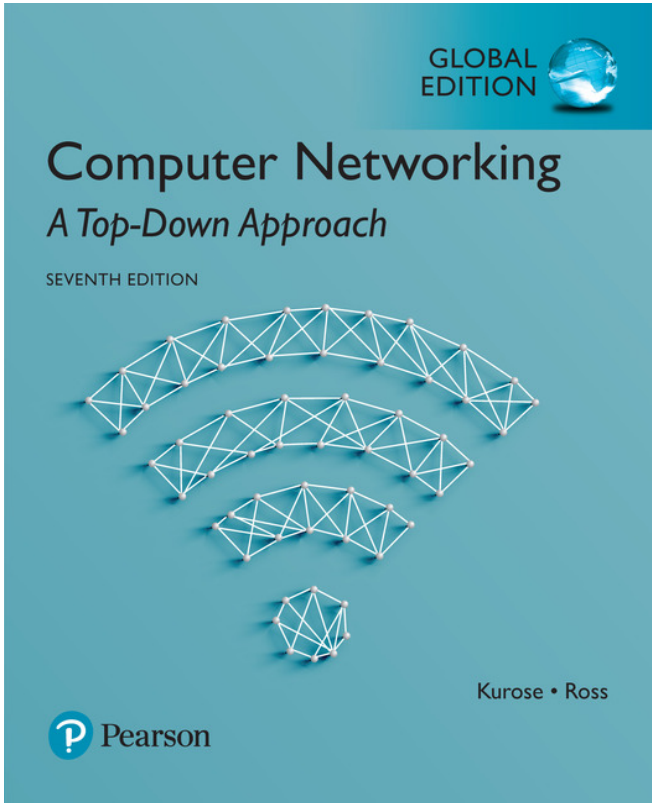
# Chapter 4
# The Network Layer: Data Plane




*Computer Networking: A Top-Down Approach*

7th Edition, Global Edition
Jim Kurose, Keith Ross
Pearson
April 2016

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# Chapter 4: outline

4.1 Overview of Network layer
- data plane
- control plane

4.2 What's inside a router?

4.3 IP: Internet Protocol
- datagram format
- fragmentation
- IPv4 addressing
- network address translation
- IPv6

4.4 Generalized Forwarding and SDN
- match
- action
- OpenFlow examples of match-plus-action in action

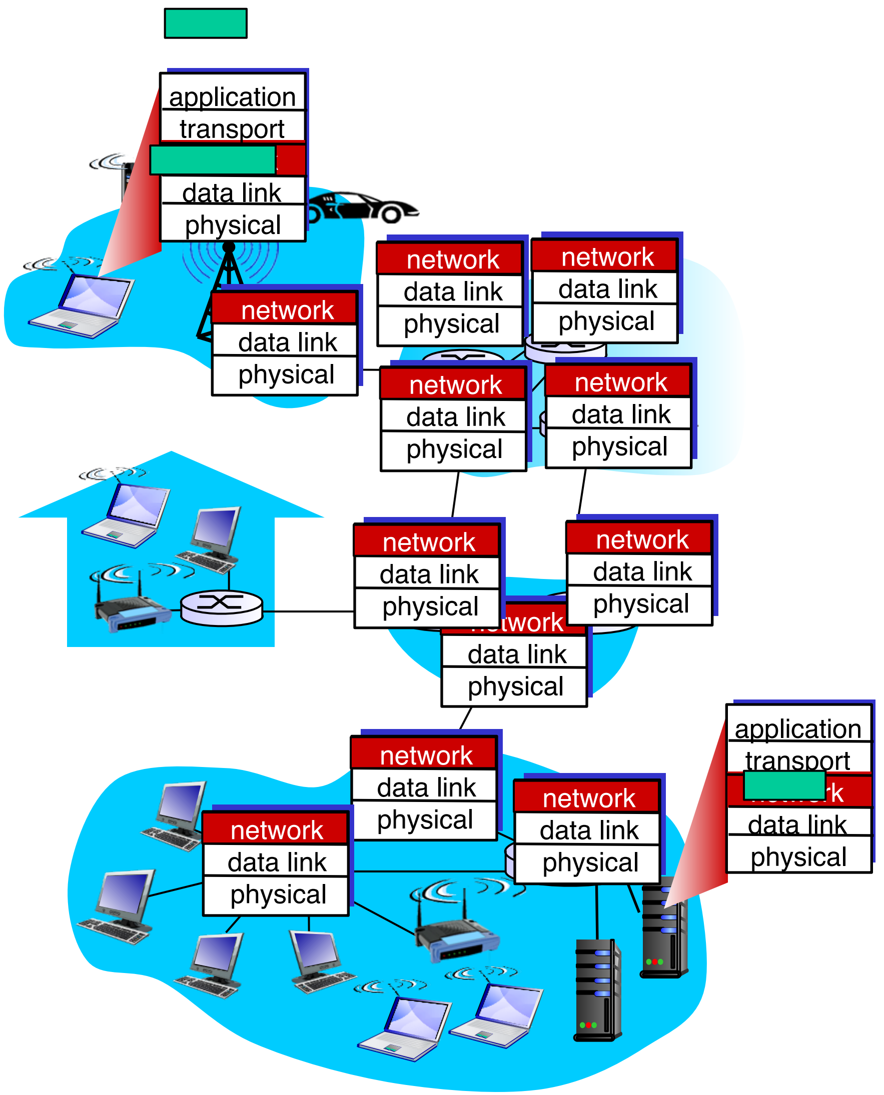
# Chapter 4: network layer

*chapter goals:*

- understand principles behind network layer services, focusing on data plane:
  - network layer service models
  - forwarding versus routing
  - how a router works
  - generalized forwarding
- instantiation, implementation in the Internet

# Network layer

- transport segment from sending to receiving host
- on sending side encapsulates segments into datagrams
- on receiving side, delivers segments to transport layer
- network layer protocols in *every* host, router
- router examines header fields in all IP datagrams passing through it




• no upper layers above the network layer in the router

# Two key network-layer functions

*network-layer functions:*

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

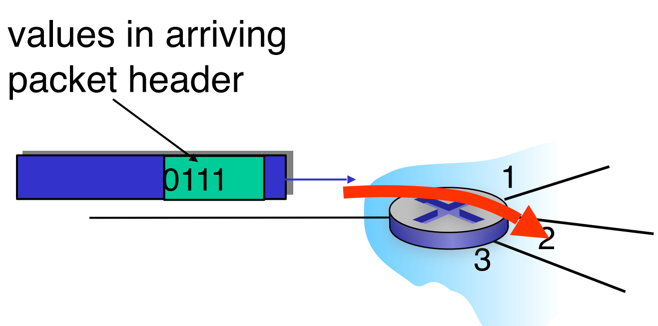
*analogy: taking a trip*

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

# 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
- forwarding function

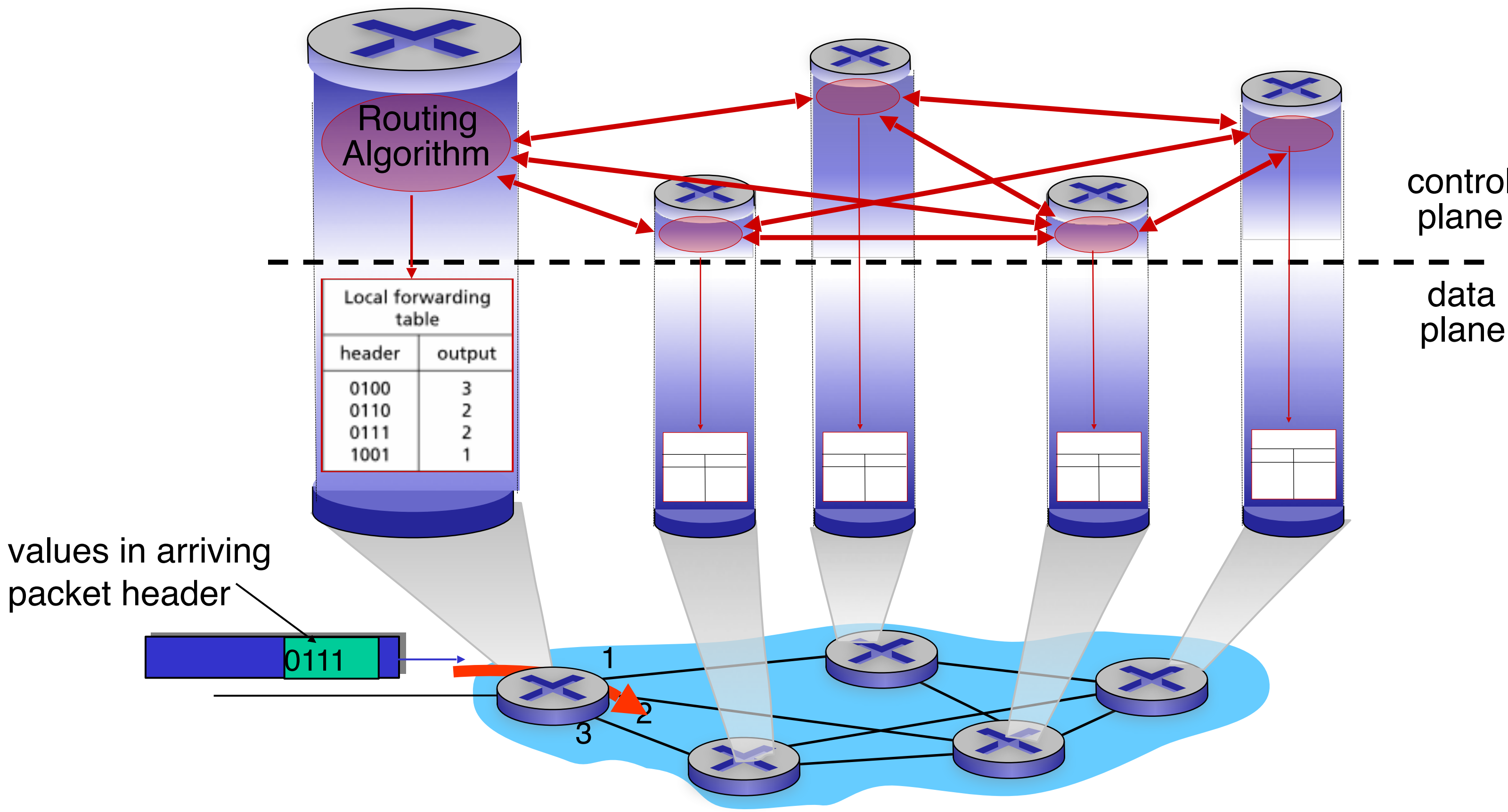



## *Control plane*

- network-wide logic
- determines how datagram is routed among routers along end-to-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

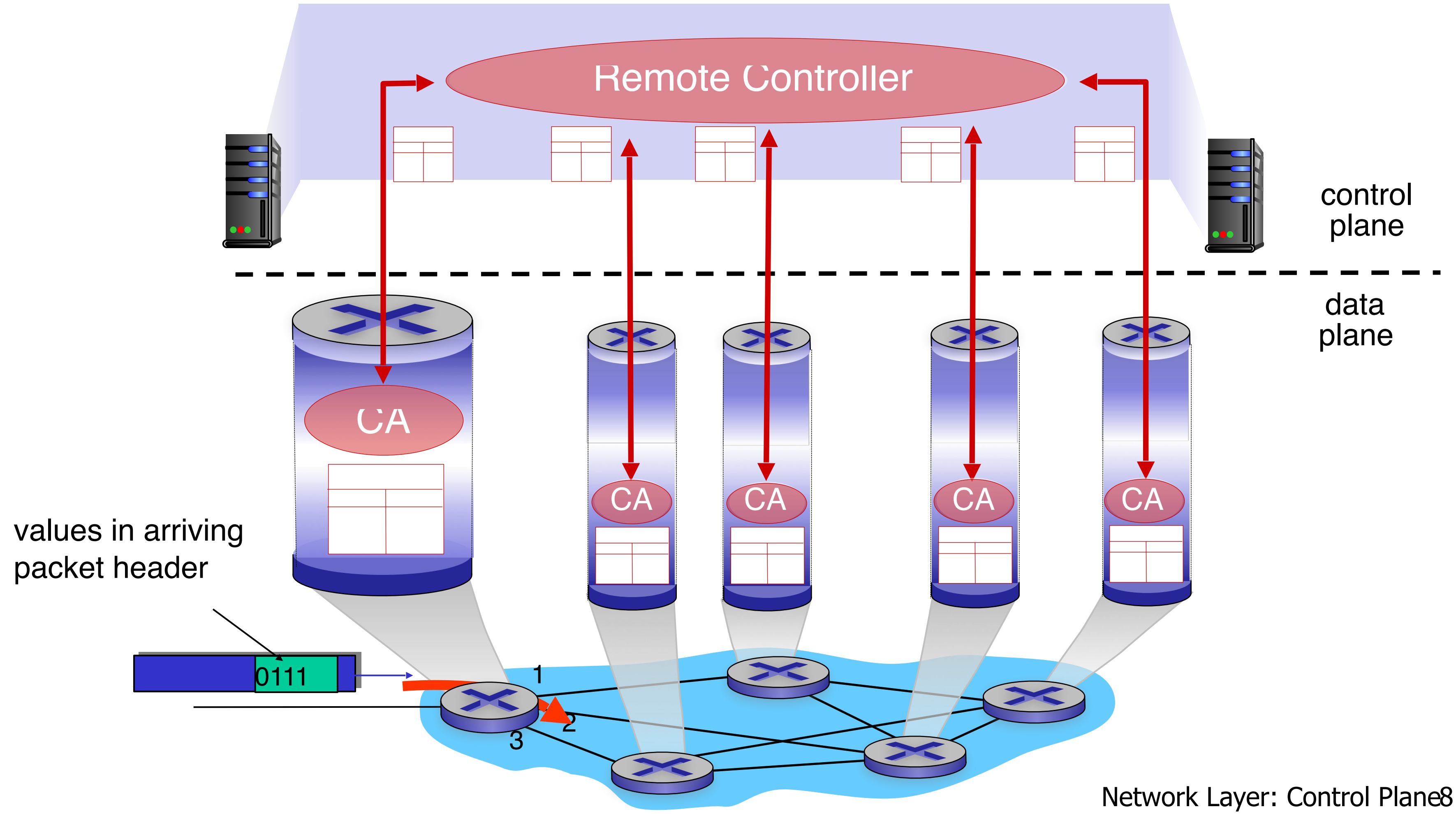
# Per-router control plane

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



# Logically centralized control plane

A distinct (typically remote) controller interacts with local control agents (CAs)



# 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 bounded delay (e.g., less than 100 msec delay)

*example services for a flow of datagrams:*

- in-order packet delivery
- guaranteed minimal bandwidth to flow
- guaranteed maximum jitter: restrictions on changes in inter-packet spacing
- security

• jitter: the variability in a cell's end-to-end delay

# Network layer service models:

| Network Architecture | Service Model | Guarantees? Bandwidth | Loss | Order | Timing | Congestion feedback |
|---|---|---|---|---|---|---|
| Internet | best effort | none | no | no | no | no (inferred via loss) |
| ATM | CBR | constant rate | yes | yes | yes | no congestion |
| ~~ATM~~ | ~~VBR~~ | ~~guaranteed rate~~ | ~~yes~~ | ~~yes~~ | ~~yes~~ | ~~no congestion~~ |
| ATM | ABR | guaranteed minimum | no | yes | no | yes |
| ~~ATM~~ | ~~UBR~~ | ~~none~~ | ~~no~~ | ~~yes~~ | ~~no~~ | ~~no~~ |

- best-effort service: no service at all

- CBR: constant bit rate, suitable for real-time, constant bit rate audio and video
- ABR: available bit rate, slightly-better-than-best-effort service

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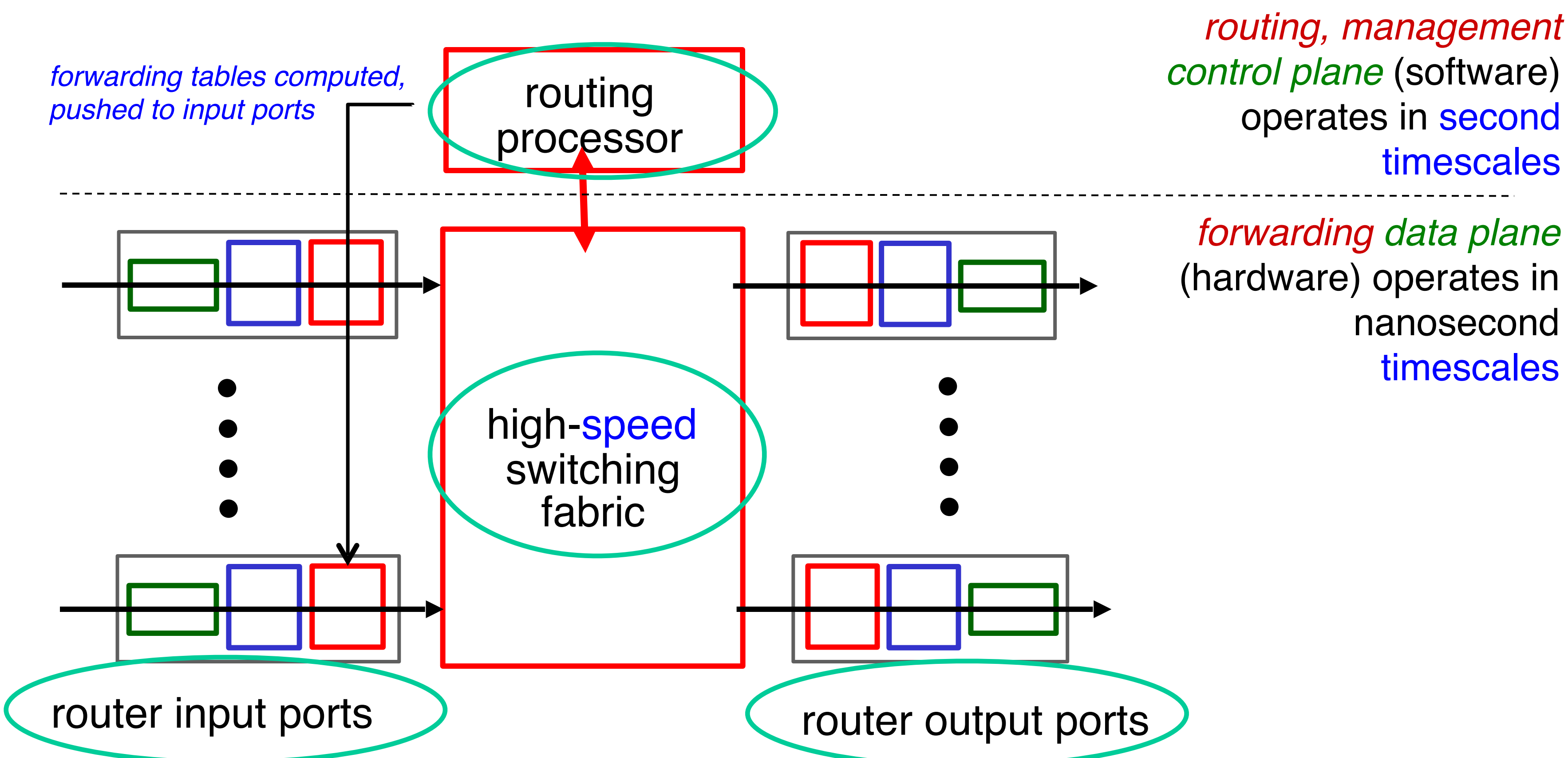
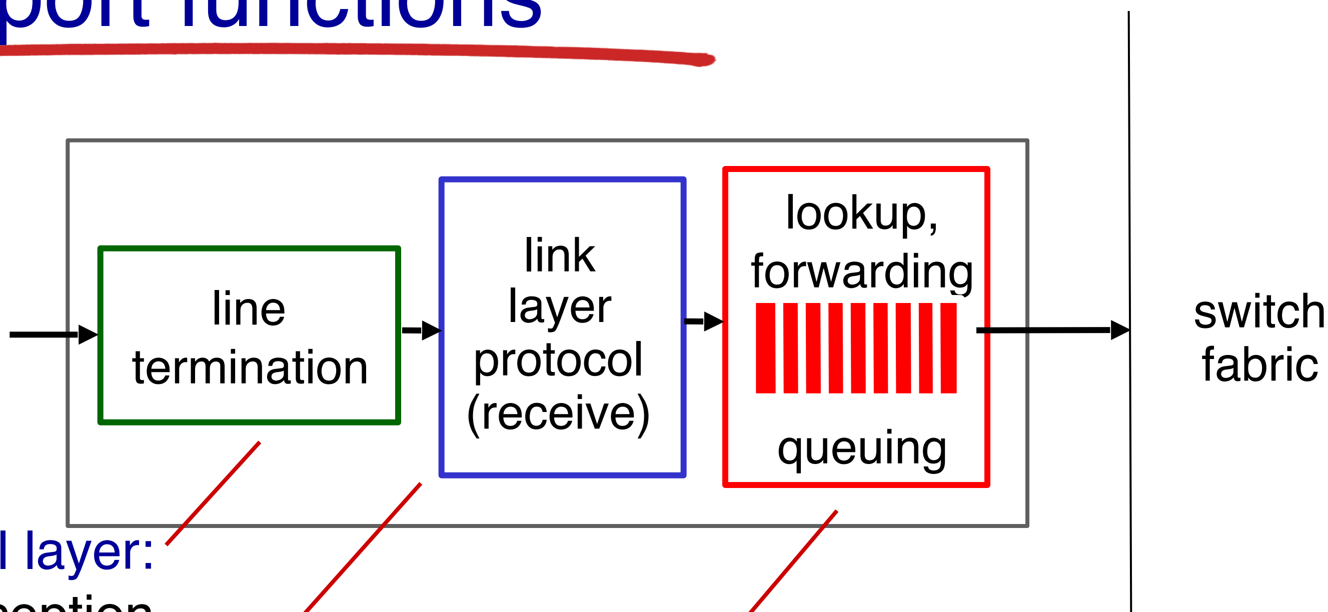
# Router architecture overview

- high-level view of generic router architecture:




• four components of a router

# Input port functions




physical layer:
bit-level reception

data link layer:
e.g., Ethernet
see chapter 6

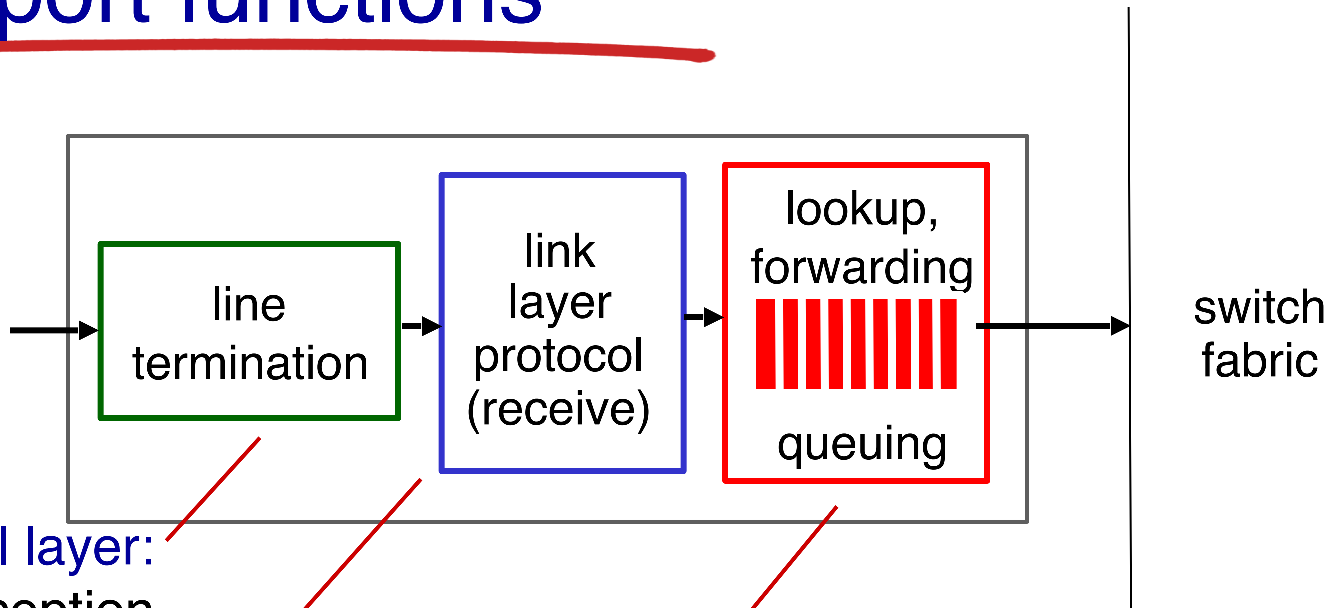
decentralized switching*:*

- 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'
- queuing: if datagrams arrive faster than forwarding rate into switch fabric

• 10 Gbps input link, 64-byte IP datagram
→ only 51.2 ns (nanosecond) to process the datagram
→ hardware based

• decentralized forwarding v.s. centralized routing processor

# Input port functions




physical layer:
bit-level reception

data link layer:
e.g., Ethernet
see chapter 6

decentralized switching:

- using header field values, lookup output port using forwarding table in input port memory *("match plus action")*
- *destination-based forwarding:* forward based only on destination IP address (traditional)
- *generalized forwarding:* forward based on any set of header field values

# Destination-based forwarding

*forwarding table*

| **Destination Address Range** | Link Interface |
|---|---|
| 11001000 00010111 00010000 00000000<br>through<br>11001000 00010111 00010111 11111111 | 0 |
| 11001000 00010111 00011000 00000000<br>through<br>11001000 00010111 00011000 11111111 | 1 |
| 11001000 00010111 00011000 00000000<br>through<br>11001000 00010111 00011111 11111111 | 2 |
| otherwise | 3 |

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

# Longest prefix matching

*longest prefix matching*

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

- the router matches a prefix of the packet's destination address

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

examples: DA: 11001000 00010111 00010110 10100001 which interface?

DA: 11001000 00010111 00011000 10101010 which interface?

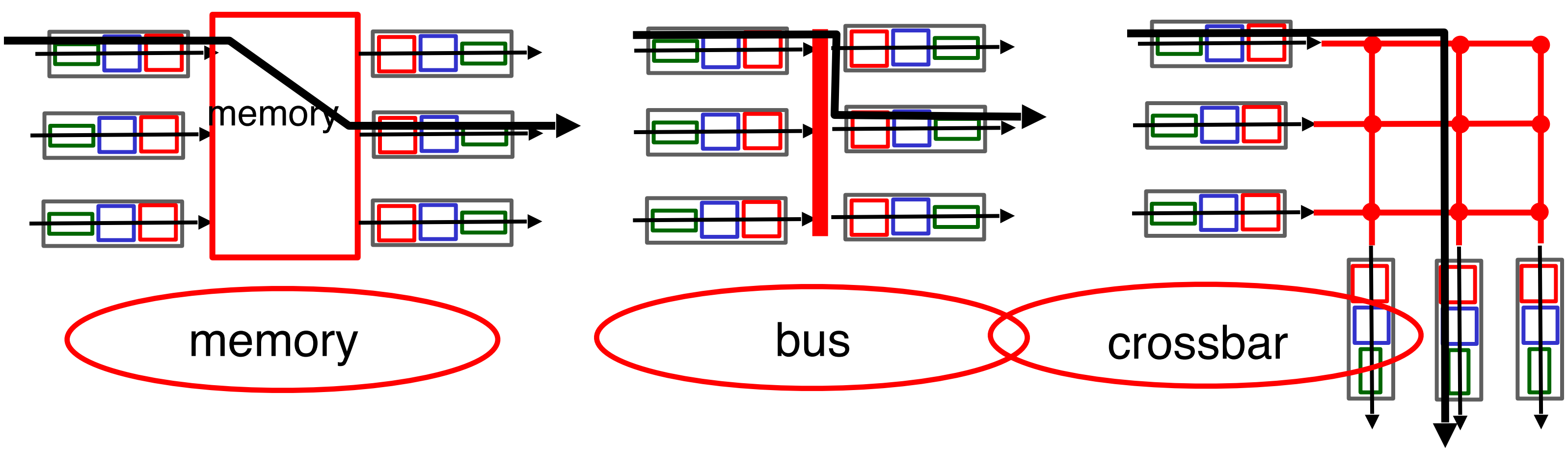
- when there are multiple matches,
  the router uses the **longest prefix matching rule**
- the IP addresses are assigned hierarchical → contiguous address

# 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: can up ~1M forwarding table entries in TCAM

# Switching fabrics

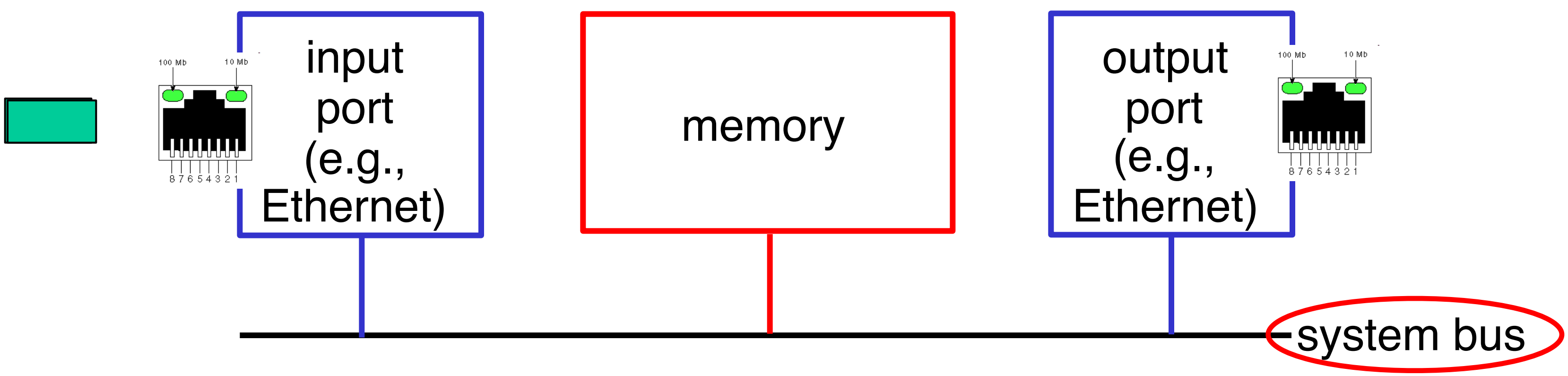
- transfer packet from input buffer to appropriate output buffer
- switching rate: rate at which packets can be transfer from inputs to outputs
  - often measured as multiple of input/output line rate
  - N inputs: switching rate N times line rate desirable
- three types of switching fabrics



# 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)



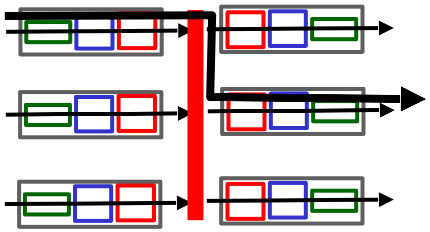

- memory bandwidth = B packets/sec

→ forwarding throughput < B/2 packets/sec

# Switching via a bus

- the bus is shared only one packet at a time

- datagram from input port memory to output port memory via a shared bus
- without intervention by the routing processor
- *bus contention:* switching speed limited by bus bandwidth
- 32 Gbps bus, Cisco 5600: sufficient speed for access and enterprise routers

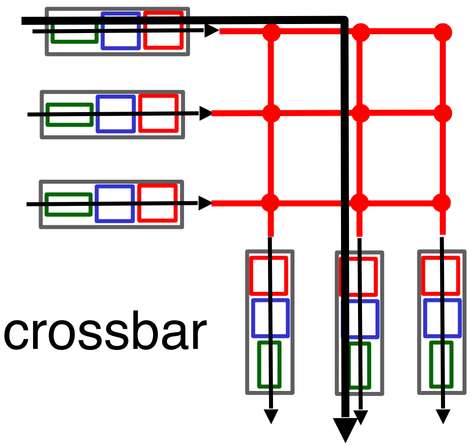


bus

- Cisco 1900: 1 Gbps Packet Exchange Bus
- 3Com CoreBuilder 5000 system: 2 Gbps Packet Channel data bus

# Switching via an interconnection network

- overcome bus bandwidth limitations
- banyan networks, crossbar, other interconnection nets initially developed to connect processors in multiprocessor
- advanced design: fragmenting datagram into fixed length cells, switch cells through the fabric
- Cisco 12000: switches 60 Gbps through the interconnection network

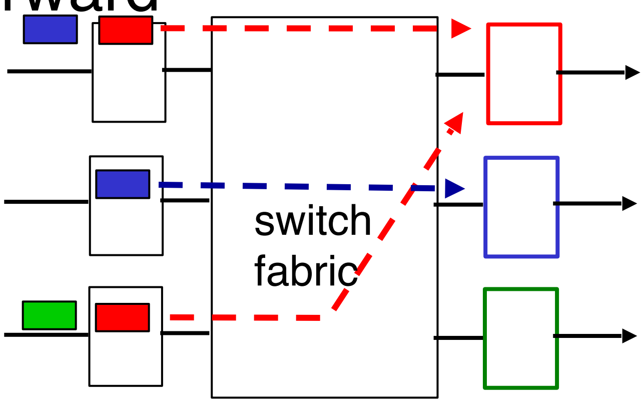


crossbar

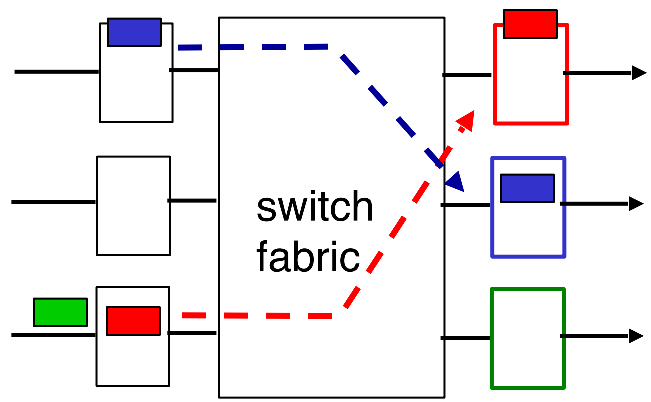
- n input ports * n output ports

# Input port queuing

- fabric slower than input ports combined -> queuing may occur at input queues
  - *queuing 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



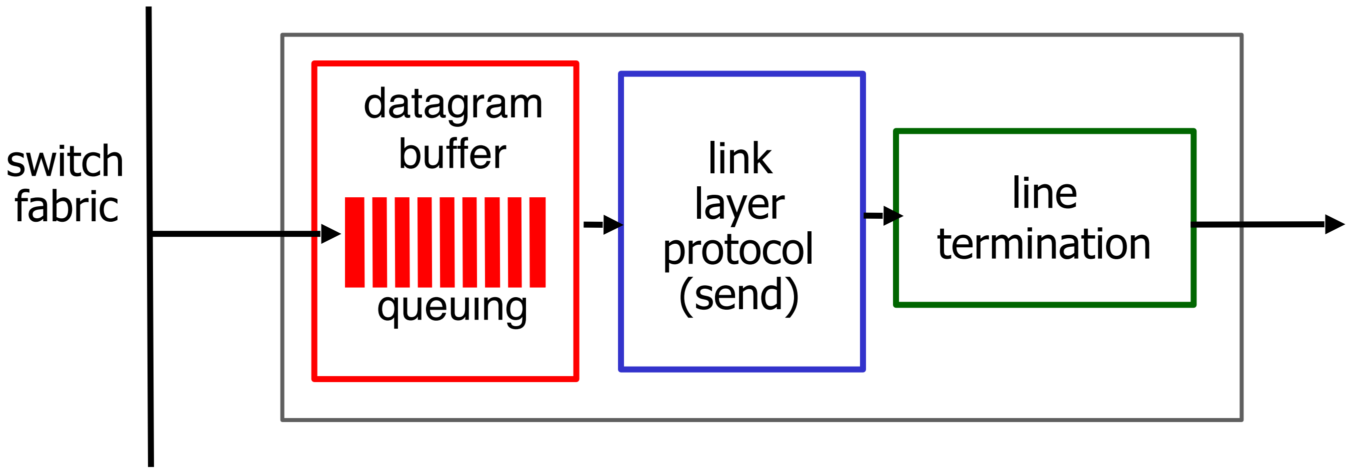

output port contention:
only one red datagram can be transferred.
*lower red packet is blocked*




one packet time later: green packet experiences HOL blocking

# Output ports

This slide in HUGELY important!




- *buffering* required when datagra
  transmission rate
- *scheduling discipline* chooses a

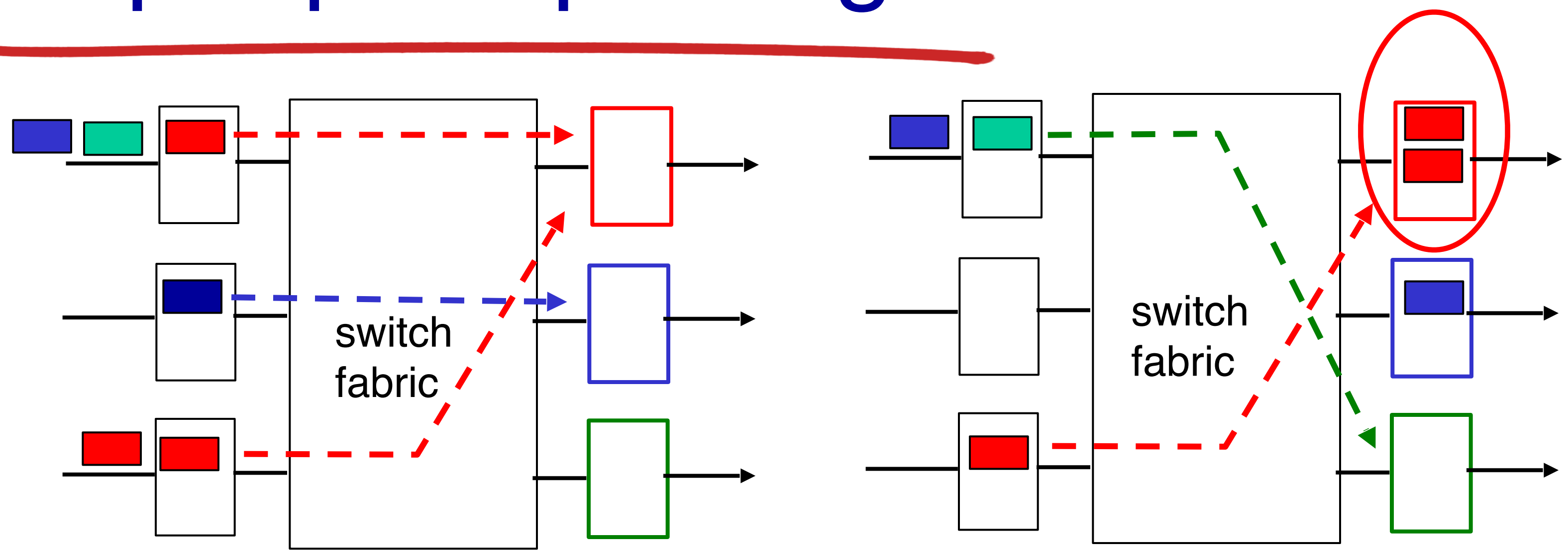
Datagram (packets) can be lost due to congestion, lack of buffers

Priority scheduling – who gets best performance, network neutrality

# Output Port Queuing

- It's advantageous to drop (or mark the header of) a packet before the buffer is full in order to provide a congestion signal to the sender
- Active queue management (AQM) algorithm
  - Ex. Random Early Detection (RED) algorithm
  - Average queue length < $min_{th}$ → added to the queue
  - Average queue length > $max_{th}$ → marked or dropped
  - in $[min_{th}, max_{th}]$ → marked or dropped with a probability

# Output port queuing




at *t,* packets more from input to output

one packet time later

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

•packet scheduler, ex. FCFS (first-come-first-served), WFQ (weighted fair queuing)

•QoS (quality-of-service) guarantees → Chapter 9

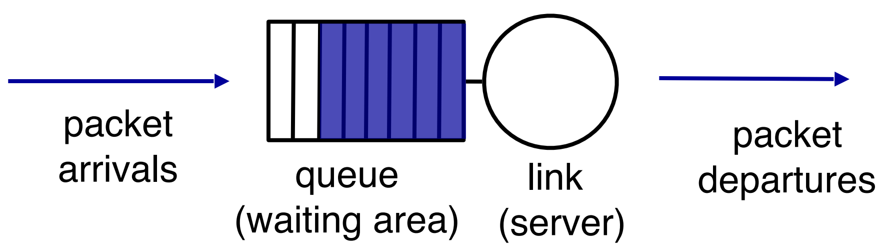
# How much buffering?

- 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
- recent recommendation: with *N* flows, buffering equal to

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

# Scheduling mechanisms

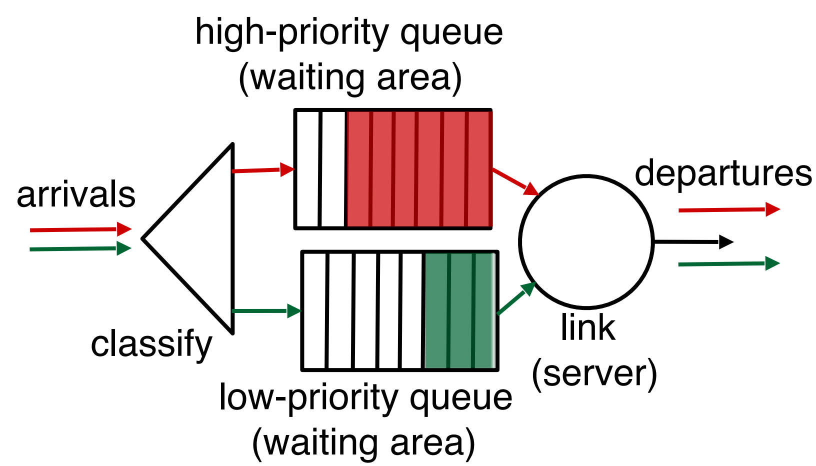
- *scheduling:* choose next packet to send on link
- *FIFO (first-in-first-out) scheduling:* send in order of arrival to queue
  - real world example?
  - *packet-discarding policy:* if packet arrives to full queue: who to discard?
    - *tail drop:* drop arriving packet
    - *priority:* drop/remove on priority basis
    - *random:* drop/remove randomly

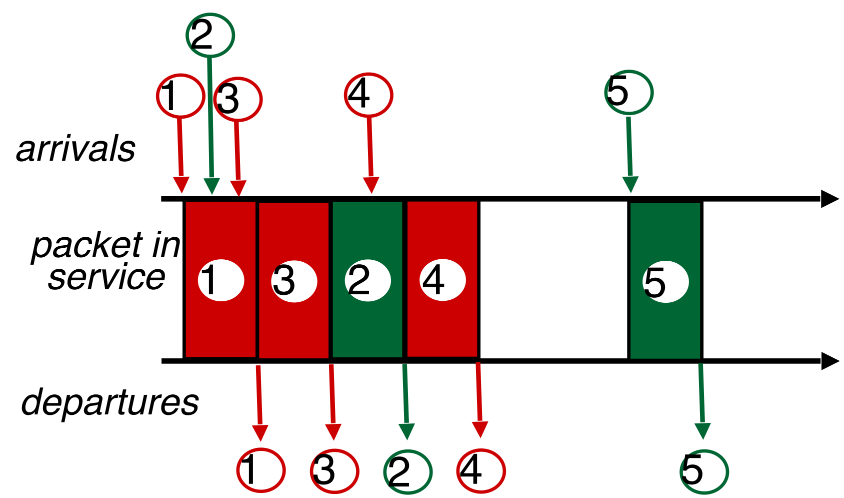


# Scheduling policies: priority

*priority scheduling:*
send highest priority queued packet

- multiple *classes*, with different priorities
  - class may depend on marking or other header info, e.g., source/dest. TCP/UDP port numbers, etc.
  - real world example?
  - non-preemptive priority queuing

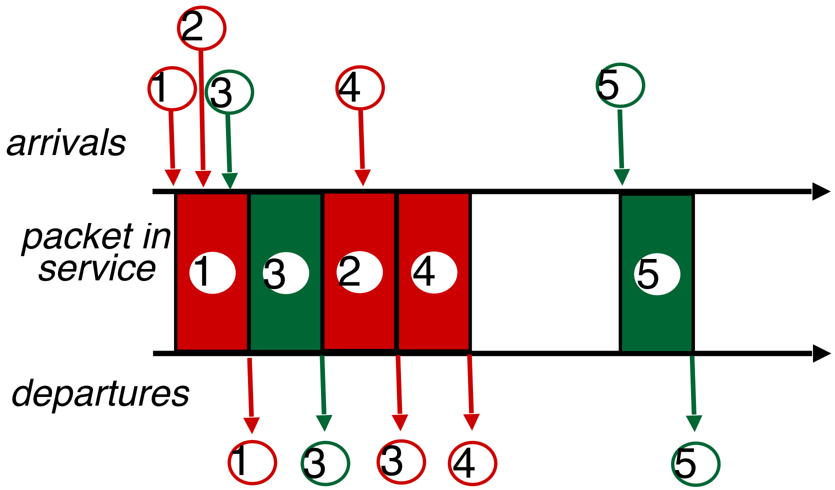


# Scheduling policies: still more

*Round Robin (RR) scheduling:*

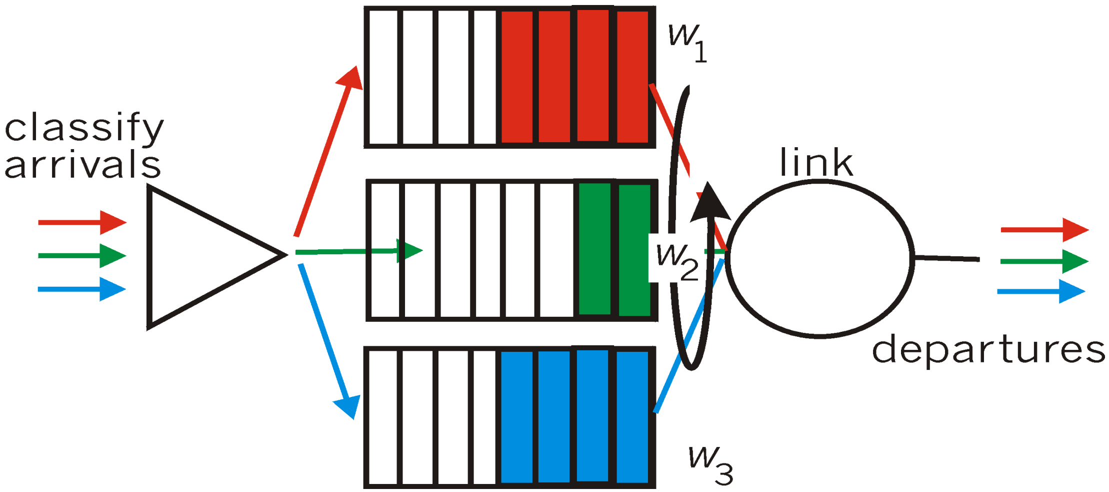
- multiple classes
- cyclically scan class queues, sending one complete packet from each class (if available)



# Scheduling policies: still more

*Weighted Fair Queuing (WFQ):*

- generalized Round Robin
- each class gets weighted amount of service in each cycle
- real world example?



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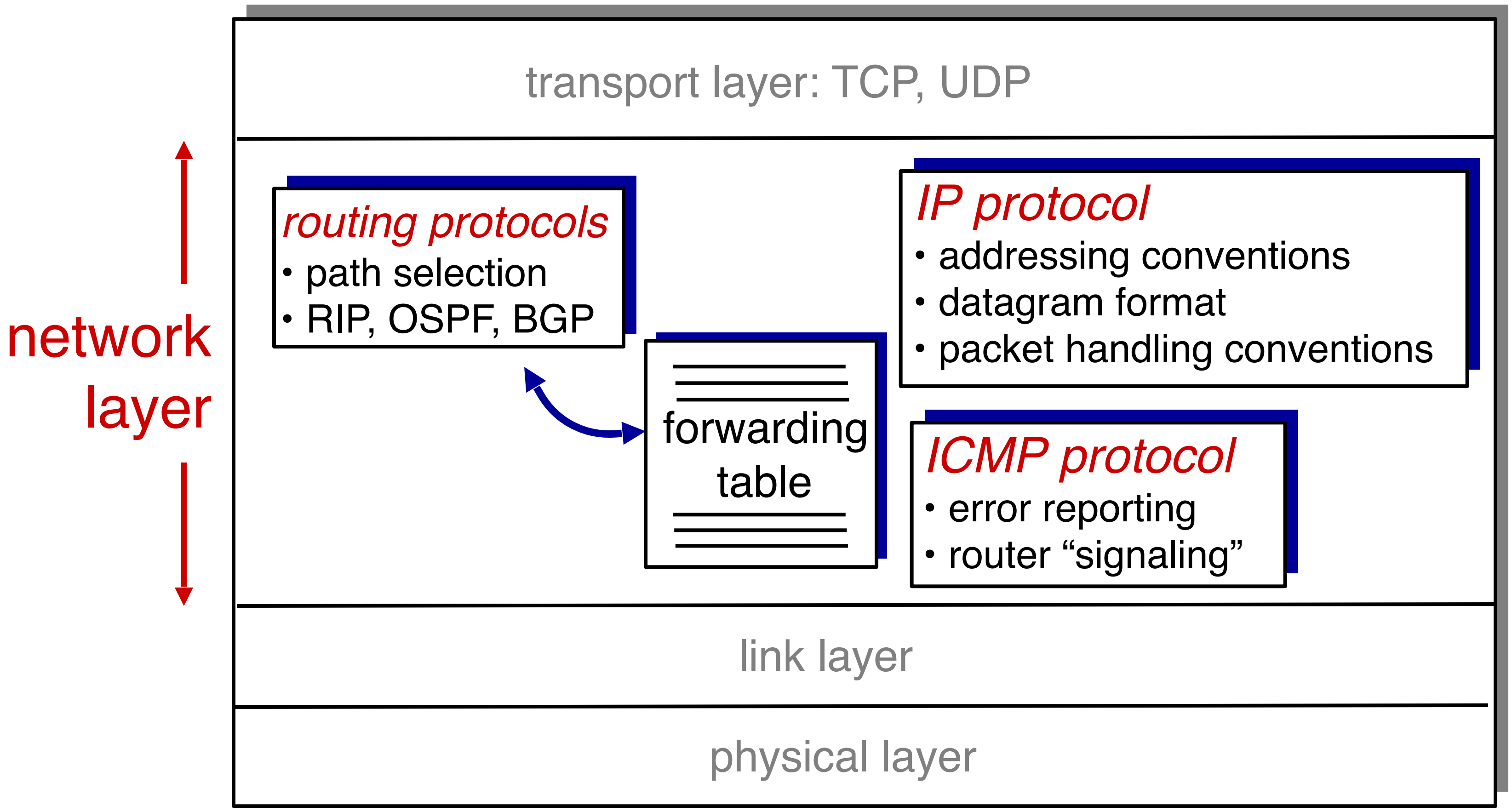
# The Internet network layer

host, router network layer functions:



# IP datagram format

Header + data
16 bits→ max?
Usually 1,500 bytes

IP protocol version number

header length (bytes)

Usually 20 bytes

"type" of data

Ex. realtime

max. number remaining hops (decremented at each router)

upper-layer protocol to deliver payload to

Ex. 1→ICMP, 6→TCP, 17→UDP

32 bits

| | | | | |
|---|---|---|---|---|
| ver | head. len | type of service | datagram length | |
| 16-bit identifier | | | flags | fragmentation offset |
| time-to-live (TTL) | | protocol | header checksum | |
| 32-bit source IP address | | | | |
| 32-bit destination IP address | | | | |
| options (if any) | | | | |
| data (payload) (variable length, typically a TCP or UDP segment, may be ICMP message) | | | | |

total datagram length (bytes)

for fragmentation/ reassembly

IPv6 does not allow for fragmentation at routers

error detection

Recomputed and stored again at each router

e.g., timestamp, record route taken, specify list of routers to visit

The options field is dropped in IPv6

*how much overhead?*

- 20 bytes of TCP
- 20 bytes of IP
- = 40 bytes + app layer overhead

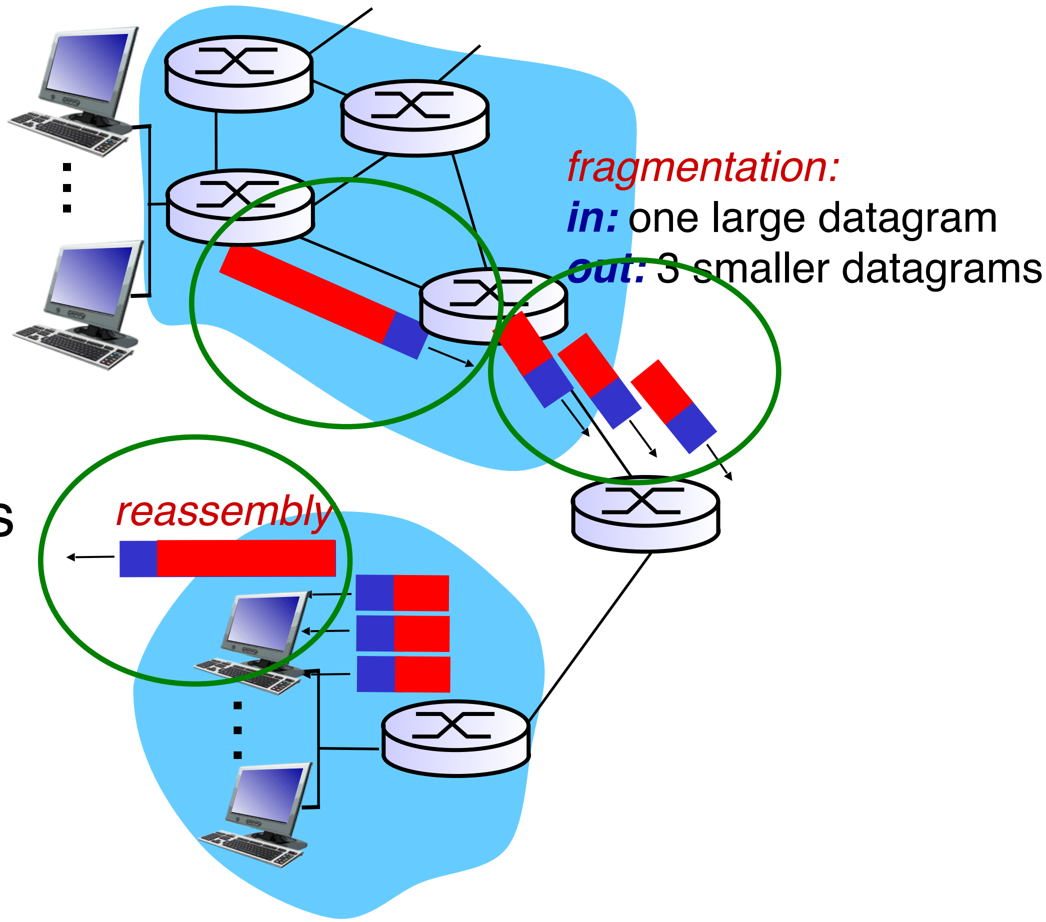
# IPv4 datagram format

- Why does TCP/IP perform error checking at both transport and network layer?
  - Only the IP header is checksummed at the IP layer, but the TCP/UDP checksum is computed over the entire TCP/UDP segment
  - TCP/UDP and IP do not necessarily both have to belong to the same protocol stack; IP may carry data that will not be passed to TCP/UDP

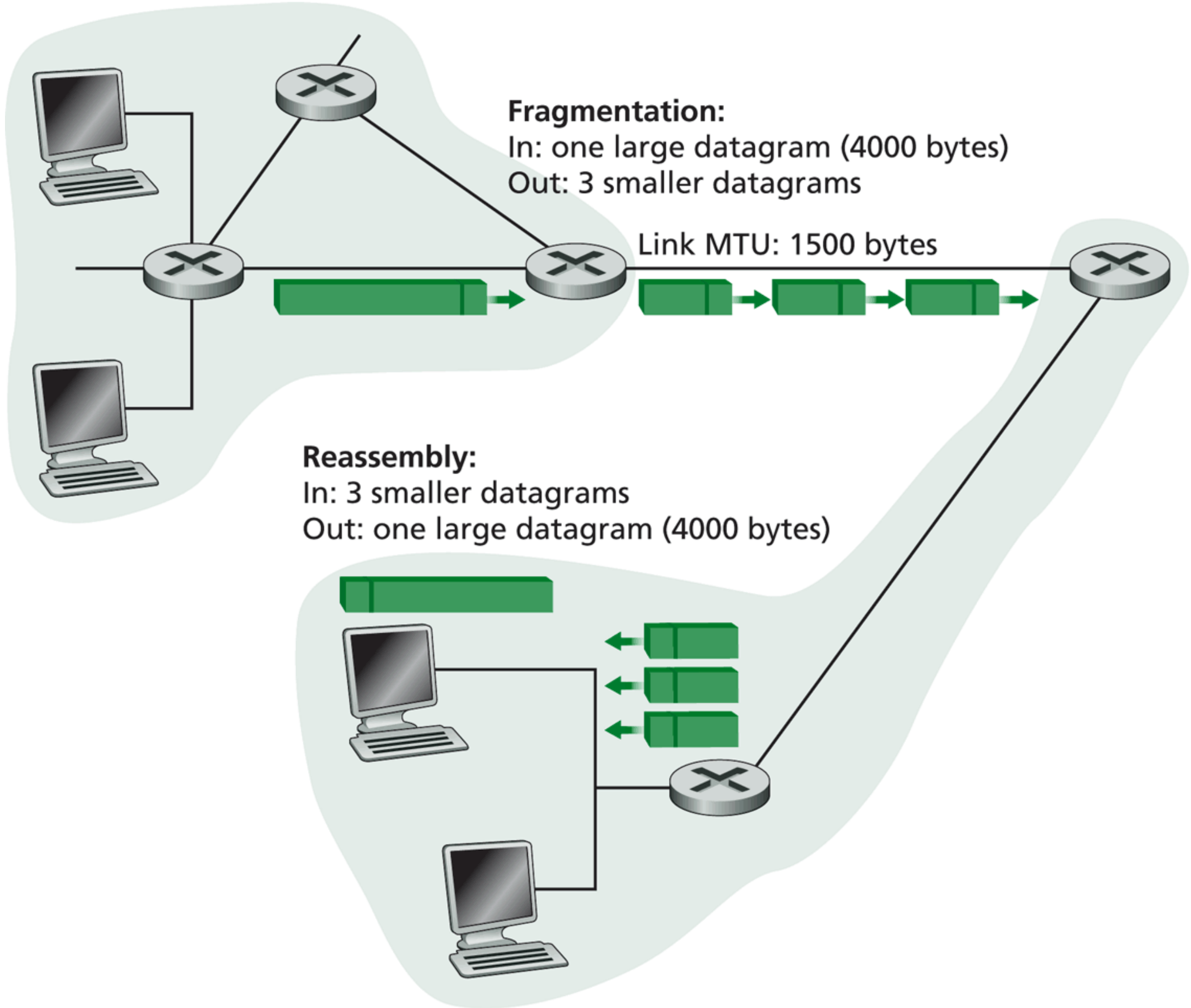
# IP fragmentation, reassembly

- network links have MTU (max. transfer size) - largest possible link-level frame
  - different link types, different MTUs
- large IP datagram divided ("fragmented") within net
  - one datagram becomes several datagrams
  - "reassembled" only at final destination
  - IP header bits used to identify, order related fragments

•MTU: Maximum Transmission Unit




•Ethernet: 1,500 bytes
•Some wide-area link: 576 bytes




**Flags: 3 bits**

- **Bit 0: reserved, must be zero**
- **Bit 1: (DF) 0 = May Fragment, 1 = Don't Fragment**
- **Bit 2: (MF) 0 = Last Fragment, 1 = More Fragments**

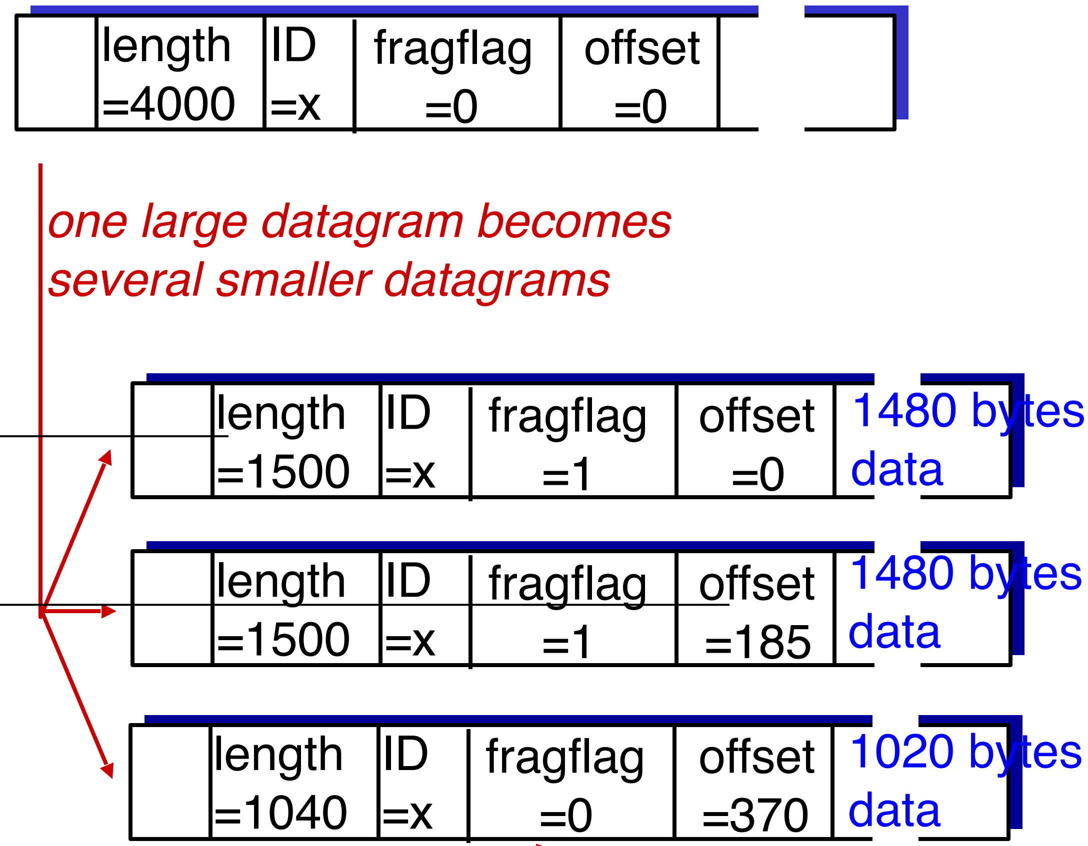
# IP fragmentation, reassembly

*example:*

- 4000-byte datagram
  data size=? 3980 bytes
- MTU = 1500 bytes

1480 bytes in data field

offset = 1480/8




•The last fragment: flag bit=0, others: 1

•where the fragment fits within the original IP datagram

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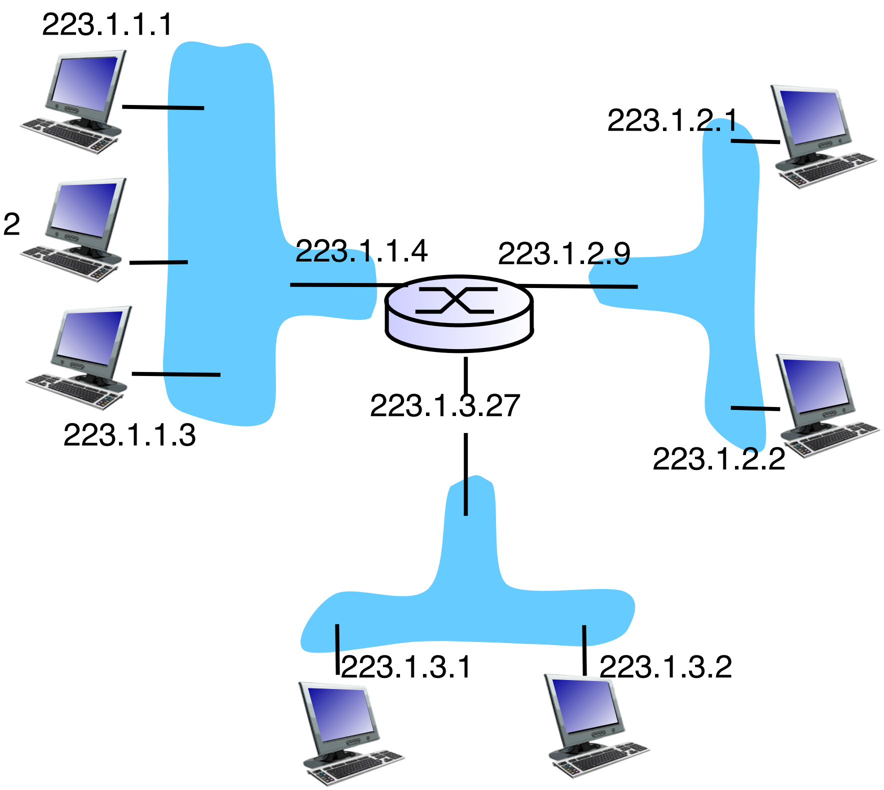
# IP addressing: introduction

- *IP address:* 32-bit identifier for host, 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)
- *IP addresses associated with each interface*
  - IP address: globally unique



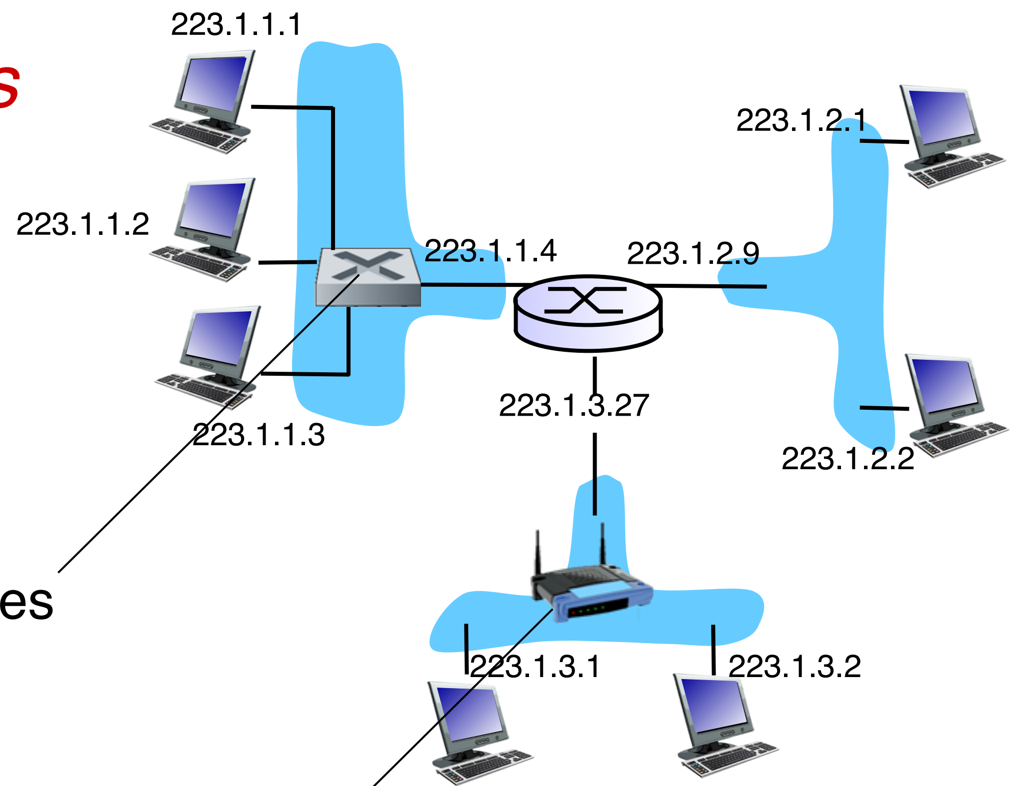

$$223.1.1.1 = \underbrace{11011111}_{223}\ \underbrace{00000001}_{1}\ \underbrace{00000001}_{1}\ \underbrace{00000001}_{1}$$

Dotted-decimal notation

# IP addressing: introduction

*Q: how are interfaces actually connected?*

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



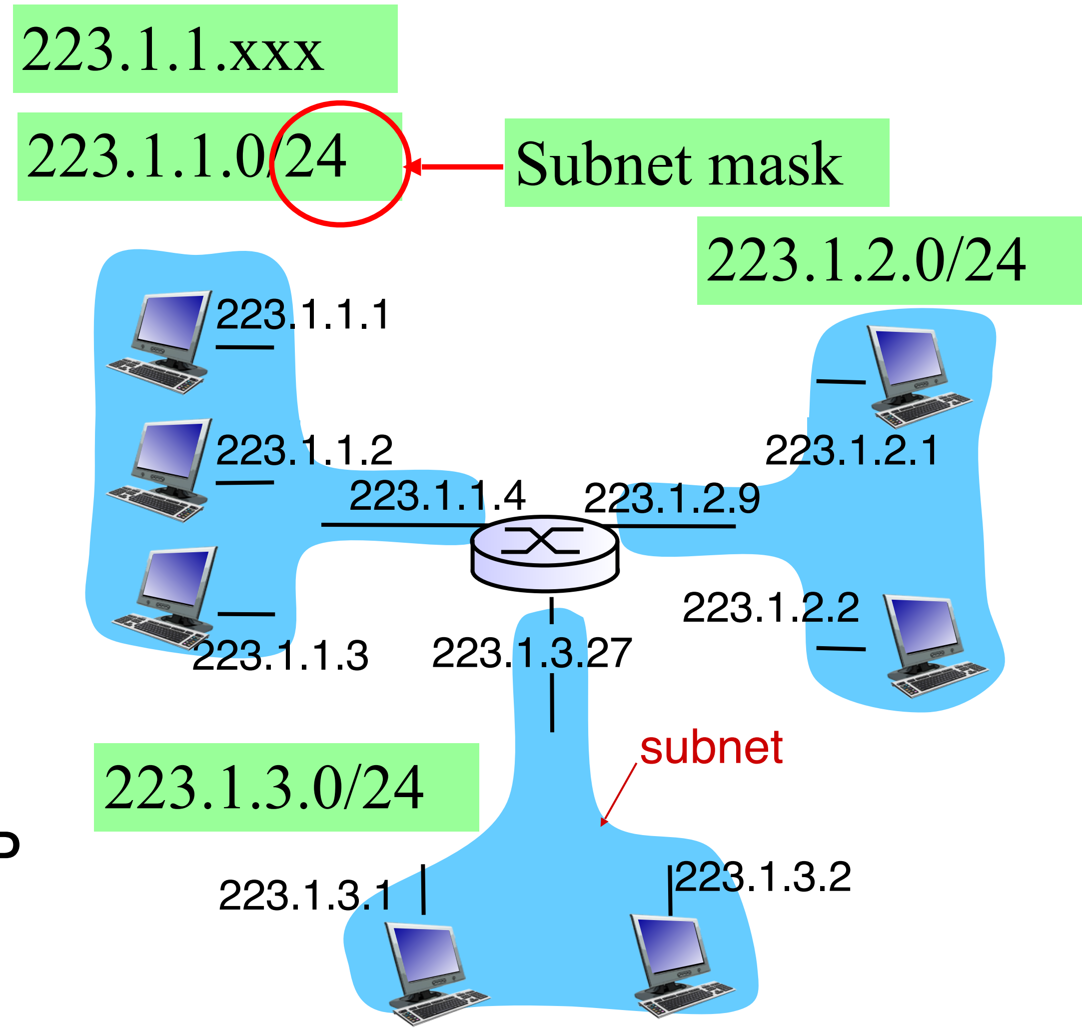

*A:* wired Ethernet interfaces connected by Ethernet switches

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

*A:* wireless WiFi interfaces connected by WiFi access point

# Subnets

- IP address:
  - subnet part - high order bits
  - host part - low order bits
- *what's a subnet?*
  - device interfaces with same subnet part of IP address
  - can physically reach each other *without intervening router*

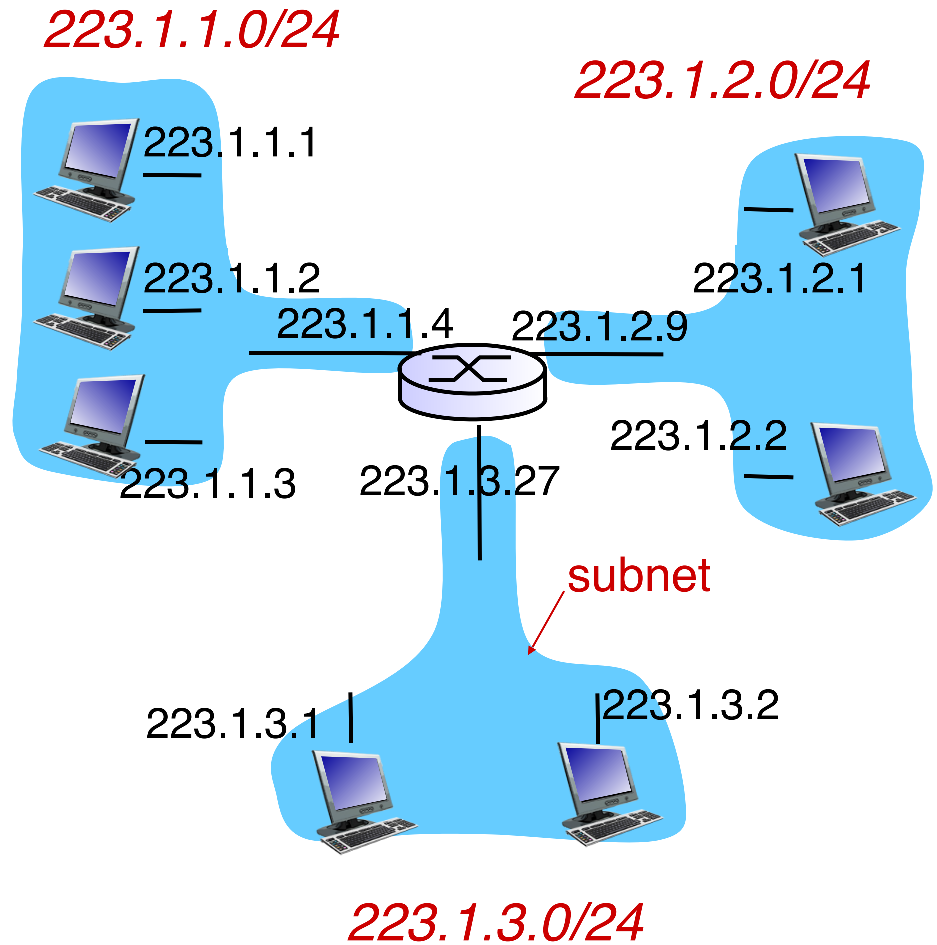



network consisting of 3 subnets

# Subnets

*recipe*

- to determine the subnets, detach each interface from its host or router, creating islands of isolated networks
- each isolated network is called a *subnet*

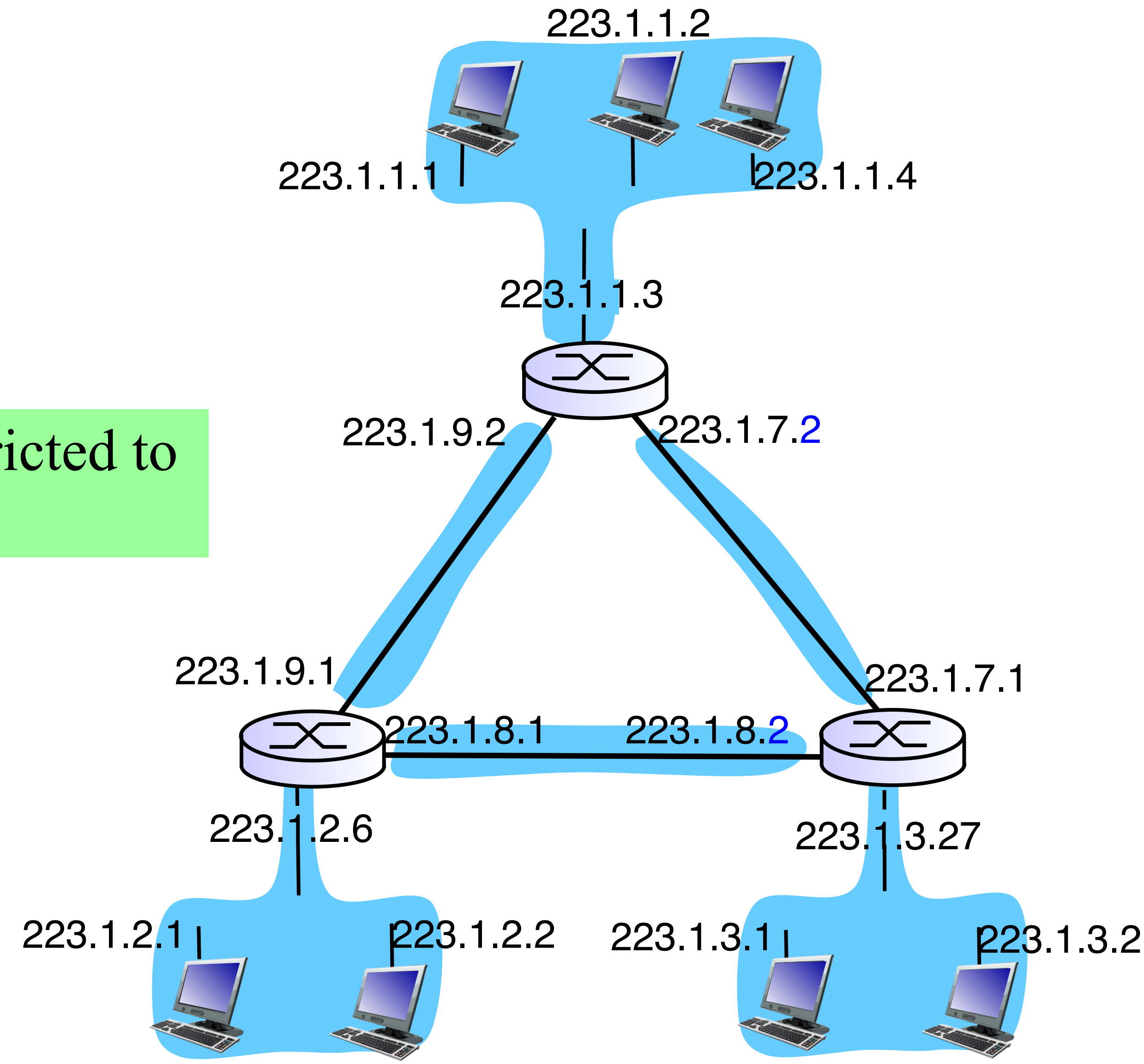



subnet mask: /24

# Subnets

how many?

six subsets




- A subnet is not restricted to Ethernet segments

# IP addressing: CIDR

CIDR: Classless InterDomain Routing

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

The router only considers the leading x bits for forwarding a datagram

subnet part | host part

11001000 00010111 00010000 00000000

200.23.16.0/23

The lower-order bits may have an additional subnetting structure

- Before CIDR was adopted, the network portions of an IP address were constrained to be 8, 16 or 24 bits, known as classful addressing
  - 8-bit subnet addresses→ class A networks
  - 16-bit subnet addresses→ class B networks
  - 24-bit subnet addresses→ class C networks
- If an organization owns 2000 hosts?
  - A class C (/24) subnet: $2^8-2=254$ hosts
  - A class B (/16) subnet: $2^{16}-2=65534$ hosts

$2^{11}=2048>2000$→ X.X.X.X/21

How about 400 IPs are required?

255.255.255.255→ IP broadcast address

# IP addresses: how to get one?

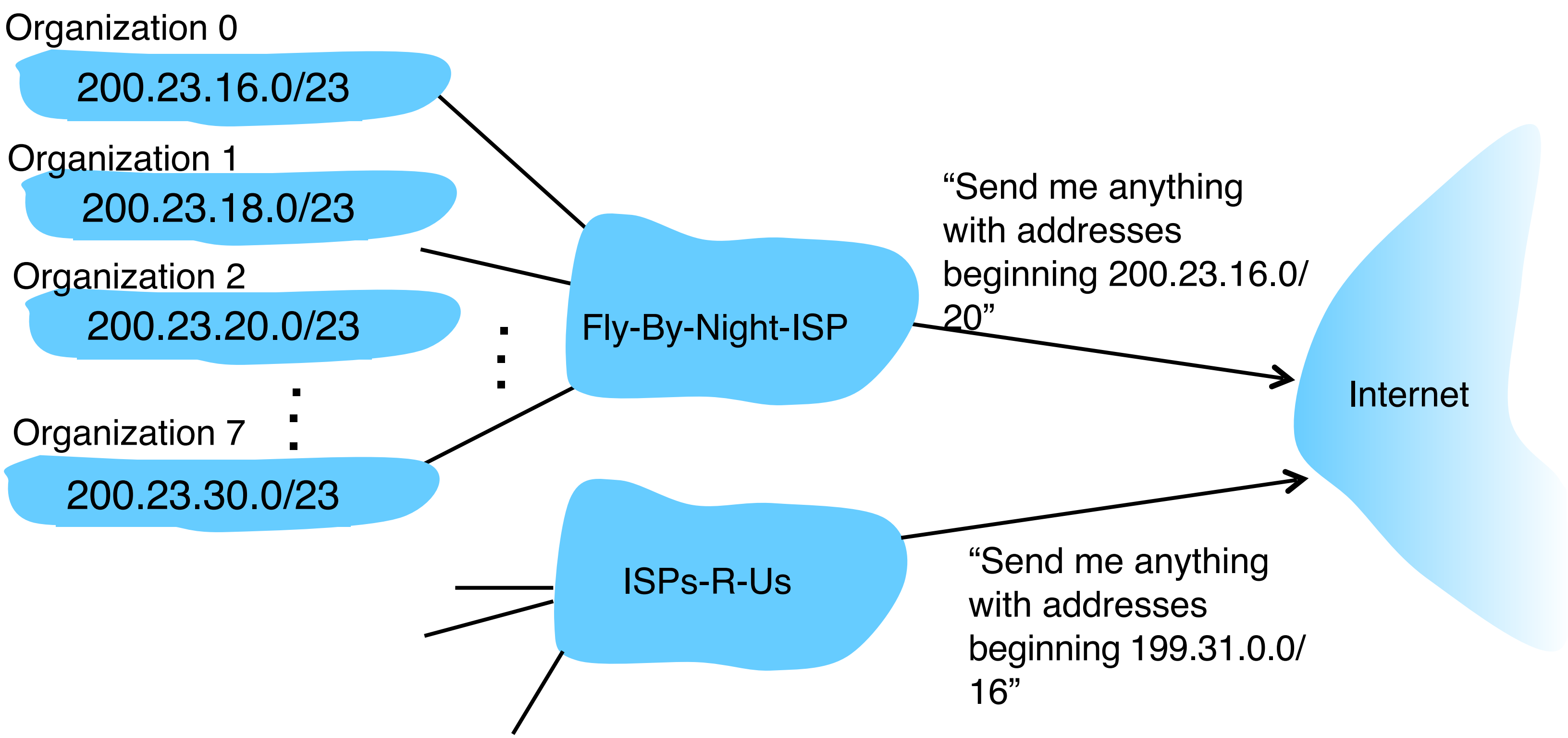
*Q:* how does *network* get subnet part of IP address?

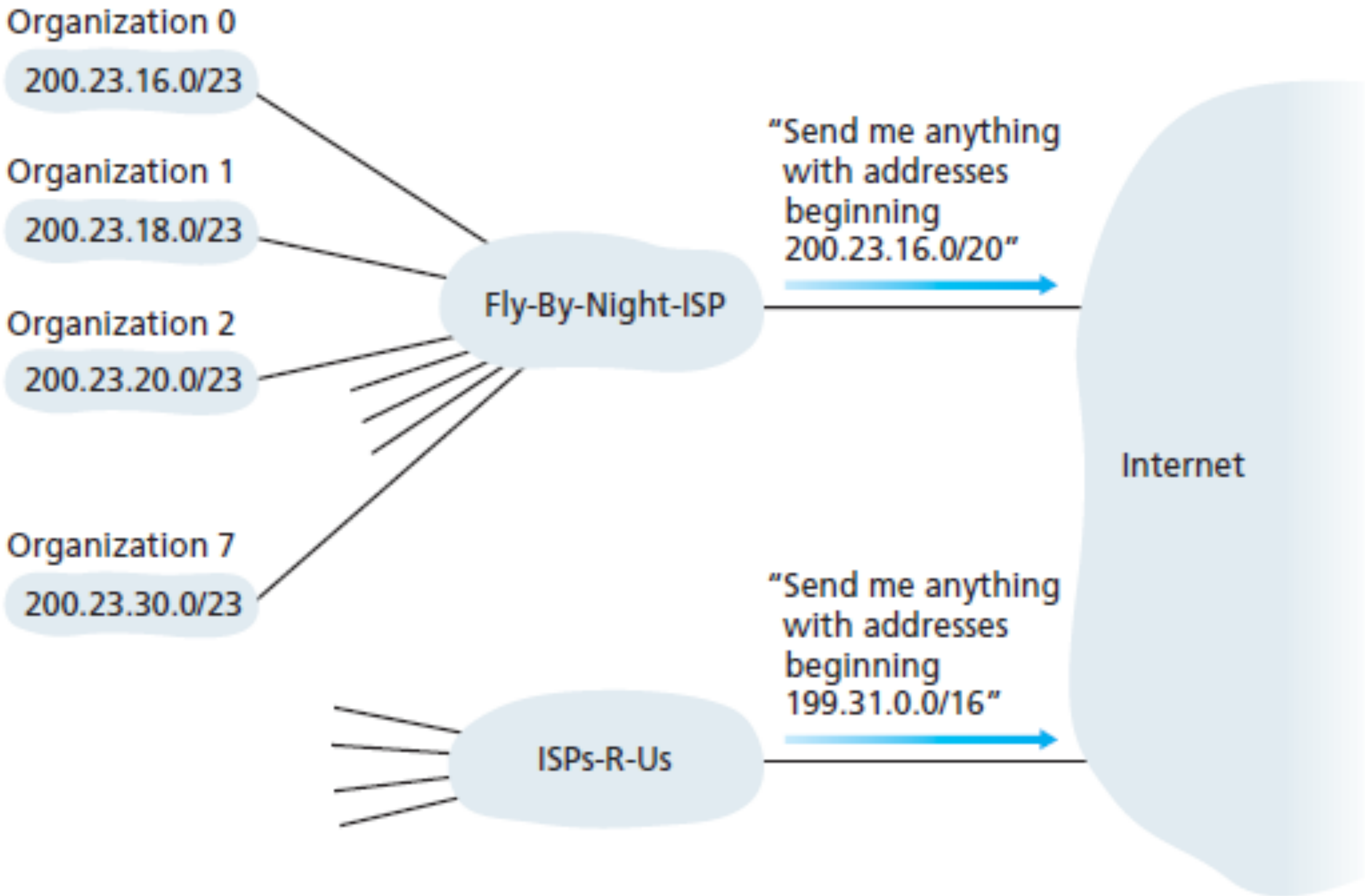
*A:* gets allocated portion of its provider ISP's address space

| | | |
|---|---|---|
| ISP's block | 11001000 00010111 00010000 00000000 | 200.23.16.0/20 |
| Organization 0 | 11001000 00010111 00010000 00000000 | 200.23.16.0/23 |
| Organization 1 | 11001000 00010111 00010010 00000000 | 200.23.18.0/23 |
| Organization 2 | 11001000 00010111 00010100 00000000 | 200.23.20.0/23 |
| ... | ..... .... | .... |
| Organization 7 | 11001000 00010111 00011110 00000000 | 200.23.30.0/23 |

# Hierarchical addressing: route aggregation

hierarchical addressing allows efficient advertisement of routing information:



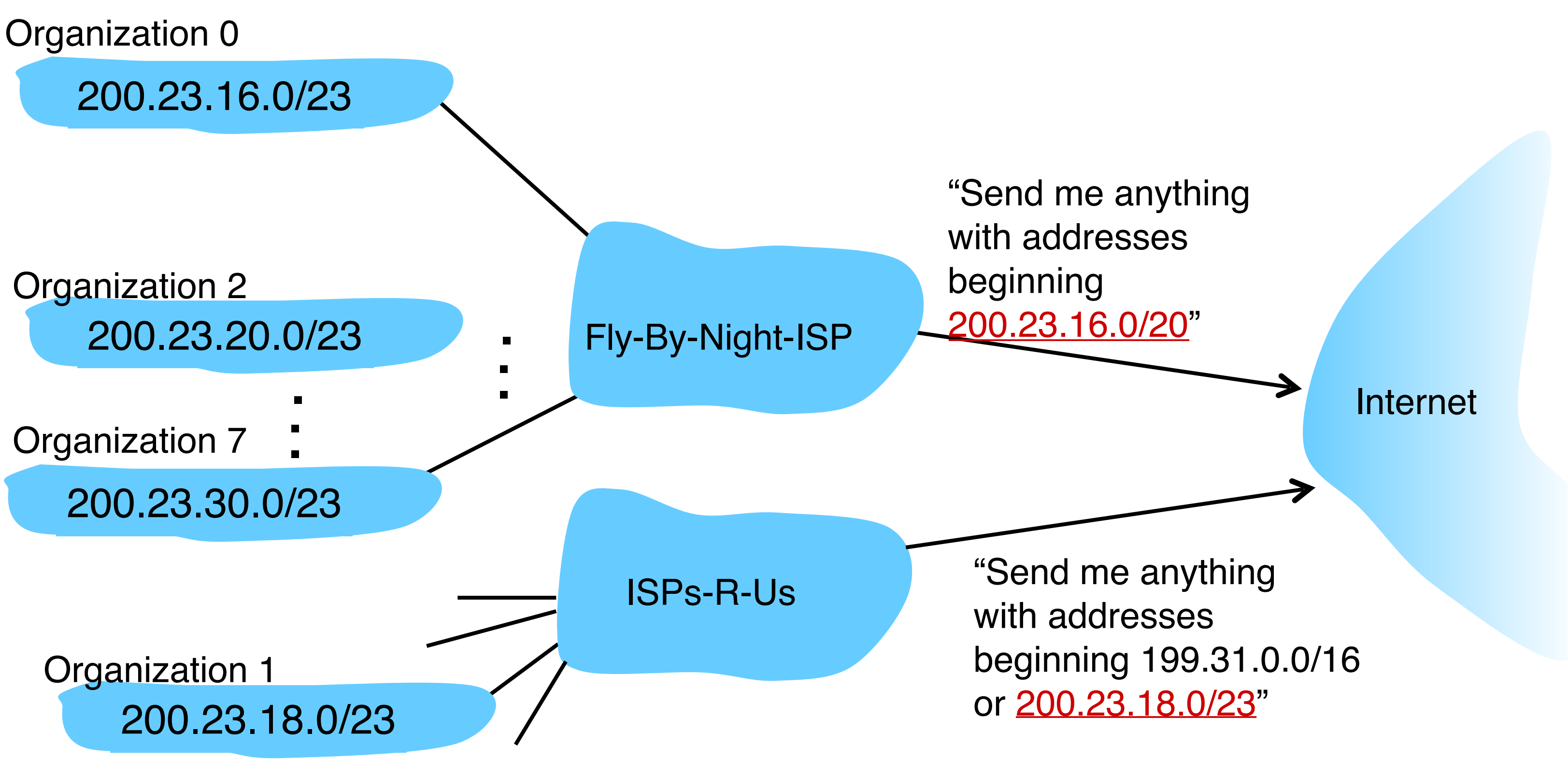


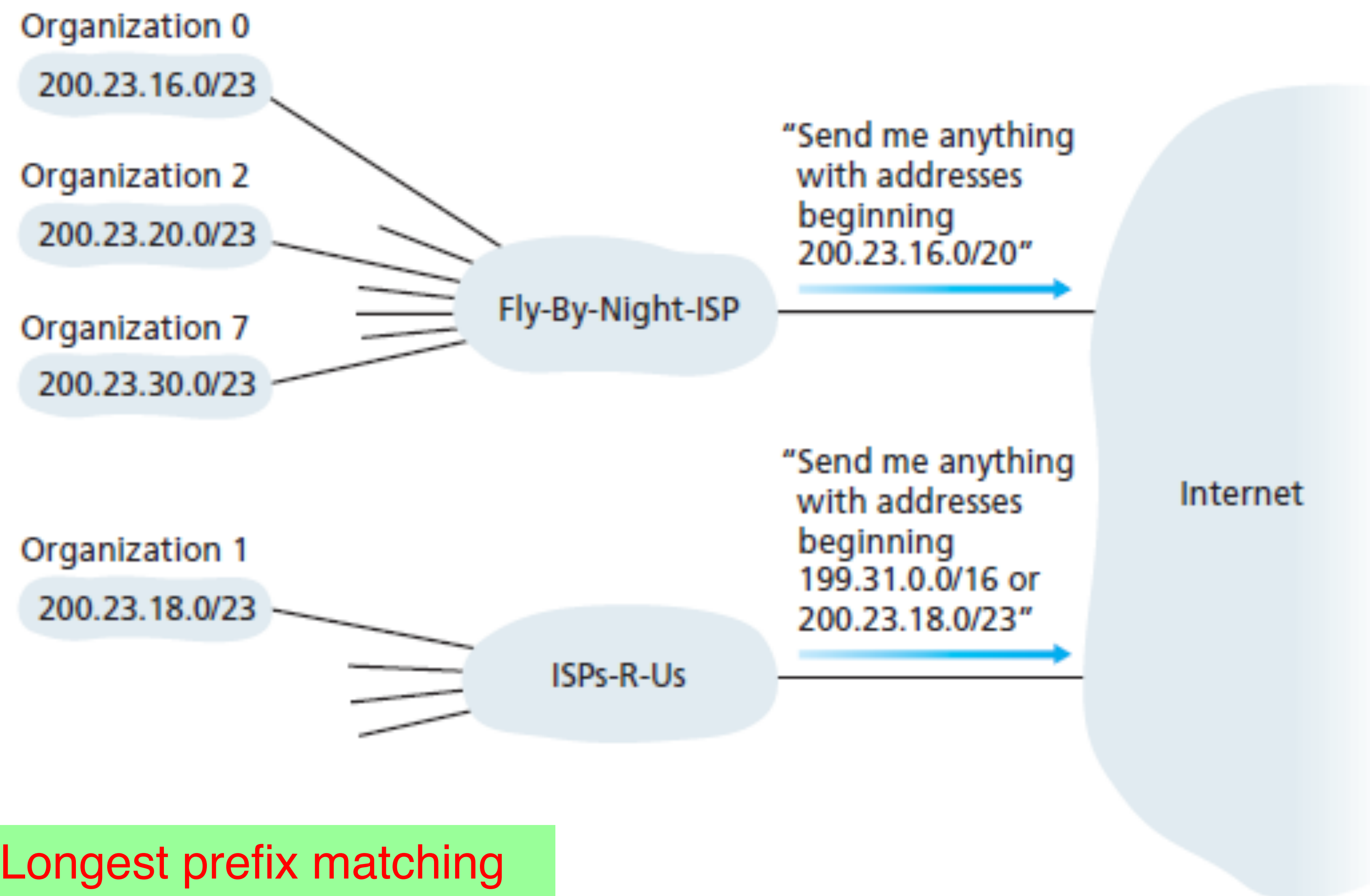

- Hierarchical addressing and route aggregation

If Fly-by-Night-ISP acquires ISPs-R-Us and then has organization 1 connect to the Internet through ISPs-R-Us?

# Hierarchical addressing: more specific routes

ISPs-R-Us has a more specific route to Organization 1






Longest prefix matching

- ISPs-R-Us has a more specific route to Organization 1

# IP addressing: the last word...

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

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

- allocates addresses
- manages DNS
- assigns domain names, resolves disputes

# IP addresses: how to get one?

Q: How does a *host* get IP address?

- hard-coded by system admin in a file
  - Windows: control-panel->network->configuration->tcp/ip->properties
  - UNIX: /etc/rc.config
- DHCP: Dynamic Host Configuration Protocol: dynamically get temporary IP address from a server
  - "plug-and-play" protocol

DHCP: obtain IP, gateway (the first-hop router), local DNS server

Why DHCP? (1) IPs are not enough (2) mobile computing

# DHCP: Dynamic Host Configuration Protocol

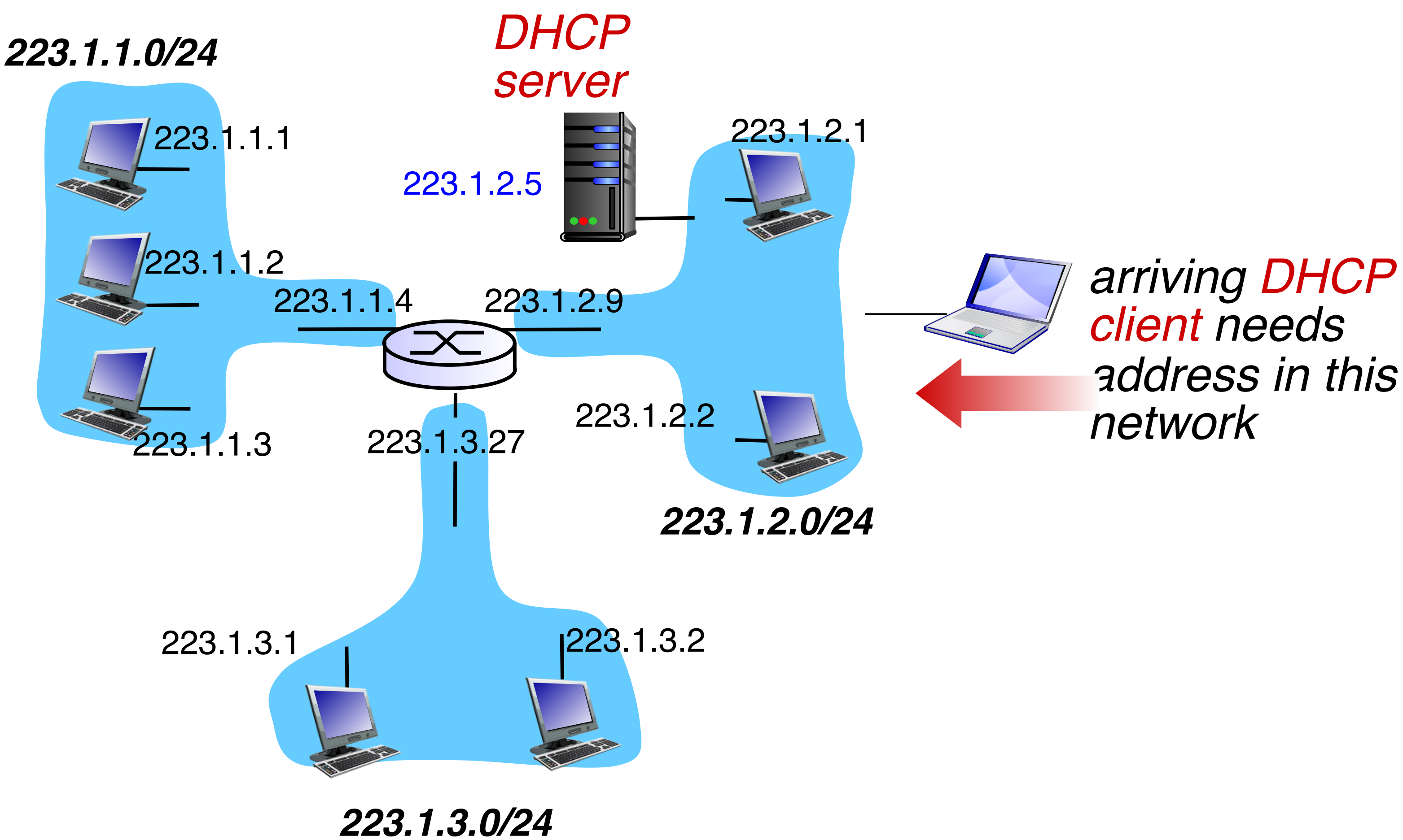
*goal:* allow host to *dynamically* obtain its IP address from network server when it joins network

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

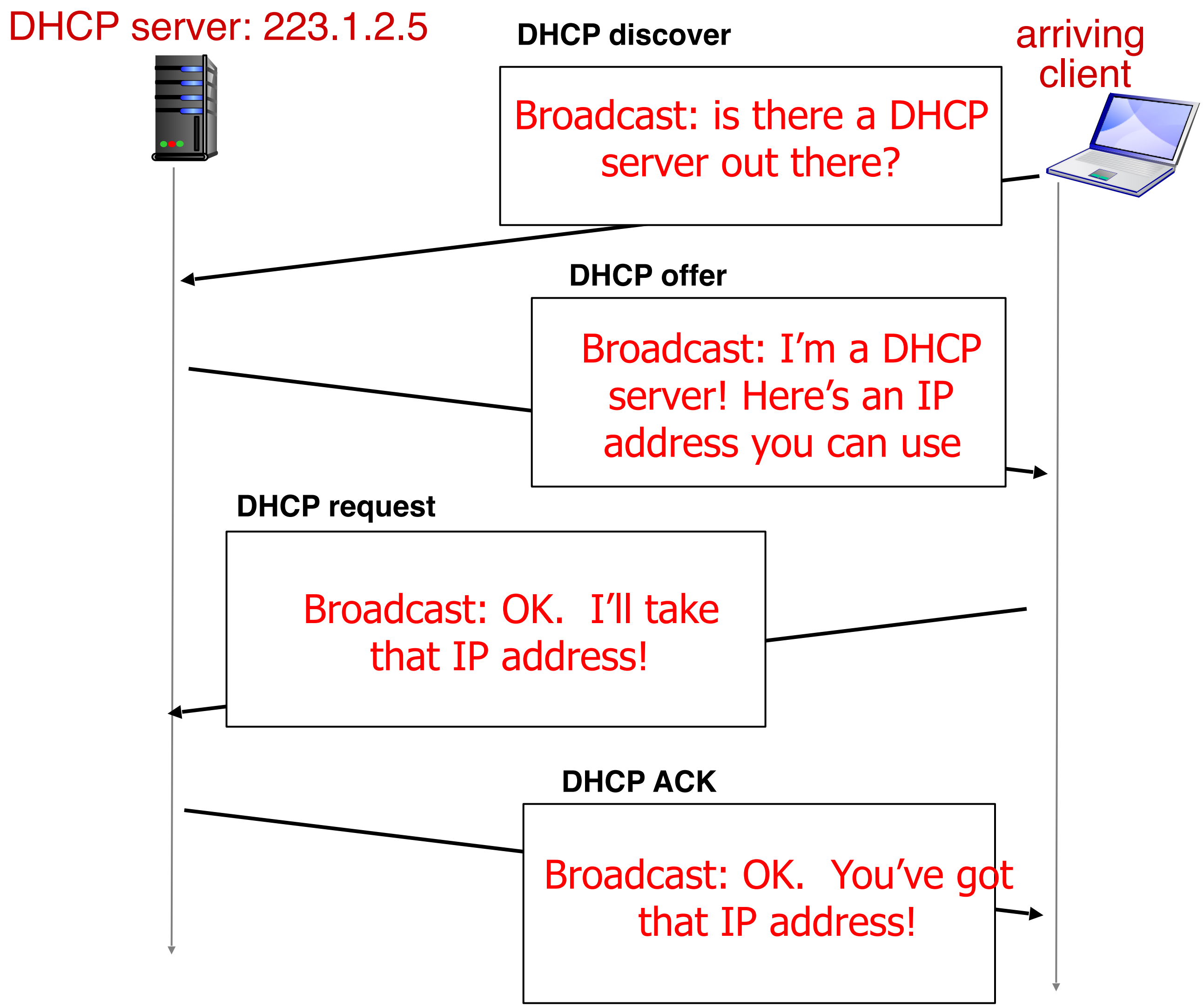
*DHCP overview:*

- 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

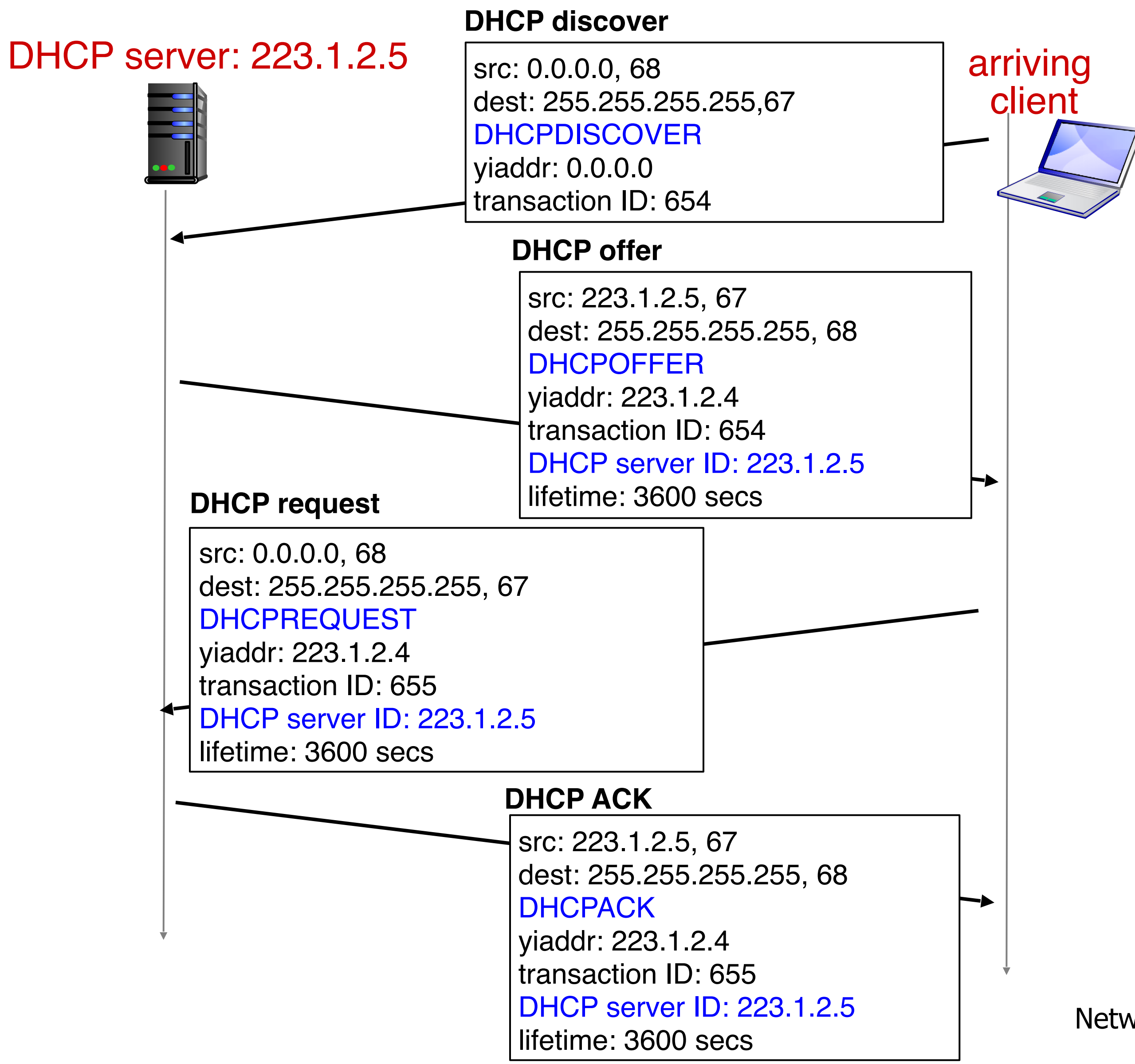
# DHCP client-server scenario



# DHCP client-server scenario



# DHCP client-server scenario

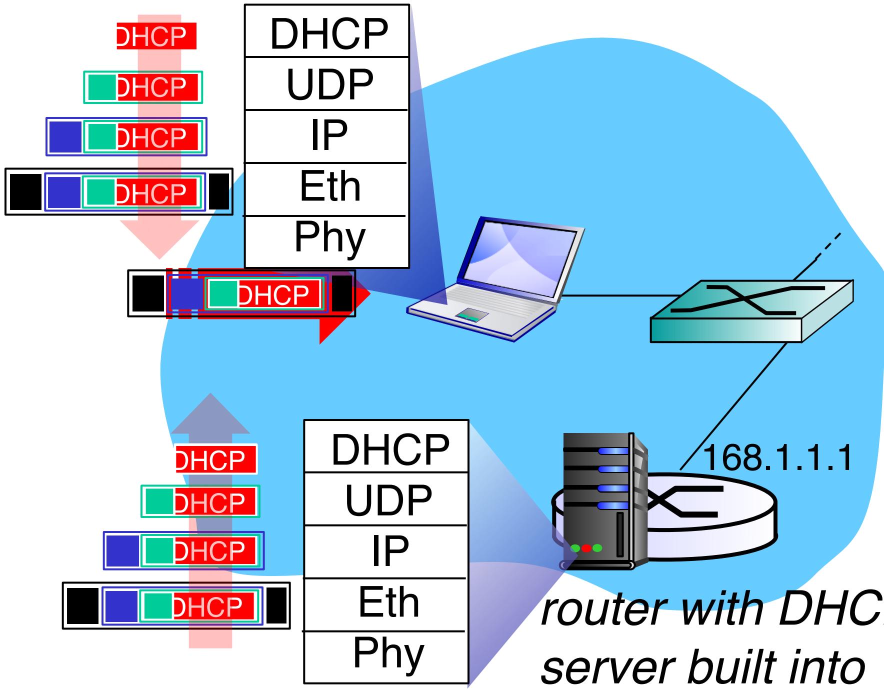


# DHCP: more than IP addresses

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

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

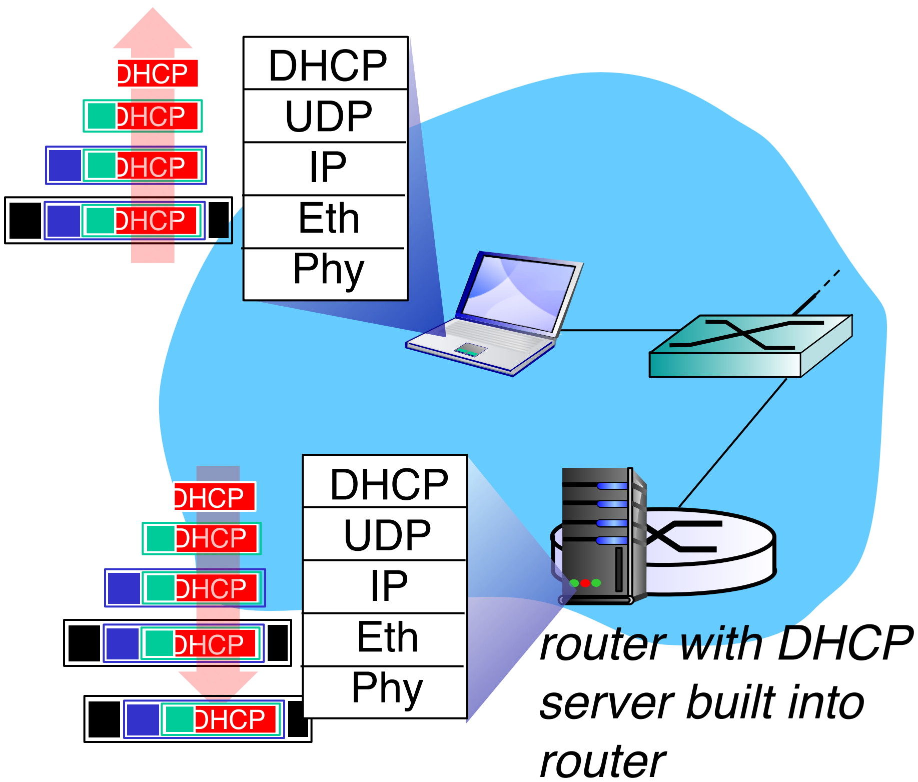
# DHCP: example




*router with DHCP server built into router*

- connecting laptop needs its IP address, addr of first-hop router, addr of DNS server: use DHCP
- DHCP request encapsulated in UDP, encapsulated in IP, encapsulated in 802.3 Ethernet frame
- Ethernet frame broadcast (dest: FF-FF-FF-FF-FF-FF) on LAN, received at router running DHCP server
- Ethernet demuxed to IP, demuxed to UDP, demuxed 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
- encapsulation of DHCP server, frame 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

# DHCP: Wireshark output (home LAN)

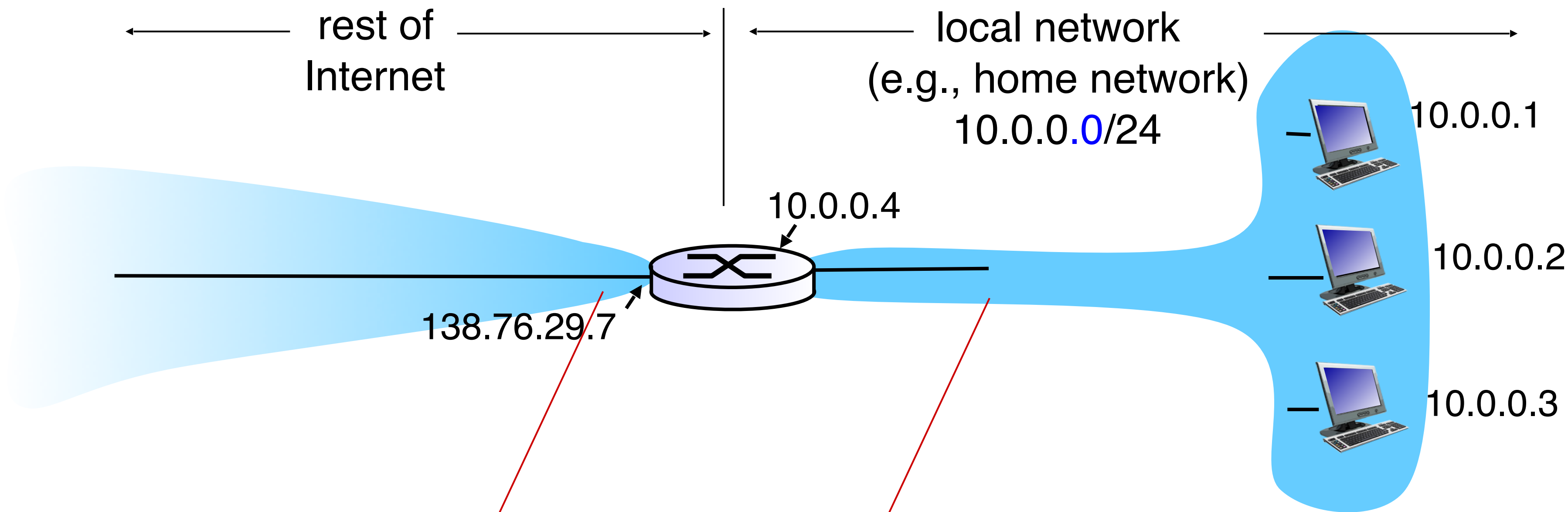
request

Message type: **Boot Request (1)**
Hardware type: Ethernet
Hardware address length: 6
Hops: 0
**Transaction ID: 0x6b3a11b7**
Seconds elapsed: 0
Bootp flags: 0x0000 (Unicast)
Client IP address: 0.0.0.0 (0.0.0.0)
Your (client) IP address: 0.0.0.0 (0.0.0.0)
Next server IP address: 0.0.0.0 (0.0.0.0)
Relay agent IP address: 0.0.0.0 (0.0.0.0)
**Client MAC address: Wistron_23:68:8a (00:16:d3:23:68:8a)**
Server host name not given
Boot file name not given
Magic cookie: (OK)
Option: (t=53,l=1) **DHCP Message Type = DHCP Request**
Option: (61) Client identifier
    Length: 7; Value: 010016D323688A;
    Hardware type: Ethernet
    Client MAC address: Wistron_23:68:8a (00:16:d3:23:68:8a)
Option: (t=50,l=4) Requested IP Address = 192.168.1.101
Option: (t=12,l=5) Host Name = "nomad"
**Option: (55) Parameter Request List**
    Length: 11; Value: 010F03062C2E2F1F21F92B
    **1 = Subnet Mask; 15 = Domain Name**
    **3 = Router; 6 = Domain Name Server**
    44 = NetBIOS over TCP/IP Name Server
    ……

reply

Message type: **Boot Reply (2)**
Hardware type: Ethernet
Hardware address length: 6
Hops: 0
**Transaction ID: 0x6b3a11b7**
Seconds elapsed: 0
Bootp flags: 0x0000 (Unicast)
**Client IP address: 192.168.1.101 (192.168.1.101)**
Your (client) IP address: 0.0.0.0 (0.0.0.0)
**Next server IP address: 192.168.1.1 (192.168.1.1)**
Relay agent IP address: 0.0.0.0 (0.0.0.0)
Client MAC address: Wistron_23:68:8a (00:16:d3:23:68:8a)
Server host name not given
Boot file name not given
Magic cookie: (OK)
**Option: (t=53,l=1) DHCP Message Type = DHCP ACK**
**Option: (t=54,l=4) Server Identifier = 192.168.1.1**
**Option: (t=1,l=4) Subnet Mask = 255.255.255.0**
**Option: (t=3,l=4) Router = 192.168.1.1**
**Option: (6) Domain Name Server**
    **Length: 12; Value: 445747E2445749F244574092;**
    **IP Address: 68.87.71.226;**
    **IP Address: 68.87.73.242;**
    **IP Address: 68.87.64.146**
**Option: (t=15,l=20) Domain Name = "hsd1.ma.comcast.net."**

# NAT: network address translation




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

datagrams with source or destination in this network have 10.0.0.0/24 address for source, destination (as usual)

NAT-enabled router looks like a single device with a single IP address

# NAT: network address translation

*motivation:* local network uses just one IP address as far as outside world is concerned:

- range of addresses not needed from ISP: just one IP address for all devices
- can change addresses of devices in local network without notifying outside world
- can change ISP without changing addresses of devices in local network
- devices inside local net not explicitly addressable, visible by outside world (a security plus)

# NAT: network address translation

*implementation*: NAT router must:

- *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 dest fields of every incoming datagram with corresponding (source IP address, port #) stored in NAT table

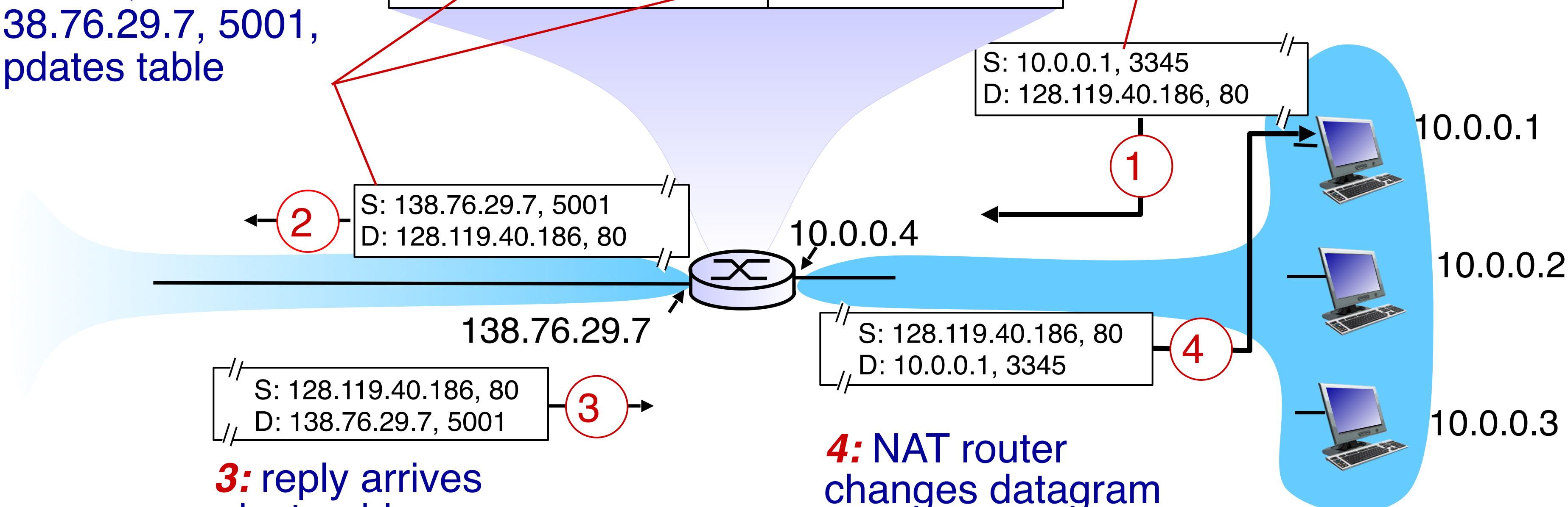
# NAT: network address translation

**NAT translation table**

| WAN side addr | LAN side addr |
| --- | --- |
| 138.76.29.7, 5001 | 10.0.0.1, 3345 |
| …… | …… |

**2:** NAT router changes datagram source addr 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



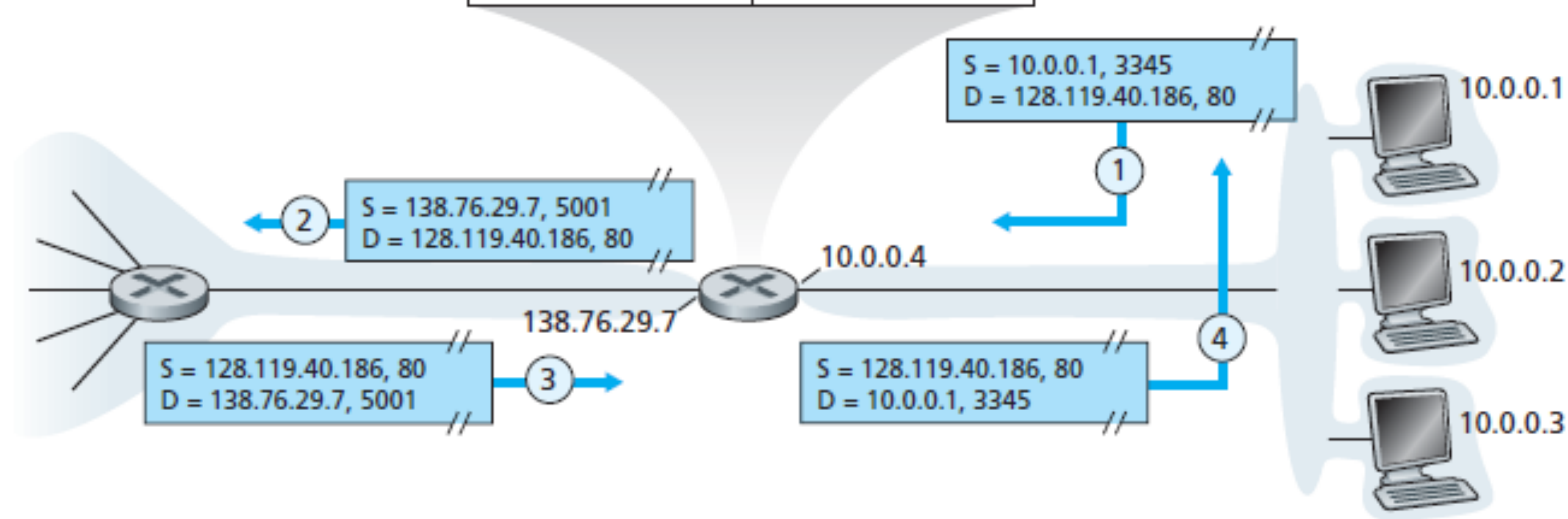

**3:** reply arrives dest. address: 138.76.29.7, 5001

**4:** NAT router changes datagram dest addr from 138.76.29.7, 5001 to 10.0.0.1, 3345

* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive/

# Why need to change port number?

| NAT translation table | |
|---|---|
| WAN side | LAN side |
| 138.76.29.7, 5001 | 10.0.0.1, 3345 |
| . . . | . . . |




♦ Network address translation

# NAT: network address translation

- 16-bit port-number field:
  - 60,000 simultaneous connections with a single LAN-side address!
- NAT is controversial:
  - routers should only process up to layer 3
  - address shortage should be solved by IPv6
  - violates end-to-end argument
    - NAT possibility must be taken into account by app designers, e.g., P2P applications
  - NAT traversal: what if client wants to connect to server behind NAT?

# Chapter 4: outline

4.1 Overview of Network layer
- data plane
- control plane

4.2 What's inside a router?

4.3 IP: Internet Protocol
- datagram format
- fragmentation
- IPv4 addressing
- network address translation
- IPv6

4.4 Generalized Forwarding and SDN
- match
- action
- OpenFlow examples of match-plus-action in action

# IPv6: motivation

- *initial motivation:* 32-bit address space soon to be completely allocated
- additional motivation:
  - header format helps speed processing/forwarding
  - header changes to facilitate QoS

*IPv6 datagram format:*

- fixed-length 40-byte header
- no fragmentation allowed at routers

# IPv6

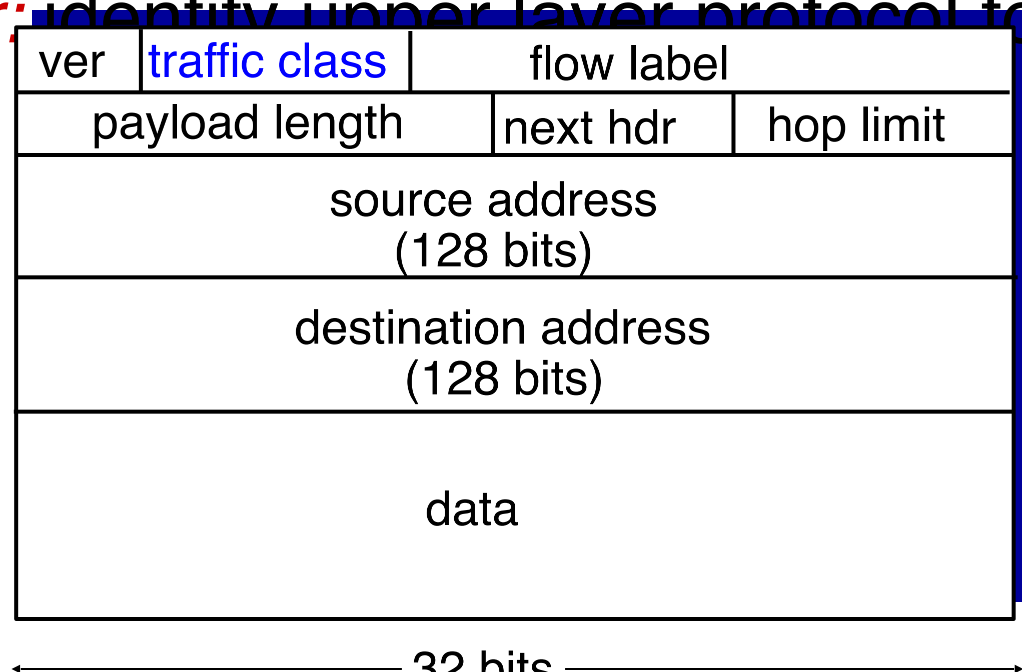
- The most important changes:
  - Expanded addressing capabilities
    - IP address: 32 bits → 128 bits
    - In addition to unicast and multicast, also provide anycast (be delivered to any one of a group)
  - A streamlined 40-byte header
    - fixed-length 40-byte header
  - Flow labeling and priority
    - For example, audio and video transmission might be treated as flows
    - The traffic carried by a high-priority user might also be treated as a flow

# IPv6 datagram format

*priority (traffic class):* identify priority among datagrams in flow

*flow label:* identify datagrams in same “flow” (concept of “flow” not well defined)

*next header:* identify upper layer protocol for data



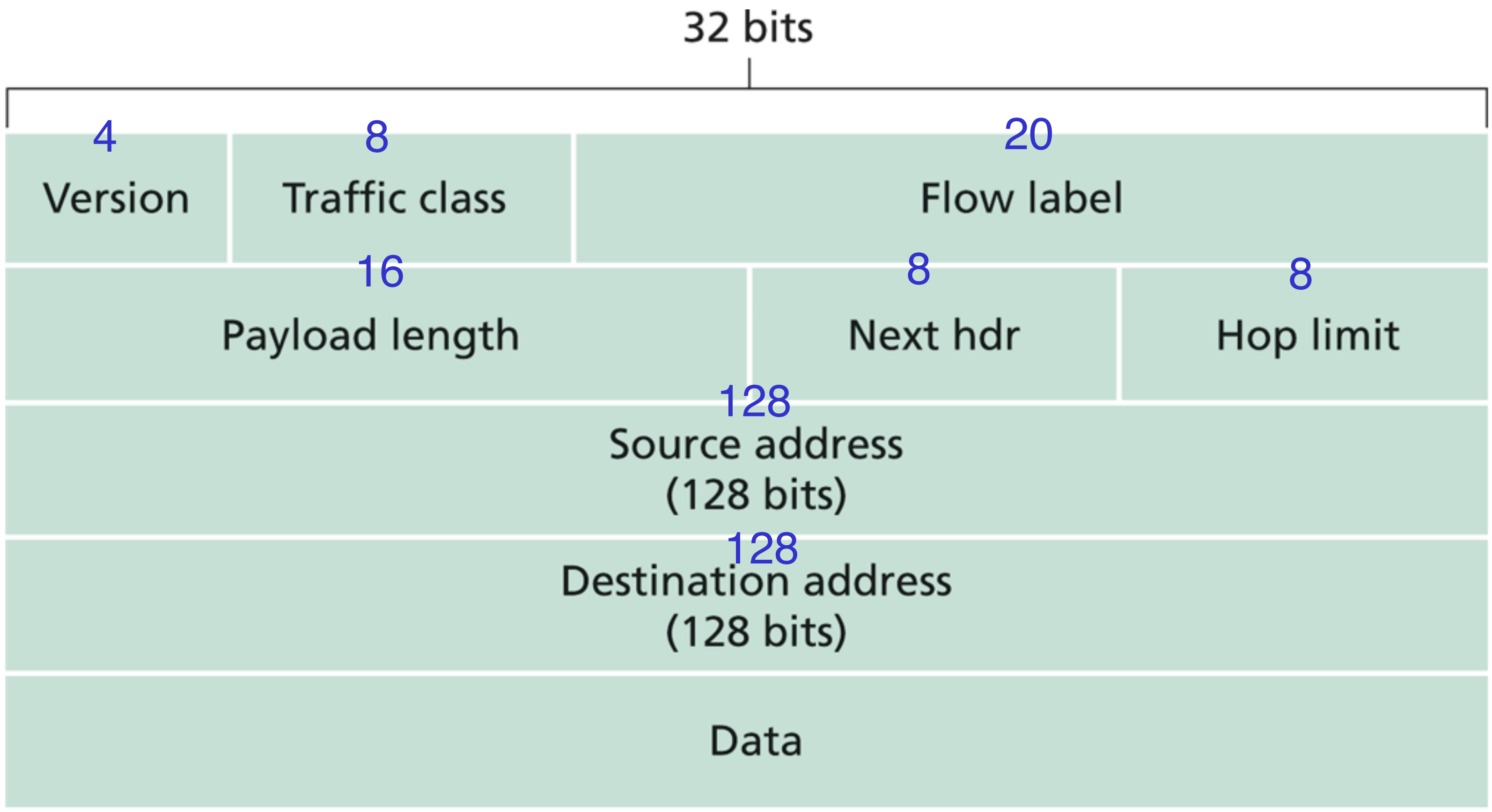



**Figure 4.24** ♦ IPv6 datagram format

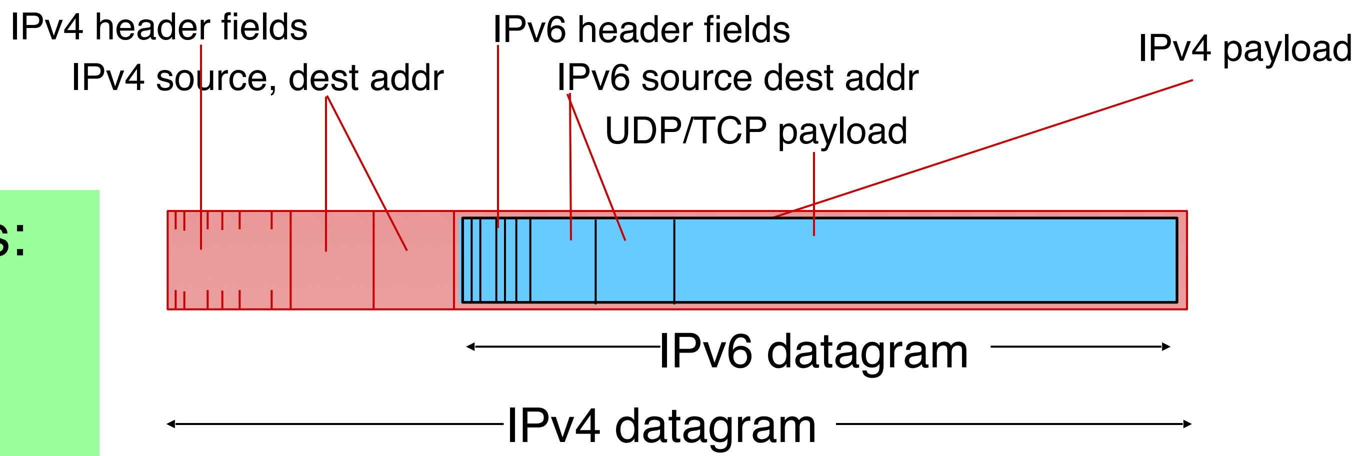
40-byte header

# Other changes from IPv4

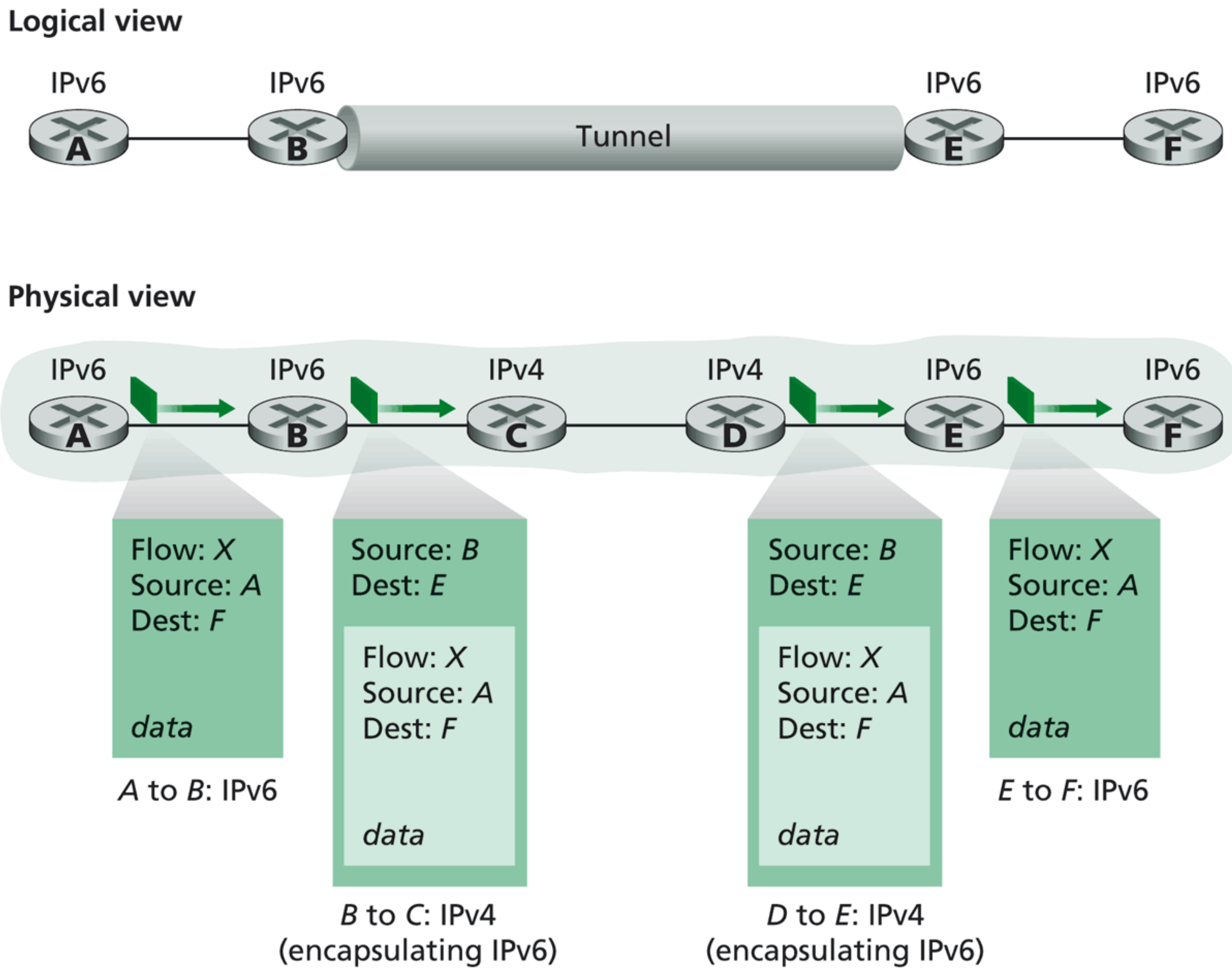
- *fragmentation/reassembly: not allow for fragmentation at intermediate routers*
  - *"Packet Too Big" ICMP error message*
- *header checksum*: removed entirely to reduce processing time at each hop
- *options:* allowed, but outside of header, indicated by "Next Header" field
  - just as TCP or UDP protocol headers
- *ICMPv6:* new version of ICMP
  - additional message types, e.g., "Packet Too Big"
  - multicast group management functions (Internet Group Management Protocol (IGMP))

# 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

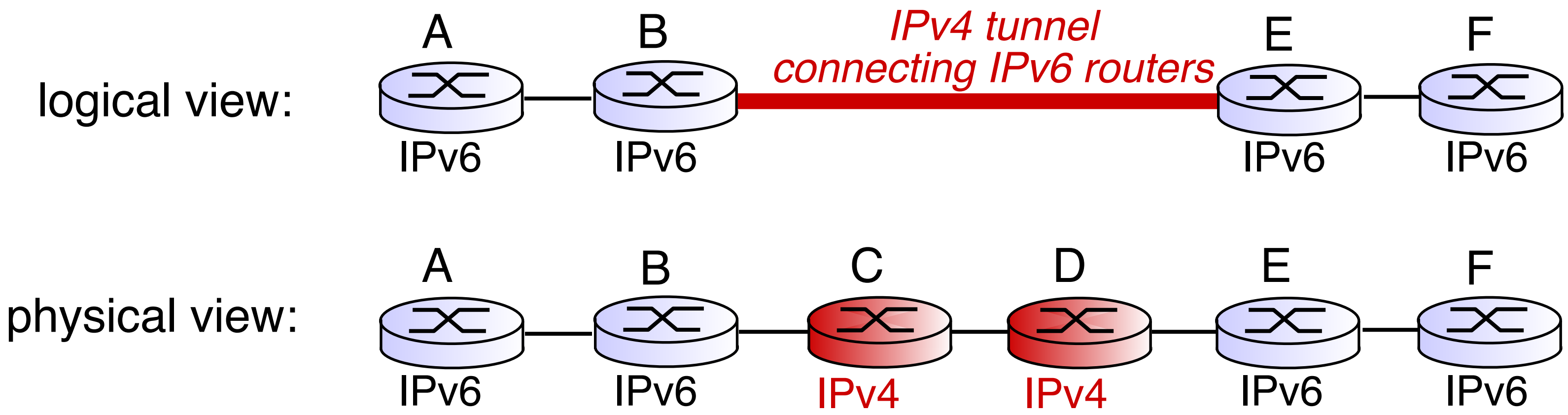



Two approaches:
1. dual-stack approach
2. tunneling

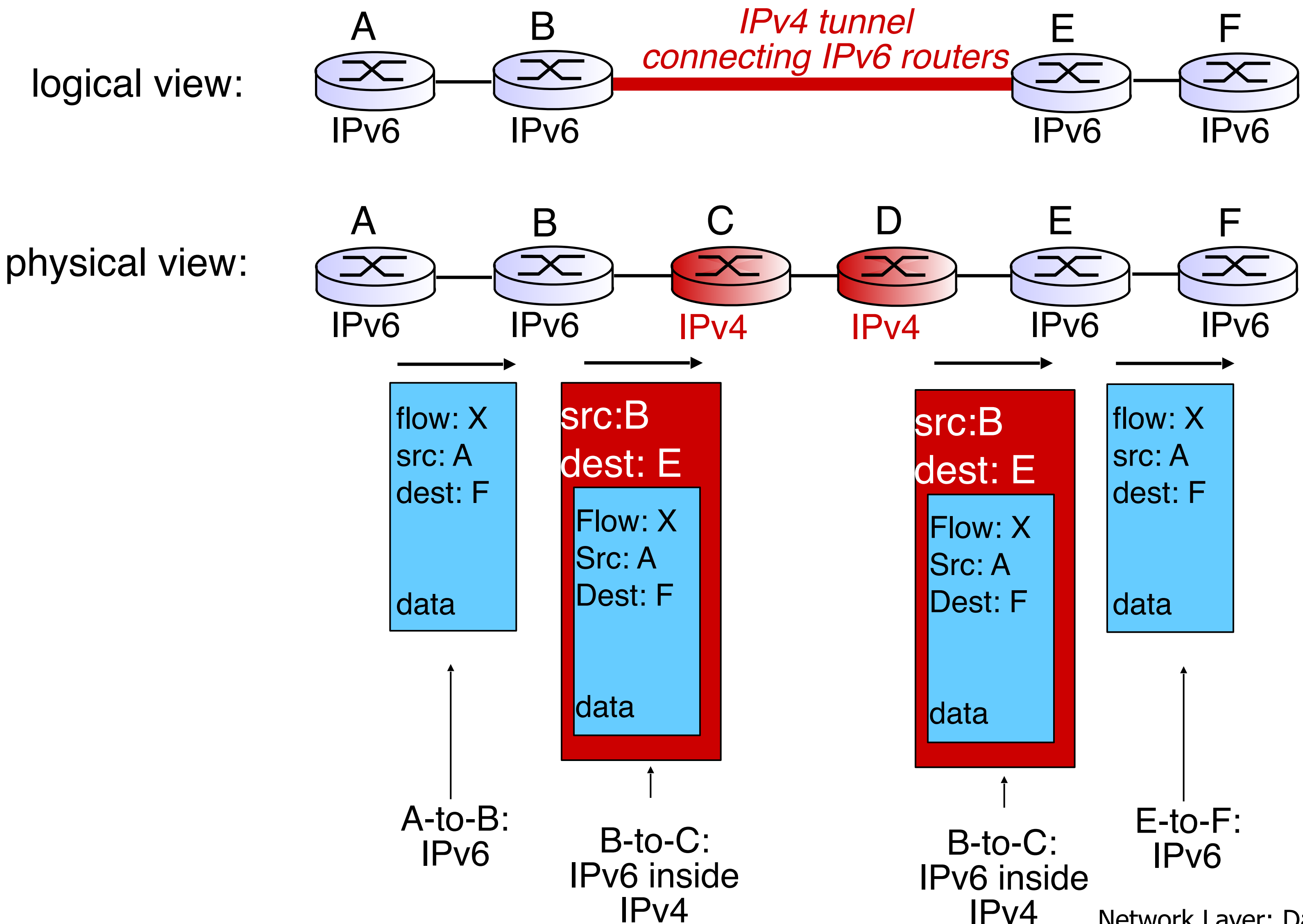

Logical view
IPv6
IPv6
IPv6
IPv6
A
B
Tunnel
E
F
Physical view
IPv6
IPv6
IPv4
IPv4
IPv6
IPv6
A
B
C
D
E
F
Flow: X
Source: A
Dest: F
data
A to B: IPv6
Source: B
Dest: E
Flow: X
Source: A
Dest: F
data
B to C: IPv4
(encapsulating IPv6)
Source: B
Dest: E
Flow: X
Source: A
Dest: F
data
D to E: IPv4
(encapsulating IPv6)
Flow: X
Source: A
Dest: F
data
E to F: IPv6

♦ Tunneling

# Tunneling


A
B
IPv4 tunnel
connecting IPv6 routers
E
F
logical view:
IPv6
IPv6
IPv6
IPv6
A
B
C
D
E
F
physical view:
IPv6
IPv6
IPv4
IPv4
IPv6
IPv6

# Tunneling



logical view:
A
B
IPv4 tunnel
connecting IPv6 routers
E
F
IPv6
IPv6
IPv6
IPv6
physical view:
A
B
C
D
E
F
IPv6
IPv6
IPv4
IPv4
IPv6
IPv6
flow: X
src: A
dest: F
data
src:B
dest: E
Flow: X
Src: A
Dest: F
data
src:B
dest: E
Flow: X
Src: A
Dest: F
data
flow: X
src: A
dest: F
data
A-to-B:
IPv6
B-to-C:
IPv6 inside
IPv4
B-to-C:
IPv6 inside
IPv4
E-to-F:
IPv6

# IPv6: adoption

- NIST: more than 1/3 of all US government second-level domains are IPv6-enabled
- Google: only about 8% of clients access services via IPv6

- *Long (long!) time for deployment, use*
  - 20 years and counting!
  - think of application-level changes in last 20 years: Web, instant messaging, streaming media, distributed games, various forms of social media (Facebook), Skype, ...
  - *Why?*
    - *It's difficult to change network-layer protocols*
    - *The deployment of new protocols at the application layer is more rapid*

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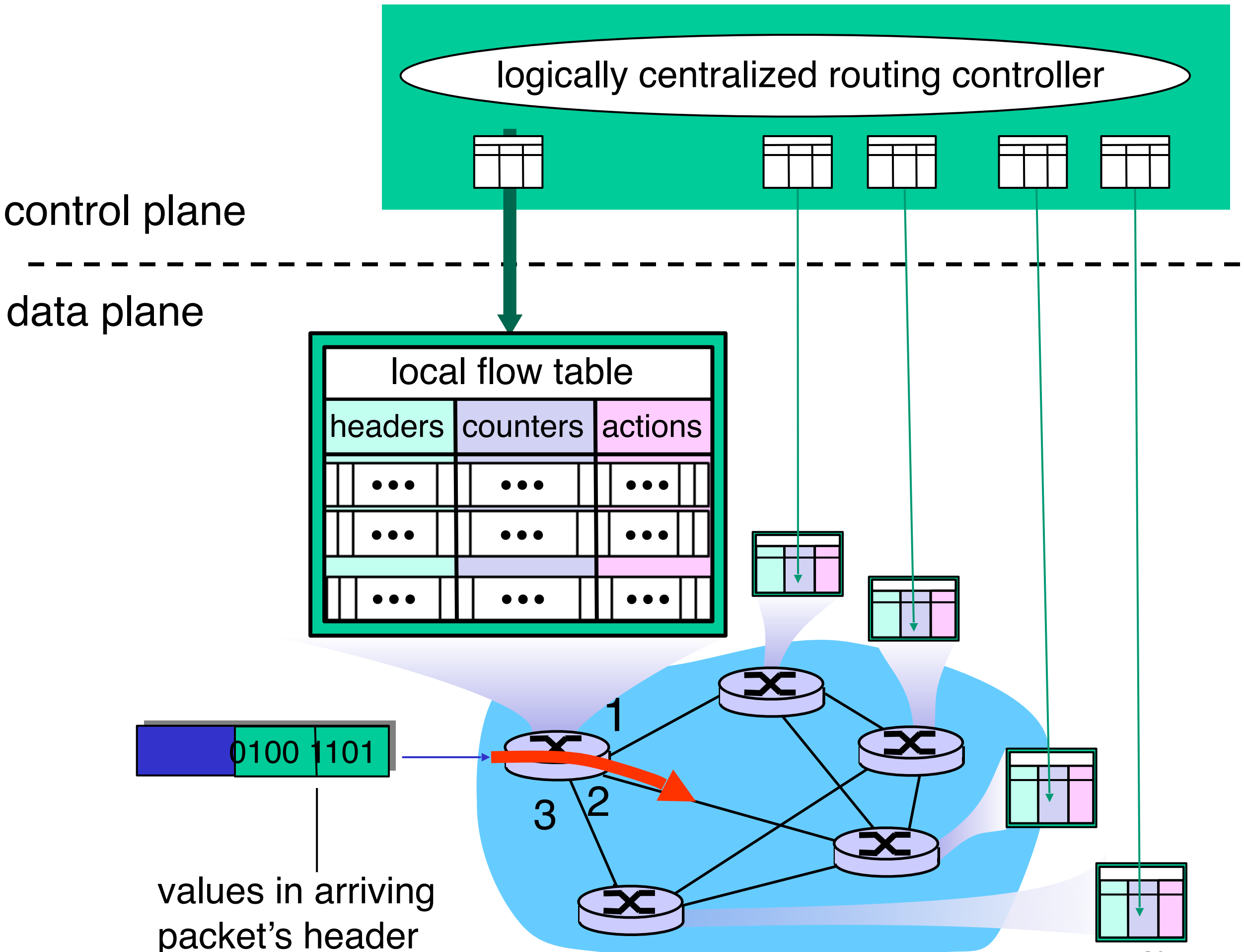
4.4 Generalized Forwarding and SDN
- match
- action
- OpenFlow examples of match-plus-action in action

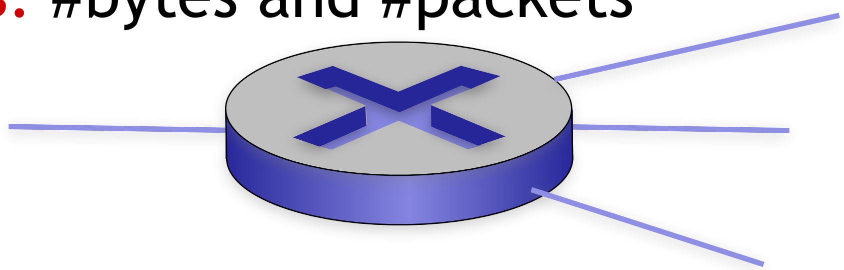
# Generalized Forwarding and SDN

Each router contains a *flow table* that is computed and distributed by a *logically centralized* routing controller



# OpenFlow data plane abstraction

- *flow*: defined by header fields
- generalized forwarding: simple packet-handling rules
  - *Pattern*: match 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 in a router (computed and distributed by controller) defines router's match+action rules*

# OpenFlow data plane abstraction

- *flow*: defined by header fields
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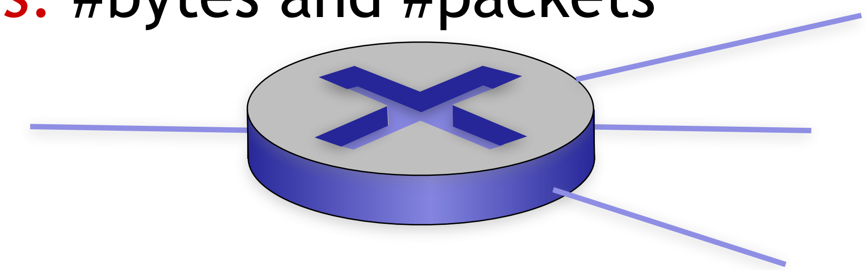


*: wildcard

1. src=1.2.*.*, dest=3.4.5.* → drop
2. src = *.*.*.*, dest=3.4.*.* → forward(2)
3. src=10.1.2.3, dest=*.*.*.* → send to controller

# OpenFlow: Flow Table Entries

OpenFlow 1.0 flow table:
1. Link layer: VLAN Pri
2. Network layer: IP TOS

| Rule | Action | Stats |
|---|---|---|

Packet + byte counters

1. Forward packet to port(s)
2. Encapsulate and forward to controller
3. Drop packet
4. Send to normal processing pipeline
5. Modify Fields

| Ingress Port | Src MAC | Dst MAC | Eth Type | VLAN ID | IP Src | IP Dst | IP Proto | TCP/UDP Src Port | TCP/UDP Dst Port |
|---|---|---|---|---|---|---|---|---|---|

Link layer: Src MAC, Dst MAC, Eth Type, VLAN ID

Network layer: IP Src, IP Dst, IP Proto

Transport layer: TCP/UDP Src Port, TCP/UDP Dst Port

# Examples

## Destination-based forwarding:

| Ingress Port | Src MAC | Dst MAC | Eth Type | VLAN ID | IP Src | IP Dst | IP Proto | TCP/UDP Src Port | TCP/UDP Dst 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:

| Ingress Port | Src MAC | Dst MAC | Eth Type | VLAN ID | IP Src | IP Dst | IP Proto | TCP/UDP Src Port | TCP/UDP Dst Port | Action |
|---|---|---|---|---|---|---|---|---|---|---|
| * | * | * | * | * | * | * | * | * | 22 | drop |

*do not forward (block) all datagrams destined to TCP port 22*

| Ingress Port | Src MAC | Dst MAC | Eth Type | VLAN ID | IP Src | IP Dst | IP Proto | TCP/UDP Src Port | TCP/UDP Dst Port | Action |
|---|---|---|---|---|---|---|---|---|---|---|
| * | * | * | * | * | 128.119.1.1 | * | * | * | * | drop |

*do not forward (block) all datagrams sent by host 128.119.1.1*

# Examples

## Destination-based layer 2 (switch) forwarding:

| Ingress Port | Src MAC | Dst MAC | Eth Type | VLAN ID | IP Src | IP Dst | IP Proto | TCP/UDP Src Port | TCP/UDP Dst Port | Action |
|---|---|---|---|---|---|---|---|---|---|---|
| * | 22:A7:23:<br>11:E1:02 | * | * | * | * | * | * | * | * | port3 |

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

# OpenFlow abstraction

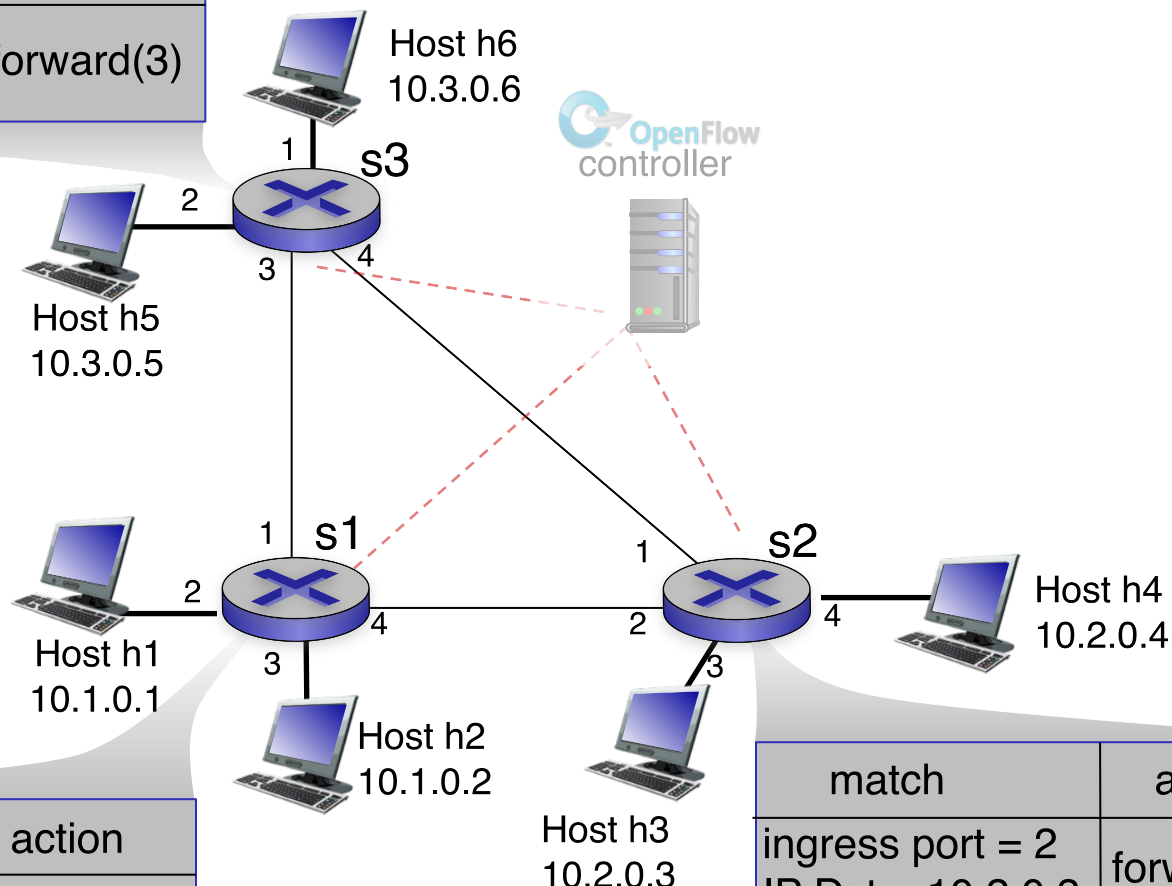
- *match+action:* unifies different kinds of devices

- 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

*Example:* datagrams from hosts h5 and h6 should be sent to h3 or h4 via s1 and from there to s2

| match | action |
|---|---|
| IP Src = 10.3.*.*<br>IP Dst = 10.2.*.* | forward(3) |




| match | action |
|---|---|
| ingress port = 1<br>IP Src = 10.3.*.*<br>IP Dst = 10.2.*.* | forward(4) |

| match | action |
|---|---|
| ingress port = 2<br>IP Dst = 10.2.0.3 | forward(3) |
| ingress port = 2<br>IP Dst = 10.2.0.4 | forward(4) |

# Chapter 4: *done!*

4.1 Overview of Network layer: data plane and control plane

4.2 What's inside a router?

4.3 IP: Internet Protocol
- datagram format
- fragmentation
- IPv4 addressing
- NAT
- IPv6

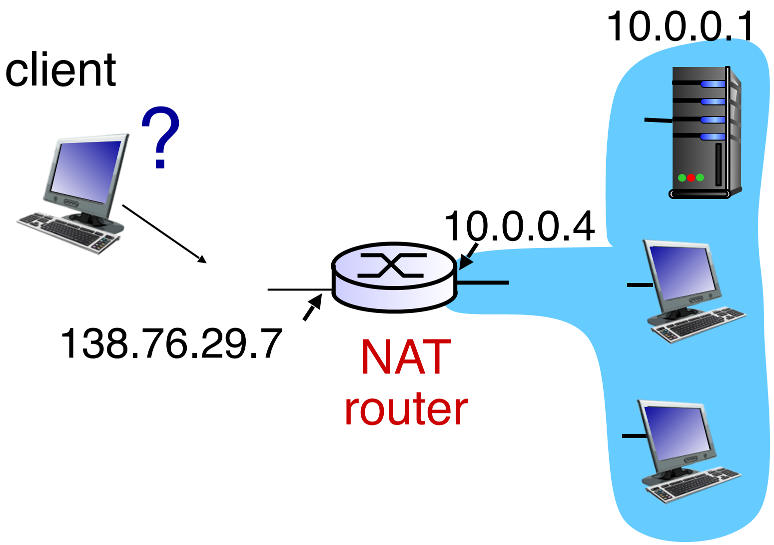
4.4 Generalized Forwarding and SDN
- match plus action
- OpenFlow example

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

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

# NAT traversal problem

- client wants to connect to server with address 10.0.0.1
  - server address 10.0.0.1 local to LAN (client can't use it as destination address)
  - only one externally visible NATed address: 138.76.29.7
- *solution 1:* statically configure NAT to forward incoming connection requests at given port to server
  - e.g., (138.76.29.7, port 80) always forwarded to 10.0.0.1 port 8080



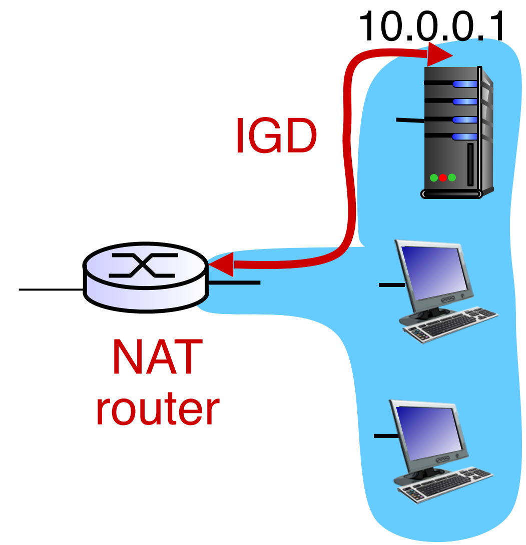

IP 分享器
- Port Forwarding
- Virtual Server

# NAT traversal problem

- *solution 2:* Universal Plug and Play (UPnP) Internet Gateway Device (IGD) Protocol. Allows NATed host to:
  - learn public IP address (138.76.29.7)
  - add/remove port mappings (with lease times)

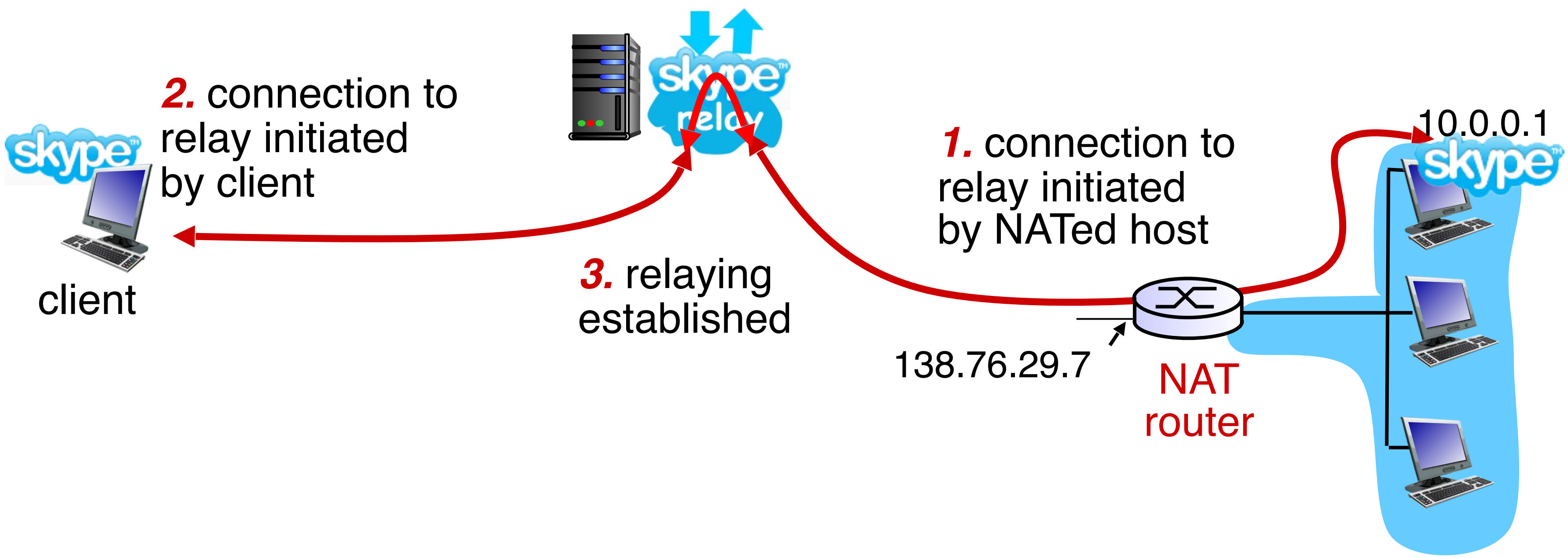
  i.e., automate static NAT port map configuration

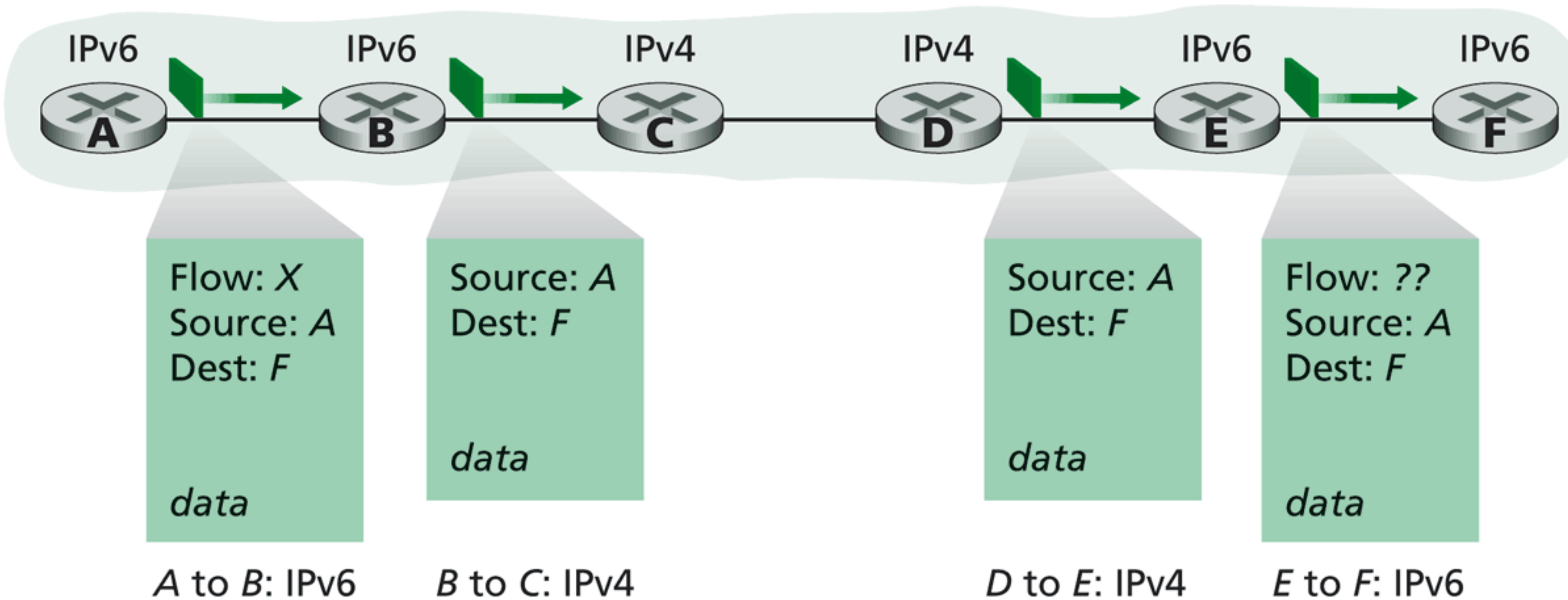
  Maps (10.0.0.1, 3345) to (138.76.29.7, 5001)



# NAT traversal problem

- *solution 3:* relaying (used in Skype)
  - NATed client establishes connection to relay
  - external client connects to relay
  - relay bridges packets between two connections






- A dual-stack approach