Communication Networks

Spring 2018

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Materials inspired from Scott Shenker, Jennifer Rexford, Changhoon Kim, and Ankit Singla

Last week on

Communication Networks

Video Streaming

HTTP-based

E-mail

MX, SMTP, POP, IMAP

Video Streaming

E-mail

HTTP-based

We want the highest video quality

Without seeing this …

Encoding

Replication

Adaptation

Encoding

Replication

Adaptation

[bitmovin.com]

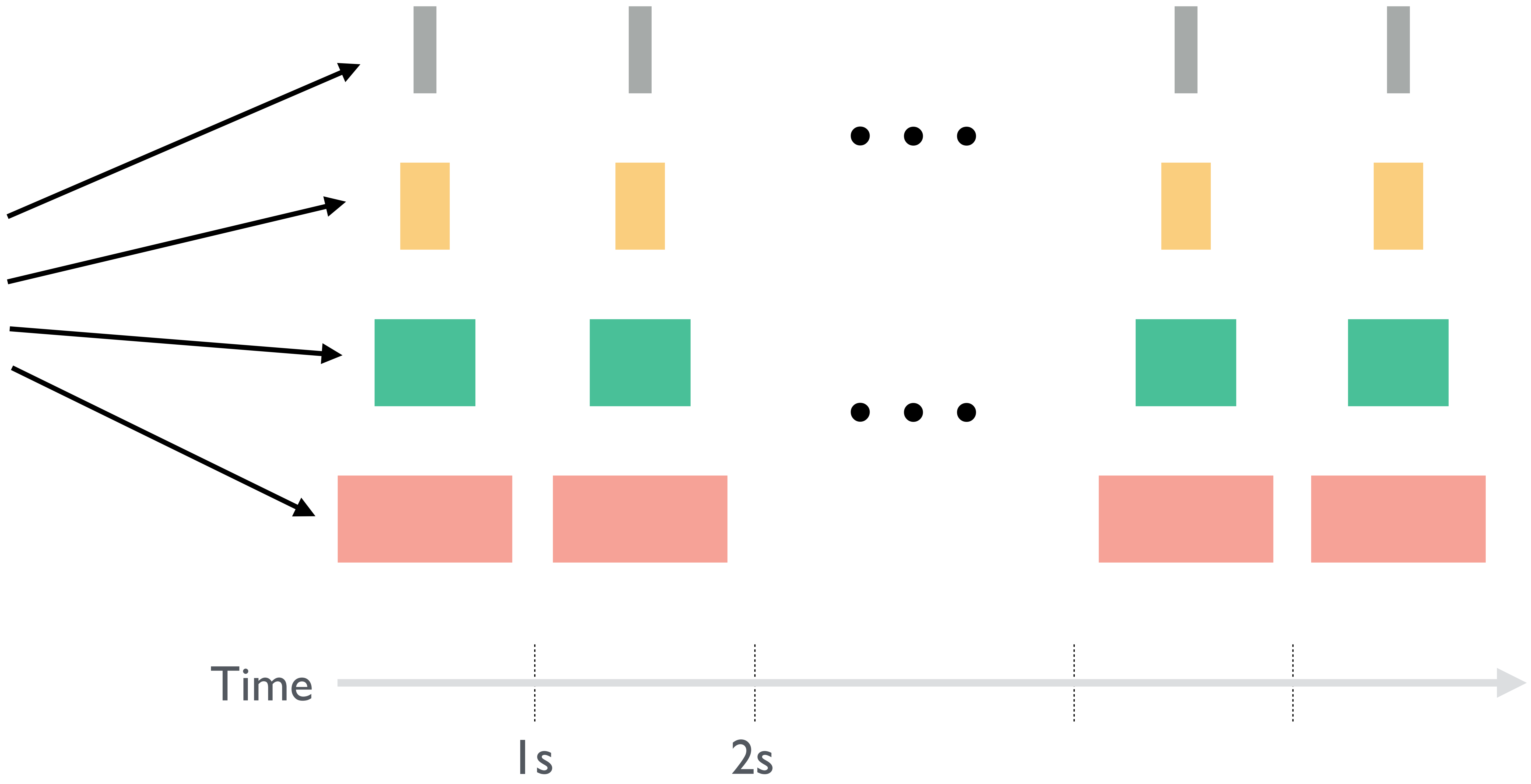
Simple solution for encoding: use a "bitrate ladders"

Bitrate (kbps)	Resolution
235	320x240
375	384x288
560	512x384
750	512x384
1050	640x480
1750	720x480
2350	1280x720
3000	1280x720
4300	1920x1080
5800	1920x1080

[netflix.com]

Your player download “chunks” of video at different bitrates

[netflix.com]



Depending on your network connectivity, your player fetches chunks of different qualities


[netflix.com]

Your player gets metadata about chunks via "Manifest"

```xml
<?xml version="1.0" encoding="UTF-8"?>
<MPD xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
    xmlns="urn:mpeg:DASH:schema:MPD:2011"
    xsi:schemaLocation="urn:mpeg:DASH:schema:MPD:2011"
    profiles="urn:mpeg:dash:profile:isoff-main:2011"
    type="static"
    mediaPresentationDuration="PT0H9M56.46S"
    minBufferTime="PT15.0S">
  <BaseURL>http://witestlab.poly.edu/~ffund/video/2s_480p_only/</BaseURL>
  <Period start="PT0S">
         <AdaptationSet bitstreamSwitching="true">
     <Representation id="0" codecs="avc1" mimeType="video/mp4"
        width="480" height="360" startWithSAP="1" bandwidth="101492">
       <SegmentBase>
         <Initialization sourceURL="bunny_2s_100kbit/bunny_100kbit.mp4"/>
       </SegmentBase>
       <SegmentList duration="2">
         <SegmentURL media="bunny_2s_100kbit/bunny_2s1.m4s"/>
         <SegmentURL media="bunny_2s_100kbit/bunny_2s2.m4s"/>
         <SegmentURL media="bunny_2s_100kbit/bunny_2s3.m4s"/>
         <SegmentURL media="bunny_2s_100kbit/bunny_2s4.m4s"/>
         <SegmentURL media="bunny_2s_100kbit/bunny_2s5.m4s"/>
         <SegmentURL media="bunny_2s_100kbit/bunny_2s6.m4s"/>
```

[witestlab.poly.edu]

Encoding

Replication

Adaptation

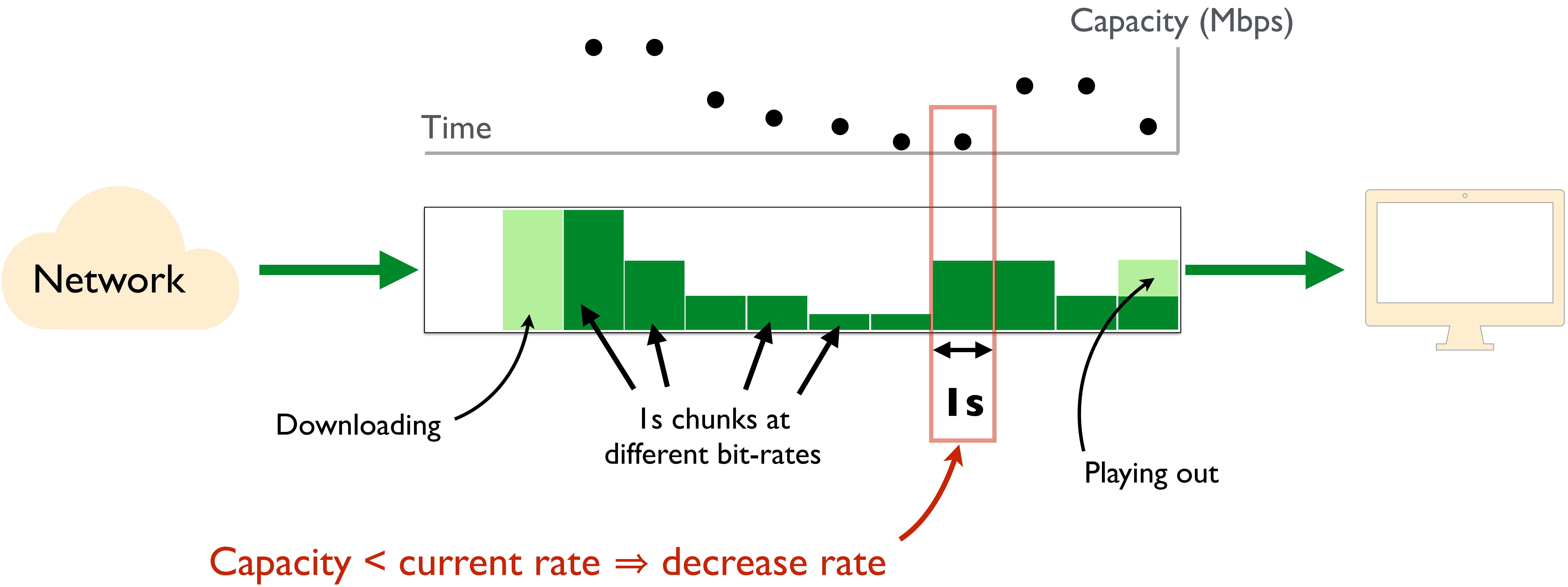

Greenland
Canada
Mexico
Brazil
Peru
Sweden
Norway
Finland
Belarus
Ukraine
France
Turkey
Russia
Kazakhstan
Mongolia
China
Iraq
Iran
Pakistan
India
Algeria
Libya
Egypt
Saudi Arabia
Sudan
Yemen
Congo (Kinshasa)
South Africa
Australia
New Zealand

[netflix.com]

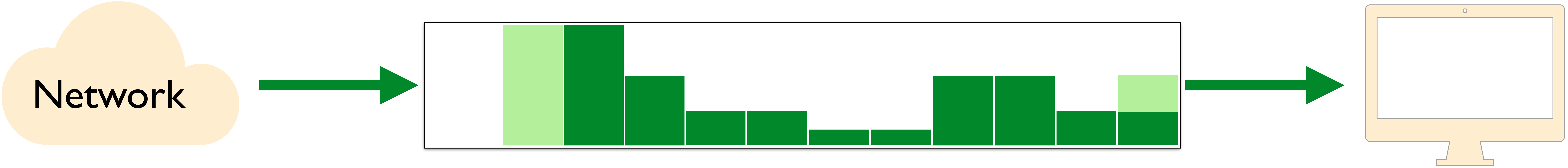
Encoding

Replication

Adaptation


Capacity (Mbps)
Time
Network
Downloading
1s chunks at
different bit-rates
1s
Playing out
Capacity < current rate ⇒ decrease rate

Buffer-based adaptation

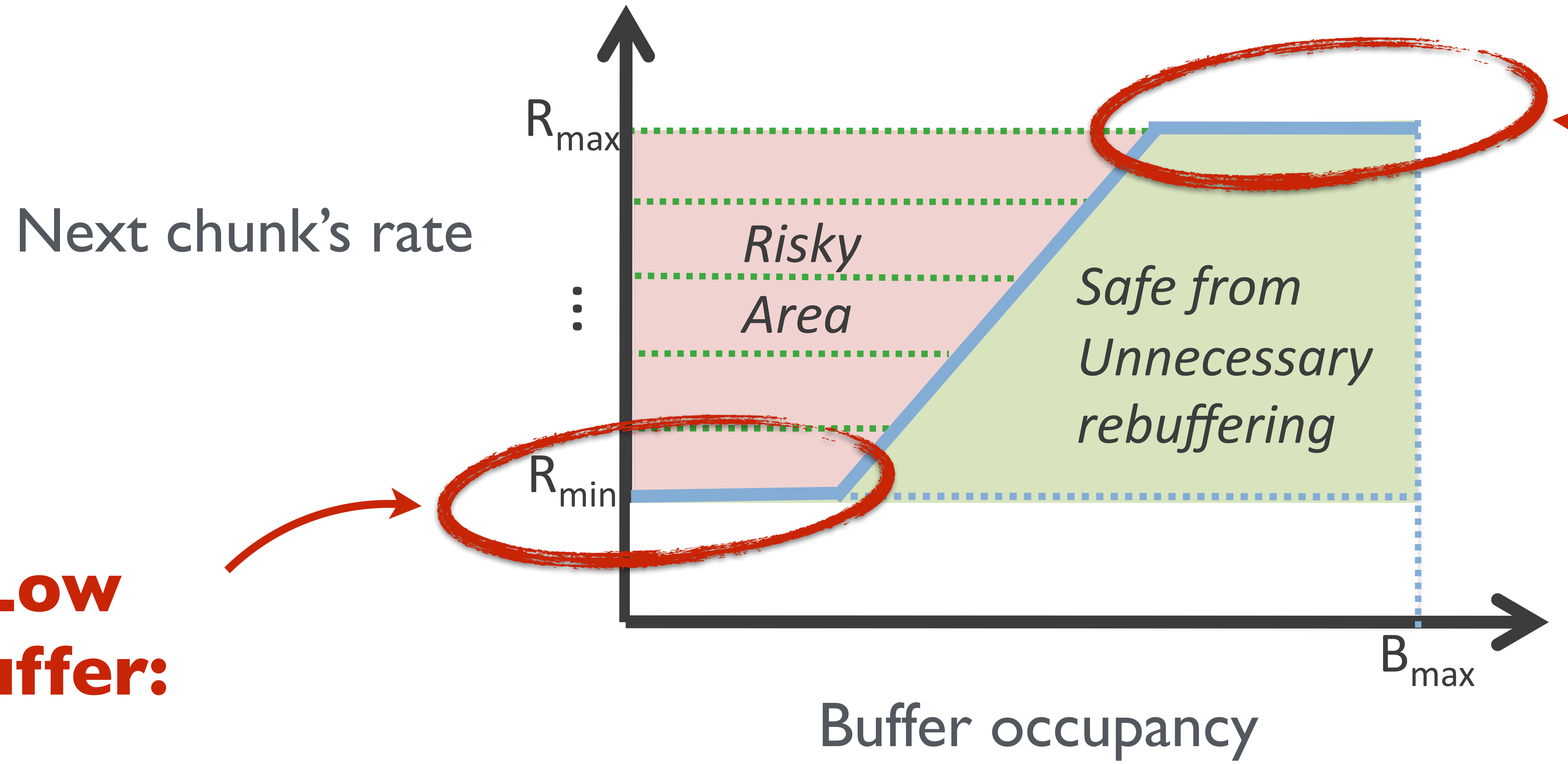


Nearly full buffer ⇒ large rate

Buffer-based adaptation

Nearly empty buffer ⇒ small rate

Buffer-based adaptation



High buffer:

Low buffer:

[A Buffer-Based Approach to Rate Adaptation: Evidence from a Large Video Streaming Service, Huang et al., ACM SIGCOMM 2014]

Video Streaming

E-mail

MX, SMTP, POP, IMAP

We looked at e-mail from three different perspectives

Content	Infrastructure/ Transmission	Retrieval
Format: Header/Content	SMTP: Simple Mail Transfer Protocol	POP: Post Office Protocol
Encoding: MIME	Infrastructure mail servers	IMAP: Internet Message Access Protocol

Content

Infrastructure/
Transmission

Retrieval

Format: Header/Content

Encoding: MIME

Email relies on 7-bit U.S. ASCII…

How do you send non-English text? Binary files?

Solution

Multipurpose Internet Mail Extensions

commonly known as MIME, standardized in RFC 822

MIME defines

- additional headers for the email body
- a set of content types and subtypes
- base64 to encode binary data in ASCII

MIME relies on Base64 as binary-to-text encoding scheme

Relies on 64 characters out of the 128 ASCII characters

the most common *and* printable ones, i.e. A-Z, a-z, 0-9, +, /

Divides the bytes to be encoded into sequences of 3 bytes

each group of 3 bytes is then encoded using 4 characters

Uses padding if the last sequence is partially filled

i.e. if the |sequence| to be encoded is not a multiple of 3

Binary input	0x14fb9c03d97e
8-bits	00010100 11111011 10011100 00000011 11011001 01111110
6-bits	000101 001111 101110 011100 000000 111101 100101 111110
Decimal	5 15 46 28 0 61 37 62
base64	F P u c A 9 l +

Content

Infrastructure/
Transmission

Retrieval

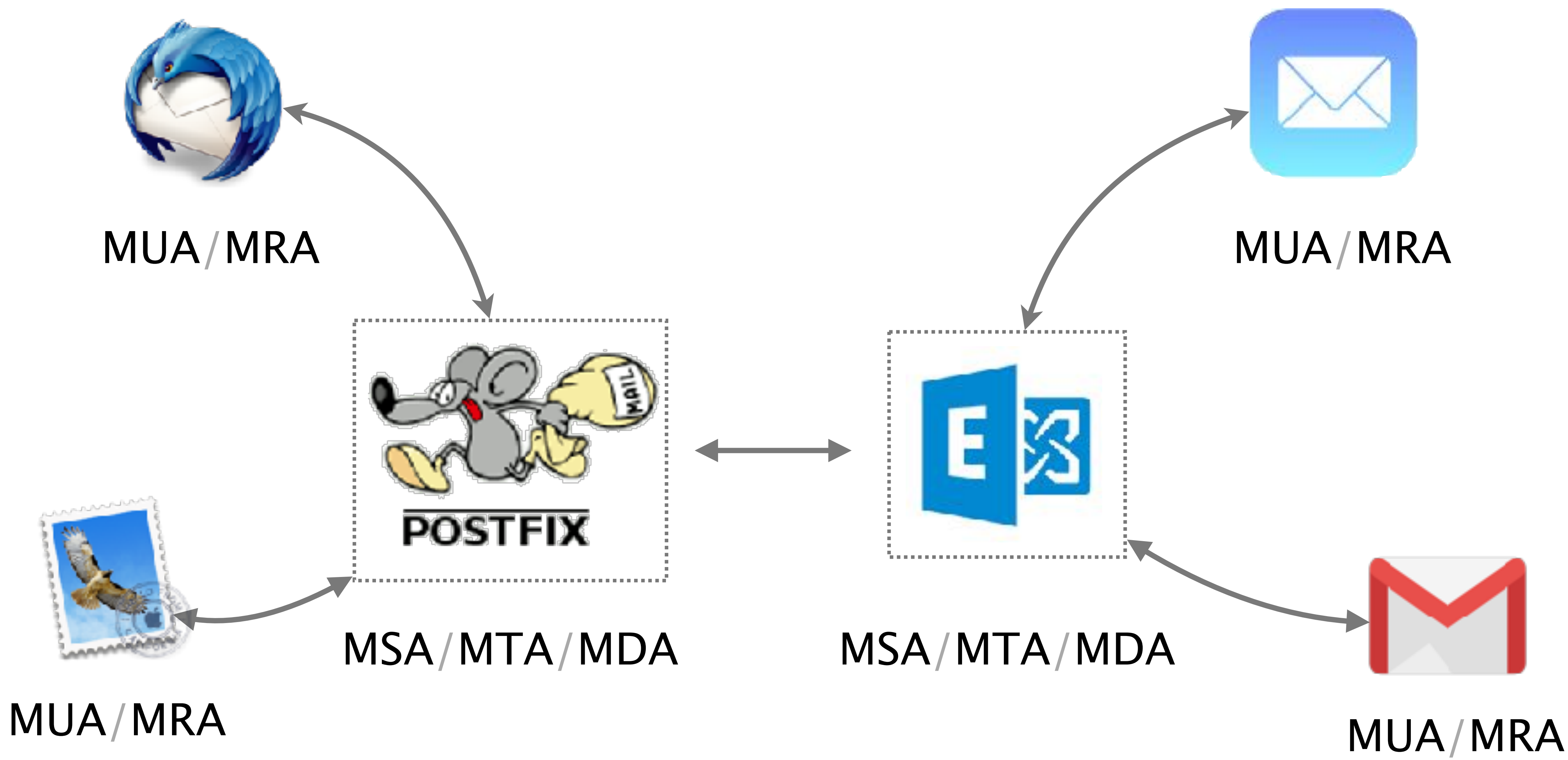
SMTP: Simple Mail
Transfer Protocol

Infrastructure
mail servers

We can divide the e-mail infrastructure into five functions

Mail	User	Agent	Use to read/write emails (mail client)
Mail	Submission	Agent	Process email and forward to local MTA
Mail	Transmission	Agent	Queues, receives, sends mail to other MTAs
Mail	Delivery	Agent	Deliver email to user mailbox
Mail	Retrieval	Agent	Fetches email from user mailbox

MSA/MTA/MDA and MRA/MUA are often packaged together leading to simpler workflows



Simple Mail Transfer Protocol (SMTP) is the current standard for transmitting e-mails

SMTP is a text-based, client-server protocol

client sends the e-mail, server receives it

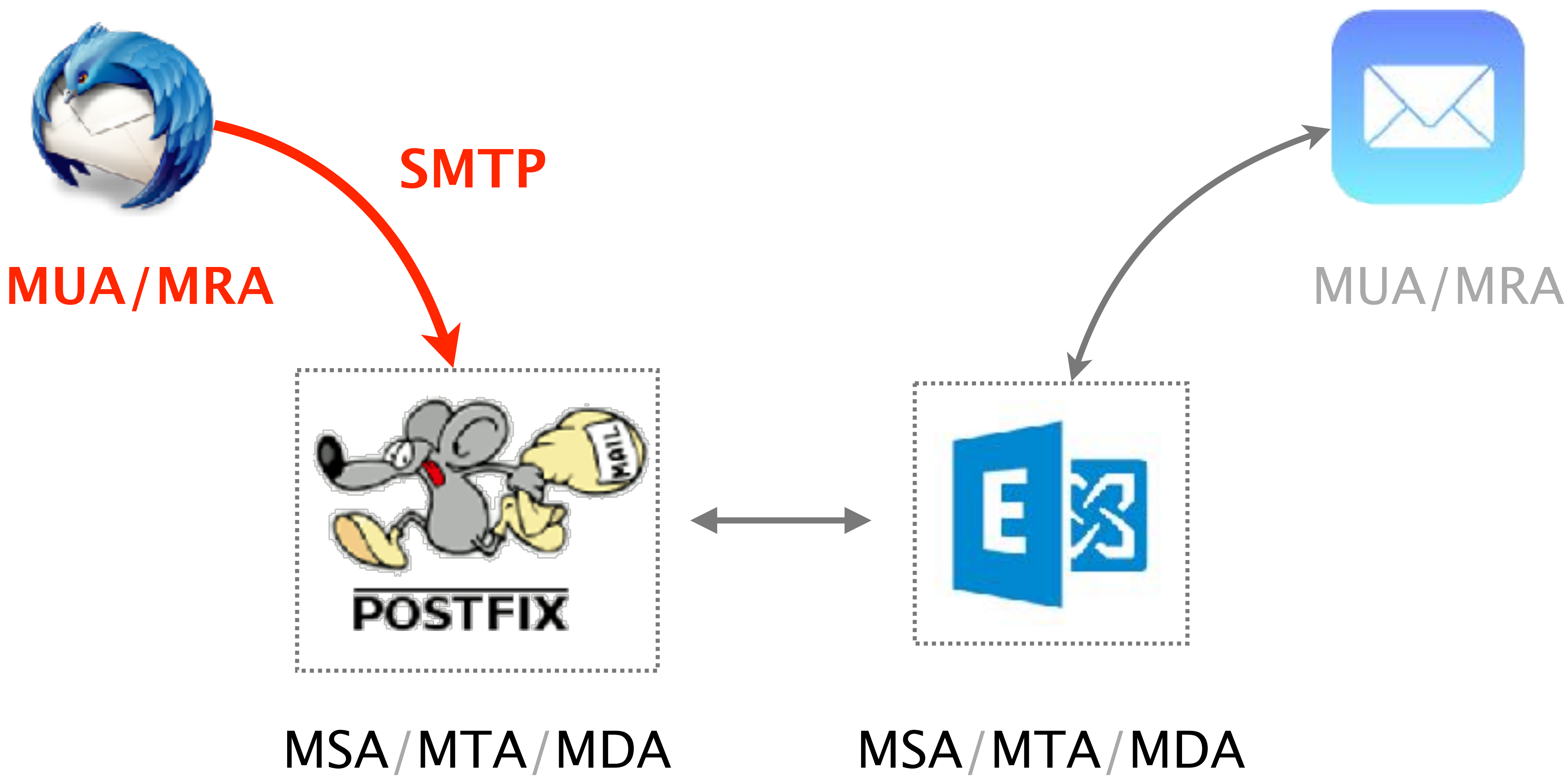
SMTP uses reliable data transfer

built on top of TCP (port 25 and 465 for SSL/TLS)

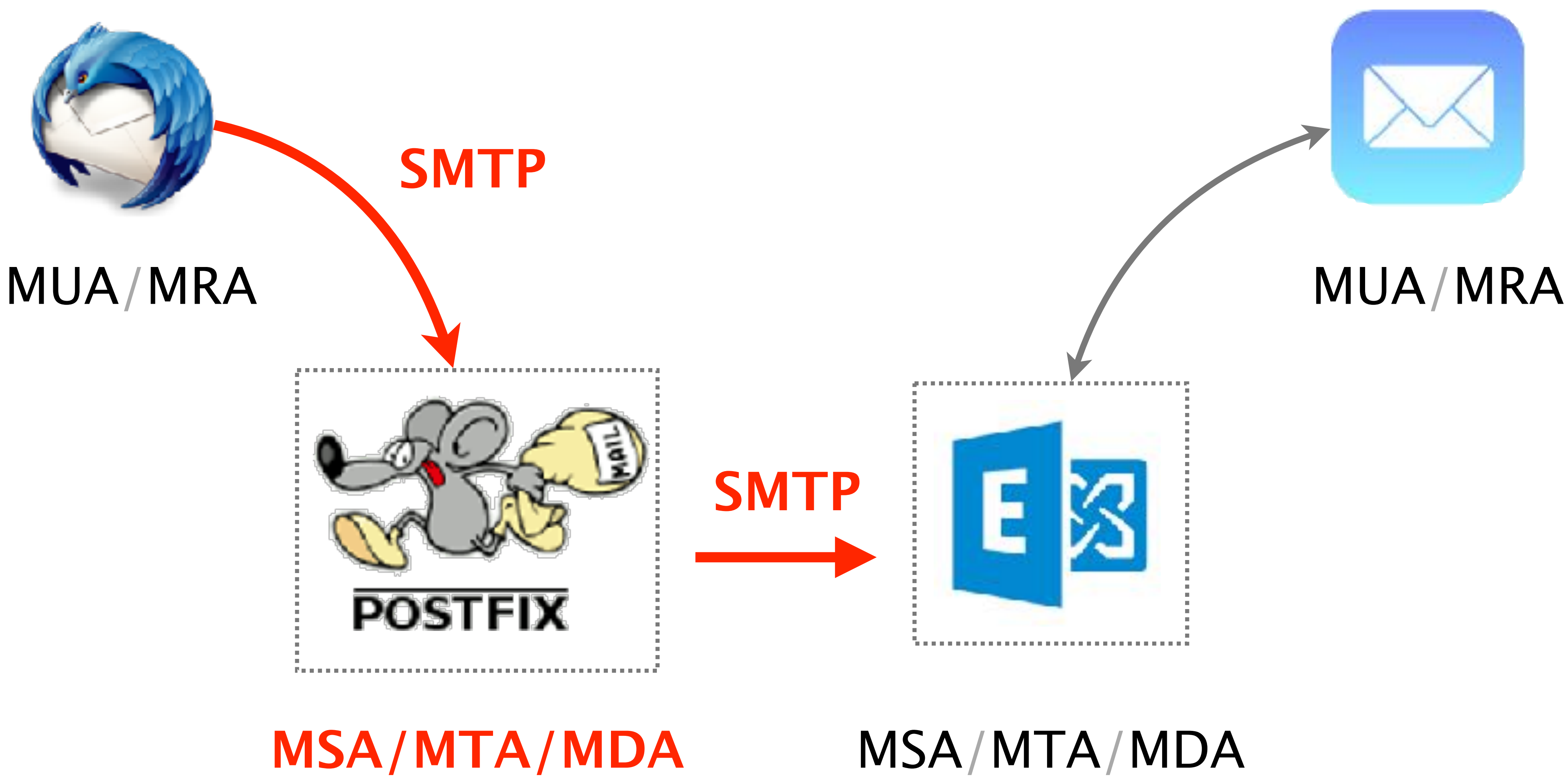
SMTP is a push-like protocol

sender pushes the file to the receiving server (no pull)

The sender MUA uses SMTP to transmit the e-mail first to a local MTA (e.g. mail.ethz.ch, gmail.com, hotmail.com)



The local MTA then looks up the MTA of the recipient domain (DNS MX) and transmits the e-mail further



8 Received: from edge20.ethz.ch (82.130.99.26) by CAS10.d.ethz.ch (172.31.38.210) with Microsoft SMTP Server (TLS) id 14.3.361.1; Fri, 23 Feb 2018 01:48:56 +0100

7 Received: from phil4.ethz.ch (129.132.183.133) by edge20.ethz.ch (82.130.99.26) with Microsoft SMTP Server id 14.3.361.1; Fri, 23 Feb 2018 01:48:57 +0100

6 Received: from outprodmail02.cc.columbia.edu ([128.59.72.51]) by phil4.ethz.ch with esmtps (TLSv1:AES256-SHA:256) (Exim 4.69) (envelope-from <ethan@ee.columbia.edu>) id 1ep1Xg-0002s3-FH for lvanbever@ethz.ch; Fri, 23 Feb 2018 01:48:55 +0100

5 Received: from hazelnut (hazelnut.cc.columbia.edu [128.59.213.250]) by outprodmail02.cc.columbia.edu (8.14.4/8.14.4) with ESMTP id w1N0iAu4026008 for <lvanbever@ethz.ch>; Thu, 22 Feb 2018 19:48:51 -0500

4 Received: from hazelnut (localhost.localdomain [127.0.0.1]) by hazelnut (Postfix) with ESMTP id 421126D for <lvanbever@ethz.ch>; Thu, 22 Feb 2018 19:48:52 -0500 (EST)

3 Received: from sendprodmail01.cc.columbia.edu (sendprodmail01.cc.columbia.edu [128.59.72.13]) by hazelnut (Postfix) with ESMTP id 211526D for <lvanbever@ethz.ch>; Thu, 22 Feb 2018 19:48:52 -0500 (EST)

2 Received: from mail-pl0-f43.google.com (mail-pl0-f43.google.com [209.85.160.43]) (user=ebk2141 mech=PLAIN bits=0) by sendprodmail01.cc.columbia.edu (8.14.4/8.14.4) with ESMTP id w1N0mnlx052337 (version=TLSv1/SSLv3 cipher=AES128-GCM-SHA256 bits=128 verify=NOT) for <lvanbever@ethz.ch>; Thu, 22 Feb 2018 19:48:50 -0500

1 Received: by mail-pl0-f43.google.com with SMTP id u13so3927207plq.1 for <lvanbever@ethz.ch>; Thu, 22 Feb 2018 16:48:50 -0800 (PST)

Today on

Communication Networks

ICMP

Network Control Messages

its use for discovery

NAT

Network Address Translation

its use for sharing IPs

+ a little bit of SDN and course recap.

ICMP

NAT

Network Control Messages

its use for discovery

What Errors Might A Router See?

- Dead-end: No route to destination
- Sign of a loop: TTL expires
- Can’t physically forward: packet too big
  - And has DF flag set
- Can’t keep up with traffic: buffer overflowing
- Header corruption or ill-formed packets
- ….

What should network tell host about?

- No route to destination?
  - Host can’t detect or fix routing failure.
- TTL expires?
  - Host can’t detect or fix routing loop.
- Packet too big (with DF set)?
  - Host can adjust packet size, but can’t tell difference between congestion drops and MTU drops
- Buffer overflowing?
  - Transport congestion control can detect/deal with this
- Header corruption or ill-formed packets?
  - Host can’t fix corruption, but can fix formatting errors

Router Response to Problems?

- Router doesn't really need to respond
  - Best effort means never having to say you're sorry
  - IP could conceivably just silently drop packets
- Network is already trying its best
  - Routing is already trying to avoid loops/dead-ends
  - Network can't reduce packet size (in DF packets)
  - Network can't reduce load, nor fix format problems
- What more can/should it do?

Error Reporting Helps Diagnosis

- Silent failures are **really hard to diagnose**
- IP includes feedback mechanism for network problems, so they don't go undetected
- Internet Control Message Protocol (ICMP)
- The Internet "print" statement
- Runs on IP, but viewed as *integral* part of IP

Internet Control Message Protocol

- Triggered when IP packet encounters a problem
  - E.g., **Time Exceeded** or **Destination Unreachable**
- ICMP packet sent back to the source IP address
  - Includes the error information (e.g., type and code)
  - IP header plus 8+ byte *excerpt* from original packet
- Source host receives the ICMP packet
  - Inspects *excerpt* (e.g., protocol/ports) to identify socket
- **Exception**: not sent if problem packet is ICMP
  - And just for fragment 0 of a group of fragments

Types of Control Messages

- **Need Fragmentation**
  - IP packet too large for link layer, DF set
- **TTL Expired**
  - Decremented at each hop; generated if $\Rightarrow 0$
- **Unreachable**
  - Subtypes: network / host / port
    - (who generates Port Unreachable?)
- **Source Quench**
  - Old-style signal asking sender to slow down
- **Redirect**
  - Tells source to use a different local router

Using ICMP

- ICMP intended to tell host about network problems
  - **Diagnosis**
  - Won't say more about this….
- Can exploit ICMP to elicit network information
  - **Discovery**
  - Will focus on this….

Discovering Network Path Properties

- *PMTU Discovery*: Largest packet that can go through the network w/o needing fragmentation
  - Most efficient size to use
  - (Plus fragmentation can amplify loss)

- *Traceroute:*
  - What is the series of routers that a packet traverses as it travels through the network?

- *Ping:*
  - Simple RTT measurements

Ping: Echo and Reply

- ICMP includes simple “echo” functionality
  - Sending node sends an ICMP Echo Request message
  - Receiving node sends an ICMP Echo Reply
- Ping tool
  - Tests connectivity with a remote host
  - … by sending regularly spaced Echo Request
  - … and measuring delay until receiving replies

Path MTU Discovery

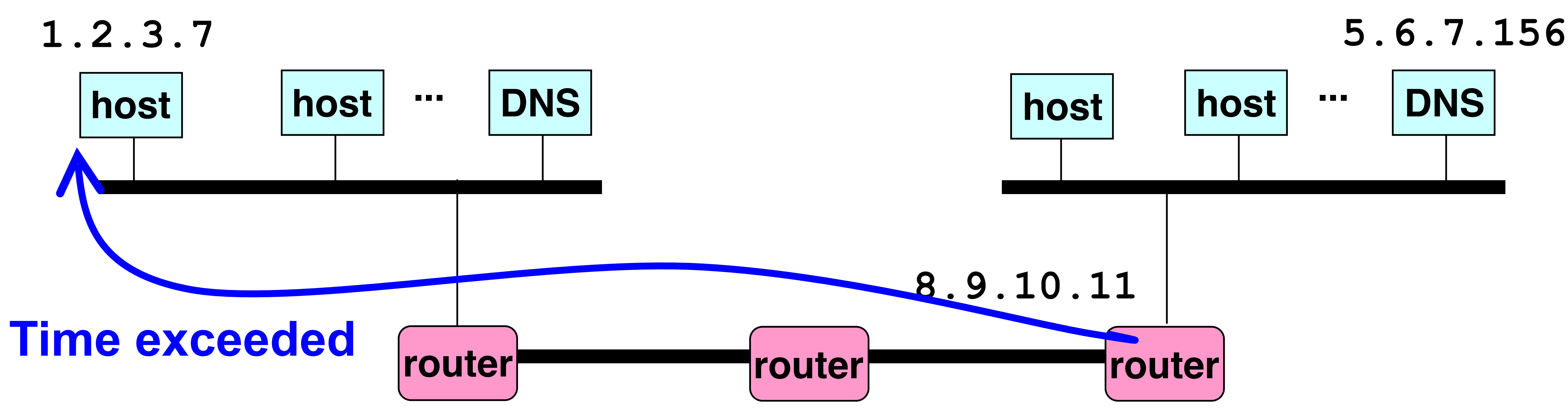
- MTU = Maximum Transmission Unit
  - Largest IP packet that a link supports
- Path MTU (PMTU) = minimum end-to-end MTU
  - Must keep datagrams no larger to avoid fragmentation
- How does the sender know the PMTU is?
- Strategy (RFC 1191):
  - **Try** a desired value
  - Set **DF** to prevent fragmentation
  - Upon receiving **Need Fragmentation** ICMP …
    - … oops, that didn’t work, try a smaller value

Issues with Path MTU Discovery

- What set of values should the sender try?
  - Usual strategy: work through “likely suspects”
  - E.g., 4352 (FDDI), 1500 (Ethernet),
    1480 (IP-in-IP over Ethernet), 296 (some modems)
- What if the PMTU changes? (how could it?)
  - Sender will immediately see *reductions* in PMTU (how?)
  - Sender can periodically try larger values
- What if **Needs Fragmentation** ICMP is lost?
  - Retransmission will elicit another one
- How can **The Whole Thing Fail**?
  - “PMTU **Black Holes**”: routers that don’t send the ICMP

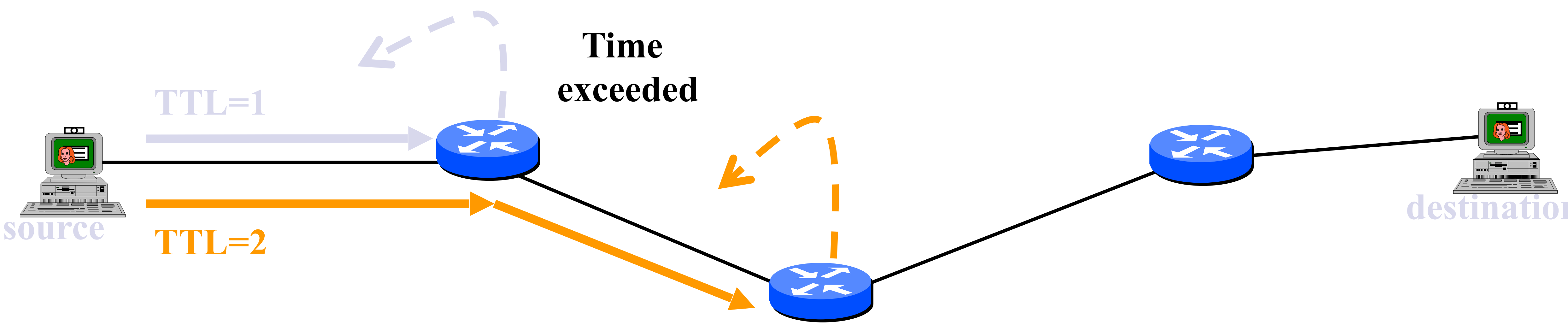
Discovering Routing via *Time Exceeded*

- Host sends an IP packet
  - Each router decrements the time-to-live field
- If **TTL** reaches 0
  - Router sends **Time Exceeded** ICMP back to the source
  - Message identifies router sending it
    - Since ICMP is sent using IP, it's just the IP source address
    - And can use PTR record to find name of router



Traceroute: Exploiting *Time Exceeded*

- Time-To-Live field in IP packet header
  - Source sends a packet with TTL ranging from ***1*** to ***n***
  - Each router along the path decrements the TTL
  - “TTL exceeded” sent when TTL reaches *0*
- *Traceroute* tool exploits this TTL behavior



Send packets with TTL=1, 2, …
and record source of *Time Exceeded* message

ICMP

NAT

Network Address Translation

its use for sharing IPs

Sharing Single Address Across Hosts

- Network Address Translation (NAT) enables many hosts to share a single address
  - Uses port numbers (fields in transport layer)

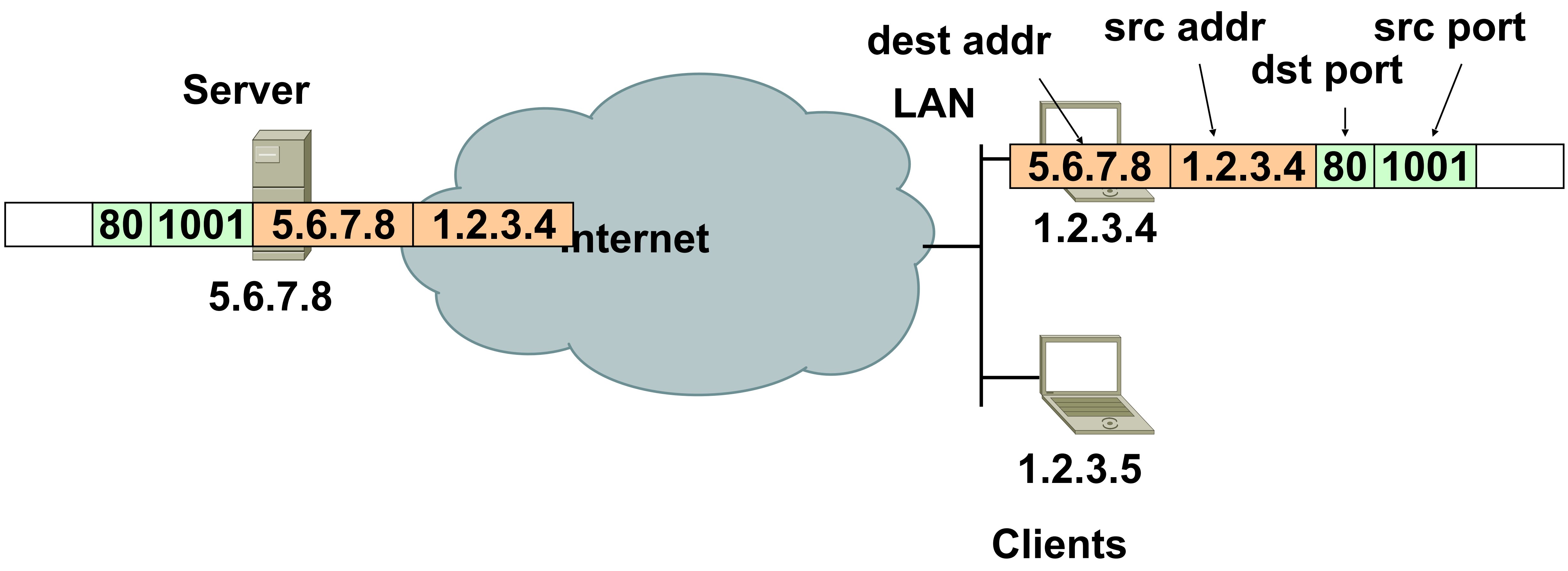
- Was thought to be an architectural abomination when first proposed, but it:
  - Probably saved us from address exhaustion
  - And reflects a modern design paradigm (indirection)

Special-Purpose Address Blocks

- Limited broadcast
  - Sent to every host attached to the local network
  - Block: **255.255.255.255/32**
- Loopback
  - Address blocks that refer to the local machine
  - Block: **127.0.0.0/8**
  - Usually only **127.0.0.1/32** is used
- Link-local
  - By agreement, not forwarded by any router
  - Used for single-link communication only
  - Intent: autoconfiguration (especially when *DHCP* fails)
  - Block: **169.254.0.0/16**
- Private addresses
  - By agreement, not routed in the public Internet
  - For networks not meant for general Internet connectivity
  - Blocks: **10.0.0.0/8**, **172.16.0.0/12**, **192.168.0.0/16**

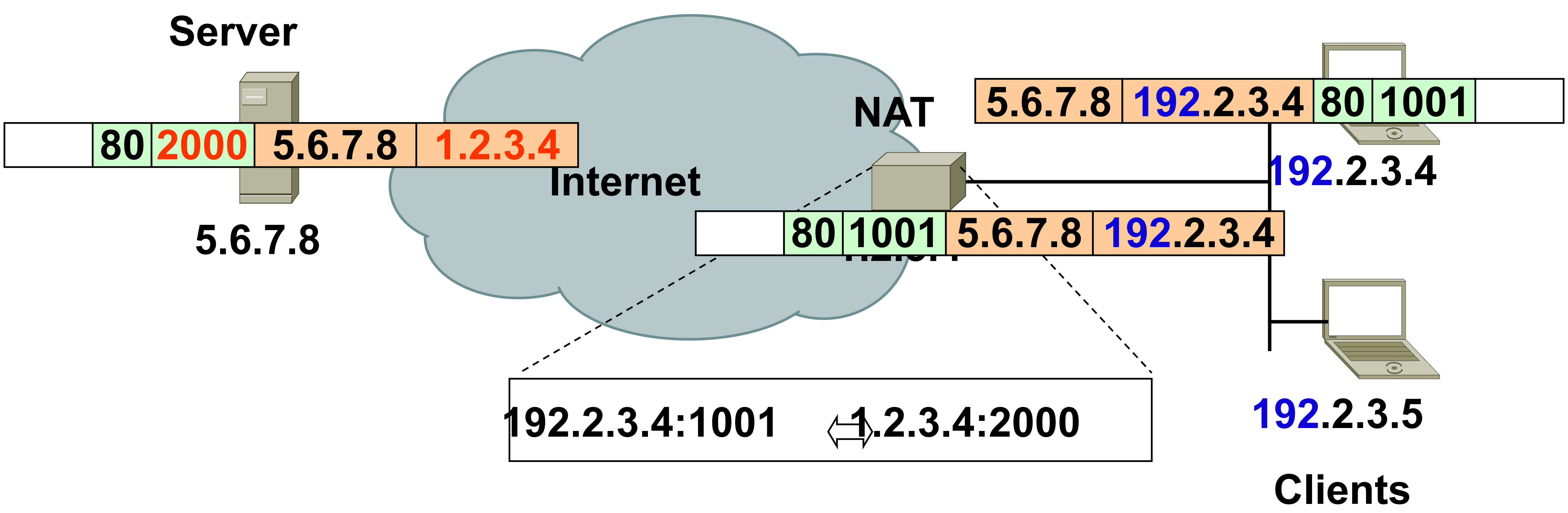
Network Address Translation (NAT)

Before NAT…every machine connected to Internet had unique IP address



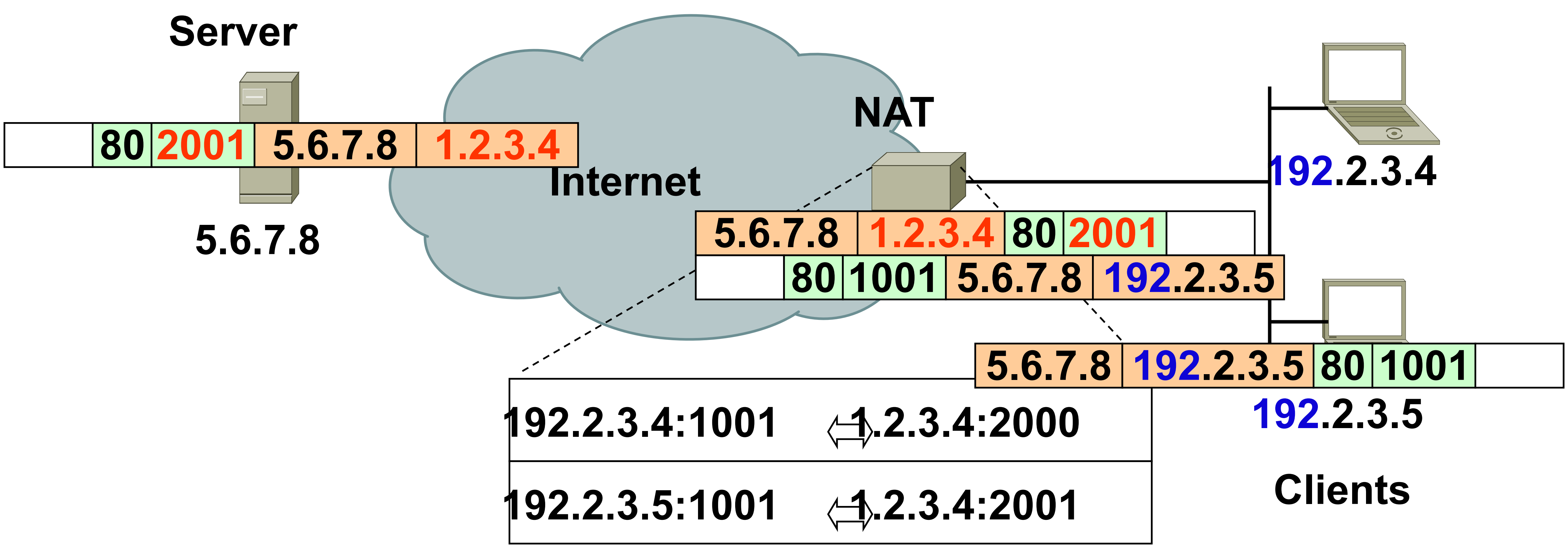
NAT (cont'd)

- Assign addresses to machines behind same NAT
  - Can be any private address range
  - e.g. **192.168.0.0/16**
- Use **port numbers** to multiplex single address



NAT (cont'd)

- Assign addresses to machines behind same NAT
  - Usually in address block **192.168.0.0/16**
- Use port numbers to multiplex single address



NAT: Early Example of “Middlebox”

- Boxes stuck into network to delivery functionality
  - NATs, Firewalls,….
- Don’t fit into architecture, violate E2E principle
- But a very handy way to inject functionality that:
  - Does not require end host changes or cooperation
  - **Is under operator control (e.g., security)**
- An interesting architectural challenge:
  - How to incorporate middleboxes into architecture

Programmable Data Planes: The future of networking?

QCon
SAN FRANCISCO

Programming
The Network Data Plane

Changhoon Kim

P4.org

BAREFOOT NETWORKS

Beautiful ideas: What if you could …

- Realize a small, but super-fast DNS cache
- Perform TCP SYN authentication for billions of SYNs per sec
- Build a replicated key-value store ensuring RW ops in a few usecs
- Improve your consensus service performance by ~100x
- Boost your Memcached cluster's throughput by ~10x
- Speed up your DNN training dramatically by realizing parameter servers

… using ***switches*** in your network?

You couldn’t do any of those so far because …

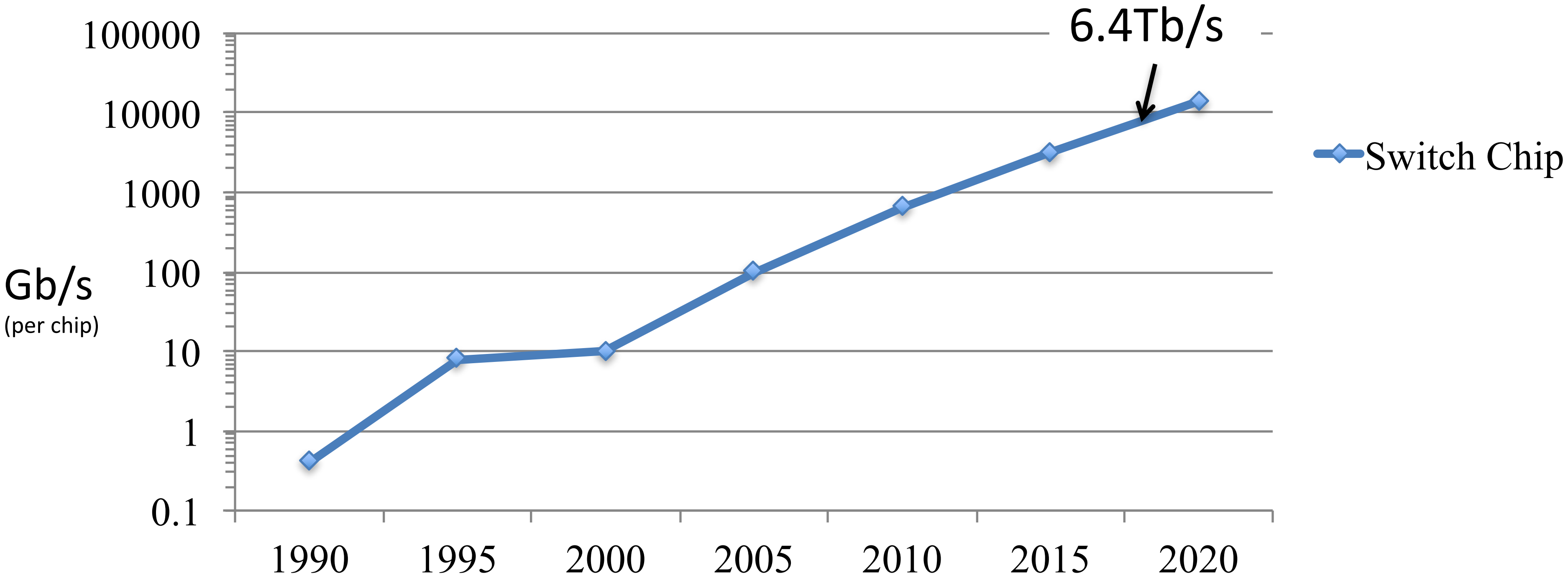
- No DIY – must work with vendors at feature level
- Excruciatingly complicated and involved process to build consensus and pressure for features
- Painfully long and unpredictable lead time
- To use new features, you must get new switches
- What you finally get != what you asked for

This is very unnatural to developers

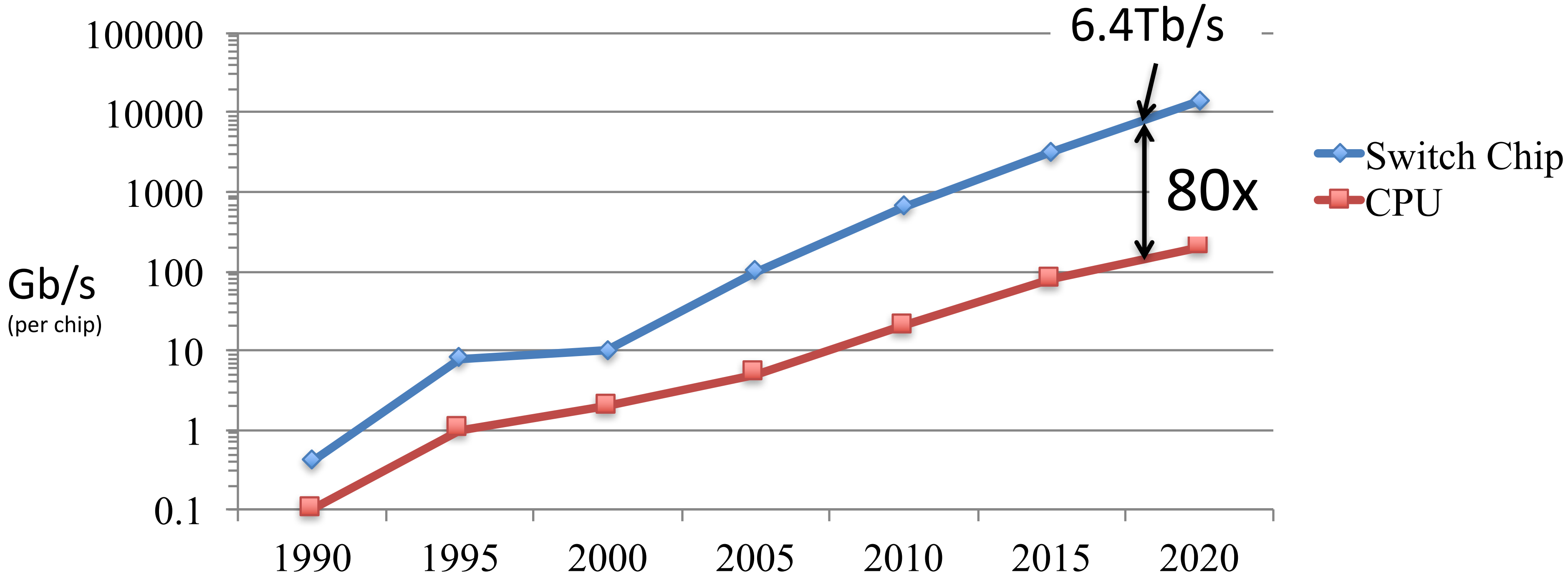
- Because you all know how to realize your own ideas by "programming" CPUs
  - Programs used in every phase (implement, test, and deploy)
  - Extremely fast iteration and differentiation
  - You own your own ideas
  - A sustainable ecosystem where all participants benefit

Can we replicate this healthy, sustainable ecosystem for networking?

Reality: Packet forwarding speeds

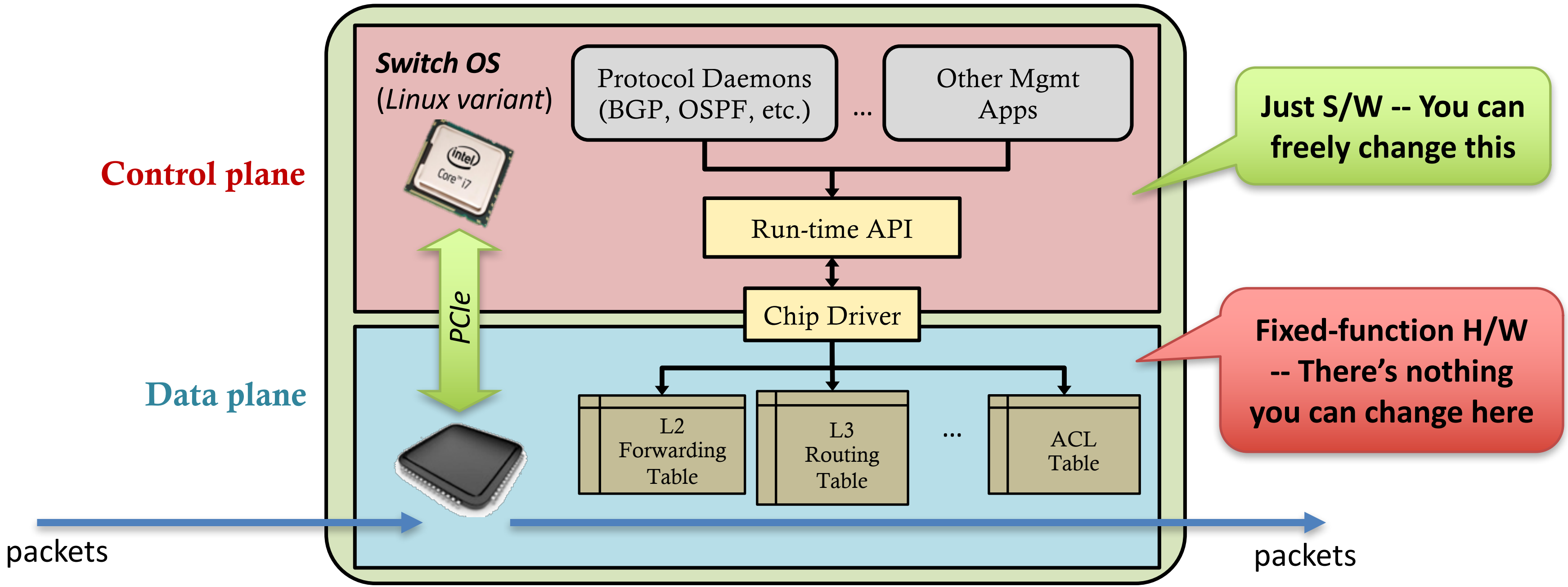


Reality: Packet forwarding speeds



What does a typical switch look like?

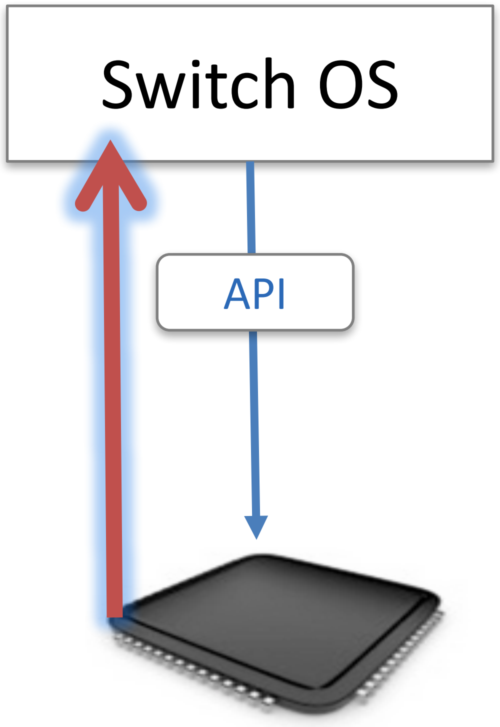
A switch is just a Linux box with a high-speed switching chip



Networking systems have been built "bottoms-up"

in English

"This is roughly how I process packets …"

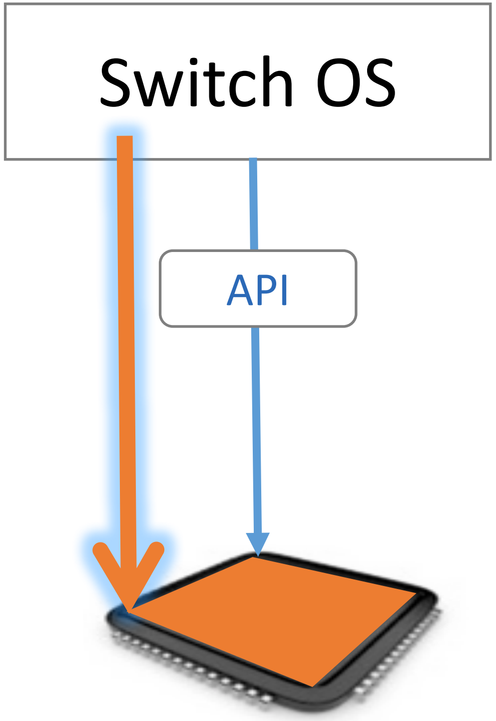


Fixed-function switch

Turning the tables "top-down"

in P4

"This is precisely how you must process packets"



Programmable Switch

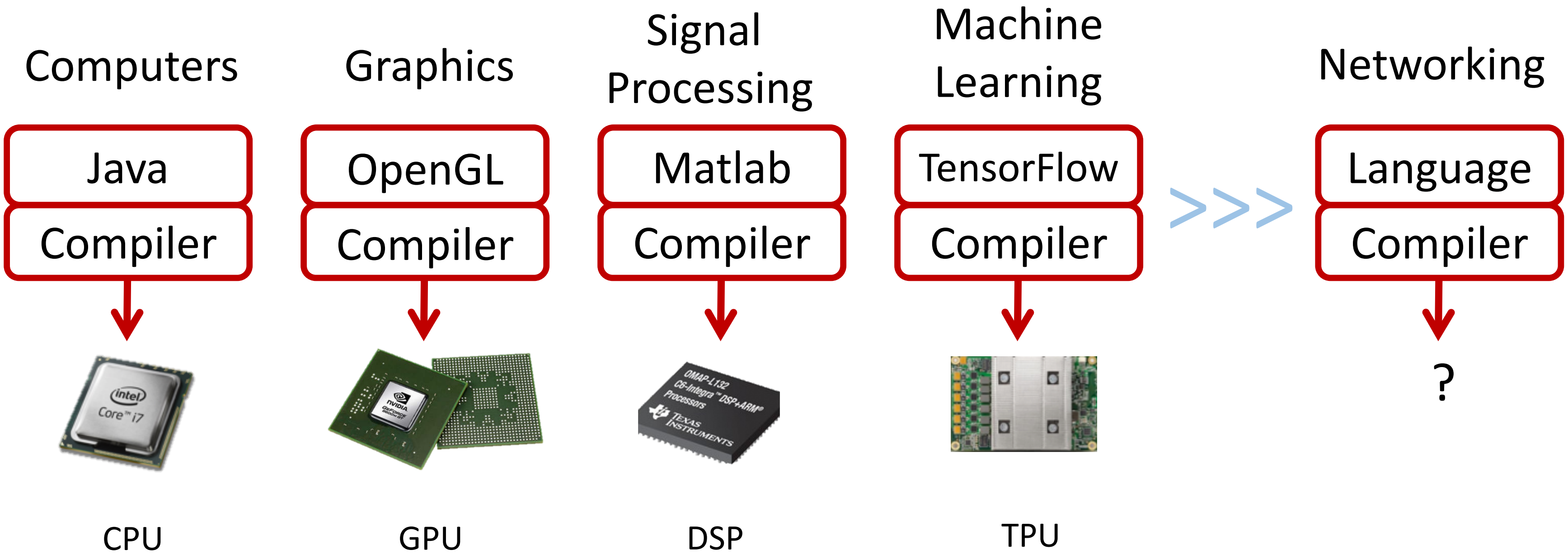
Evidence: Tofino 6.5Tb/s switch (arrived Dec 2016)

The world's fastest and most programmable switch.

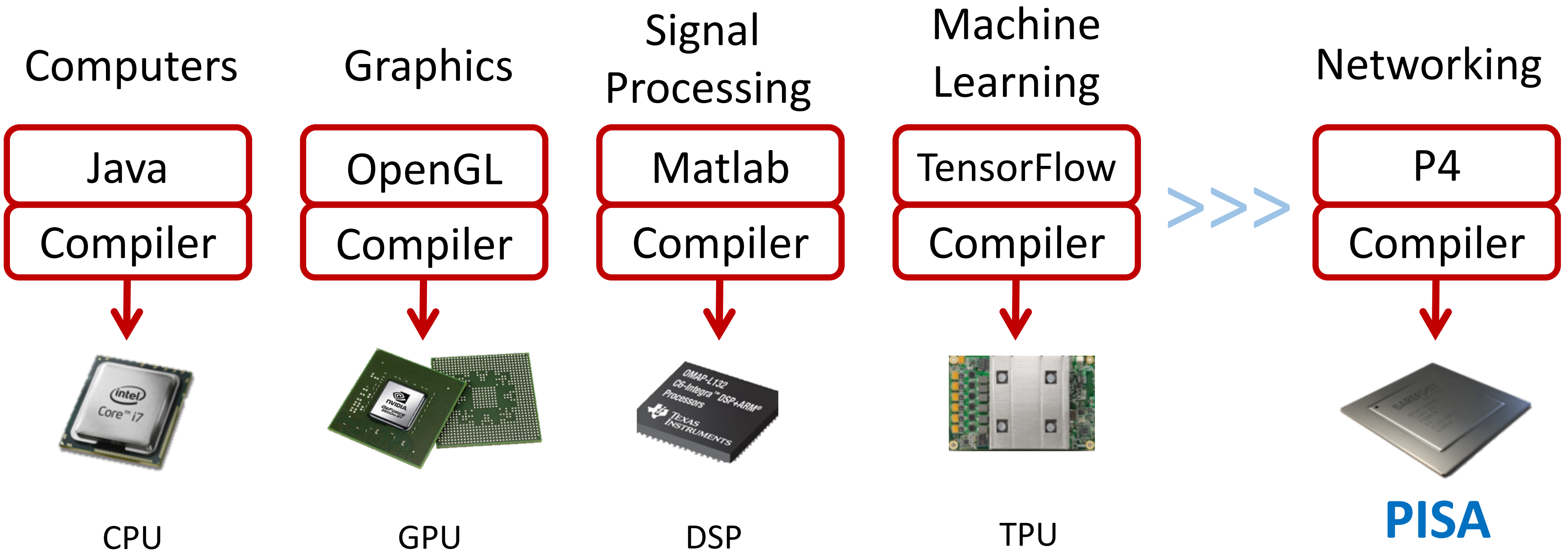
No power, cost, or power penalty compared to fixed-function switches.

An incarnation of **PISA (Protocol Independent Switch Architecture)**

Domain-specific processors

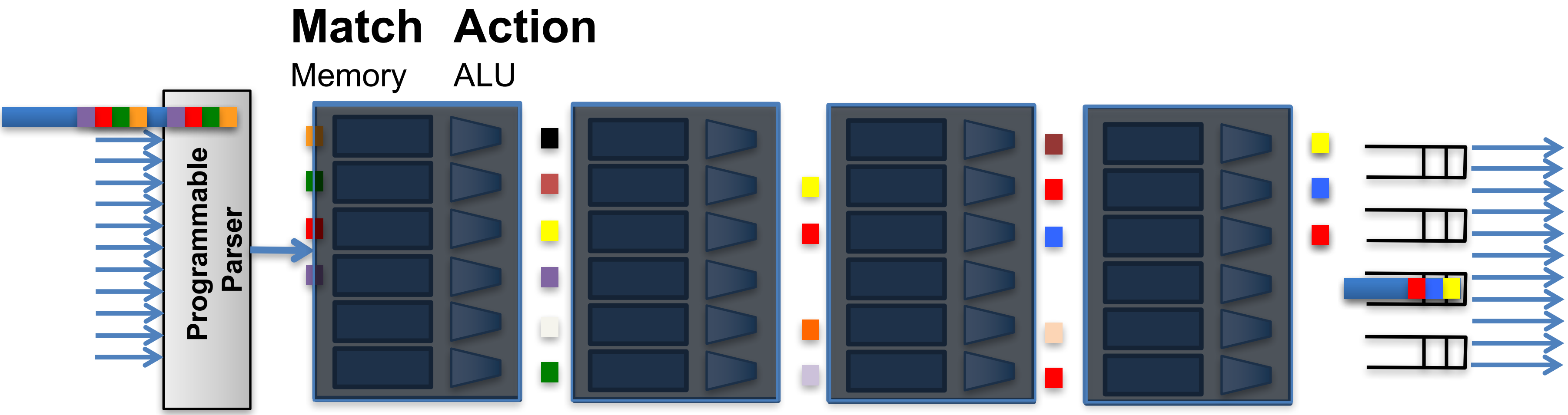


Domain-specific processors

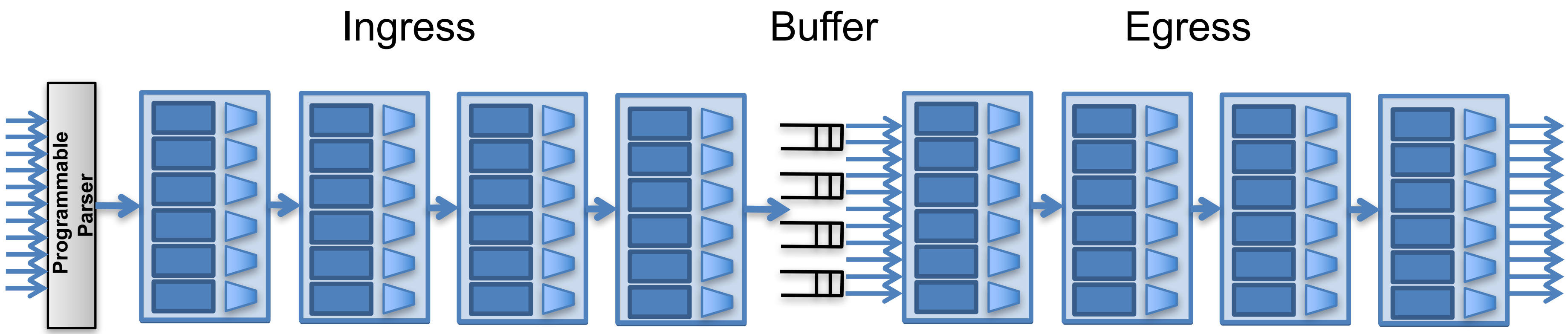


PISA: An architecture for high-speed programmable packet forwarding

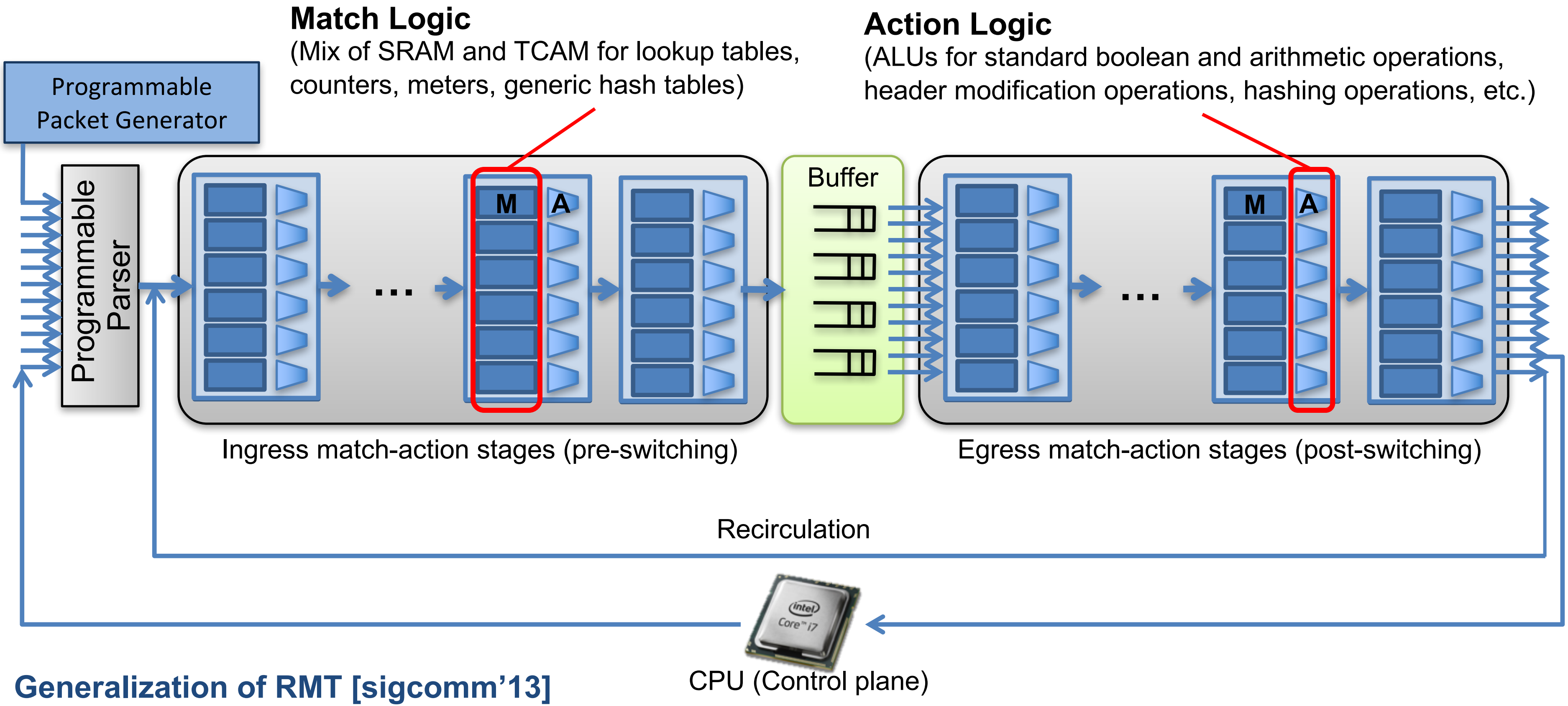
PISA: Protocol Independent Switch Architecture



PISA: Protocol Independent Switch Architecture



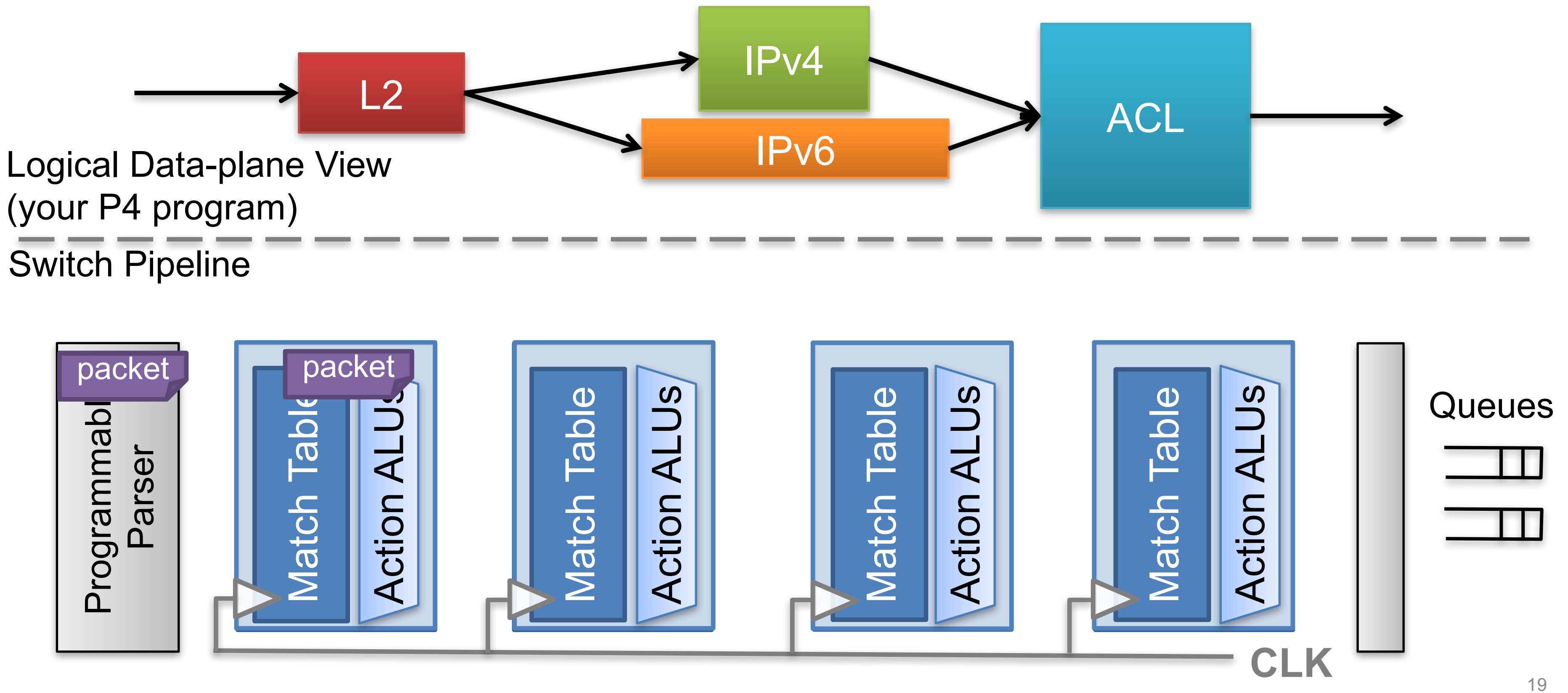
PISA: Protocol Independent Switch Architecture



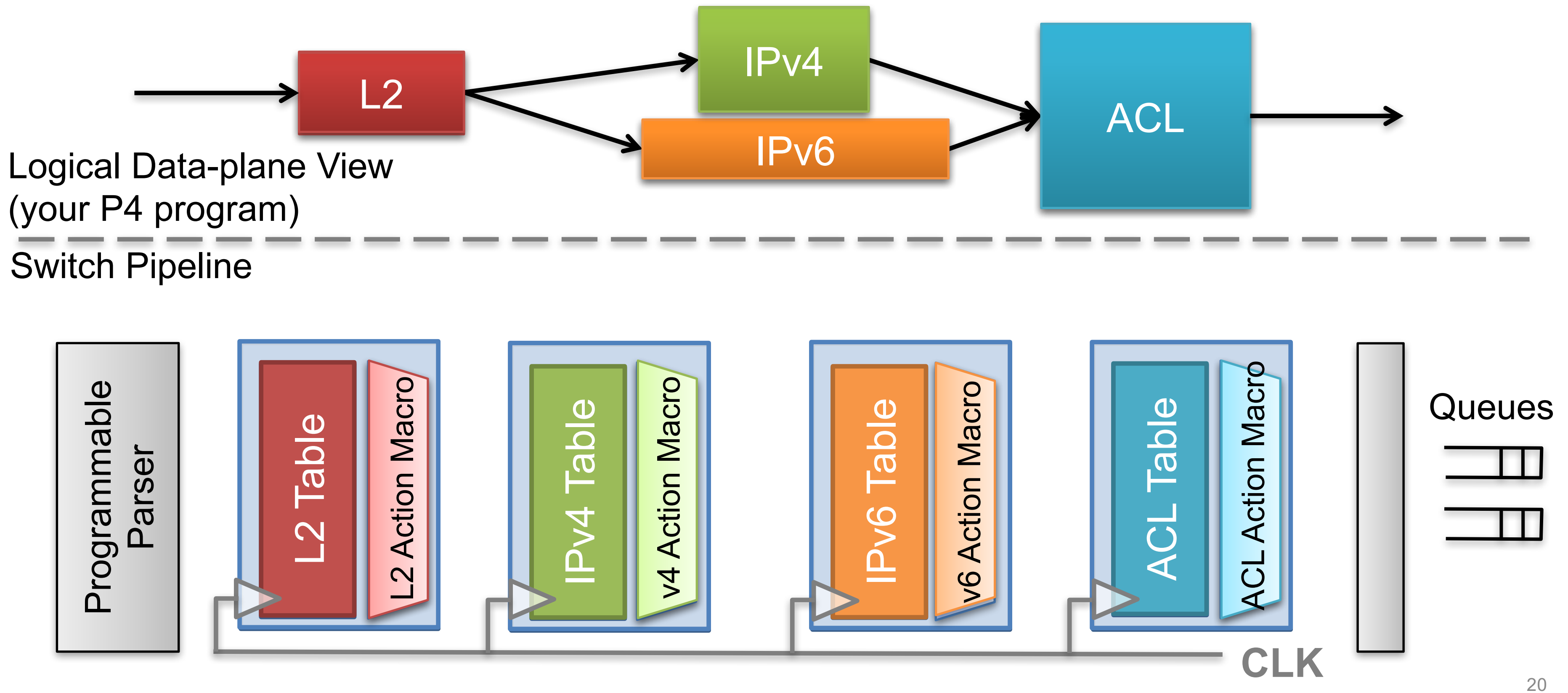
Generalization of RMT [sigcomm'13]

Why we call it protocol-independent packet processing

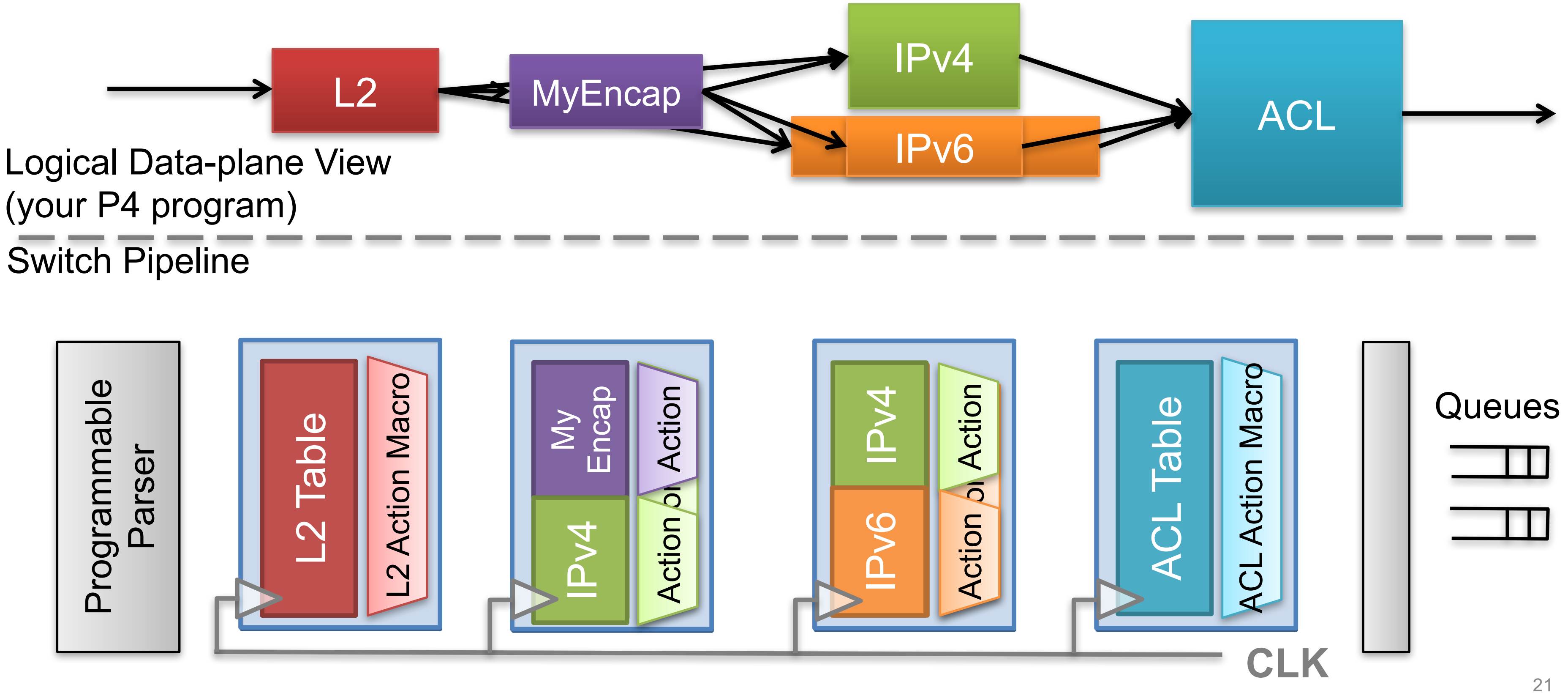
Device does not understand any protocols until it gets programmed



Mapping logical data-plane design to physical resources



Re-program in the field

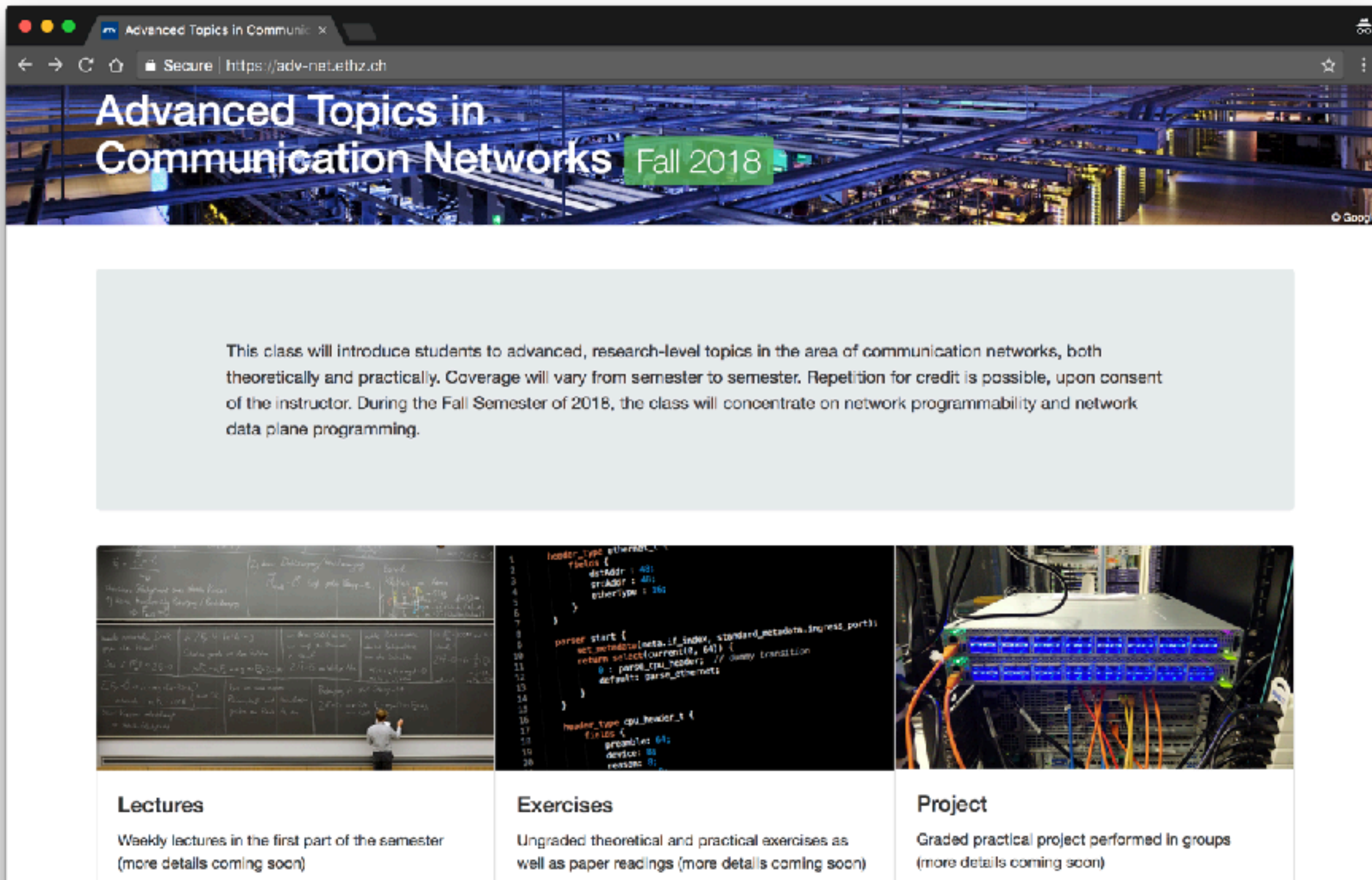


P4.org (http://p4.org)

- **Open-source community to nurture the language**
  - Open-source software – Apache license
  - A common language: $P4_{16}$
  - Support for various types of devices and targets
- **Enable a wealth of innovation**
  - Diverse “apps” (including proprietary ones) running on commodity targets
- **With no barrier to entry**
  - Free of membership fee, free of commitment, and simple licensing

If you are interested, consider taking

Advanced Topics in Communication Networks [adv-net.ethz.ch]



Communication Networks

So what?!

Knowledge

Understand how the Internet works and why

from your
network plug...

...to Google's data-center

List any

technologies, principles, applications...

used after typing in:

> www.google.ch

and pressing enter in your browser

Insight

Key concepts and problems in Networking

Naming Layering Routing Reliability Sharing

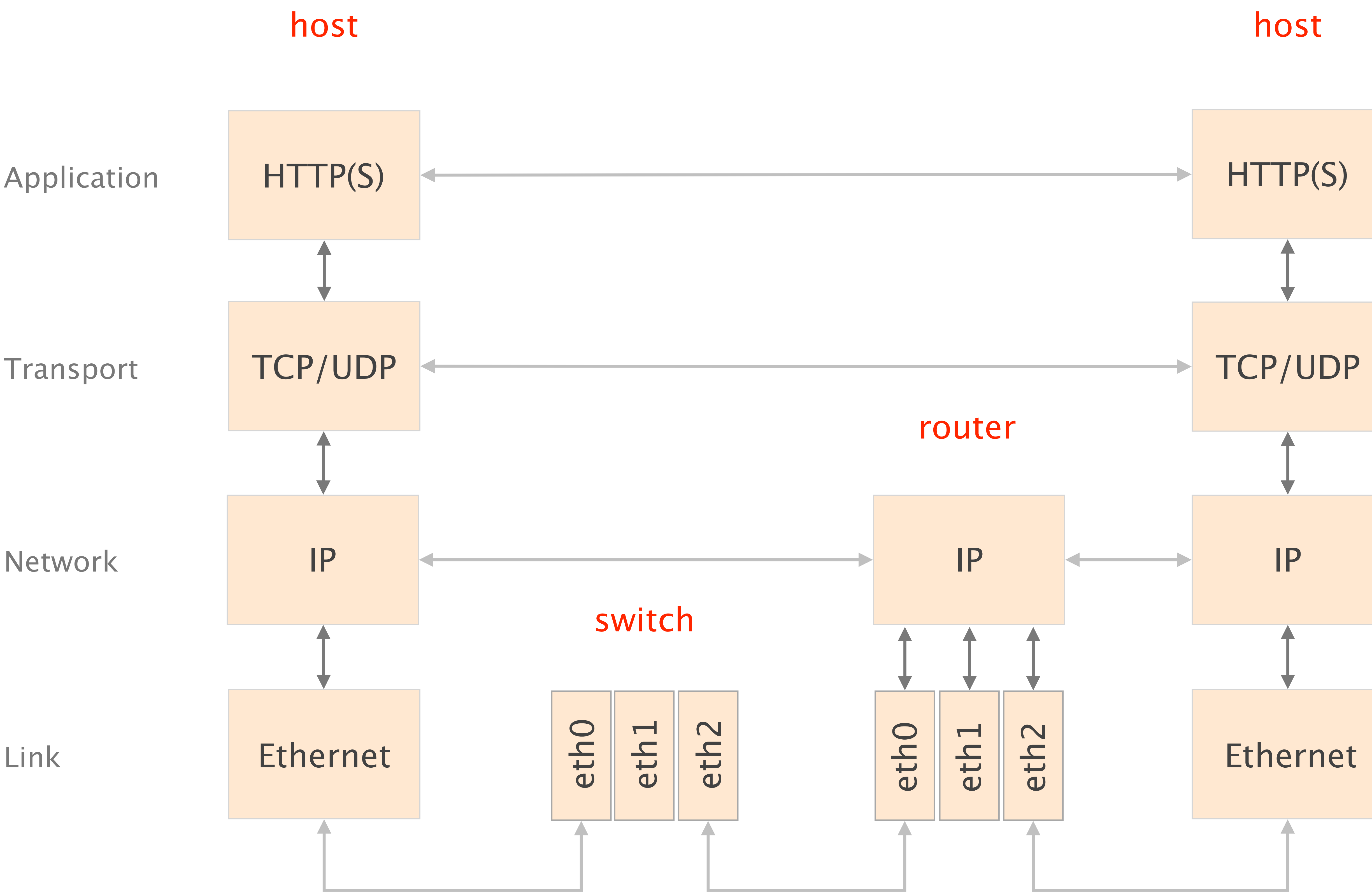
Skill

Build, operate and configure networks

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

The Internet is organized as layers, providing a set of services

	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


host
host
Application
HTTP(S)
HTTP(S)
Transport
TCP/UDP
TCP/UDP
router
Network
IP
IP
IP
switch
Link
Ethernet
eth0
eth1
eth2
eth0
eth1
eth2
Ethernet

We started with the fundamentals of routing and reliable transport

	Application	network access
L4	Transport	end-to-end delivery (reliable or not)
L3	Network	global best-effort delivery
	Link	local best-effort delivery
	Physical	physical transfer of bits

We saw **three ways to compute** valid routing state

	Intuition	Example
#1	Use tree-like topologies	Spanning-tree
#2	Rely on a global network view	Link-State SDN
#3	Rely on distributed computation	Distance-Vector BGP

We saw how to design a reliable transport protocol

goals

correctness	ensure data is delivered, in order, and untouched
timeliness	minimize time until data is transferred
efficiency	optimal use of bandwidth
fairness	play well with other concurrent communications

In each case, we explored the rationale behind each protocol and why they came to be

Why did the protocols end up looking like this?

minimum set of features required

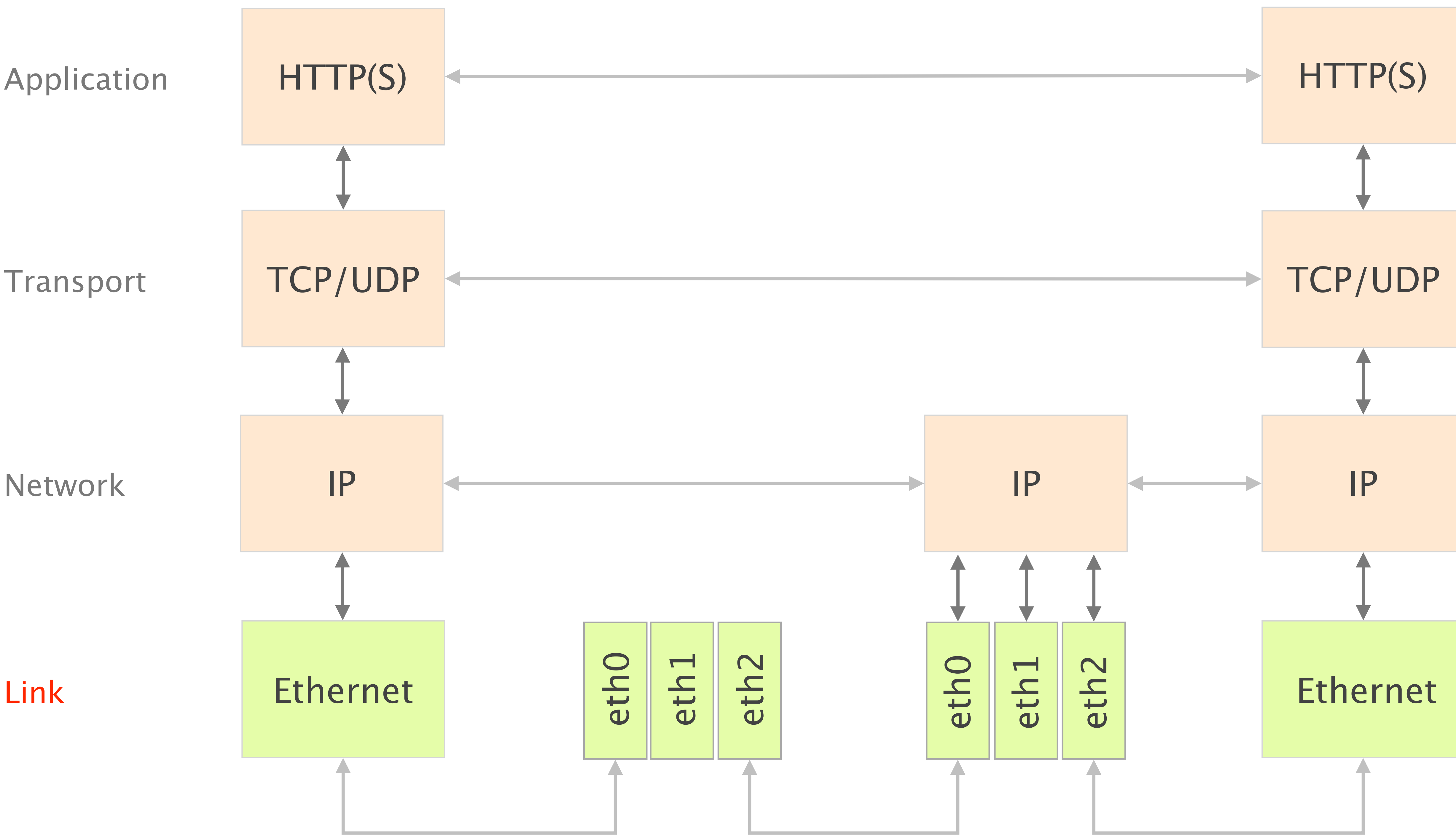
What tradeoffs do they achieve?

efficiency, cost,…

When is one design more adapted than another?

packet switching *vs* circuit switching, DV *vs* LS,…

We then climbed up the layers, starting from layer 2

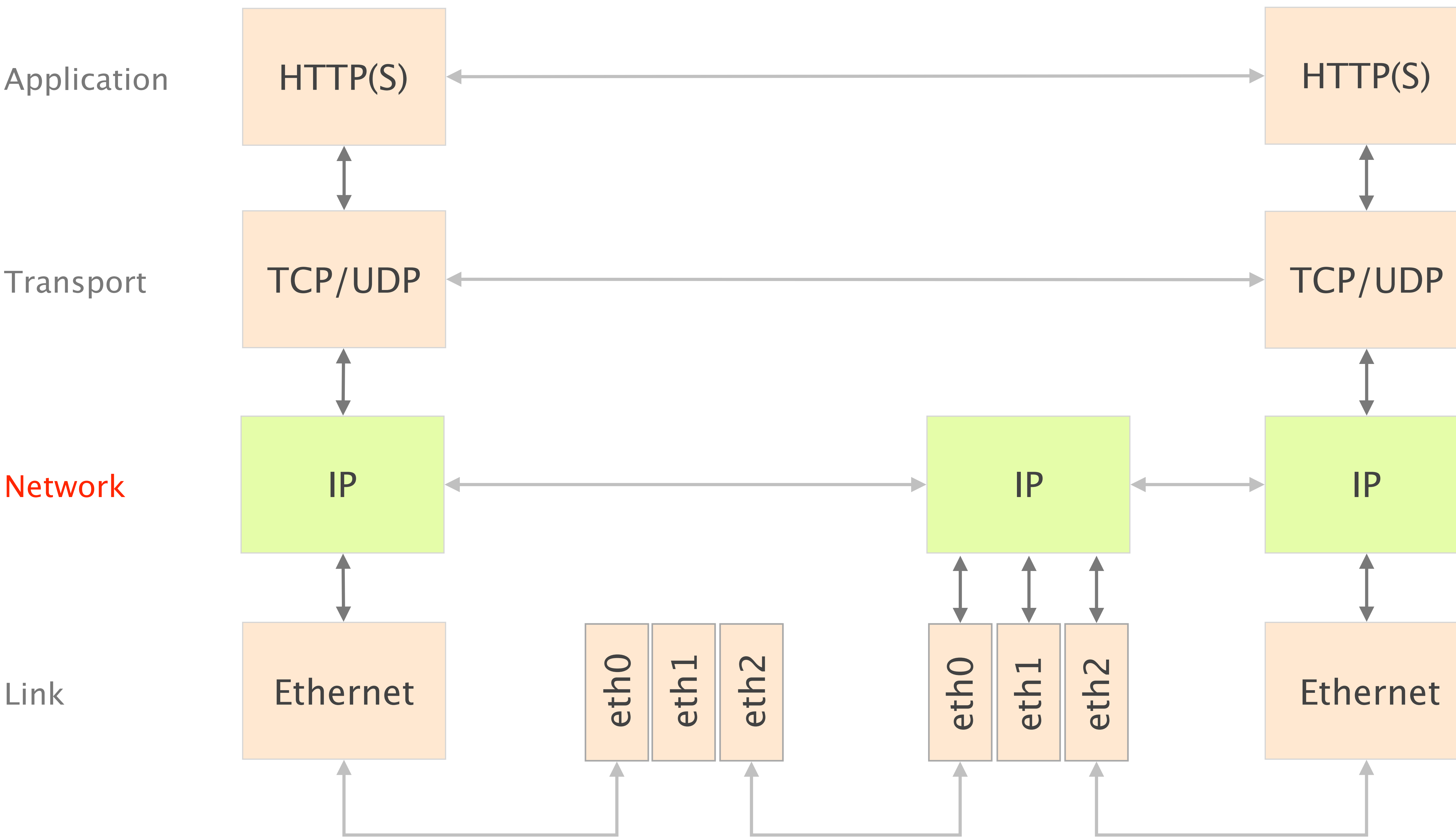


Communication Networks

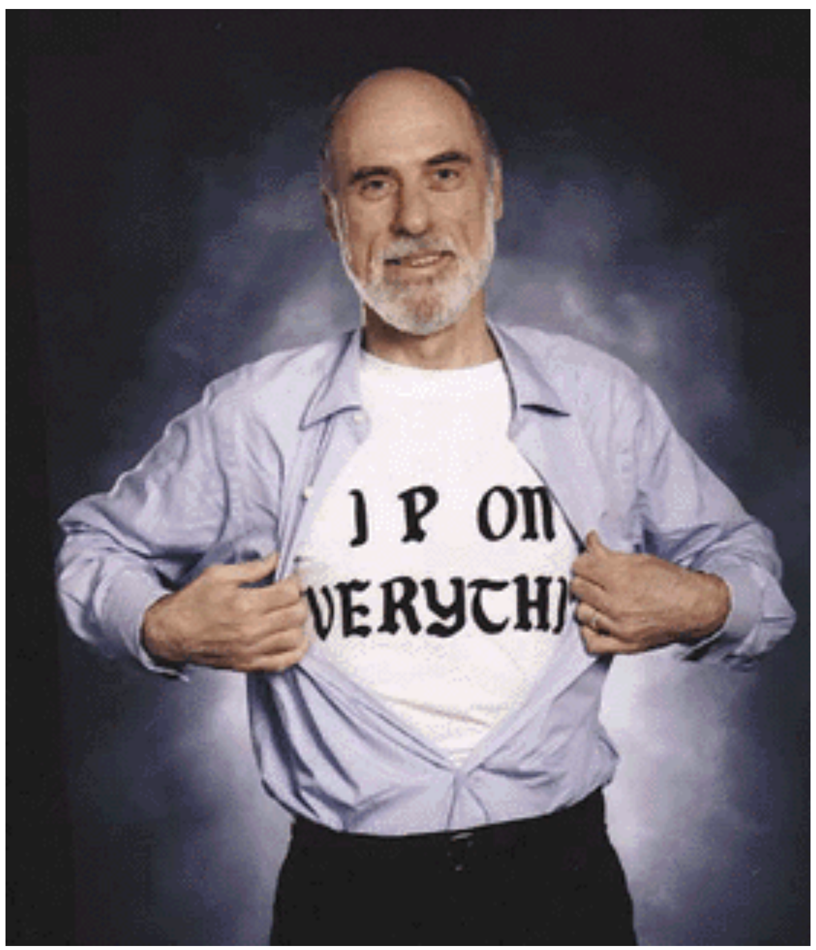
Part 2: The Link Layer

#1	What is a link?
#2	How do we identify link adapters?
#3	How do we share a network medium?
#4	What is Ethernet?
#5	How do we interconnect segments at the link layer?

We then spent multiple weeks on layer 3



Internet Protocol and Forwarding



source: Boardwatch Magazine

1 **IP addresses**
use, structure, allocation

2 **IP forwarding**
longest prefix match rule

3 **IP header**
IPv4 and IPv6, wire format

Internet routing

from here to there, and back

1 **Intra-domain routing**

Link-state protocols

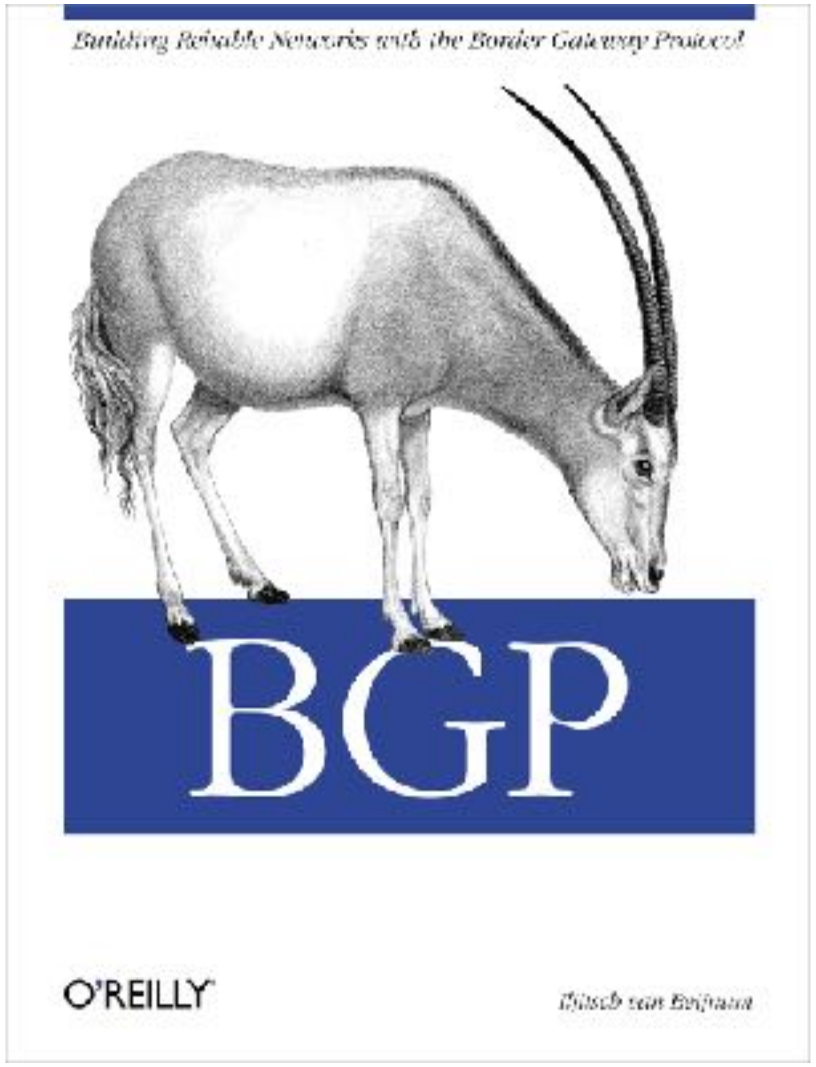
Distance-vector protocols

2 **Inter-domain routing**

Path-vector protocols

Border Gateway Protocol

policies and more

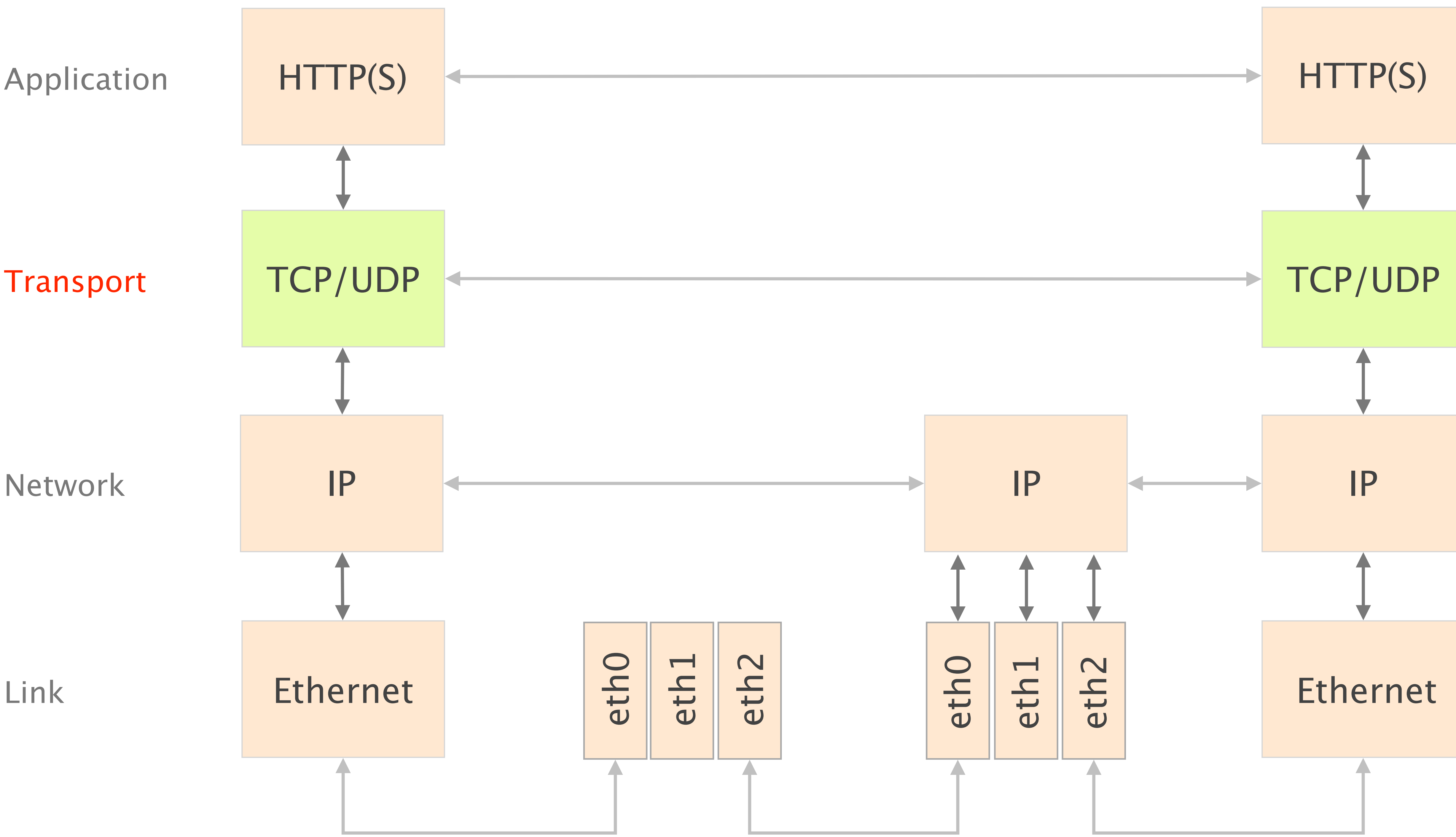


1 **BGP Policies**
Follow the Money

2 **Protocol**
How does it work?

3 **Problems**
security, performance, …

4 = 3+1



Application
HTTP(S)
HTTP(S)
Transport
TCP/UDP
TCP/UDP
Network
IP
IP
IP
Link
Ethernet
eth0
eth1
eth2
eth0
eth1
eth2
Ethernet

We looked at the requirements and implementation of transport protocols (UDP/TCP)

Data delivering, to the *correct* application

- IP just points towards next protocol
- *Transport needs to demultiplex incoming data (ports)*

Files or bytestreams abstractions for the applications

- Network deals with packets
- *Transport layer needs to translate between them*

Reliable transfer (if needed)

Not overloading the receiver

Not overloading the network

We then looked at Congestion Control
and how it solves three fundamental problems

#1	bandwidth estimation	How to adjust the bandwidth of a single flow to the bottleneck bandwidth? could be 1 Mbps or 1 Gbps…
#2	bandwidth adaptation	How to adjust the bandwidth of a single flow to variation of the bottleneck bandwidth?
#3	fairness	How to share bandwidth “fairly" among flows, without overloading the network

… by combining two key mechanisms

detecting
congestion

reacting to
congestion

We finally looked at
what's running on top of all this …

DNS

google.ch ⟷ 172.217.16.131

Web

http://www.google.ch

We finally looked at
what's running on top of all this …

Video Streaming

HTTP-based

E-mail

MX, SMTP, POP, IMAP

… and filled-up some holes with 2 helpers protocols

ICMP

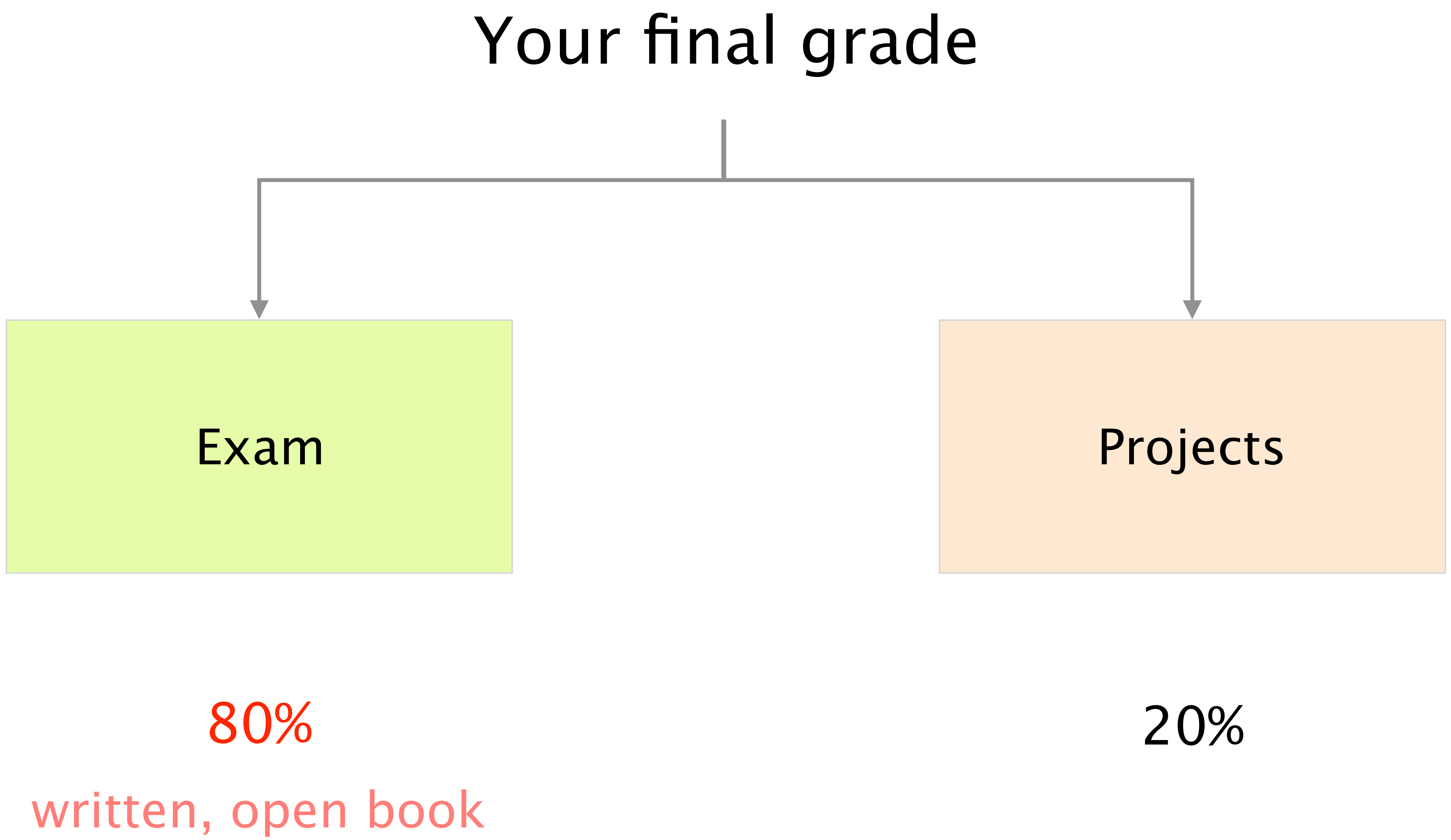
Network Control Messages

its use for discovery

NAT

Network Address Translation

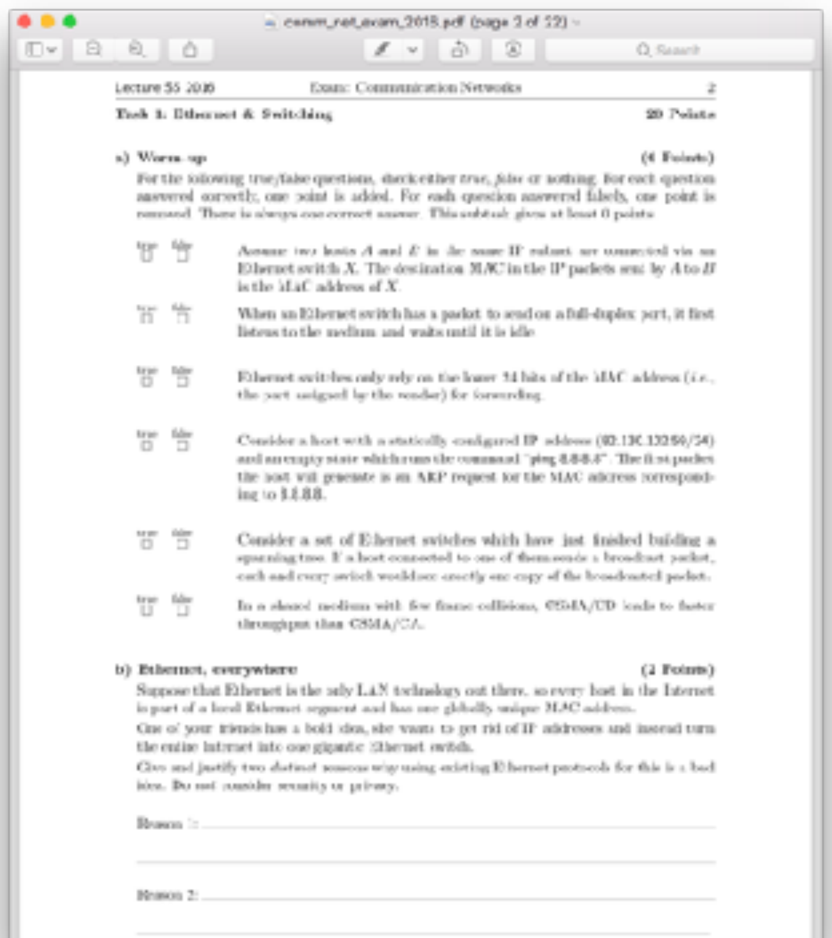
its use for sharing IPs


Your final grade
Exam
Projects
80%
written, open book
20%

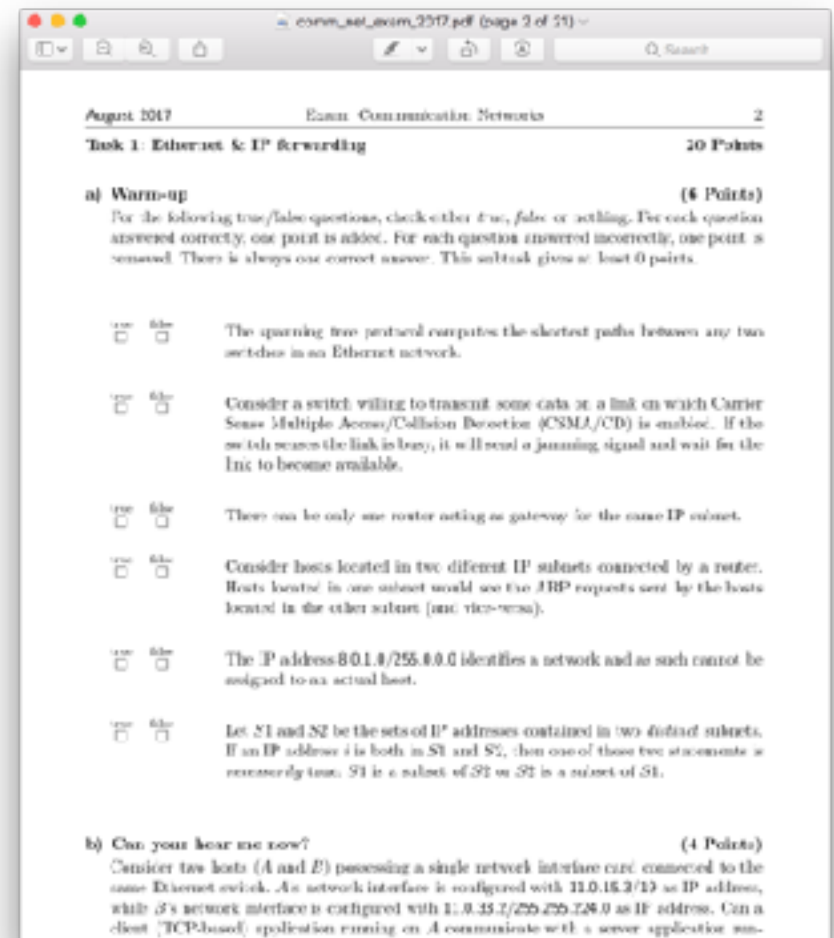
The exam will be open book, most of the questions will be open-ended, with some multiple choices

verify your understanding of the material

Make sure you can do *all* the exercises, including the ones in previous exams



Millesime 2016



Millesime 2017

https://comm-net.ethz.ch/#tab-exam

Don't forget the assignments, *they matter*

No programming question — no Python at the exam

but I could ask you to describe a procedure in English

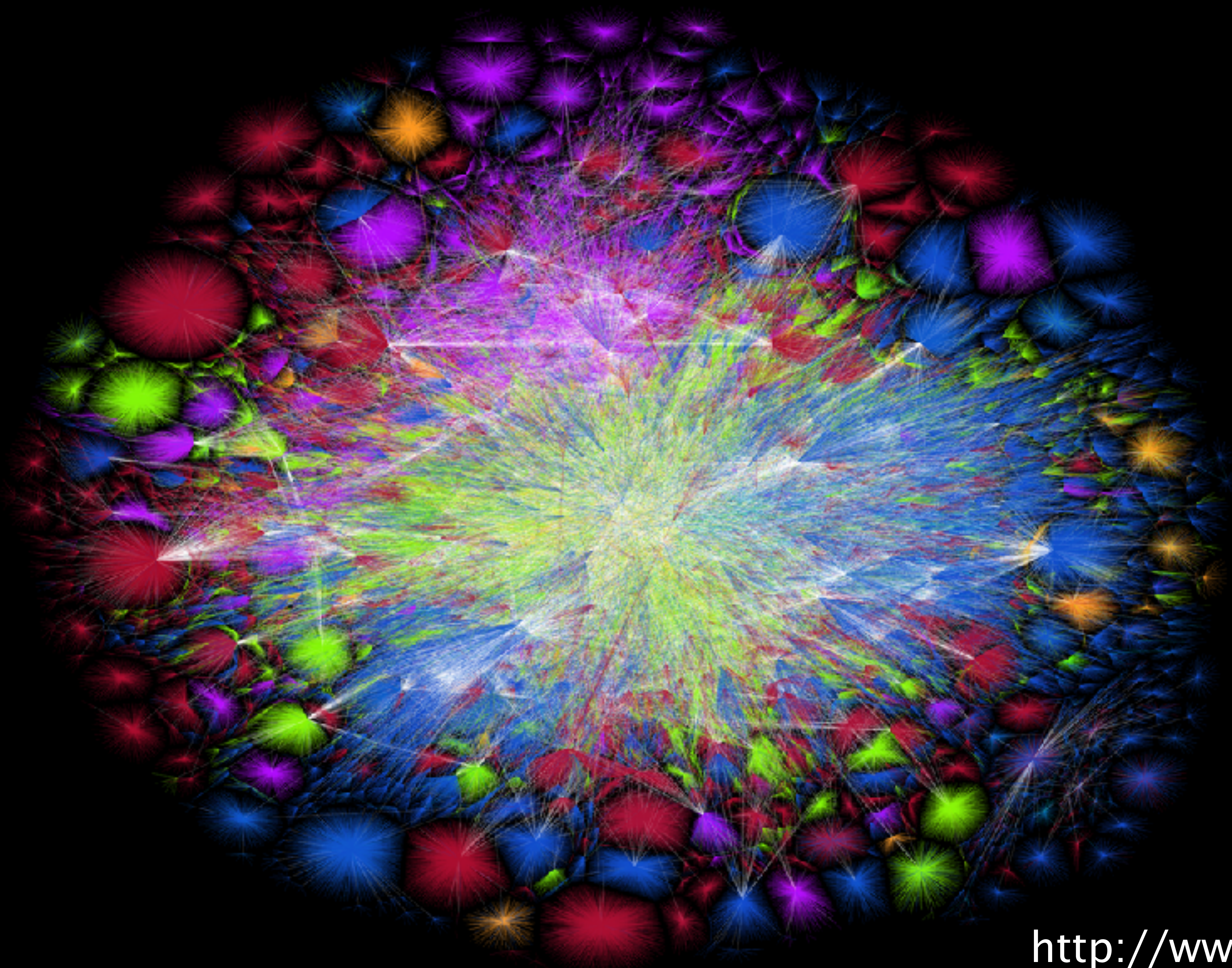
What would you change in your solution to achieve *X*?

No configuration question — no Quagga at the exam

but I could ask you to describe a configuration in English

How would you realize policy *X*?

Now you (better) understand this!



http://www.opte.org

Communication Networks

Spring 2018

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May 28 2018