

# Chapter 4

## Network Layer: The Data Plane

Applications

... built on ...

Reliable (or unreliable) transport

... built on ...

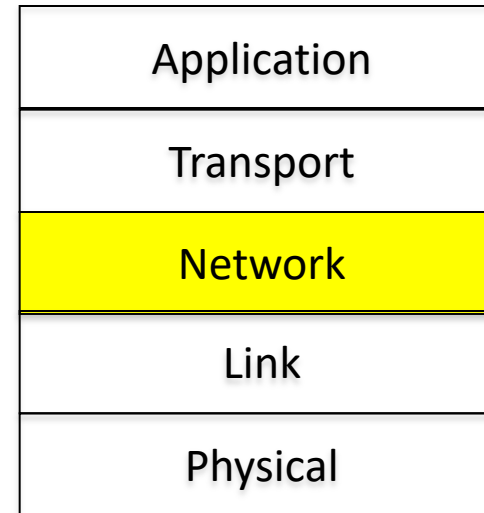
Best-effort global packet delivery

... **built on** ...

Best-effort local packet delivery

... built on ...

Physical transfer of bits



Source: Scott Shenker (UC Berkeley): slide 7 at The Future of Networking, and the Past of Protocols

<https://www.youtube.com/watch?v=YHeyuD89nIY&t=111s>

# Network layer: “data plane” roadmap

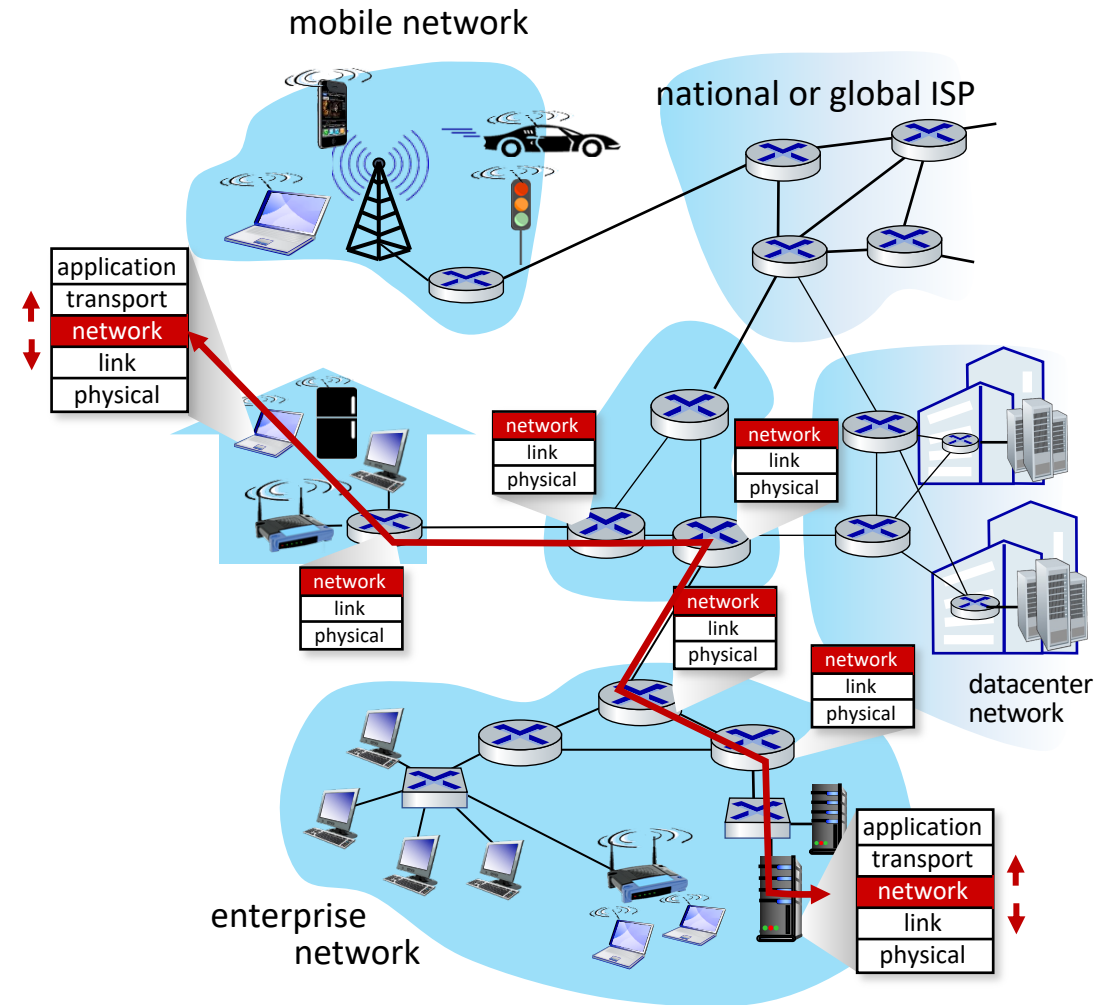
- Network layer: overview
  - data plane
  - control plane
- What’s inside a router
  - input ports, switching, output ports
  - buffer management, scheduling
- IP: the Internet Protocol
  - datagram format
  - addressing
  - network address translation
  - IPv6



- ~~Generalized Forwarding, SDN~~
  - ~~Match+action~~
  - ~~OpenFlow: match+action in action~~
- ~~Middleboxes~~

# Network-layer services and protocols

- transport segment from sending to receiving host
  - **sender:** encapsulates segments into datagrams, passes to link layer
  - **receiver:** delivers segments to transport layer protocol
- network layer protocols in *every Internet device*: hosts, routers
- **routers:**
  - examines header fields in all IP datagrams passing through it
  - moves datagrams from input ports to output ports to transfer datagrams along end-end path



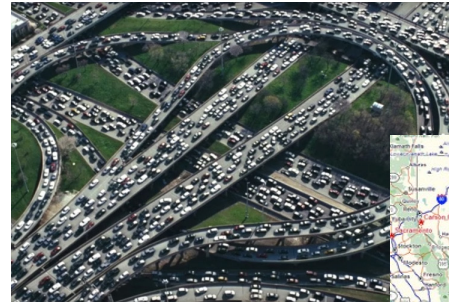
# Two key network-layer functions

## network-layer functions:

- *forwarding*: move packets from a router's input link to appropriate router output link
- *routing*: determine route taken by packets from source to destination
  - *routing algorithms*

## analogy: taking a trip

- *forwarding*: process of getting through single interchange
- *routing*: process of planning trip from source to destination



forwarding

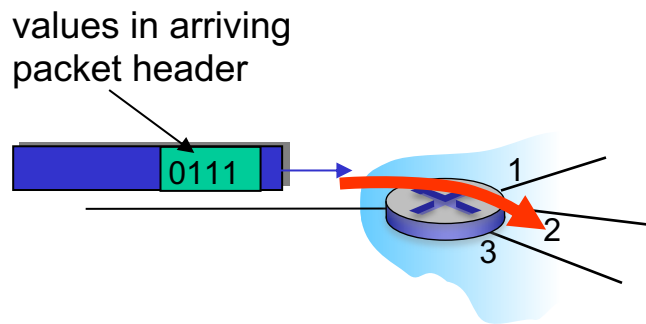


routing

# Network layer: data plane, control plane

## Data plane:

- *local*, per-router function
- determines how datagram arriving on router input port is forwarded to router output port

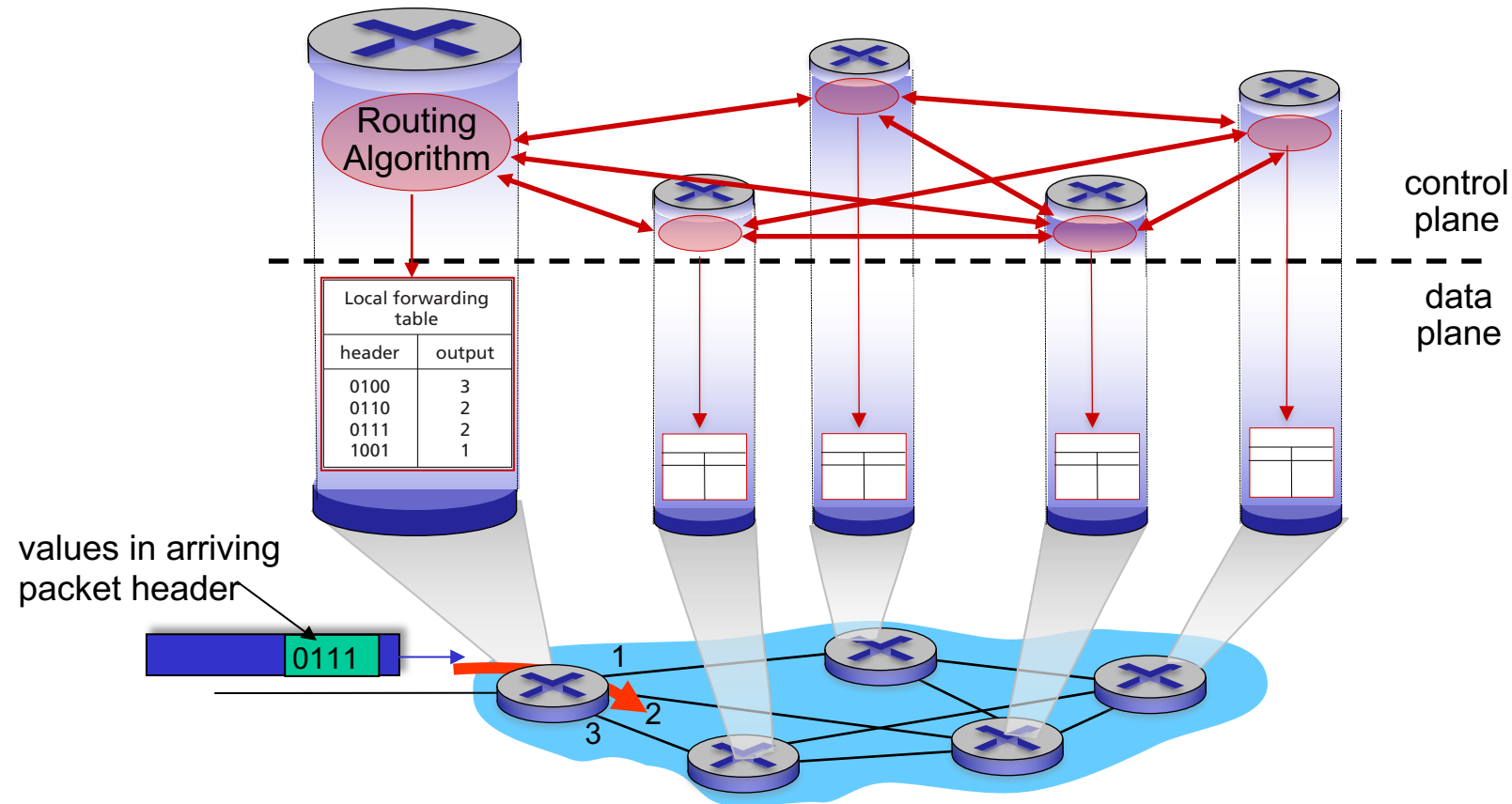


## Control plane

- *network-wide* logic
- determines how datagram is routed among routers along end-end path from source host to destination host
- two control-plane approaches:
  - *traditional routing algorithms*: implemented in routers
  - *software-defined networking (SDN)*: implemented in (remote) servers

# Per-router control plane

Individual routing algorithm components *in each and every router* interact in the control plane



# Network service model

*Q:* What *service model* for “channel” transporting datagrams from sender to receiver?

example services for  
*individual* datagrams:

- guaranteed delivery
- guaranteed delivery with less than 40 msec delay

example services for a *flow* of  
datagrams:

- in-order datagram delivery
- guaranteed minimum bandwidth to flow
- restrictions on changes in inter-packet spacing

# Network-layer service model

Network Architecture	Service Model	Quality of Service (QoS) Guarantees ?			
		Bandwidth	Loss	Order	Timing
Internet	best effort	none	no	no	no

Internet “best effort” service model

*No* guarantees on:

- i. successful datagram delivery to destination
- ii. timing or order of delivery
- iii. bandwidth available to end-end flow



# Network-layer service model

Network Architecture	Service Model	Quality of Service (QoS) Guarantees ?			
		Bandwidth	Loss	Order	Timing
Internet	best effort	none	no	no	no
ATM	Constant Bit Rate	Constant rate	yes	yes	yes
ATM	Available Bit Rate	Guaranteed min	no	yes	no
Internet	Intserv Guaranteed (RFC 1633)	yes	yes	yes	yes
Internet	Diffserv (RFC 2475)	possible	possibly	possibly	no

# Reflections on best-effort service:

- **simplicity of mechanism** has allowed Internet to be widely deployed adopted
- sufficient **provisioning of bandwidth** allows performance of real-time applications (e.g., interactive voice, video) to be “good enough” for “most of the time”
- **replicated, application-layer distributed services** (datacenters, content distribution networks) connecting close to clients’ networks, allow services to be provided from multiple locations
- congestion control of “elastic” services helps

*It's hard to argue with success of best-effort service model*

# Network layer: “data plane” roadmap

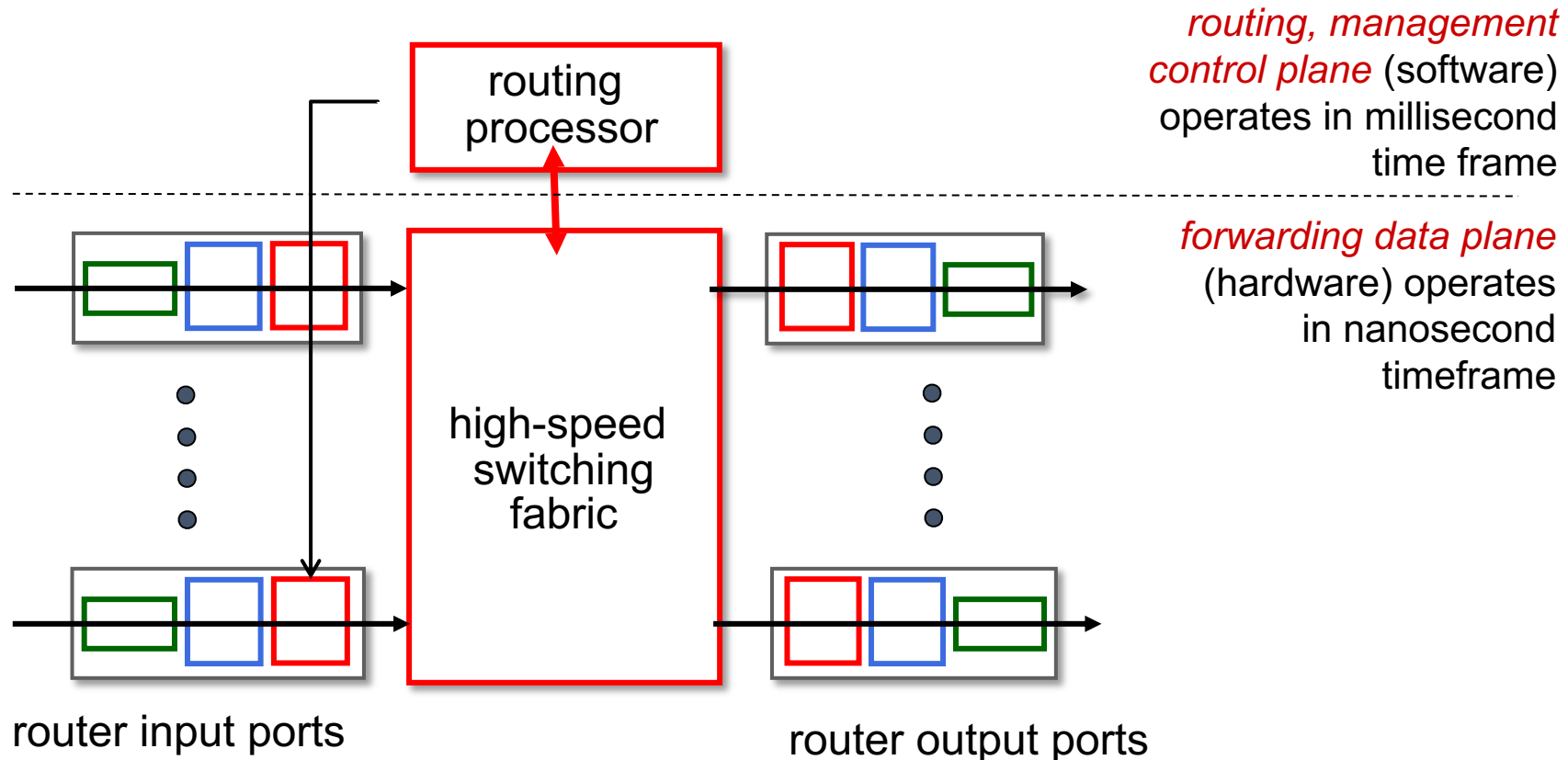
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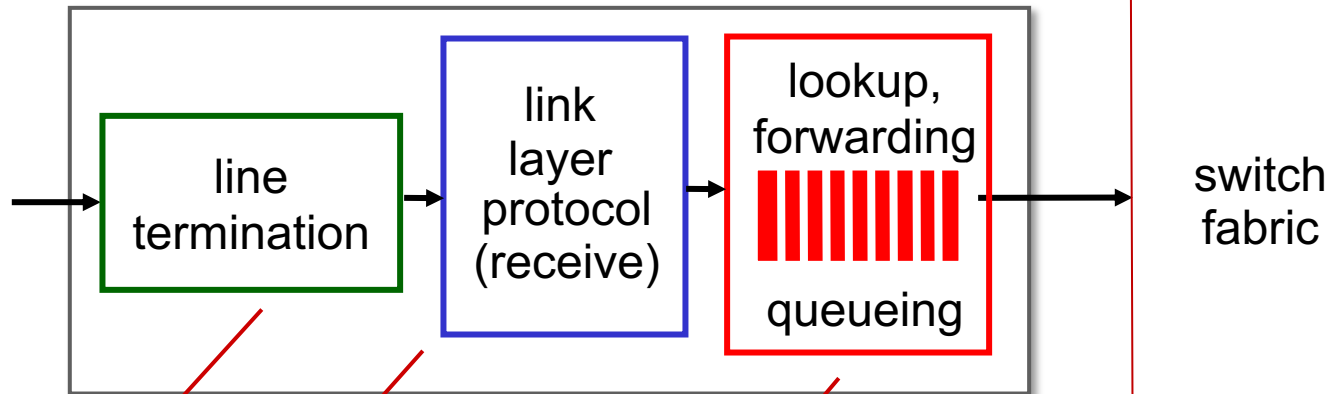
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# Router architecture overview

high-level view of generic router architecture:



# Input port functions



physical layer:  
bit-level reception

link layer:  
e.g., Ethernet  
(chapter 6)

## decentralized switching:

- using header field values, lookup output port using forwarding table in input port memory (*“match plus action”*)
- goal: complete input port processing at ‘line speed’
- **input port queuing**: if datagrams arrive faster than forwarding rate into switch fabric
- **destination-based forwarding**: forward based only on destination IP address (traditional)

# Destination-based forwarding

*forwarding table*

Destination Address Range	Link Interface
11001000 00010111 00010000 00000000 through 11001000 00010111 00010000 00000100	n
11001000 00010111 00010000 00000111	3
11001000 00010111 00011000 11111111	
11001000 00010111 00011001 00000000 through 11001000 00010111 00011111 11111111	2
otherwise	3

*Q:* but what happens if ranges don't divide up so nicely?

# Longest prefix matching

## longest prefix match

when looking for forwarding table entry for given destination address, use *longest* address prefix that matches destination address.

Destination Address Range	Link interface
11001000 00010111 00010*** *****	0
11001000 00010111 00011000 *****	1
11001000 00010111 00011*** *****	2
otherwise	3

examples:

11001000 00010111 00010110 10100001    which interface?

11001000 00010111 00011000 10101010    which interface?

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11001000 00010111 00011000 *****	1
11001000 <b>match!</b> 1 00011*** *****	2
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examples:

11001000 00010111 00010110 10100001	which interface?
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↑  
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match!

examples:

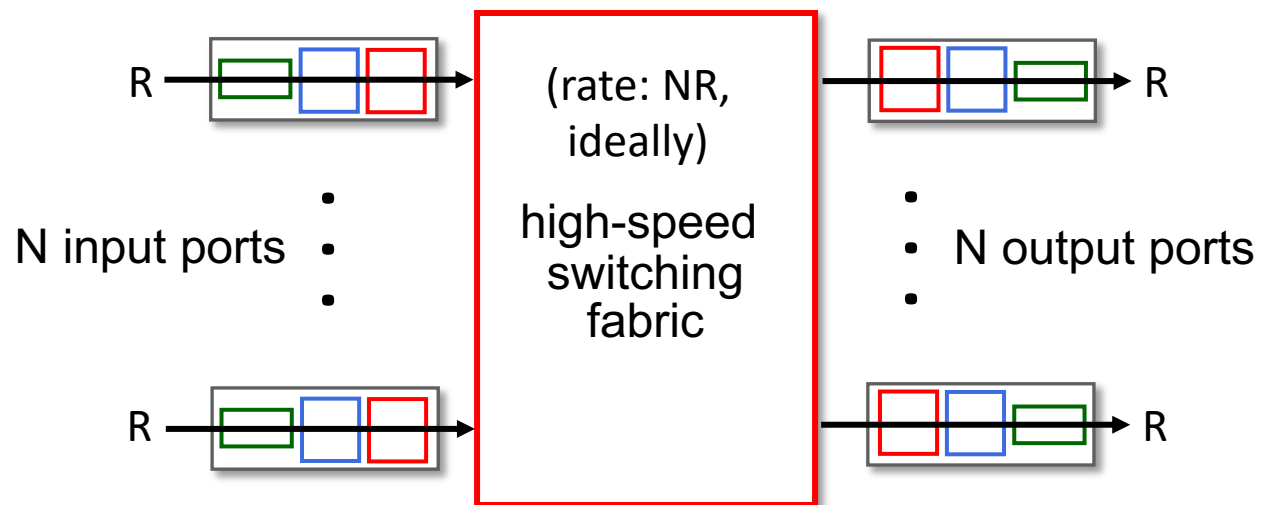
11001000 00010111 00010110	10100001	which interface?
11001000 00010111 00011000	10101010	which interface?

# Longest prefix matching

- we'll see *why* longest prefix matching is used shortly, when we study addressing
- longest prefix matching: often performed using ternary content addressable memories (TCAMs)
  - *content addressable*: present address to TCAM: retrieve address in one clock cycle, regardless of table size
  - Cisco Catalyst: ~1M routing table entries in TCAM

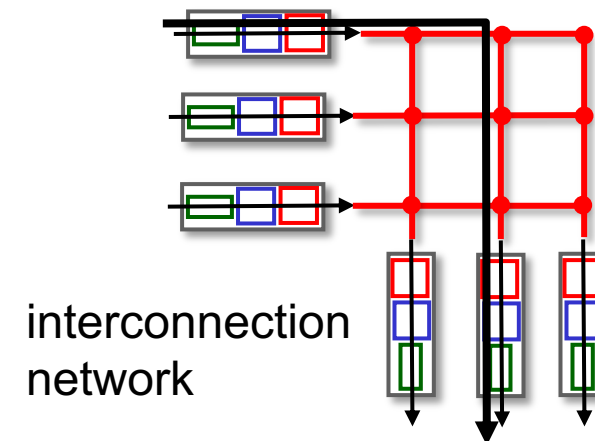
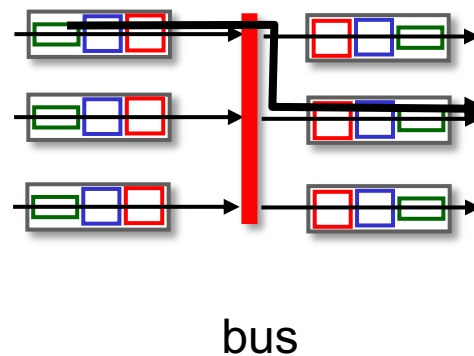
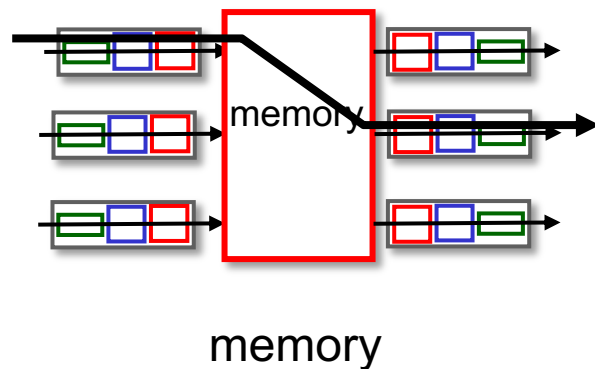
# Switching fabrics

- transfer packet from input link to appropriate output link
- **switching rate**: rate at which packets can be transfer from inputs to outputs
  - often measured as multiple of input/output line rate
  - N inputs: switching rate N times line rate desirable



# Switching fabrics

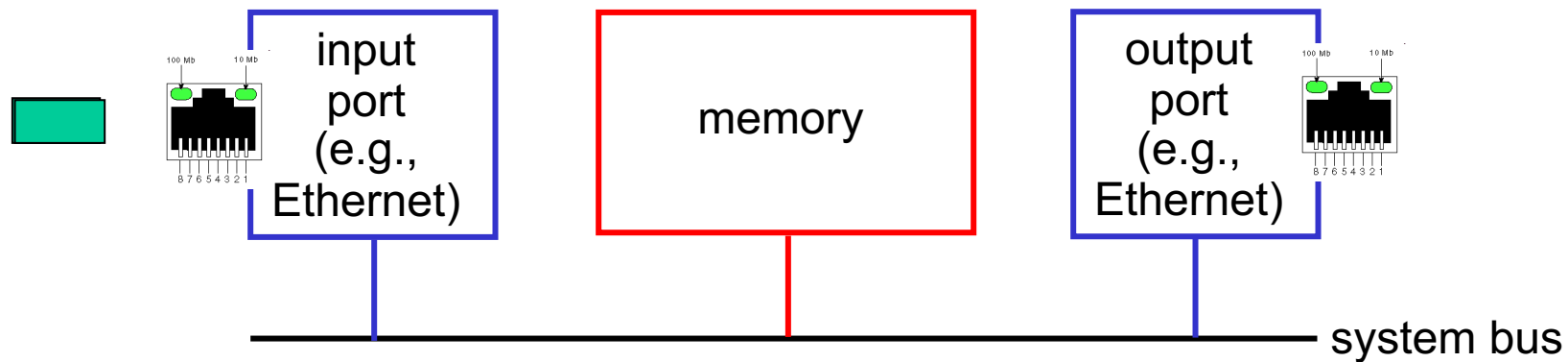
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  - often measured as multiple of input/output line rate
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- three major types of switching fabrics:



# Switching via memory

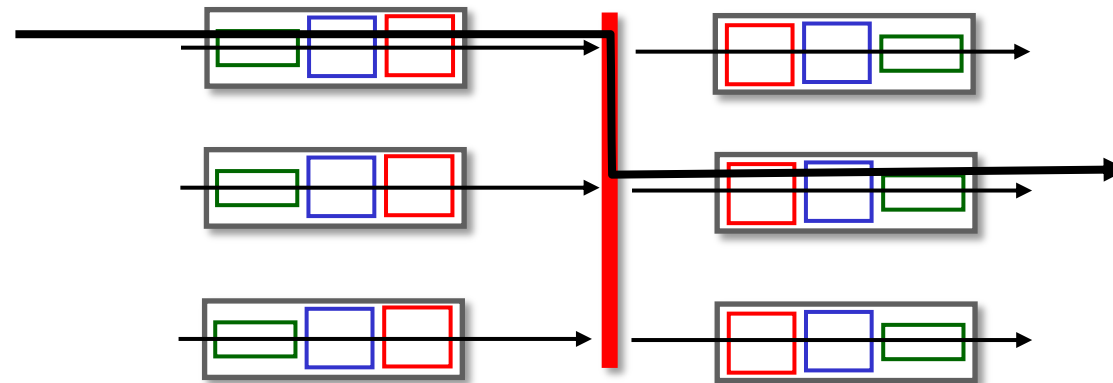
## first generation routers:

- traditional computers with switching under direct control of CPU
- packet copied to system's memory
- speed limited by memory bandwidth (2 bus crossings per datagram)



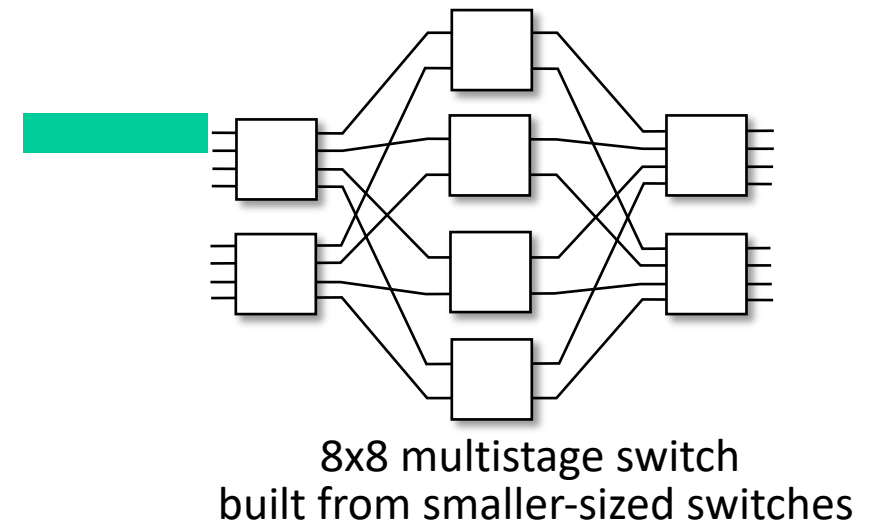
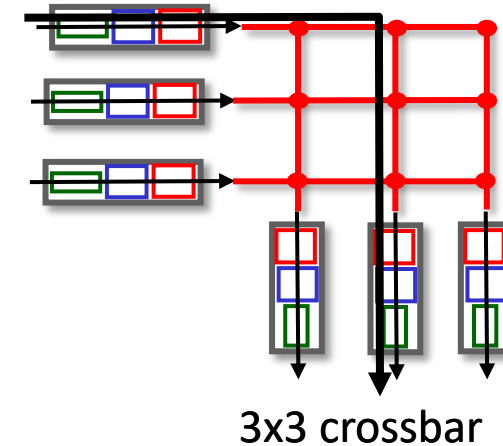
# Switching via a bus

- datagram from input port memory to output port memory via a shared bus
- *bus contention*: switching speed limited by bus bandwidth
- 32 Gbps bus, Cisco 5600: sufficient speed for access routers



# Switching via interconnection network

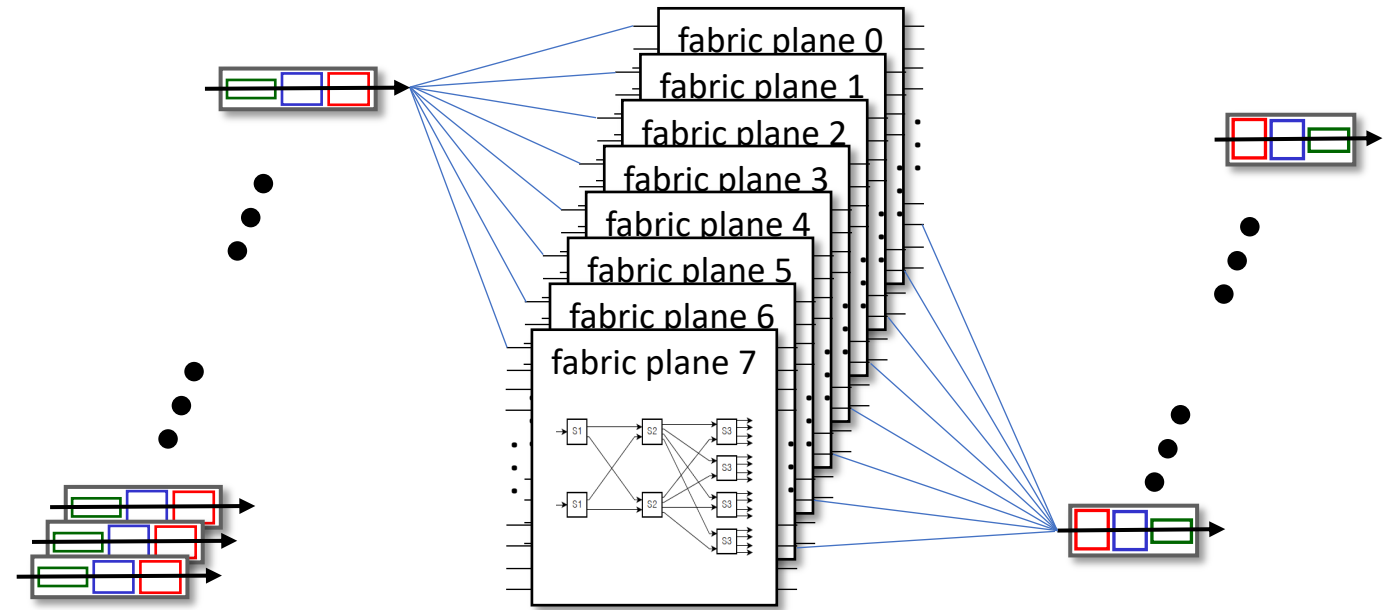
- Crossbar, Clos networks, other interconnection nets initially developed to connect processors in multiprocessor
- **multistage switch**:  $n \times n$  switch from multiple stages of smaller switches
- **exploiting parallelism**:
  - fragment datagram into fixed length cells on entry
  - switch cells through the fabric, reassemble datagram at exit





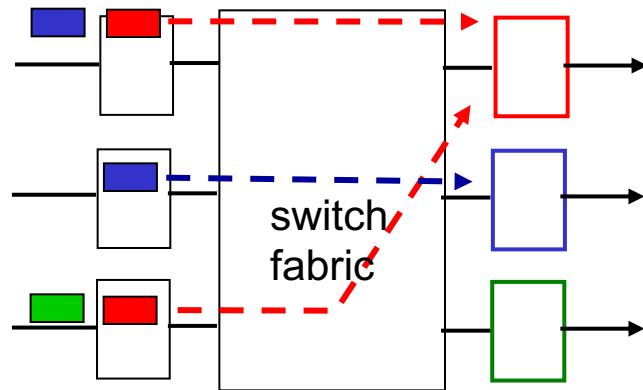
# Switching via interconnection network

- scaling, using multiple switching “planes” in parallel:
  - speedup, scaleup via parallelism
- Cisco CRS router:
  - basic unit: 8 switching planes
  - each plane: 3-stage interconnection network
  - up to 100’s Tbps switching capacity

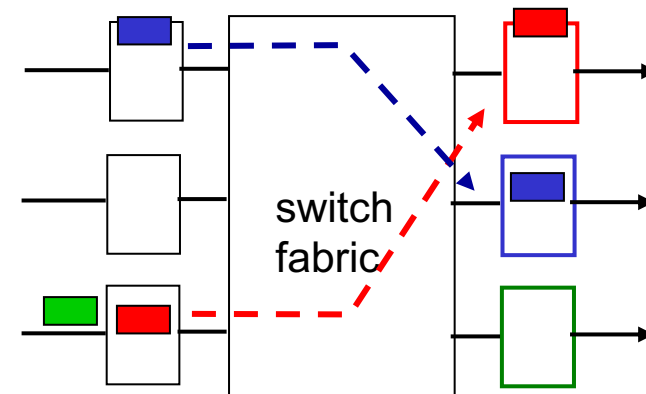


# Input port queuing

- If switch fabric slower than input ports combined -> queueing may occur at input queues
  - queueing delay and loss due to input buffer overflow!
- **Head-of-the-Line (HOL) blocking:** queued datagram at front of queue prevents others in queue from moving forward

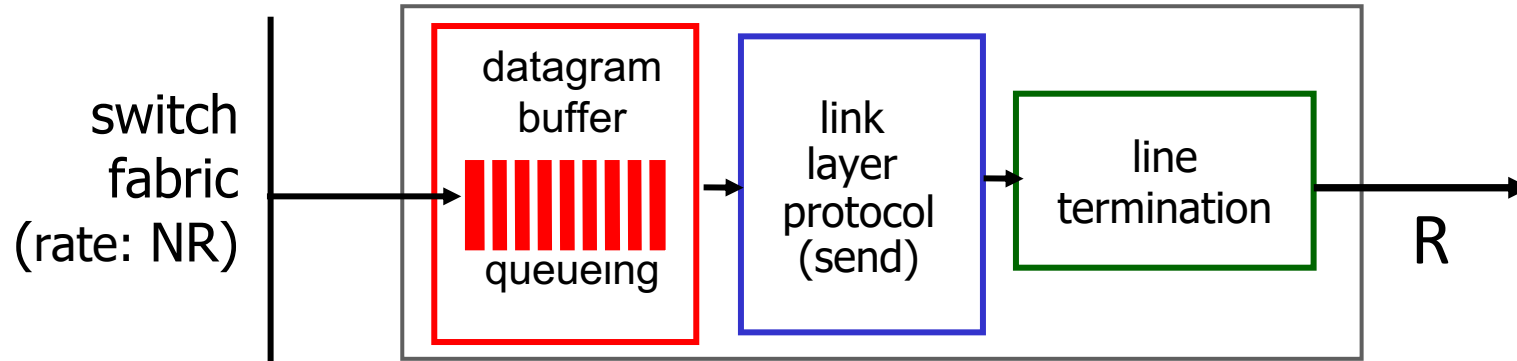


output port contention: only one red datagram can be transferred. lower red packet is *blocked*



one packet time later: green packet experiences HOL blocking

# Output port queuing



This is a really important slide

- **Buffering** required when datagrams arrive from fabric faster than link transmission rate. **Drop policy**: which datagrams to drop if no free buffers?
- **Scheduling discipline** chooses among queued datagrams for transmission

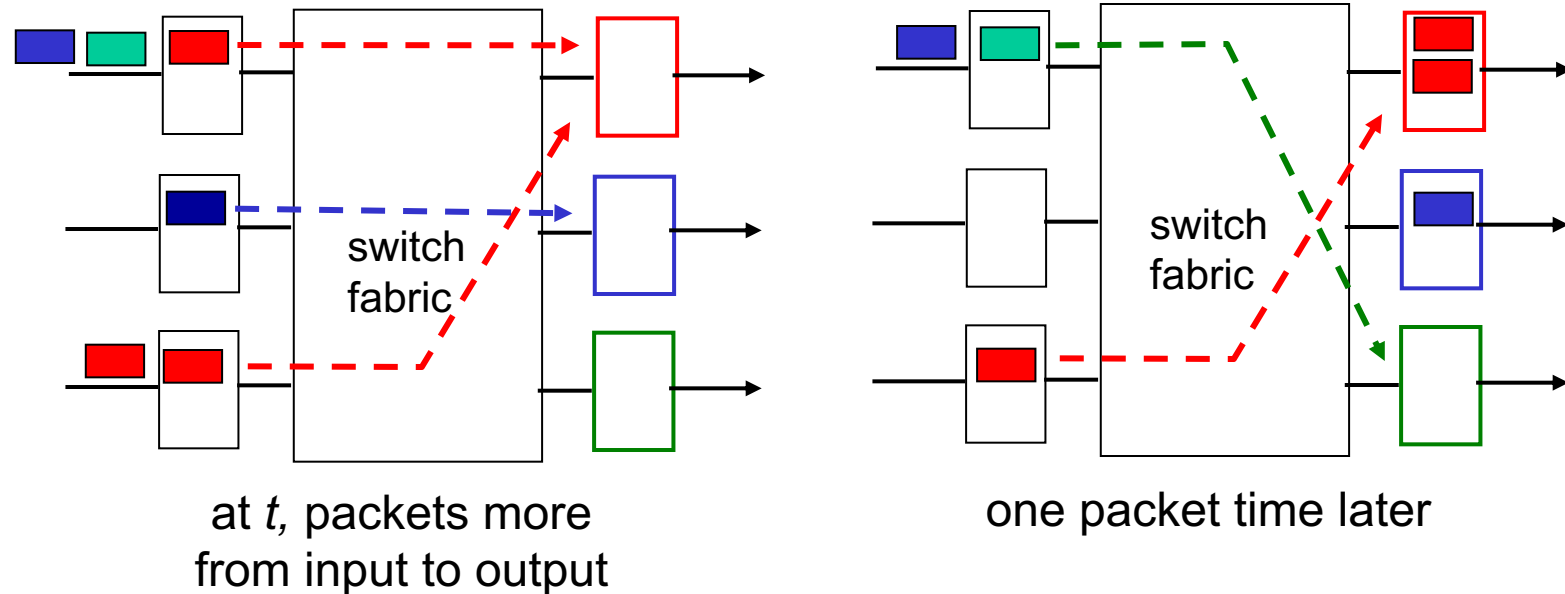


Datagrams can be lost due to congestion, lack of buffers



Priority scheduling – who gets best performance, network neutrality

# Output port queuing



- buffering when arrival rate via switch exceeds output line speed
- *queueing (delay) and loss due to output port buffer overflow!*

# How much buffering?

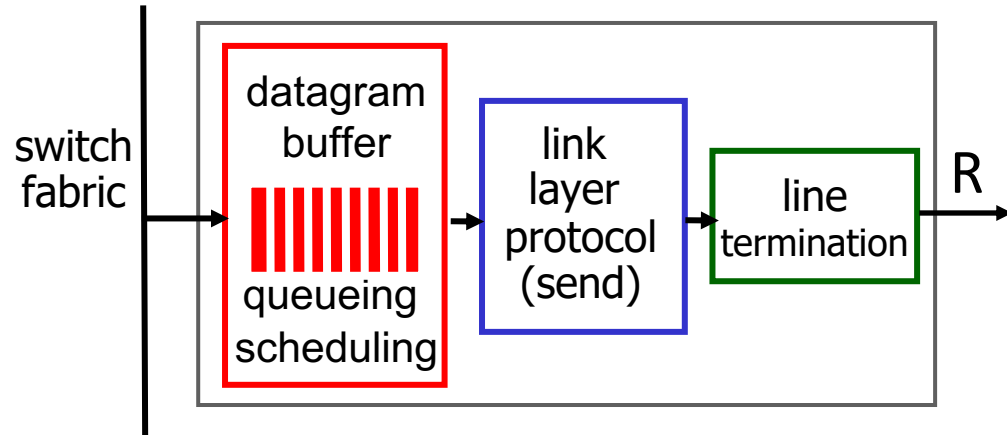
- RFC 3439 rule of thumb: average buffering equal to “typical” RTT (say 250 msec) times link capacity  $C$ 
  - e.g.,  $C = 10$  Gbps link: 2.5 Gbit buffer

- more recent recommendation: with  $N$  flows, buffering equal to

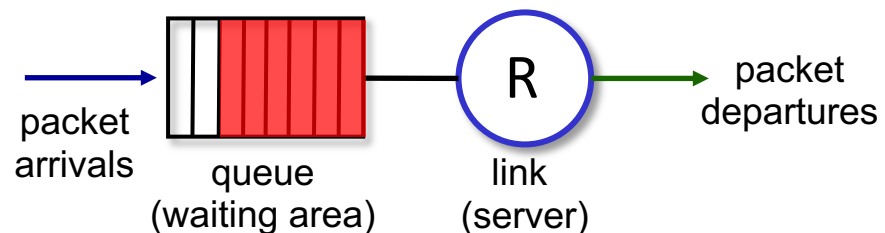
$$\frac{RTT \cdot C}{\sqrt{N}}$$

- but *too* much buffering can increase delays (particularly in home routers)
  - long RTTs: poor performance for realtime apps, sluggish TCP response
  - recall delay-based congestion control: “keep bottleneck link just full enough (busy) but no fuller”

# Buffer Management



## Abstraction: queue



## buffer management:

- **drop**: which packet to add, drop when buffers are full
  - **tail drop**: drop arriving packet
  - **priority**: drop/remove on priority basis
- **marking**: which packets to mark to signal congestion (ECN, RED)

# Packet Scheduling: FCFS

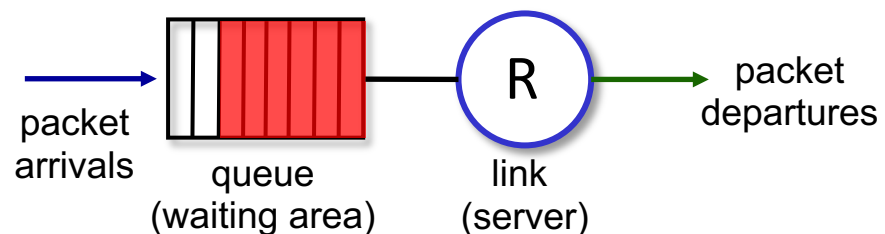
**packet scheduling:** deciding which packet to send next on link

- first come, first served
- priority
- round robin
- weighted fair queueing

**FCFS:** packets transmitted in order of arrival to output port

- also known as: First-in-first-out (FIFO)
- real world examples?

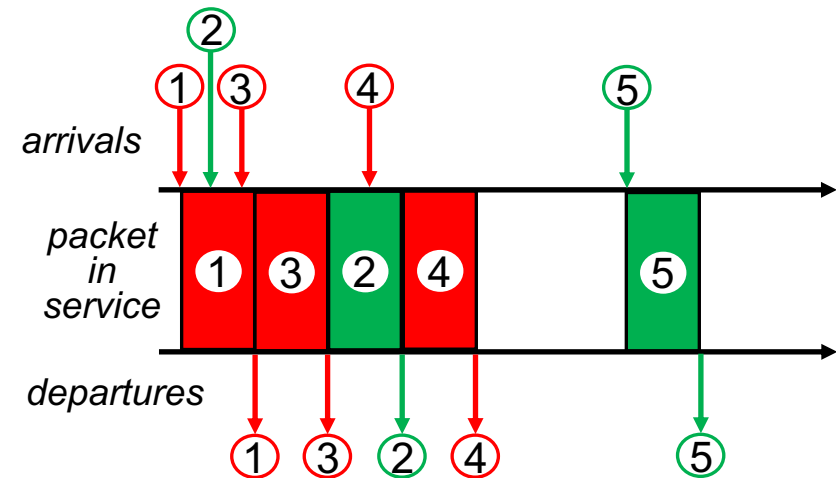
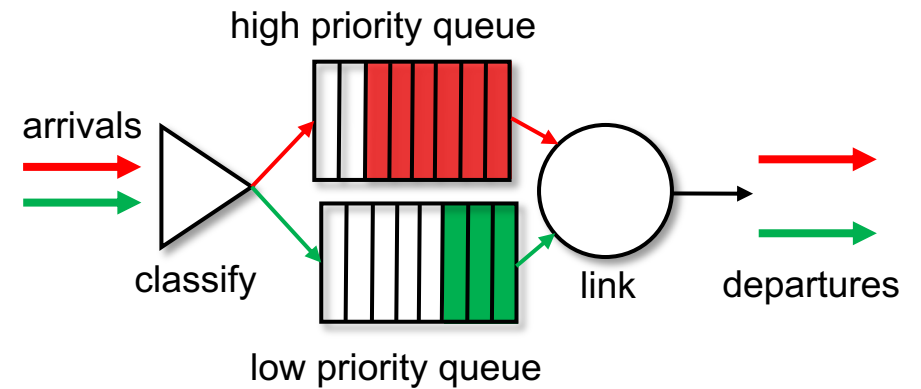
Abstraction: queue



# Scheduling policies: priority

## *Priority scheduling:*

- arriving traffic classified, queued by class
  - any header fields can be used for classification
- send packet from highest priority queue that has buffered packets
  - FCFS within priority class

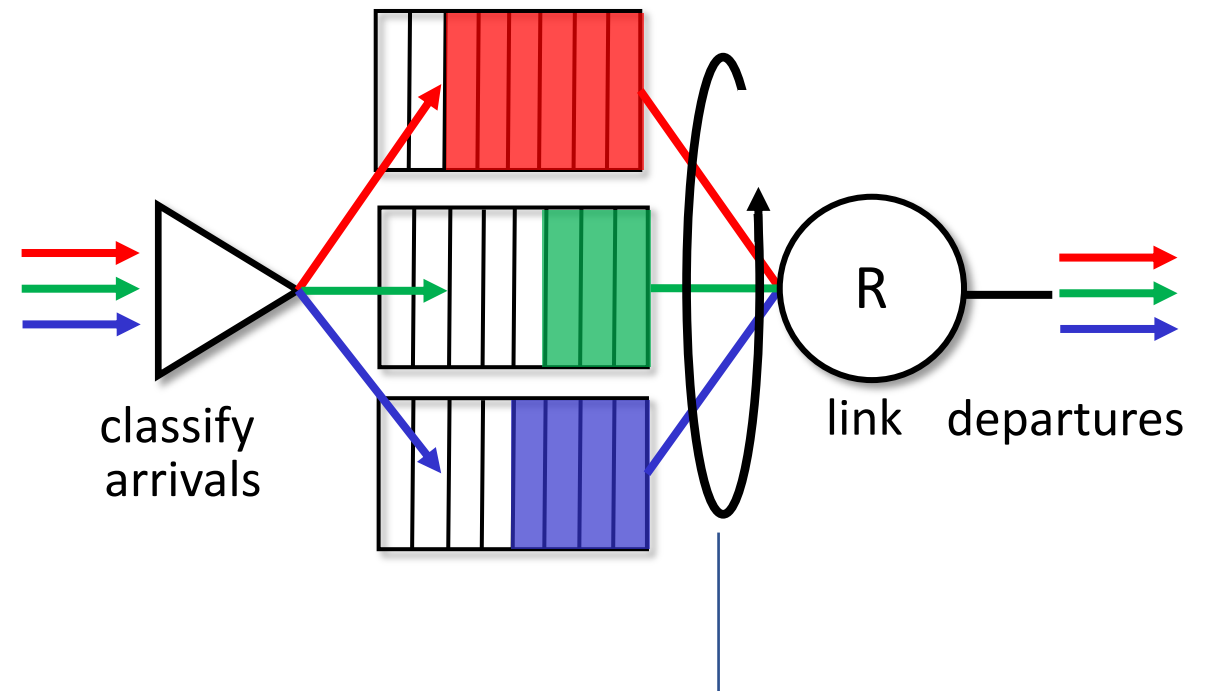




# Scheduling policies: round robin

## *Round Robin (RR) scheduling:*

- arriving traffic classified, queued by class
  - any header fields can be used for classification
- server cyclically, repeatedly scans class queues, sending one complete packet from each class (if available) in turn



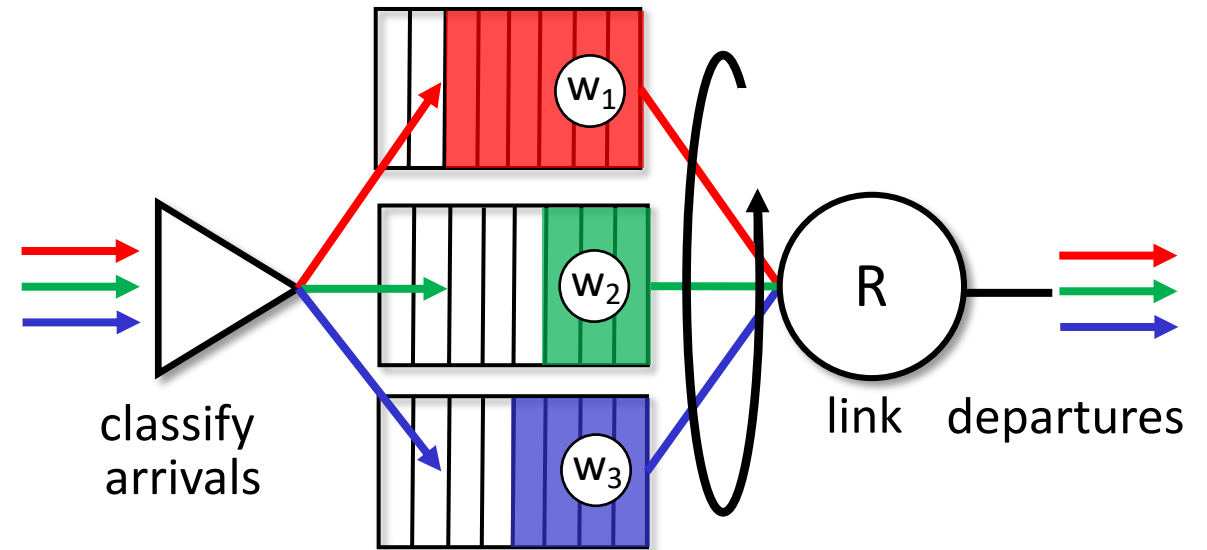
# Scheduling policies: weighted fair queueing

## *Weighted Fair Queueing (WFQ):*

- generalized Round Robin
- each class,  $i$ , has weight,  $w_i$ , and gets weighted amount of service in each cycle:

$$\frac{w_i}{\sum_j w_j}$$

- minimum bandwidth guarantee (per-traffic-class)



# Sidebar: Network Neutrality

What is network neutrality?

- *technical*: how an ISP should share/allocation its resources
  - packet scheduling, buffer management are the *mechanisms*
- *social, economic* principles
  - protecting free speech
  - encouraging innovation, competition
- enforced *legal* rules and policies

*Different countries have different “takes” on network neutrality*

# Sidebar: Network Neutrality

2015 US FCC *Order on Protecting and Promoting an Open Internet*: three “clear, bright line” rules:

- **no blocking** ... “shall not block lawful content, applications, services, or non-harmful devices, subject to reasonable network management.”
- **no throttling** ... “shall not impair or degrade lawful Internet traffic on the basis of Internet content, application, or service, or use of a non-harmful device, subject to reasonable network management.”
- **no paid prioritization.** ... “shall not engage in paid prioritization”

# ISP: telecommunications or information service?

Is an ISP a “telecommunications service” or an “information service” provider?

- the answer *really* matters from a regulatory standpoint!

US Telecommunication Act of 1934 and 1996:

- *Title II*: imposes “common carrier duties” on *telecommunications services*: reasonable rates, non-discrimination and *requires regulation*
- *Title I*: applies to *information services*:
  - no common carrier duties (*not regulated*)
  - but grants FCC authority “... as may be necessary in the execution of its functions”<sub>4</sub>

# Network layer: “data plane” roadmap

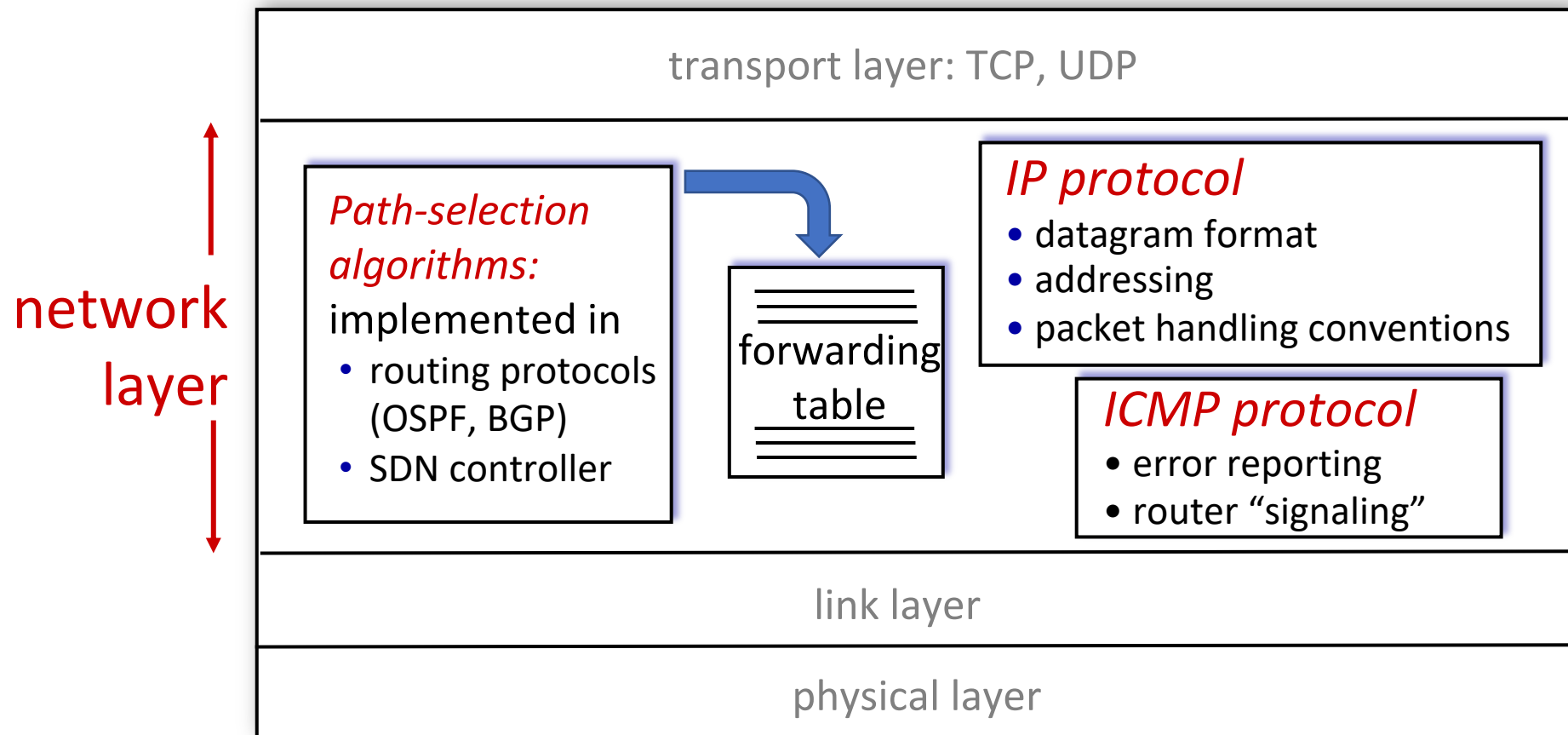
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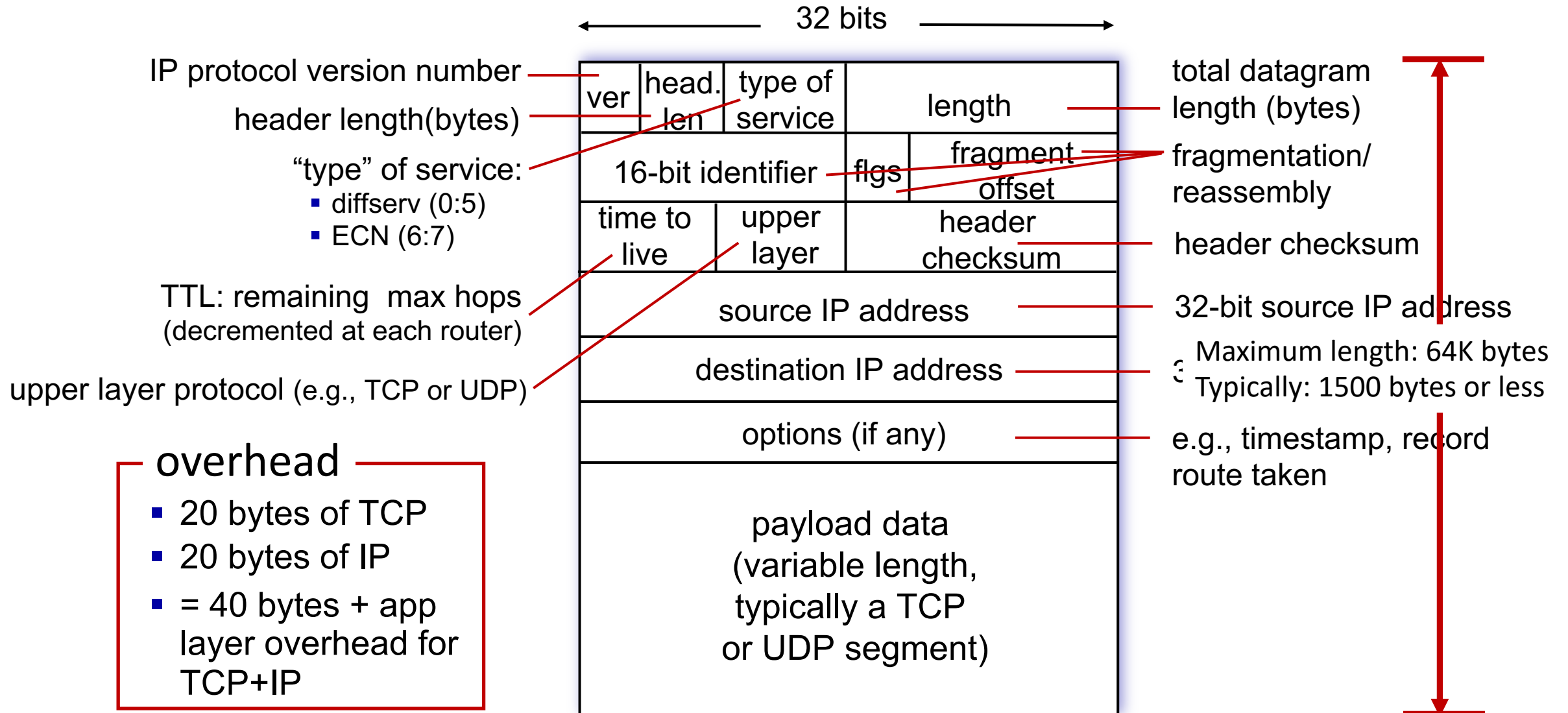
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# Network Layer: Internet

host, router network layer functions:



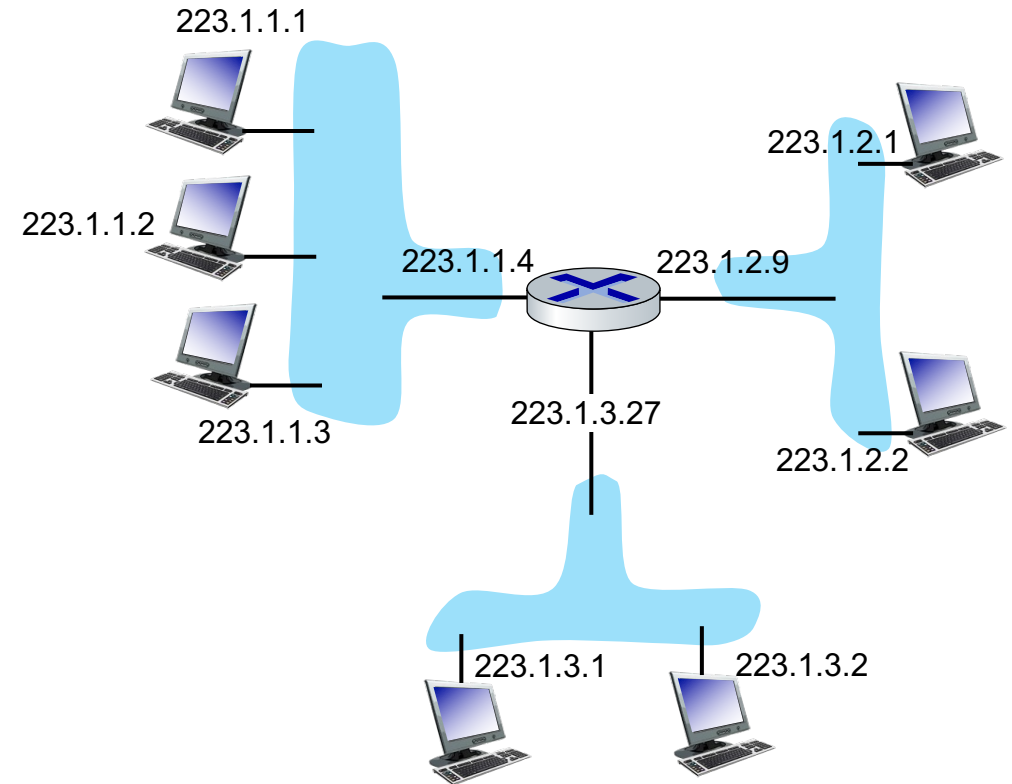
# IP Datagram format





# 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)



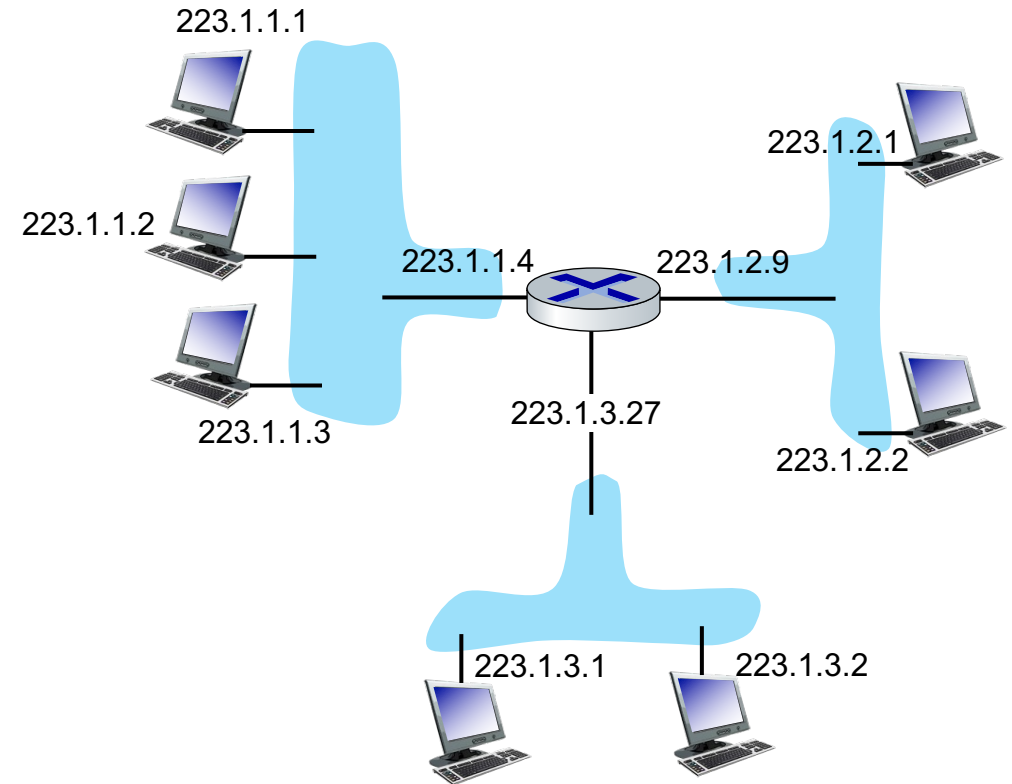
dotted-decimal IP address notation:

223.1.1.1 = 11011111 00000001 00000001 00000001

223                    1                    1                    1

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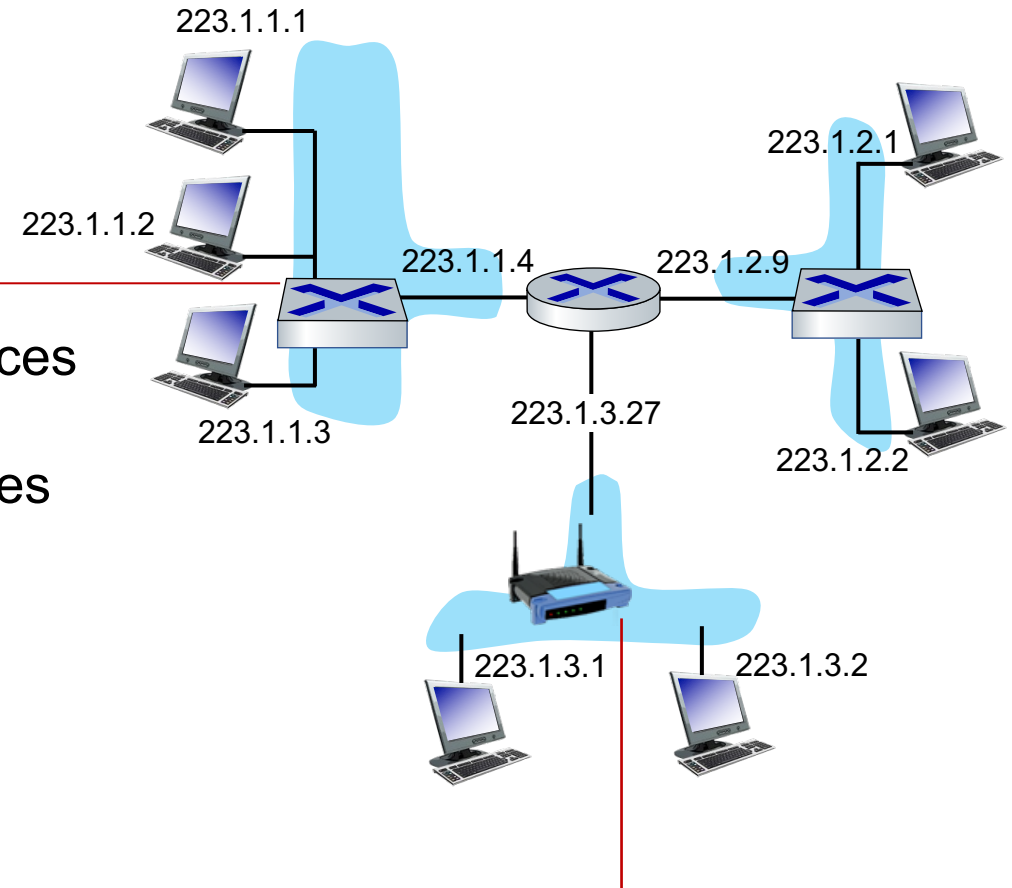
# IP addressing: introduction

**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)

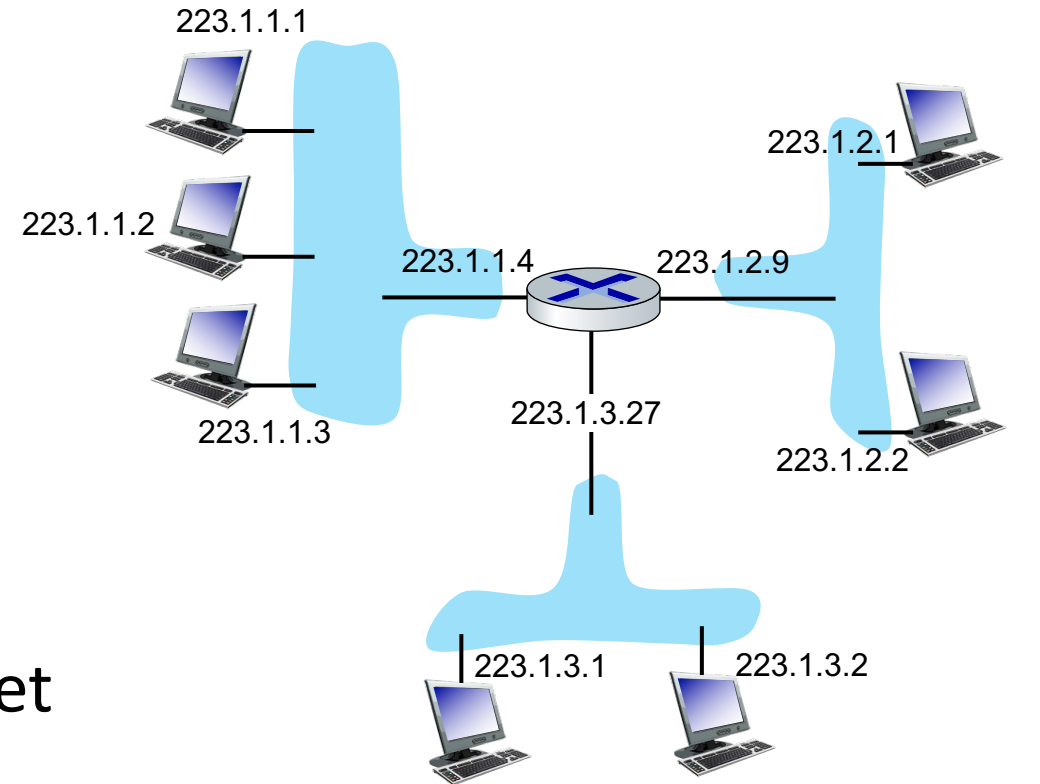
**A:** wired Ethernet interfaces connected by Ethernet switches



**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

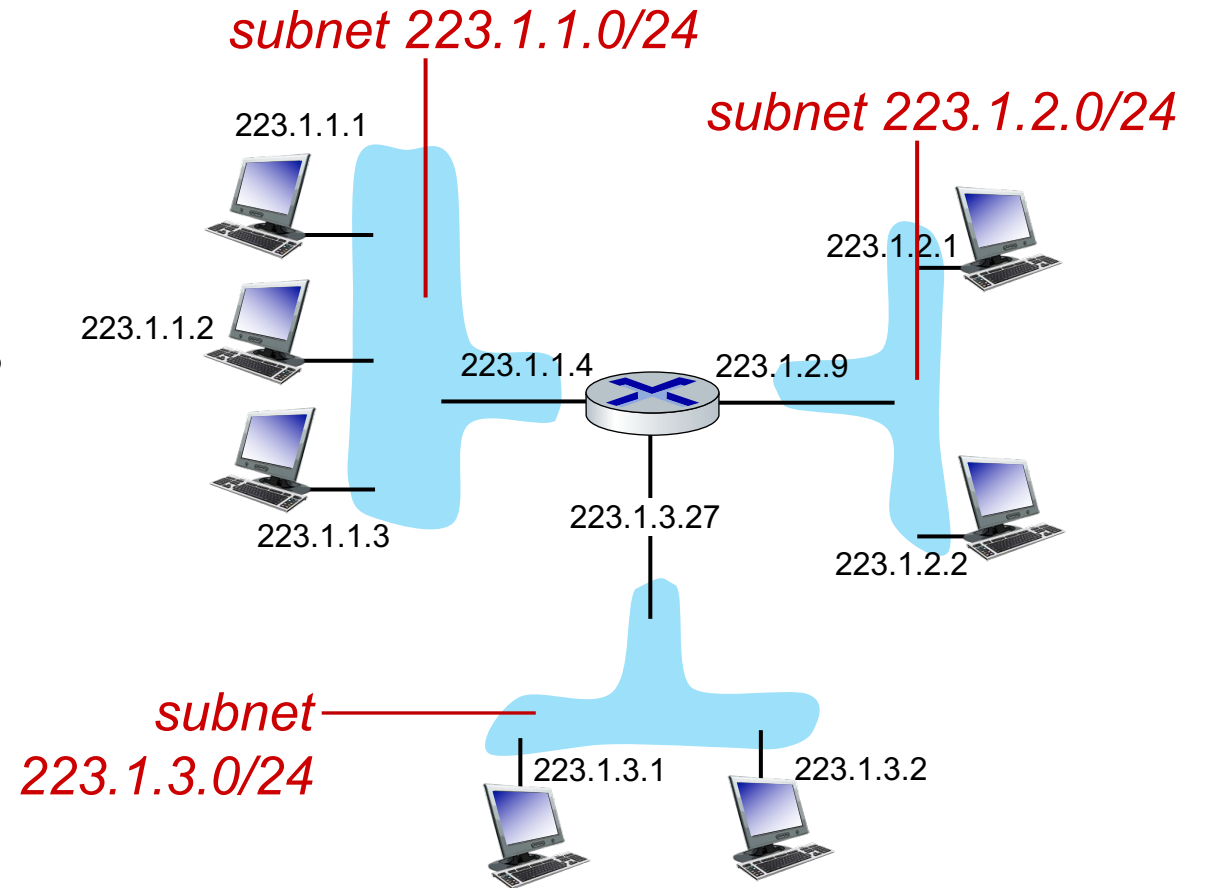


network consisting of 3 subnets

# 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*

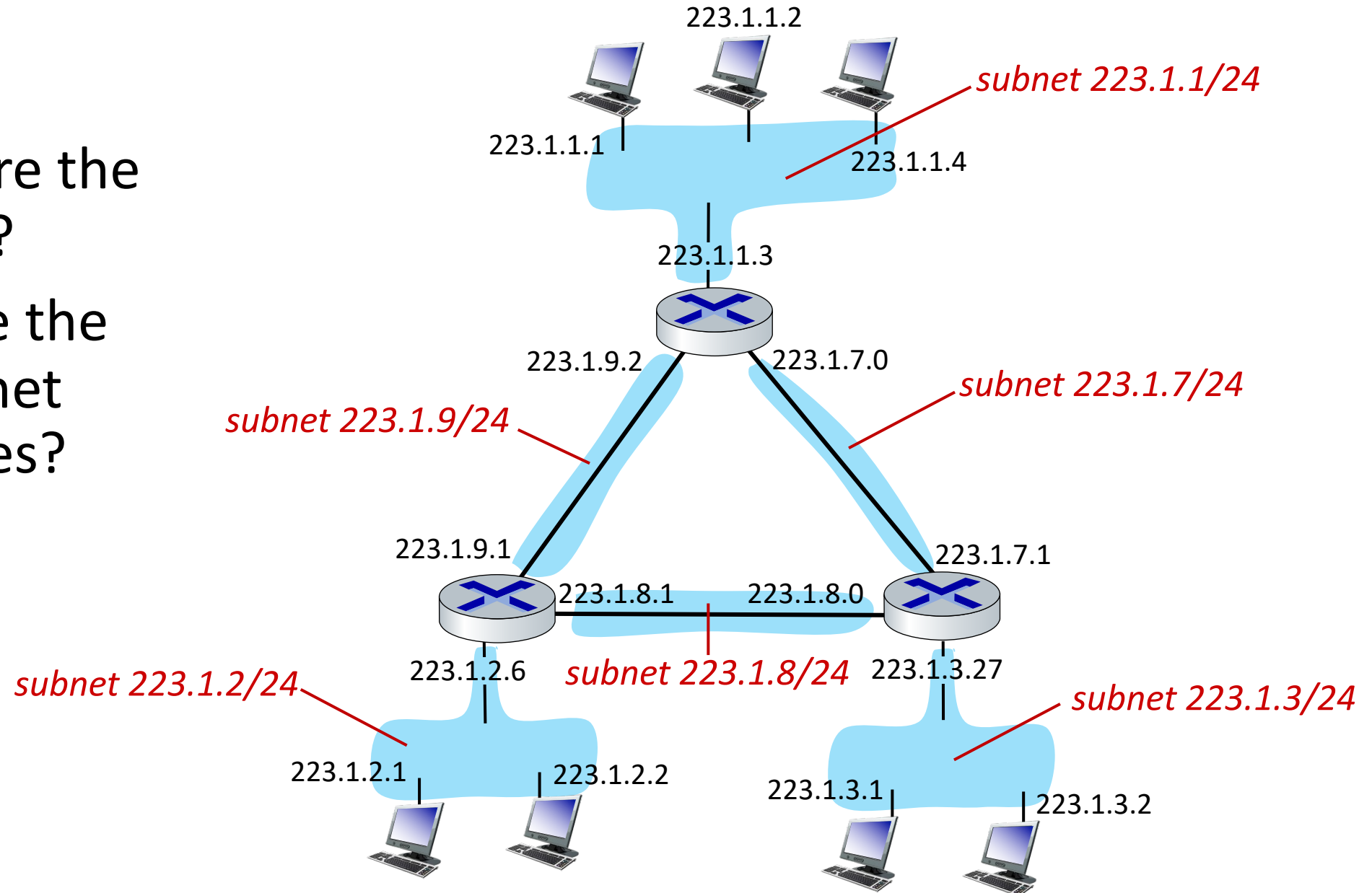


subnet mask: /24

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

# Subnets

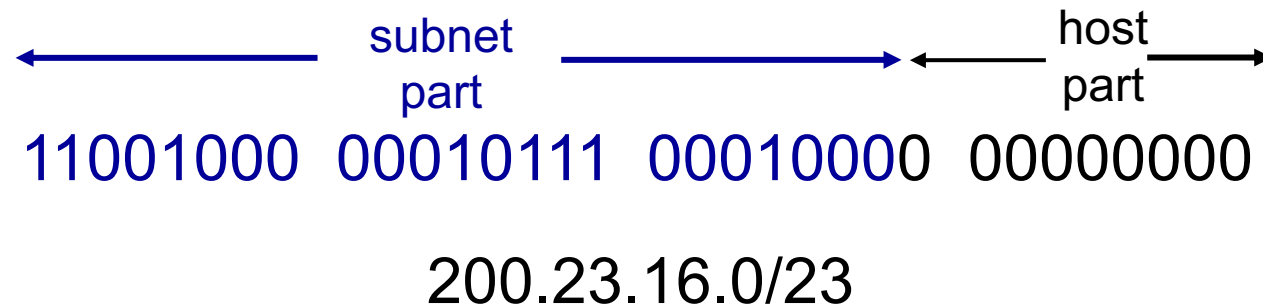
- where are the subnets?
- what are the /24 subnet addresses?



# IP addressing: 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

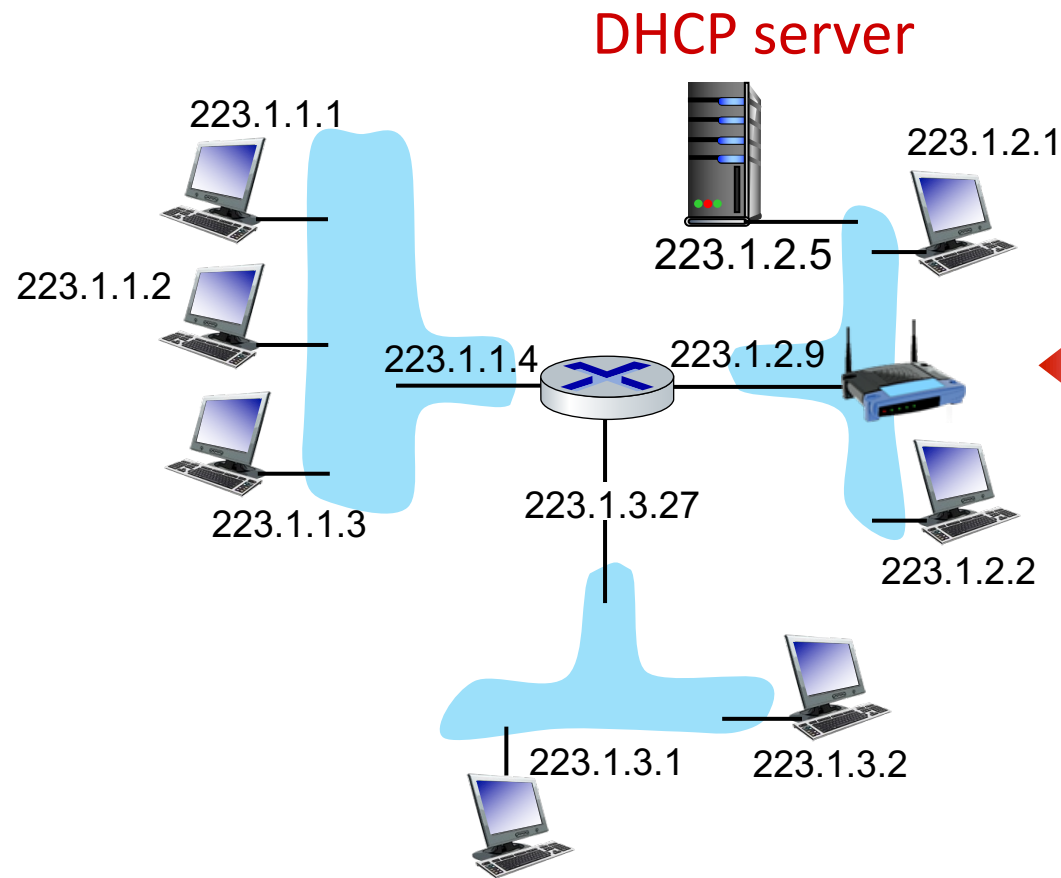
**goal:** host *dynamically* obtains IP address from network server when it “joins” network

- 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



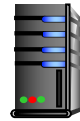
Typically, DHCP server will be co-located in router, serving all subnets to which router is attached



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!

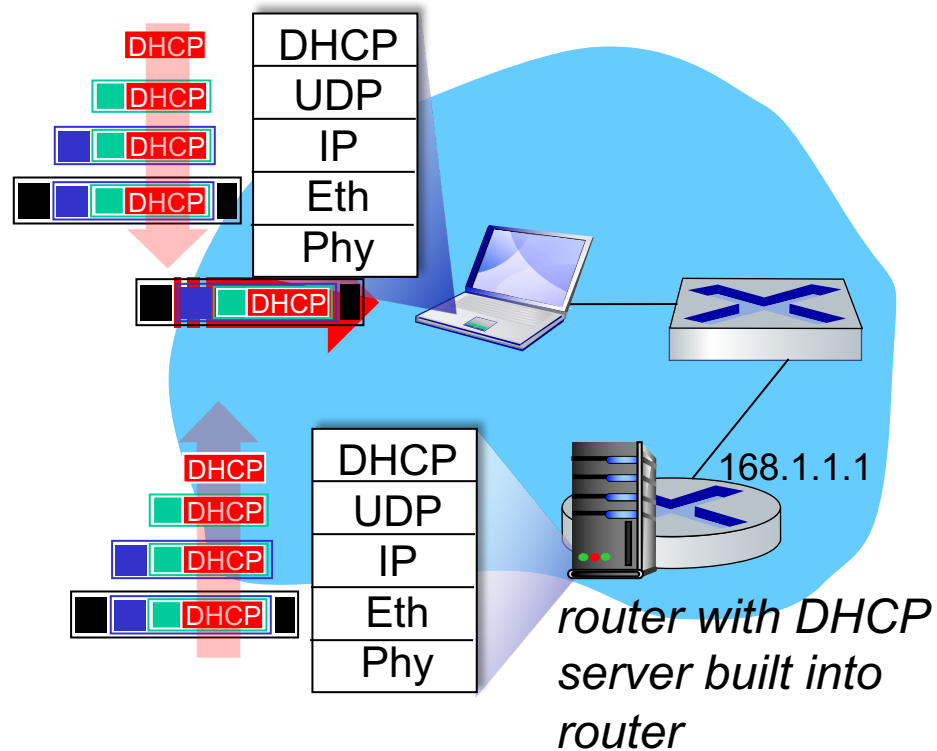
The two steps above can be skipped "if a client remembers and wishes to reuse a previously allocated network address" [RFC 2131]

# DHCP: more than IP addresses

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

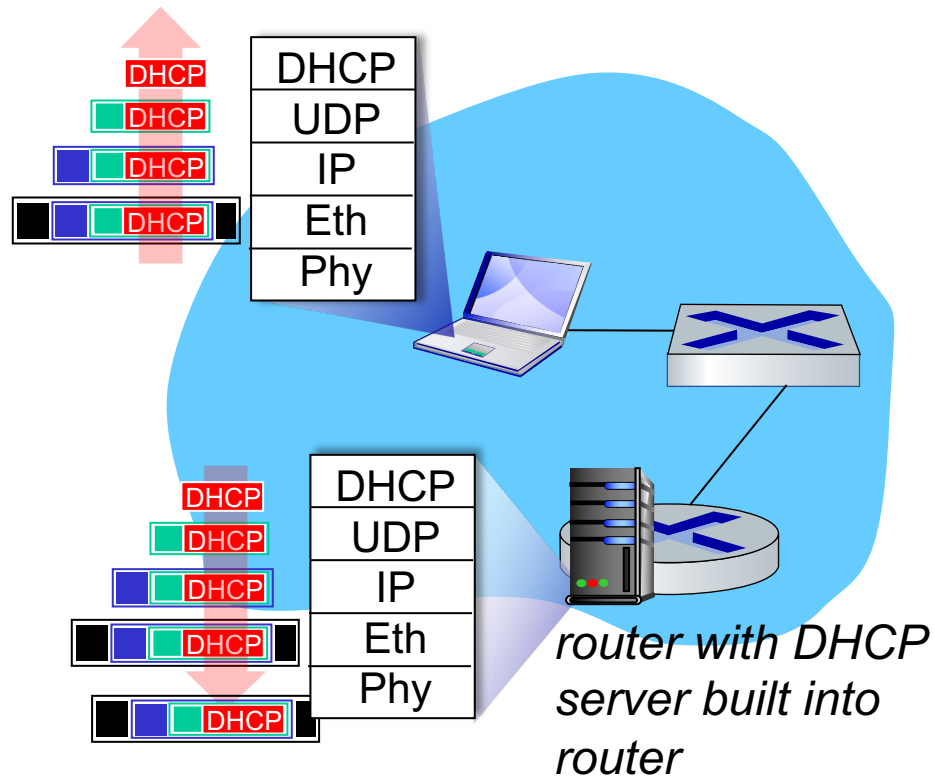
- address of first-hop router for client
- name and IP address of DNS sever
- network mask (indicating network versus host portion of address)

# 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 demux'ed to IP demux'ed, UDP demux'ed to DHCP

# DHCP: example



- DCP 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

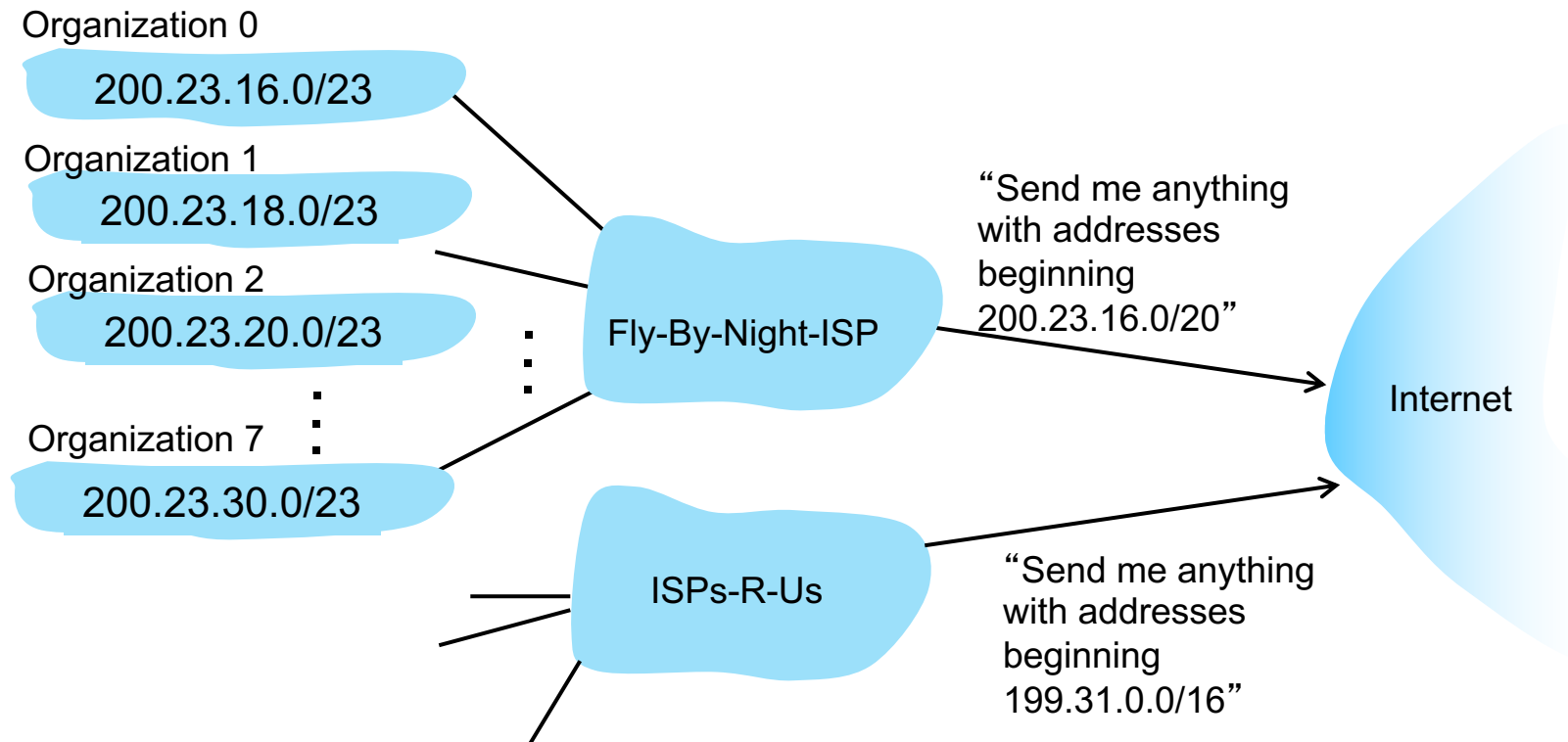
ISP's block      11001000 00010111 00010000 00000000      200.23.16.0/20

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

# Hierarchical addressing: route aggregation

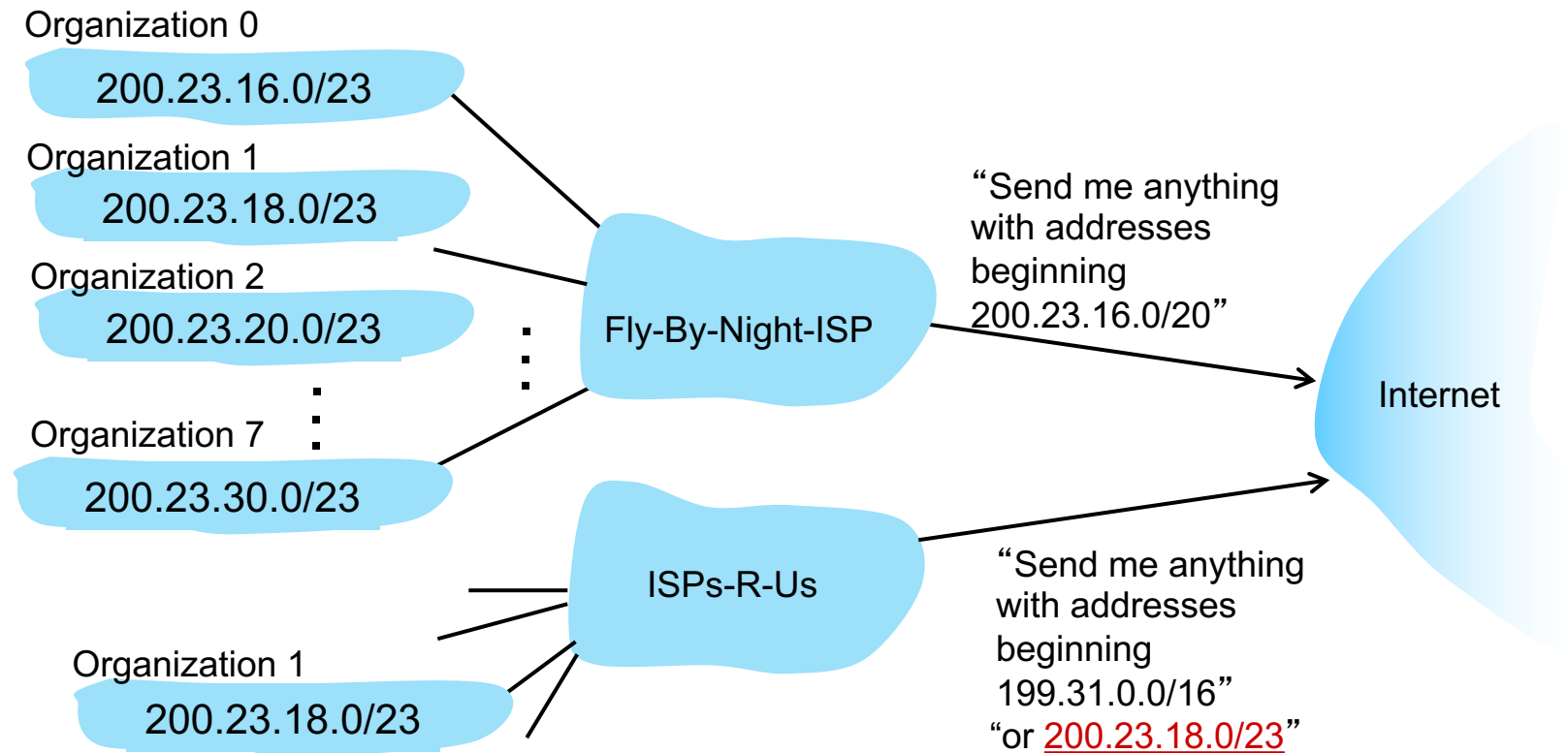
hierarchical addressing allows efficient advertisement of routing information:





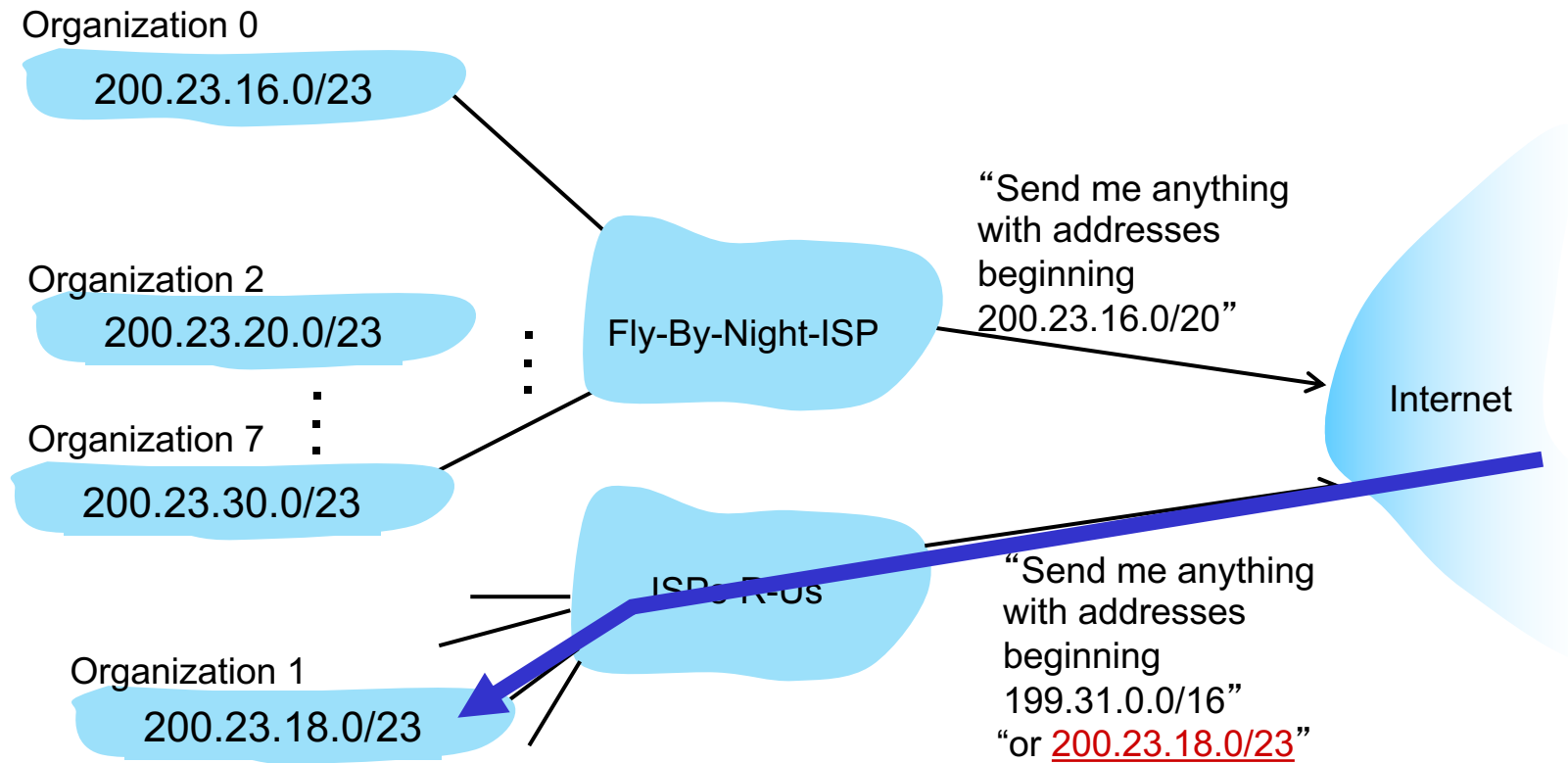
# Hierarchical addressing: more specific routes

- 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)

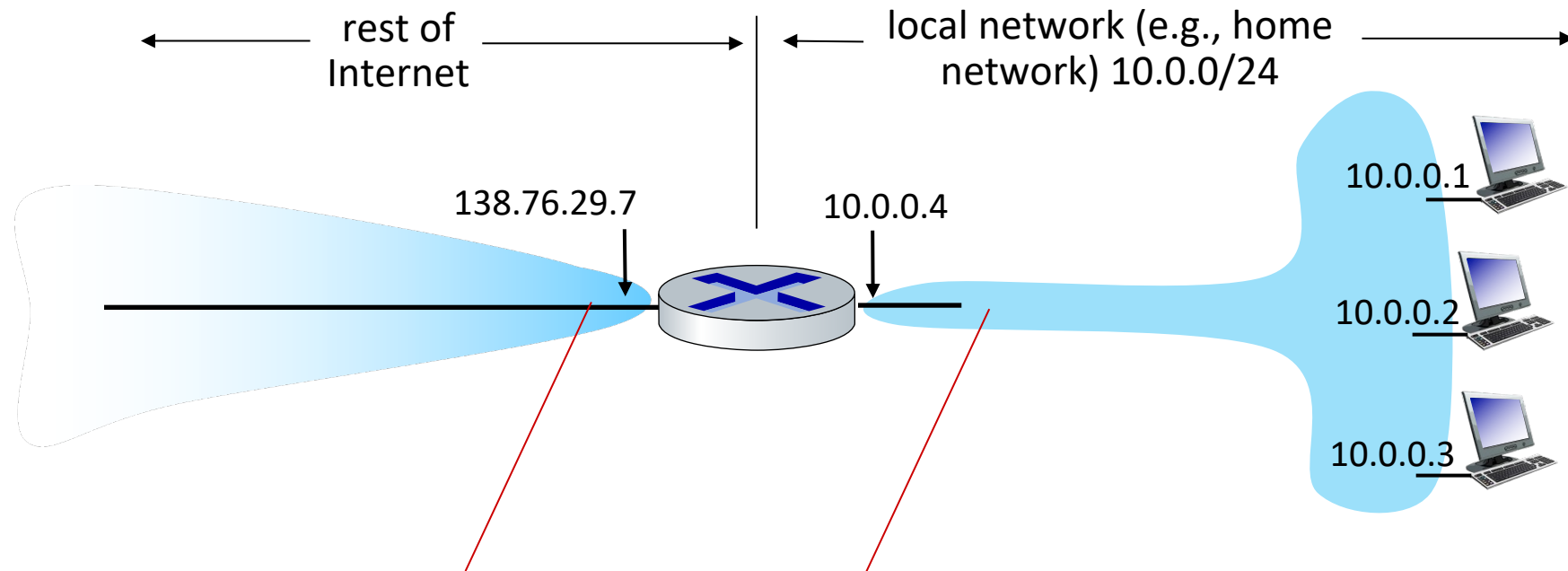
# Network layer: “data plane” roadmap

- 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~~



# 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

# Dedicated Space for Carrier-Grade NAT (RFC6598)

- 100.64.0.0/10, used for carrier-grade NAT only
  - About 4 million addresses
  - Used for internal operations of carrier networks
  - Should NOT be used in private networks or public Internet

# Private IP Address Spaces

## IPv4 (RFC1918):

- 24-bit block: 10.0.0.0 ~ 10.255.255.255 (10.0.0.0/8)
  - 16,777,216 addresses
- 20-bit block: 172.16.0.0~172.31.255.255 (172.16.0.0/12)
  - 1,048,576 addresses
- 16-bit block: 192.168.0.0~192.168.255.255 (192.168.0.0/16)
  - 65,536 addresses

IPv6 (RFC4193): fc00::/7



# NAT: network address translation

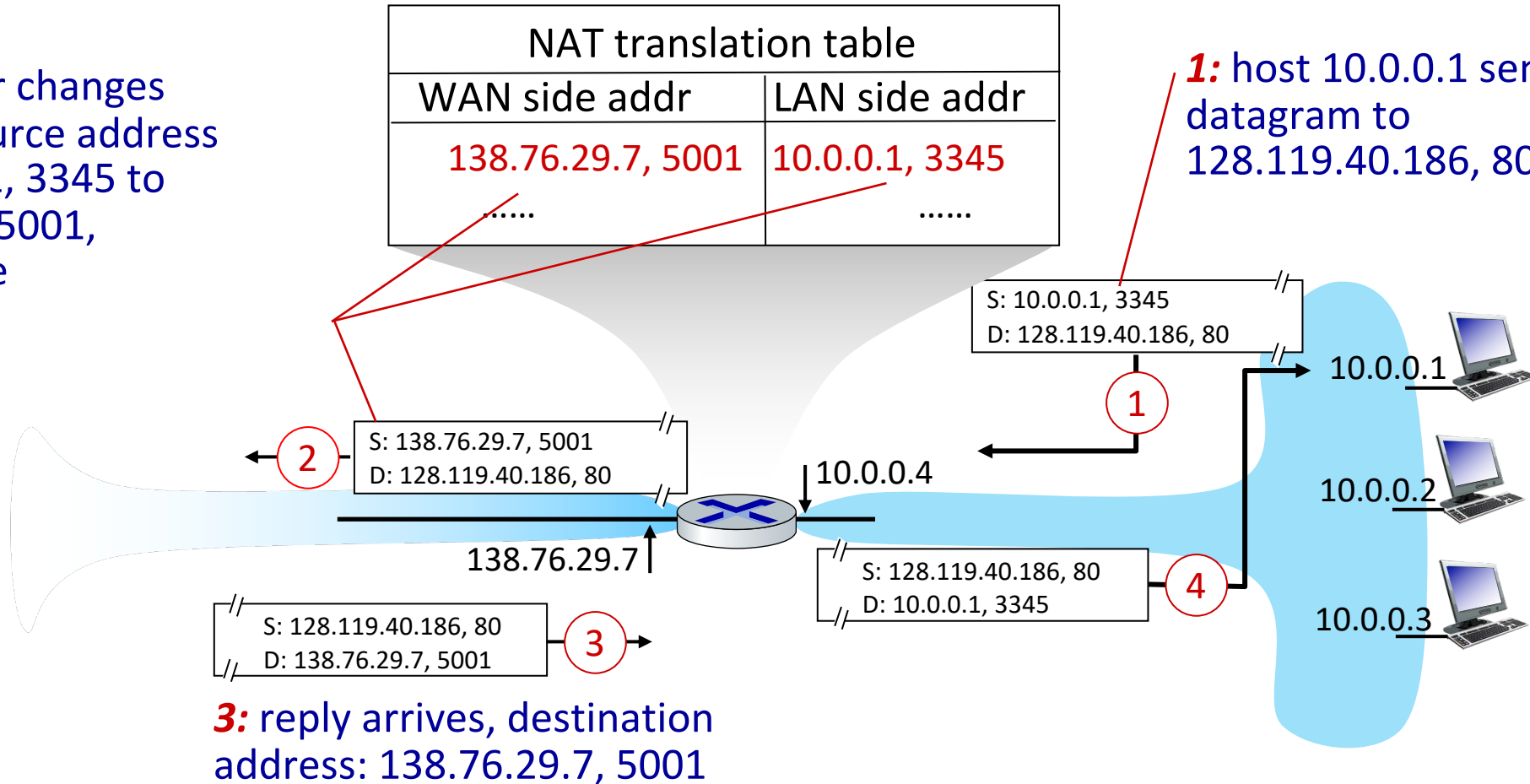
**implementation:** NAT router must (transparently):

- **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

**1:** host 10.0.0.1 sends datagram to 128.119.40.186, 80



# 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

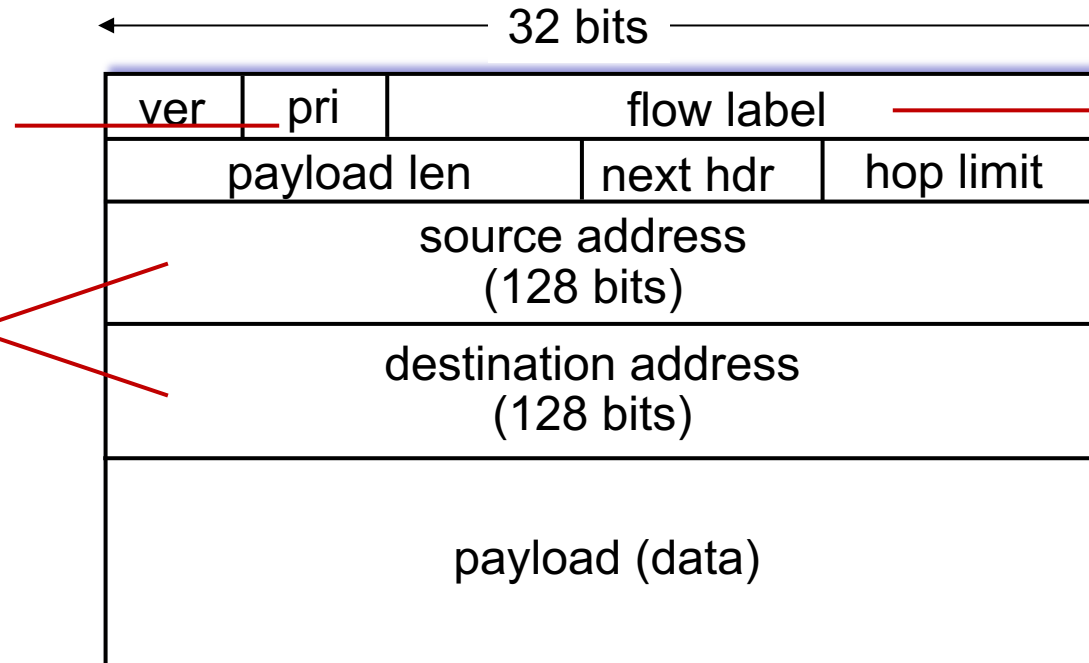
# IPv6: motivation

- **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



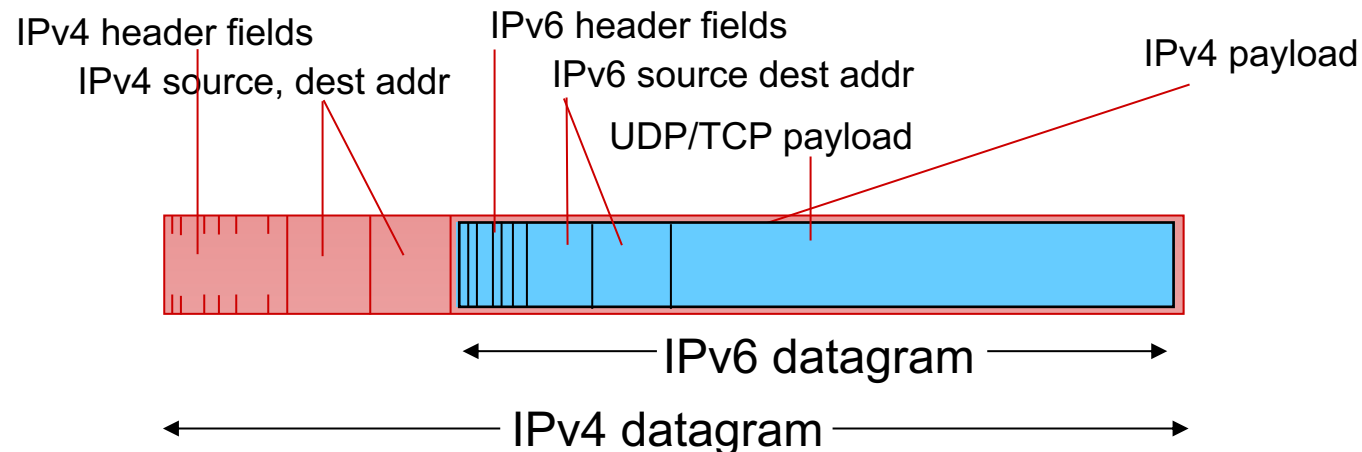
**flow label:** identify datagrams in same "flow." (concept of "flow" not well defined).

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)

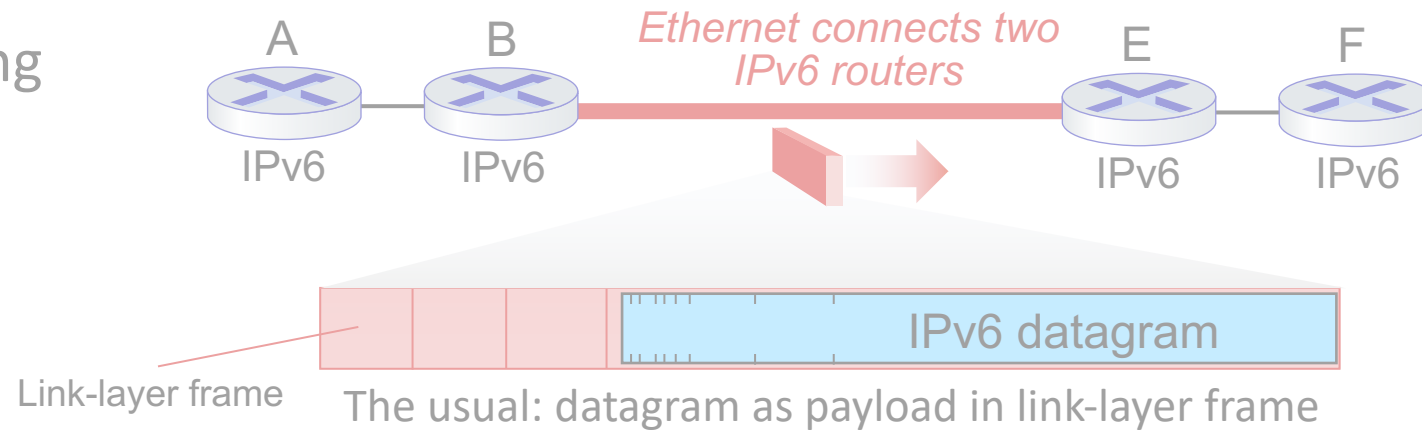
# Transition from IPv4 to IPv6

- 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)

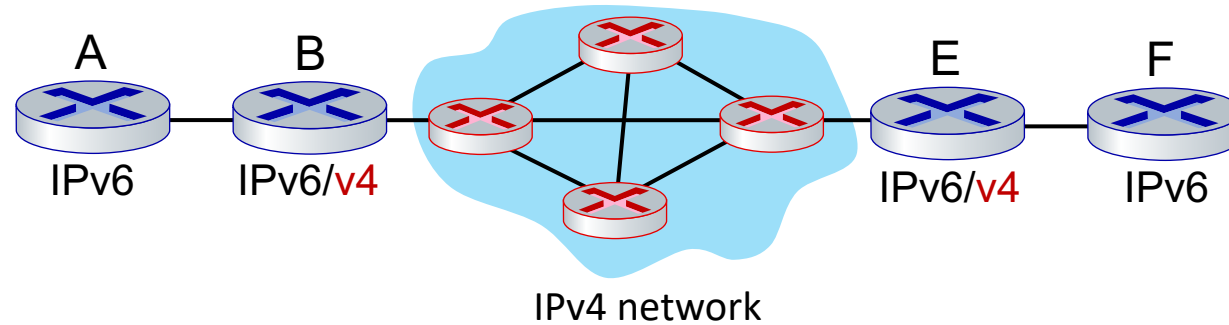


# Tunneling and encapsulation

Ethernet connecting two IPv6 routers:

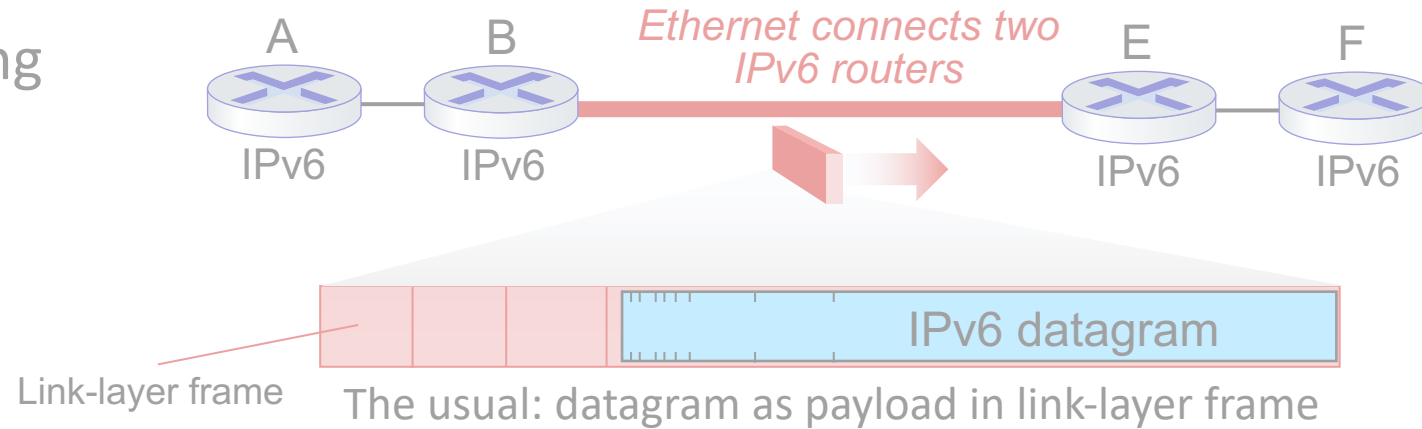


IPv4 network connecting two IPv6 routers

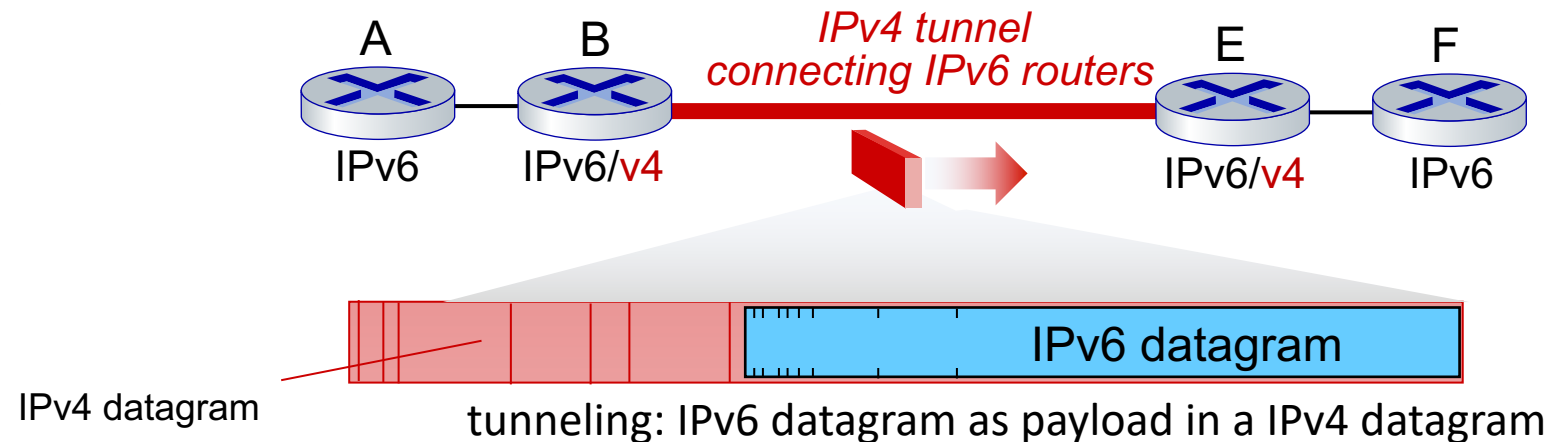


# Tunneling and encapsulation

Ethernet connecting two IPv6 routers:



IPv4 tunnel connecting two IPv6 routers



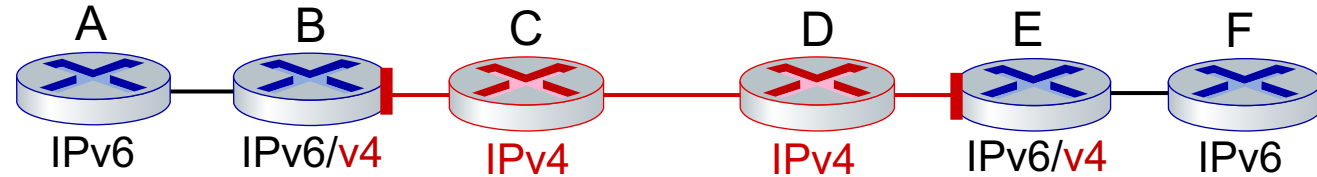


# Tunneling

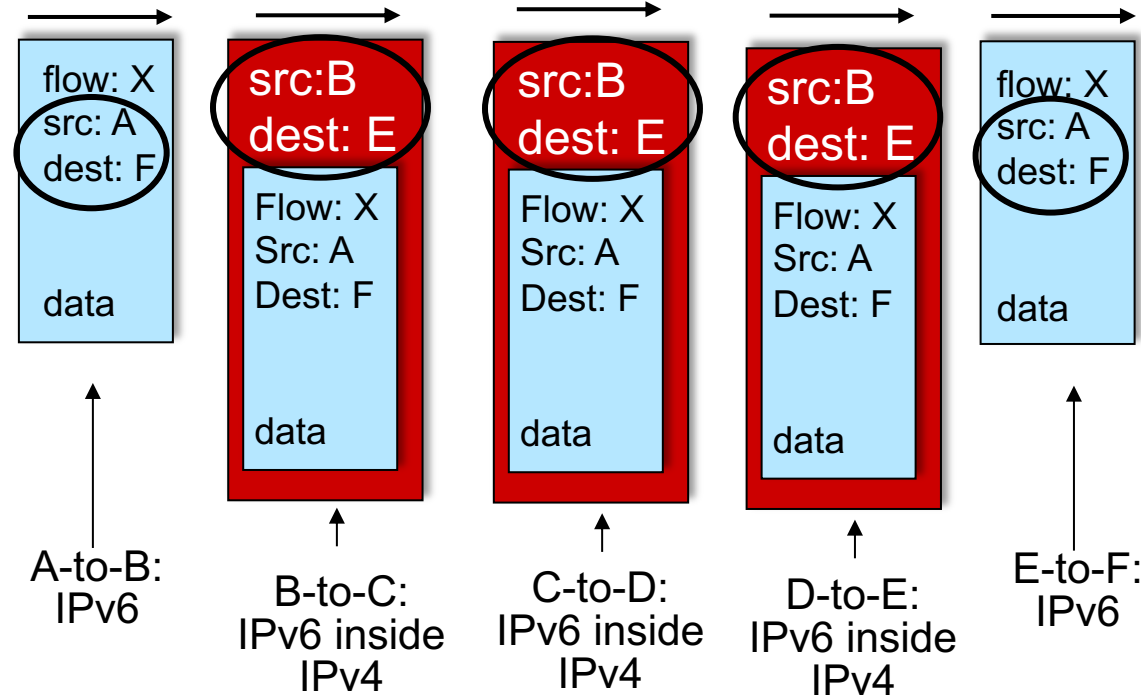
logical view:



physical view:



Note source and destination addresses!

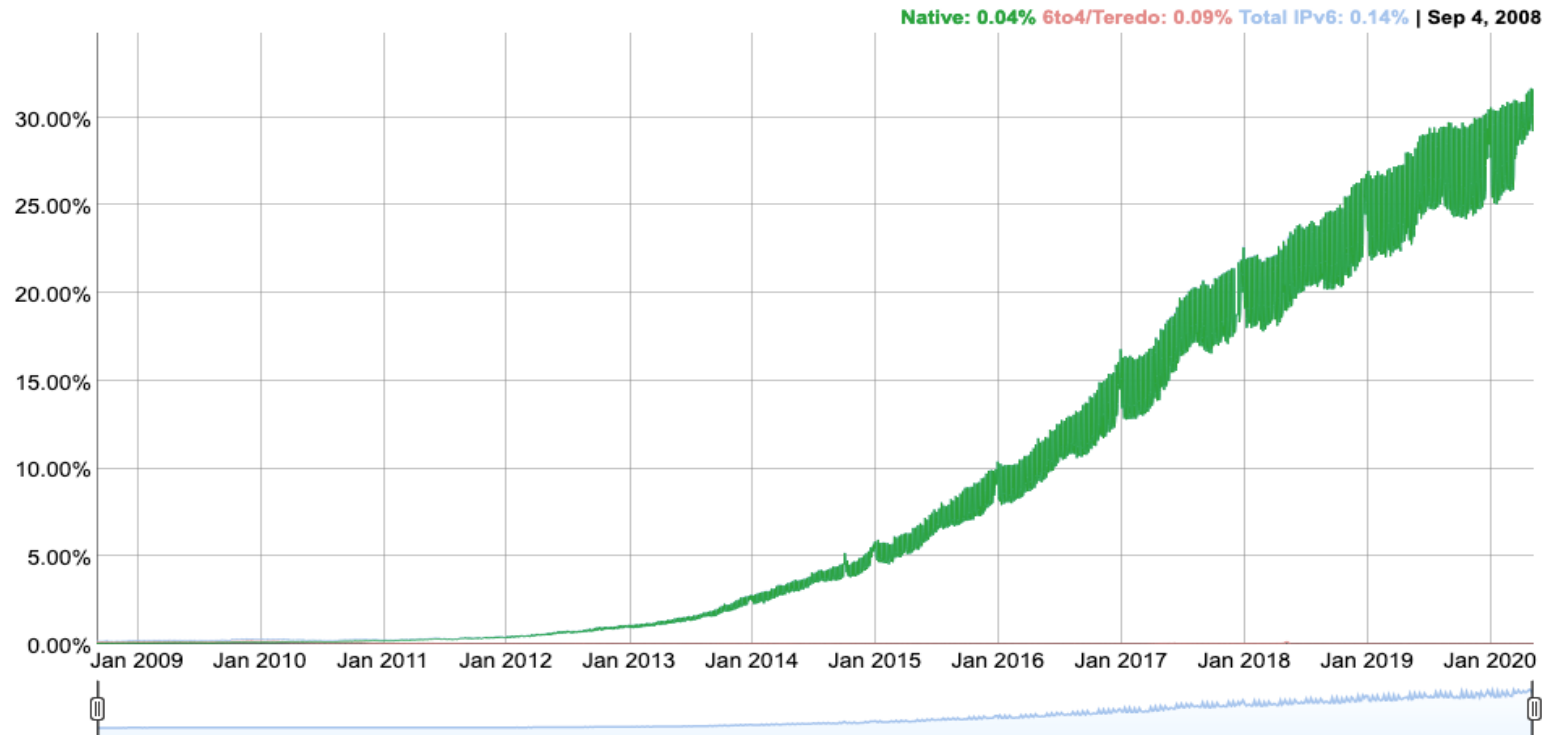


# IPv6: adoption

- 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>

# Chapter 4: done!

- Network layer: overview
- What's inside a router
- IP: the Internet Protocol
- ~~■ Generalized Forwarding, SDN~~
- ~~■ Middleboxes~~



*Question:* how are forwarding tables (destination-based forwarding) or flow tables (generalized forwarding) computed?

*Answer:* by the control plane (next chapter)