Computer Networks

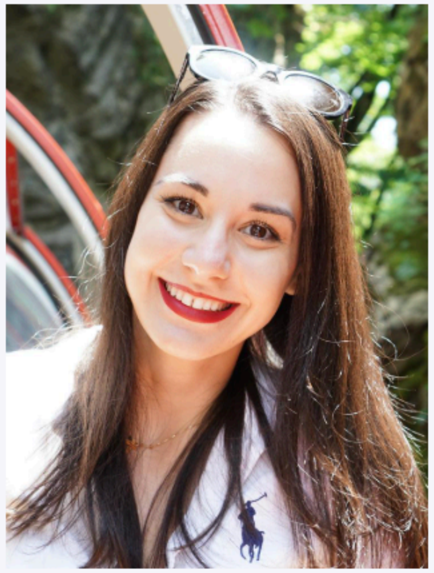
COS 461/ ECE 471

Maria Apostolaki

netsyn.princeton.edu/

Sep 2 2025

Materials from Laurent Vanbever, Scott Shenker & Jennifer Rexford



EMAIL

apostolaki@princeton.edu

OFFICE

C330 Engineering Quadrangle

Maria Apostolaki

Assistant Professor, Department of Electrical and Computer Engineering

Associated Faculty, Department of Computer Science

Associated Faculty, Center for Information Technology Policy

About

Maria Apostolaki joined Princeton University as an Assistant Professor of Electrical and Computer Engineering in August 2022. She is associated with the CS Department, CITP, DeCenter, and AI Lab. She is also a fellow at Forbes college. Her research draws from networking, security, formal methods, and machine learning. Overall, her goal is to design and build networked systems that are secure, reliable, and performant.

Maria has been named a rising star in Computer Networking and Communications (2021) and has received the NSF CAREER award (2025), the Google Research Scholar Award (2023), multiple Commendations for Outstanding Teaching (2023, 2024, 2025), and multiple IETF/IRTF Applied Networking Research Prizes (2018, 2025).

Maria completed her PhD in 2021 at ETH Zurich under the guidance of Laurent Vanbever. During her studies, she was a visiting student at MIT and a research intern at Microsoft Research and Google. After her PhD, she spent a year at Carnegie Mellon University working with Vyas Sekar as a postdoctoral researcher. Prior to her PhD, she earned her diploma in Electrical and Computer Engineering at the National Technical University of Athens, Greece.

Photo

NetΣyn's Cheerleader

Website

Google Scholar

PRINCETON UNIVERSITY

NetΣyn Lab

PhD Students

Sophia Yoo

PhD Student
(co-advised with Jennifer Rexford)
🏆 Wallace Fellowship

sophiayoo@cs.princeton.edu
Website

Fengchen Gong

PhD Student

fg3738@cs.princeton.edu
Website

Ann Zhou

PhD Student

az6922@cs.princeton.edu

Constantine Doumanidis

PhD Student

doumanidis@princeton.edu

Minhao Jin

PhD Student
🏆 Pramod Subramanyan *17 Early Career Award

minhaoj@princeton.edu
Website

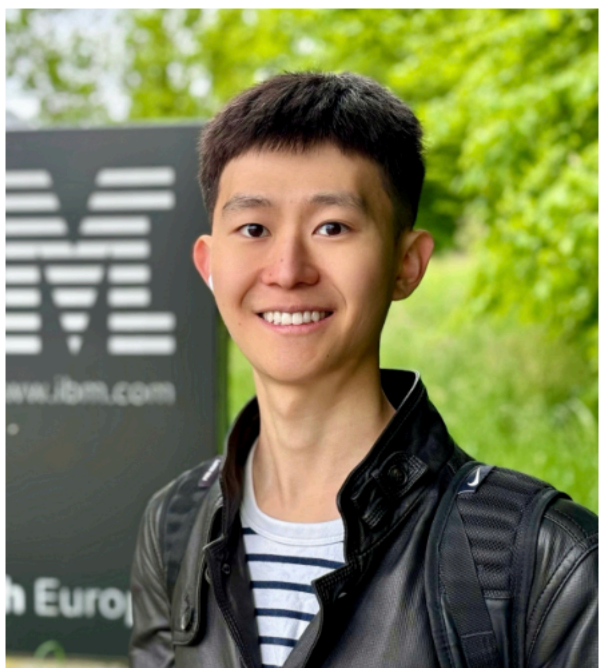
Hongyu Hè

PhD Student

hhy@princeton.edu
Website

Cleef

You'll work with a **dream team of assistants in instruction** throughout the semester



Hongyu Hè
hhy@princeton.edu

Constantine Doumanidis
doumanidis@princeton.edu

Yunxiang Chi
yc3926@princeton.edu

Your turn…

What is your name?

What is your major?

Why are you here?

Organization

Our website: https://www.cs.princeton.edu/courses/archive/fall25/cos461/ check it out regularly

COS 461/ECE 471 - Fall 2025

Overview Schedule Projects Resources

Date	Topic	Media	Optional Reading
Part 1: Network Foundations			
Tue Sep 2	Introduction		
Thu Sep 4	Fundamental Network concepts		
Tue Sep 9	Routing Foundations		
Thu Sep 11	[Buffer]		
Part 2: Internet			
Tue Sep 16	Ethernet & Switching (Link Layer)		
Thu Sep 18	Internet Protocol (IP) & Forwarding (Network layer)		
Tue Sep 23	Internet Routing		
Tue Sep 23	Project 1 (Internet Routing) released		
Thu Sep 25	[Buffer]		
Tue Sep 30	Routing Policies		
Thu Oct 2	BGP's challenges (and solutions)		
Tue Oct 7	Hackathon		
Thu Oct 9	[Buffer]		
Tue Oct 14	*Fall Recess*		
Thu Oct 16	*Fall Recess*		

The course will be split in three parts

Part 1	Part 2	Part 3
Foundations	Today's Internet	Special Topics
~4 lectures	~12 lectures	~6 lectures

Your final grade

- We do not use a grading curve in this class.
- If everyone does excellent work, everyone can earn an excellent grade.
- The focus is on mastering the material, not outperforming your peers.

Your final grade

Exam

40%

written,
open book

Projects

60%

continuous
performance assessments

Bonus

4% Class participation

1% Peer Bonus

Your final grade

Exam

40%

written,
open book

Projects

60%

continuous
performance assessments

Bonus

4% Class participation

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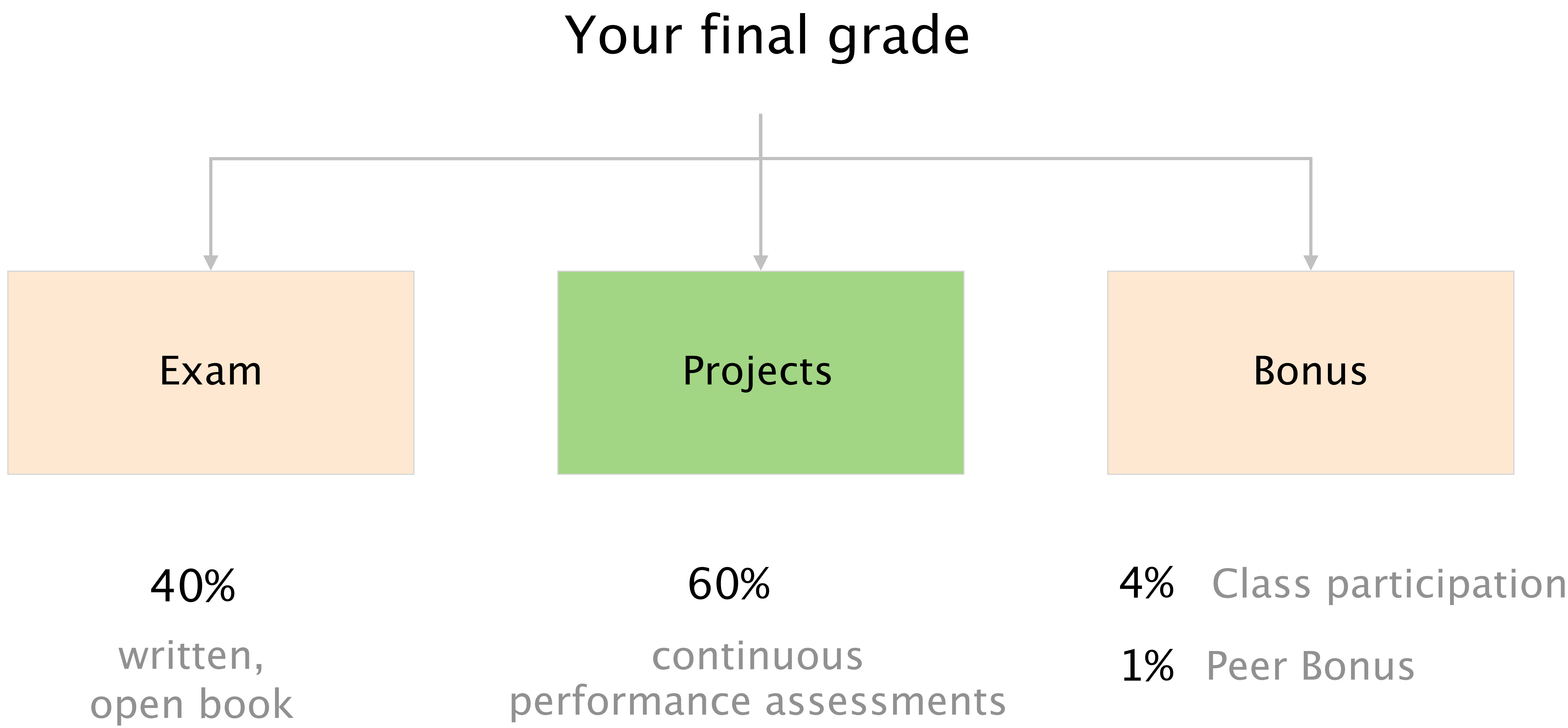

Your final grade
Exam
Projects
Bonus
40%
written,
open book
60%
continuous
performance assessments
4% Class participation
1% Peer Bonus

There will be **two practical projects**
which you'll do in group of three students

#1 Build and operate a real, working Internet (40%)

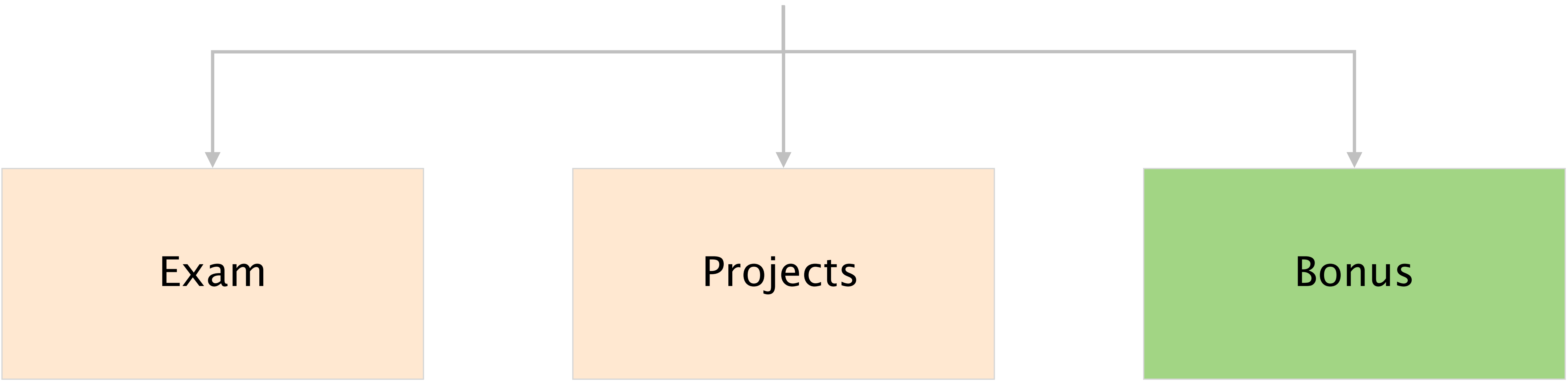
~4 weeks

#2 Implement an interoperable reliable protocol (20%)

~3 weeks

Detailed instructions will follow

Your final grade



Exam

40%

written,
open book

Projects

60%

continuous
performance assessments

Bonus

4% Class participation*

1% Peer Bonus

* in person or Ed

Peer Bonus: Thank You Credits

Peer Bonus is awarded for meaningful assistance received in-person or Ed.

The student who received help must submit a form describing the help.

The submission must happen < 48h after the help was received.

8 peer bonus == 1% bonus — (<=2 from the same person & not within group)

The instructor or AIs may verify help.

Each class will contain theoretical concepts and practical problem-solving.

Lecture

Quick Quizzes

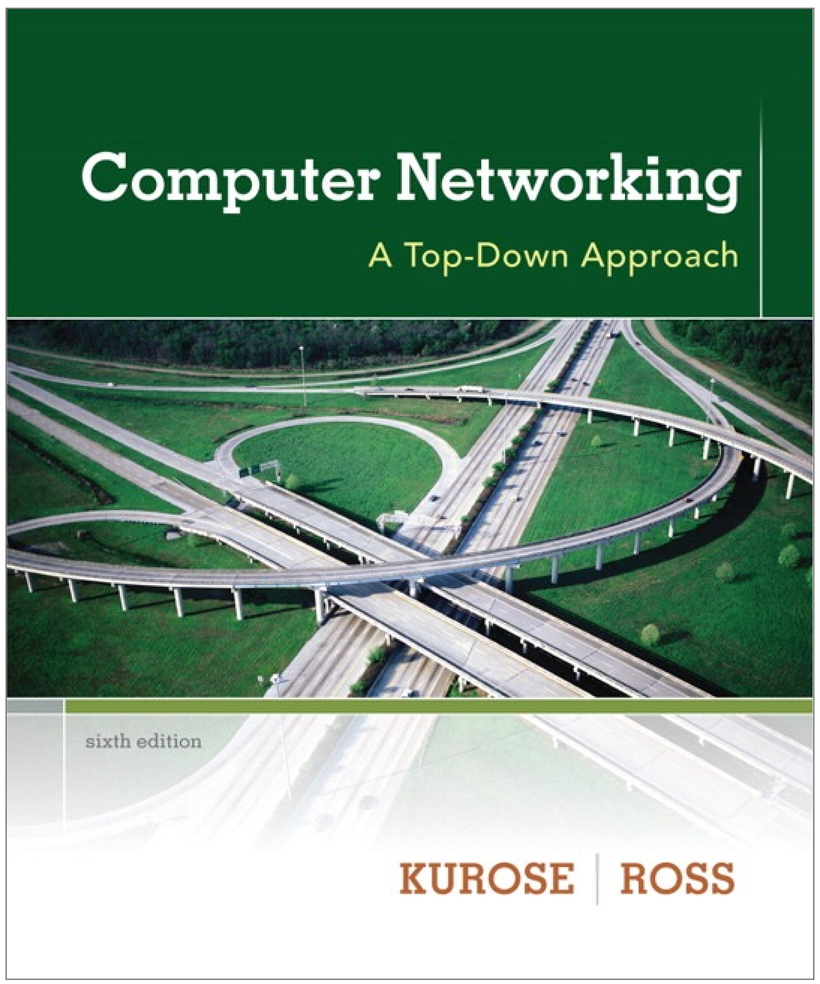
Problem Sets

~50-60 min

~20-30min

Your grade does not depend on your answers!

The course closely follows the textbook
Computer Networking: a Top-Down Approach

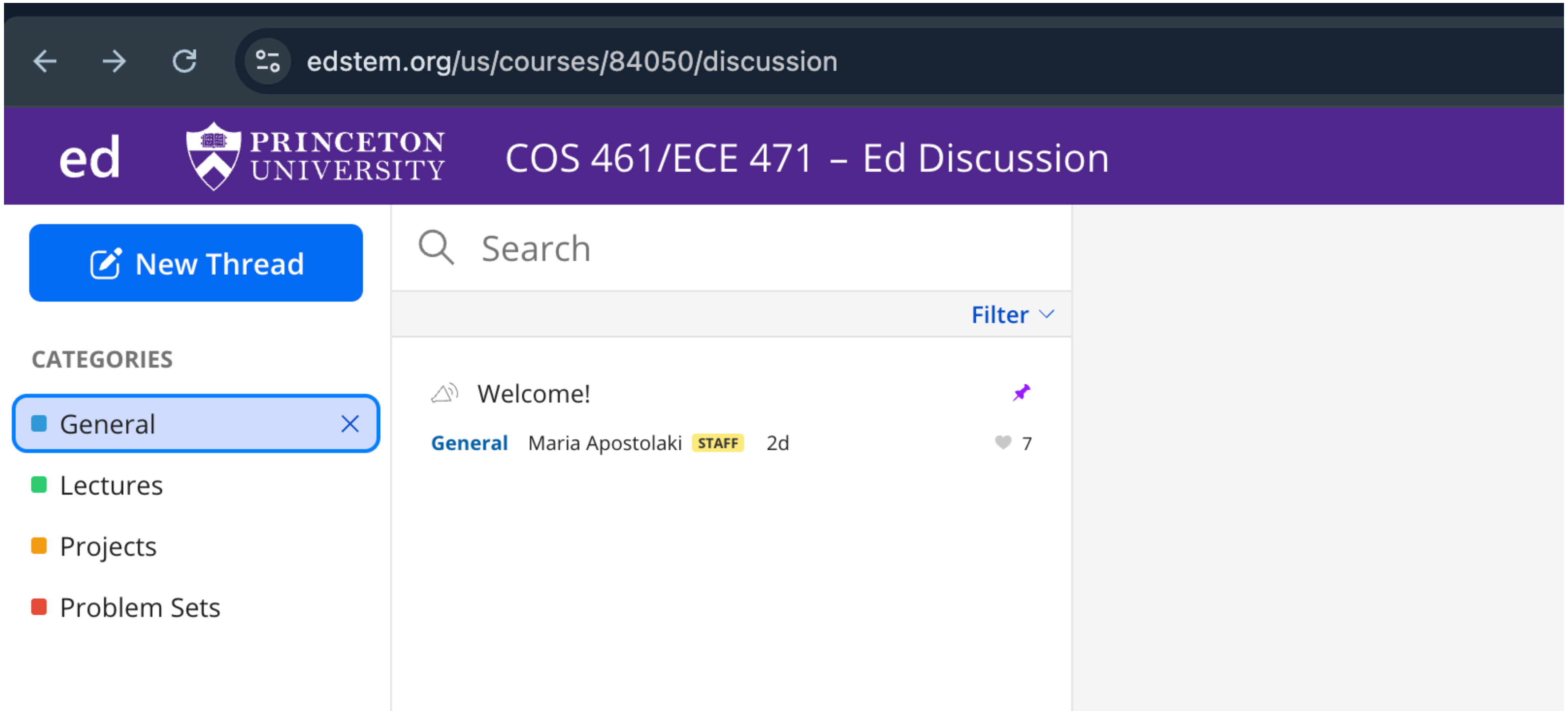


6th edition

using another edition is okay
but numbering might vary

see sections indicated
on our website

We’ll use Ed to discuss about the course and assignments

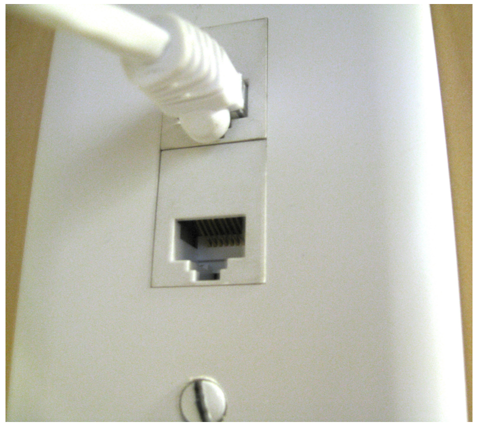


Computer Networks

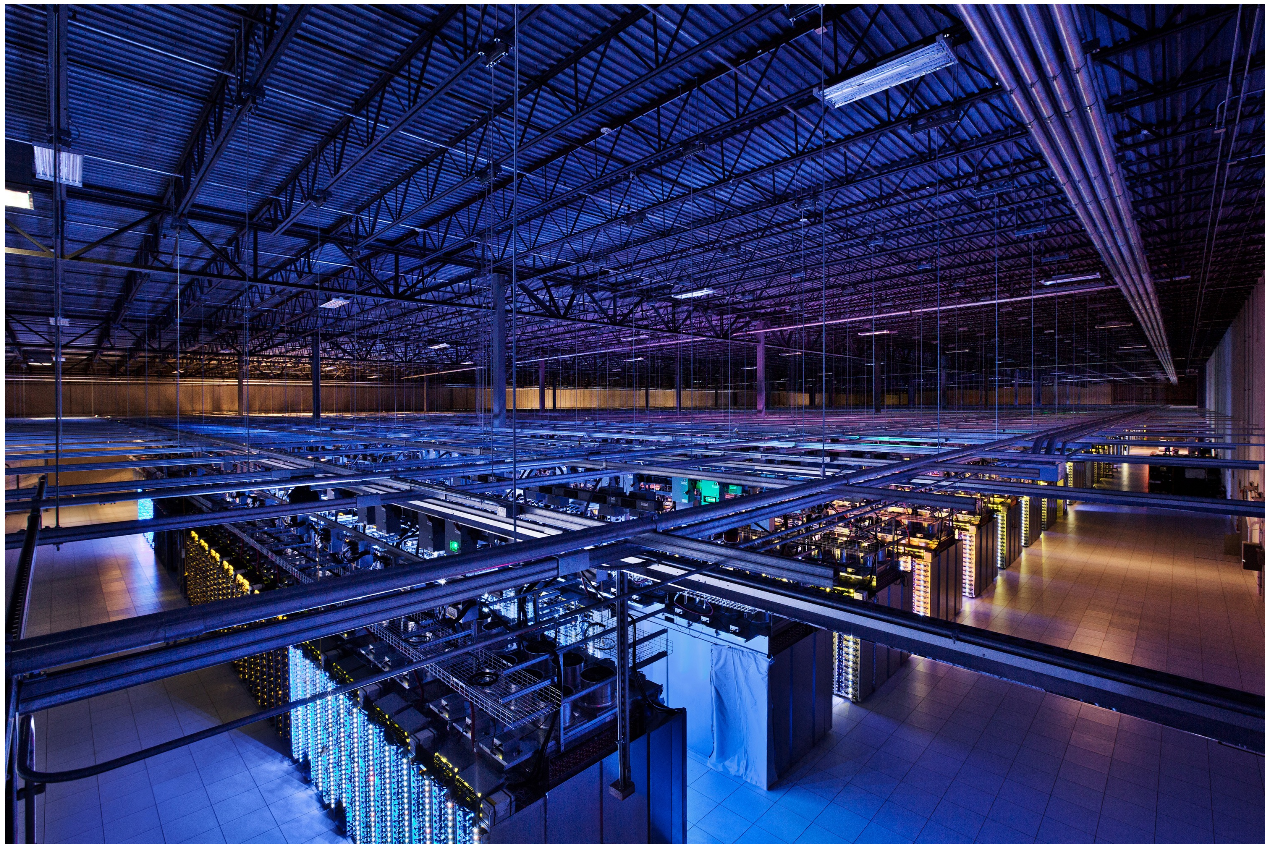
Course goals

Knowledge

Understand how the Internet works and why



from your
network plug…



…to mega-scale data-centers

Insights

Key concepts and problems in Networking

Naming Layering Routing Reliability Sharing

Naming Layering Routing Reliability Sharing

How do you address computers, services, protocols?

Naming Layering Routing Reliability Sharing

How do you manage complexity?

Naming Layering **Routing** Reliability Sharing

How do you **find a path from A to B?**

Naming Layering Routing Reliability Sharing

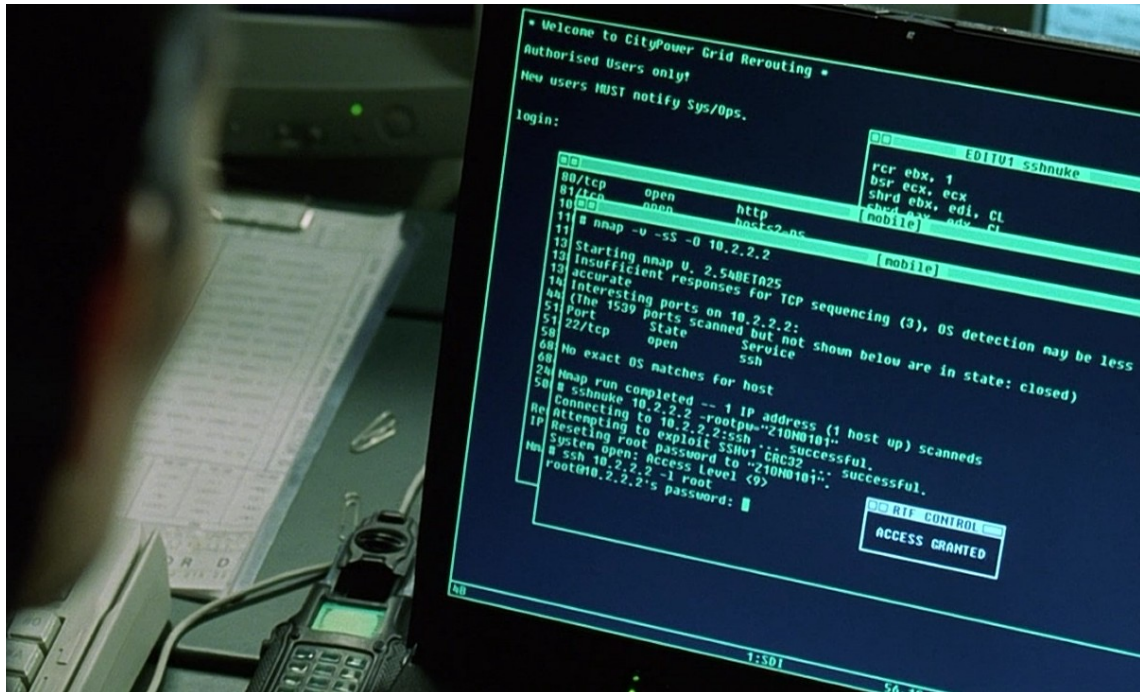
How do you communicate reliably using unreliable mediums?

Naming Layering Routing Reliability Sharing

How do you divide scarce resources among competing parties?

Skills

Build, operate and configure networks



Trinity using a port scanner (nmap) in Matrix Reloaded™

Internet

Let’s walk through an example of how we use the Internet

Step 1. Encapsulation & Packetization

When a user uploads a video, the application data (video file) is split into packets and encapsulated with multiple headers to travel across the network.

Step 2. Switching (Link Layer)

Packets first move through local Ethernet switches or WiFi access points at Princeton, which forward them based on MAC addresses.

Step 3. Interdomain Routing & BGP Policies

Princeton’s border routers use BGP to decide which upstream provider carries the traffic. Routing choices reflect both technical paths and business policies.

Step 4. Congestion Control (Transport Layer)

TCP or QUIC ensures packets are sent at a rate that avoids overwhelming the network. Congestion signals (loss, delay, ECN marks) adjust transmission speed dynamically.

Let's walk through an example of how we use the Internet

Step 5. Queue & Buffer Management

Routers and switches temporarily store packets in queues. Buffer management ensures fairness, prevents bufferbloat, and balances throughput vs. latency.

Step 6. Data Centers & Content Distribution

Uploaded videos are stored and replicated in Google's global data centers. When viewers request a video, it is served from the closest CDN cache to minimize delay. Players use adaptive bitrate streaming, requesting higher or lower quality video chunks depending on current network conditions.

Step 7. Machine Learning for Networks

ML for Networks: Google uses ML to predict congestion and assign viewers to the best CDN node. The YouTube player uses ML to predict the most suitable bit rate for the next time interval.

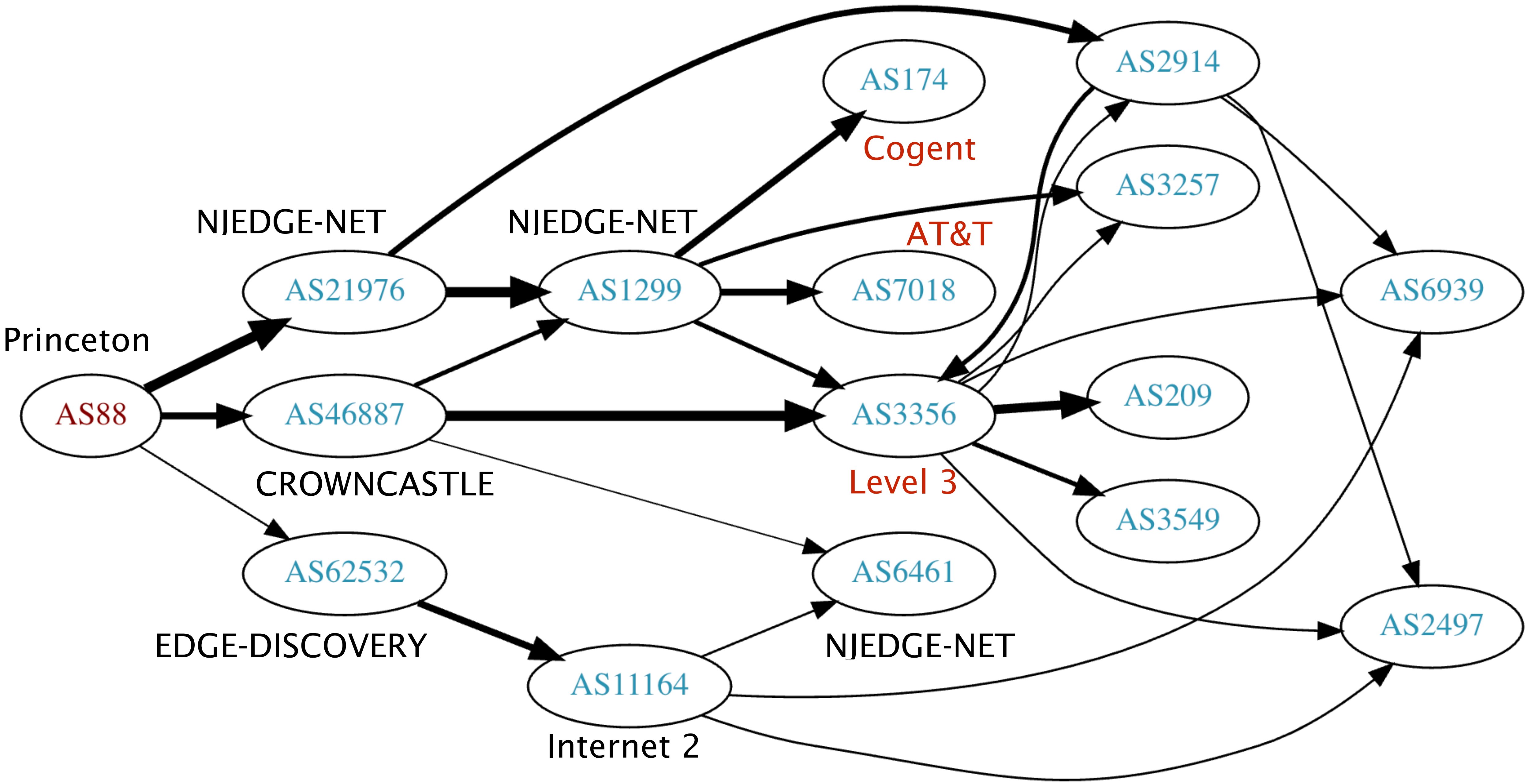
The Internet

*What is **it**—really?*

Internet

Internet

A network of *networks*


Princeton
AS88
NJEDGE-NET
AS21976
AS46887
CROWNCASTLE
AS62532
EDGE-DISCOVERY
NJEDGE-NET
AS1299
AS11164
Internet 2
AS174
Cogent
AT&T
AS7018
AS3356
Level 3
AS6461
NJEDGE-NET
AS2914
AS3257
AS209
AS3549
AS6939
AS2497

The Internet "glues together" many networks

this is its most important & fundamental goal

The Internet solves a problem of interoperability

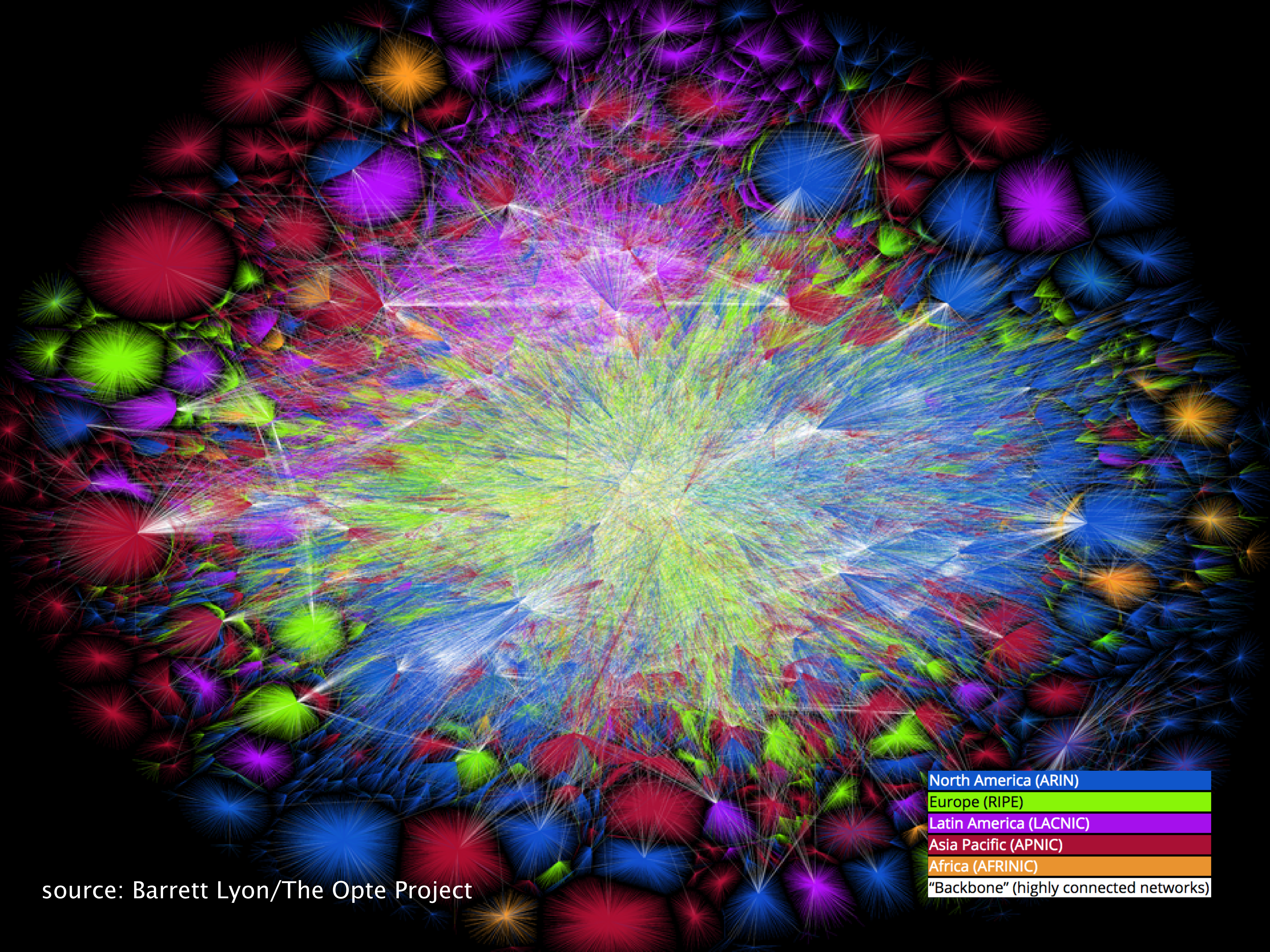
across different networks *and* technologies

Doing so is hard when considering competing interests

Competing networks must cooperate to connect their clients

This leads to many tussles across business & technology

Economic incentives often shape Internet paths



source: Barrett Lyon/The Opte Project

~100,000

~100,000

# of interconnected networks

as of Aug 2025

The Internet is huge

~30 billion

~30 billion

estimated* # of connected devices

in **2023**

* Cisco Visual Networking Index

~13 exabytes

estimated* daily global IP traffic

in 2022

* Cisco Visual Networking Index

If 

= 1 Gigabyte


volume(Great Wall of China) = 1 exabyte

~91% of all Internet traffic

estimated* percentage of **video traffic**

in 2024

* marketing reports

Every second, we consume/generate…

Every second, we consume/generate…

>47k	>96k	>4.2M
TikTok videos	Google searches	emails

Every second, we consume/generate...

>47k	>96k	>4.2M
TikTok videos	Google searches	emails

We refer to such systems as "Internet scale"

The Internet is incredibly diverse

The Internet is incredibly diverse

what

it connects

The Internet is incredibly diverse

what it connects	devices	phones, servers, sensors, pacemakers, …
	applications	web, video streaming, gaming, …
	users	governments, operators, malicious, …

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how
it connects

The Internet is incredibly diverse

what it connects	devices	phones, servers, sensors, pacemakers, …
	applications	web, video streaming, gaming, …
	users	governments, operators, malicious, …

how it connects	technology	optical fiber, satellite, wireless, copper, …		
		from	to	delta
	latency	microseconds	seconds	10^6
	bandwidth	kilobits/sec	terabits/sec	10^9
	loss rate	0%	100%	

The Internet is prone to failure

Many components lie alongside any path

Network cards, switches, routers, access points, …

Any single one of them failing disrupt communication

50 components working 99% of time $\Rightarrow$ ~40% failure rate

Handling failures at scale is a key feature of the Internet

Principles are now used widely, e.g. within a datacenter

“Human factors are responsible

for 50% to 80% of network outages”

Juniper Networks, *What’s Behind Network Downtime?*, 2008

TECHNOLOGY

The New York Times

PLAY THE CROSSWORD

Account

Gone in Minutes, Out for Hours: Outage Shakes Facebook

When apps used by billions of people worldwide blinked out, lives were disrupted, businesses were cut off from customers — and some Facebook employees were locked out of their offices.

889

Source: [NYtimes]

Our engineering teams have learned that
configuration changes on the backbone routers
that coordinate network traffic between our data centers
caused issues that interrupted this communication.

This disruption to network traffic had a cascading effect
on the way our data centers communicate,
bringing our services to a halt.

Source: [fb.com]

The New York Times

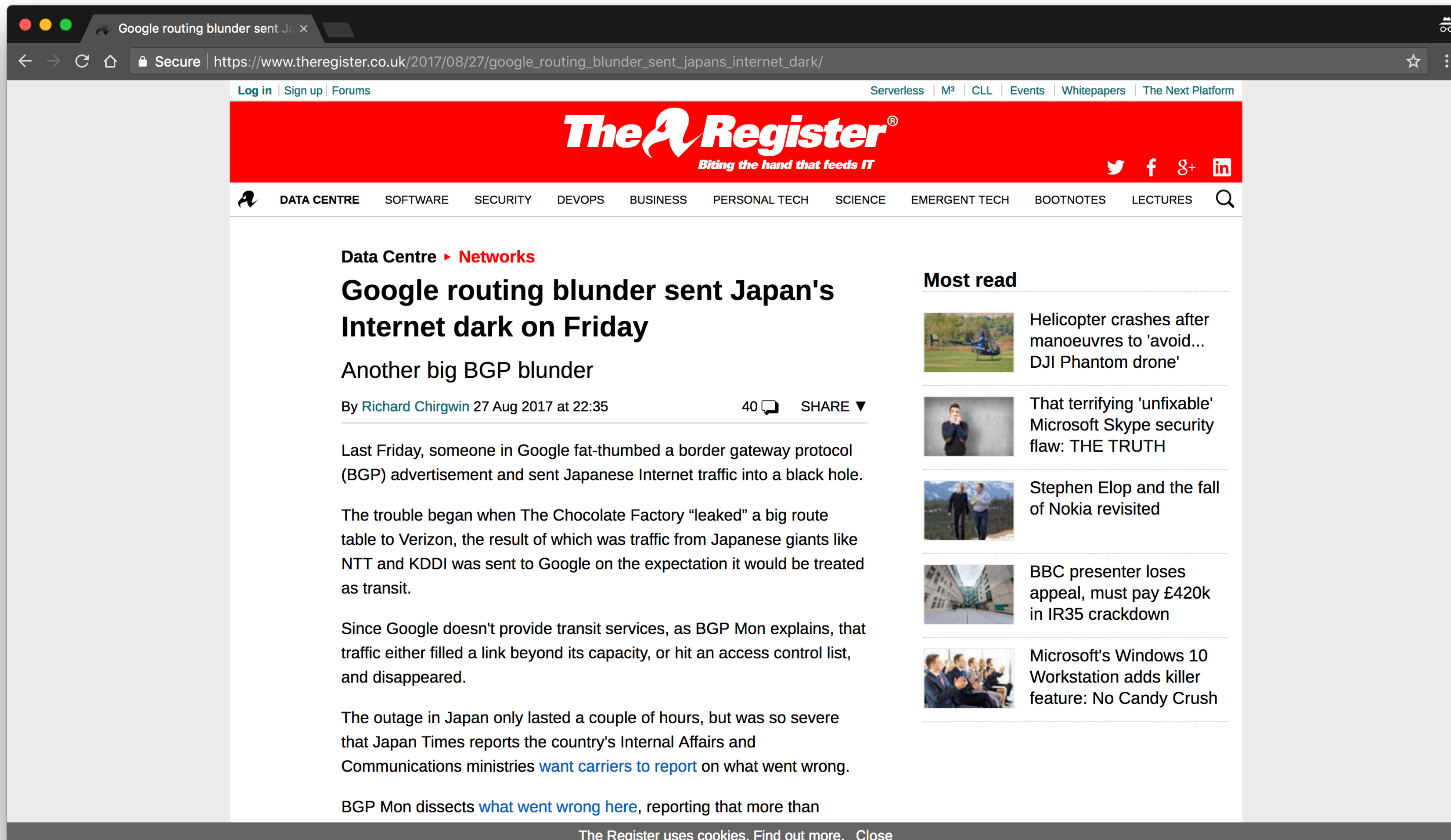
Microsoft Services Back Online After Morning Outages

The widely used Microsoft Teams and Outlook email services were unavailable for thousands of users early Wednesday.

Share full article

Microsoft is investigating an issue affecting multiple servers on Wednesday. Justin Lane/EPA, via Shutterstock

August 2017



Google routing blunder sent Ja

Secure https://www.theregister.co.uk/2017/08/27/google_routing_blunder_sent_japans_internet_dark/

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Data Centre ▸ Networks

Google routing blunder sent Japan's Internet dark on Friday

Another big BGP blunder

By Richard Chirgwin 27 Aug 2017 at 22:35

40 SHARE ▼

Last Friday, someone in Google fat-thumbed a border gateway protocol (BGP) advertisement and sent Japanese Internet traffic into a black hole.

The trouble began when The Chocolate Factory "leaked" a big route table to Verizon, the result of which was traffic from Japanese giants like NTT and KDDI was sent to Google on the expectation it would be treated as transit.

Since Google doesn't provide transit services, as BGP Mon explains, that traffic either filled a link beyond its capacity, or hit an access control list, and disappeared.

The outage in Japan only lasted a couple of hours, but was so severe that Japan Times reports the country's Internal Affairs and Communications ministries want carriers to report on what went wrong.

BGP Mon dissects what went wrong here, reporting that more than

Most read

Helicopter crashes after manoeuvres to 'avoid... DJI Phantom drone'

That terrifying 'unfixable' Microsoft Skype security flaw: THE TRUTH

Stephen Elop and the fall of Nokia revisited

BBC presenter loses appeal, must pay £420k in IR35 crackdown

Microsoft's Windows 10 Workstation adds killer feature: No Candy Crush

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https://www.theregister.co.uk/2017/08/27/google_routing_blunder_sent_japans_internet_dark/

Someone in Google fat-thumbed a
Border Gateway Protocol (BGP) advertisement
and sent Japanese Internet traffic into a black hole.

[…] the result of which was traffic from Japanese giants
like NTT and KDDI was sent to Google
on the expectation it would be treated as transit.

The outage in Japan only lasted a couple of hours,
but was so severe that […] the country's
Internal Affairs and Communications ministries
want carriers to report on what went wrong.

On average, a company experiences 5 network outages/year due to network failure, spikes, human error.

LogicMonitor 2019

OCCUPATIONAL OUTLOOK HANDBOOK

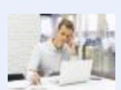
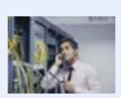
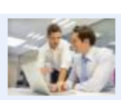
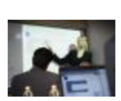
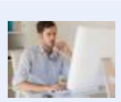
Computer and Information Technology Occupations

These workers create or support computer applications, systems, and networks.

Overall employment in computer and information technology occupations is projected to grow much faster than the average for all occupations from 2023 to 2033. About 356,700 openings are projected each year, on average, in these occupations due to employment growth and the need to replace workers who leave the occupations permanently.

The median annual wage for this group was $105,990 in May 2024, which was higher than the median annual wage for all occupations of $49,500.

BLS employment projections, wage, and other data for related occupations not shown in the following table are available on the Data for Occupations Not Covered in Detail page. Information highlighting physical demands, cognitive and mental requirements, and other qualifications for workers in this group are available in a BLS Occupational Requirements Survey (ORS) profile.

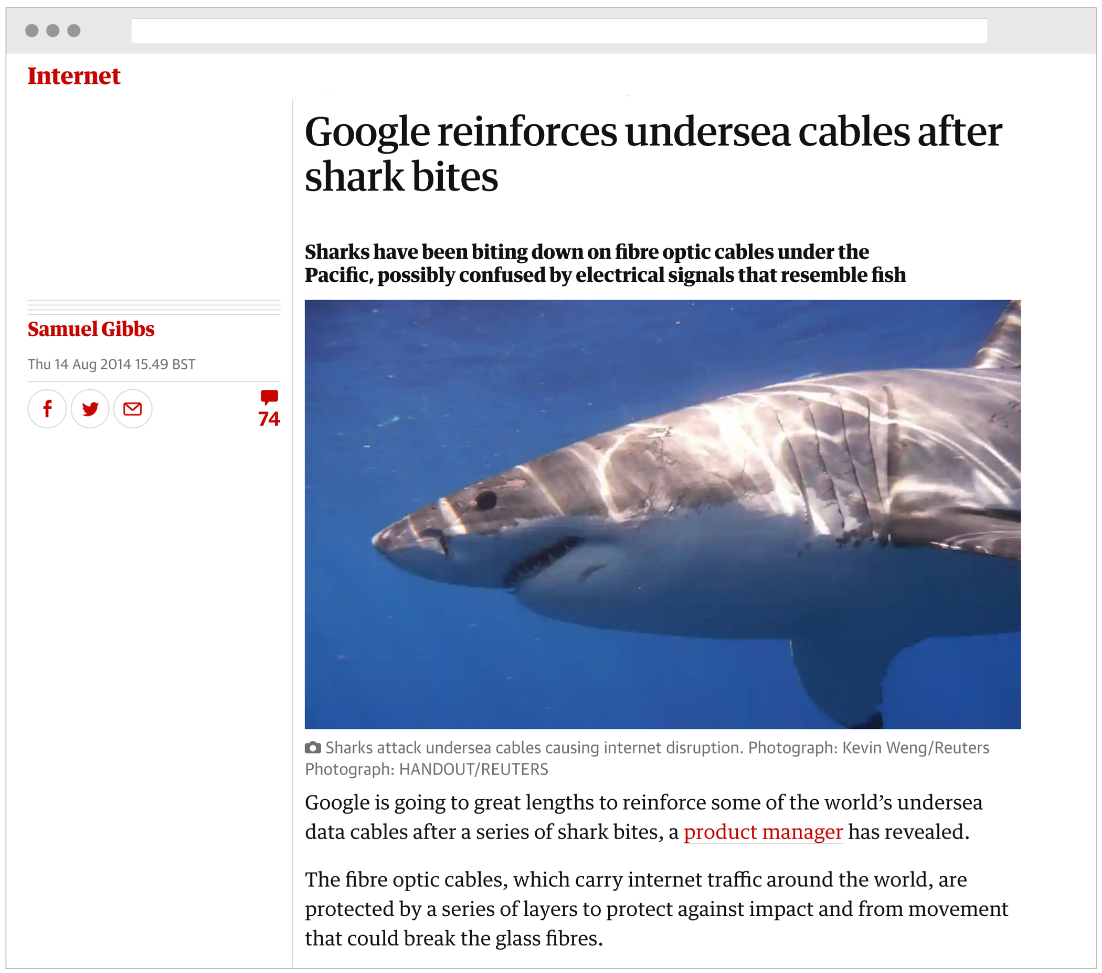
	OCCUPATION	JOB SUMMARY	ENTRY-LEVEL EDUCATION	2024 MEDIAN PAY
	**Computer and Information Research Scientists**	Computer and information research scientists design innovative uses for new and existing computing technology.	Master's degree	$140,910
	**Software Developers, Quality Assurance Analysts, and Testers**	Software developers design computer applications or programs. Software quality assurance analysts and testers identify problems with applications or programs and report defects.	Bachelor's degree	$131,450
	**Computer Network Architects**	Computer network architects design and implement data communication networks, including local area networks (LANs), wide area networks (WANs), and intranets.	Bachelor's degree	$130,390
	**Information Security Analysts**	Information security analysts plan and carry out security measures to protect an organization's computer networks and systems.	Bachelor's degree	$124,910
	**Database Administrators and Architects**	Database administrators and architects create or organize systems to store and secure data.	Bachelor's degree	$123,100
	**Computer Systems Analysts**	Computer systems analysts study an organization's current computer systems and design ways to improve efficiency.	Bachelor's degree	$103,790
	**Computer Programmers**	Computer programmers write, modify, and test code and scripts that allow computer software and applications to function properly.	Bachelor's degree	$98,670

Summary

Quick Facts: Computer Network Architects	
2024 Median Pay	$130,390 per year $62.69 per hour
Typical Entry-Level Education	Bachelor's degree
Work Experience in a Related Occupation	5 years or more
On-the-job Training	None
Number of Jobs, 2023	177,800
Job Outlook, 2023–33	13% (Much faster than average)
Employment Change, 2023–33	23,900

https://www.bls.gov/ooh/computer-and-information-technology/computer-network-architects.htm

… but human factors are not responsible for all outages



Internet

Google reinforces undersea cables after shark bites

Sharks have been biting down on fibre optic cables under the Pacific, possibly confused by electrical signals that resemble fish

Samuel Gibbs

Thu 14 Aug 2014 15.49 BST

74

Sharks attack undersea cables causing internet disruption. Photograph: Kevin Weng/Reuters Photograph: HANDOUT/REUTERS

Google is going to great lengths to reinforce some of the world's undersea data cables after a series of shark bites, a product manager has revealed.

The fibre optic cables, which carry internet traffic around the world, are protected by a series of layers to protect against impact and from movement that could break the glass fibres.

The Internet is always changing

The Internet is always changing

	1970s	2025s
bandwidth		
# hosts		
killer app		

The Internet is always changing

	1970s	2025s
bandwidth	$O(10^4)$ bits/second	$O(10^{15})$
# hosts	$O(10^2)$	$O(10^{11})$
killer app	copy files	video streaming, gaming

One cannot design for a fixed target!

	1970s	2025s	2030s
bandwidth	$O(10^4)$ bits/second	$O(10^{15})$	?
# hosts	$O(10^2)$	$O(10^{11})$	
killer app	copy files	Video…	

To sum up

To sum up,

the Internet is…

To sum up,

the Internet is…

A network of networks…

of enormous scale and diversity…

prone to failures…

in perpetual evolution.

These characteristics led to a complete new at the time design paradigm which…

These characteristics led to a complete new at the time design paradigm which…

… relies on decentralized control

… routes around failures

… tries to deliver traffic, without guarantees

… pushes the complexity towards the end hosts

… relies upon one federating Internet Protocol, **IP**

Computer Networks

Computer Networks

Part 1: Foundations

#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: Concepts

#1 **What is a network made of?**

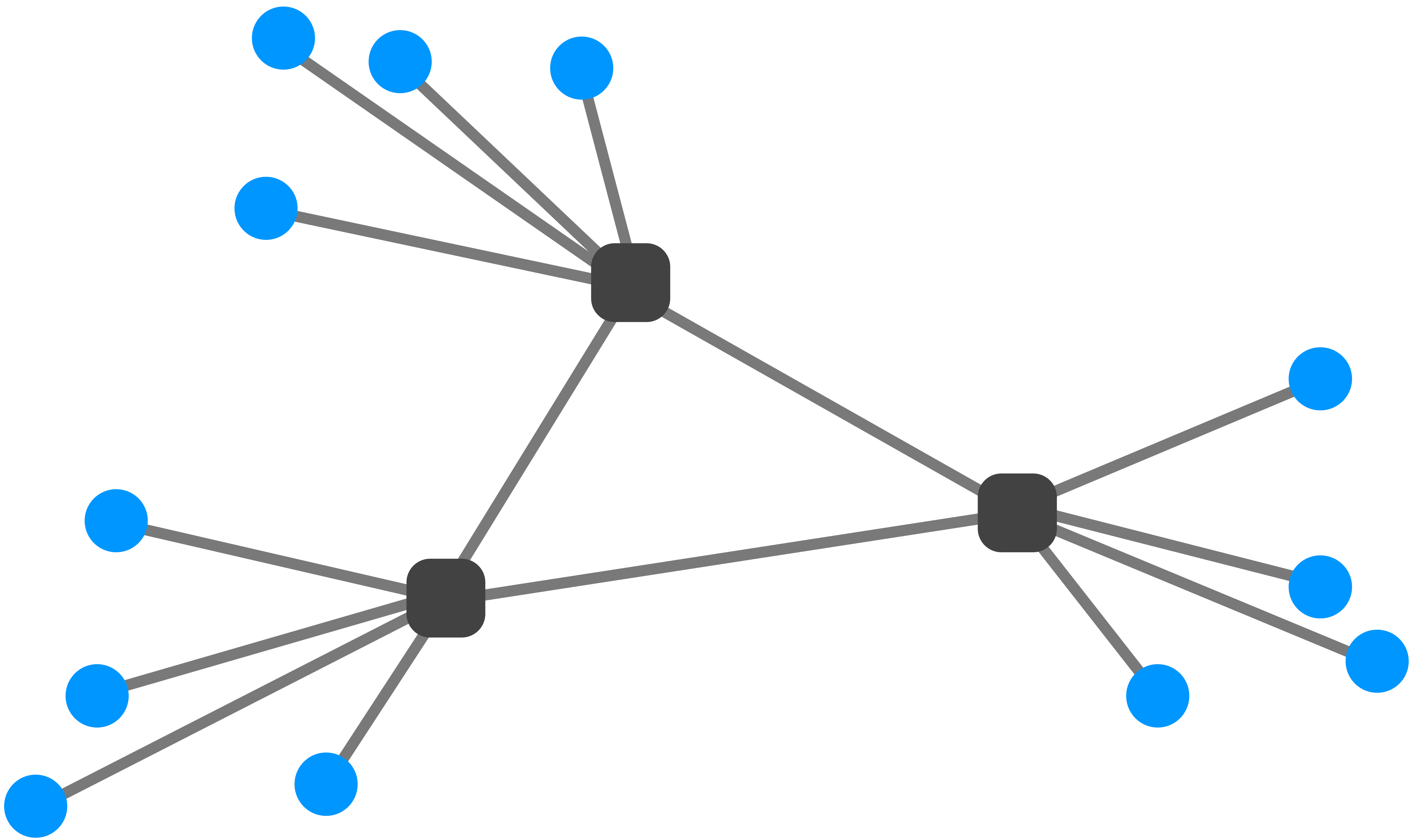
How is it shared?

How is it organized?

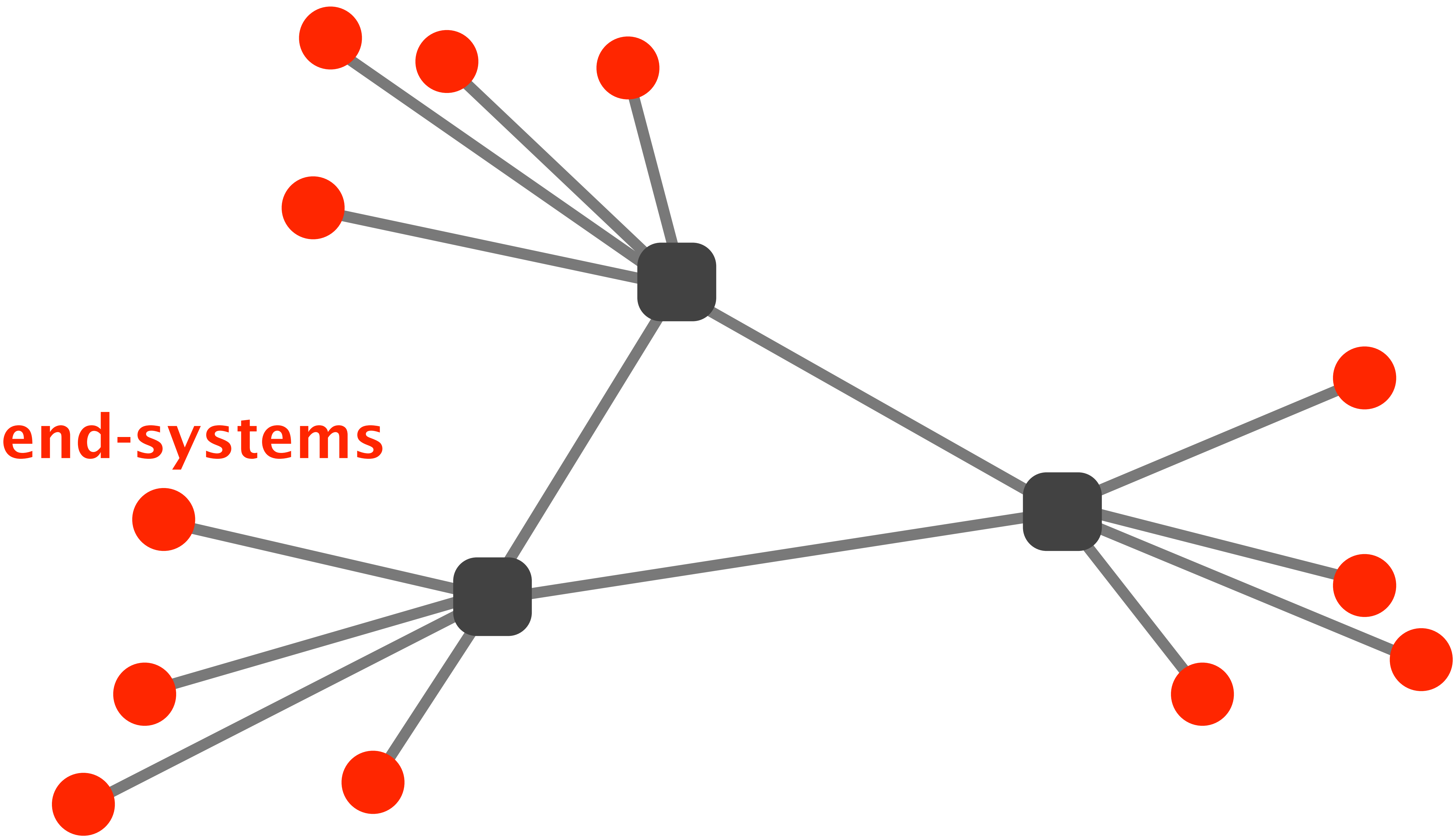
How does communication happen?

How do we characterize it?

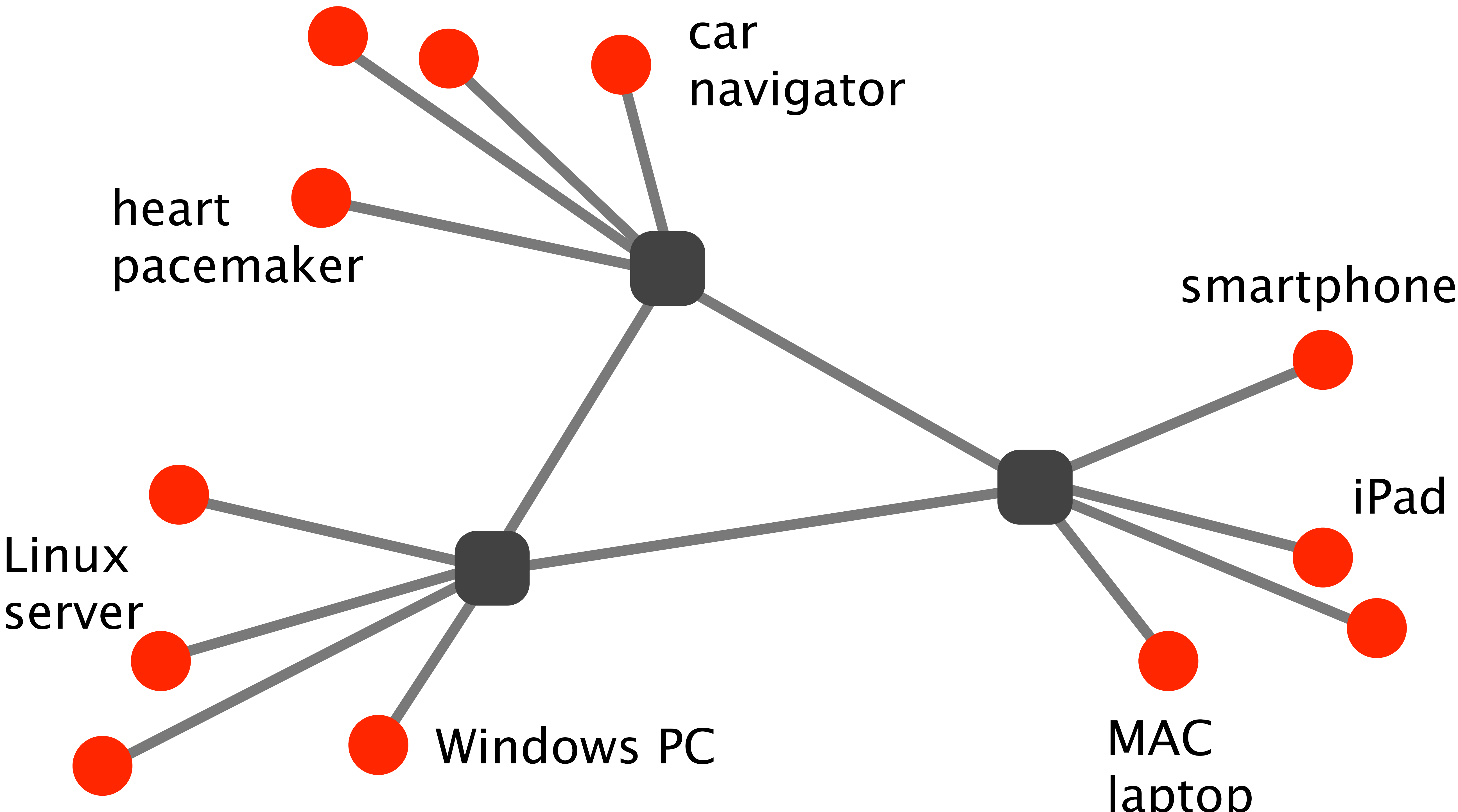
Networks are composed of three basic components



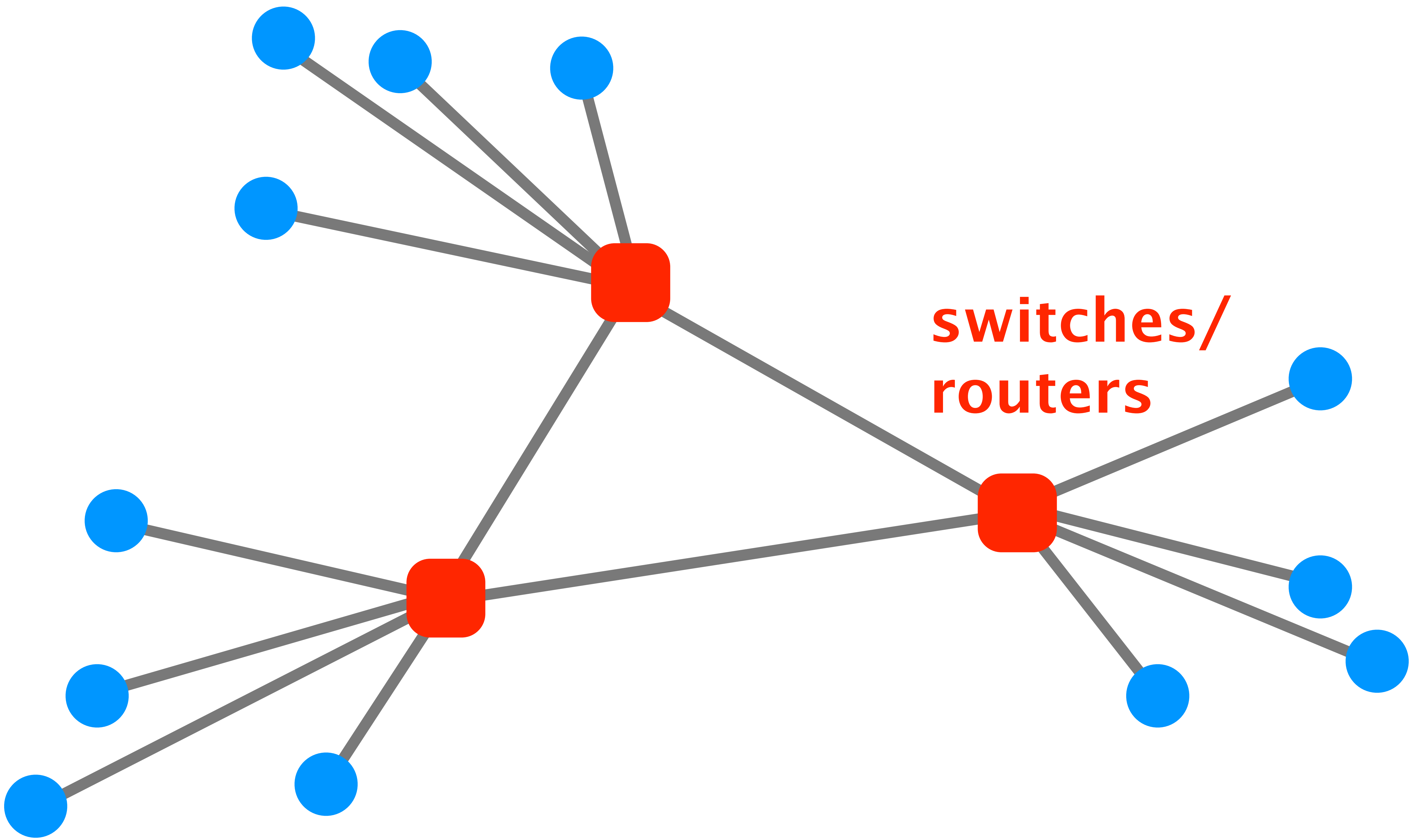
End-systems send & receive data



End-systems come in a wide variety



Routers & switches forward data to the destination



Routers & switches also come in a wide variety

Home router

~20 cm

0,5 kg

1 Gbps

Internet core router

>200cm

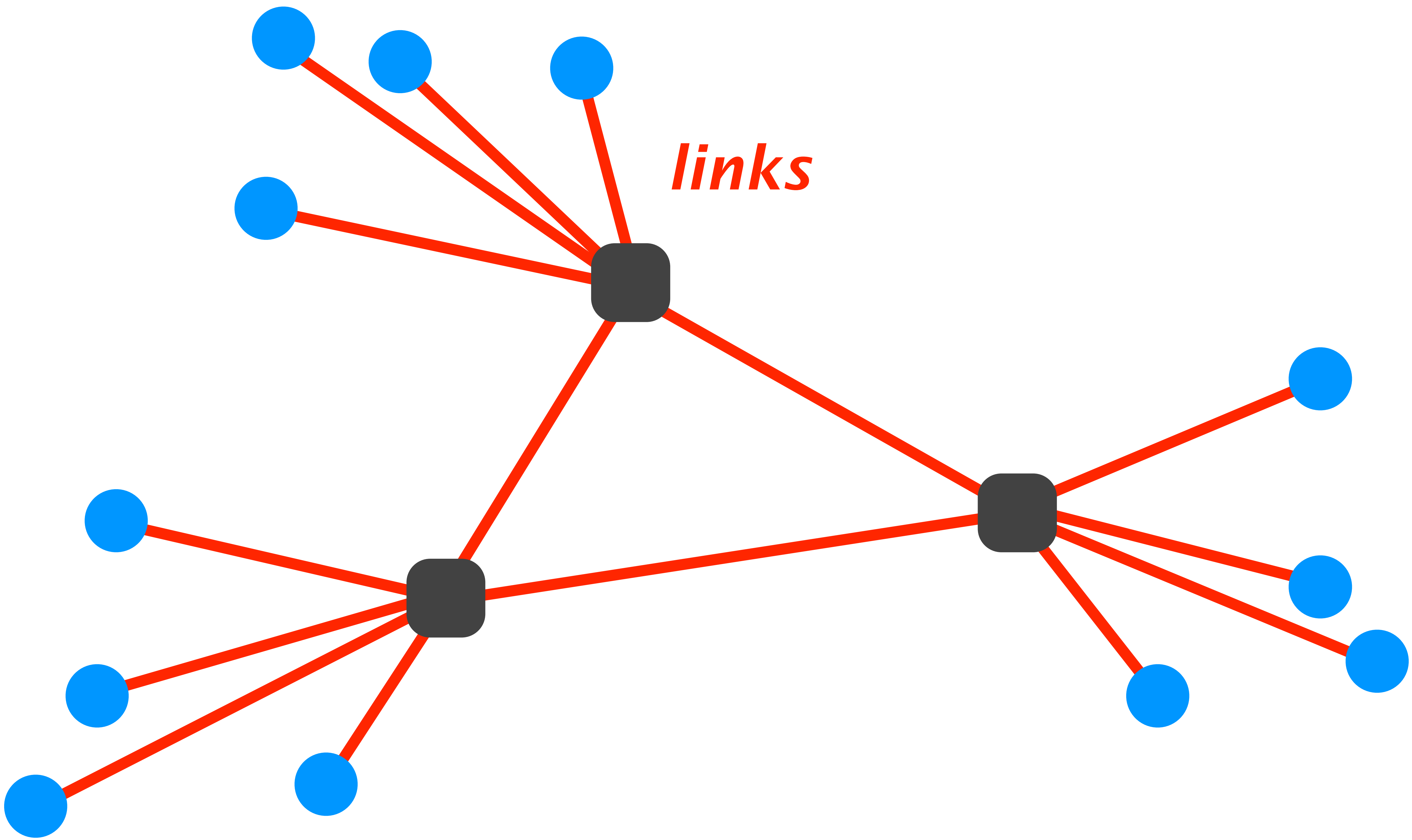
700kg

>12 Tbps

(>920 Tbps in multi-chassis*)

*https://www.cisco.com/c/en/us/products/collateral/routers/carrier-routing-system/data_sheet_c78-726136.html

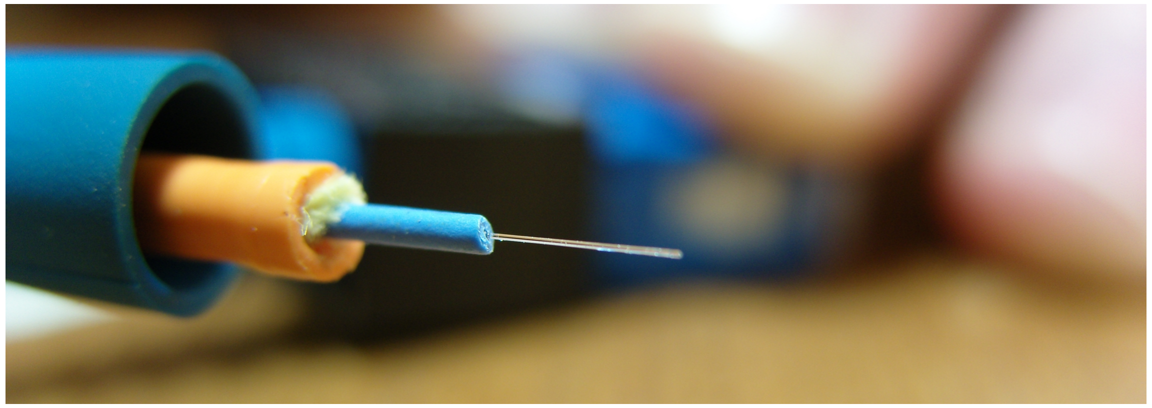
Links connect end-systems to switches and switches to each other



Yes. Links, too, vary in size and usage

Copper

ADSL, RJ-45,…



Optical fibers

Wireless link

There exists a huge amount of access technologies

Ethernet	most common, symmetric
DSL	over phone lines, asymmetric
CATV	via cable TV, shared
Cellular	smart phones
Satellite	remote areas
FTTH	household
Fibers	Internet backbone
Infiniband	High performance computing

Communication Networks

Part 1: Foundations

What is a network made of?

#2 How is it shared?

How is it organized?

How does communication happen?

How do we characterize it?

A good network topology strikes a tradeoff between at least three requirements

Tolerate failures

>1 path should exist between each node

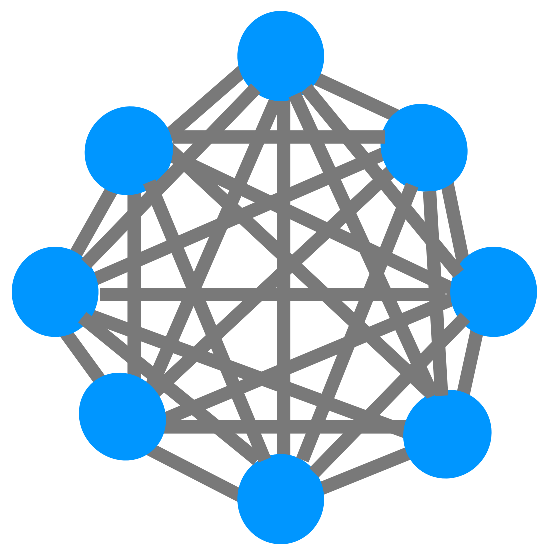
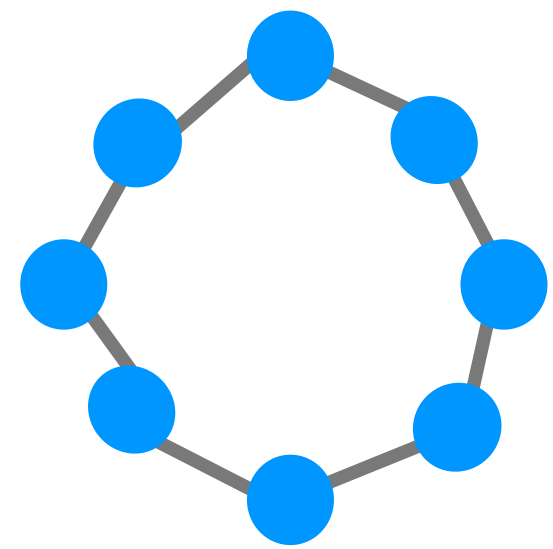
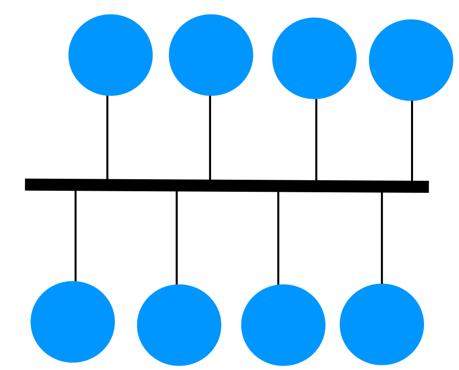
Enable sharing to be feasible & cost-effective

links should not be too high

Provide ample capacity

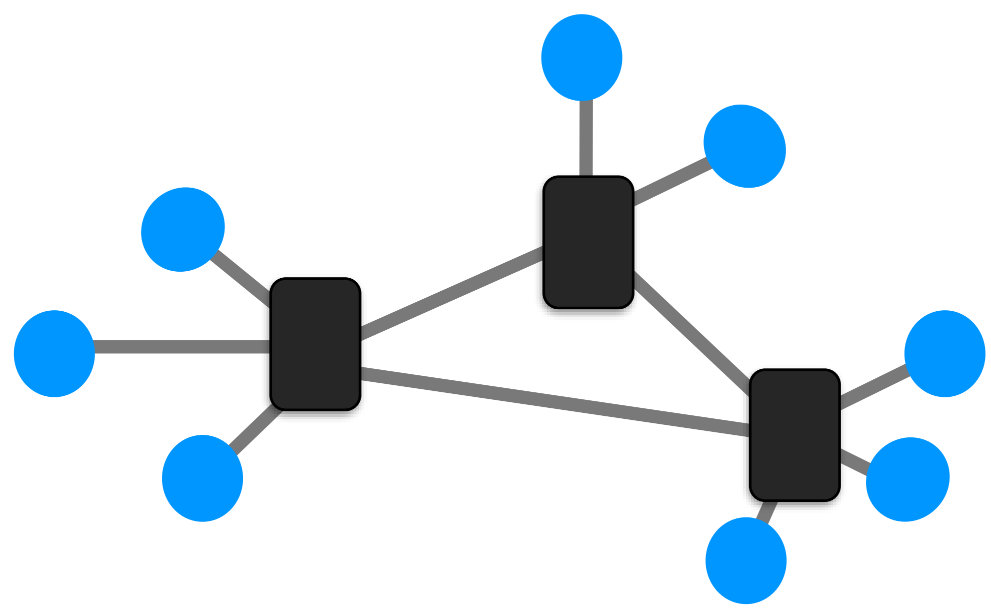
links should not be too small

Compare these network topologies in terms of resiliency, sharing and per-node capacity

design	full-mesh	ring	bus
			
advantages			
disadvantages			

Switched networks provide a reasonable and adaptable compromise

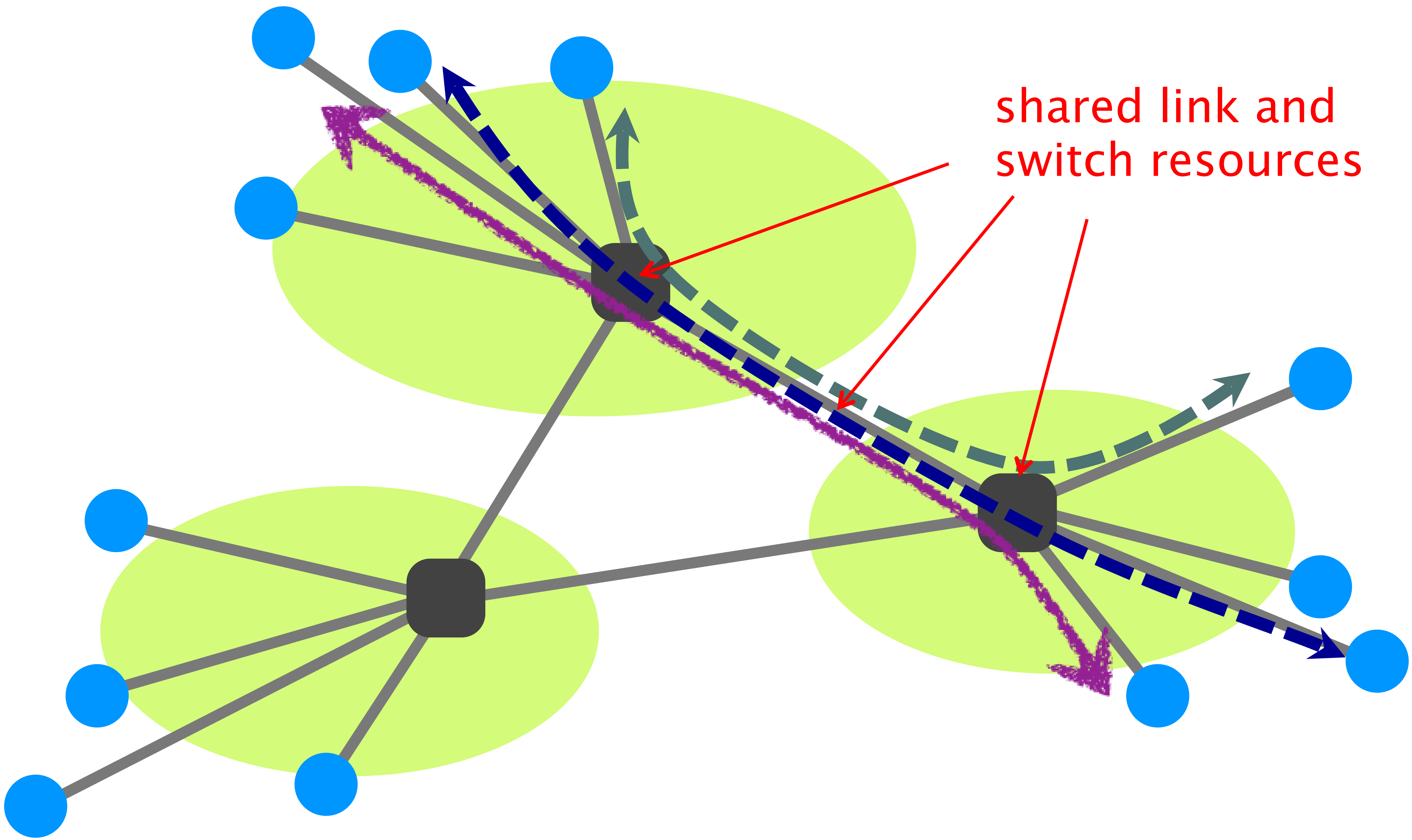
design switched



advantages sharing and per-node capacity can be adapted to fit the network needs

disadvantages require smart devices to perform: forwarding, routing, resource allocation

Links and switches are shared between flows

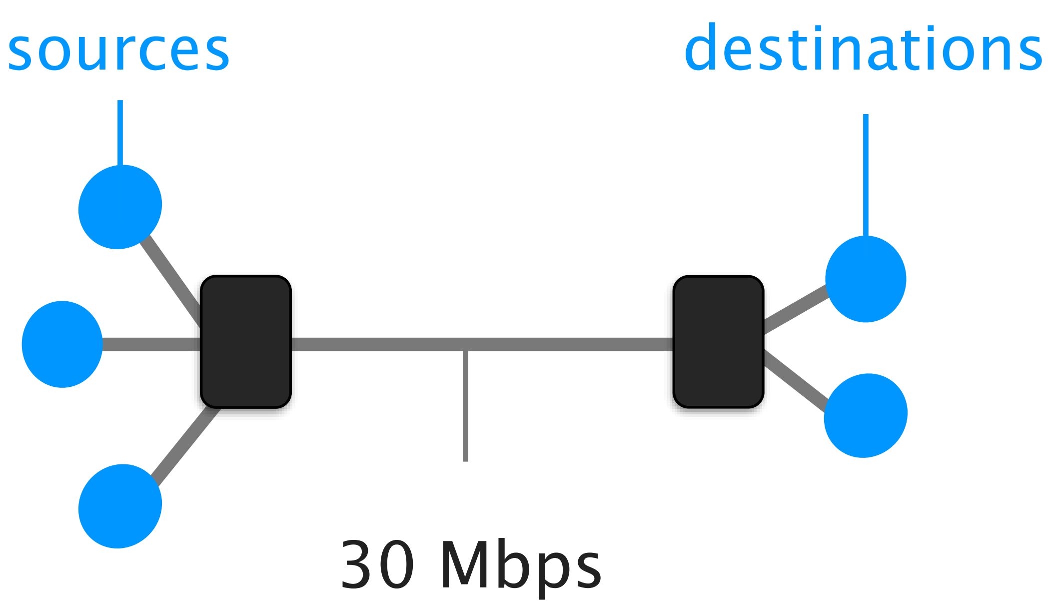


There exist two approaches to sharing: reservation and on-demand

	Reservation	On-demand
principle	reserve the bandwidth you need in advance	send data when you need

Between reservation and on-demand:

Which one do you pick?

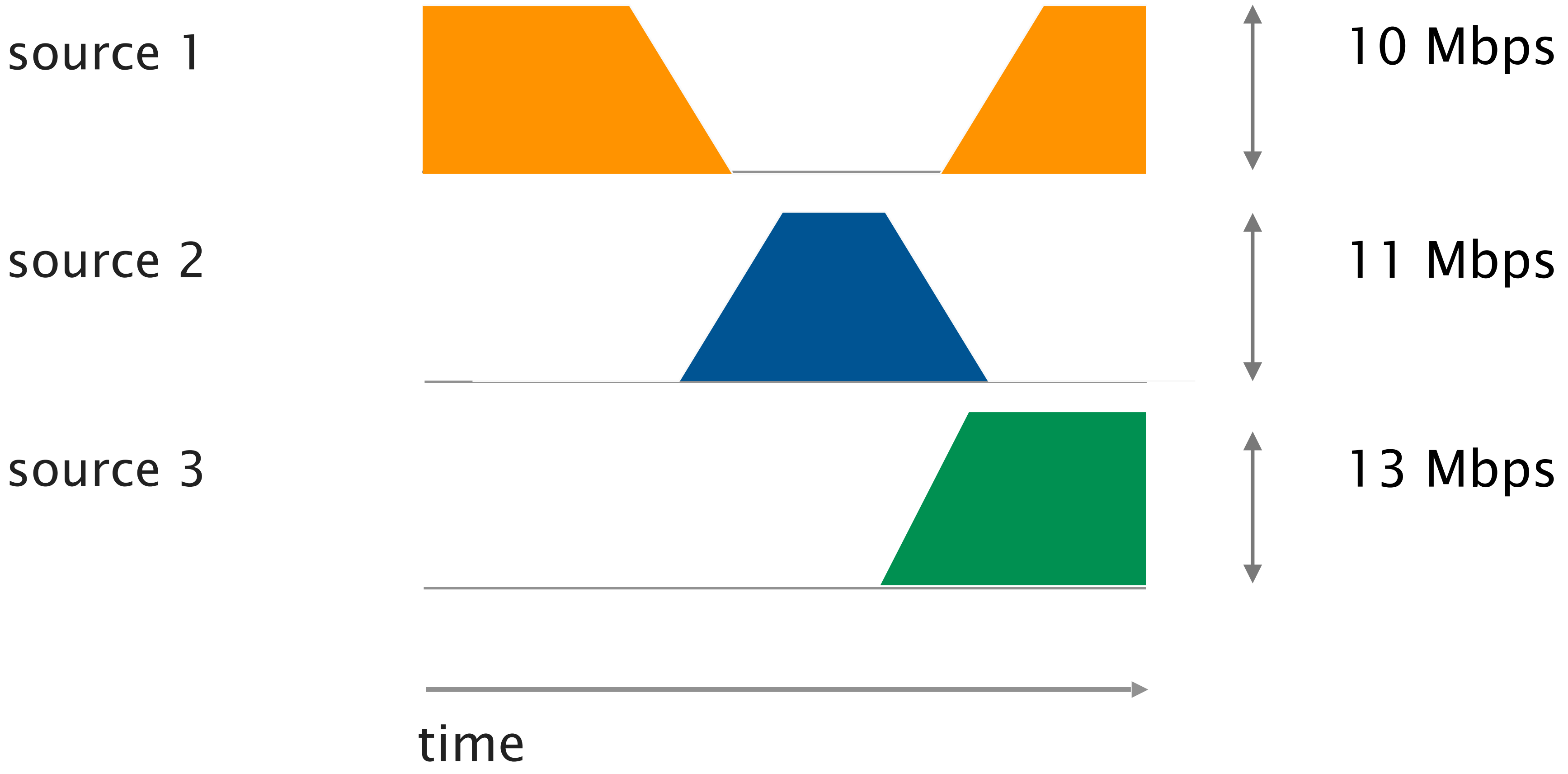


Consider that each source needs 10 Mbps

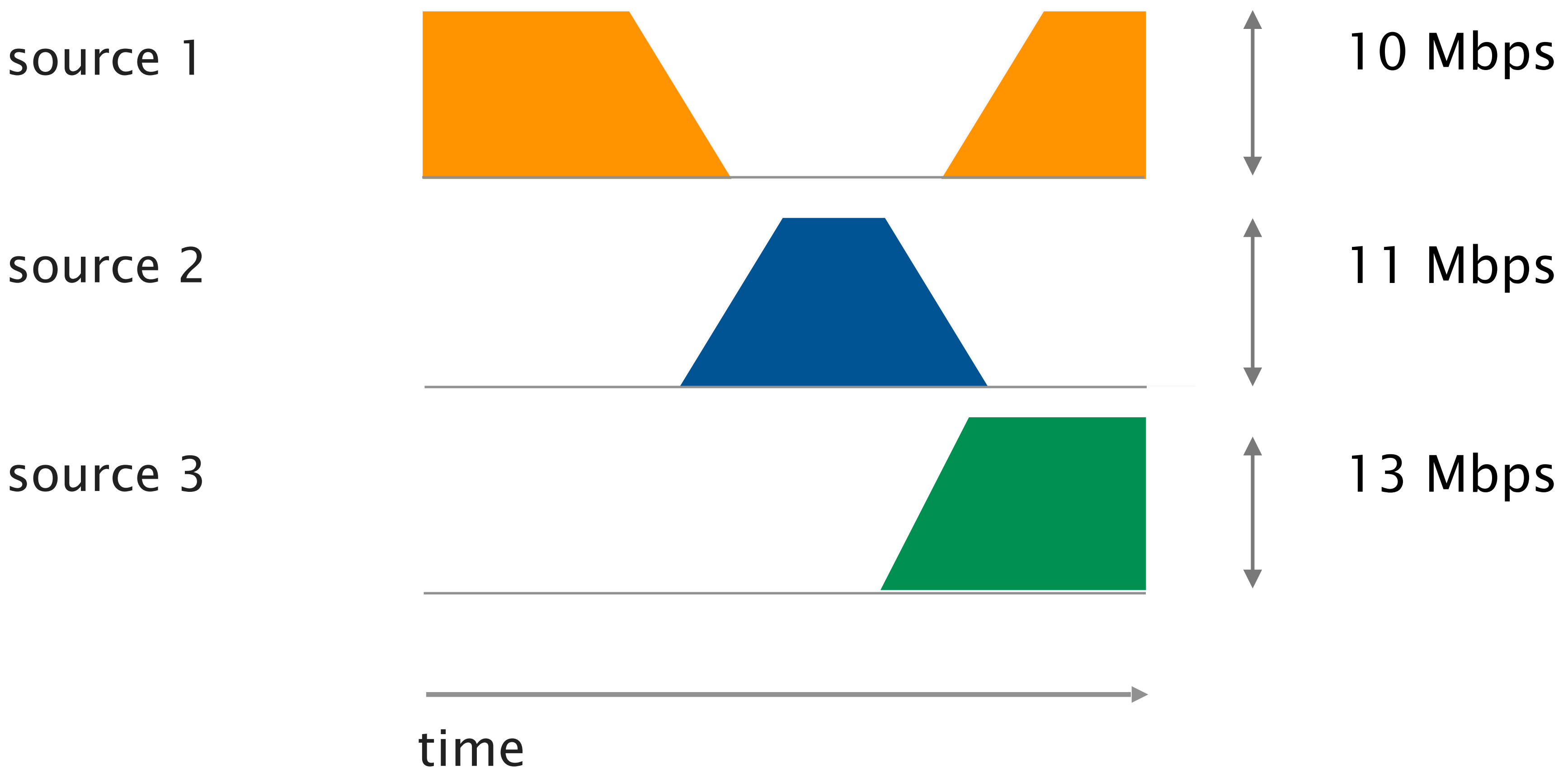
What do they get with:

- reservation
- on-demand

Assume the following peak demand and flow duration



Assume the following peak demand and flow duration



What does each source get with reservation and on-demand?

- first-come first-served
- equal (10 Mbps)

Peak vs average rates

Each flow has	Peak rate	P
	Average rate	A

Reservation must reserve P, but level of utilization is A/P

P=100 Mbps, A=10 Mbps, level of utilization=10%

On-demand can usually achieve higher level of utilization

depends on degree of sharing and burstiness of flows

Ultimately, it depends on the application

Reservation makes sense when P/A is small

voice traffic has a ratio of 3 or so

Reservation wastes capacity when P/A is big

data applications are bursty, ratios >100 are common

Reservation makes sense when P/A is small

voice traffic has a ratio of 3 or so

Reservation wastes capacity when P/A is big

data applications are bursty, ratios >100 are common

That's why the phone network used reservations

… and why the Internet does not!

The two approaches are implemented using circuit-switching or packet-switching, respectively

	Reservation	On-demand
implem.	circuit switching	packet switching

Reservation

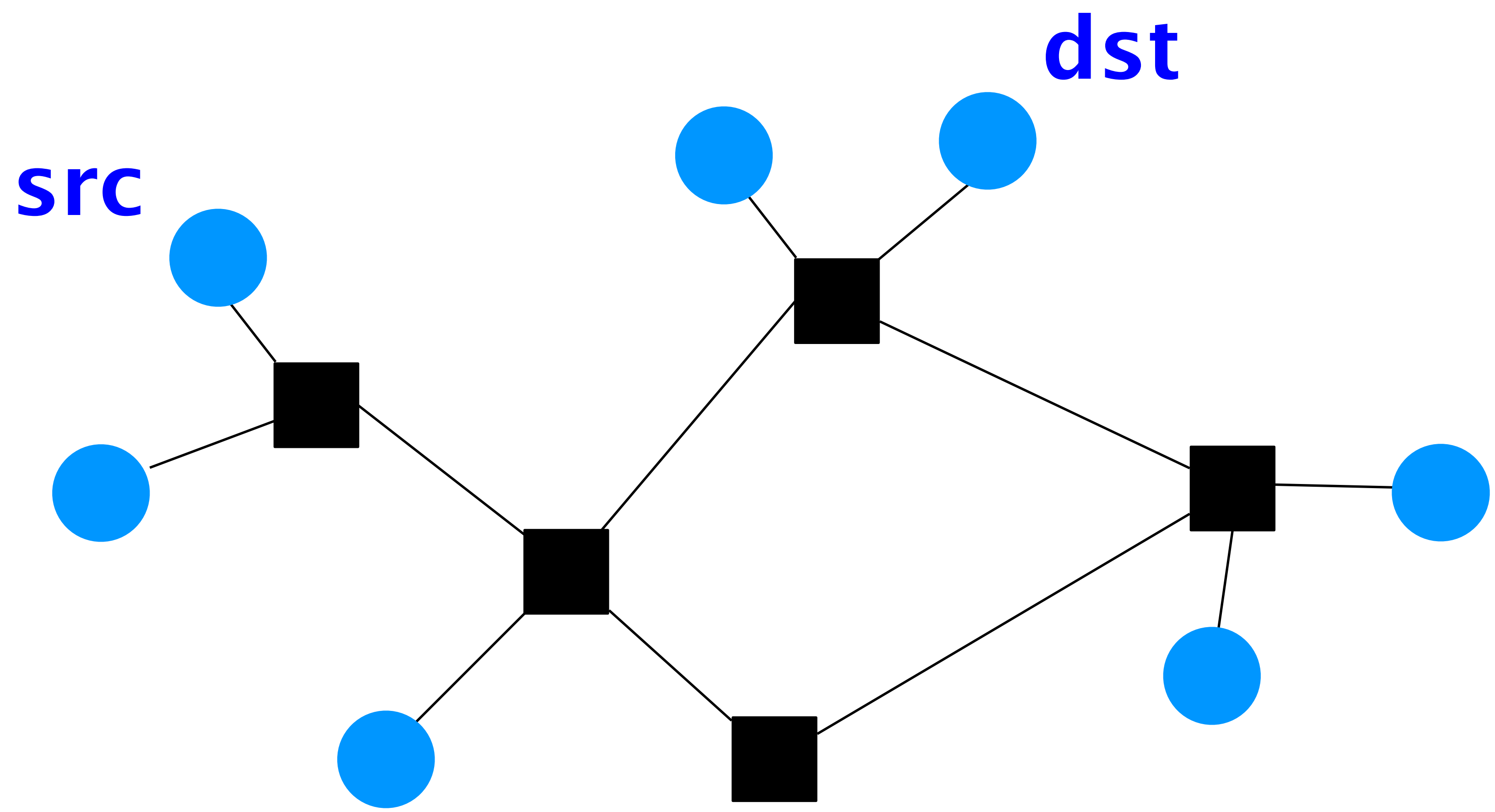
On-demand

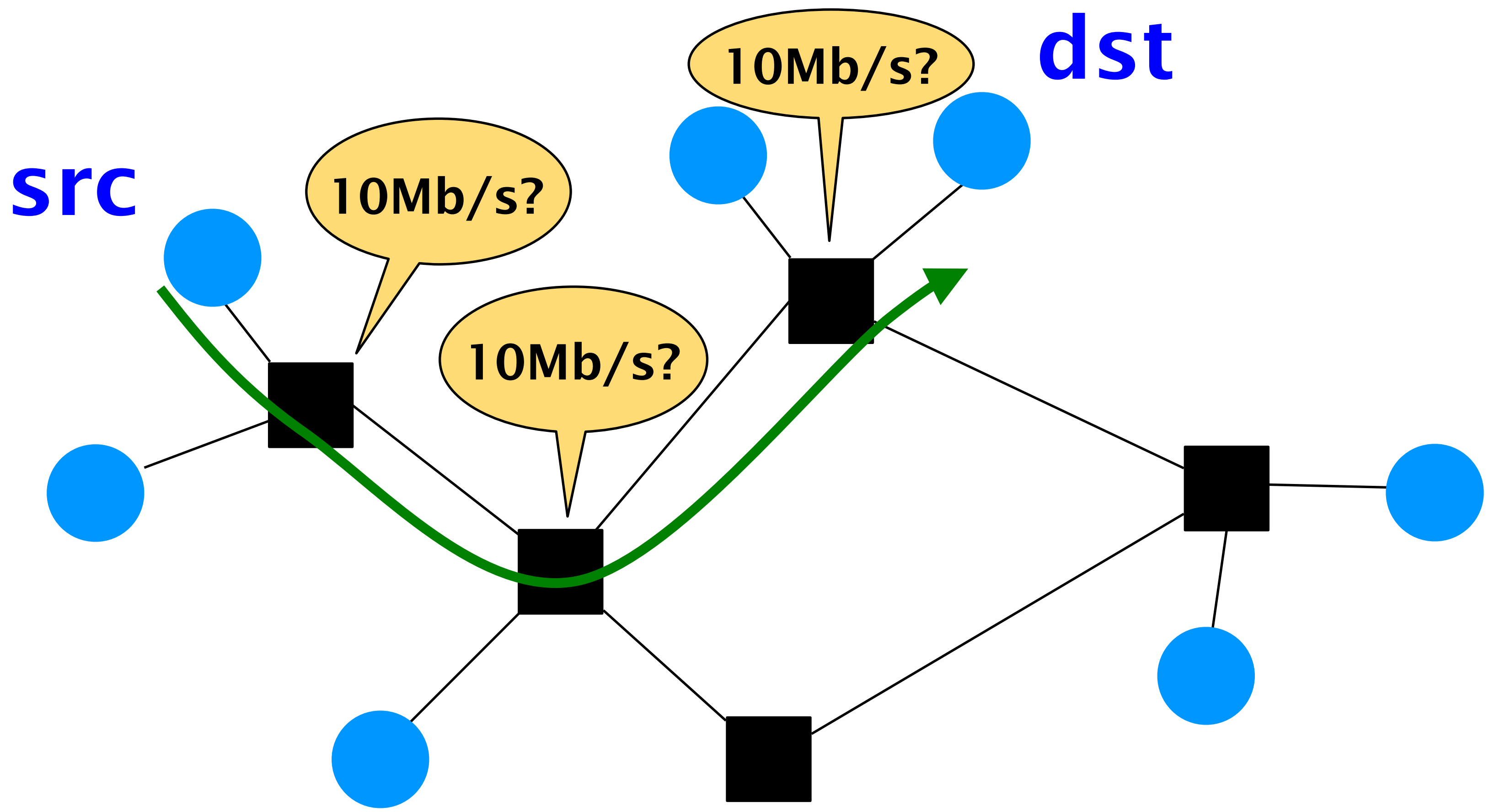
implem.

circuit-switching

packet-switching

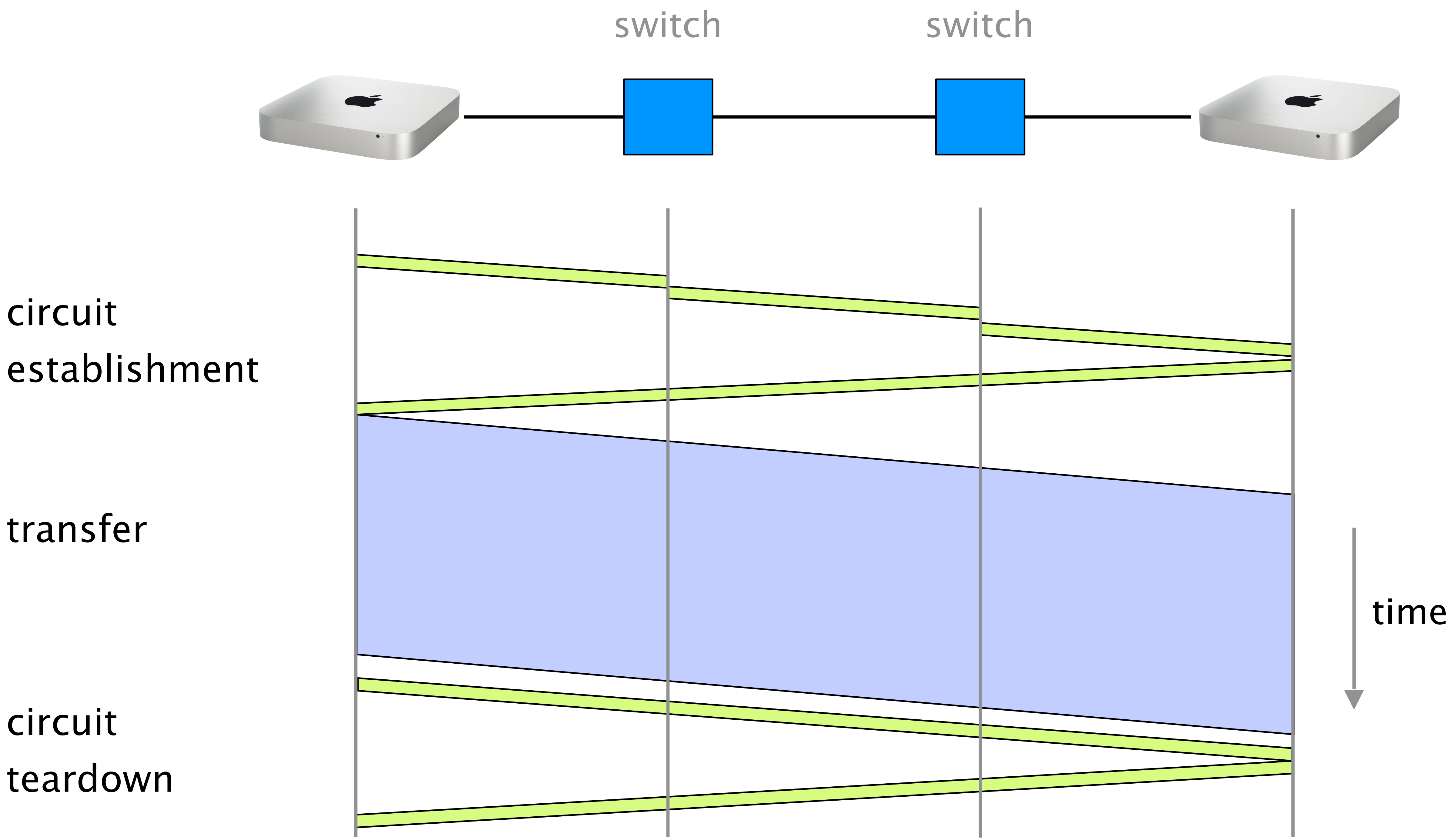
Circuit switching relies on
the Resource Reservation Protocol





(1) src sends a reservation request for 10Mbps to dst
(2) switches "establish a circuit"
(3) src starts sending data
(4) src sends a "teardown circuit" message

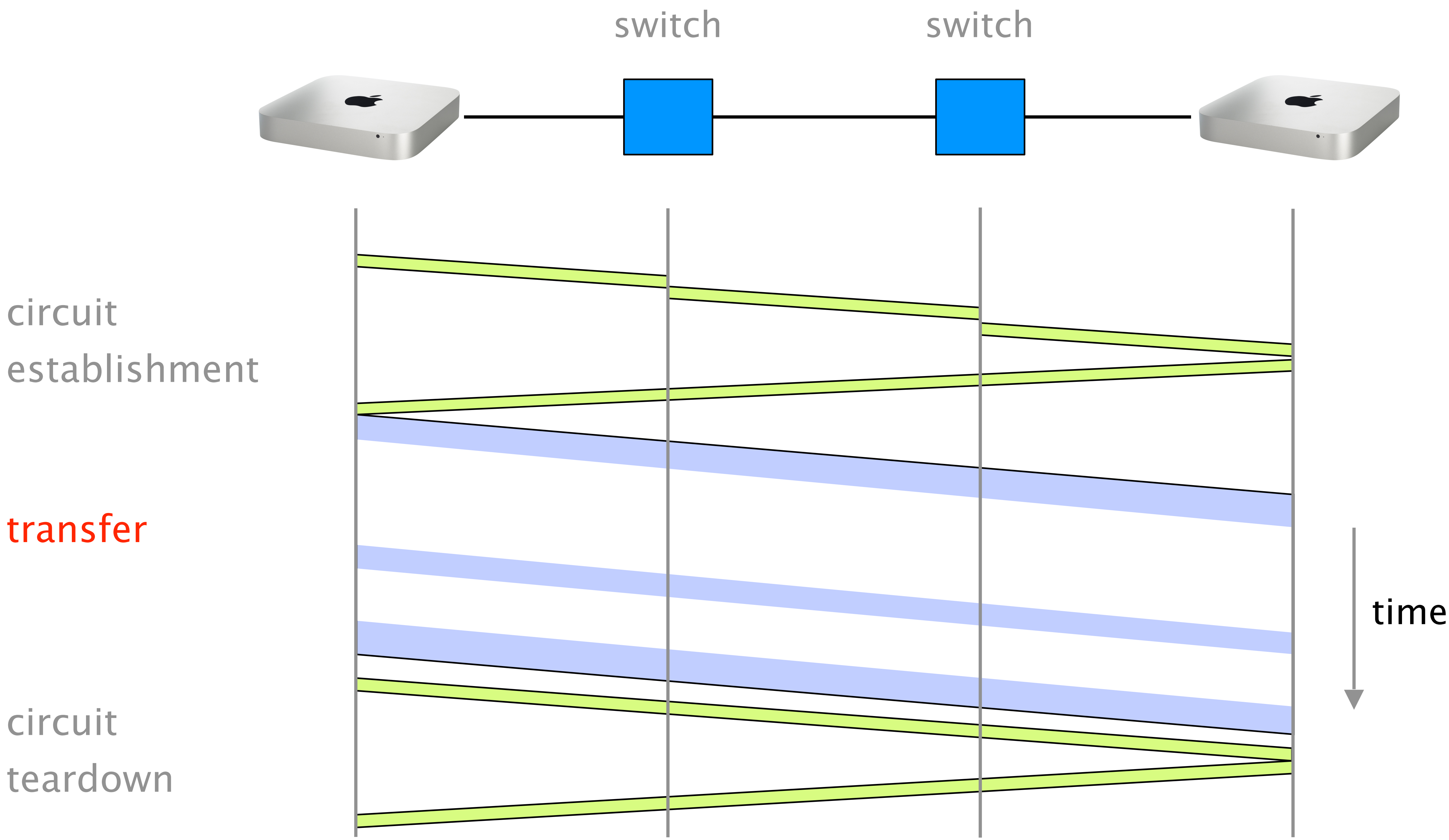
Let’s walk through example of data transfer using circuit switching



The efficiency of the transfer depends on how utilized the circuit is once established

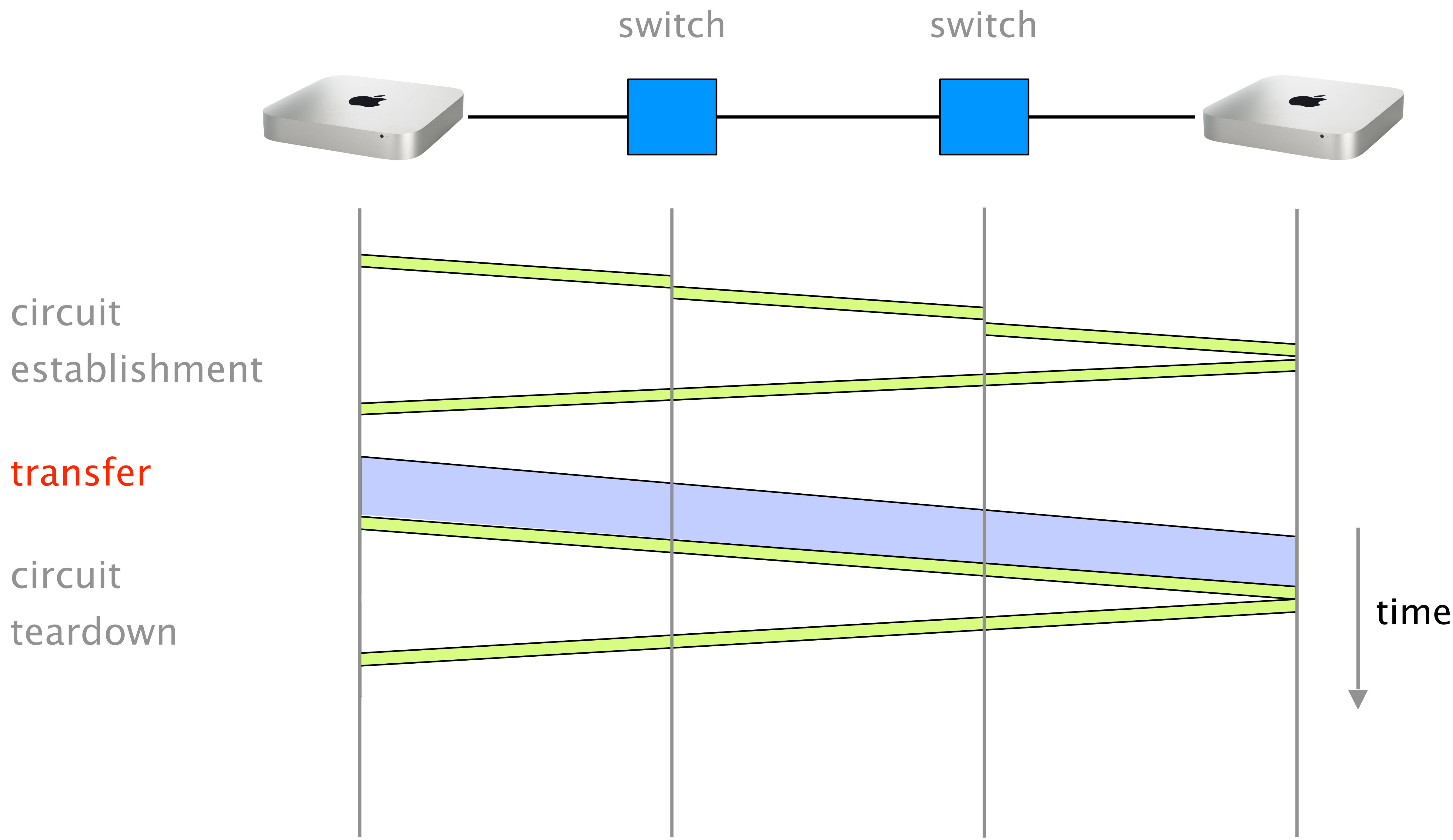
This is an example of poor efficiency.

The circuit is mostly idle due to traffic bursts

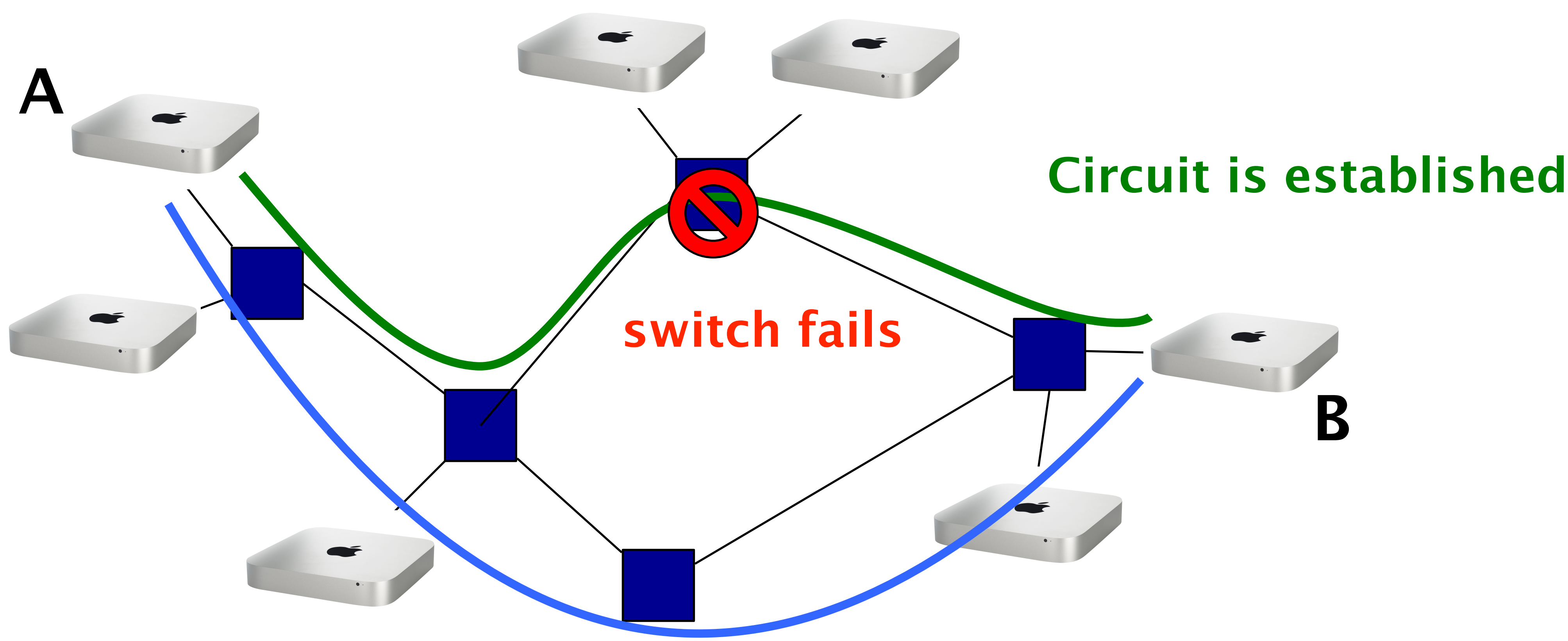


This is another example of poor efficiency.

The circuit is used for a short amount of time



Another problem of circuit switching is that it doesn’t route around trouble



A is forced to signal a new circuit to restore communication

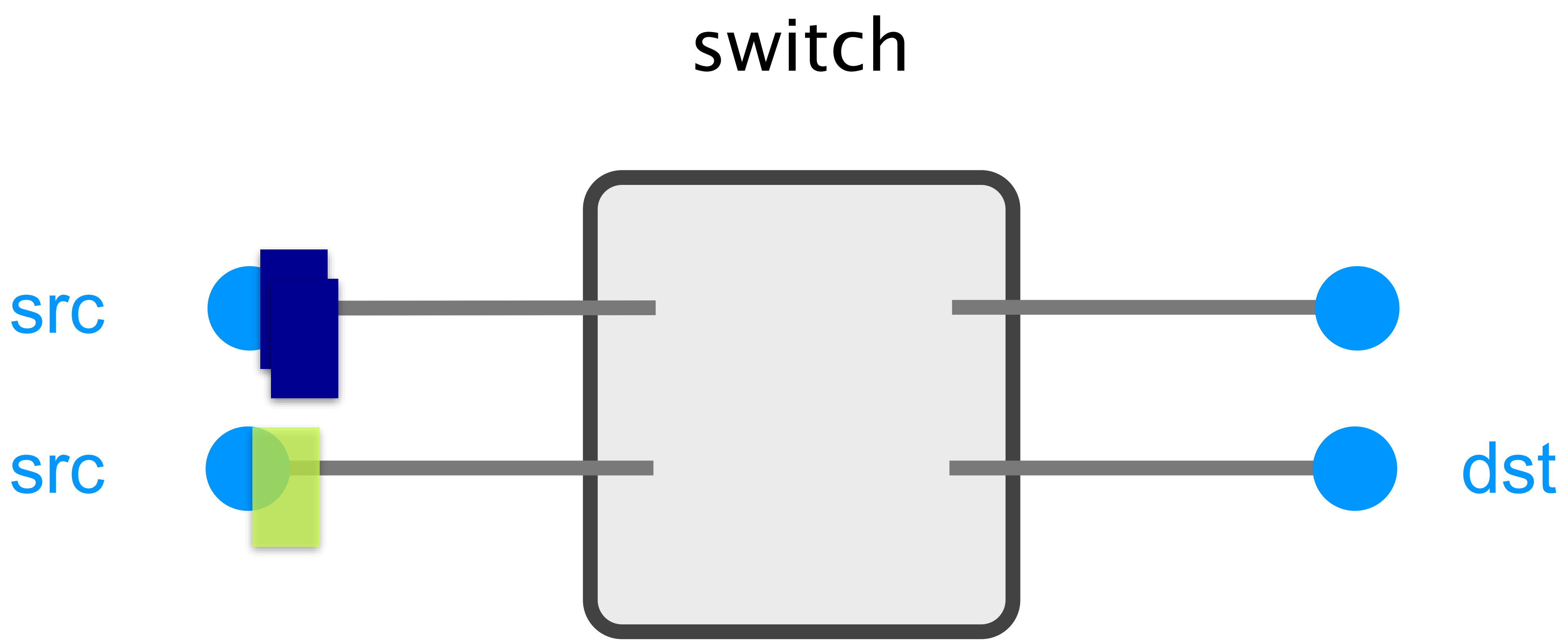
Pros and cons of circuit switching

advantages	disadvantages
predictable performance	inefficient if traffic is bursty or short
simple & fast switching once circuit established	complex circuit setup/teardown which adds delays to transfer
	requires new circuit upon failure

What about packet switching?

Reservation	On-demand
circuit switching	packet switching

In packet switching,
data transfer is done using independent packets

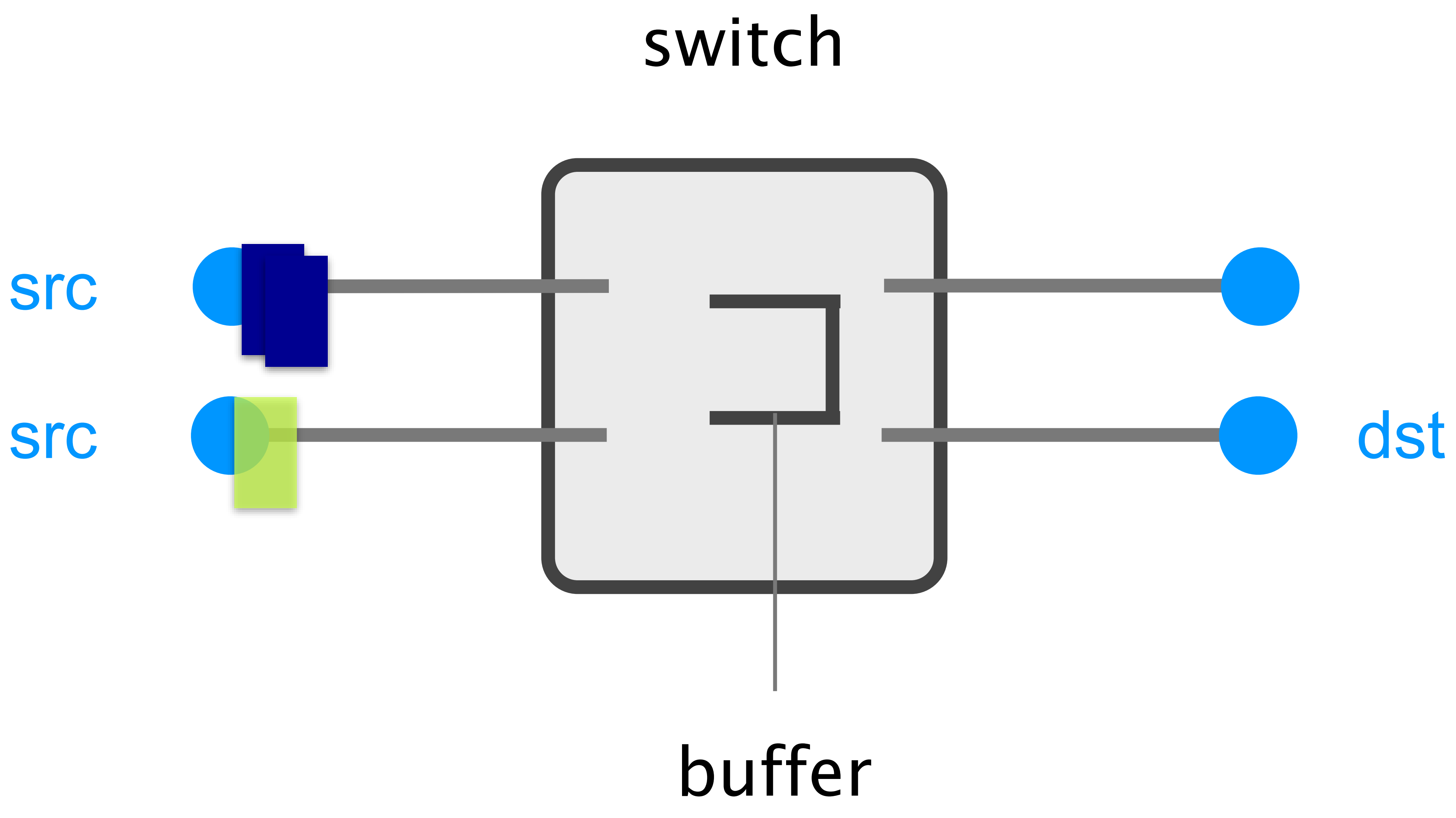


Each packet contains a destination (dst)

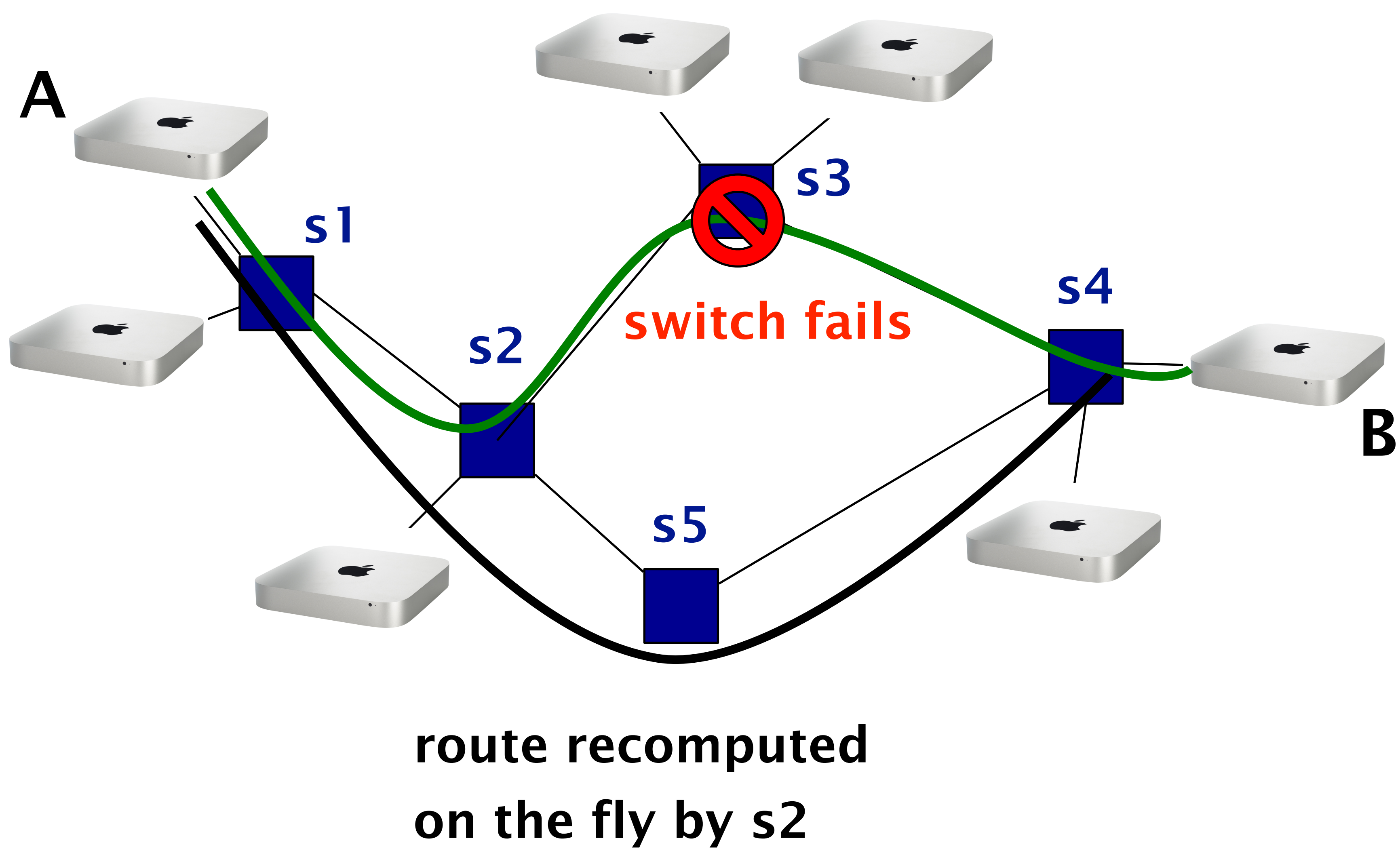
Since packets are sent without global coordination, they can “clash” with each other

To absorb transient overload,
packet switching relies on buffers

To absorb transient overload,
packet switching relies on buffers



Packet switching routes around trouble



Pros and cons of packet switching

advantages

efficient use of resources

requires no coordination

route around trouble

disadvantages

unpredictable performance

requires buffer management and congestion control

Packet switching beats circuit switching
with respect to *resiliency* and *efficiency*

Internet ❤ packets

Packet switching will be our focus for the rest of the course

Communication Networks

Part 1: Overview

What is a network made of?

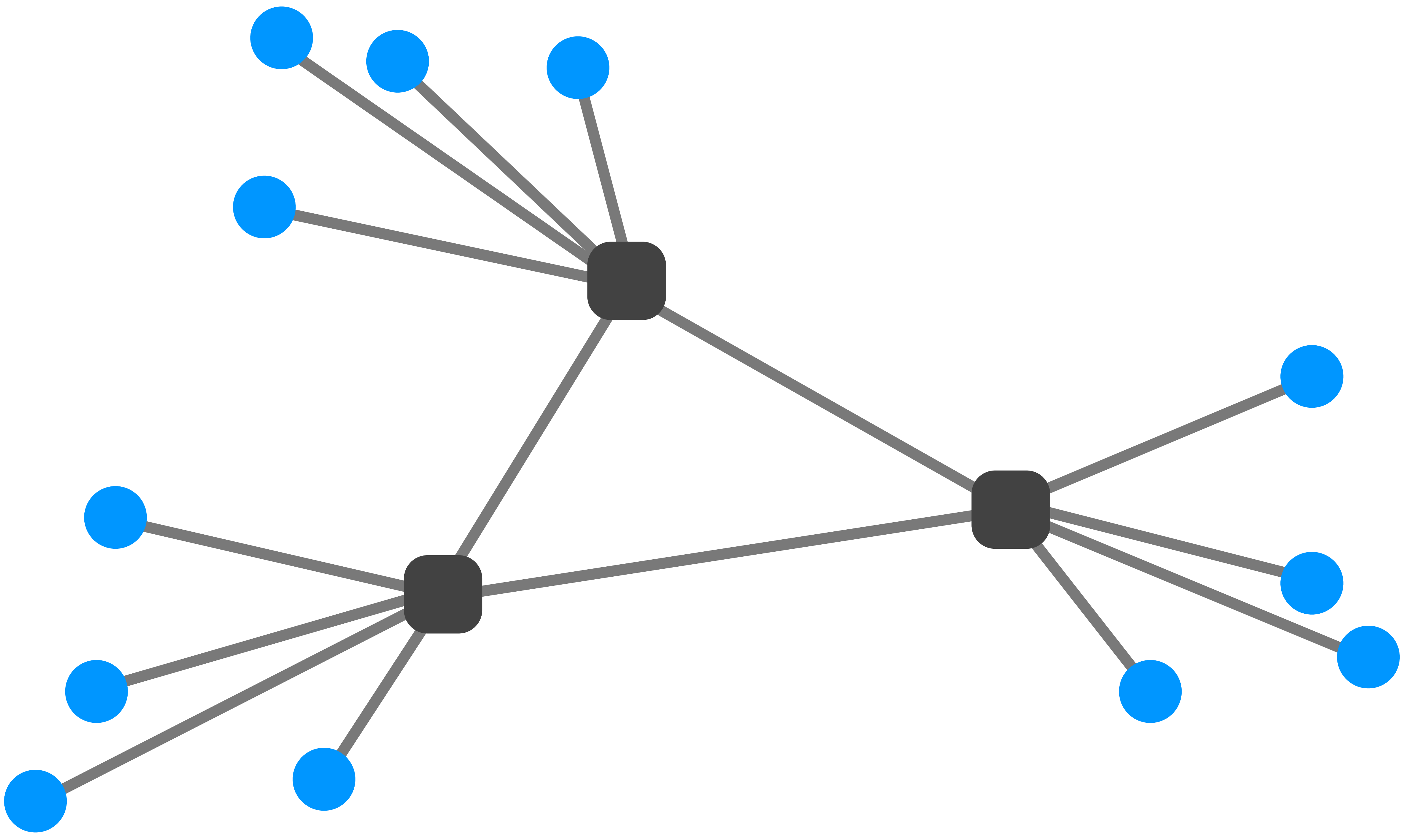
How is it shared?

#3 How is it organized?

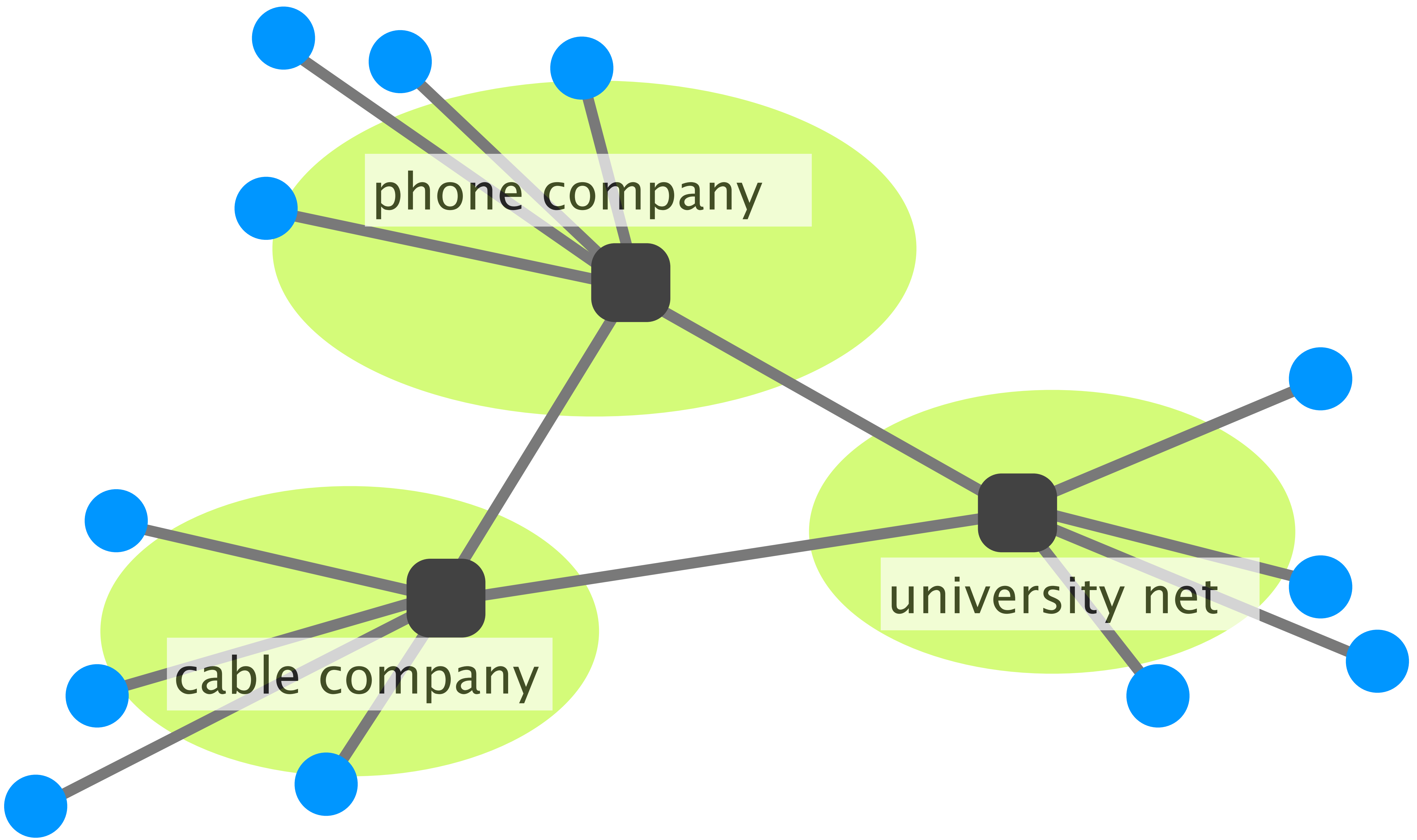
How does communication happen?

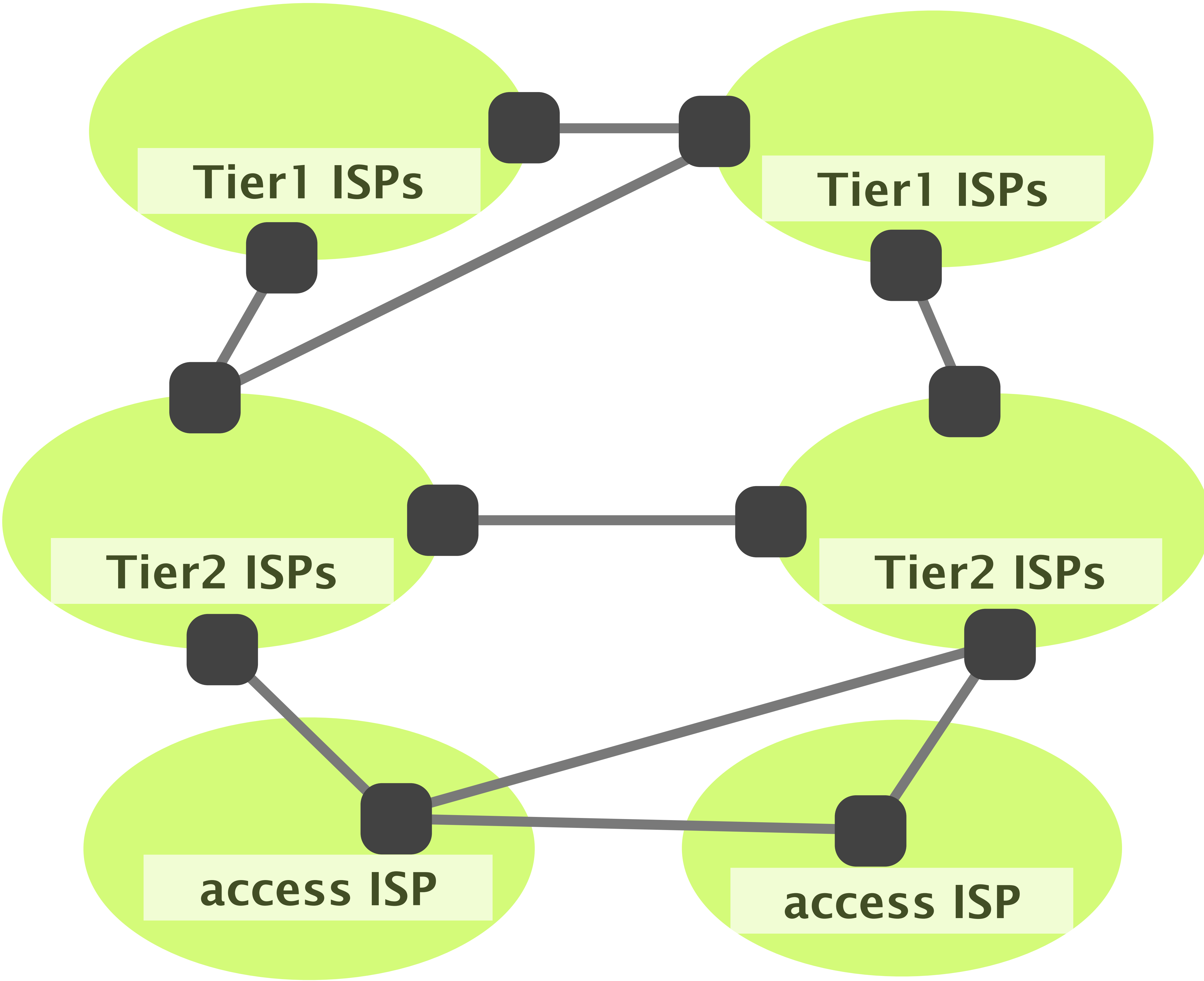
How do we characterize it?

The *Inter*net is a network of networks



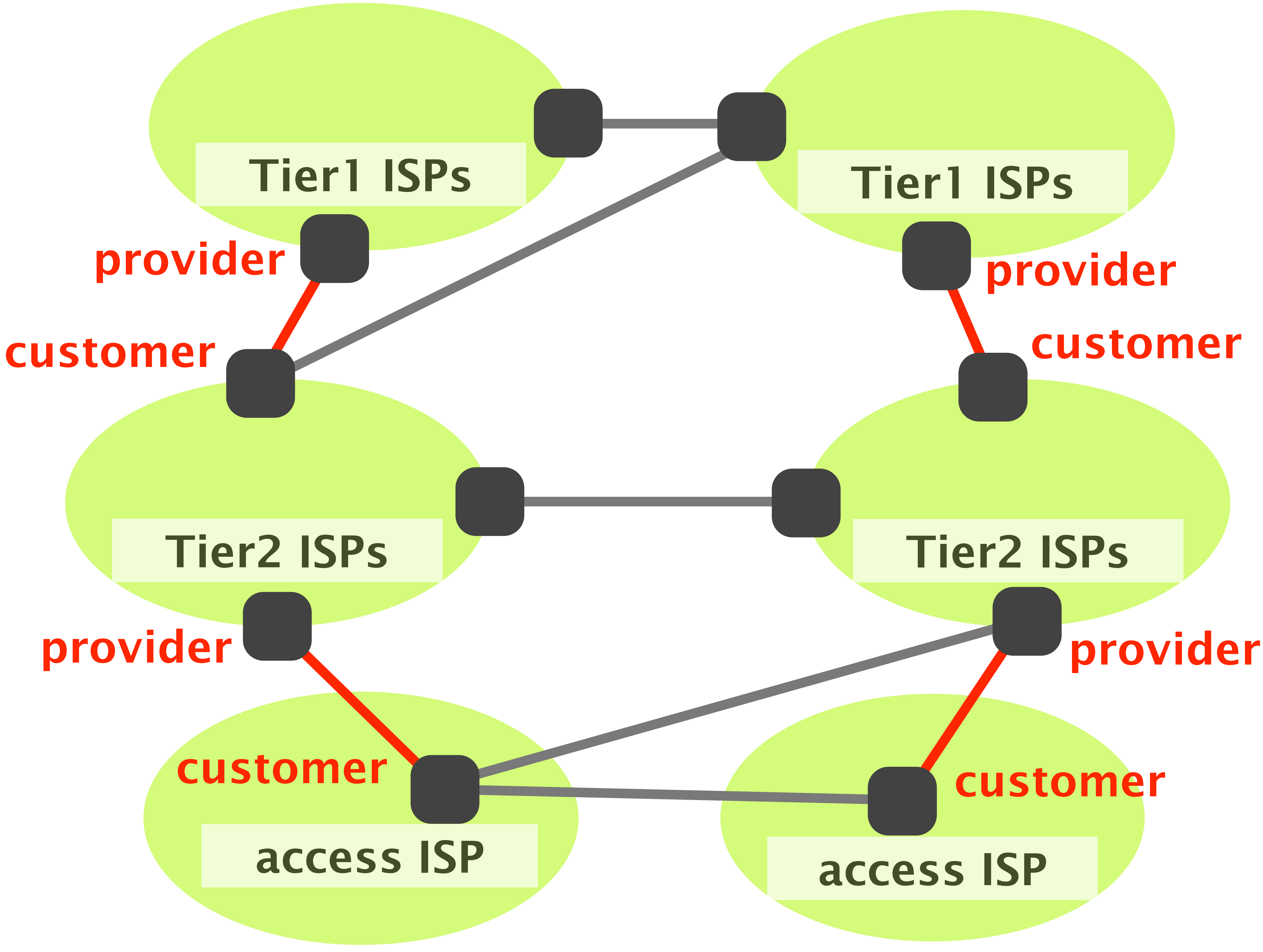
Internet Service Providers




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

The Internet has a hierarchical structure

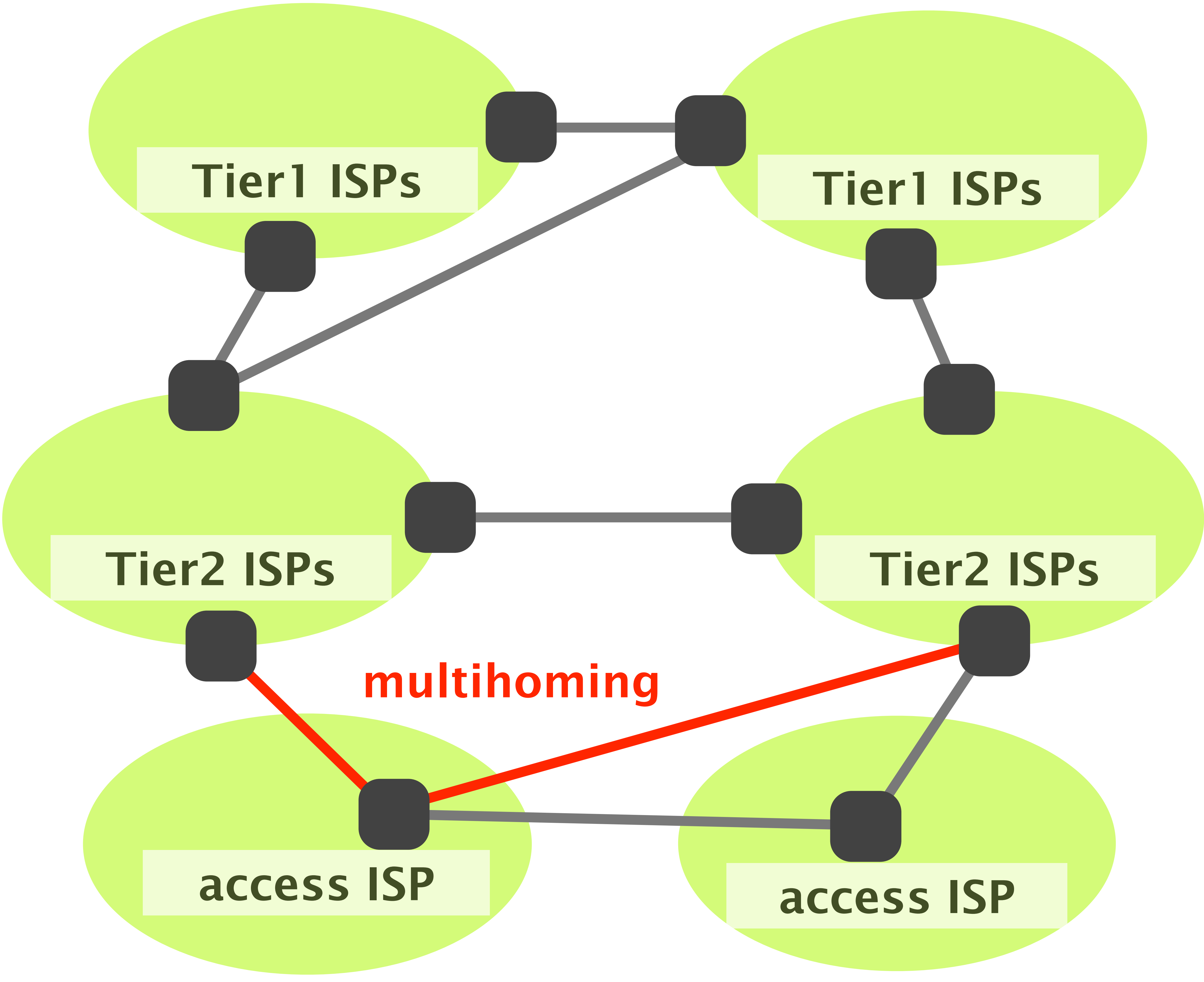
Tier-1 international	have no provider
Tier-2 national	provide transit to Tier-3s have at least one provider
Tier-3 local	do not provide any transit have at least one provider



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

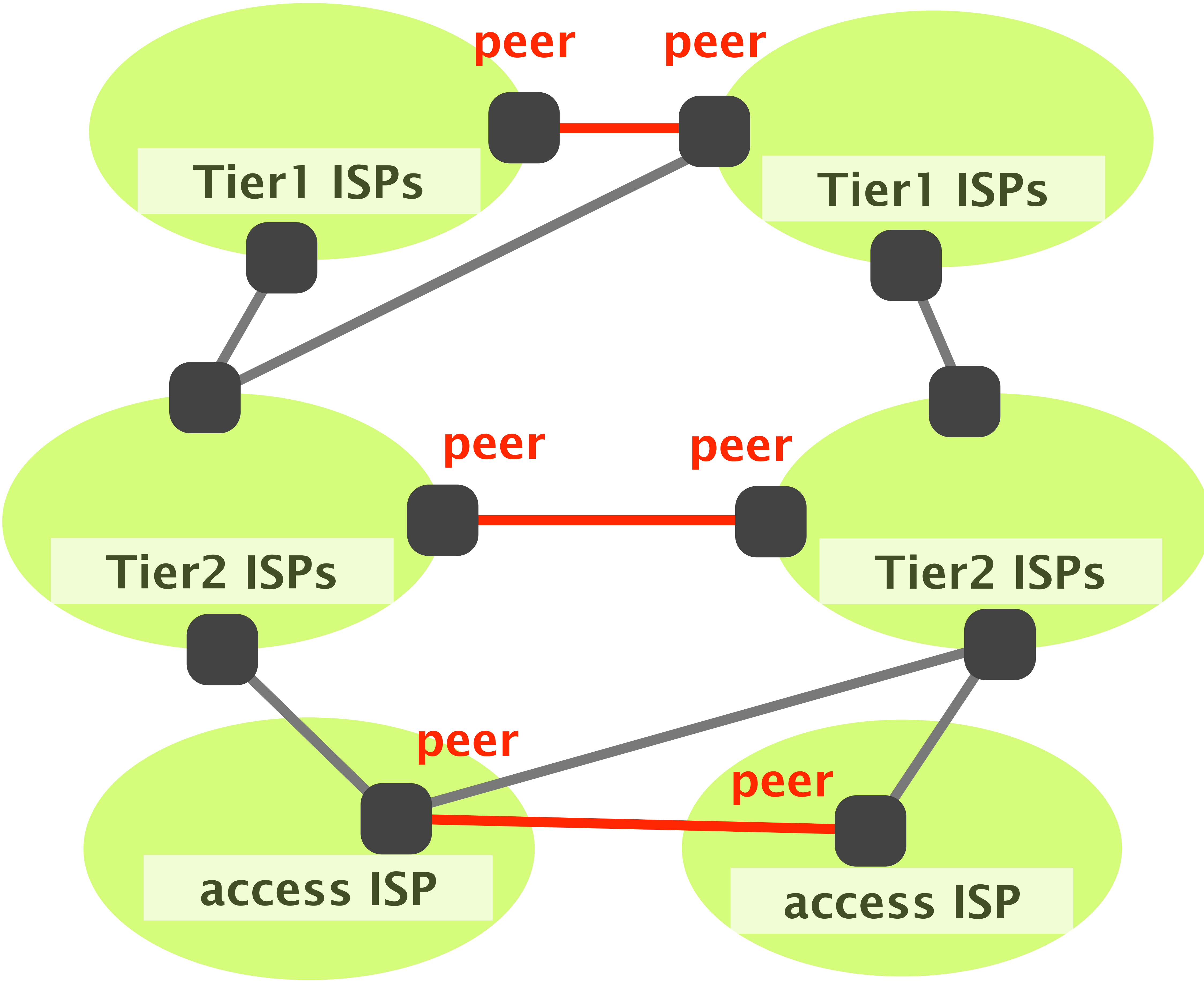
The distribution of networks in Tiers is extremely skewed towards Tier-3s

	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

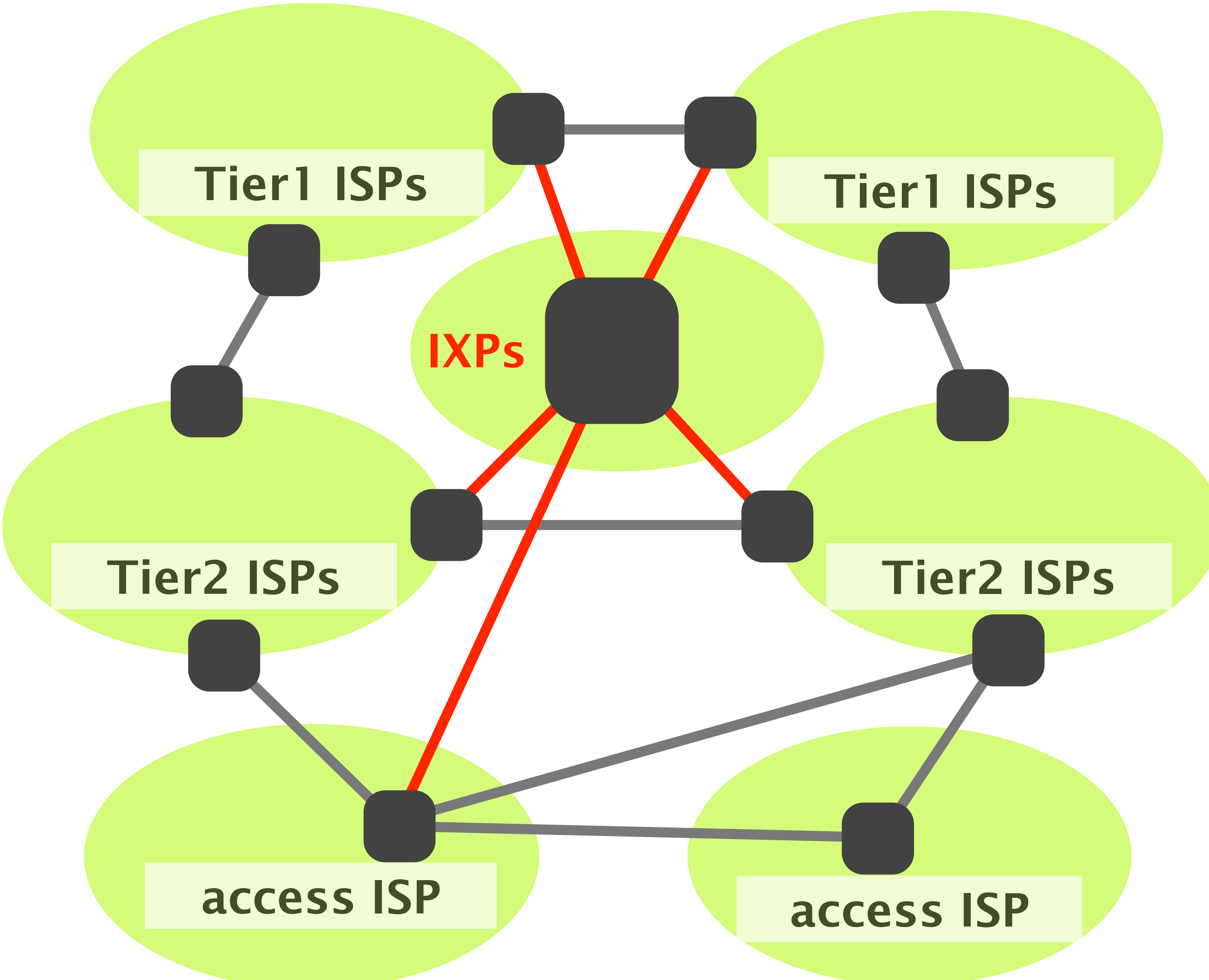
Bandwidth costs

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