Communication Networks

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Communication Networks

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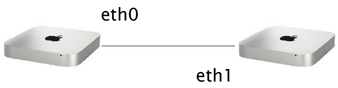
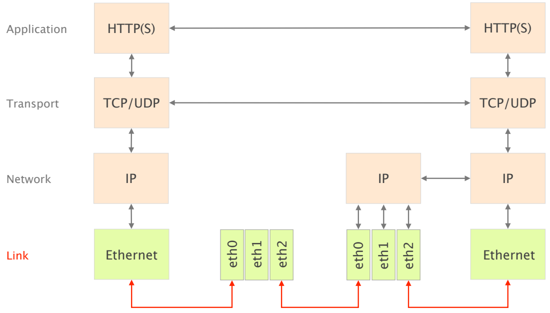
Material inspired from Scott Shenker & Jennifer Rexford

Last week on

Communication Networks

How do local computers communicate?





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?

Communication Networks

Part 2: The Link Layer

#1 What is a link?

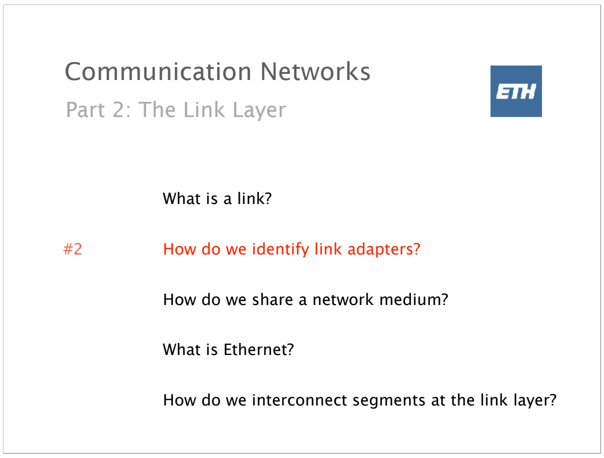
How do we identify link adapters?

How do we share a network medium?

What is Ethernet?

How do we interconnect segments at the link layer?

Link	Communication medium	and	Network adapter
		Wifi	
		Ethernet	
		Fiber	



Communication Networks

Part 2: The Link Layer

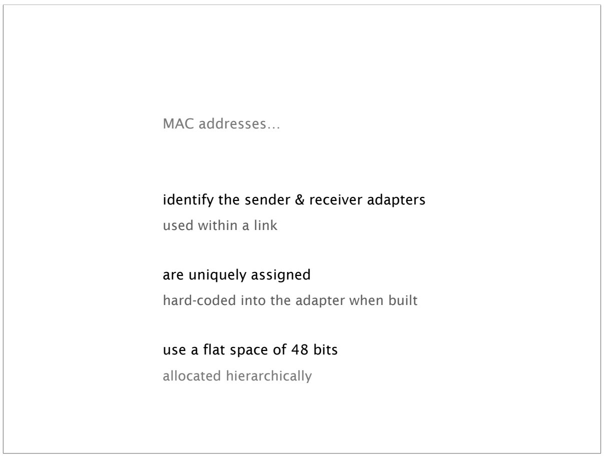
What is a link?

#2 How do we identify link adapters?

How do we share a network medium?

What is Ethernet?

How do we interconnect segments at the link layer?

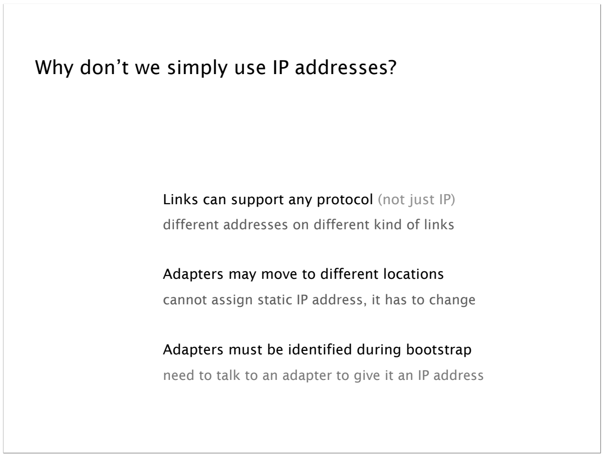


MAC addresses…

identify the sender & receiver adapters
used within a link

are uniquely assigned
hard-coded into the adapter when built

use a flat space of 48 bits
allocated hierarchically

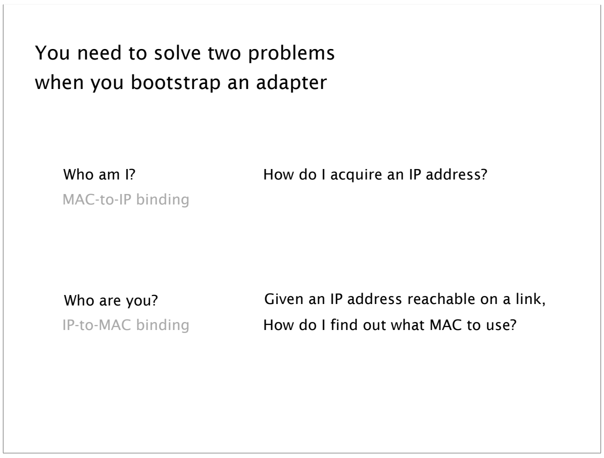


Why don't we simply use IP addresses?

Links can support any protocol (not just IP)
different addresses on different kind of links

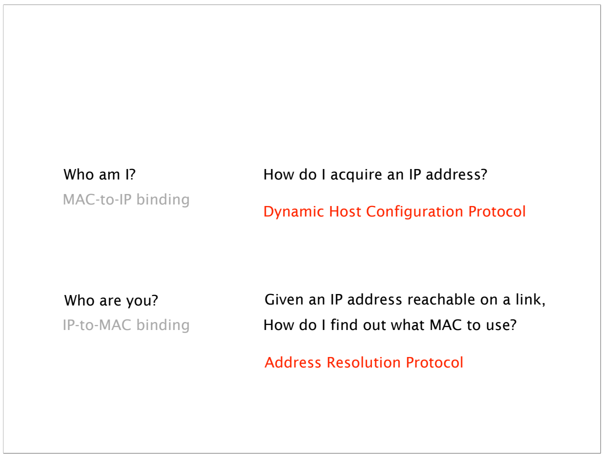
Adapters may move to different locations
cannot assign static IP address, it has to change

Adapters must be identified during bootstrap
need to talk to an adapter to give it an IP address

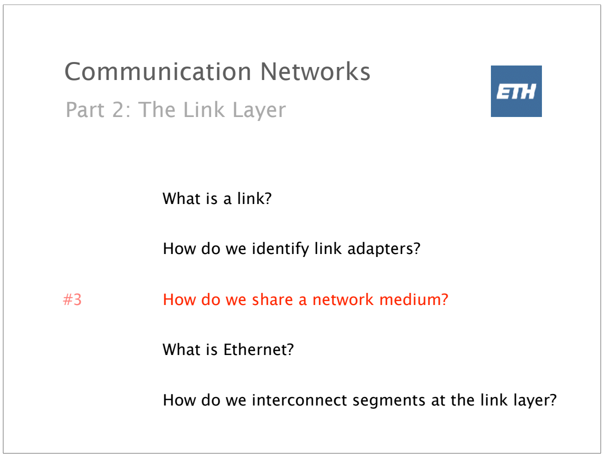


You need to solve two problems when you bootstrap an adapter

Who am I? MAC-to-IP binding	How do I acquire an IP address?
Who are you? IP-to-MAC binding	Given an IP address reachable on a link, How do I find out what MAC to use?



Who am I? MAC-to-IP binding	How do I acquire an IP address? Dynamic Host Configuration Protocol
Who are you? IP-to-MAC binding	Given an IP address reachable on a link, How do I find out what MAC to use? Address Resolution Protocol



Communication Networks

Part 2: The Link Layer

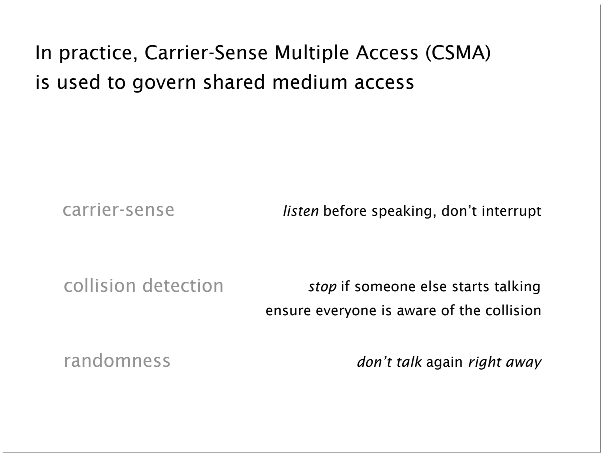
What is a link?

How do we identify link adapters?

#3 How do we share a network medium?

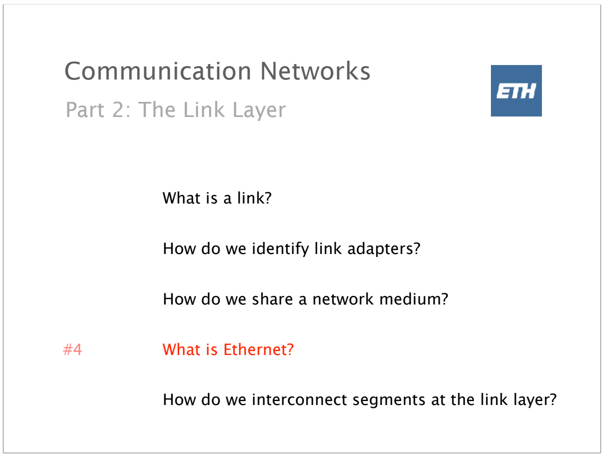
What is Ethernet?

How do we interconnect segments at the link layer?



In practice, Carrier-Sense Multiple Access (CSMA) is used to govern shared medium access

carrier-sense	*listen* before speaking, don't interrupt
collision detection	*stop* if someone else starts talking ensure everyone is aware of the collision
randomness	*don't talk* again *right away*



Communication Networks

Part 2: The Link Layer

What is a link?

How do we identify link adapters?

How do we share a network medium?

#4 What is Ethernet?

How do we interconnect segments at the link layer?

Ethernet…

was invented as a broadcast technology

each packet was received by all attached hosts

is now *the* dominant wired LAN technology

by far the most widely used

has managed to keep up with the speed race

from 10 Mbps to 400 Gbps

Communication Networks

Part 2: The Link Layer

What is a link?

How do we identify link adapters?

How do we share a network medium?

What is Ethernet?

#5 How do we interconnect segments at the link layer?

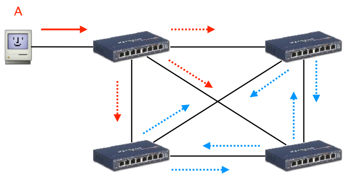
Switches connect two or more LANs together at the Link layer, acting as L2 gateways

Switches are "store-and-forward" devices, they

- extract the destination MAC from the frame
- look up the MAC in a table (using exact match)
- forward the frame on the appropriate interface

Switches are similar to IP routers,
except that they operate one layer below

While flooding enables automatic discovery of hosts, it also creates problems when the networks has loops



Each frame leads to the creation of *at least two new frames!*

exponential increase, with no TTL to remove looping frames…

Algorhyme

I think that I shall never see
A graph more lovely than a tree.
A tree whose crucial property
Is loop-free connectivity.

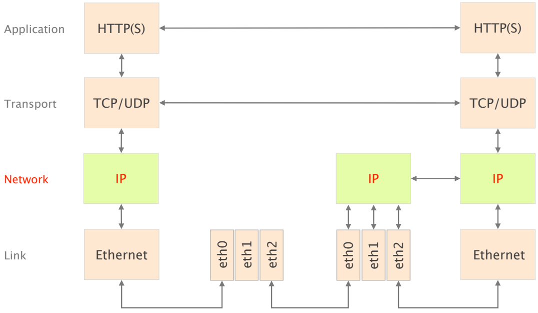
A tree that must be sure to span
So packets can reach every LAN.
First, the root must be selected.
By ID, it is elected.

Least-cost paths from root are traced.
In the tree, these paths are placed.
A mesh is made by folks like me,
Then bridges find a spanning tree.

— *Radia Perlman*

This week on
Communication Networks

IP and the Network layer!



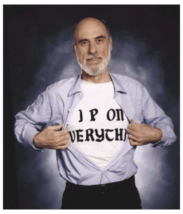
Application: HTTP(S) ⟷ HTTP(S)

Transport: TCP/UDP ⟷ TCP/UDP

Network: IP — IP ⟷ IP

Link: Ethernet — eth0 eth1 eth2 — eth0 eth1 eth2 — Ethernet

Internet Protocol and Forwarding



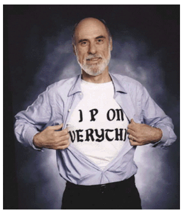
source: Boardwatch Magazine

1 IP addresses
use, structure, allocation

2 IP forwarding
longest prefix match rule

3 IP header
IPv4 and IPv6, wire format

Internet Protocol and Forwarding



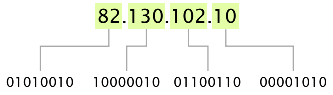
1 IP addresses
use, structure, allocation

IP forwarding
longest prefix match rule

IP header
IPv4 and IPv6, wire format

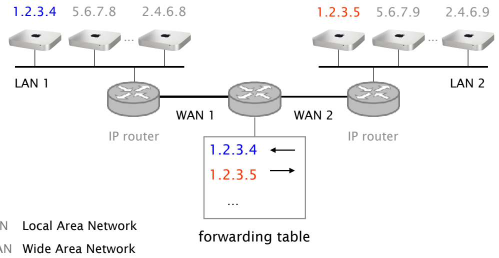
IPv4 addresses are unique 32-bits number
associated to a network interface (on a host, a router, ...)

IP addresses are usually written
using dotted-quad notation



Routers forwards IP packets
based on their destination IP address

If IP addresses were assigned arbitrarily,
routers would require forwarding entries for all of them



LAN Local Area Network
WAN Wide Area Network

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8 billion

estimated* # of Internet connected devices
in 2016

* Cisco Visual Networking Index 2017

11.6 billion

estimated* # of Internet connected devices
in 2021

* Cisco Visual Networking Index 2017

Two universal tricks you can apply
to any computer sciences problem

When you need... more flexibility,
you add... a layer of indirection

When you need... more scalability,
you add... a hierarchical structure

When you need... more scalability,
you add... a hierarchical structure

IP addresses are hierarchically allocated, similarly to the postal service

Address	
Zip	8092
Street	Gloriastrasse
Building	35 (ETZ)
Location in building	G 90
Name	Laurent Vanbever

Nobody in the Swiss mail system knows where every single house or building is

principle

Routing tables are separated
at each level of the hierarchy

each one with a manageable scale

Forwarding in the Swiss mail
in 4 steps

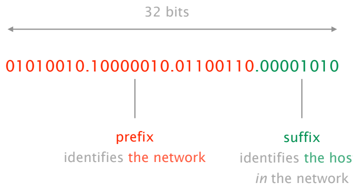
1 Deliver the letter to the post office responsible for the zip code

2 Assign letter to the mail person covering the street

3 Drop letter into the mailbox attached to the building

4 Hand in the letter to the appropriate person

IP addressing is hierarchical, composed of a prefix (network address) and a suffix (host address)



32 bits

01010010.10000010.01100110.00001010

prefix
identifies the network

suffix
identifies the hosts
in the network

Each prefix has a given length, usually written using a “slash notation”

IP prefix

82.130.102.0 /24

prefix length (in bits)

Here, a /24 means that we have 8 bits left to address hosts address, enough for 256 hosts

82.130.102.0 /24

prefix part	host part	IP address
01010010.10000010.01100110.	00000000	82.130.102.0
01010010.10000010.01100110.	00000001	82.130.102.1
01010010.10000010.01100110.	00000010	82.130.102.2
01010010.10000010.01100110.	11111110	82.130.102.254
01010010.10000010.01100110.	11111111	82.130.102.255

In practice, the first and last IP address of a prefix are not usable

prefix part	host part	IP address
01010010.10000010.01100110.	00000000	82.130.102.0
01010010.10000010.01100110.	11111111	82.130.102.255

The address with the host part being all 0s identifies the network itself

prefix part	host part	IP address
01010010.10000010.01100110.	00000000	82.130.102.0

The address with the host part being all 1s identifies the broadcast address

prefix part	host part	IP address
01010010.10000010.01100110.	11111111	82.130.102.255

A /24 has therefore only 254 addresses that can be allocated to hosts

Prefixes are also sometimes specified using an address and a mask

Address	82.130.102.0
	01010010.10000010.01100110. 00000000
	11111111.11111111.11111111. 00000000
Mask	255.255.255.0

ANDing the address and the mask gives you the prefix

Address	82.130.102.0
	01010010.10000010.01100110. 00000000
	11111111.11111111.11111111. 00000000
Mask	255.255.255.0

Given this IP prefix 82.130.0.0/17

Compute

# of addressable hosts

the prefix mask

network address

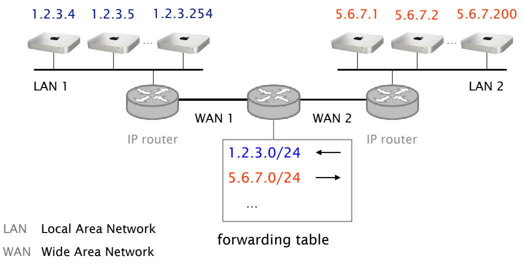
1st host address

last host address

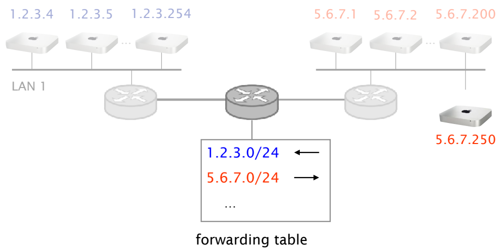
broadcast address

Routers forward packet to their destination according to the network part, *not* the host part

Doing so enables to scale the forwarding tables



Hierarchical addressing enables to add new hosts without changing or adding forwarding rules



Originally, there were only 5 fixed allocation sizes, (or classes)—known as classful networking

	leading bits	prefix length	# hosts	start address	end address
class A	0	8	2^{24}	0.0.0.0	127.255.255.255
class B	10	16	2^{16}	128.0.0.0	191.255.255.255
class C	110	24	2^{8}	192.0.0.0	223.255.255.255
class D multicast	1110			224.0.0.0	239.255.255.255
class E reserved	1111			240.0.0.0	255.255.255.255

Classful networking was quite wasteful leading to IP address exhaustion

problem — Class C was too small, so everybody requested class B

which where: *i)* too big and *ii)* too few (wasted space)

solution — Classless Inter-Domain Routing (CIDR)

introduced in 1993

CIDR enabled flexible division between network and hosts addresses

CIDR must specify both the address and the mask

classful was communicating this in the first address bits

Masks are carried by the routing algorithms

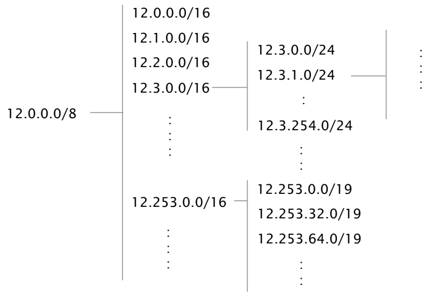
it is *not* implicitly carried in the address

Say that an organization needs 500 addresses…

with…	it gets a…	leading to a waste of…
classful	class B (/16)	99%
CIDR	/23 (=2 class C's)	2%

With CIDR, the max. waste is bounded to 50% (why?)

Today, addresses are allocated in contiguous chunks


12.0.0.0/8

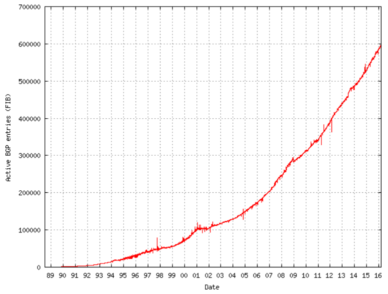
12.0.0.0/16
12.1.0.0/16
12.2.0.0/16
12.3.0.0/16
⋮
12.253.0.0/16
⋮

12.3.0.0/24
12.3.1.0/24
⋮
12.3.254.0/24
⋮

12.253.0.0/19
12.253.32.0/19
12.253.64.0/19
⋮

⋮

As of now, the Internet has around 600,000 IPv4 prefixes

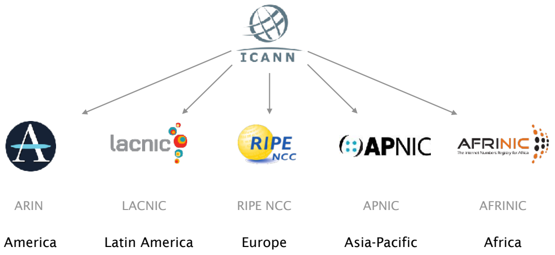


source http://www.cidr-report.org/

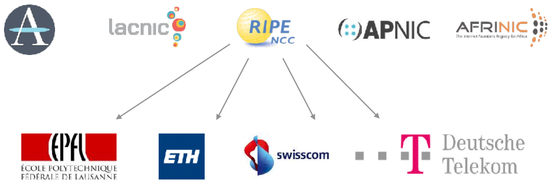
The allocation process of IP address is also hierarchical

The root is held by Internet Corporation for Assigned Names and Numbers, aka ICANN

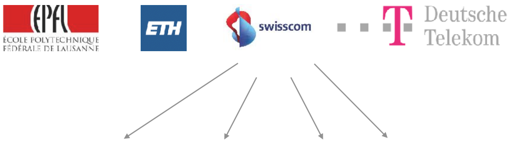
ICANN allocates large prefixes blocks to Regional Internet Registries (RIRs)



RIRs allocates parts of these prefixes blocks to Internet Service Providers (ISPs) and large institutions



ISPs and large institutions may, in turn, allocate even smaller prefixes to their own customers

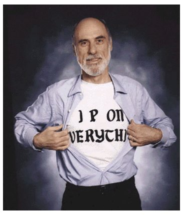


ICANN	ICANN gives RIPE Prefix	82.0.0.0/8 01010010
RIPE NCC	RIPE gives ETHZ Prefix	82.130.64.0/18 010100101000001001
ETH	ETHZ gives ITET/TIK Prefix	82.130.102.0/23 01010010100000100110011
D ITET	ITET gives me Address	82.130.102.254 01010010100000100110011011111110

IP prefixes @ ETH

1	82.130.64.0/18	6	192.33.88.0/21
2	129.132.0.0/16	7	192.33.96.0/21
3	148.187.192.0/19	8	192.33.104.0/22
4	195.176.96.0/19	9	192.33.108.0/23
5	192.33.87.0/24	10	192.33.110.0/24

Internet Protocol and Forwarding

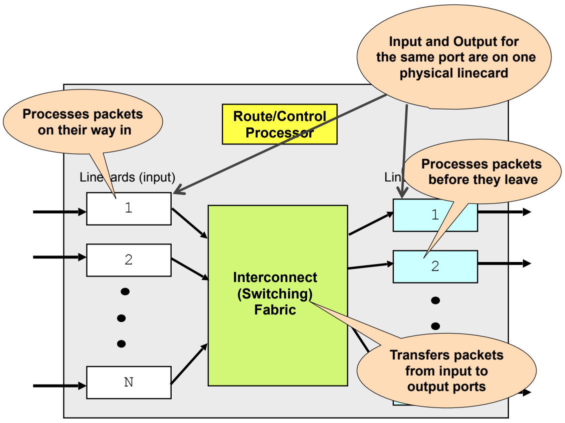


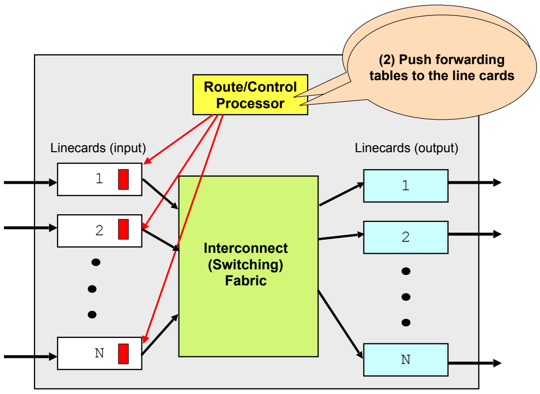
IP addresses
use, structure, allocation

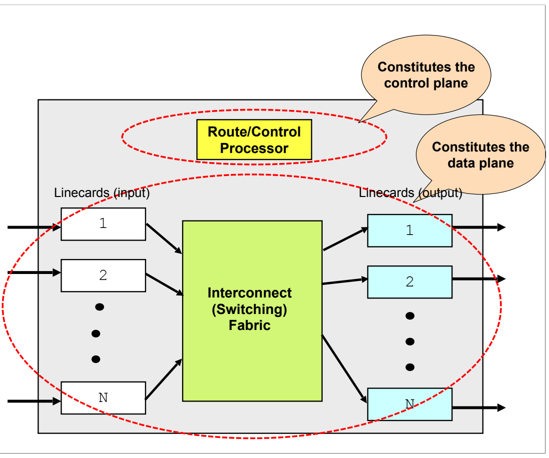
2 IP forwarding
longest prefix match rule

IP header
IPv4 and IPv6, wire format

What's inside an IP router?


Input and Output for the same port are on one physical linecard
Processes packets on their way in
Route/Control Processor
Line ards (input)
Lin
Processes packets before they leave
1
2
N
Interconnect (Switching) Fabric
1
2
Transfers packets from input to output ports

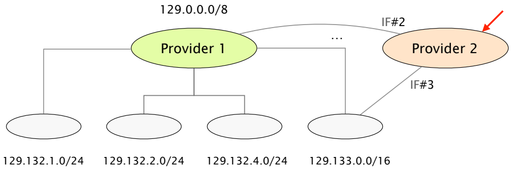

(2) Push forwarding tables to the line cards
Route/Control Processor
Linecards (input)
Linecards (output)
1
2
N
Interconnect (Switching) Fabric
1
2
N


Constitutes the control plane
Constitutes the data plane
Route/Control Processor
Linecards (input)
Linecards (output)
1
2
N
Interconnect (Switching) Fabric
1
2
N

Routers maintain forwarding entries
for each Internet prefix

Provider 2's Forwarding table

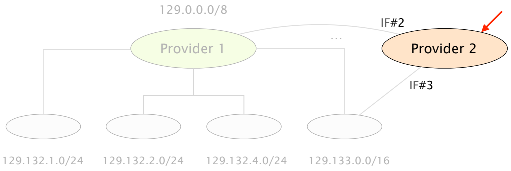
IP prefix	Output
129.0.0.0/8	IF#2
129.132.1.0/24	IF#2
129.132.2.0/24	IF#2
129.133.0.0/16	IF#3



Let's say a packet for 129.0.1.1
arrives at Provider 2

Provider 2's Forwarding table

IP prefix	Output
129.0.0.0/8	IF#2
129.132.1.0/24	IF#2
129.132.2.0/24	IF#2
129.133.0.0/16	IF#3



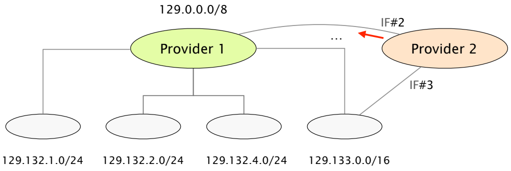
When a router receives an IP packet, it performs an
IP lookup to find the matching prefix

Let's say a packet for 129.0.1.1
arrives at Provider 2

> Provider 2 forwards it to IF#2

Provider 2's Forwarding table

IP prefix	Output
129.0.0.0/8	IF#2
129.132.1.0/24	IF#2
129.132.2.0/24	IF#2
129.133.0.0/16	IF#3

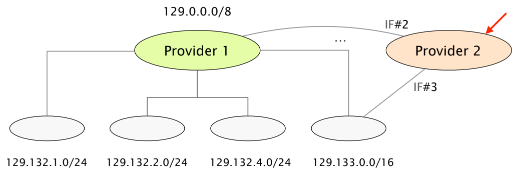


CIDR makes forwarding harder though,
as one packet can match many IP prefixes

Let's say a packet for 129.133.0.1 arrives at Provider 2

Provider 2's Forwarding table

IP prefix	Output
129.0.0.0/8	IF#2
129.132.1.0/24	IF#2
129.132.2.0/24	IF#2
129.133.0.0/16	IF#3

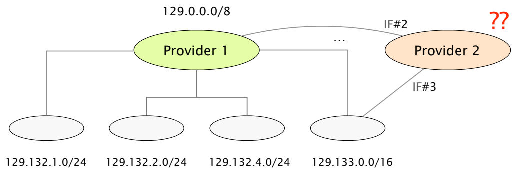


Let's say a packet for 129.133.0.1 arrives at Provider 2

We have two matches!

Provider 2's Forwarding table

IP prefix	Output
129.0.0.0/8	IF#2
129.132.1.0/24	IF#2
129.132.2.0/24	IF#2
129.133.0.0/16	IF#3



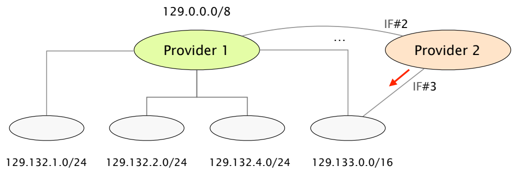
To resolve ambiguity, forwarding is done along the *most specific* prefix (*i.e.*, the longer one)

Let's say a packet for 129.133.0.1 arrives at Provider 2

> Provider 2 forwards it to IF#3

Provider 2's Forwarding table

IP prefix	Output
129.0.0.0/8	IF#2
129.132.1.0/24	IF#2
129.132.2.0/24	IF#2
129.133.0.0/16	IF#3

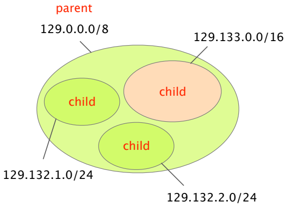


Could we do something better than maintaining one entry per prefix? *Yep!*

A child prefix can be filtered from the table whenever it shares the same output interface as its parent

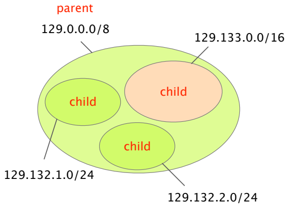
Routing Table

IP prefix	Output Interface
...	
129.0.0.0/8	IF#2
129.132.1.0/24	IF#2
129.132.2.0/24	IF#2
129.133.0.0/16	IF#3
...	



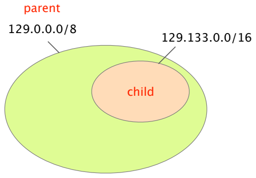
Routing Table

IP prefix	Output Interface
...	
129.0.0.0/8	IF#2
~~129.132.1.0/24~~	~~IF#2~~
~~129.132.2.0/24~~	~~IF#2~~
129.133.0.0/16	IF#3
...	



Routing Table

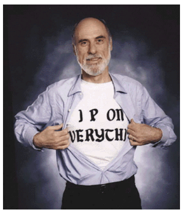
IP prefix	Output Interface
...	
129.0.0.0/8	IF#2
129.133.0.0/16	IF#3
...	



Exactly the same forwarding as before

Check out www.route-aggregation.net,
to see how filtering can be done automatically

Internet Protocol and Forwarding

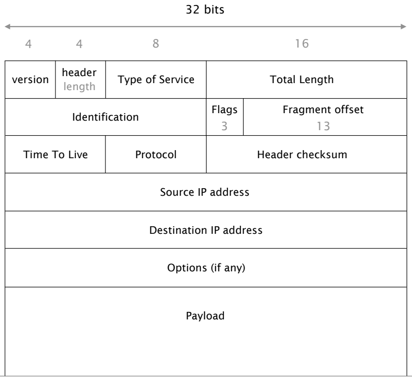


IP addresses
use, structure, allocation

IP forwarding
longest prefix match rule

3 IP header
IPv4 and IPv6, wire format

Here is what an IPv4 packet look like
on a wire



32 bits

4 4 8 16

version | header length | Type of Service | Total Length

Identification | Flags 3 | Fragment offset 13

Time To Live | Protocol | Header checksum

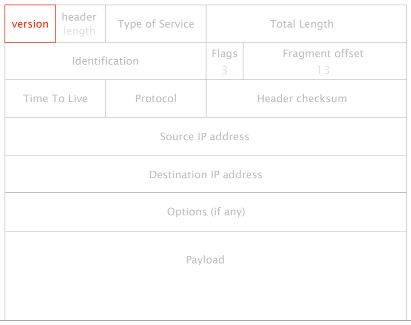
Source IP address

Destination IP address

Options (if any)

Payload

The version number tells us what other fields to expect,
typically it is set to “4” for IPv4, or “6” for IPv6



version | header length | Type of Service | Total Length

Identification | Flags 3 | Fragment offset 13

Time To Live | Protocol | Header checksum

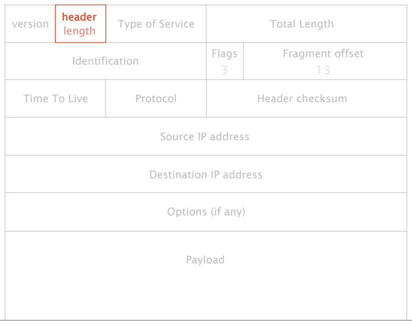
Source IP address

Destination IP address

Options (if any)

Payload

The header length denotes the number of 32-bits word
in the header, typically set to 5 (20 bytes header)



version | header length | Type of Service | Total Length

Identification | Flags 3 | Fragment offset 13

Time To Live | Protocol | Header checksum

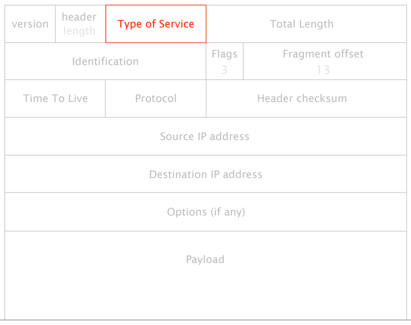
Source IP address

Destination IP address

Options (if any)

Payload

The ToS allows different packets to be treated differently,
e.g., low delay for voice, high bandwidth for video



version | header length | Type of Service | Total Length

Identification | Flags 3 | Fragment offset 13

Time To Live | Protocol | Header checksum

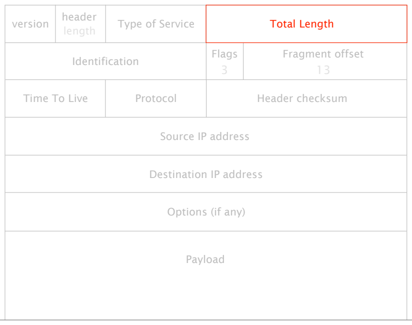
Source IP address

Destination IP address

Options (if any)

Payload

The total length denotes the # of bytes
in the entire packet, with a maximum of 65 535 bytes



version | header length | Type of Service | Total Length

Identification | Flags 3 | Fragment offset 13

Time To Live | Protocol | Header checksum

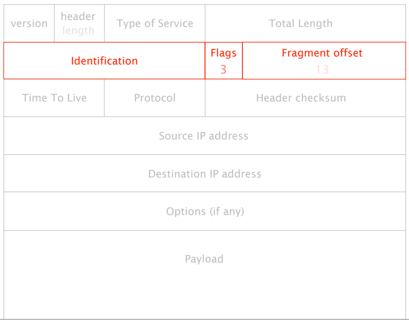
Source IP address

Destination IP address

Options (if any)

Payload

The next three fields are used when packets get fragmented



Every link in the Internet has a Maximum Transmission Unit (MTU)

MTU is the max. # of bytes a link can carry as one unit

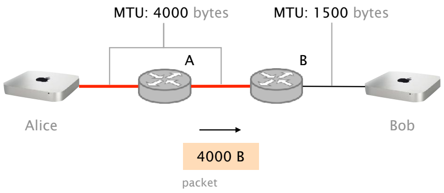
e.g., 1500 bytes for normal Ethernet

A router can fragment a packet if the outgoing link MTU is smaller than the total packet size

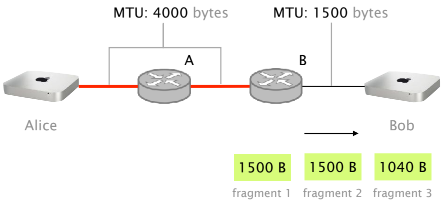
Fragmented packets are recomposed at the destination

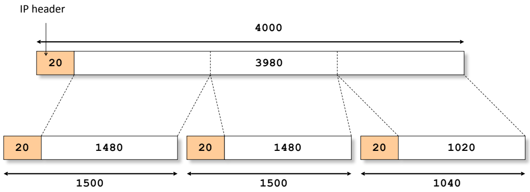
why not in the network?

Assume Alice is sending 4000B packets to Bob, who is connected to a 1500B MTU link

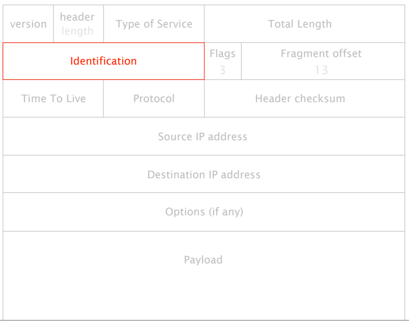


Because the packet is larger than the MTU, router B will split the packet into fragments

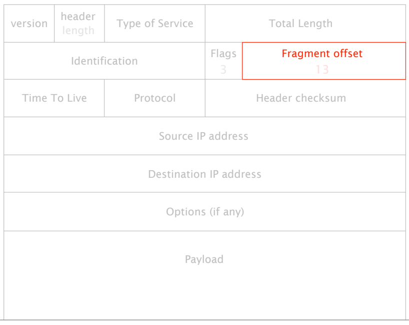




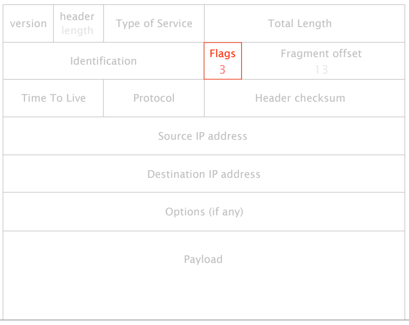
The Identification header uniquely identify the fragments of a particular packet



The fragment offset is used to put back the fragments in the right order in case of reordering



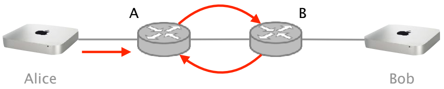
The flags is used to tell whether there are more fragments coming or not



The TTL is used to identify packets trapped in a loop, and eventually discard them

version	header length	Type of Service	Total Length	
Identification			Flags 3	Fragment offset 13
Time To Live		Protocol	Header checksum	
Source IP address				
Destination IP address				
Options (if any)				
Payload				

TTL is decremented by 1 at each router, the packet is discarded if it reaches 0



default TTL values

*nix (Linux/Mac)	64
Windows	128

(used for OS fingerprinting)

The protocol field identifies the higher level protocol carried in the packet, “6” for TCP, “17” for UDP

version	header length	Type of Service	Total Length	
Identification			Flags 3	Fragment offset 13
Time To Live		Protocol	Header checksum	
Source IP address				
Destination IP address				
Options (if any)				
Payload				

The checksum is the sum of all the 16 bits words in the header (does not protect the payload)

version	header length	Type of Service	Total Length	
Identification			Flags 3	Fragment offset 13
Time To Live		Protocol	Header checksum	
Source IP address				
Destination IP address				
Options (if any)				
Payload				

The source and destination IP uniquely identifies the source and destination host

version	header length	Type of Service	Total Length	
Identification			Flags 3	Fragment offset 13
Time To Live		Protocol	Header checksum	
Source IP address				
Destination IP address				
Options (if any)				
Payload				

Options were initially put to provide additional flexibility. For security reasons, there are often deactivated.

version	header length	Type of Service	Total Length	
Identification			Flags 3	Fragment offset 13
Time To Live		Protocol	Header checksum	
Source IP address				
Destination IP address				
Options (if any)				
Payload				

IP options

Record route

Strict source route

Loose source route

Timestamp

Traceroute

Router alert

…

see http://www.networksorcery.com/enp/protocol/ip.htm#Options for a full list

While there are no new IPv4 available,
IPv4 still accounts for more than 98% of all traffic

according to https://ams-ix.net/technical/statistics/sflow-stats/ipv6-traffic
and https://ams-ix.net/technical/statistics

With respect to IPv4, IPv6 is simpler

IPv6 was motivated by address exhaustion

IPv6 addresses are 128 bits long, that's plenty!

IPv6 got rid of anything that wasn't necessary

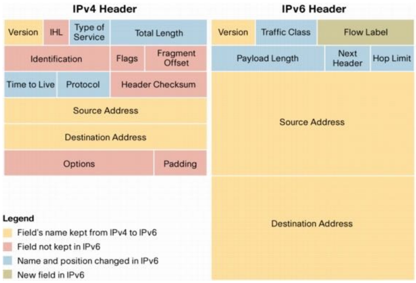
spring cleaning for IPv6

Result is an elegant, if unambitious, protocol

With respect to IPv4, IPv6 is simpler

IPv6	removed	reason
	fragmentation checksum	leave problems to the end host
	header length	simplify handling
	added…	
	new options mechanism	simplify handling
	expanded addresses	
	flow label	flexibility

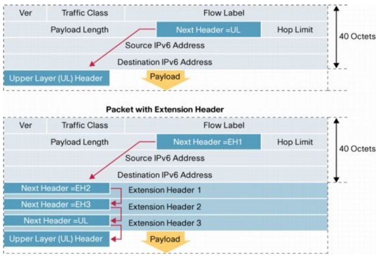
IPv4 vs IPv6



source http://bit.ly/1HXc2BS

IPv6 enables to insert arbitrary options in the packet

see RFC 2460

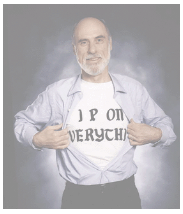


source http://bit.ly/1HXc2BS

The problem with IPv4 options is that all of them must be processed by each router, which is slow

In IPv6, only one type of optional header must be processed by each router

Internet Protocol and Forwarding



IP addresses

use, structure, allocation

IP forwarding

longest prefix match rule

IP header

IPv4 and IPv6, wire format

Next week on

Communication Networks

Internet routing!