Computer Networks

Fall 2025

Maria Apostolaki

netsyn.princeton.edu/

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Materials from Laurent Vanbever, Scott Shenker & Jennifer Rexford

Communication Networks

Part 1: Overview

What is a network made of?

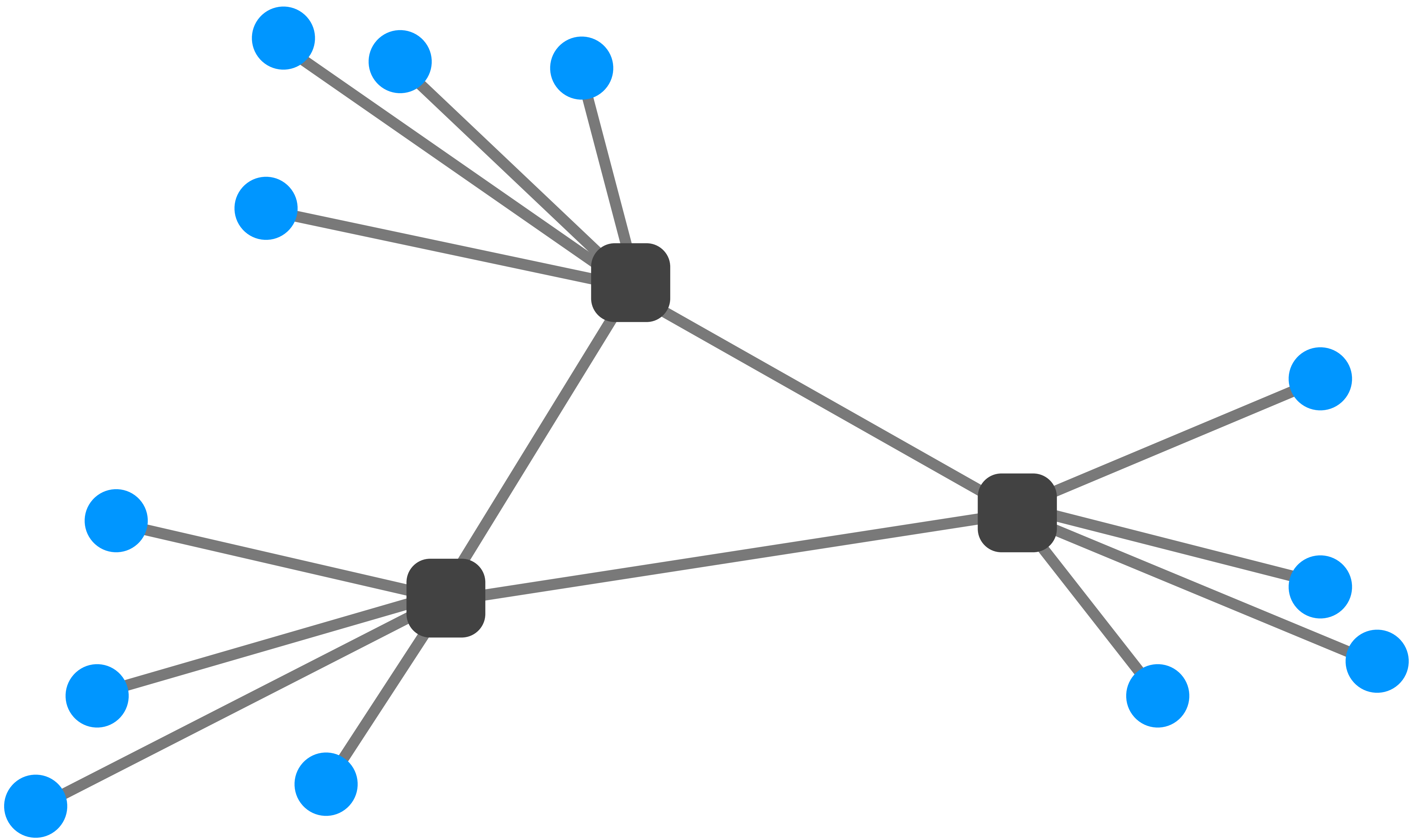
How is it shared?

#3 **How is it organized?**

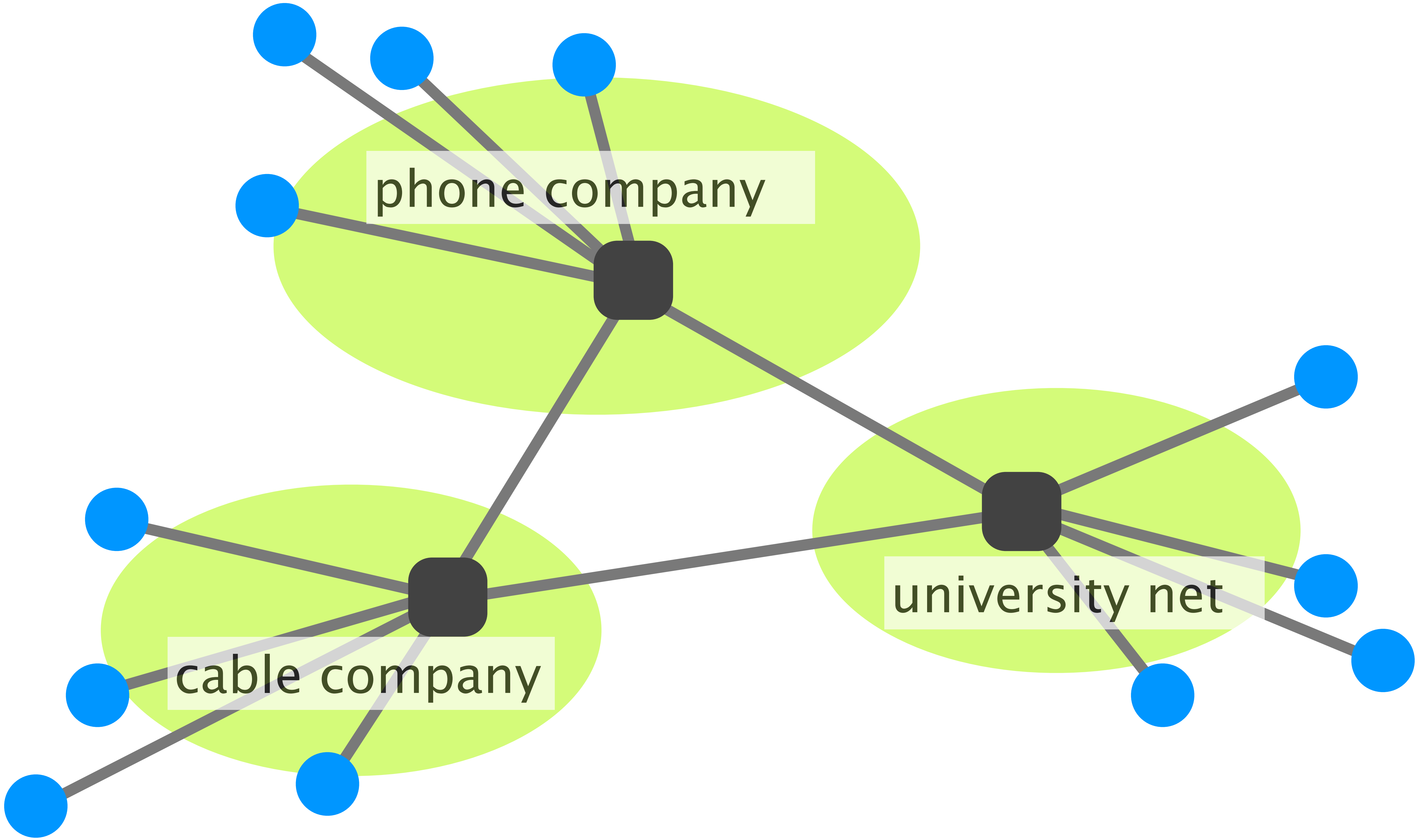
How does communication happen?

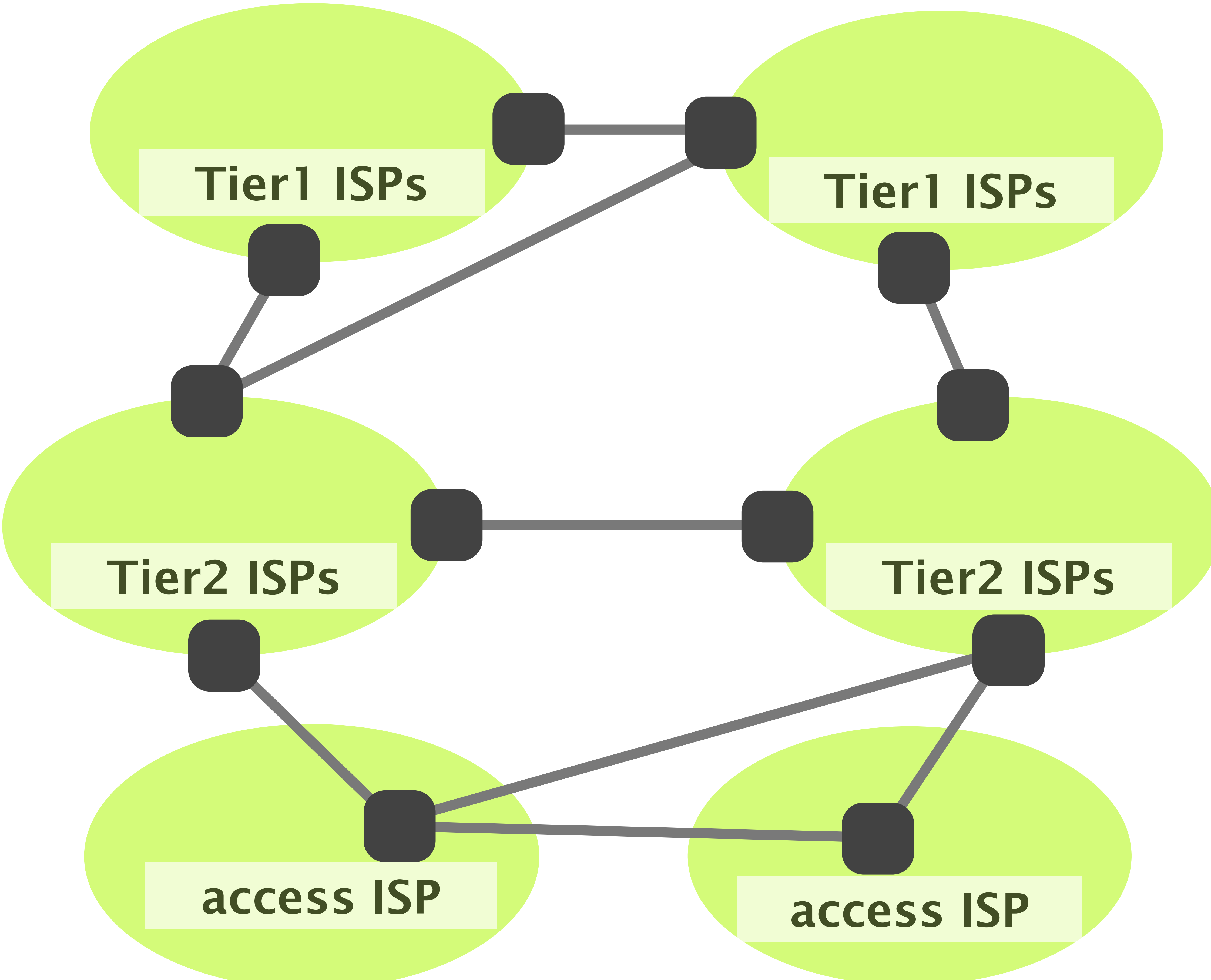
How do we characterize it?

The *Inter*net is a network of networks



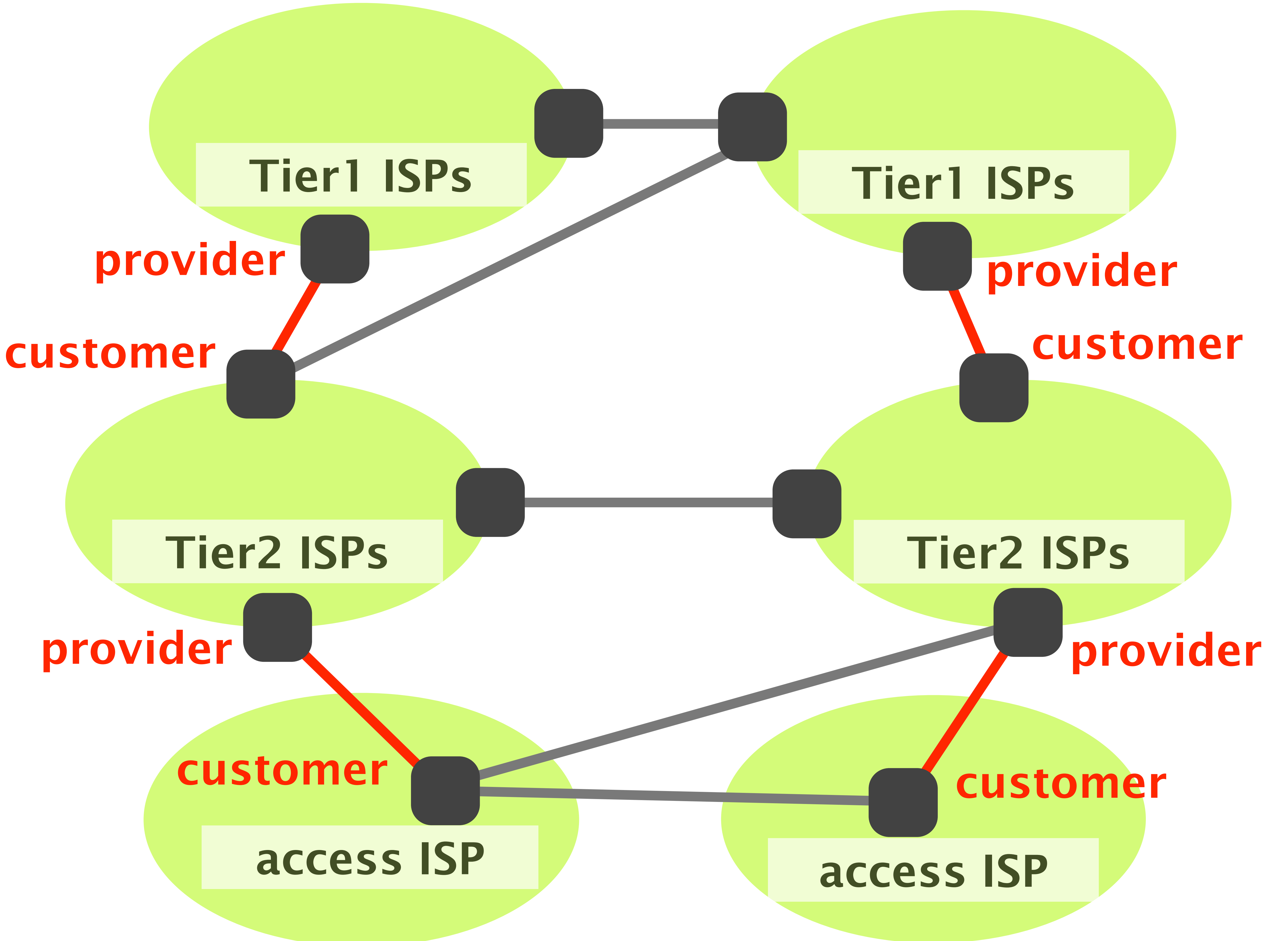
Internet Service Providers




Tier1 ISPs
Tier1 ISPs
Tier2 ISPs
Tier2 ISPs
access ISP
access ISP

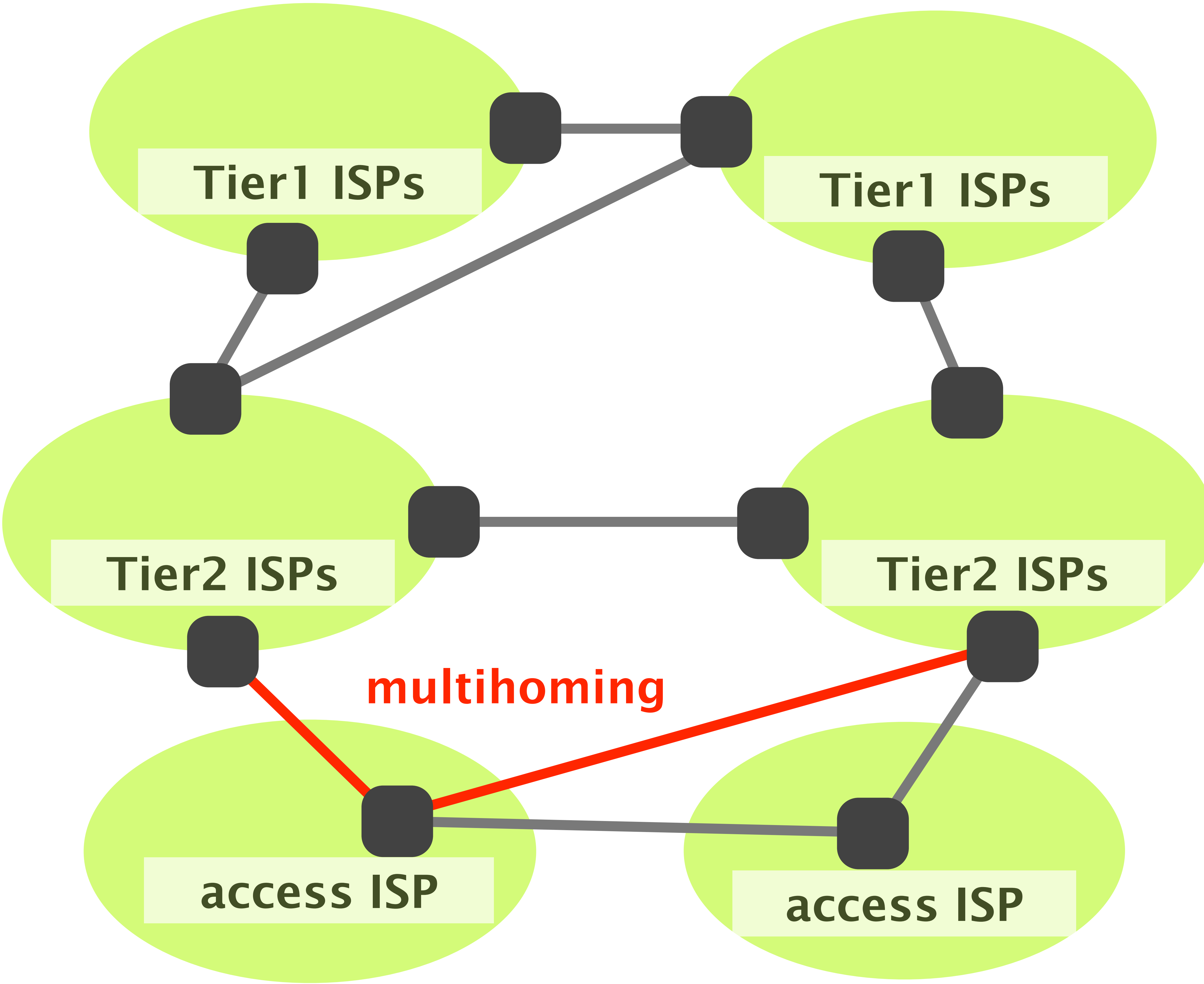
The Internet has a hierarchical structure

Tier-1 international	have no provider
Tier-2 national	provide transit to Tier-3s have at least one provider
Tier-3 local	do not provide any transit have at least one provider


Tier1 ISPs
Tier1 ISPs
provider
provider
customer
customer
Tier2 ISPs
Tier2 ISPs
provider
provider
customer
customer
access ISP
access ISP

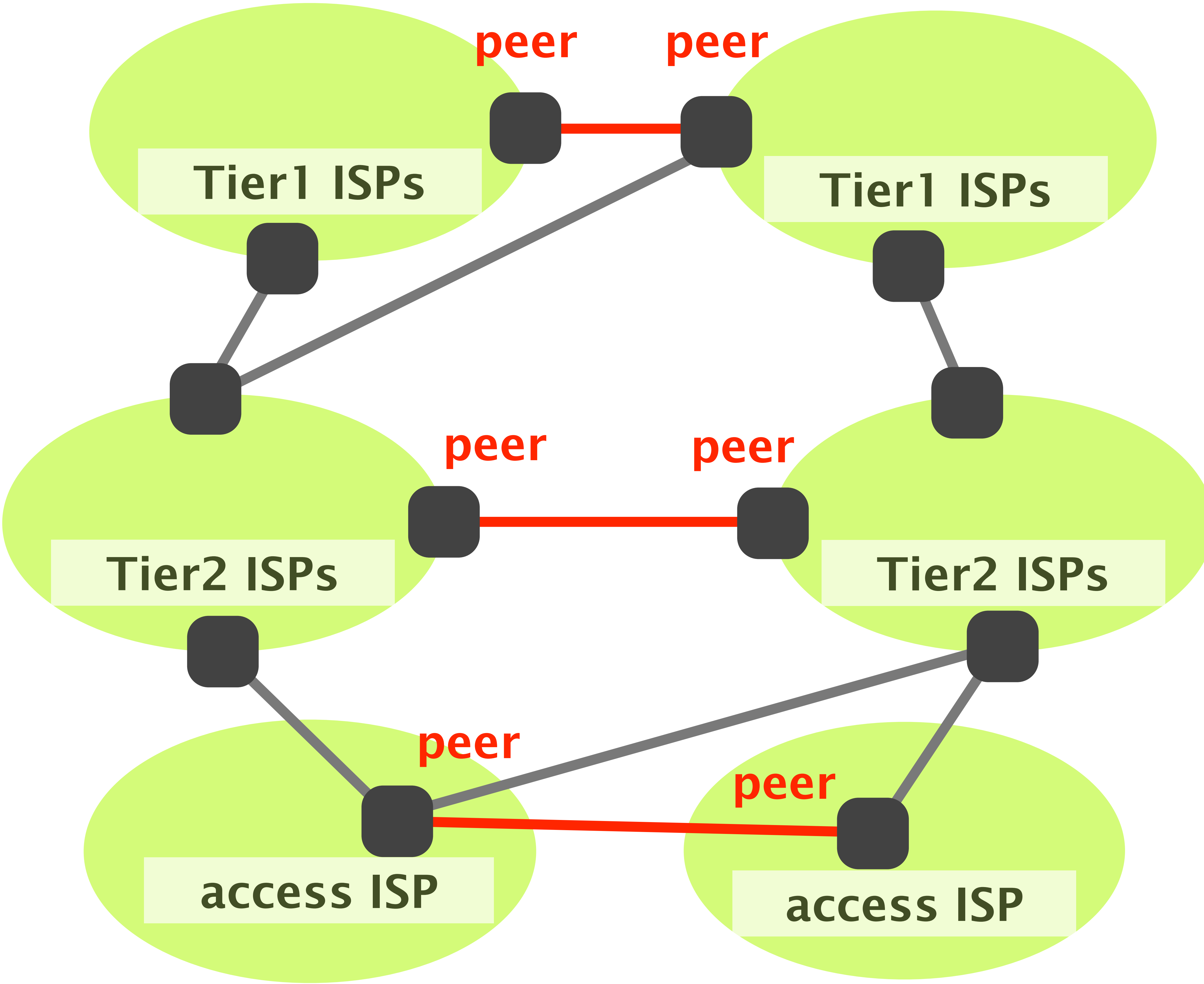
The distribution of networks in Tiers is extremely skewed towards Tier-3s

	total	~77,000 networks
Tier-1 international	have no provider	~12
Tier-2 national	provide transit to Tier-3s have at least one provider	~1,000s
Tier-3 local	do not provide any transit have at least one provider	85-90%


Tier1 ISPs
Tier1 ISPs
Tier2 ISPs
Tier2 ISPs
multihoming
access ISP
access ISP

Some networks have an incentive to connect directly,
to reduce their bill with their own provider

This is known as “peering”


peer
peer
Tier1 ISPs
Tier1 ISPs
peer
peer
Tier2 ISPs
Tier2 ISPs
peer
peer
access ISP
access ISP

Interconnecting each network to its neighbors one-by-one is not cost effective

Physical costs

of provisioning or renting physical links

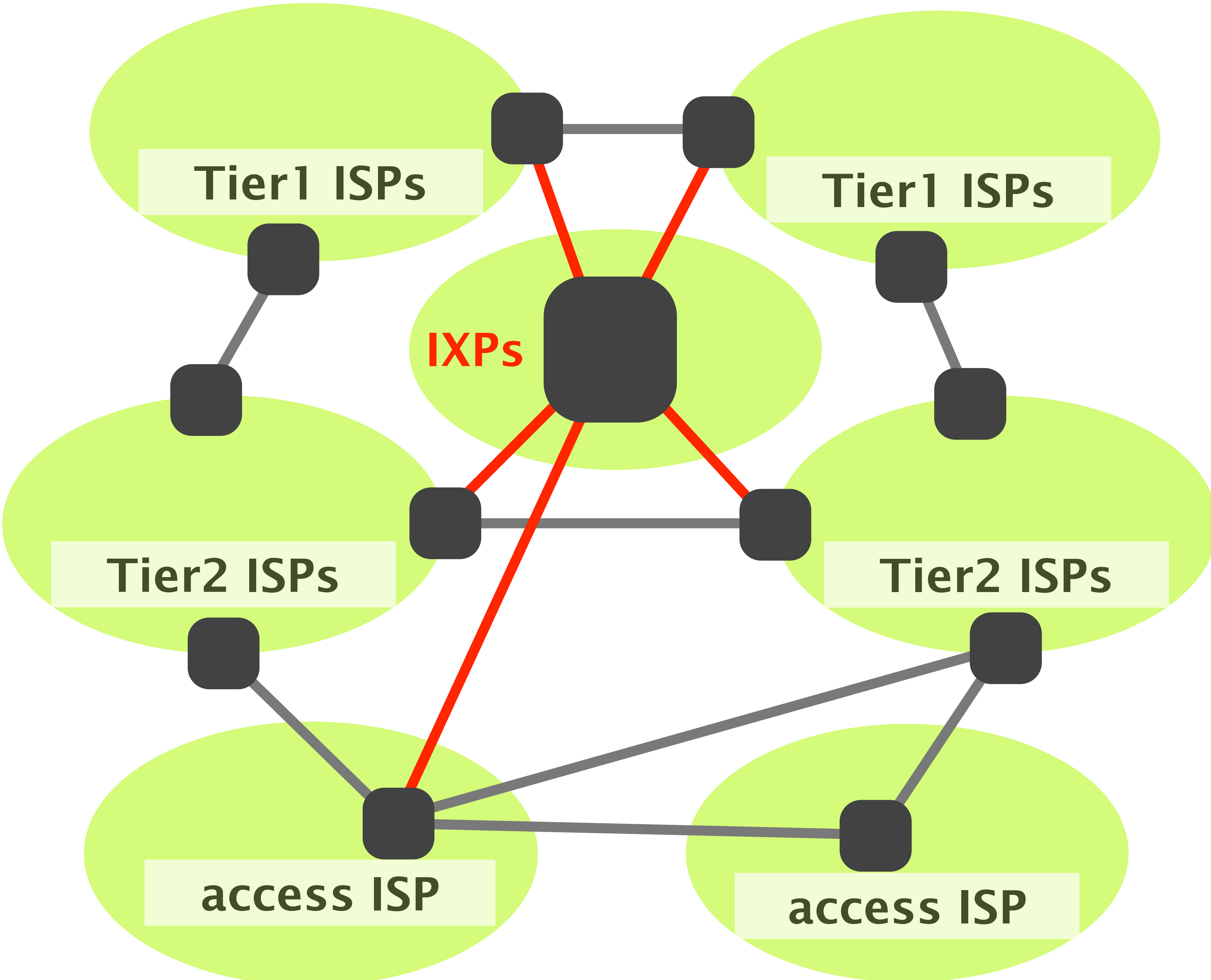
Bandwidth costs

a lot of links are not necessarily fully utilized

Human costs

to manage each connection individually

Internet eXchange Points (IXPs) solve these problems by letting *many* networks connect in one location


Tier1 ISPs
Tier1 ISPs
IXPs
Tier2 ISPs
Tier2 ISPs
access ISP
access ISP

Communication Networks

Part 1:

#1	What is a network made of?
#2	How is it shared?
#3	How is it organized?
#4	How does communication happen?
#5	How do we characterize it?

Communication Networks

Part 1:

What is a network made of?

How is it shared?

How is it organized?

#4 How does communication happen?

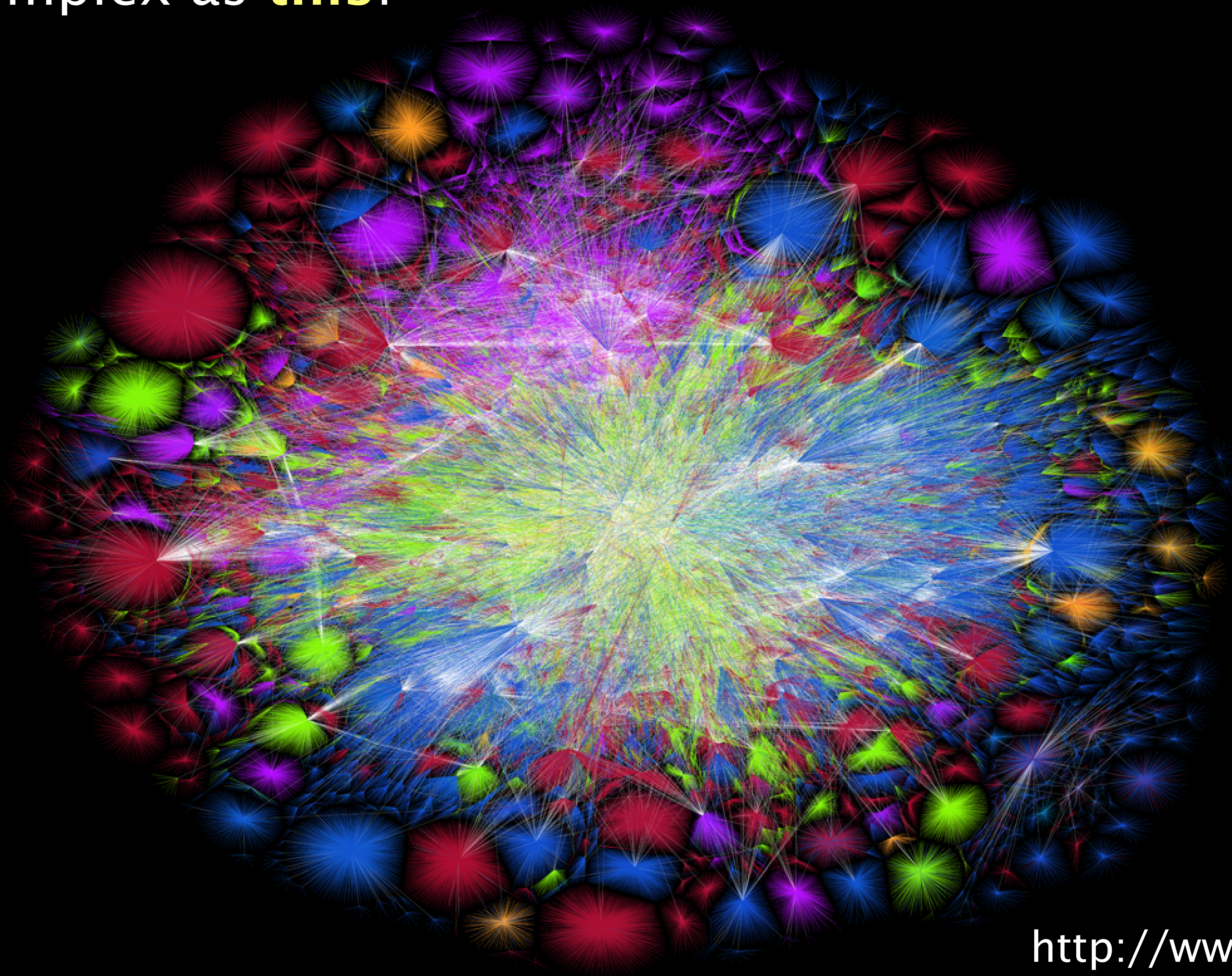
How do we characterize it?

The Internet should allow

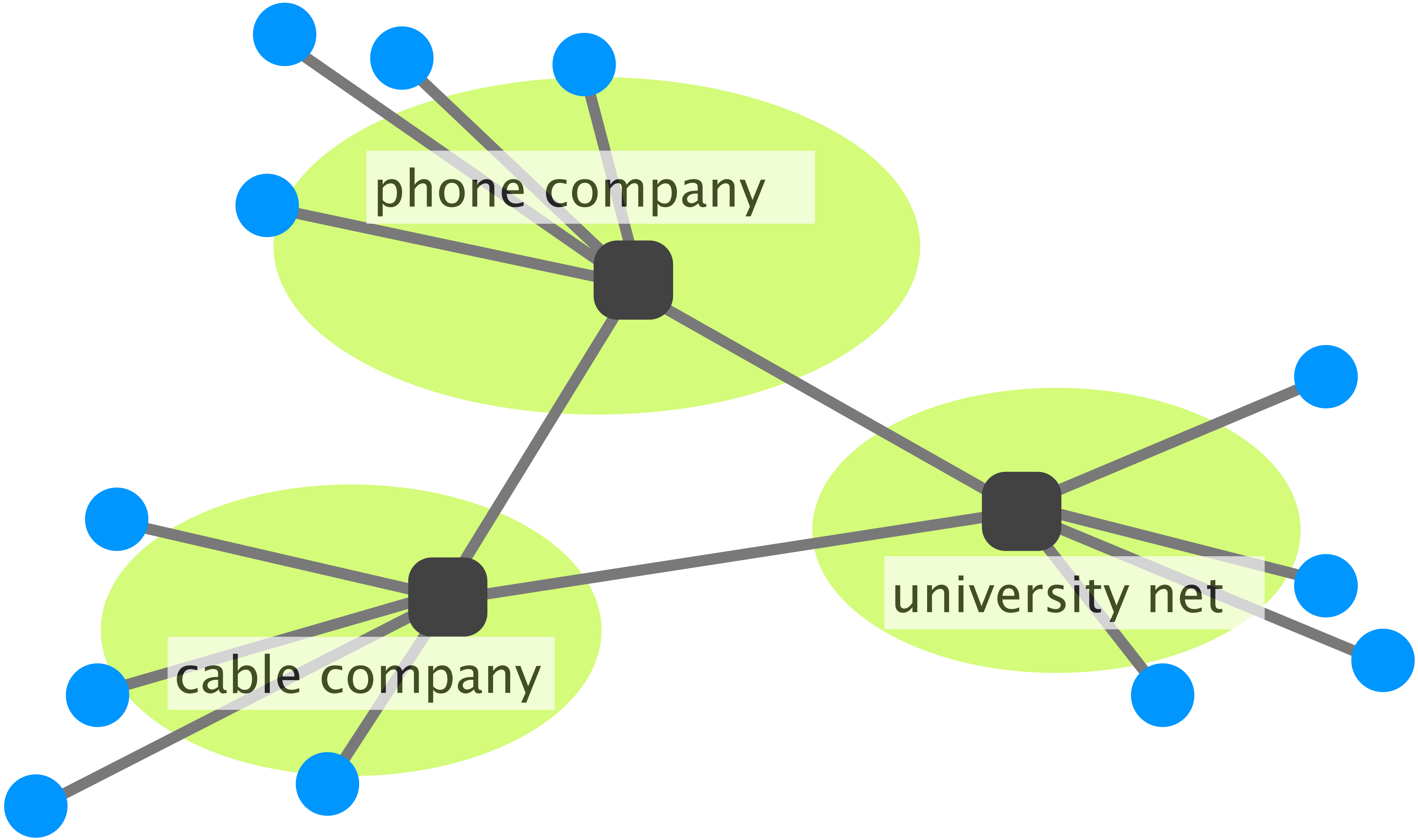
processes on different hosts
to exchange data

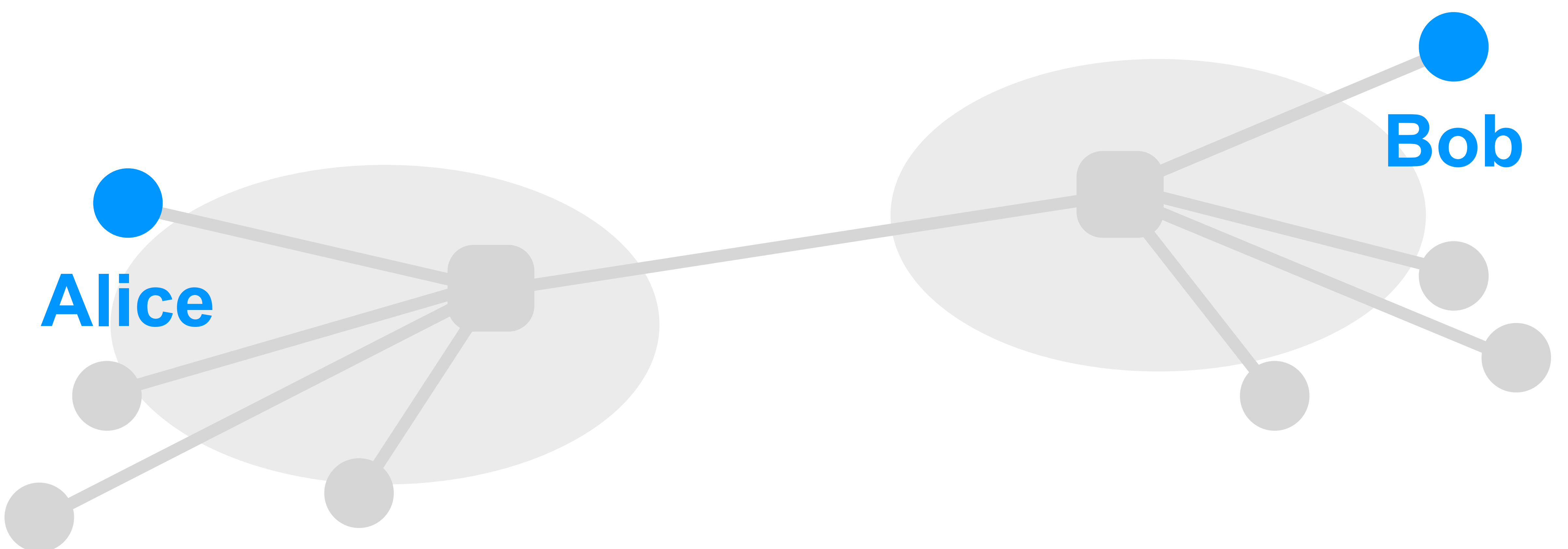
everything else is just commentary…

How do you exchange data in a network as complex as **this**?



http://www.opte.org

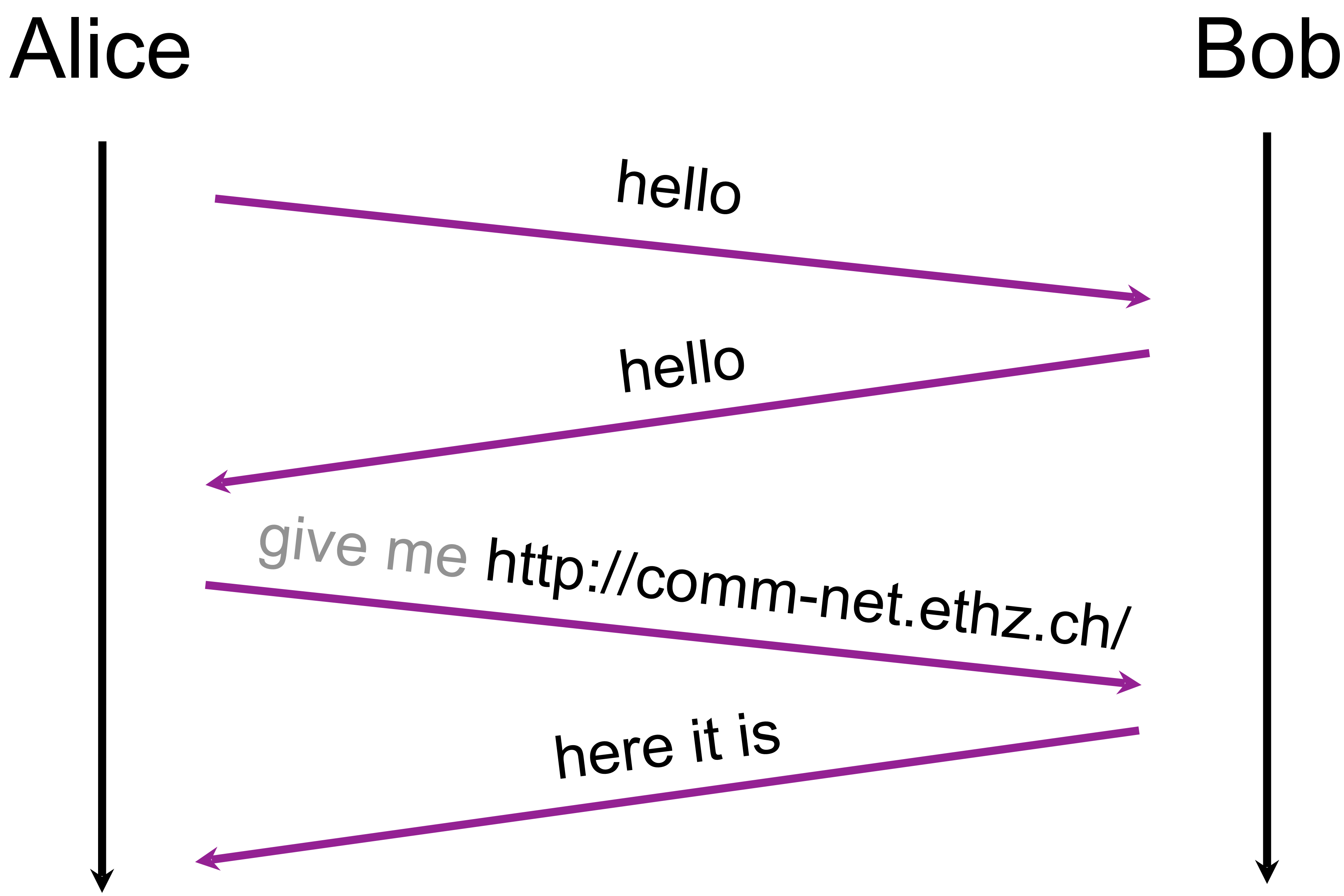

phone company
university net
cable company


Alice
Bob

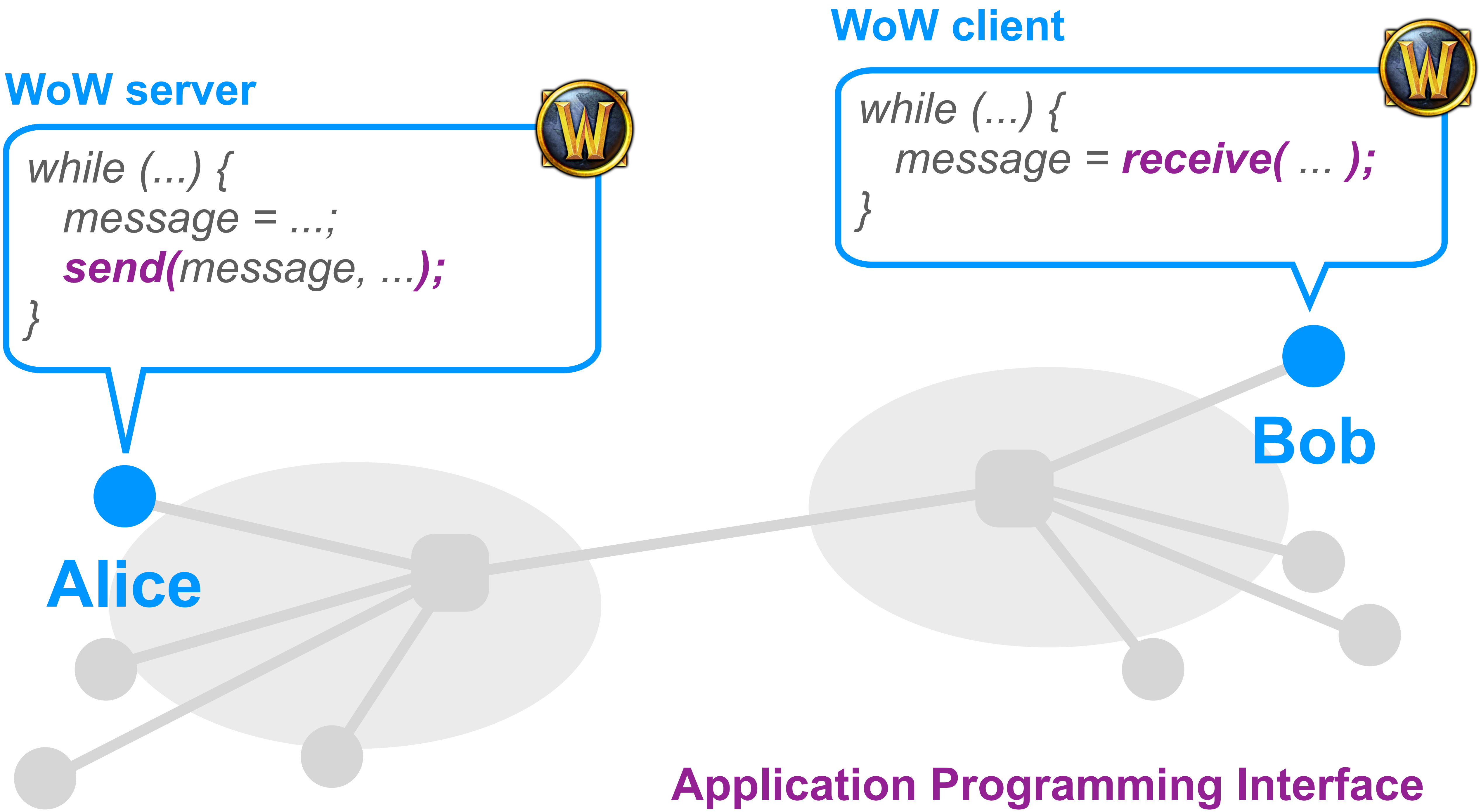
To exchange data, Alice and Bob use
a set of network protocols

A protocol is like a conversational convention:

who should talk next and how they should respond

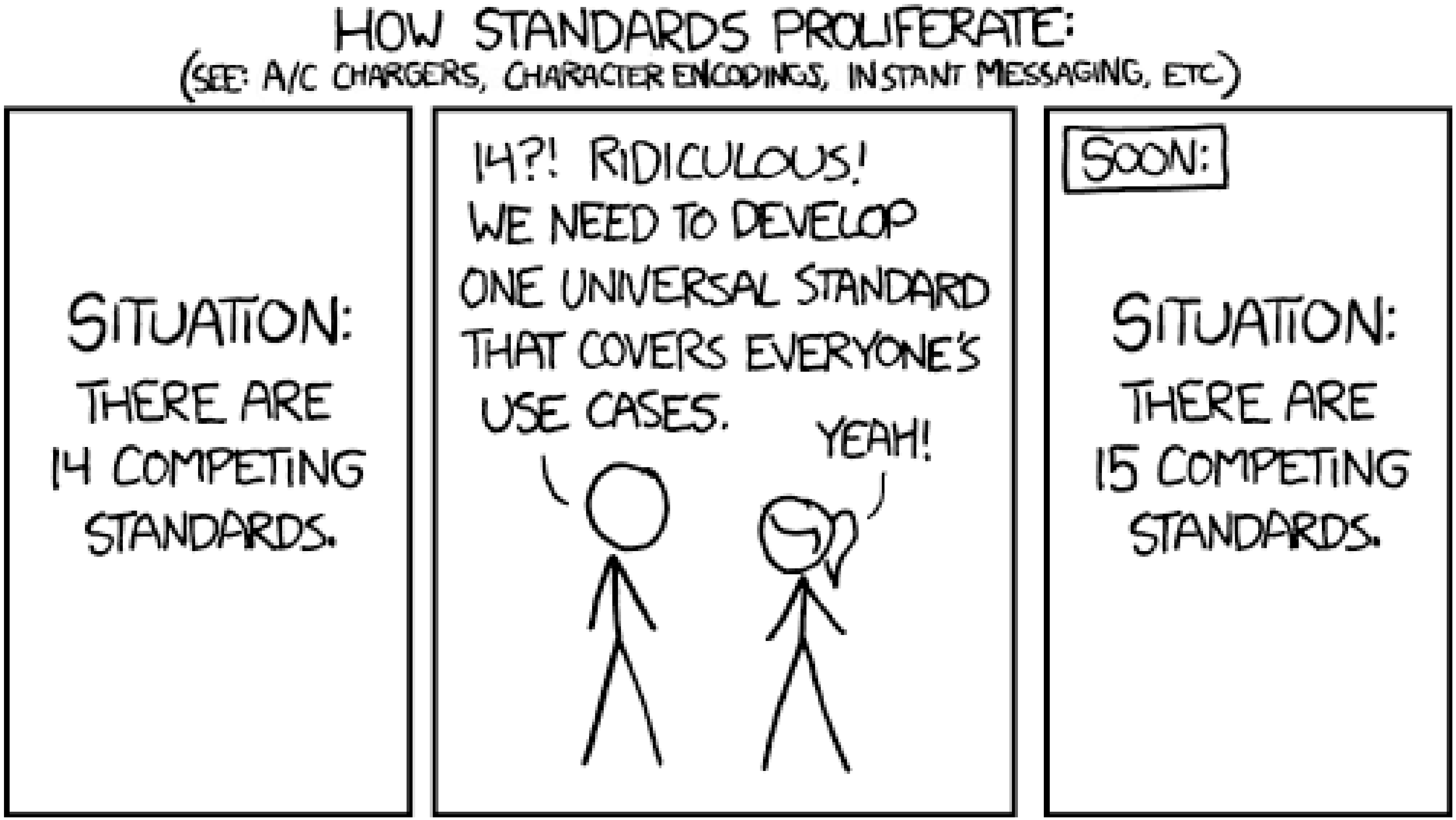


Each protocol is governed by a specific interface



In practice, there exists **a lot** of network protocols.

How does the Internet organize **this?**



https://xkcd.com/927/

Modularity is a key component of any good system

Problem

can't build large systems out of spaghetti code

hard (if not, impossible) to understand, debug, update

need to bound the scope of changes

evolve the system without rewriting it from scratch

Solution

Modularity is how we do it

…and understand the system at a higher-level

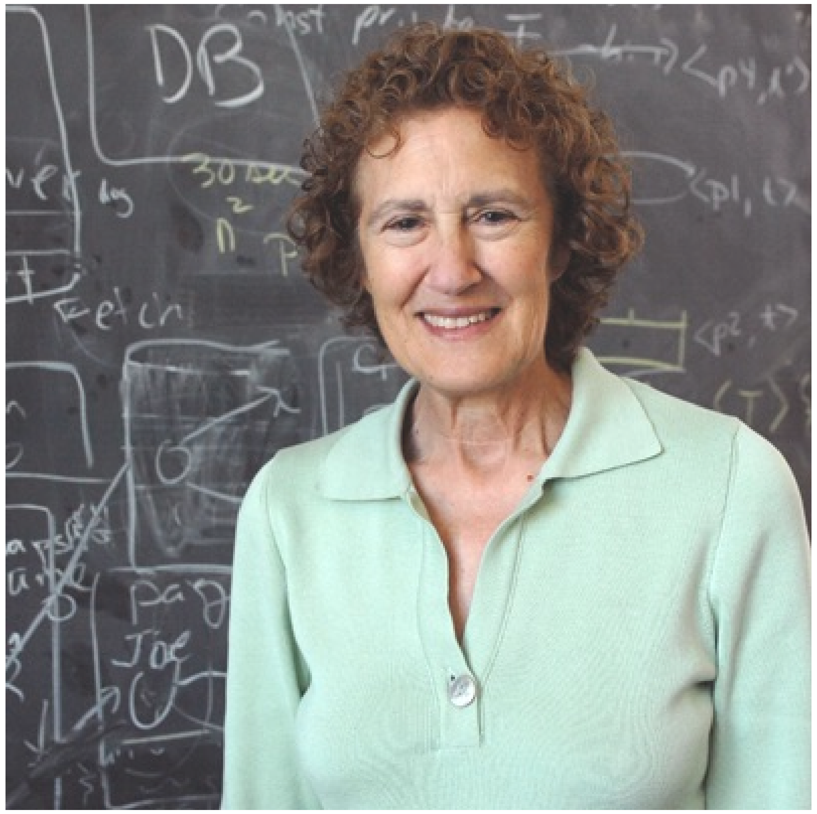


Photo: Donna Coveney

Modularity,
based on abstraction,
is ***the*** way things get done

— *Barbara Liskov*, MIT

To provide structure to the design of network protocols, network designers organize protocols in layers

To provide structure to the design of network protocols, network designers organize protocols in layers

and the network hardware/software that implement them

Internet communication can be decomposed in 5 independent layers (or 7 layers for the OSI model)

	layer
L5	Application
L4	Transport
L3	Network
L2	Link
L1	Physical

Each layer provides a service to the layer above

	layer	service provided:
L5	Application	network access
L4	Transport	end-to-end delivery (reliable or not)
L3	Network	global best-effort delivery
L2	Link	local best-effort delivery
L1	Physical	physical transfer of bits

Each layer provides a service to the layer above

by using the services of the layer directly below it

Applications

...built on...

Reliable (or unreliable) transport

...built on...

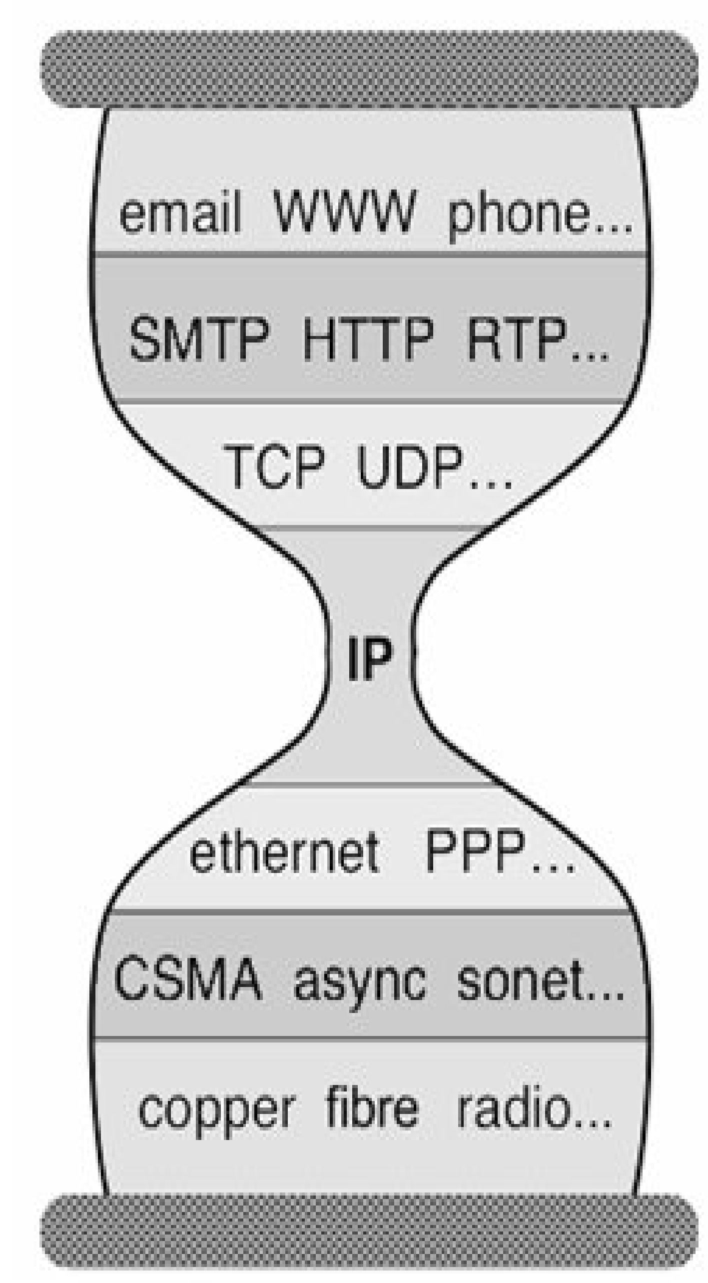
Best-effort global packet delivery

...built on...

Best-effort local packet delivery

...built on...

Physical transfer of bits



Each layer has a unit of data

	layer	data units
L5	Application	exchanges messages between processes
L4	Transport	transports segments between end systems
L3	Network	moves packets around the network
L2	Link	moves frames across a link
L1	Physical	moves bits across a physical medium

Each layer (except for L3) is implemented with different protocols

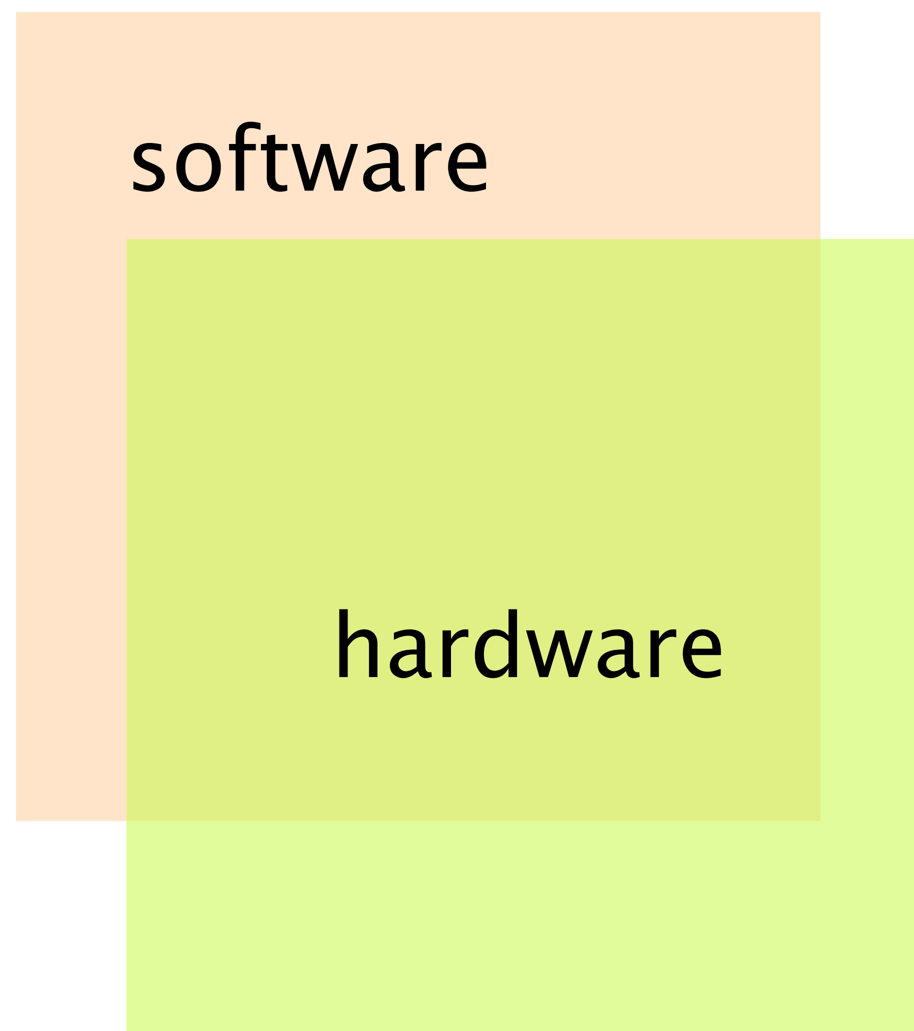
	layer	protocol
L5	Application	HTTP, SMTP, FTP, SIP, …
L4	Transport	TCP, UDP, SCTP
L3	Network	IP
L2	Link	Ethernet, Wifi, (A/V)DSL, Cable, LTE, …
L1	Physical	Twisted pair, fiber, coaxial cable, …

The Internet Protocol (IP) acts as an unifying, network, layer

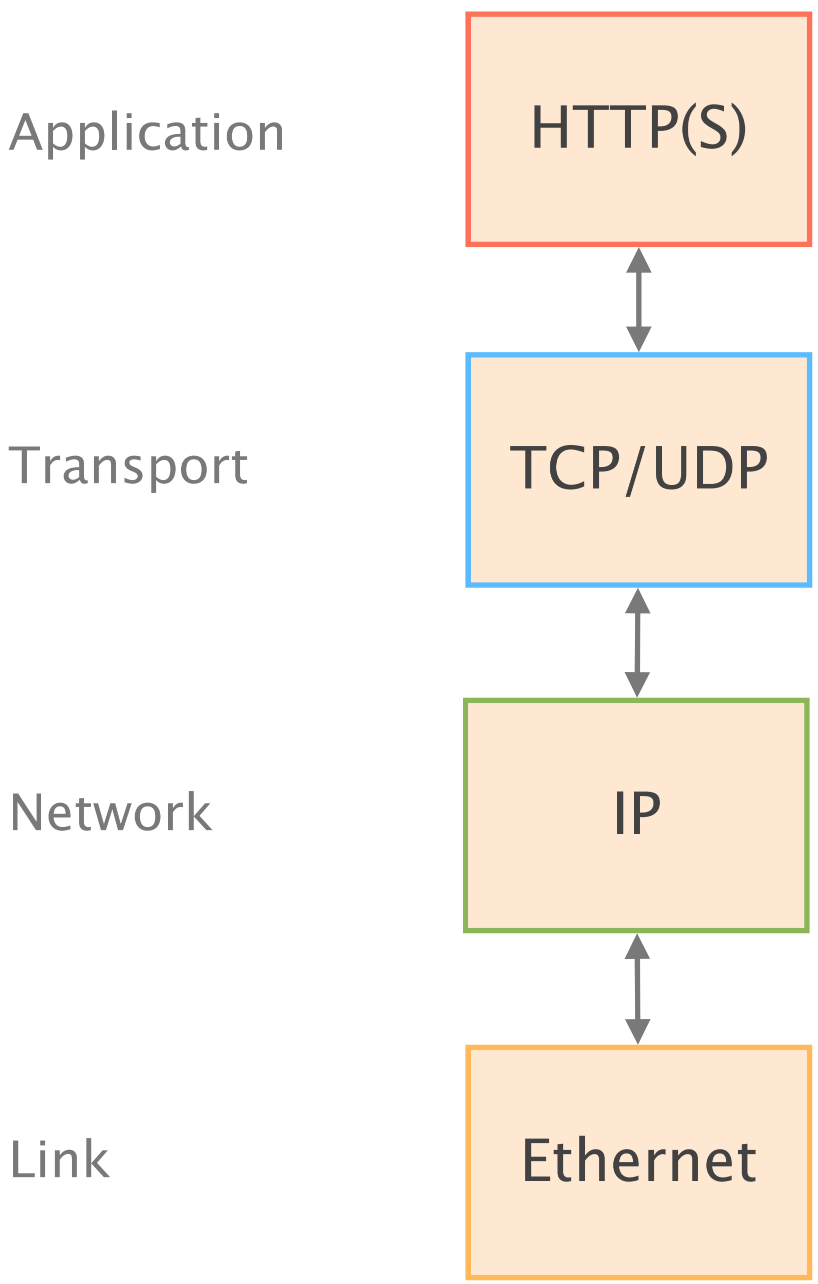
	layer	protocol
L5	Application	HTTP, SMTP, FTP, SIP, …
L4	Transport	TCP, UDP, SCTP
L3	Network	IP
L2	Link	Ethernet, Wifi, (A/V)DSL, Cable, LTE, …
L1	Physical	Twisted pair, fiber, coaxial cable, …

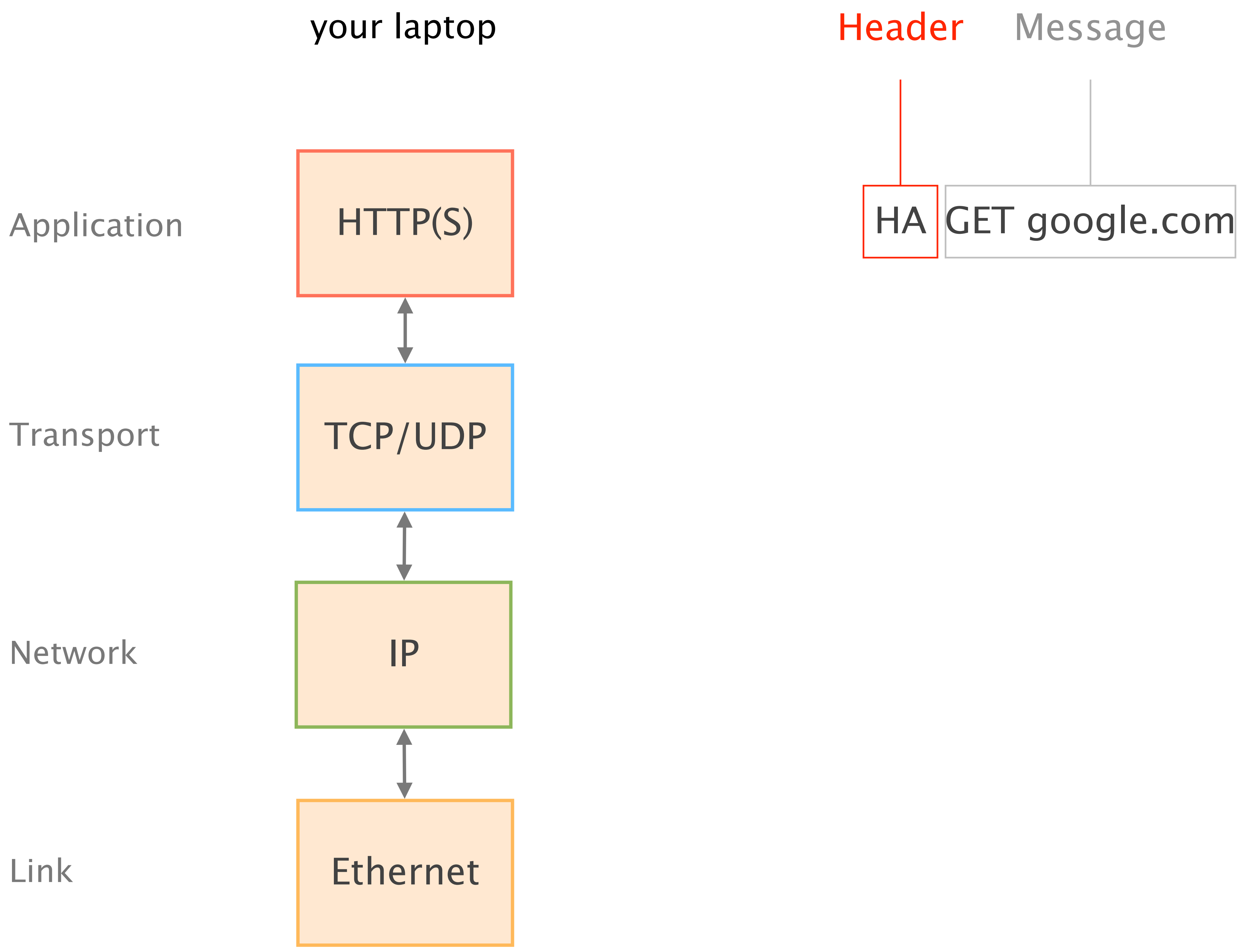
Each layer is implemented with different protocols and technologies

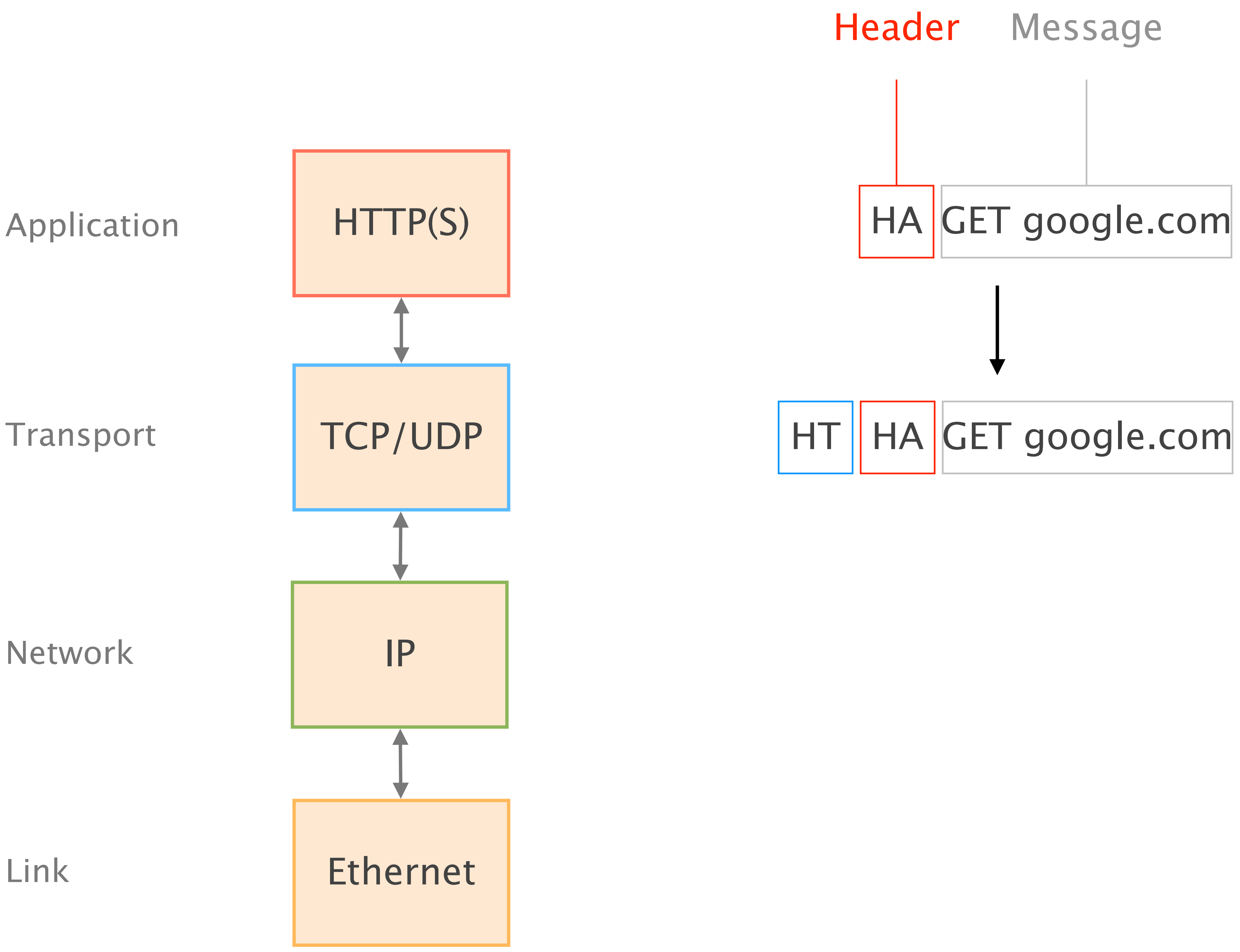
	layer	technology
L5	Application	
L4	Transport	
L3	Network	
L2	Link	
L1	Physical	

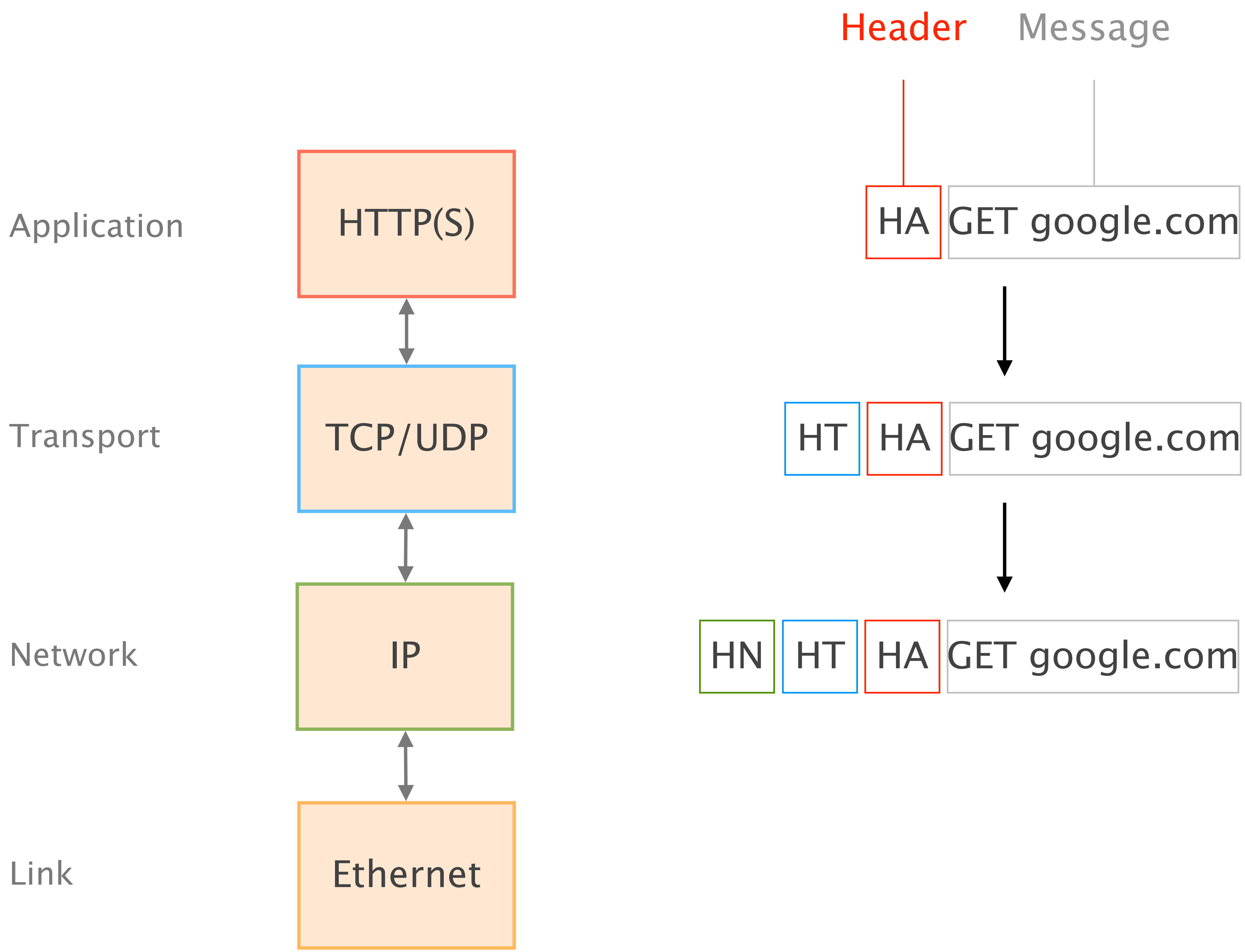


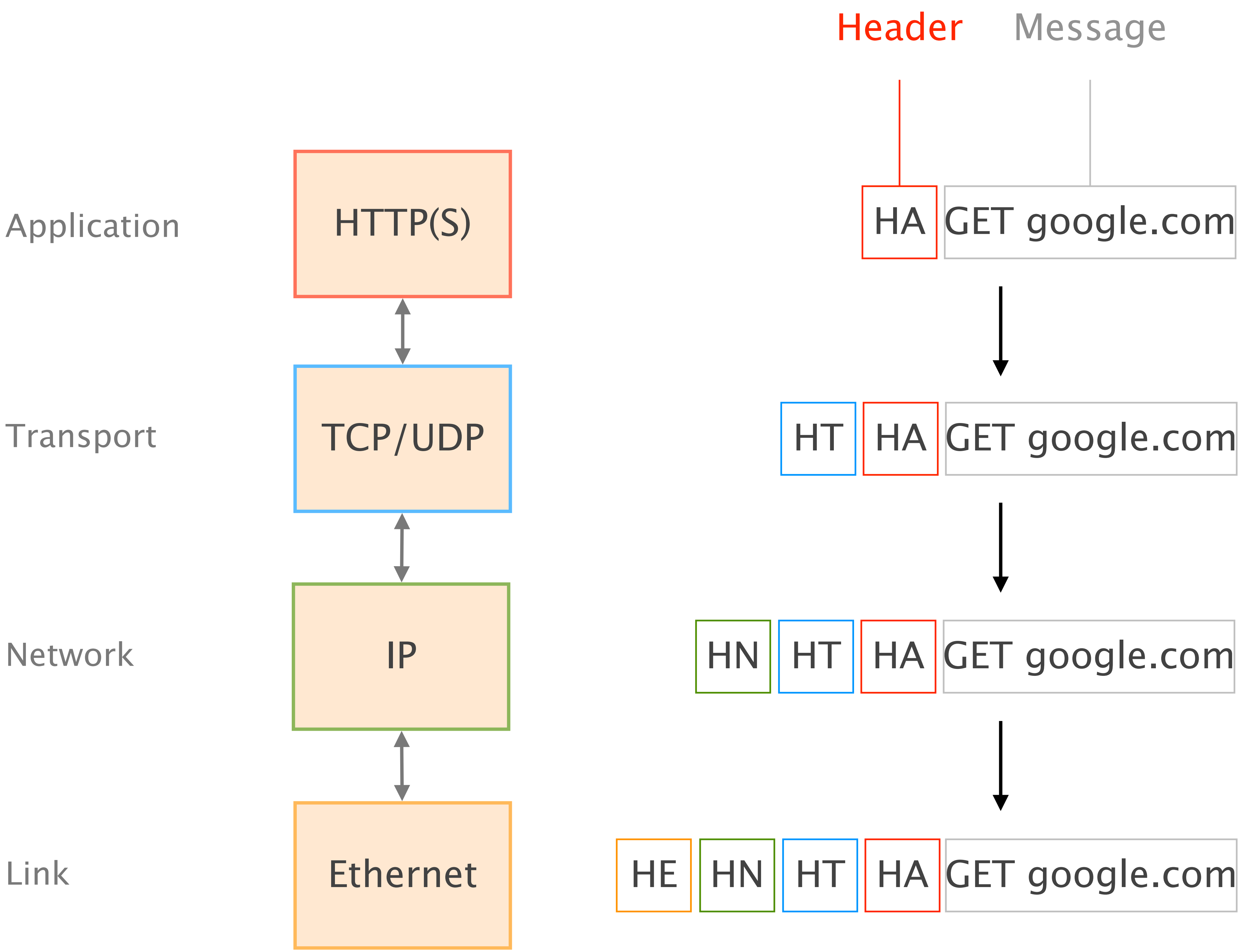
Each layer takes messages from the layer above, and *encapsulates* with its own header and/or trailer



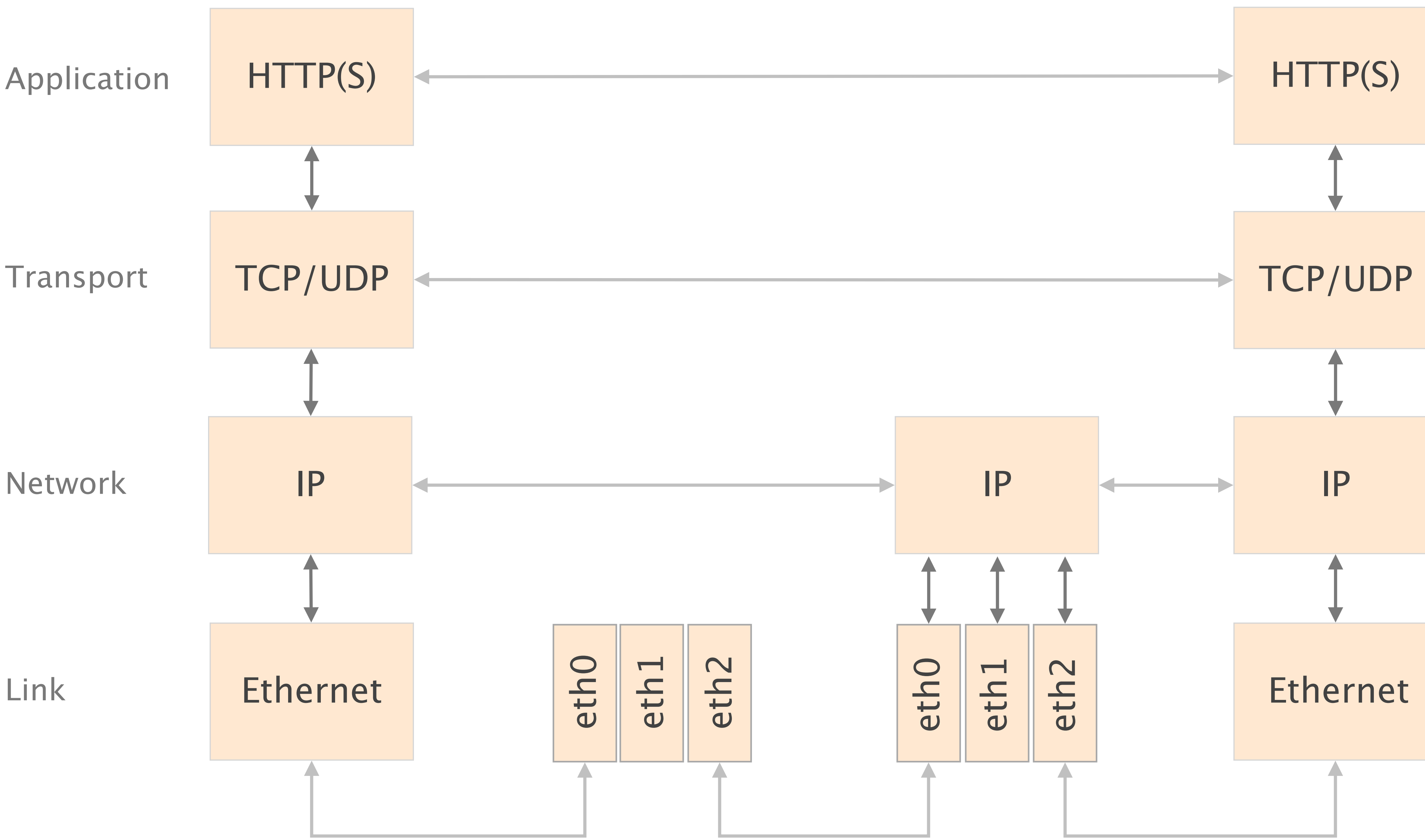

your laptop
Header
Message
Application
HTTP(S)
HA
GET google.com
Transport
TCP/UDP
Network
IP
Link
Ethernet


Header
Message
Application
HTTP(S)
HA
GET google.com
Transport
TCP/UDP
HT
HA
GET google.com
Network
IP
Link
Ethernet

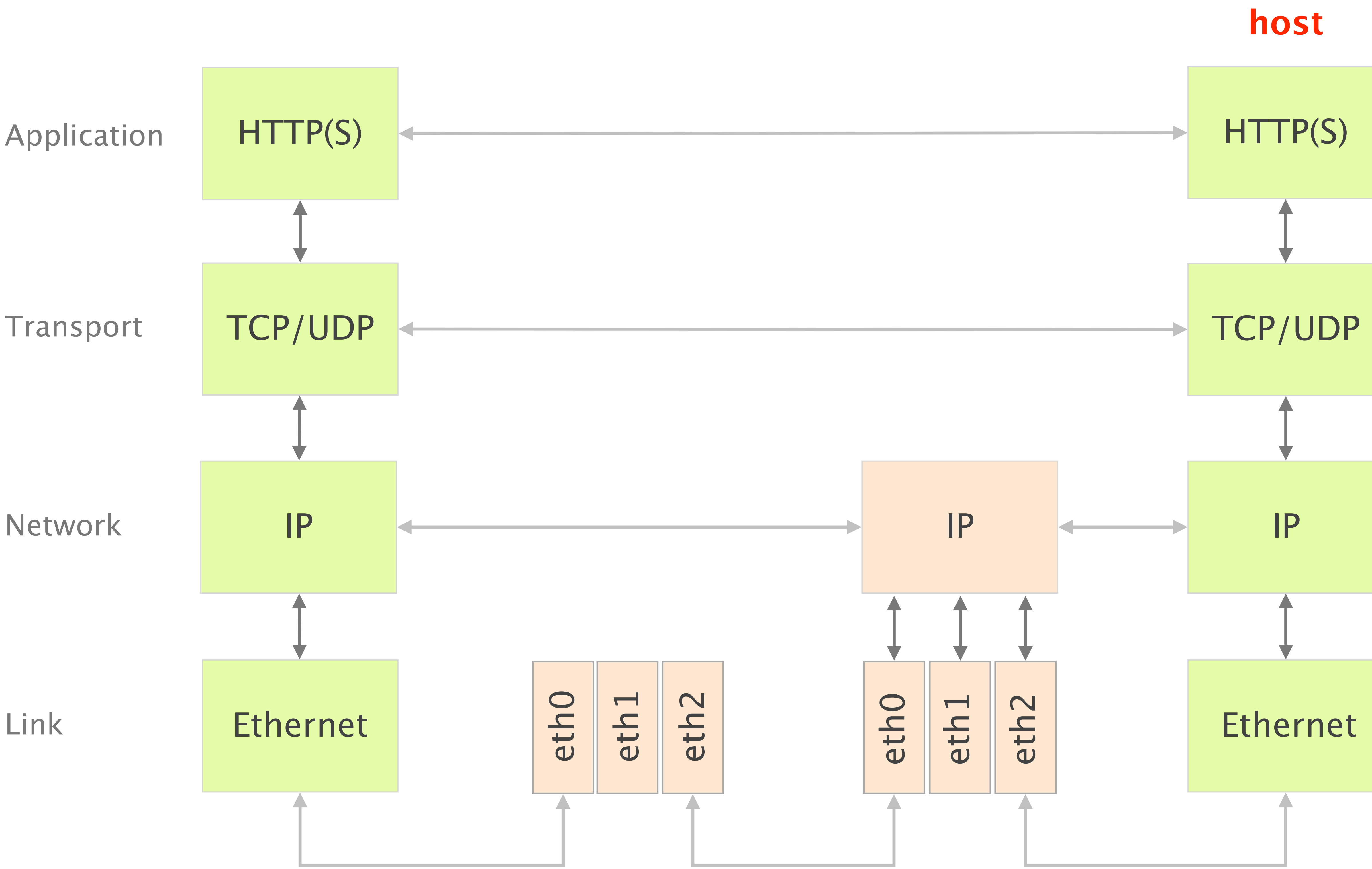

Header
Message
Application
HTTP(S)
HA
GET google.com
Transport
TCP/UDP
HT
HA
GET google.com
Network
IP
HN
HT
HA
GET google.com
Link
Ethernet


Header
Message
Application
HTTP(S)
HA
GET google.com
Transport
TCP/UDP
HT
HA
GET google.com
Network
IP
HN
HT
HA
GET google.com
Link
Ethernet
HE
HN
HT
HA
GET google.com

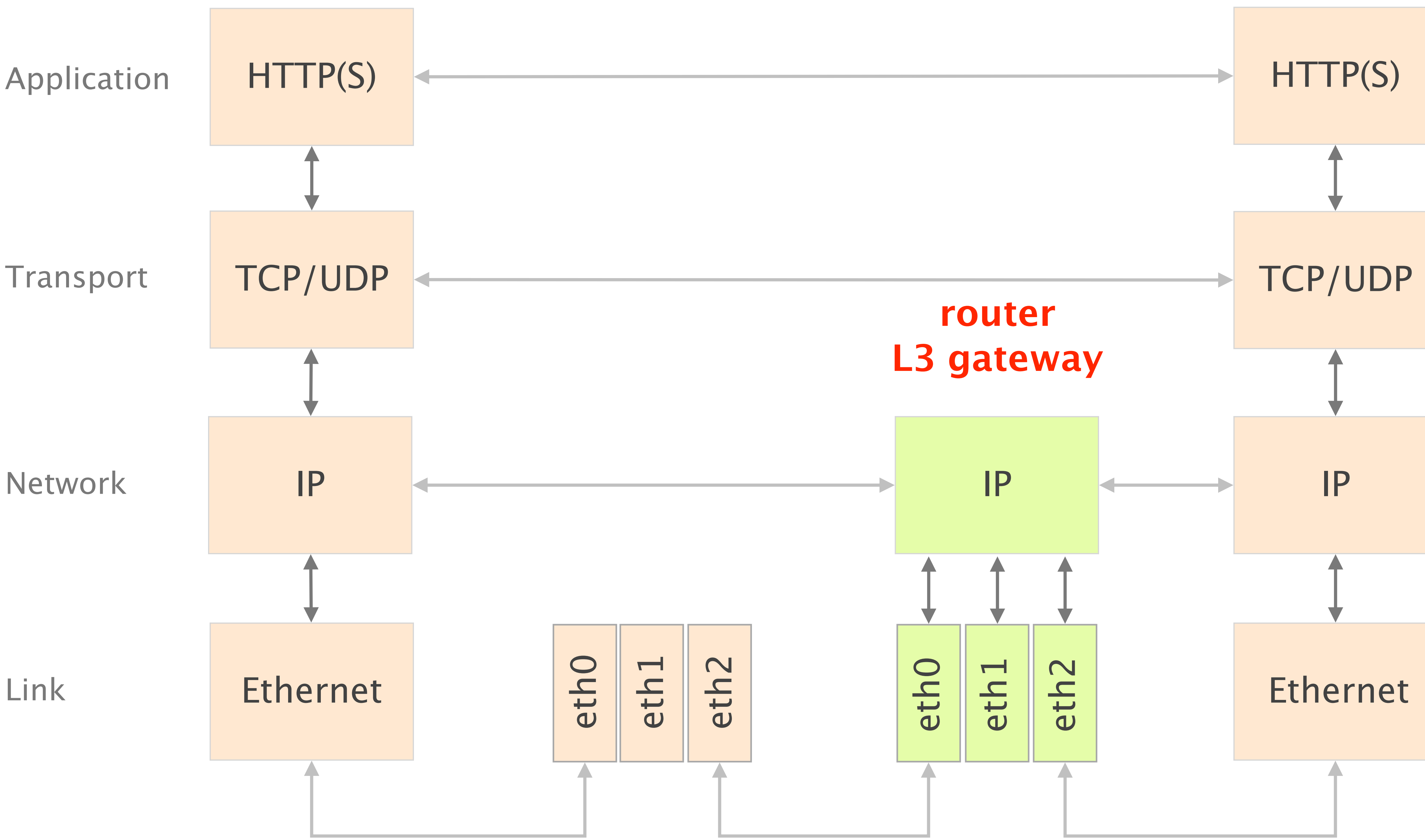
In practice, layers are distributed on every network device



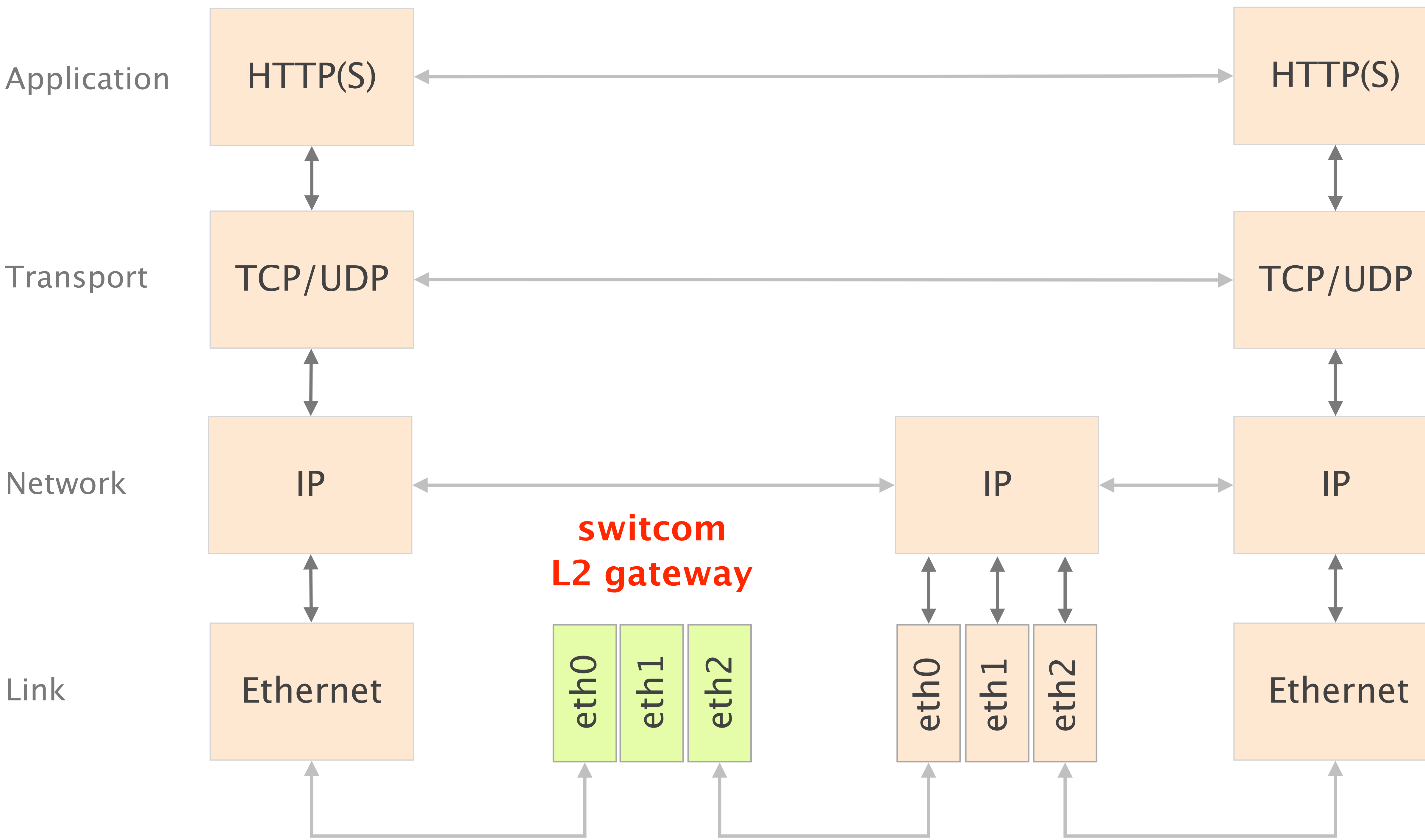
Since when bits arrive they must make it to the application, all the layers exist on a host



Routers act as L3 gateway
as sucom they implement L2 and L3



Switcomes act as L2 gateway
as sucom they only implement L2



Let’s see how it looks like in practice

on a host, using Wireshark https://www.wireshark.org

Communication Networks

Part 1: General overview

What is a network made of?

How is it shared?

How is it organized?

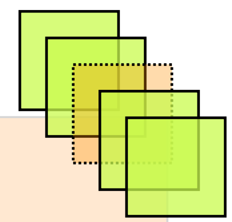
How does communication happen?

#5 How do we characterize it?

A network *connection* is characterized by its delay, loss rate and throughput

delay

loss



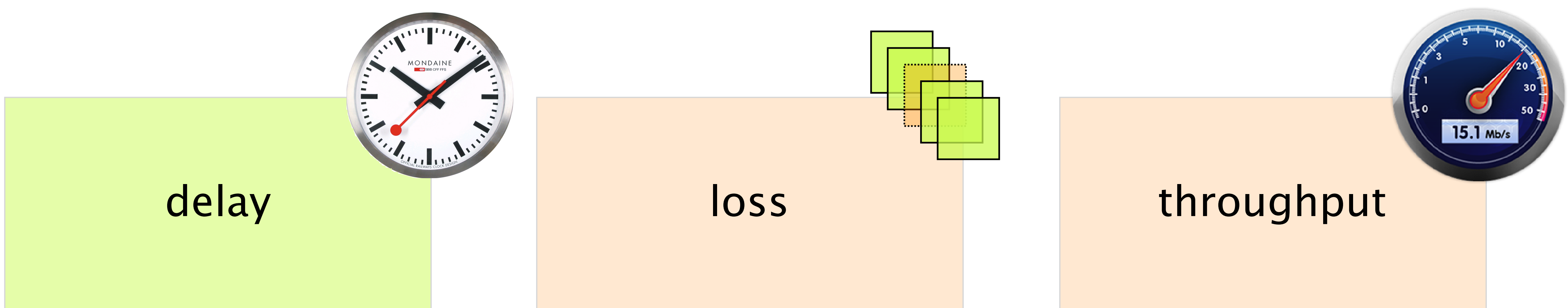
throughput

How long does it take for a packet to reach the destination

What fraction of packets sent to a destination are dropped?

At what rate is the destination receiving data from the source?

A network *connection* is characterized by its delay, loss rate and throughput

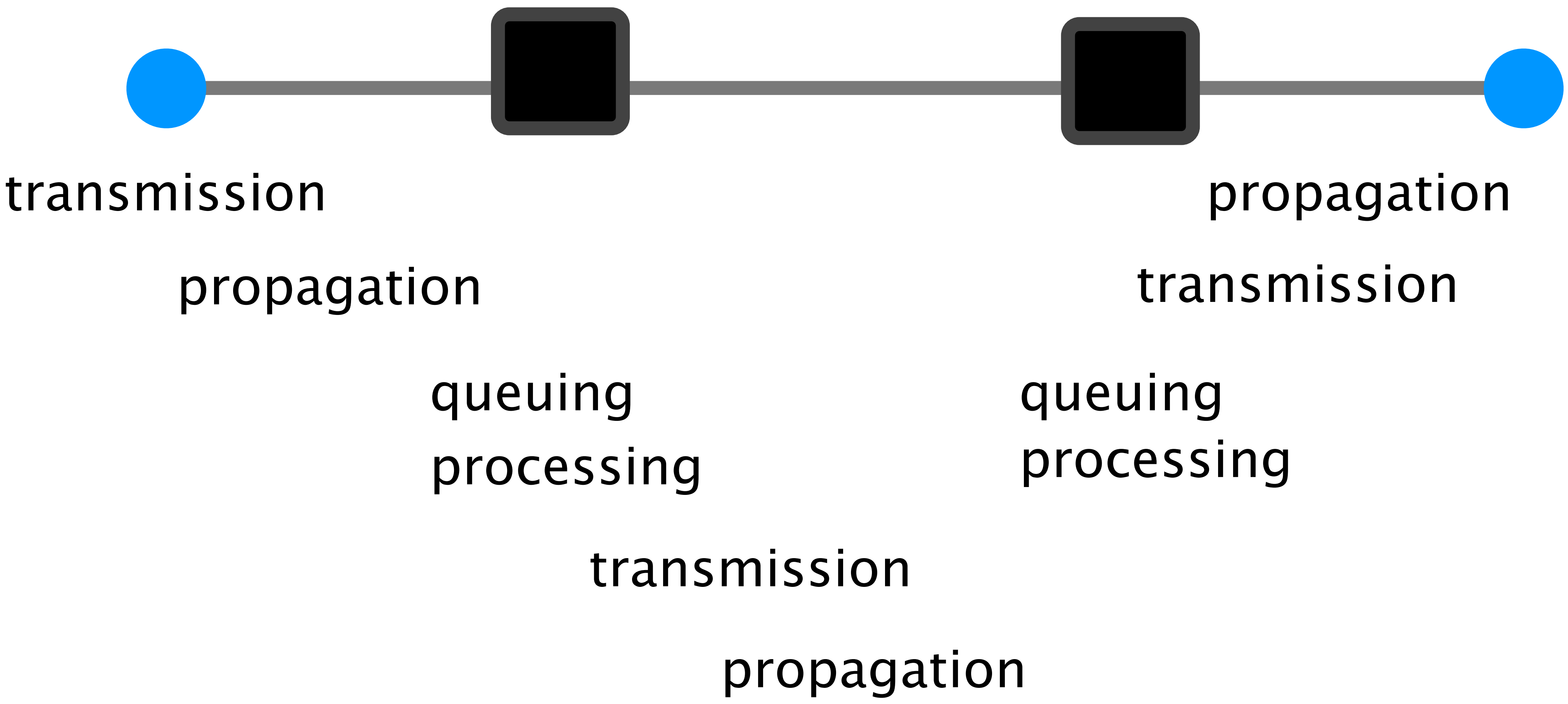


Each packet suffers from several types of delays at *each node* along the path

	transmission	delay	due to link properties
⊕	propagation	delay	
⊕	processing	delay	due to traffic mix & switch internals
⊕	queuing	delay	
=	total	delay	

The main culprits for the overall delay are the transmission, propagation and queuing delays

	transmission	delay	
⊕	propagation	delay	
⊕	processing	delay	*tend to be tiny*
⊕	queuing	delay	
=	total	delay	


transmission
propagation
queuing
processing
transmission
propagation
propagation
transmission
queuing
processing

The transmission delay is the amount of time required to push all of the bits onto the link

$$\text{Transmission delay [sec]} = \frac{\text{packet size [\#bits]}}{\text{link bandwidth [\#bits/sec]}}$$

Example

$$\frac{1000 \text{ bits}}{100 \text{ Gbps}} \quad 10 \text{ ns}$$

The propagation delay is the amount of time required for a bit to travel to the end of the link

$$\text{Propagation delay [sec]} = \frac{\text{link length [m]}}{\text{propagation speed [m/sec]}}$$

(fraction of speed of light)

Example

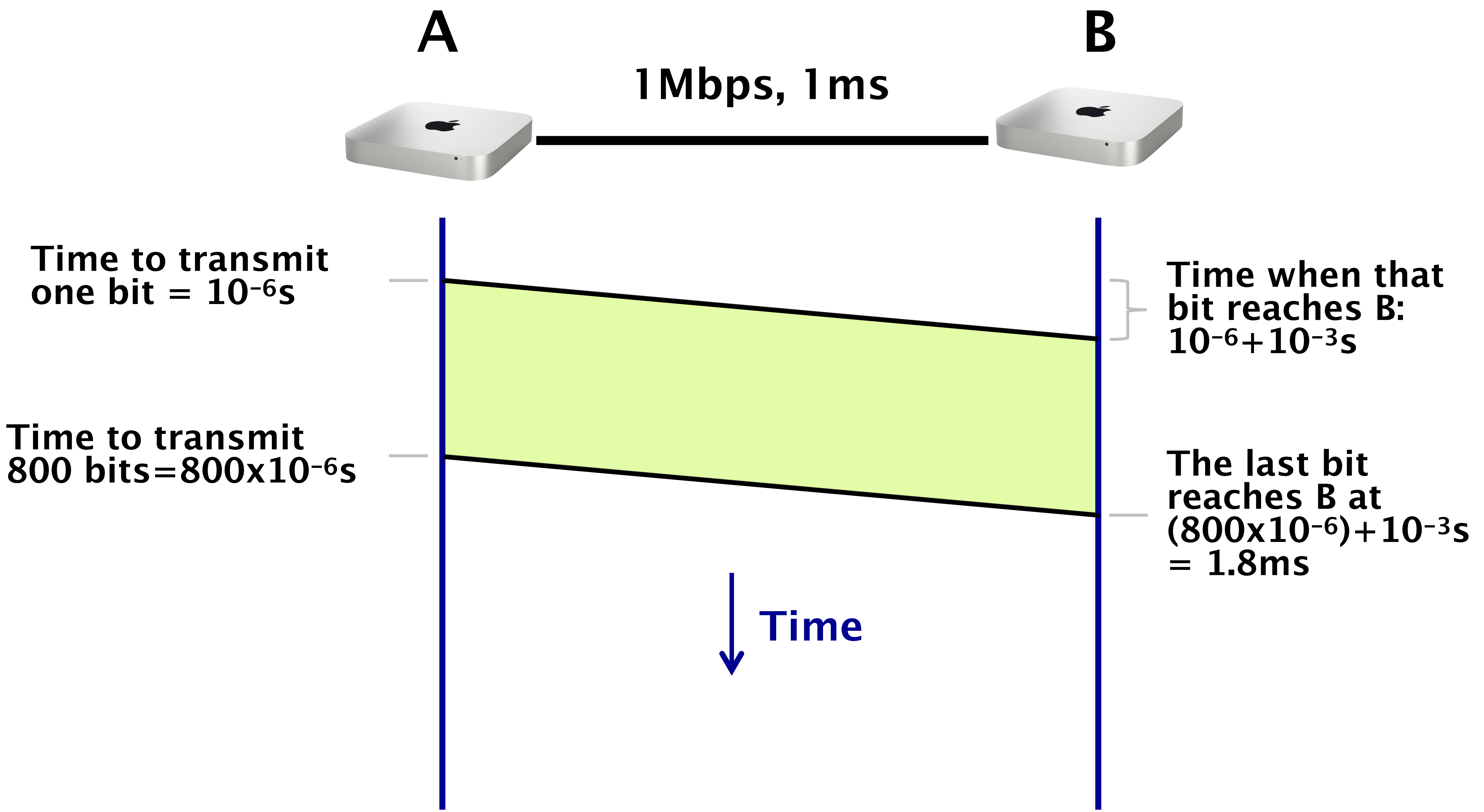
$$\frac{30\,000 \text{ m}}{2\times10^{8} \text{ m/sec}} \quad 150\ \mu\text{sec}$$

(speed of light in fiber)

How long does it take for a packet to travel from A to B?

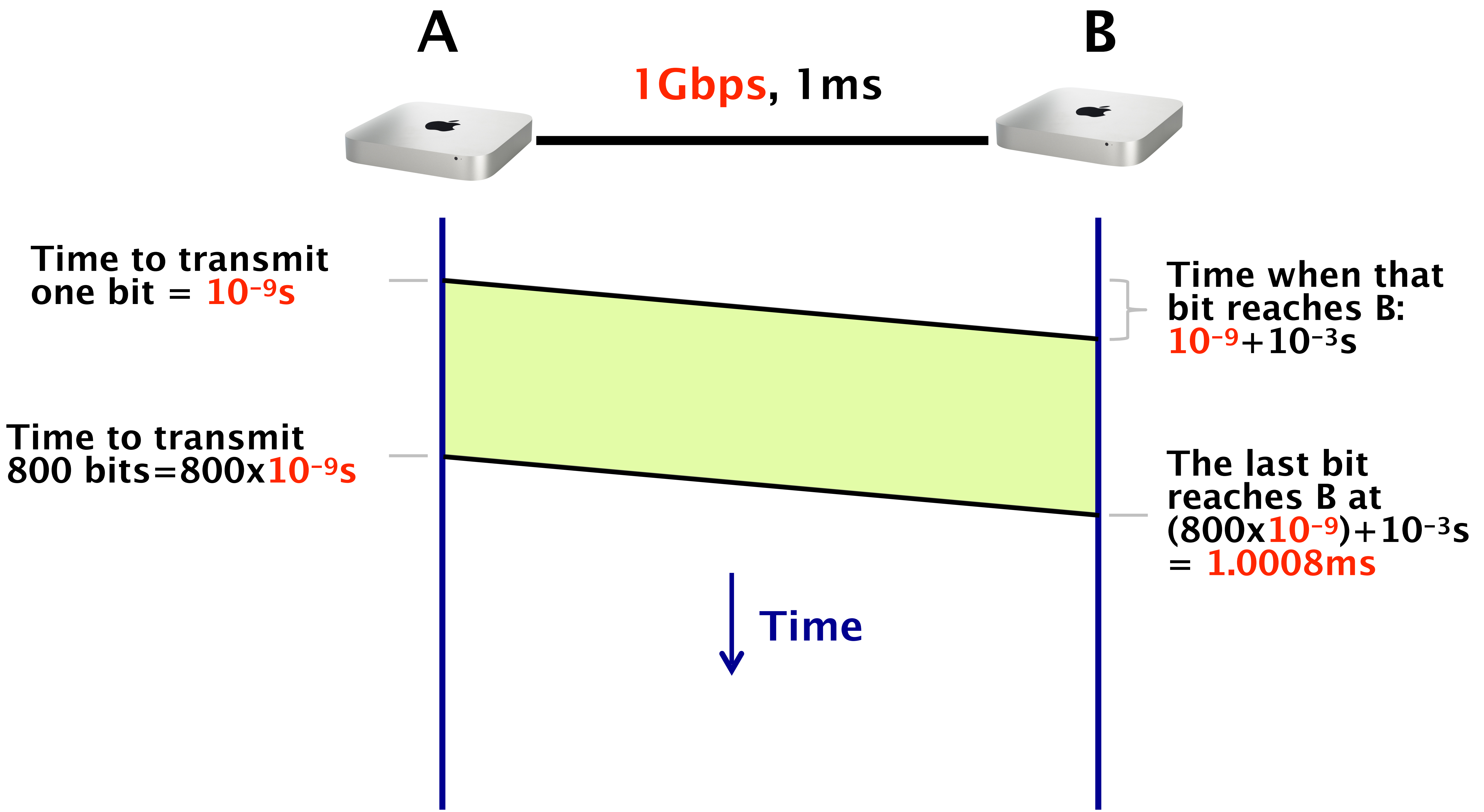
(not considering queuing for now)

How long does it take to exchange 100 Bytes packet?

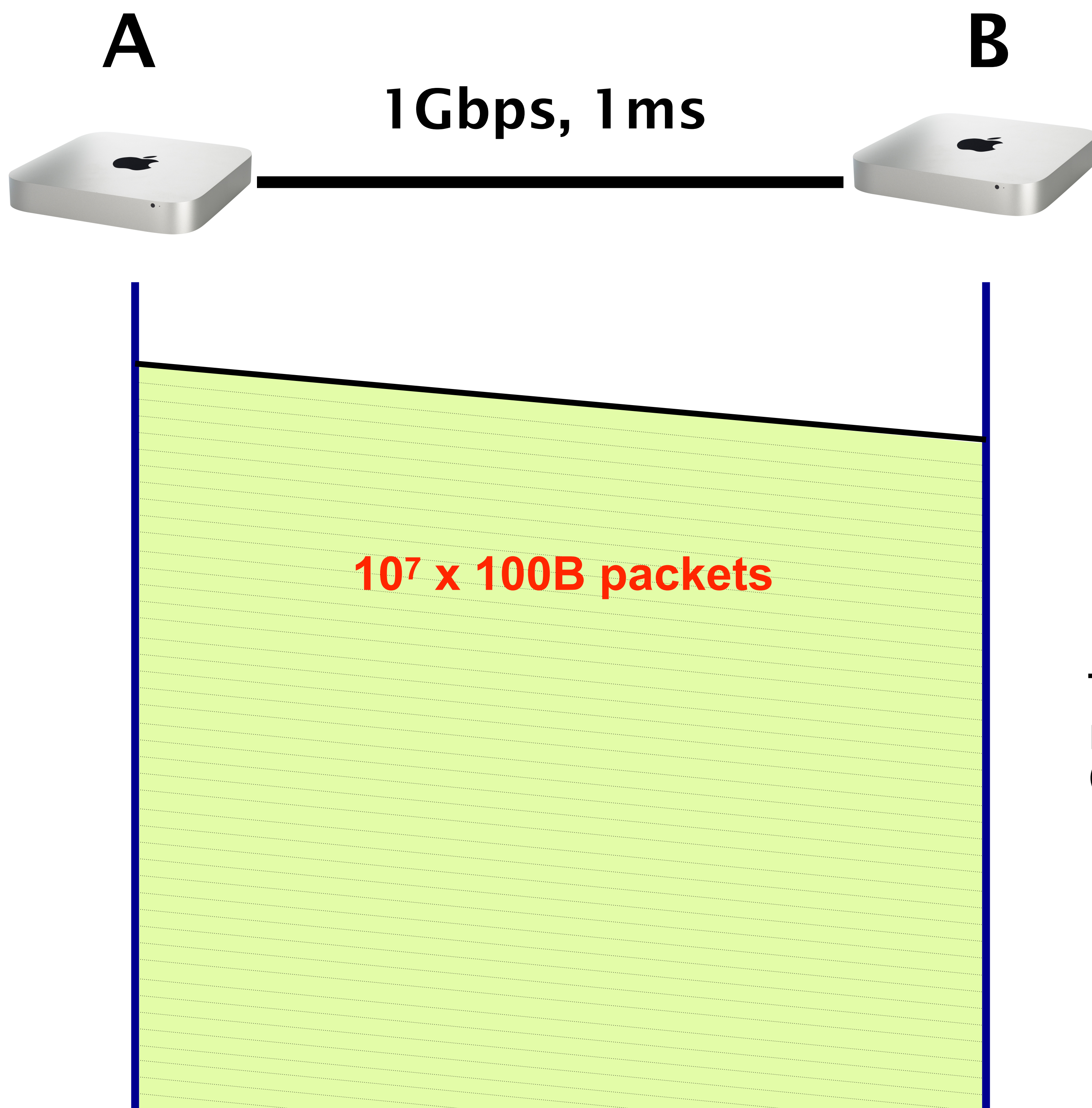


If we have a 1 Gbps link,

the total time decreases to 1.0008ms



If we now exchange a 1GB file
split in 100B packets



The last bit reaches B at
$(10^{7} \times 800 \times 10^{-9})$
$+10^{-3}$s
= 8001ms

Different transmission characteristics imply different tradeoffs in terms of which delay dominates

10^7x100B pkt	1Gbps link	transmission delay dominates
1x100B pkt	1Gbps link	propagation delay dominates
1x100B pkt	1Mbps link	both matter

In the Internet, we **can't know** in advance which one matters!

The queuing delay is the amount of time a packet waits in a buffer to be transmitted on a link

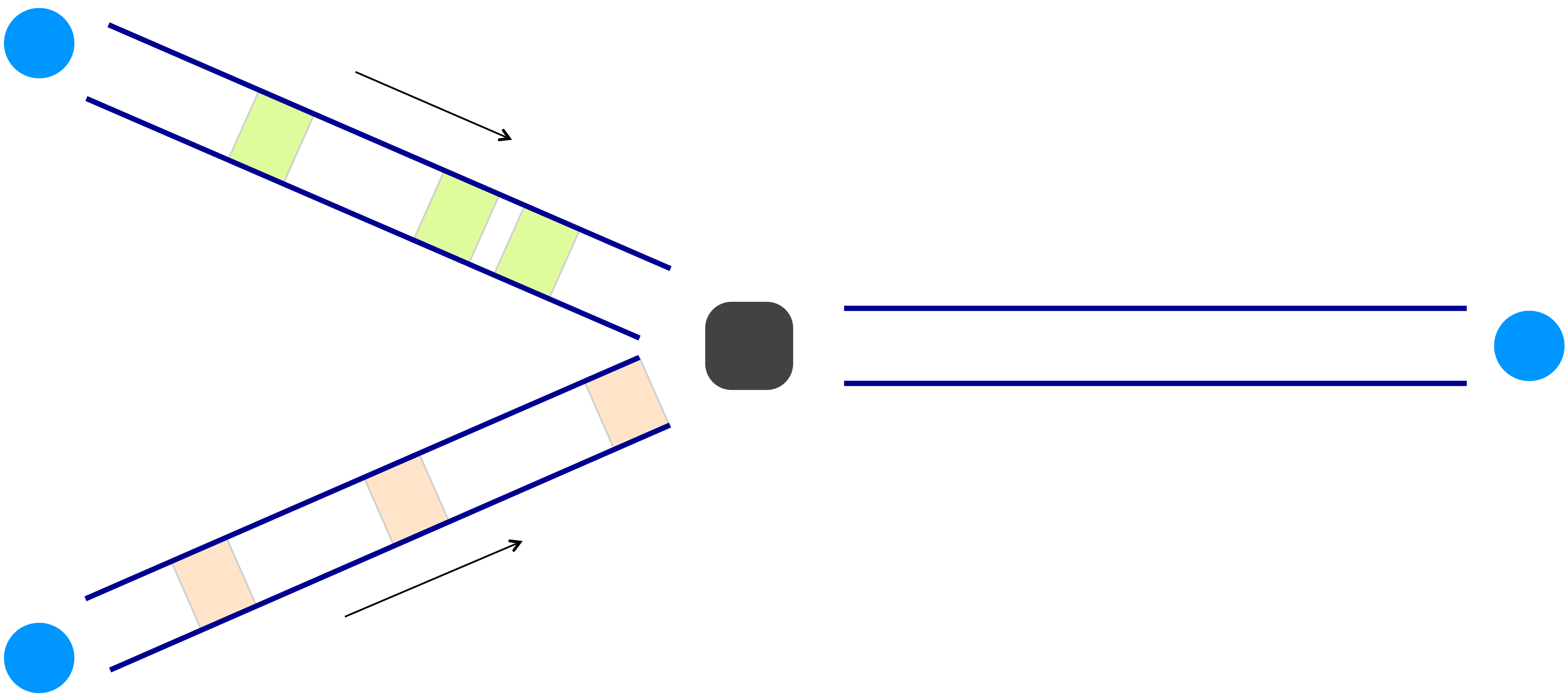
Queuing delay is the hardest to evaluate

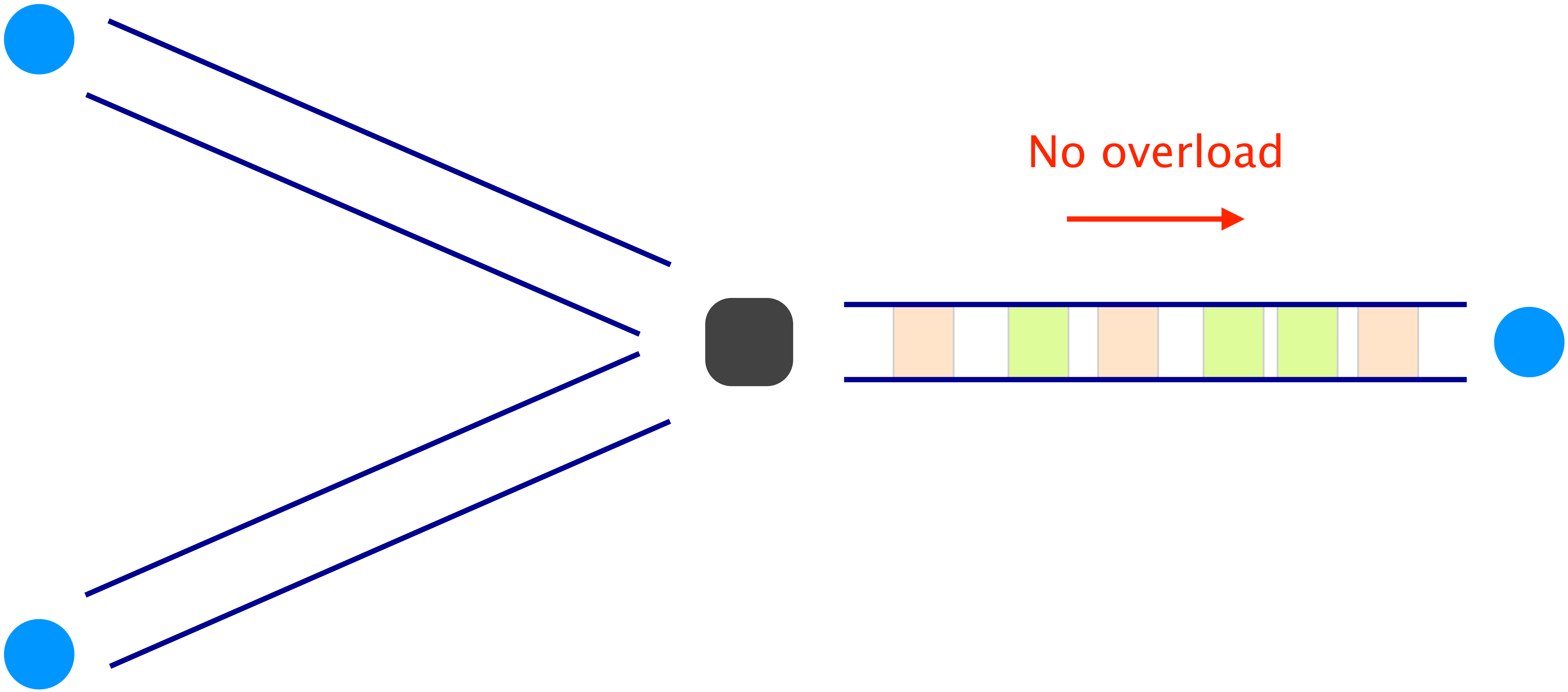
as it varies from packet to packet

It is characterized with statistical measures

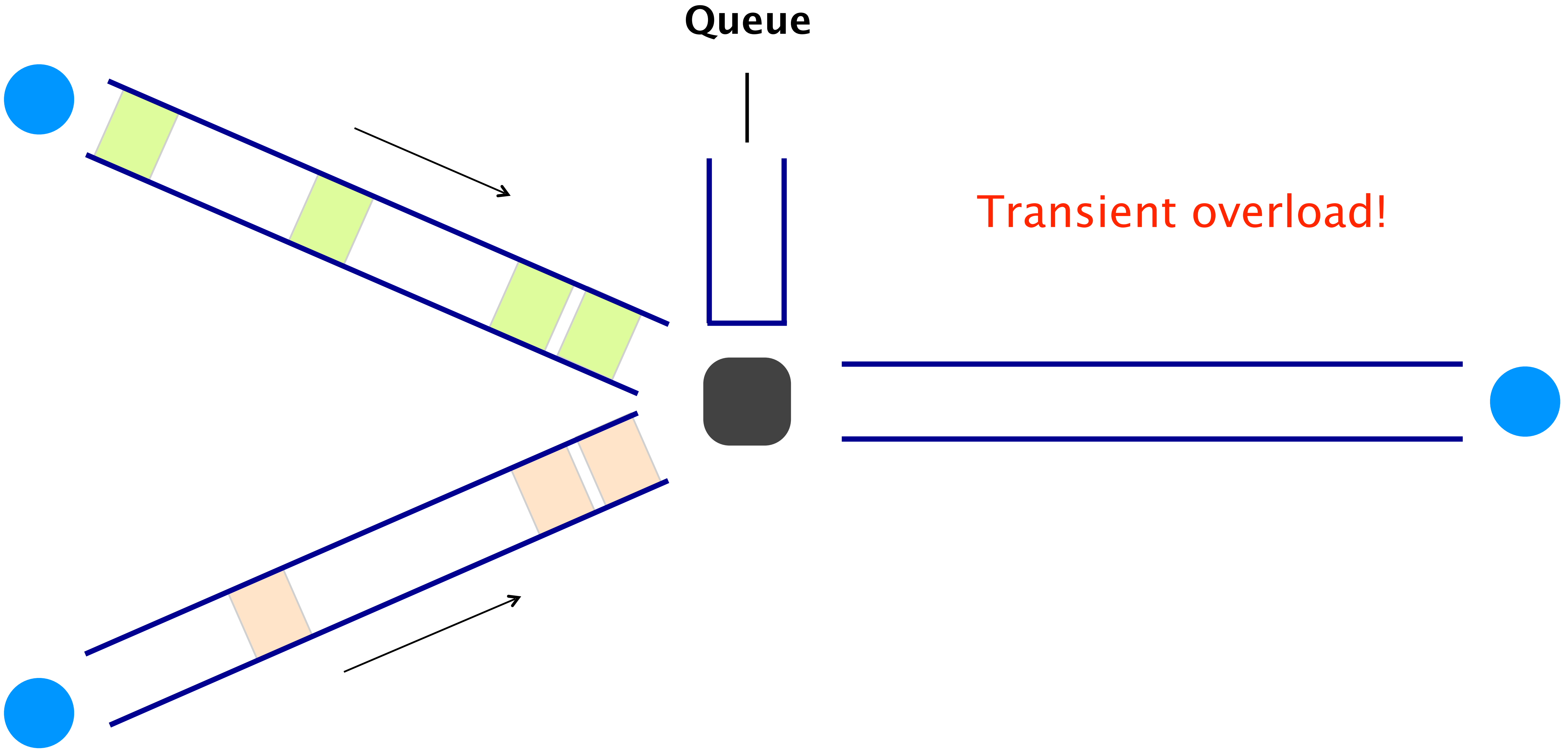
e.g., average delay & variance, probability of exceeding *x*

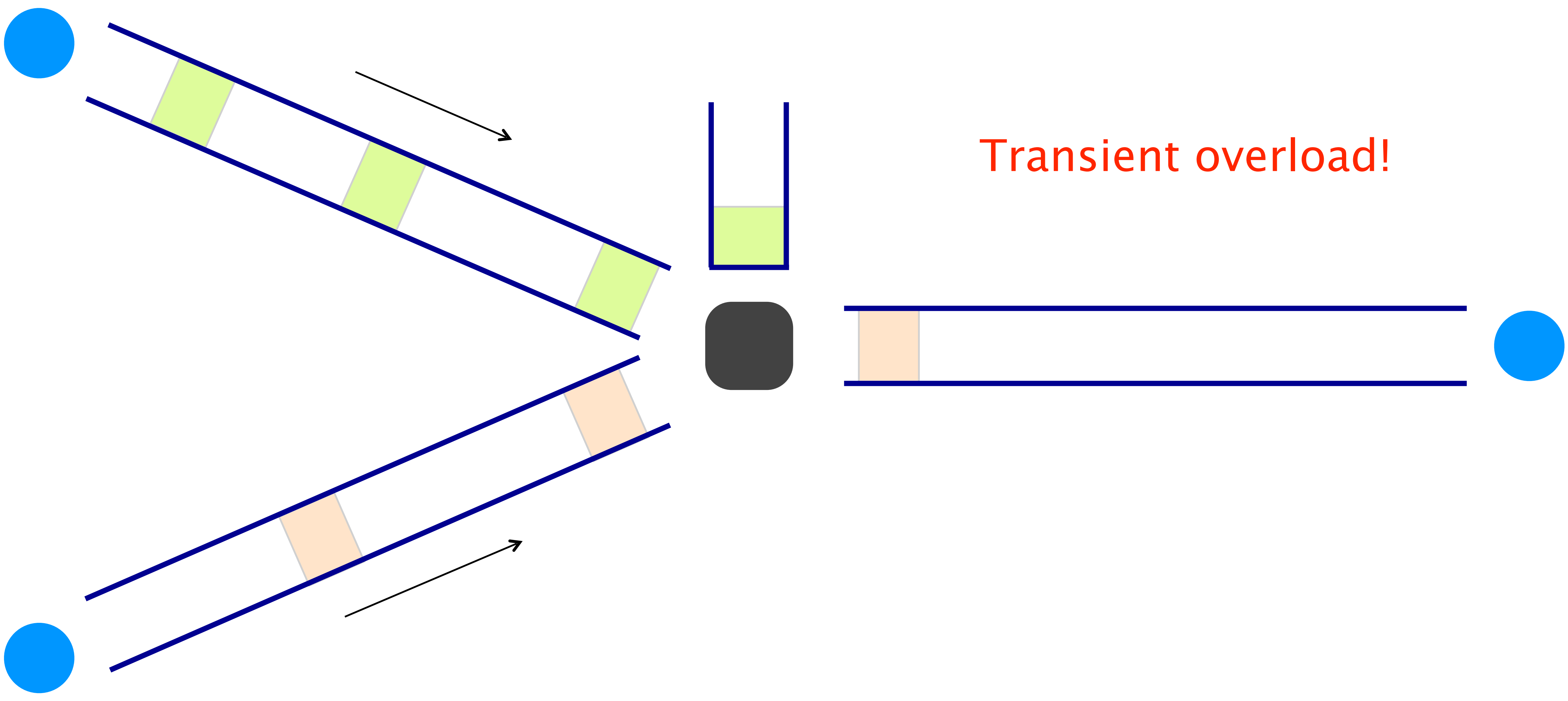
Queuing delay depends on the traffic pattern

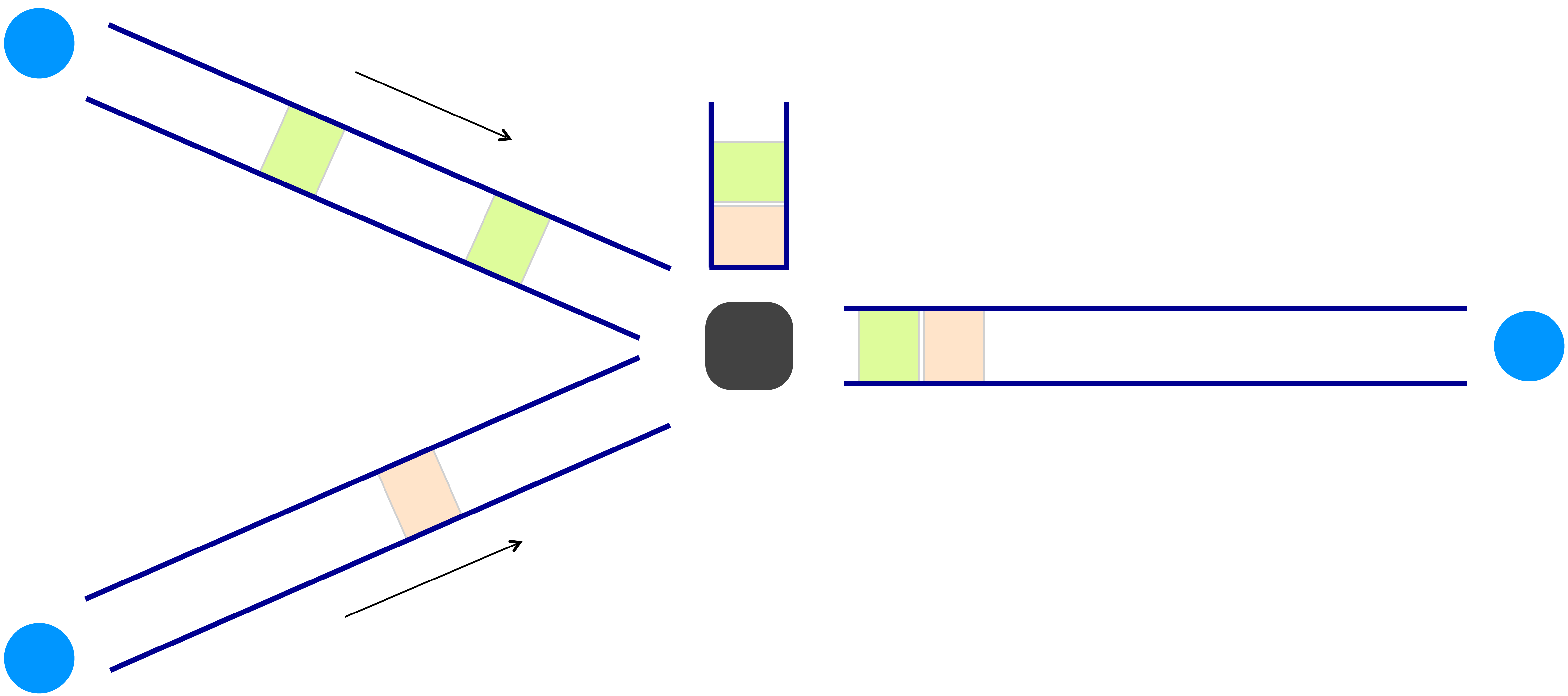


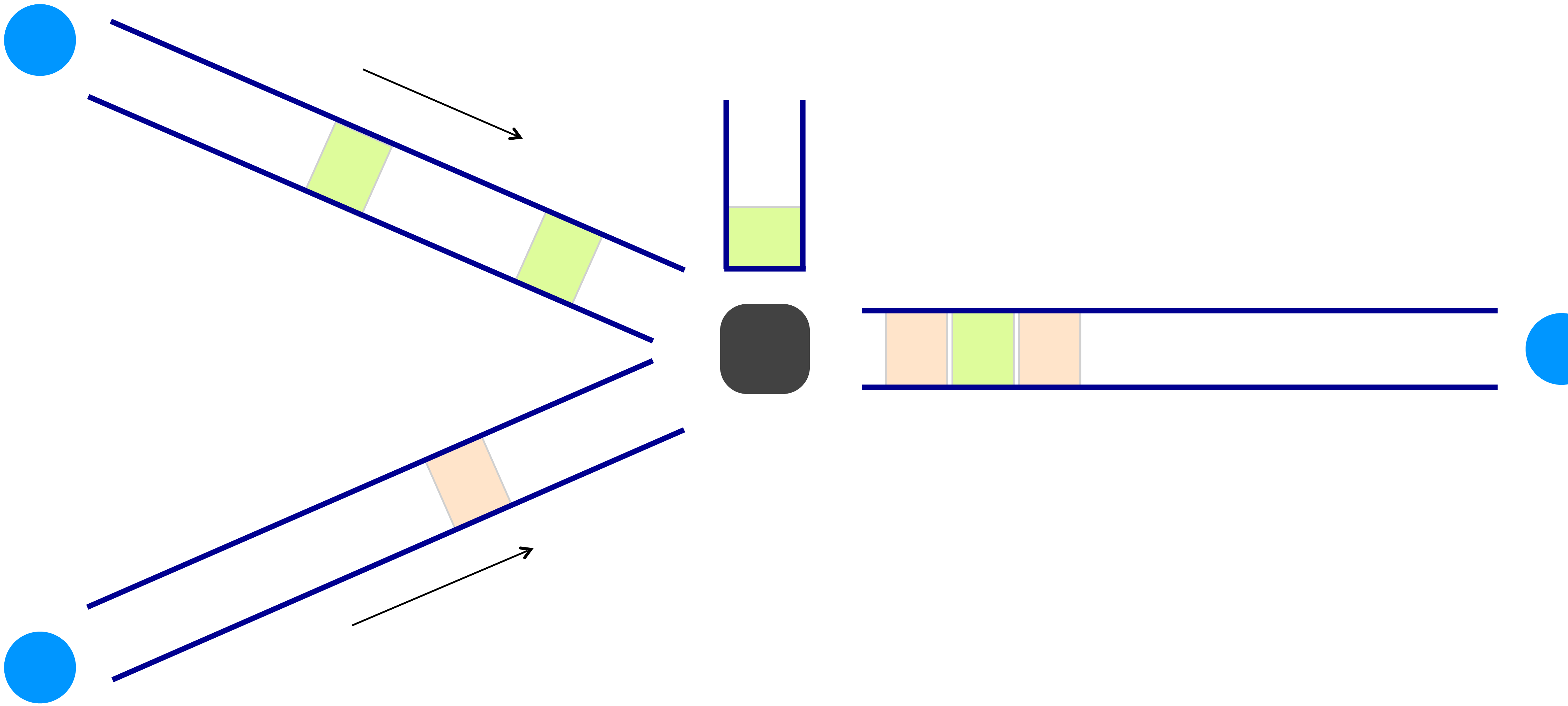

No overload

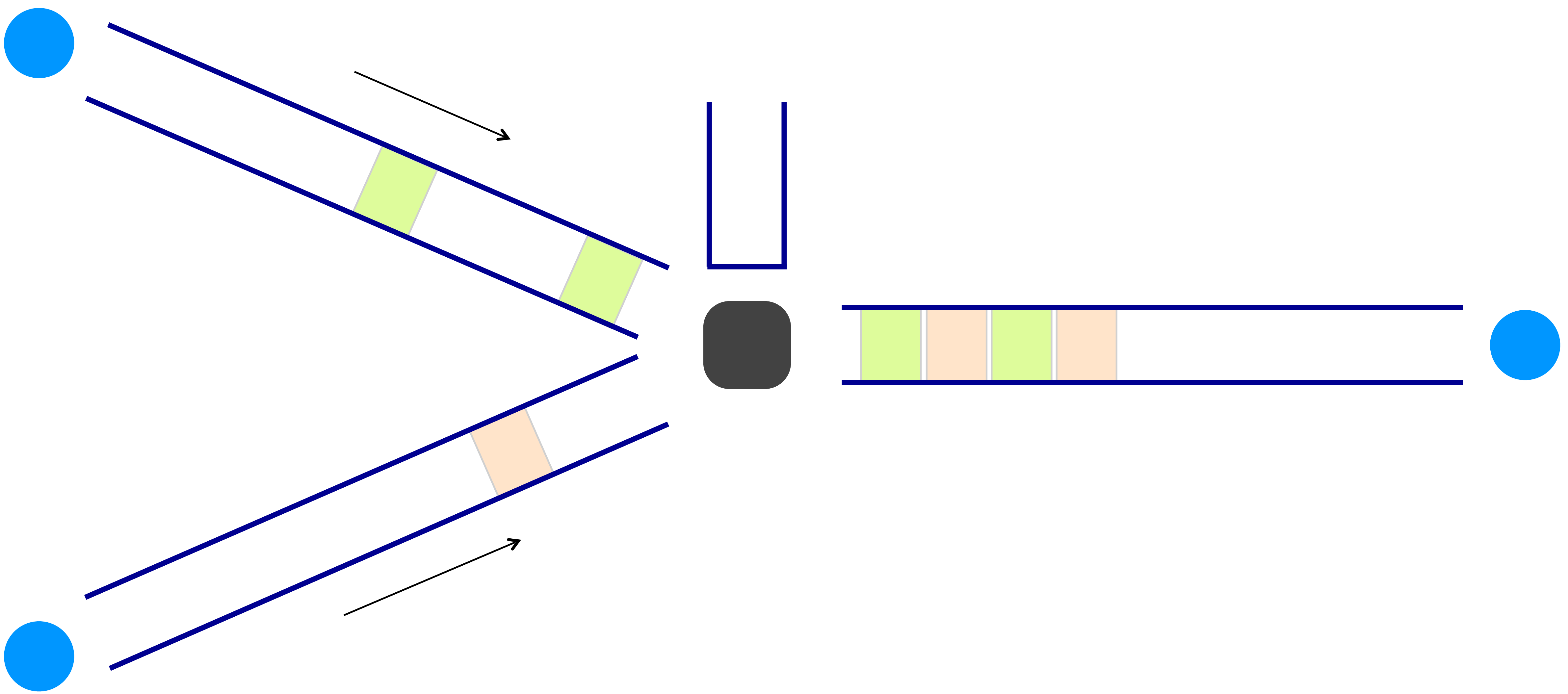
Queuing delay depends on the traffic pattern



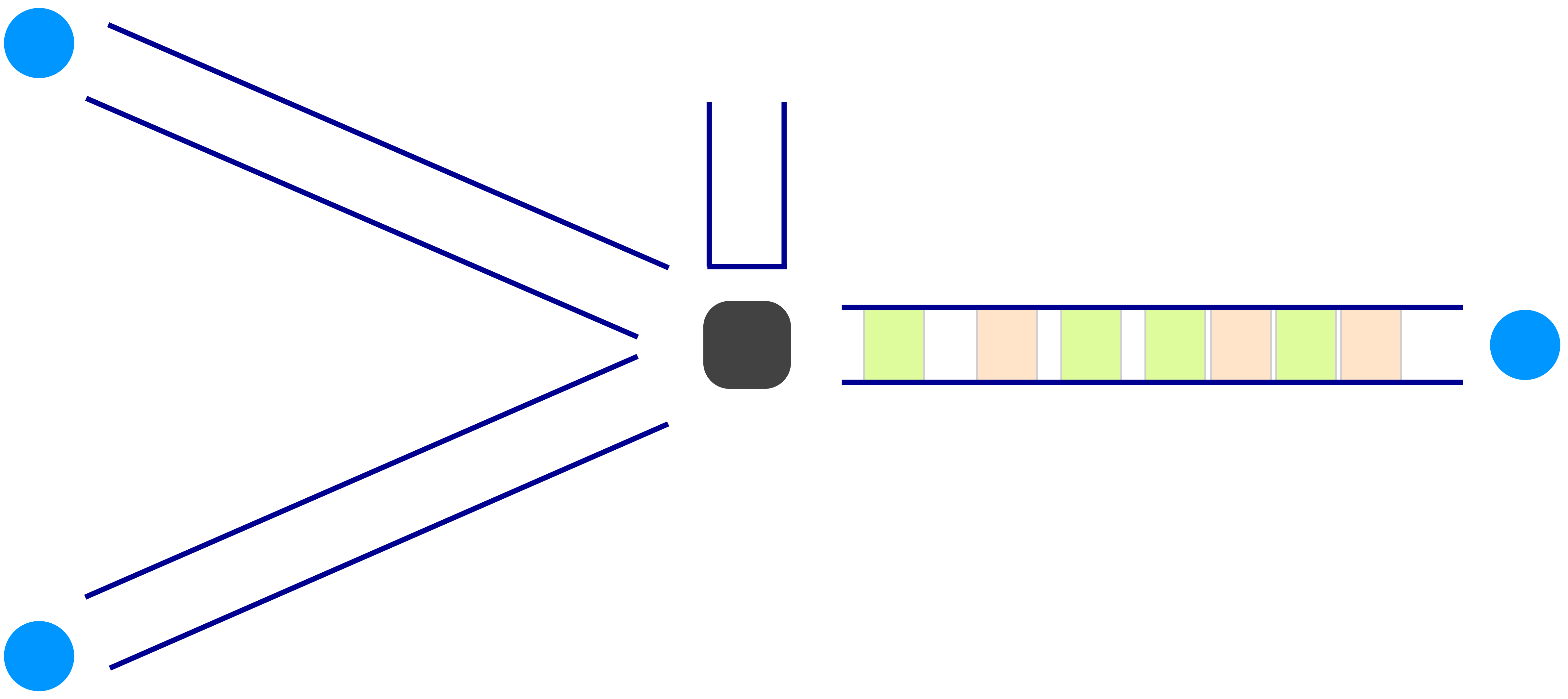

Transient overload!







Queues absorb transient bursts,
but introduce queueing delays



The time a packet has to sit in a buffer before being processed depends on the traffic pattern

Queueing delay depends on:

- arrival rate at the queue
- transmission rate of the outgoing link
- traffic burstiness

average packet arrival rate	a	[packet/sec]
transmission rate of outgoing link	R	[bit/sec]
fixed packets length	L	[bit]
average bits arrival rate	La	[bit/sec]
traffic intensity	La/R	

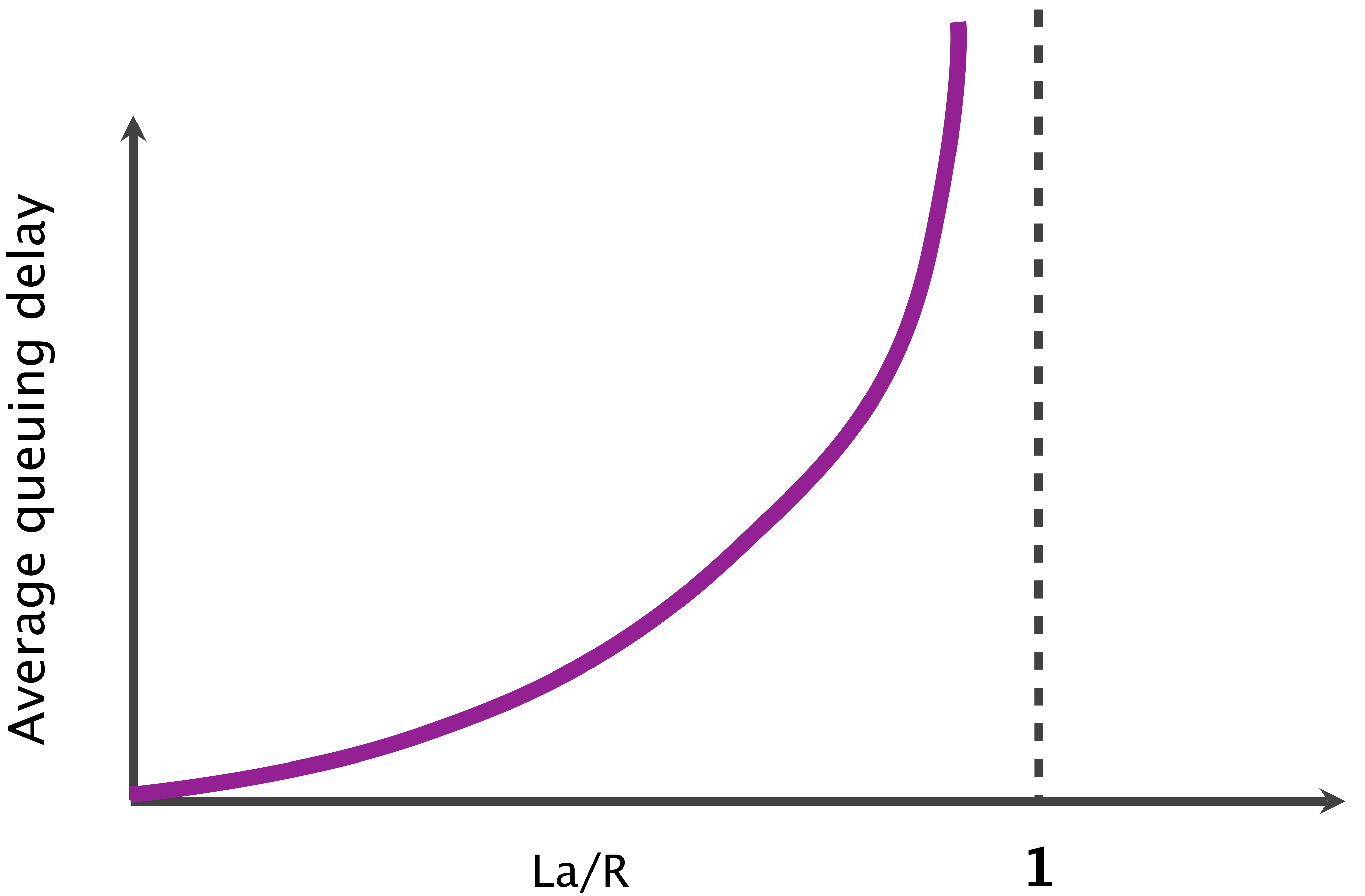
When the traffic intensity is >1, the queue will increase without bound, and so does the queuing delay

Golden rule

Design your queuing system,

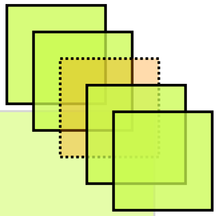
so that it operates far from that point

When the traffic intensity is <=1,
queueing delay depends on the burst size



A network *connection* is characterized by its delay, loss rate and throughput

delay

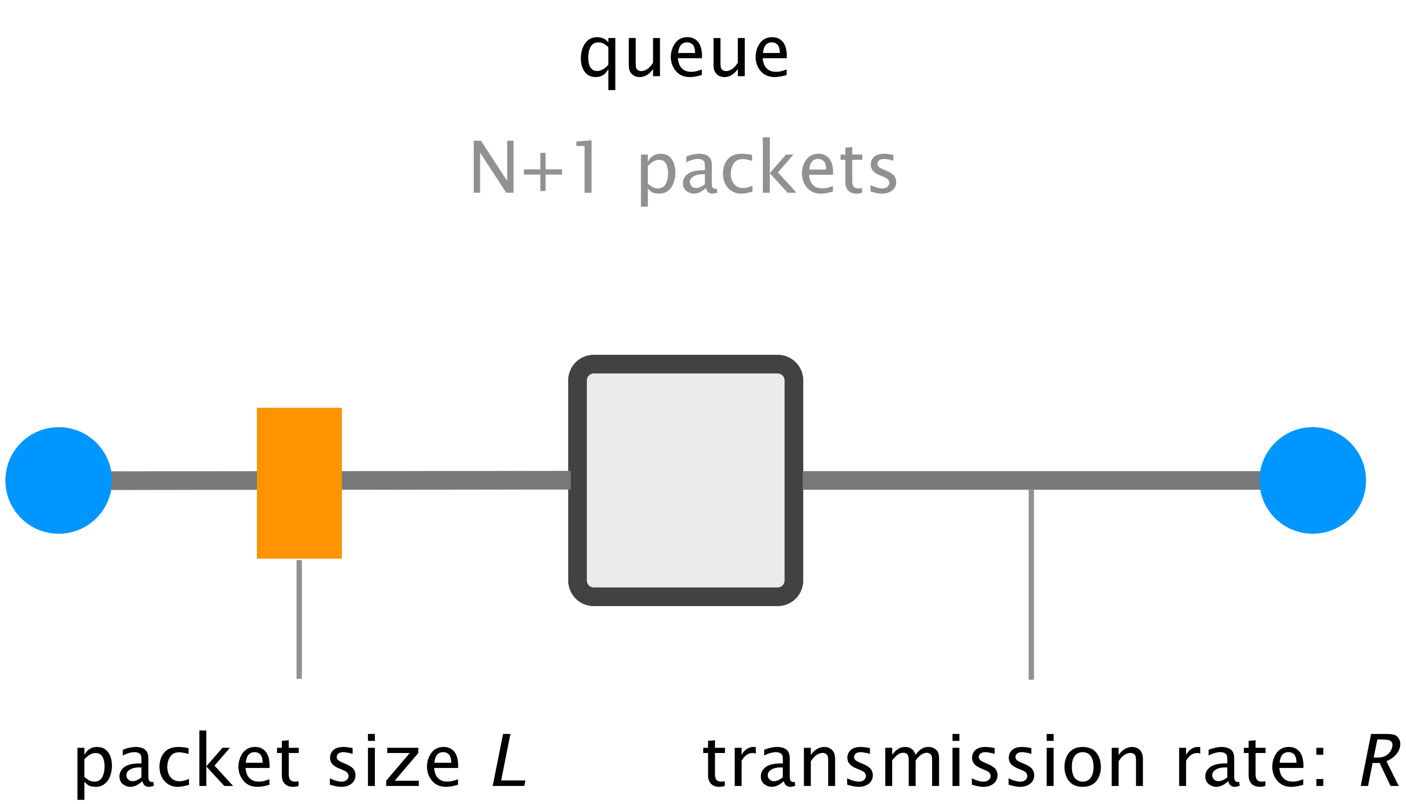


loss

throughput

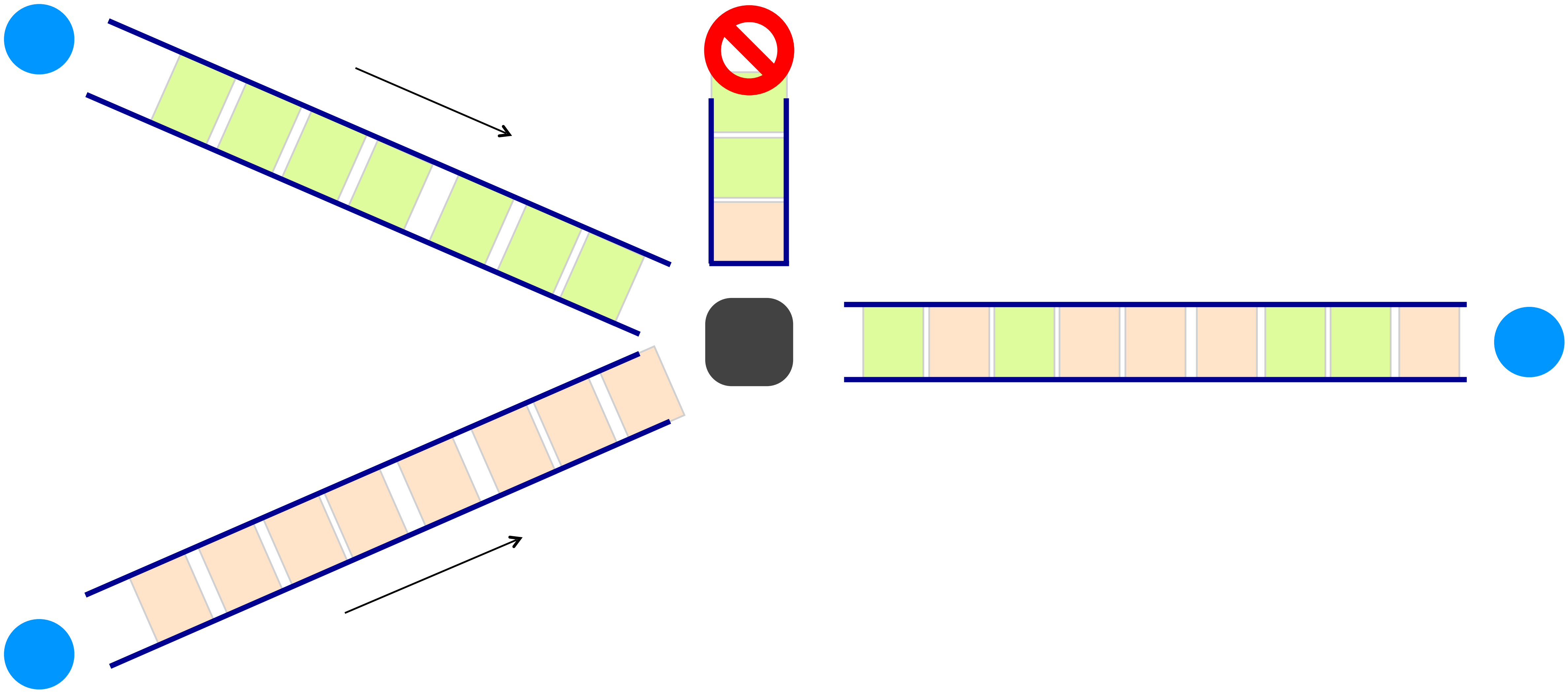
In practice, queues are not infinite.

There is an upper bound on queuing delay.

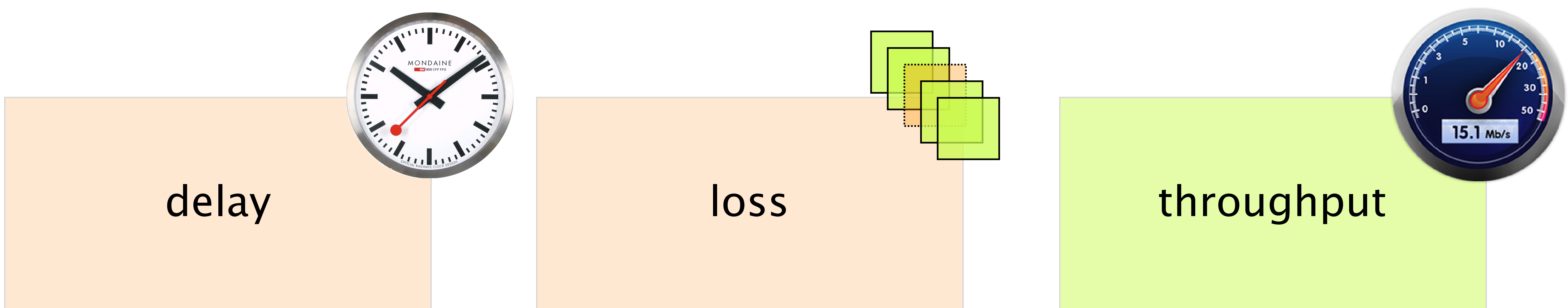


queuing delay upper bound: N*L/R

If the queue is persistently overloaded,
it will eventually drop packets (loss)



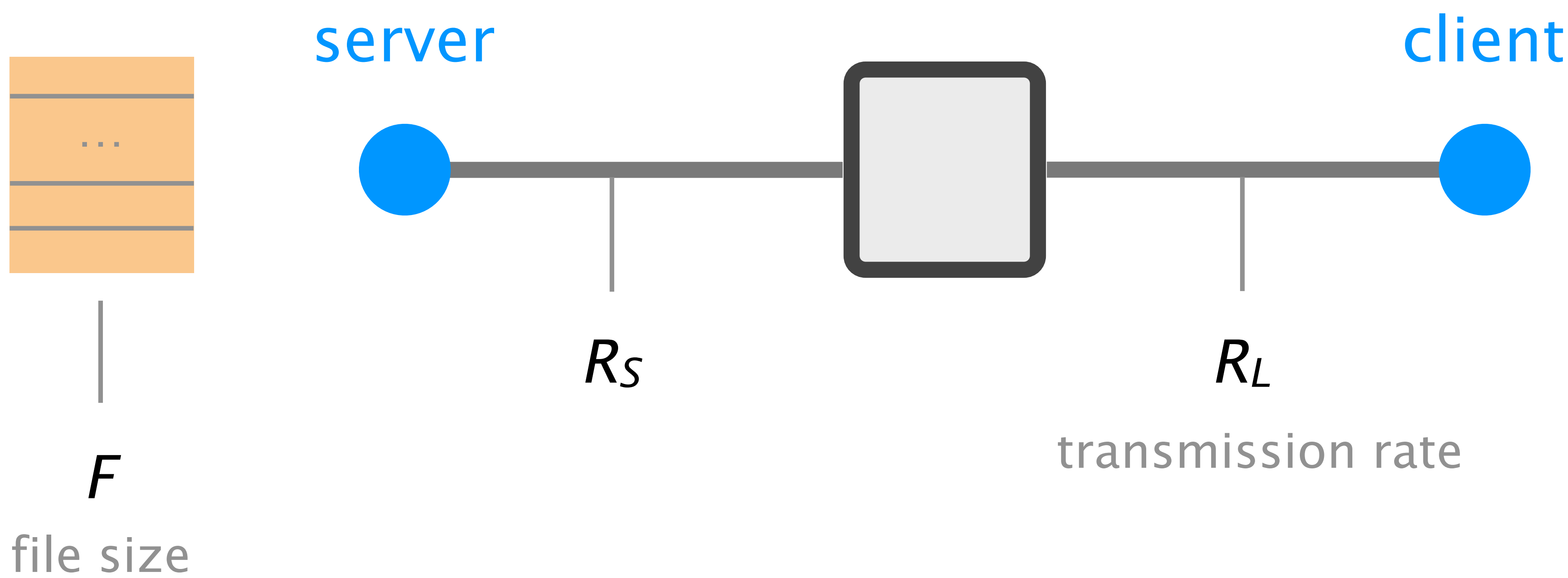
A network *connection* is characterized by its delay, loss rate and throughput



The throughput is the instantaneous rate at which a host receives data

$$\underset{[\#bits/sec]}{\text{Average throughput}} = \frac{\text{data size} \quad [\#bits]}{\text{transfer time} \quad [sec]}$$

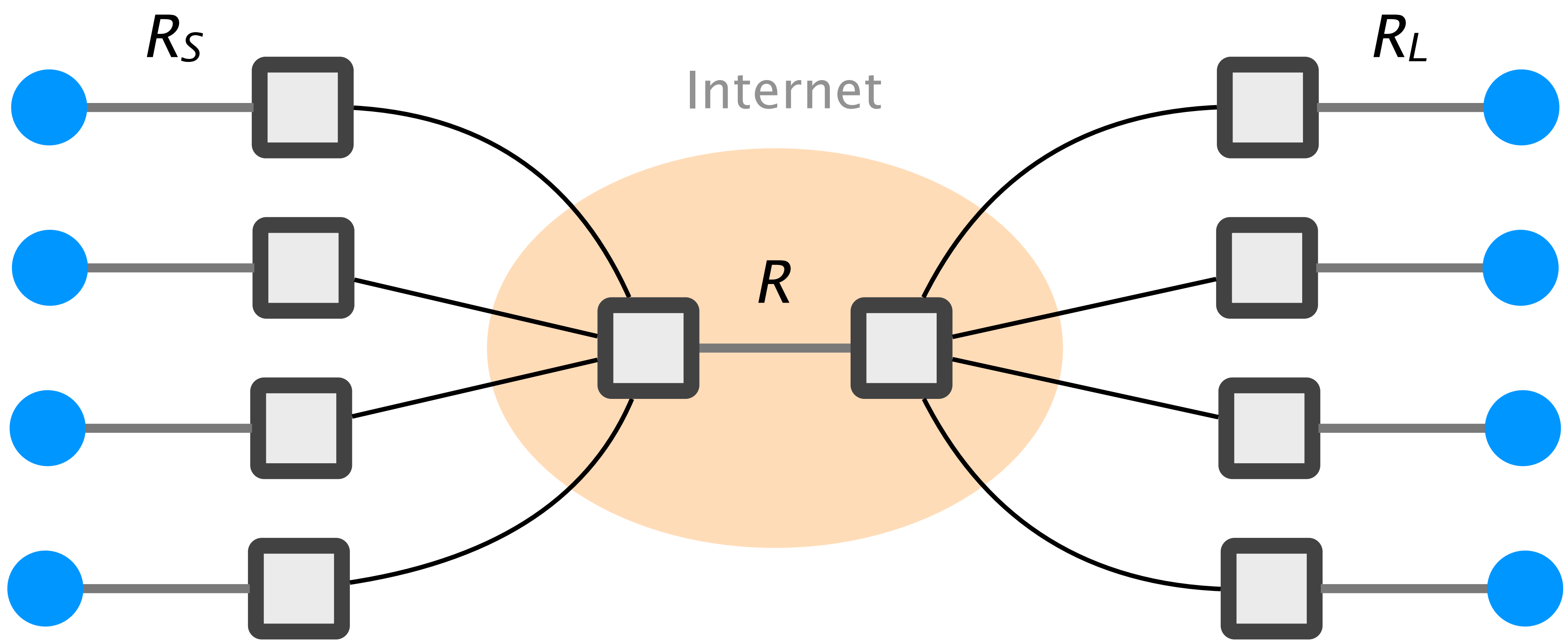
To compute throughput, one has to consider the bottleneck link



Average throughput $\quad \min(R_S, R_L)$

= transmission rate of the bottleneck link

To compute throughput, one has to consider the bottleneck link… **and the intervening traffic**

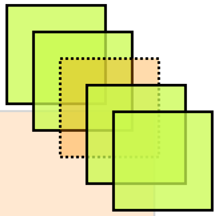


if $4*\min(R_S,R_L) > R$

the bottleneck is now in the core, providing each download R/4 of throughput

A network *connection* is characterized by its delay, loss rate and throughput

delay

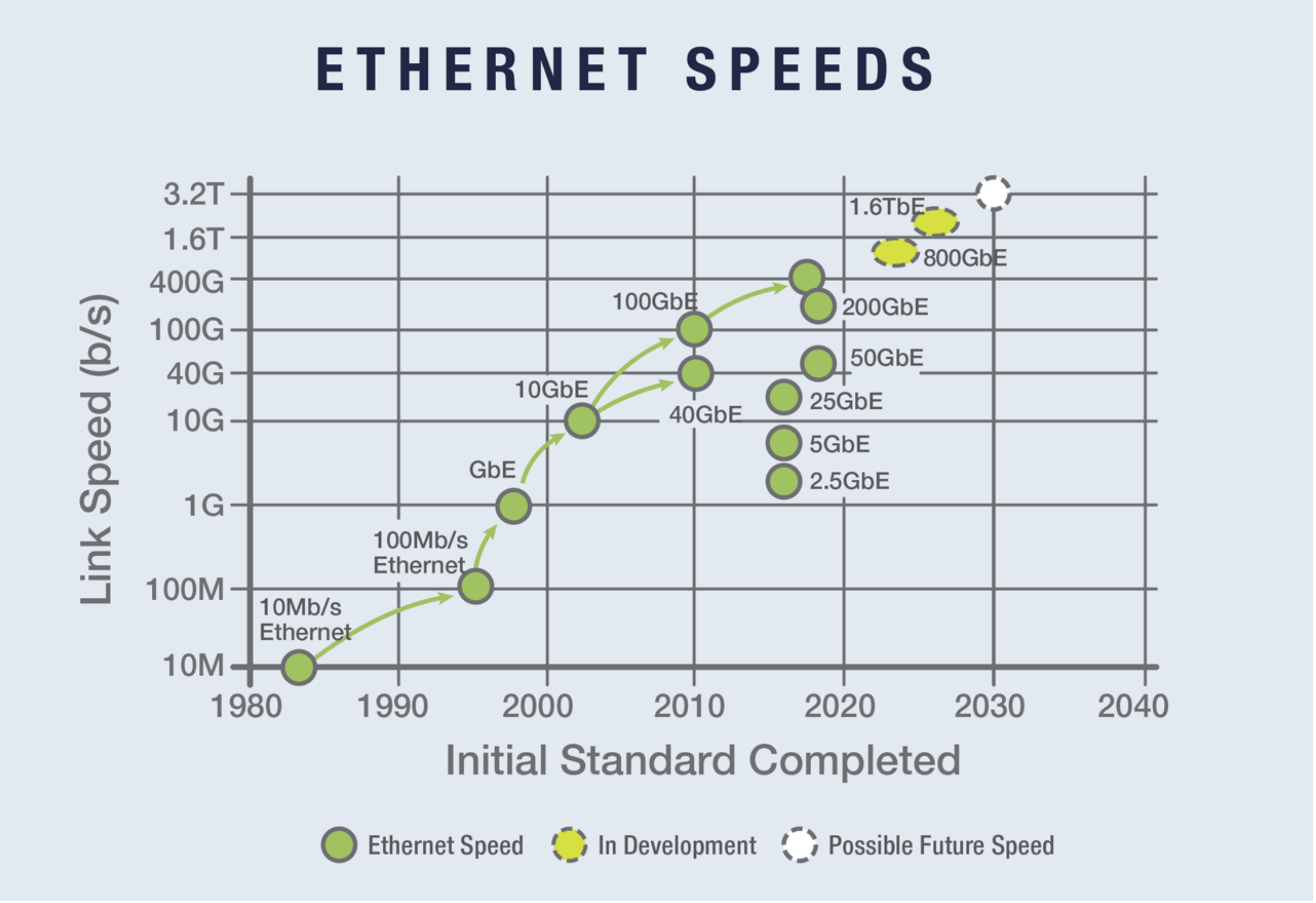


loss

throughput

As technology improves, throughput increase & delays are getting lower except for propagation

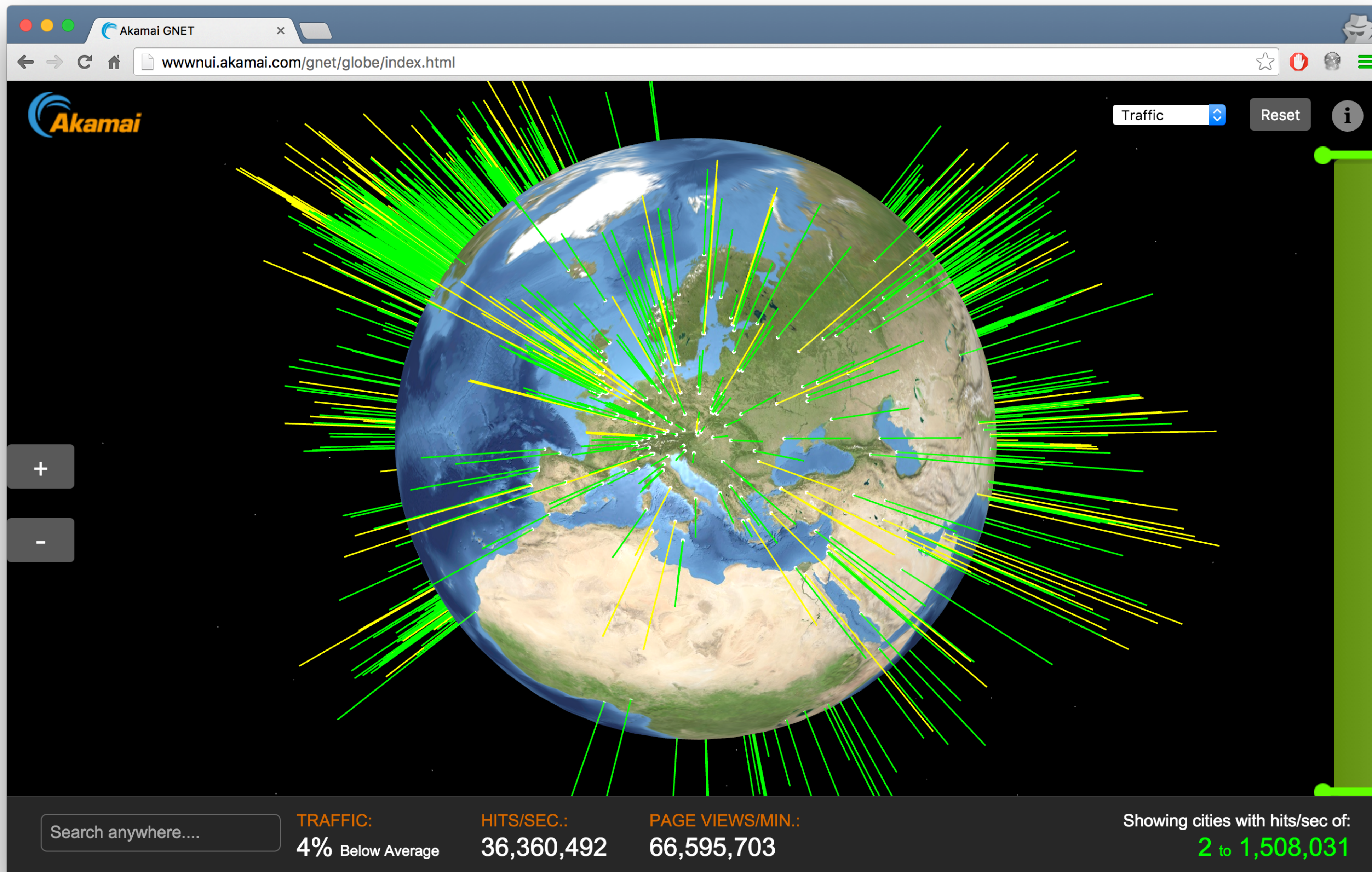
(speed of light)



source: Ethernet Alliance

Because of propagation delays,

Content Delivery Networks move content closer to you



Communication Networks

Part 1: General overview

What is a network made of?

How is it shared?

How is it organized?

How does communication happen?

How do we characterize it?

Computer Networks

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Maria Apostolaki

netsyn.princeton.edu/

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Materials from Laurent Vanbever, Scott Shenker & Jennifer Rexford