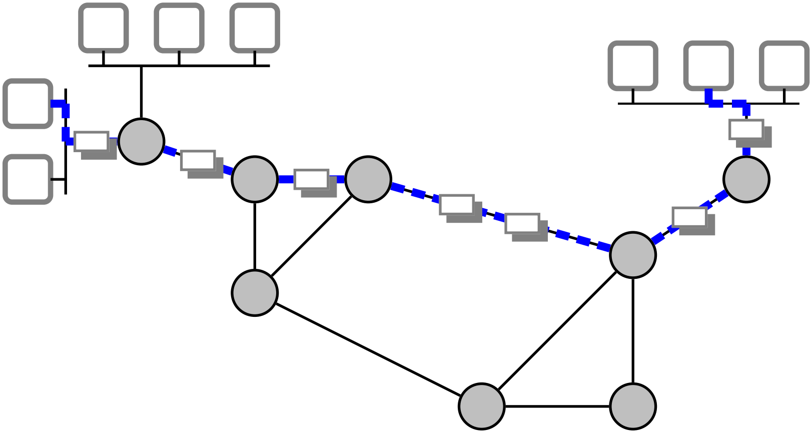
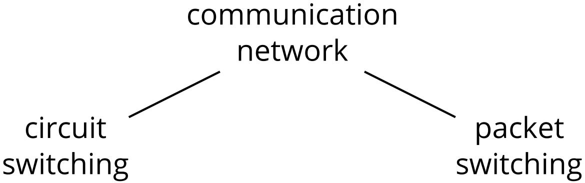


communication
network

Taxonomy of Networks



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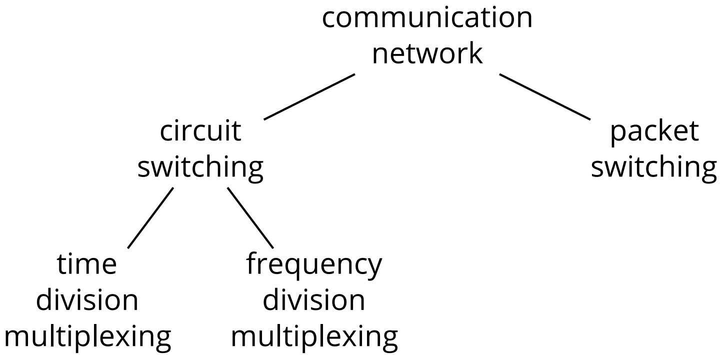

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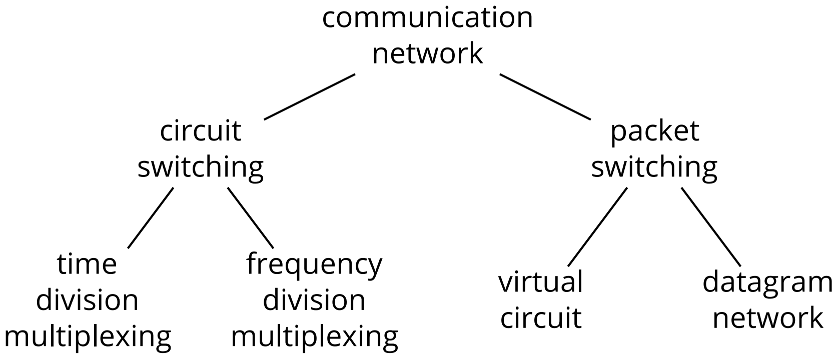

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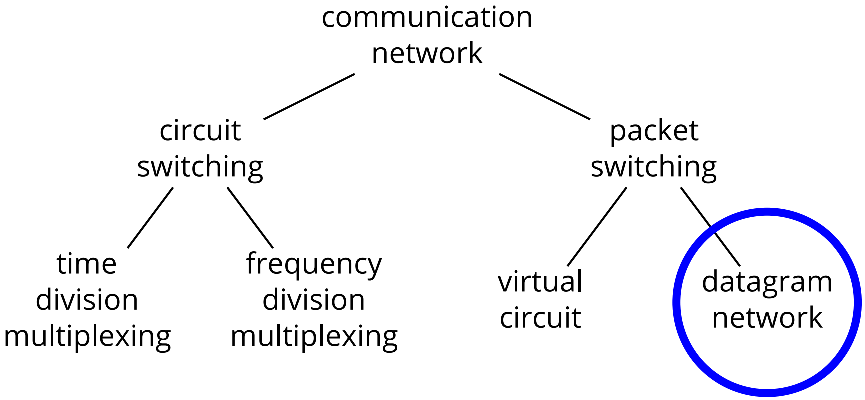
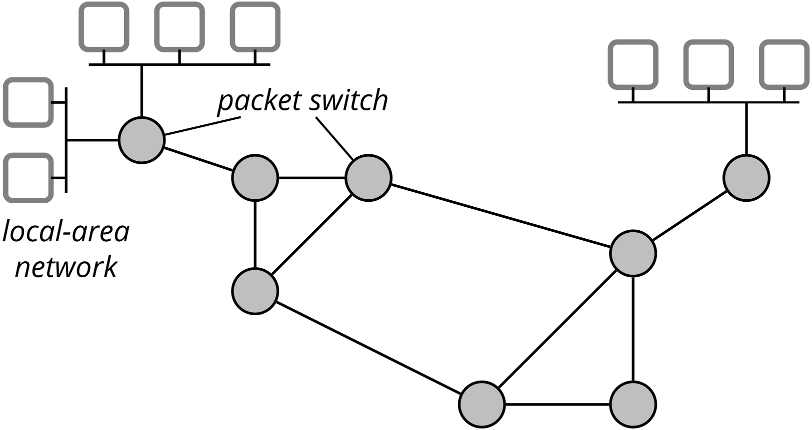
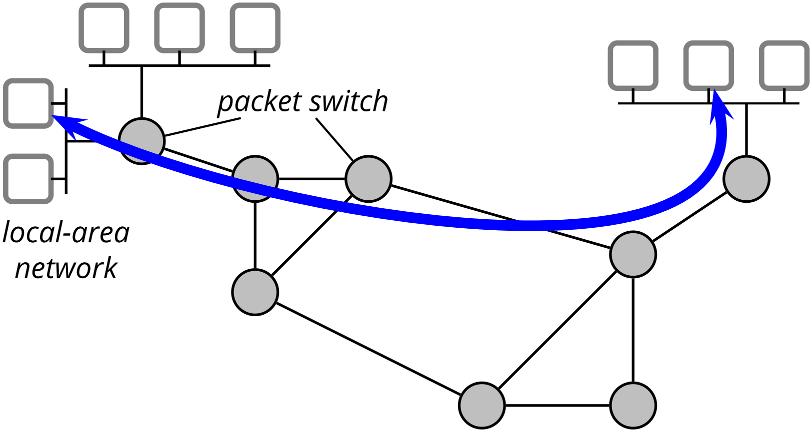


Service Perspective





- What kind of ***service*** does the Internet offer to end systems?

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- Two end systems can communicate through the Internet, but exactly what kind of communication service is that of the Internet?

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- ***Connection-oriented, reliable***
  - virtual duplex communication channel ($A \leftrightarrow B$)—conceptually similar to a telephone service
  - information is transmitted "reliably" and in order

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- The term “reliable” means that information will eventually reach its destination if a route is viable within a certain amount of time
- The network makes absolutely no guarantees on *latency* (i.e., the time it takes to transmit some information from a source to a destination)

Internet Protocol Stack

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application

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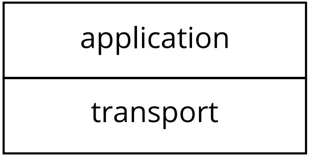

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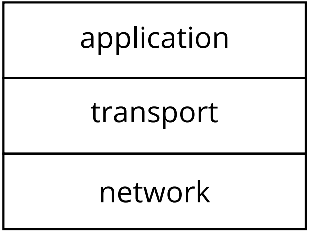

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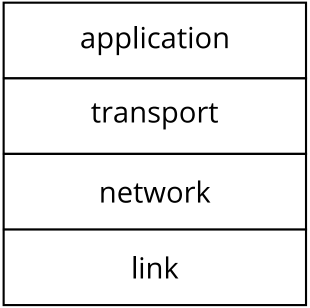

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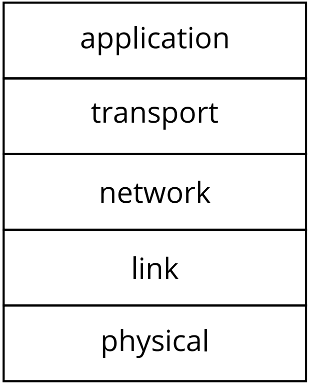

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  - application functionalities
  - application messages

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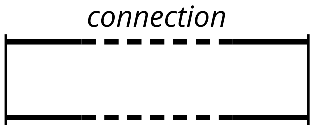
Delay (Latency) and Rate (Throughput)



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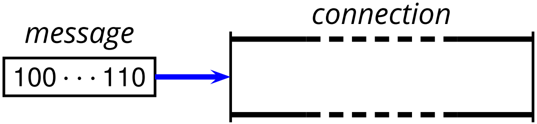

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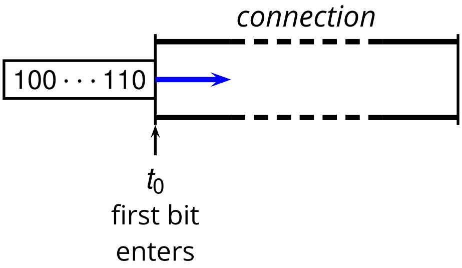

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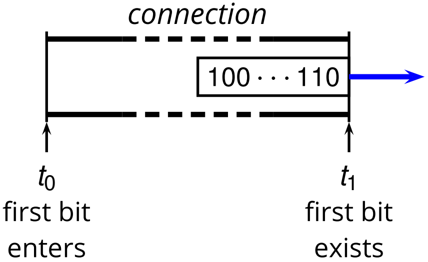

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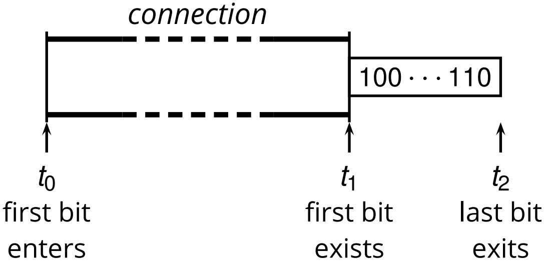

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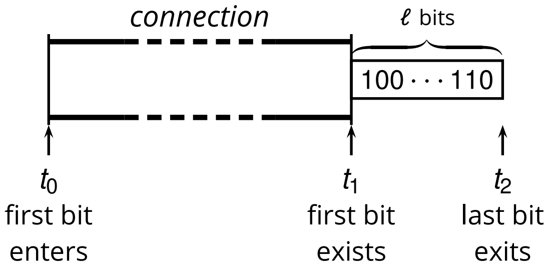

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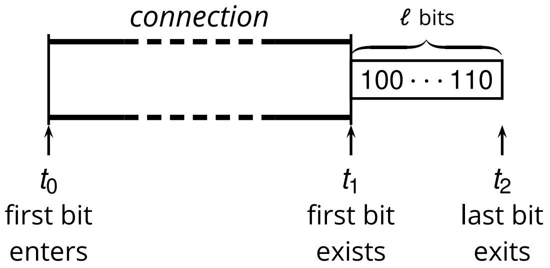

Propagation ***Delay*** $d_{prop} = t_1 - t_0$ sec

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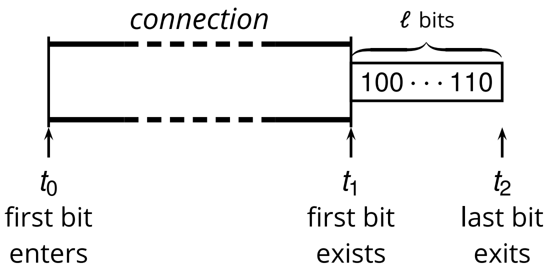

Propagation ***Delay***	$d_{prop} = t_1 - t_0$	sec
Transmission ***Rate***	$R = \dfrac{\ell}{t_2 - t_1}$	bits/sec

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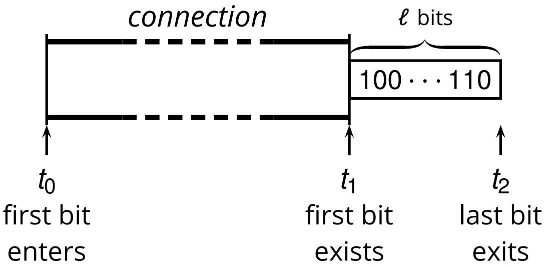

*Propagation **Delay***	$d_{prop} = t_1 - t_0$	sec
*Transmission **Rate***	$R = \dfrac{\ell}{t_2 - t_1}$	bits/sec
Total transfer time	$d_{end\text{-}end} = d + \dfrac{\ell}{R}$	sec

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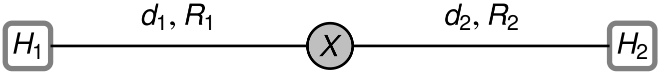

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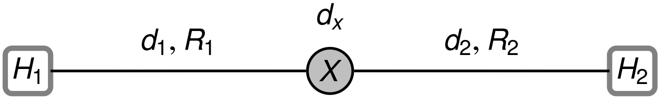

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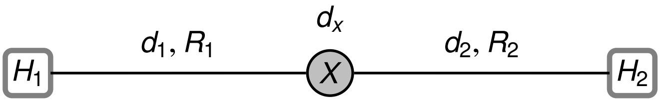

$$d_{end\text{-}end} = d_1 + \frac{\ell}{R_1}$$

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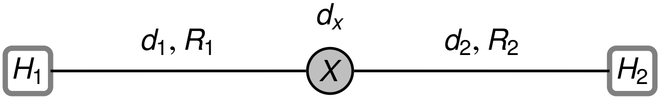
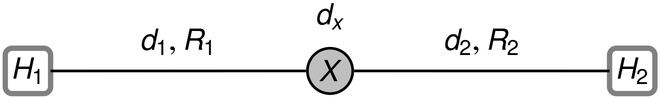


$$d_{end\text{-}end} = d_1 + \frac{\ell}{R_1} + d_x$$



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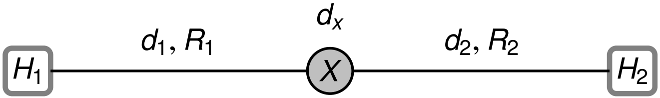

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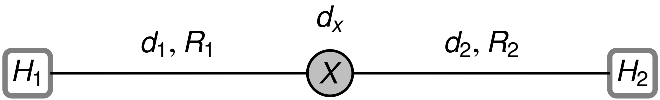

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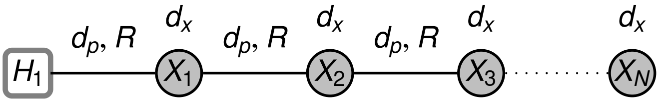

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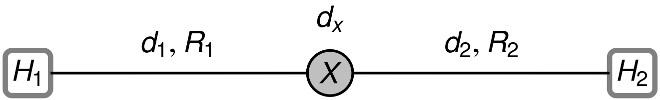

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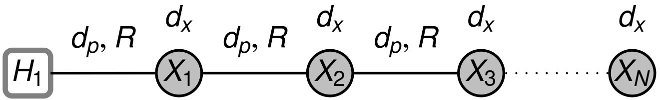

$$d_{end\text{-}end} = N\left(d_p + \frac{\ell}{R} + d_x\right)$$

End-toEnd Throughput

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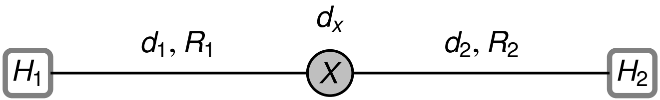

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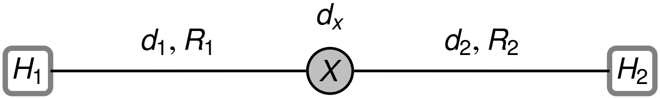
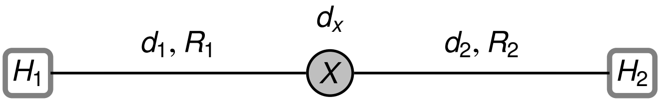


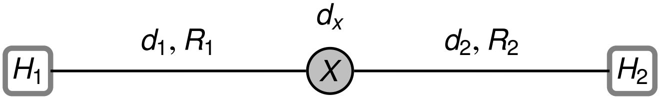
$$R_{end\text{-}end} =$$

End-toEnd Throughput



$$R_{end\text{-}end} = \min\{R_1, R_2\}$$

End-toEnd Throughput



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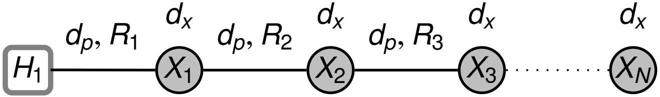

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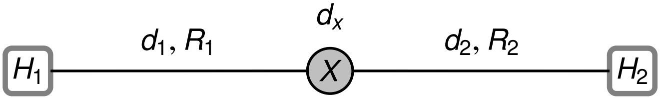

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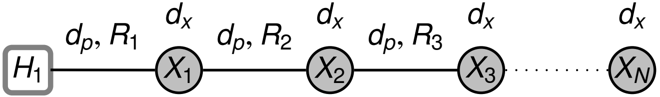

$$R_{end\text{-}end} = \min\{R_1, R_2, \ldots, R_N\}$$

Processing and Queuing Delays

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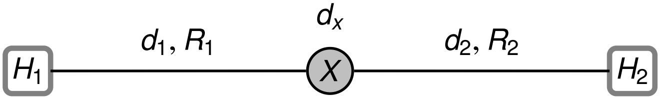

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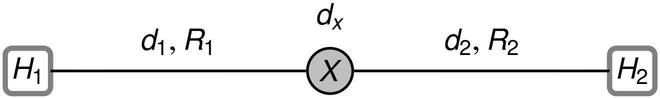

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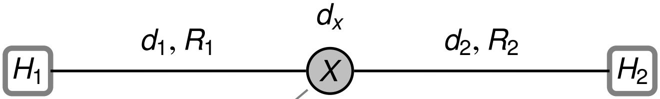

$$d_x = d_{cpu} + d_{queue}$$

$$d_{queue} = |q| / R_x$$

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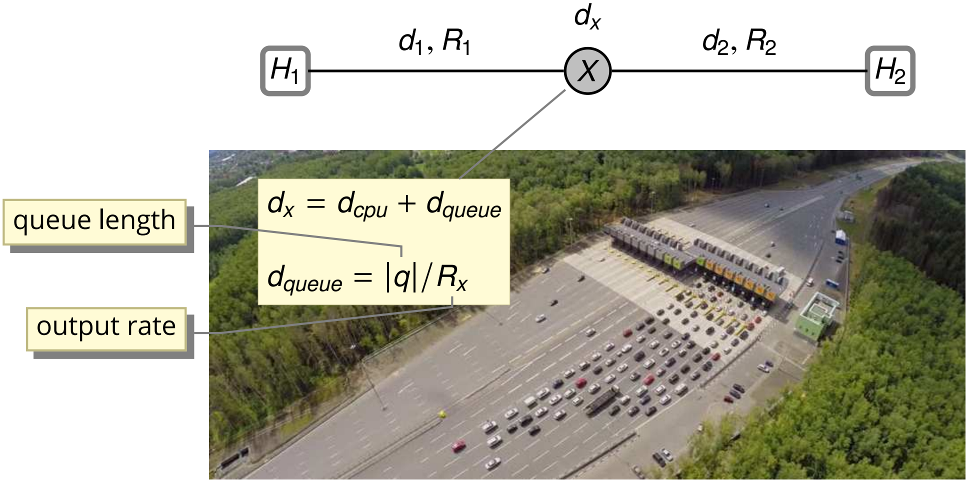

Queuing Delay

$$d_x = d_{cpu} + d_{queue}$$

queue length

where

$$d_{queue} = |q| / R_x$$

output rate

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$\ldots R_x$ is also the rate at which packets get out of the queue

Application Protocols

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HTTP

Application Protocols

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SMTP

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DNS

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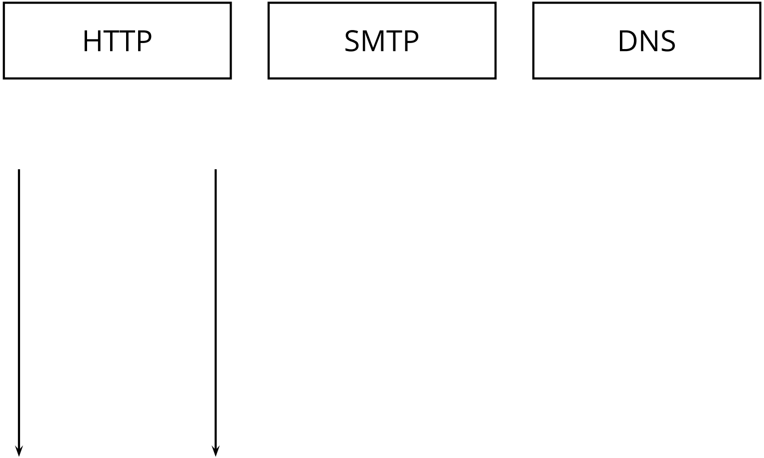

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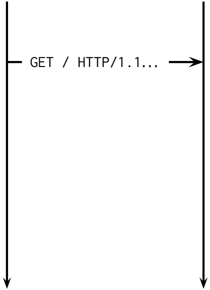

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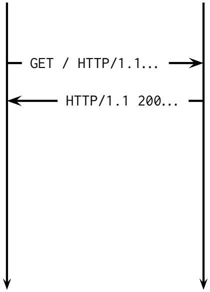

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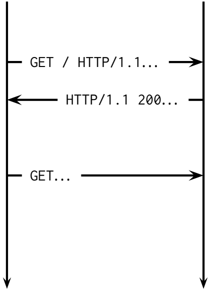

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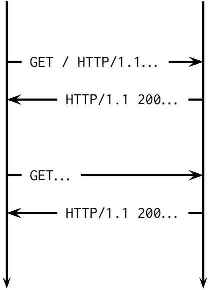

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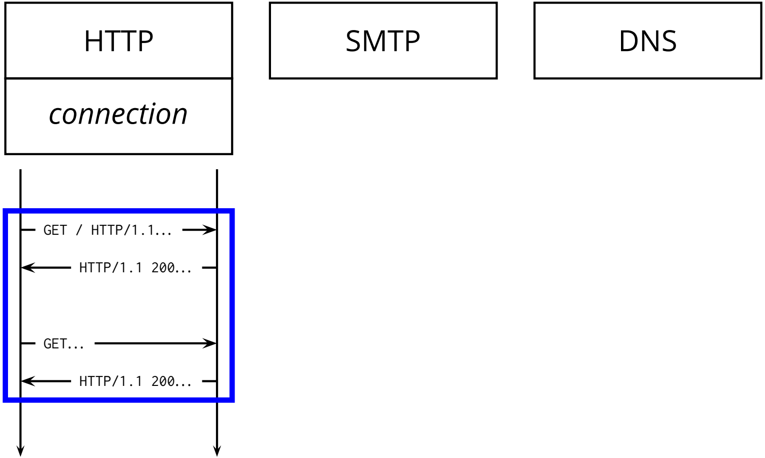

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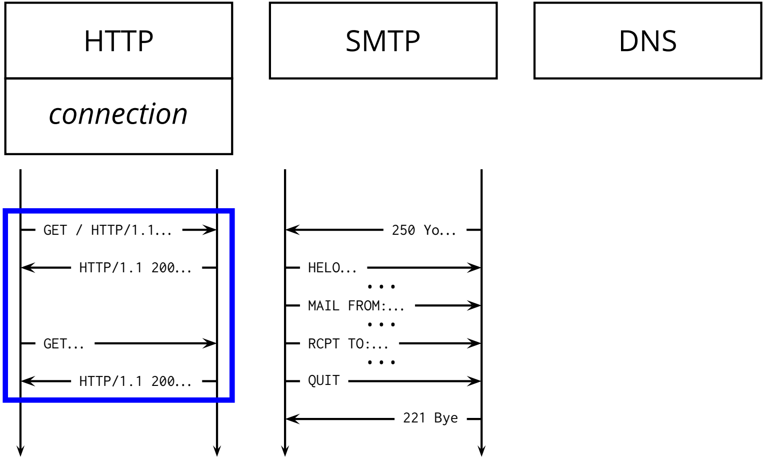

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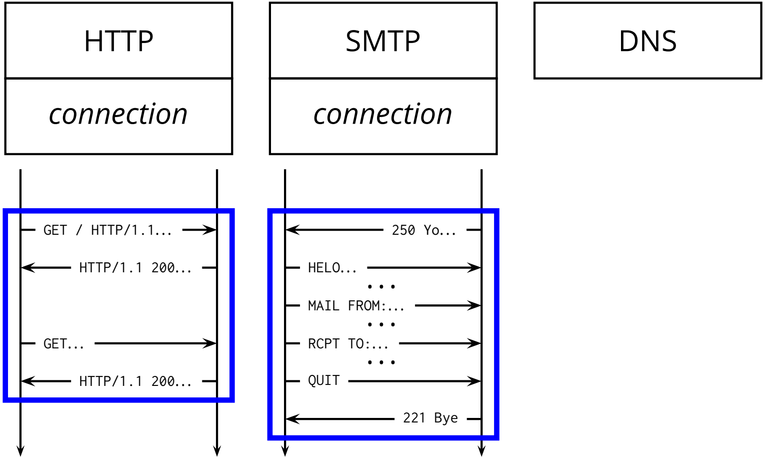

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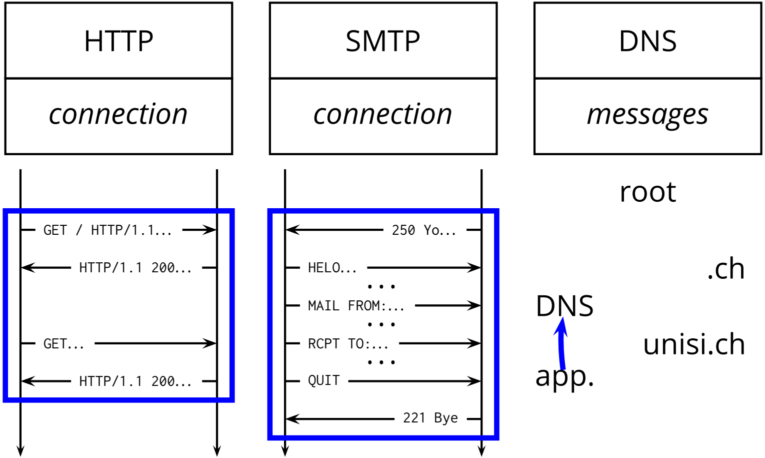

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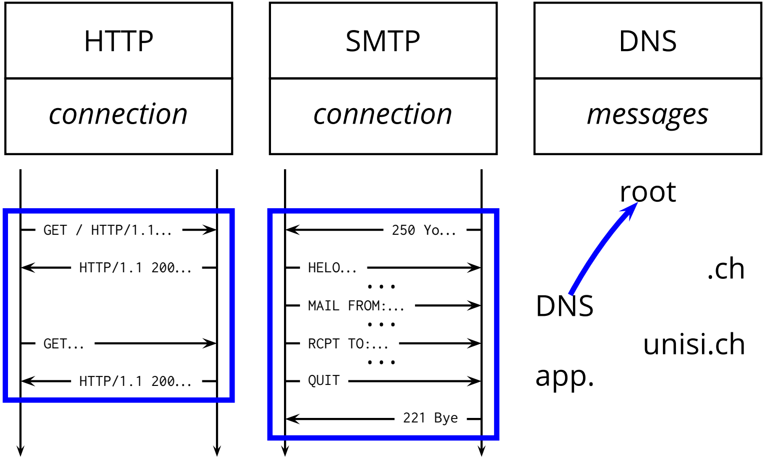

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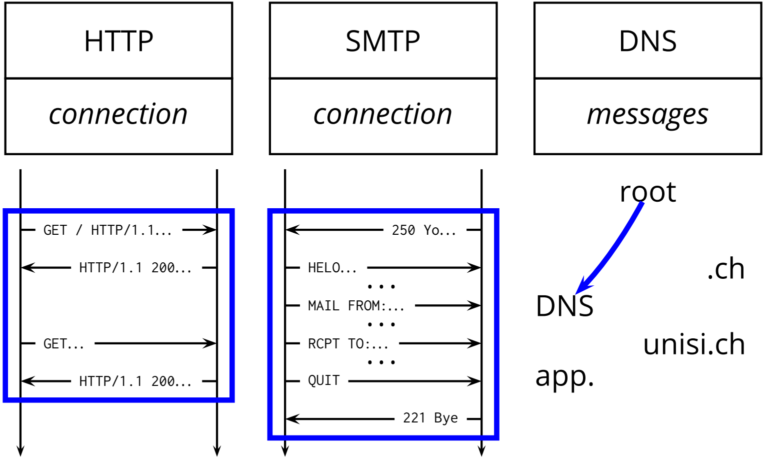

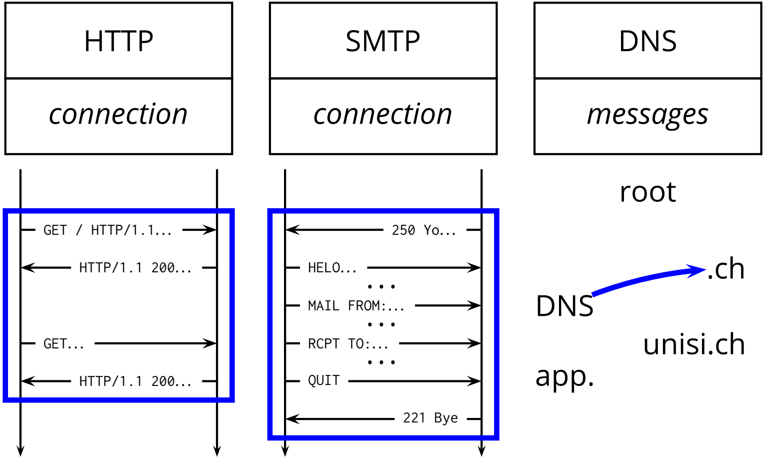
HTTP
connection
SMTP
connection
DNS
messages
GET / HTTP/1.1...
HTTP/1.1 200...
GET...
HTTP/1.1 200...
250 Yo...
HELO...
...
MAIL FROM:...
...
RCPT TO:...
...
QUIT
221 Bye
root
.ch
DNS
unisi.ch
app.

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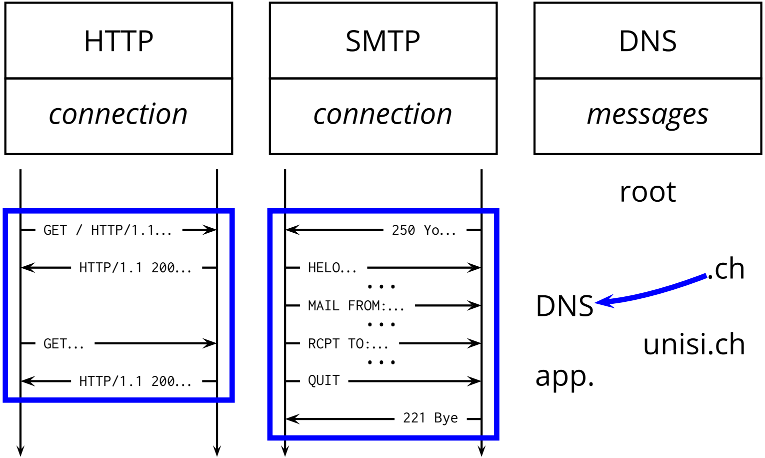

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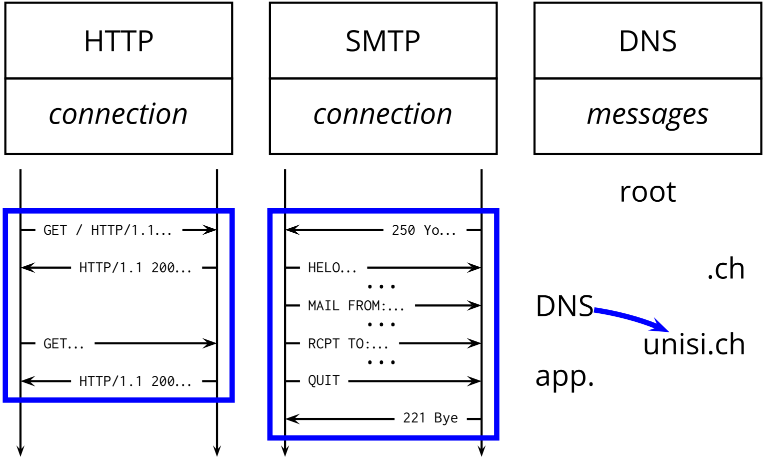

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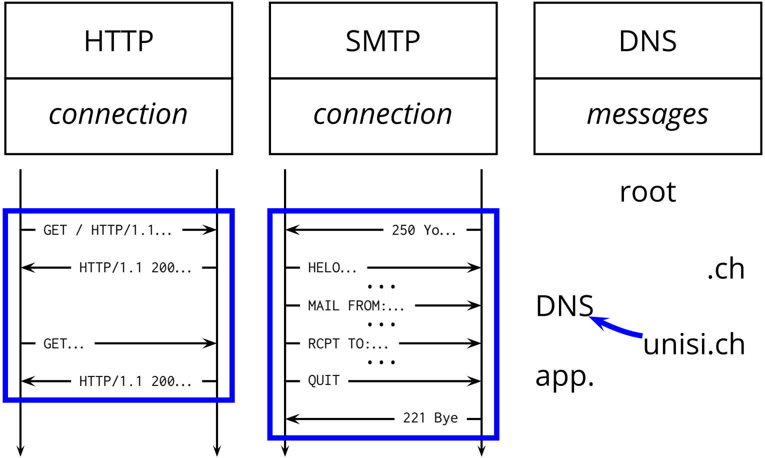

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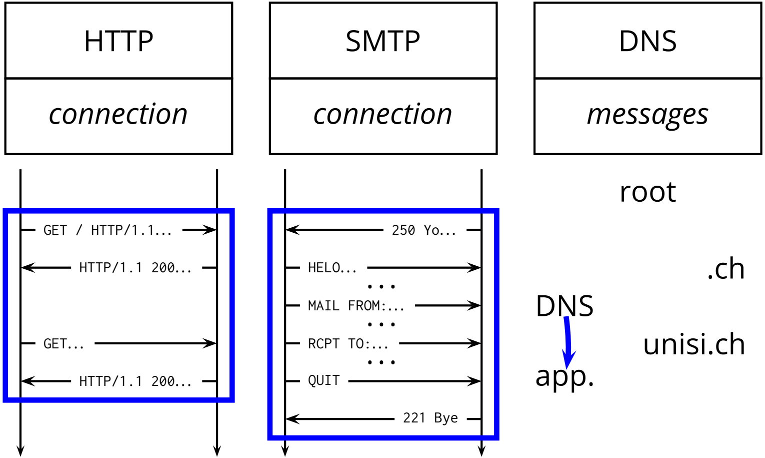

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  - best-effort delivery service
    - no guarantees on the integrity of segments
    - no guarantees on the order in which segments are delivered

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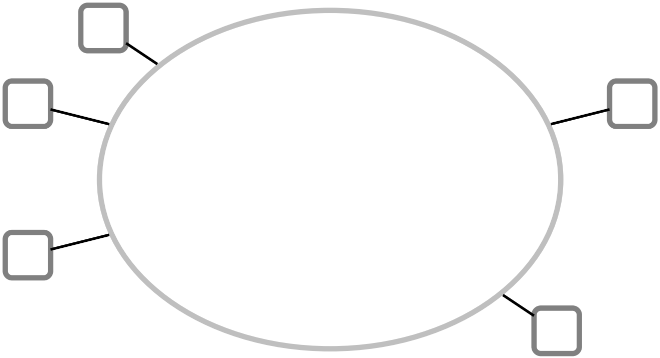
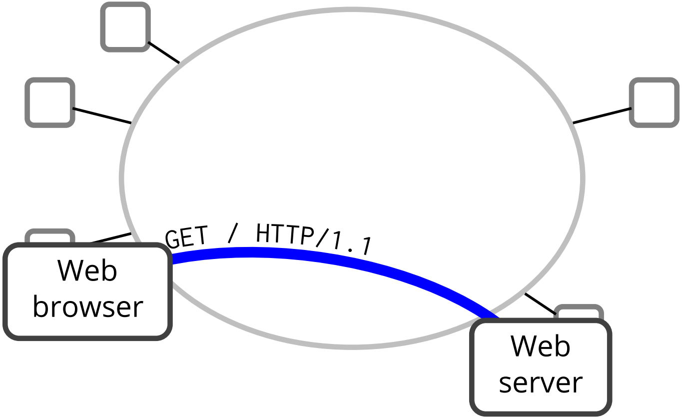
- ***Congestion control***
  - i.e., end-to-end traffic (admission) control so as to avoid destructive congestions within the network

Multiplexing/Demultiplexing




GET / HTTP/1.1
Web browser
Web server

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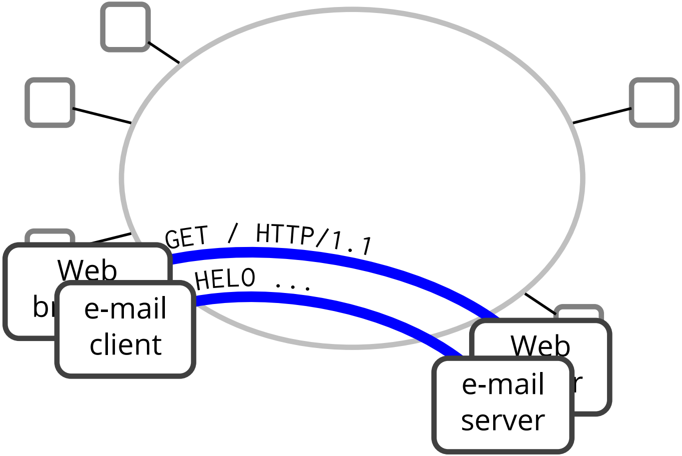

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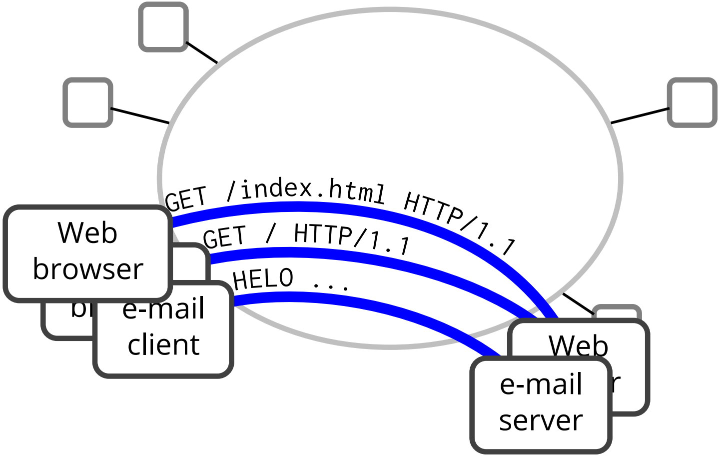

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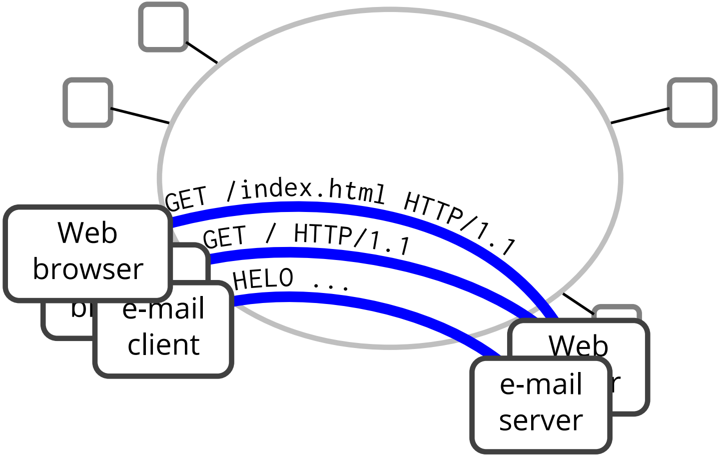

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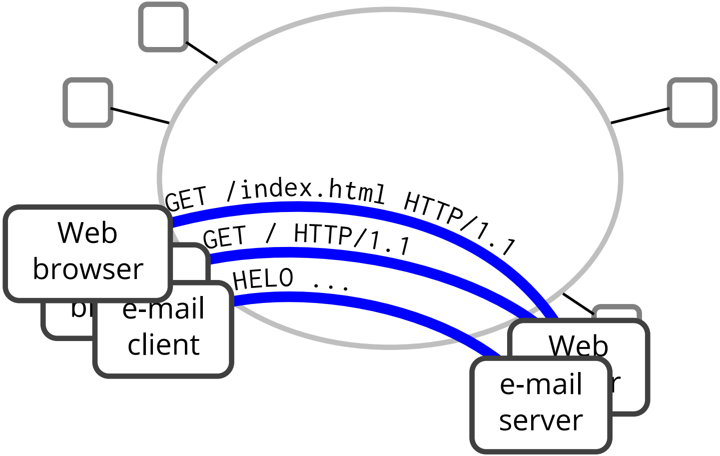

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(in this case, connections between the same two hosts)

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  - outside the scope of the definition of the transport layer
  - but of course we can have “well-known” service numbers

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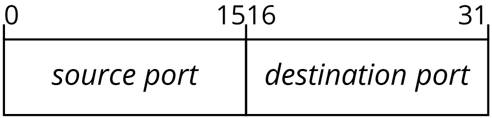

. . .

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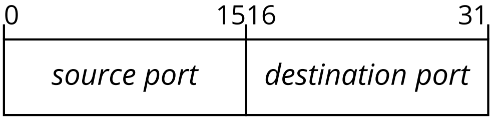

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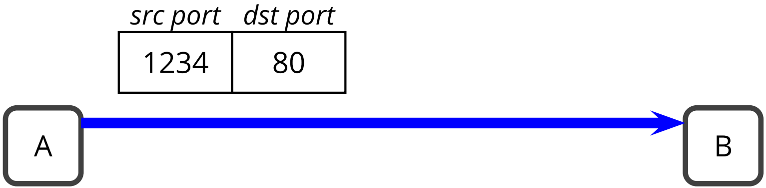

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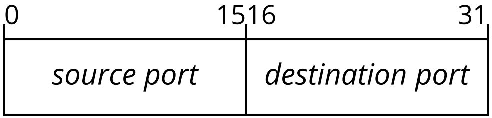

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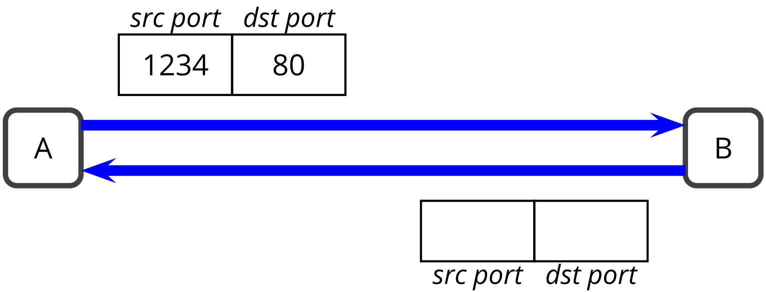

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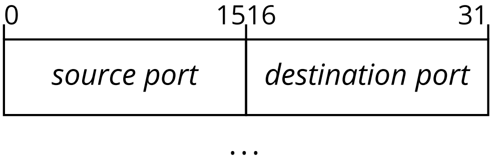

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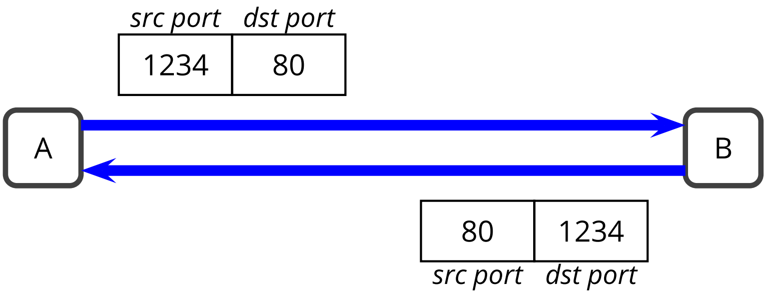

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- Full-duplex service
  - both endpoints can both send and receive, at the same time

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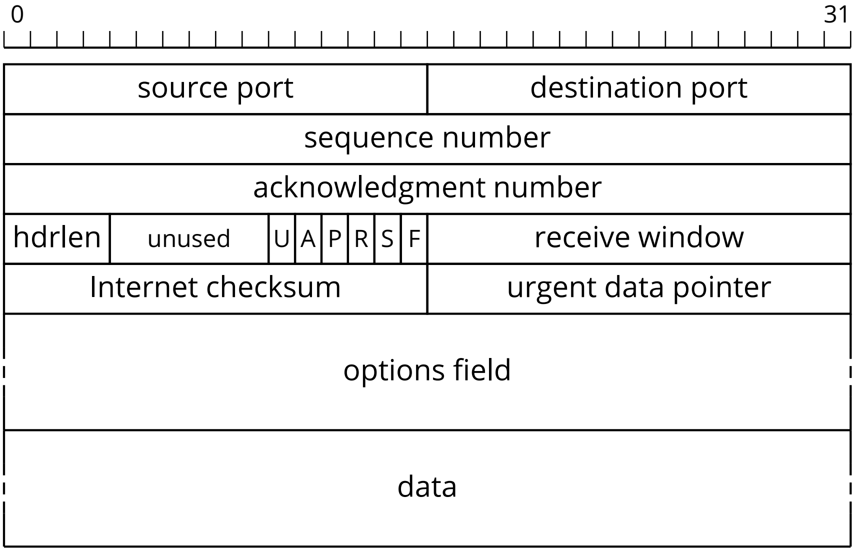
- ***Maximum transmission unit (MTU):*** largest link-layer frame available to the sender host
  - *path MTU:* largest link-layer frame that can be sent on all links from the sender host to the receiver host

TCP Segment Format



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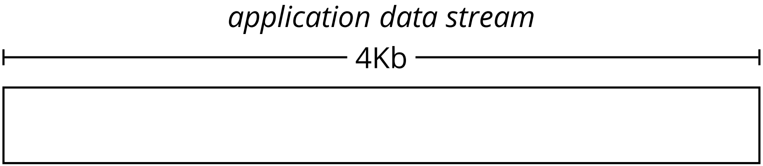

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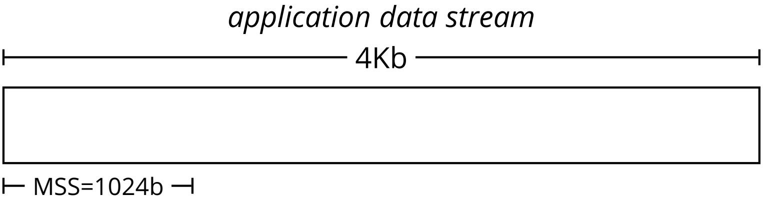

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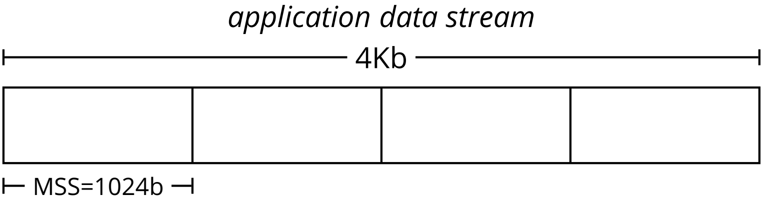

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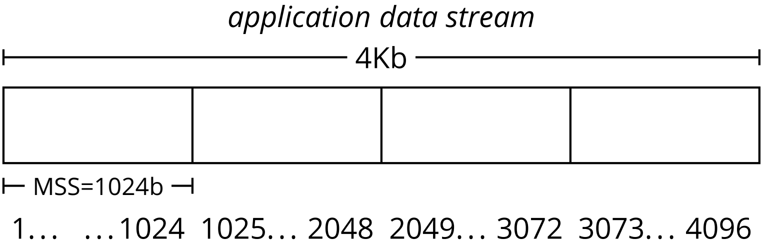

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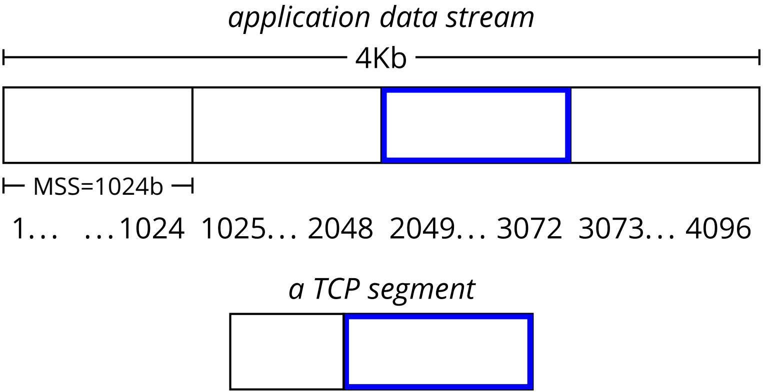

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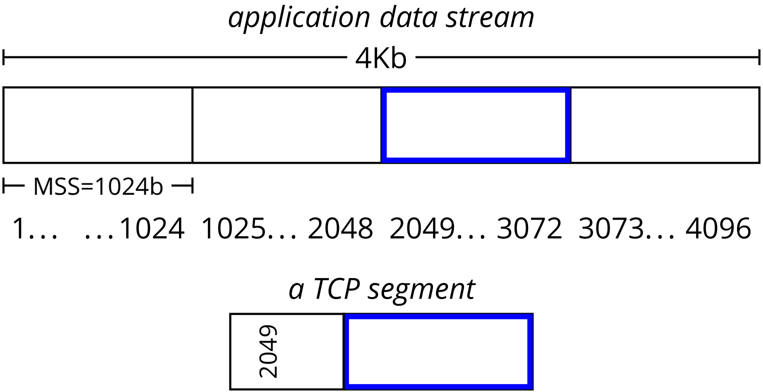

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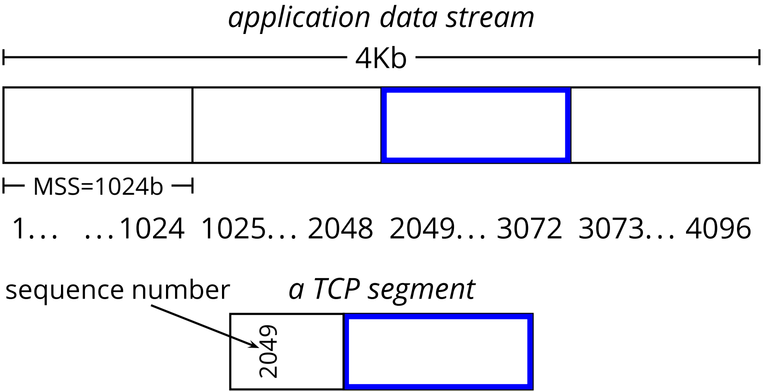

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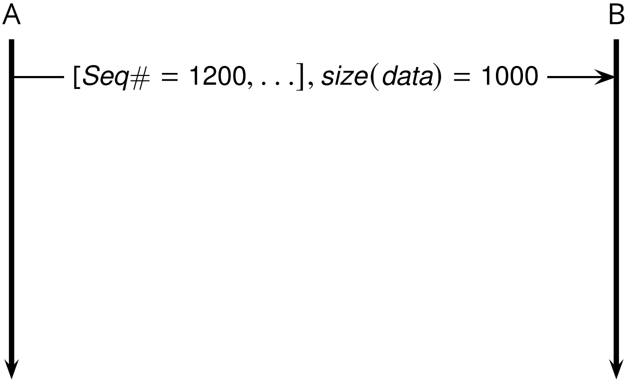

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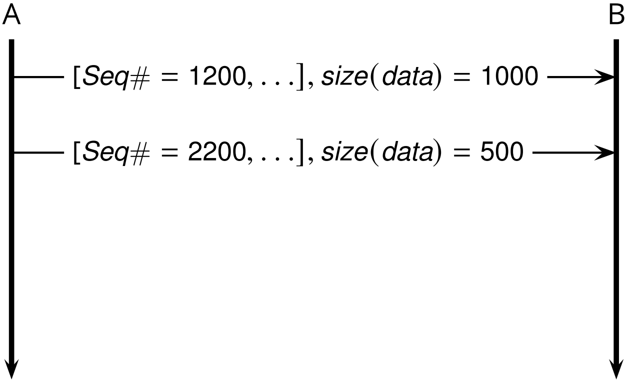

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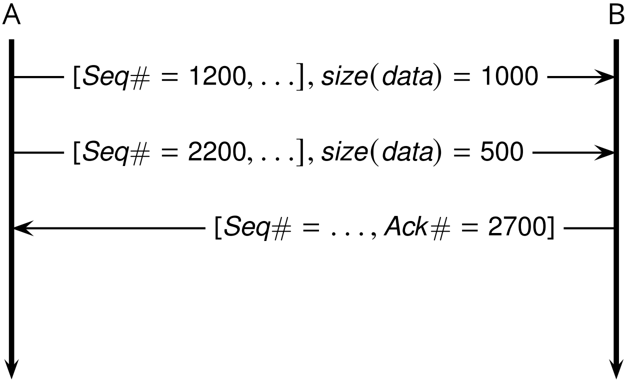

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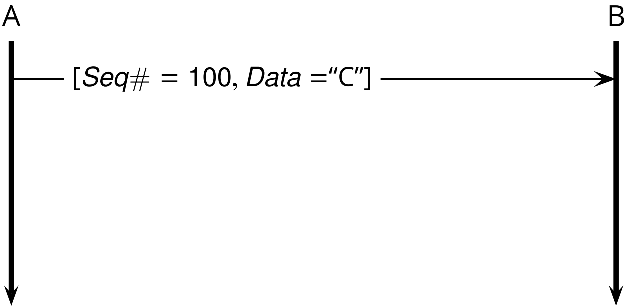

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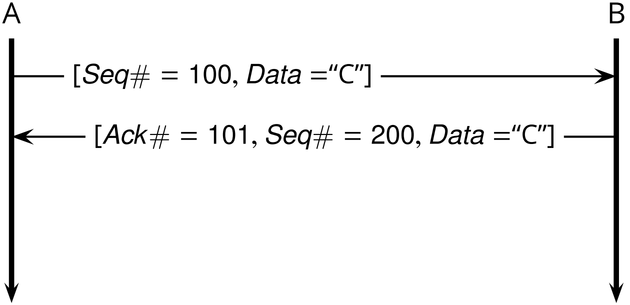

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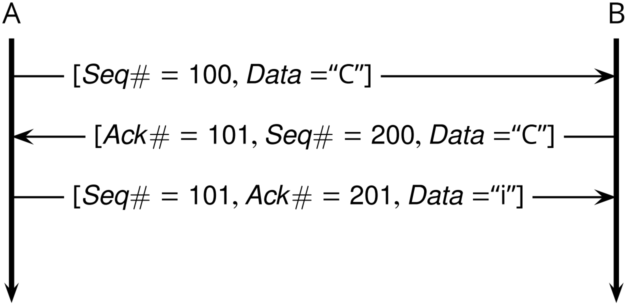

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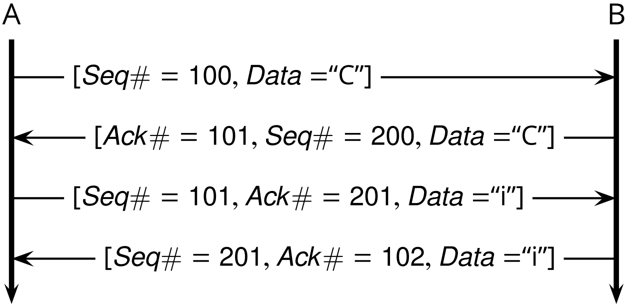

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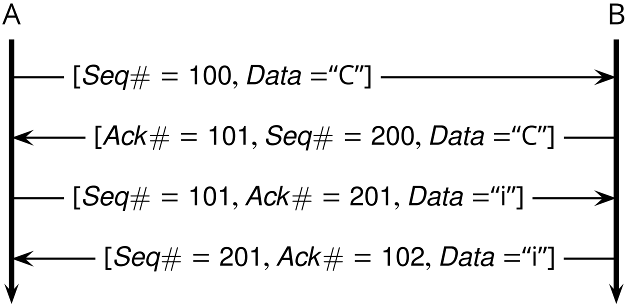

- Acknowledgments are “piggybacked” on data segments

Reliability and Timeout

- Duplicate acknowledgments to detect lost segments
  - receiver notices a missing packet $\longrightarrow$ duplicate ACKs $\longrightarrow$ retransmission by sender
- A *timer* to detect lost segments
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- TCP controls its timeout by continuously *estimating the current RTT*

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- TCP sets its timeouts using the estimated RTT ($\overline{RTT}$) and the variability estimate $\overline{DevRTT}$:

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A simplified TCP sender

- r_send(*data*)

  if (timer not running)
  start_timer()
  u_send([*data*,*next_seq_num*])
  $next\_seq\_num \leftarrow next\_seq\_num + length(data)$

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

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Three-way handshake

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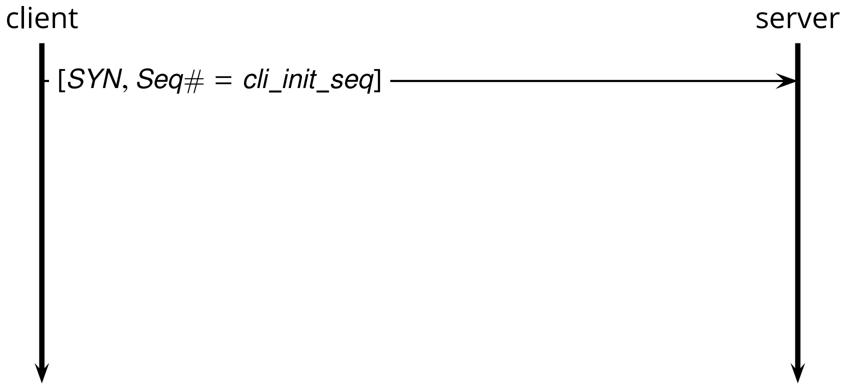

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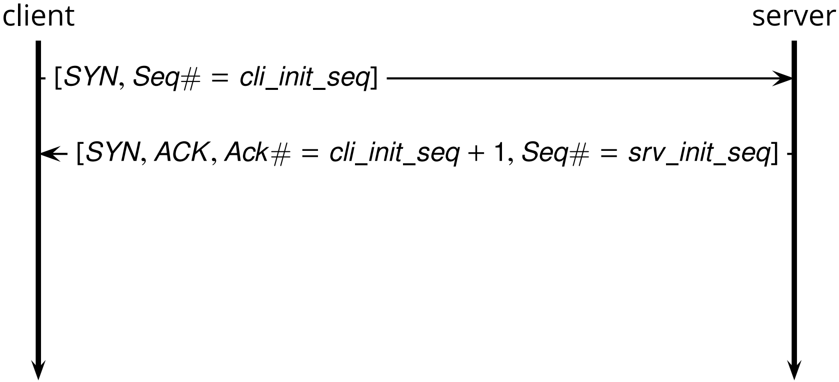

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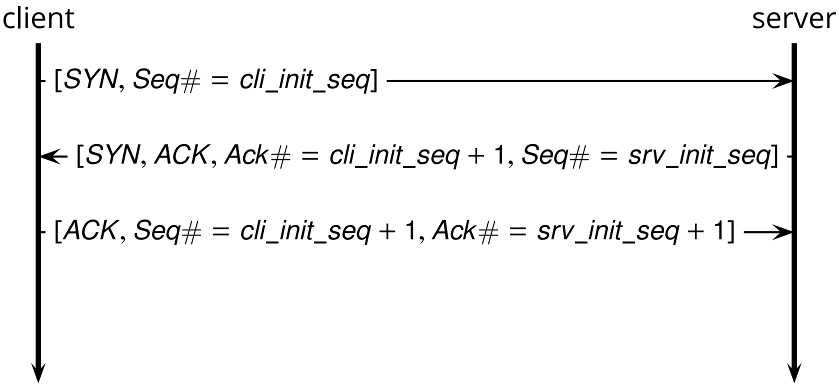

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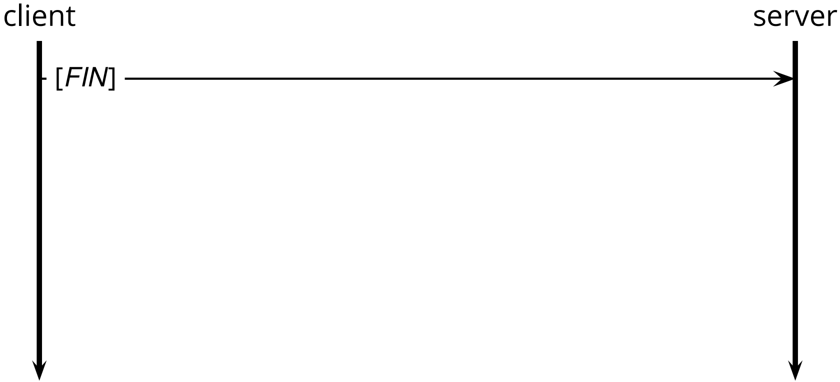

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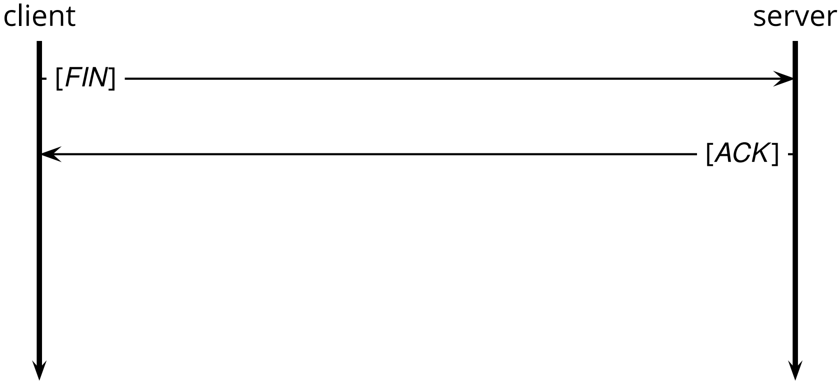

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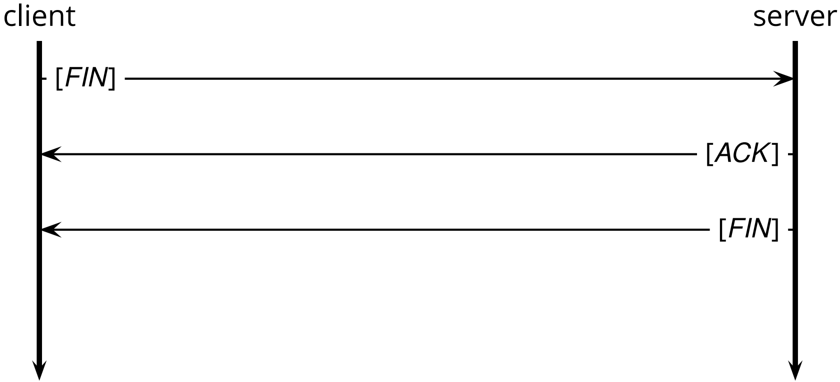

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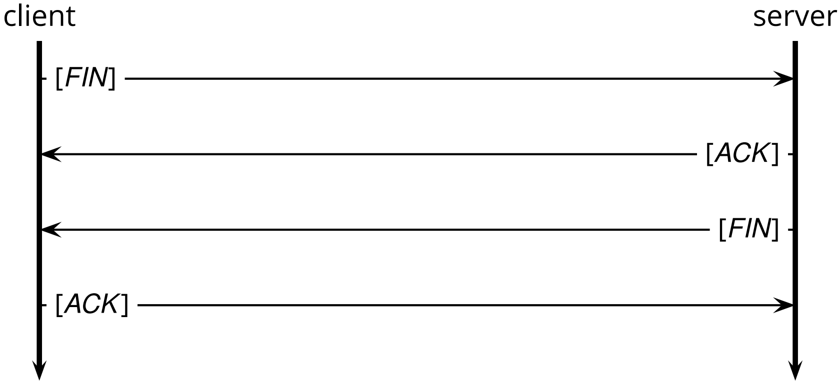

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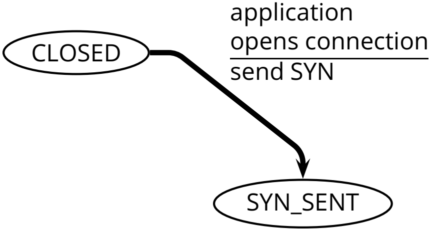

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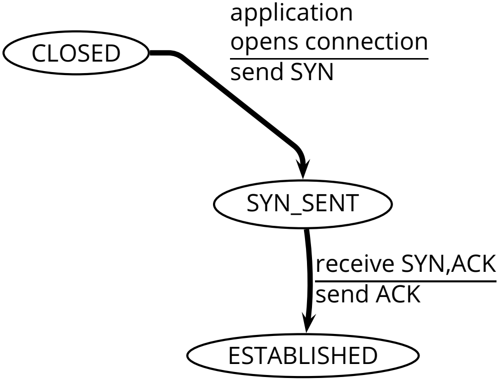

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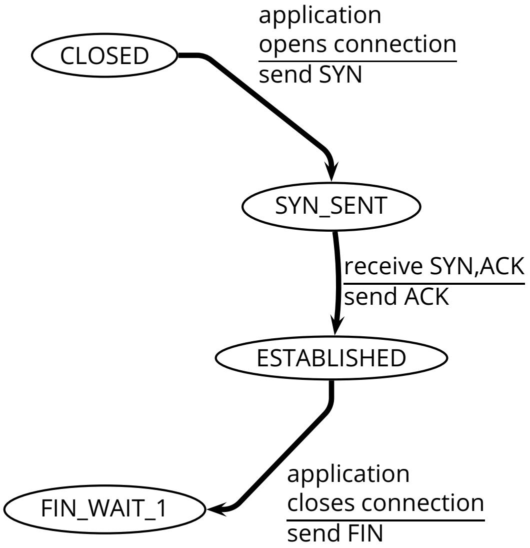

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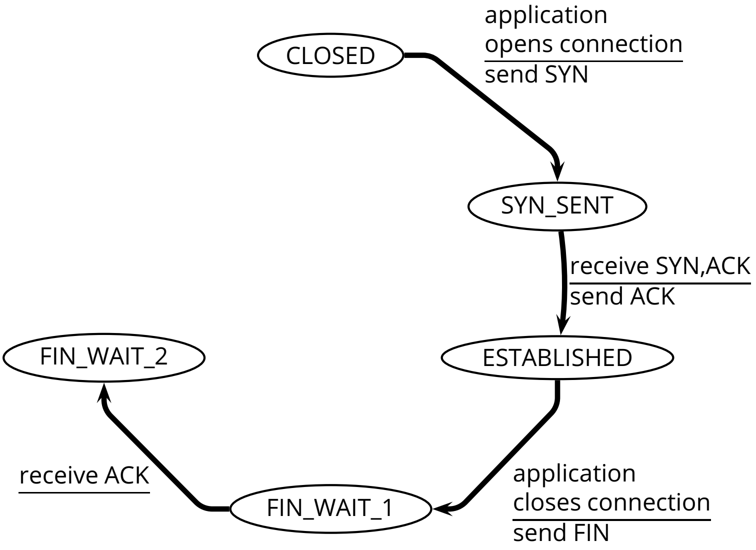

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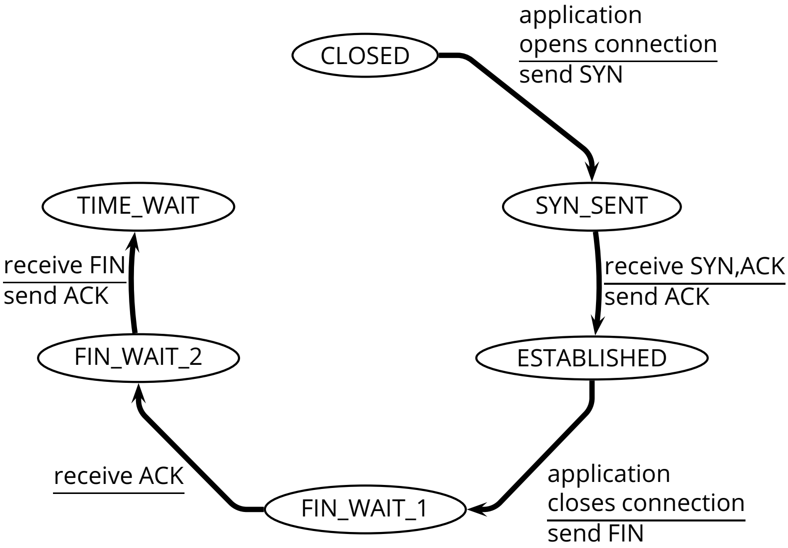

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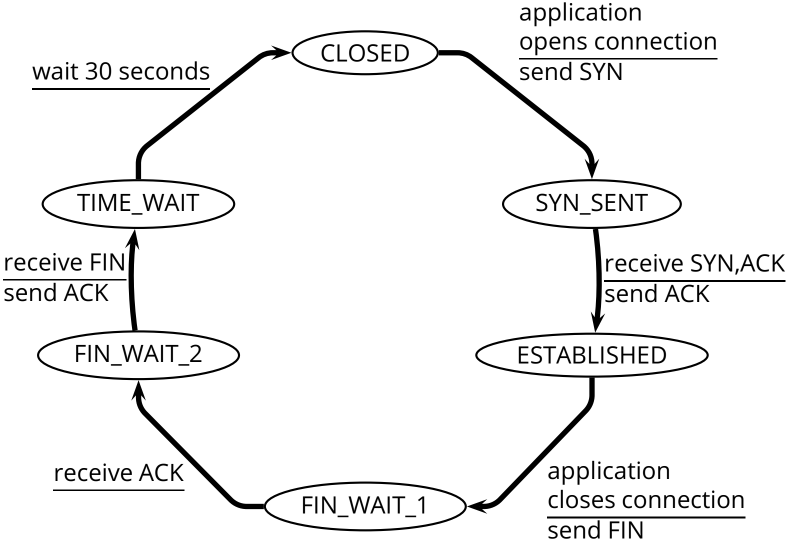

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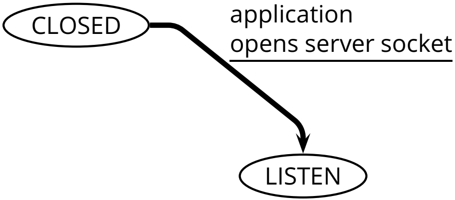

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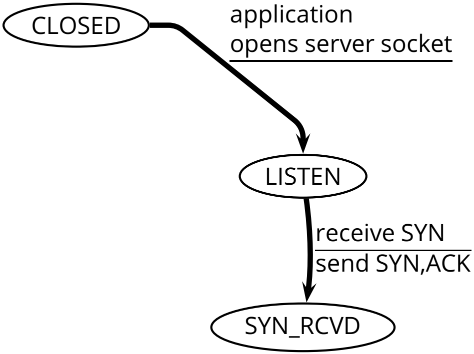

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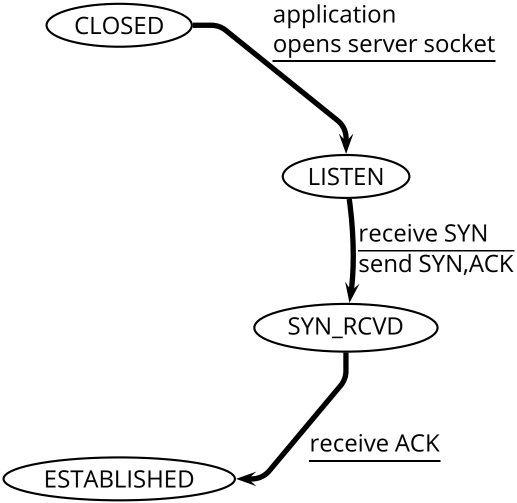

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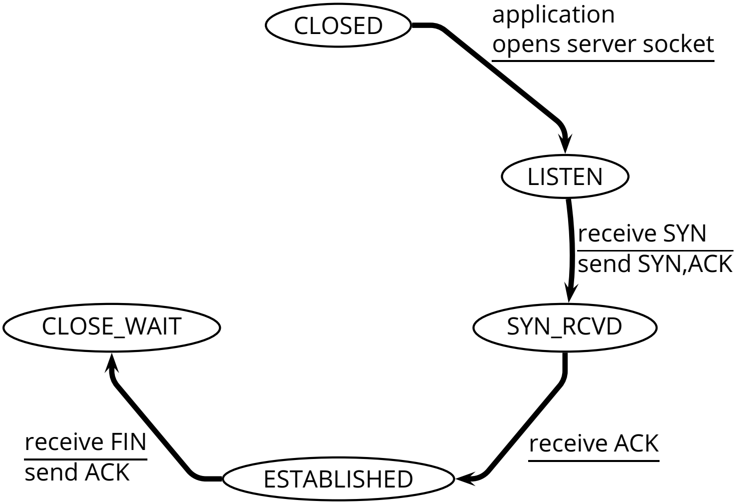

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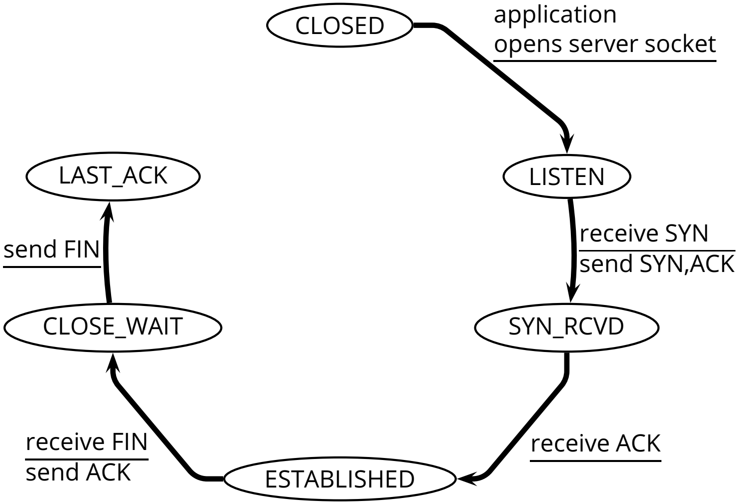

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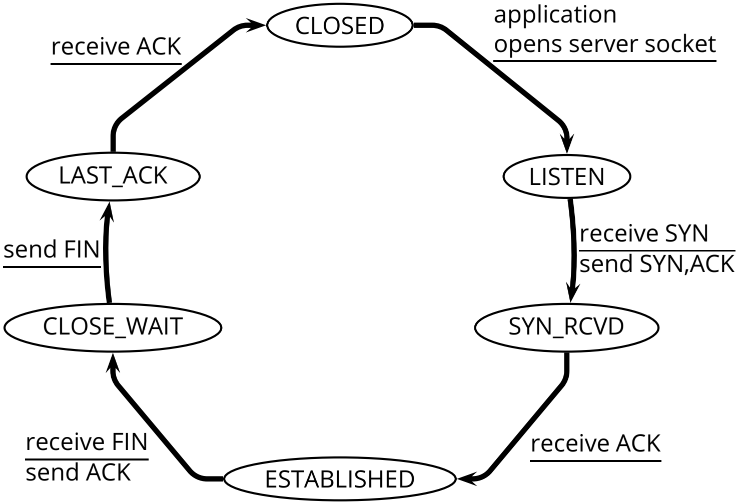

Understanding Congestion

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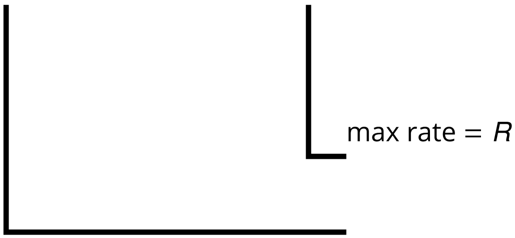

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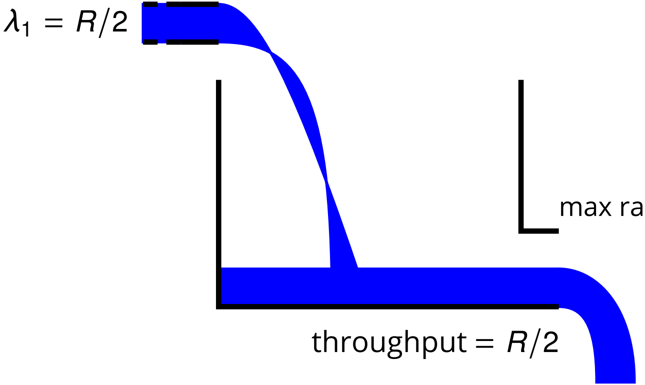

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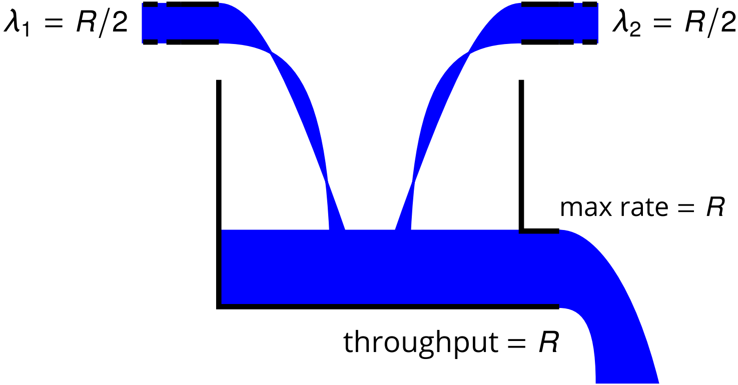

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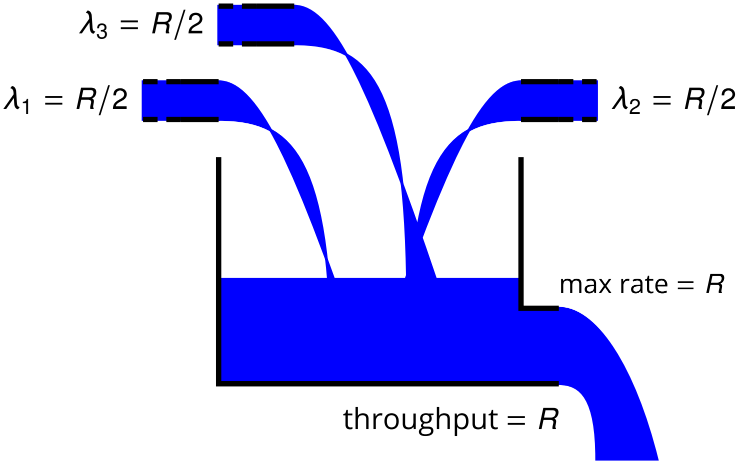

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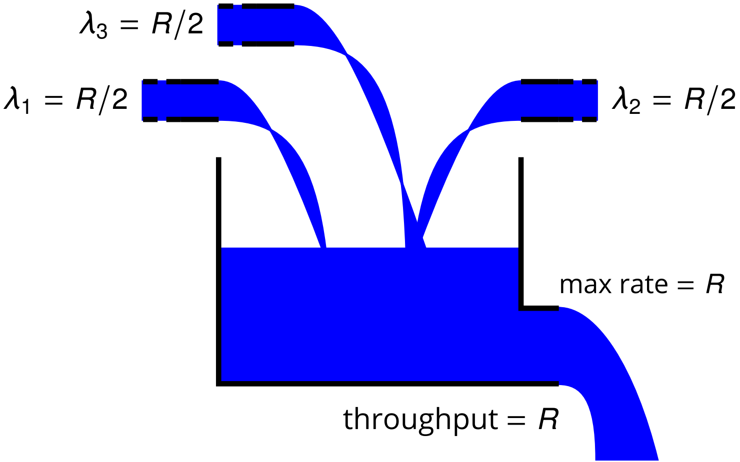

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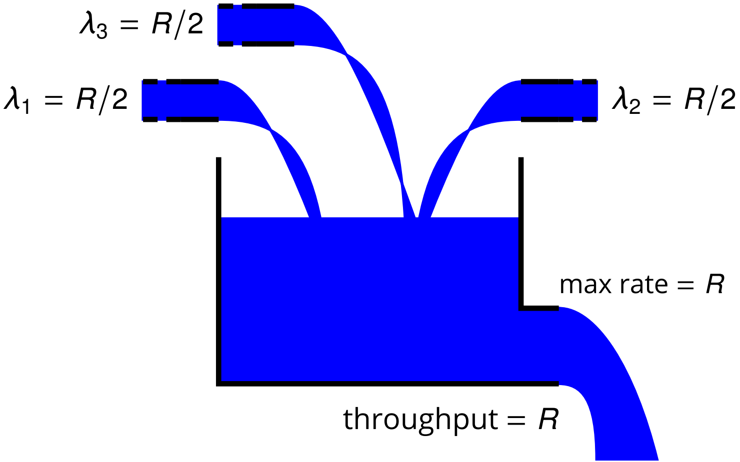

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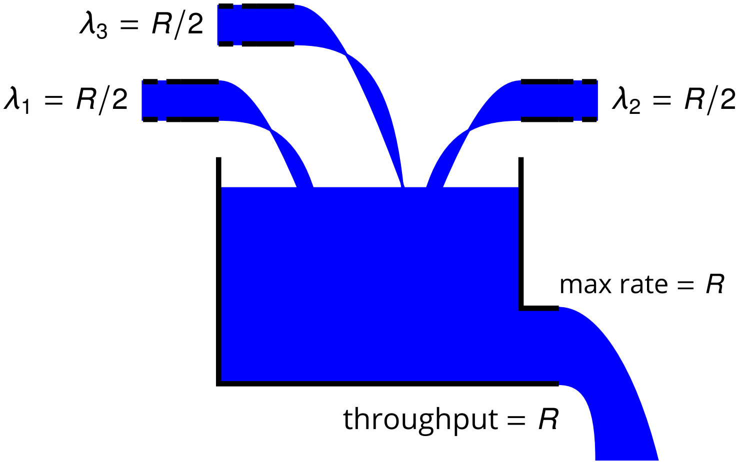

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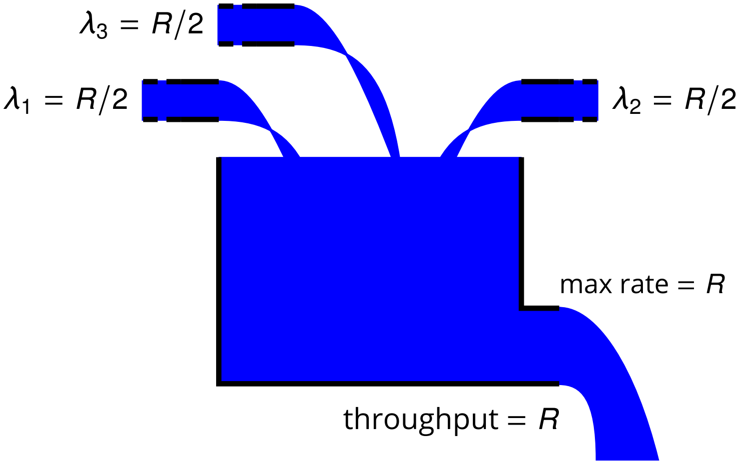

Queuing Delay

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- ***Ideal case:*** constant input data rate

$$\lambda_{in} < R$$

In this case the $d_q = 0$, because $|q| = 0$ (ideal input flow)

- Total latency is the sum of link latency, processing time, and the time that a packet spends in the input queue

$$L = d_{TX} + d_{CPU} + d_q \quad \text{where } d_q = |q|/R$$

- ***Ideal case:*** constant input data rate

$$\lambda_{in} < R$$

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- ***Extreme case:*** constant input data rate

$$\lambda_{in} > R$$

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

$$d_q = \frac{\lambda_{in} - R}{R} t$$

Queuing Delay

- Steady-state queuing delay

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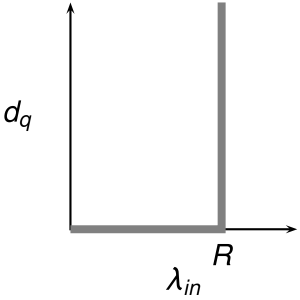

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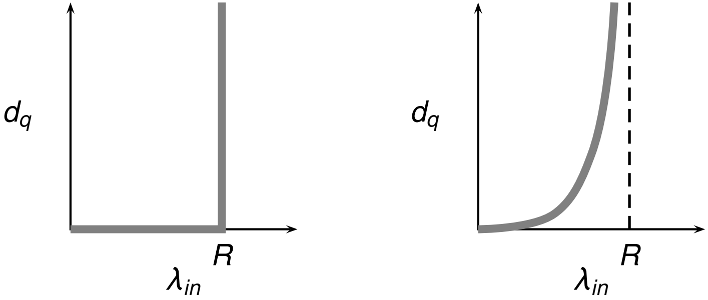

ideal input flow
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Queuing Delay

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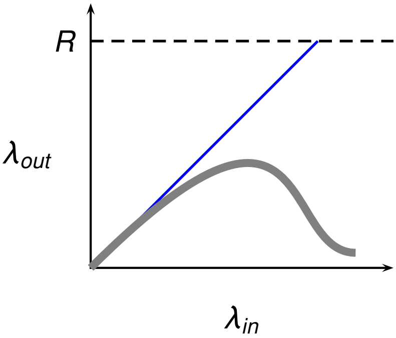

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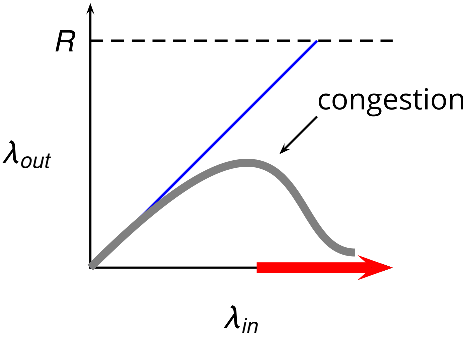

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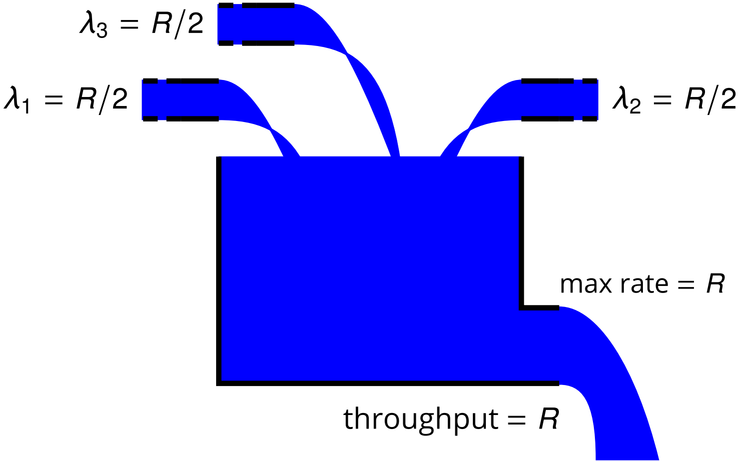

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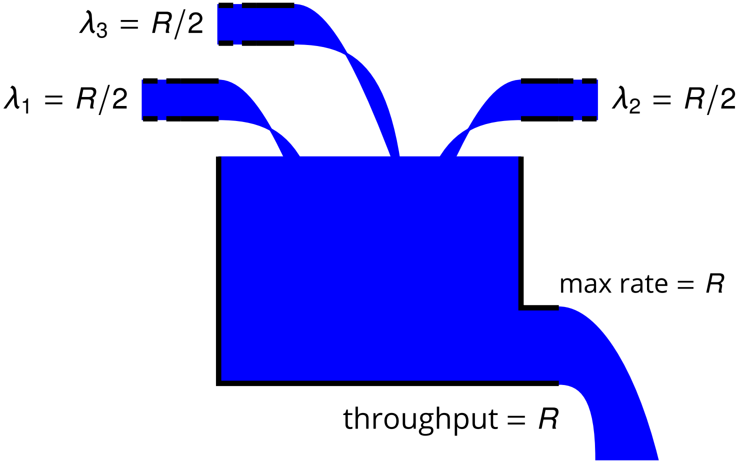

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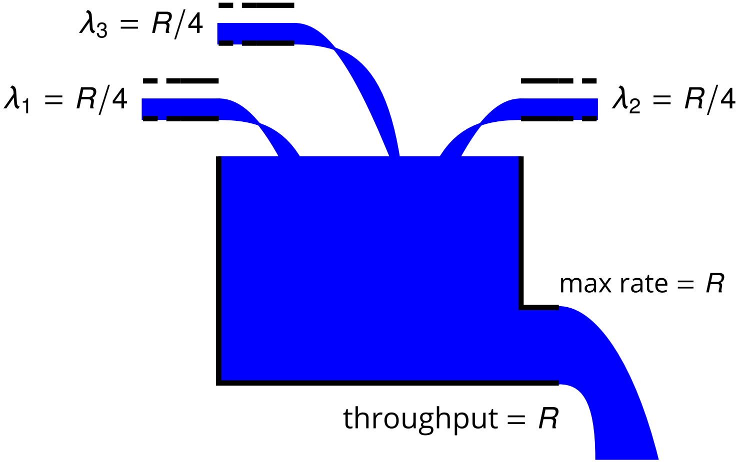

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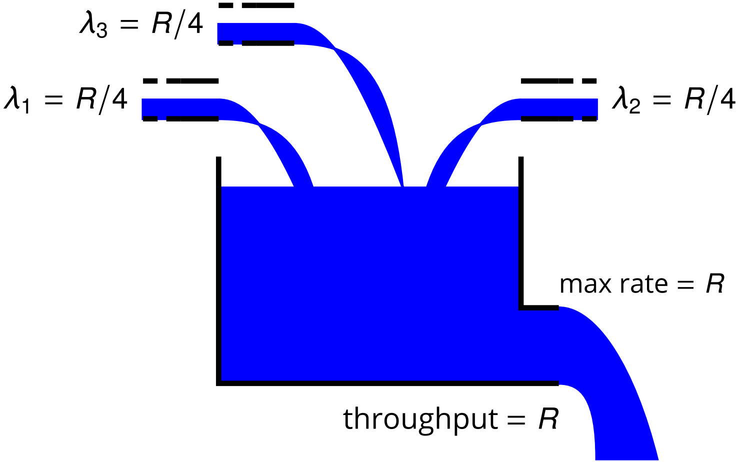

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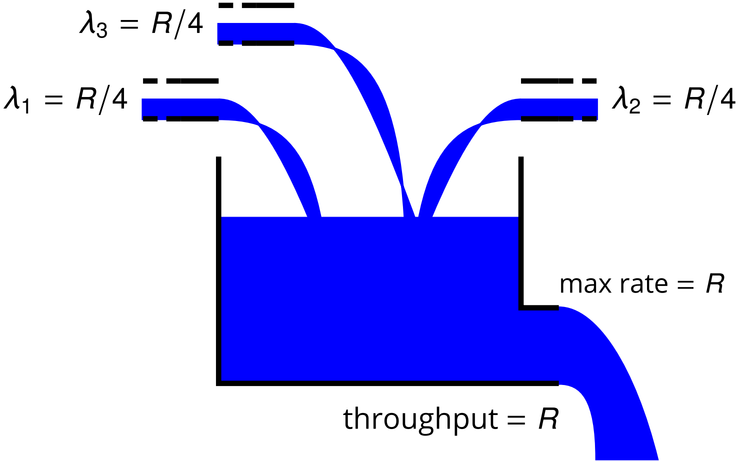

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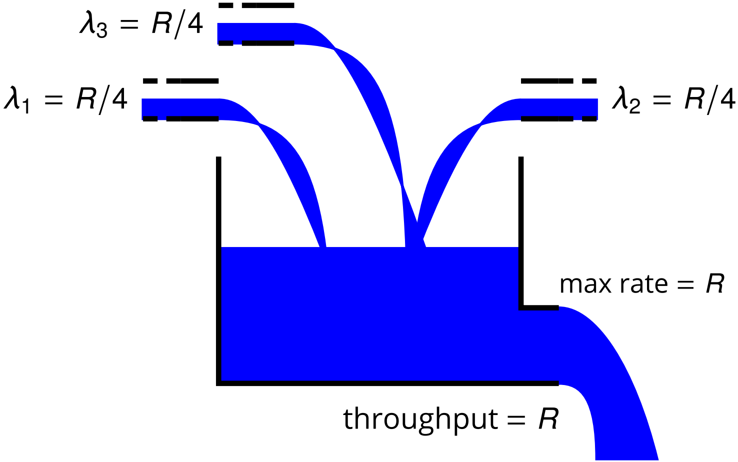

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3. how should the sender ***control its output rate***?
   - we need a ***brain*** and we need to know ***how to drive!***

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- Congestion means that some queues overflow in one or more routers between the sender and the receiver
  - the visible effect is that some segments are dropped
- Therefore the sender assumes that the network is congested when it (the sender) detects a segment loss
  - duplicate acknowledgements (i.e., NACK)
  - time out (i.e., no ACKs at all)

Congestion Window (Accelerator/Brakes)

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- The resulting maximum output rate is roughly

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

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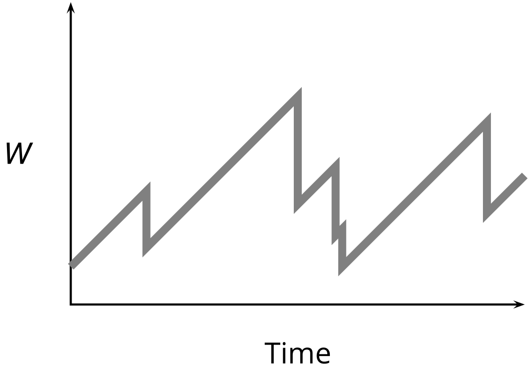
  - e.g., suppose $W = 14600$ and $MSS = 1460$, then the sender increases W to 16060 after 10 acknowledgments acknowledgments

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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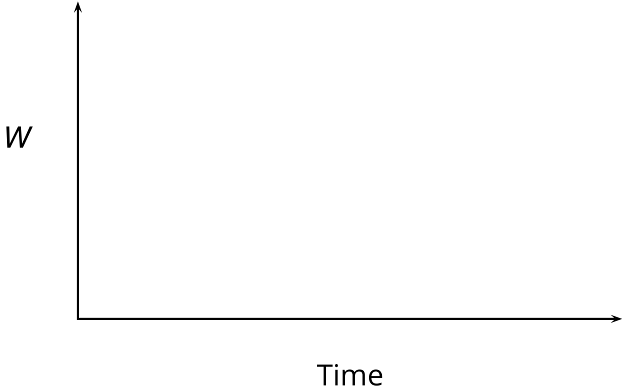
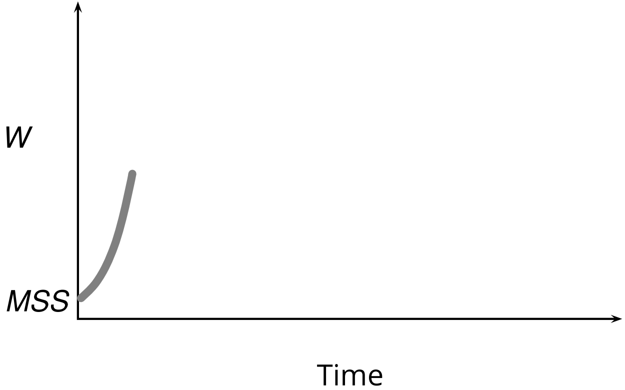
- *NACK* (i.e., triple duplicate-ack)
  - set $ssthresh = \overline{W}/2$
  - cut W in half: $W = \overline{W}/2$
  - run *congestion avoidance*, ramping up W linearly
  - This is called ***fast recovery***


W
Time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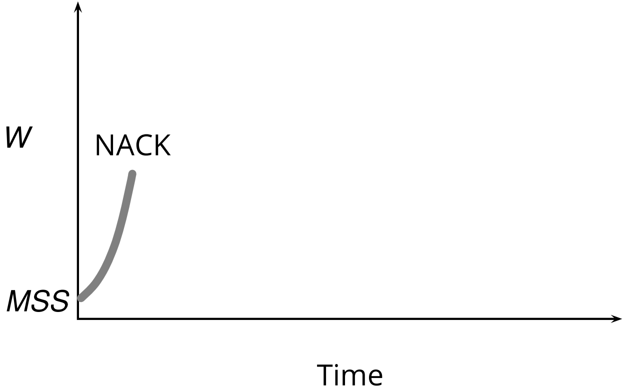
Sender Behavior



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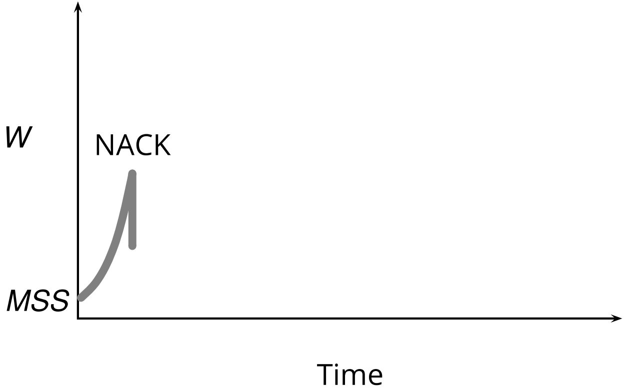

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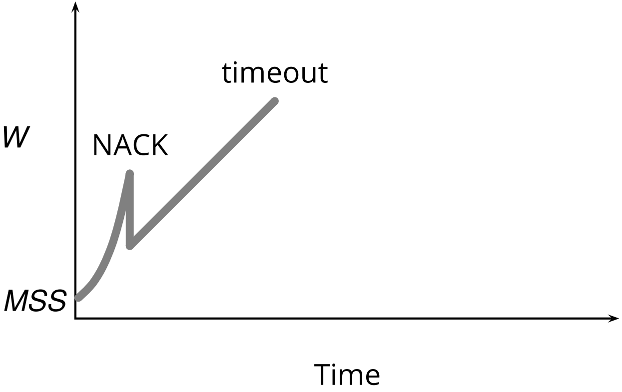

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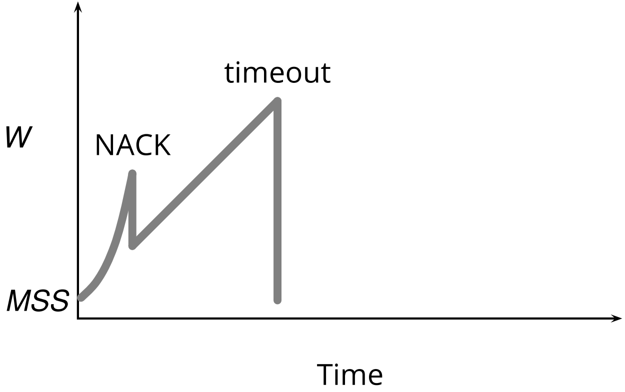

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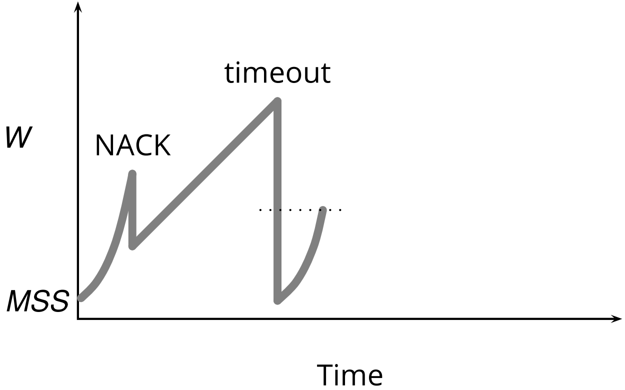

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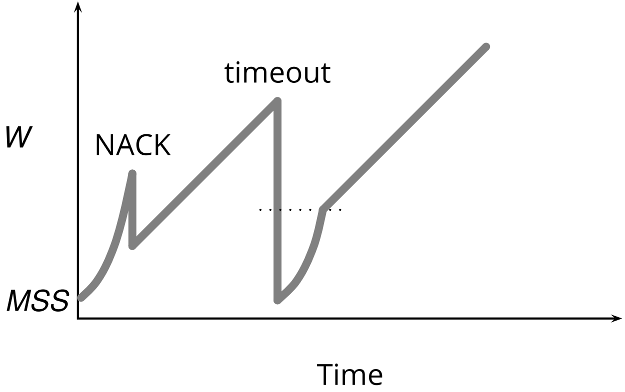

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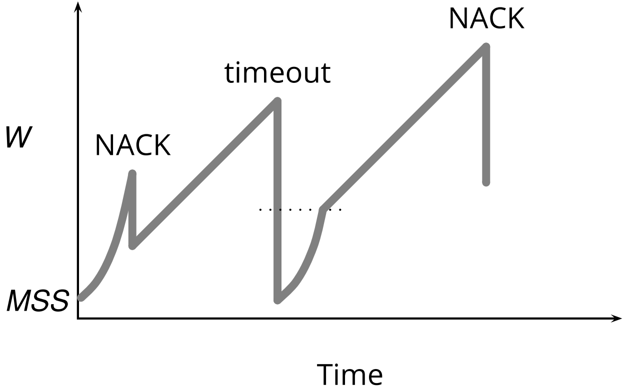

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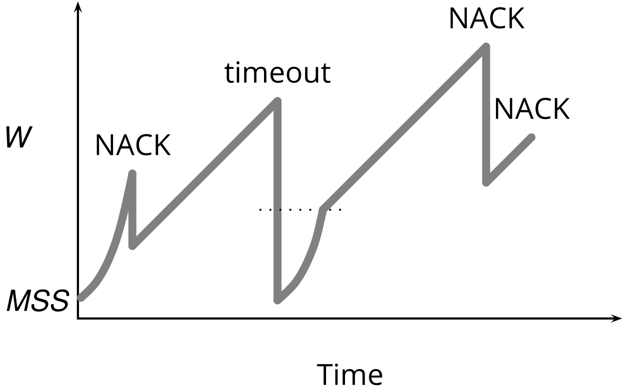

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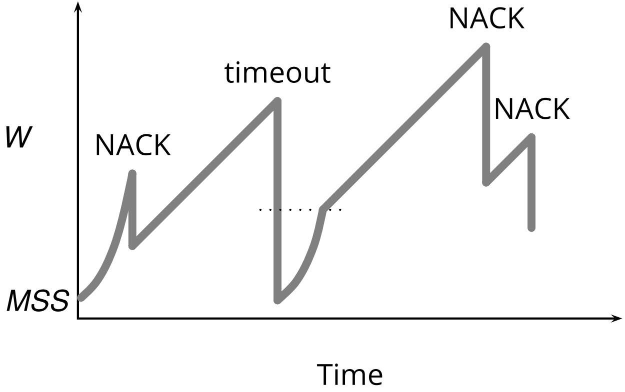

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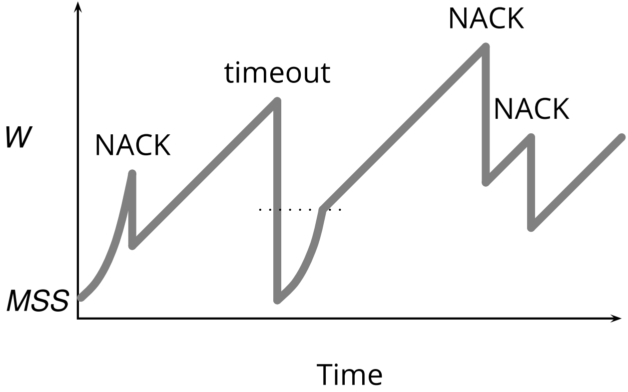
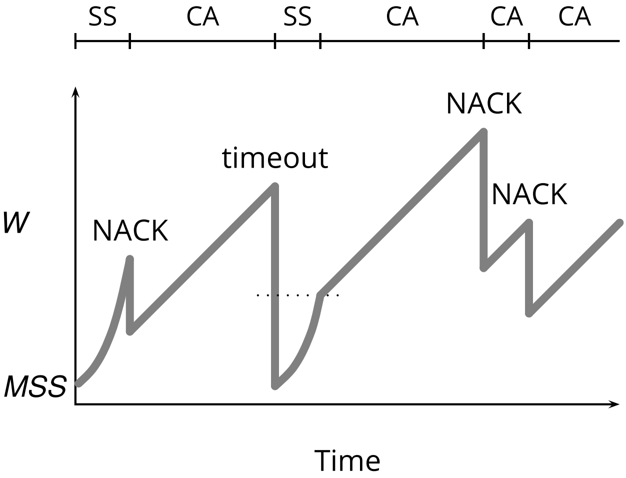
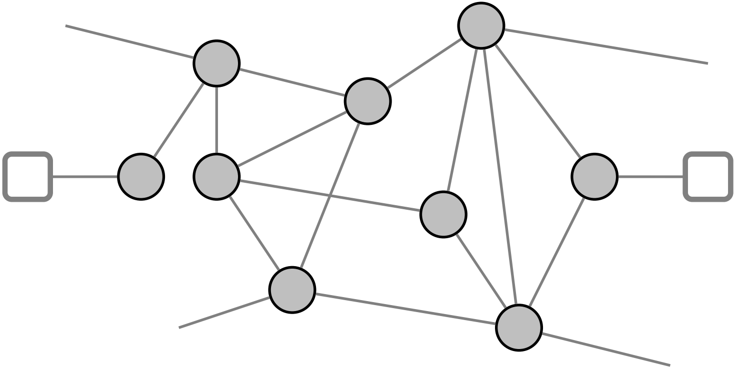


Sender Behavior

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



Datagram Network



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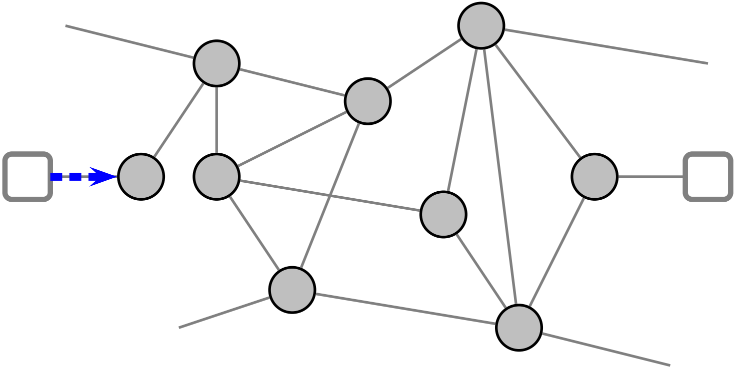

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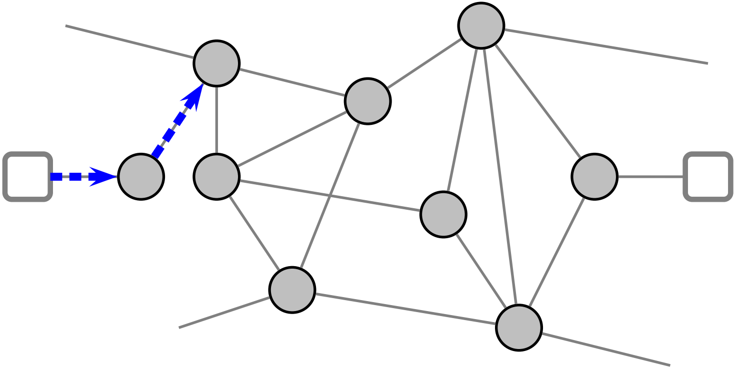

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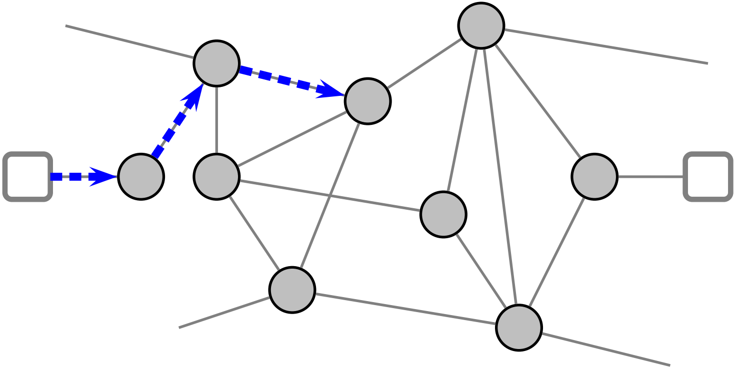

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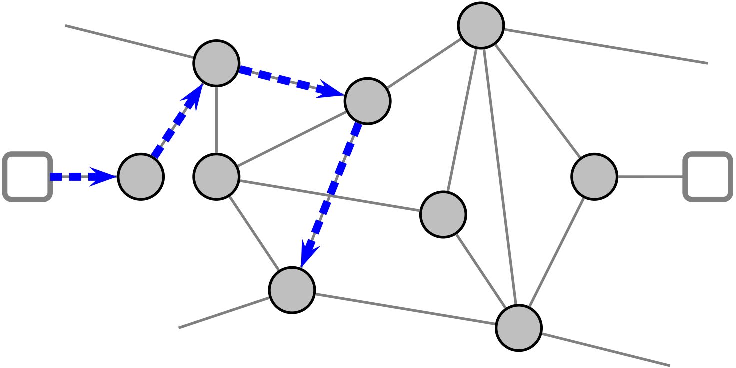

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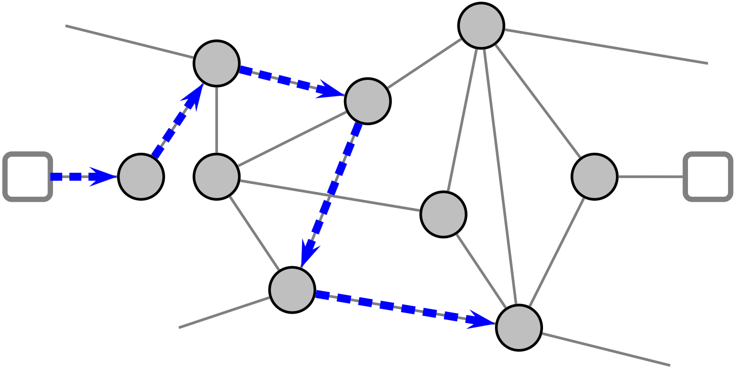

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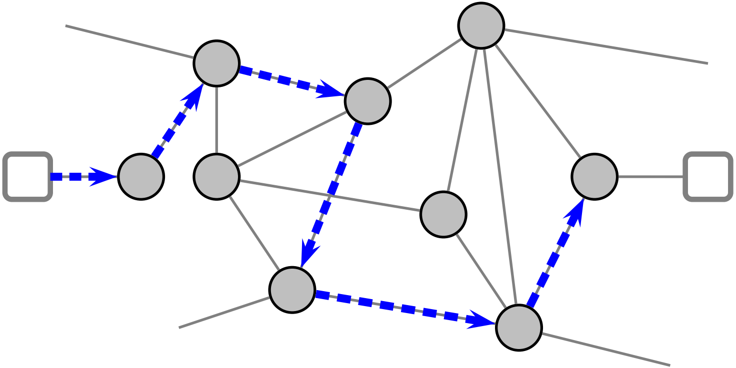

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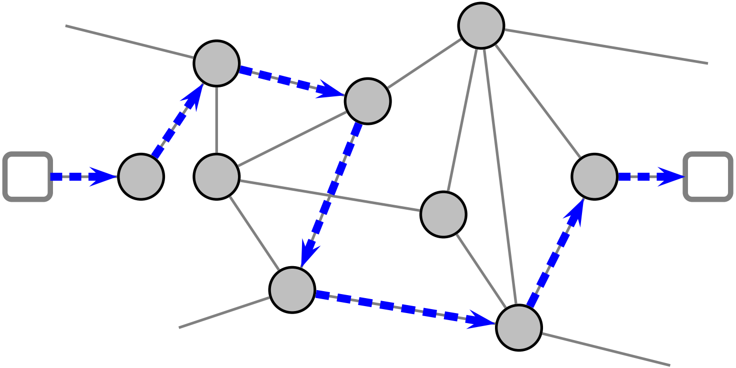

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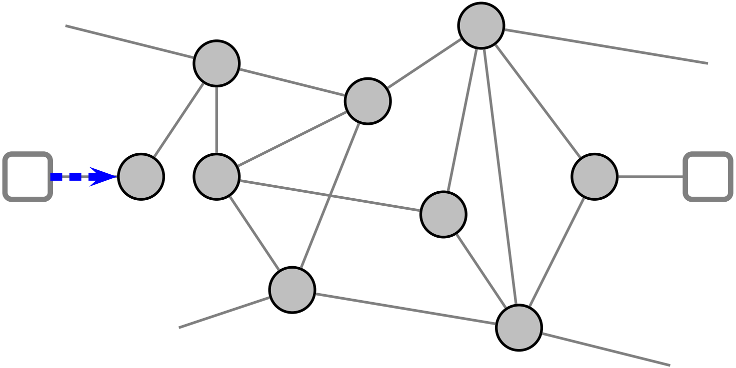

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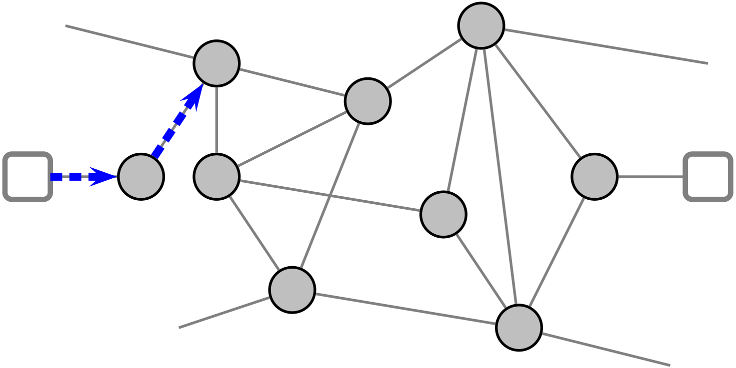

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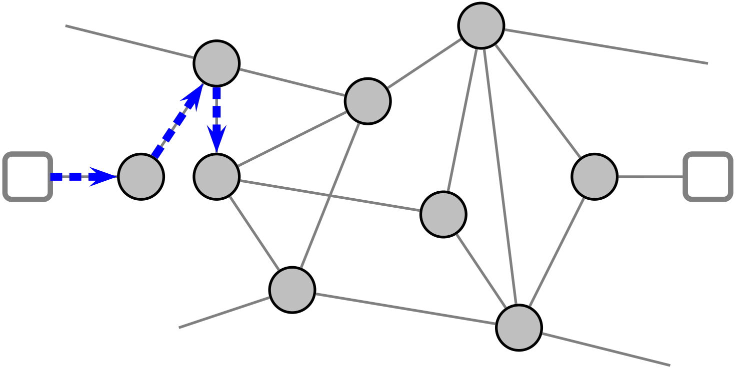

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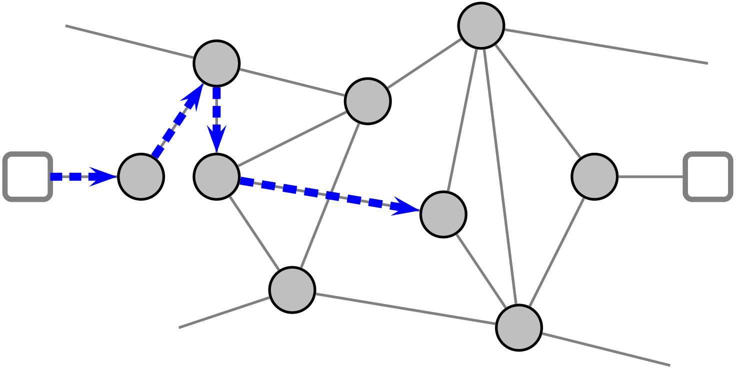

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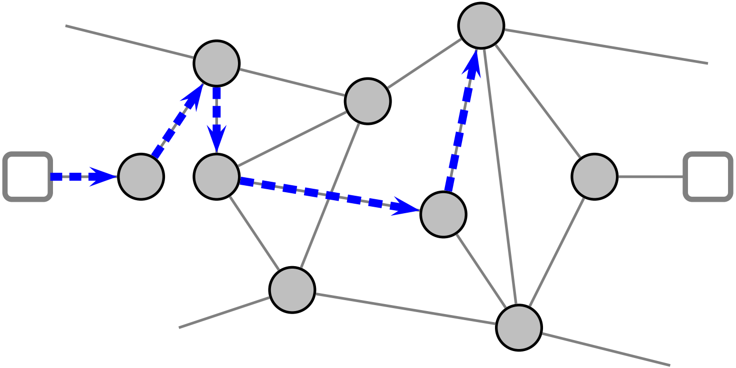

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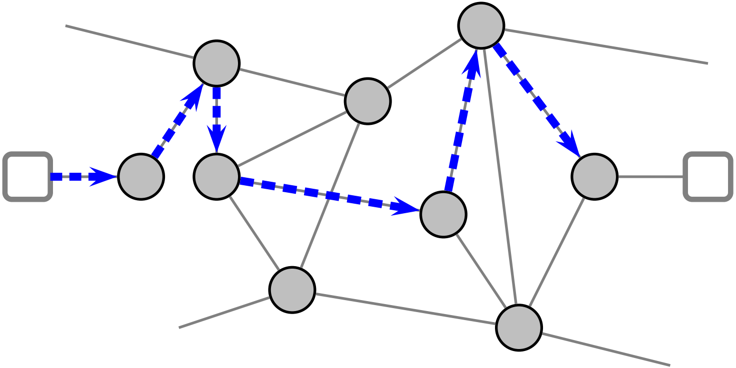

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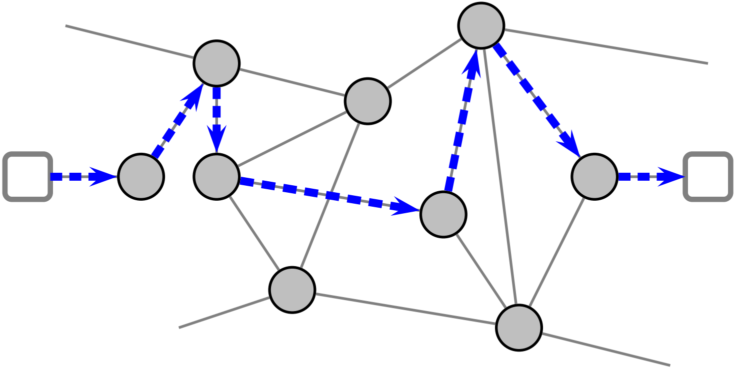

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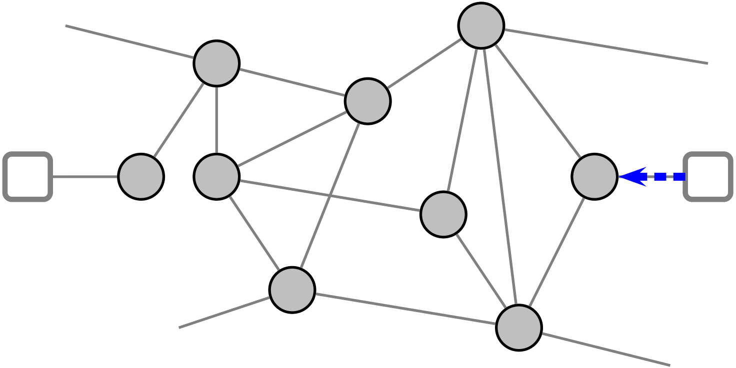

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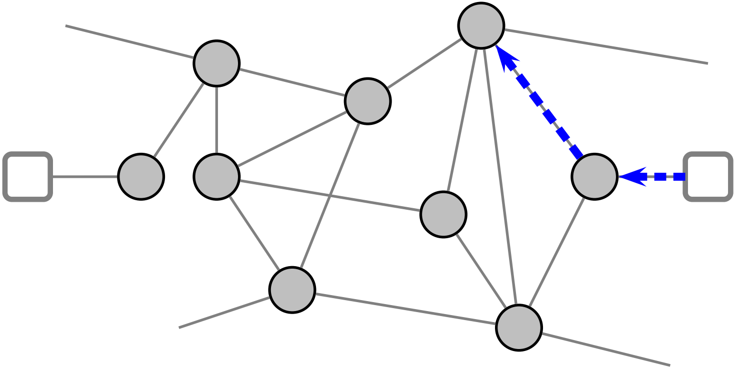

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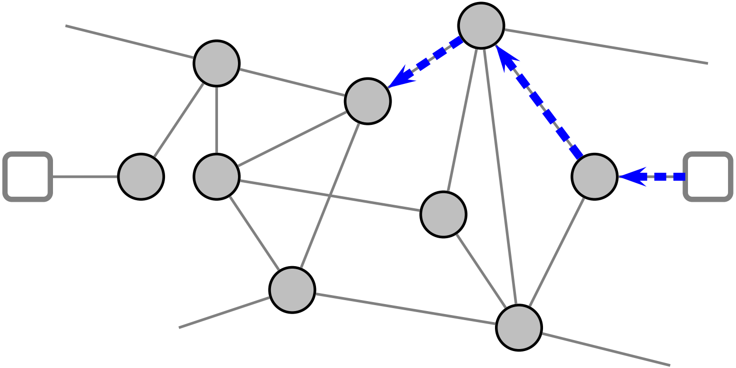

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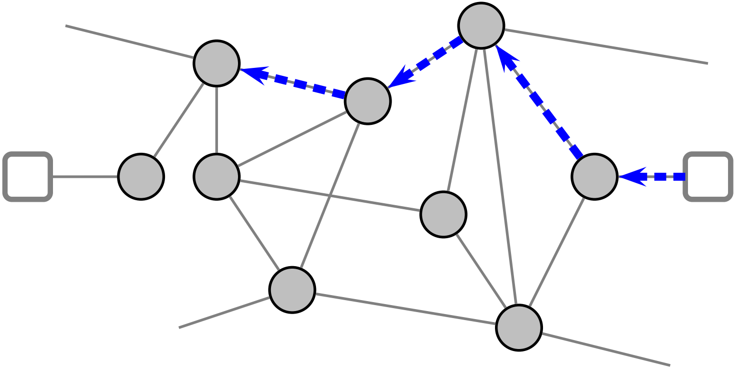

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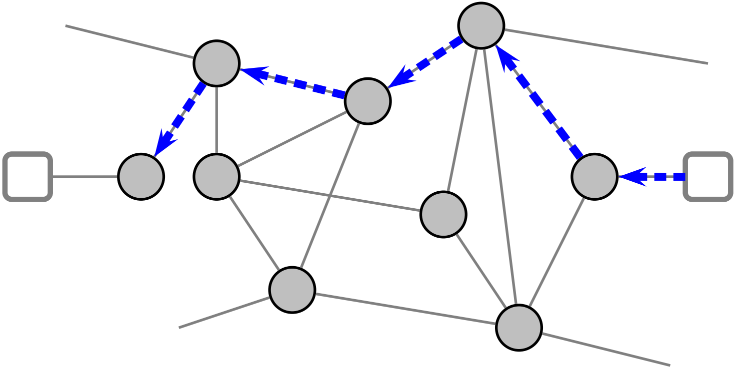
Datagram Network



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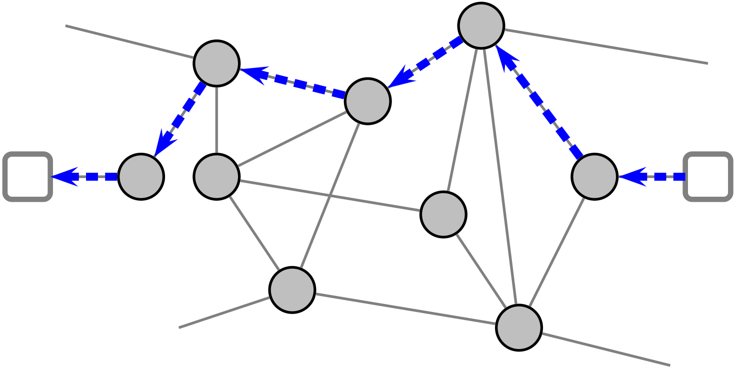

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Forwarding

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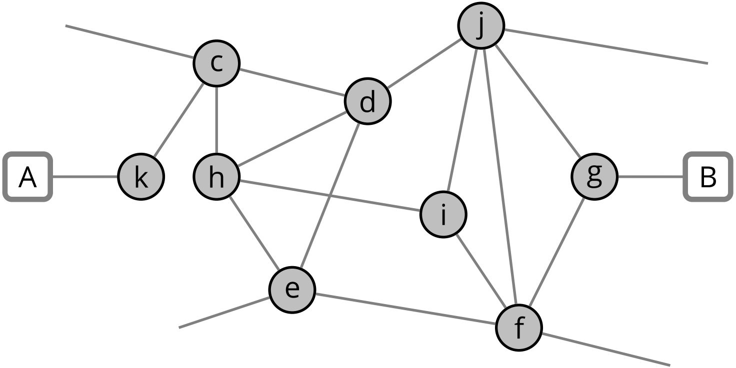

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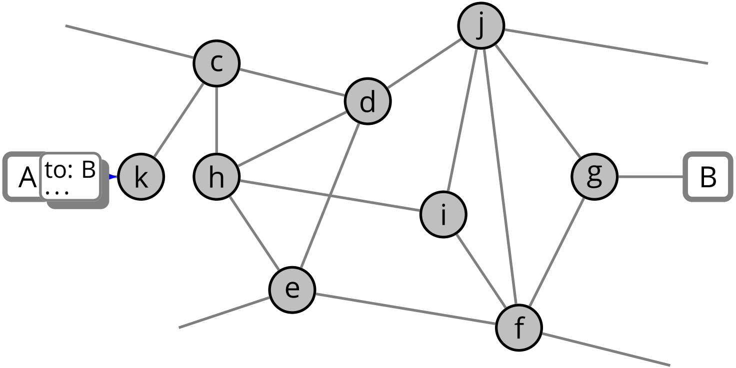

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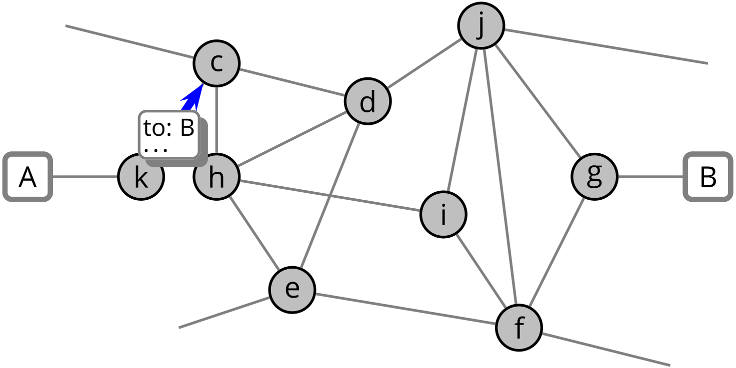

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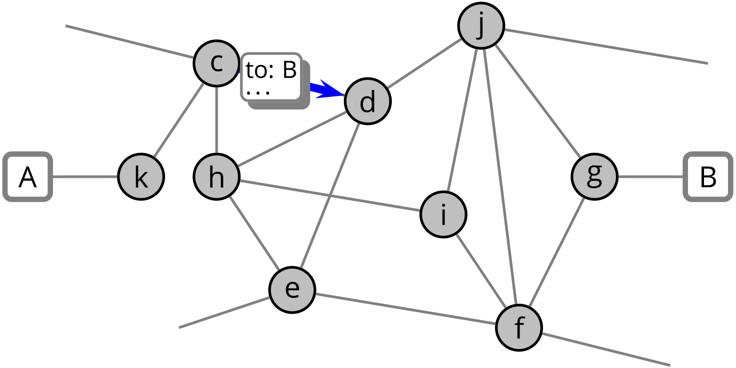

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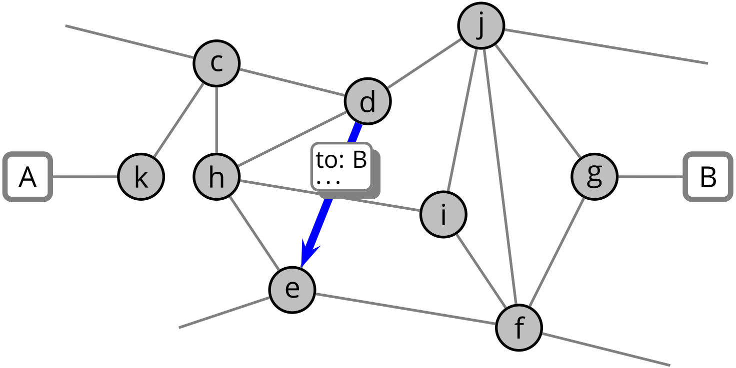
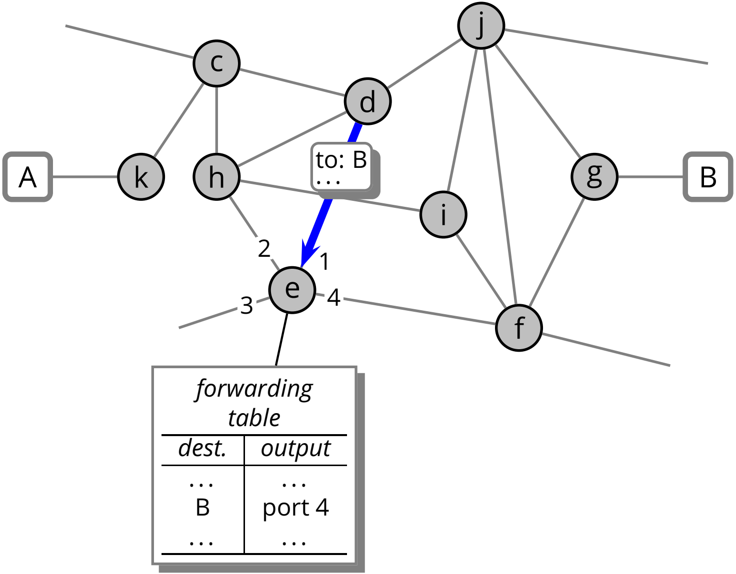
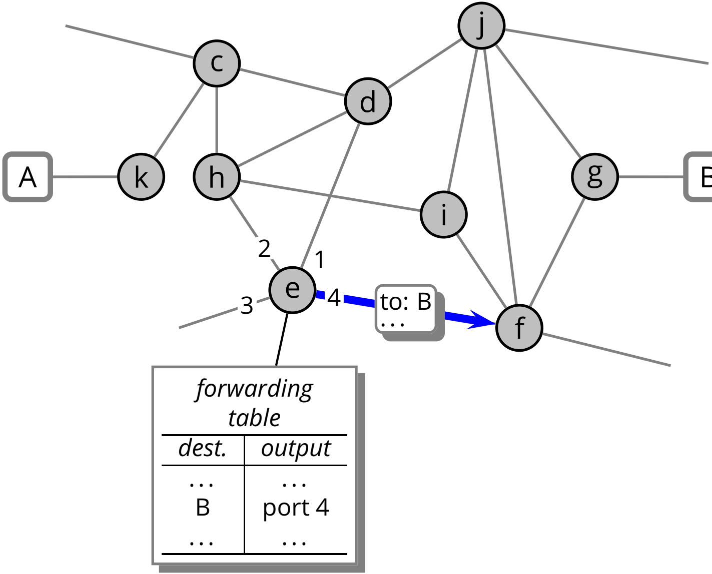




A
k
c
h
d
j
i
g
B
e
f
to: B
. . .
1
2
3
4
forwarding table
dest.
output
. . .
. . .
B
port 4
. . .
. . .

Forwarding



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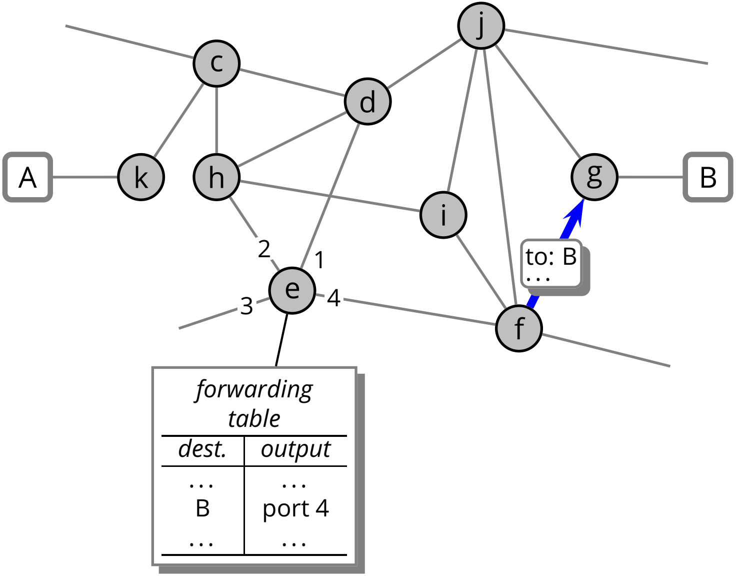

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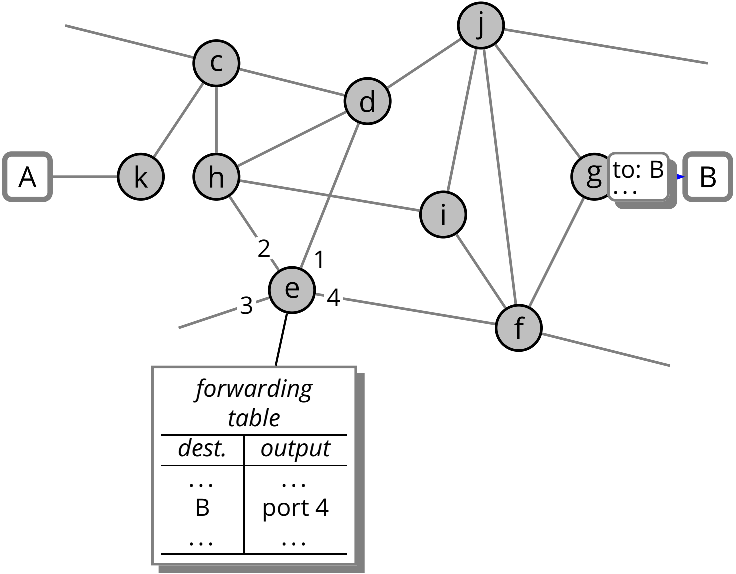

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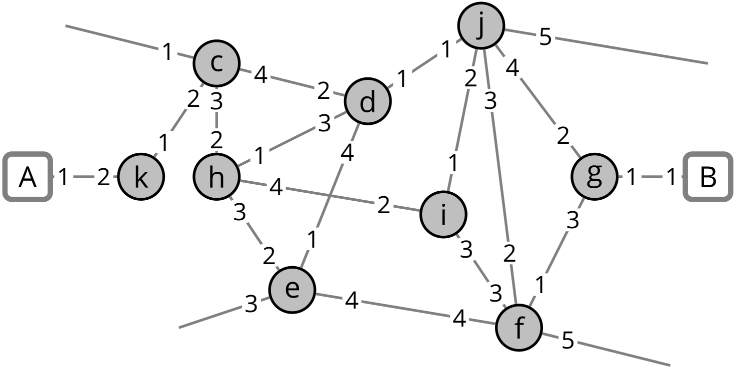
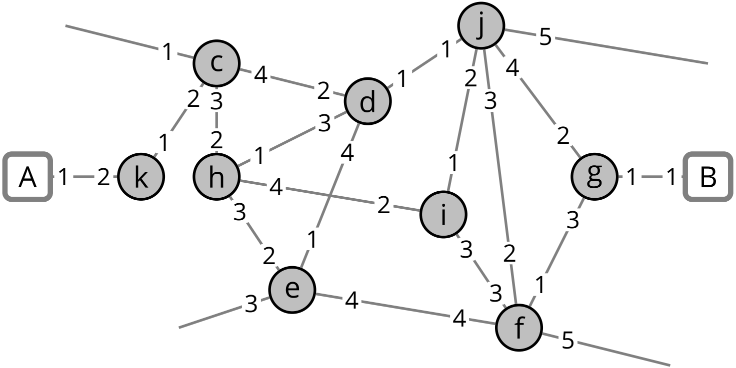
  - how does the router build and maintain the forwarding table?

Routing

Routing



Routing

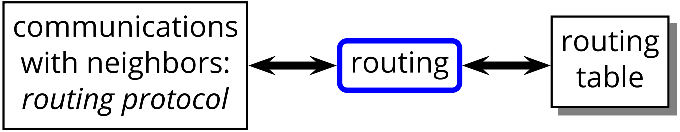


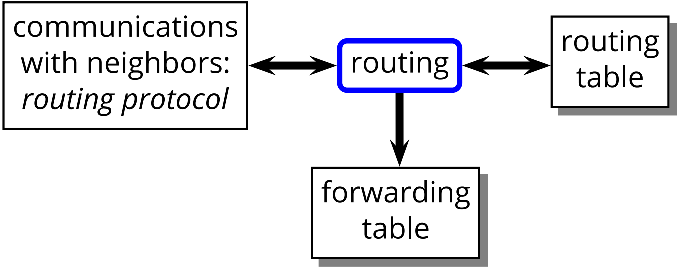
router k	
A	2
B	1

…

Router Functions

Router Functions




communications
with neighbors:
routing protocol
routing
routing
table
forwarding
table

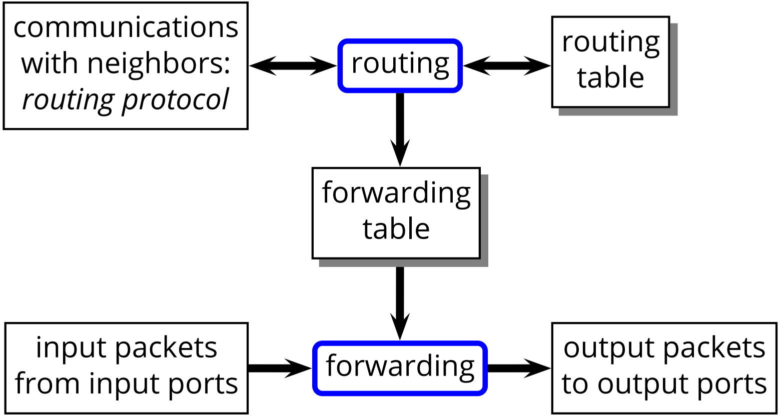

communications
with neighbors:
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table
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table
input packets
from input ports
forwarding
output packets
to output ports

Routing Problem

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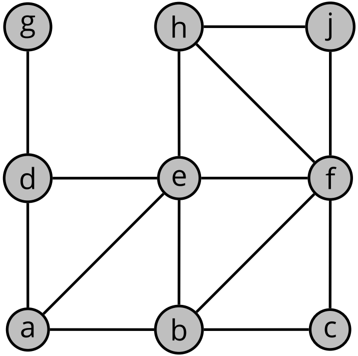

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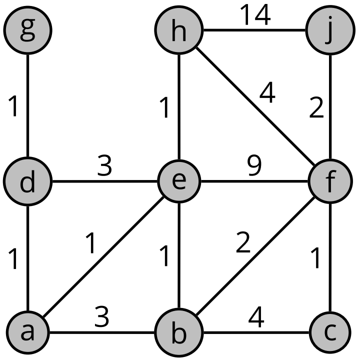

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  - A ***cost*** function $c : E \longrightarrow \mathbb{R}$
    - costs are always positive: $c(e) > 0$ for all $e \in E$
    - links are symmetric: $c(u, v) = c(v, u)$ for all $u, v \in N$

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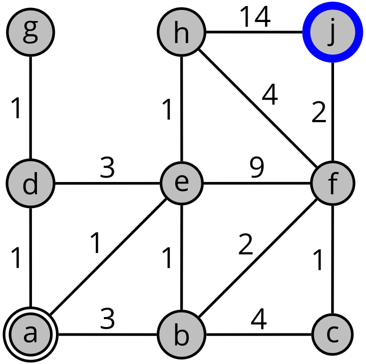
- Compile u's forwarding table by adding the following entry:

$$A(v) \longrightarrow I_u(x_1)$$

  - $A(v)$ is the address (or set of addresses) of router v
  - $I_u(x_1)$ is the interface that connects u to the first next-hop router x_1 in $P_{u \to v} = u, x_1, x_2, \ldots, x_n, v$



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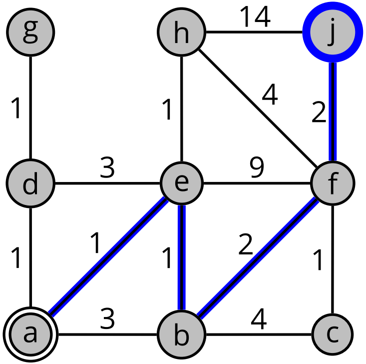

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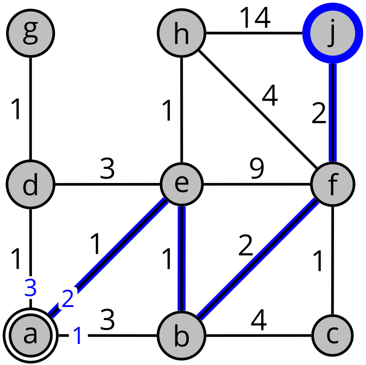
Back To The Example



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  - least-cost path is $P_{a \to j} = a, e, b, f, j$
  - a's forwarding table will contain an entry $\boxed{j \longrightarrow 2}$ since $l_a(e) = 2$

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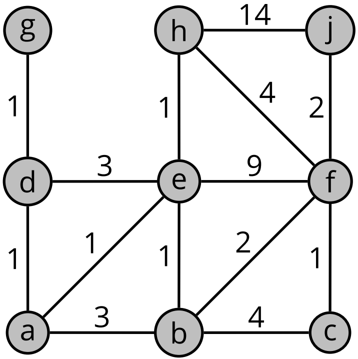
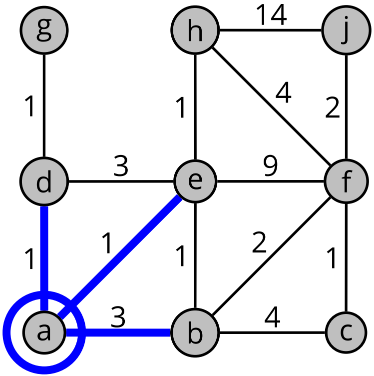
Link-State Advertisements





$LSA_a = \{(a, b, 3), (a, e, 1), (a, d, 1)\}$

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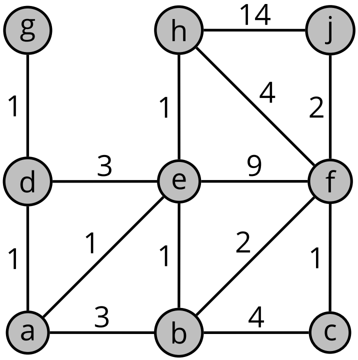

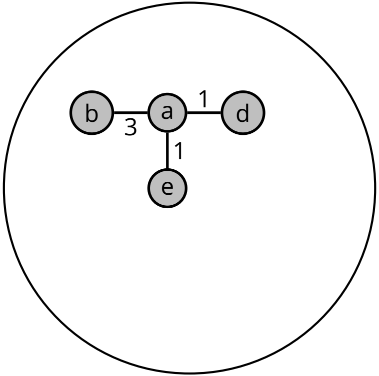

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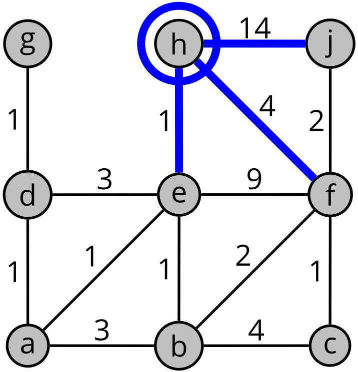

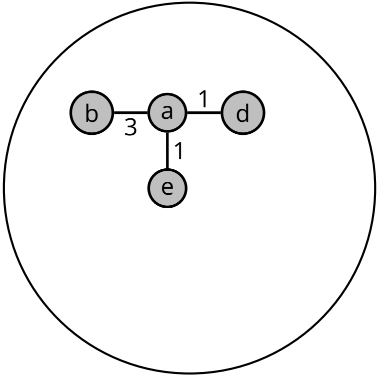

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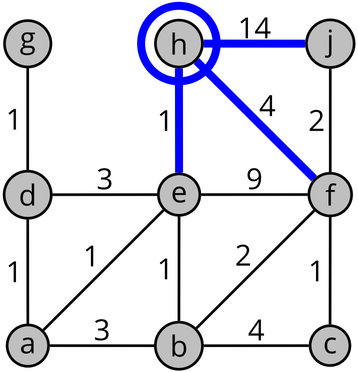

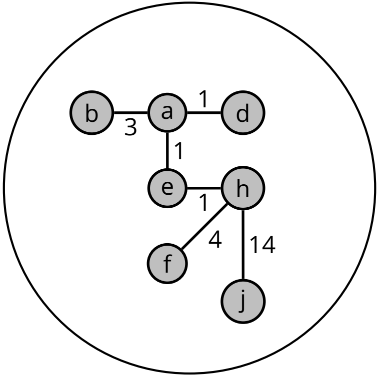

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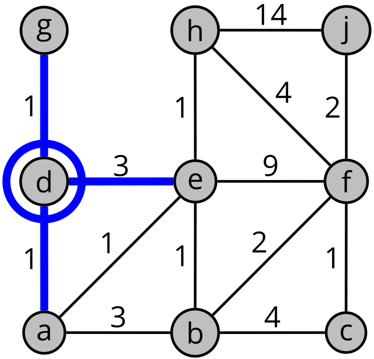

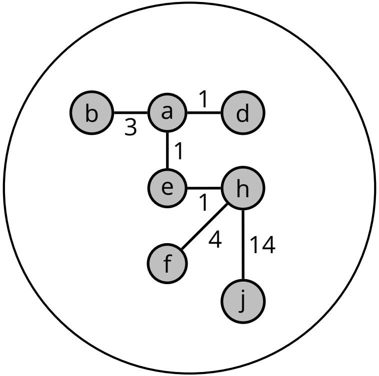

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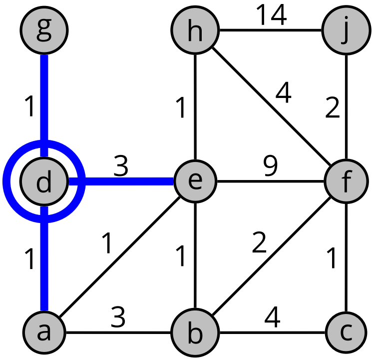

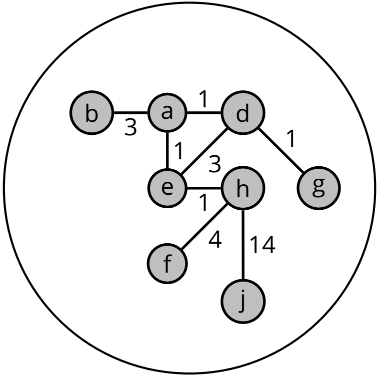

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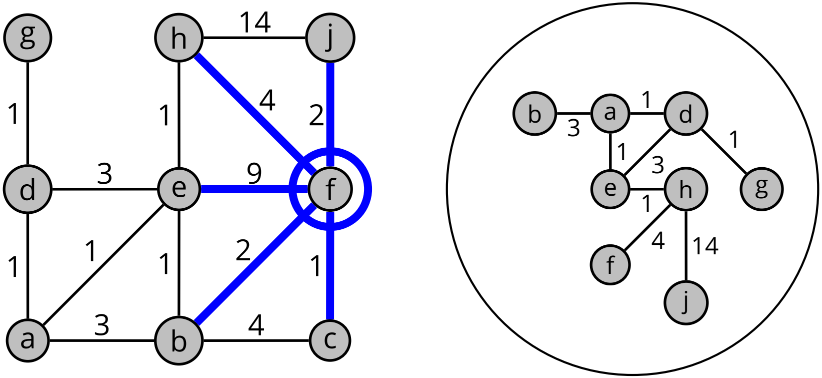

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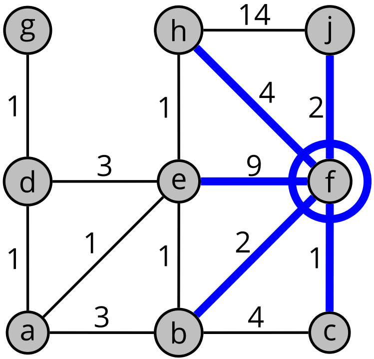

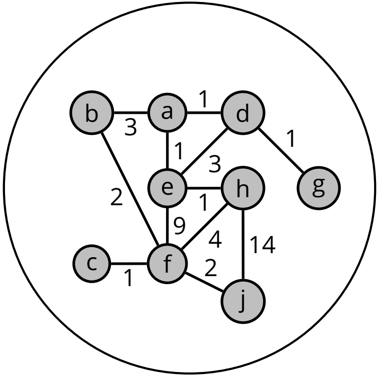

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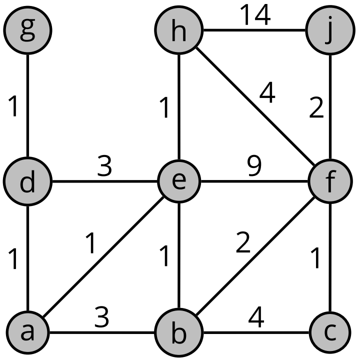

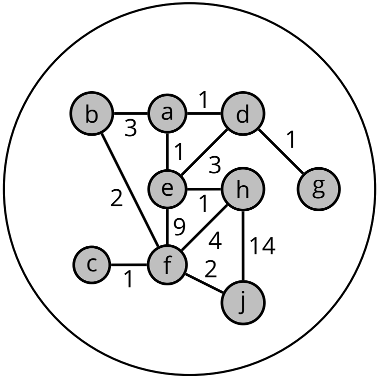

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- Once we have all the LSAs from every router, and therefore we complete knowledge of G, we need an ***algorithm to compute least-cost paths in a graph***

Broadcast Routing

- ***Flooding***
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  - cycles in the network create *packet storms*

Broadcast Routing (2)

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- ***Reverse-path broadcast***
  - every router forwards a broadcast packet to every adjacent router, except the one where it received the packet router
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  - u updates its table of sequence numbers $n_s \leftarrow seq(p)$

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- An *intra-autonomous system routing protocol* runs within an autonomous system (e.g., OSPF)
  - this protocol determines internal routes
    - internal router ↔ internal router
    - internal router ↔ gateway router
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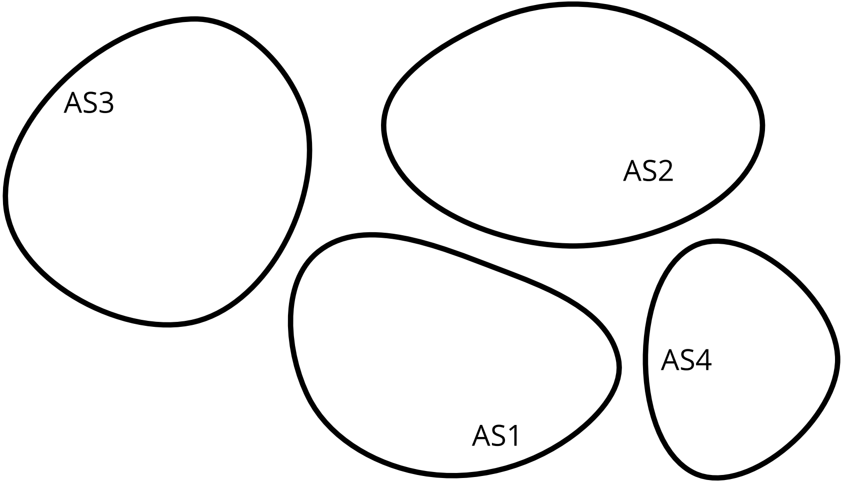
Hierarchical Structure



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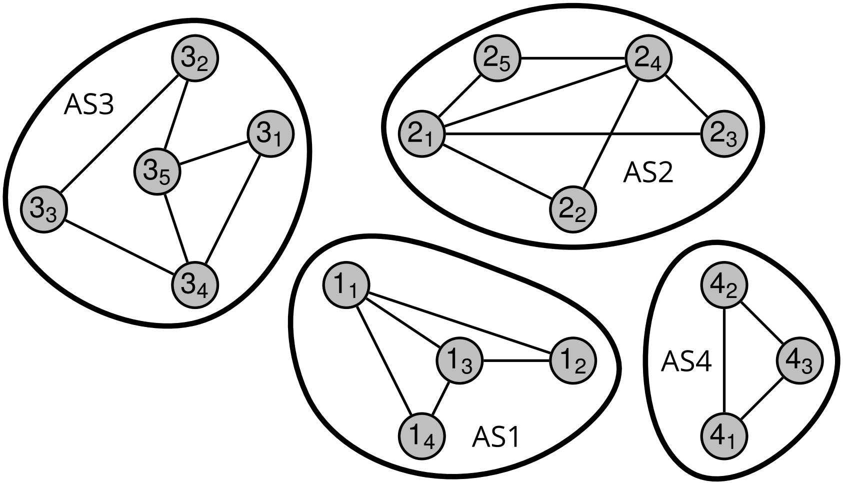

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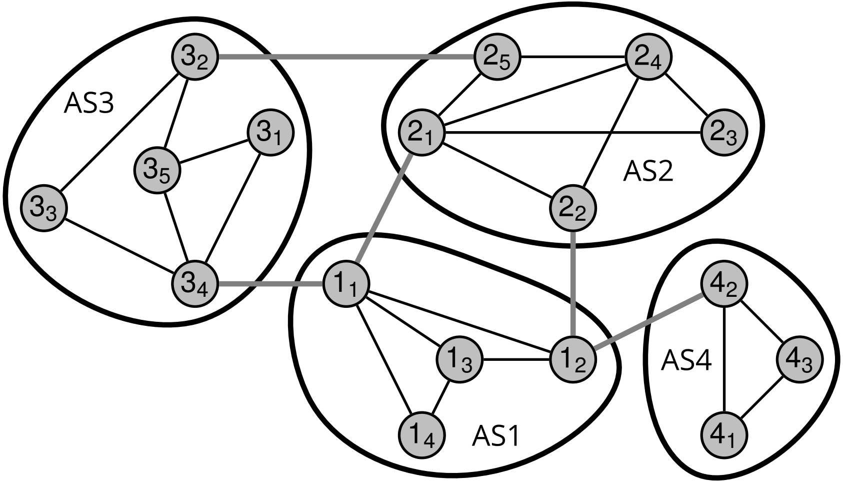

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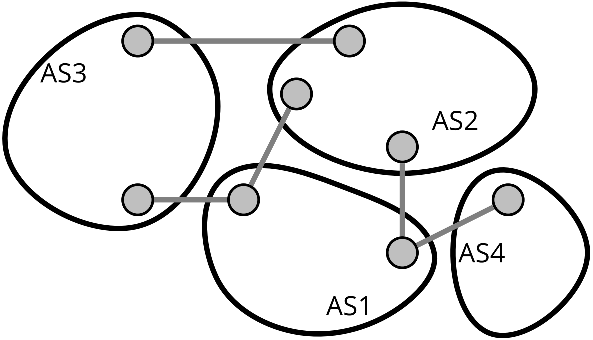

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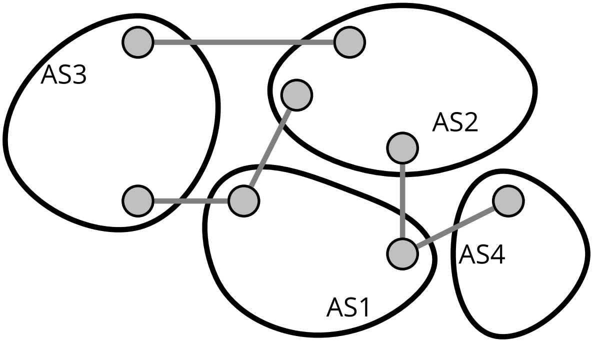

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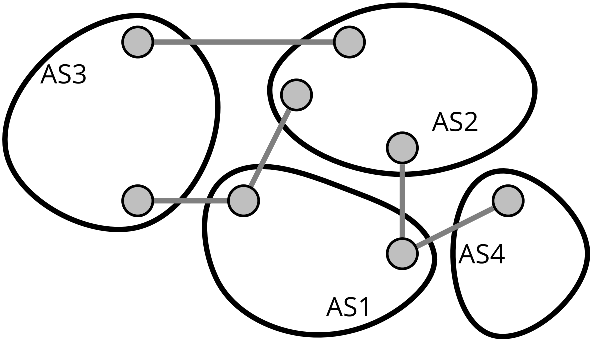

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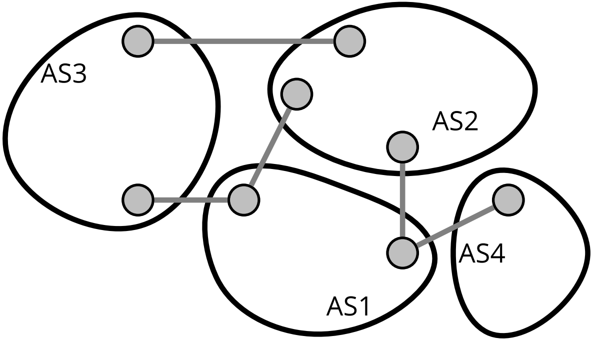

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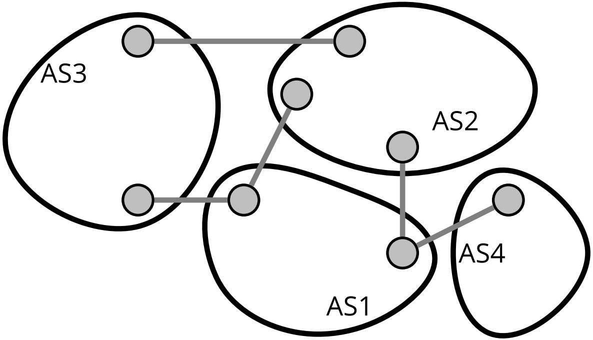

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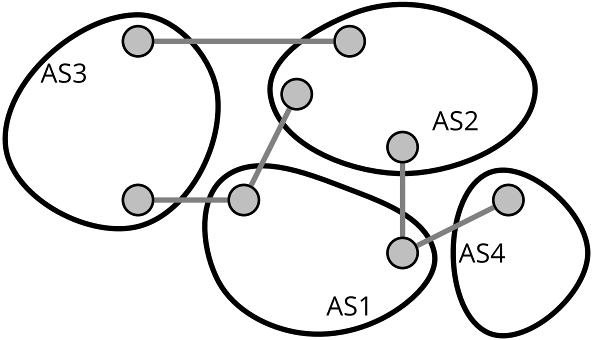

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    - use *intra-AS* routing information to determine the costs of the (least-cost) paths to $G_x, G'_x, \ldots$
    - "hot-potato" routing: send it through the closest gateway

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- External subnet addresses are likely to “aggregate” in groups that admit compact representations
  - this process is called *supernetting*

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  - note that internal sessions carry *inter-AS* information
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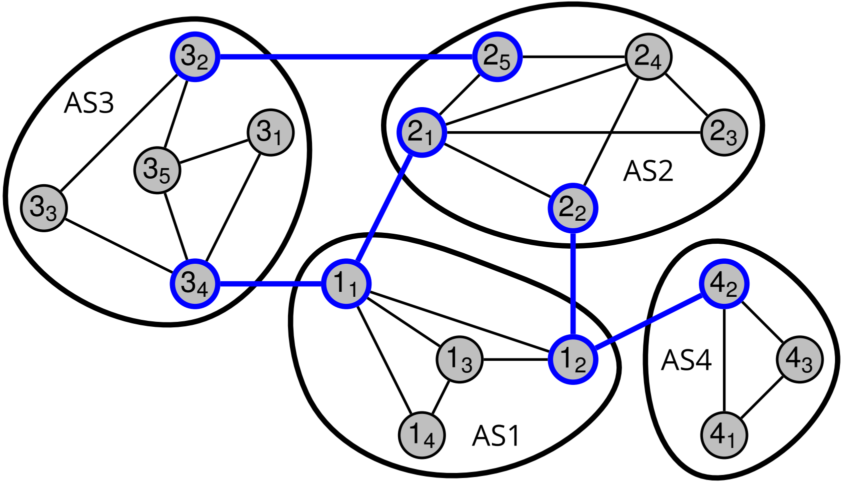
Gateway Routers and *eBGP*



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- ***BGP import policy:*** used to decide whether to accept or reject the route advertisement
  - e.g., a router may not want to send its traffic through one of the AS listed in *AS-PATH*

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