# Communication Networks

Spring 2017


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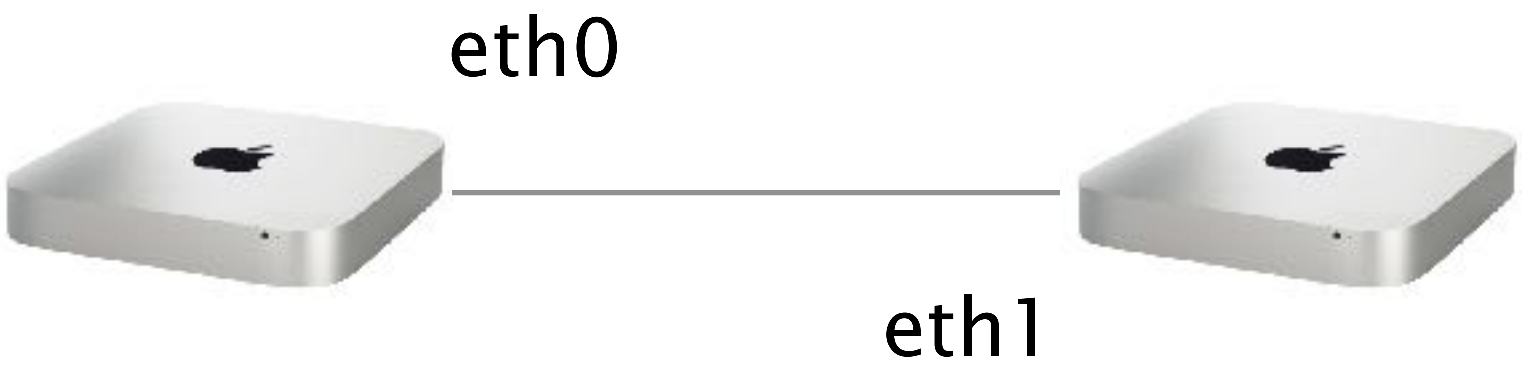
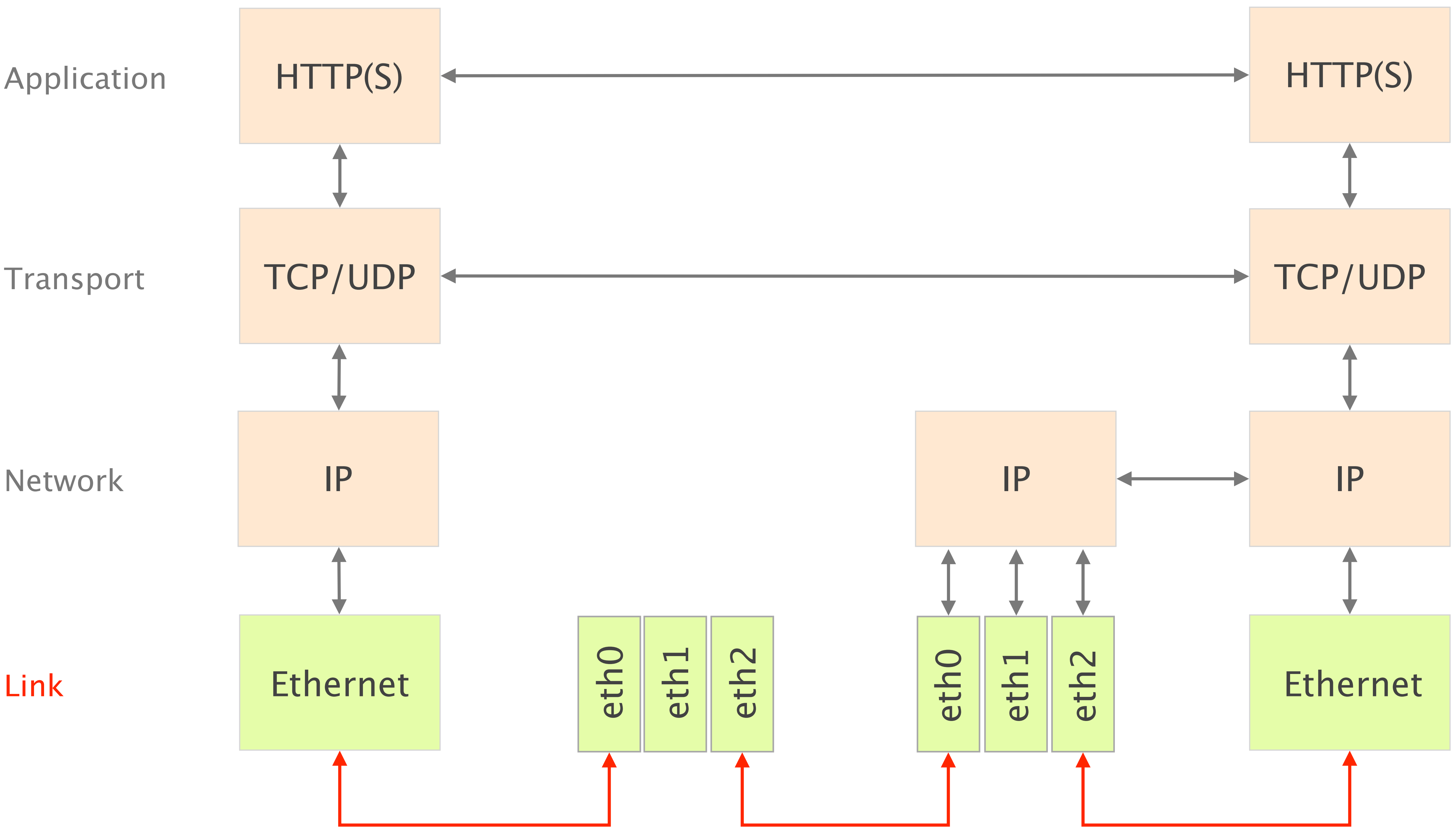
Material inspired from Scott Shenker & Jennifer Rexford

Last week on

# Communication Networks

How do local computers communicate?




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

# 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?

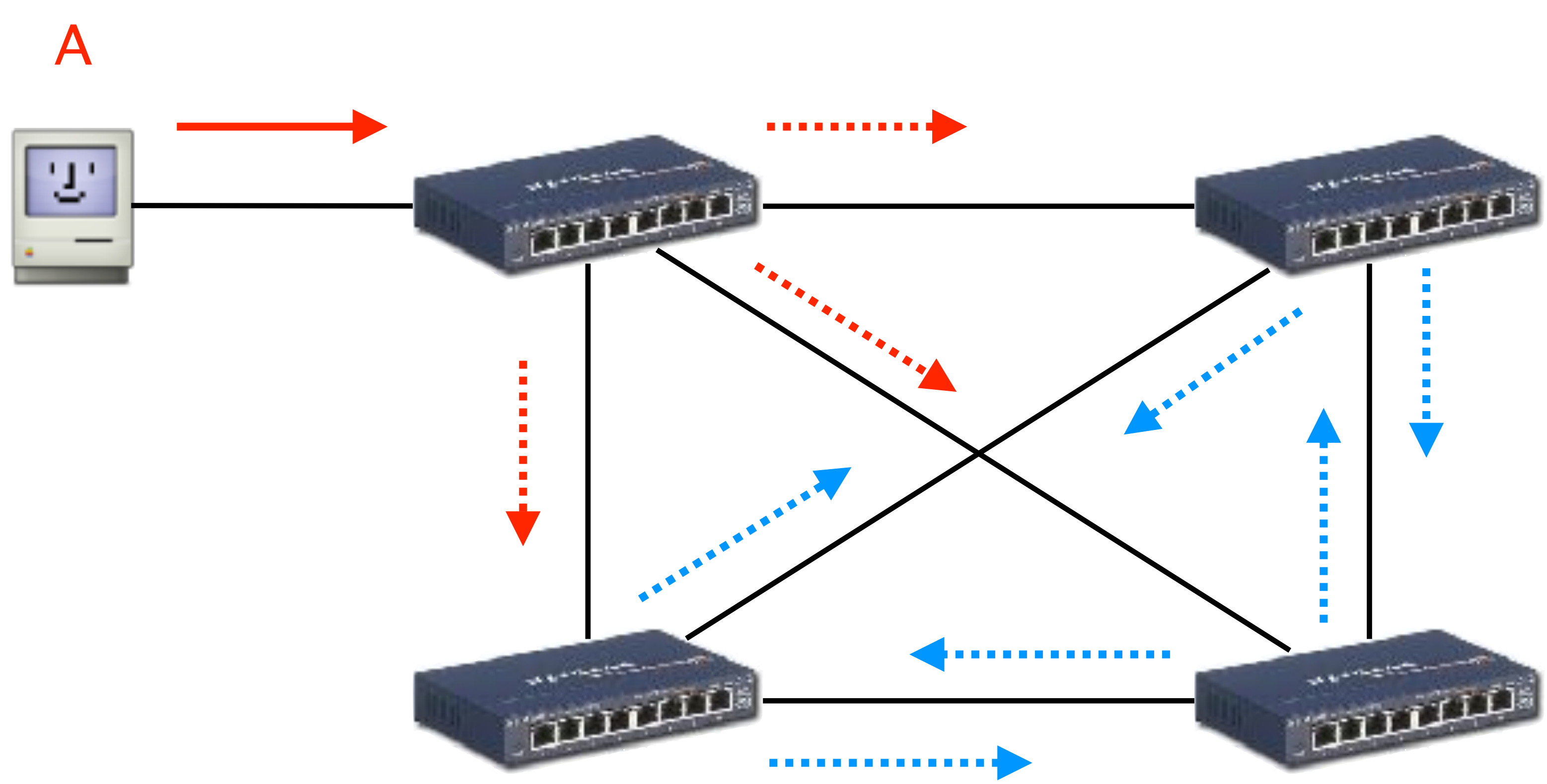
# Switches connect two or more LANs together at the Link layer, acting as L2 gateways

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.

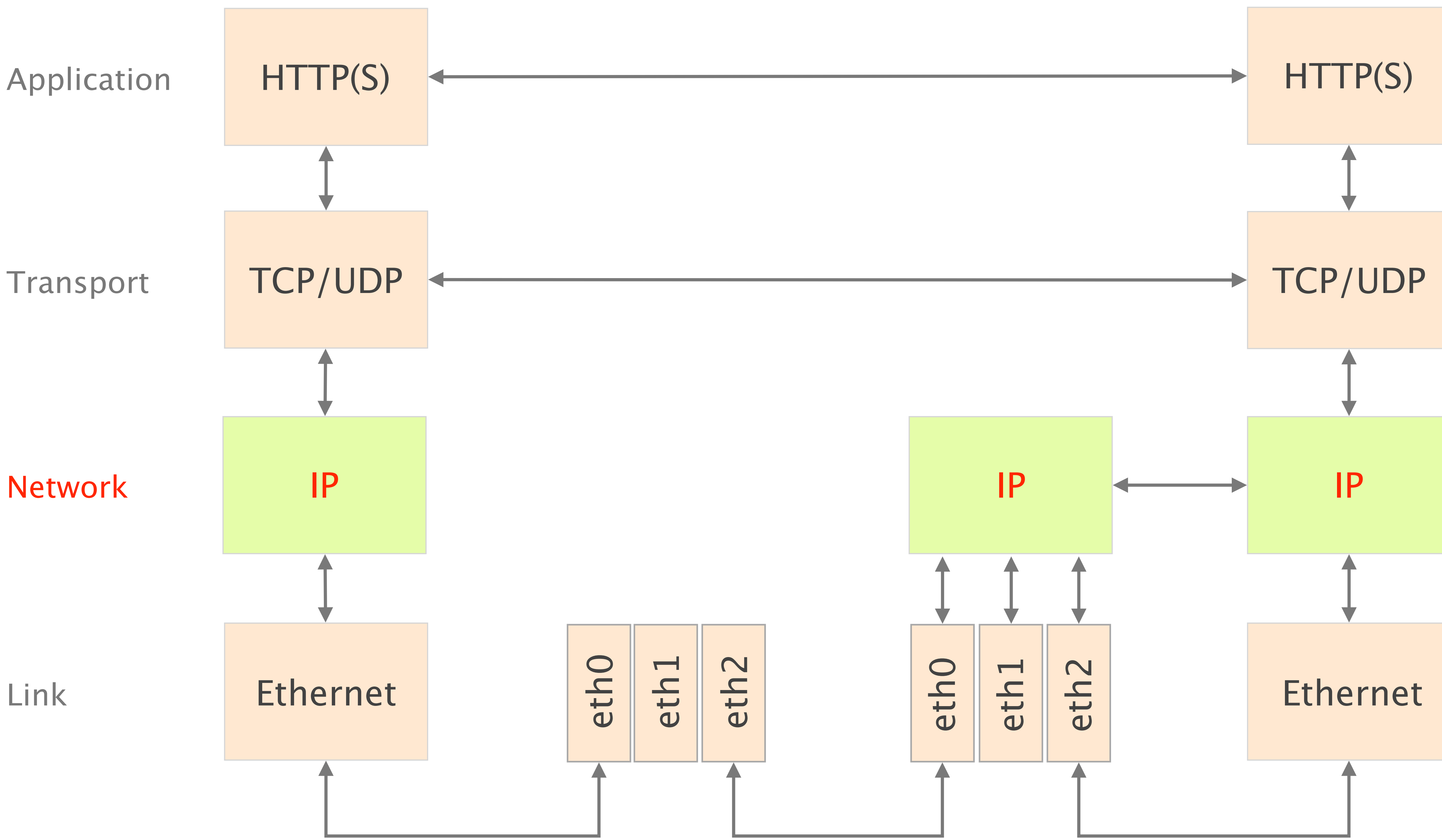
Least-cost paths from root are traced.
In the tree, these paths are placed.
A mesh is made by folks like me,
Then bridges find a spanning tree.

*— Radia Perlman*

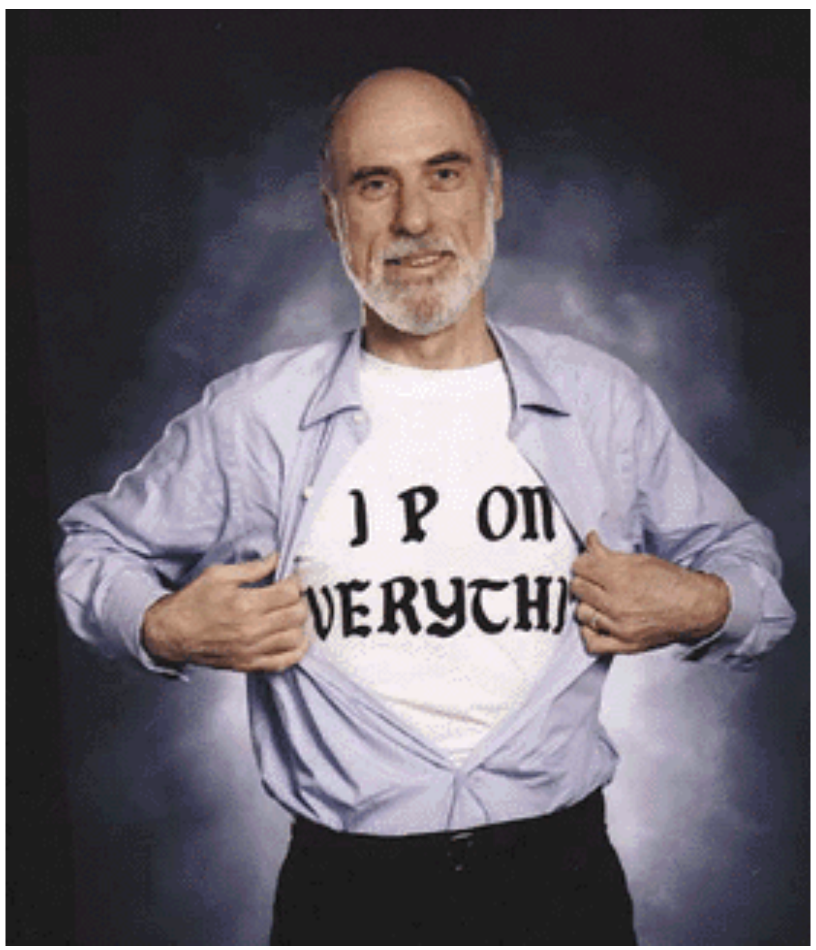
This week on

Communication Networks

# IP and the Network layer!



# Internet Protocol and Forwarding



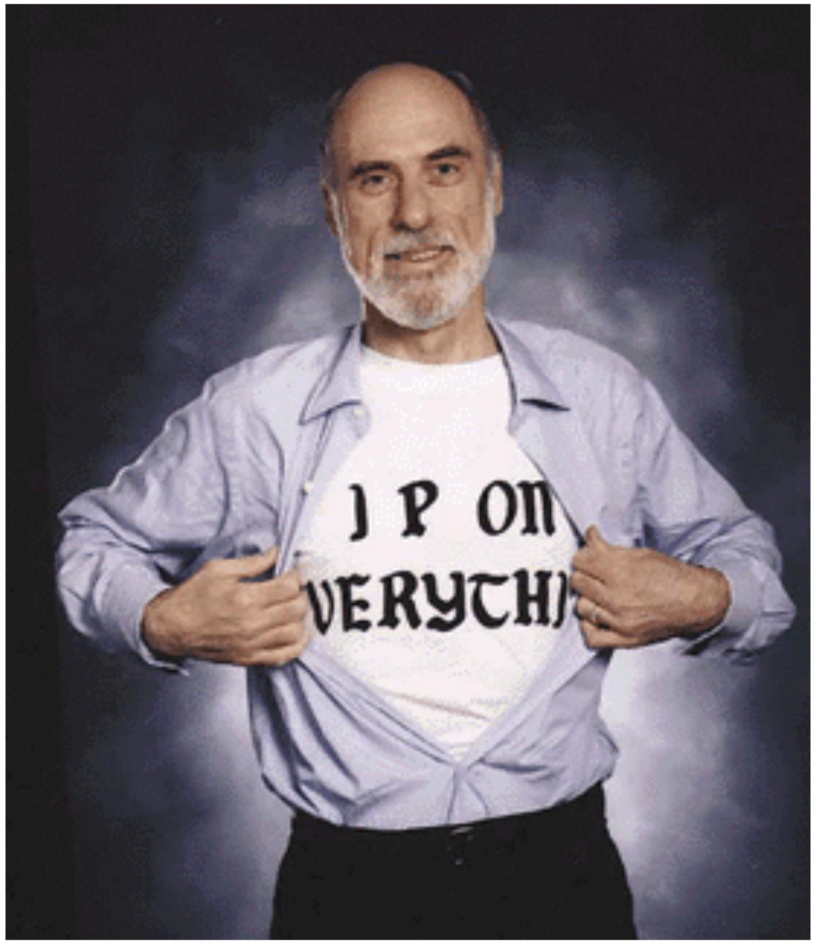

source: Boardwatch Magazine

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, …)

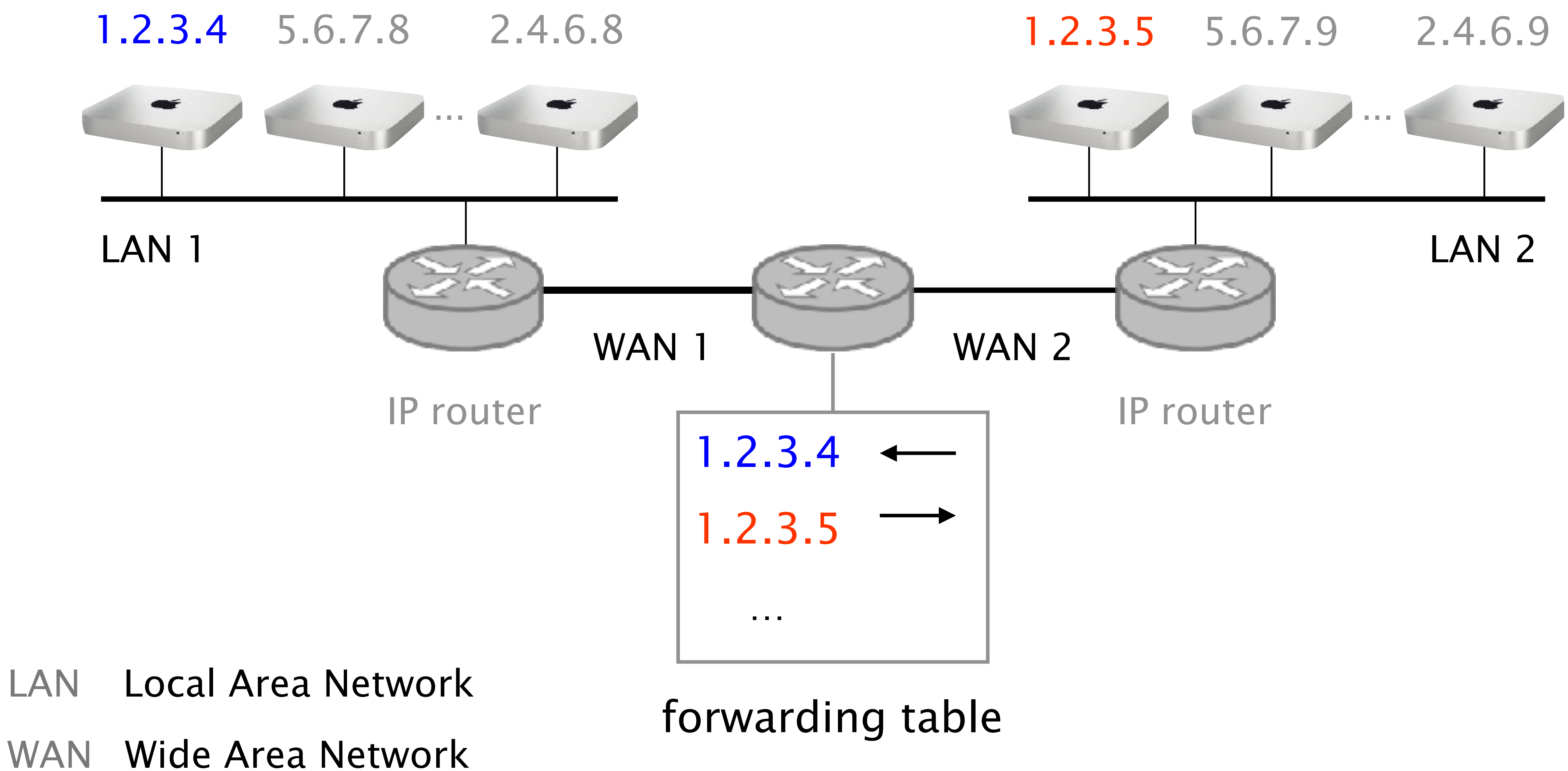
IP addresses are usually written using dotted-quad notation

82.130.102.10

01010010 10000010 01100110 00001010

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



# 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

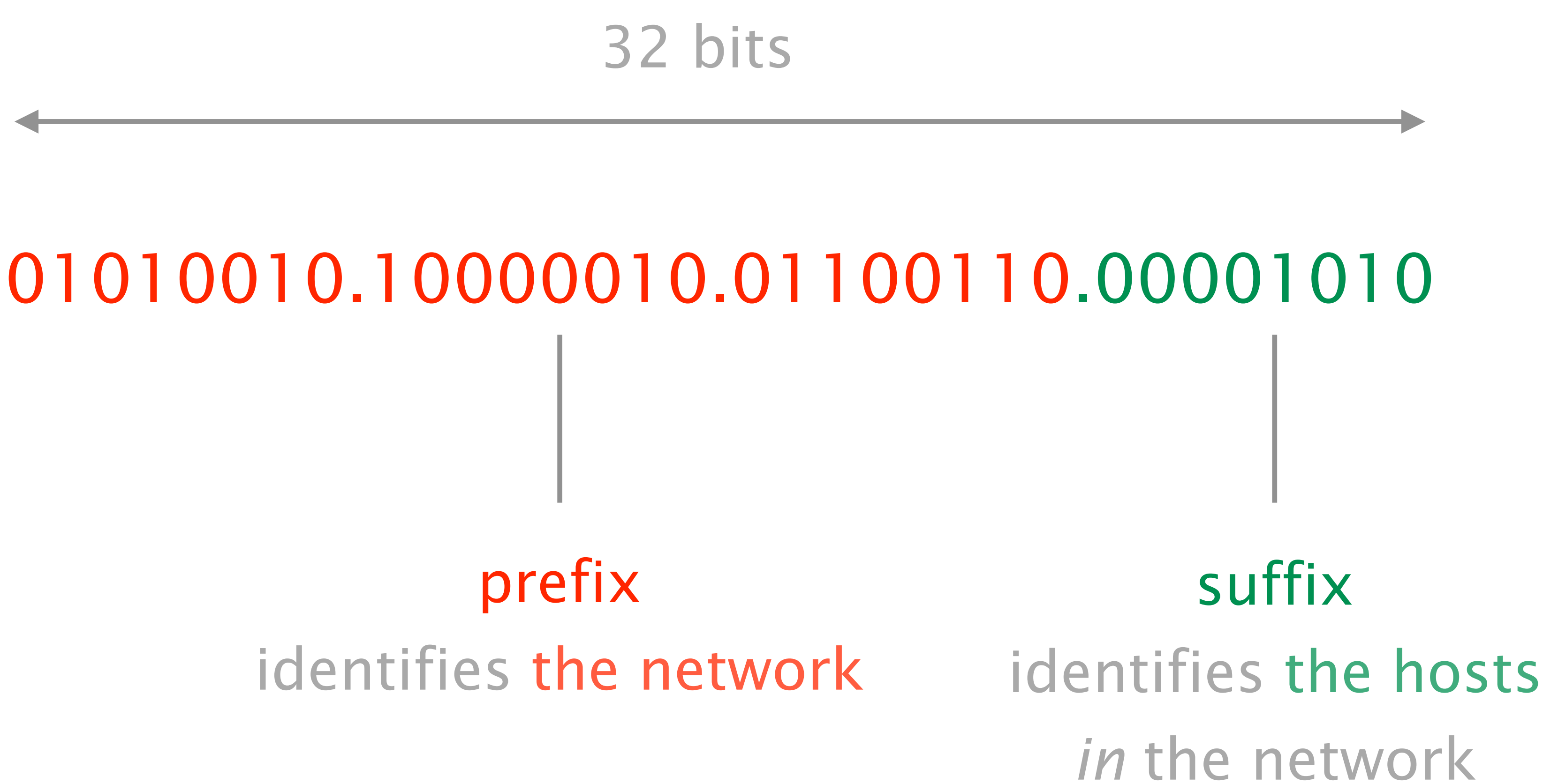
each one with a manageable scale

# 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)



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

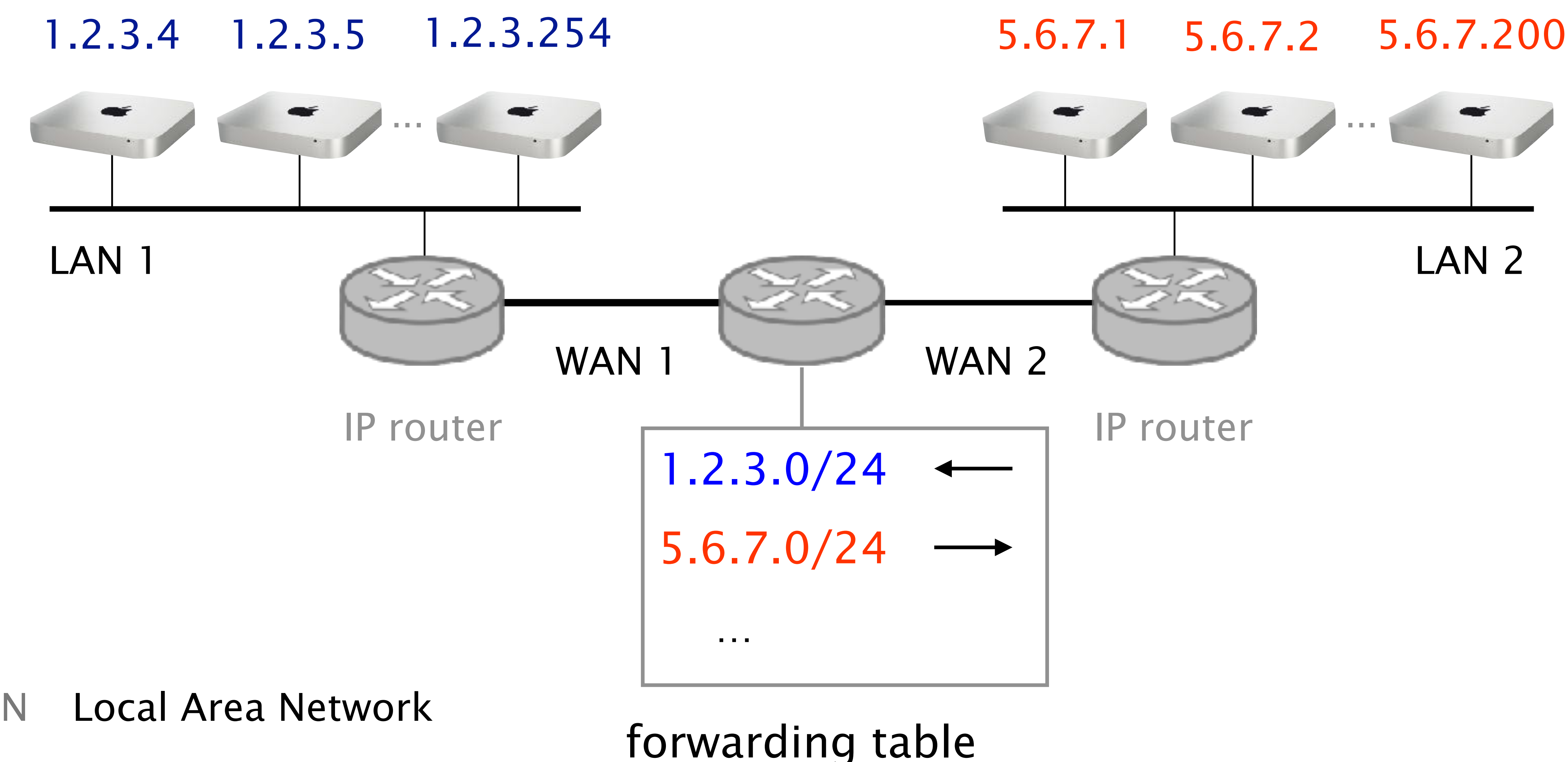
1st host address

last host address

broadcast address

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

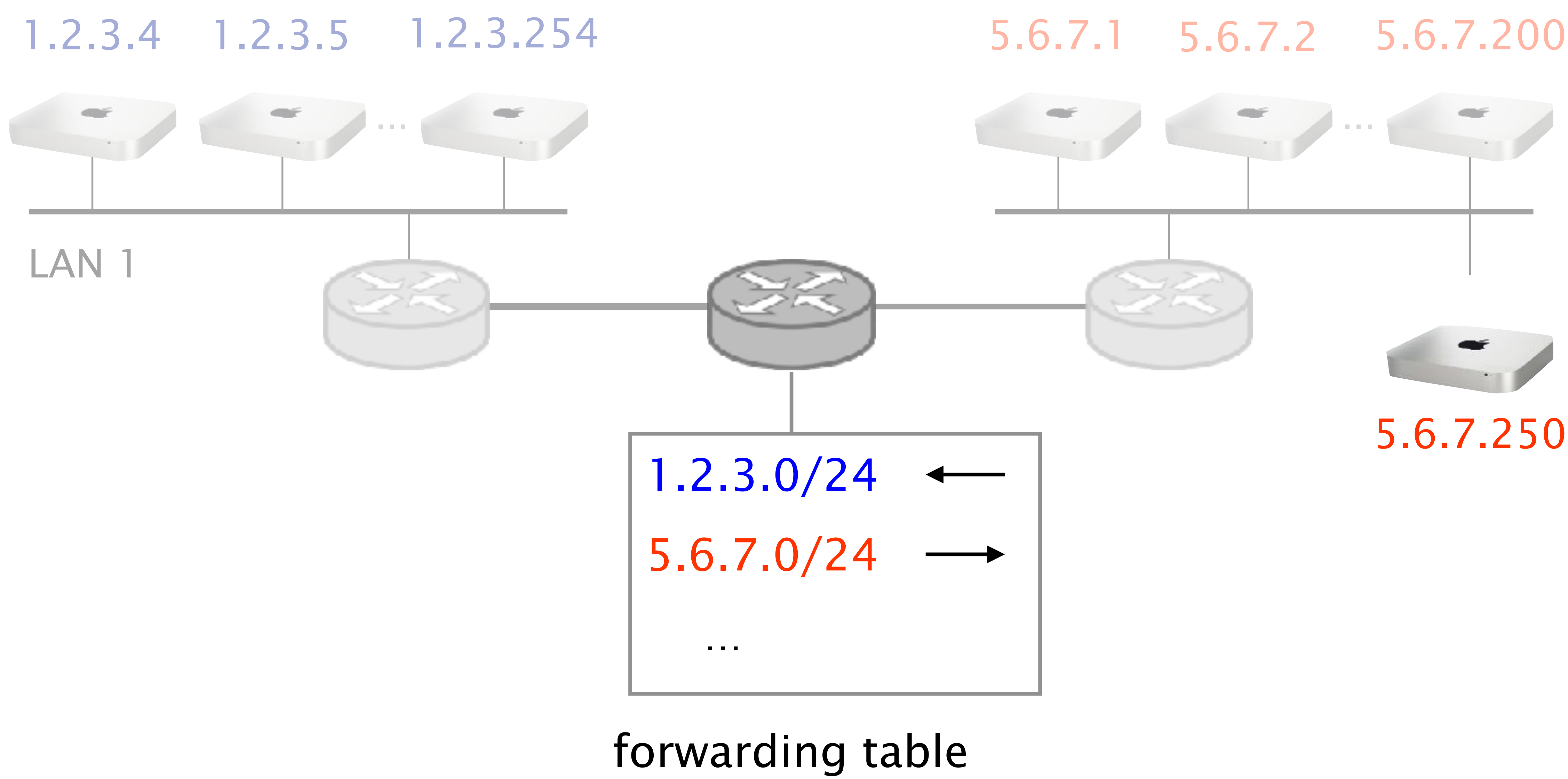
# Doing so enables to scale the forwarding tables




LAN Local Area Network

WAN Wide Area Network

# 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

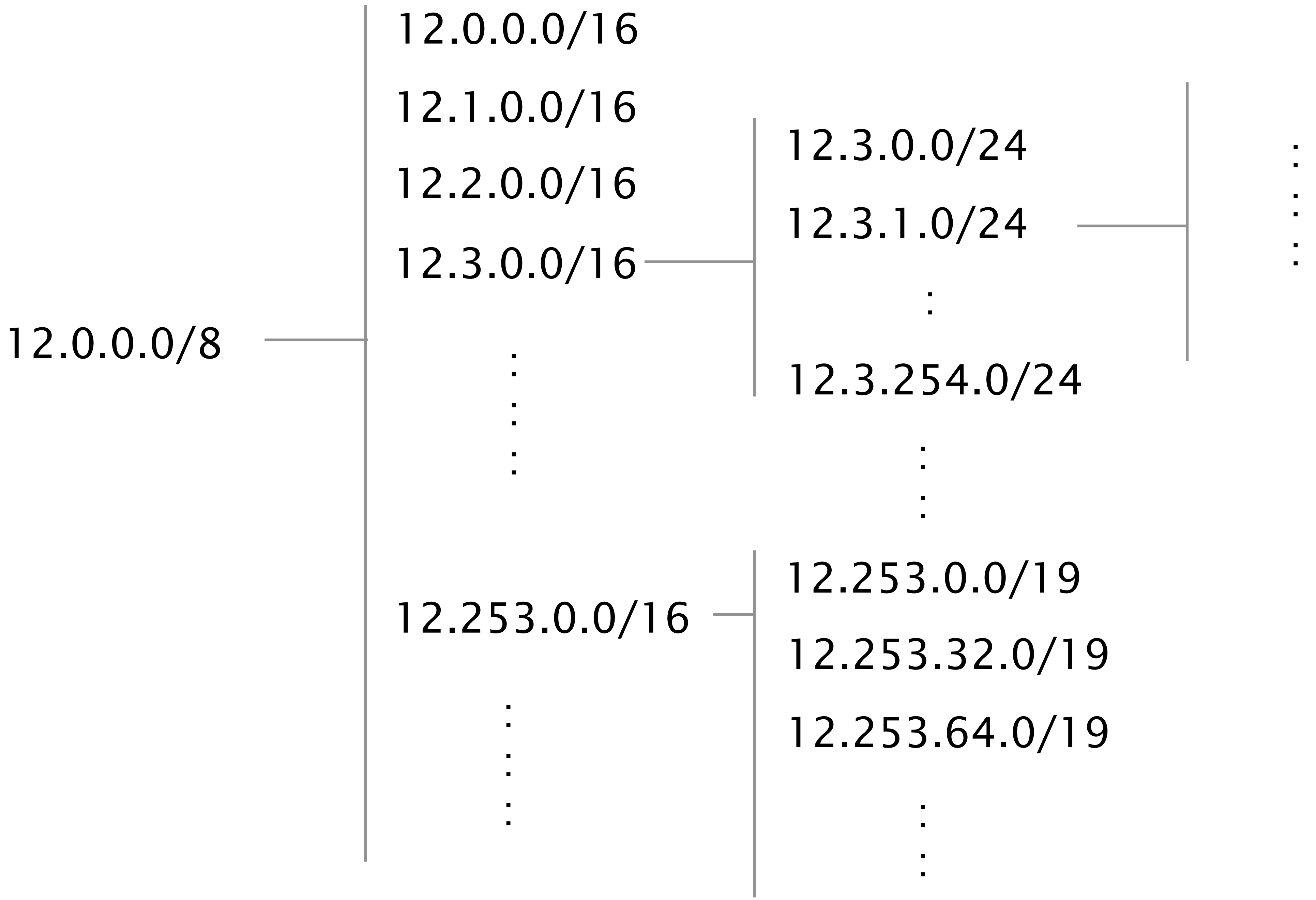
it is *not* implicitly carried in the address

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% |

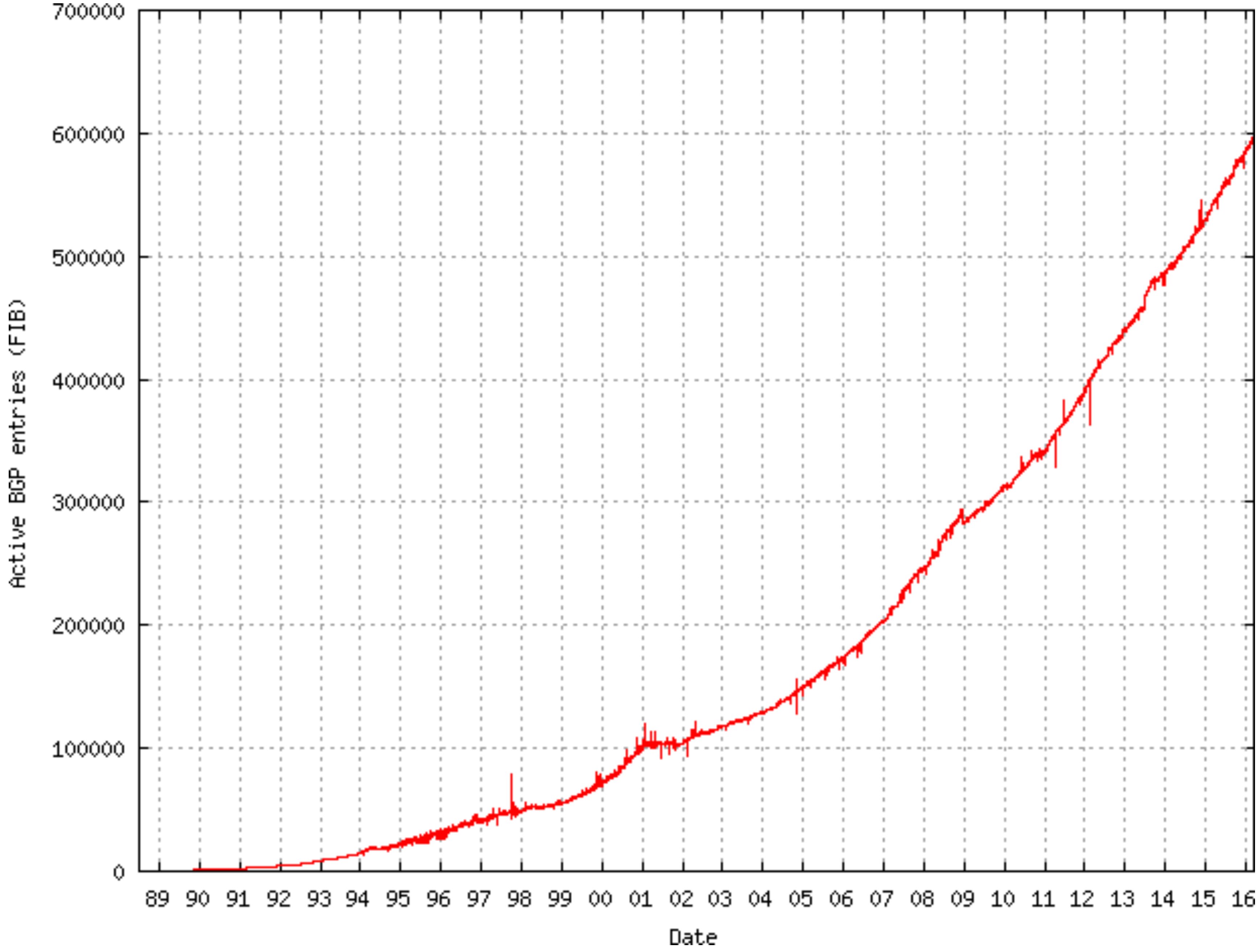
With CIDR, the max. waste is bounded to 50% (why?)

# Today, addresses are allocated in contiguous chunks



As of now,

the Internet has around 600,000 IPv4 prefixes



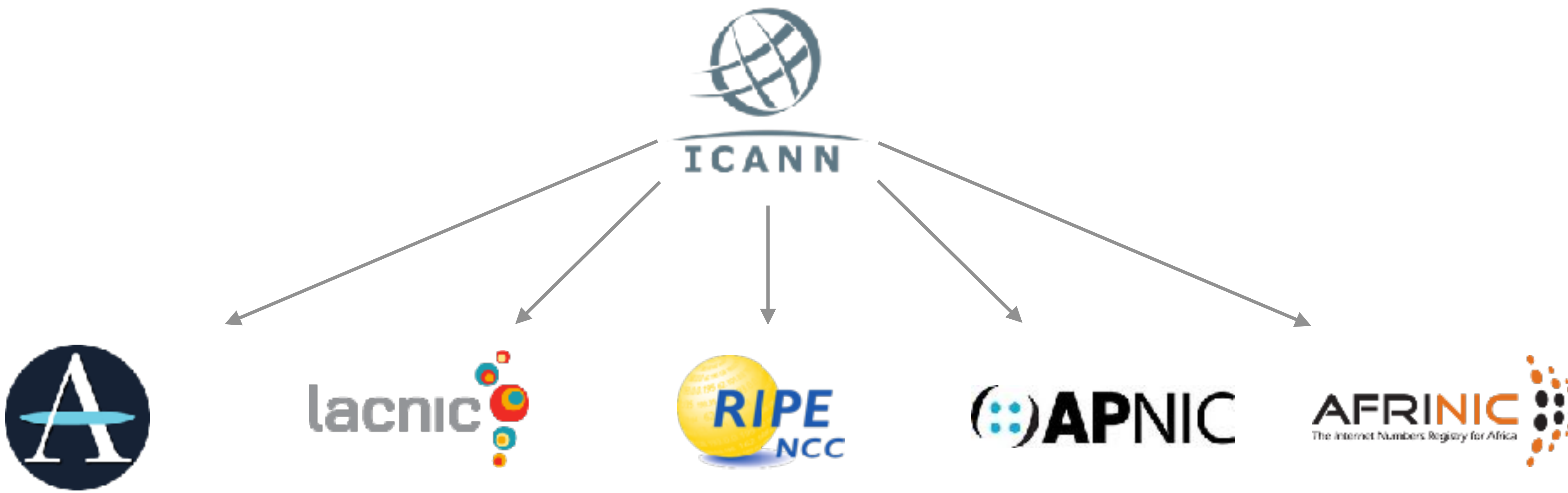

source http://www.cidr-report.org/

The allocation process of IP address is also hierarchical

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

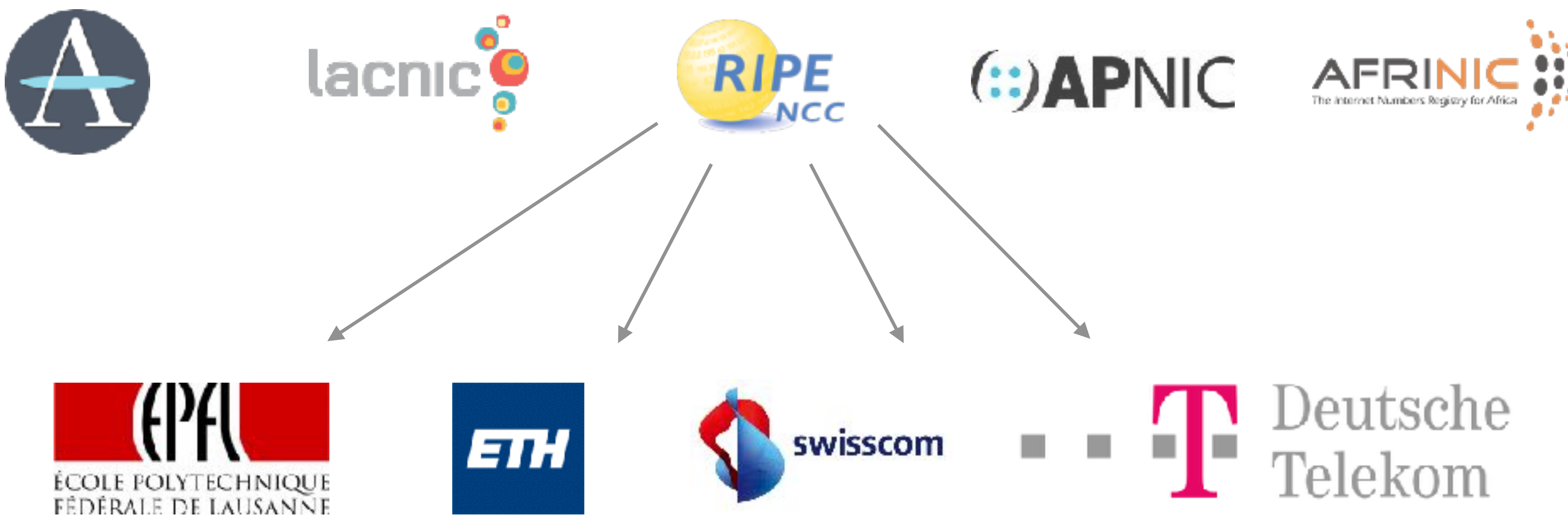
ICANN

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




| ARIN | LACNIC | RIPE NCC | APNIC | AFRINIC |
|---|---|---|---|---|
| America | Latin America | Europe | Asia-Pacific | Africa |

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



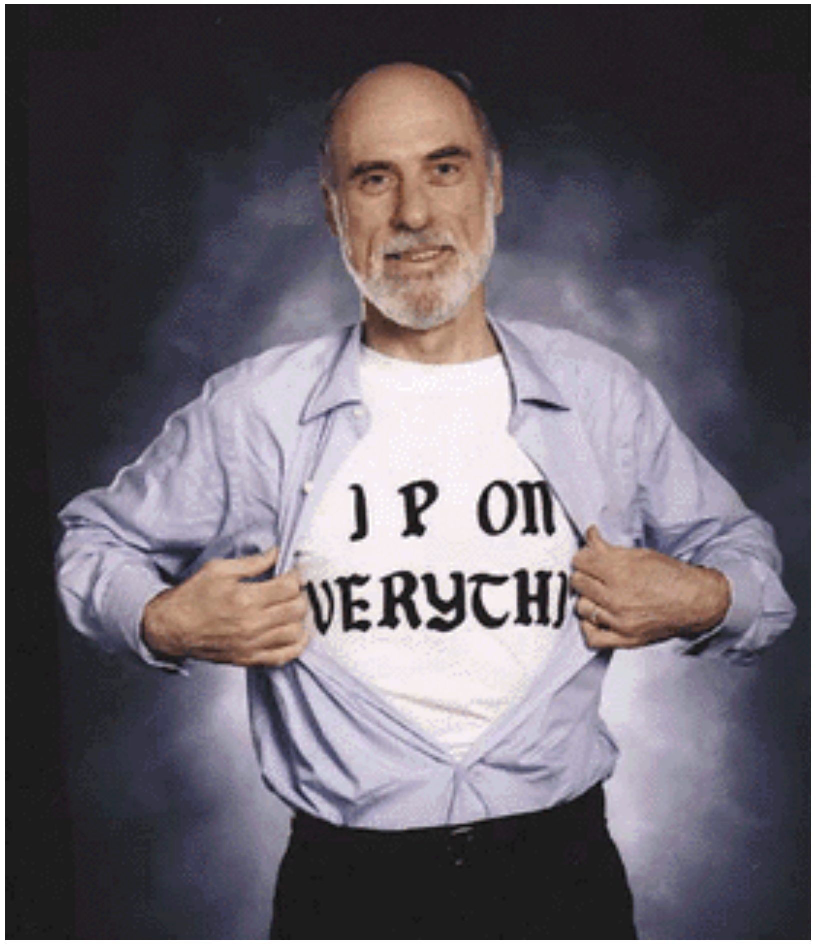
ISPs and large institutions may, in turn,
allocate even smaller prefixes to their own customers

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

# IP prefixes @ ETH

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

# Internet Protocol and Forwarding




IP addresses

use, structure, allocation

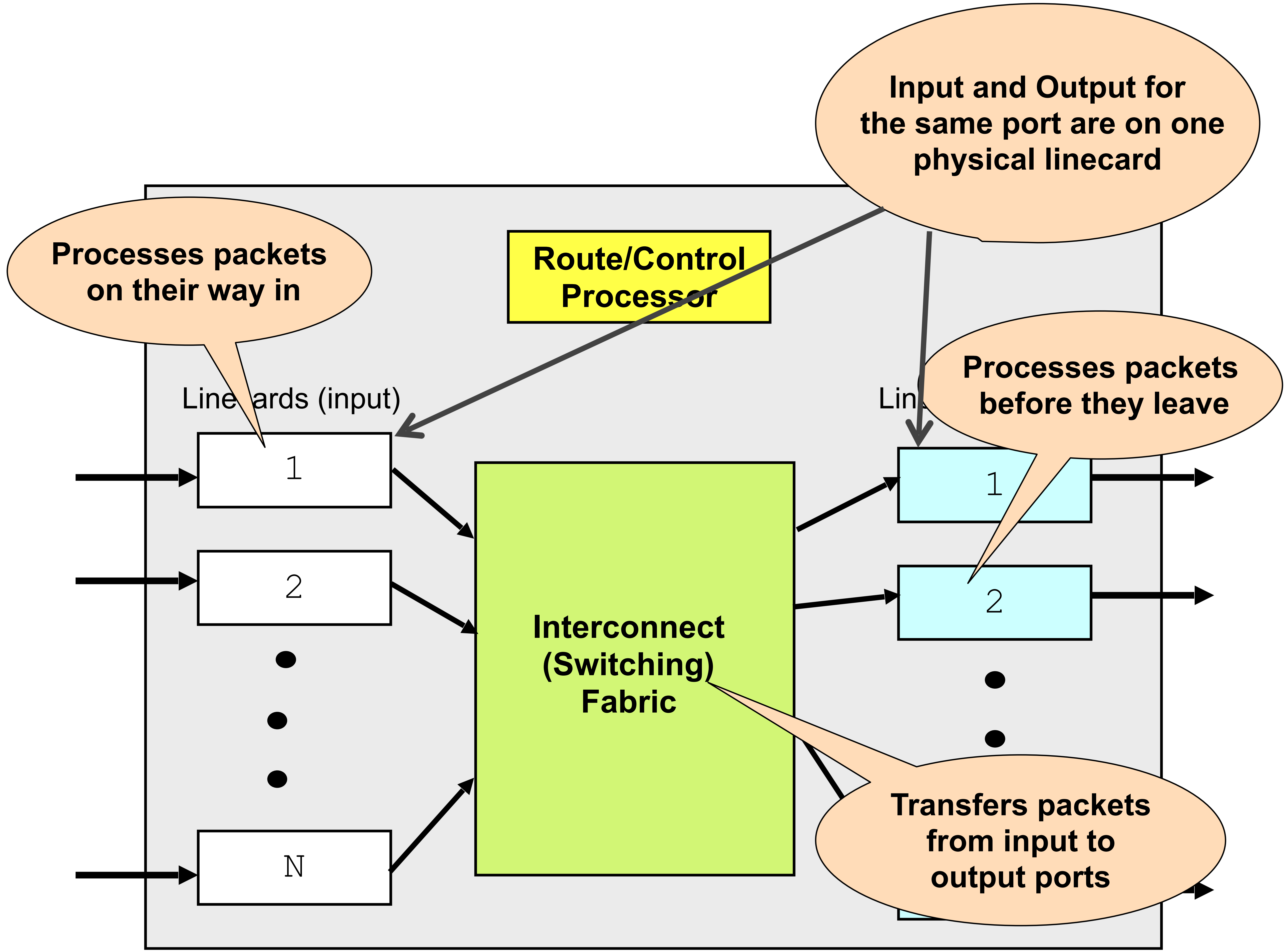
2 IP forwarding

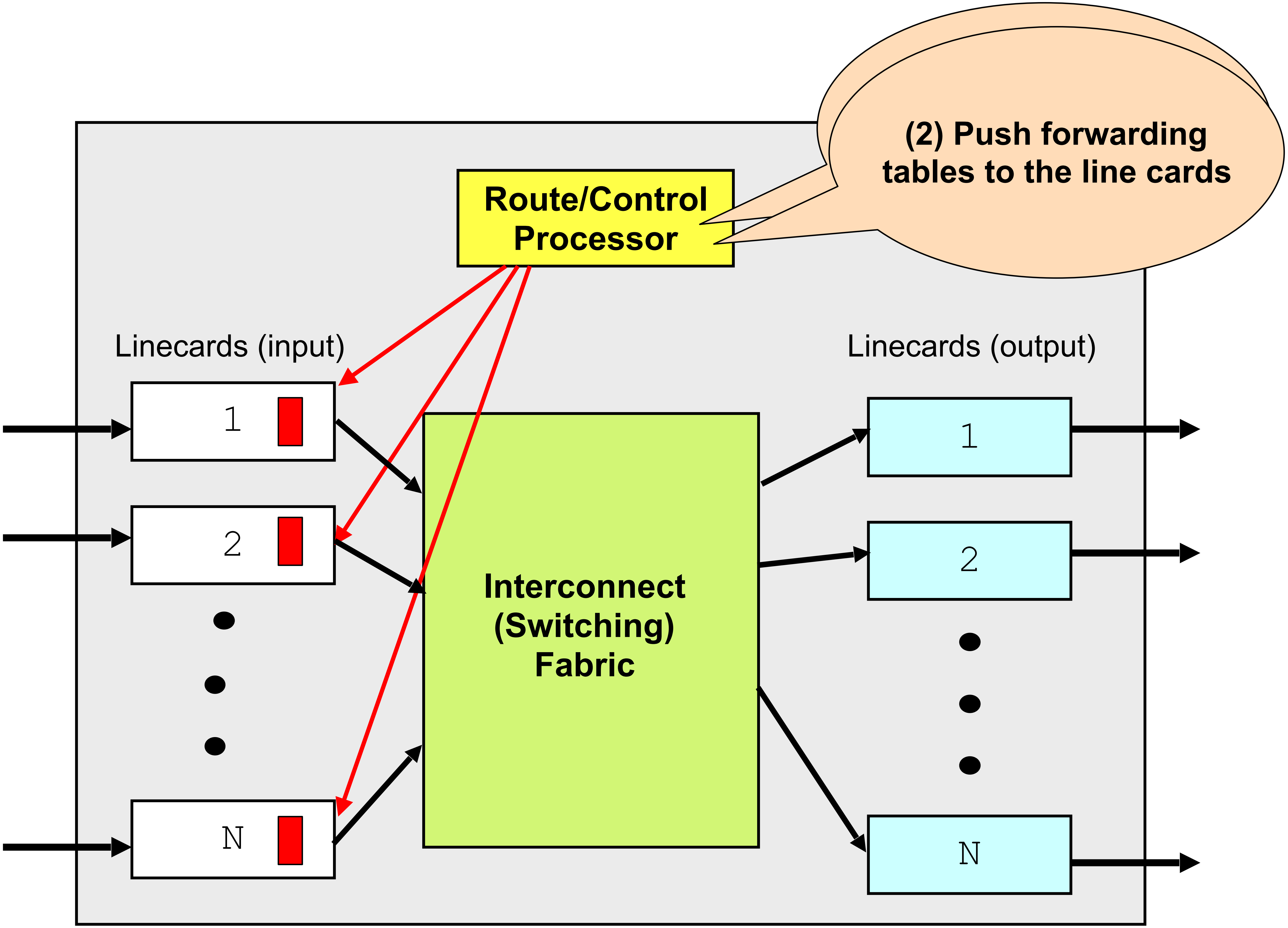
longest prefix match rule

IP header

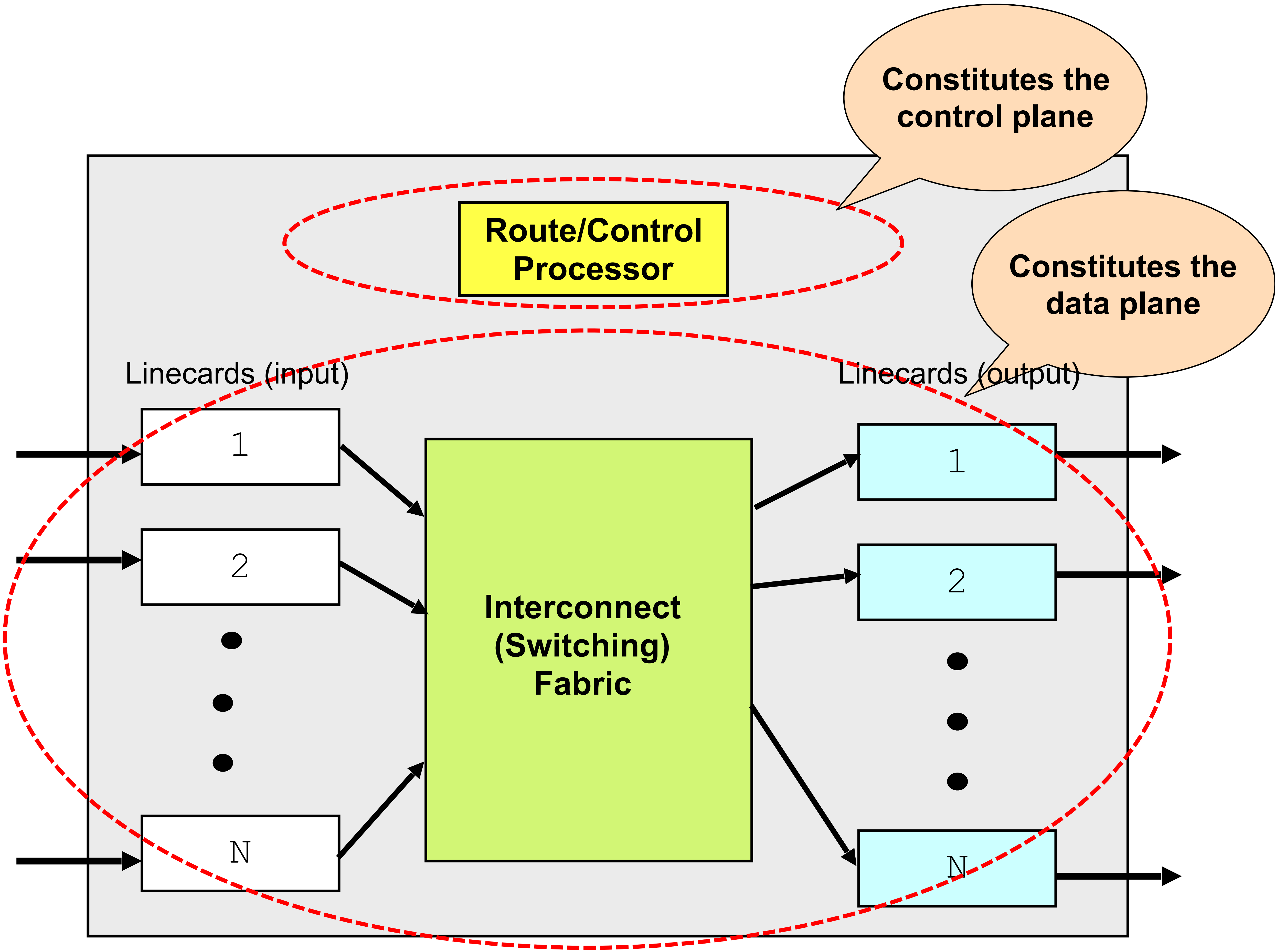
IPv4 and IPv6, wire format

# 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 cards (input)
Processes packets before they leave
1
2
N
1
2
Interconnect (Switching) Fabric
Transfers packets from input to output ports



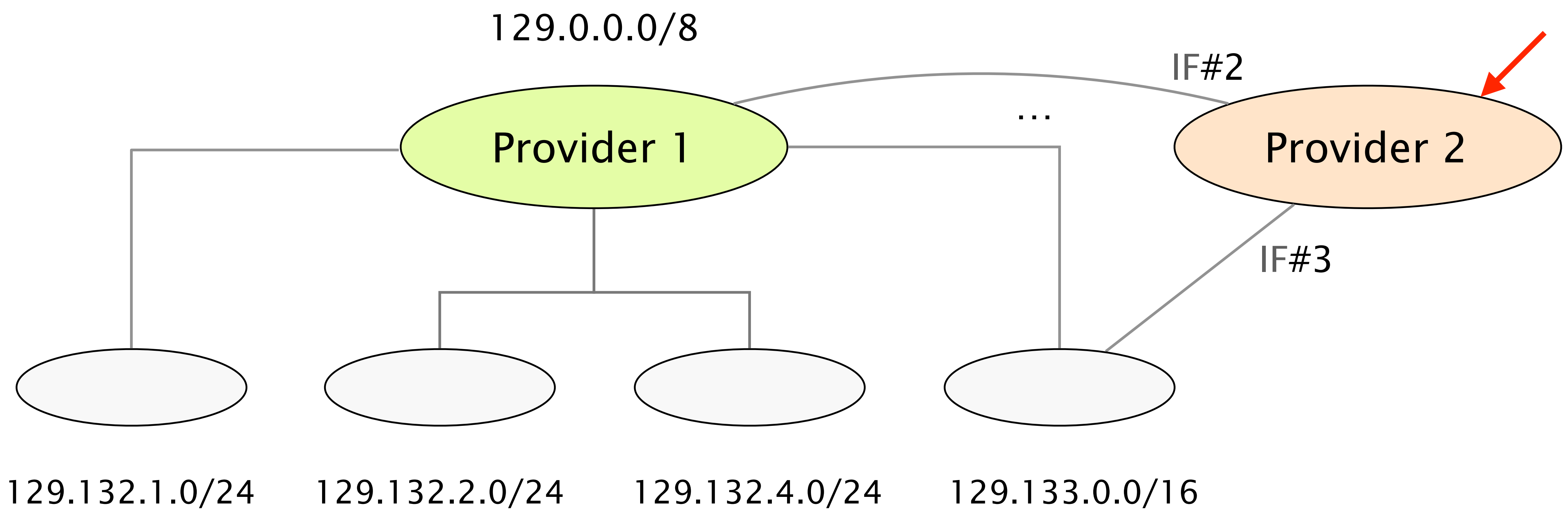
(2) Push forwarding tables to the line cards
Route/Control Processor
Linecards (input)
Linecards (output)
1
2
N
Interconnect (Switching) Fabric
1
2
N


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

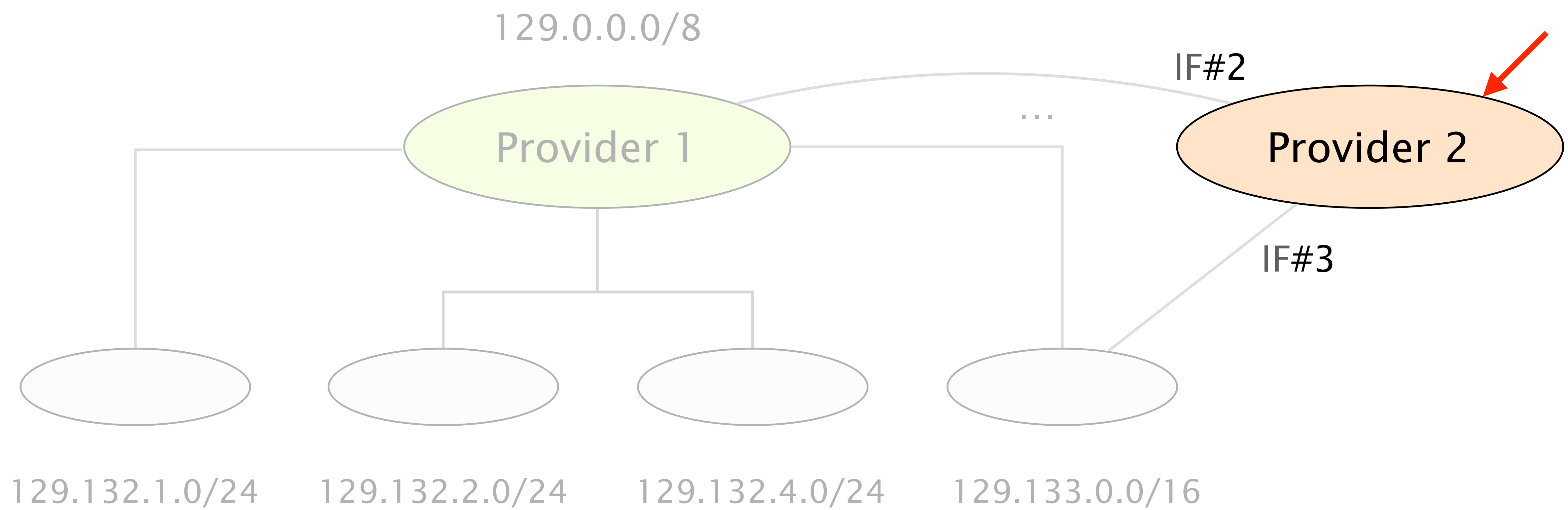
| IP prefix | Output |
|---|---|
| 129.0.0.0/8 | IF#2 |
| 129.132.1.0/24 | IF#2 |
| 129.132.2.0/24 | IF#2 |
| 129.133.0.0/16 | IF#3 |



Provider 2’s Forwarding table

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

| 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 |



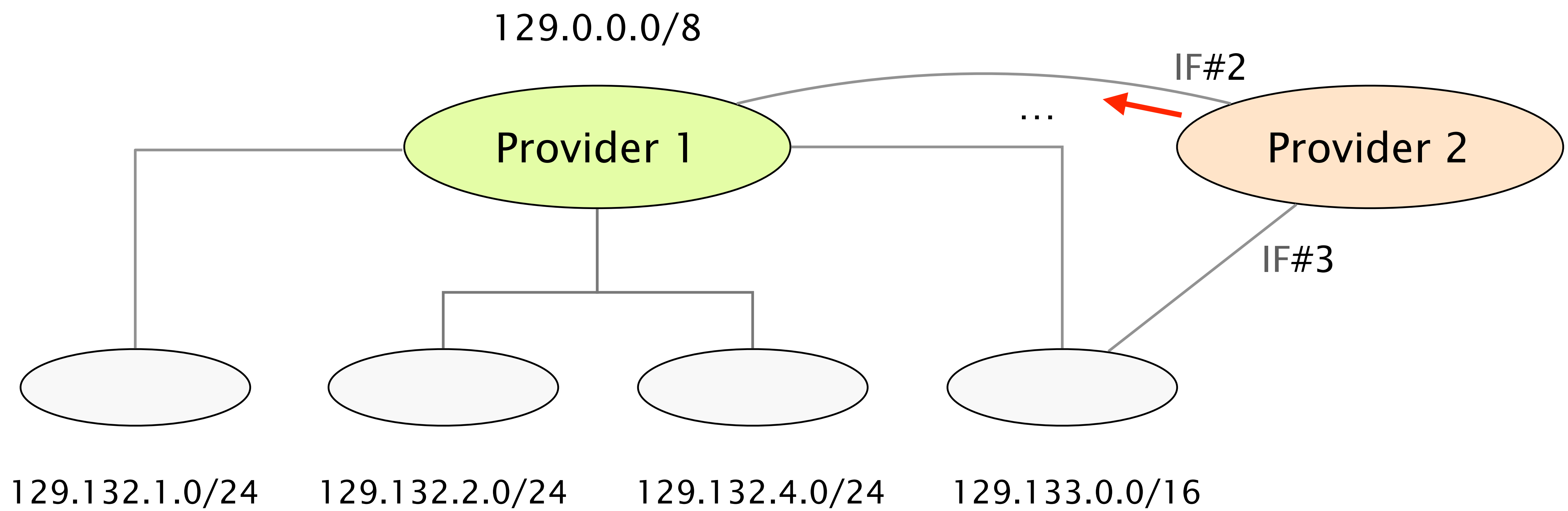
When a router receives an IP packet, it performs an IP lookup to find the matching prefix

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 forwards it to IF#2

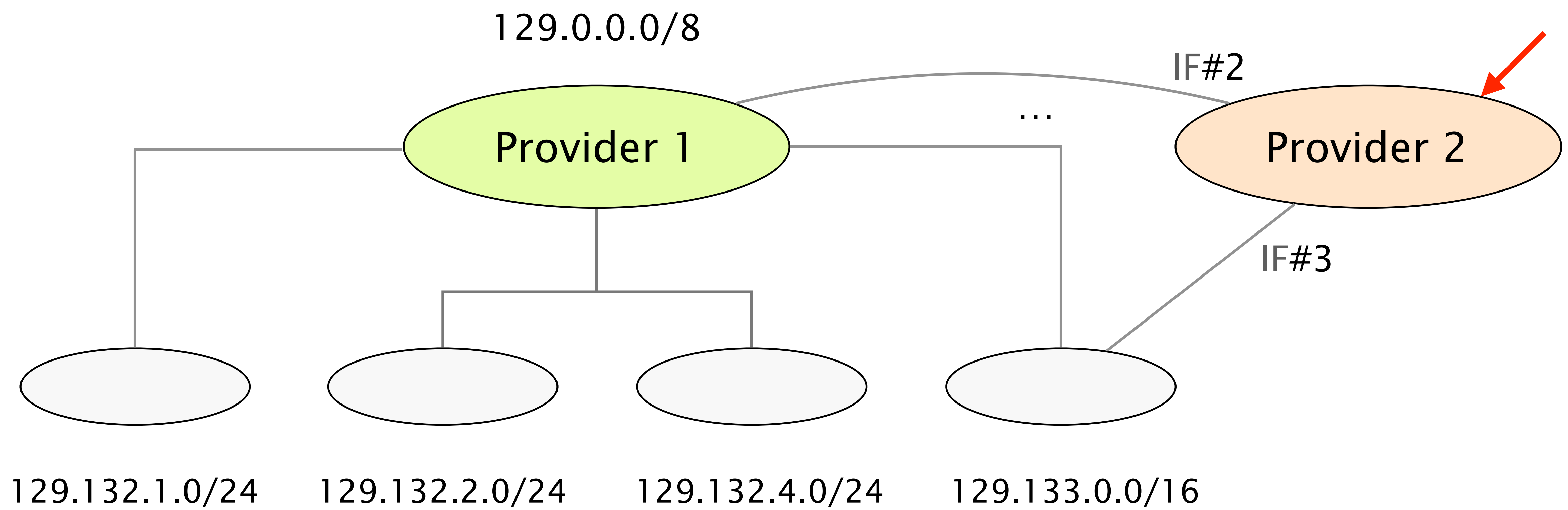


CIDR makes forwarding harder though,
as one packet can match many IP prefixes

Provider 2's Forwarding table

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

| 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 |

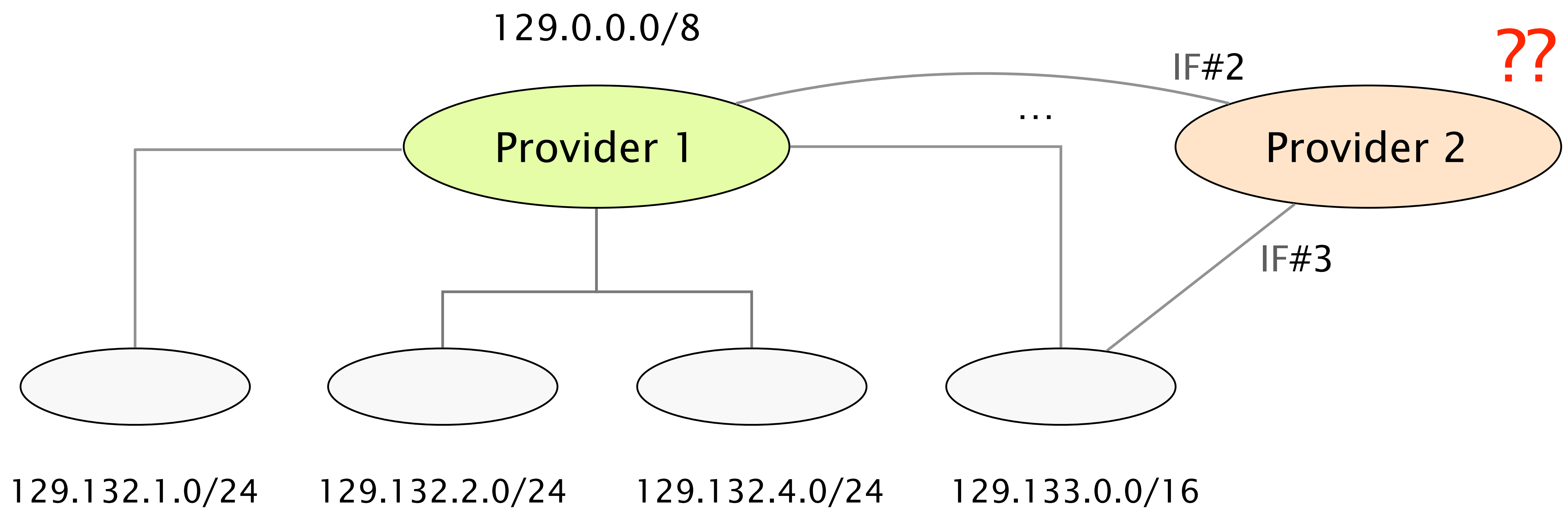


Let's say a packet for 129.133.0.1 arrives at Provider 2

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 |



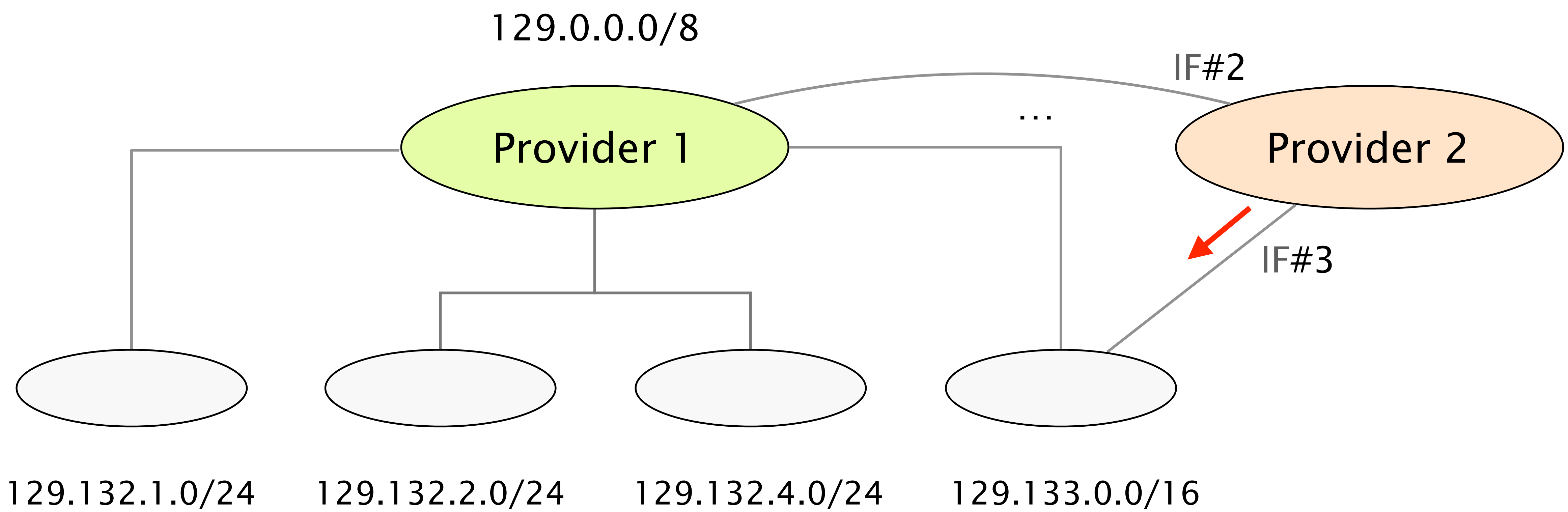
To resolve ambiguity, forwarding is done along the *most specific* prefix (*i.e.*, the longer one)

Provider 2's Forwarding table

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

> Provider 2 forwards it to IF#3

| 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 |

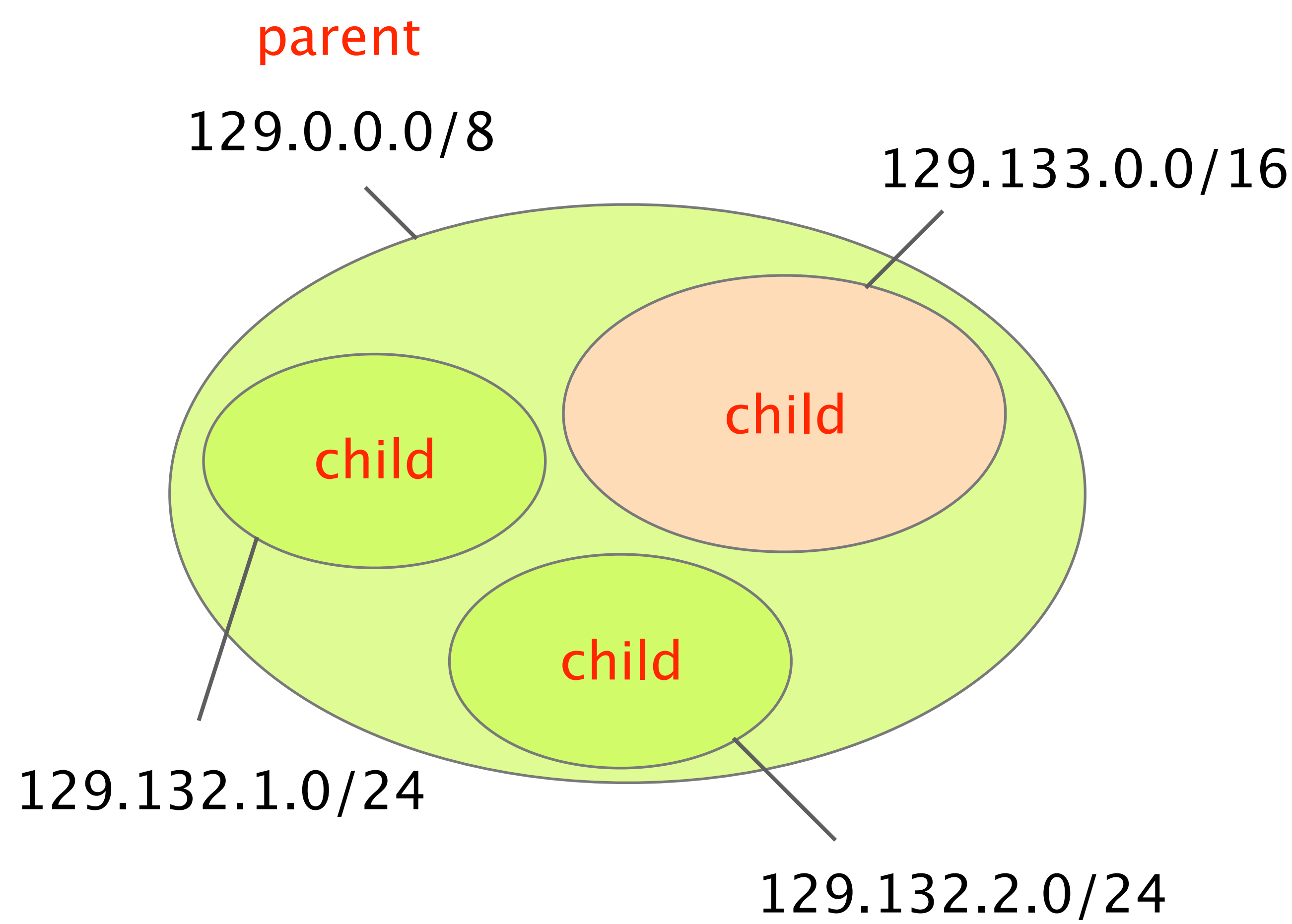


Could we do something better than maintaining one entry per prefix? *Yep!*

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

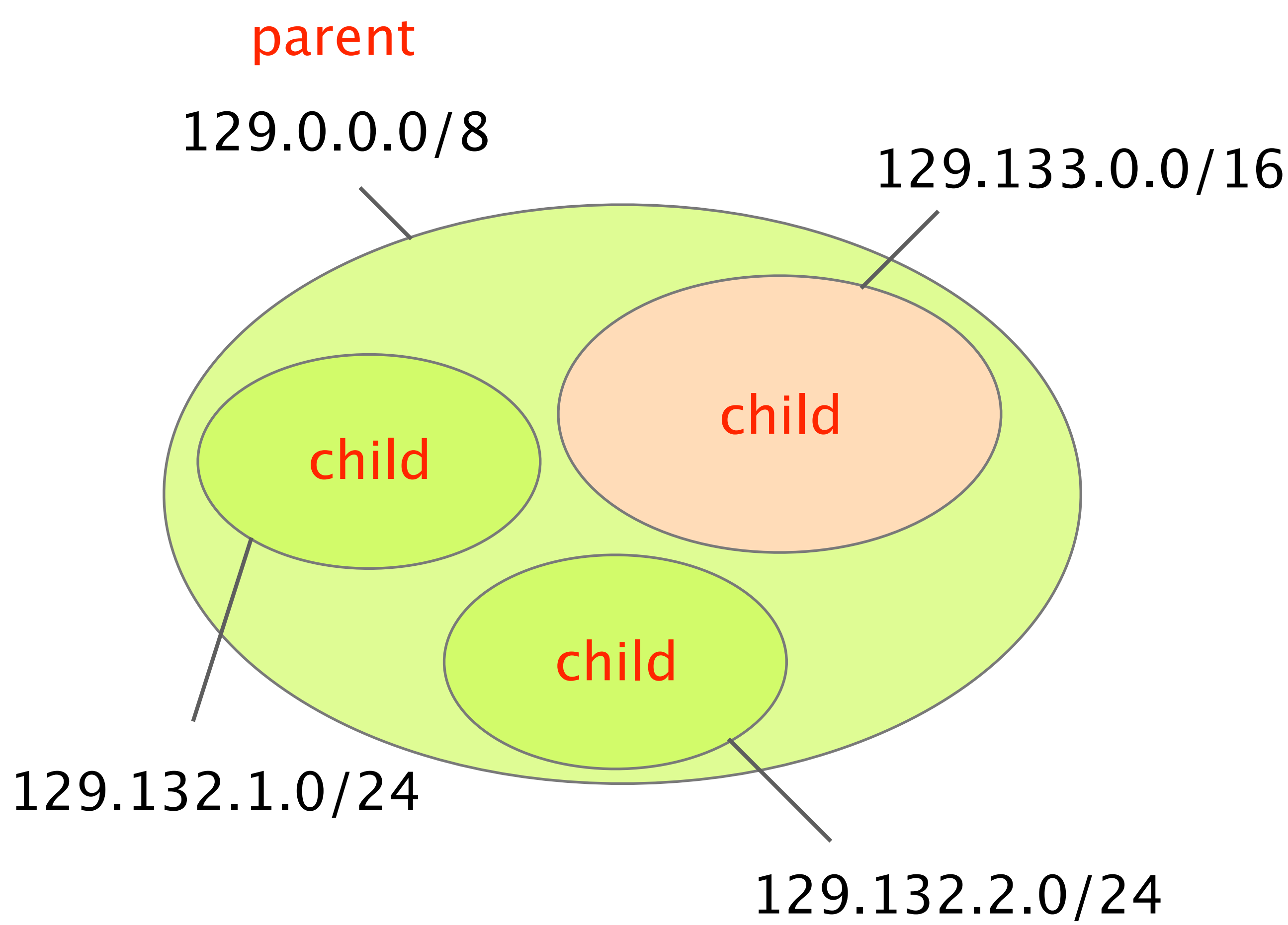
Routing Table

| 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 |
| ... | |



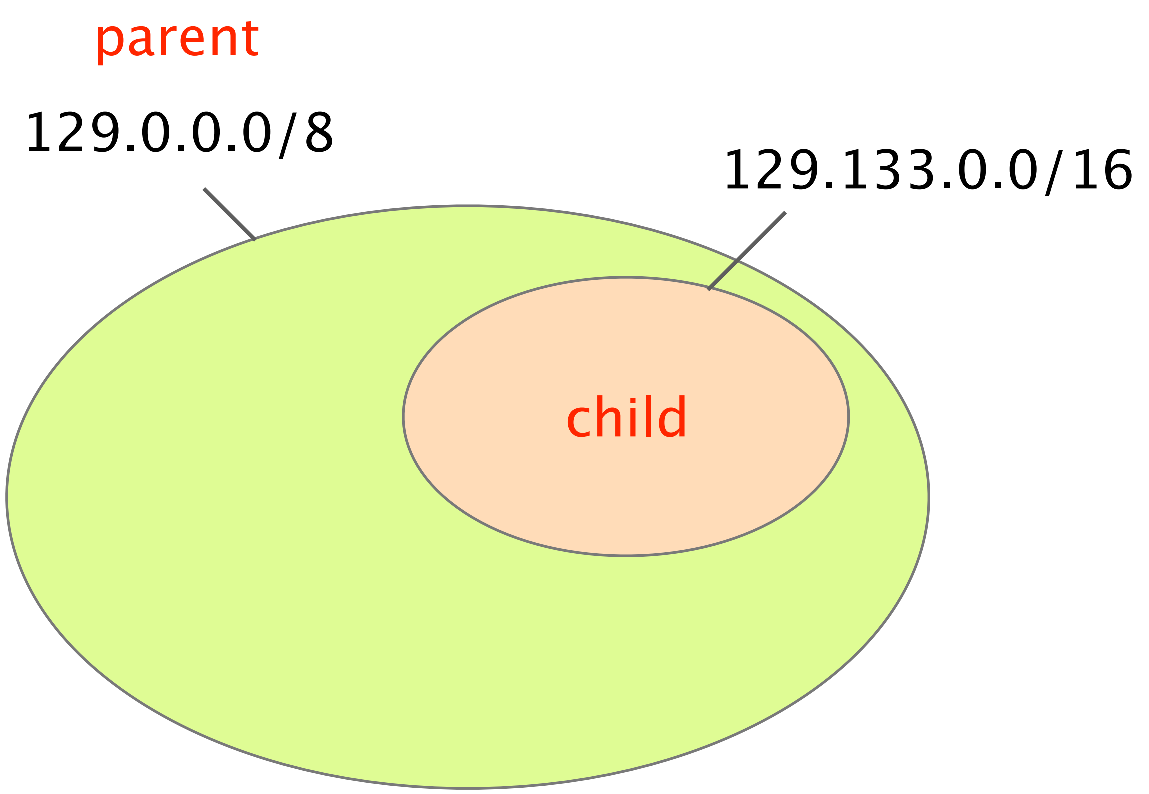
Routing Table

| 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

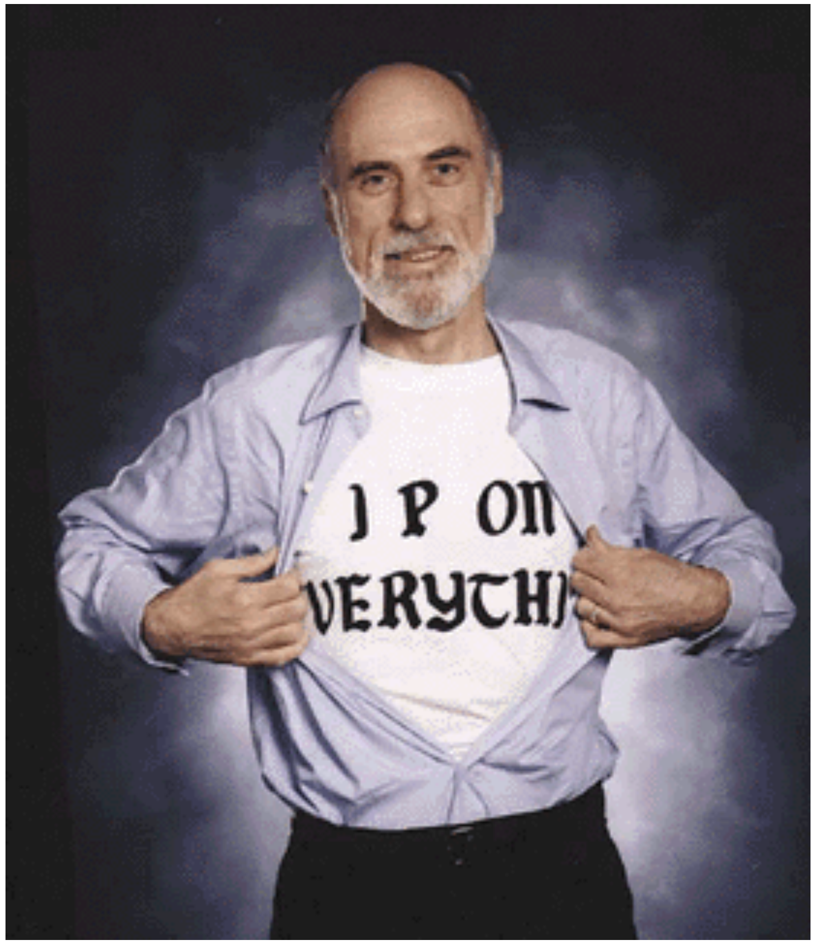
| IP prefix | Output Interface |
|---|---|
| ... | |
| 129.0.0.0/8 | IF#2 |
| 129.133.0.0/16 | IF#3 |
| ... | |




**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

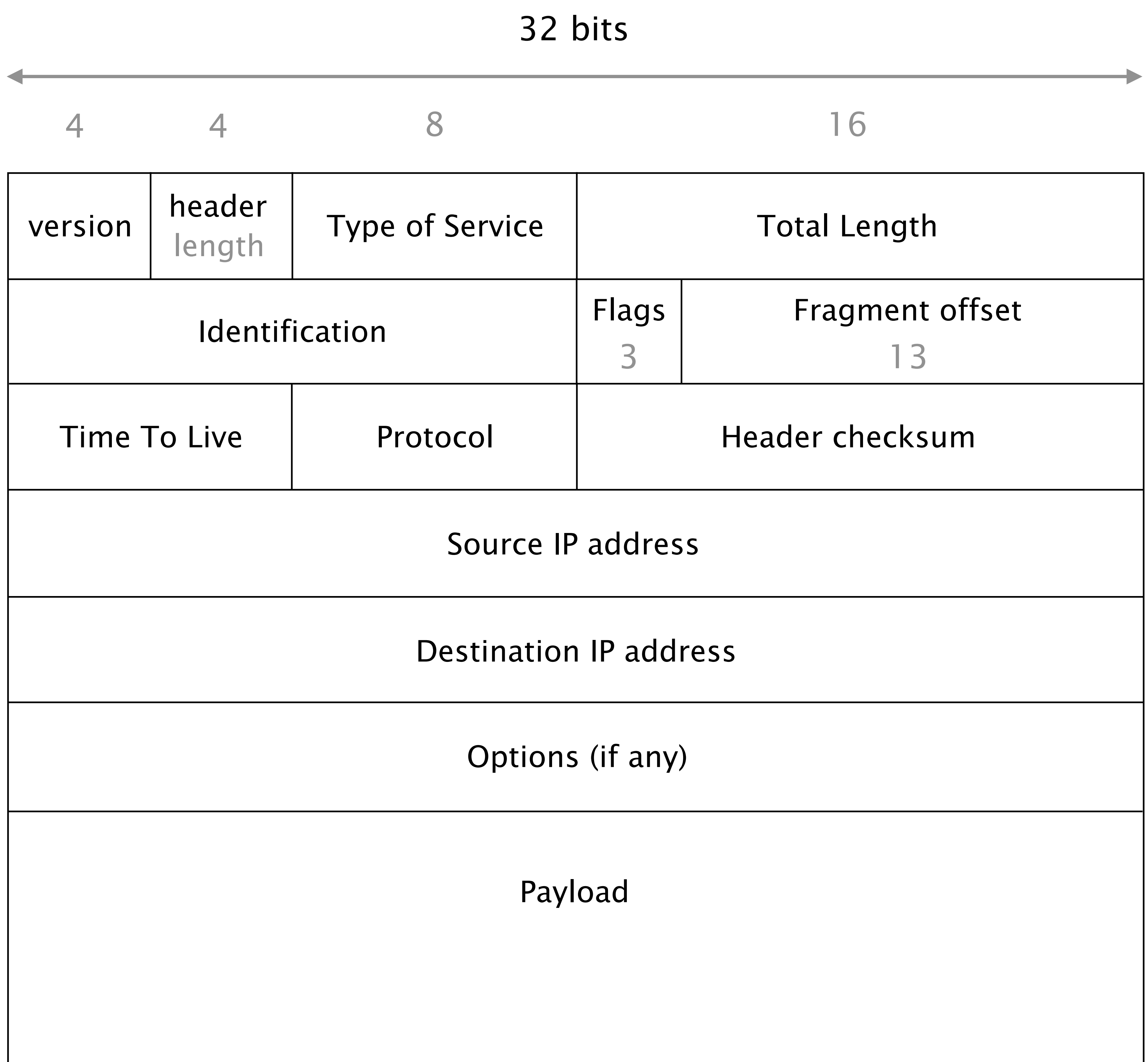
IP forwarding

longest prefix match rule

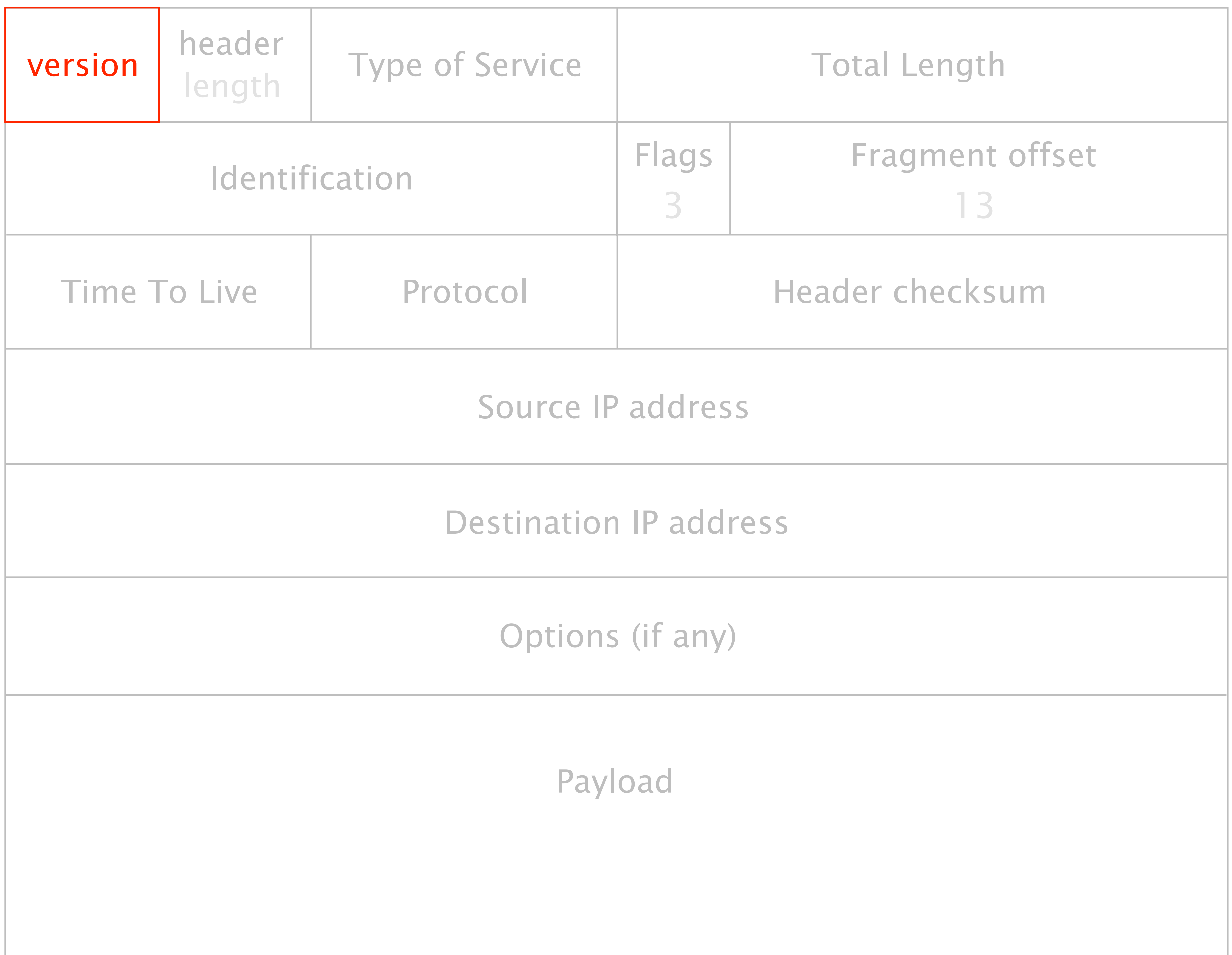
3 IP header

IPv4 and IPv6, wire format

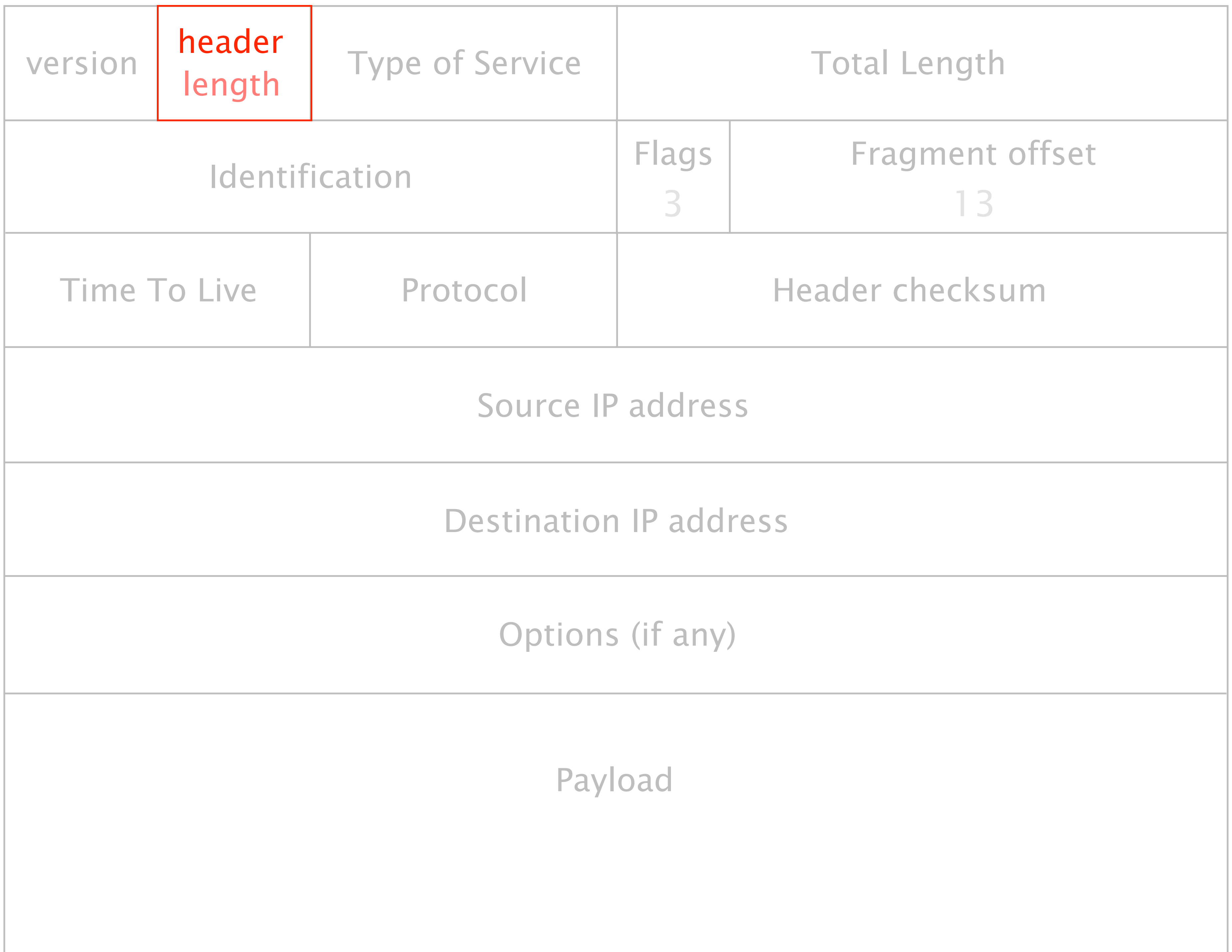
Here is what an IPv4 packet look like on a wire


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

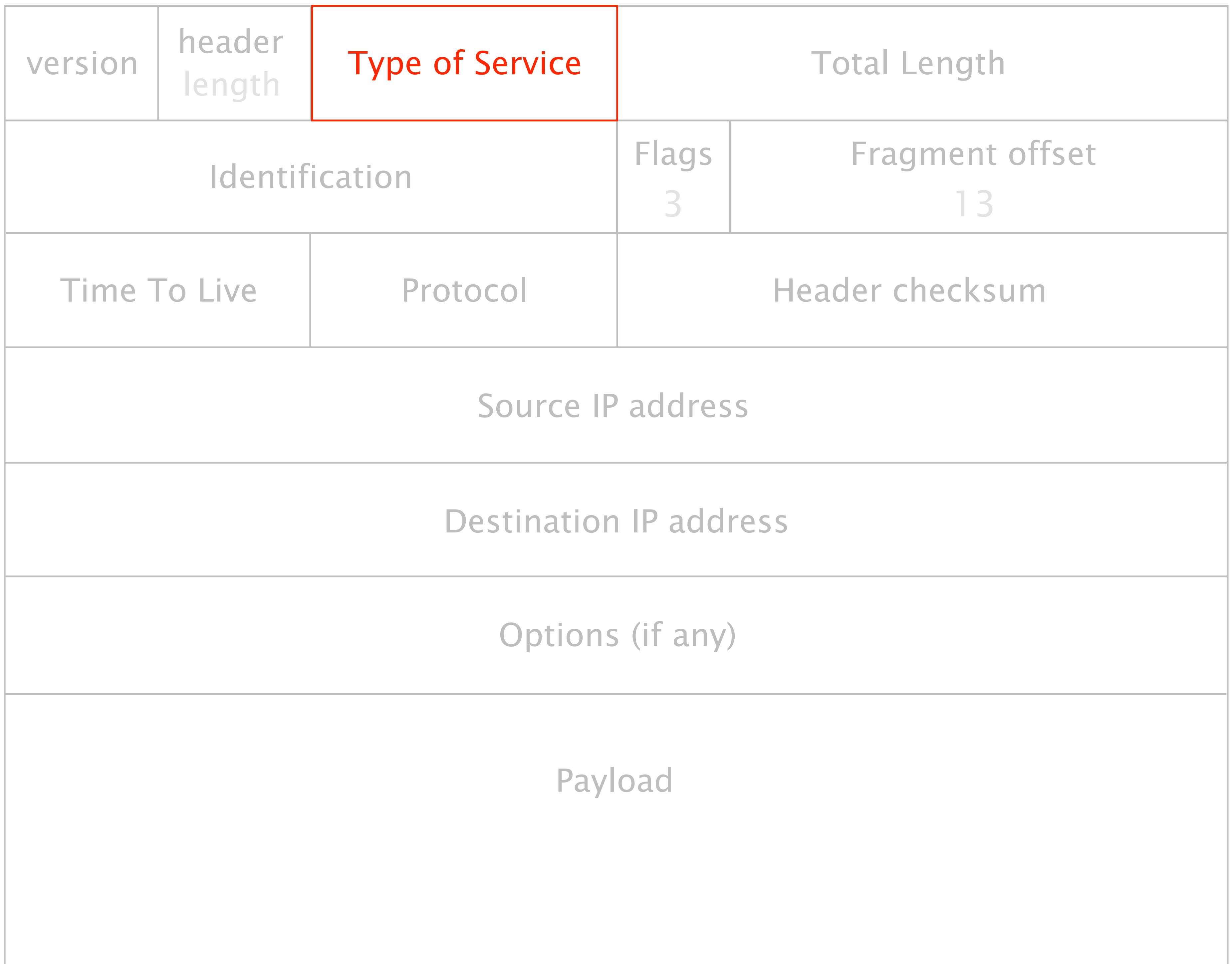
The version number tells us what other fields to expect, typically it is set to “4” for IPv4, or “6” for IPv6



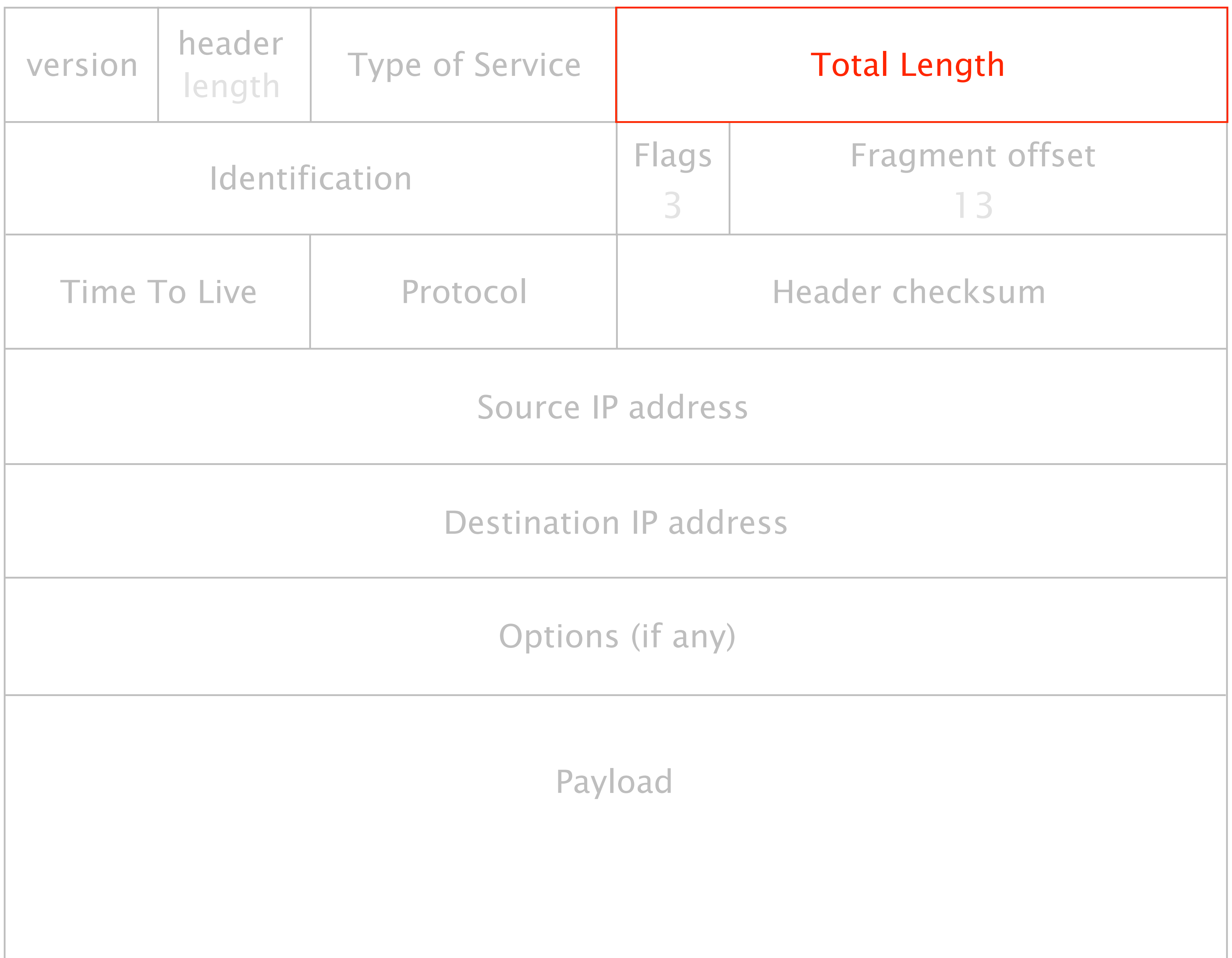
The header length denotes the number of 32-bits word in the header, typically set to 5 (20 bytes header)



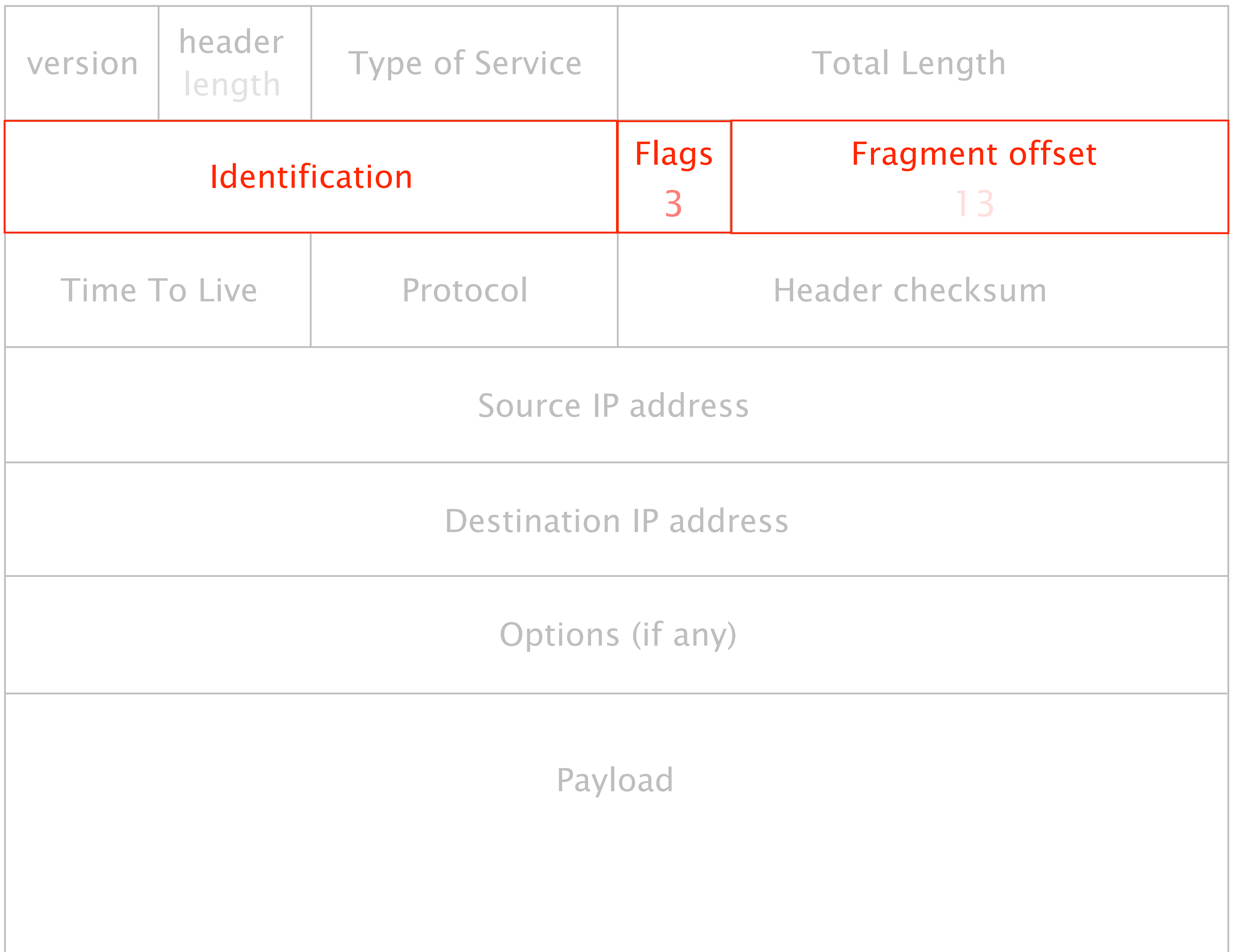
The ToS allows different packets to be treated differently, e.g., low delay for voice, high bandwidth for video



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



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

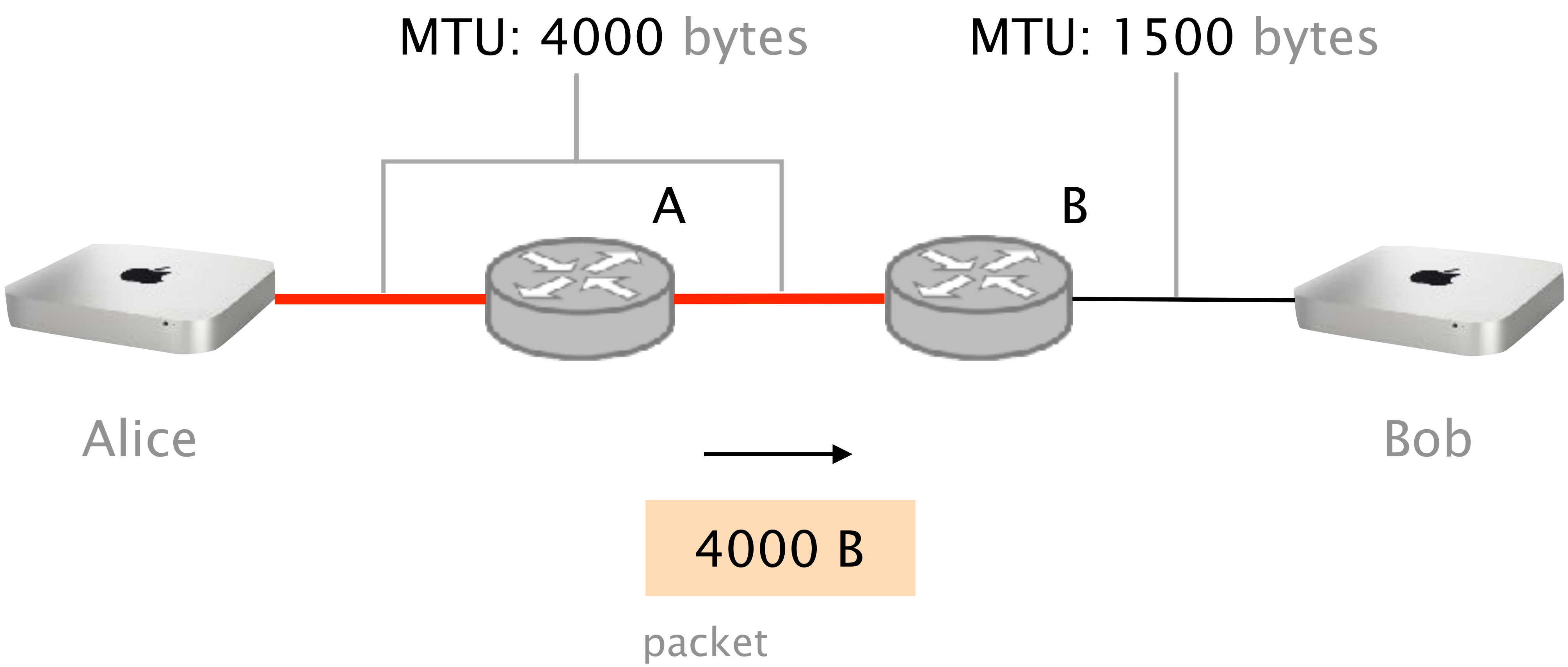
*e.g.*, 1500 bytes for normal Ethernet

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

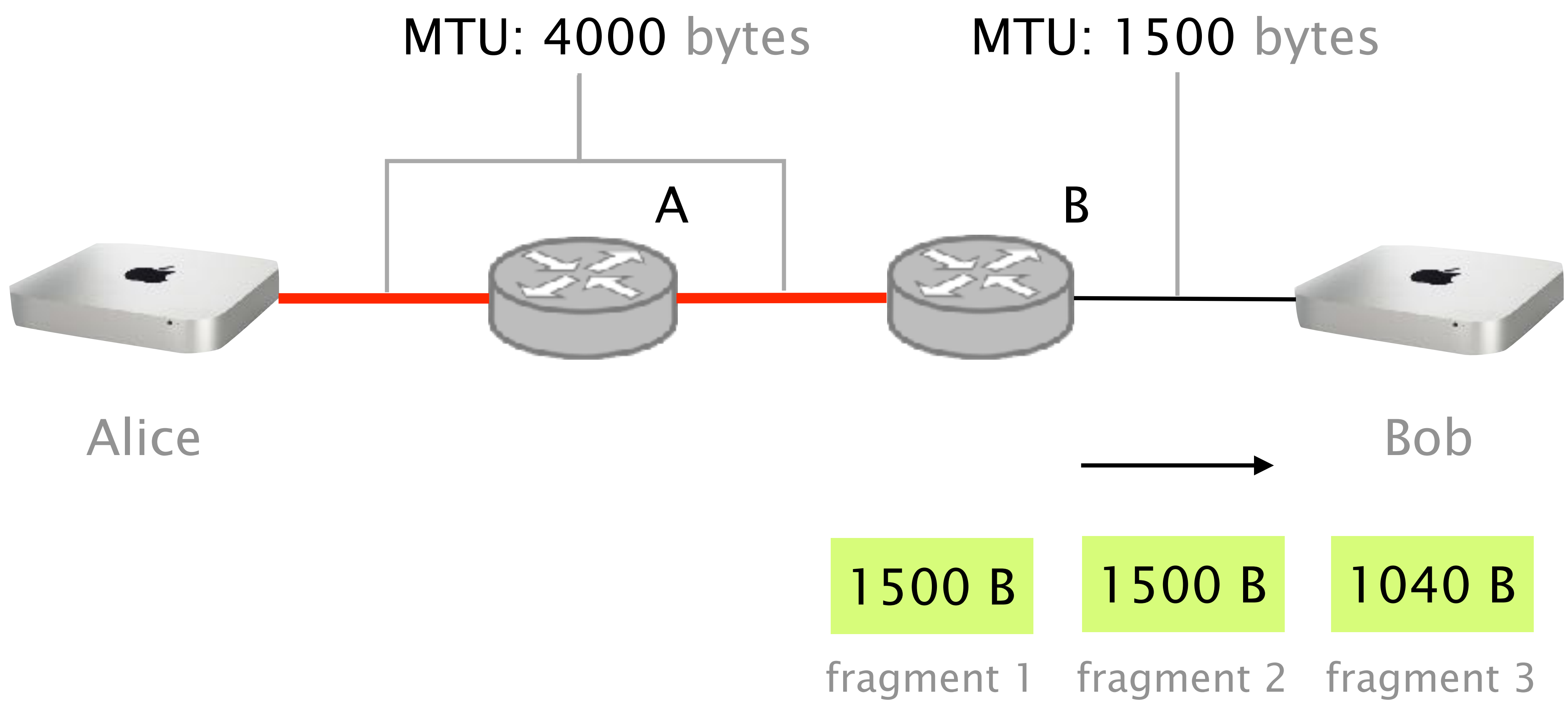
Fragmented packets are recomposed at the destination

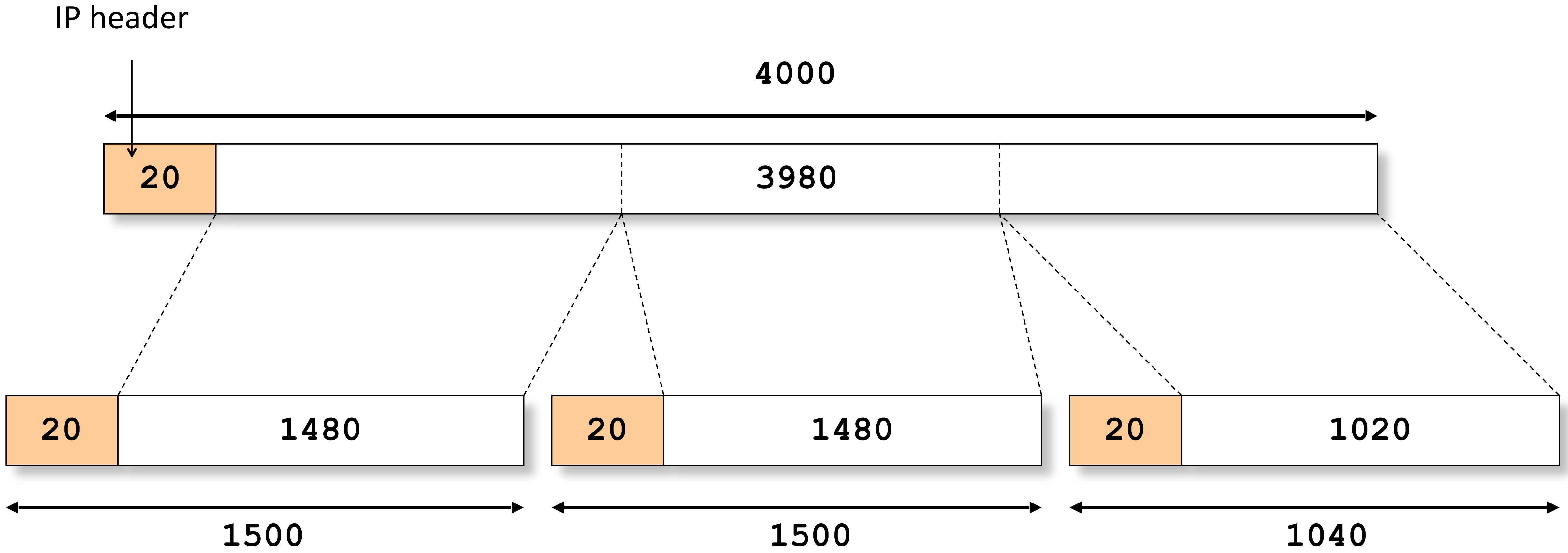
why not in the network?

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

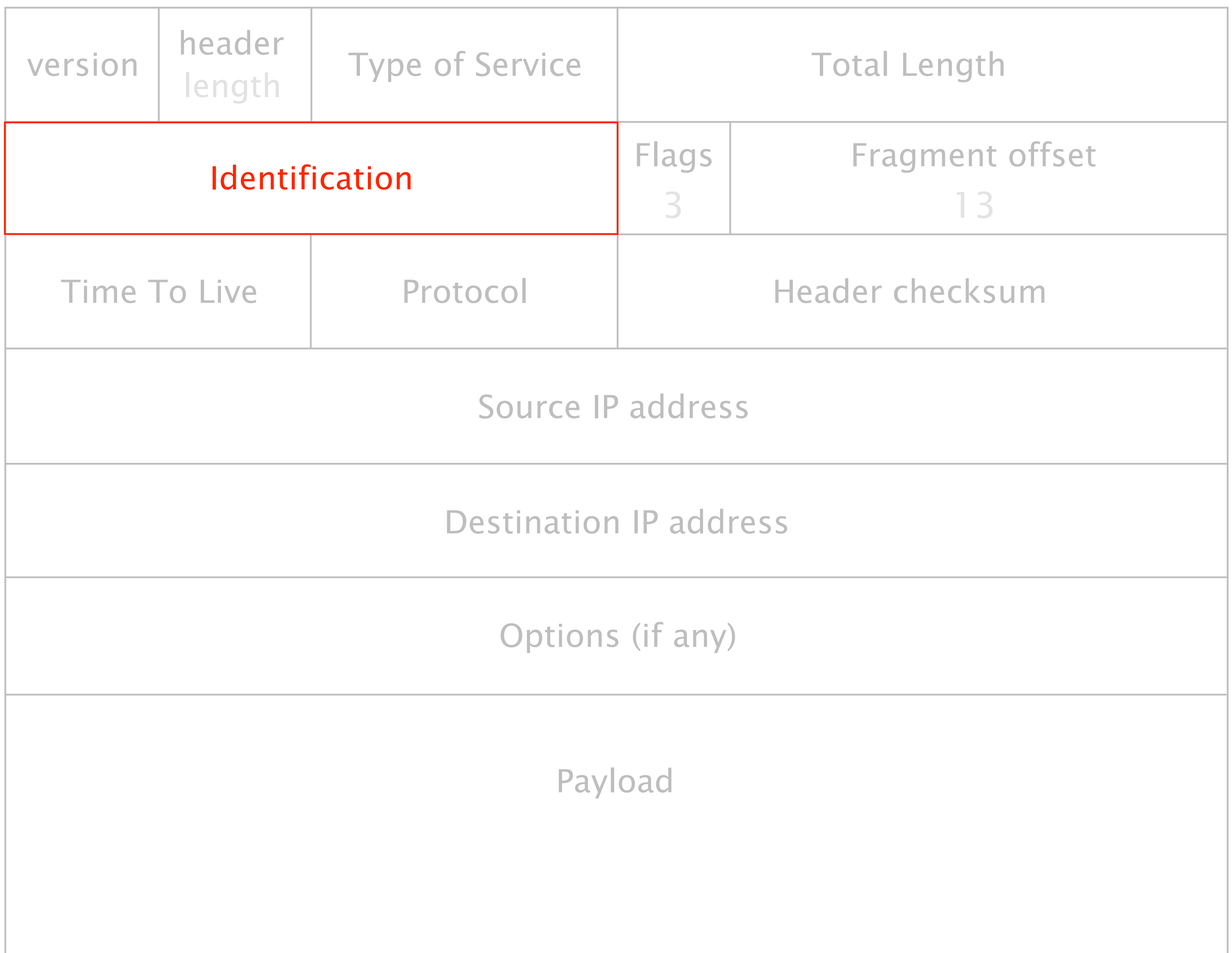


Because the packet is larger than the MTU, router B will split the packet into fragments

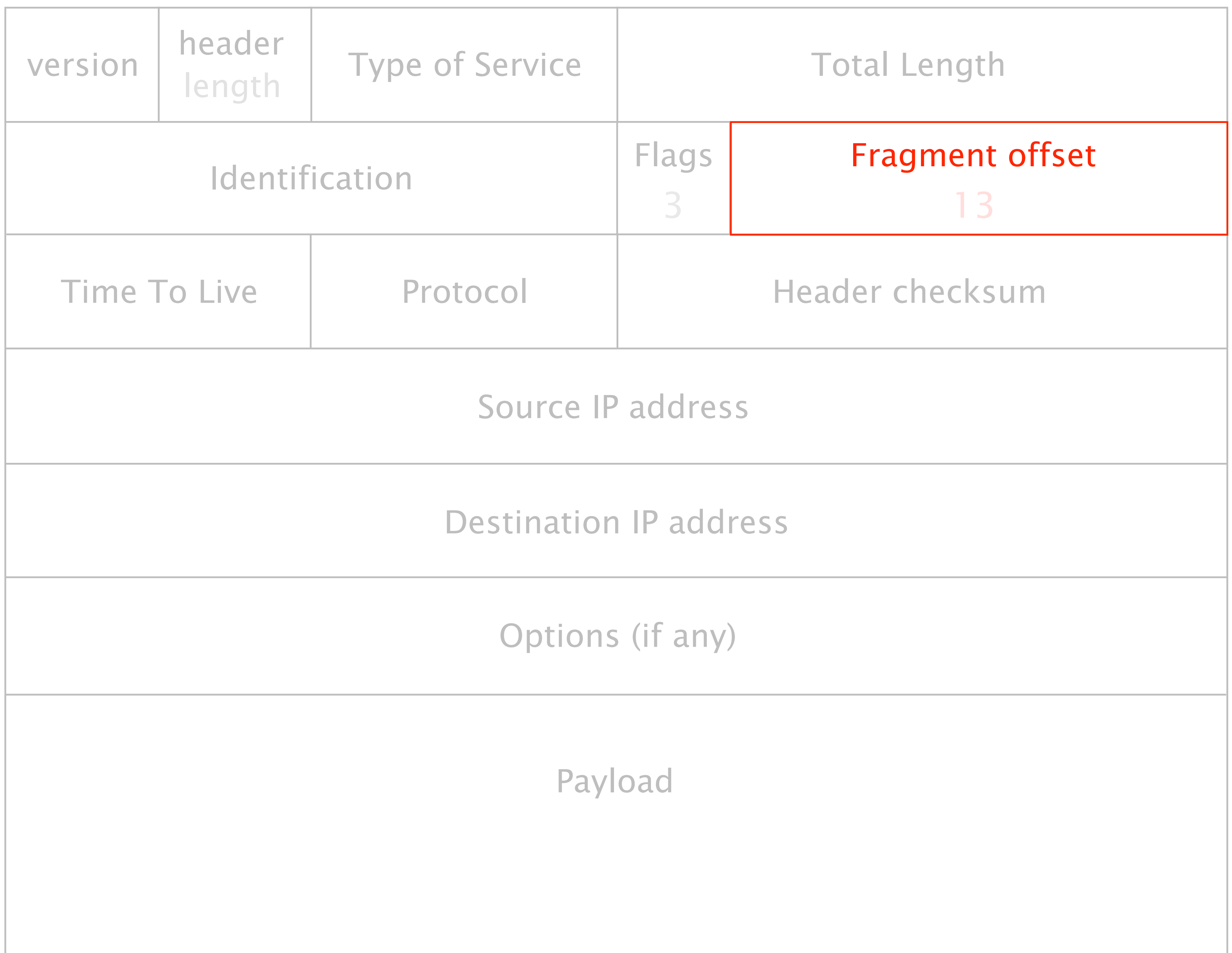



IP header
4000
20
3980
20
1480
20
1480
20
1020
1500
1500
1040

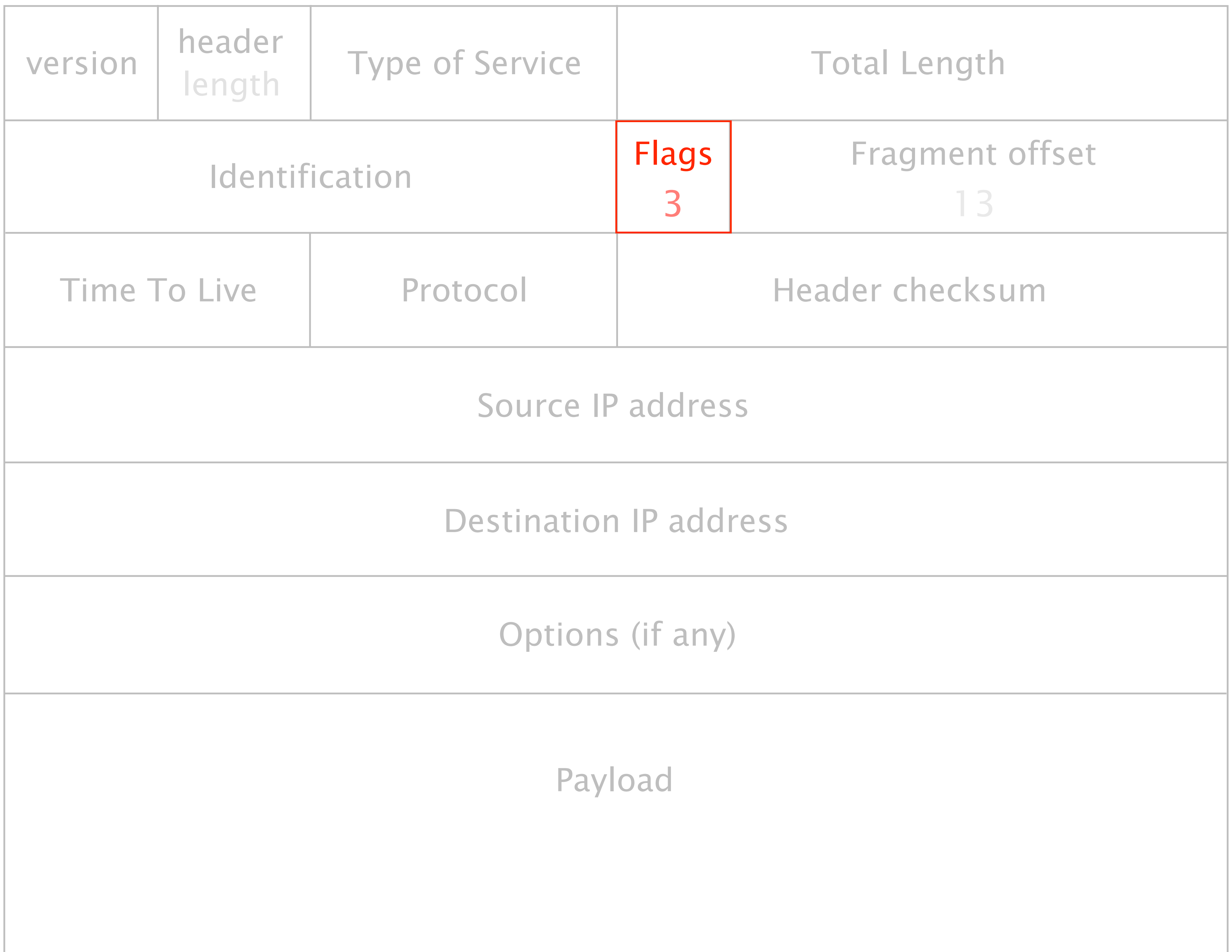
The Identification header uniquely identify the fragments of a particular packet



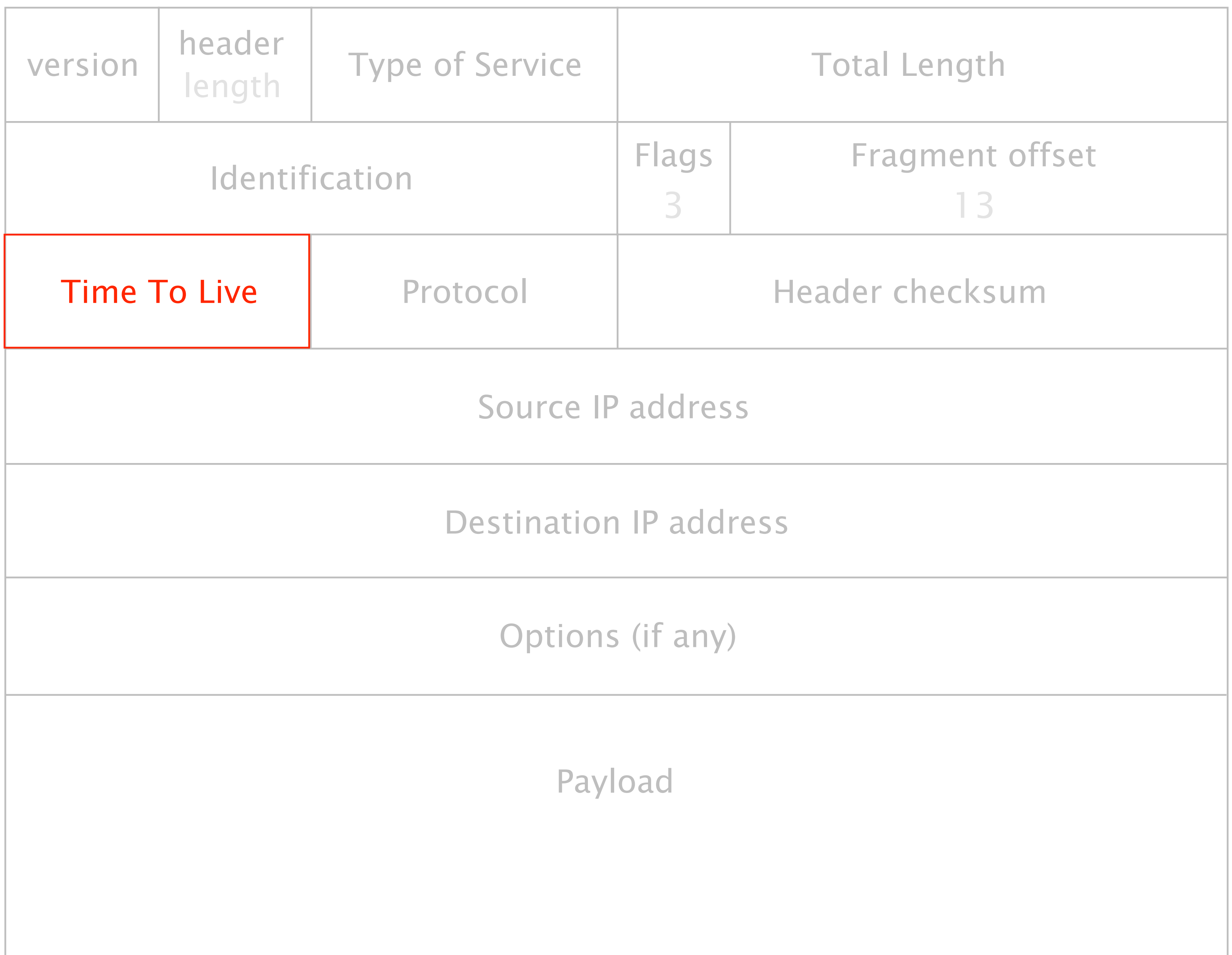
The fragment offset is used to put back the fragments in the right order in case of reordering



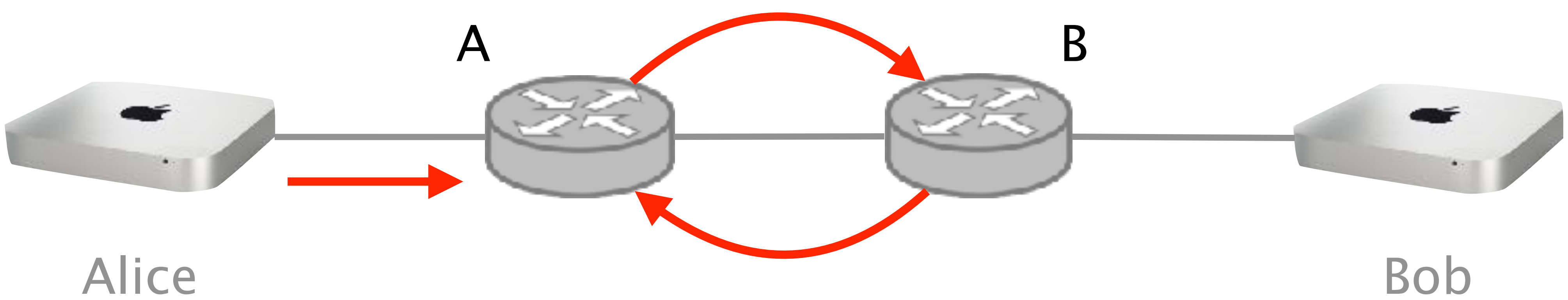
The flags is used to tell whether there are more fragments coming or not



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



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

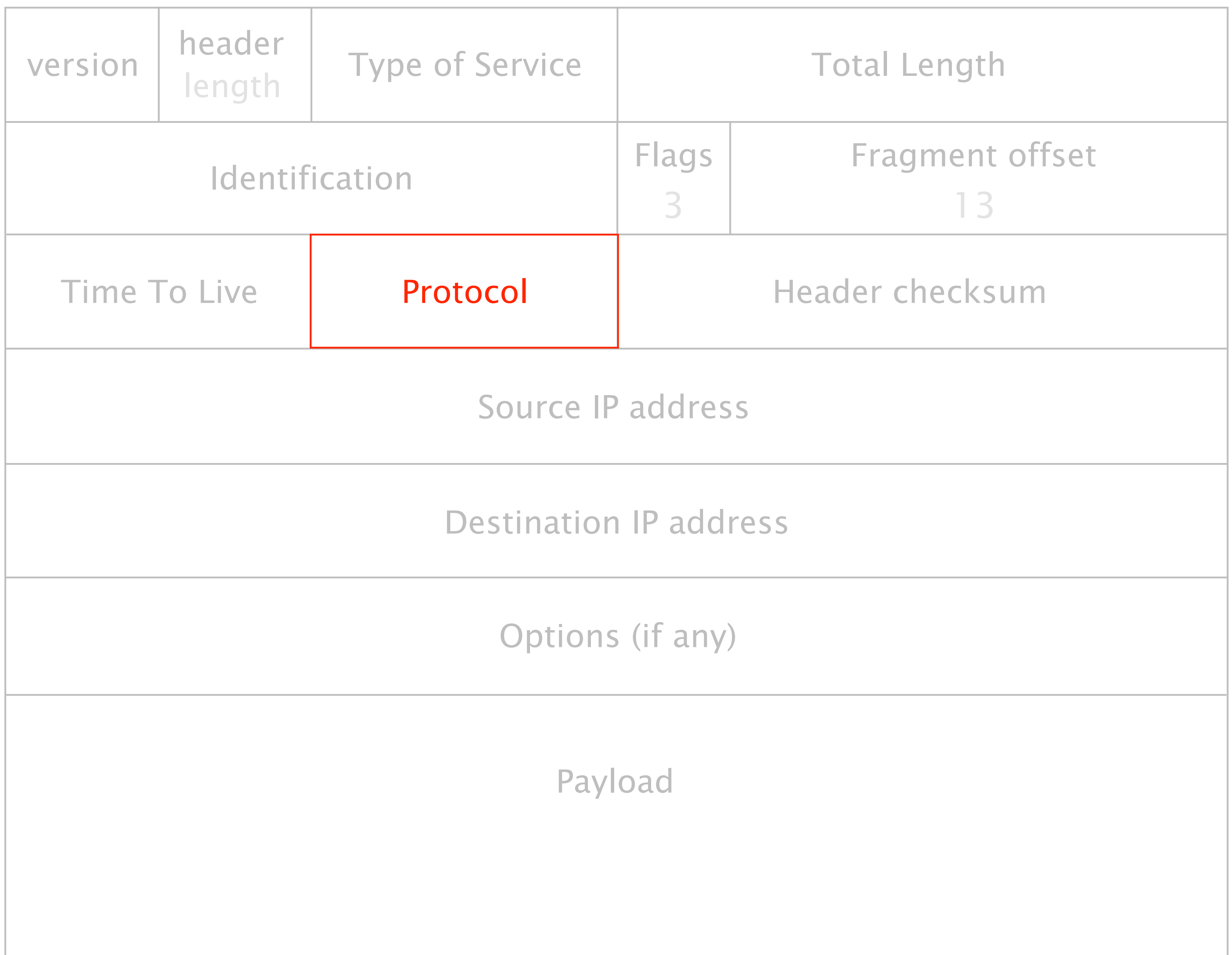



default TTL values

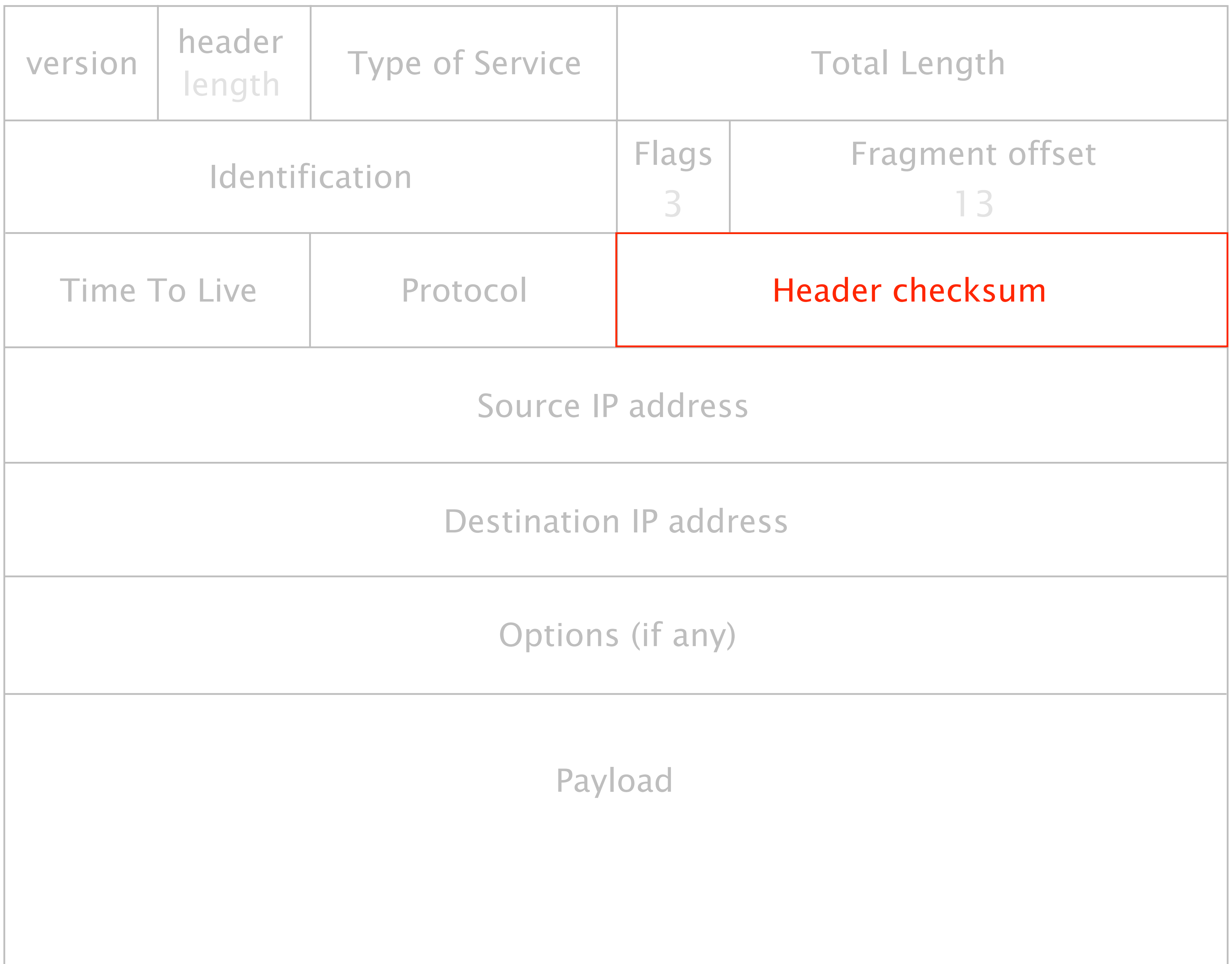
| | |
|---|---|
| *nix (Linux/Mac) | 64 |
| Windows | 128 |

(used for OS fingerprinting)

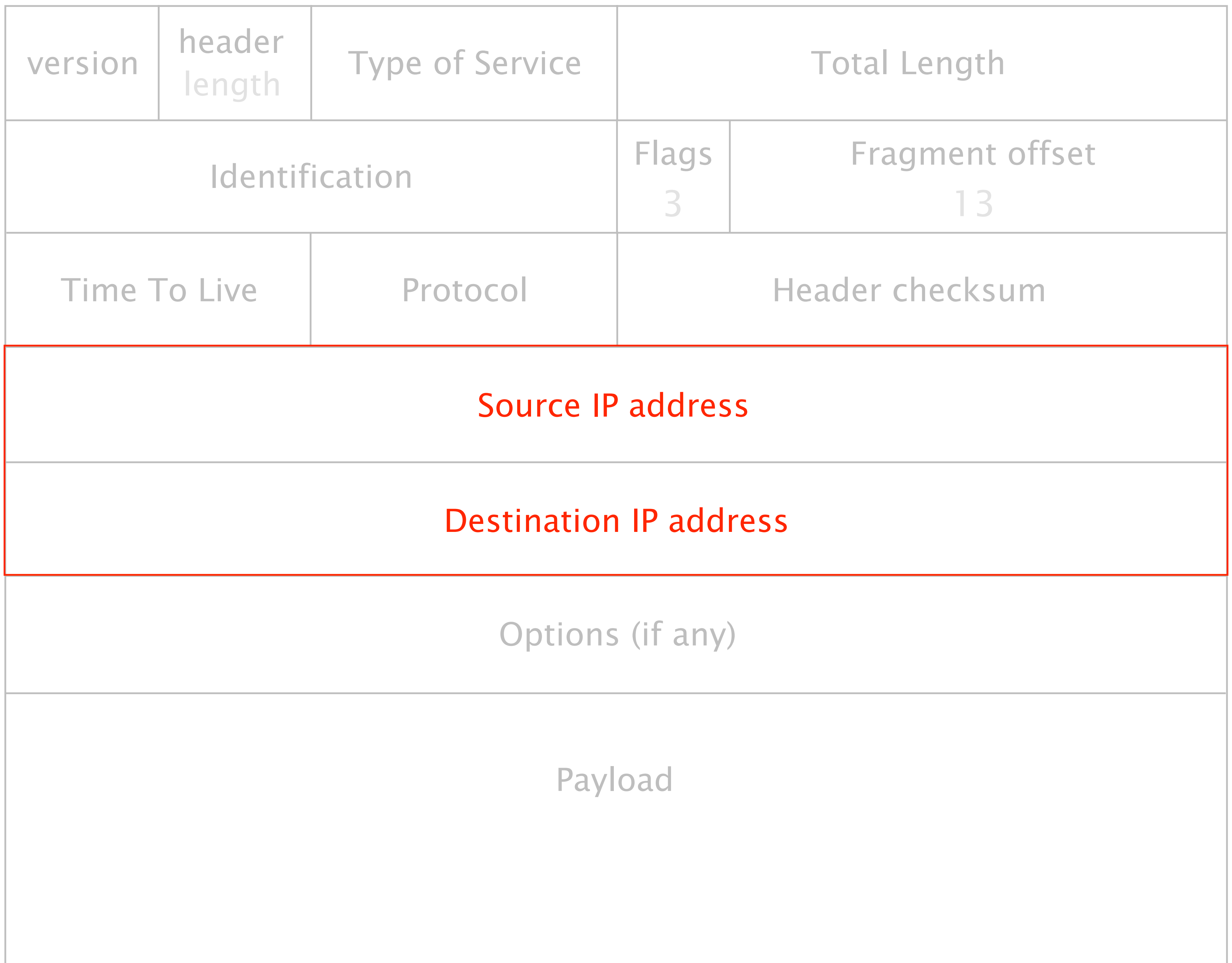
The protocol field identifies the higher level protocol carried in the packet, “6” for TCP, “17” for UDP



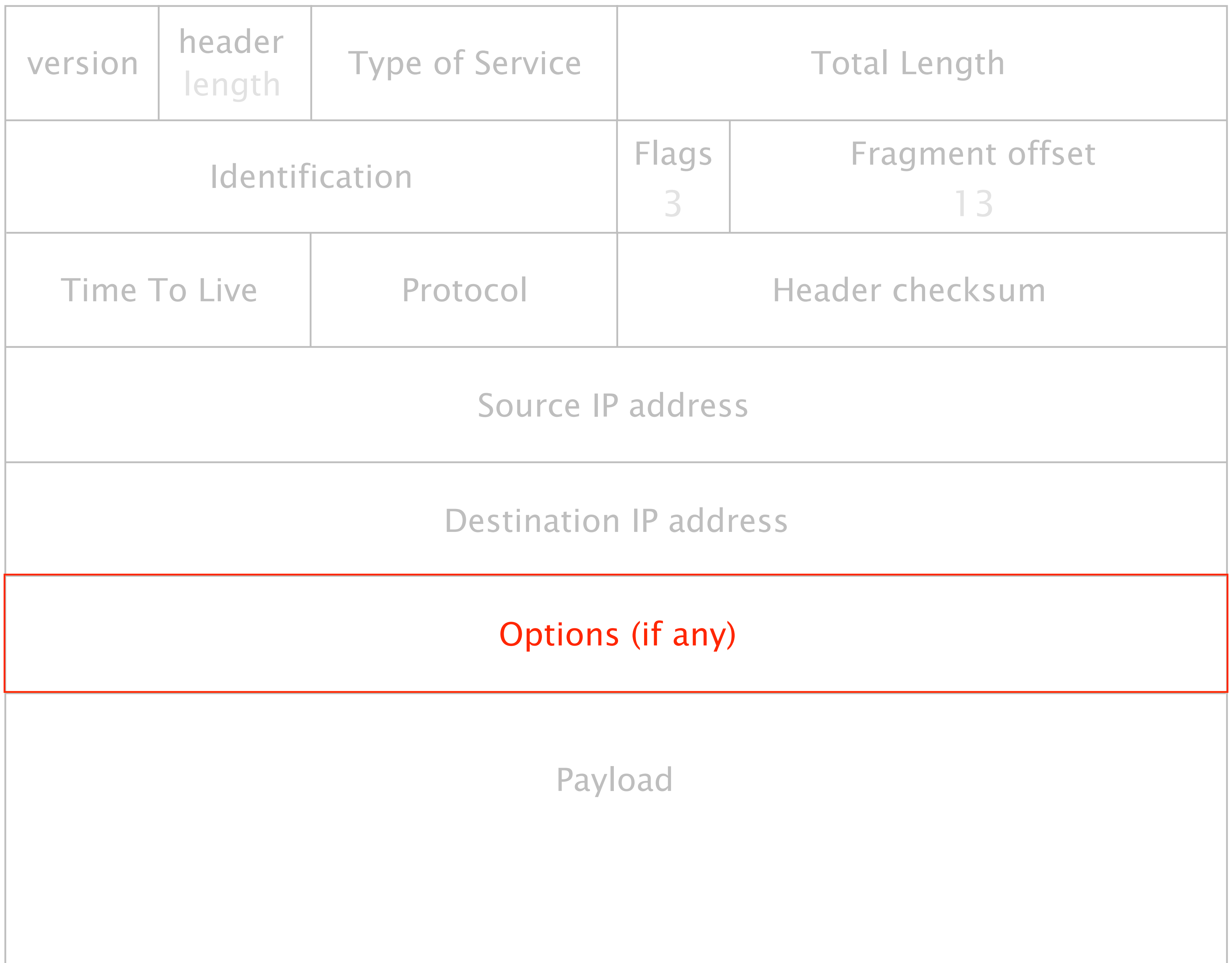
The checksum is the sum of all the 16 bits words in the header (does not protect the payload)



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



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



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

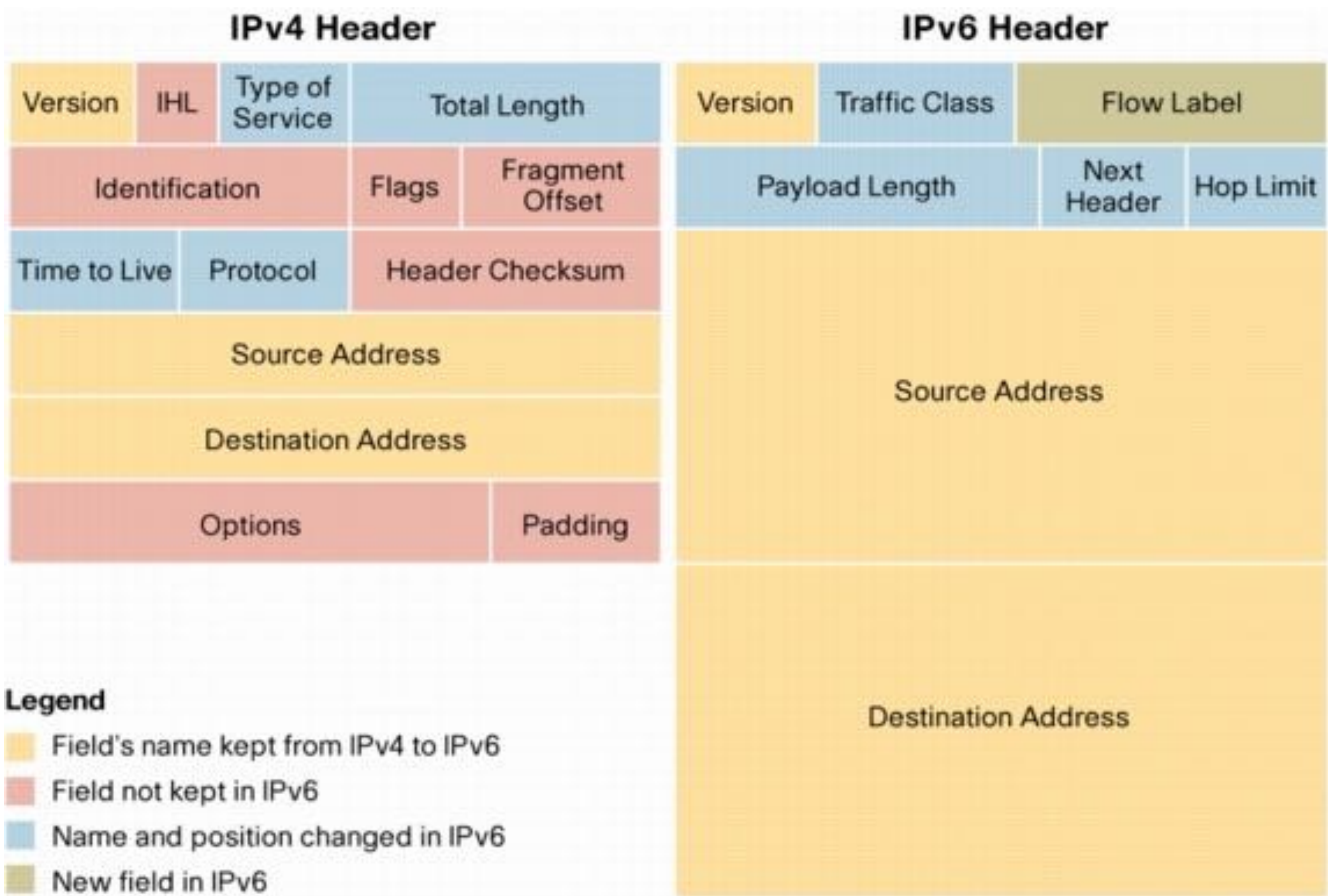
# With respect to IPv4, IPv6 is simpler

IPv6

| removed | reason |
| --- | --- |
| fragmentation | leave problems to the end host |
| checksum | leave problems to the end host |
| header length | simplify handling |

| added… | reason |
| --- | --- |
| new options mechanism | simplify handling |
| expanded addresses | |
| flow label | flexibility |

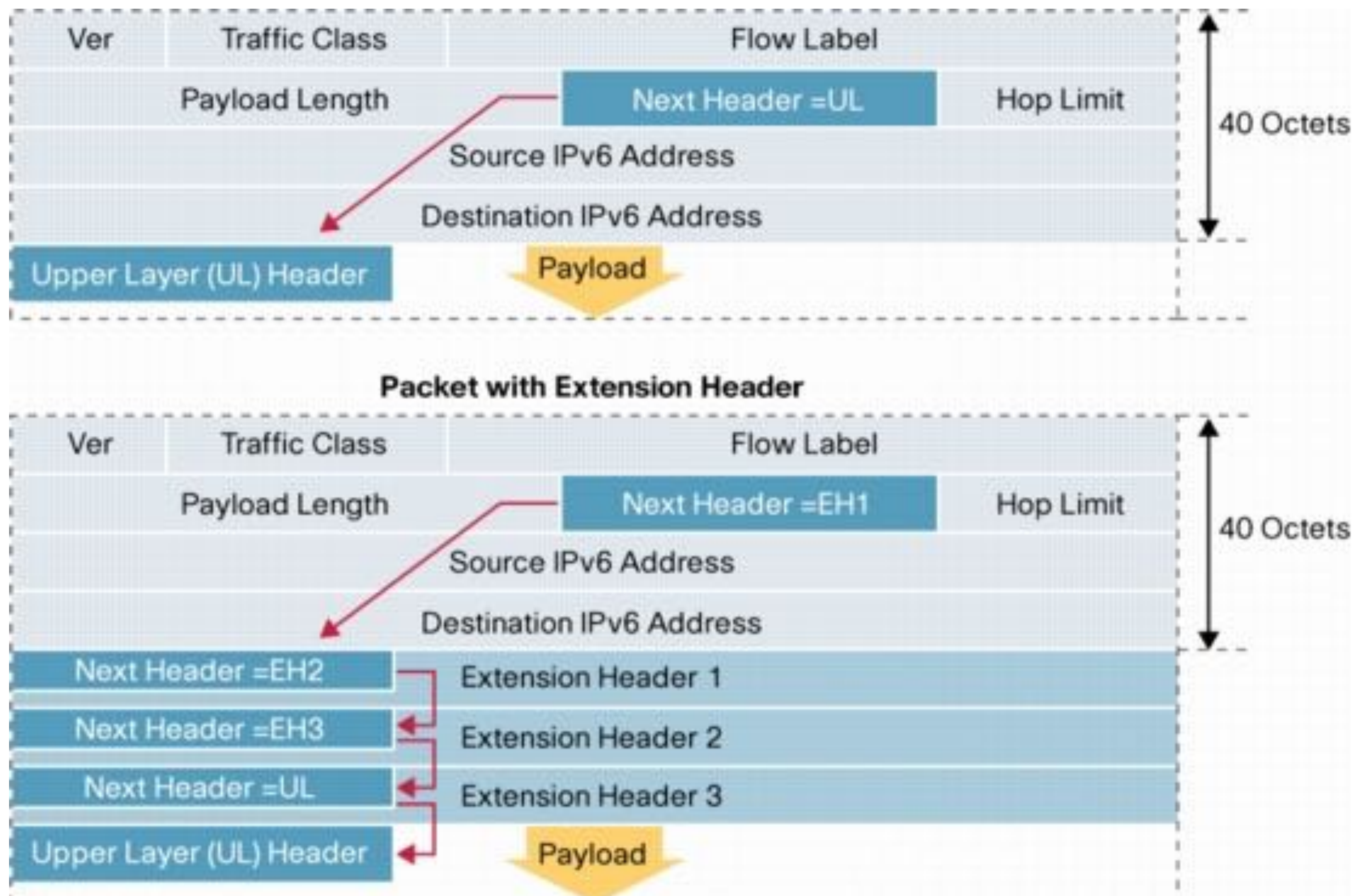
# IPv4 vs IPv6




source http://bit.ly/1HXc2BS

# IPv6 enables to insert arbitrary options in the packet

see RFC 2460

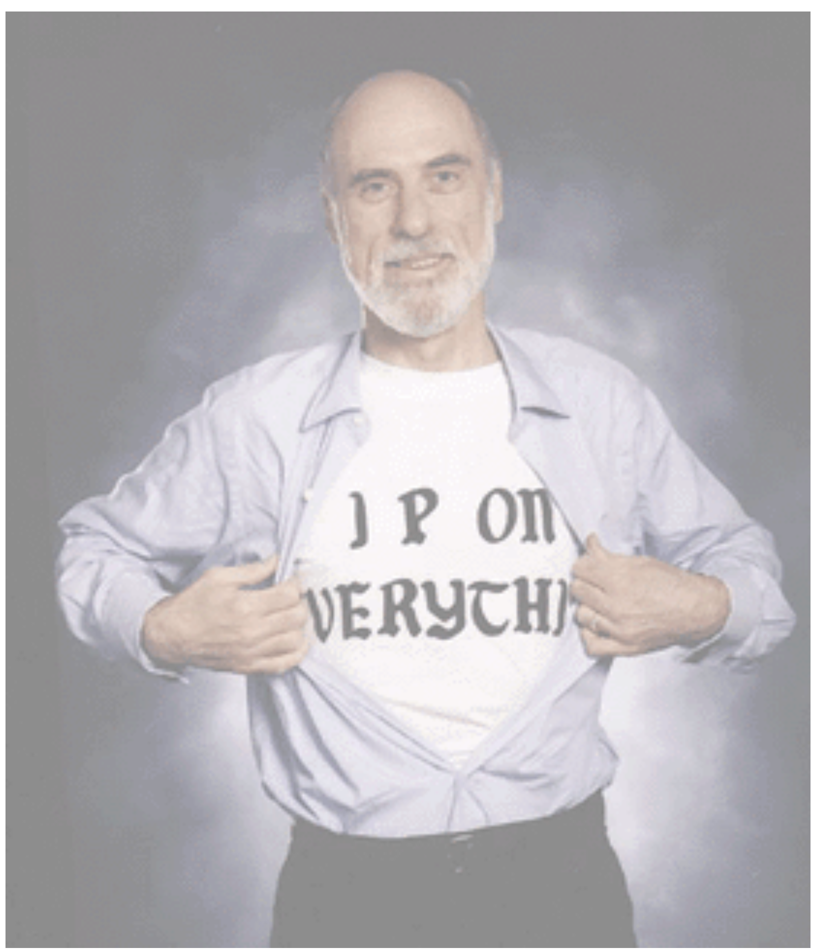



source http://bit.ly/1HXc2BS

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!

# Communication Networks

## Spring 2017

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March, 27 2016