Communication Networks

Spring 2022

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Materials inspired from Scott Shenker & Jennifer Rexford

Announcing our 2022

"Connectivity Fäscht"

2017 edition

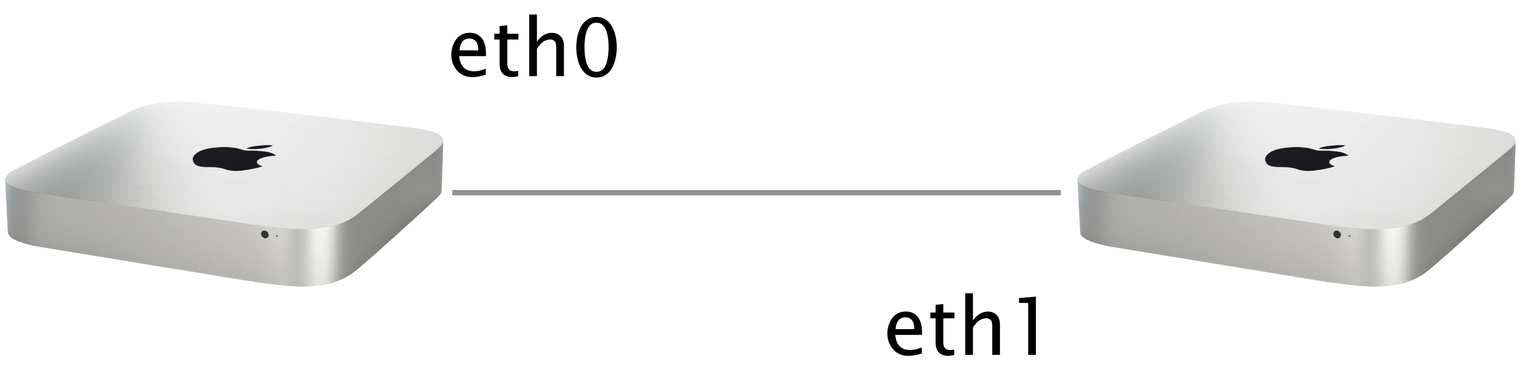
Announcing our 2022
“Connectivity Fäscht”

When	Thursday, 07.04.2022, 18:00—21:30
Where	HG E7
Topics	Awakening of the mini-Internet we'll connect all ASes together! Interesting demos and detailed explanations Great possibility to work on the project a lot of TAs will be there to support you
Attendance	*Not* mandatory… but try to make it: *it's fun!*

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?

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

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,

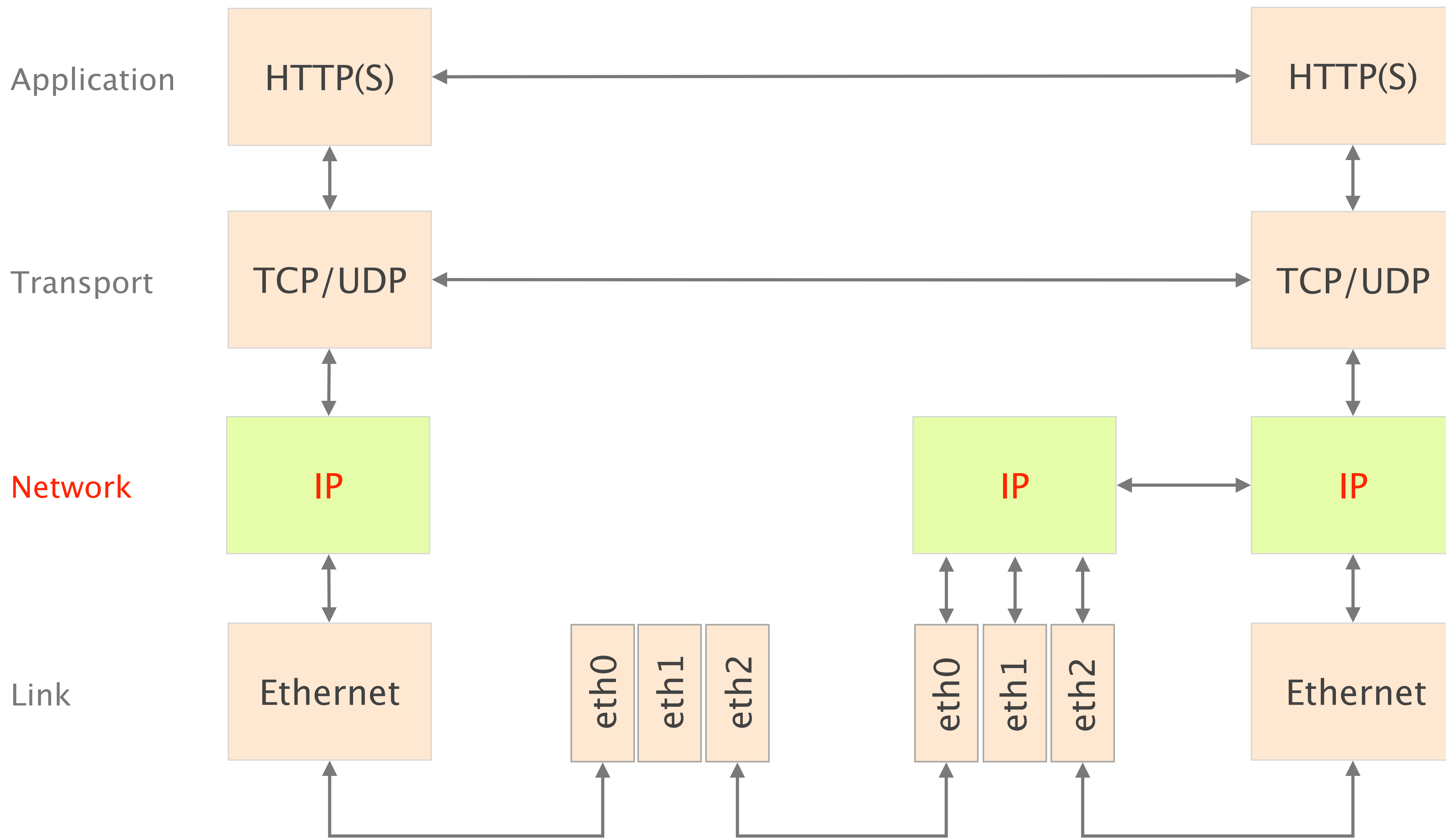
How do I find out what MAC to use?

Address Resolution Protocol

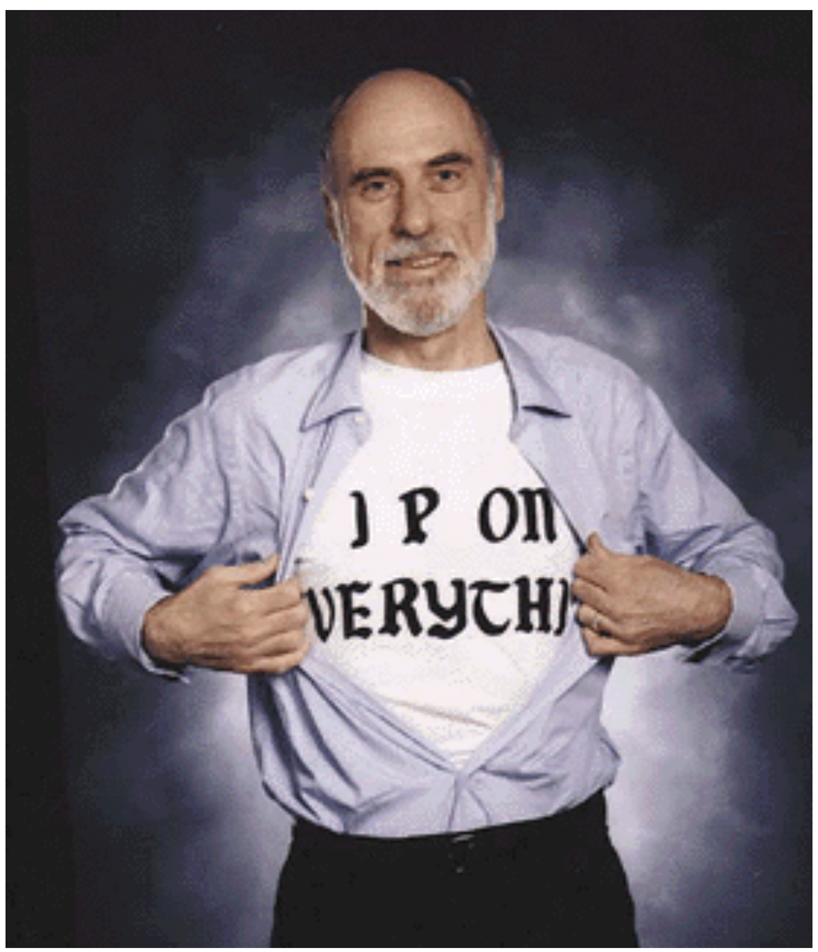
This week on

Communication Networks

Moving on to IP and the network layer



Internet Protocol and Forwarding



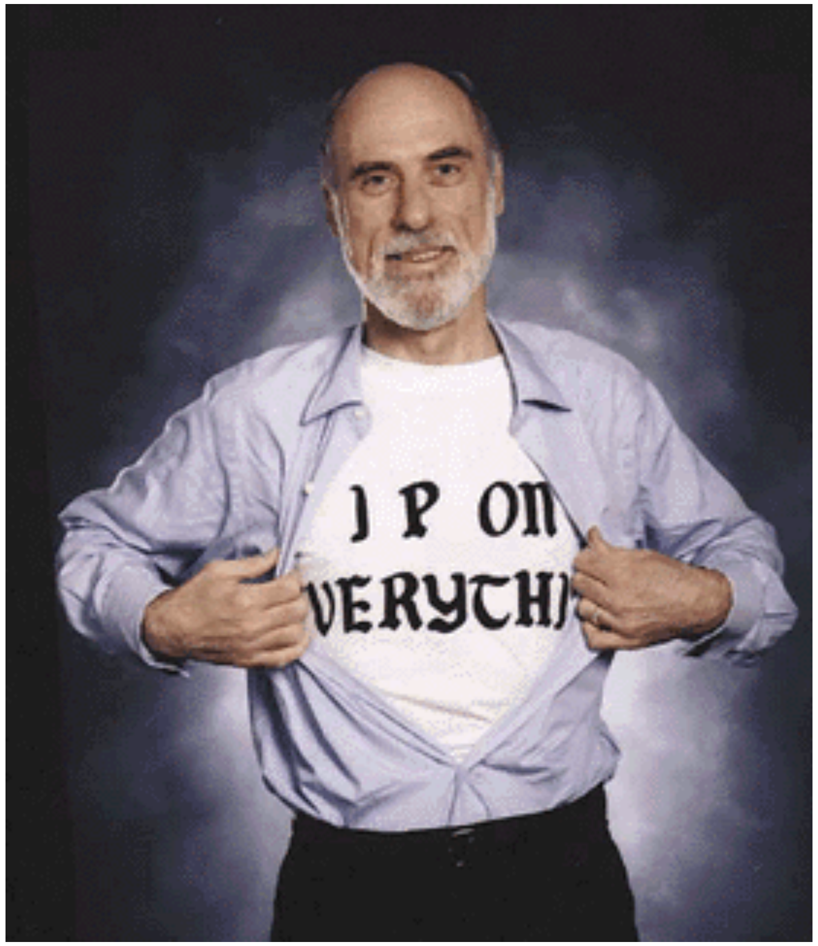
source: Boardwatch Magazine

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

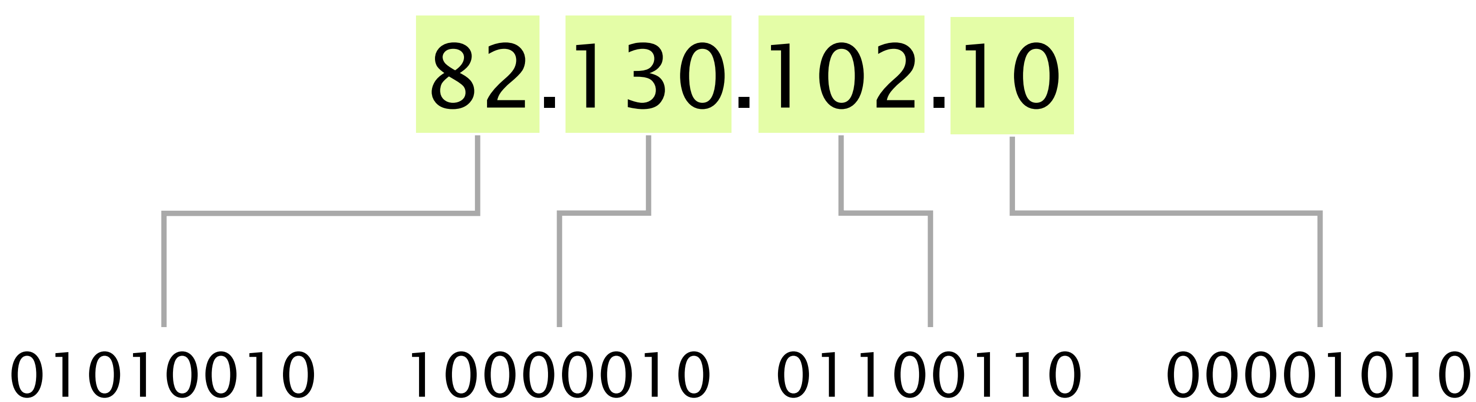
longest prefix match rule

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



IPv6 addresses are unique 128-bits number associated to a network interface (on a host, a router, ...)

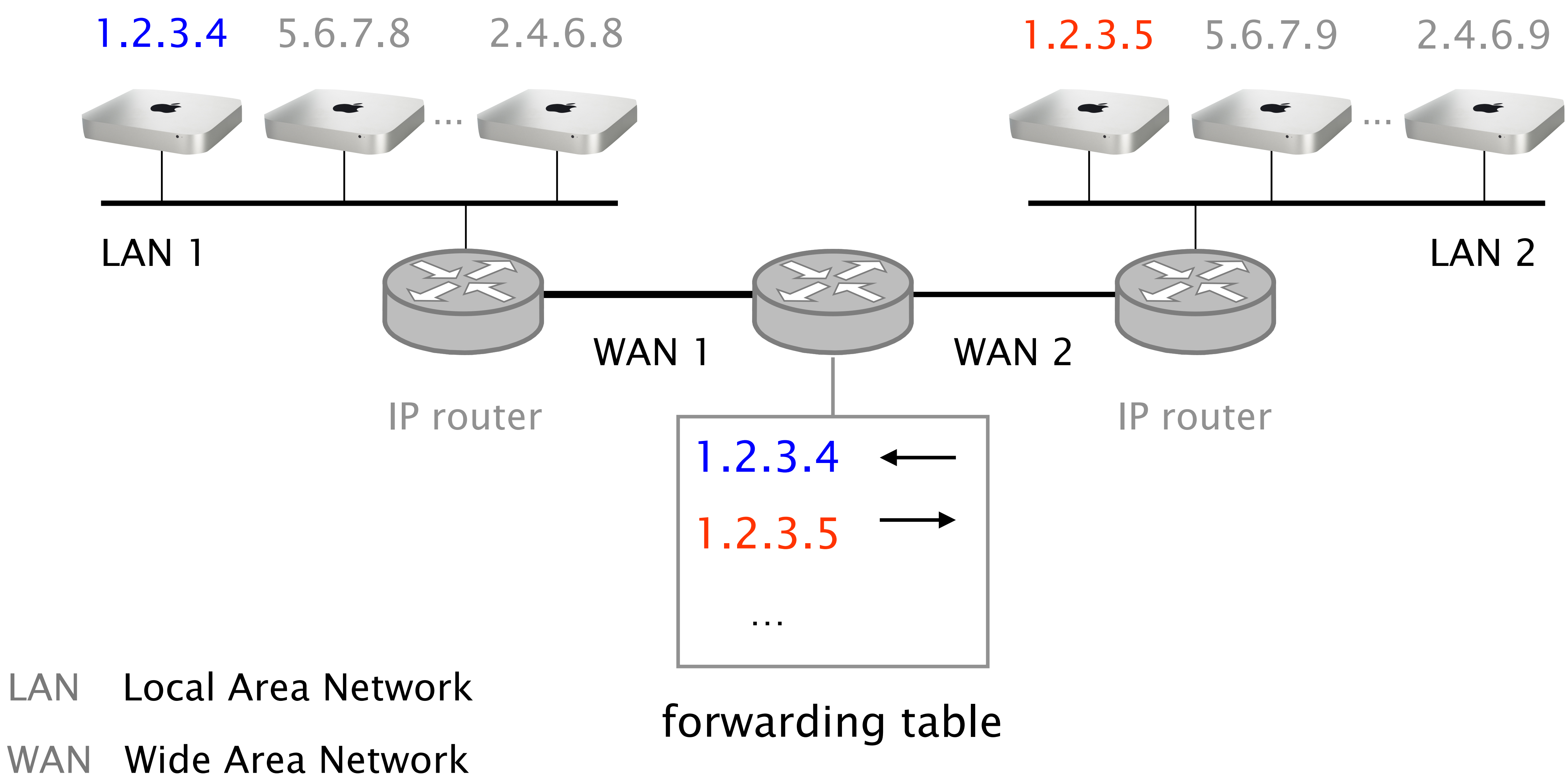
Notation	8 groups of 16 bits each separated by colons (:)
	Each group is written as four hexadecimal digits
Simplification	Leading zeros in any group are removed
	One section of zeros is replaced by a double colon (::)
	Normally the longest section

Examples

- 1080:0:0:0:8:800:200C:417A → 1080::8:800:200C:417A
- FF01:0:0:0:0:0:0:0101 → FF01::101
- 0:0:0:0:0:0:0:1 → ::1

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



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

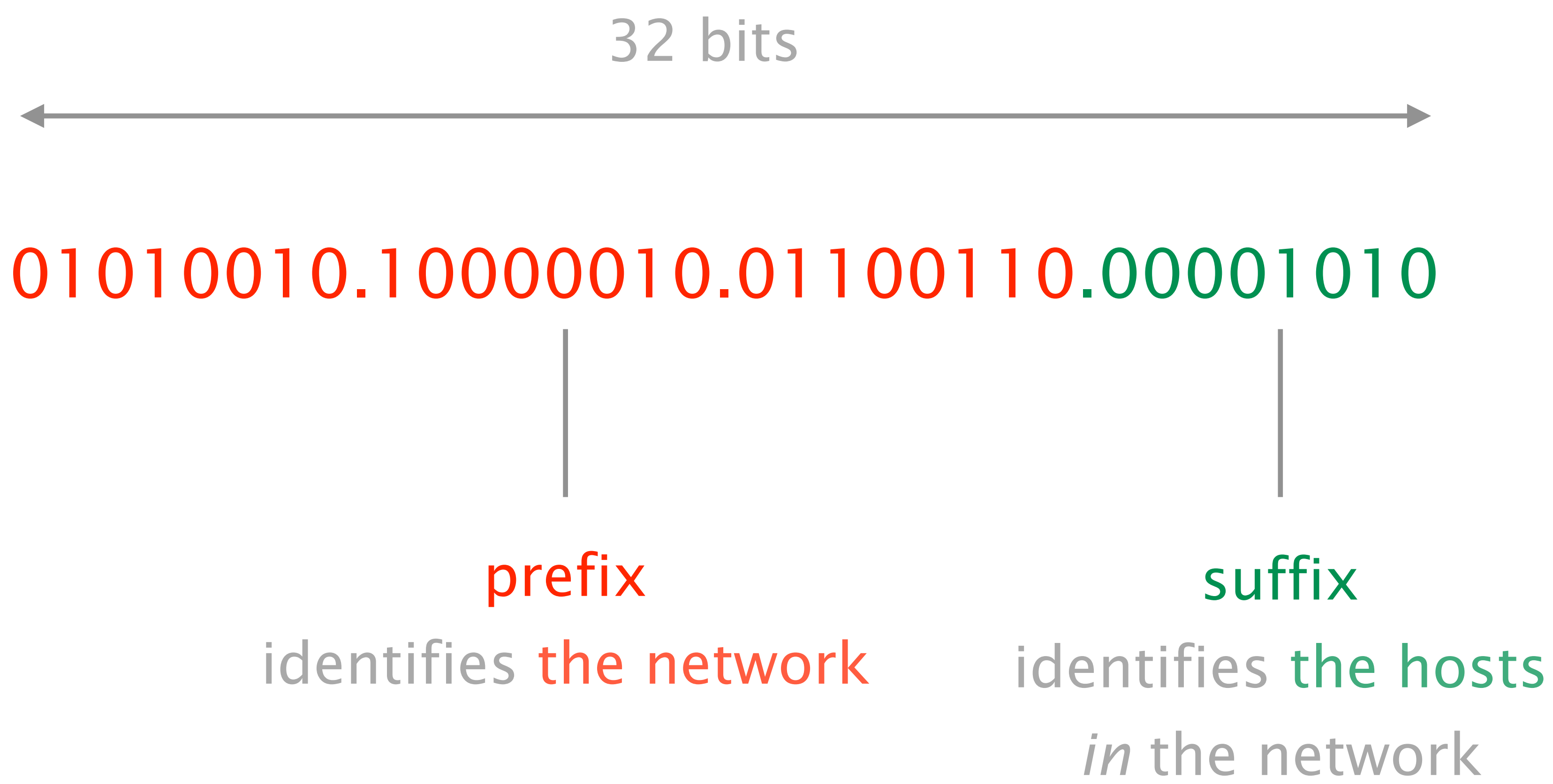
1 Deliver the letter to the post office responsible for the zip code

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

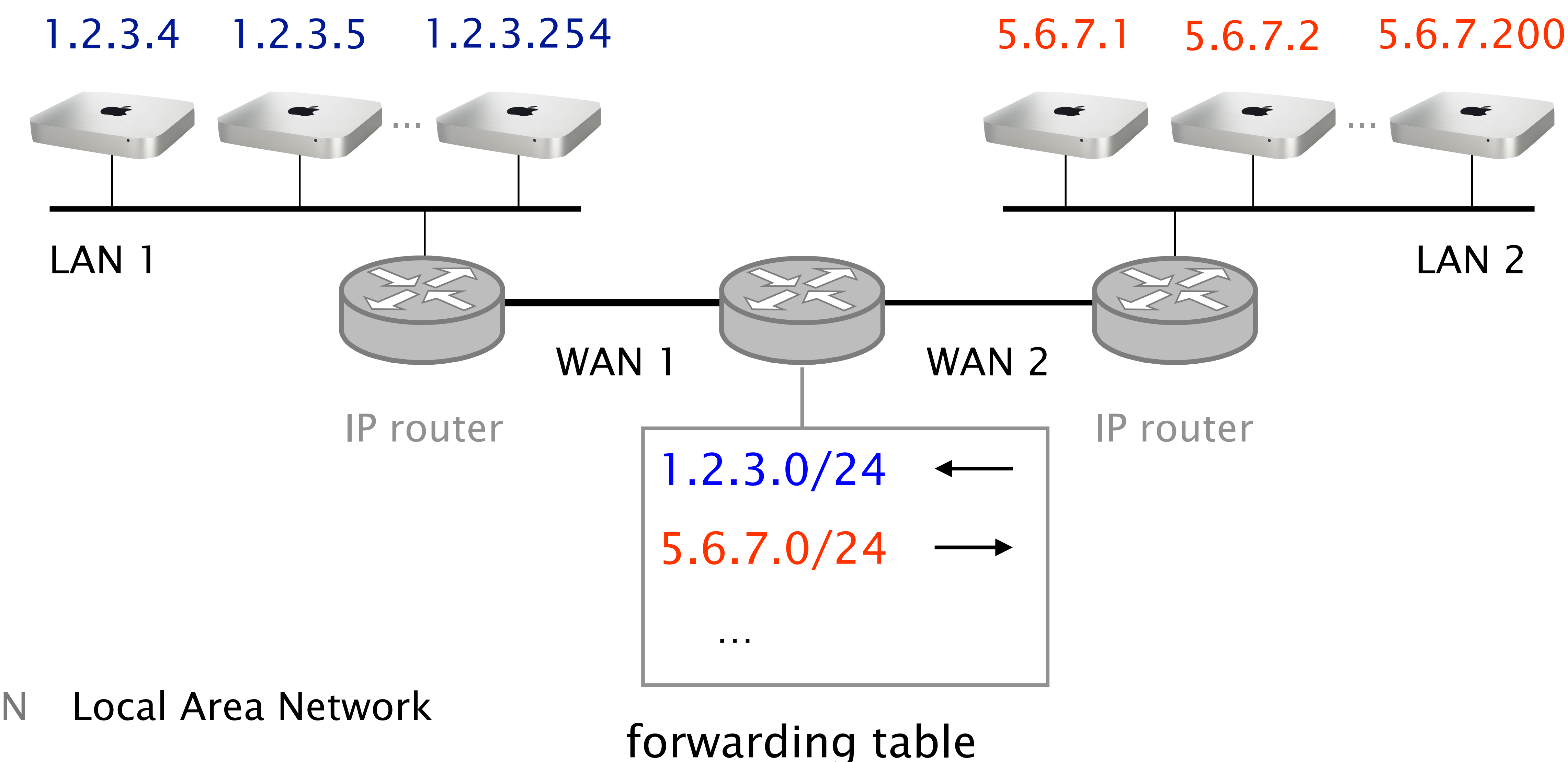
1st host address

last host address

broadcast address

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

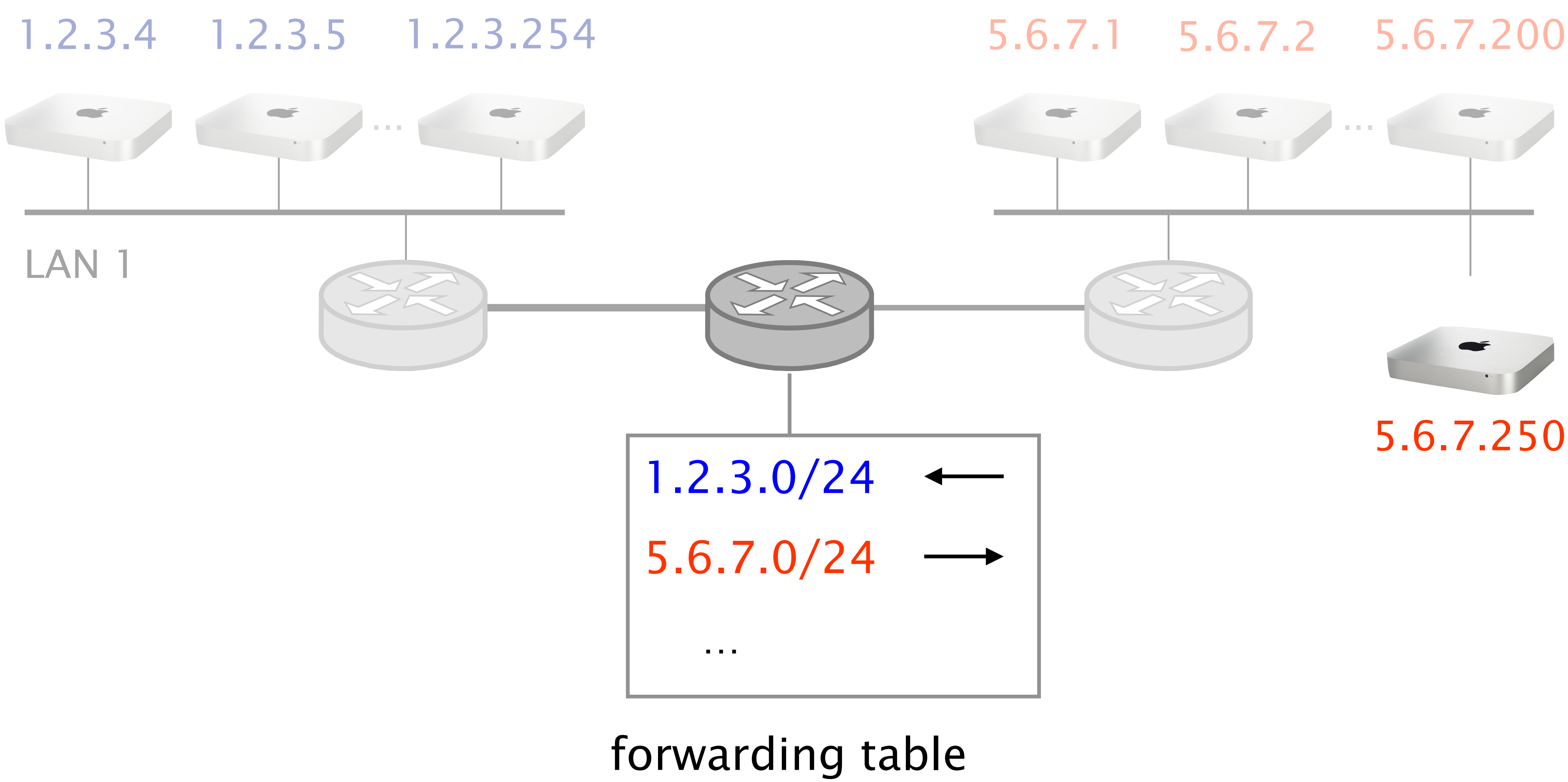
Doing so enables to scale the forwarding tables



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

but class Bs is too big, which led to 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

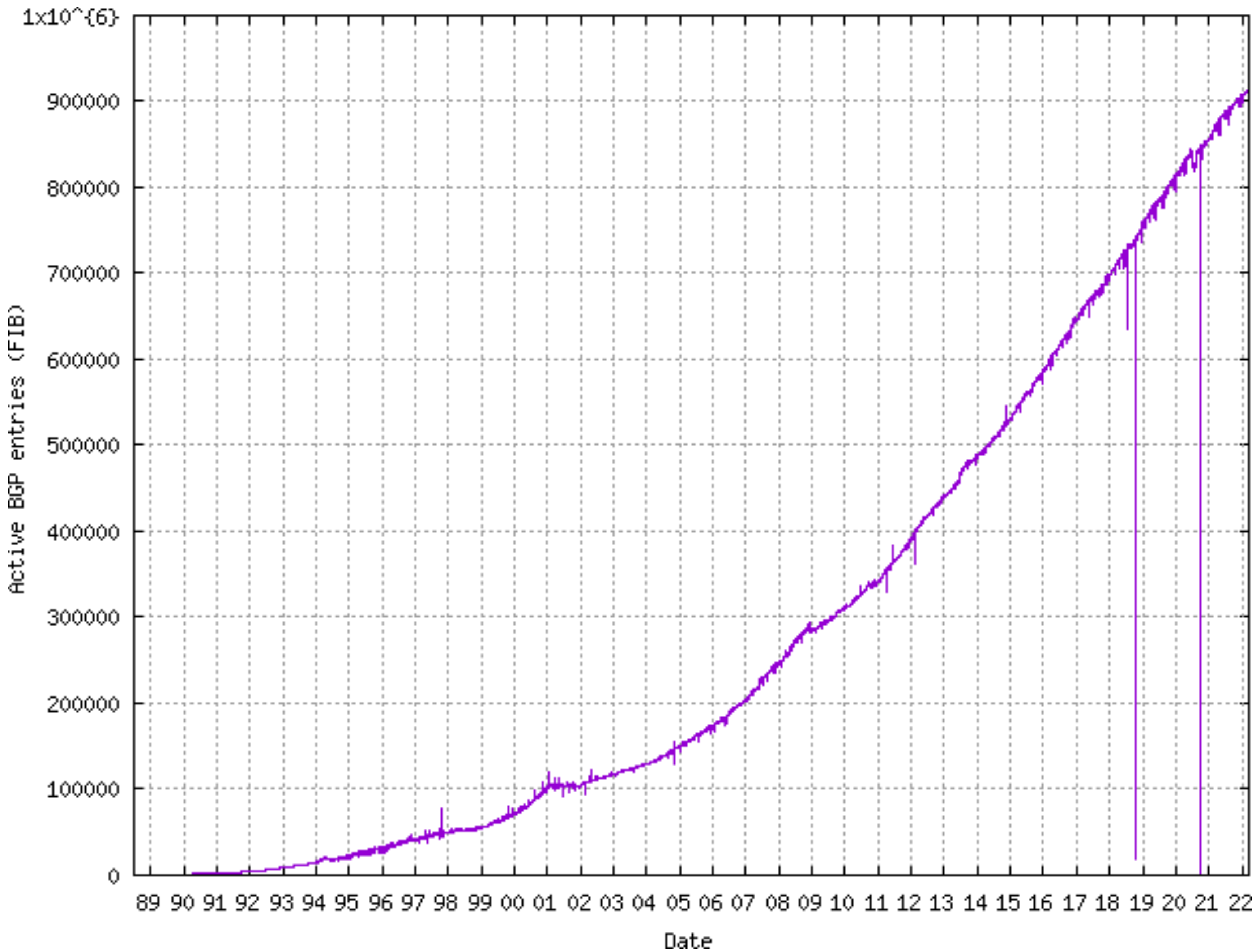
Say that an organization needs 500 addresses…

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?)

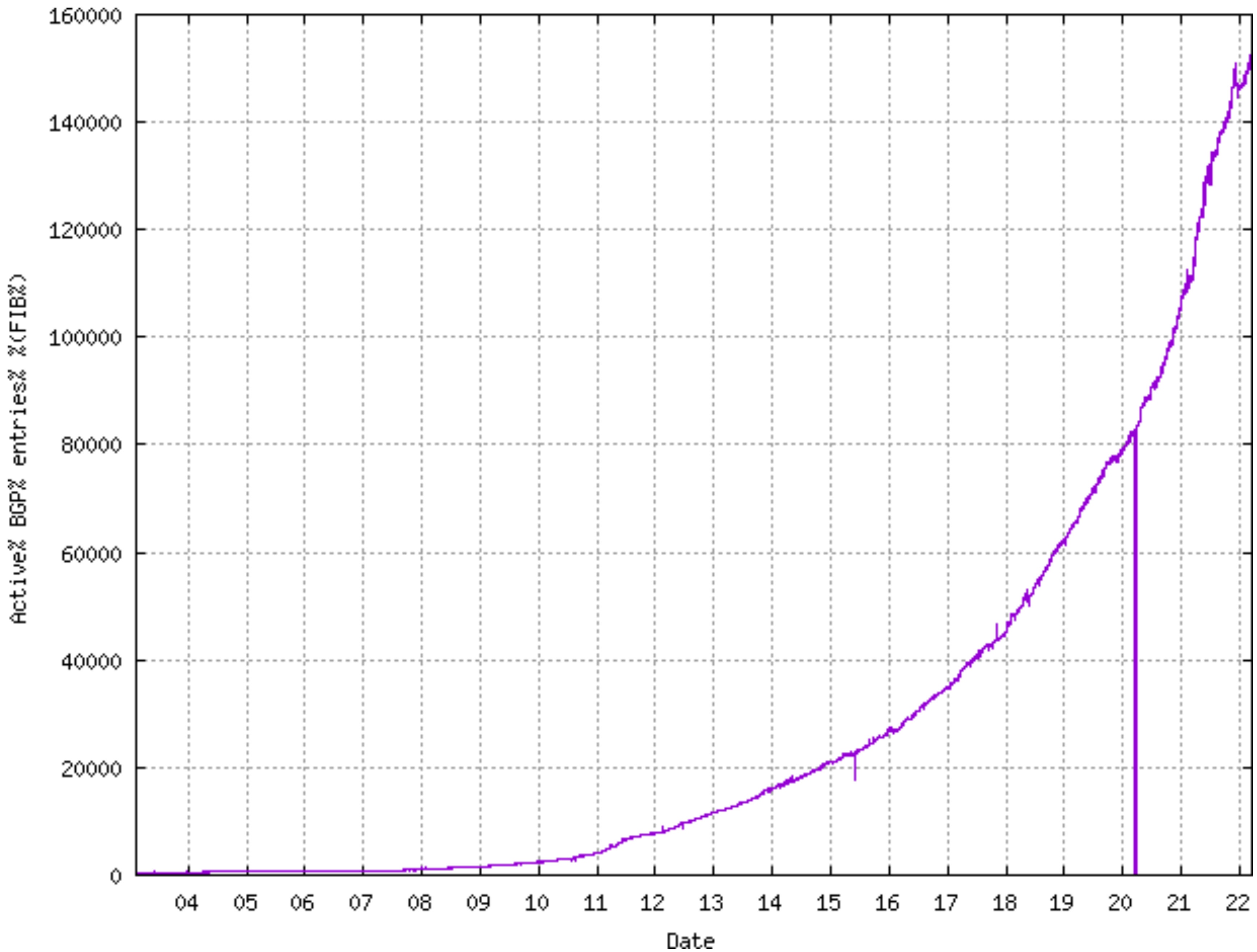
As of last week,

the Internet has >900,000 IPv4 prefixes



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

As of last week,
the Internet has ~150,000 IPv6 prefixes



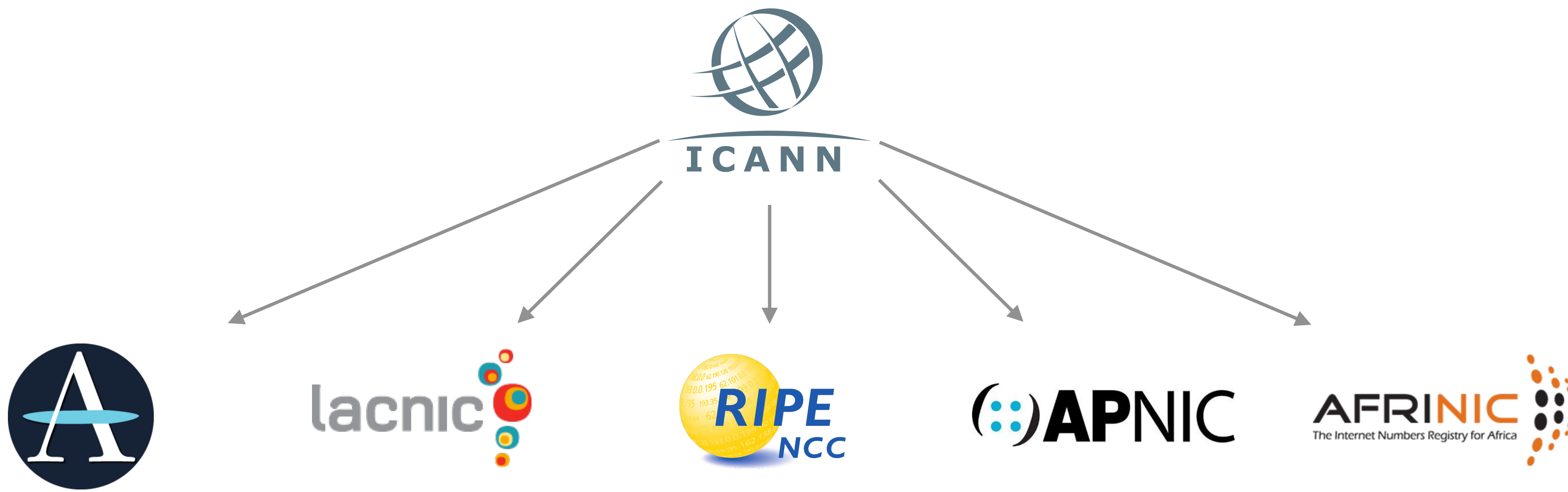
source https://www.cidr-report.org/v6/as2.0/

The allocation process of IP address is also hierarchical

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

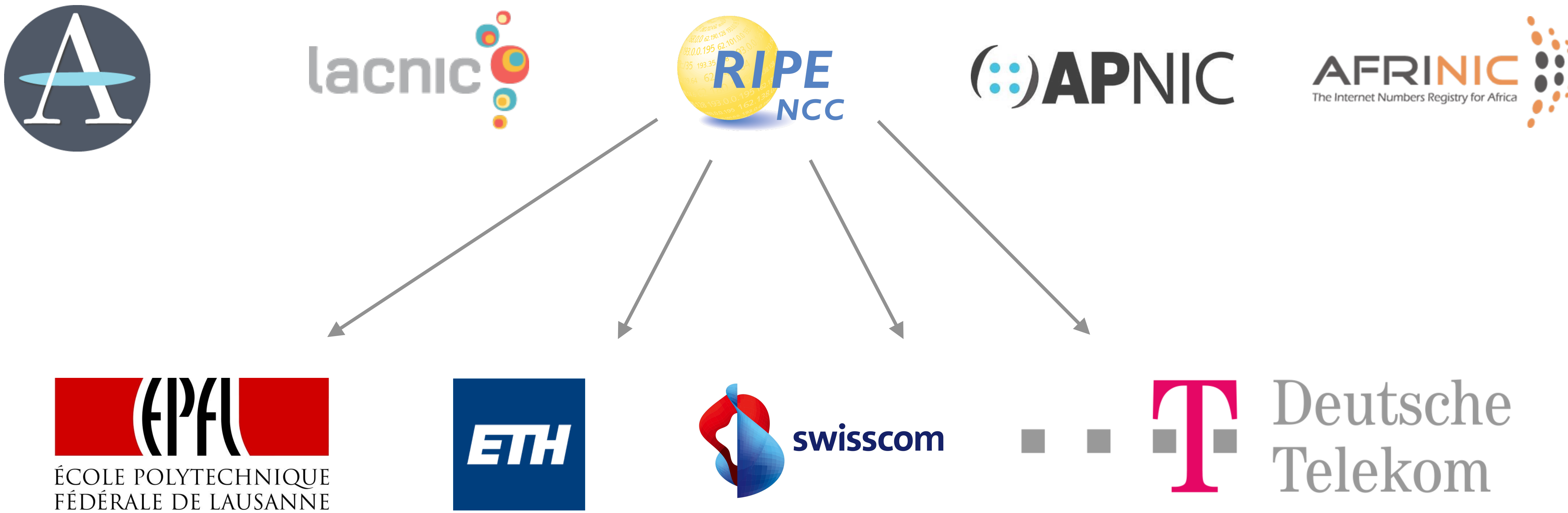
ICANN

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

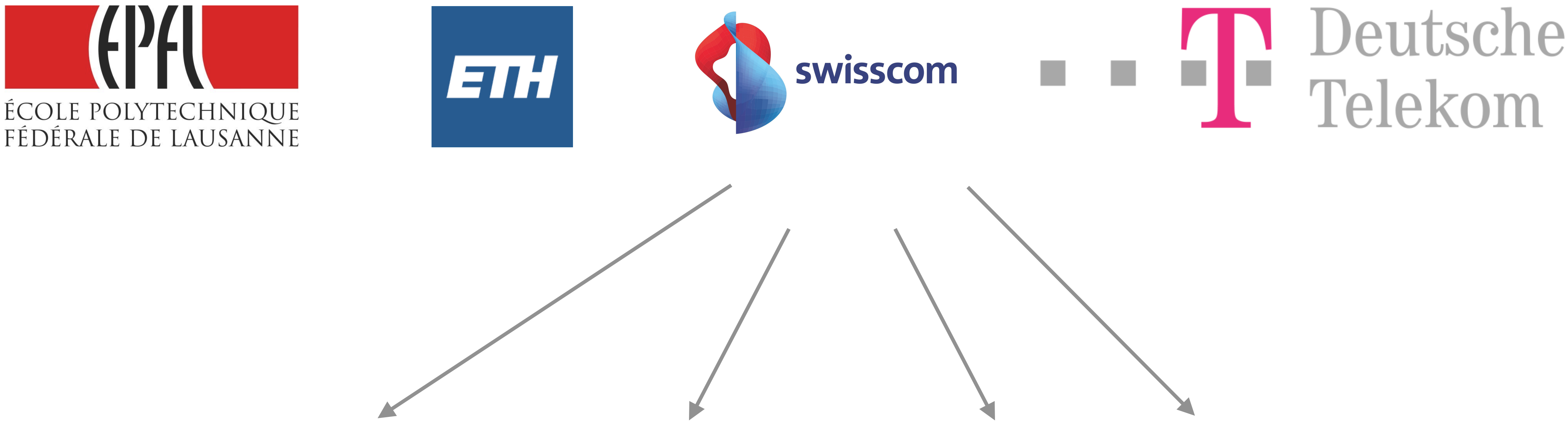


ARIN	LACNIC	RIPE NCC	APNIC	AFRINIC
America	Latin America	Europe	Asia-Pacific	Africa

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

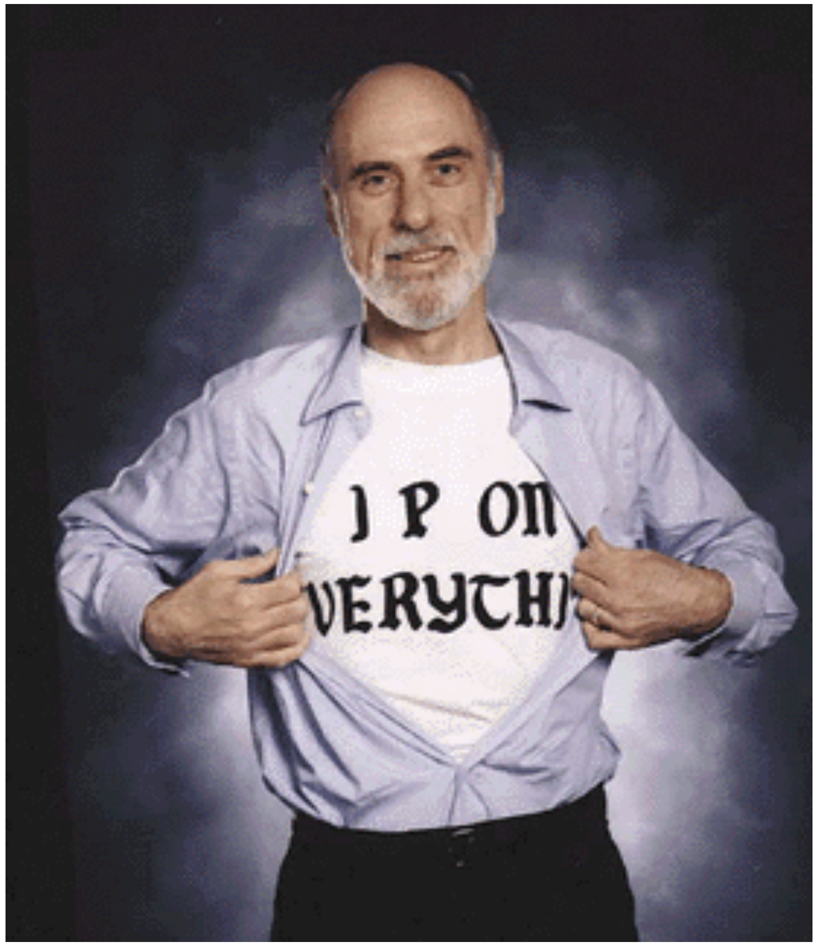


ICANN	ICANN gives RIPE	82.0.0.0/8
	Prefix	01010010
RIPE NCC	RIPE gives ETHZ	82.130.64.0/18
	Prefix	010100101000001001
ETH	ETHZ gives ITET/TIK	82.130.102.0/23
	Prefix	01010010100000100110011
D ITET	ITET gives me	82.130.102.254
	Address	01010010100000100110011011111110

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

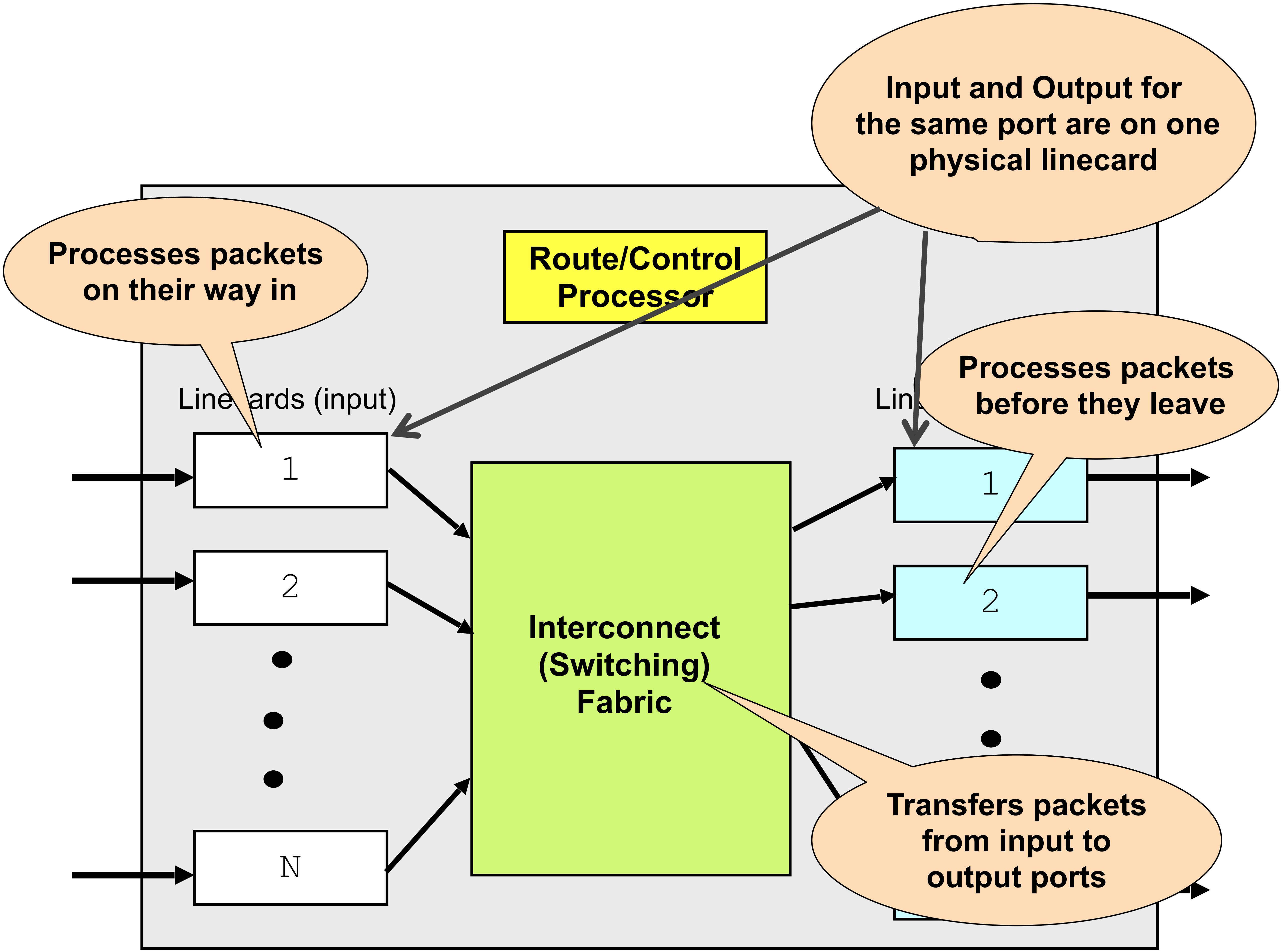
2 IP forwarding

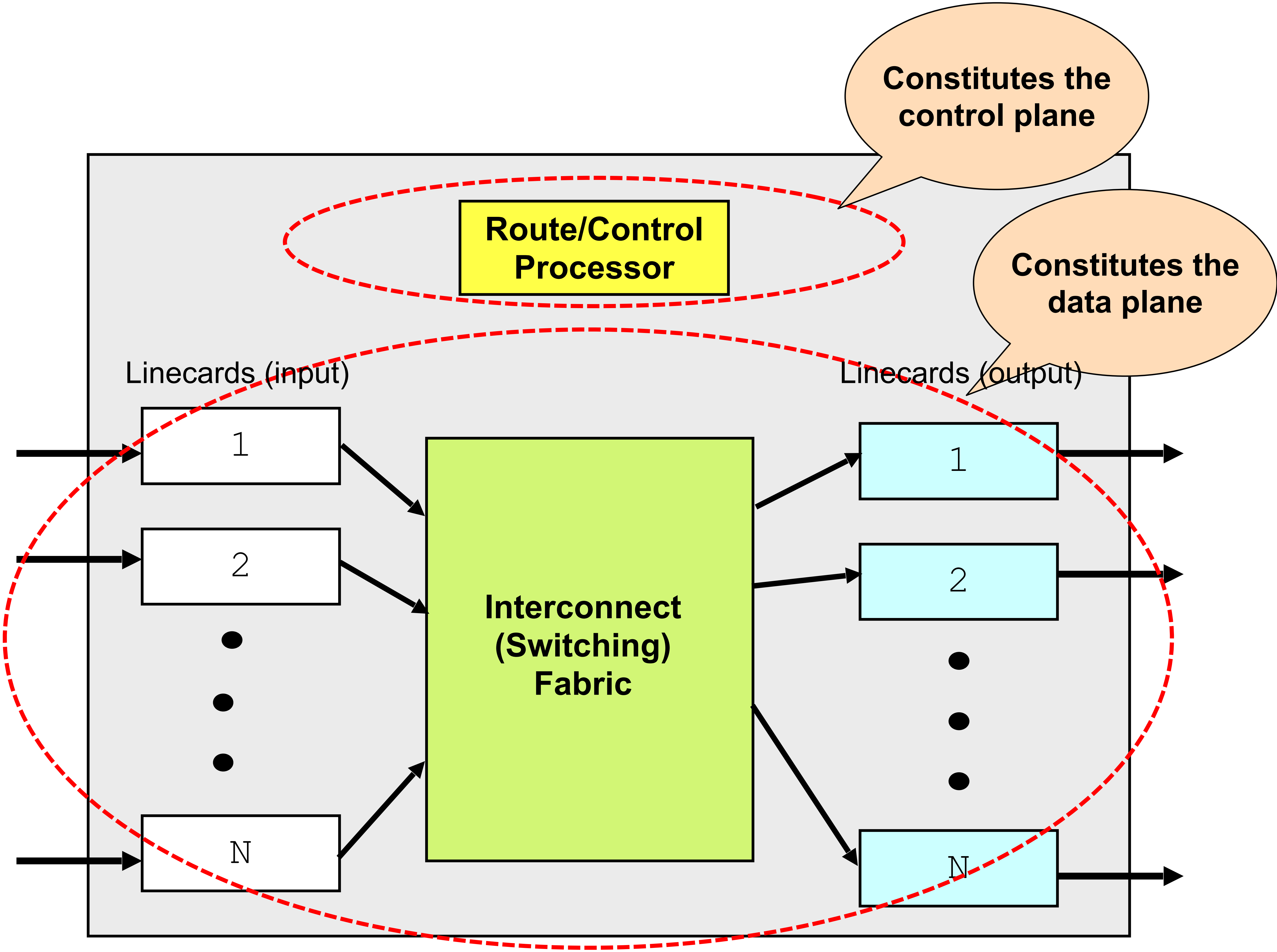
longest prefix match rule

IP header

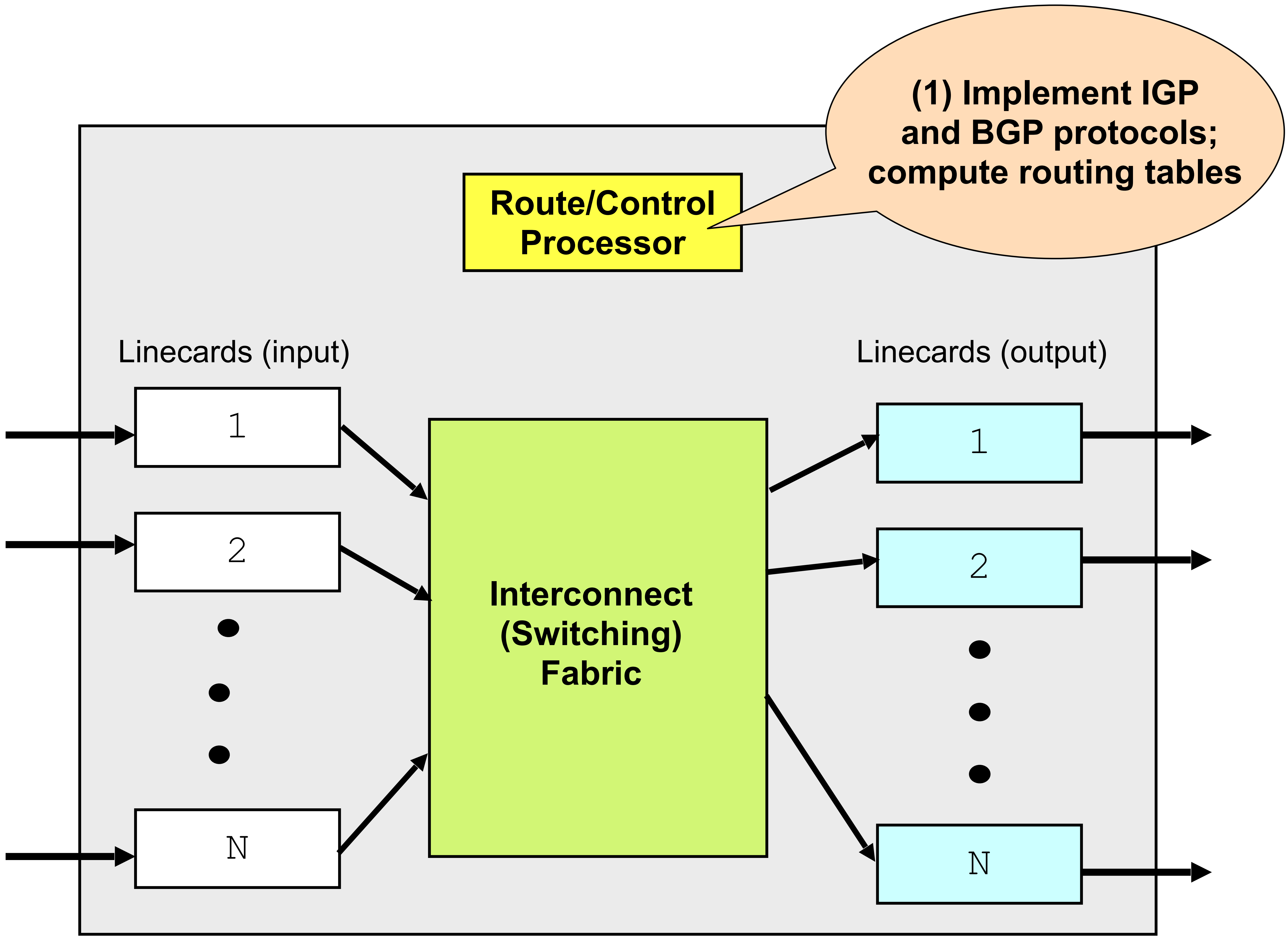
IPv4 and IPv6, wire format

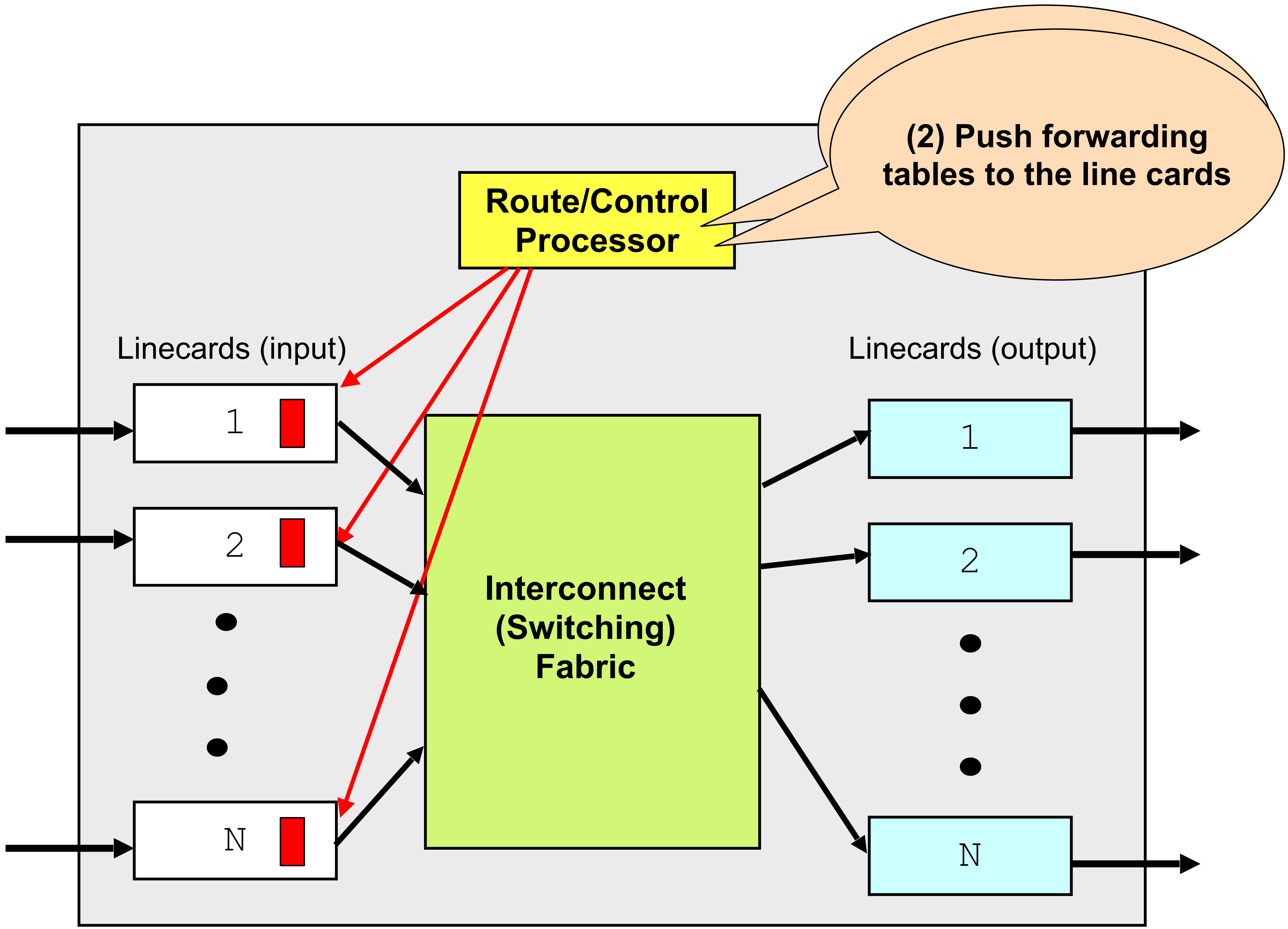
What’s inside an IP router?


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



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

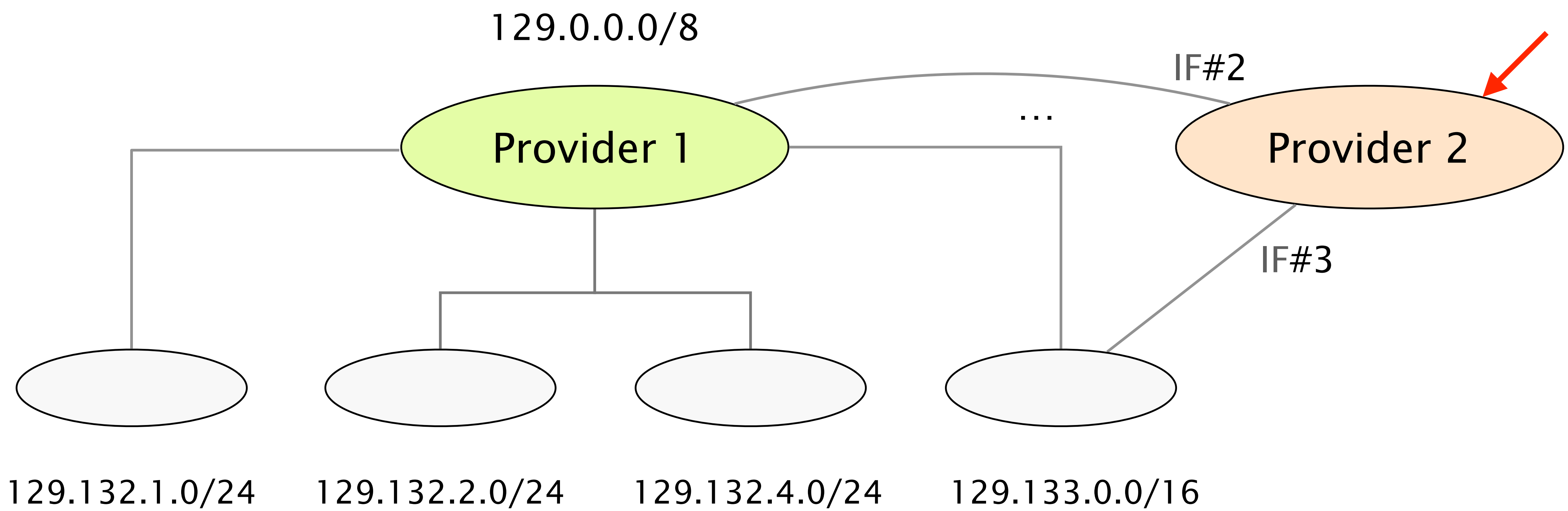

(1) Implement IGP and BGP protocols; compute routing tables
Route/Control Processor
Linecards (input)
Linecards (output)
1
2
N
Interconnect (Switching) Fabric
1
2
N


(2) Push forwarding tables to the line cards
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

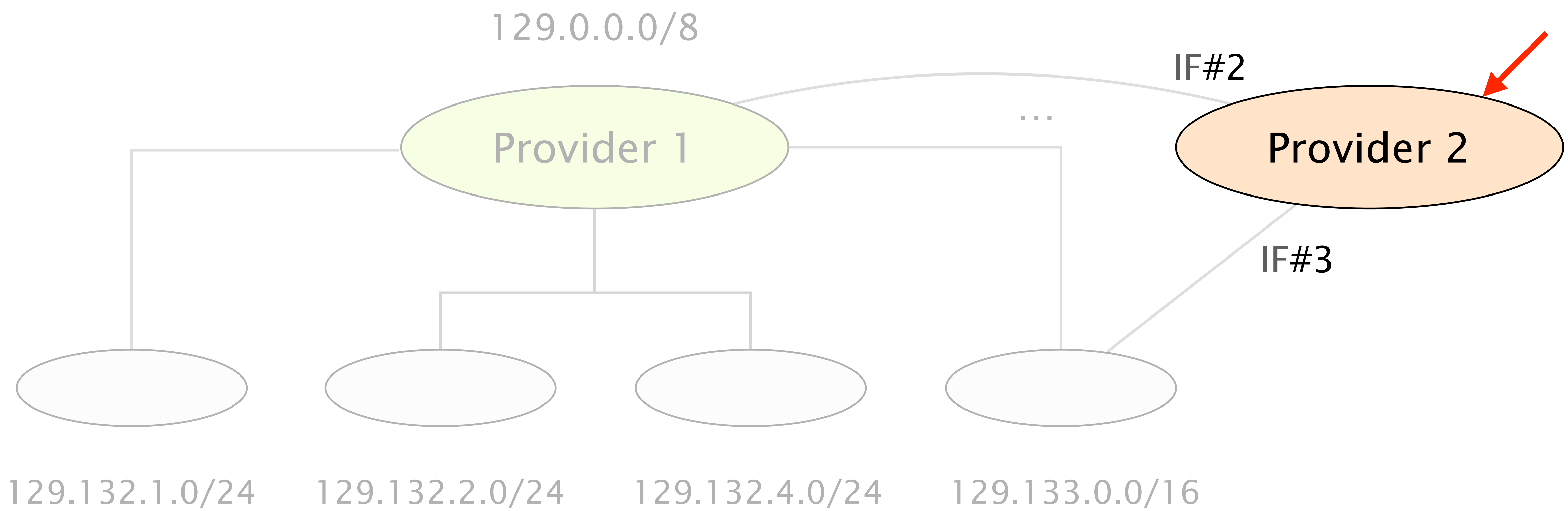
IP prefix	Output
129.0.0.0/8	IF#2
129.132.1.0/24	IF#2
129.132.2.0/24	IF#2
129.133.0.0/16	IF#3



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



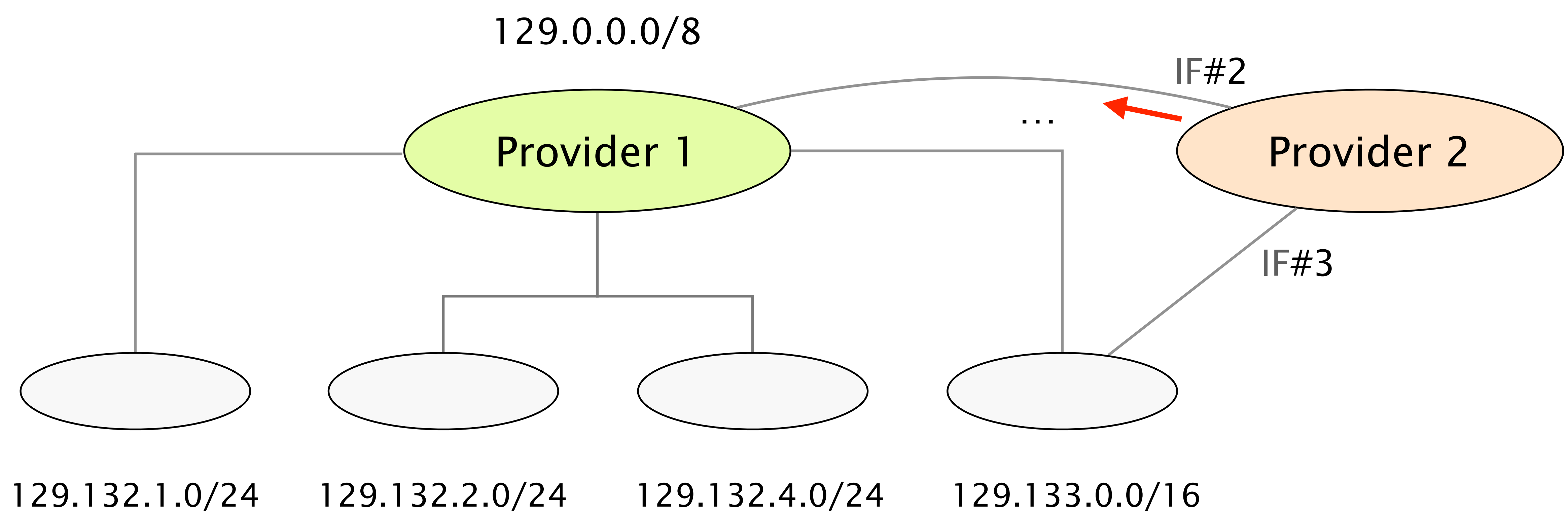
When a router receives an IP packet, it performs an IP lookup to find the matching prefix

Provider 2's Forwarding table

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

> Provider 2 forwards it to IF#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

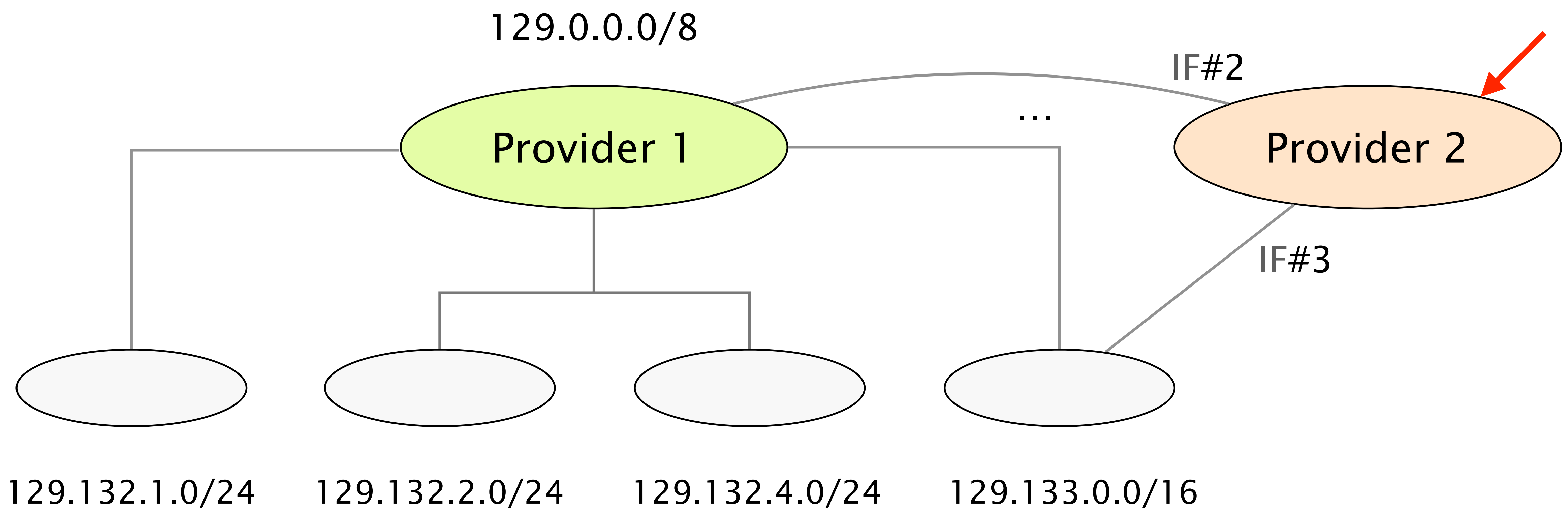


CIDR makes forwarding harder though,
as one packet can match many IP prefixes

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

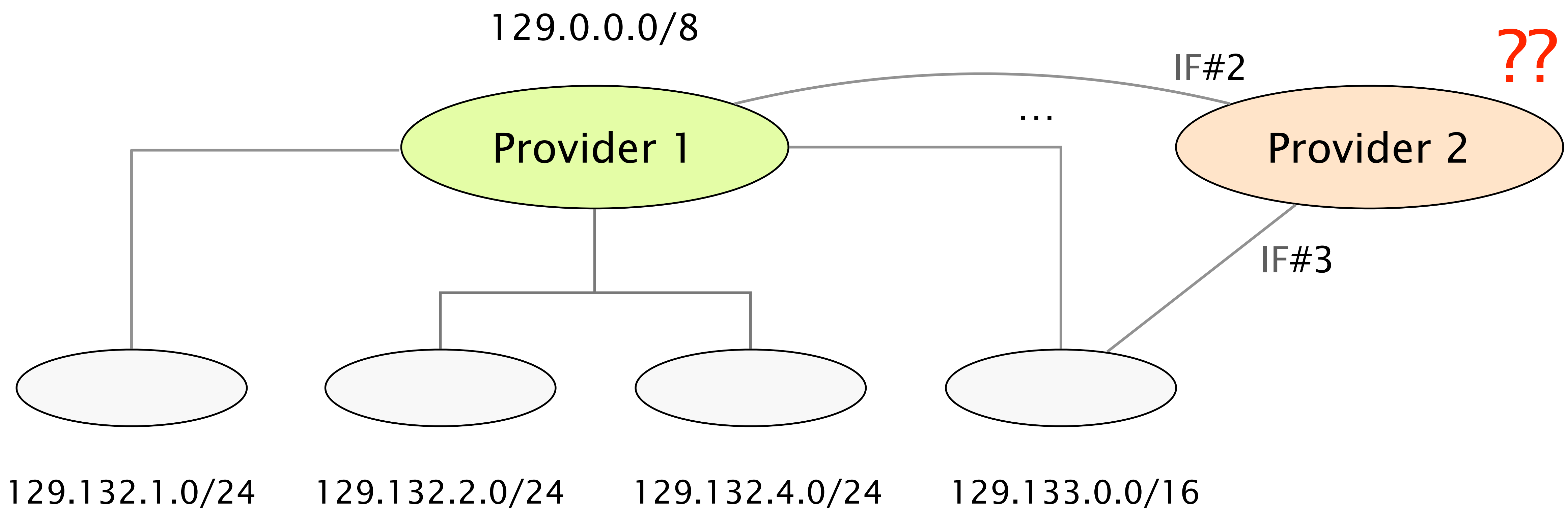


Provider 2's Forwarding table

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

We have two matches!

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



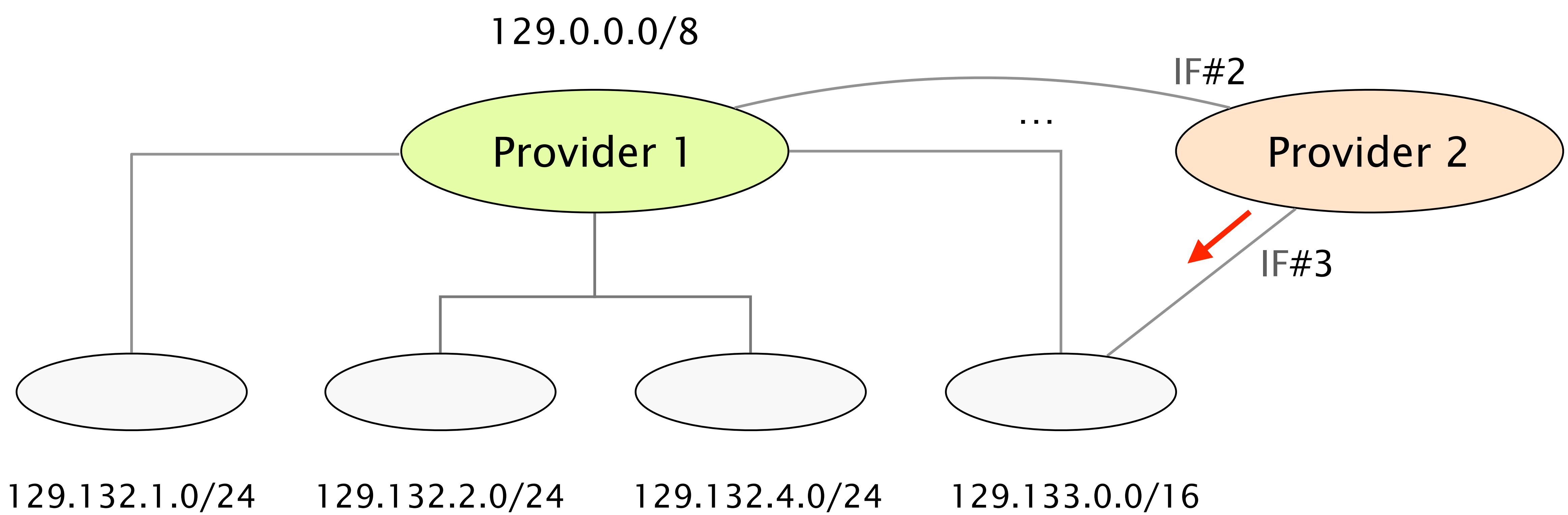
To resolve ambiguity, forwarding is done along the *most specific* prefix (*i.e.*, the longer one)

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

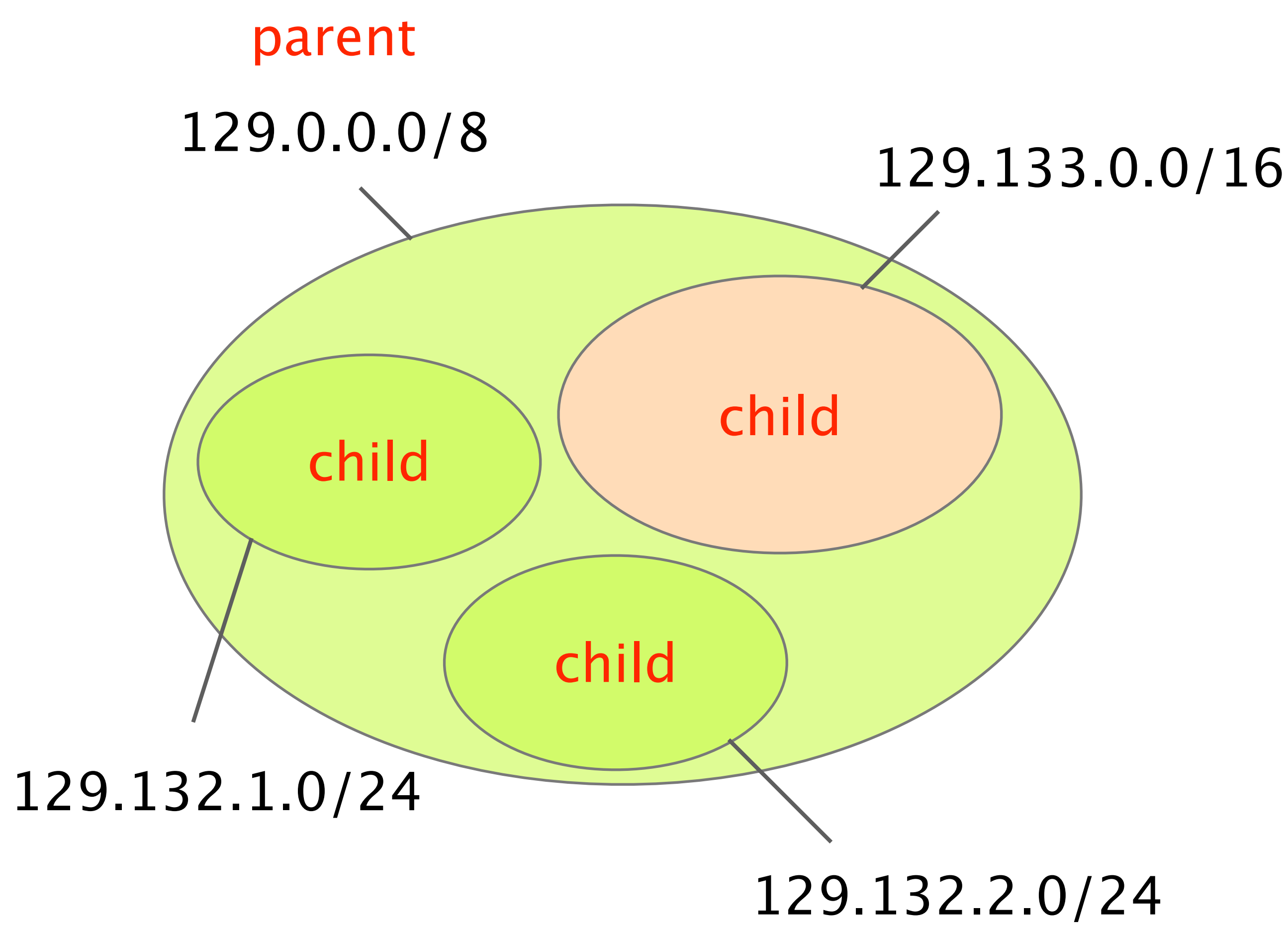


Could we do something better than maintaining one entry per prefix? *Yep!*

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

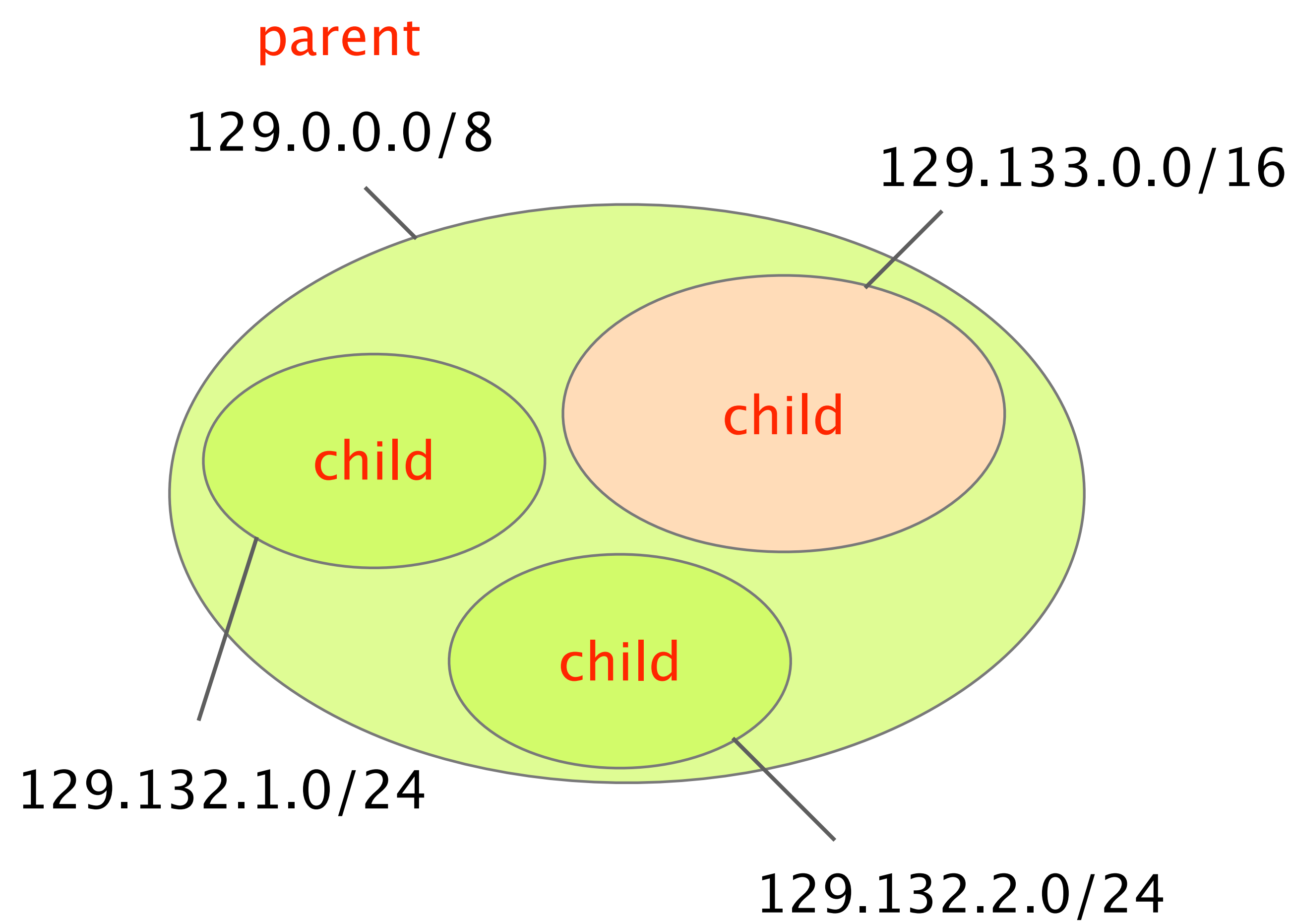
Routing Table

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
...	



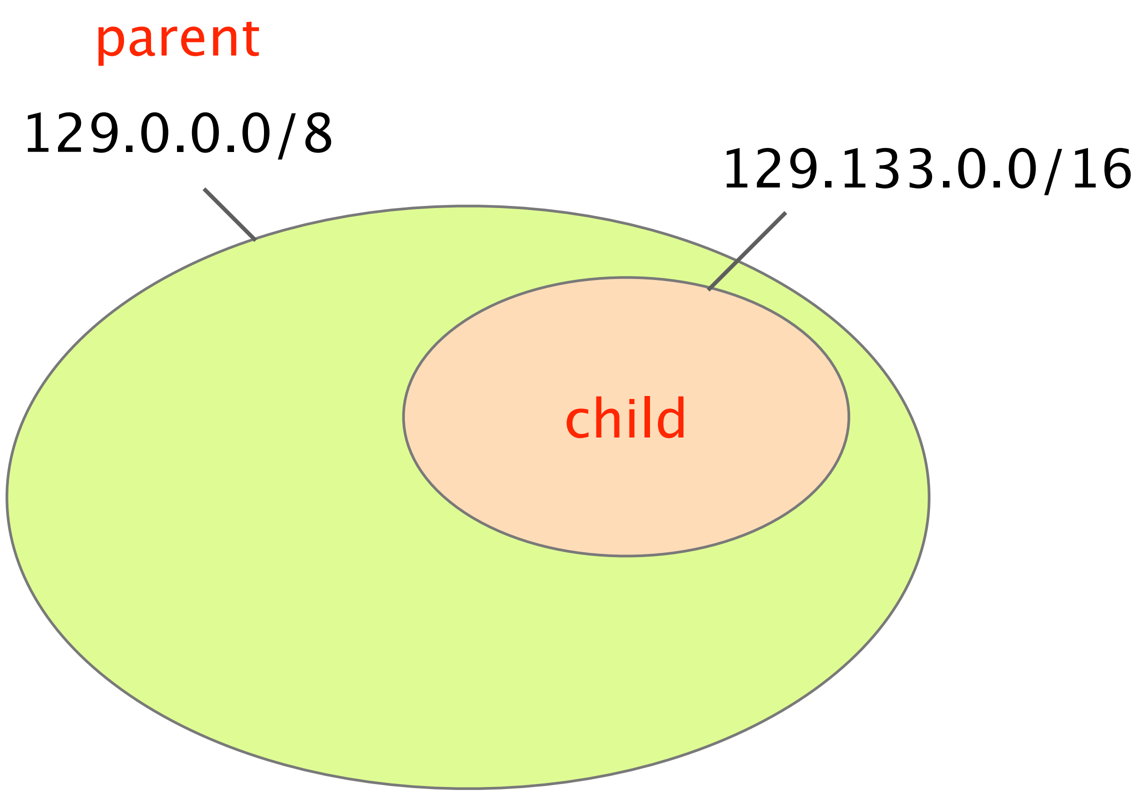
Routing Table

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

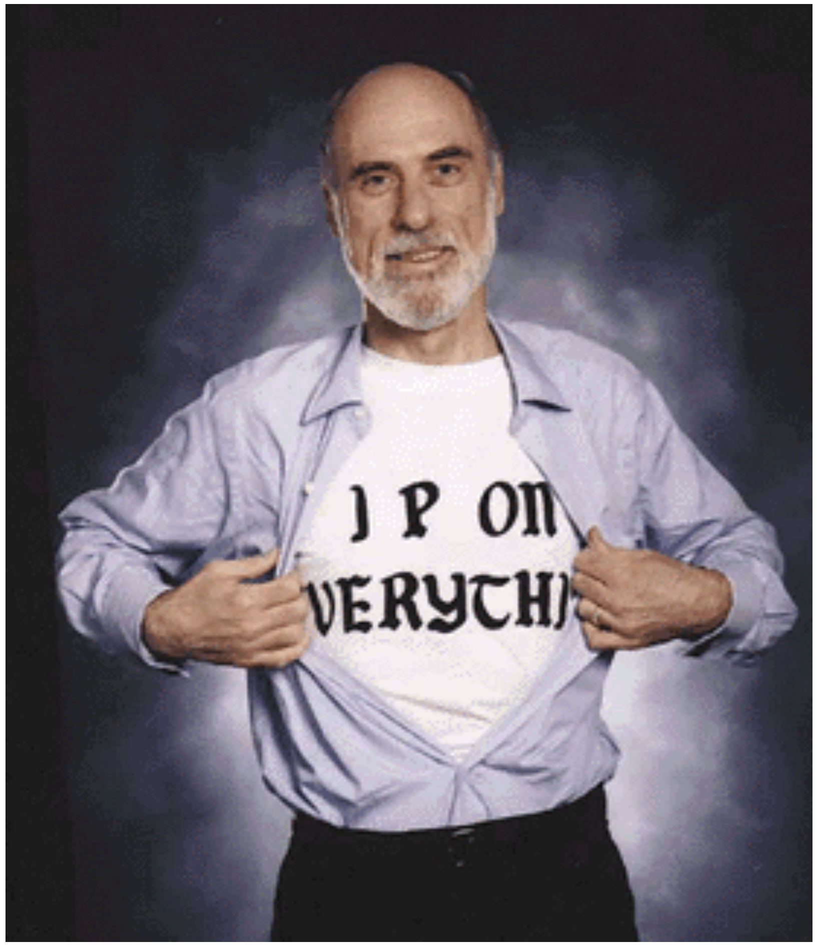
IP prefix	Output Interface
...	
129.0.0.0/8	IF#2
129.133.0.0/16	IF#3
...	



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

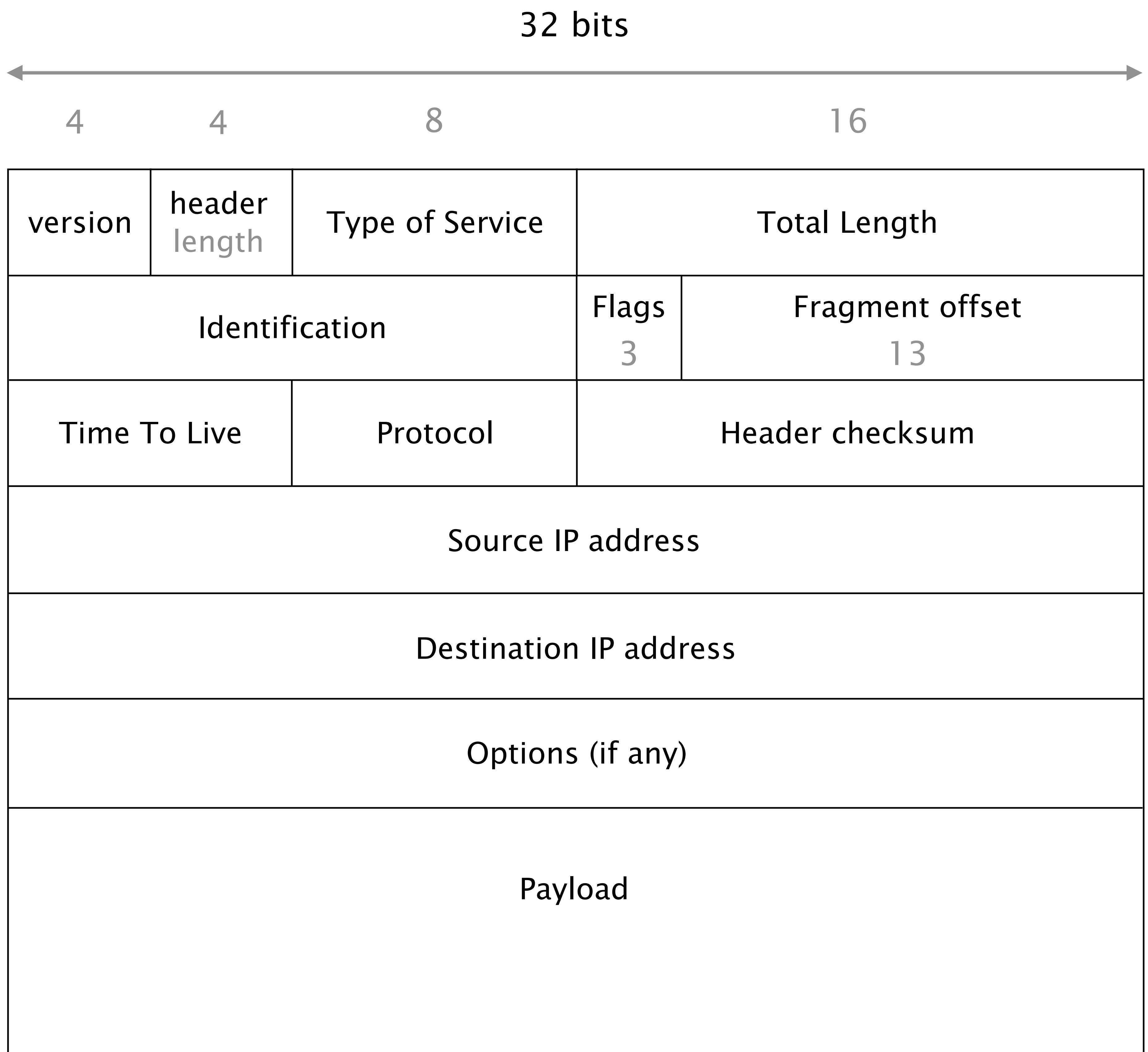
IP forwarding

longest prefix match rule

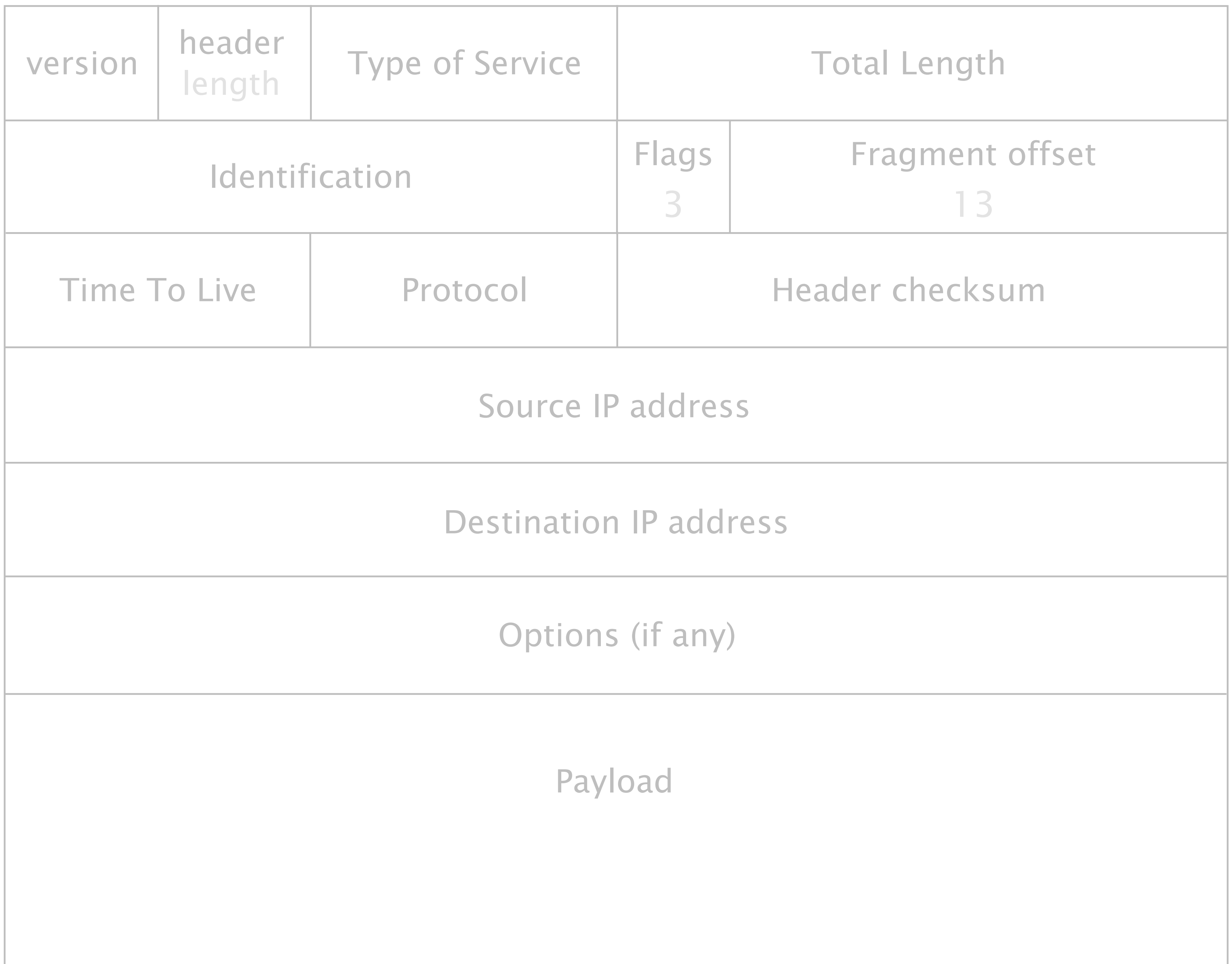
3 IP header

IPv4 and IPv6, wire format

Here is what an IPv4 packet look like on a wire

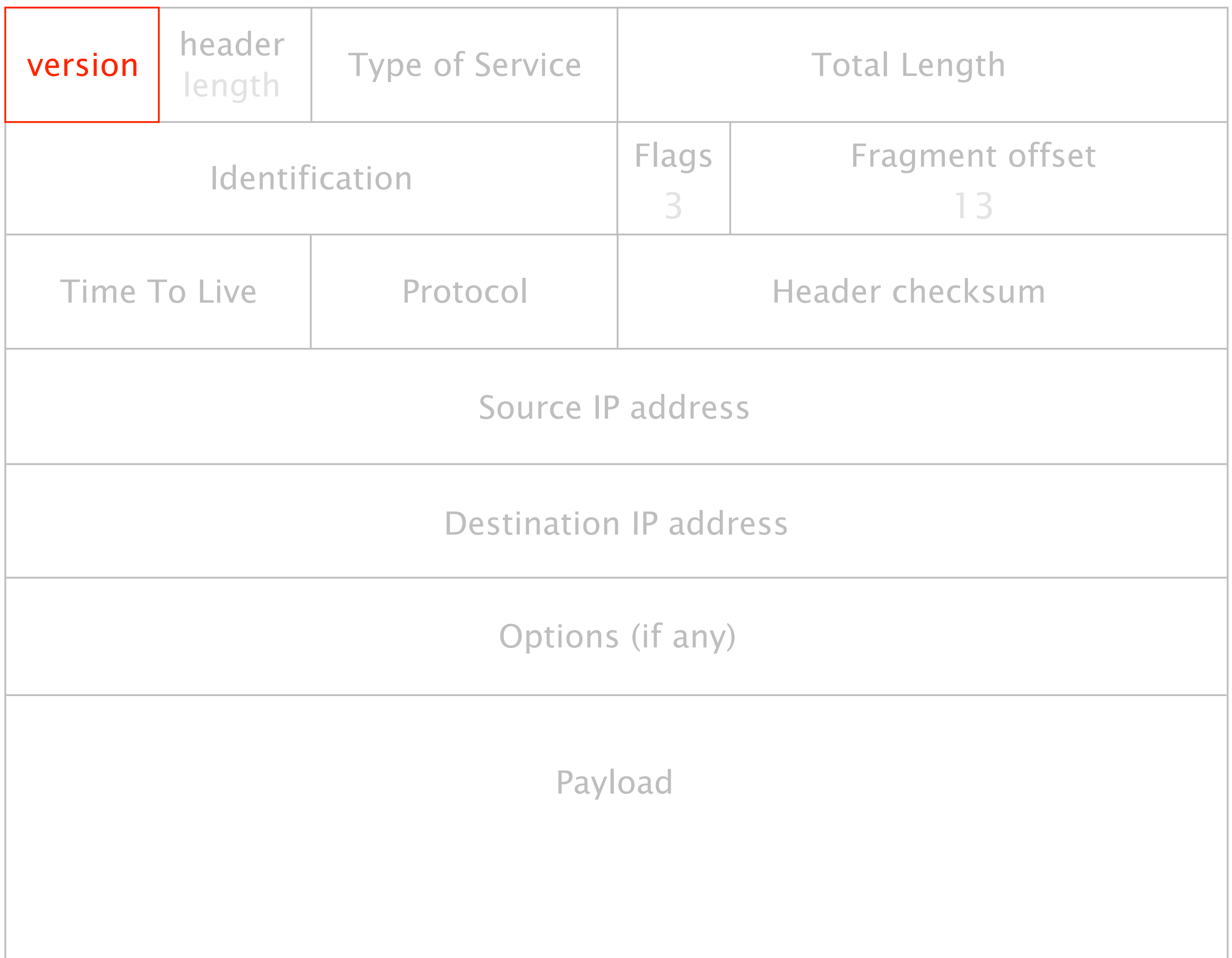


32 bits
4
4
8
16
version
header length
Type of Service
Total Length
Identification
Flags 3
Fragment offset 13
Time To Live
Protocol
Header checksum
Source IP address
Destination IP address
Options (if any)
Payload

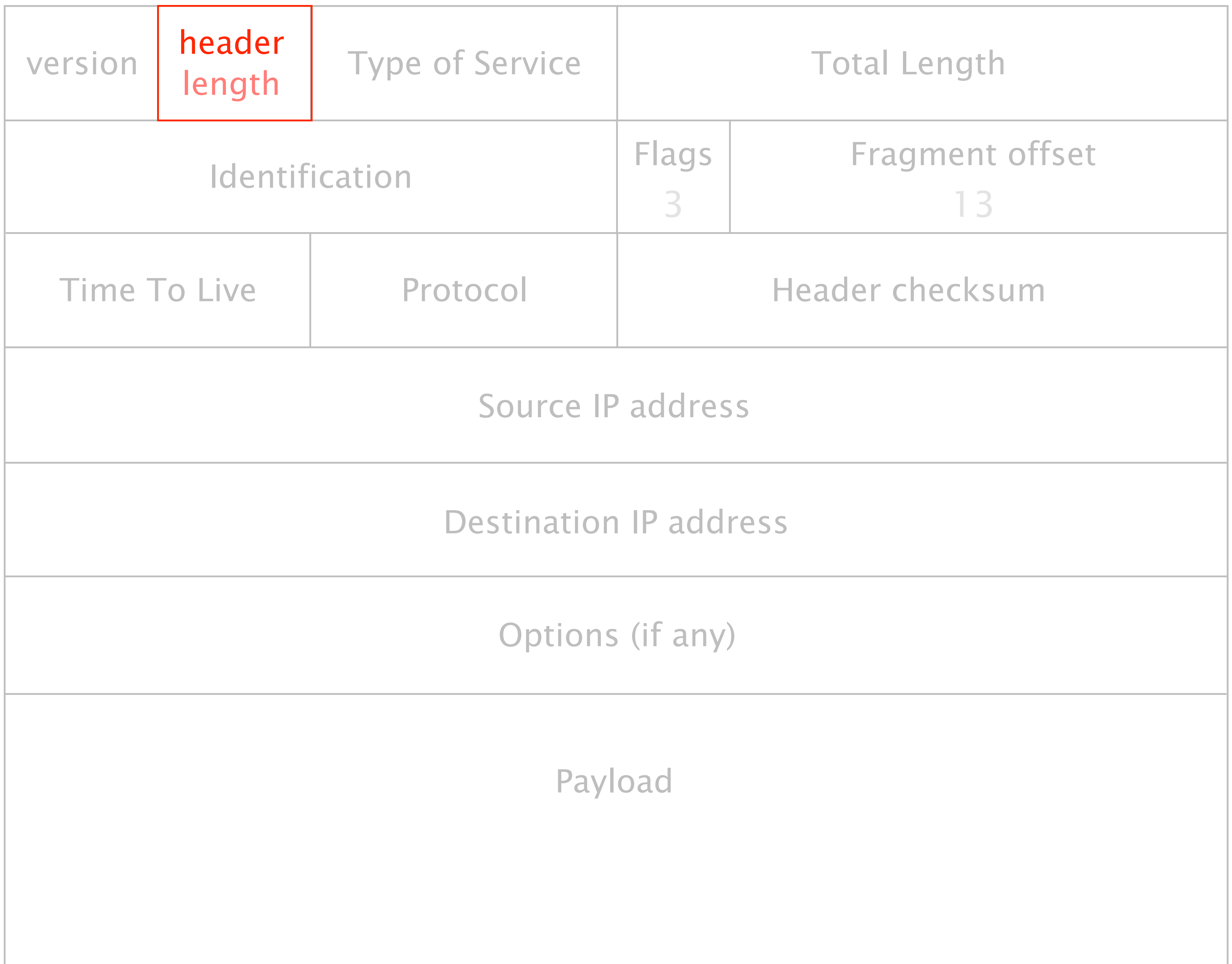


version
header length
Type of Service
Total Length
Identification
Flags 3
Fragment offset 13
Time To Live
Protocol
Header checksum
Source IP address
Destination IP address
Options (if any)
Payload

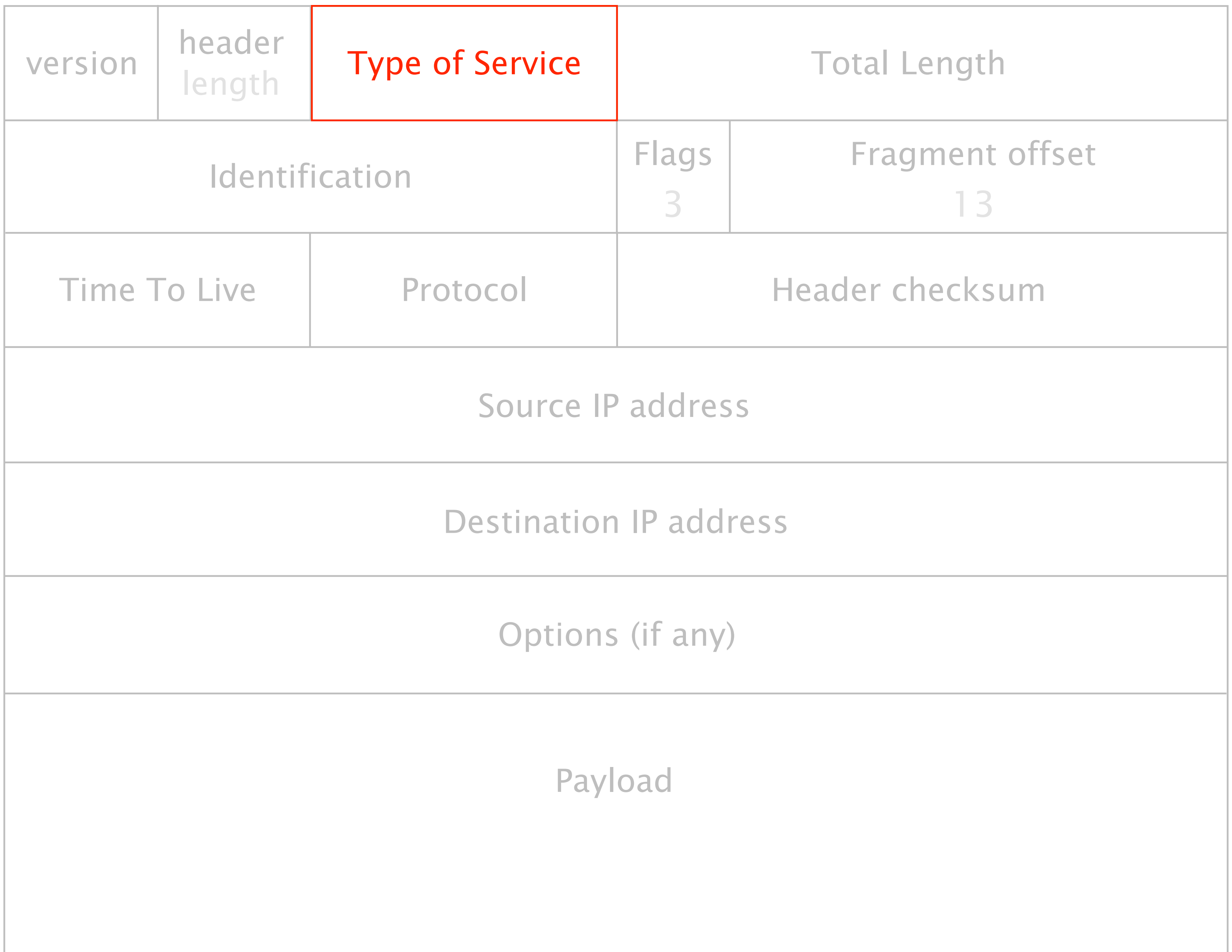
The version number tells us what other fields to expect, typically it is set to “4” for IPv4, or “6” for IPv6



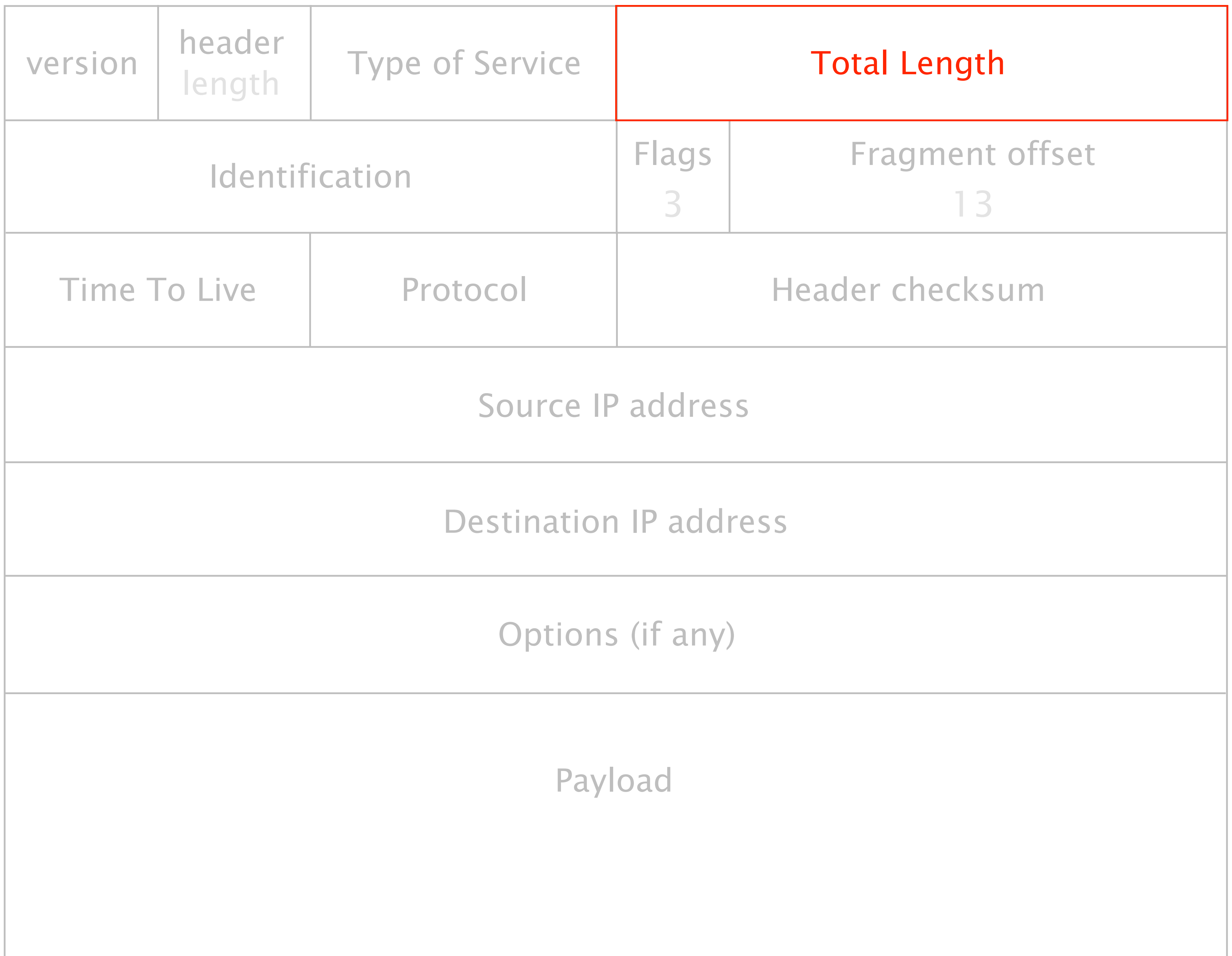
The header length denotes the number of 32-bits word in the header, typically set to 5 (20 bytes header)



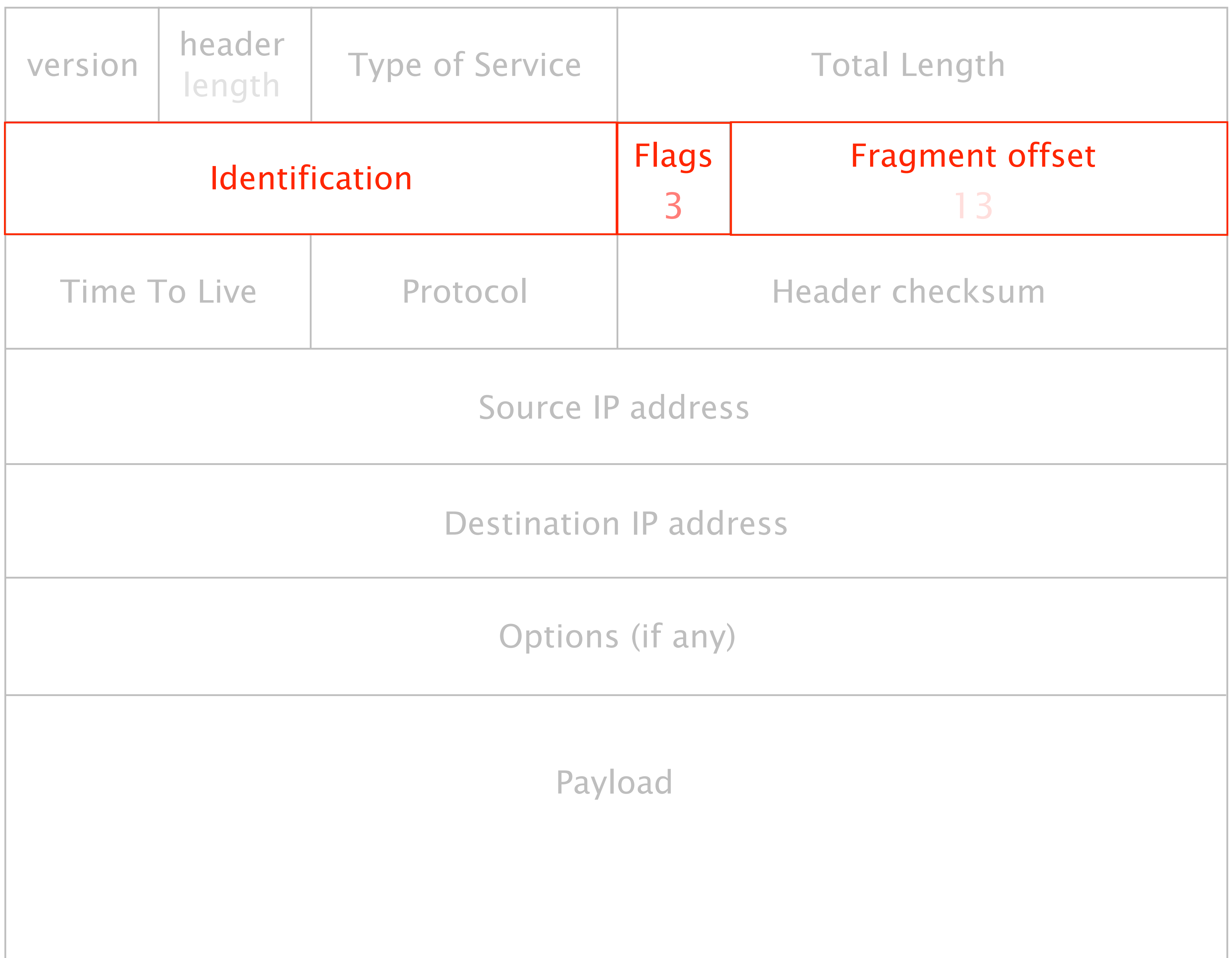
The ToS allows different packets to be treated differently, e.g., low delay for voice, high bandwidth for video



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

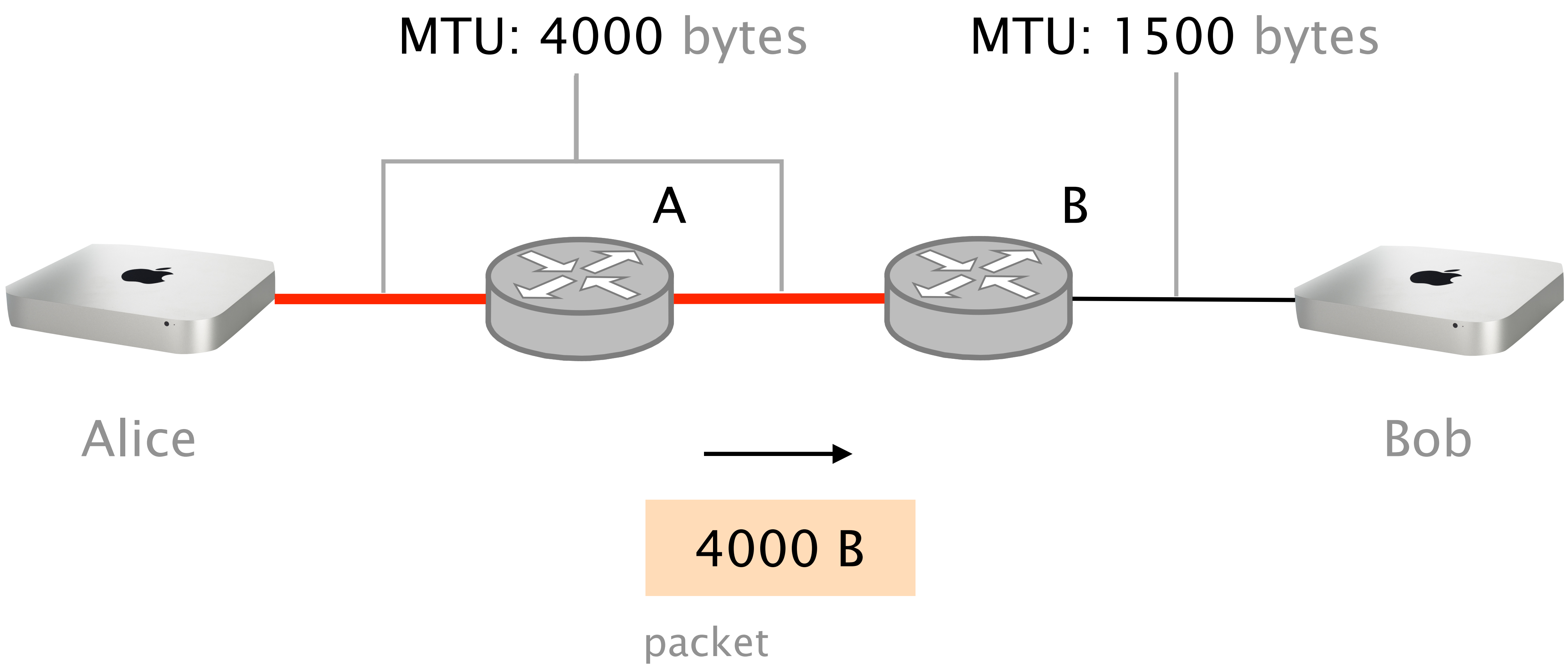
e.g., 1500 bytes for normal Ethernet

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

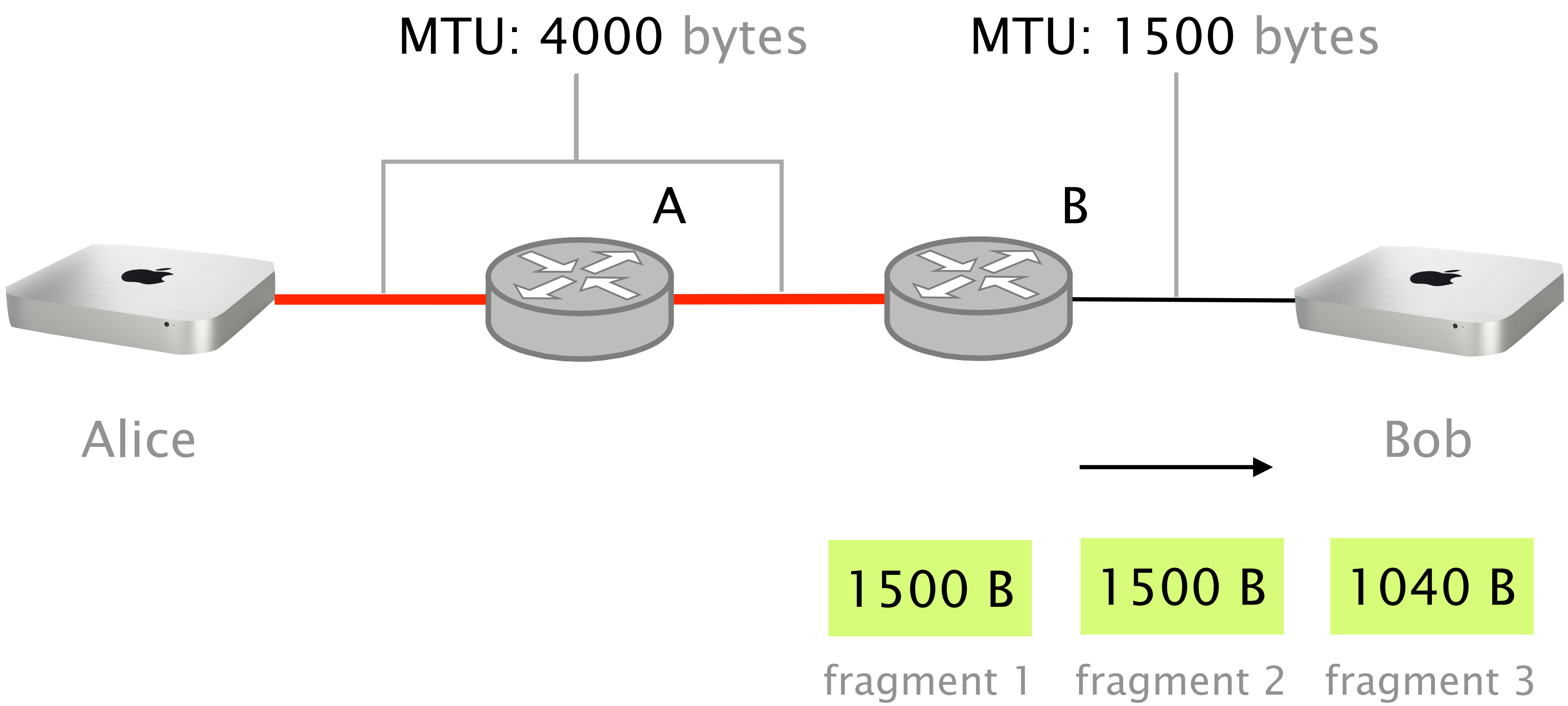
Fragmented packets are recomposed at the destination

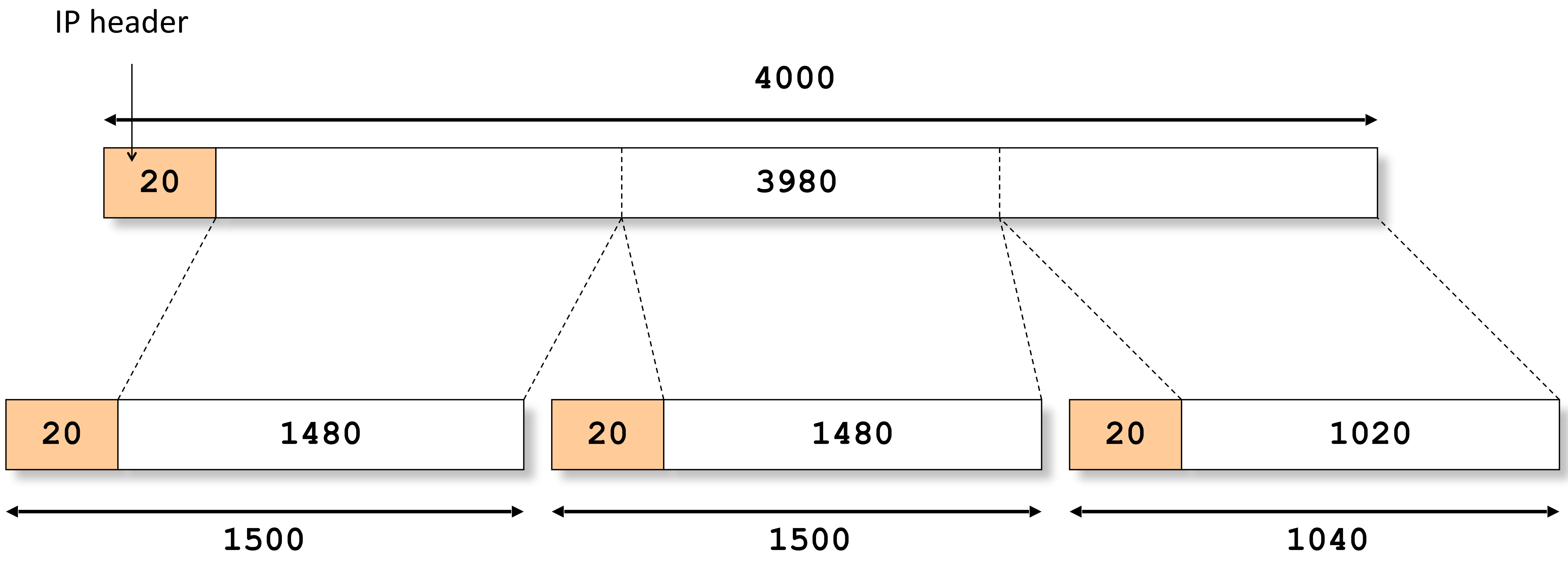
why not in the network?

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

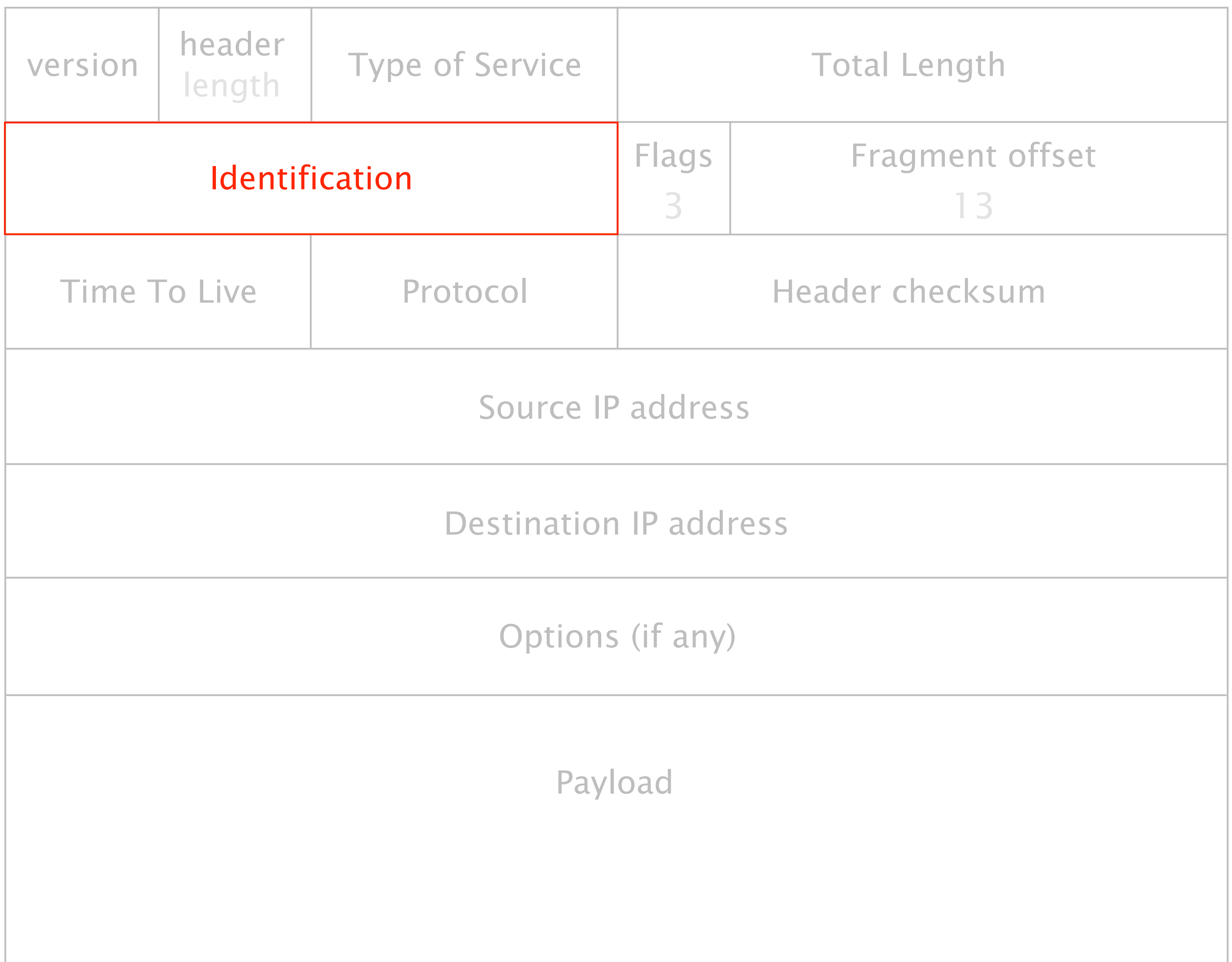


Because the packet is larger than the MTU, router B will split the packet into fragments

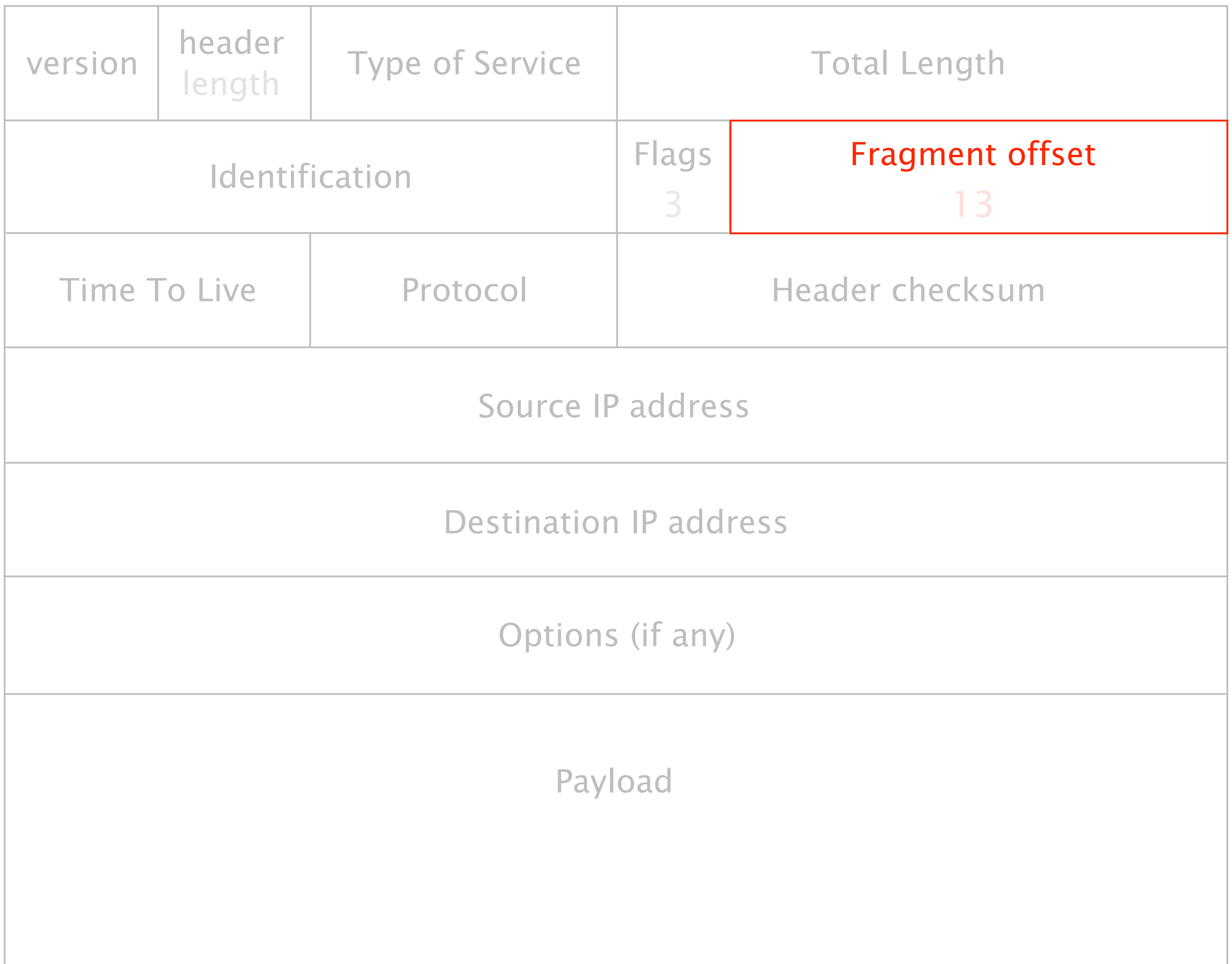



IP header
4000
20
3980
20
1480
20
1480
20
1020
1500
1500
1040

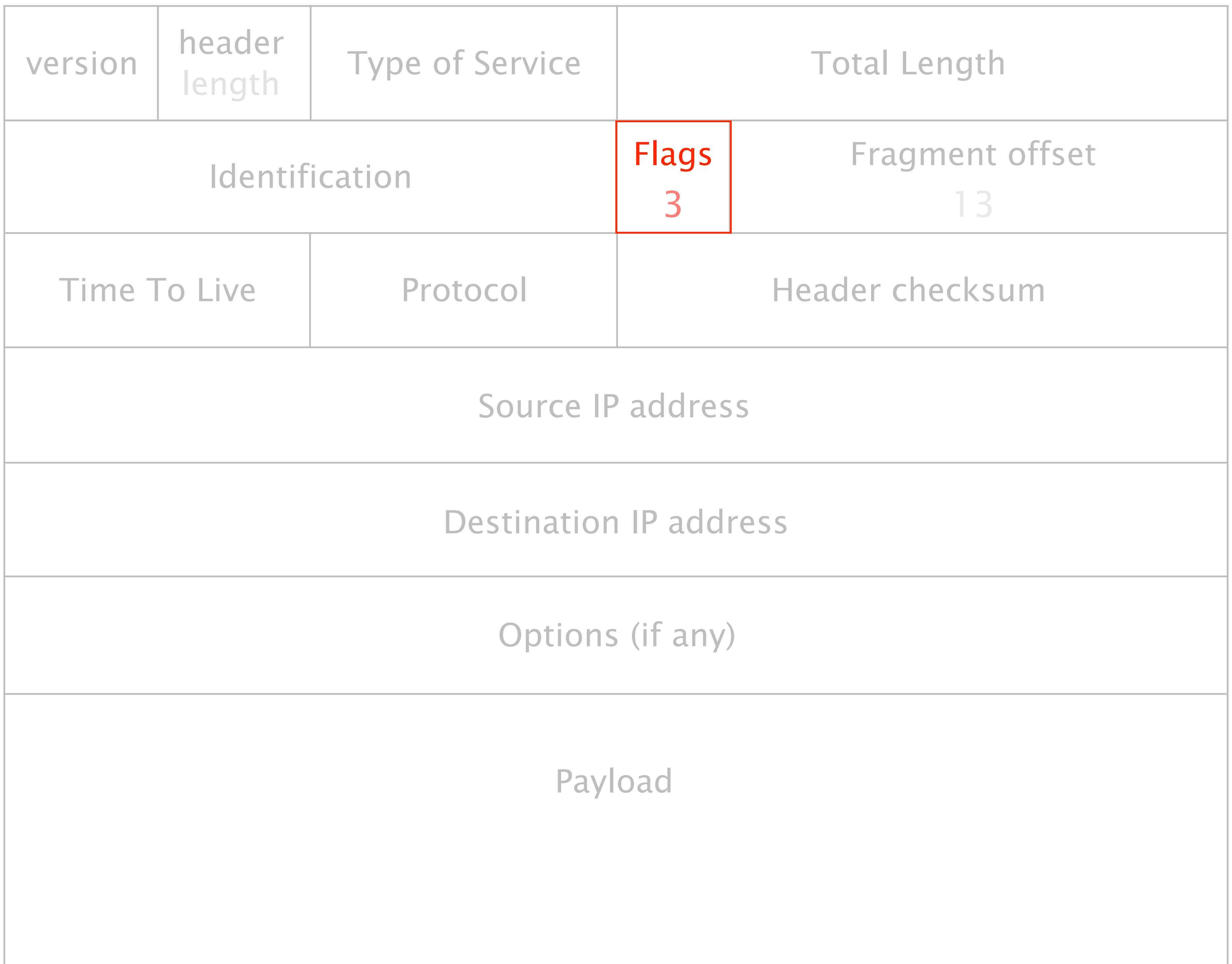
The Identification header uniquely identify the fragments of a particular packet



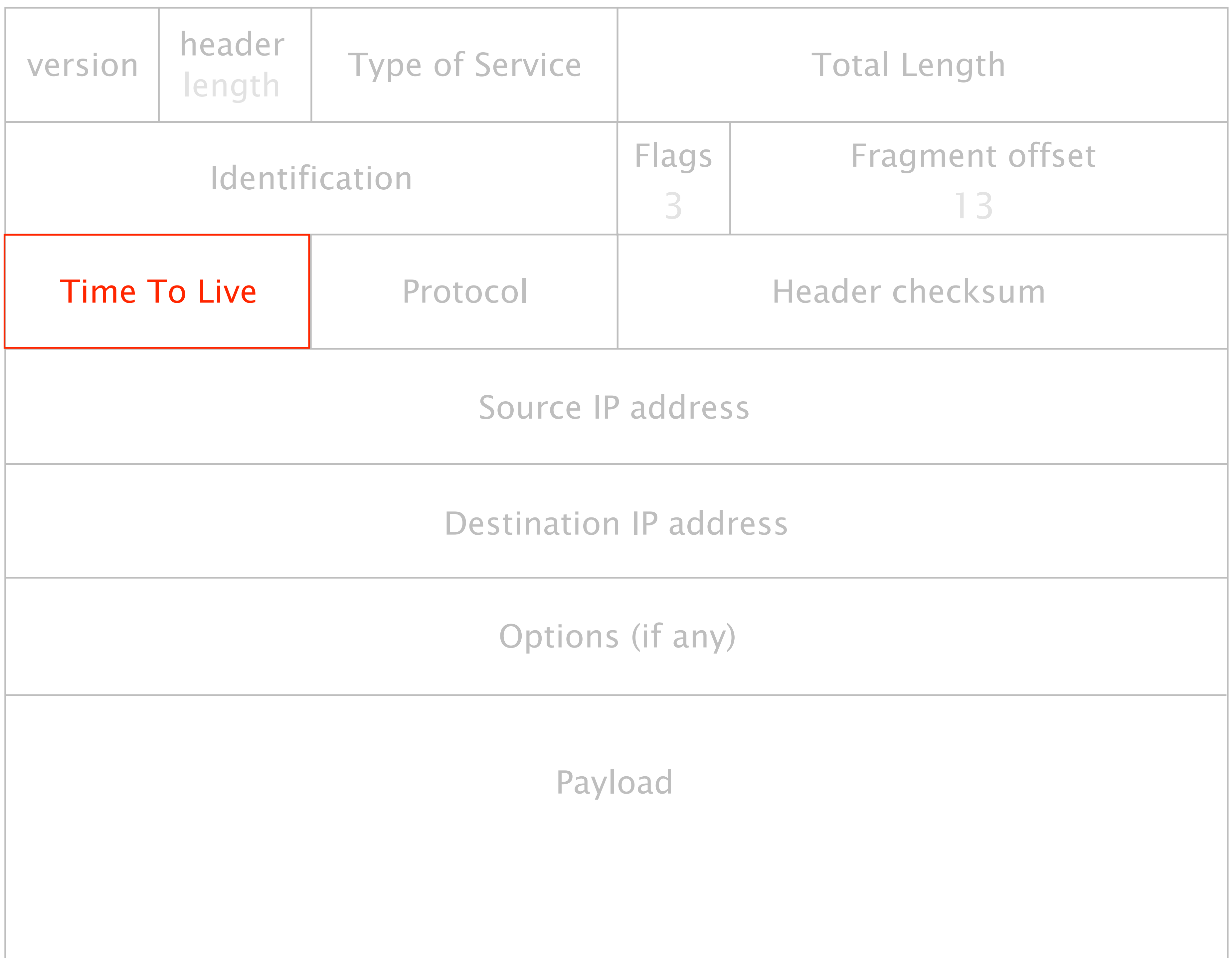
The fragment offset is used to put back the fragments in the right order in case of reordering



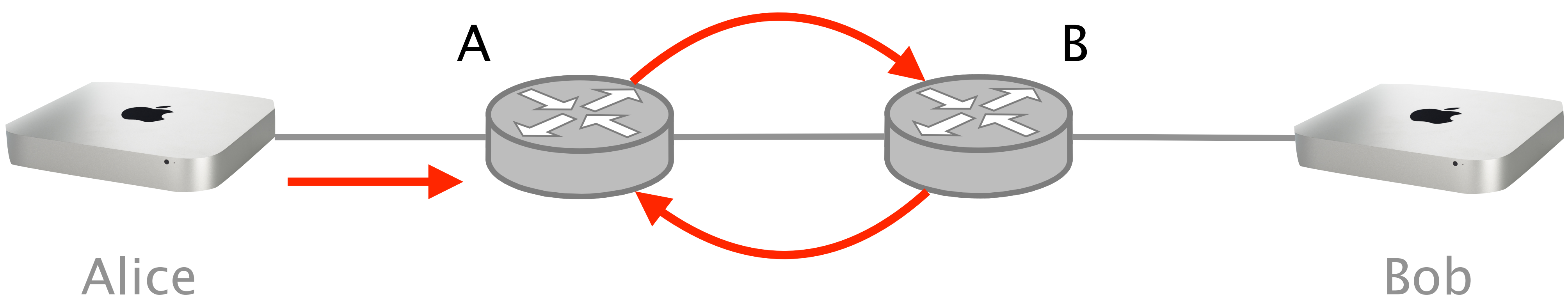
The flags is used to tell whether there are more fragments coming or not



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

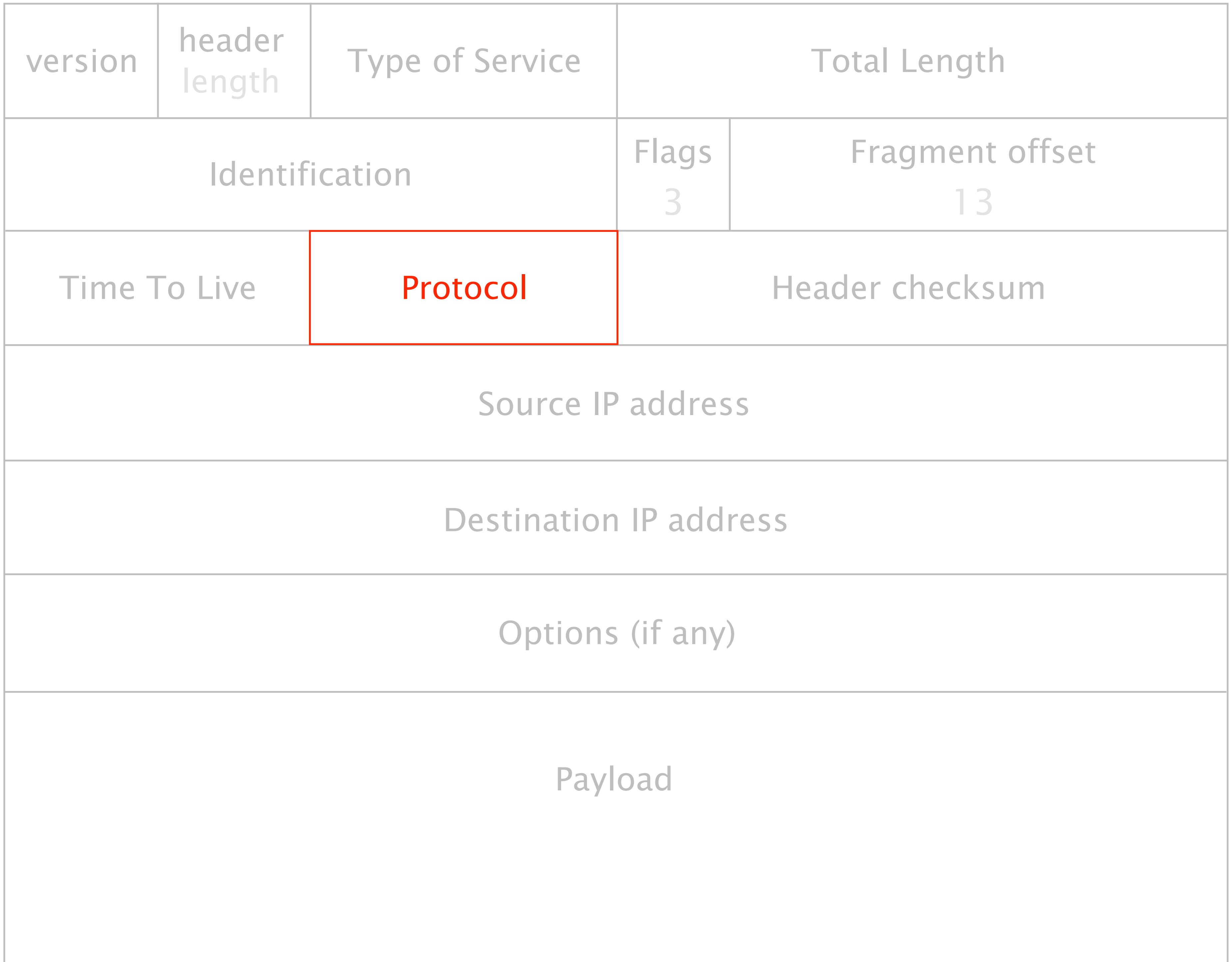


default TTL values

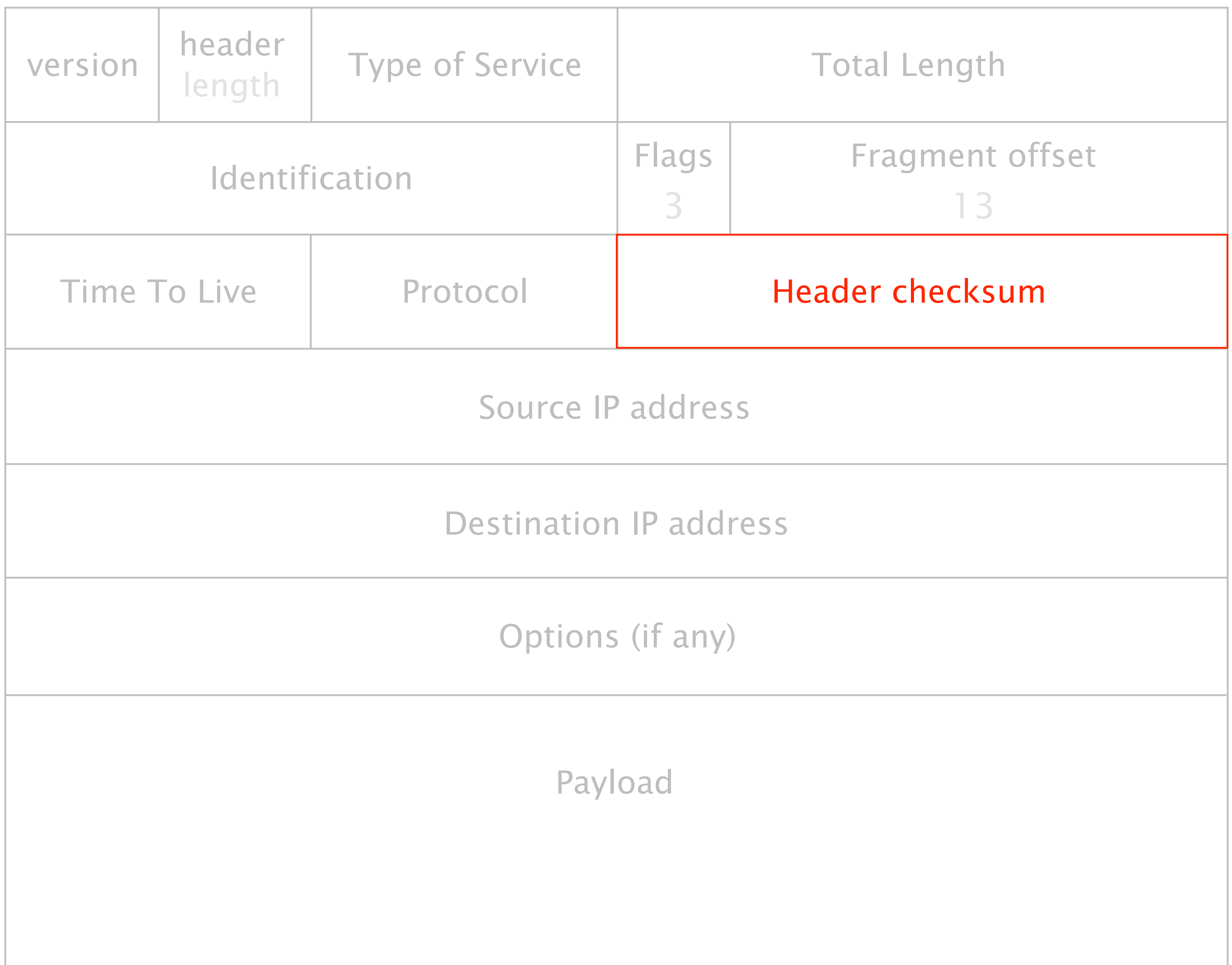
*nix (Linux/Mac)	64
Windows	128

(used for OS fingerprinting)

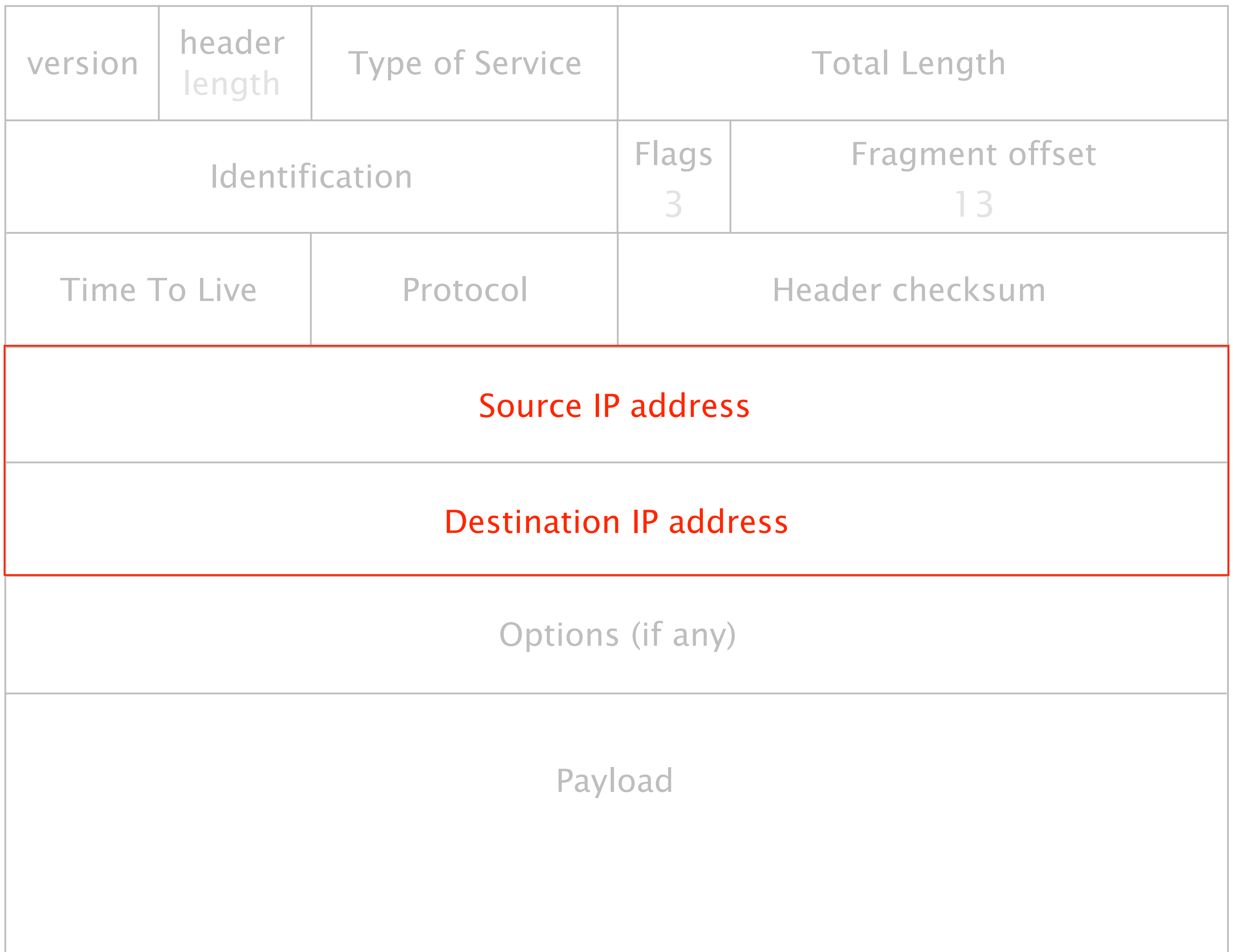
The protocol field identifies the higher level protocol carried in the packet, “6” for TCP, “17” for UDP



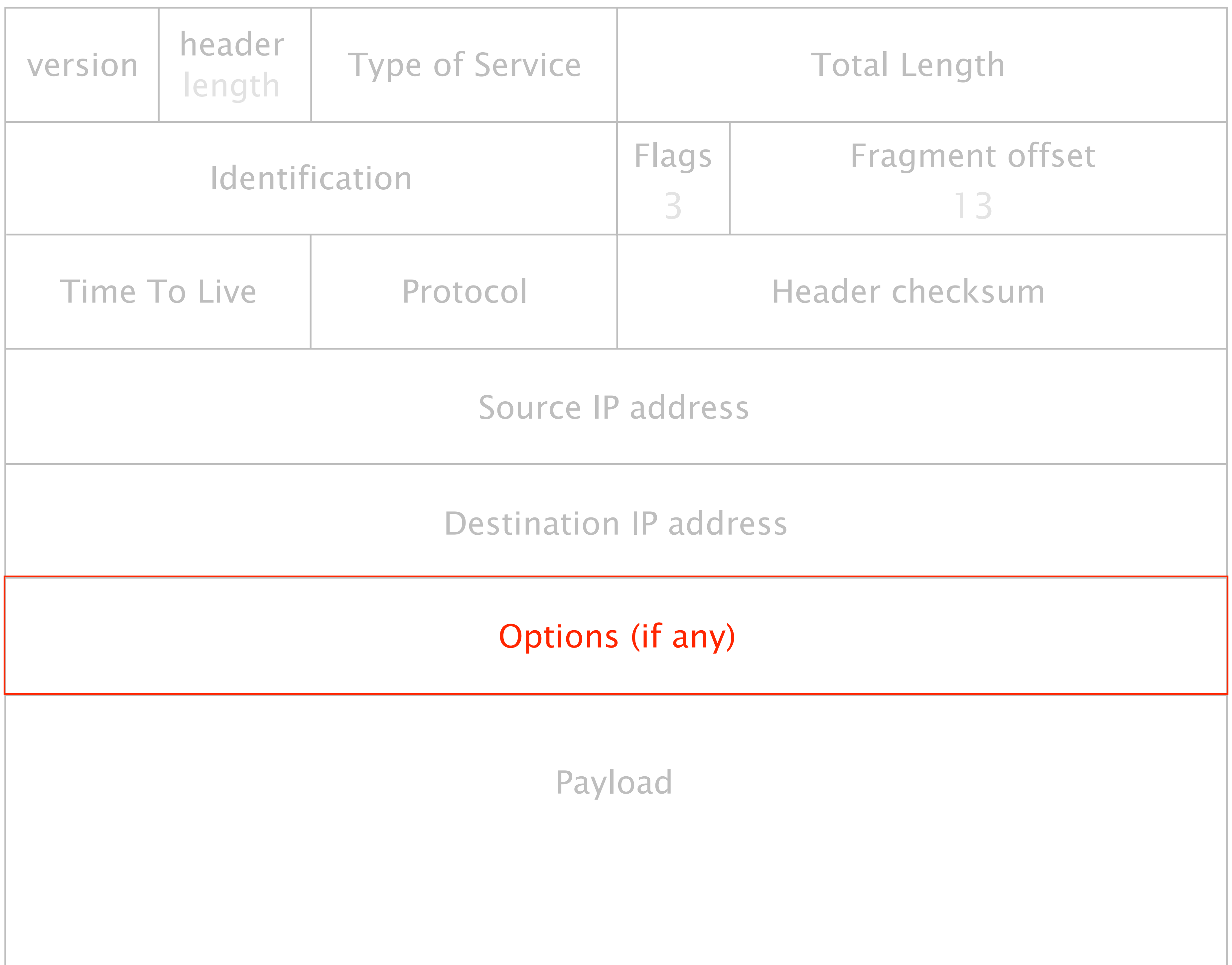
The checksum is the sum of all the 16 bits words in the header (does not protect the payload)



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 most of the Internet traffic (for now)

IPv6 addresses are unique 128-bits number associated to a network interface (on a host, a router, ...)

Notation	8 groups of 16 bits each separated by colons (:)
	Each group is written as four hexadecimal digits
Simplification	Leading zeros in any group are removed
	One section of zeros is replaced by a double colon (::)
	Normally the longest section

Examples

1080:0:0:0:8:800:200C:417A → 1080::8:800:200C:417A

FF01:0:0:0:0:0:0:0101 → FF01::101

0:0:0:0:0:0:0:1 → ::1

IPv6 is simpler than IPv4

IPv6 was motivated by address exhaustion

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

IPv6 got rid of anything that wasn't necessary

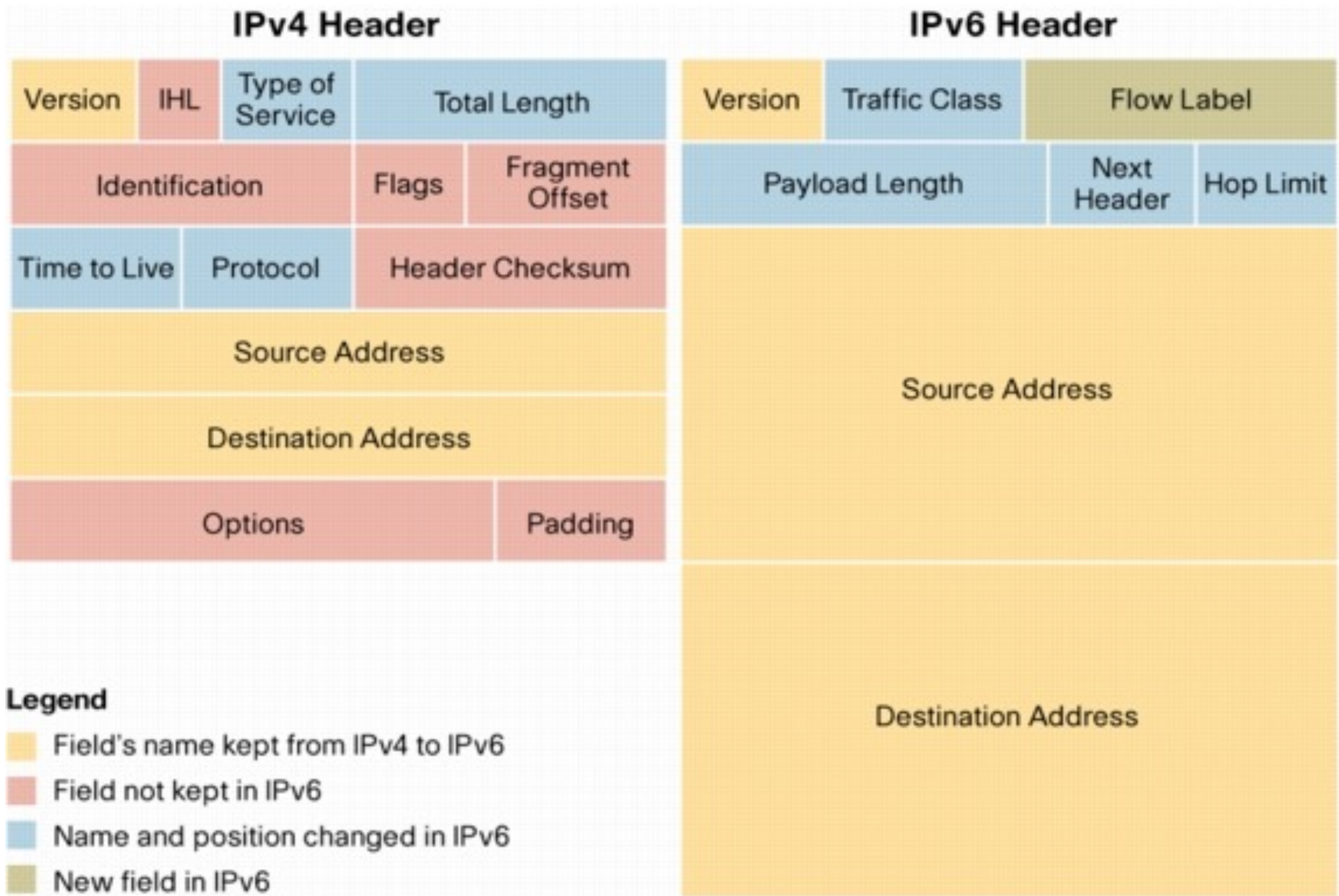
spring cleaning

Result is an elegant, if unambitious, protocol

IPv6 is simpler than IPv4

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

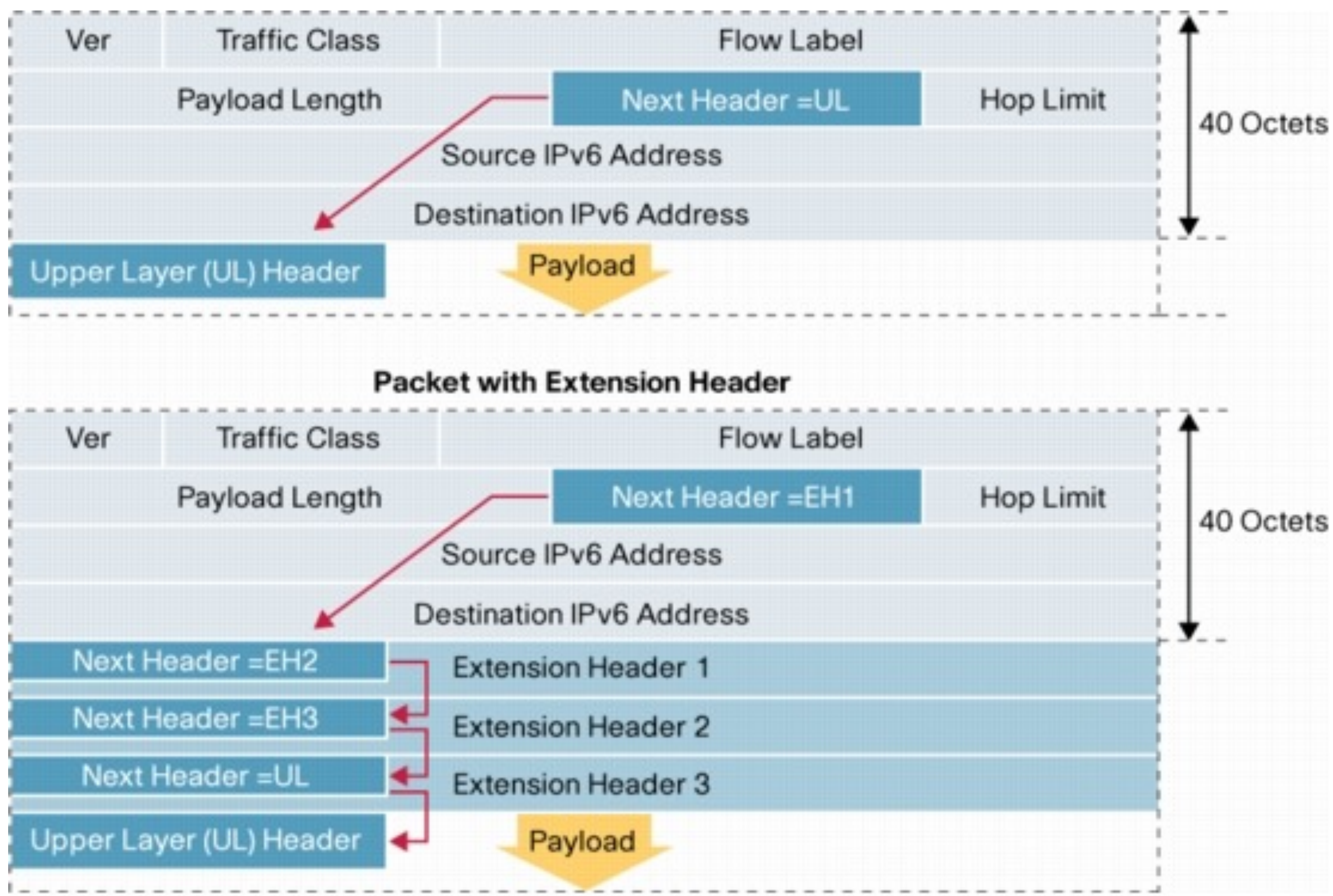
IPv4 vs IPv6



source http://bit.ly/1HXc2BS

IPv6 enables to insert arbitrary options in the packet

see RFC 2460



source http://bit.ly/1HXc2BS

One 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

There are three types of IPv6 addresses: unicast, anycast, and multicast

Unicast	Identifies a single interface Packets are delivered to this specific interface
Anycast	Identifies a set of interfaces Packets are delivered to the "nearest" interface
Multicast	Identifies a set of interfaces Packets are delivered to **all** interfaces

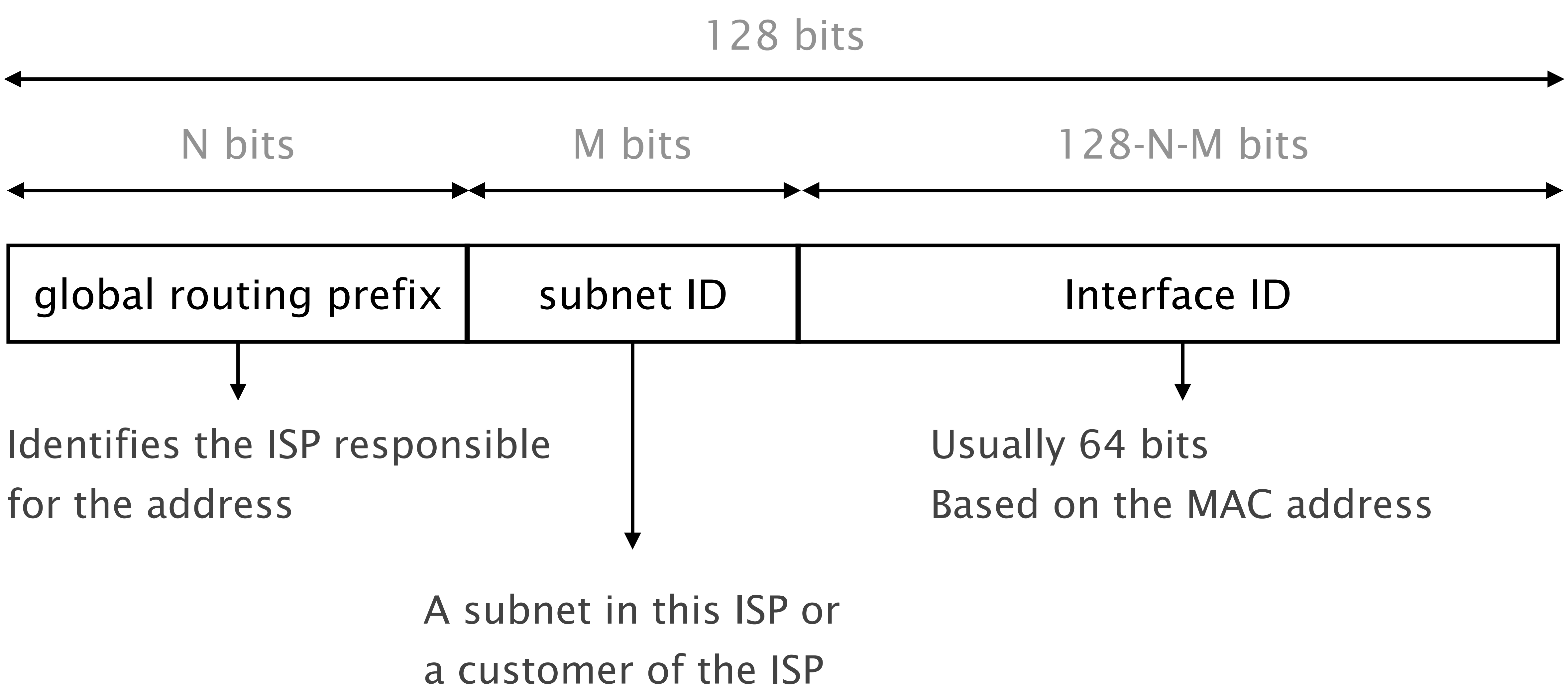
Unicast

Identifies a single interface

Packets are delivered to this specific interface

Global unicast addresses
are hierarchically allocated

similar to global IPv4 addresses



Allocation of IPv6 (global unicast) addresses

Internet Assigned Numbers Authority

The Internet Assigned Numbers Authority (IANA)
assigns blocks to Regional IP address Registries (RIR)

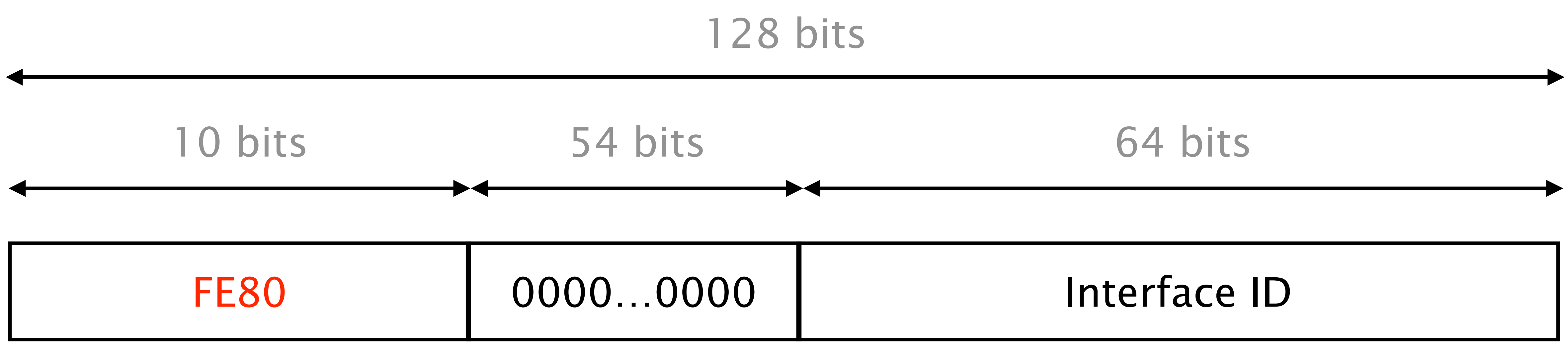
For example RIPE, ARIN, APNIC, …

Currently, only 2000::/3 is used for global unicast

All addresses are in the range of 2000 to 3FFF

Link-local addresses are unique to a single link (subnet)

same as private IPv4 addresses



Each host/router **must** generate a link-local address for **each** of its interfaces

An interface therefore can have multiple IPv6 addresses

Thus far IPv4 has been very persistent, and that's quite understandable

Deploying IPv6 require every device to support it

All routers, middleboxes, end hosts, applications, …

Most of IPv6 new features were back-ported to IPv4

No obvious advantage in using IPv6

Network Address Translation is working well

The pain of address depletion is not obvious

Network Address Translation (NAT)

Sharing a single (public) address between hosts

Port numbers (transport layer) are used to distinguish

One of the main reasons why we can still use IPv4

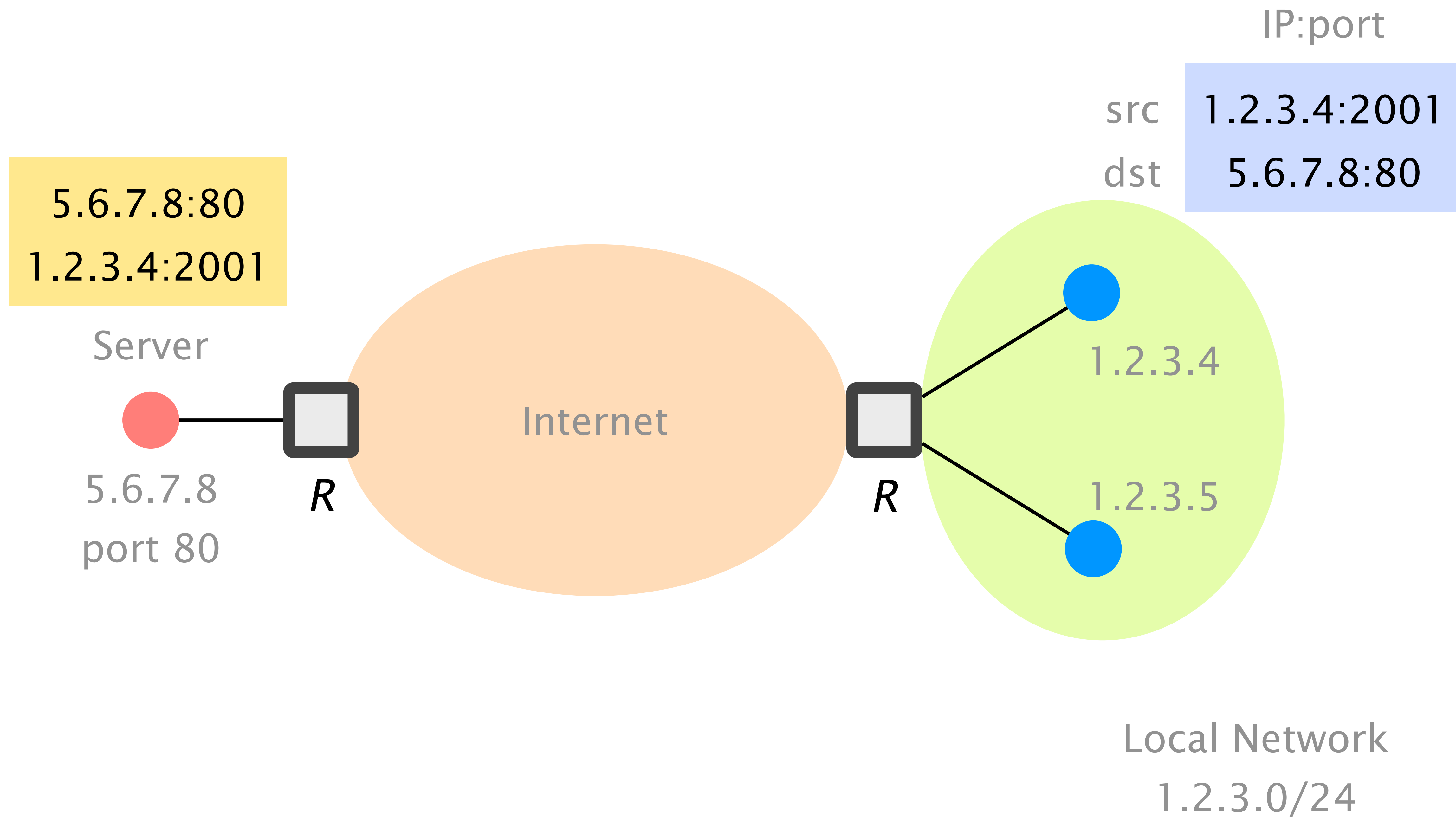
Saved us from address depletion

Violates the general end-to-end principle of the Internet

A NAT box adds a layer of indirection

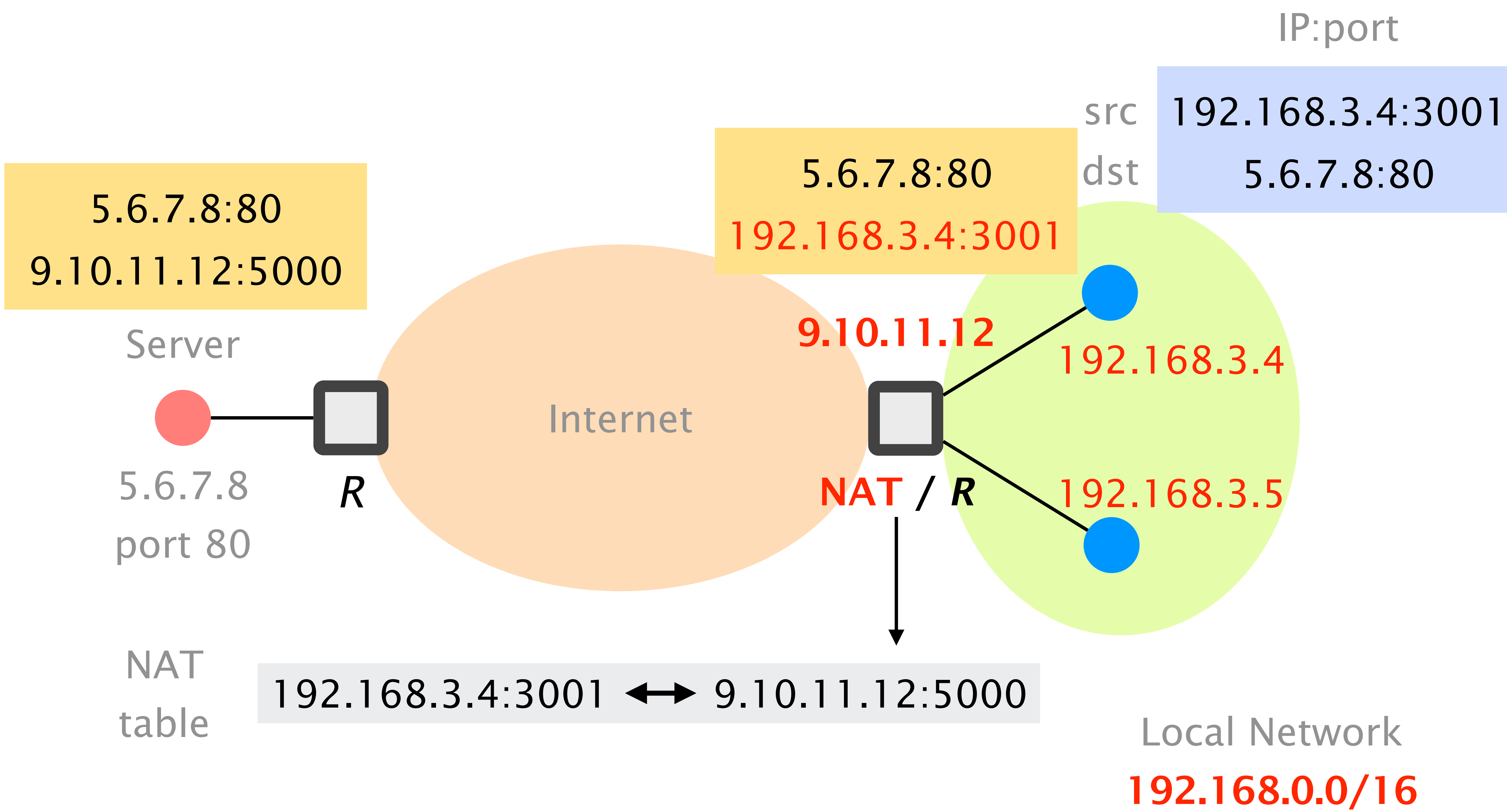
The Internet before NAT

Every machine connected to the Internet had a unique IP



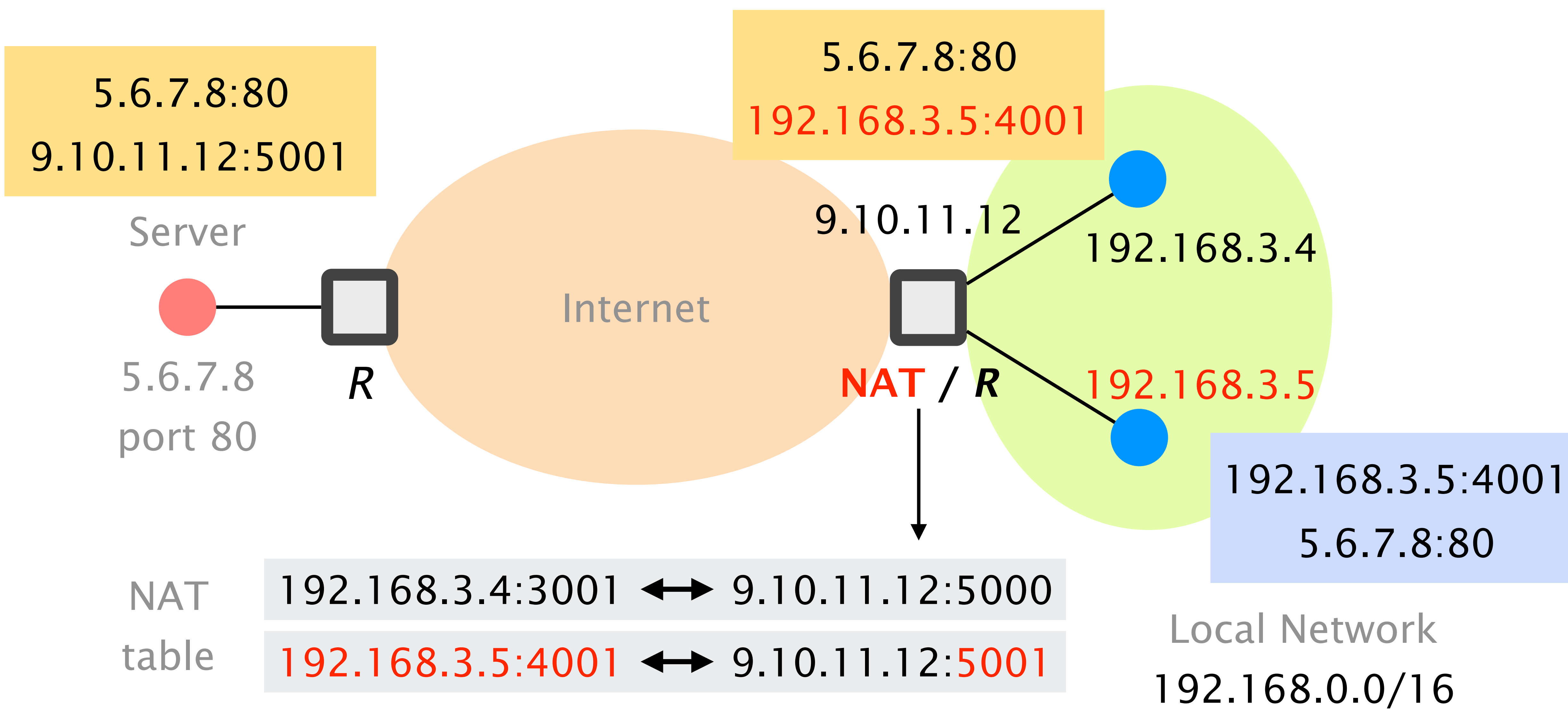
The Internet with NAT

Hosts behind NAT get a private address



The Internet with NAT

The port numbers are used to multiplex single addresses



NAT also provides other (dis-)advantages

Better privacy/anonymization

All hosts in one network get the same public IP

But, cookies, browser version, … still identify hosts

Better security

From the outside you cannot directly reach the hosts

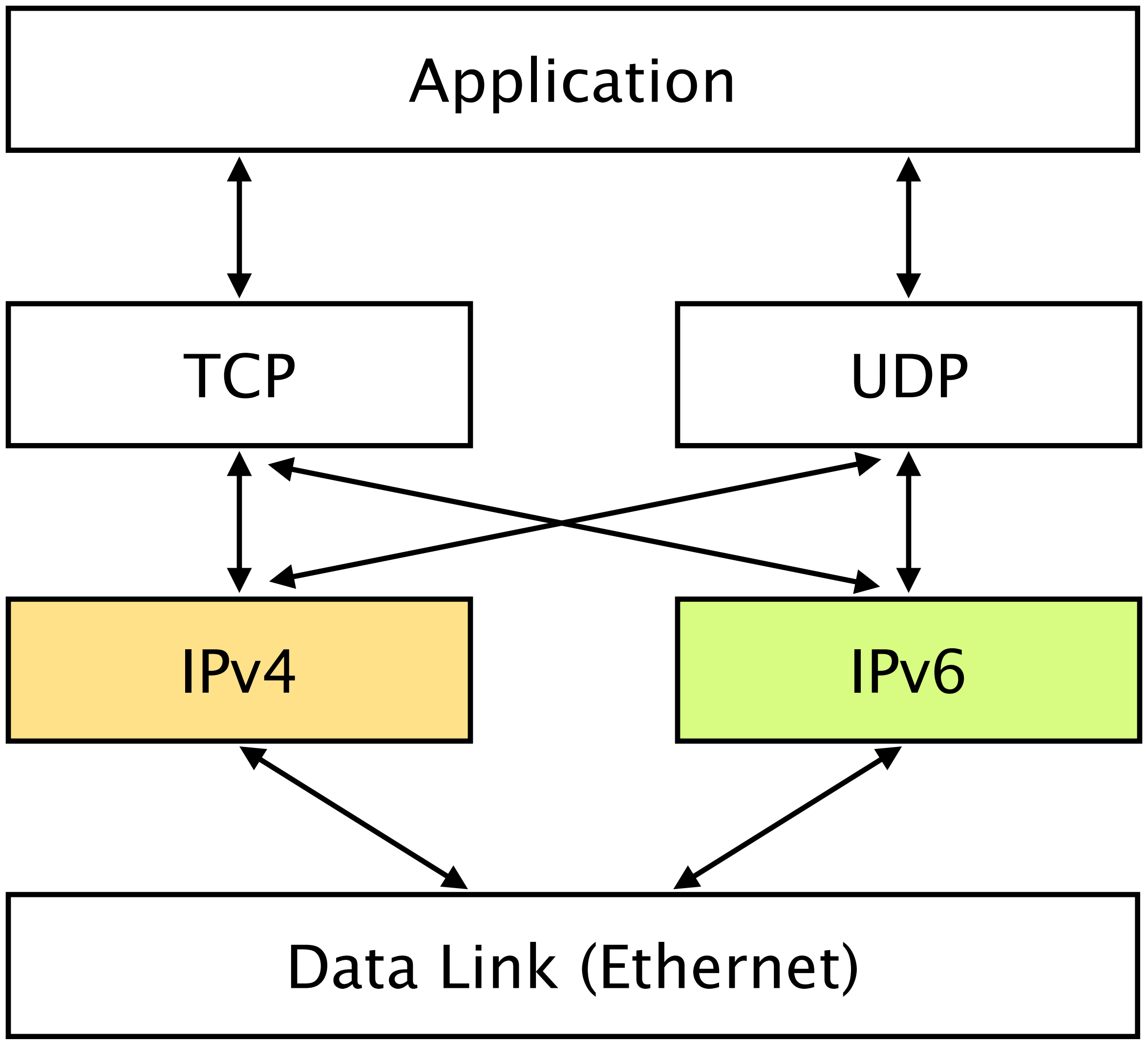
Problematic e.g., for online gaming

Limited scalability (size of the mapping table)

Example: Wi-Fi access problems in public places

(e.g., lecture hall) often due to a full NAT table

Today, a lot of applications and OSes use a dual stack approach



Over the years, a lot of

transition mechanisms were developed

6in4

6to4

Teredo

SIIT

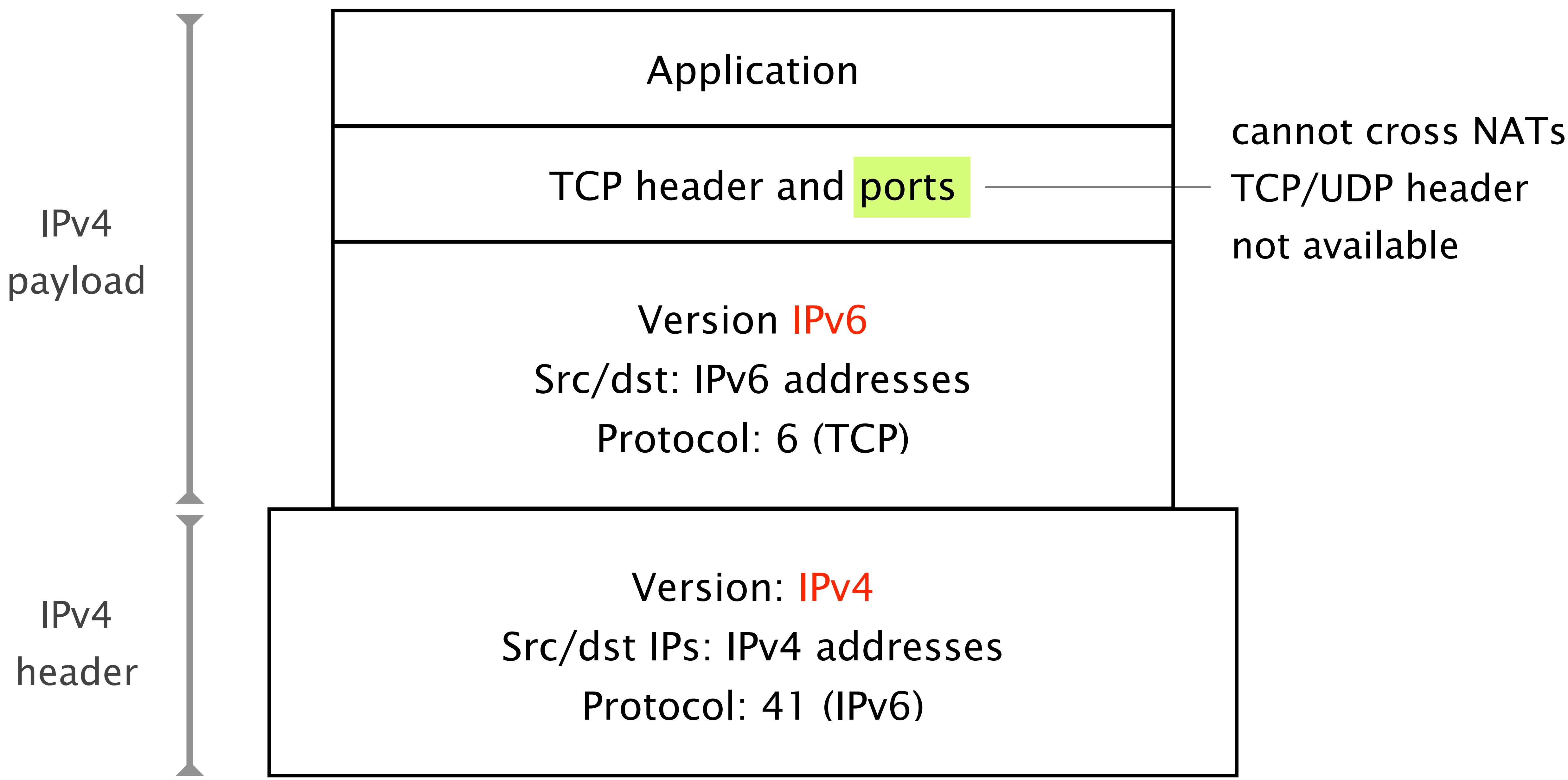
6rd

GRE

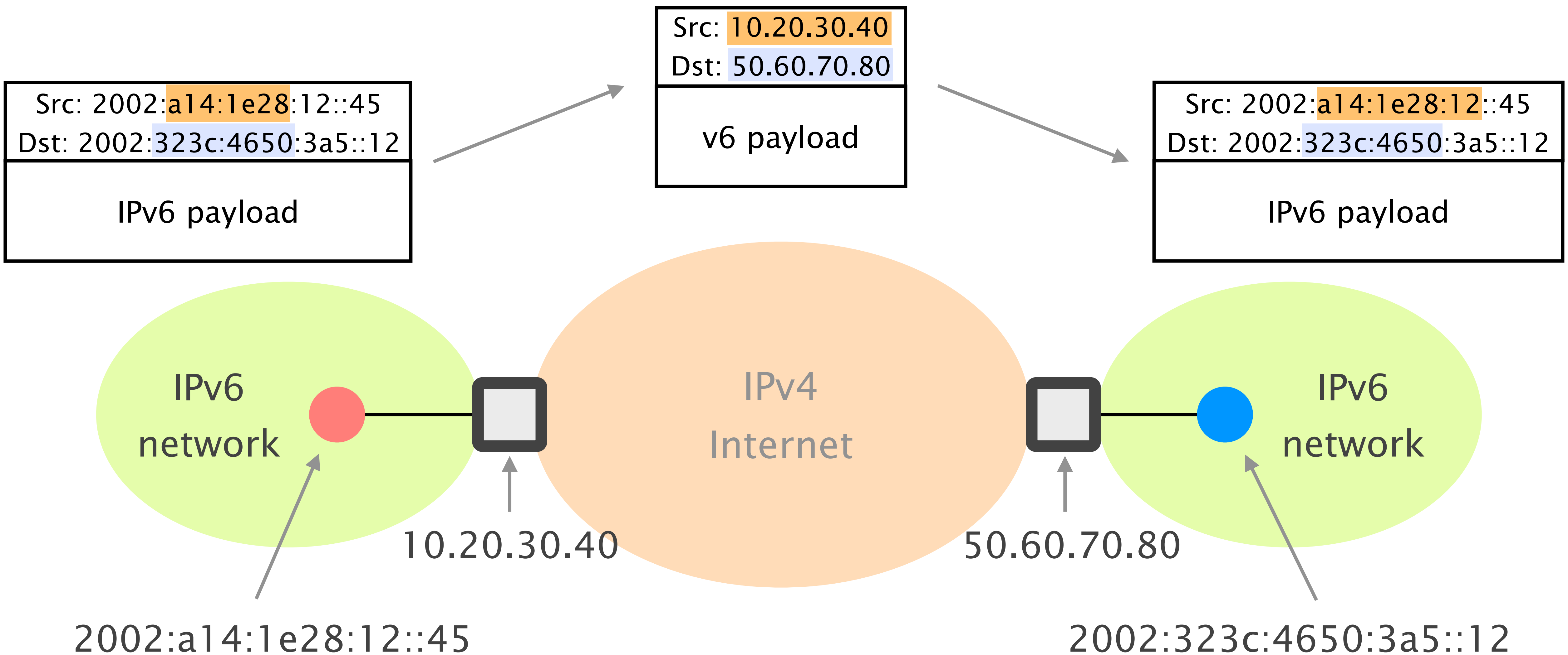
AYiYA

...

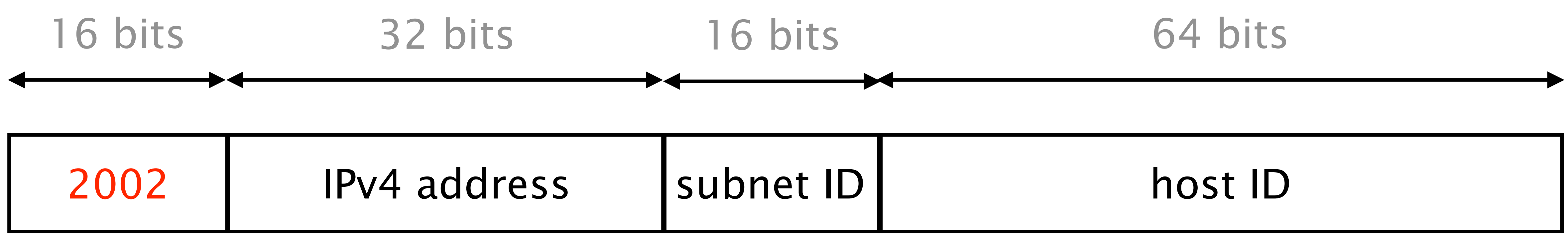
6in4 transmits IPv6 packets over statically-configured IPv4 tunnels



6to4 transmits IPv6 packets over IPv4 networks without explicit tunnels



6to4 uses special IPv6 addresses



IPv4: 192.15.3.73

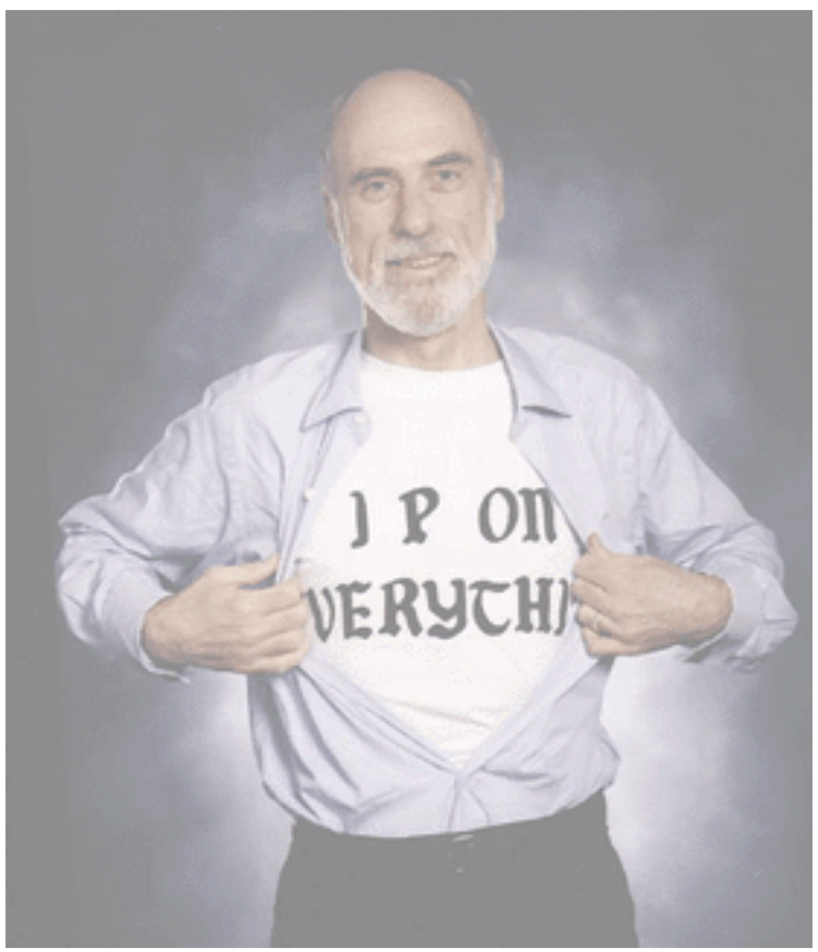
c0.0f.03.49

6to4: 2002:c00f:0349::/48

IPv6 @ home (Swisscom Internet access box)

You will be assigned an IPv4 and IPv6 address

Internet Protocol and Forwarding



IP addresses

use, structure, allocation

IP forwarding

longest prefix match rule

IP header

IPv4 and IPv6, wire format

Communication Networks

Spring 2022

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