

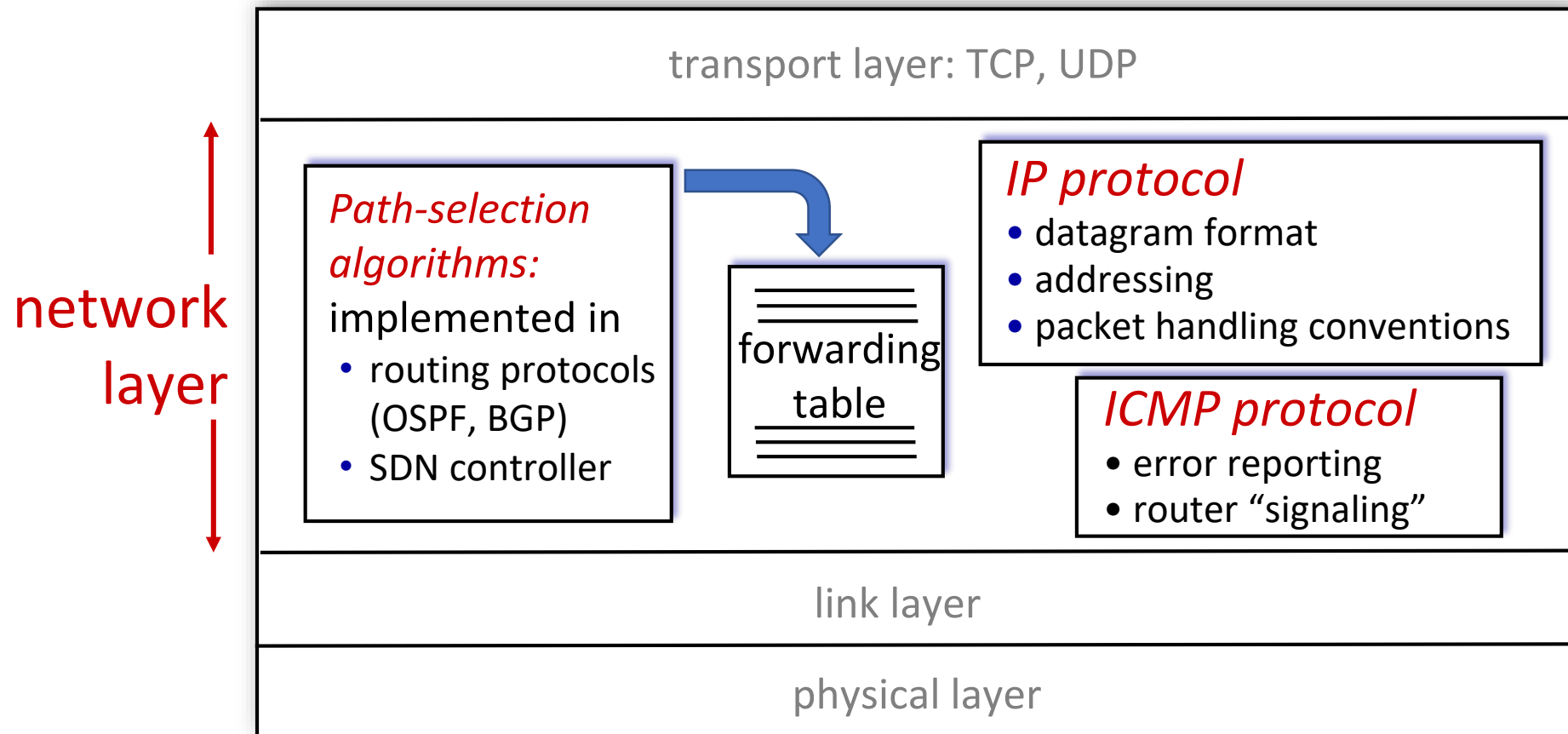
**COMP 445**  
**Data Communications & Computer networks**  
**Winter 2022**

## Network Layer – Data plane

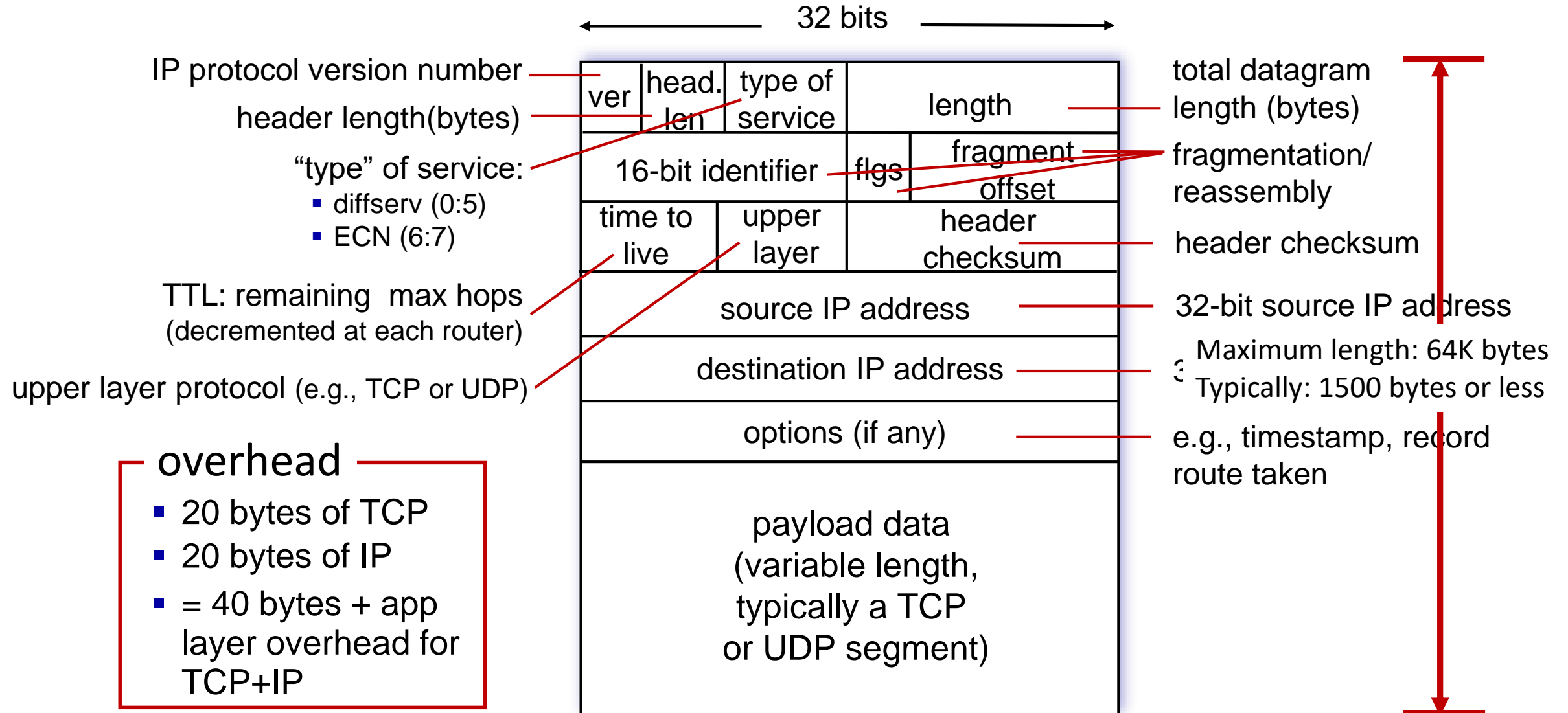
- ✓ Network layer: services and overview
- ✓ Routers
- ✓ Internet protocol
- ✓ Generalized forwarding and SDN

# Network Layer: Internet

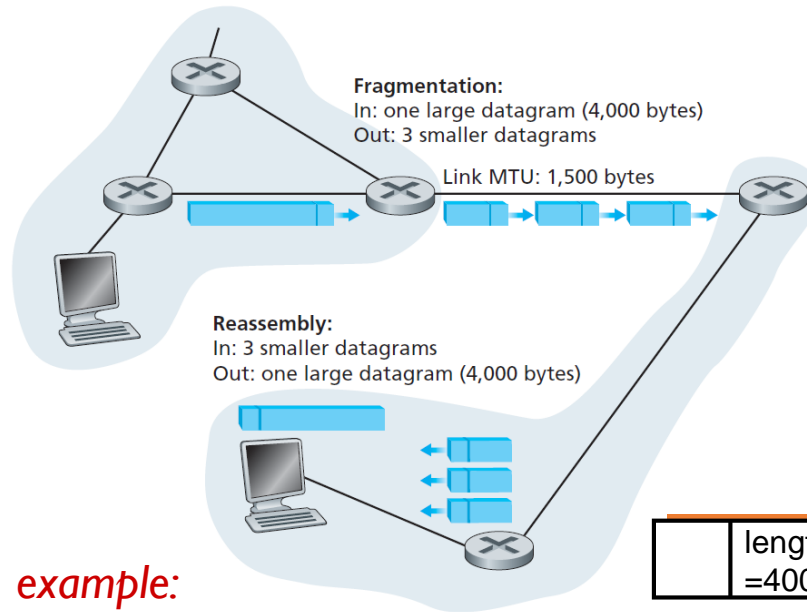
host, router network layer functions:



# IP Datagram format



# IPv4 Fragmentation



*example:*

- ❖ 4000 byte datagram
- ❖ MTU = 1500 bytes

	length	ID	fragflag	offset	
	=4000	=x	=0	=0	

*one large datagram becomes  
several smaller datagrams*

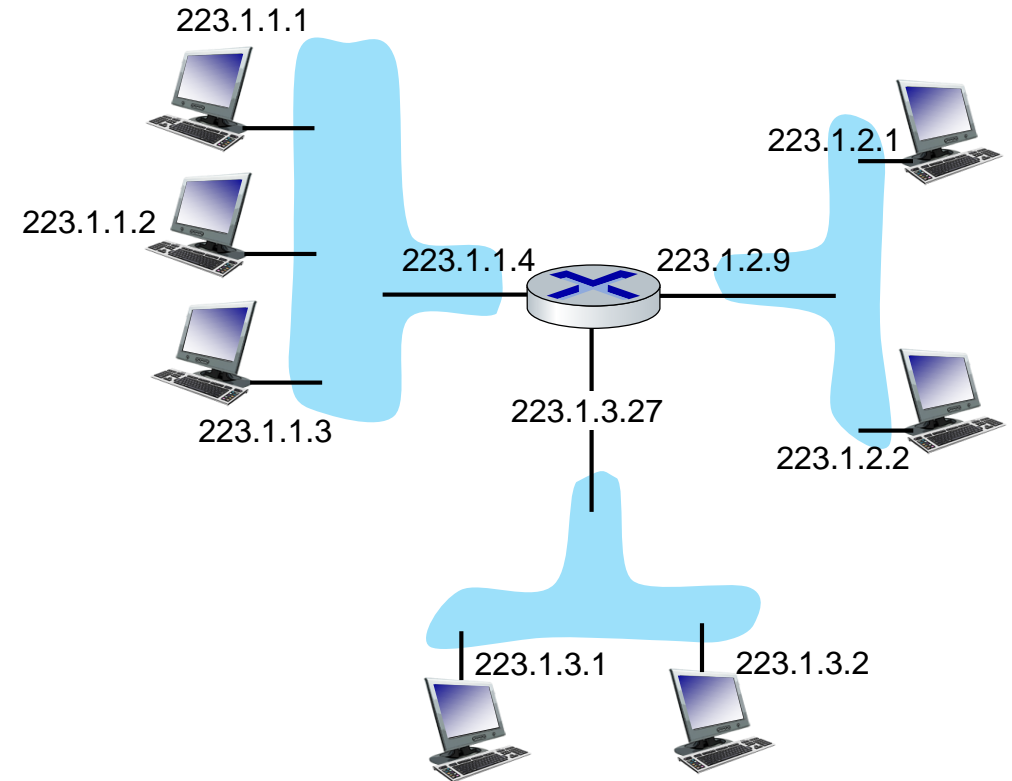
1480 bytes in  
data field

offset =  
 $1480/8$

	length	ID	fragflag	offset	
	=1500	=x	=1	=0	
	=1500	=x	=1	=185	
	=1040	=x	=0	=370	

# 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)

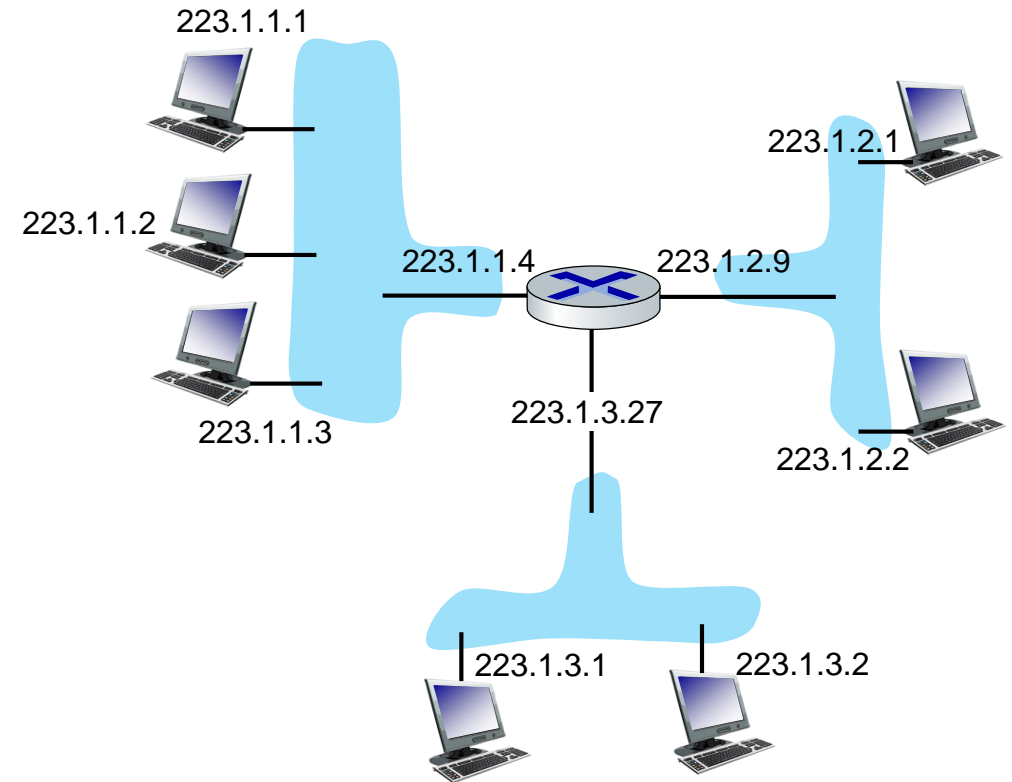


dotted-decimal IP address notation:

223.1.1.1 =  $\underbrace{11011111}_{223} \underbrace{00000001}_1 \underbrace{00000001}_1 \underbrace{00000001}_1$

# IP addressing: introduction

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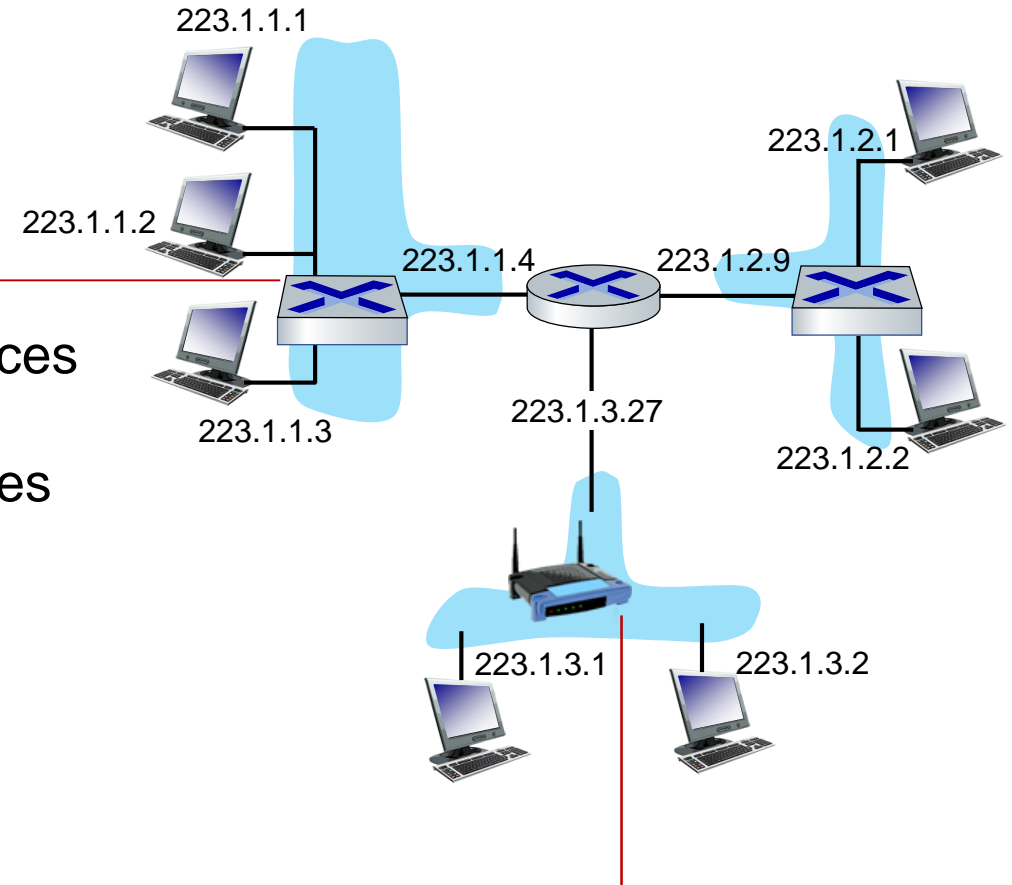
# IP addressing: introduction

**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

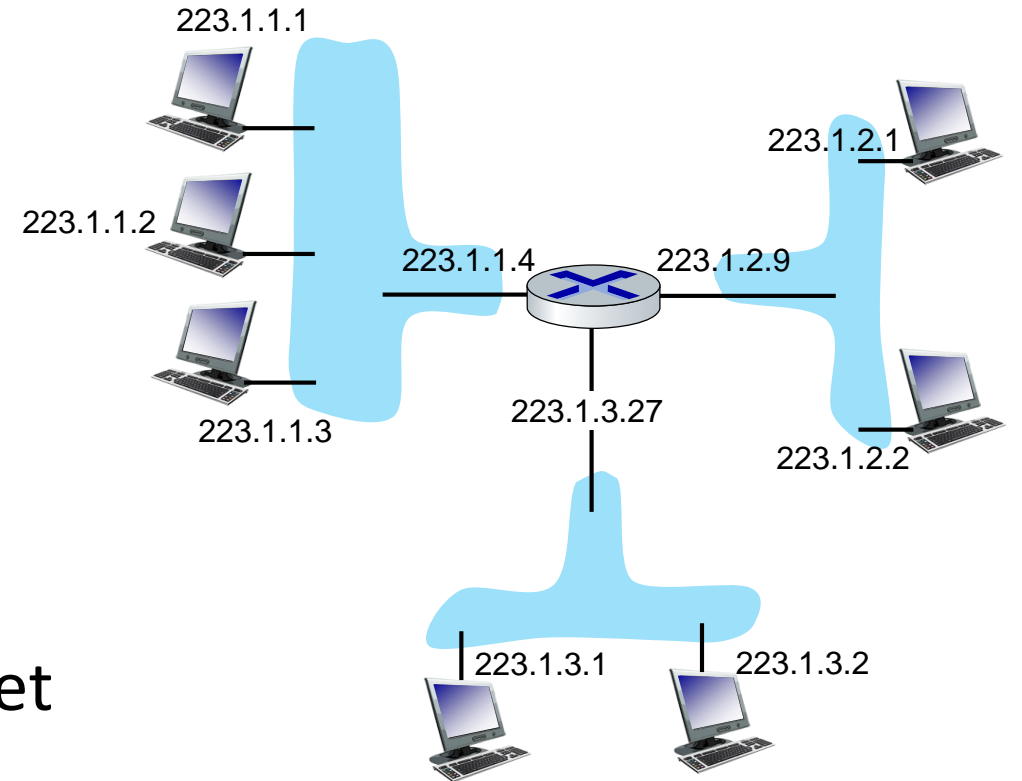


**A:** wireless WiFi interfaces connected by WiFi base station



# 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

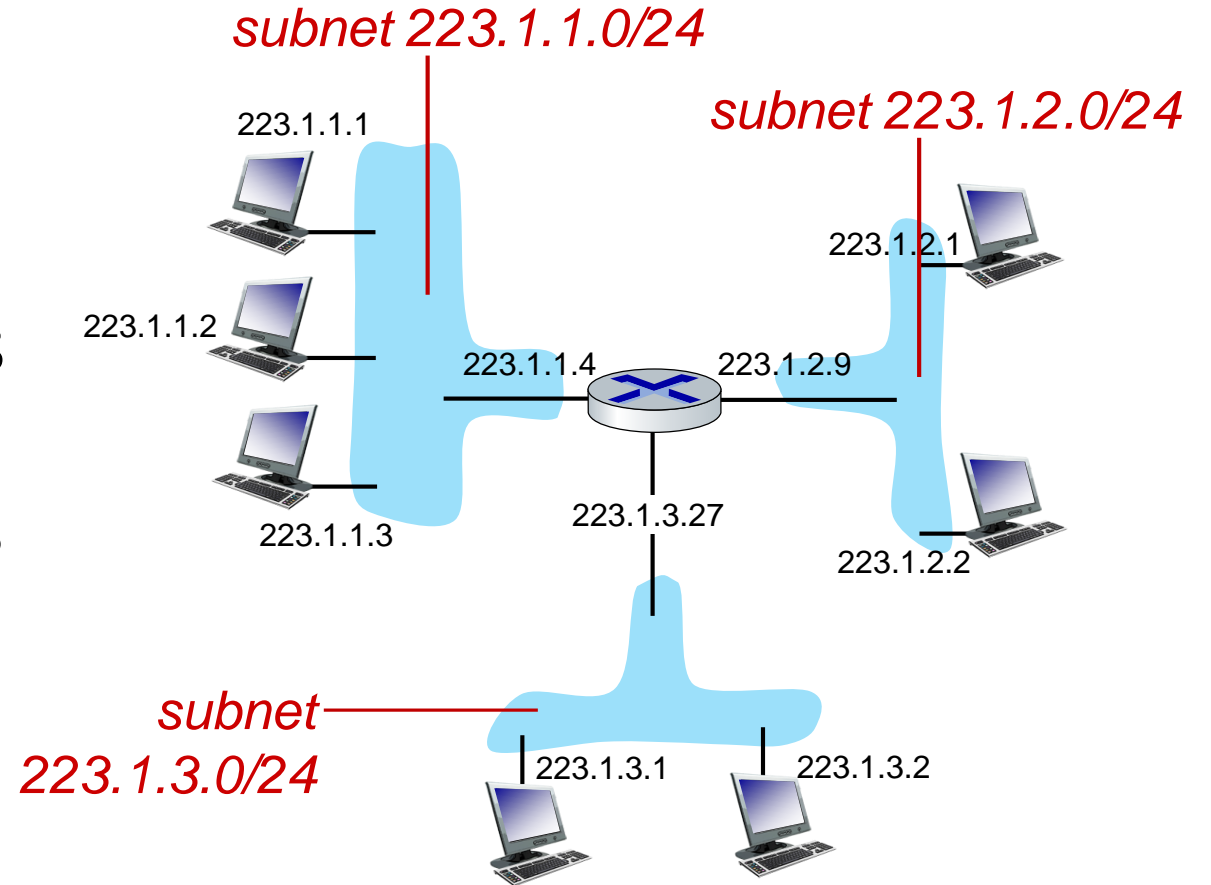


network consisting of 3 subnets

# 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*

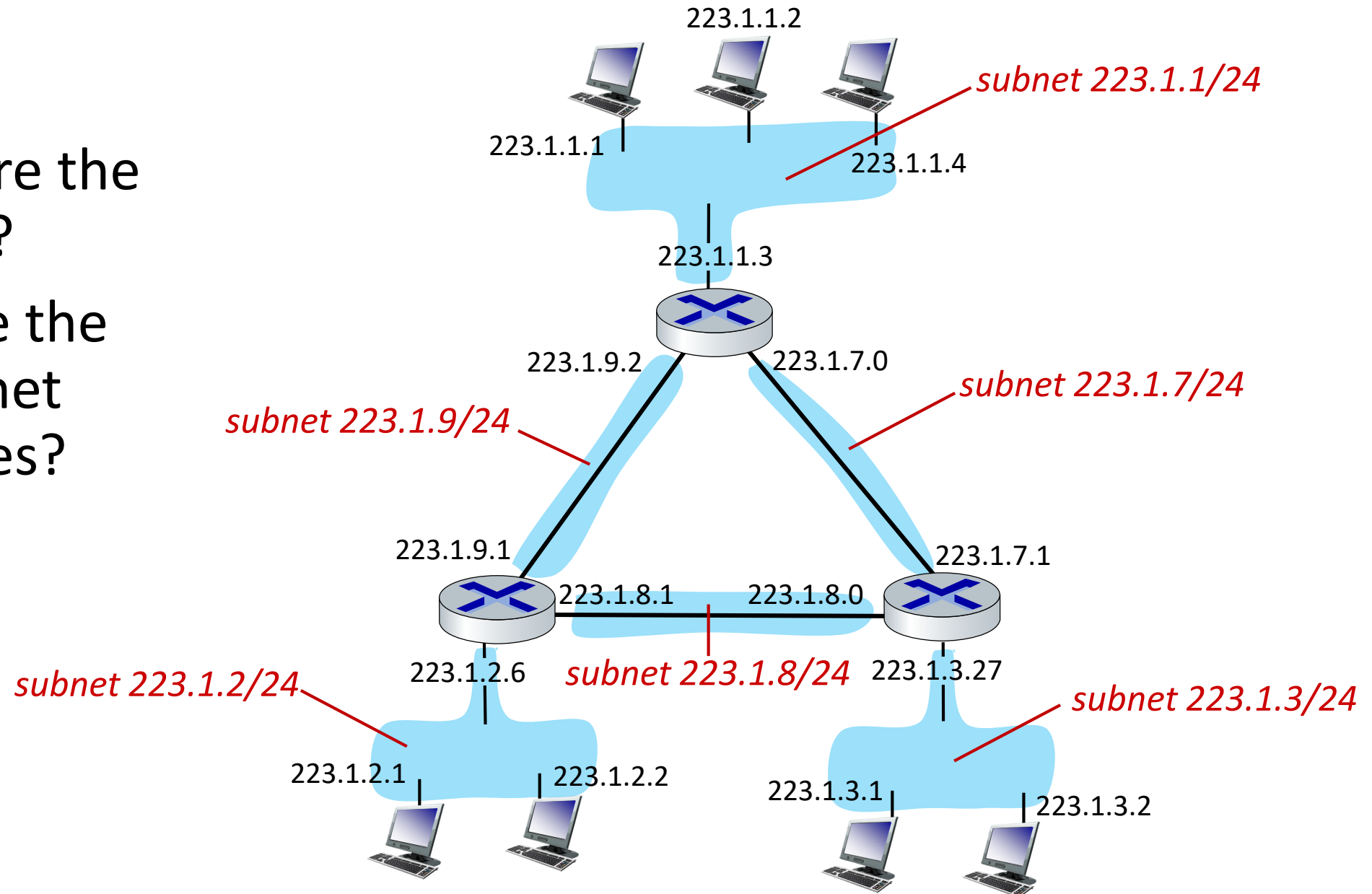


subnet mask: /24

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

# Subnets

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



# IP addressing: before CIDR (classful)

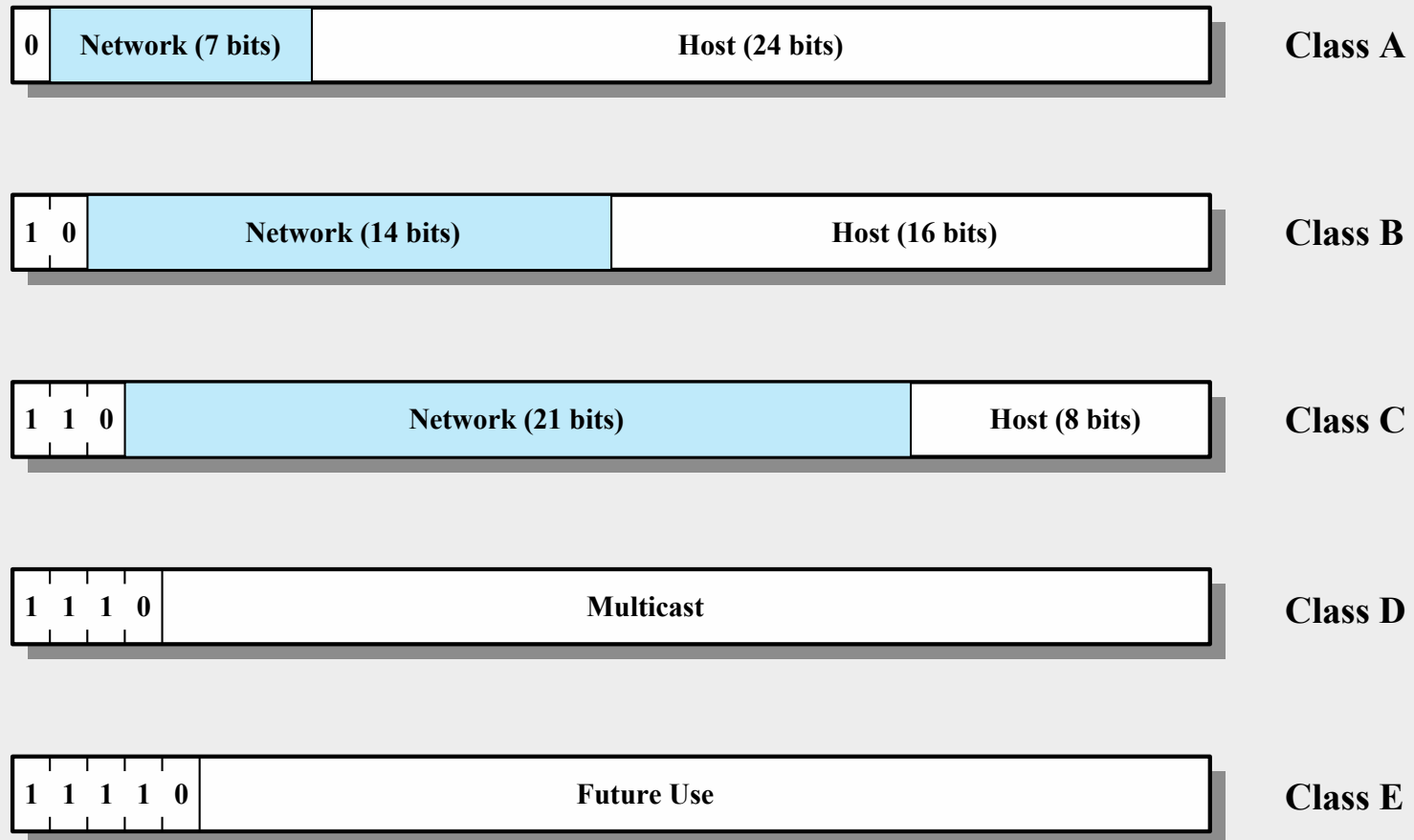
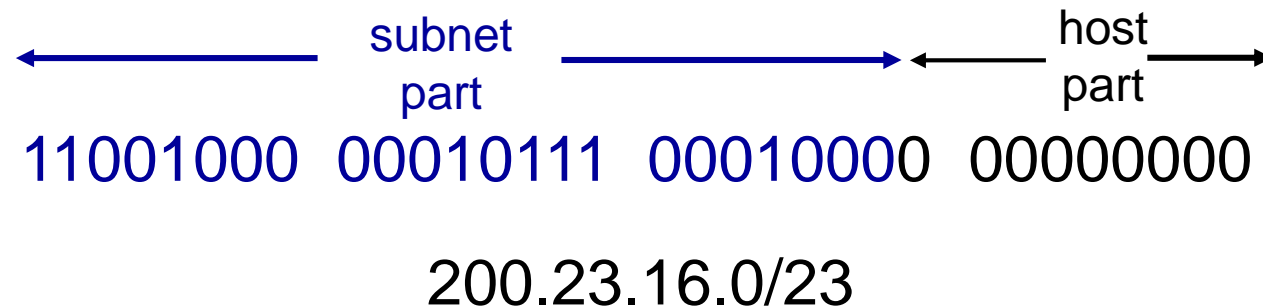


Figure 14.6 IPv4 Address Formats

# IP addressing: CIDR

**CIDR: C**lassless **I**nter**D**omain **R**outing (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

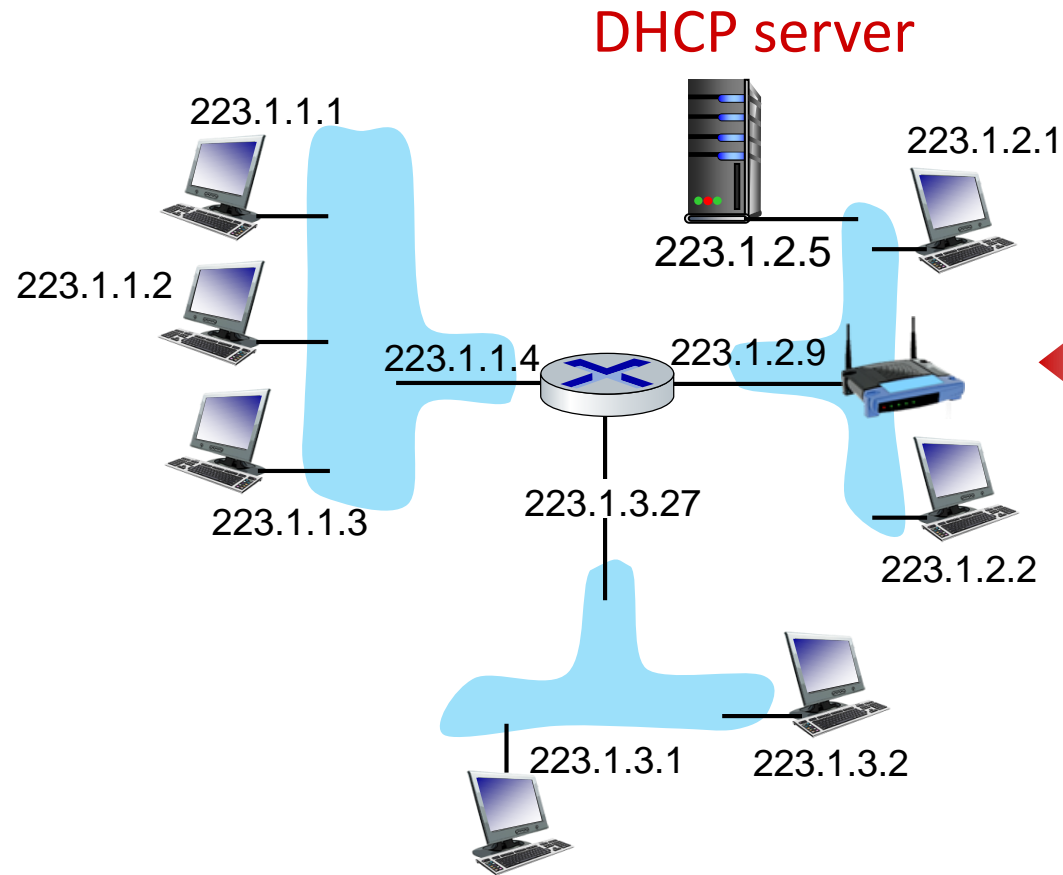
**goal:** host *dynamically* obtains IP address from network server when it “joins” network

- 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!

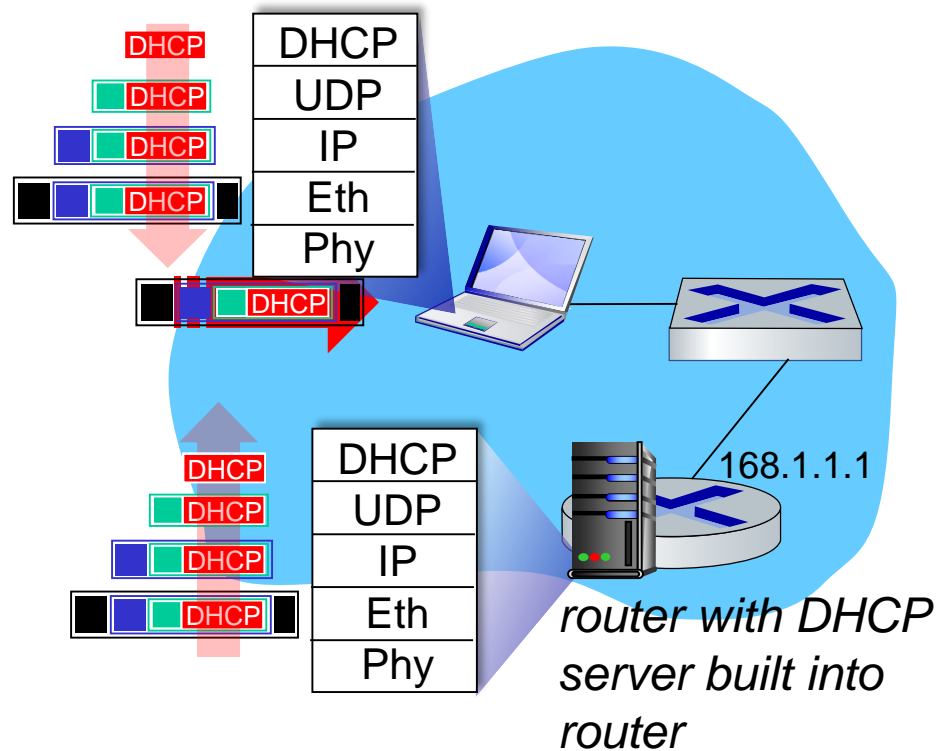
The two steps above can  
be skipped "if a client  
remembers and wishes to  
reuse a previously  
allocated network address"  
[RFC 2131]

# DHCP: more than IP addresses

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

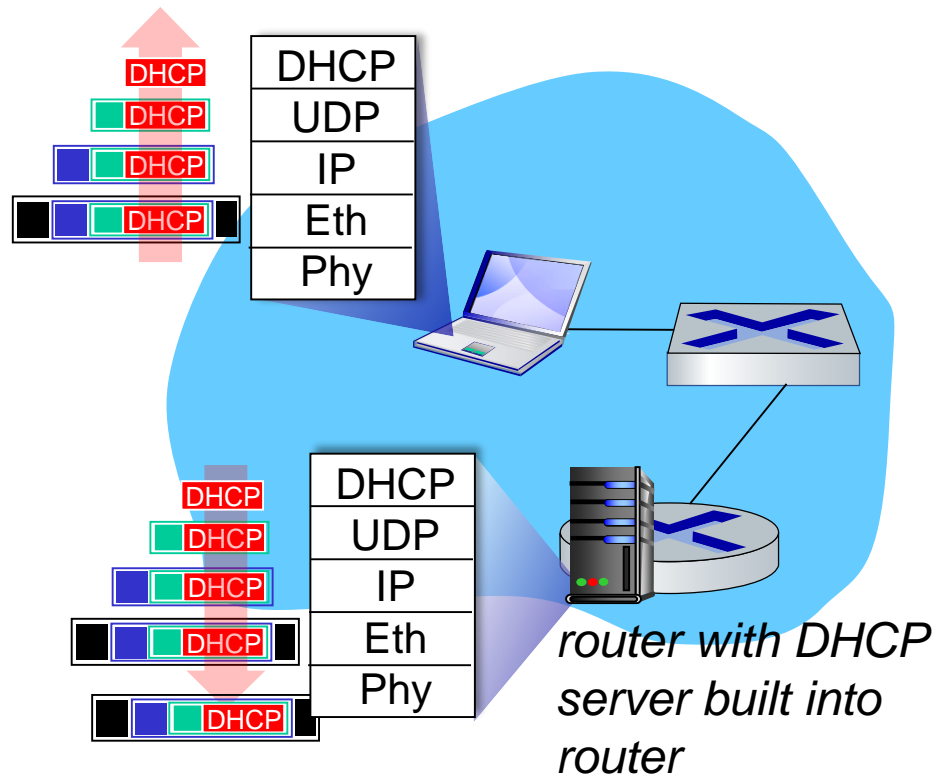
- address of first-hop router for client
- name and IP address of DNS sever
- network mask (indicating network versus host portion of address)

# 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 demux'ed to IP demux'ed, UDP demux'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, demuxing 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:

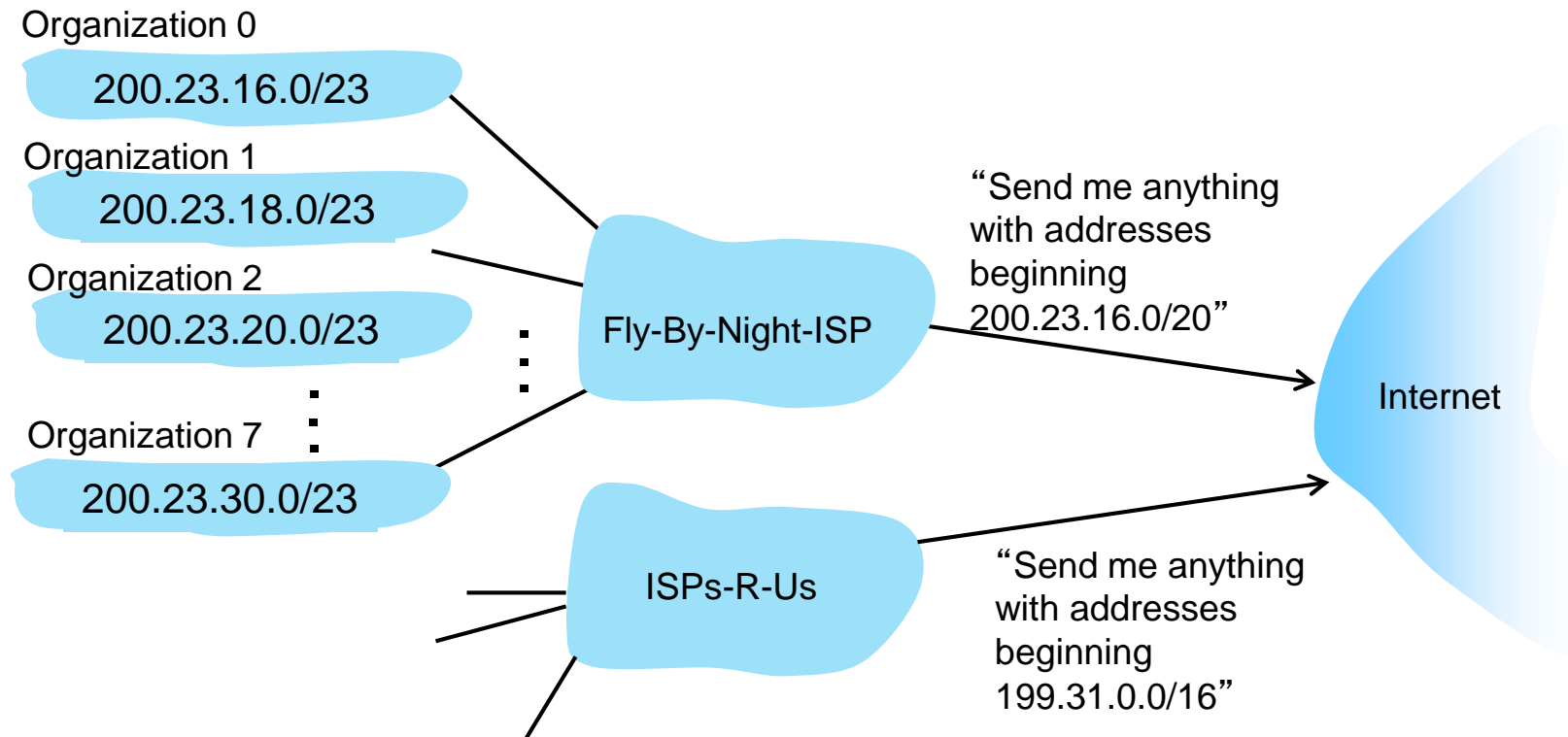
Organization 0	<u>11001000 00010111 00010000</u>	00000000	200.23.16.0/23
Organization 1	<u>11001000 00010111 00010010</u>	00000000	200.23.18.0/23
Organization 2	<u>11001000 00010111 00010100</u>	00000000	200.23.20.0/23
...	.....	....	....
Organization 7	<u>11001000 00010111 00011110</u>	00000000	200.23.30.0/23

Network Address	Class	*CIDR	Subnet Mask	#Subnets	# Hosts/ Subnet
128.123.0.0	B	/30	255.255.255.252	16384	2
135.45.0.0		/25			
193.10.10.0		/28			
211.123.83.0		/26			
10.0.0.0		/13			
32.0.0.0		/20			
204.204.5.0		/28			
		/27			
156.35.0.0		/21			
116.0.0.0		/14			
145.23.0.0		/29			
199.12.1.0		/30			
15.0.0.0		/29			

\*CIDR = Classless Inter-Domain Routing

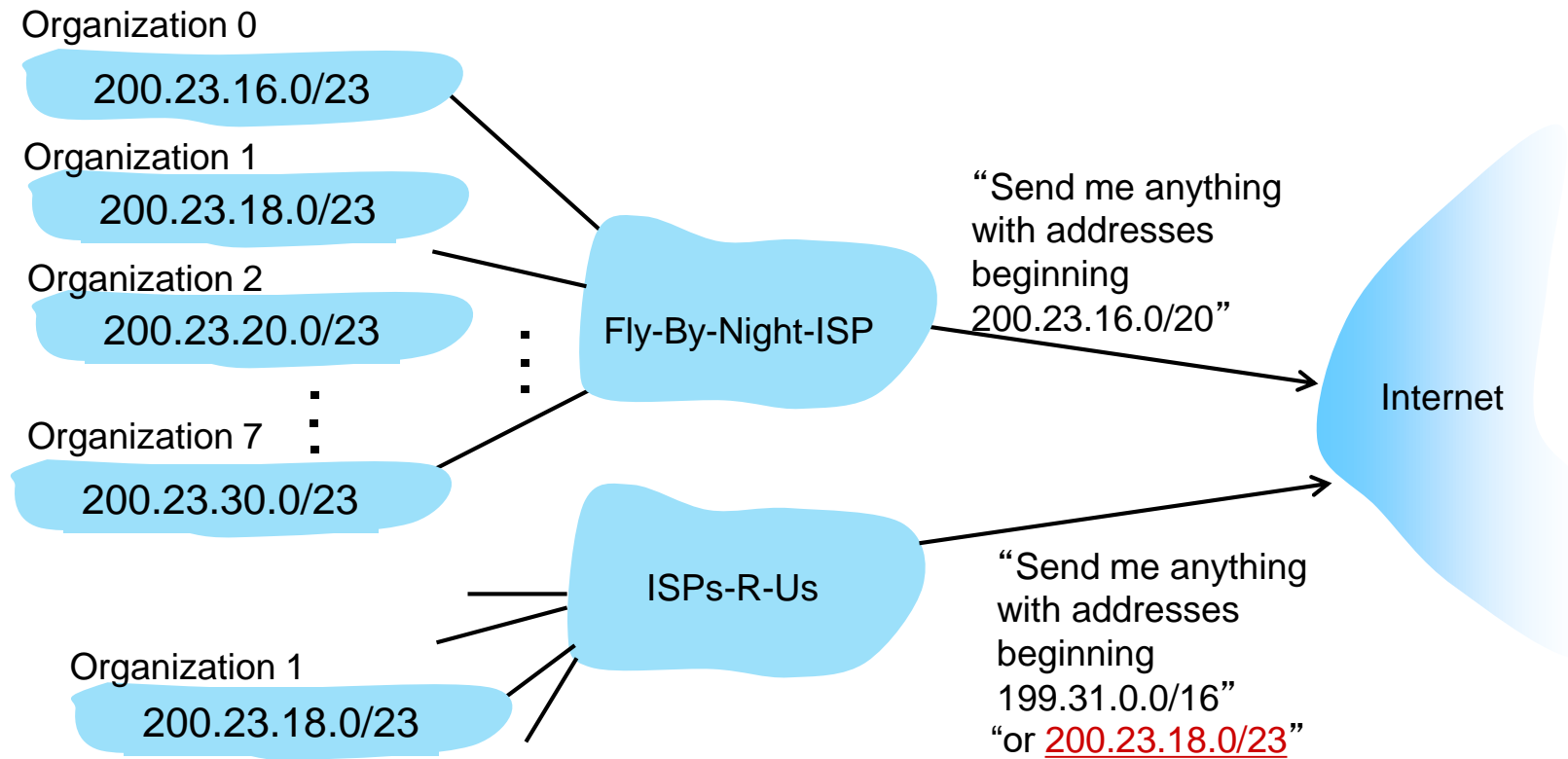
# Hierarchical addressing: route aggregation

hierarchical addressing allows efficient advertisement of routing information:



# Hierarchical addressing: more specific routes

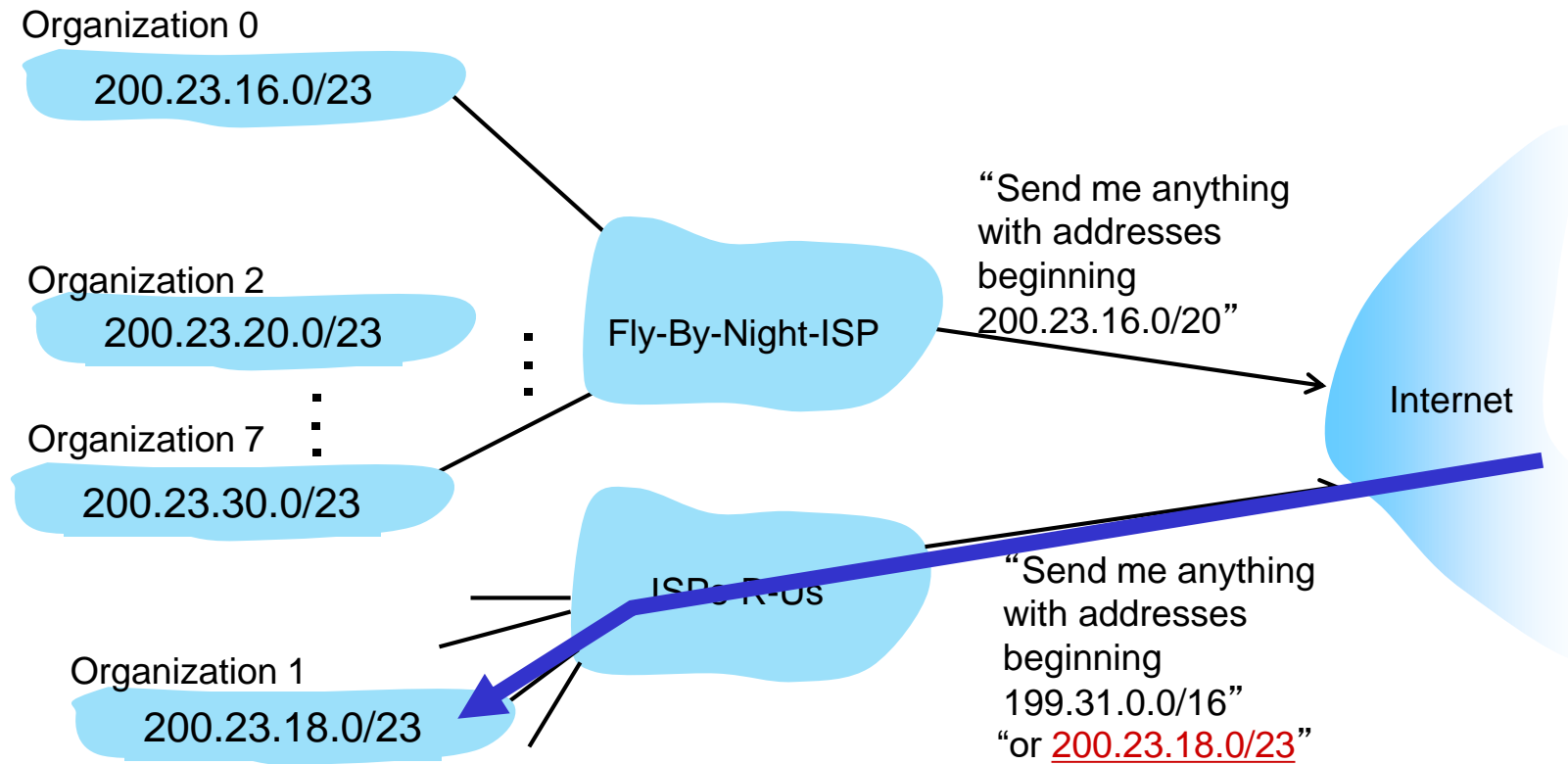
- Organization 1 moves from Fly-By-Night-ISP to ISPs-R-Us
- ISPs-R-Us now advertises a more specific route to Organization 1





# 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

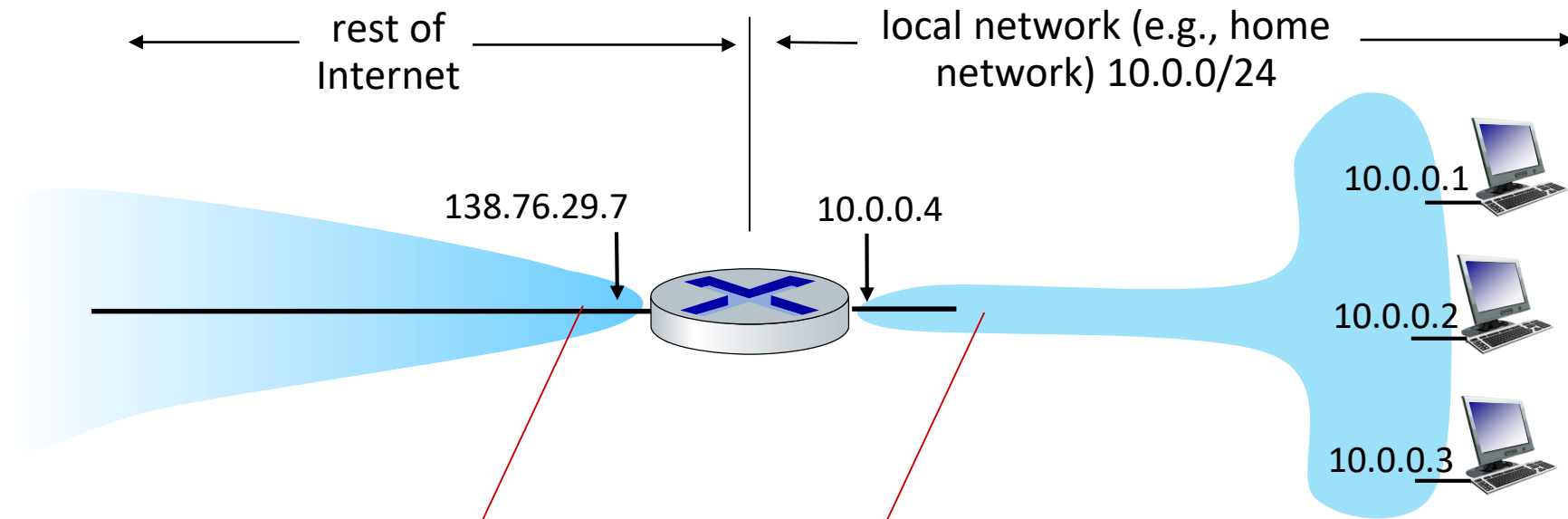
**Q:** are there enough 32-bit IP addresses?

- 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)

# 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

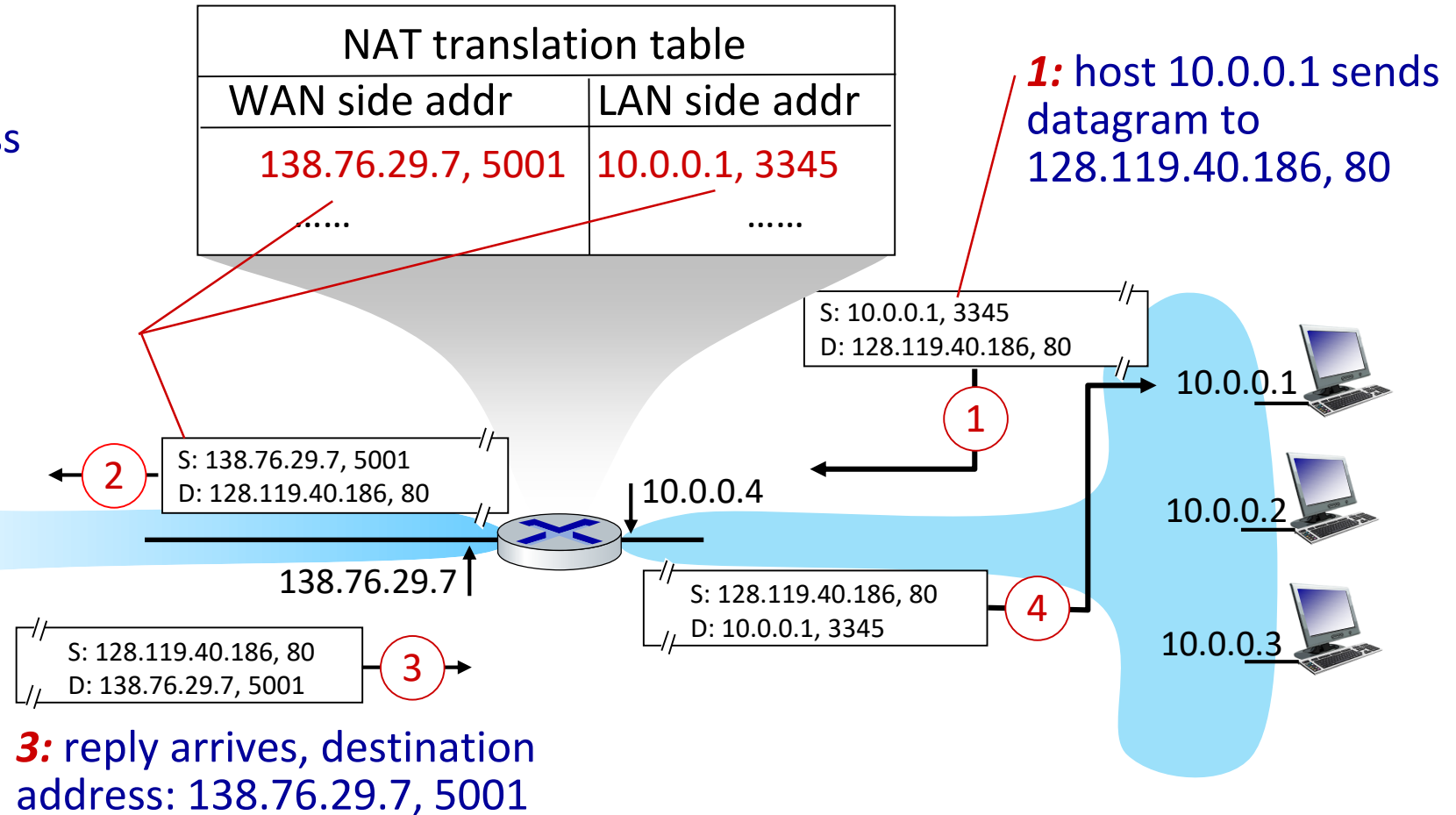
# NAT: network address translation

**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

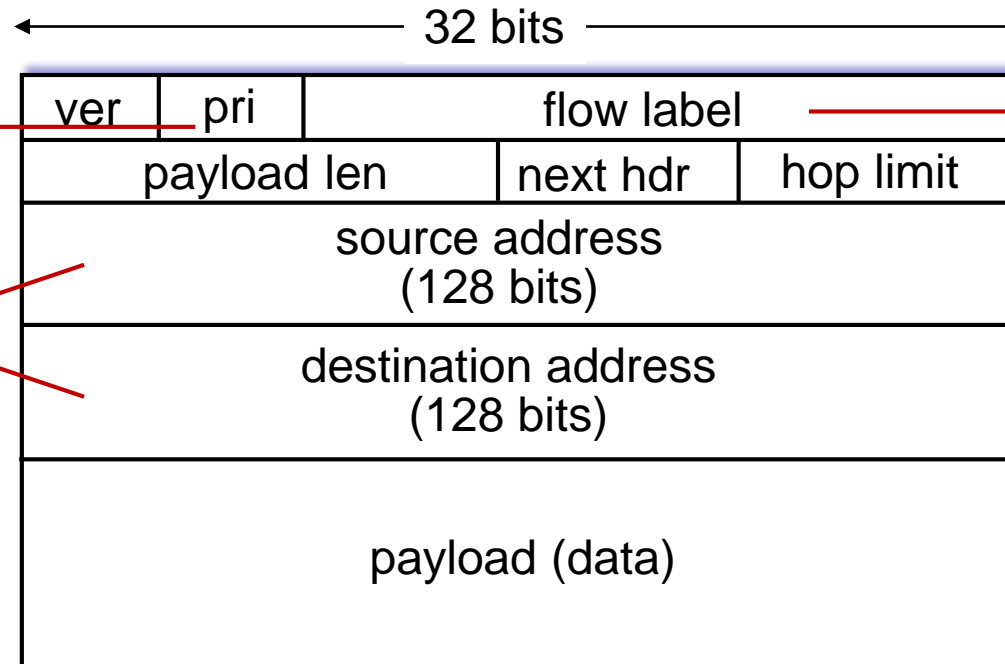
- **initial motivation:** 32-bit IPv4 address space would be completely allocated
- additional motivation:
  - speed processing/forwarding: 40-byte fixed length header
  - enable different network-layer treatment of “flows”



# IPv6 datagram format

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

**128-bit**  
IPv6 addresses



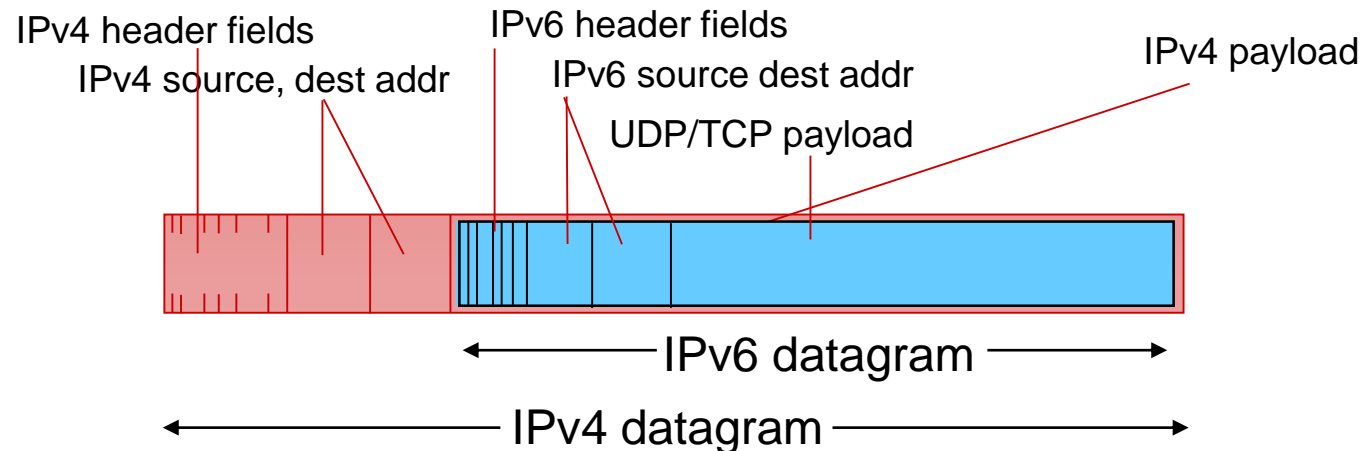
**flow label:** identify  
datagrams in same  
"flow." (concept of  
"flow" not well defined).

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)

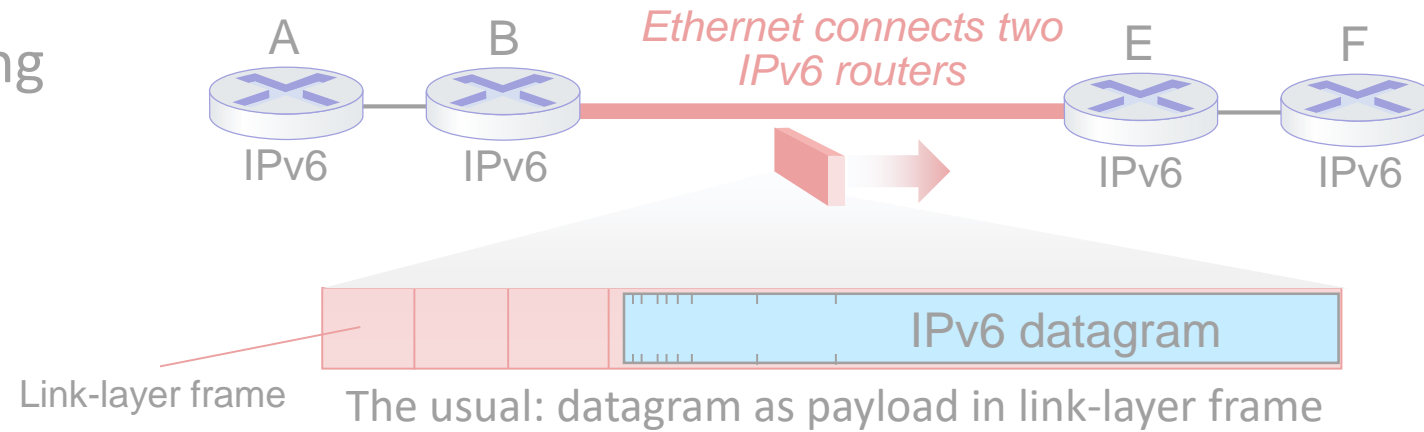
# Transition from IPv4 to IPv6

- 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)

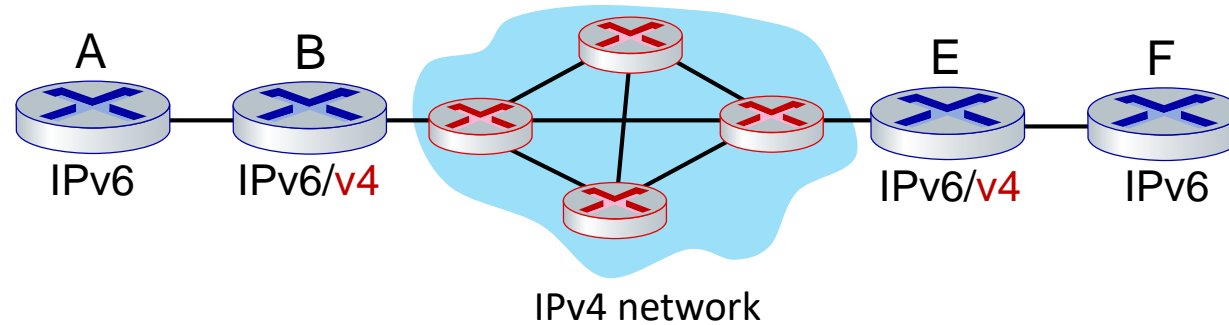


# Tunneling and encapsulation

Ethernet connecting two IPv6 routers:

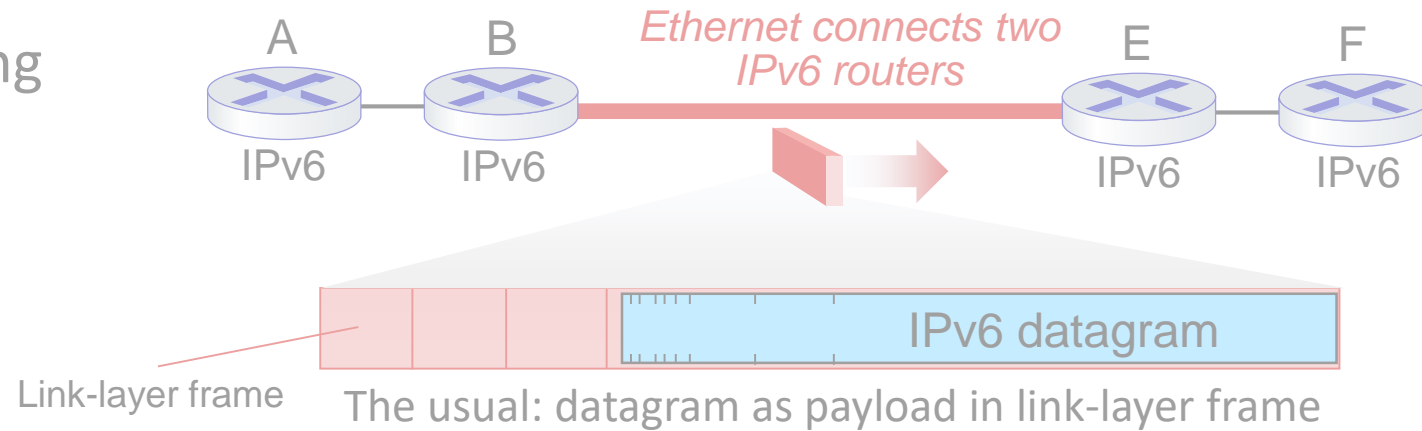


IPv4 network connecting two IPv6 routers

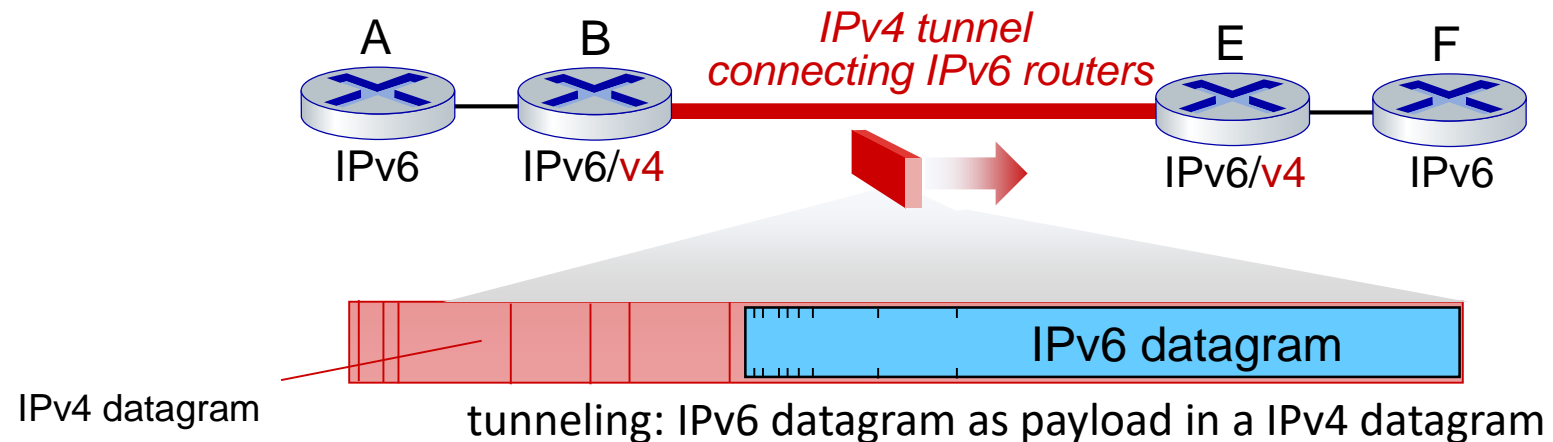


# Tunneling and encapsulation

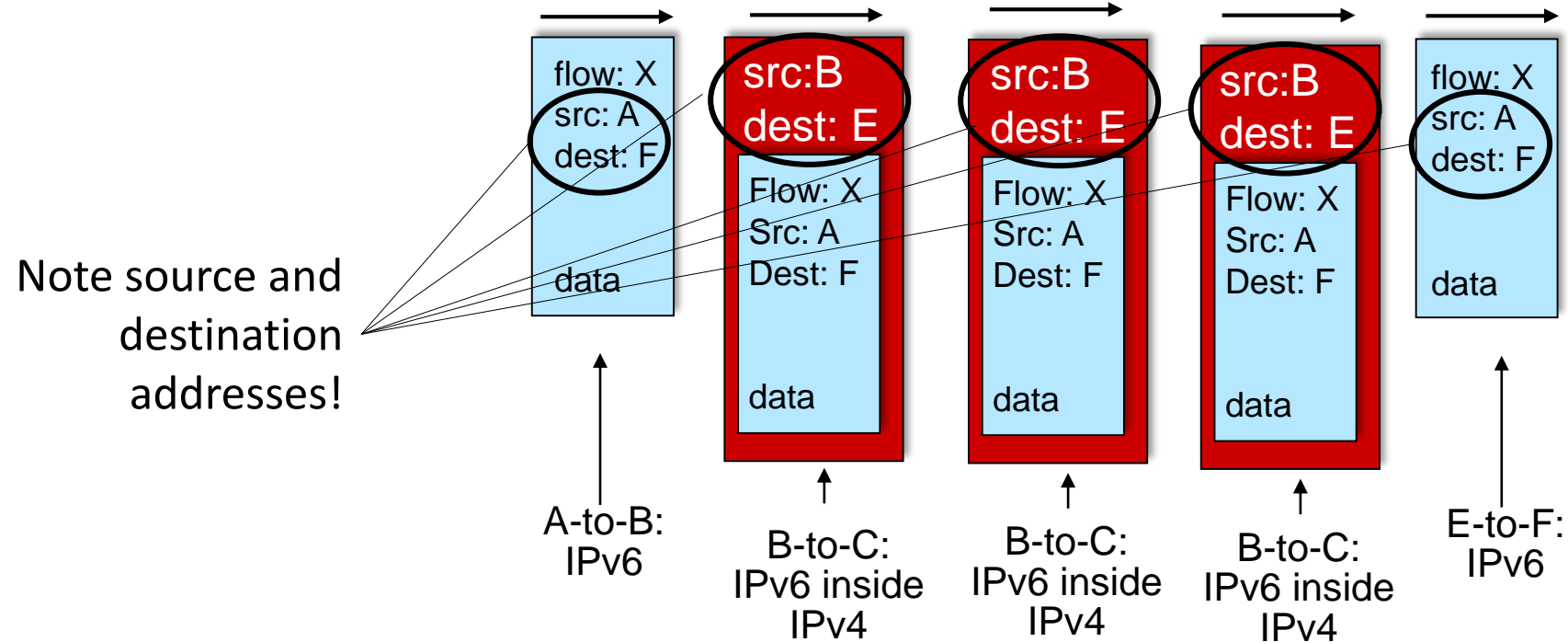
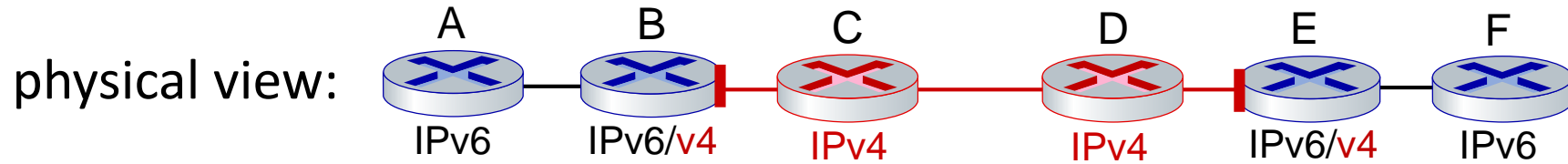
Ethernet connecting two IPv6 routers:



IPv4 tunnel connecting two IPv6 routers



# Tunneling

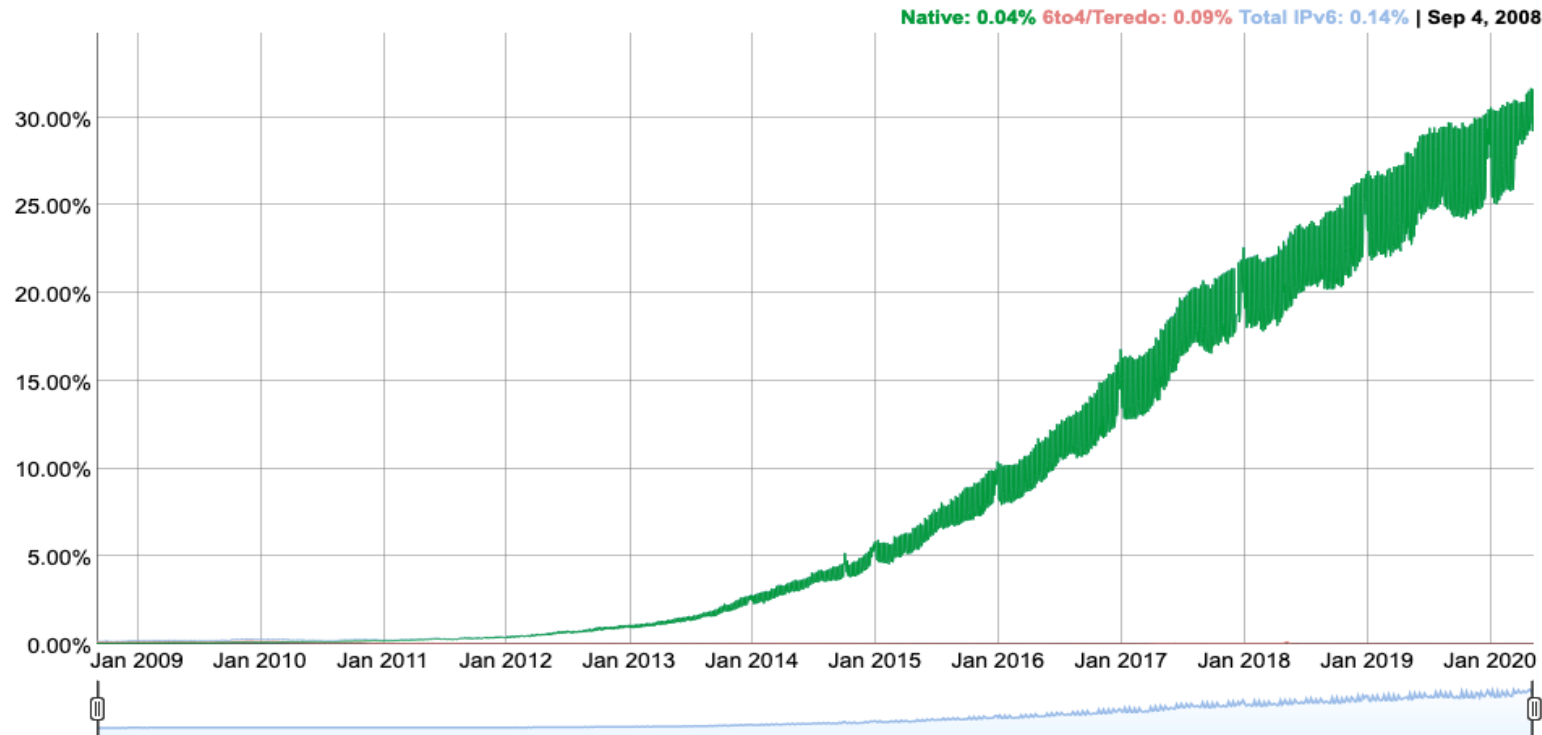


# IPv6: adoption

- Google<sup>1</sup>: ~ 30% of clients access services via IPv6
- 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.



1

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

# IPv6: adoption

- Google<sup>1</sup>: ~ 30% of clients access services via IPv6
- 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>

## Network Layer – Data plane

- ✓ Network layer: services and overview
- ✓ Routers
- ✓ Internet protocol
- ✓ Generalized forwarding and SDN

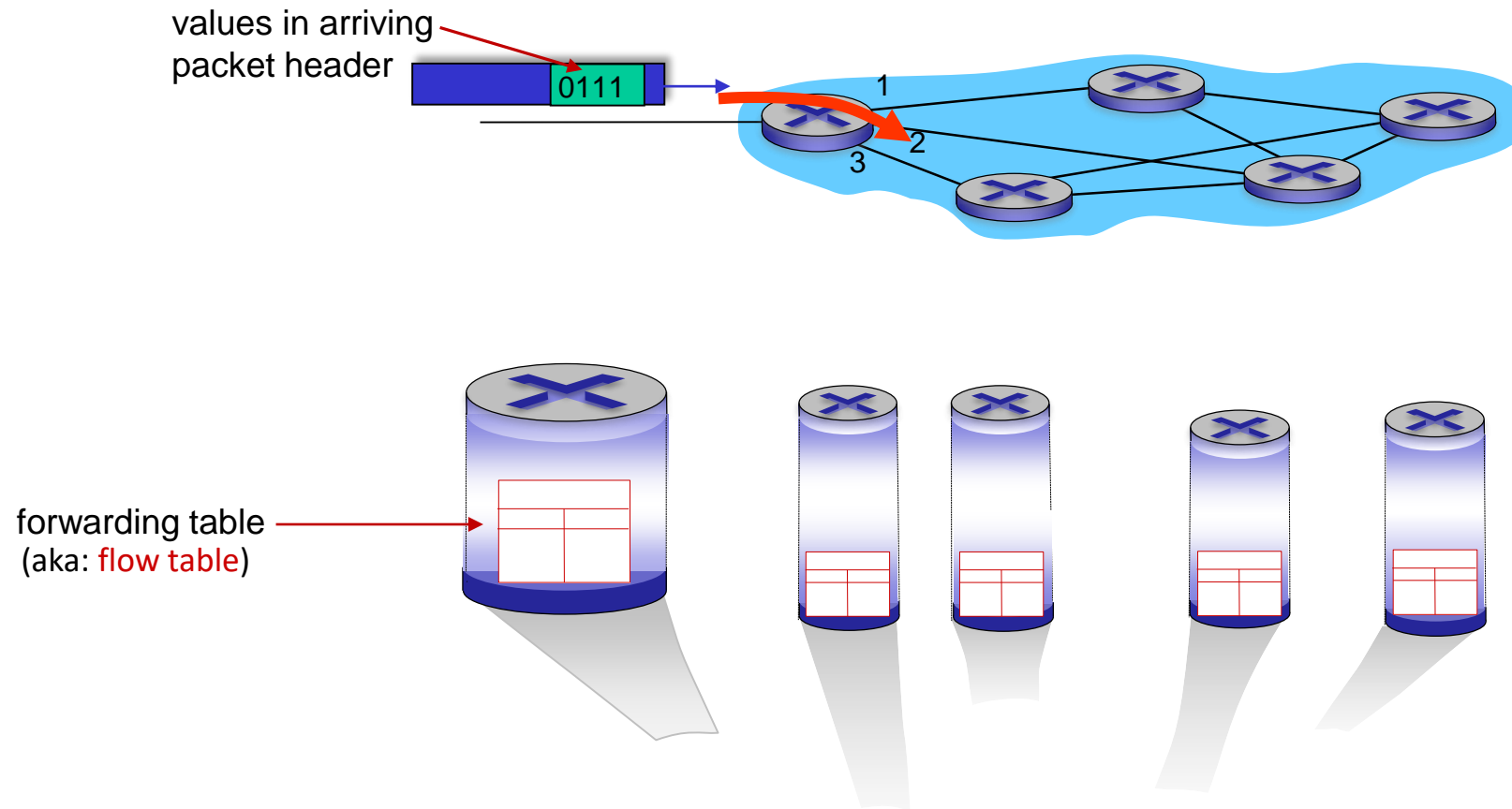


# Generalized forwarding: match plus action

*Review:* each router contains a **forwarding table** (aka: **flow table**)

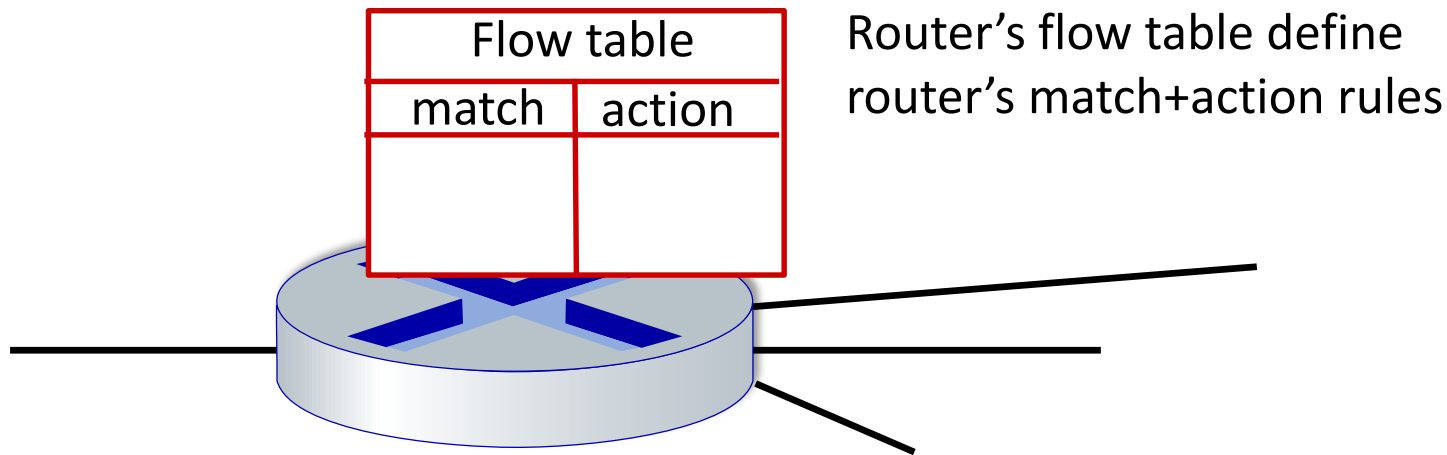
- “**match plus action**” abstraction: match bits in arriving packet, take action
  - *destination-based forwarding*: forward based on dest. IP address
  - *generalized forwarding*:
    - many header fields can determine action
    - many action possible: drop/copy/modify/log packet

# Generalized forwarding: match plus action



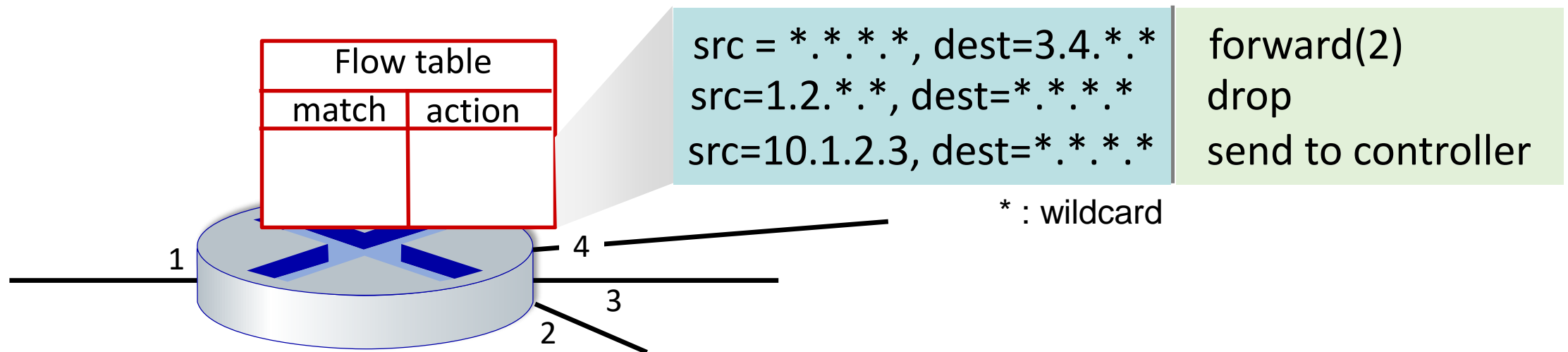
# Flow table abstraction

- **flow**: defined by header field values (in link-, network-, transport-layer fields)
- **generalized forwarding**: simple packet-handling rules
  - **match**: pattern values in packet header fields
  - **actions**: for matched packet: drop, forward, modify, matched packet or send matched packet to controller
  - **priority**: disambiguate overlapping patterns
  - **counters**: #bytes and #packets

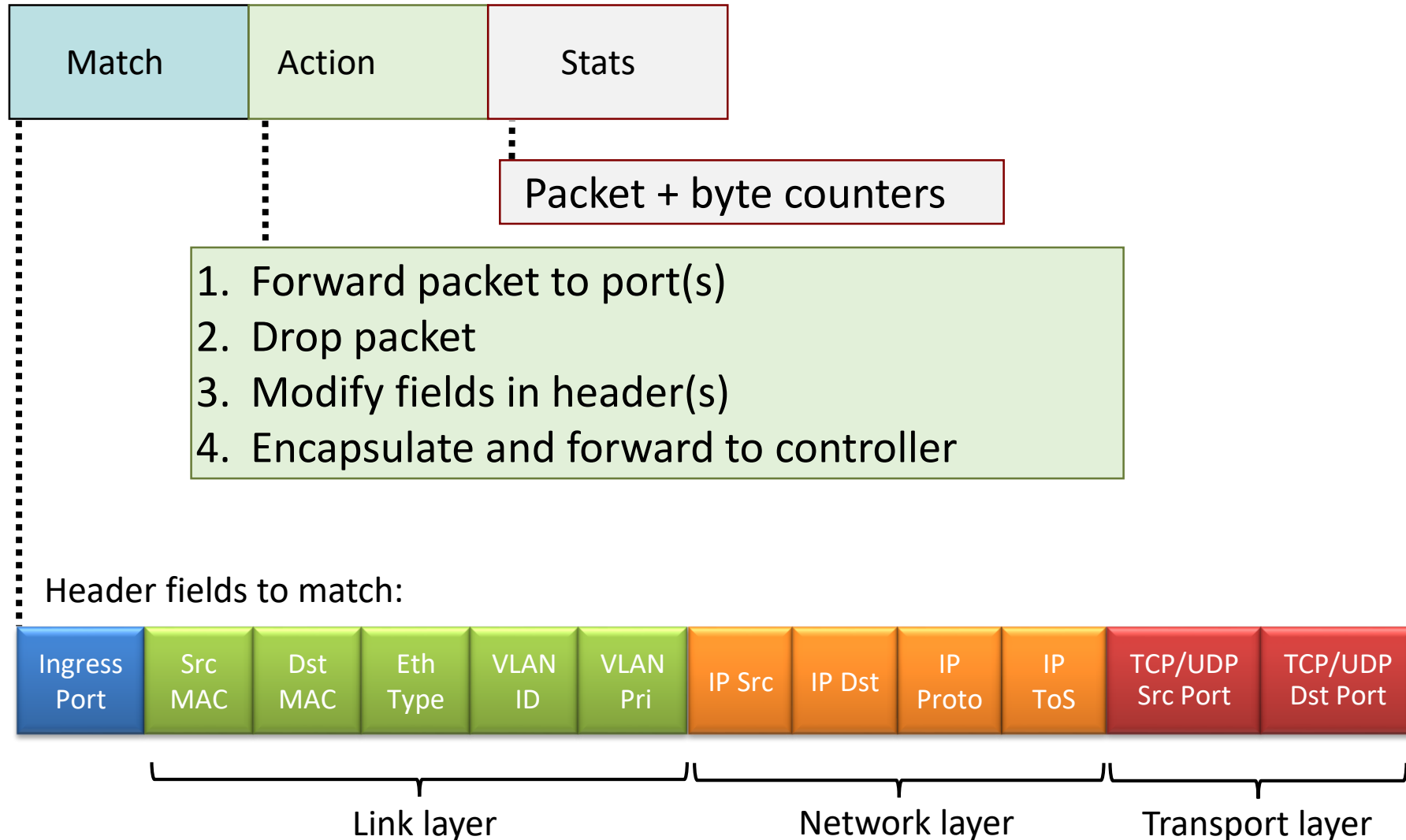


# Flow table abstraction

- **flow**: defined by header fields
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# OpenFlow: flow table entries



# OpenFlow: examples

## Destination-based forwarding:

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	VLAN Pri	IP Src	IP Dst	IP Prot	IP ToS	TCP s-port	TCP d-port	Action
*	*	*	*	*	*	*	51.6.0.8	*	*	*	*	port6

IP datagrams destined to IP address 51.6.0.8 should be forwarded to router output port 6

## Firewall:

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	VLAN Pri	IP Src	IP Dst	IP Prot	IP ToS	TCP s-port	TCP d-port	Action
*	*	*	*	*	*	*	*	*	*	*	22	drop

Block (do not forward) all datagrams destined to TCP port 22 (ssh port #)

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	VLAN Pri	IP Src	IP Dst	IP Prot	IP ToS	TCP s-port	TCP d-port	Action
*	*	*	*	*	*	128.119.1.1	*	*	*	*	*	drop

Block (do not forward) all datagrams sent by host 128.119.1.1

# OpenFlow: examples

Layer 2 destination-based forwarding:

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	VLAN Pri	IP Src	IP Dst	IP Prot	IP ToS	TCP s-port	TCP d-port	Action
*	*	22:A7:23:11:E1:02	*	*	*	*	*	*	*	*	*	port3

layer 2 frames with destination MAC address 22:A7:23:11:E1:02 should be forwarded to output port 3

# OpenFlow abstraction

- **match+action**: abstraction unifies different kinds of devices

## Router

- *match*: longest destination IP prefix
- *action*: forward out a link

## Switch

- *match*: destination MAC address
- *action*: forward or flood

## Firewall

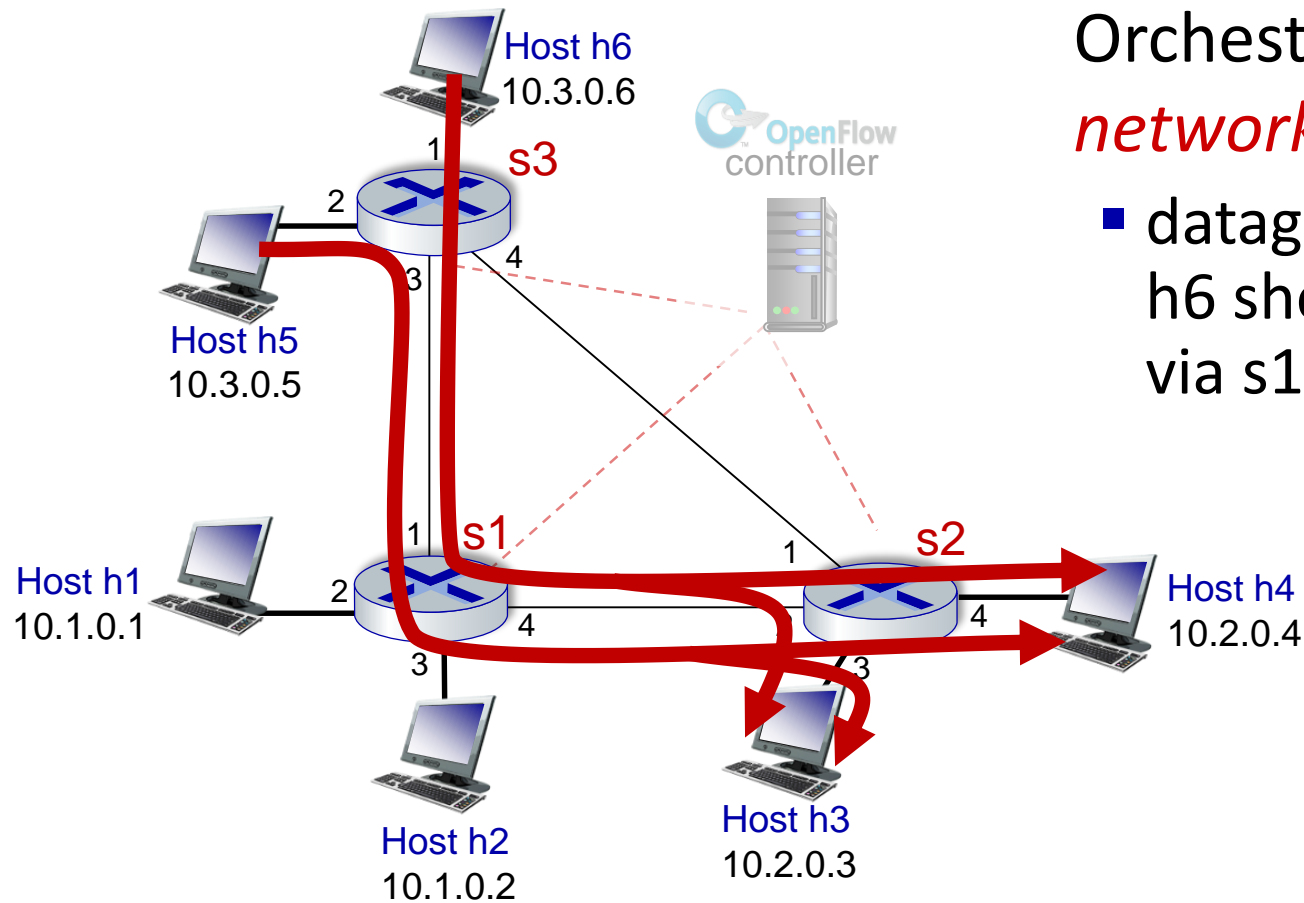
- *match*: IP addresses and TCP/UDP port numbers
- *action*: permit or deny

## NAT

- *match*: IP address and port
- *action*: rewrite address and port



# OpenFlow example

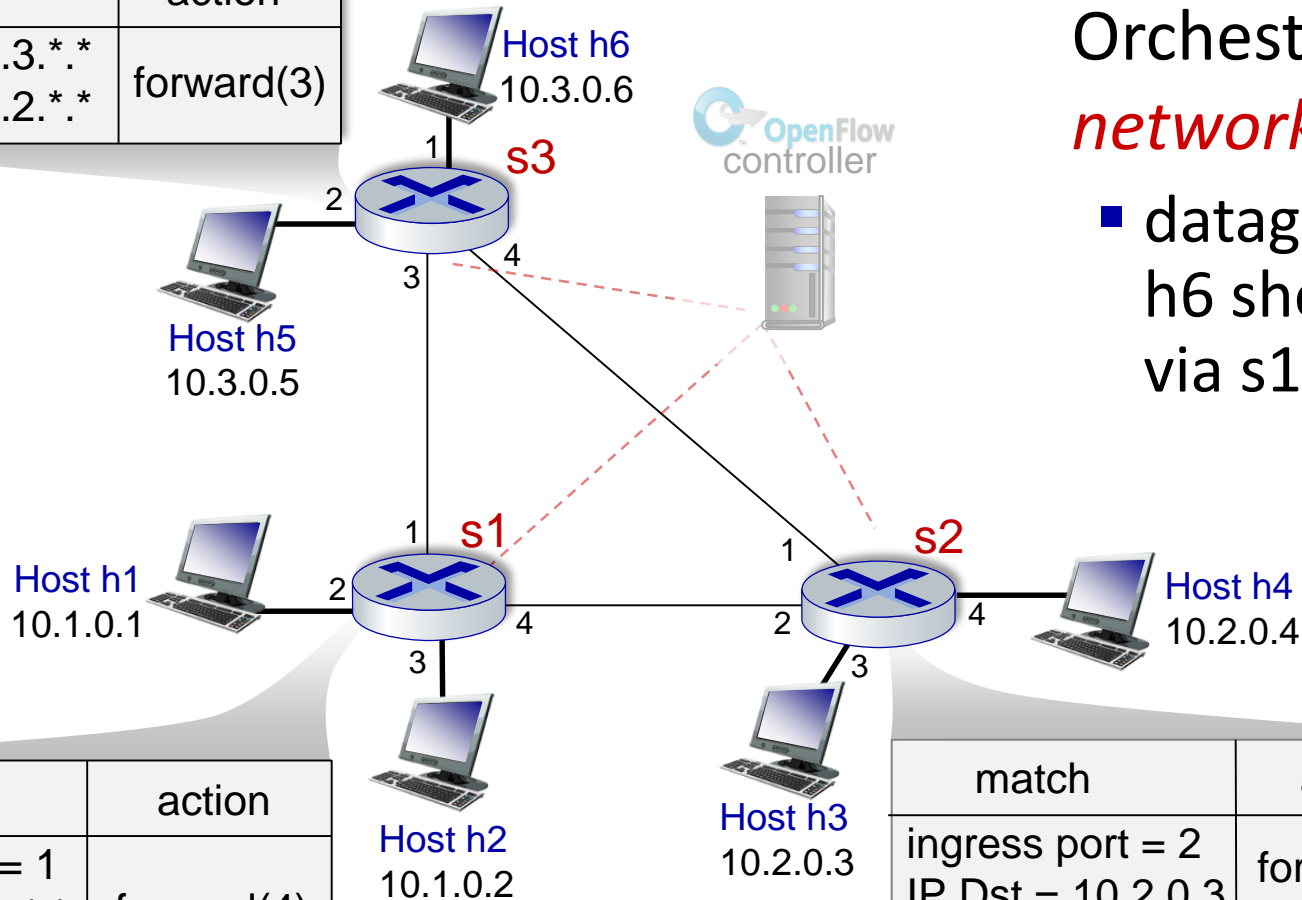


Orchestrated tables can create *network-wide* behavior, e.g.,:

- datagrams from hosts h5 and h6 should be sent to h3 or h4, via s1 and from there to s2

# OpenFlow example

match	action
IP Src = 10.3.*.* IP Dst = 10.2.*.*	forward(3)



match	action
ingress port = 1 IP Src = 10.3.*.* IP Dst = 10.2.*.*	forward(4)

match	action
ingress port = 2 IP Dst = 10.2.0.3	forward(3)
ingress port = 2 IP Dst = 10.2.0.4	forward(4)

Orchestrated tables can create *network-wide* behavior, e.g.,:

- datagrams from hosts h5 and h6 should be sent to h3 or h4, via s1 and from there to s2

# Generalized forwarding: summary

- “match plus action” abstraction: match bits in arriving packet header(s) in any layers, take action
  - matching over many fields (link-, network-, transport-layer)
  - local actions: drop, forward, modify, or send matched packet to controller
  - “program” *network-wide* behaviors
- simple form of “network programmability”
  - programmable, per-packet “processing”
  - *historical roots*: active networking
  - *today*: more generalized programming: P4 (see [p4.org](http://p4.org)).

# References

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Figures and slides are taken/adapted from:

- Jim Kurose, Keith Ross, "Computer Networking: A Top-Down Approach", 7th ed. Addison-Wesley, 2012. All material copyright 1996-2016 J.F Kurose and K.W. Ross, All Rights Reserved
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