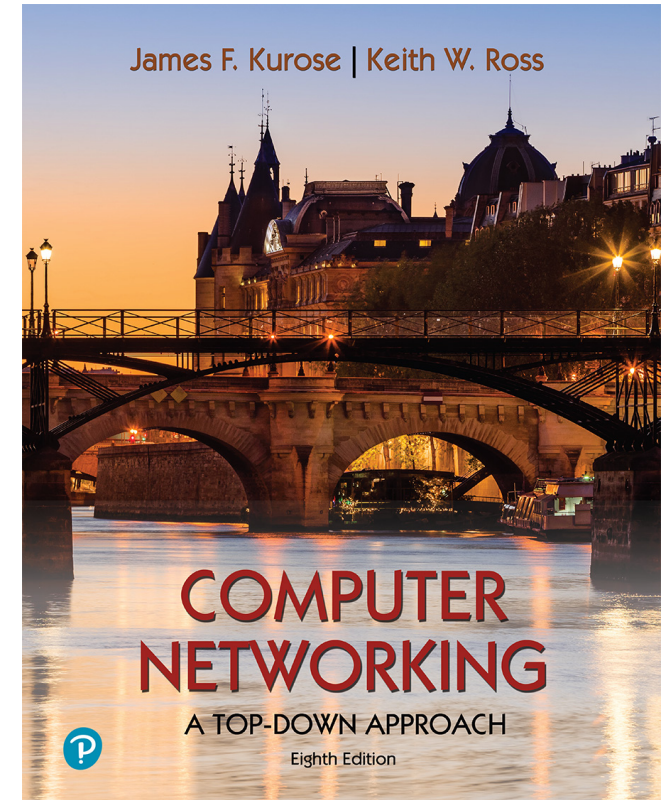


# Chapter 4

## Network Layer: Data Plane



### *Computer Networking: A Top-Down Approach*

8<sup>th</sup> edition

Jim Kurose, Keith Ross  
Pearson, 2020

Acknowledgement: Based on the textbook's website:  
[https://gaia.cs.umass.edu/kurose\\_ross/index.php](https://gaia.cs.umass.edu/kurose_ross/index.php)

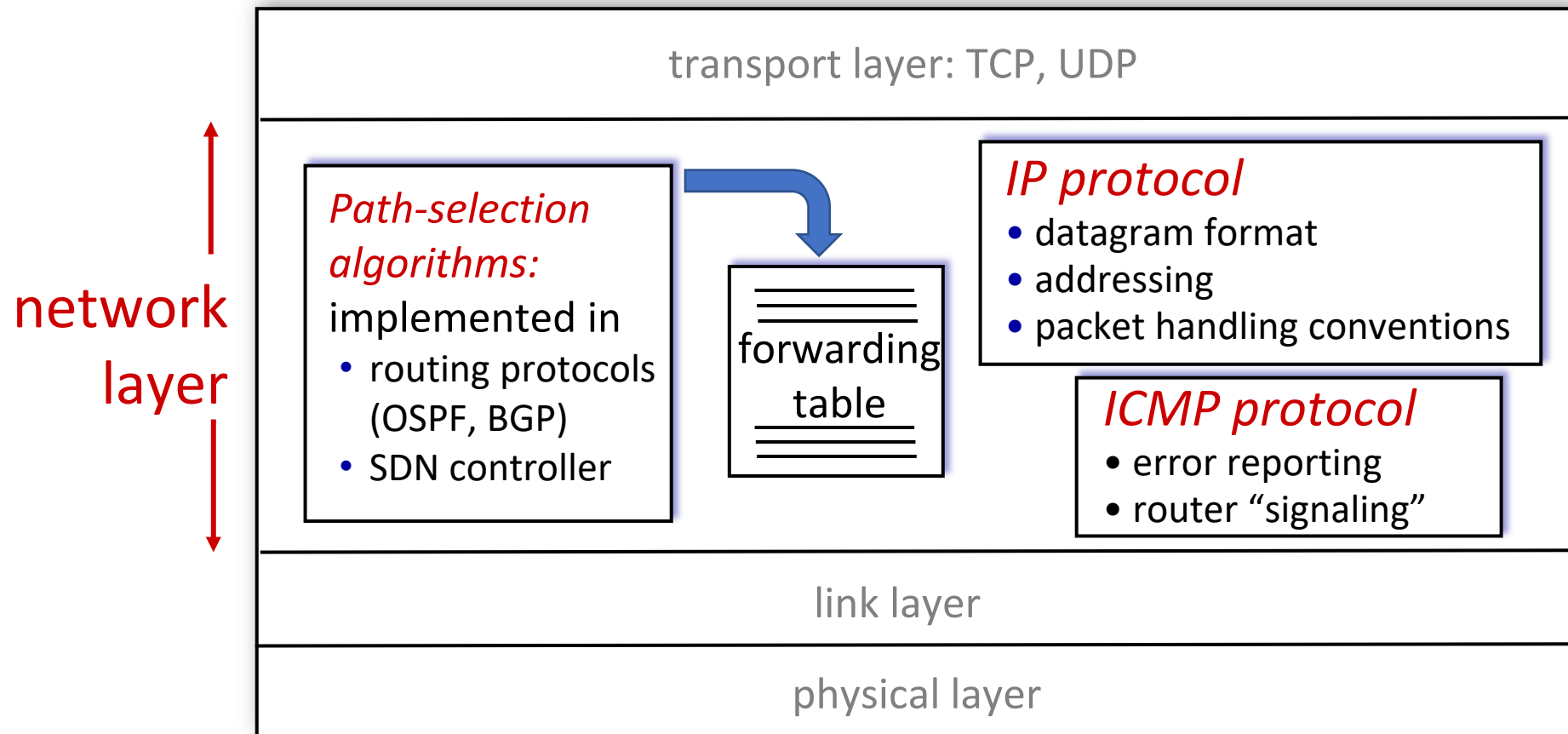
# Network layer: “data plane” roadmap

- Network layer: overview
  - data plane
  - control plane
- What’s inside a router
  - input ports, switching, output ports
  - buffer management, scheduling
- IP: the Internet Protocol
  - datagram format
  - addressing
  - network address translation
  - IPv6
- Generalized Forwarding, SDN
  - match+action
  - OpenFlow: match+action in action
- Middleboxes

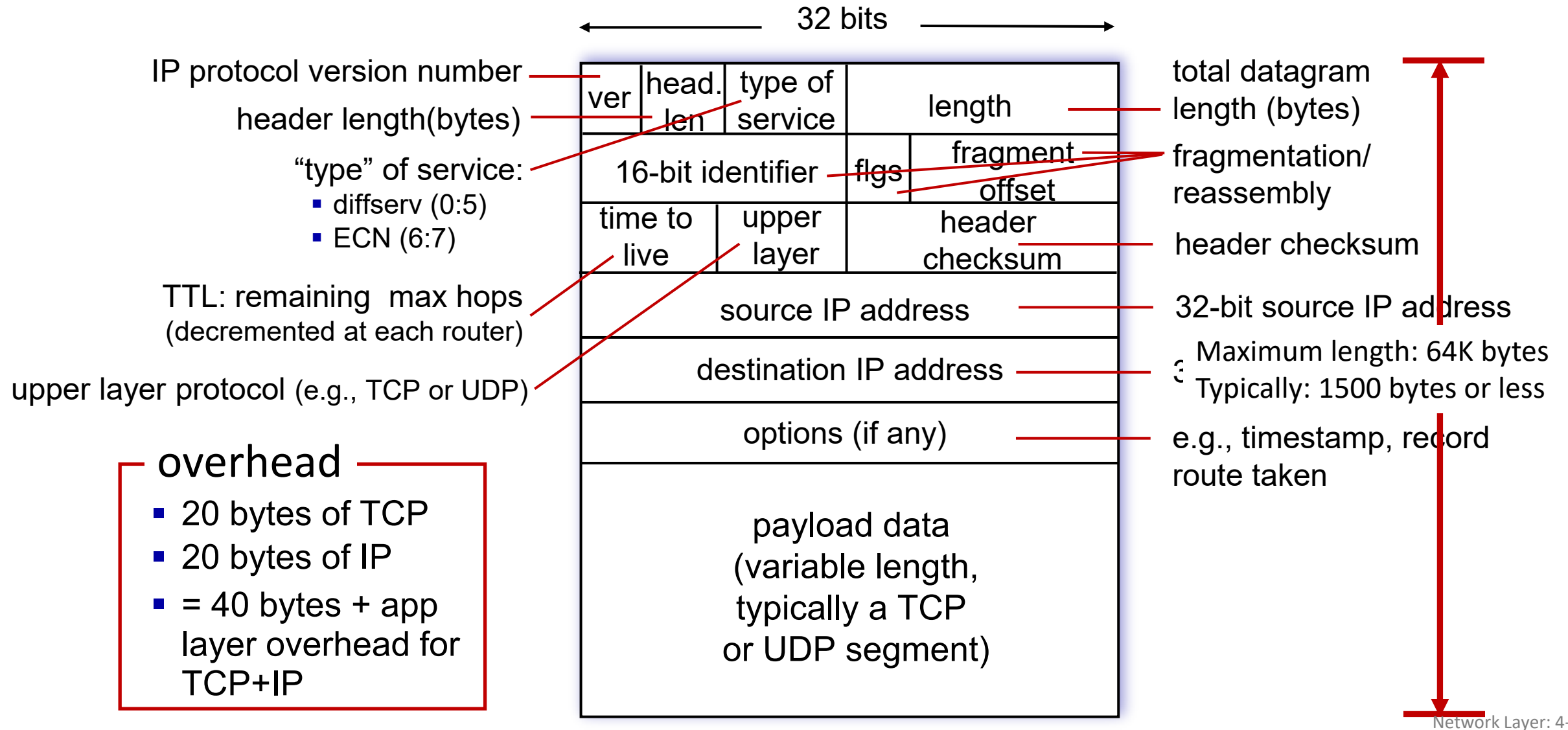


# Network Layer: Internet

host, router network layer functions:

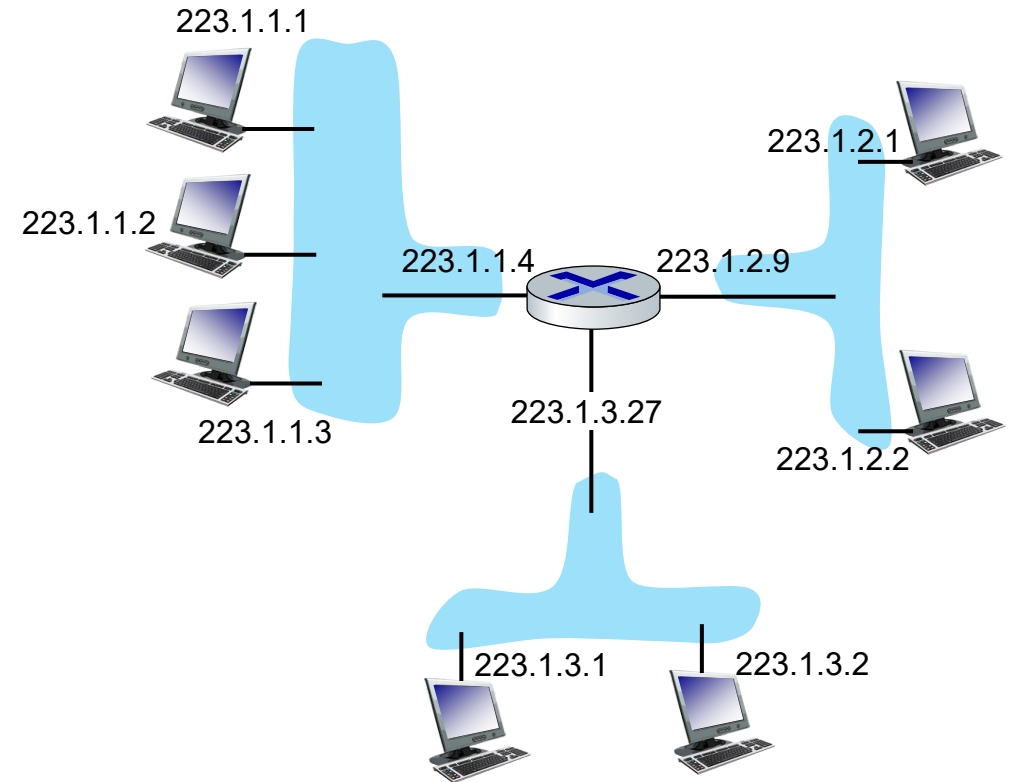


# IP Datagram format



# IP addressing: introduction

- **IP address:** 32-bit identifier associated with each host or router *interface*
- **interface:** connection between host/router and physical link
  - router's typically have multiple interfaces
  - host typically has one or two interfaces (e.g., wired Ethernet, wireless 802.11)



dotted-decimal IP address notation:

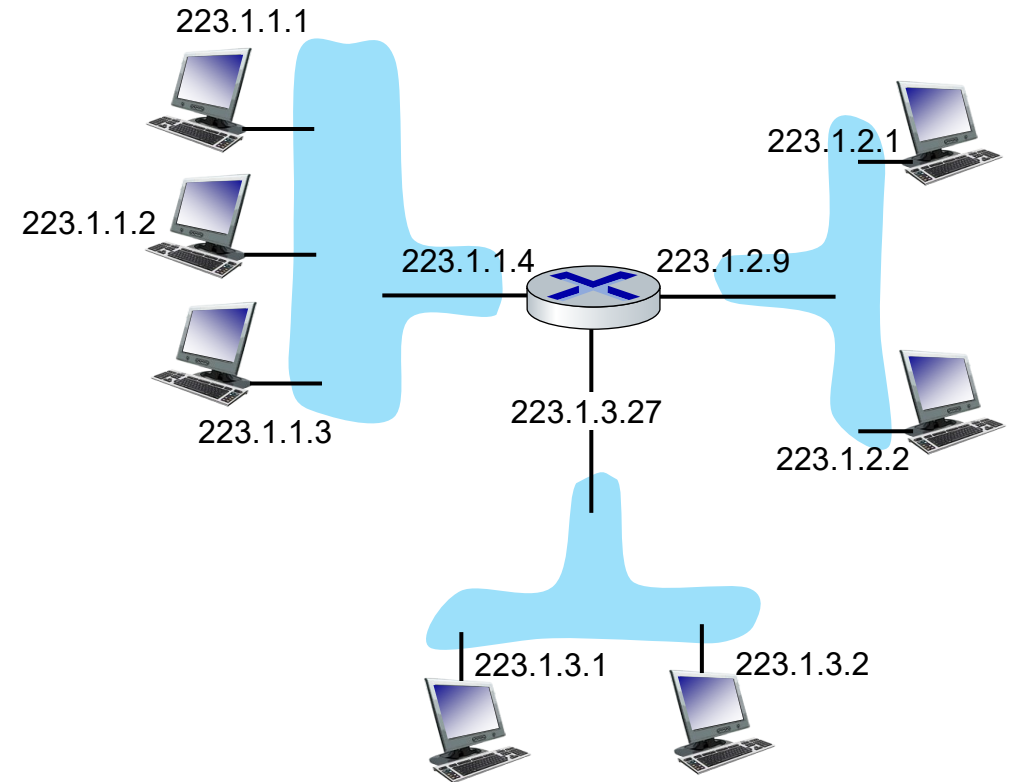
223.1.1.1 = 11011111 00000001 00000001 00000001

223                      1                      1                      1

Network Layer: 4-5

# IP addressing: introduction

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Network Layer: 4-6

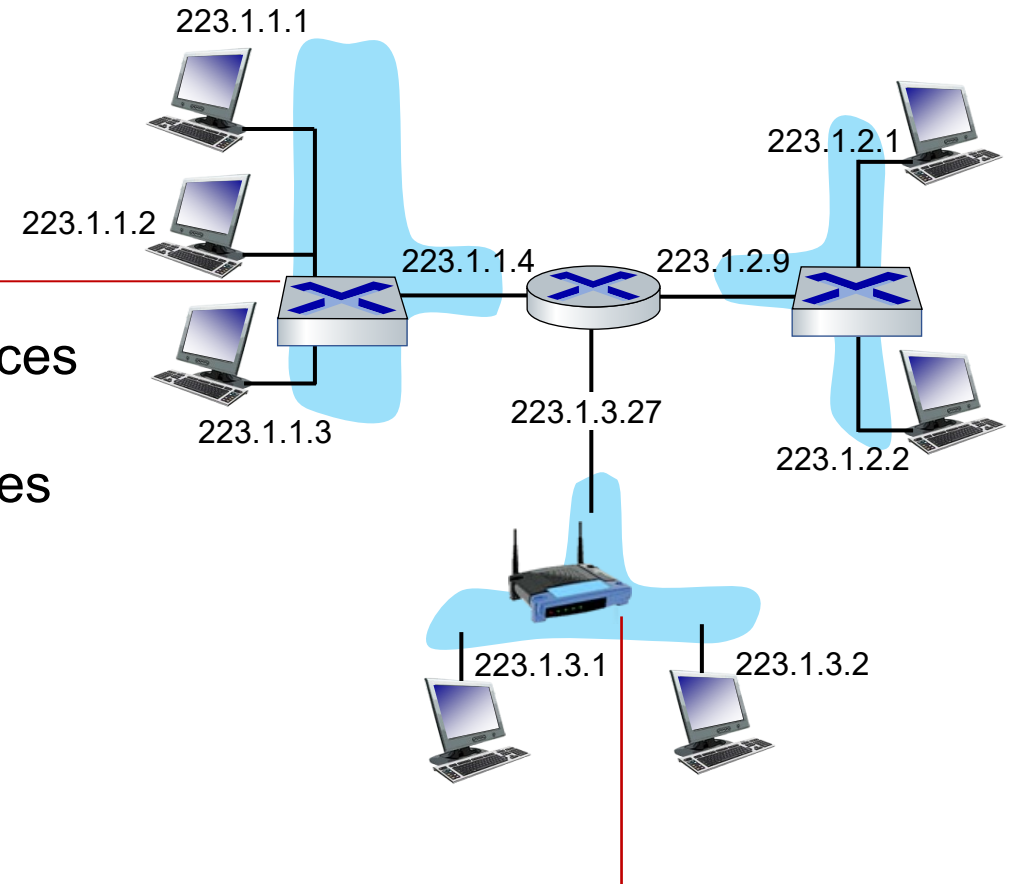
# IP addressing: introduction

**Q:** how are interfaces actually connected?

**A:** we'll learn about that in chapters 6, 7

*For now:* don't need to worry about how one interface is connected to another (with no intervening router)

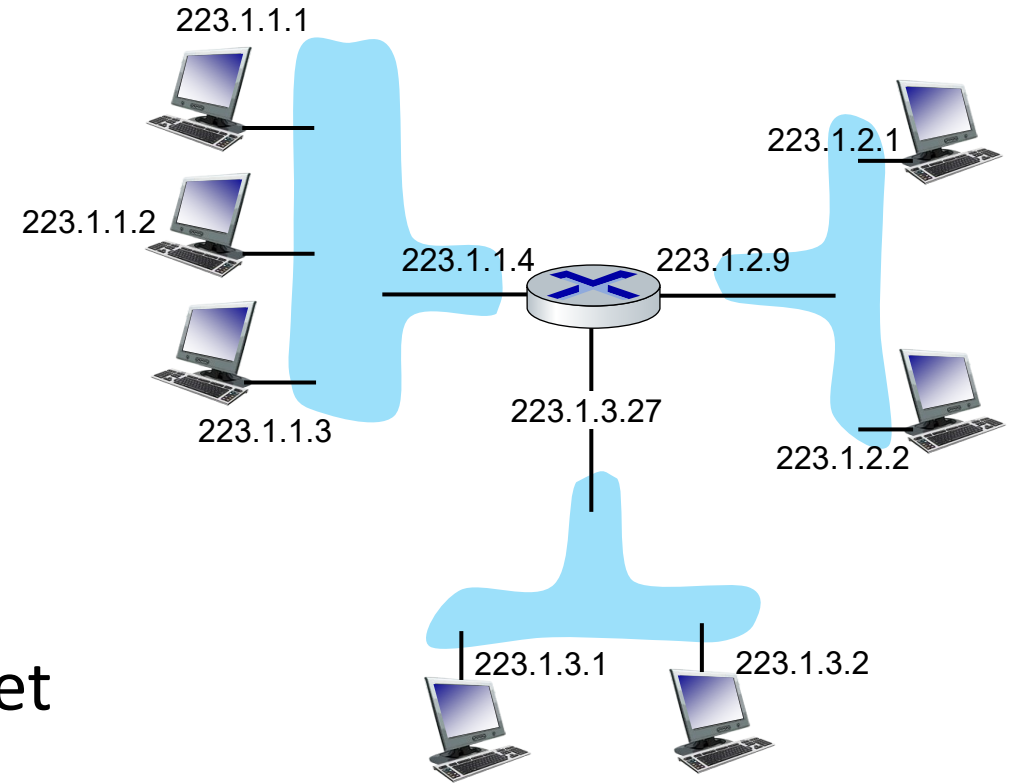
**A:** wired Ethernet interfaces connected by Ethernet switches



**A:** wireless WiFi interfaces connected by WiFi base station

# Subnets

- *What's a subnet ?*
  - device interfaces that can physically reach each other **without passing through an intervening router**
- IP addresses have structure:
  - **subnet part:** devices in same subnet have common high order bits
  - **host part: remaining** low order bits



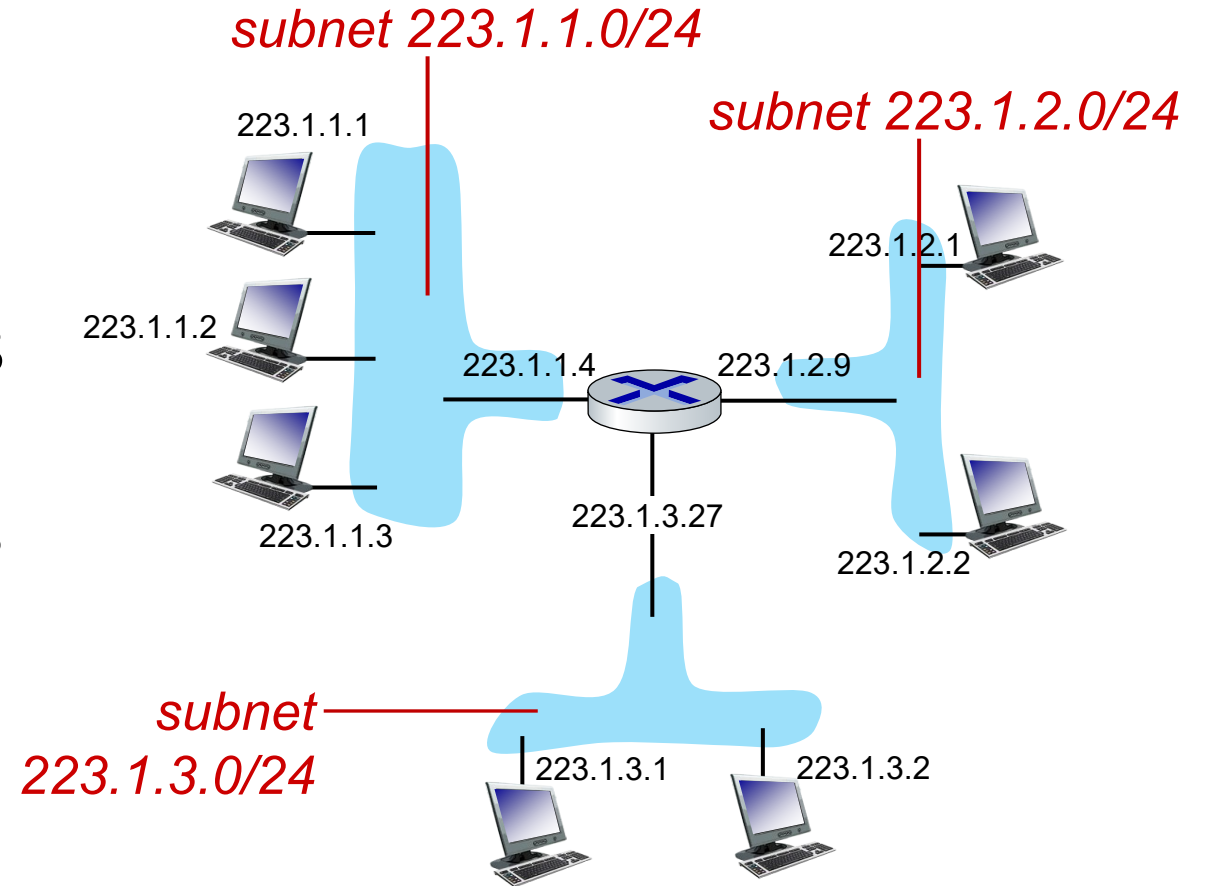
network consisting of 3 subnets



# Subnets

## *Recipe for defining subnets:*

- detach each interface from its host or router, creating “islands” of isolated networks
- each isolated network is called a *subnet*

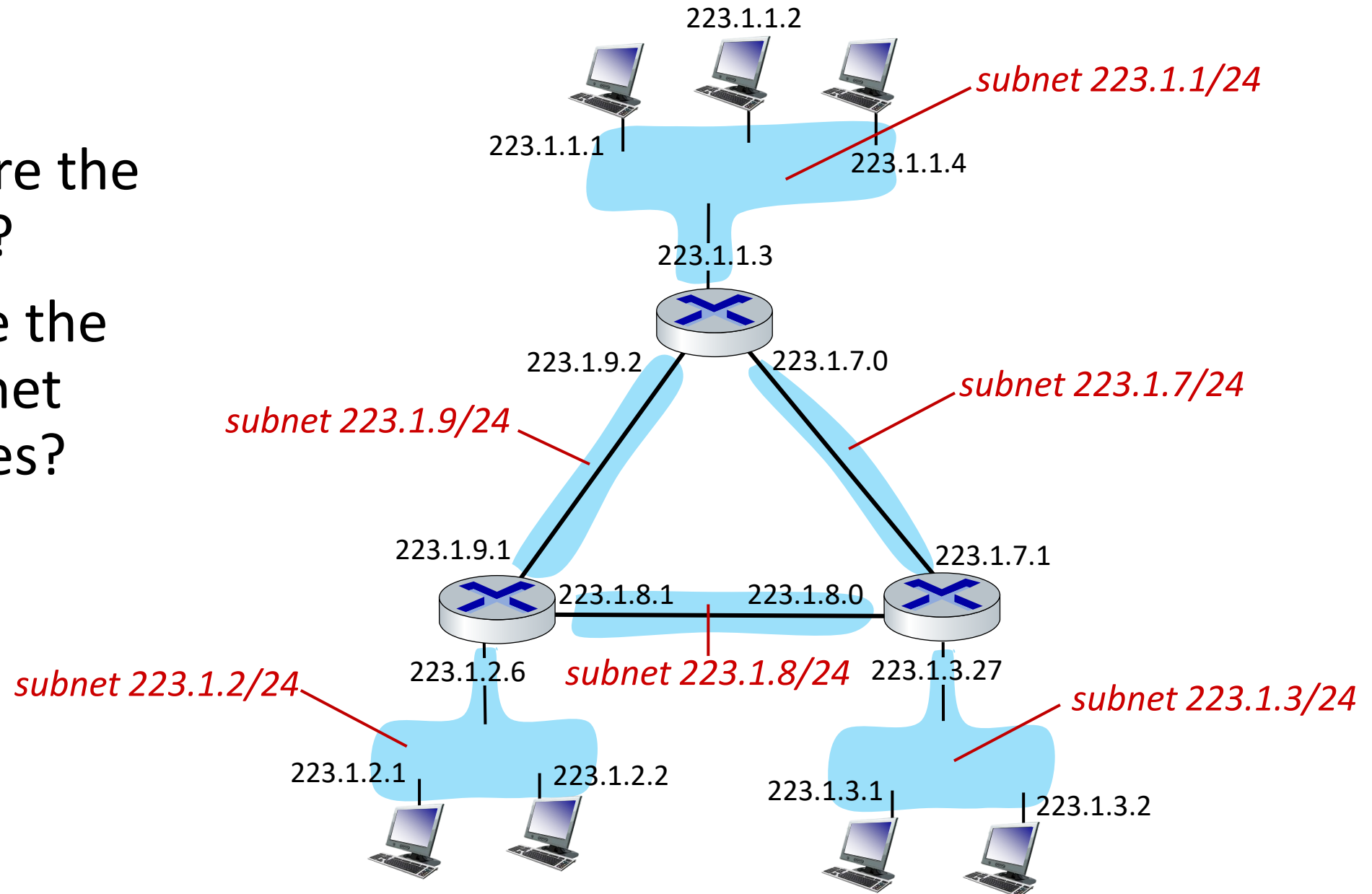


subnet mask: /24

(high-order 24 bits: subnet part of IP address)

# Subnets

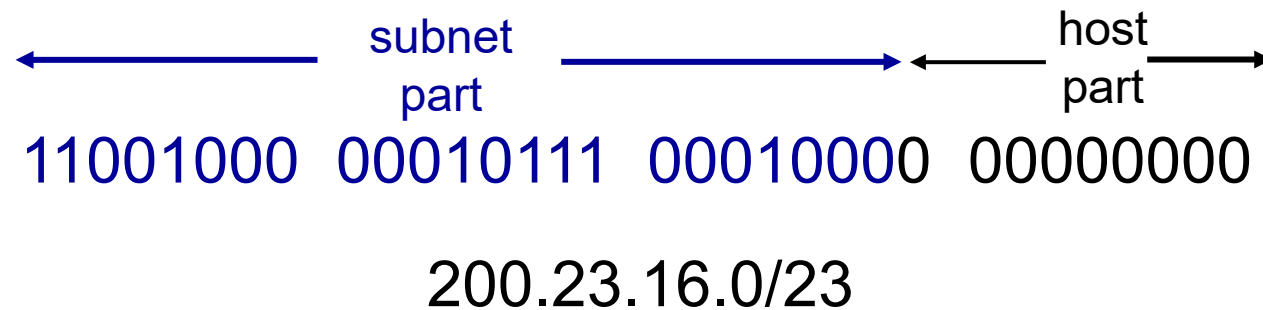
- where are the subnets?
- what are the /24 subnet addresses?



# IP addressing: CIDR

**CIDR: Classless InterDomain Routing** (pronounced “cider”)

- subnet portion of address of arbitrary length
- address format: **a.b.c.d/x**, where x is # bits in subnet portion of address



# IP addresses: how to get one?

That's actually **two** questions:

1. Q: How does a *host* get IP address within its network (host part of address)?
2. Q: How does a *network* get IP address for itself (network part of address)?

How does *host* get IP address?

- hard-coded by sysadmin in config file (e.g., /etc/rc.config in UNIX)
- **DHCP**: Dynamic Host Configuration Protocol: dynamically get address from as server
  - “plug-and-play”

# DHCP: Dynamic Host Configuration Protocol

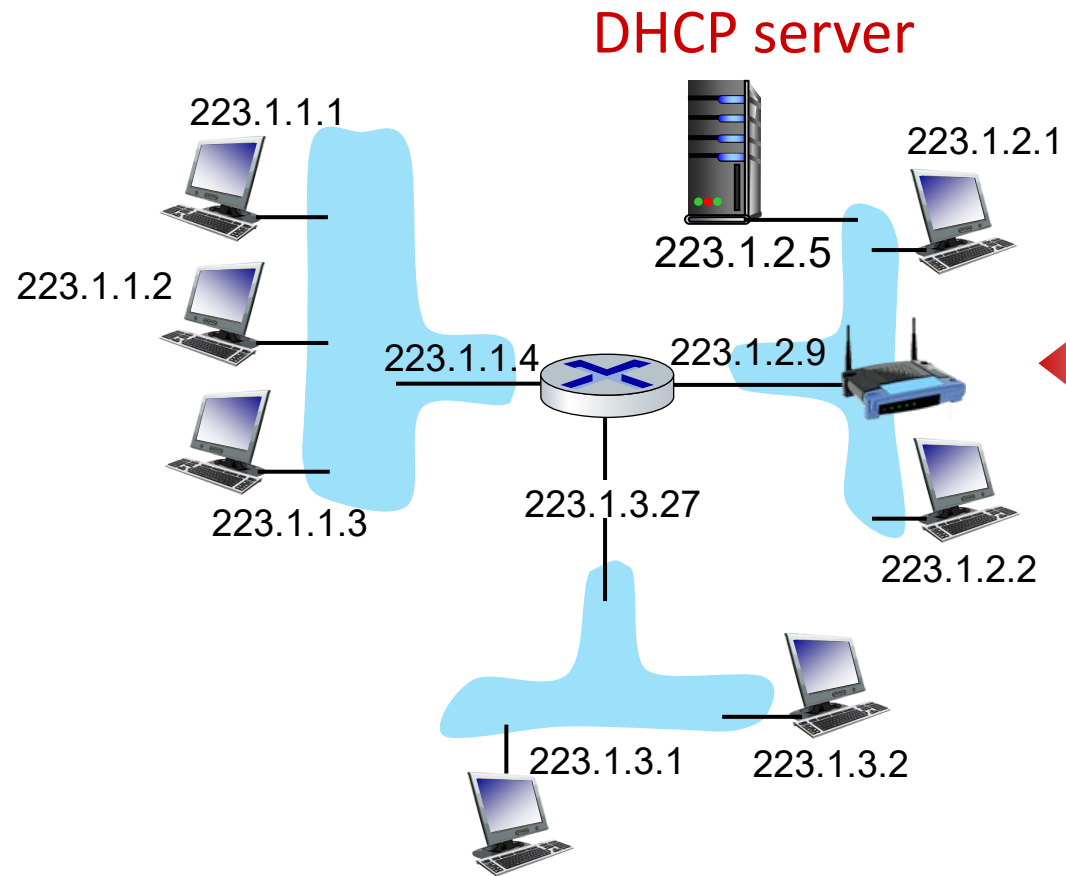
**goal:** host *dynamically* obtains IP address from network server when it “joins” network

- can renew its lease on address in use
- allows reuse of addresses (only hold address while connected/on)
- support for mobile users who join/leave network

## DHCP overview:

- host broadcasts **DHCP discover** msg [optional]
- DHCP server responds with **DHCP offer** msg [optional]
- host requests IP address: **DHCP request** msg
- DHCP server sends address: **DHCP ack** msg

# DHCP client-server scenario



Typically, DHCP server will be co-located in router, serving all subnets to which router is attached



arriving **DHCP client** needs address in this network

# DHCP client-server scenario

DHCP server: 223.1.2.5



**DHCP discover**

Broadcast: is there a  
DHCP server out there?

Arriving client



**DHCP offer**

Broadcast: I'm a DHCP  
server! Here's an IP  
address you can use

**DHCP request**

Broadcast: OK. I would  
like to use this IP address!

**DHCP ACK**

Broadcast: OK. You've  
got that IP address!

The two steps above can  
be skipped "if a client  
remembers and wishes to  
reuse a previously  
allocated network address"  
[RFC 2131]

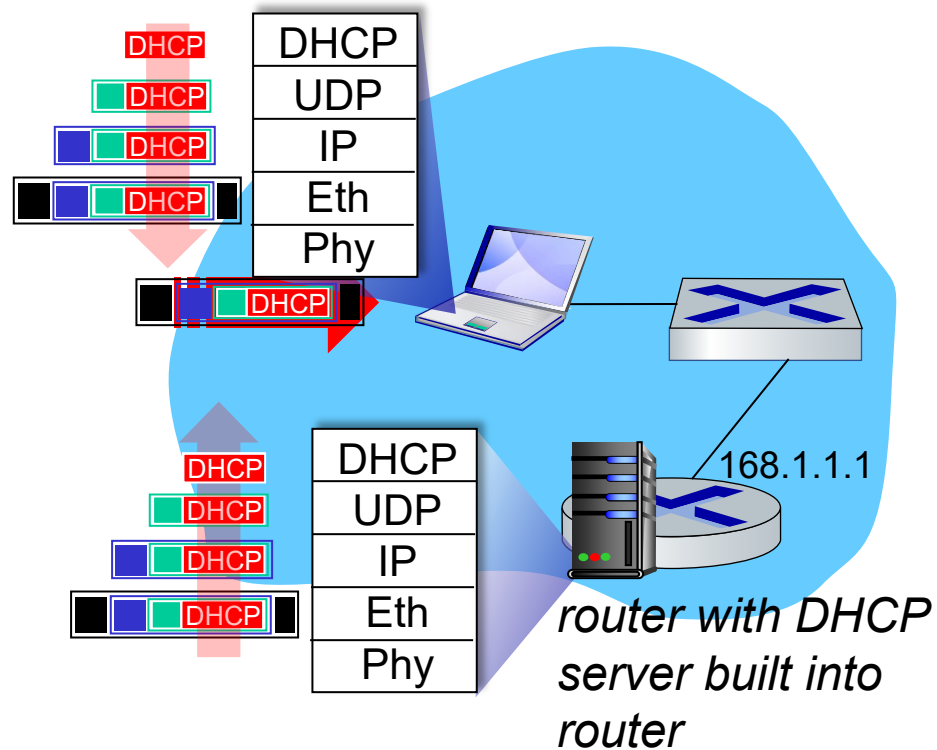
# DHCP: more than IP addresses

DHCP can return more than just allocated IP address on subnet:

- address of first-hop router for client
- name and IP address of DNS sever
- network mask (indicating network versus host portion of address)

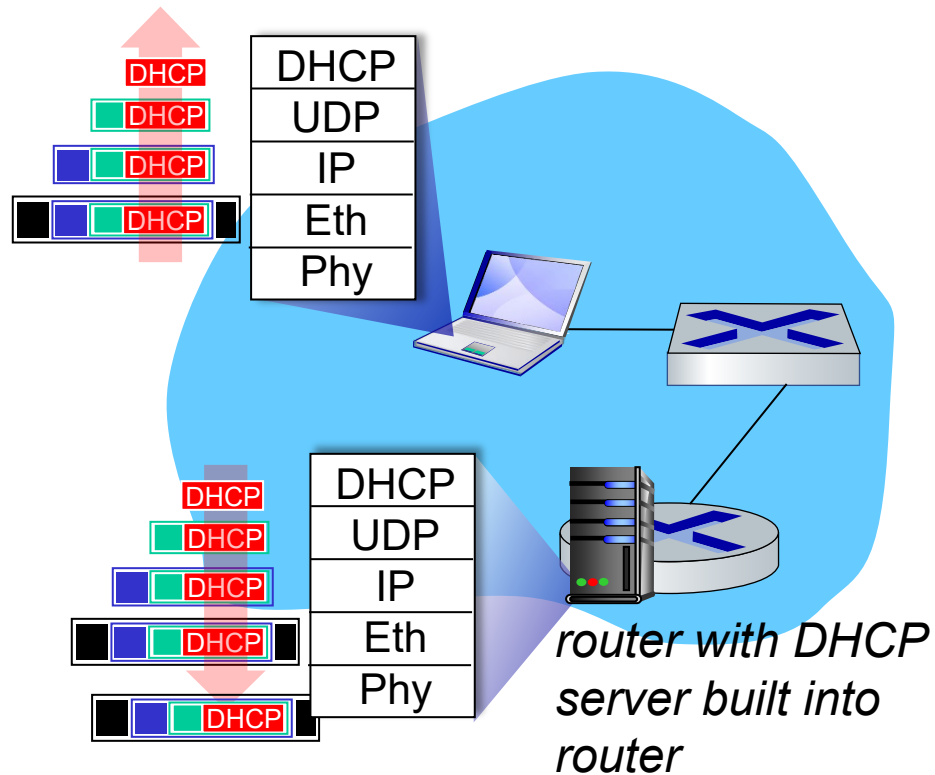


# DHCP: example



- Connecting laptop will use DHCP to get IP address, address of first-hop router, address of DNS server.
- DHCP REQUEST message encapsulated in UDP, encapsulated in IP, encapsulated in Ethernet
- Ethernet frame broadcast (dest: FFFFFFFF) on LAN, received at router running DHCP server
- Ethernet de-mux'ed to IP de-mux'ed, UDP de-mux'ed to DHCP

# DHCP: example



- DHCP server formulates DHCP ACK containing client's IP address, IP address of first-hop router for client, name & IP address of DNS server
- encapsulated DHCP server reply forwarded to client, de-muxing up to DHCP at client
- client now knows its IP address, name and IP address of DNS server, IP address of its first-hop router

# IP addresses: how to get one?

**Q:** how does *network* get subnet part of IP address?

**A:** gets allocated portion of its provider ISP's address space

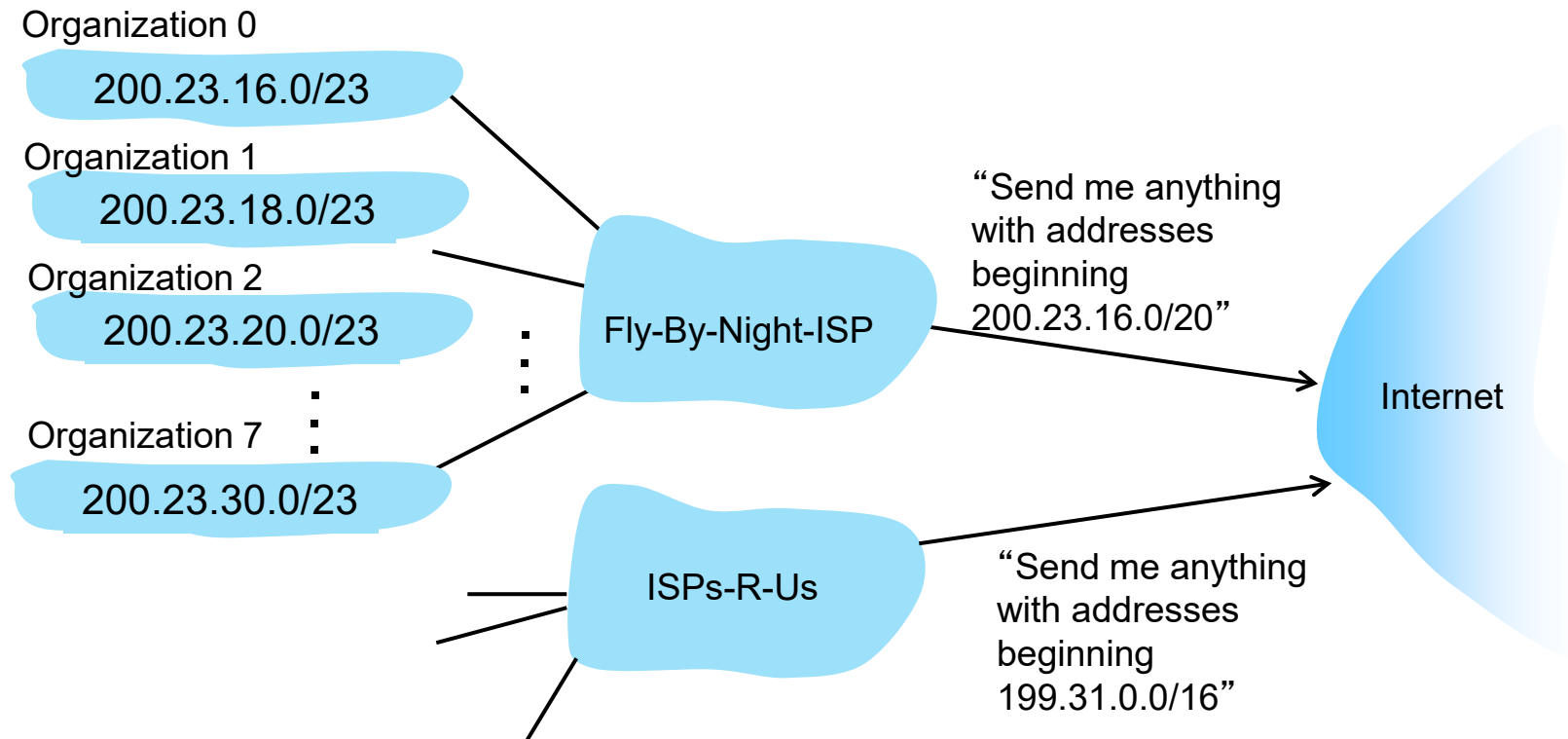
ISP's block      11001000 00010111 00010000 00000000    200.23.16.0/20

ISP can then allocate out its address space in 8 blocks:

Organization 0	<u>11001000 00010111 00010000</u>	00000000	200.23.16.0/23
Organization 1	<u>11001000 00010111 00010010</u>	00000000	200.23.18.0/23
Organization 2	<u>11001000 00010111 00010100</u>	00000000	200.23.20.0/23
...	.....	....	....
Organization 7	<u>11001000 00010111 00011110</u>	00000000	200.23.30.0/23

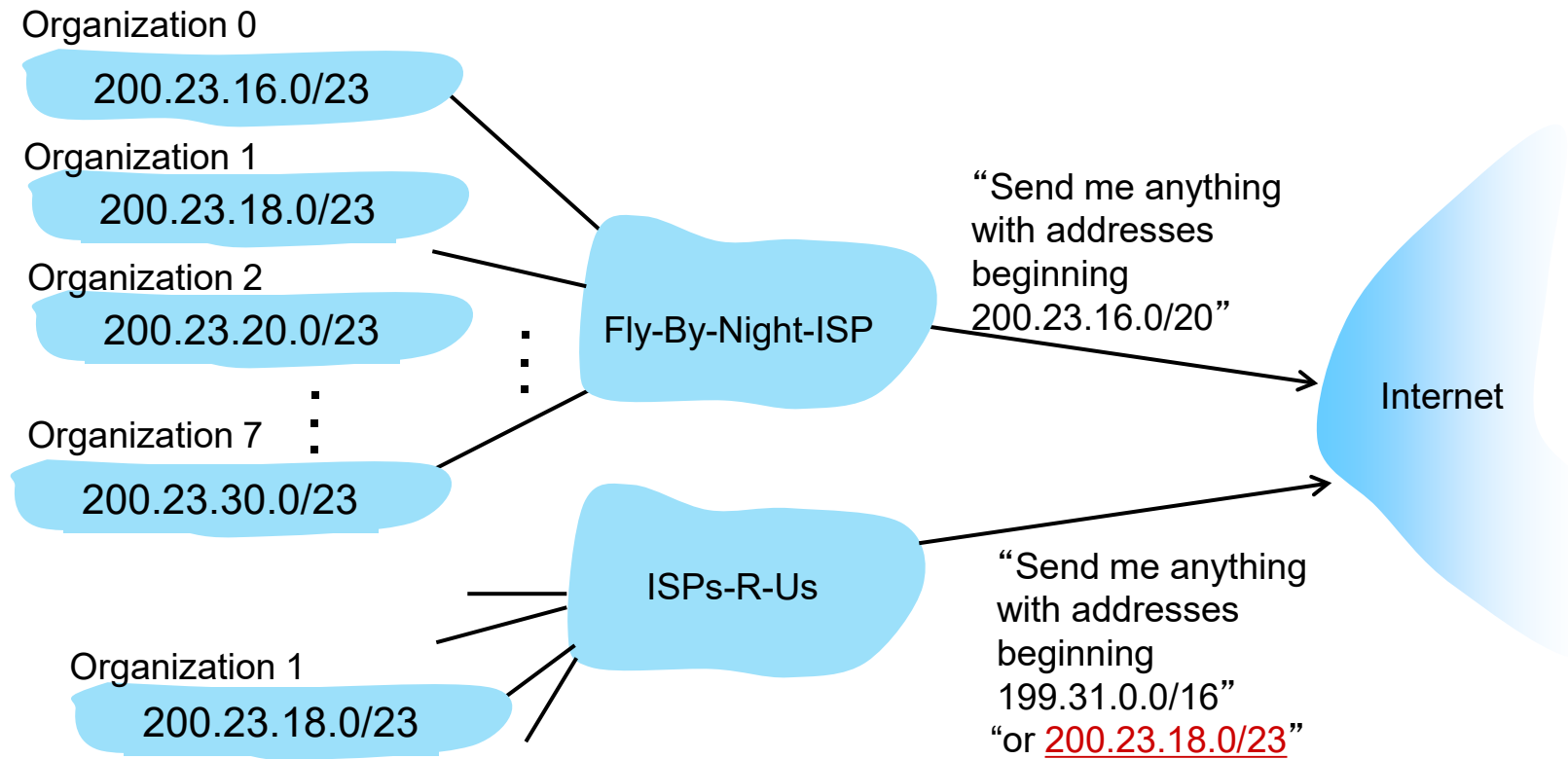
# Hierarchical addressing: route aggregation

hierarchical addressing allows efficient advertisement of routing information:



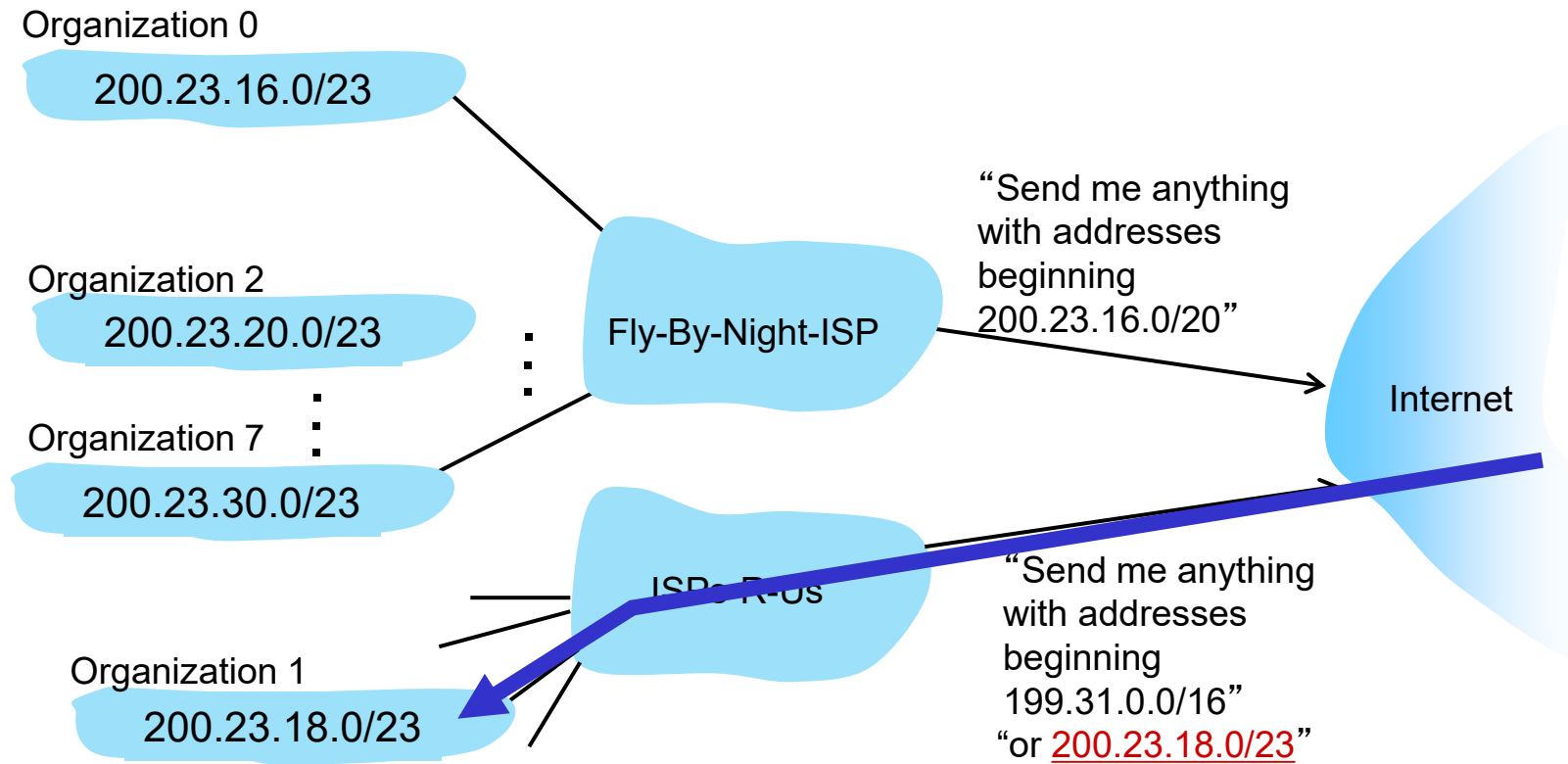
# Hierarchical addressing: more specific routes

- Organization 1 moves from Fly-By-Night-ISP to ISPs-R-Us
- ISPs-R-Us now advertises a more specific route to Organization 1



# Hierarchical addressing: more specific routes

- Organization 1 moves from Fly-By-Night-ISP to ISPs-R-Us
- ISPs-R-Us now advertises a more specific route to Organization 1



# IP addressing: last words ...

**Q:** how does an ISP get block of addresses?

**A:** ICANN: Internet Corporation for Assigned Names and Numbers  
<http://www.icann.org/>

- allocates IP addresses, through 5 regional registries (RRs) (who may then allocate to local registries)
- manages DNS root zone, including delegation of individual TLD (.com, .edu , ...) management

**Q:** are there enough 32-bit IP addresses?

- ICANN allocated last chunk of IPv4 addresses to RRs in 2011
- NAT (next) helps IPv4 address space exhaustion
- IPv6 has 128-bit address space

"Who the hell knew how much address space we needed?" Vint Cerf (reflecting on decision to make IPv4 address 32 bits long)

# Network layer: “data plane” roadmap

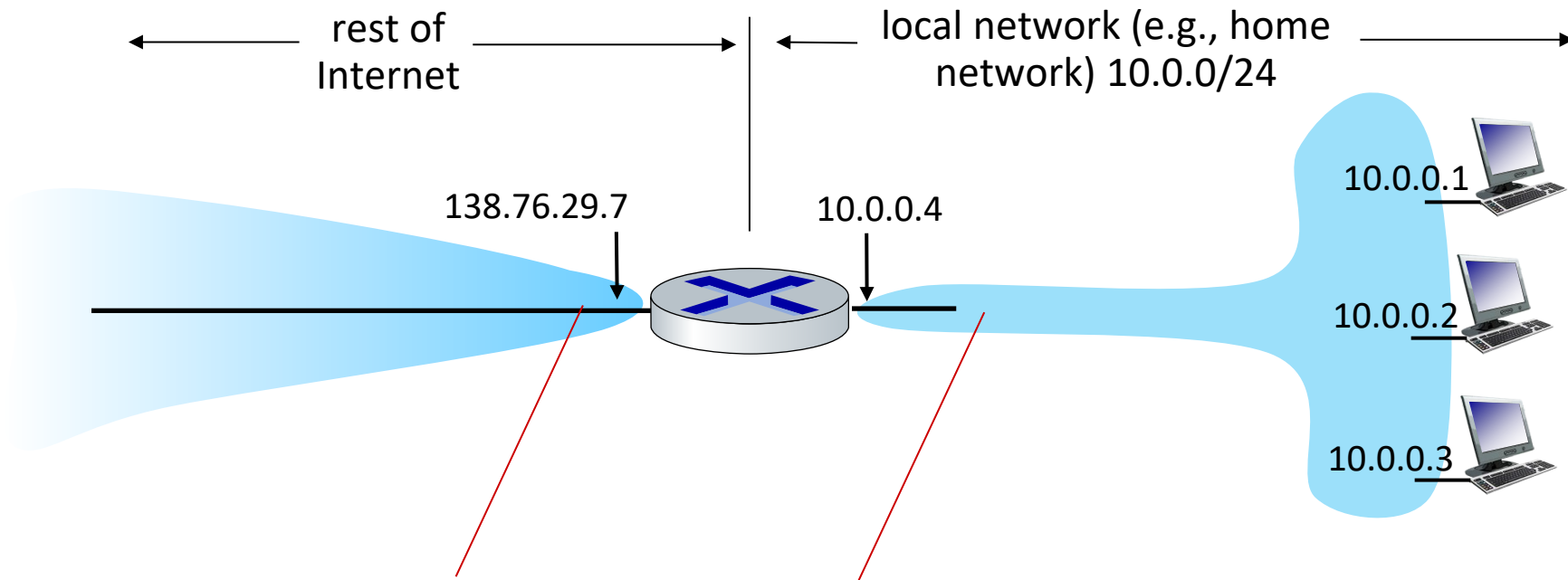
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# NAT: network address translation

**NAT:** all devices in local network share just **one** IPv4 address as far as outside world is concerned



*all* datagrams *leaving* local network have *same* source NAT IP address: 138.76.29.7, but *different* source port numbers

datagrams with source or destination in this network have 10.0.0/24 address for source, destination (as usual)

# NAT: network address translation

- all devices in local network have 32-bit addresses in a “private” IP address space (10/8, 172.16/12, 192.168/16 prefixes) that can only be used in local network
- advantages:
  - just **one** IP address needed from provider ISP for *all* devices
  - can change addresses of host in local network without notifying outside world
  - can change ISP without changing addresses of devices in local network
  - security: devices inside local net not directly addressable, visible by outside world

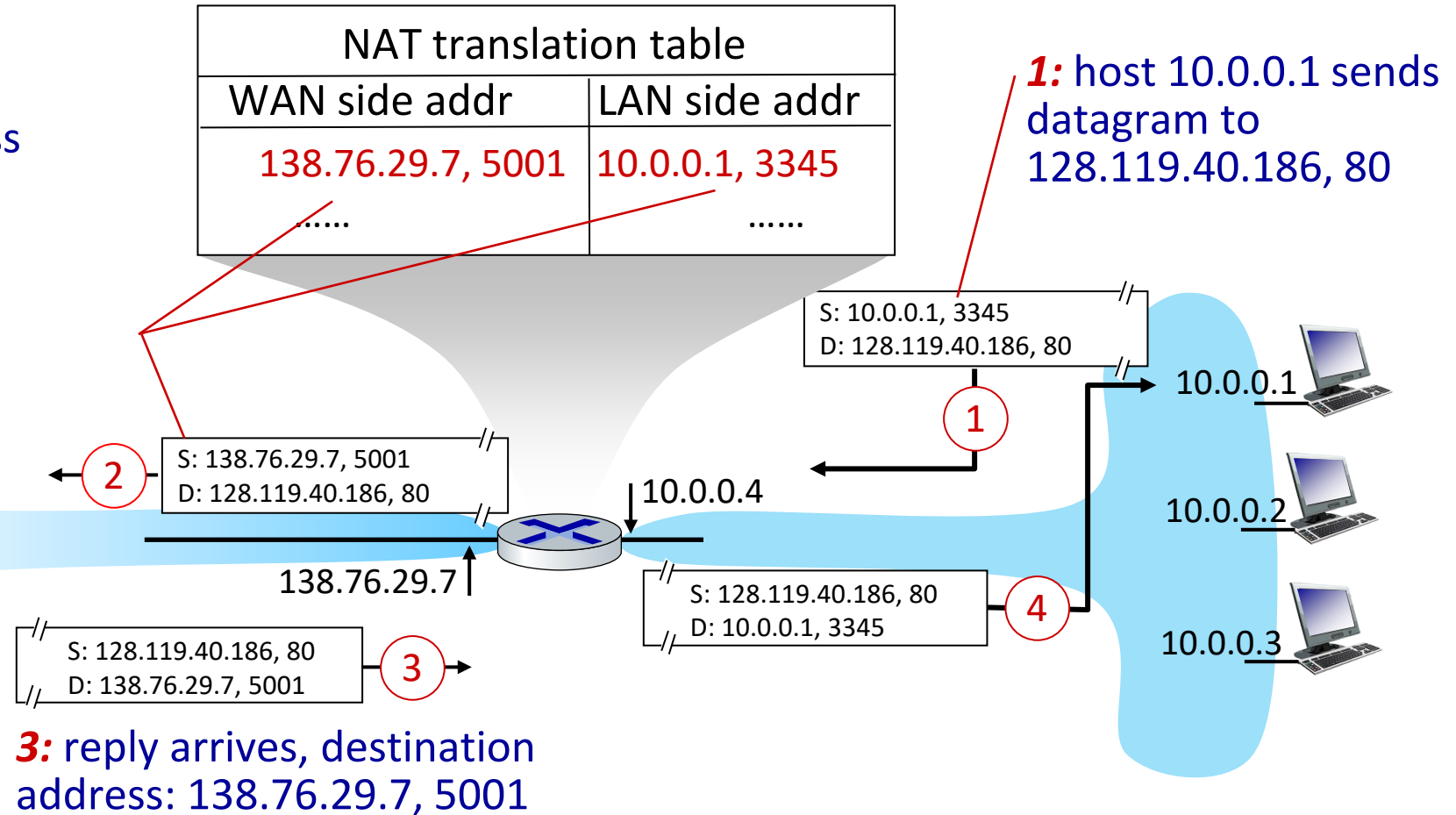
# NAT: network address translation

**implementation:** NAT router must (transparently):

- **outgoing datagrams: replace** (source IP address, port #) of every outgoing datagram to (NAT IP address, new port #)
  - remote clients/servers will respond using (NAT IP address, new port #) as destination address
- **remember (in NAT translation table)** every (source IP address, port #) to (NAT IP address, new port #) translation pair
- **incoming datagrams: replace** (NAT IP address, new port #) in destination fields of every incoming datagram with corresponding (source IP address, port #) stored in NAT table

# NAT: network address translation

**2:** NAT router changes datagram source address from 10.0.0.1, 3345 to 138.76.29.7, 5001, updates table



# NAT: network address translation

- NAT has been controversial:
  - routers “should” only process up to layer 3
  - address “shortage” should be solved by IPv6
  - violates end-to-end argument (port # manipulation by network-layer device)
  - NAT traversal: what if client wants to connect to server behind NAT?
- but NAT is here to stay:
  - extensively used in home and institutional nets, 4G/5G cellular nets

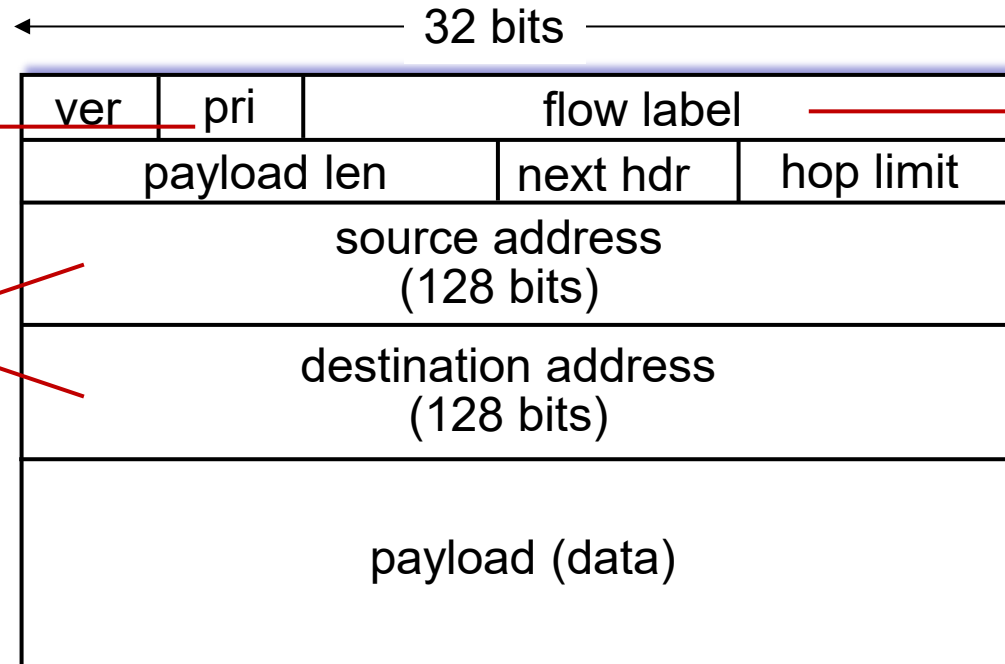
# IPv6: motivation

- **initial motivation:** 32-bit IPv4 address space would be completely allocated
- additional motivation:
  - speed processing/forwarding: 40-byte fixed length header
  - enable different network-layer treatment of “flows”

# IPv6 datagram format

**priority:** identify priority among datagrams in flow

**128-bit** IPv6 addresses



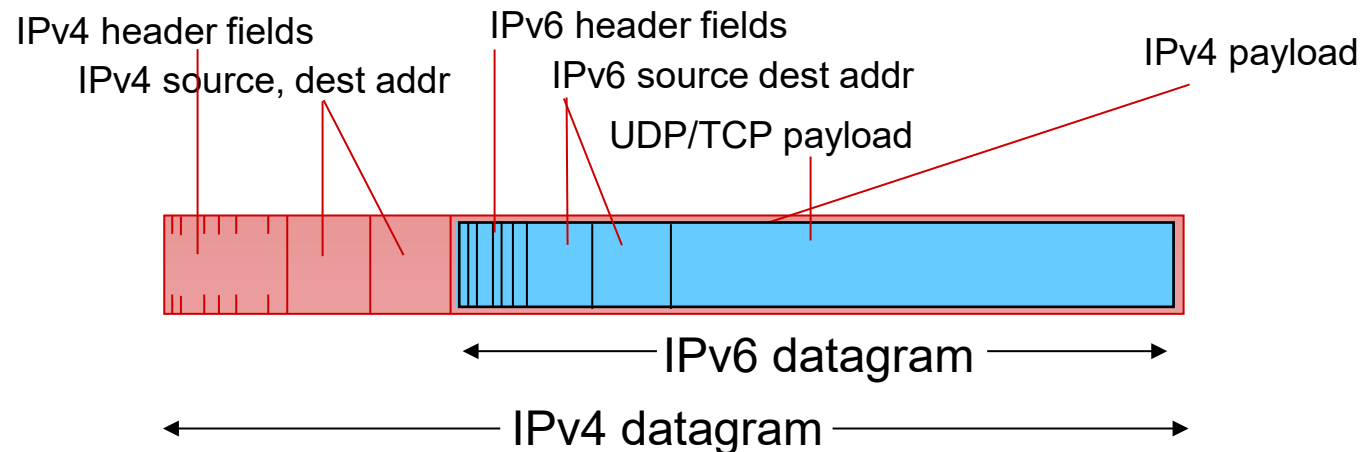
**flow label:** identify datagrams in same "flow." (concept of "flow" not well defined).

What's missing (compared with IPv4):

- no checksum (to speed processing at routers)
- no fragmentation/reassembly
- no options (available as upper-layer, next-header protocol at router)

# Transition from IPv4 to IPv6

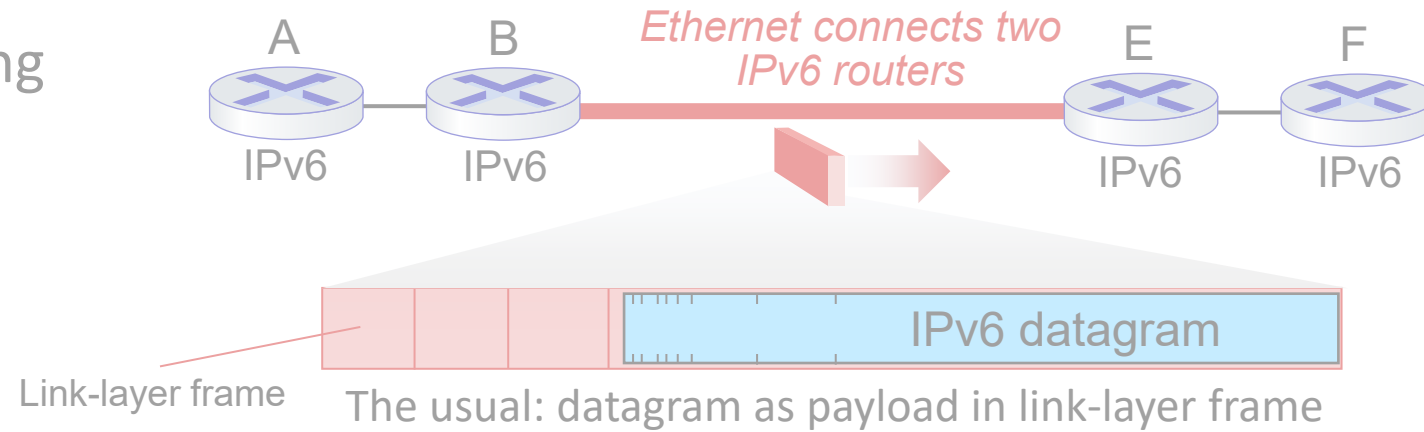
- not all routers can be upgraded simultaneously
  - no “flag days”
  - how will network operate with mixed IPv4 and IPv6 routers?
- **tunneling**: IPv6 datagram carried as *payload* in IPv4 datagram among IPv4 routers (“packet within a packet”)
  - tunneling used extensively in other contexts (4G/5G)



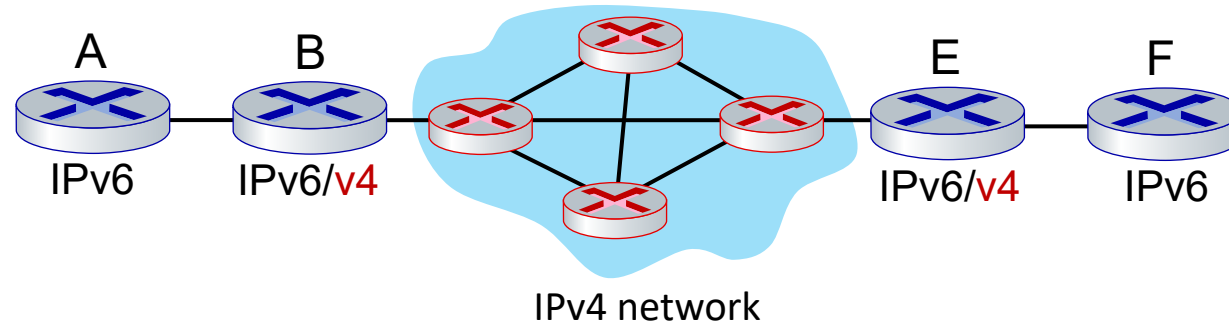


# Tunneling and encapsulation

Ethernet connecting two IPv6 routers:

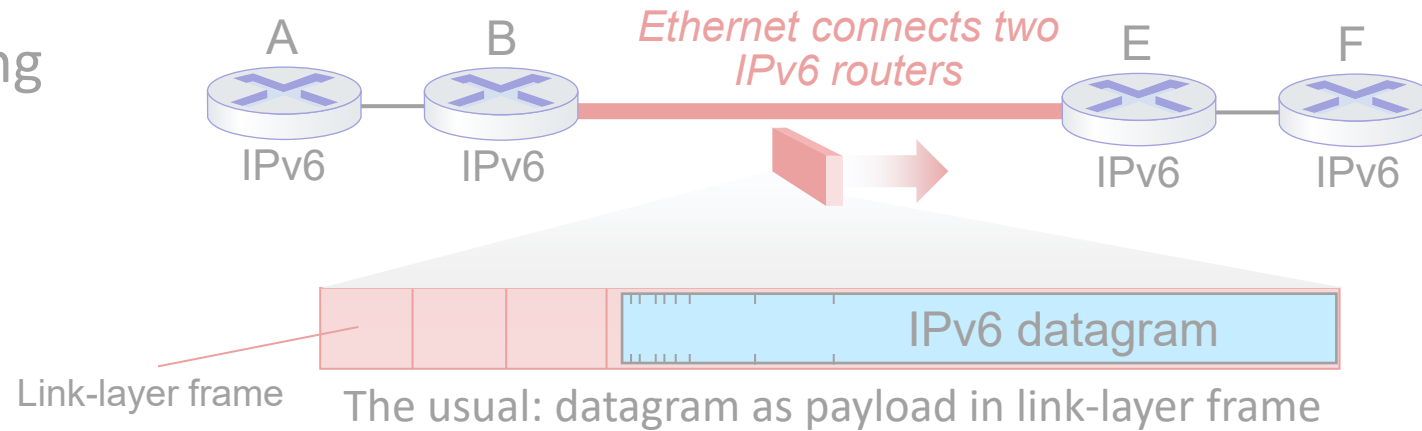


IPv4 network connecting two IPv6 routers

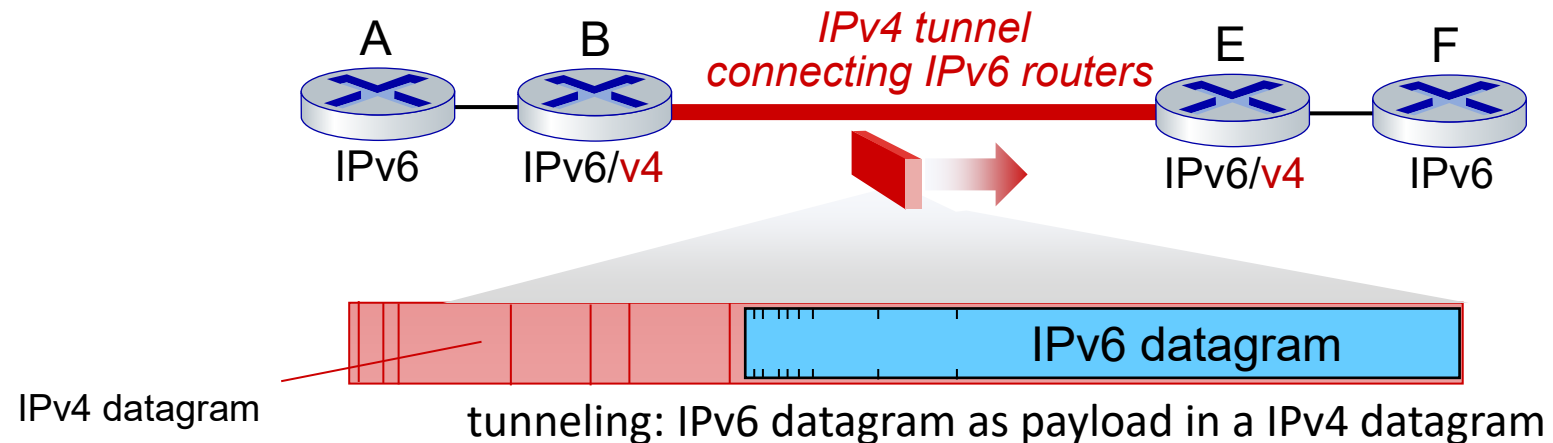


# Tunneling and encapsulation

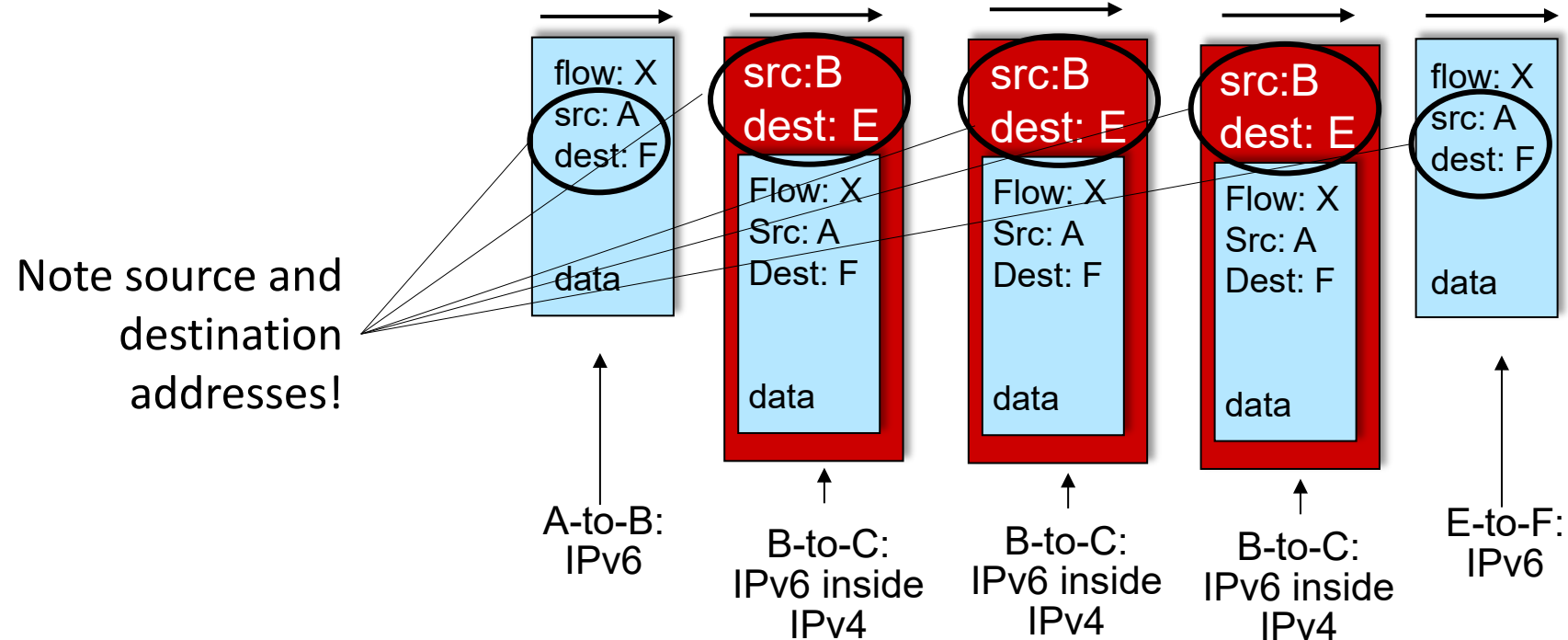
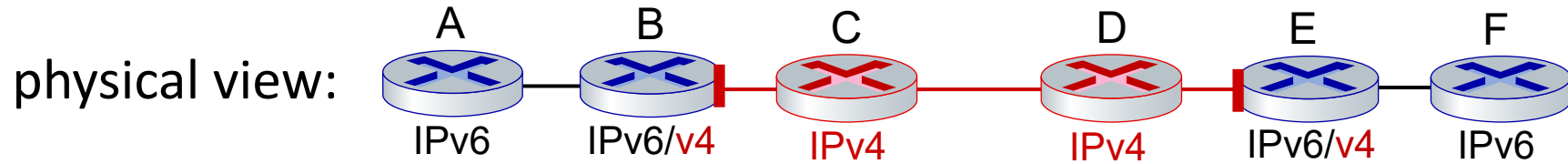
Ethernet connecting two IPv6 routers:



IPv4 tunnel connecting two IPv6 routers



# Tunneling

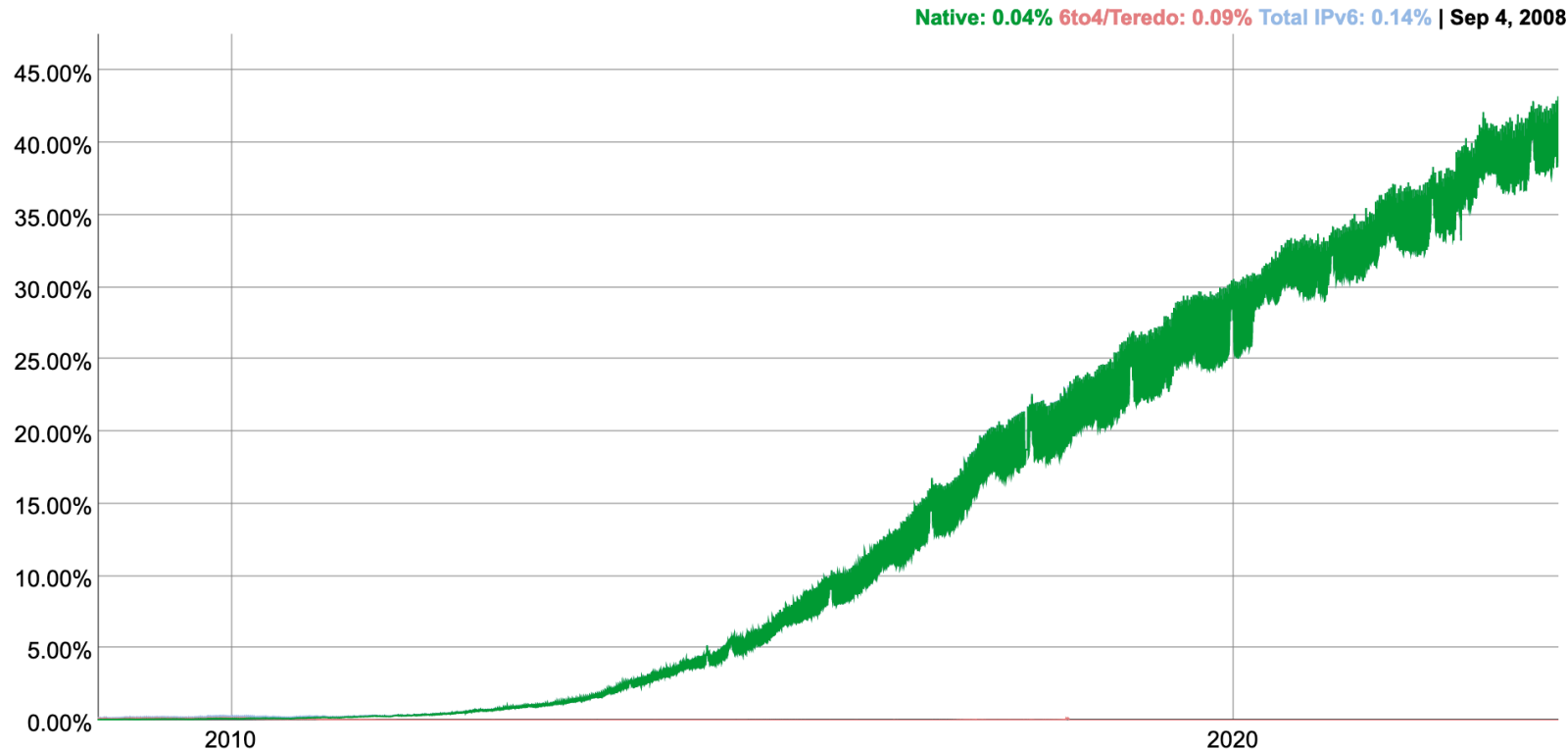


# IPv6: adoption

- Google<sup>1</sup>: ~ 40% of clients access services via IPv6 (2023)
- NIST: 1/3 of all US government domains are IPv6 capable

## IPv6 Adoption

We are continuously measuring the availability of IPv6 connectivity among Google users. The graph shows the percentage of users that access Google over IPv6.



# IPv6: adoption

- Google<sup>1</sup>: ~ 40% of clients access services via IPv6 (2023)
- NIST: 1/3 of all US government domains are IPv6 capable
- Long (long!) time for deployment, use
  - 25 years and counting!
  - think of application-level changes in last 25 years: WWW, social media, streaming media, gaming, telepresence, ...
  - *Why?*

<sup>1</sup> <https://www.google.com/intl/en/ipv6/statistics.html>