# A Quick Review of Computer Networking

## Architecture, Applications, Transport (TCP), Routing

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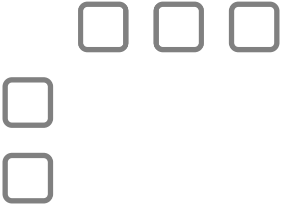
Faculty of Informatics
Università della Svizzera italiana

February 19, 2020

# What is *Inside* the Internet?



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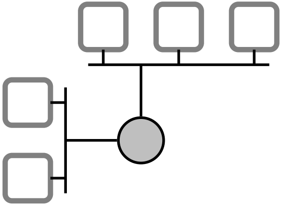

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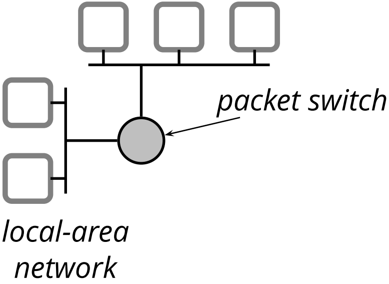

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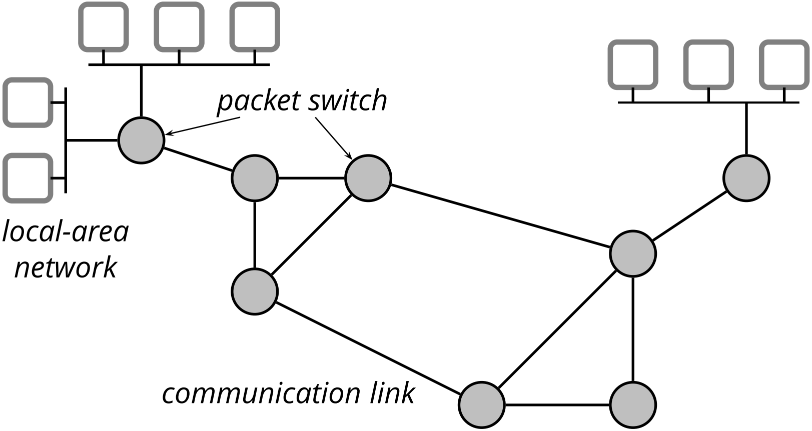

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- ***Packet switch:*** a *link-layer switch* or a ***router***
- ***Communication link:*** a connection between packet switches and/or end systems
- ***Route:*** sequence of switches that a packet goes through (a.k.a. *path*)
- ***Protocol:*** control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

# Communication Links

- Various types and forms of medium

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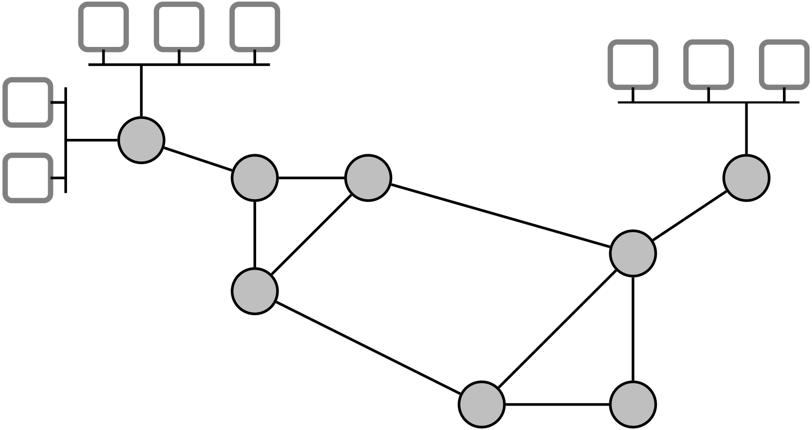
- Various types and forms of medium
    - Fiber-optic cable
    - Twisted-pair copper wire
    - Coaxial cable
    - Wireless local-area links (e.g., 802.11, Bluetooth)
    - Satellite channel
    - . . .

# Packet Switching



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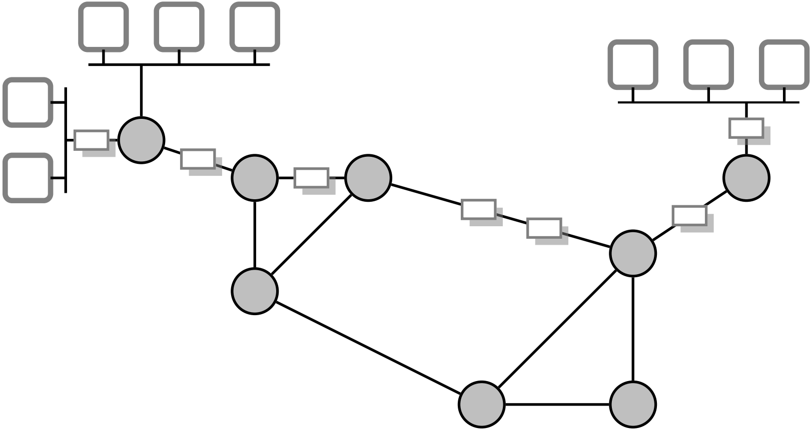

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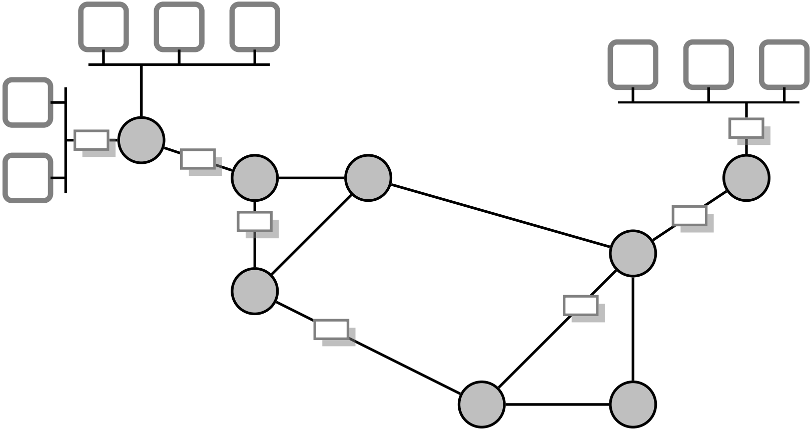

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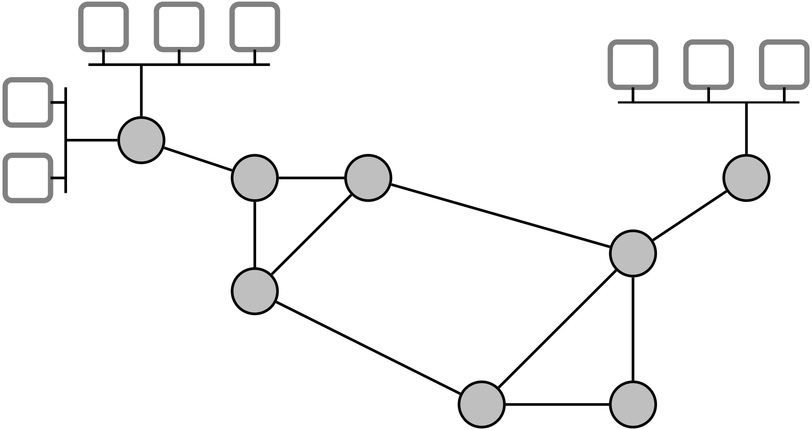
- A switch (router) receives packets and *forwards* them along to other switches or to end systems
- Every forwarding decision is taken on the basis of the information contained in the packet

# Circuit Switching



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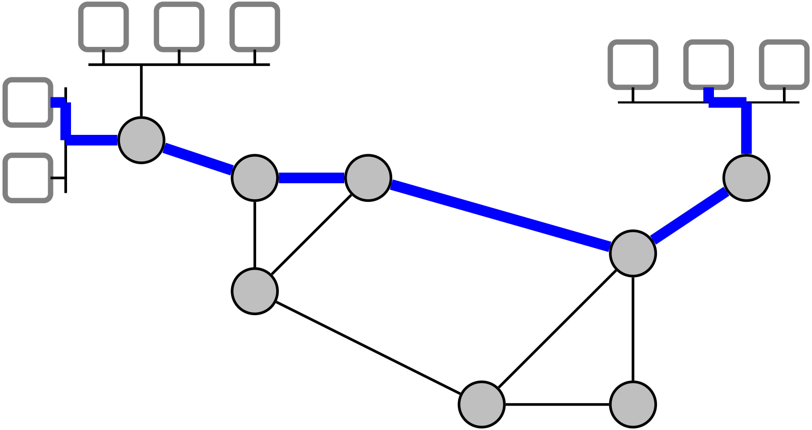

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- After a successful setup, the communicating systems are connected by ***a set of links dedicated to the connection*** for the entire duration of their conversation

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

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- 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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- Guaranteeing any quality of service with packet switching is very difficult
    - no concept of a “connection”
    - and again, processing, space overhead, etc.

# Circuit vs. Packet Switching (3)

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  - i.e., circuit switching is an inefficient way to use the network

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- Packet switching achieves a much better utilization of network resources
  - it is designed specifically to share links
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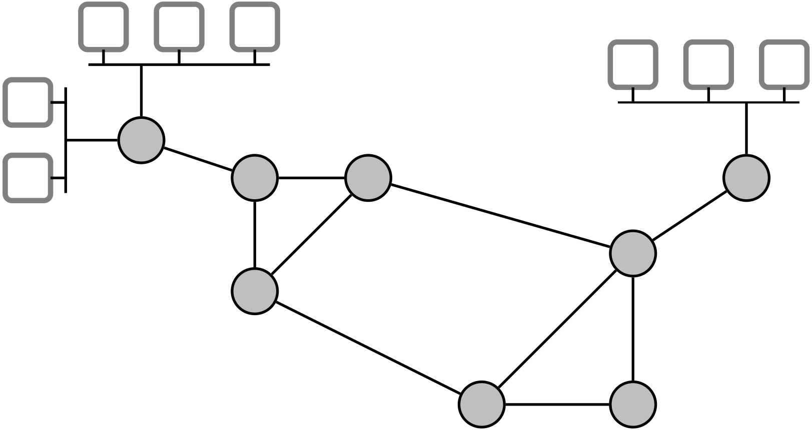
- Information is sent in packets, so links can be shared more effectively
- Packets carry a *virtual circuit identifier* instead of the destination address
  - *Important observation:* at any given time there are much fewer *connections* than *destinations*
    - much faster per-packet processing (forwarding)
    - lower per-packet space overhead

# Virtual Circuit



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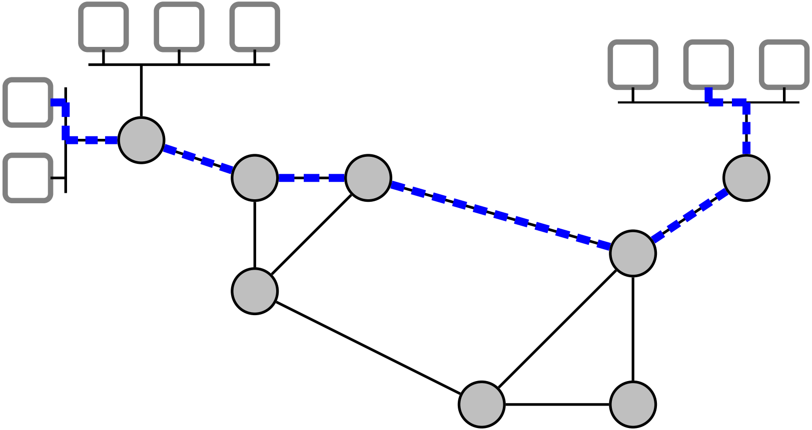

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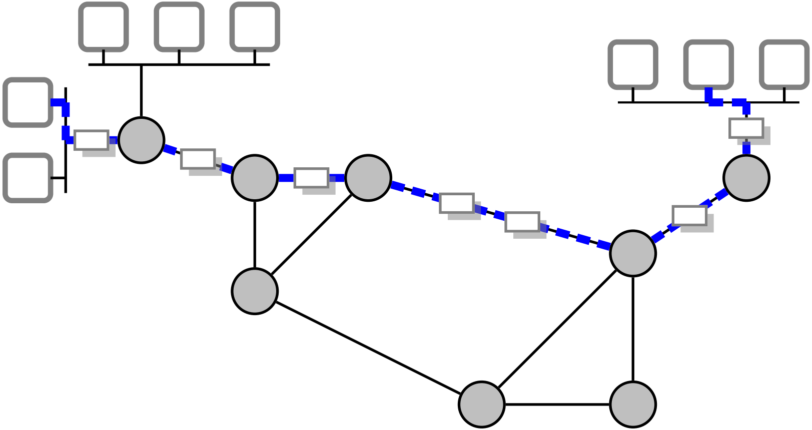

# Taxonomy of Networks

communication
network

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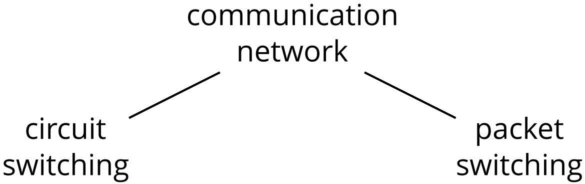

communication network

circuit switching

packet switching

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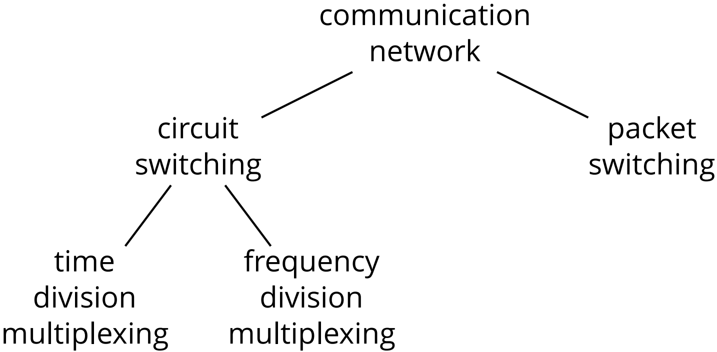

communication network

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time division multiplexing

frequency division multiplexing

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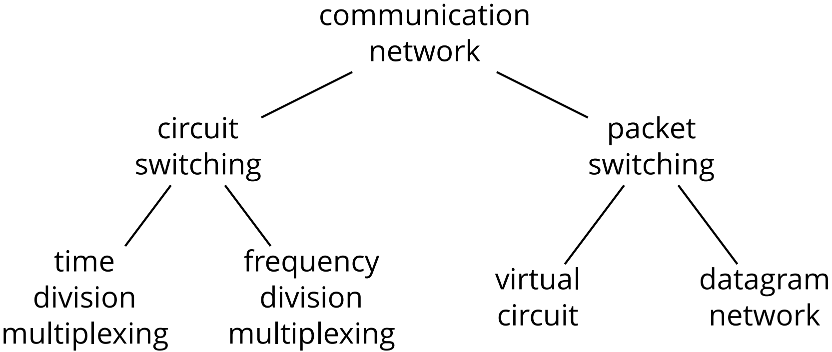

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virtual circuit

datagram network

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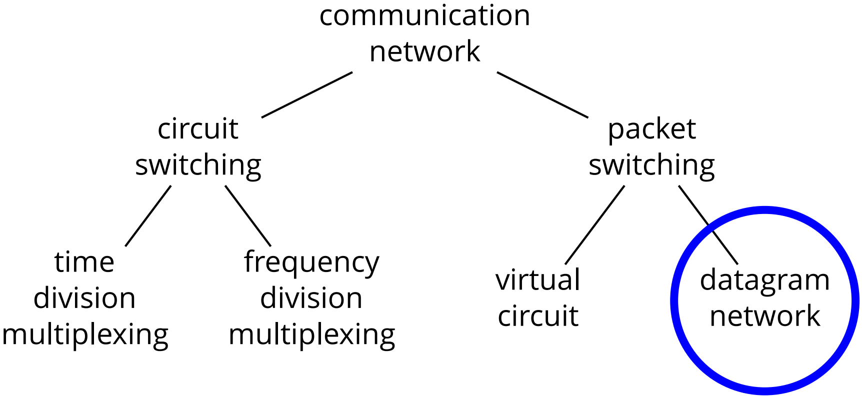
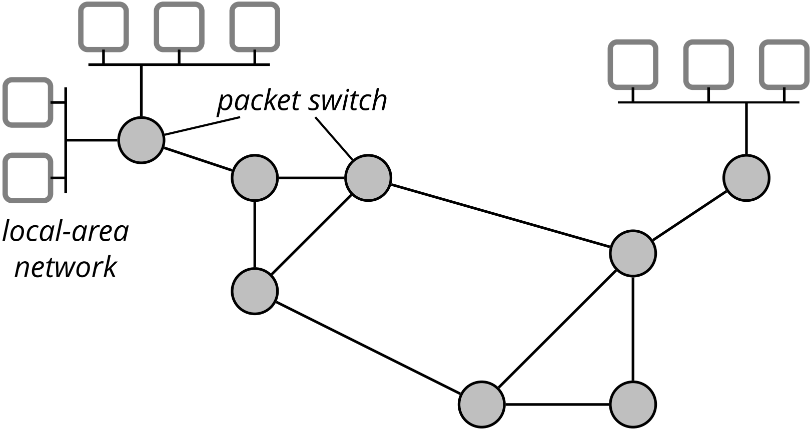


# Service Perspective



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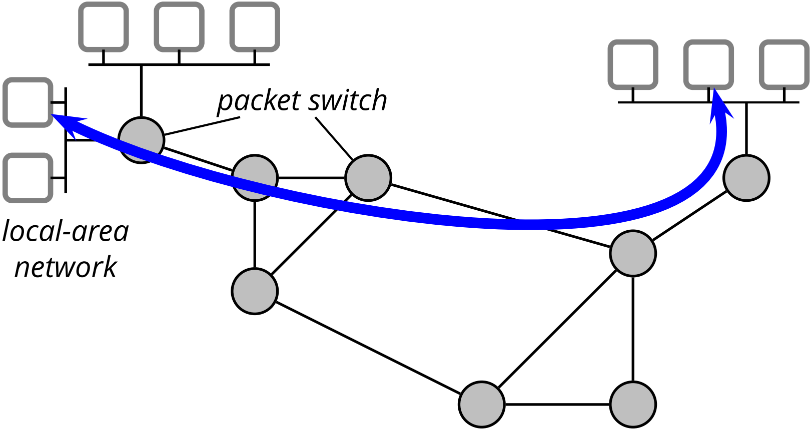

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- ***Connection-oriented, reliable***
  - virtual duplex communication channel ($A \leftrightarrow B$)—conceptually similar to a telephone service
  - information is transmitted "reliably" and in order

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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)

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application

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application

transport

# Internet Protocol Stack

application

transport

network

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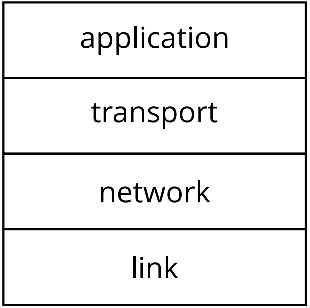

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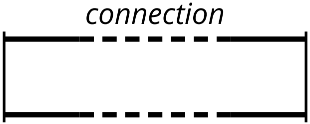

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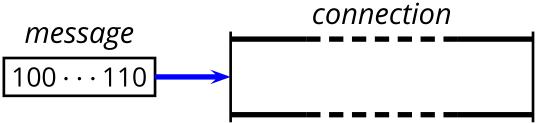

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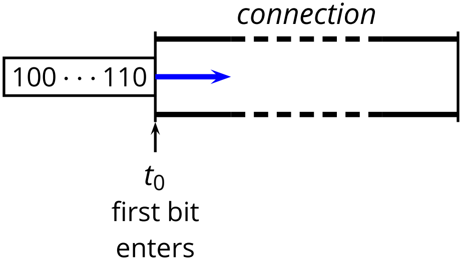

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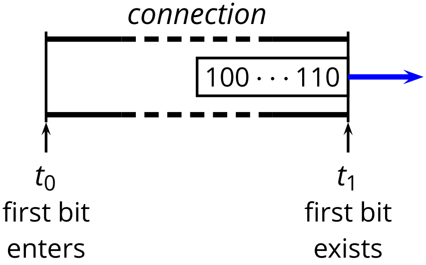

*connection*

100 · · · 110

$t_0$
first bit
enters

$t_1$
first bit
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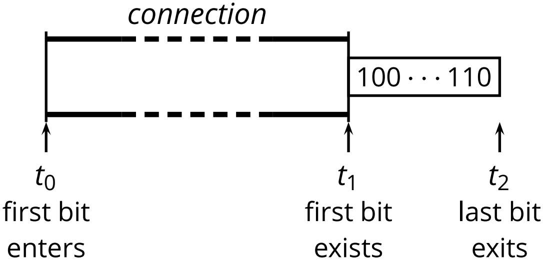

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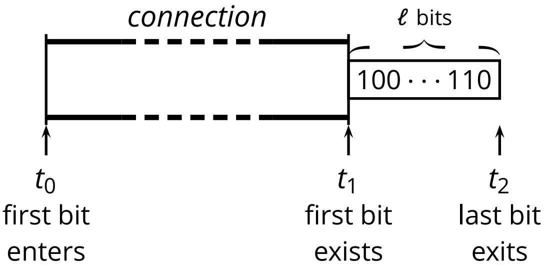

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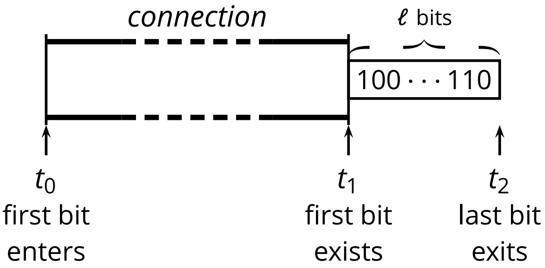

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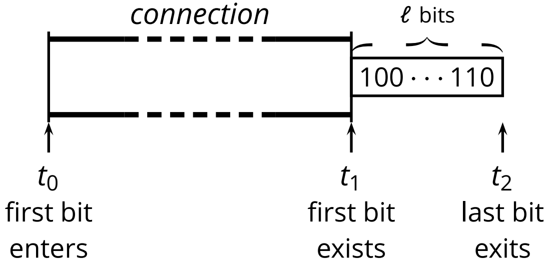

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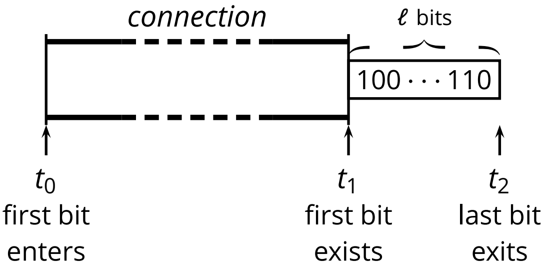

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| | | |
|---|---|---|
| *Propagation **Delay*** | $d_{prop} = t_1 - t_0$ | sec |
| *Transmission **Rate*** | $R = \dfrac{\ell}{t_2 - t_1}$ | bits/sec |
| *Total transfer time* | $d_{end\text{-}end} = d + \dfrac{\ell}{R}$ | sec |

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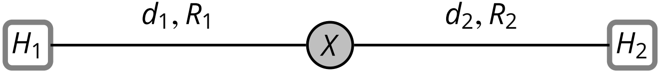

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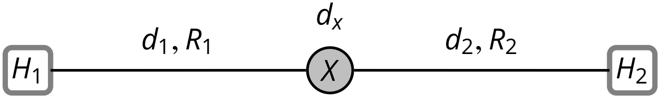

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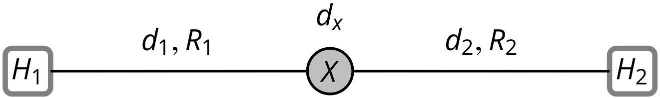

$$d_{\text{end-end}} = d_1 + \frac{\ell}{R_1}$$

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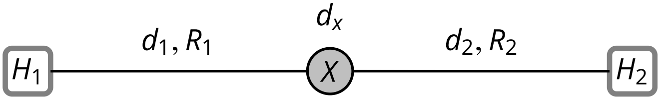

$$d_{end\text{-}end} = d_1 + \frac{\ell}{R_1} + d_x$$

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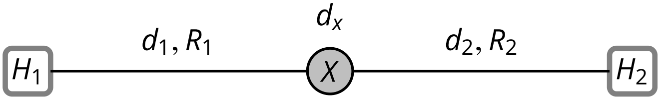

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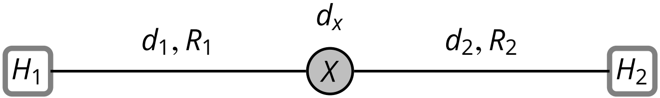

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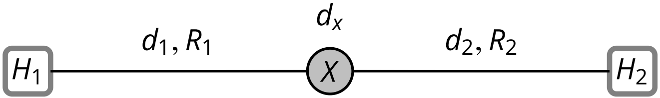

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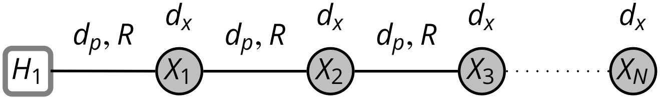

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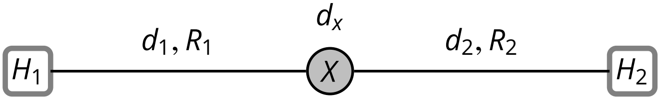

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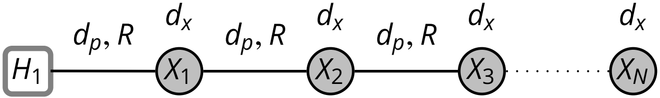

$$d_{end\text{-}end} = N\left(d_p + \frac{\ell}{R} + d_x\right)$$

# End-toEnd Throughput

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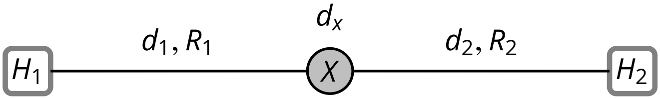

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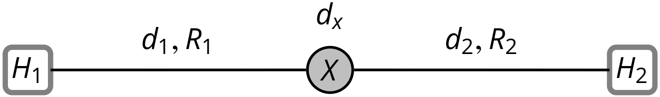

$$R_{\textit{end-end}} =$$

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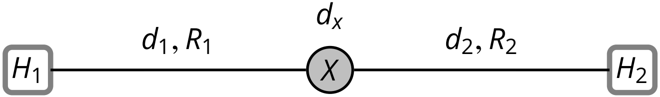

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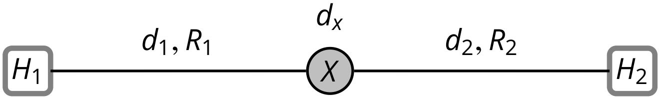

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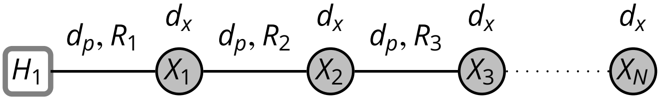

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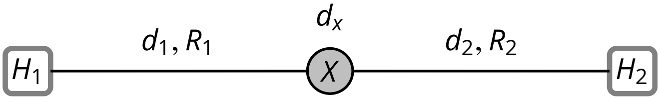

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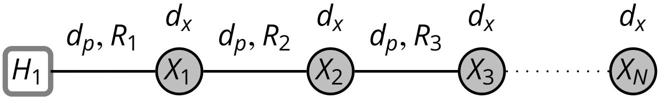

$$R_{end\text{-}end} = \min\{R_1, R_2, \ldots, R_N\}$$

# Processing and Queuing Delays

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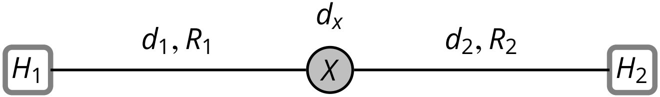

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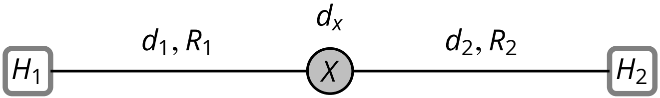

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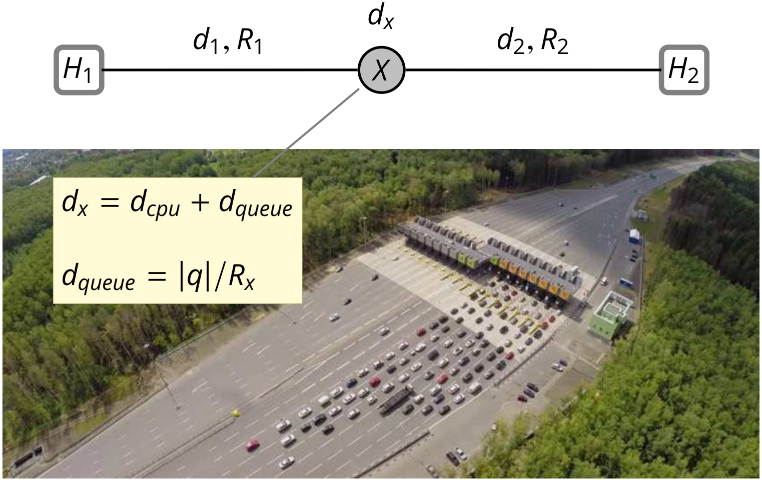

$$d_x = d_{cpu} + d_{queue}$$

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

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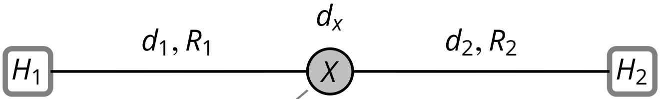

$$d_x = d_{cpu} + d_{queue}$$

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

queue length

output rate

# Queuing Delay

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where

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output rate

# Queuing Delay

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

where

$$d_{queue} = \overbrace{|q|}^{\text{queue length}} / \underbrace{R_x}_{\text{output rate}}$$

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

# Application Protocols

# Application Protocols

HTTP

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HTTP

SMTP

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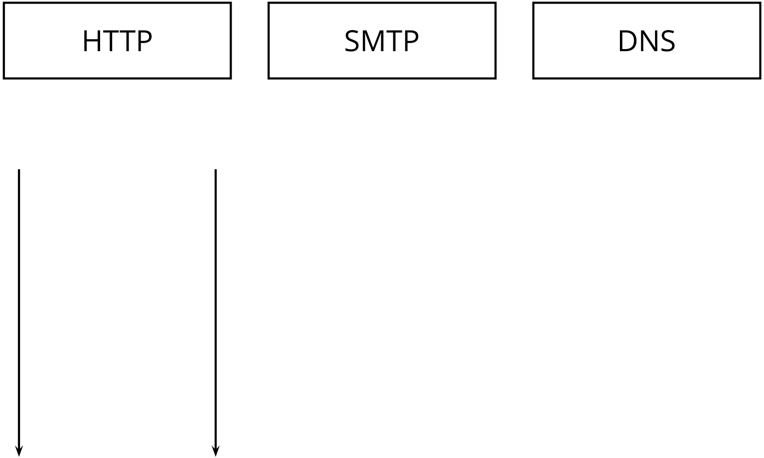
HTTP

SMTP

DNS

# Application Protocols



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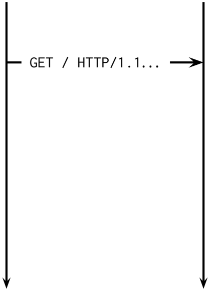

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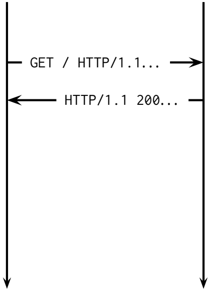

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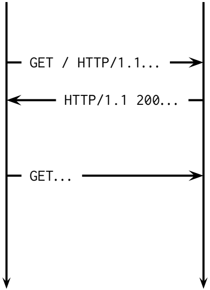

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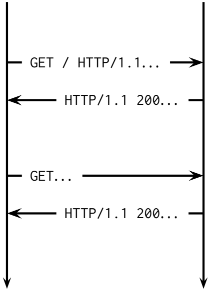

GET / HTTP/1.1...

HTTP/1.1 200...

GET...

HTTP/1.1 200...

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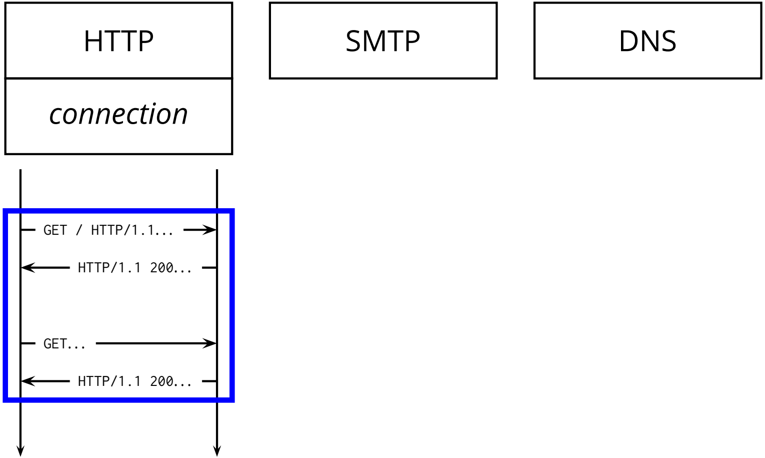

HTTP

*connection*

SMTP

DNS

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GET...

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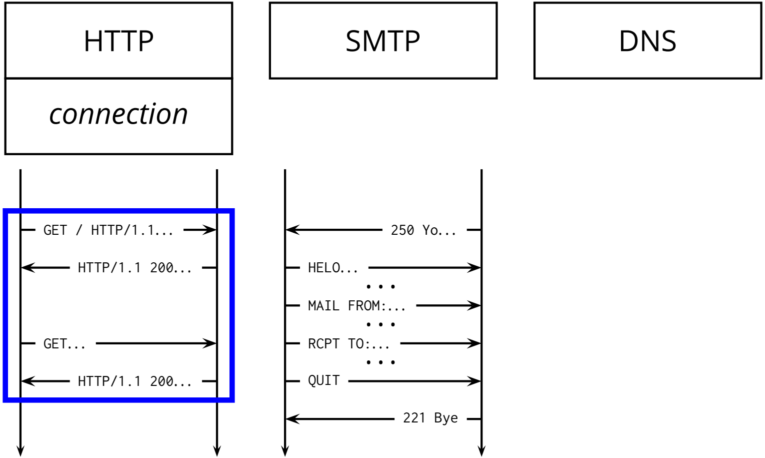

HTTP

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SMTP

DNS

GET / HTTP/1.1...

HTTP/1.1 200...

GET...

HTTP/1.1 200...

250 Yo...

HELO...

...

MAIL FROM:...

...

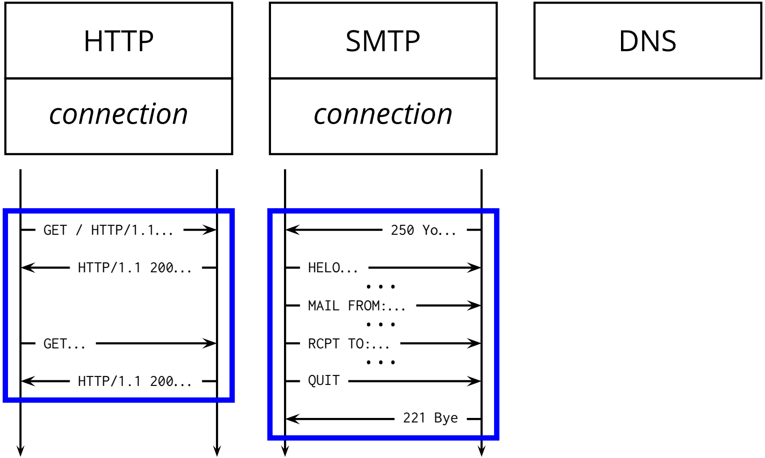
RCPT TO:...

...

QUIT

221 Bye

# Application Protocols



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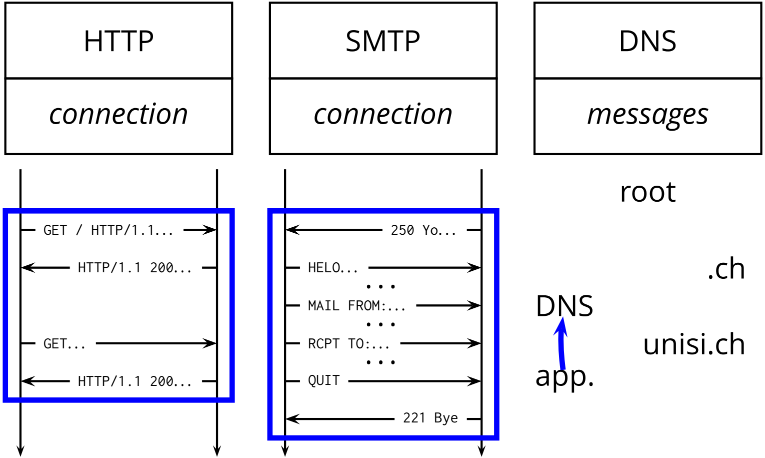

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SMTP

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250 Yo...

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...

MAIL FROM:...

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221 Bye

DNS

*messages*

root

.ch

unisi.ch

DNS

app.

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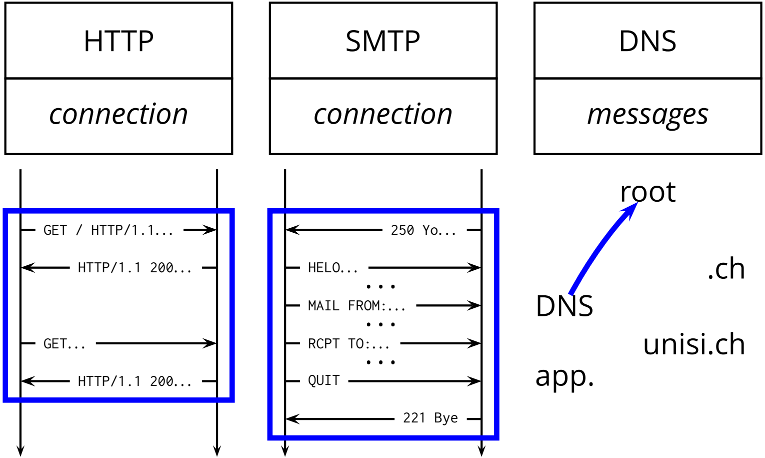

HTTP

*connection*

SMTP

*connection*

DNS

*messages*

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HTTP/1.1 200...
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250 Yo...
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QUIT
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root
.ch
DNS
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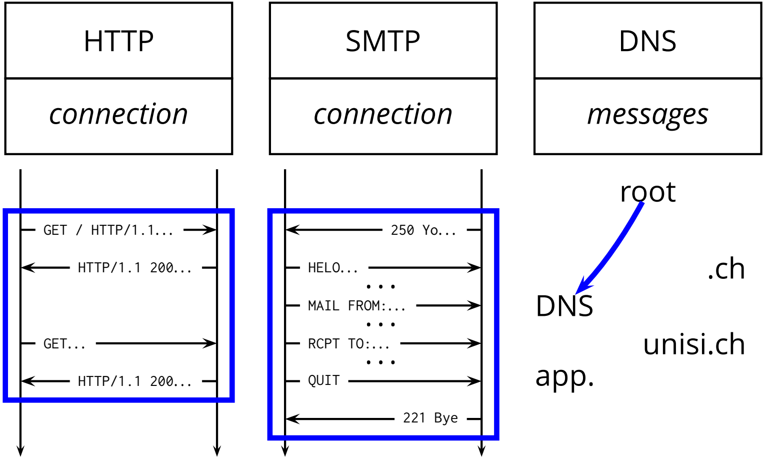

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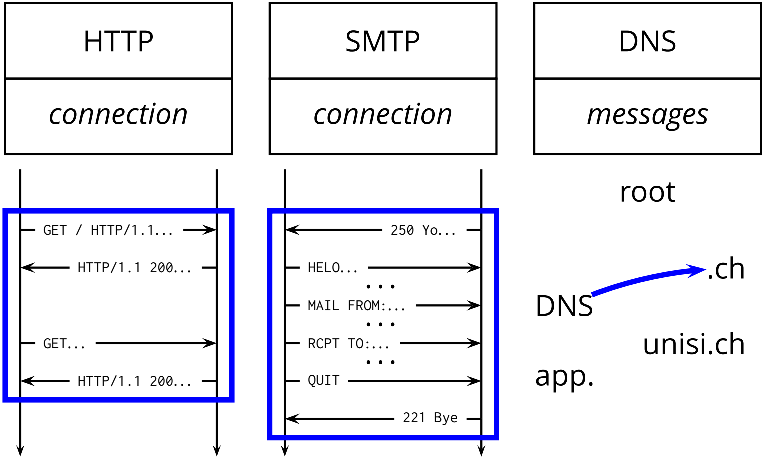

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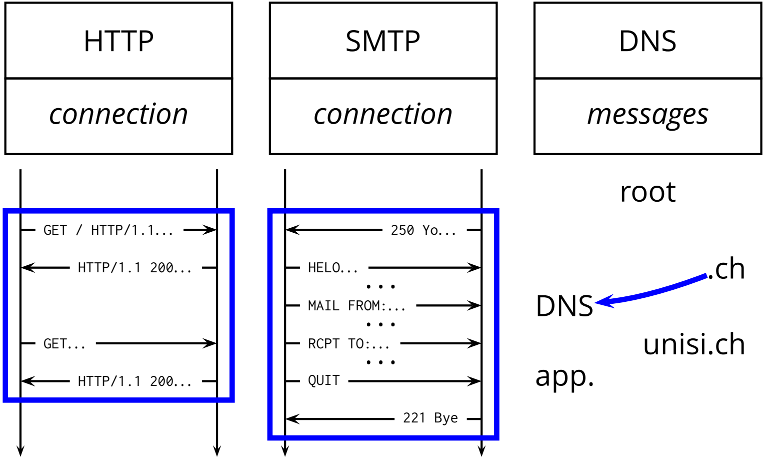

| HTTP | SMTP | DNS |
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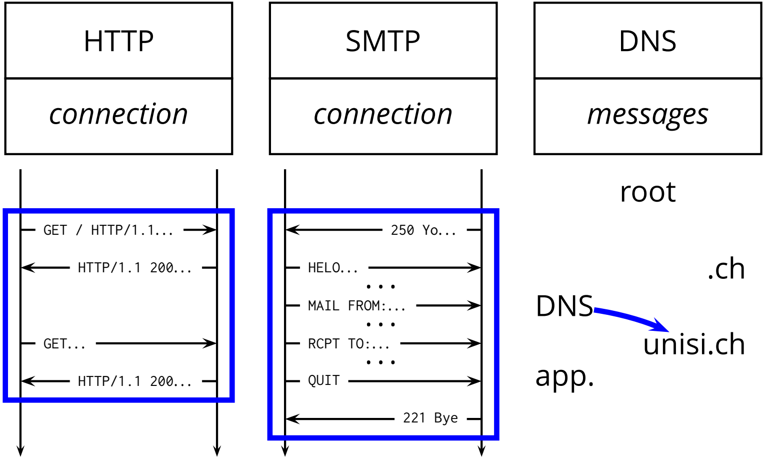

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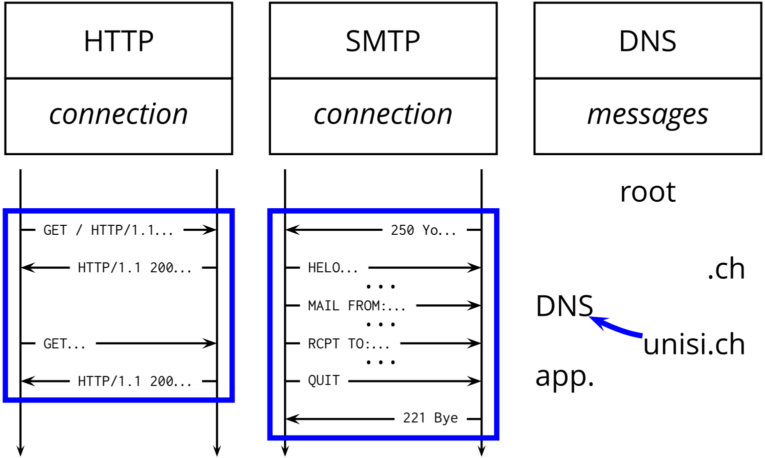

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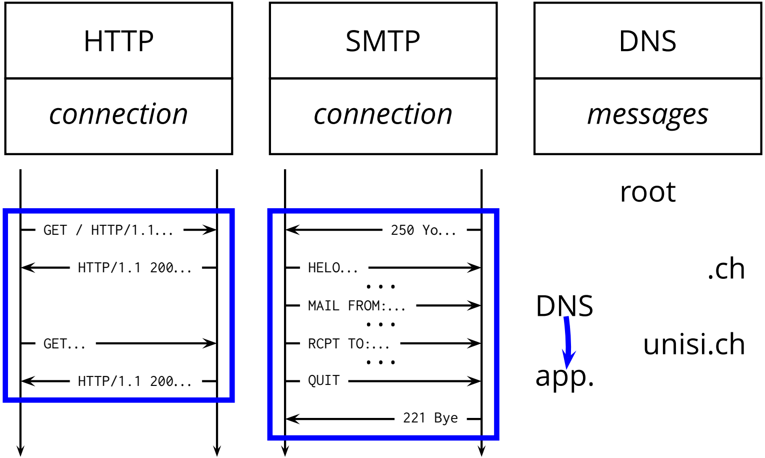

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  - transport-layer packets are called ***segments***

- Basic assumptions on the underlying network layer
  - every host has one unique *IP address*
  - 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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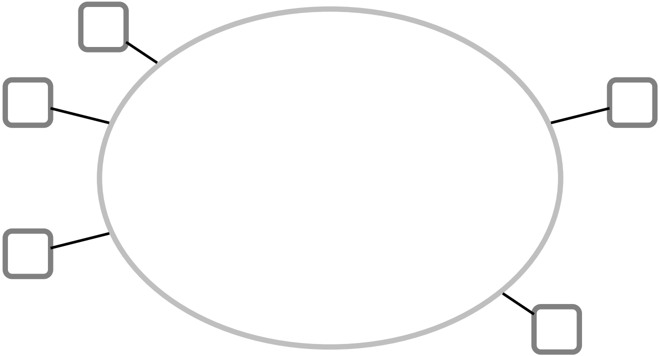
  - i.e., streams
  - can be seen as the same as ordered delivery
- ***Congestion control***
  - i.e., end-to-end traffic (admission) control so as to avoid destructive congestions within the network

# Multiplexing/Demultiplexing



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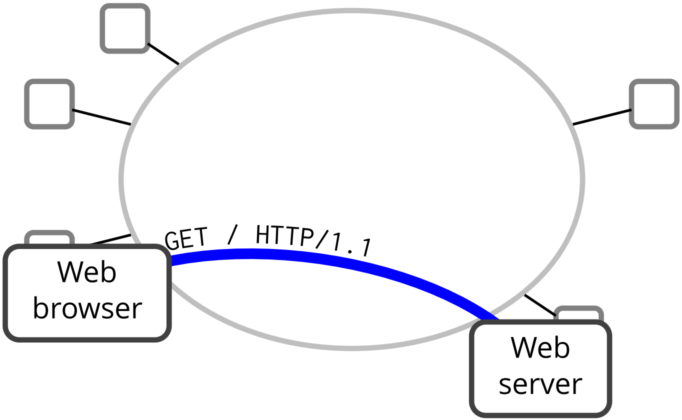

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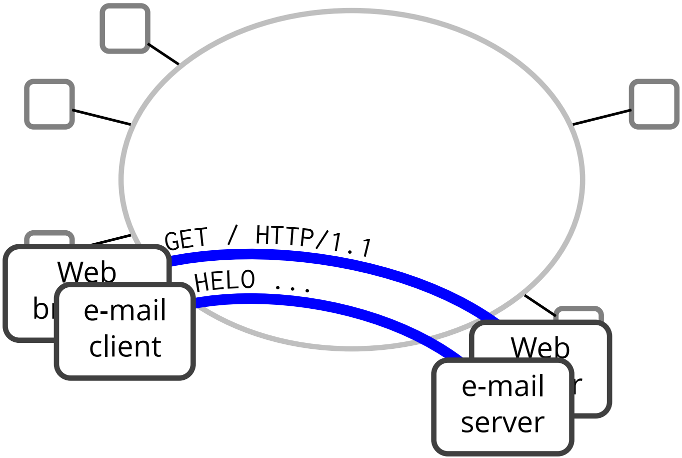

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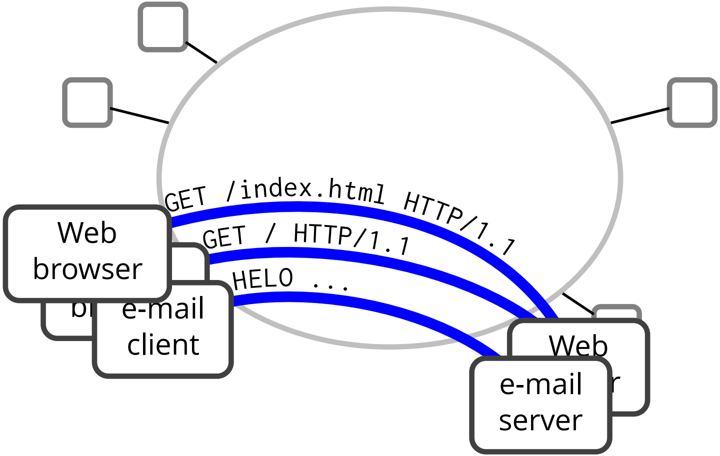

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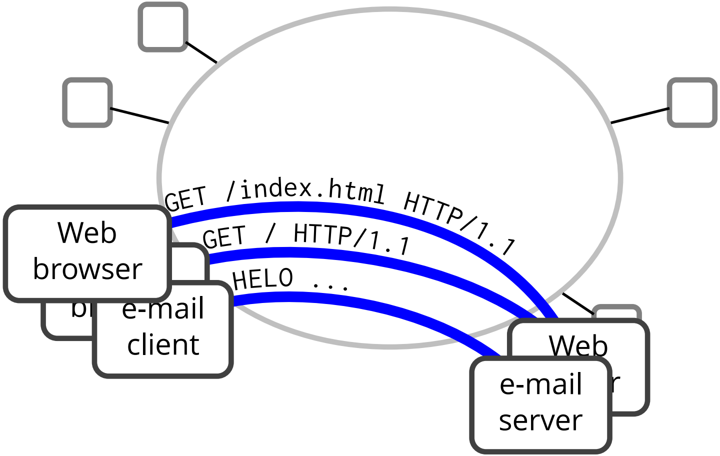

How do we distinguish all these “connections”?

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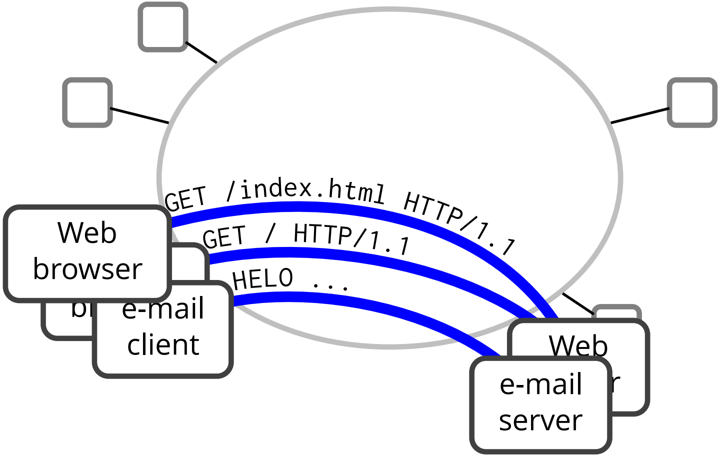

How do we distinguish all these “connections”?
(in this case, connections between the same two hosts)

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- How do we find out which application (host and port number) to connect to?
  - outside the scope of the definition of the transport layer
  - but of course we can have “well-known” service numbers

# Ports

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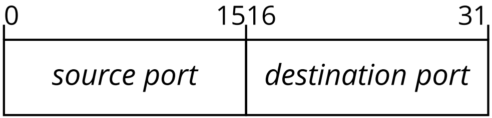

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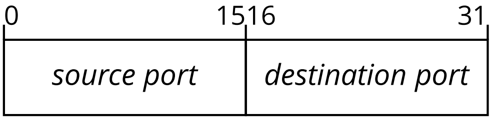

. . .

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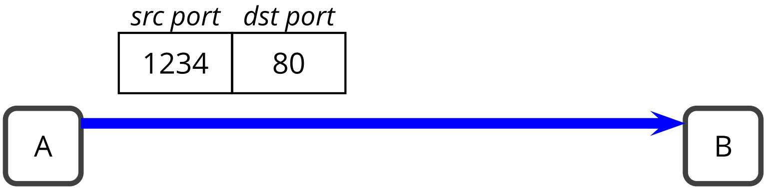

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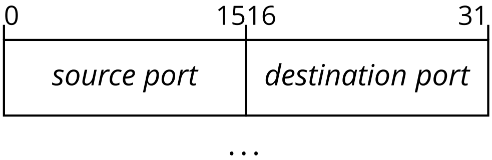

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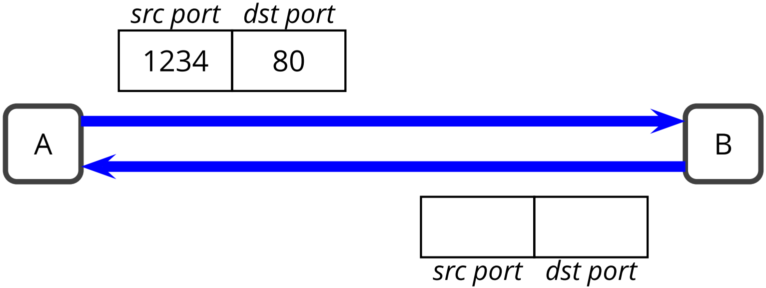

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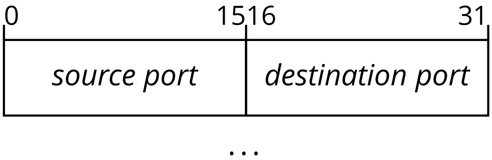

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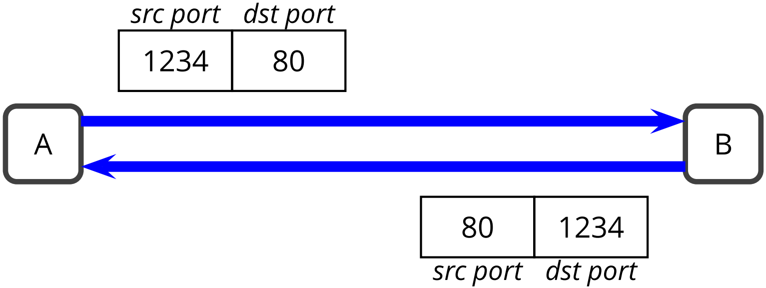

# Transmission Control Protocol

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

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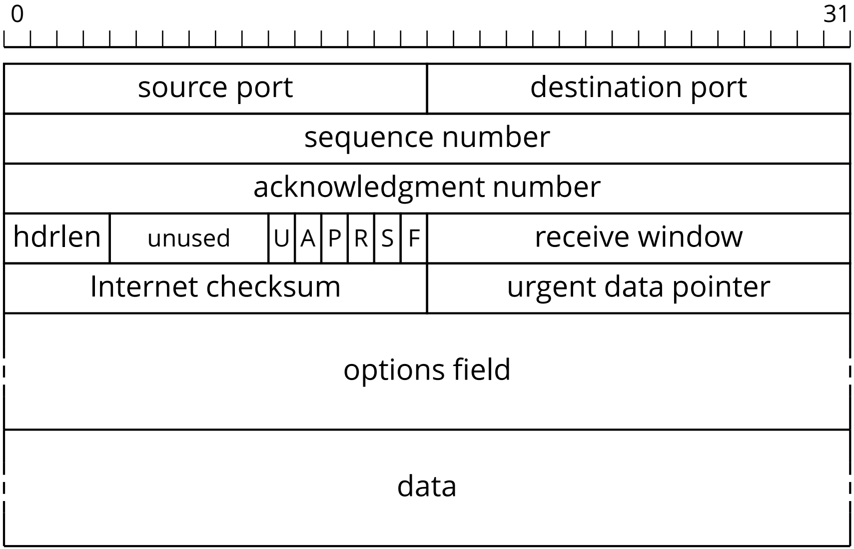
- ***Maximum transmission unit (MTU):*** largest link-layer frame available to the sender host
  - *path MTU:* largest link-layer frame that can be sent on all links from the sender host to the receiver host

# TCP Segment Format



0

31

source port

destination port

sequence number

acknowledgment number

hdrlen

unused

U

A

P

R

S

F

receive window

Internet checksum

urgent data pointer

options field

data

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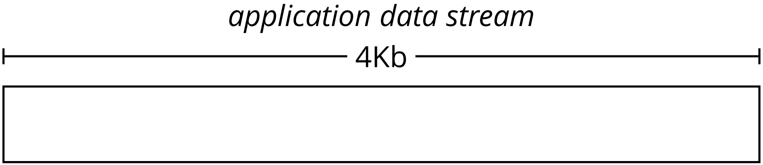

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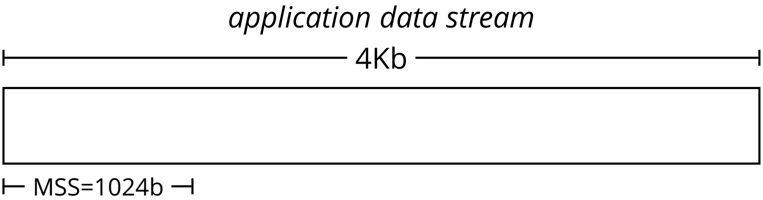

*application data stream*

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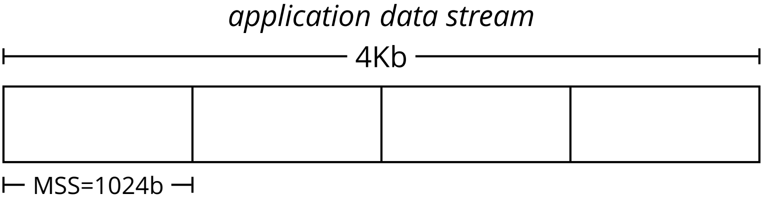

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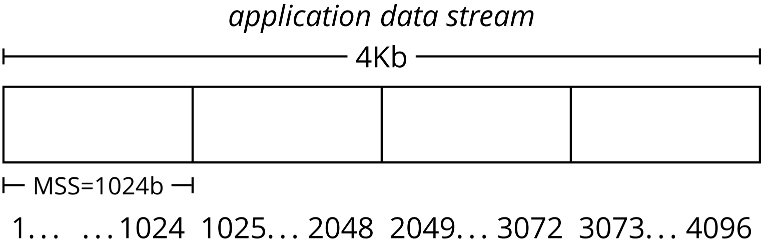

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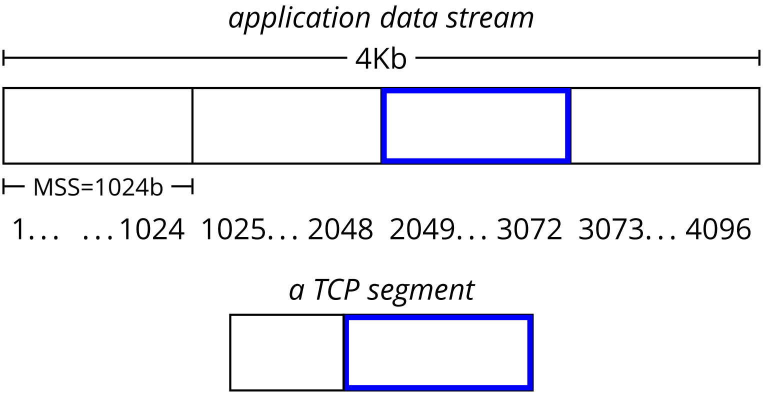

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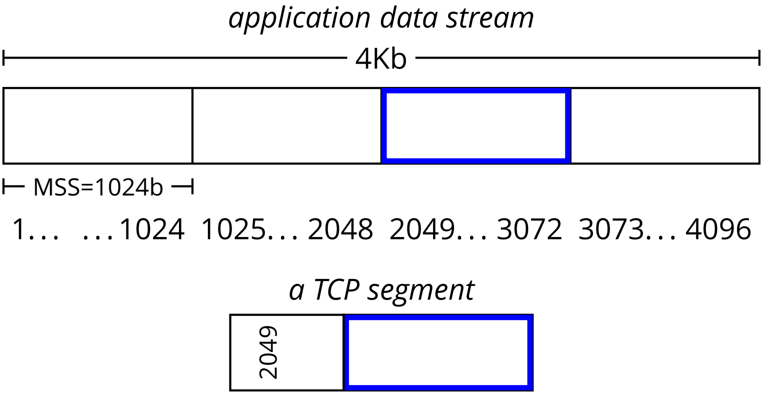

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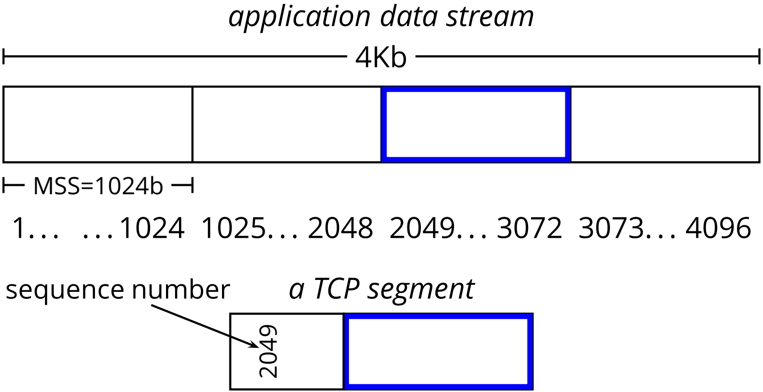

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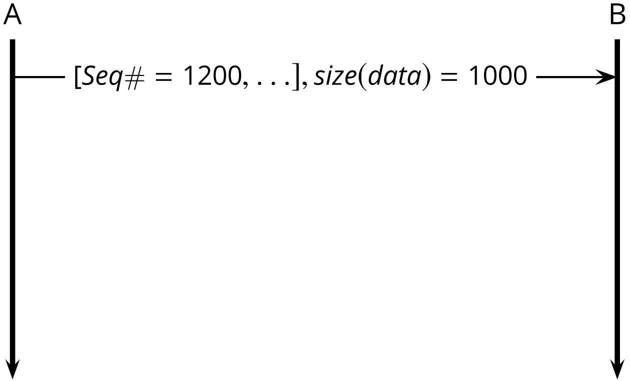

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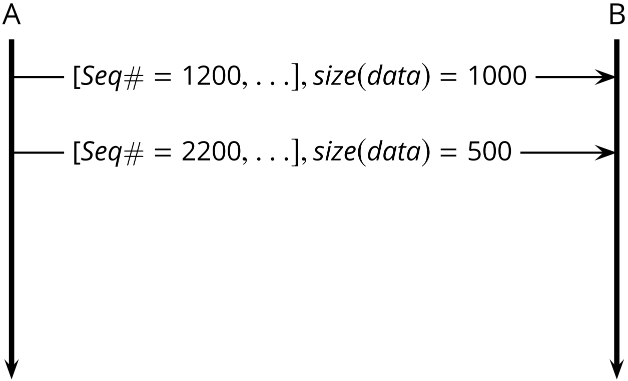

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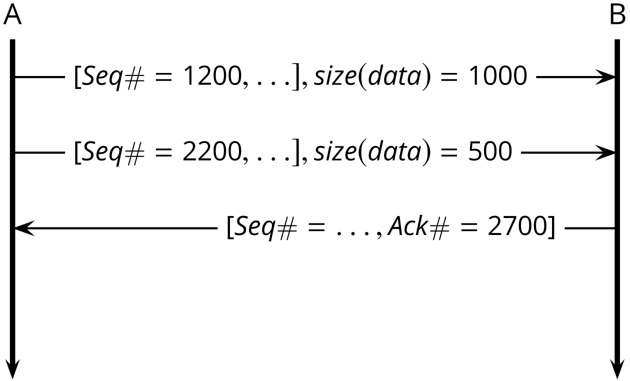

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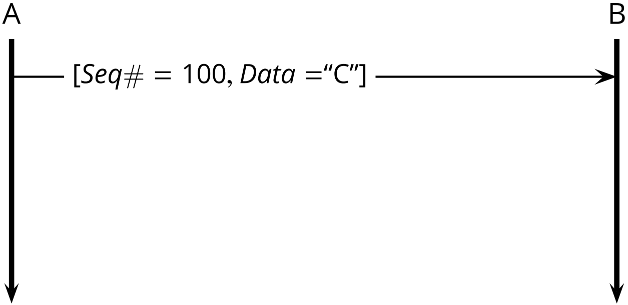

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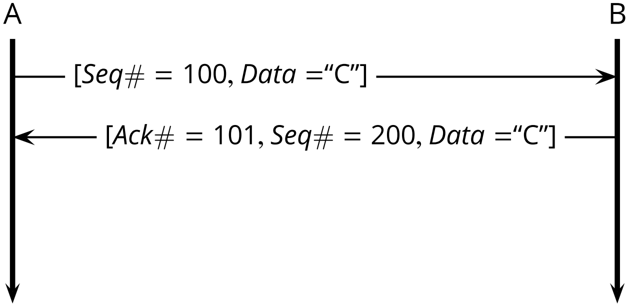

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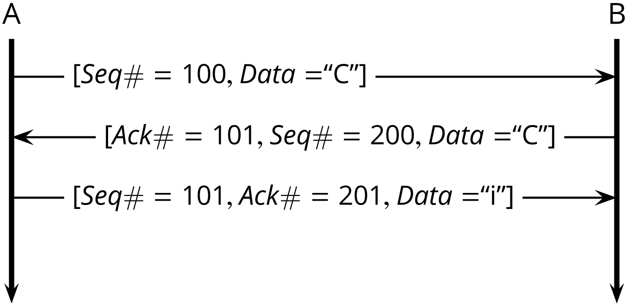

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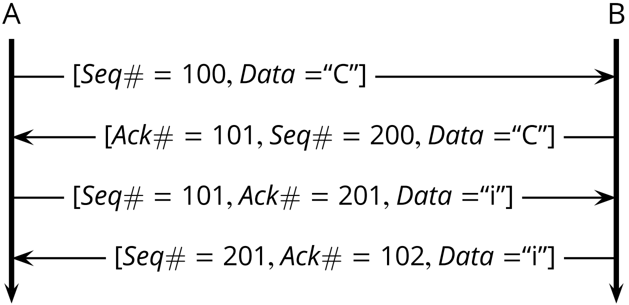

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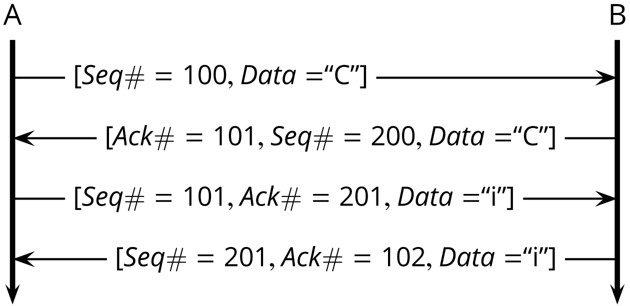

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- Acknowledgments are “piggybacked” on data segments

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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 $\overline{DevRTT}$:

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

# Reliable Data Transfer (Sender)

A simplified TCP sender

- r_send(*data*)

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    start_timer()
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else ...
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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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client

server

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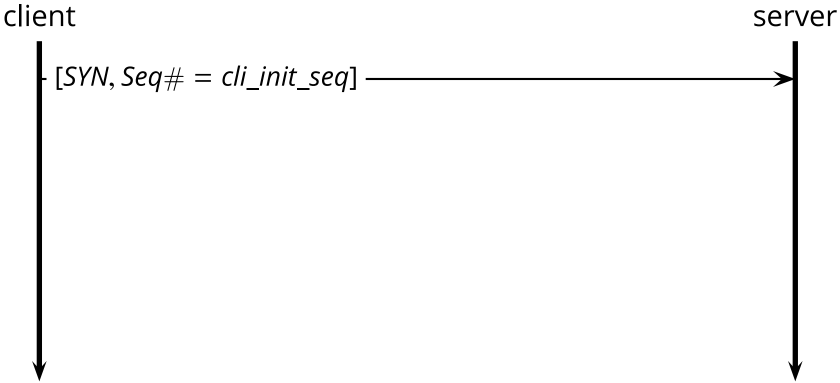
Three-way handshake



client

server

[$SYN, Seq\# = cli\_init\_seq$]

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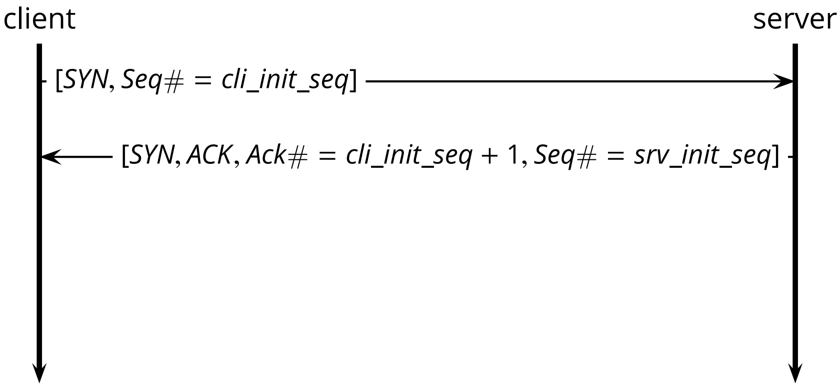

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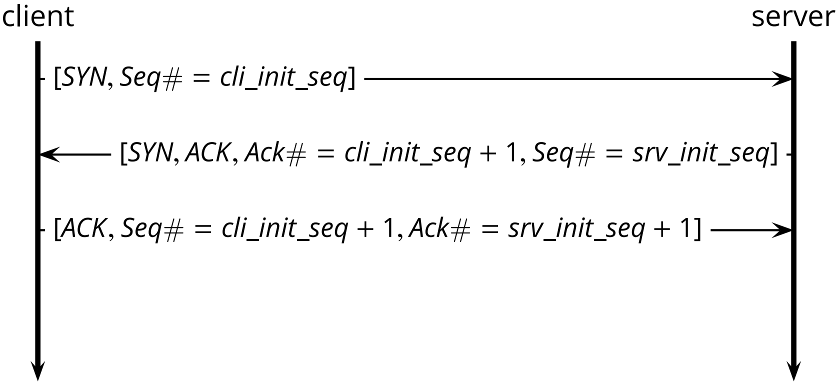

client

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“Okay, Bye now.”
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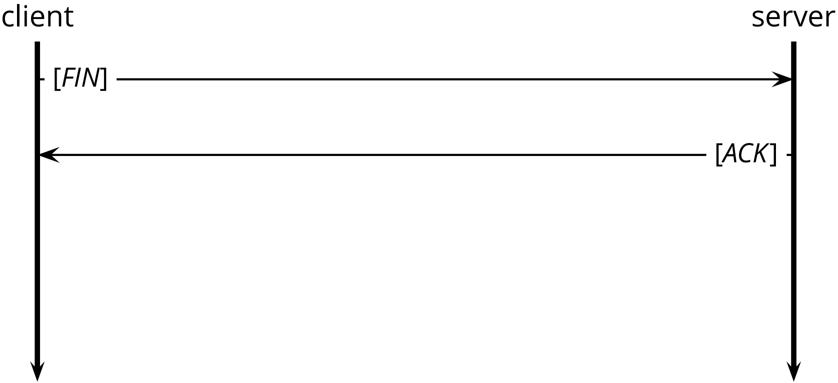

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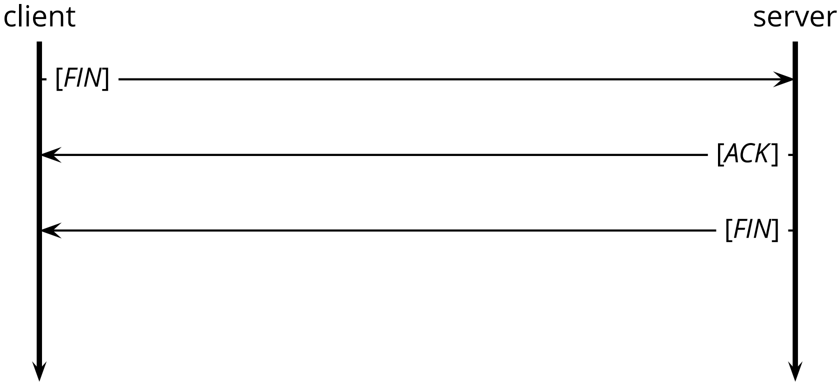

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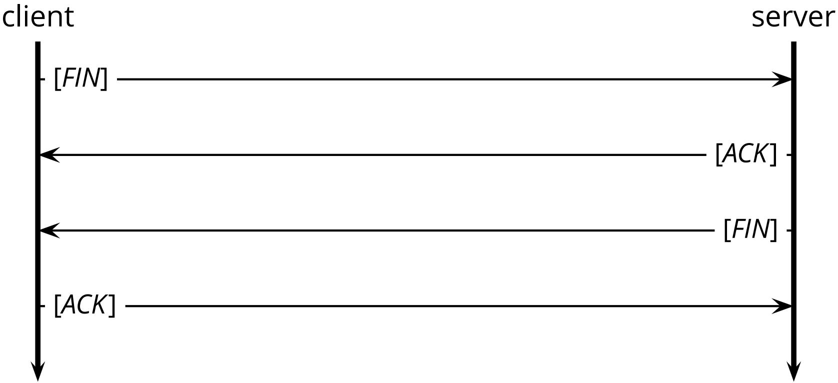
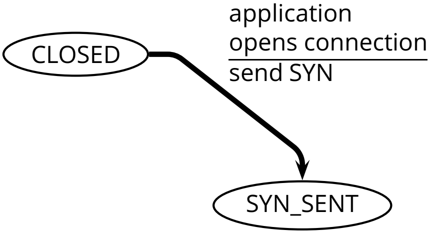


# The TCP State Machine (Client)

CLOSED

# The TCP State Machine (Client)



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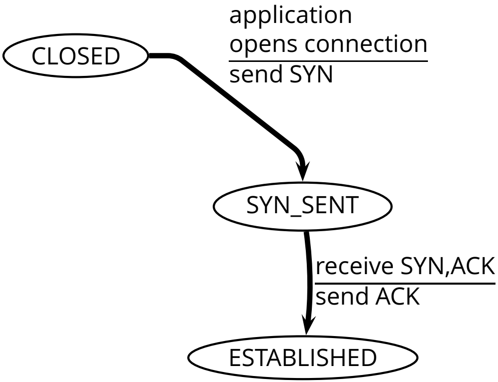

CLOSED

application
opens connection
send SYN

SYN_SENT

receive SYN,ACK
send ACK

ESTABLISHED

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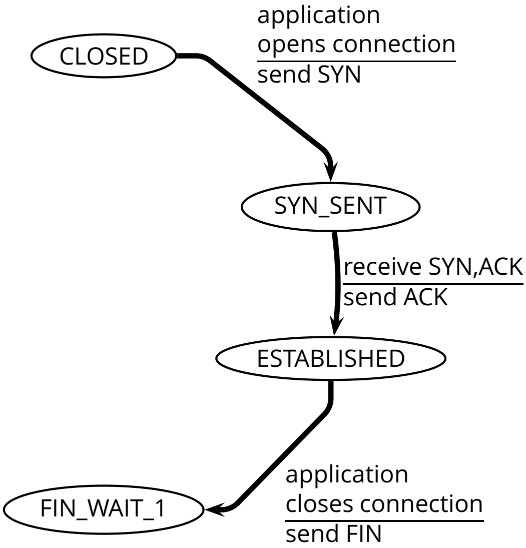

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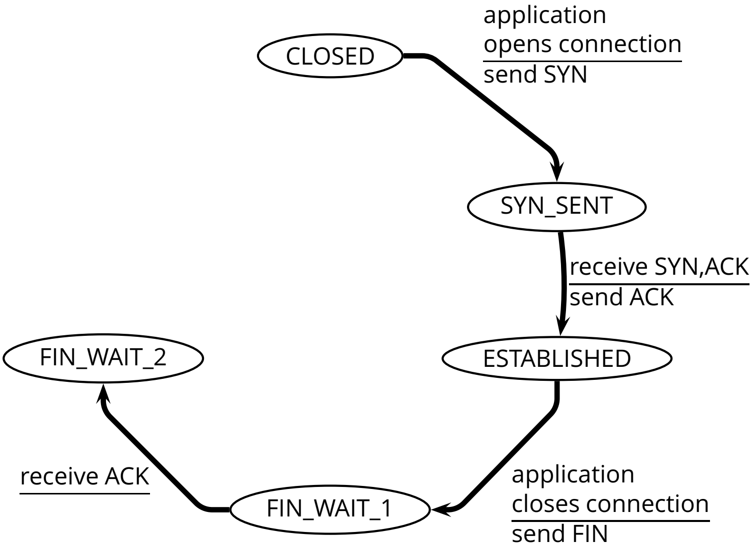

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ESTABLISHED

application
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send FIN

FIN_WAIT_1

receive ACK

FIN_WAIT_2

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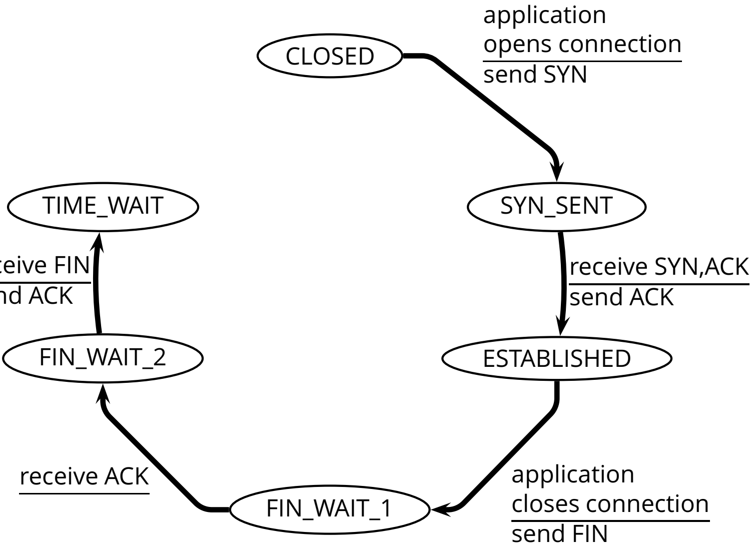

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TIME_WAIT

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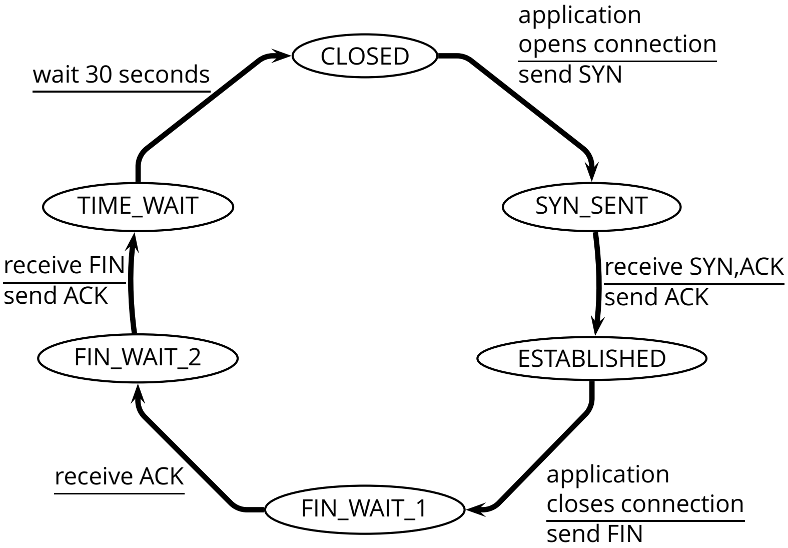

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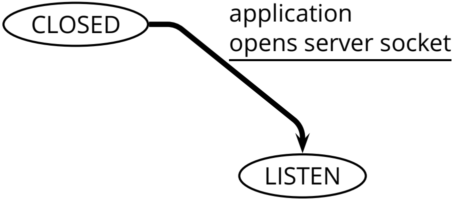

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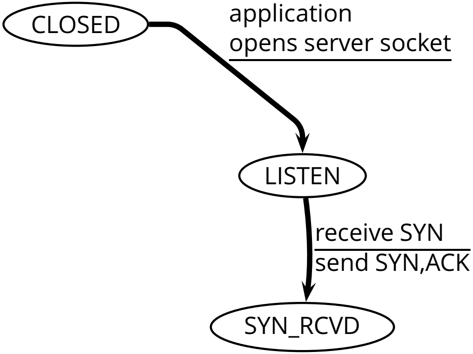

CLOSED

application
opens server socket

LISTEN

receive SYN
send SYN,ACK

SYN_RCVD

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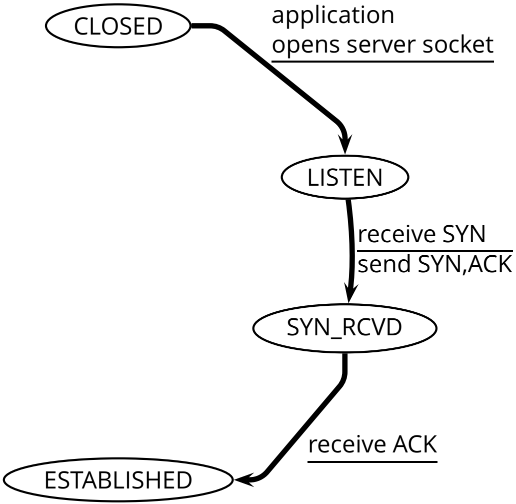

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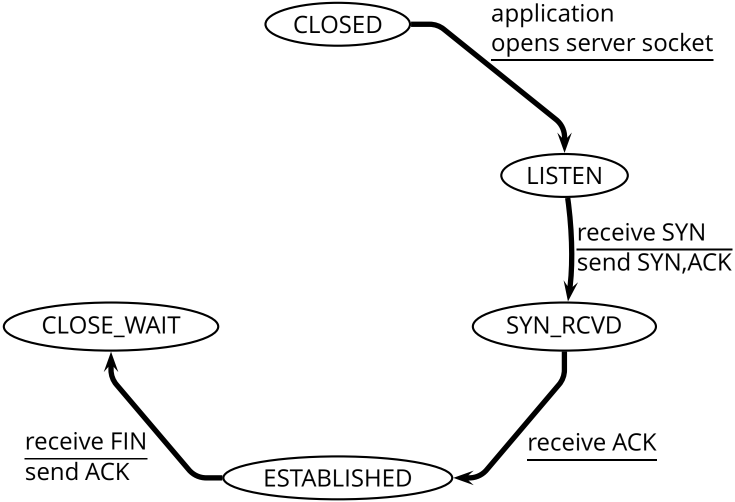

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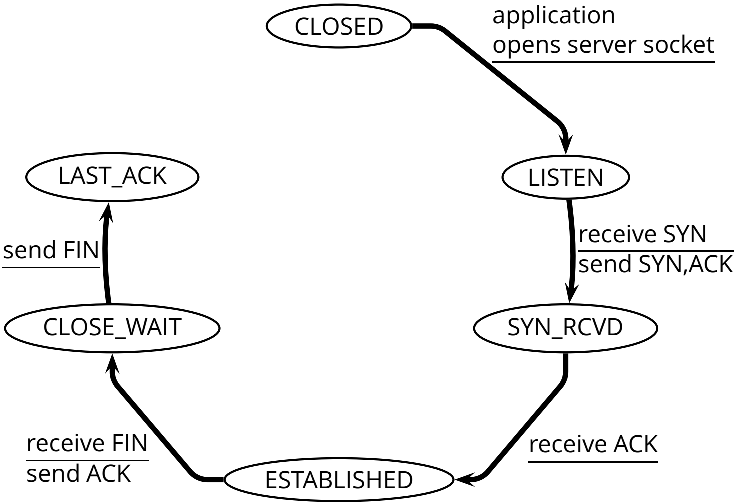

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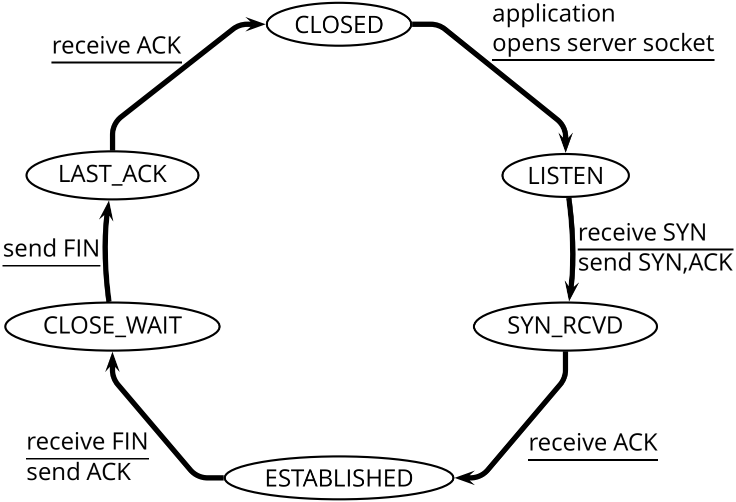

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send SYN,ACK

SYN_RCVD

receive ACK

ESTABLISHED

receive FIN
send ACK

CLOSE_WAIT

send FIN

LAST_ACK

receive ACK

# Understanding Congestion

- A router behaves a lot like a kitchen sink

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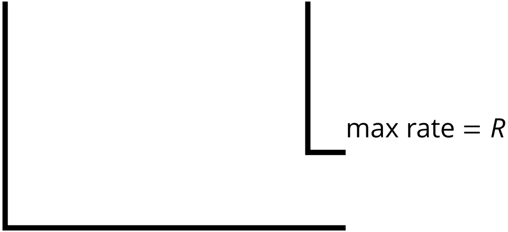

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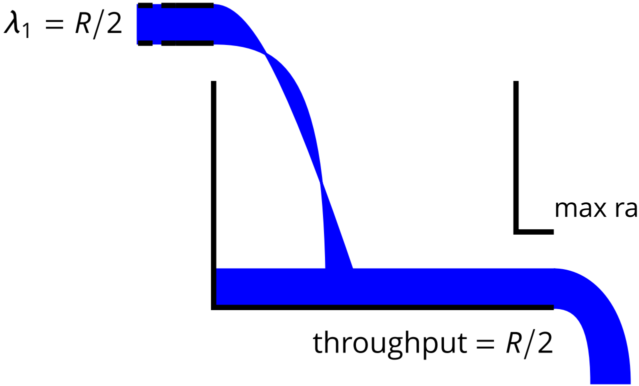

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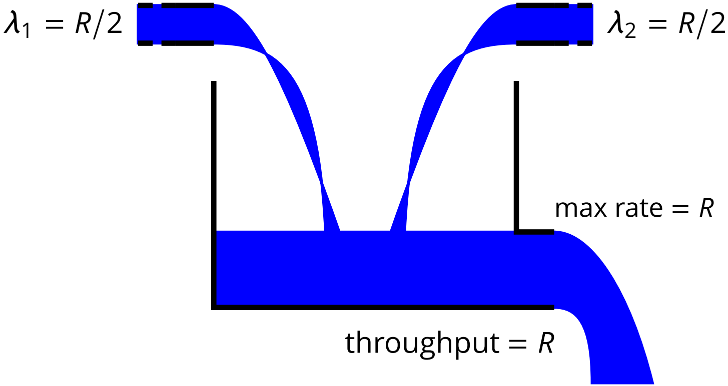

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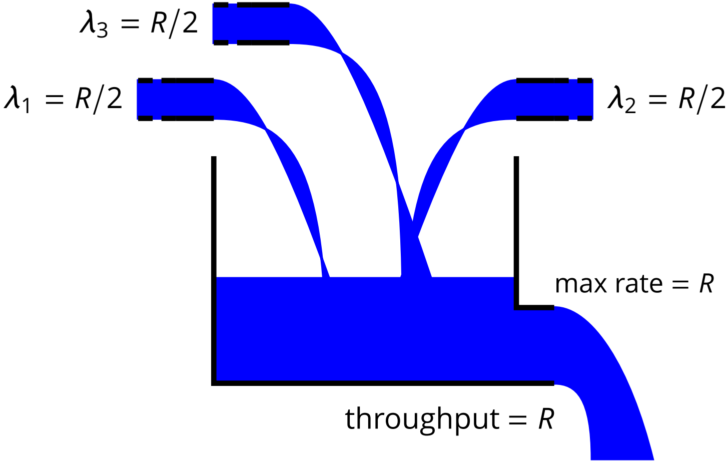

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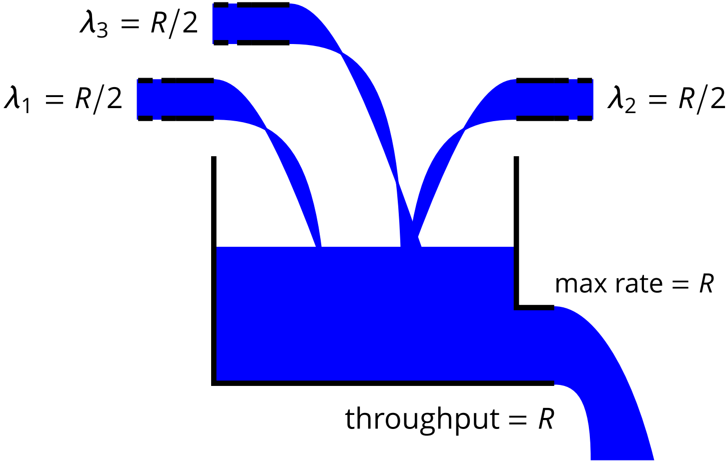

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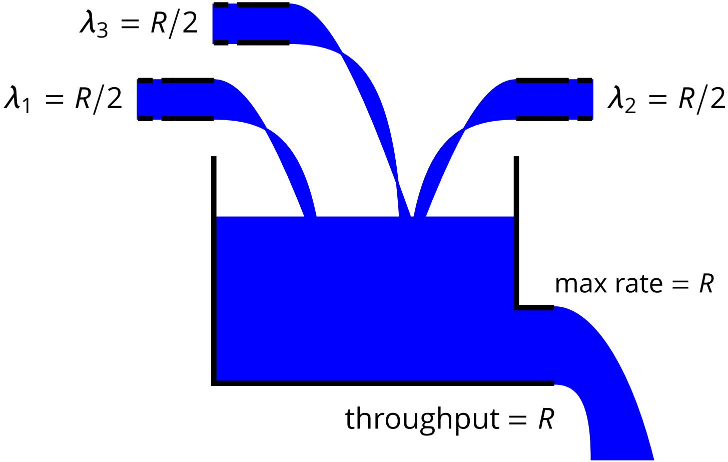

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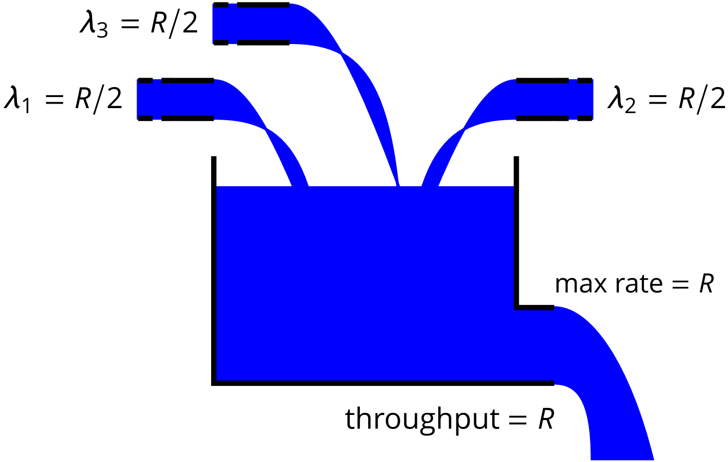

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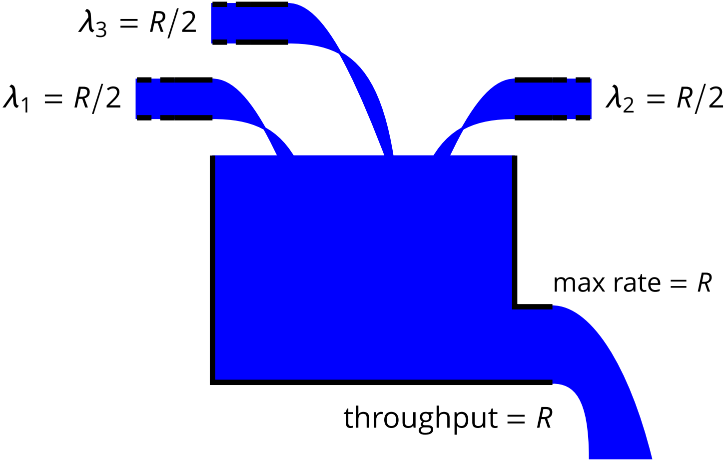

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In this case $|q| = (\lambda_{in} - R)t$ and therefore

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

# Queuing Delay

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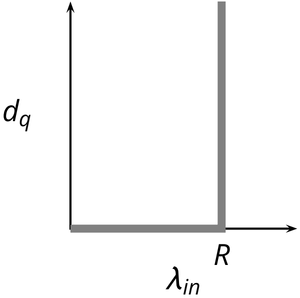

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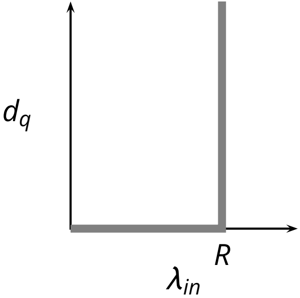

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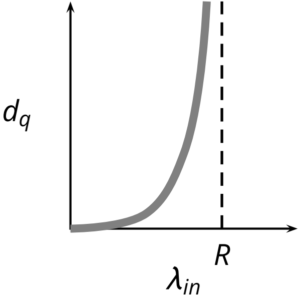

realistic input flow
$\lambda_{in}$ variable

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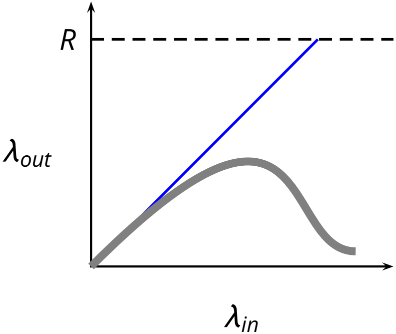

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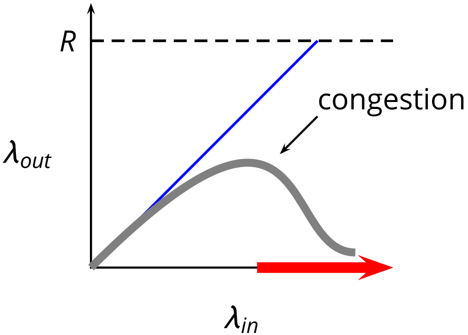

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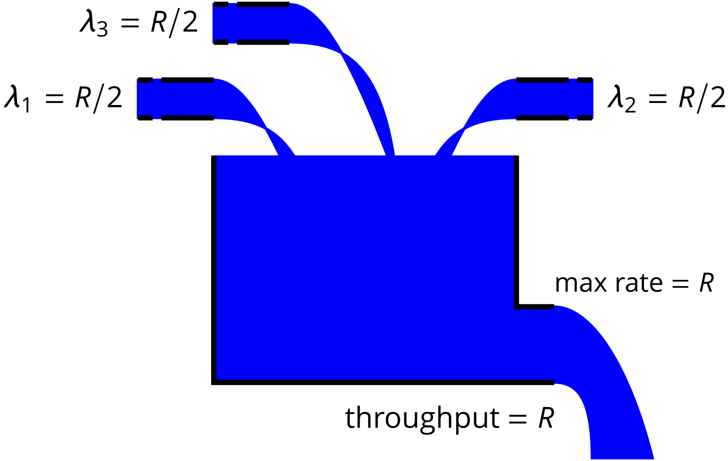

$\lambda_3 = R/2$

$\lambda_1 = R/2$

$\lambda_2 = R/2$

max rate $= R$

throughput $= R$

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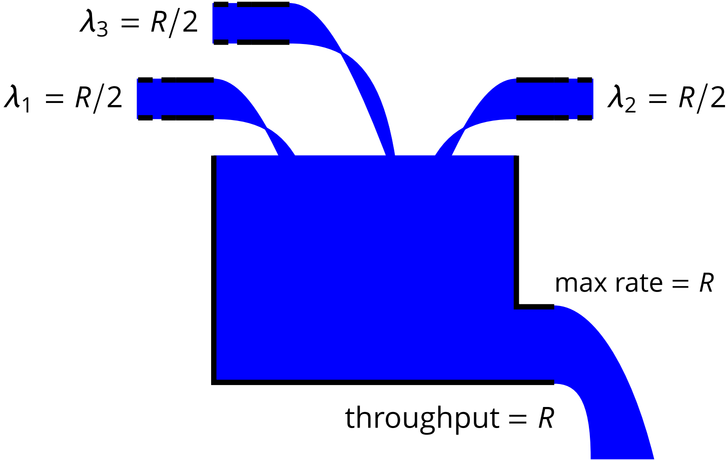

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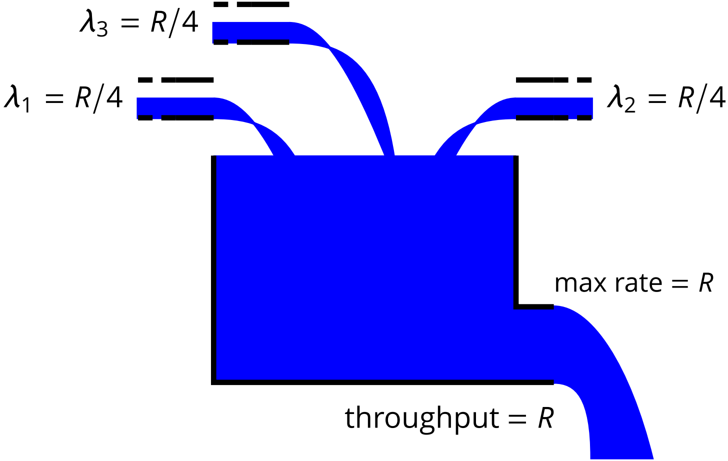

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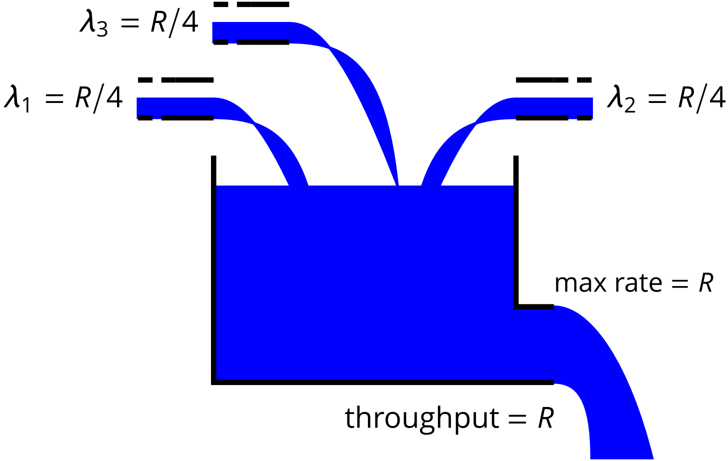

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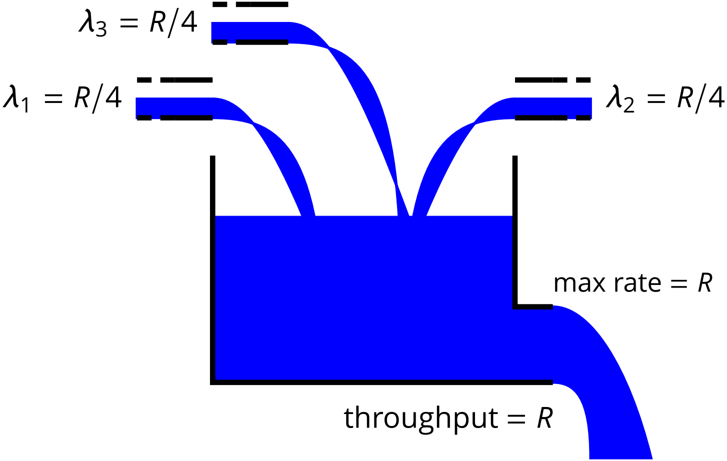

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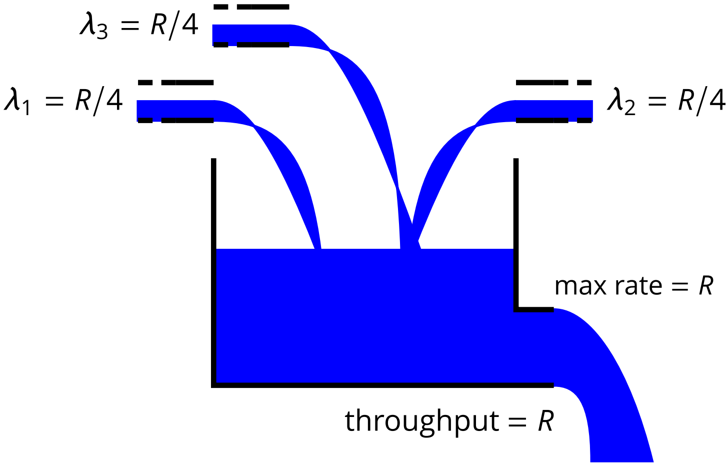

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3. how should the sender ***control its output rate***?
   - we need a ***brain*** and we need to know ***how to drive!***

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- 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)

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- The resulting maximum output rate is roughly

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

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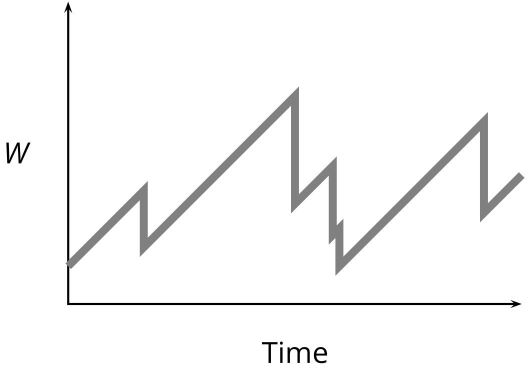
  - e.g., suppose $W = 14600$ and $MSS = 1460$, then the sender increases $W$ to 16060 after 10 acknowledgments acknowledgments

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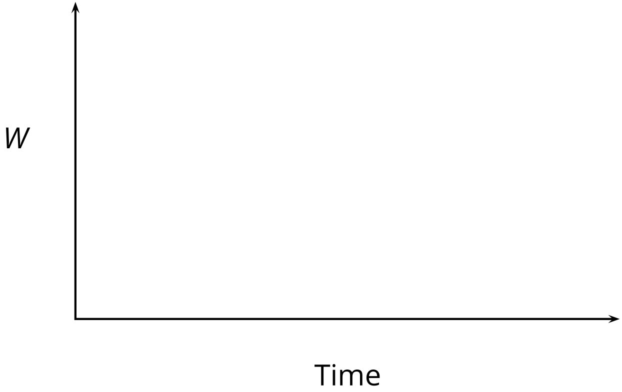
- *NACK* (i.e., triple duplicate-ack)
  - set $ssthresh = \overline{W}/2$
  - cut $W$ in half: $W = \overline{W}/2$
  - run *congestion avoidance*, ramping up $W$ linearly
  - This is called ***fast recovery***

# Sender Behavior



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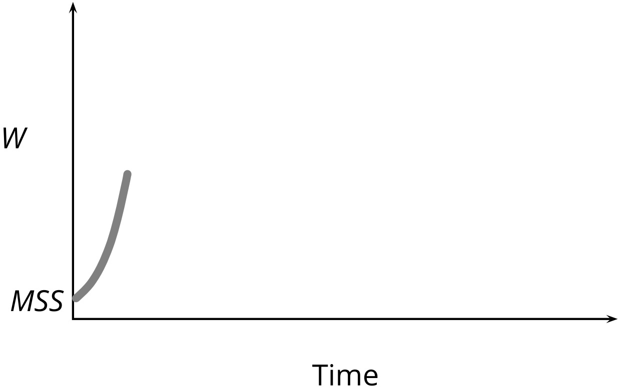

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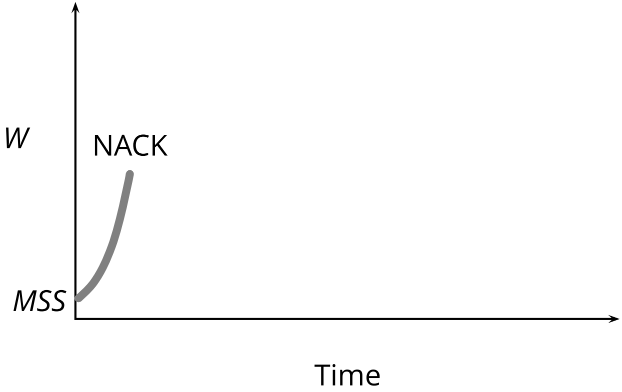

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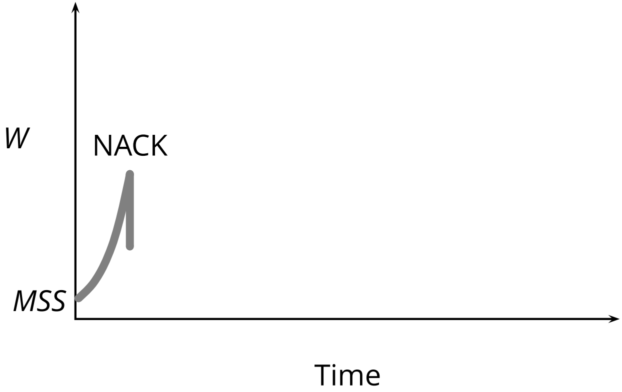

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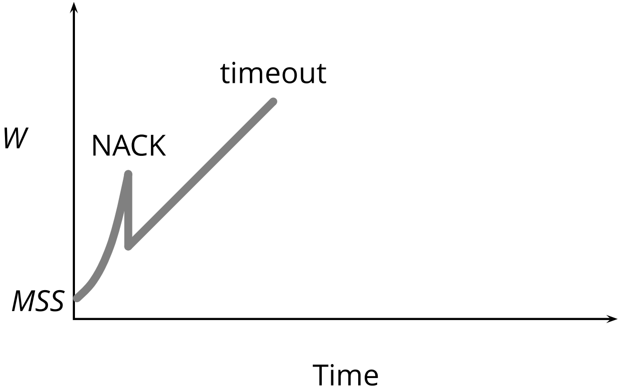

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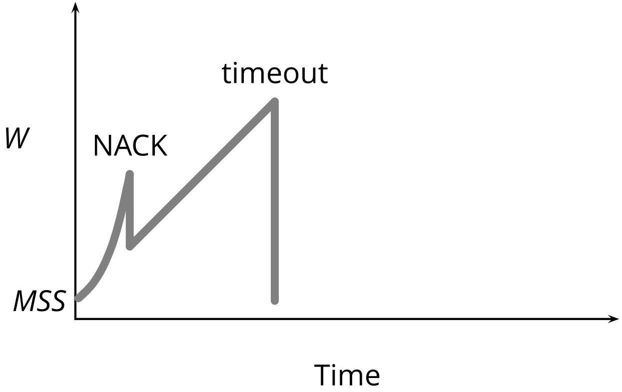

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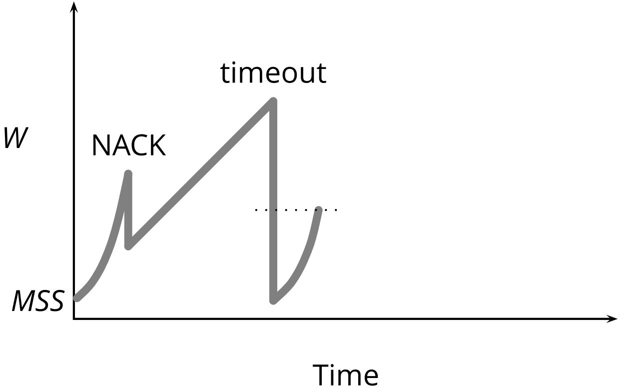

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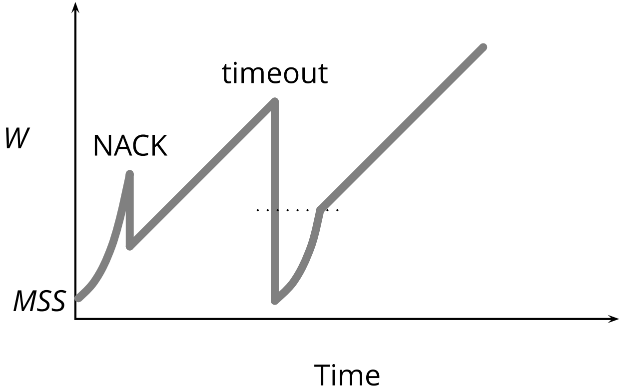

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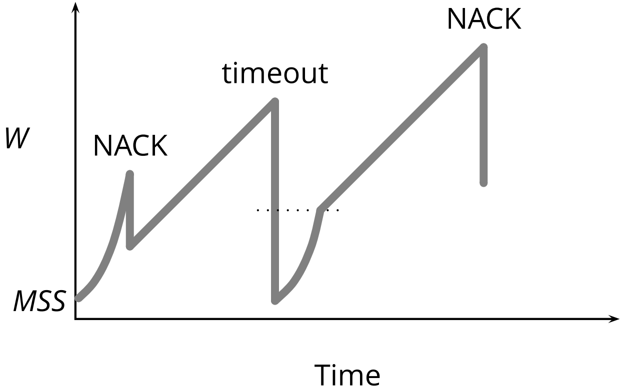

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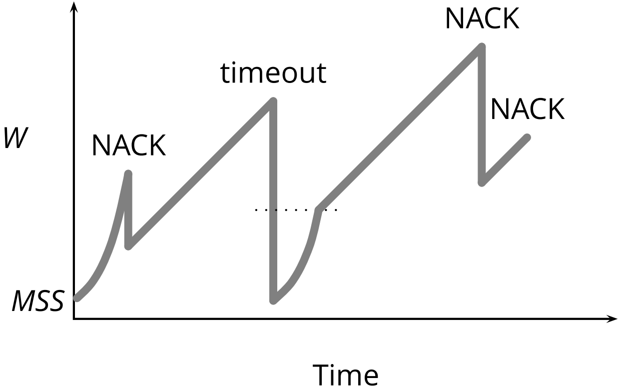

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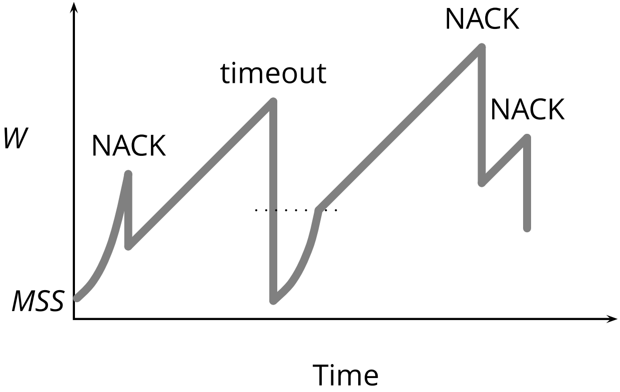

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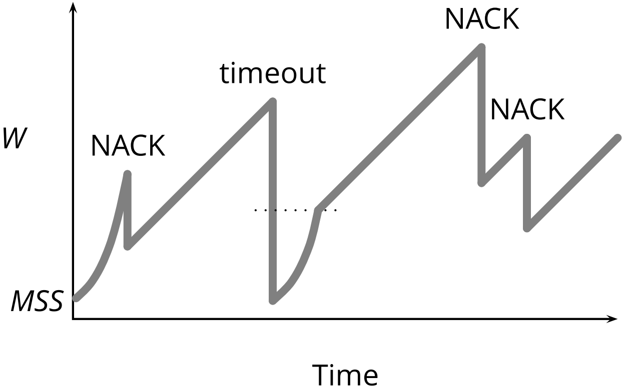

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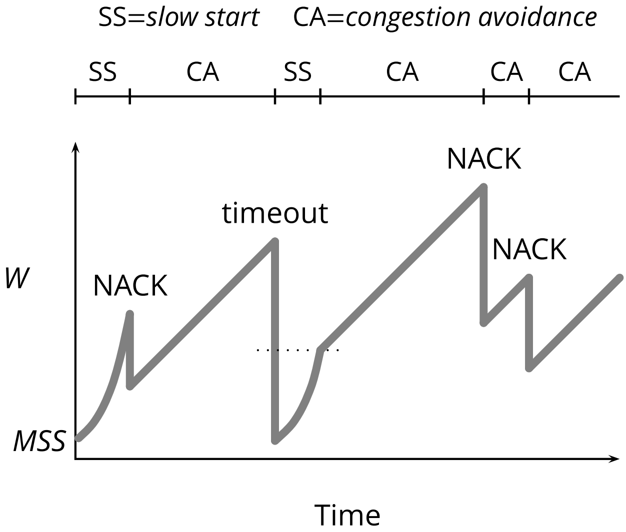

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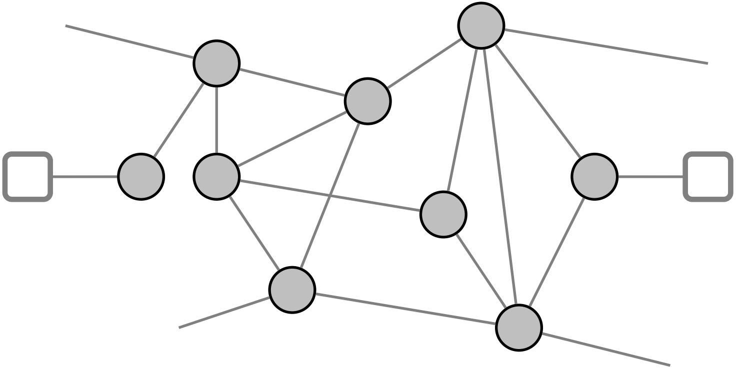

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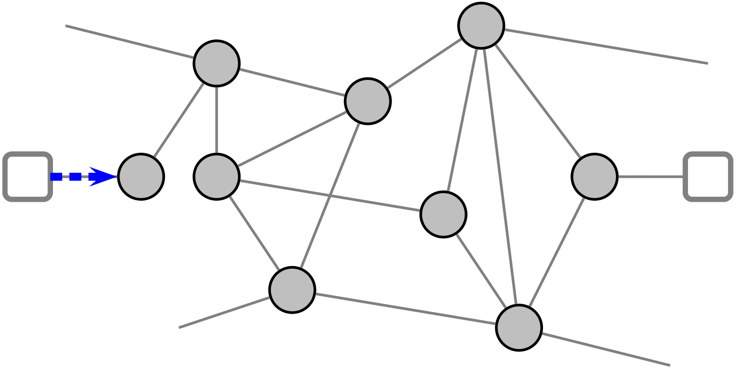

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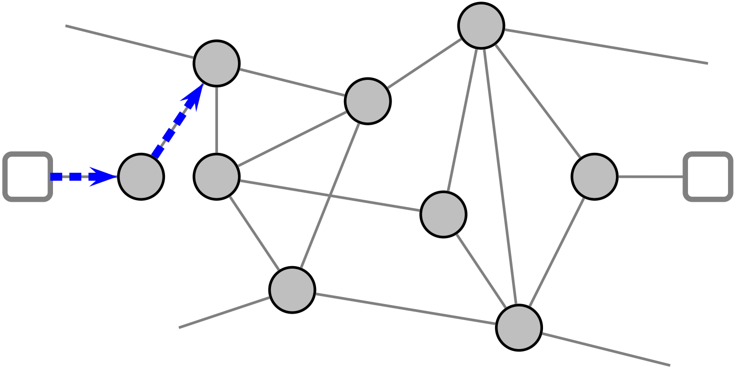

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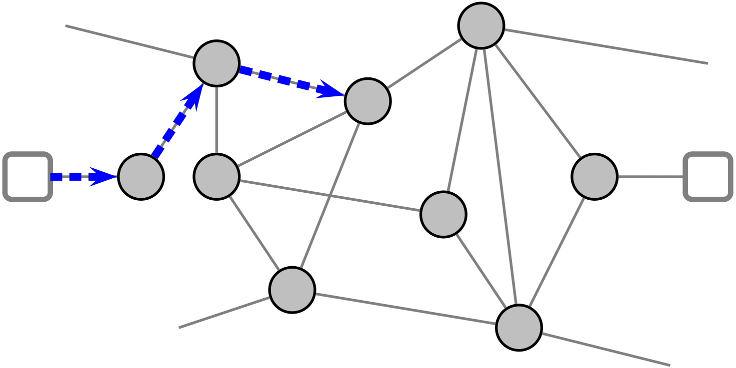

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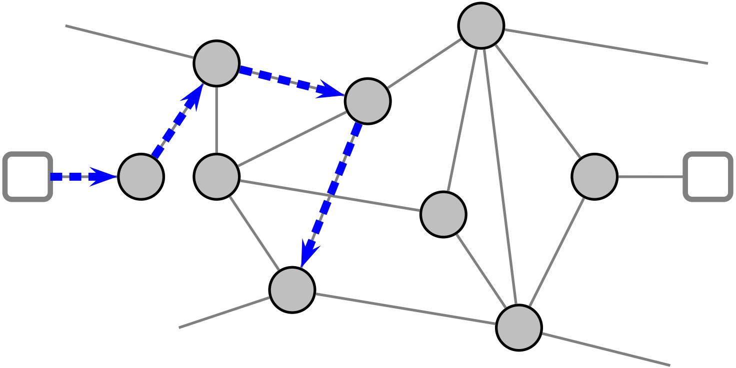

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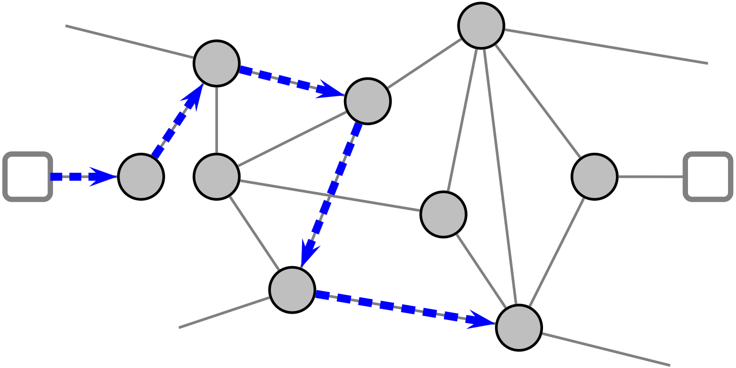

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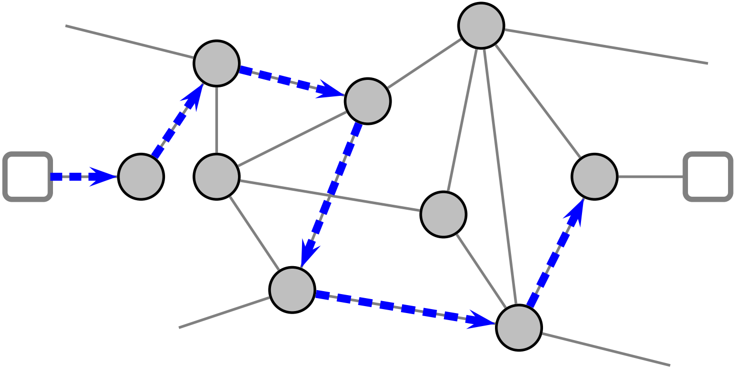

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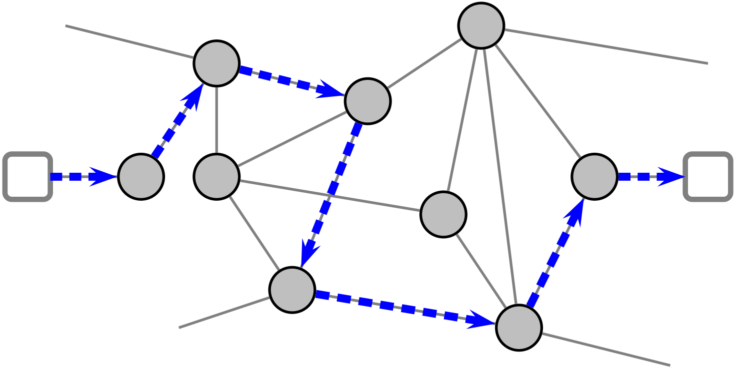

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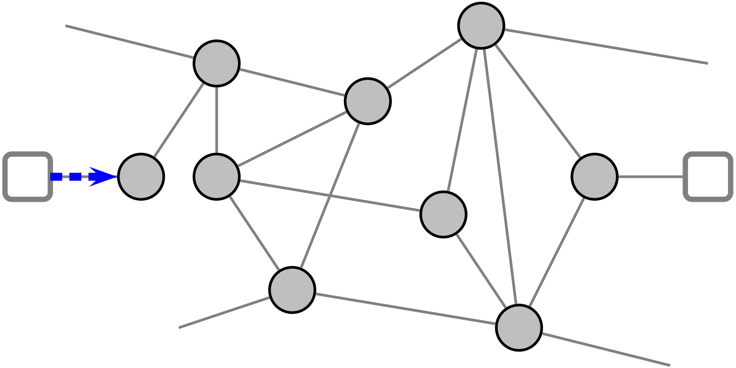

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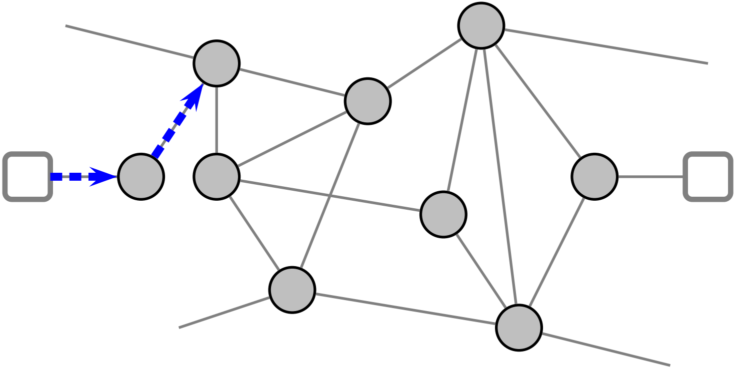

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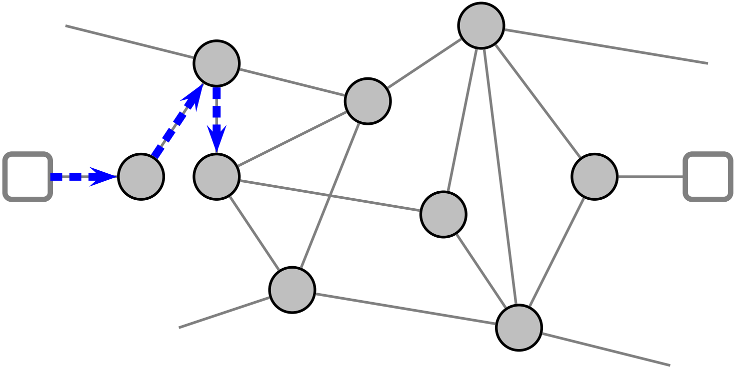

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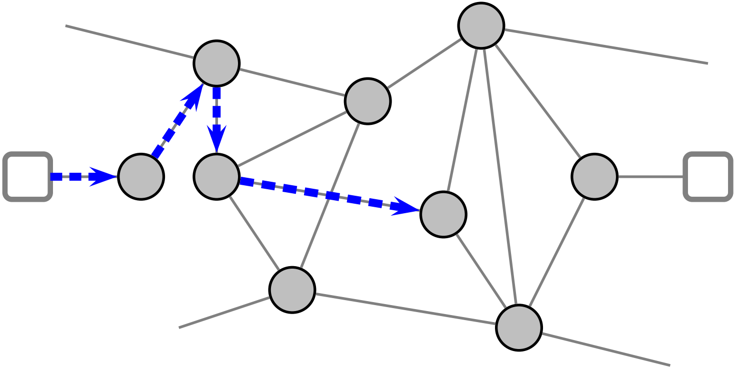

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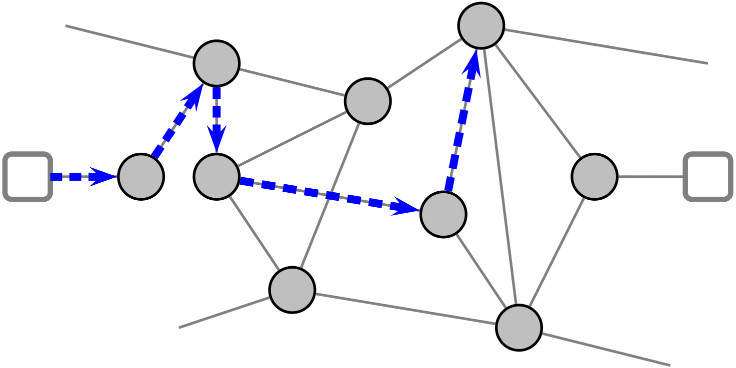

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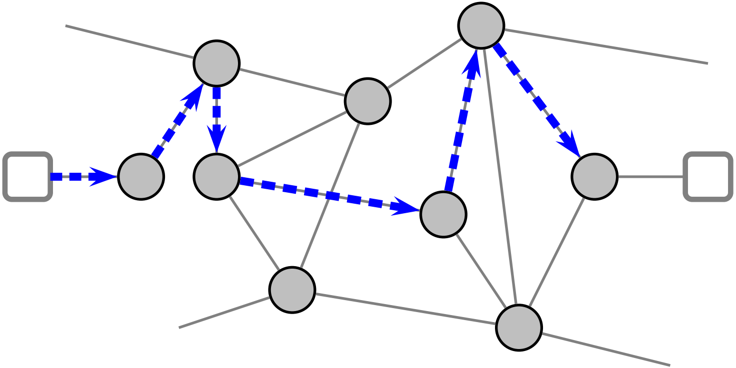

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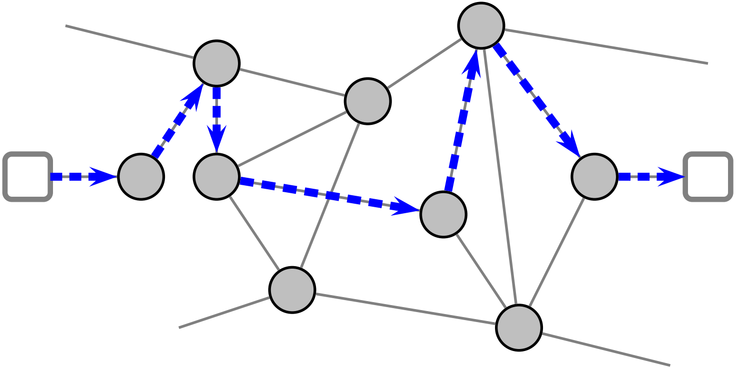

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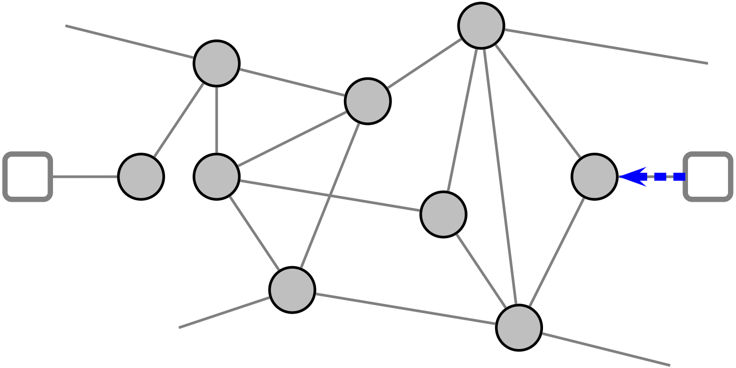

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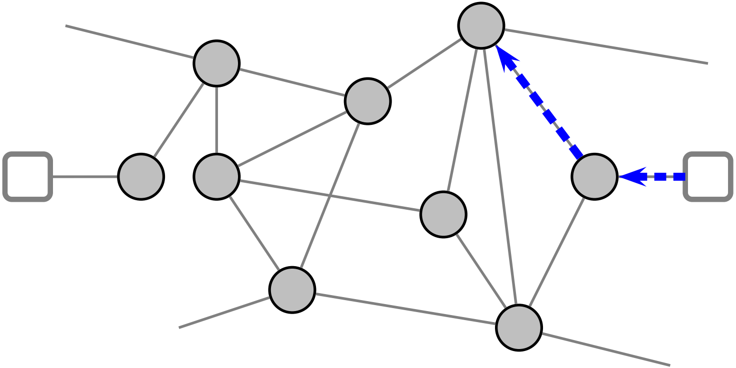

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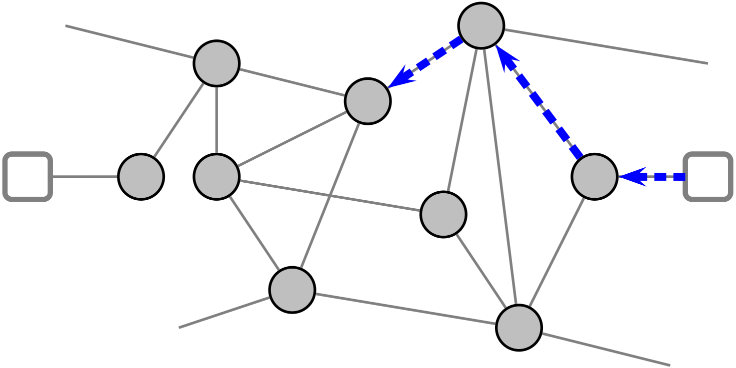

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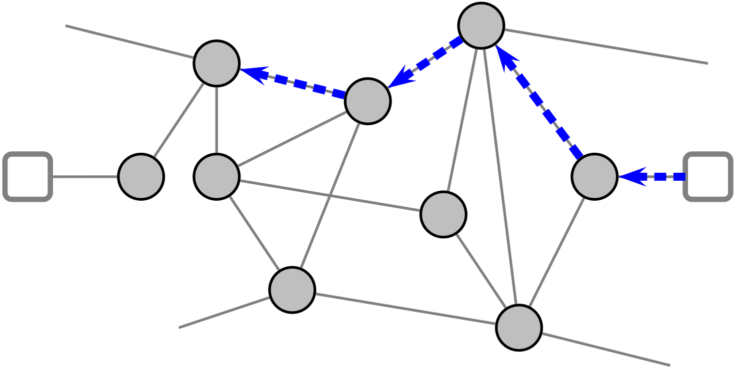

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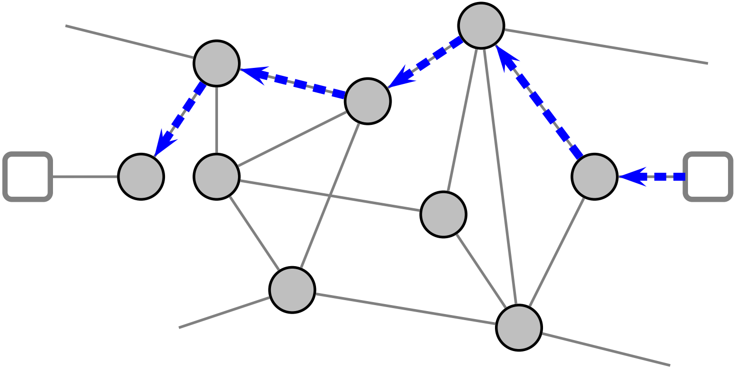

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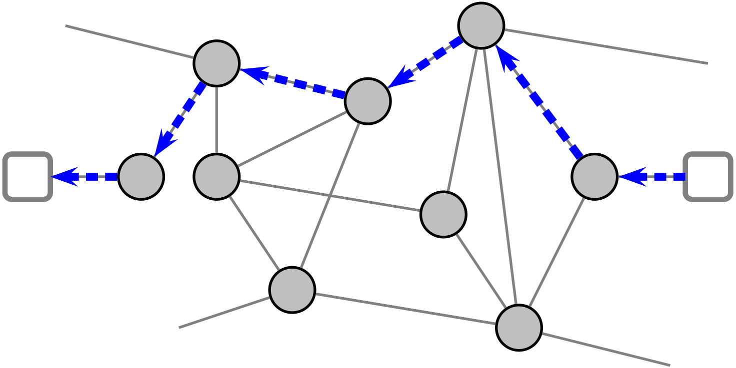

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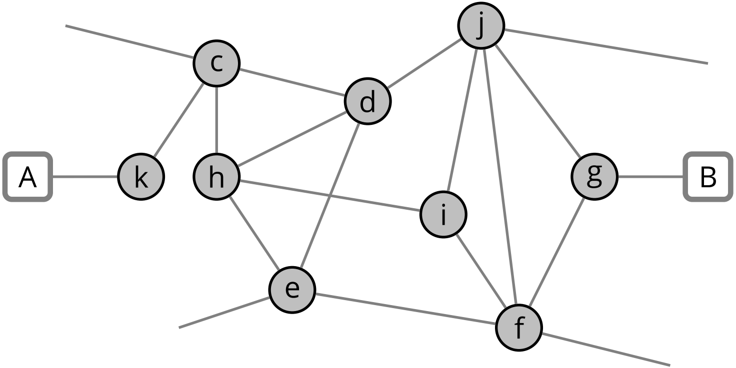

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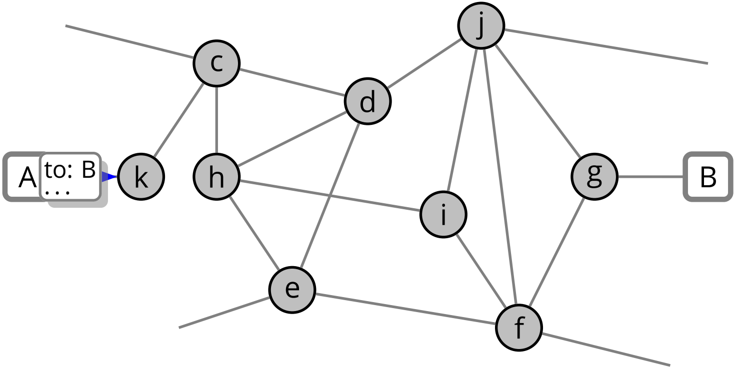

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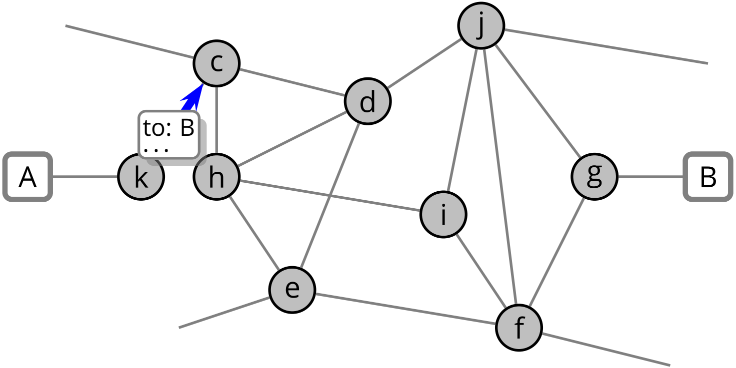

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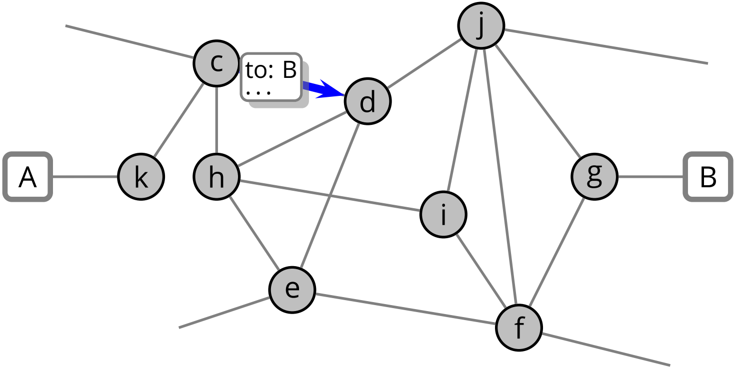

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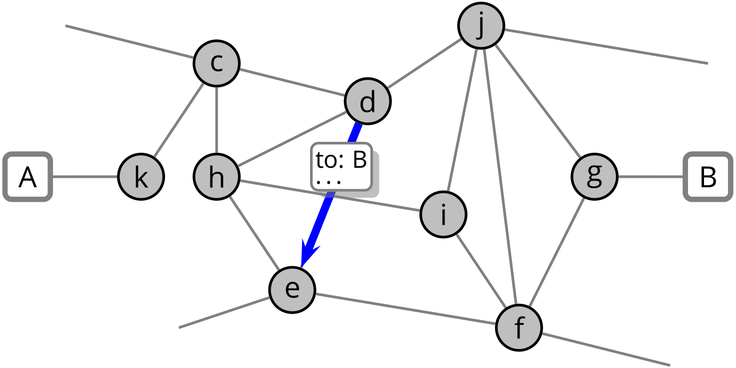

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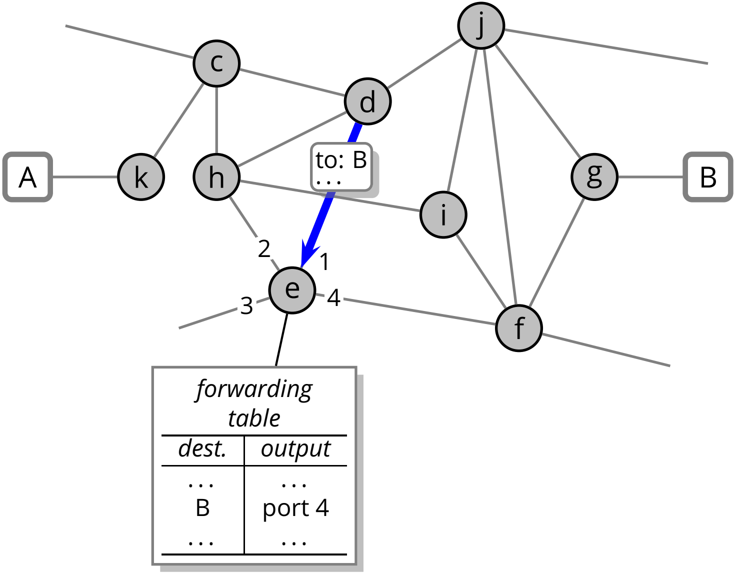

*forwarding table*

| *dest.* | *output* |
|---|---|
| . . . | . . . |
| B | port 4 |
| . . . | . . . |

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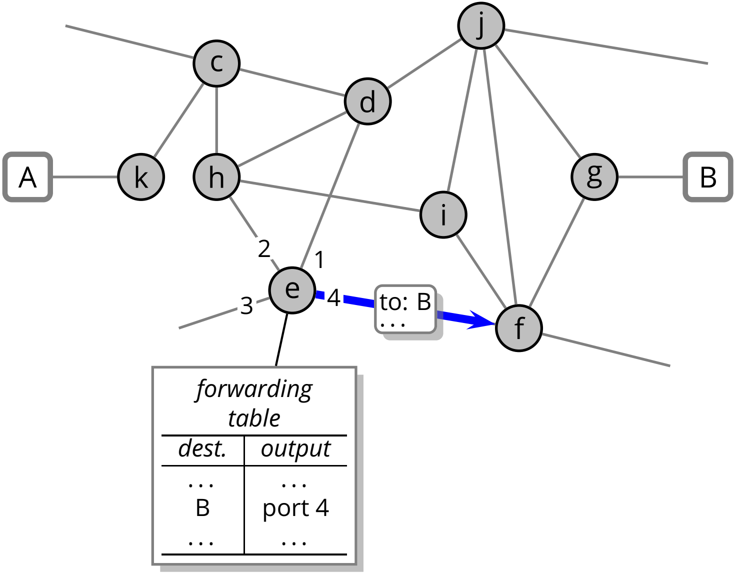

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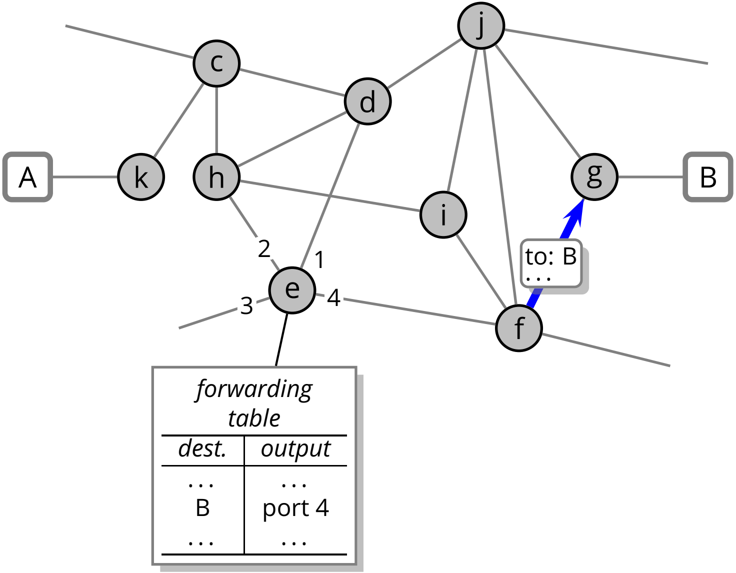

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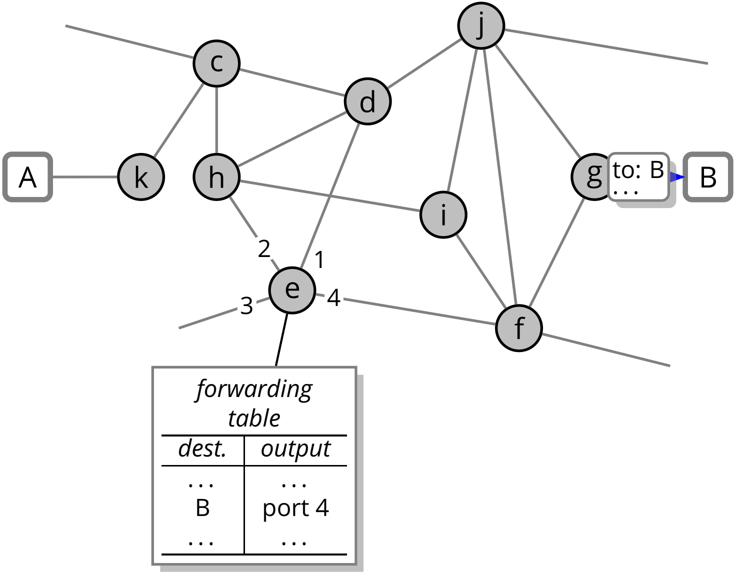

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    - how does the router build and maintain the forwarding table?

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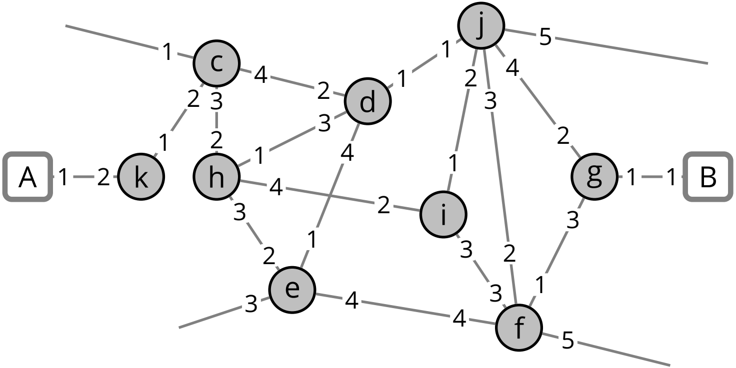

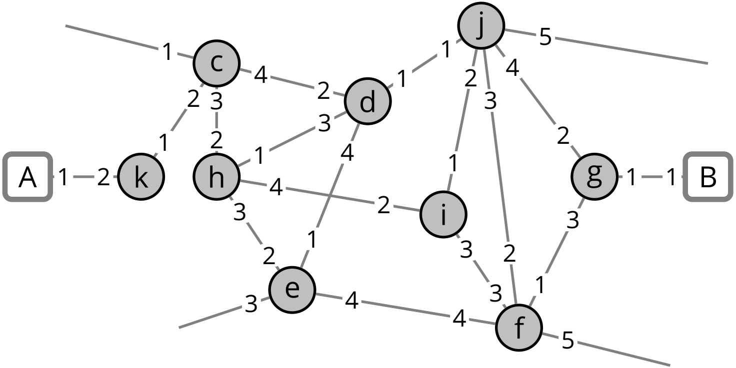

| *router k* | |
|---|---|
| A | 2 |
| B | 1 |

. . .

# Router Functions

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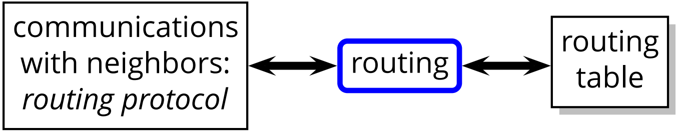

communications with neighbors: *routing protocol*

routing

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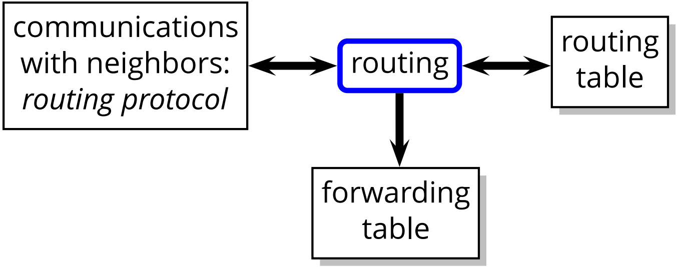

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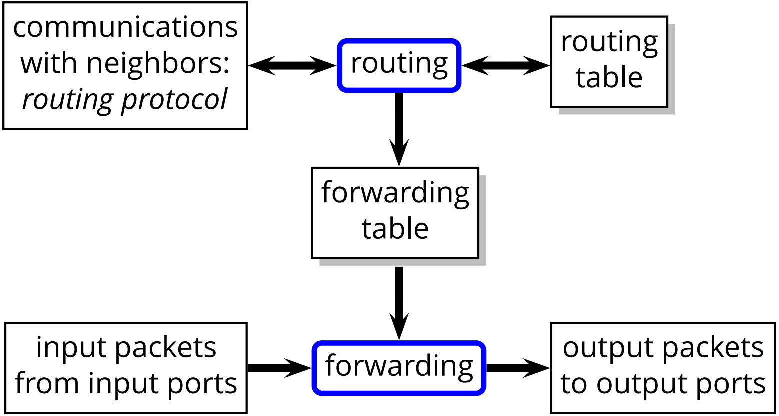

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input packets from input ports

forwarding

output packets to output ports

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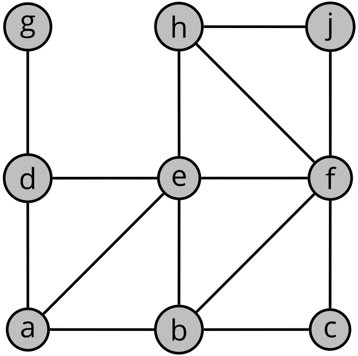

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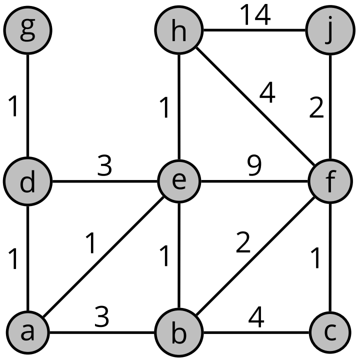

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  - A ***cost*** function $c : E \longrightarrow \mathbb{R}$
    - costs are always positive: $c(e) > 0$ for all $e \in E$
    - links are symmetric: $c(u, v) = c(v, u)$ for all $u, v \in N$

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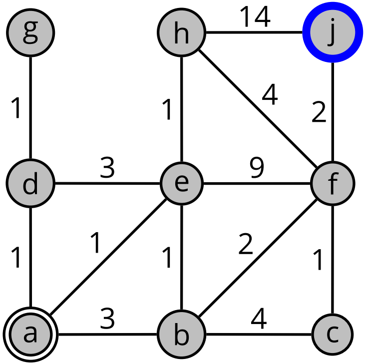
- Compile *u*'s forwarding table by adding the following entry:

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

  - $A(v)$ 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 $P_{u \to v} = u, x_1, x_2, \ldots, x_n, v$

# Back To The Example



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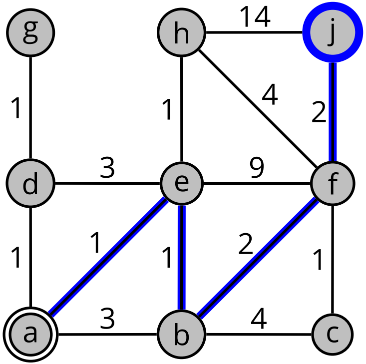

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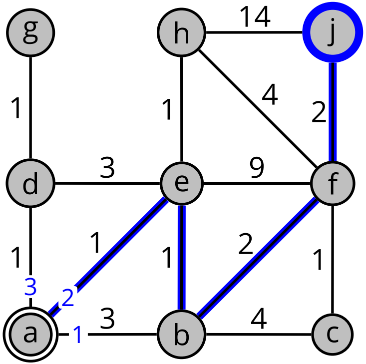

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  - $a$'s forwarding table will contain an entry $\boxed{j \longrightarrow 2}$ since $l_a(e) = 2$

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  - local computation of least-cost paths

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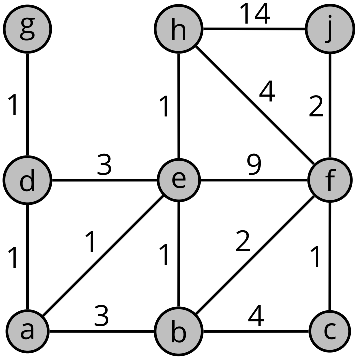

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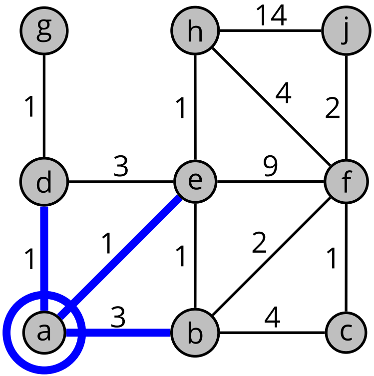

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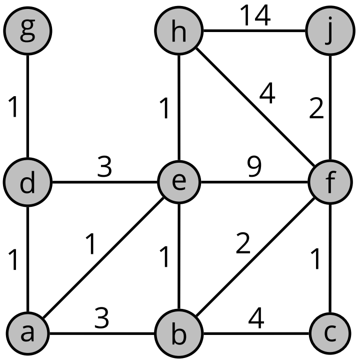

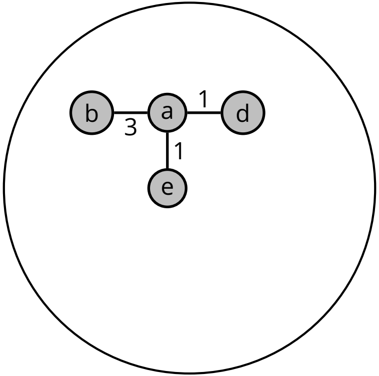

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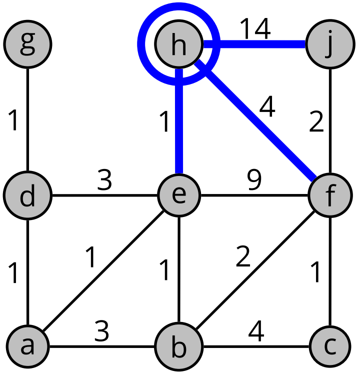

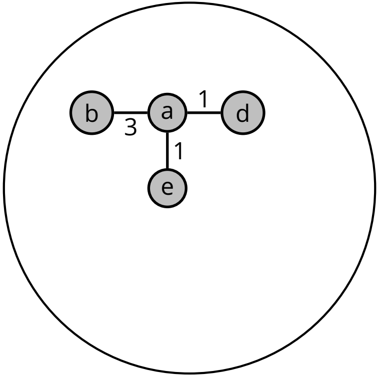

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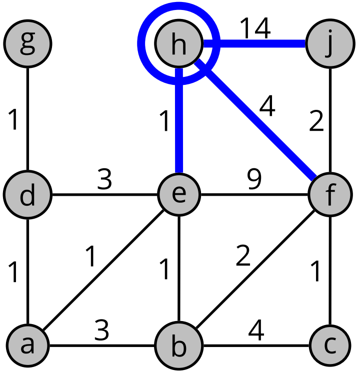

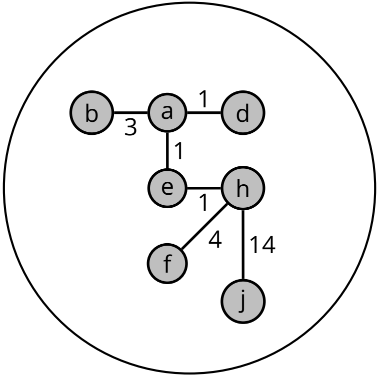

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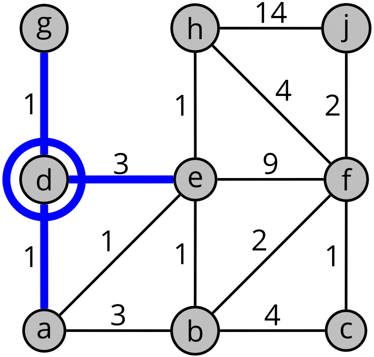

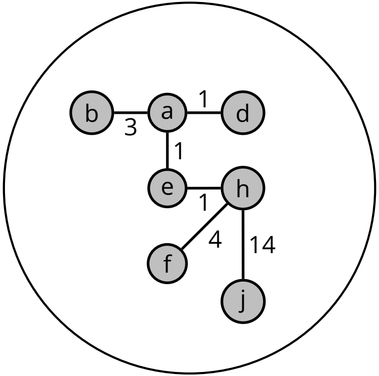

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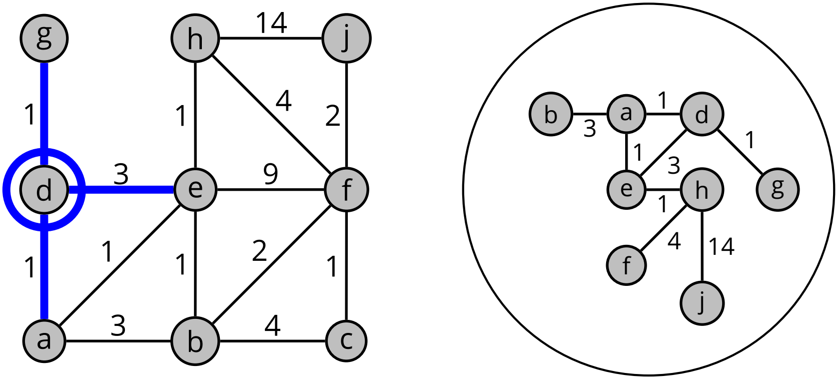

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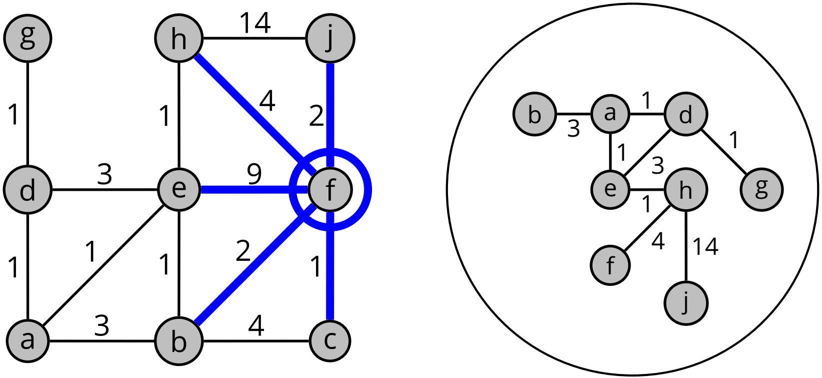

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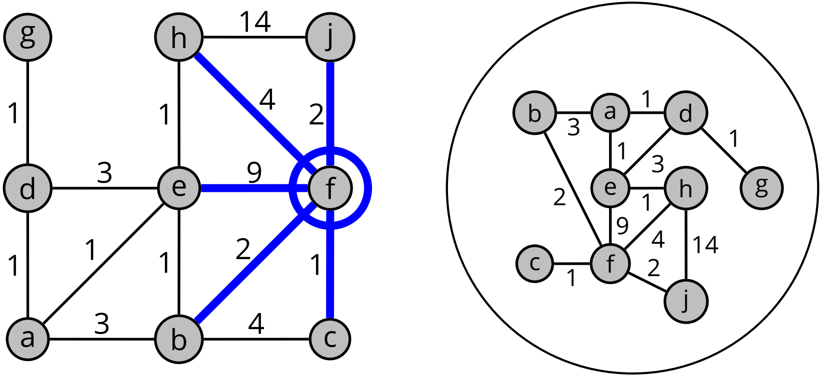

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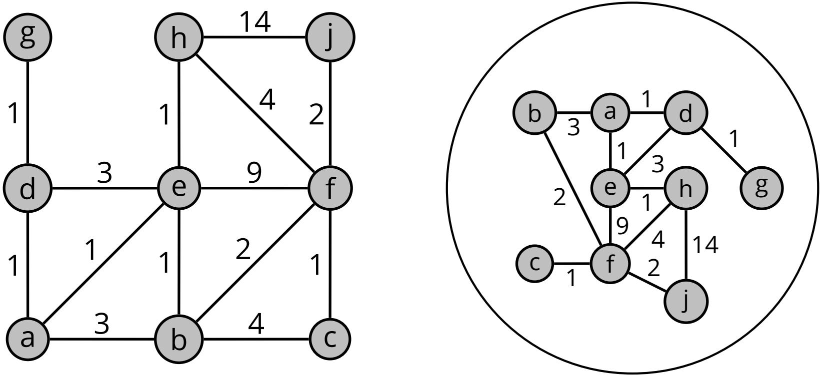

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- Once we have all the LSAs from every router, and therefore we complete knowledge of *G*, we need an ***algorithm to compute least-cost paths in a graph***

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  - it requires (unicast) routing information
  - so it is obviously useless to implement a routing algorithm

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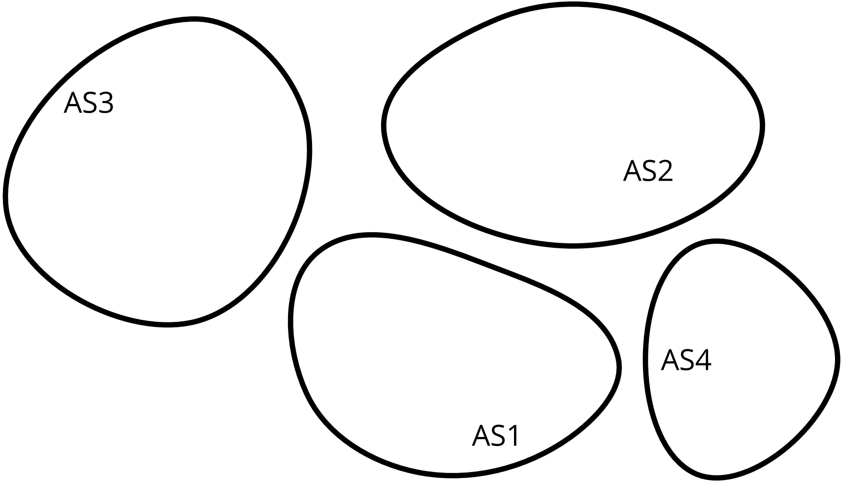

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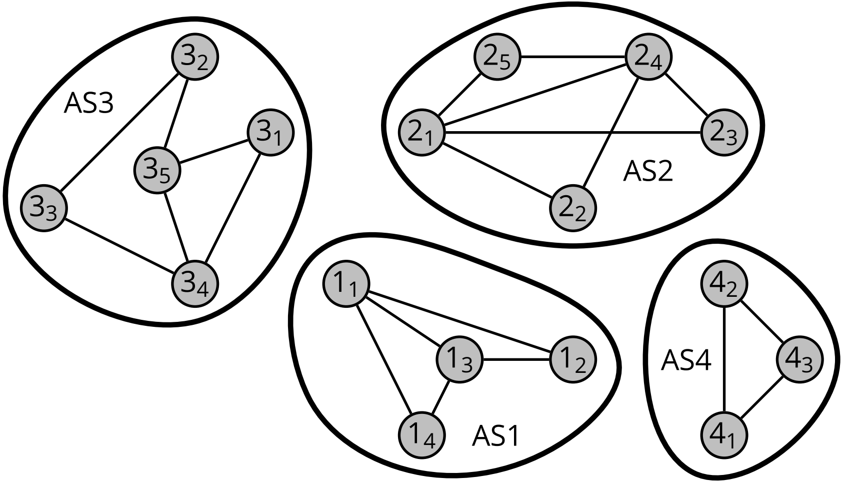

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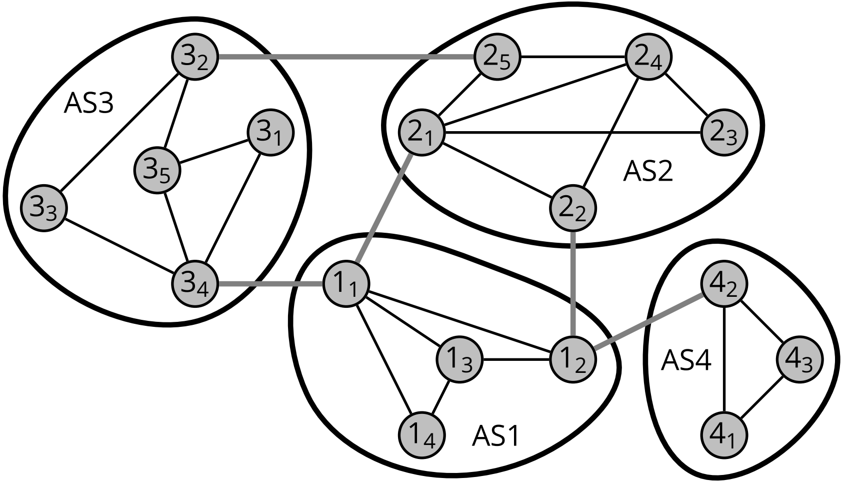

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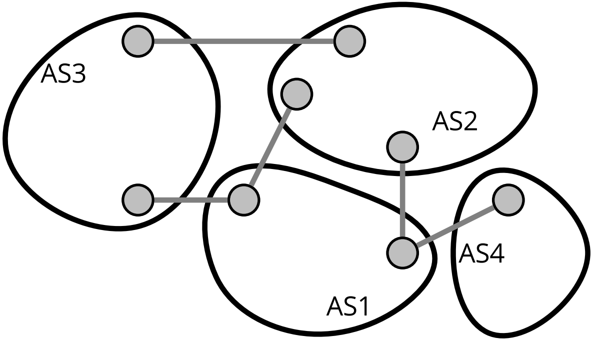

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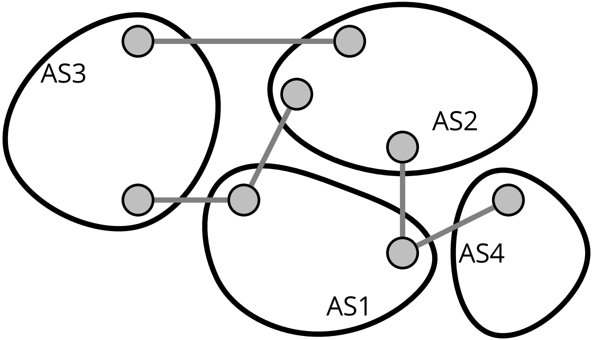

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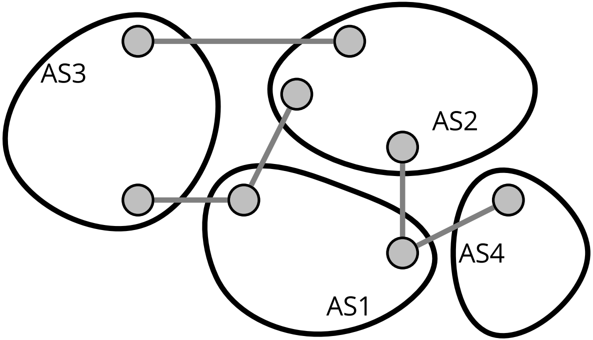

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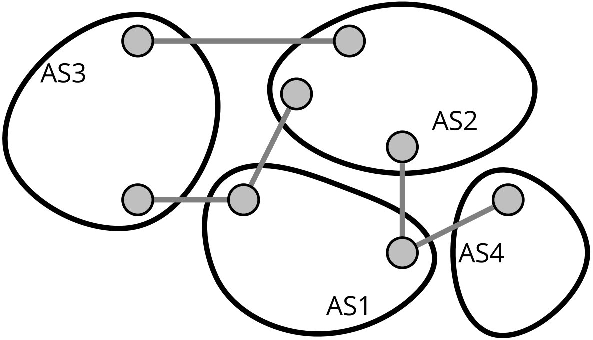

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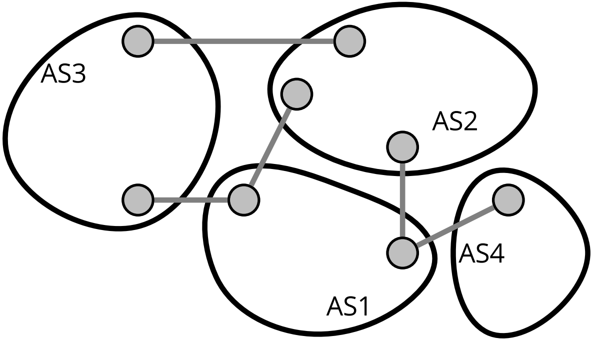

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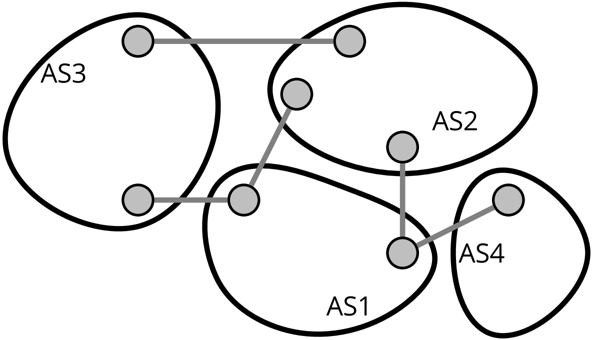

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- Both *inter-AS* and *intra-AS* routing information is used to compile the forwarding tables

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  - what if $x$ is reachable through multiple gateway routers $G_x, G'_x, \ldots$?
    - 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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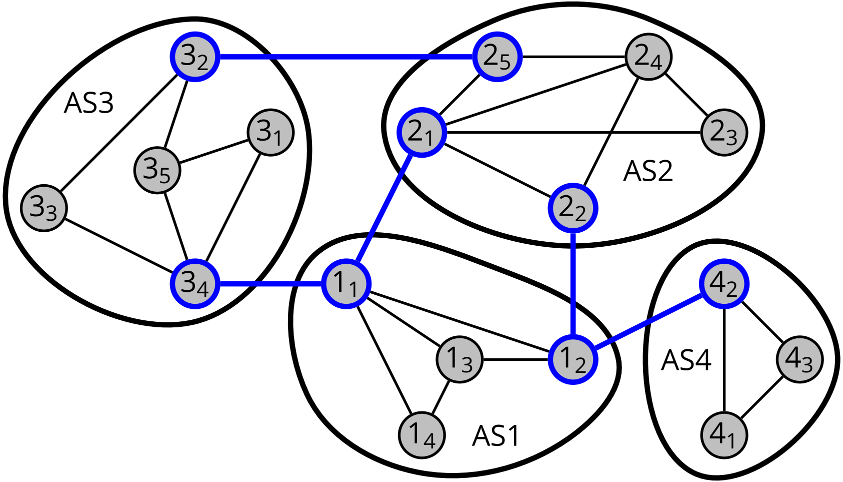
- ***BGP internal session (iBGP):*** a session within an autonomous system
  - note that internal sessions carry *inter-AS* information
  - *intra-AS* routing uses a separate protocol (e.g., OSPF)

# 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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