CSCI 6760 - Computer Networks - Fall 2024

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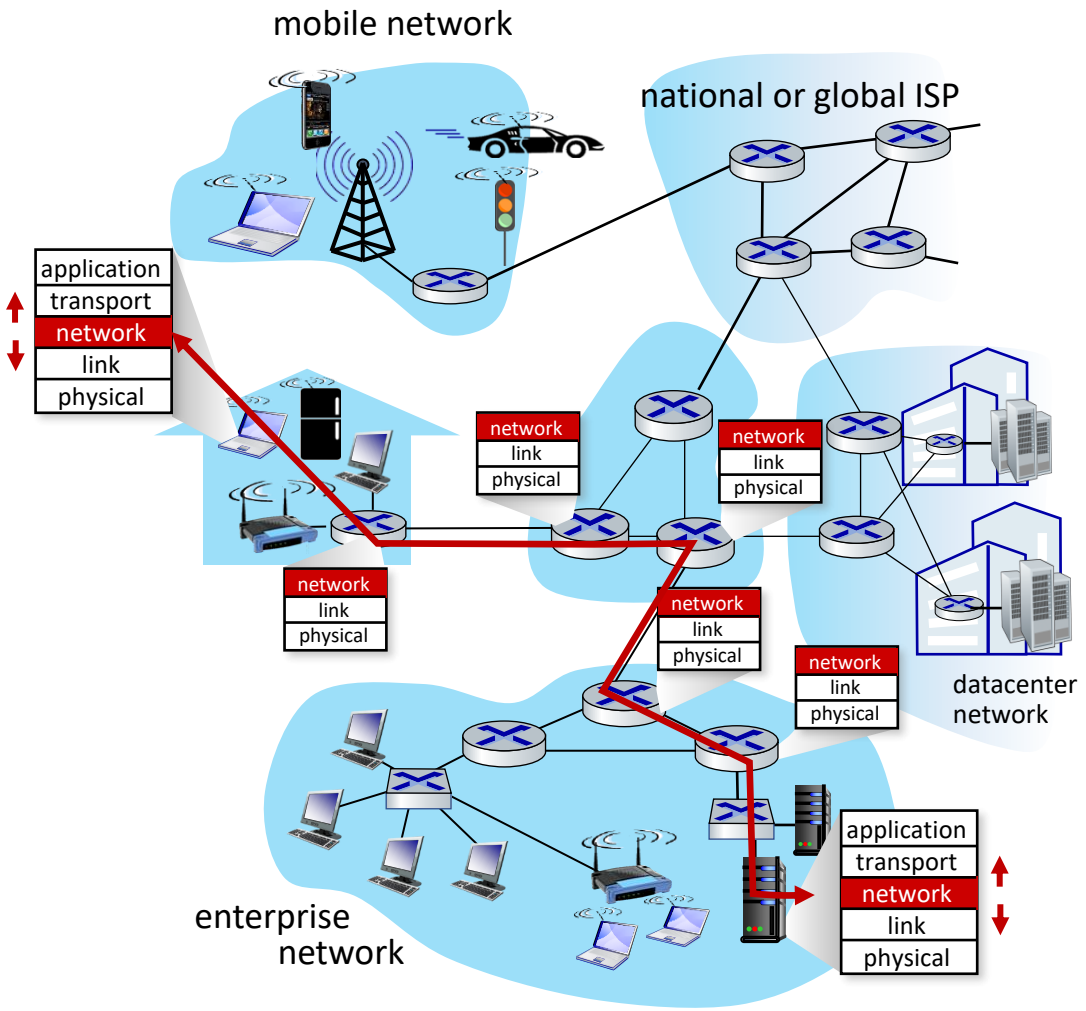
These slides are adapted from the textbook slides by J.F. Kurose and K.W. Ross

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

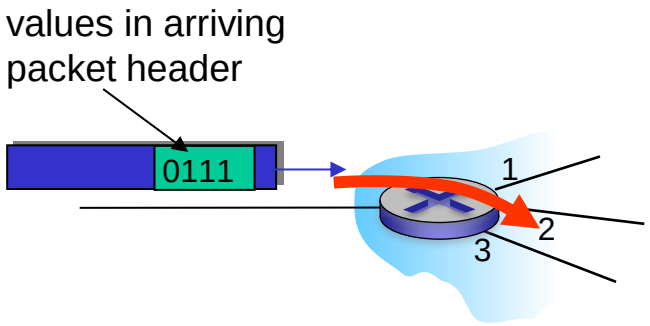
forwarding

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

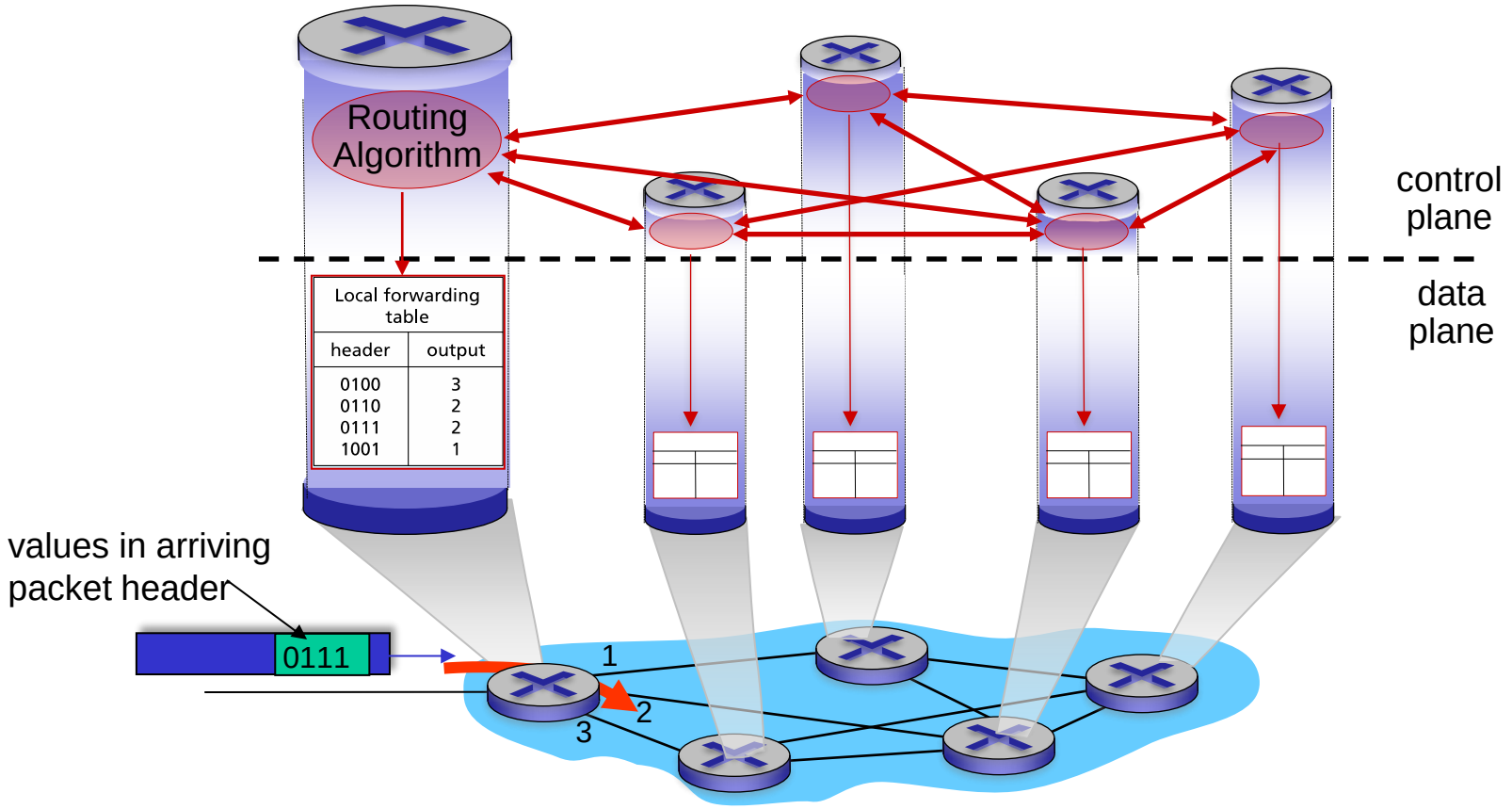


Control plane

- *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

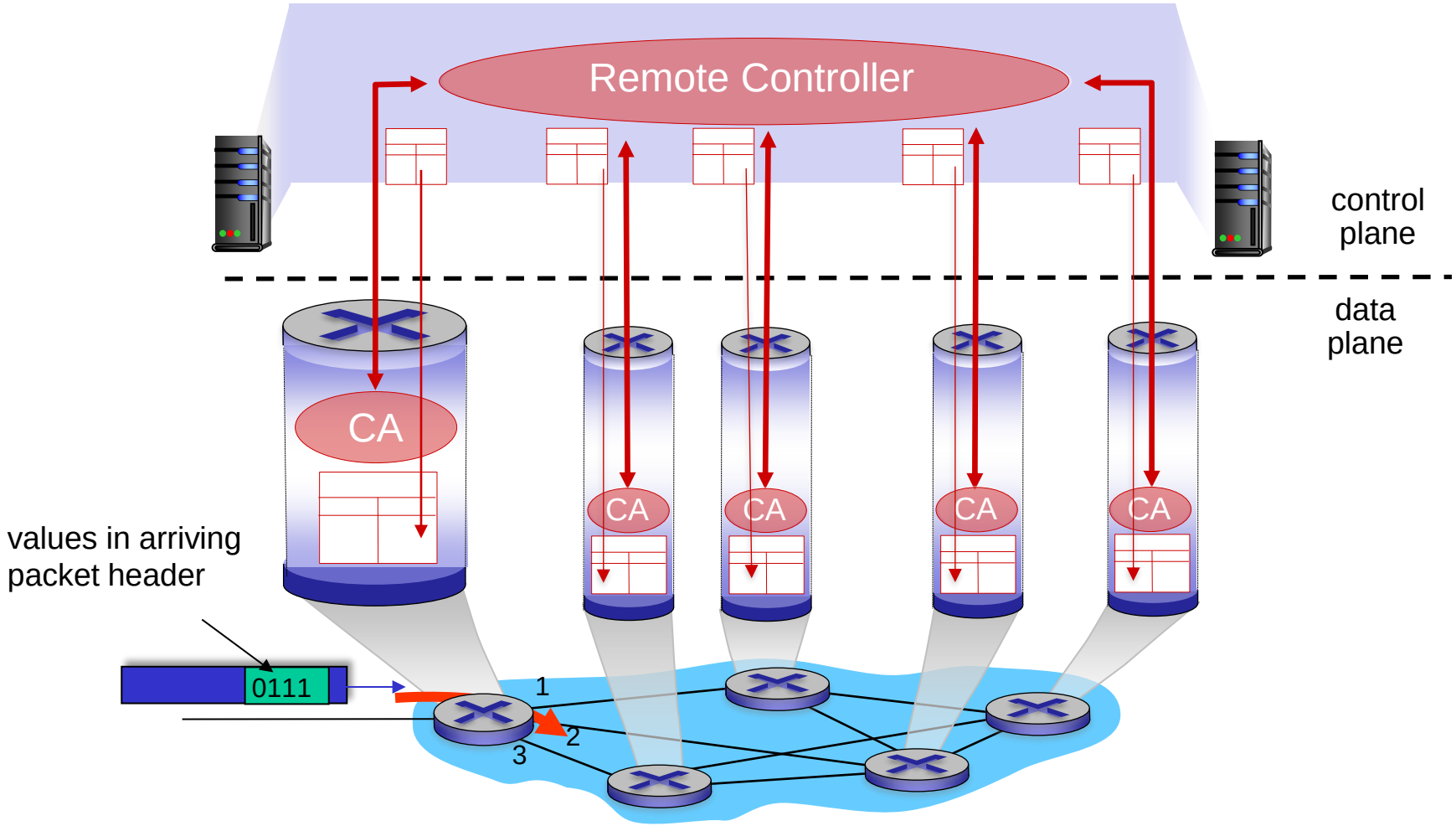
Per-router control plane

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



Software-Defined Networking (SDN) control plane

Remote controller computes, installs forwarding tables in routers



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

- 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

Destination-based forwarding

forwarding table

Destination Address Range	Link Interface
11001000 00010111 00010000 00000000 through 11001000 00010111 00010000 00000100	0
11001000 00010111 00010000 00000101 through 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?

Longest prefix matching

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match!

examples:

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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

Network layer: “data plane” roadmap

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  - addressing
  - network address translation
  - IPv6

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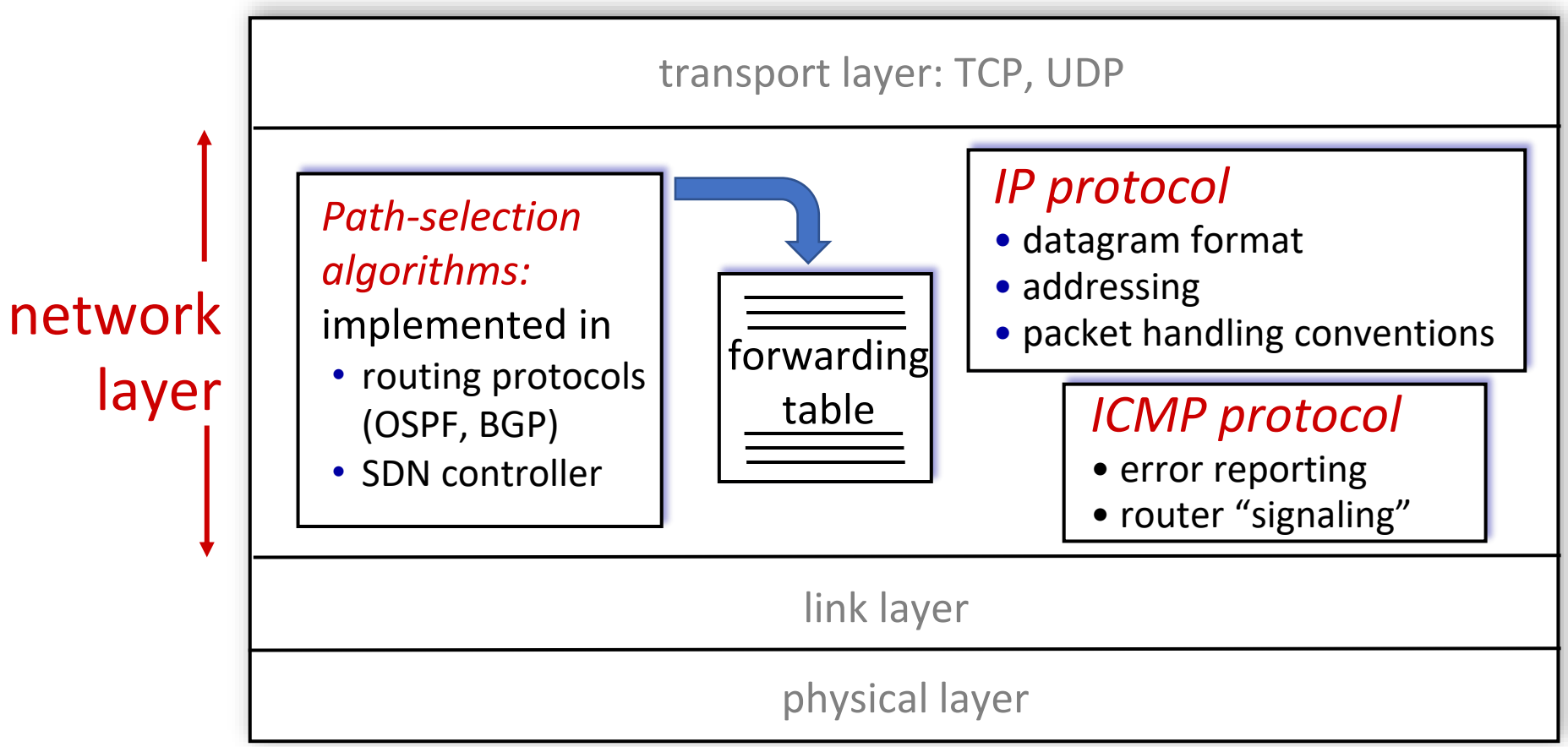
  - OpenFlow: match+action in action
- Middleboxes

Network Layer: Internet

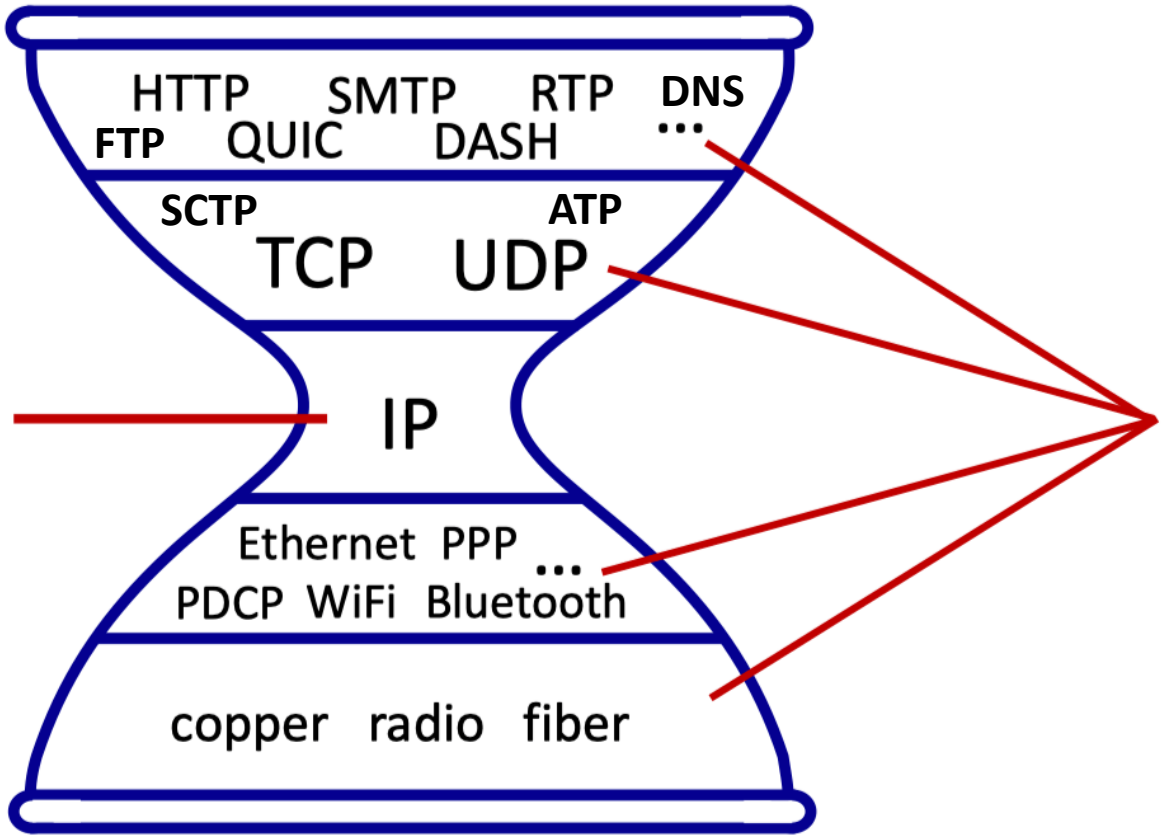
host, router network layer functions:



Internet Stack Hourglass

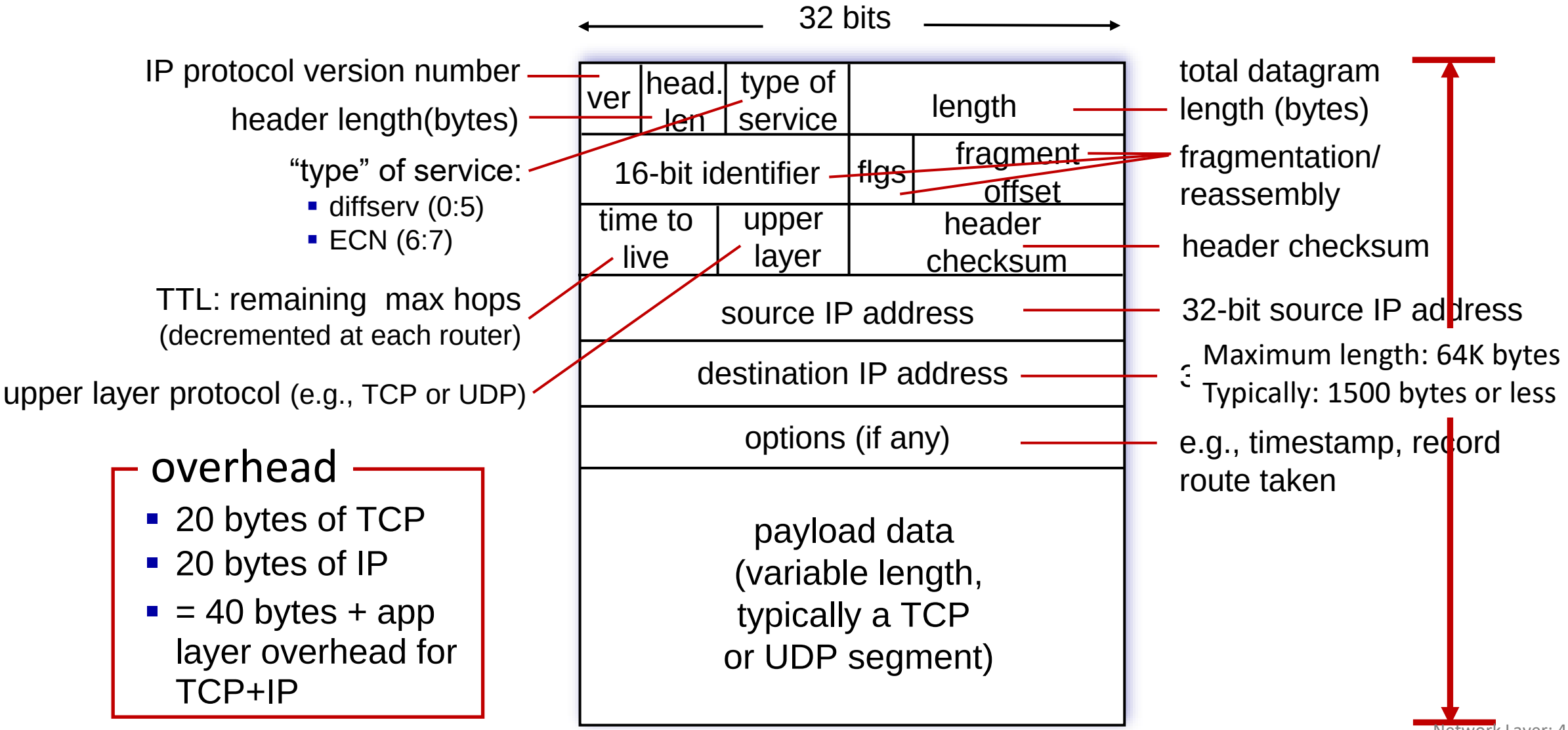
Internet's "thin waist":

- *one* network layer protocol: IP
- *must* be implemented by every (billions) of Internet-connected devices



many protocols in physical, link, transport, and application layers

IP Datagram format

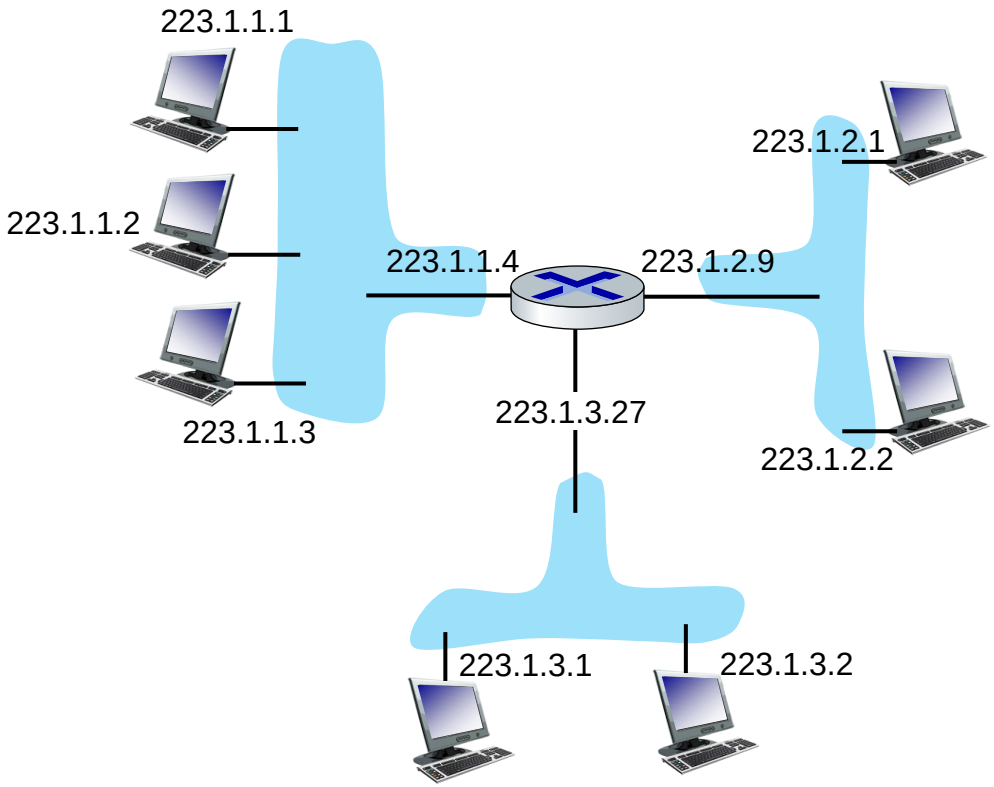


overhead

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

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

IP addressing: introduction

- **IP address:** 32-bit identifier associated with each host or router *interface*
- **interface:** connection between host/router and physical link
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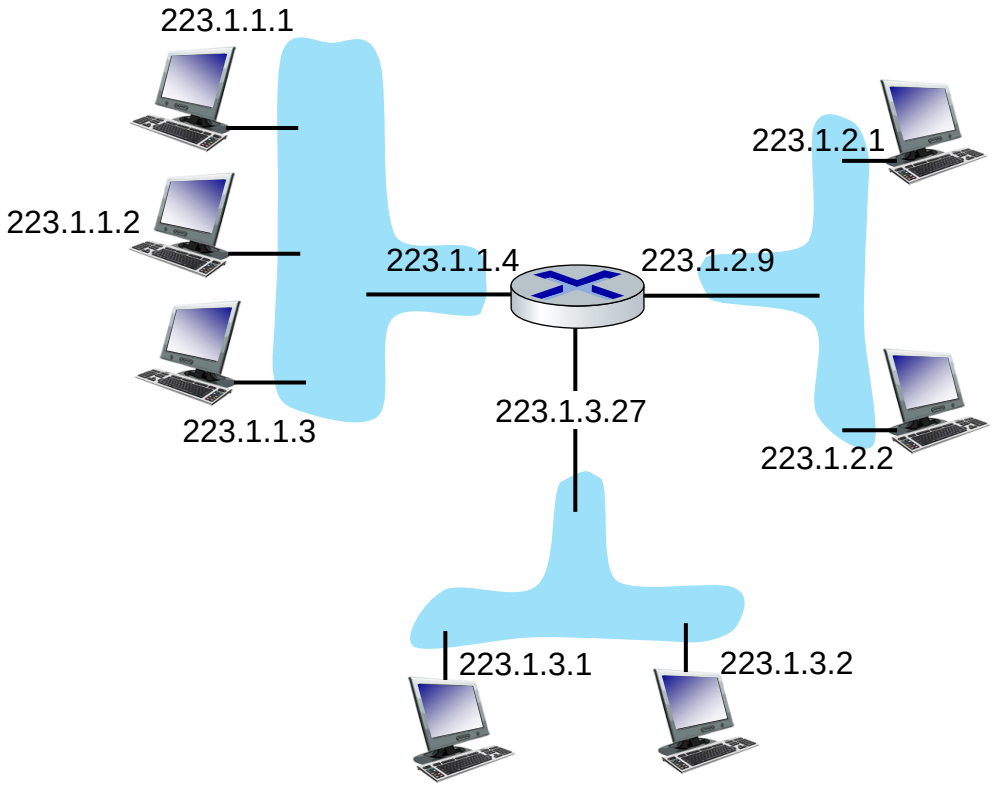


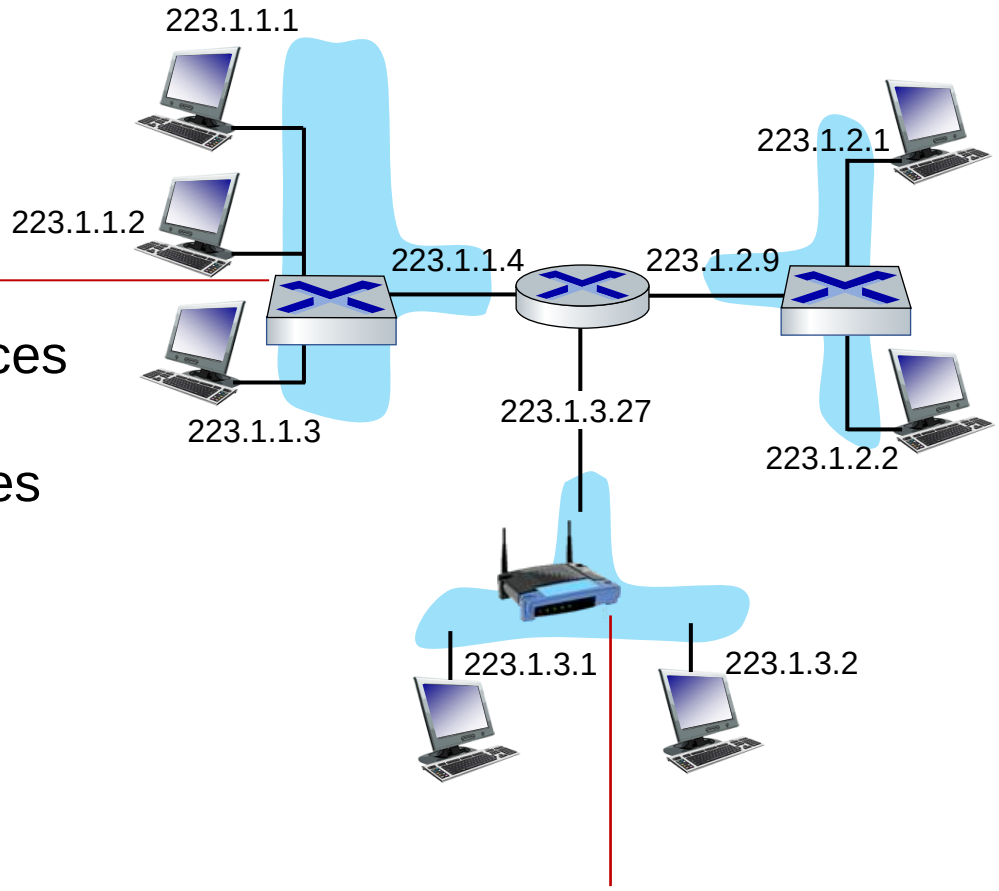
dotted-decimal IP address notation:

223.1.1.1 = 11011111 00000001 00000001 00000001

223 1 1 1

IP addressing: introduction

Q: how are interfaces actually connected?



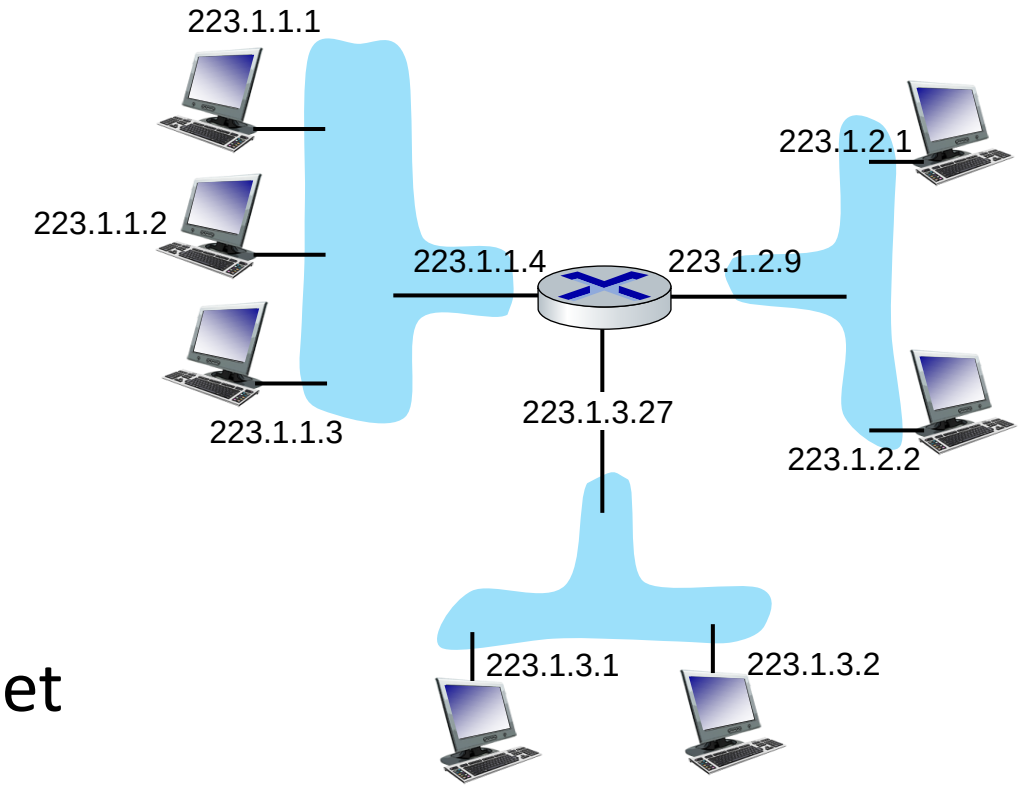
A: wired Ethernet interfaces connected by Ethernet switches

A: wireless WiFi interfaces connected by WiFi base station

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

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

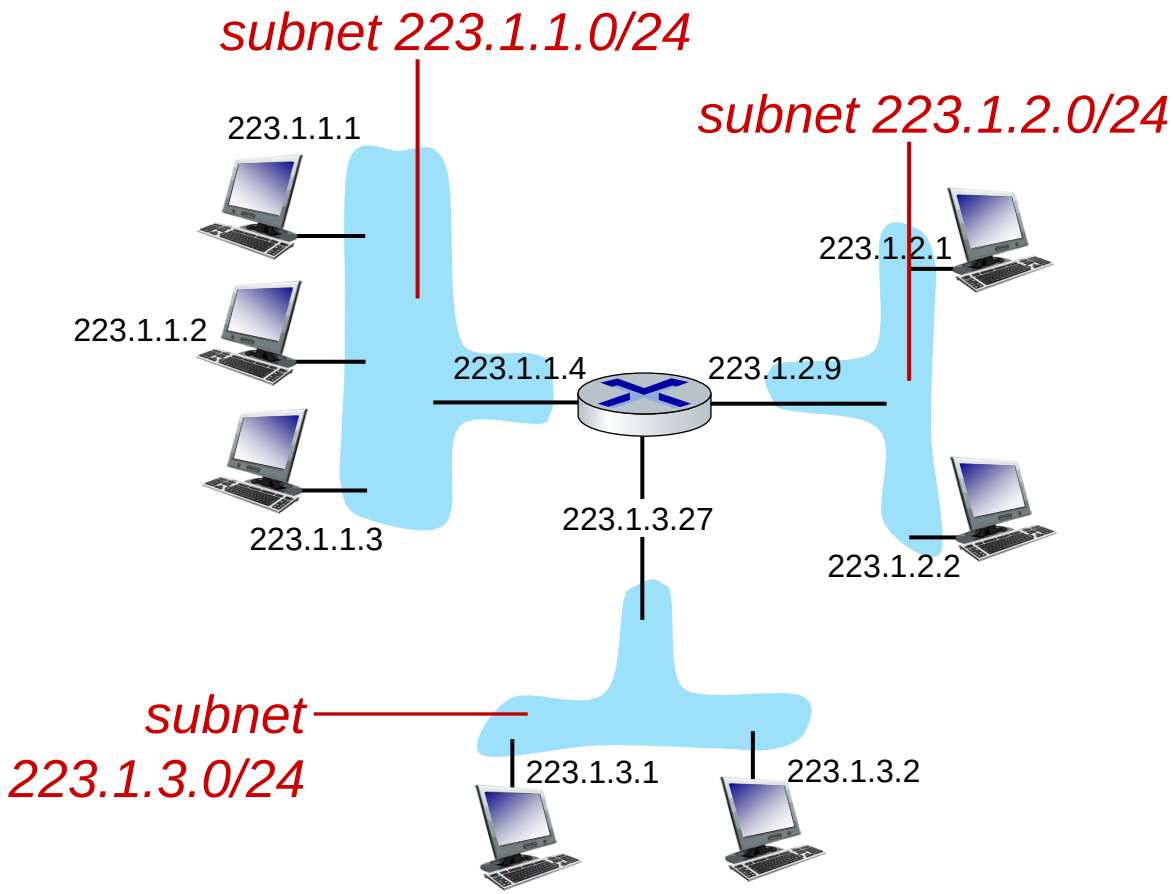


network consisting of 3 subnets

Subnets

Recipe for defining subnets:

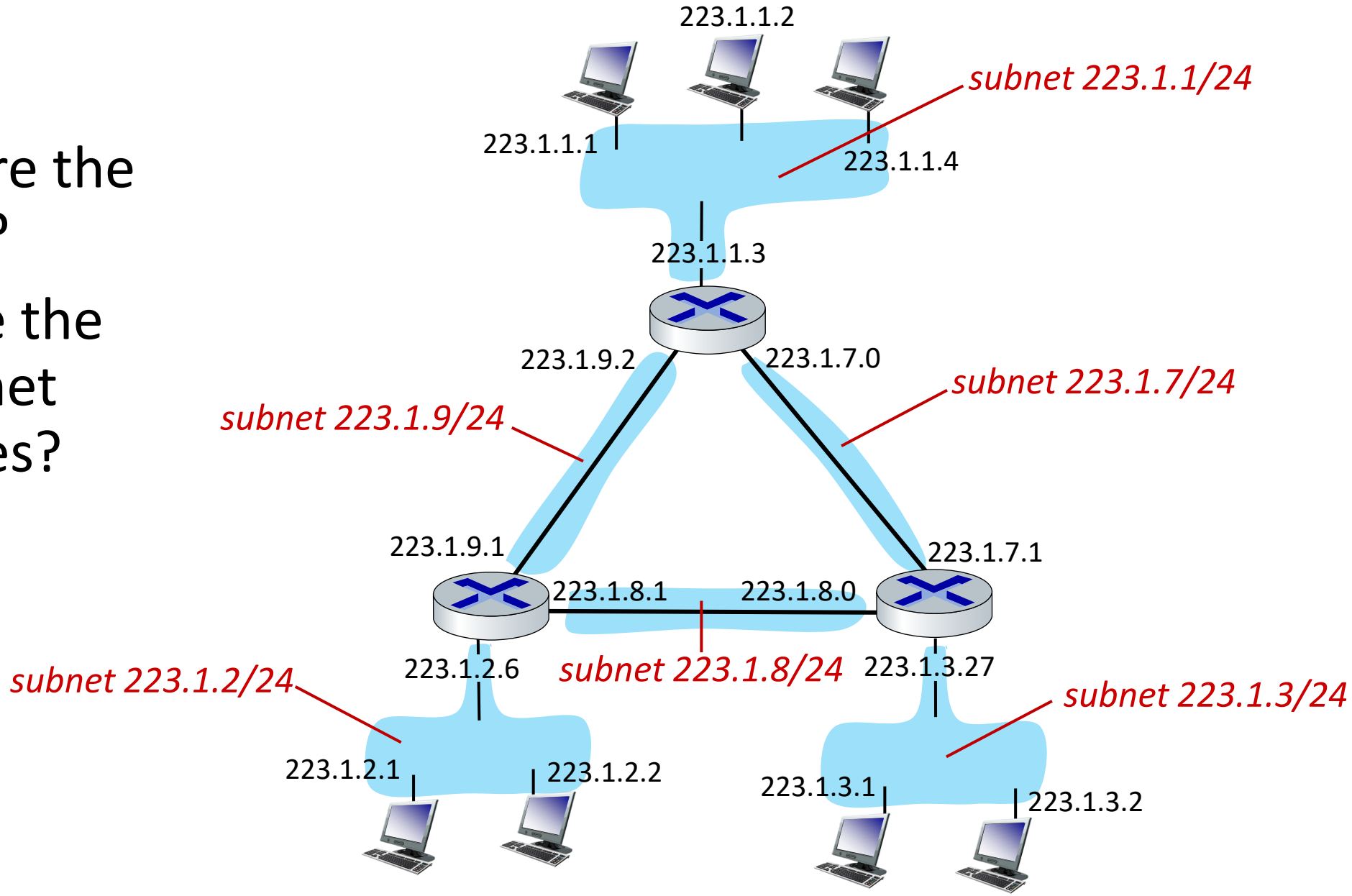
- detach each interface from its host or router, creating "islands" of isolated networks
- each isolated network is called a *subnet*



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

Subnets

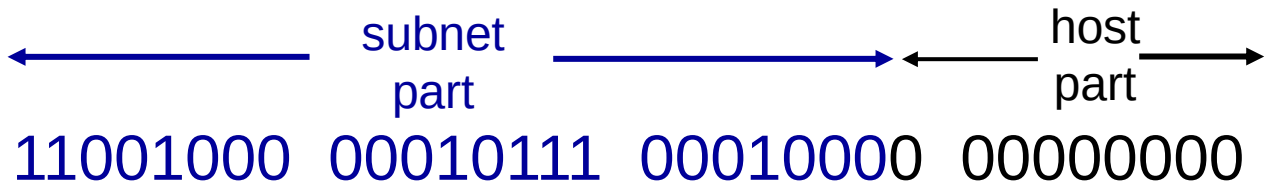
- where are the subnets?
- what are the /24 subnet addresses?



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



200.23.16.0/23

IP + Subnet Mask vs CIDR notation

- IP = 192.168.8.1
- Subnet Mask = 255.255.255.0

This is equivalent to

- 192.168.8.0/24

- IP = 192.168.8.1
- Subnet Mask = 255.255.255.128

This is equivalent to

- 192.168.8.0/25

IP + Subnet Mask vs CIDR notation

- Host's IP address = 172.16.5.12
- Subnet mask = 255.255.254.0

- What's the host's subnet, in CIDR notation?

Computing the longest common CIDR

- 192.168.6.98
  - 192.168.(00000110).(01100010)
- 192.168.65.3
  - 192.168.(01000001).(00000011)

- CIDR
  - 192.168.(00000000).(00000000)/17
  - 192.168.0.0/17

- Subnet Mask
  - 255.255.(10000000). (00000000)
  - 255.255.128.0

  - IP & SM = CIDR

- 172.18.5.215
  - 172.18.5.(11010111)
- 172.18.5.210
  - 172.18.5.(11010010)

- CIDR
  - 172.18.5.(11010000)/29
  - 172.18.5.208/29

- Subnet Mask
  - 255.255.255. (11111000)
  - 255.255.255.248

  - IP & SM = CIDR

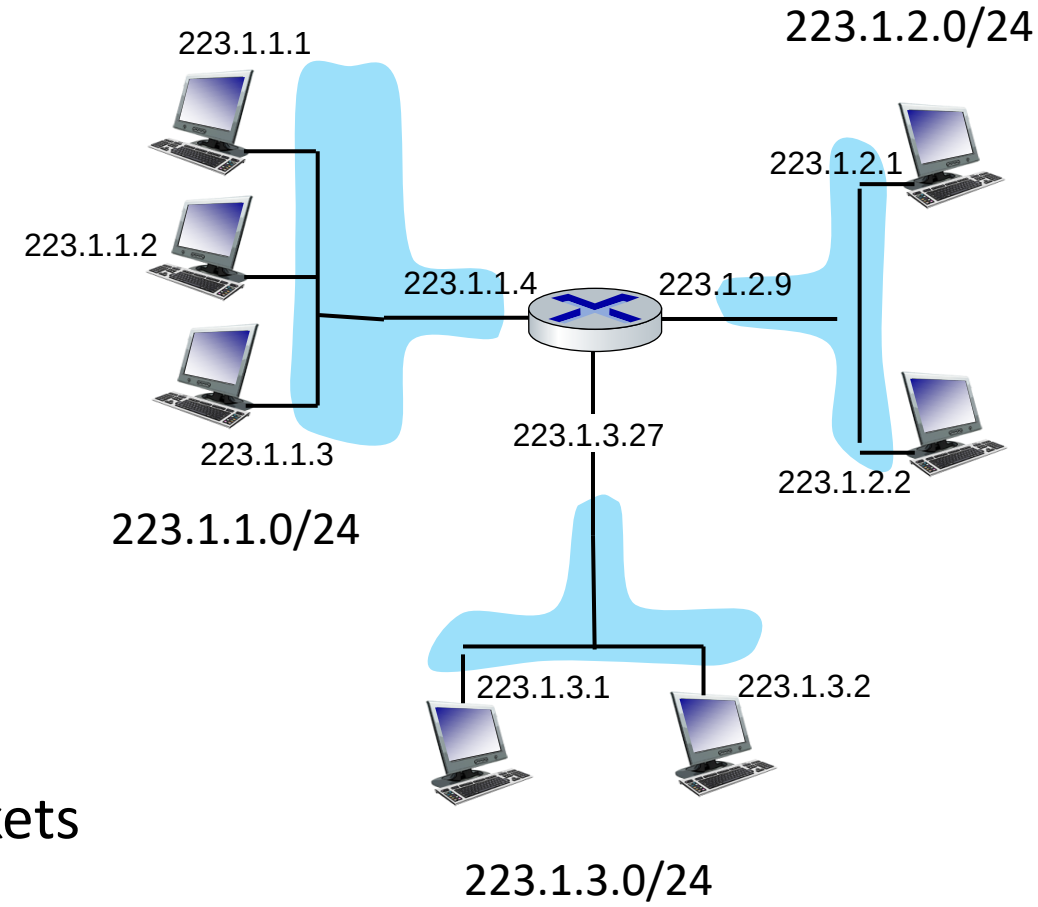
Computing the CIDR

- Assume we have the following IP addresses, what is their longest common CIDR?
  - 10.35.25.102, 10.35.27.23, 10.35.28.203, 10.35.30.124
  - CIDR = 10.35.24.0/21
  - Subnet Mask = 255.255.248.0

- Assume we have the following IP addresses, what is their longest common CIDR?
  - 172.17.2.102, 172.17.2.65, 172.17.2.87, 172.17.2.124
  - CIDR = 172.17.2.64/26
  - Subnet Mask = 255.255.255.192

How are packets routed outside a subnet?

- Question1:
  - 223.1.1.1 wants to send a packet to 223.1.1.3.
  - Will the router (223.1.1.4) need to be involved?
- Question 2:
  - 223.1.1.1 wants to send a pkt to 223.1.3.2
  - Will the router need to be involved?
  - What are the srcIP and dstIP in the packets that will be sent outside the subnet?

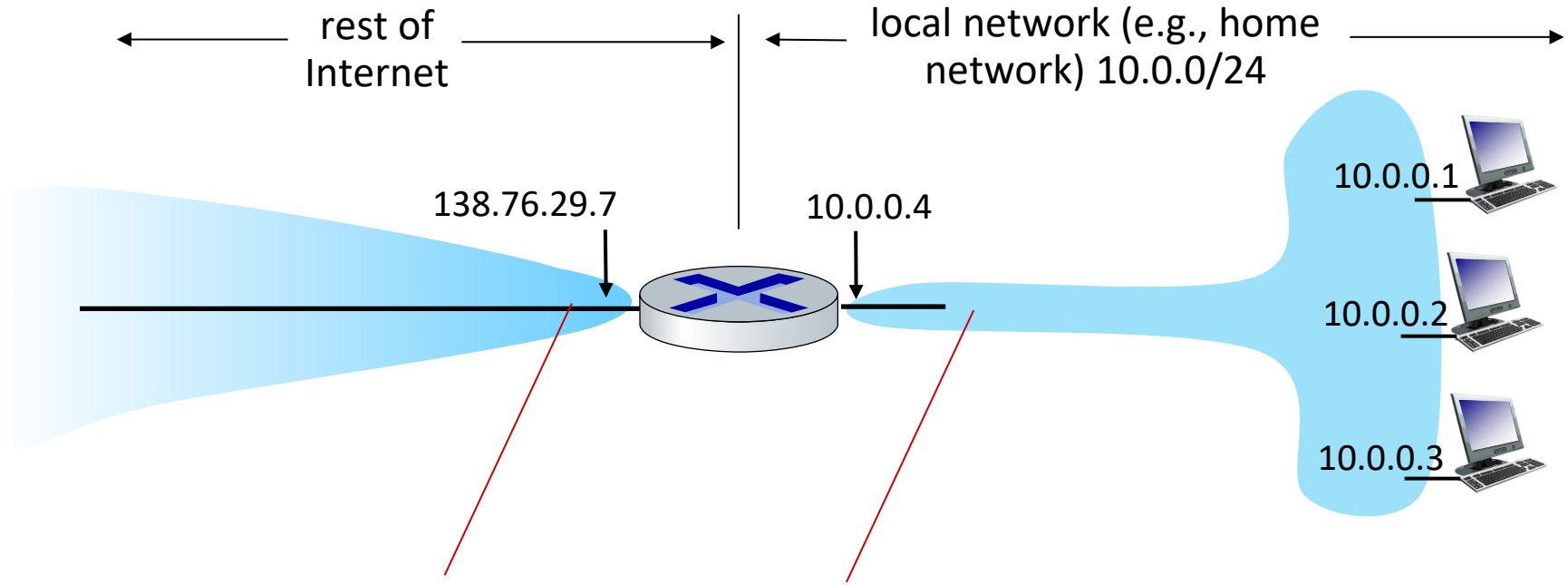


Reserved Address Blocks

- **10.0.0.0/8** **Private network** RFC 1918
- **127.0.0.0/8** **Loopback** RFC 5735
- *169.254.0.0/16* Link-Local RFC 3927
- **172.16.0.0/12** **Private network** RFC 1918
- 192.0.0.0/24 Reserved (IANA) RFC 5735
- 192.0.2.0/24 TEST-NET-1, Documentation and example code RFC 5735
- 192.88.99.0/24 IPv6 to IPv4 relay RFC 3068
- **192.168.0.0/16** **Private network** RFC 1918
- 198.18.0.0/15 Network benchmark tests RFC 2544
- 198.51.100.0/24 TEST-NET-2, Documentation and examples RFC 5737
- 203.0.113.0/24 TEST-NET-3, Documentation and examples RFC 5737
- 224.0.0.0/4 Multicasts (former Class D network) RFC 3171
- 240.0.0.0/4 Reserved (former Class E network) RFC 1700
- **255.255.255.255** **Broadcast** RFC 919

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

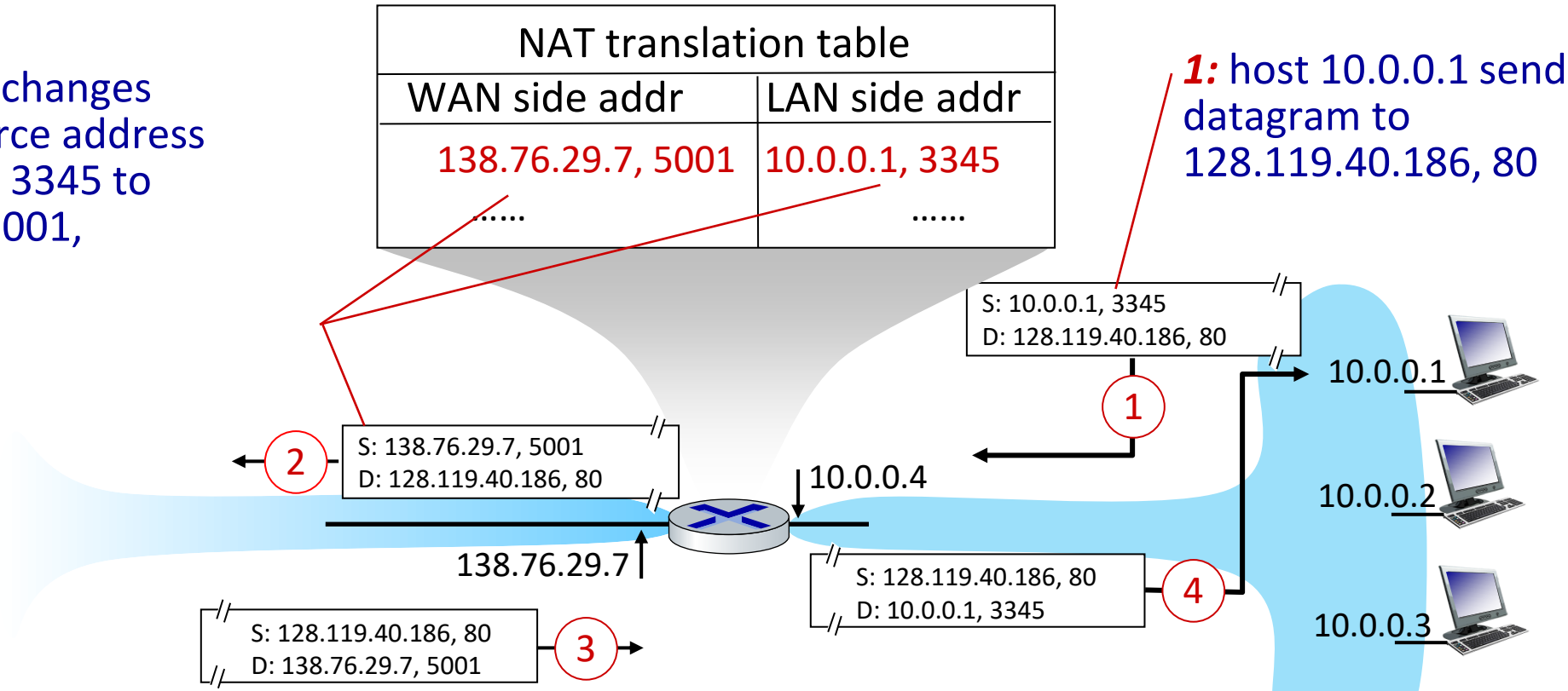
NAT: network address translation

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



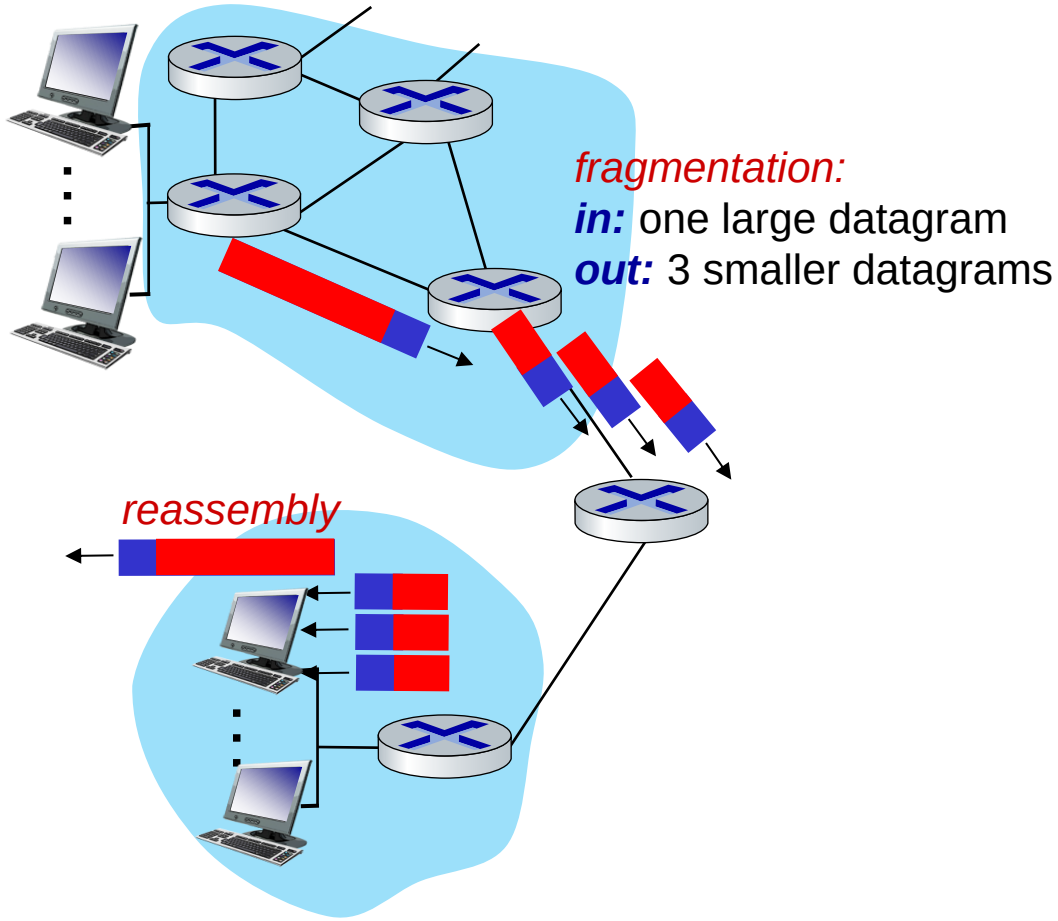
3: reply arrives, destination address: 138.76.29.7, 5001

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

IP fragmentation/reassembly

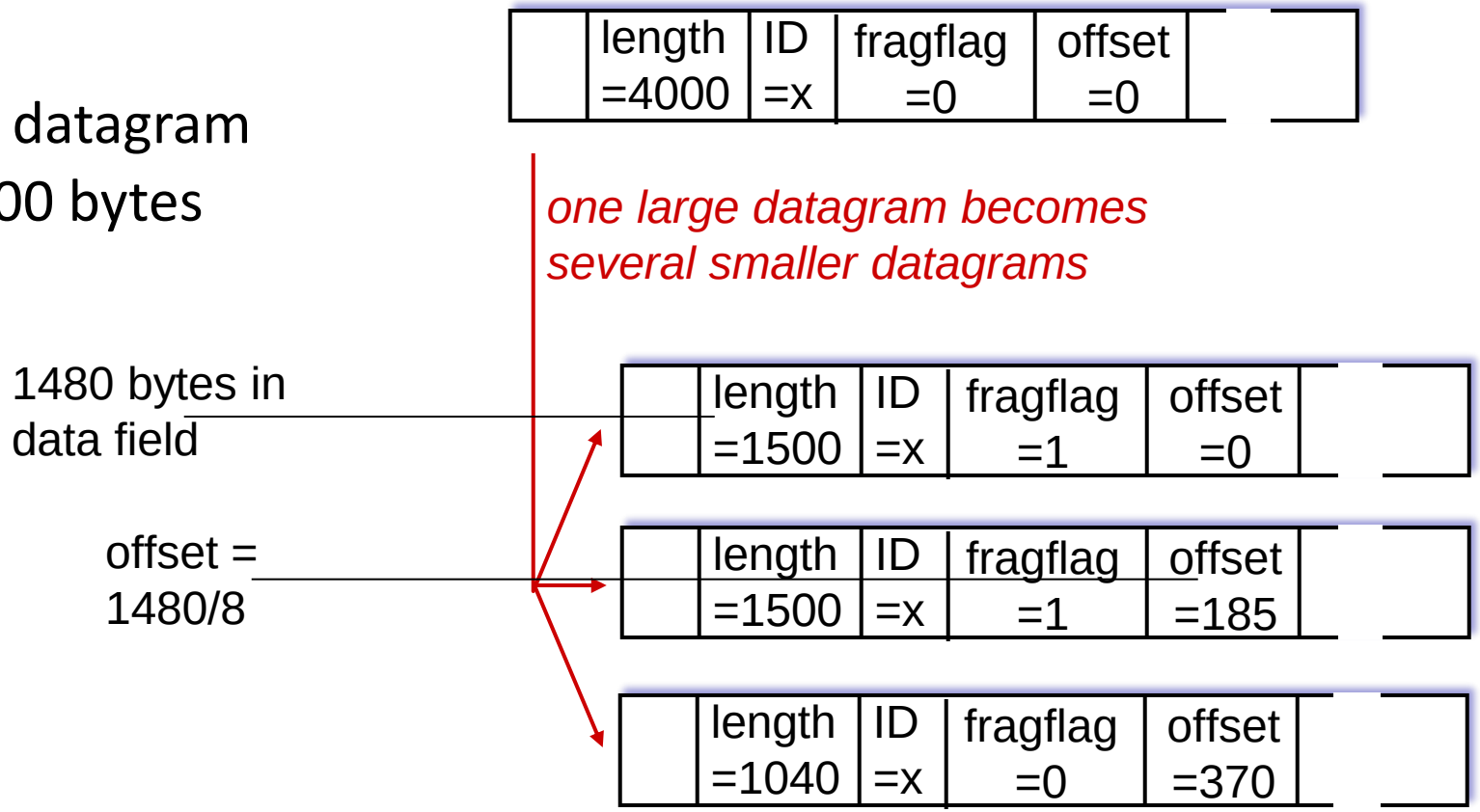
- network links have MTU (max. transfer size) - largest possible link-level frame
  - different link types, different MTUs
- large IP datagram divided ("fragmented") within net
  - one datagram becomes several datagrams
  - "reassembled" only at *destination*
  - IP header bits used to identify, order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



IP fragmentation/reassembly

example:

- 4000 byte datagram
- MTU = 1500 bytes



IP Fragmentation - Another Example

- Initial MTU = 3100 bytes (=3080 payload bytes)
- As packet is routed, it encounters a link with MTU = 820 bytes (=800 payload bytes)
- How will the fragments look like?
  - ID = 4325, Flag = 1, offset = 0, length = 820
  - ID = 4325, Flag = 1, offset = 100, length = 820
  - ID = 4325, Flag = 1, offset = 200, length = 820
  - ID = 4325, Flag = 0, offset = 300, length = 700

IP Fragmentation - Another Example

- Initial MTU = 3100 bytes (=3080 payload bytes)
- As packet is routed, it encounters a link with MTU = 930 bytes (=910 payload bytes)
- How will the fragments look like?
  - ID = 4325, Flag = 1, offset = 0, length = 924
  - ID = 4325, Flag = 1, offset = 113, length = 924
  - ID = 4325, Flag = 1, offset = 226, length = 924
  - ID = 4325, Flag = 0, offset = 339, length = 388

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

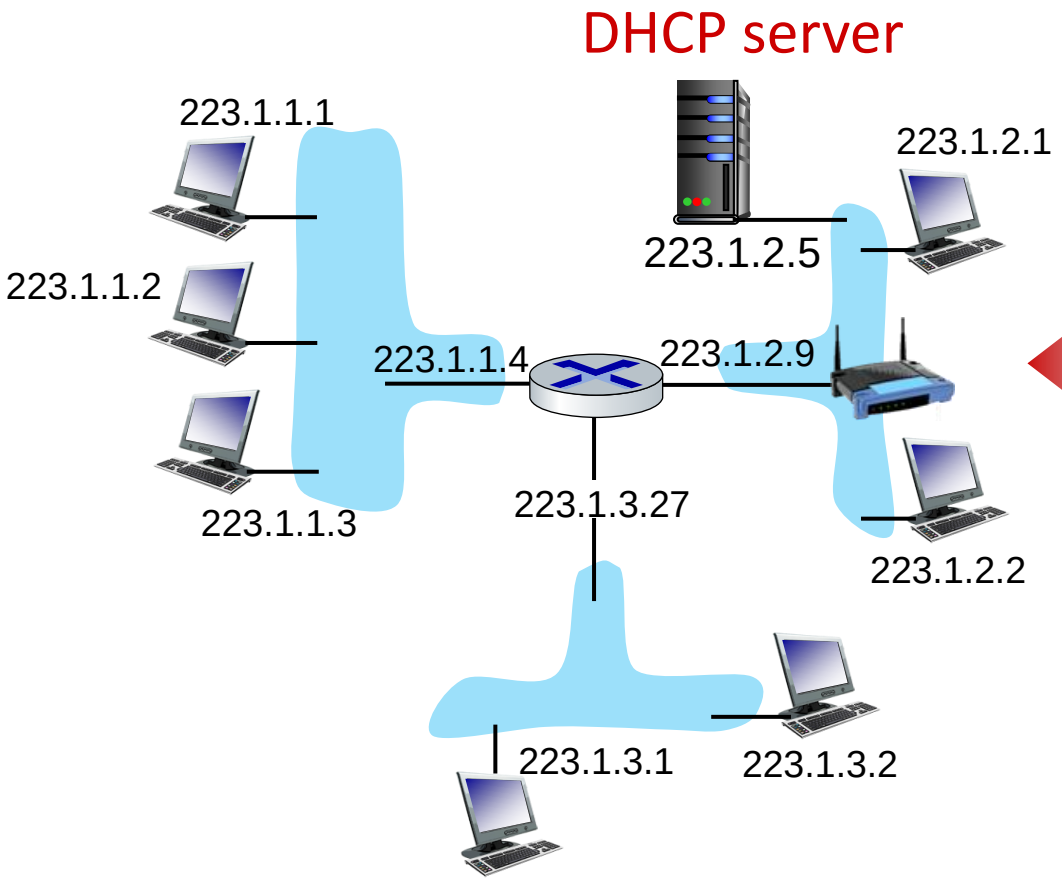
goal: host *dynamically* obtains IP address from network server when it "joins" network

- 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

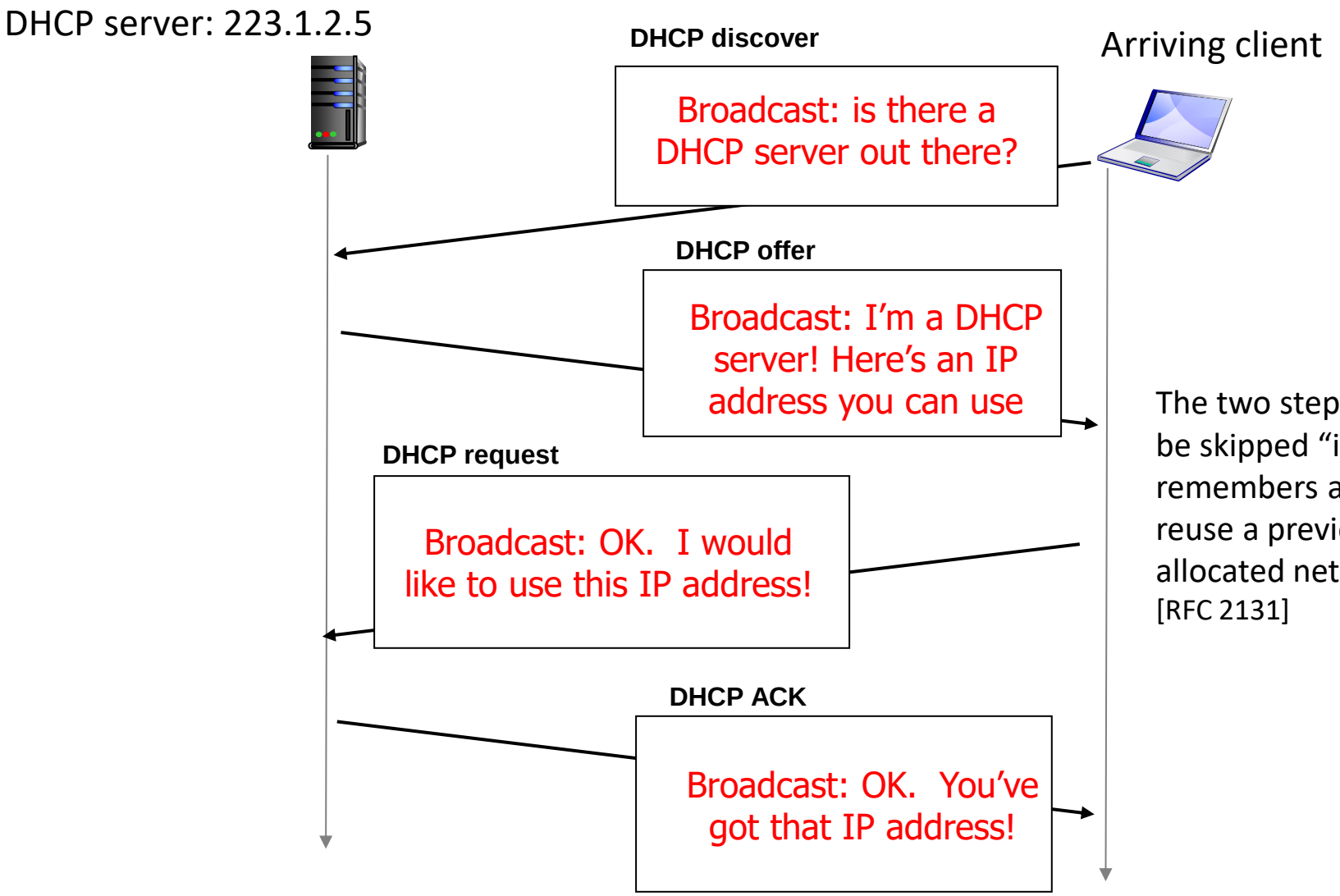
DHCP client-server scenario



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



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: Wireshark output (home LAN)

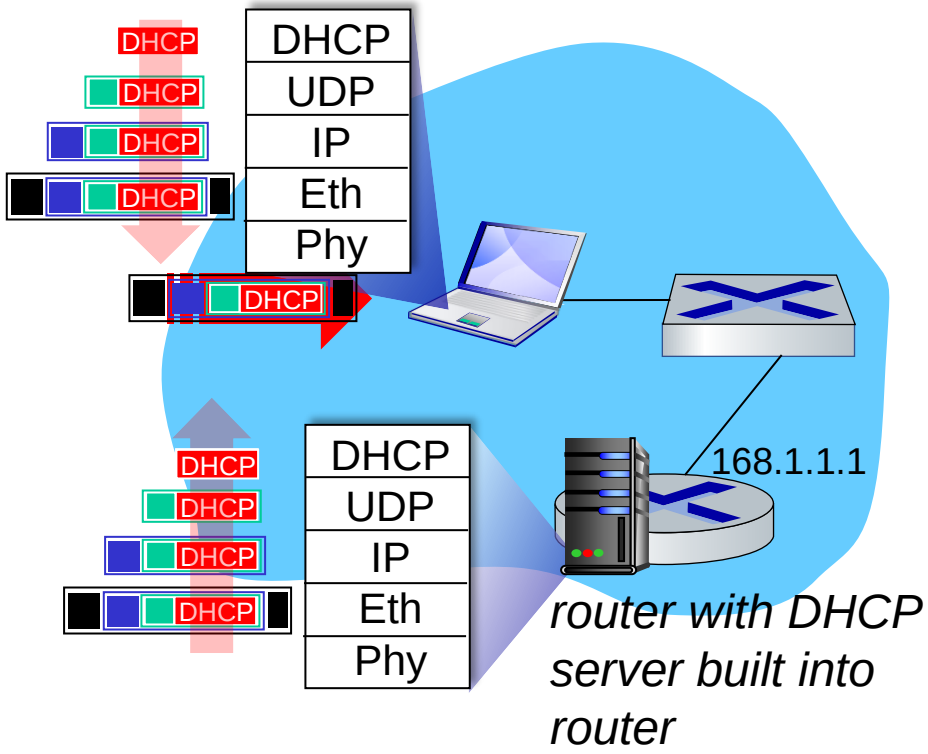
request

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

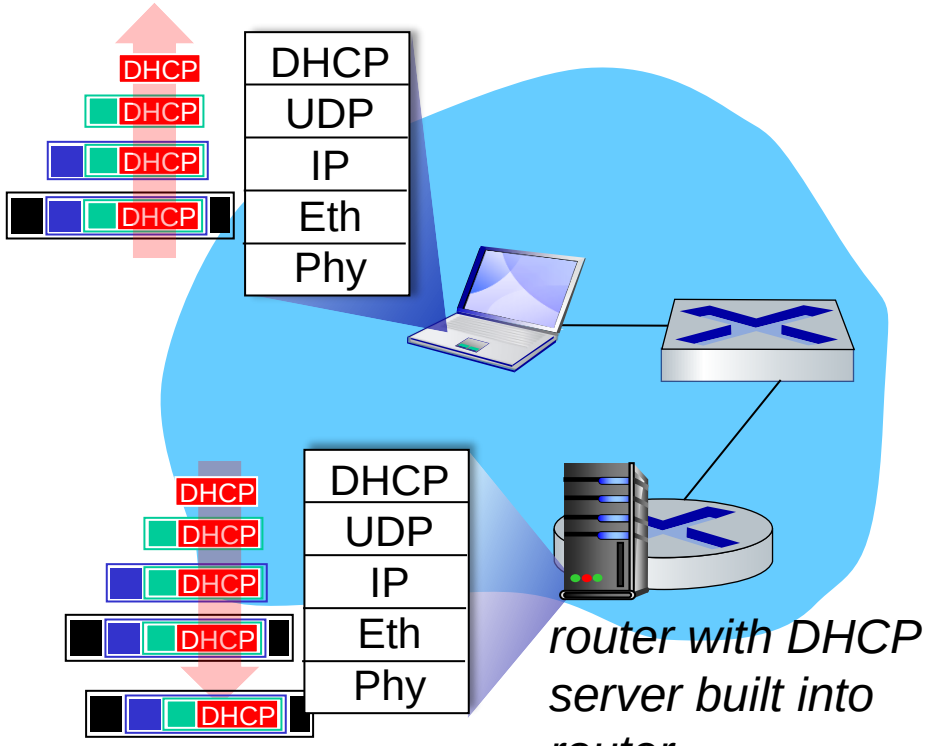
Message type: **Boot Reply (2)**
Hardware type: Ethernet
Hardware address length: 6
Hops: 0
Transaction ID: 0x6b3a11b7
Seconds elapsed: 0
Bootp flags: 0x0000 (Unicast)
Client IP address: 192.168.1.101 (192.168.1.101)
Your (client) IP address: 0.0.0.0 (0.0.0.0)
Next server IP address: 192.168.1.1 (192.168.1.1)
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."

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: FFFFFFFFFFFF) 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

Destination-based forwarding

forwarding table

Destination Address Range	Link Interface
11001000 00010111 00010000 00000000 through 11001000 00010111 00010000 00000100	0
11001000 00010111 00010000 00000101 through 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?

Longest prefix matching

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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
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match!

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11001000 00010111 00010110 10100001 which interface?

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match!

examples:

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

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

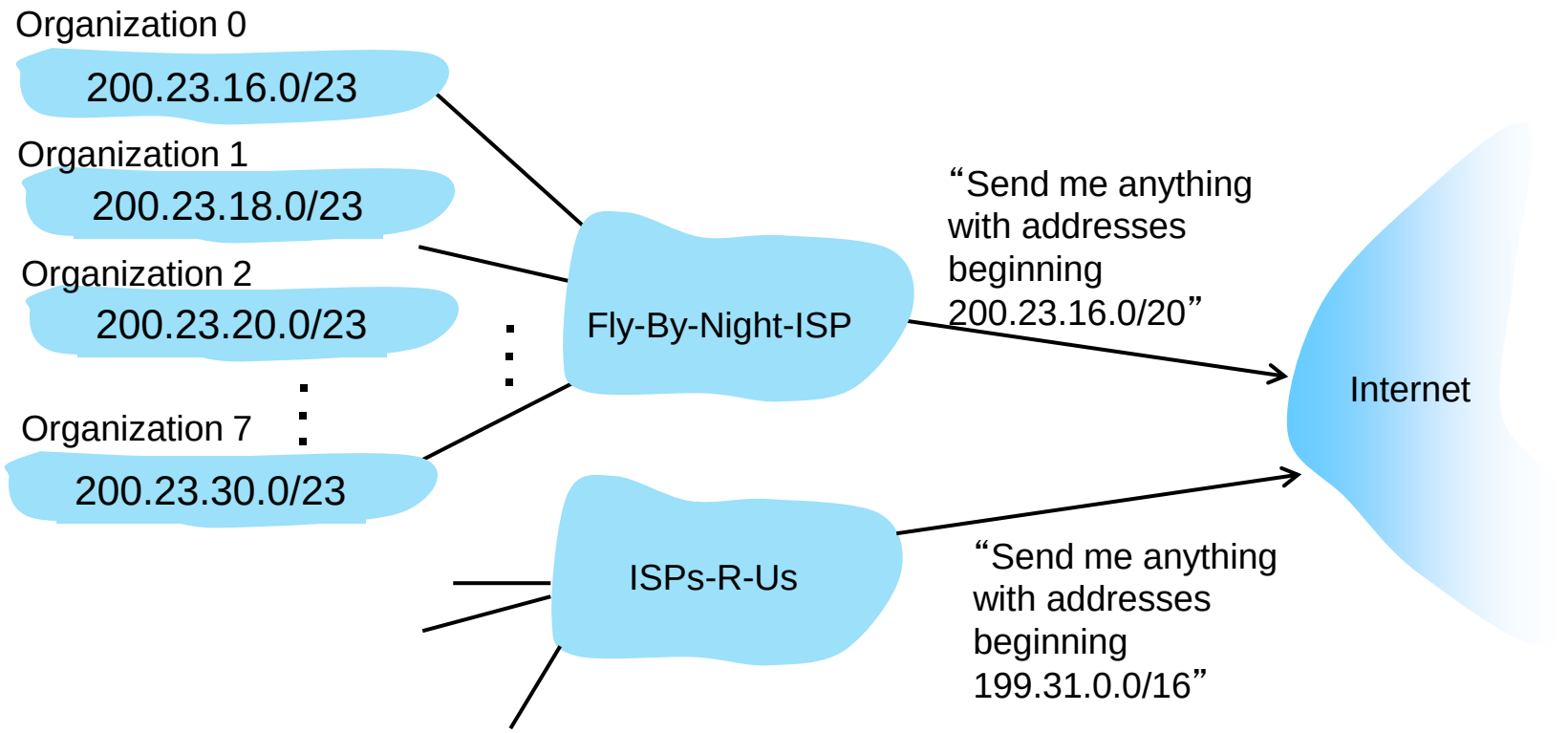
ISP's block	11001000 00010111 00010000	00000000	200.23.16.0/20

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

Organization 0	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

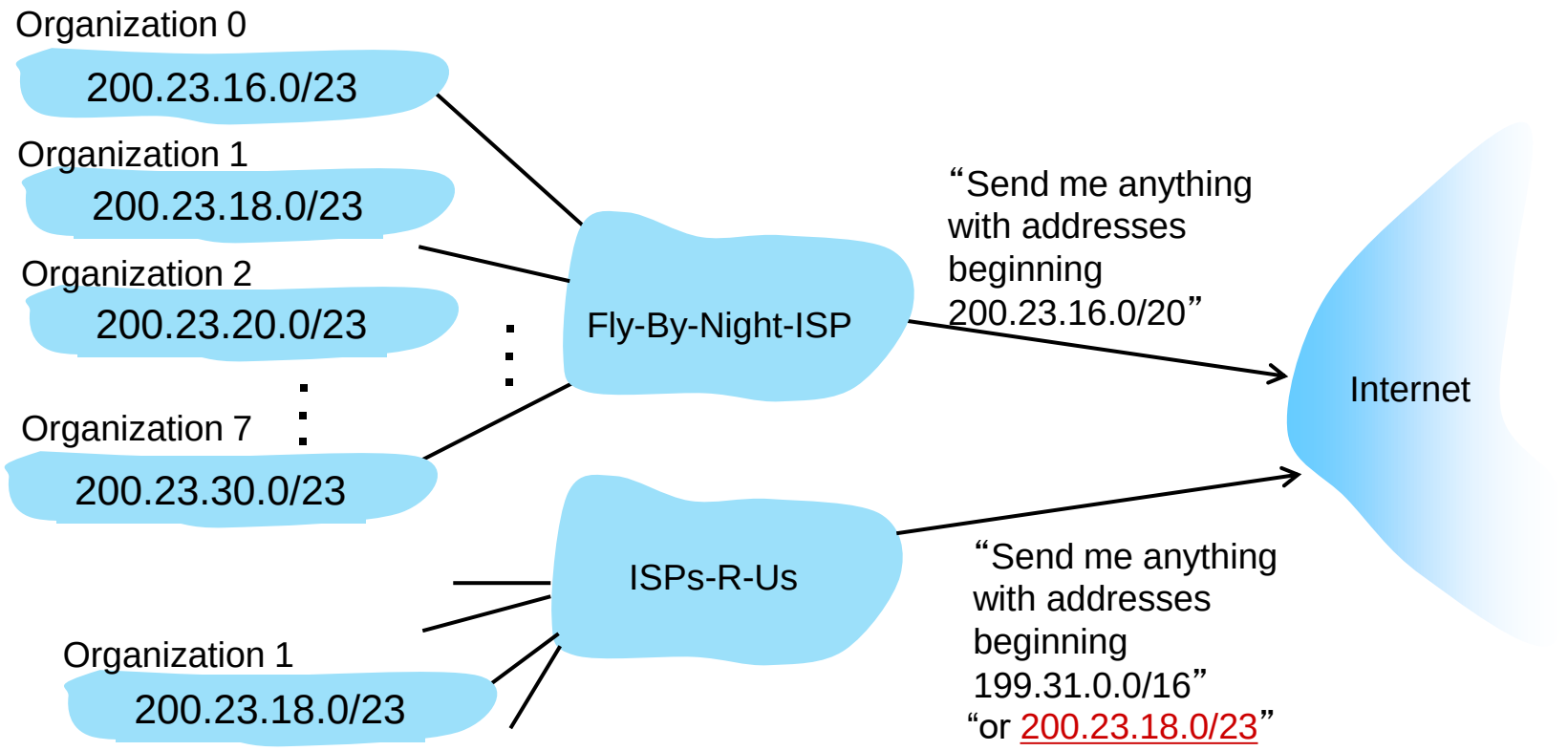
Hierarchical addressing: route aggregation

hierarchical addressing allows efficient advertisement of routing information:



Hierarchical addressing: 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

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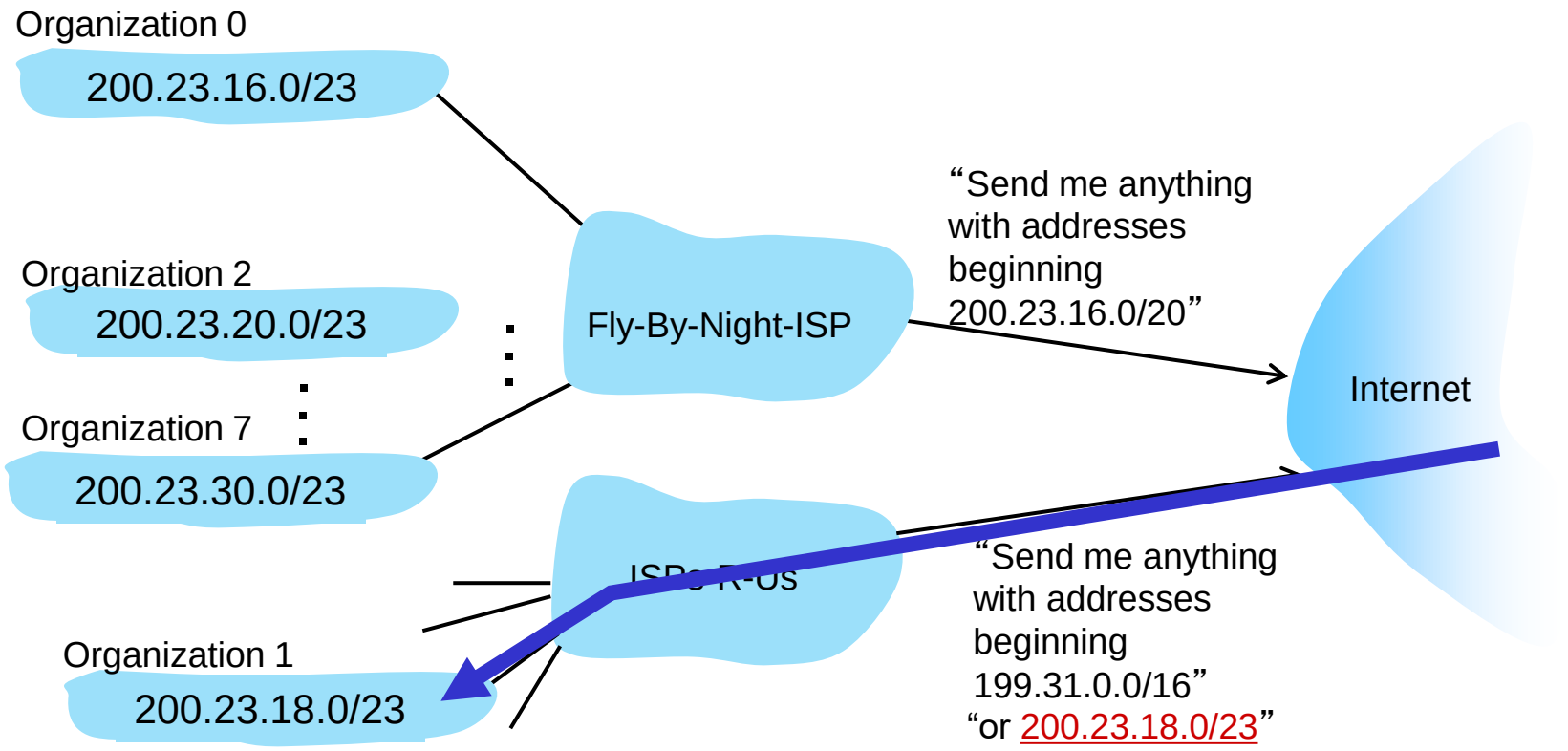


IP addressing: last words ...

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)

IPv6: motivation

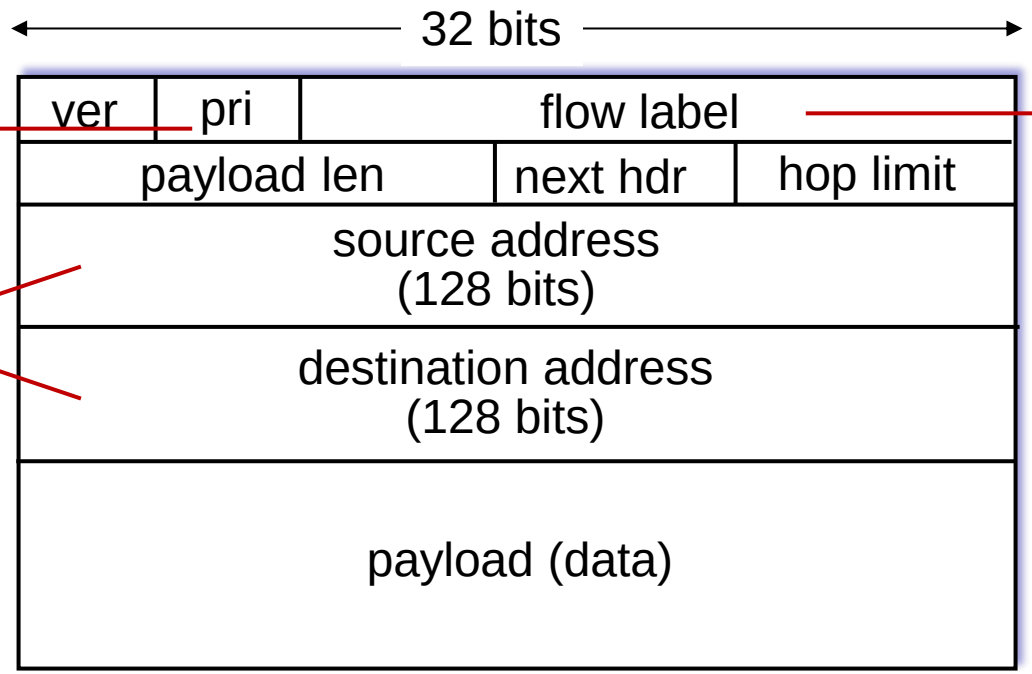
- Initial motivation:
  - IPv4 offers only 32-bit addresses
  - space soon to be (or already) completely allocated
  - See IANA IPv4 Address Space Registry
- IPv6 => 128-bit addresses
  - ~3.4E+38, i.e., ~6.7E+23 addresses per m^2
- Additional motivation:
  - header format helps speed processing/forwarding
  - header changes to facilitate QoS

  IPv6 datagram format:
  - fixed-length 40 byte header
  - no fragmentation allowed (MTU discovery is used, instead)
    - *Fragmentation can happen only at the source, not at the routers*

IPv6 datagram format

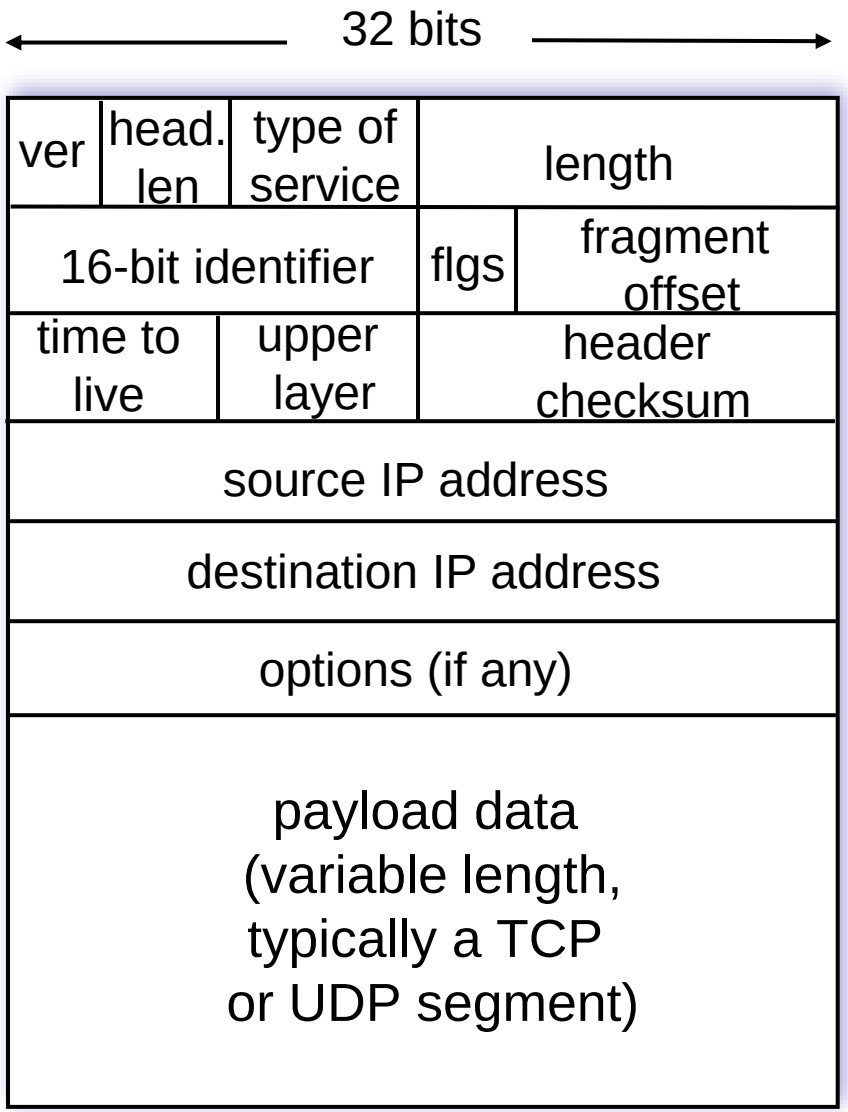
priority: identify priority among datagrams in flow

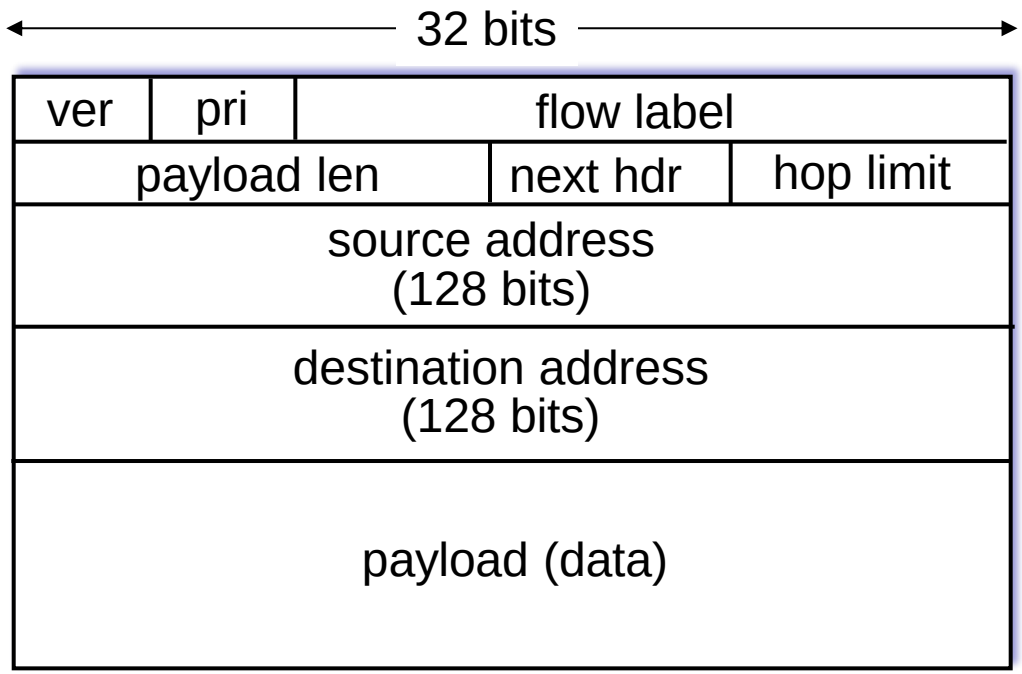
128-bit IPv6 addresses



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

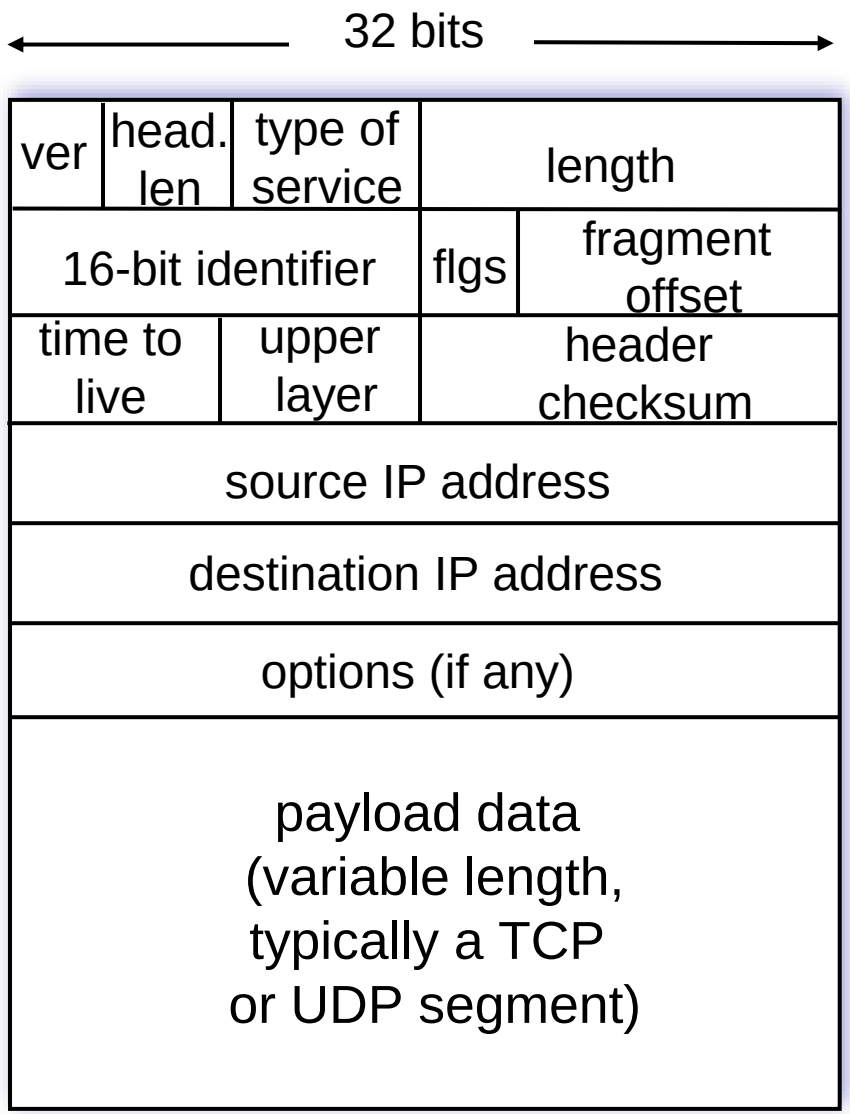
IPv4 vs IPv6 datagram format

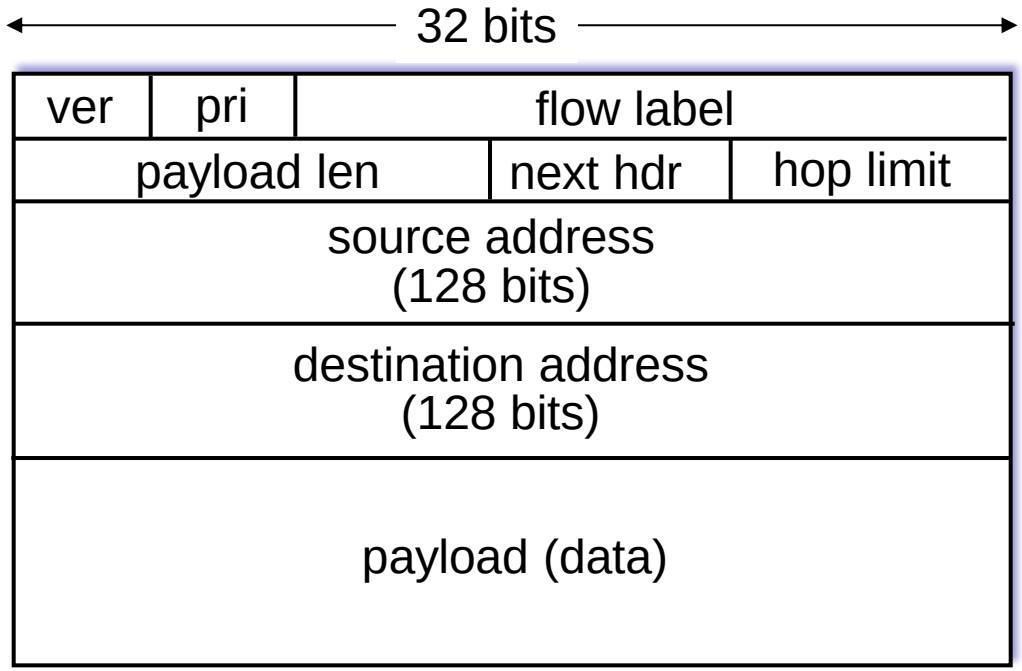




What's missing (compared with IPv4):

IPv4 vs IPv6 datagram format





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)

IPv6 Addresses

- 16 bytes, hex format, ':' separator
  - 2001:DB8:0000:0000:0202:B3FF:FE1E:8329
- Sequences of zeros can be abbreviated
  - 2001:DB8:0:0:0202:B3FF:FE1E:8329
  - 2001:DB8::0202:B3FF:FE1E:8329
- Prefix notation
  - Similar to CIDR notation for IPv4
  - 2E78:DA53:1200::/40

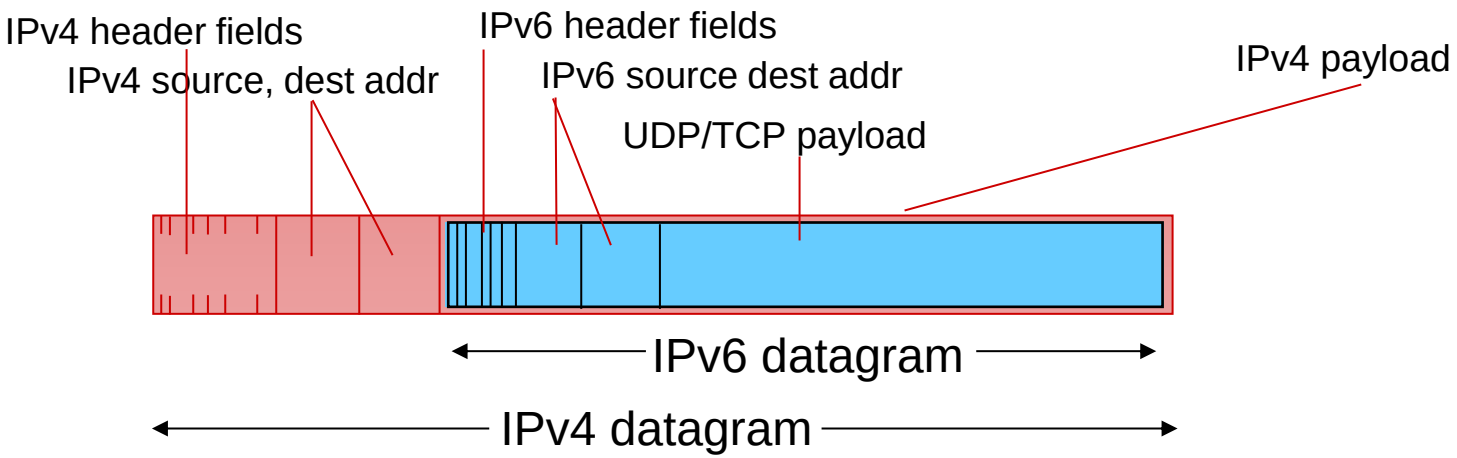
IPv6 Addresses

Allocation	Prefix binary	Prefix hex	Fraction of address space
Unassigned	0000 0000	::0/8	1/256
Reserved	0000 001		1/128
Global unicast	001	2000::/3	1/8
Link-local unicast	1111 1110 10	FE80::/10	1/1024
Reserved (formely Site-local unicast)	1111 1110 11	FEC0::/10* * deprecated	1/1024
Local IPv6 address	1111 110	FC00::/7	
Private administration	1111 1101	FD00::/8	
Multicast	1111 1111	FF00::/8	1/256

IPv6 loopback address = ::1/128
(IPv4 loopback address = 127.0.0.0/8)

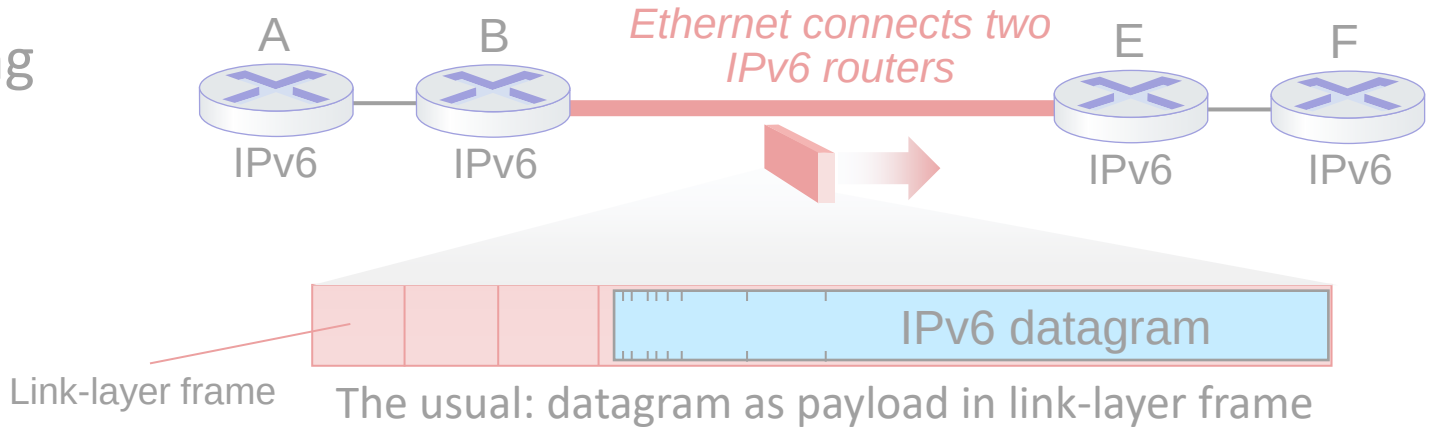
Transition from IPv4 to IPv6

- 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”)

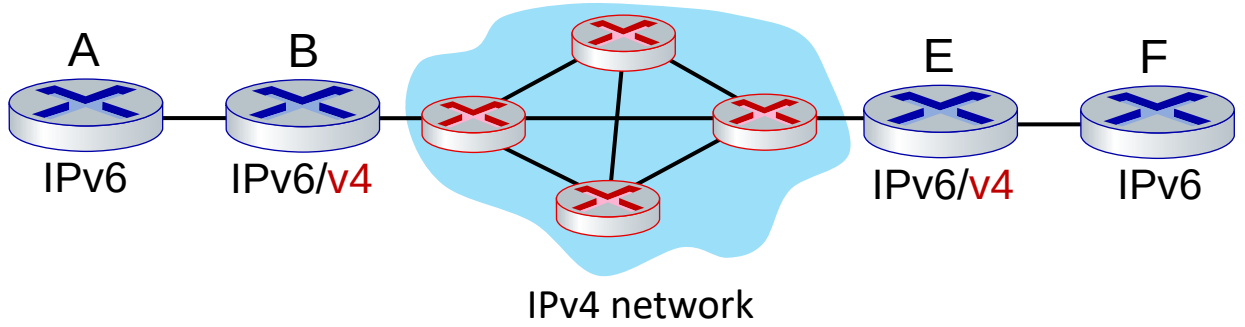


Tunneling and encapsulation

Ethernet connecting two IPv6 routers:



IPv4 network connecting two IPv6 routers



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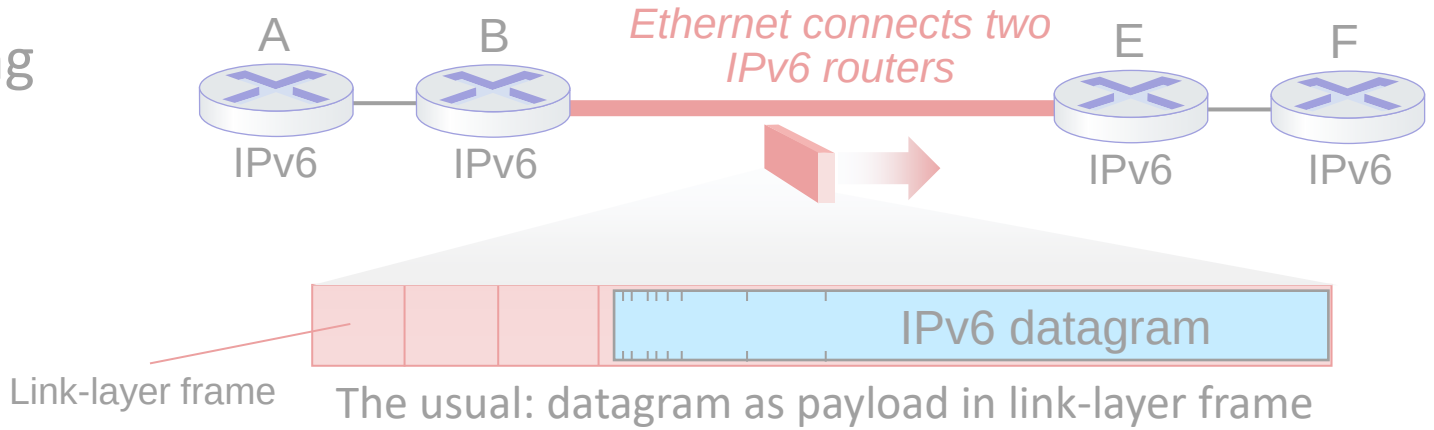
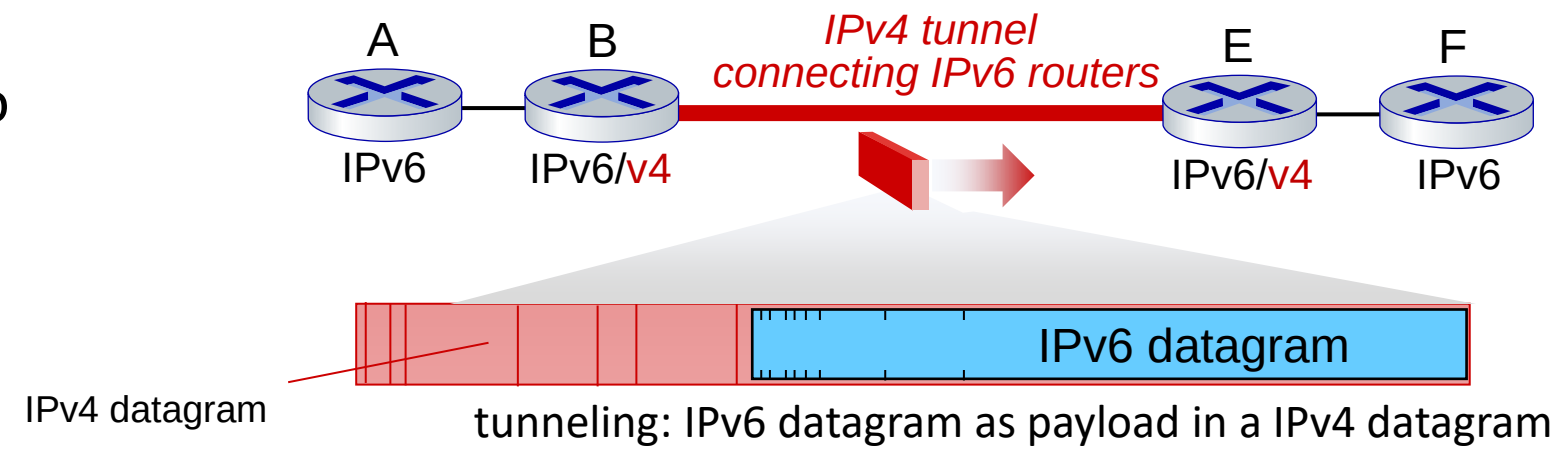
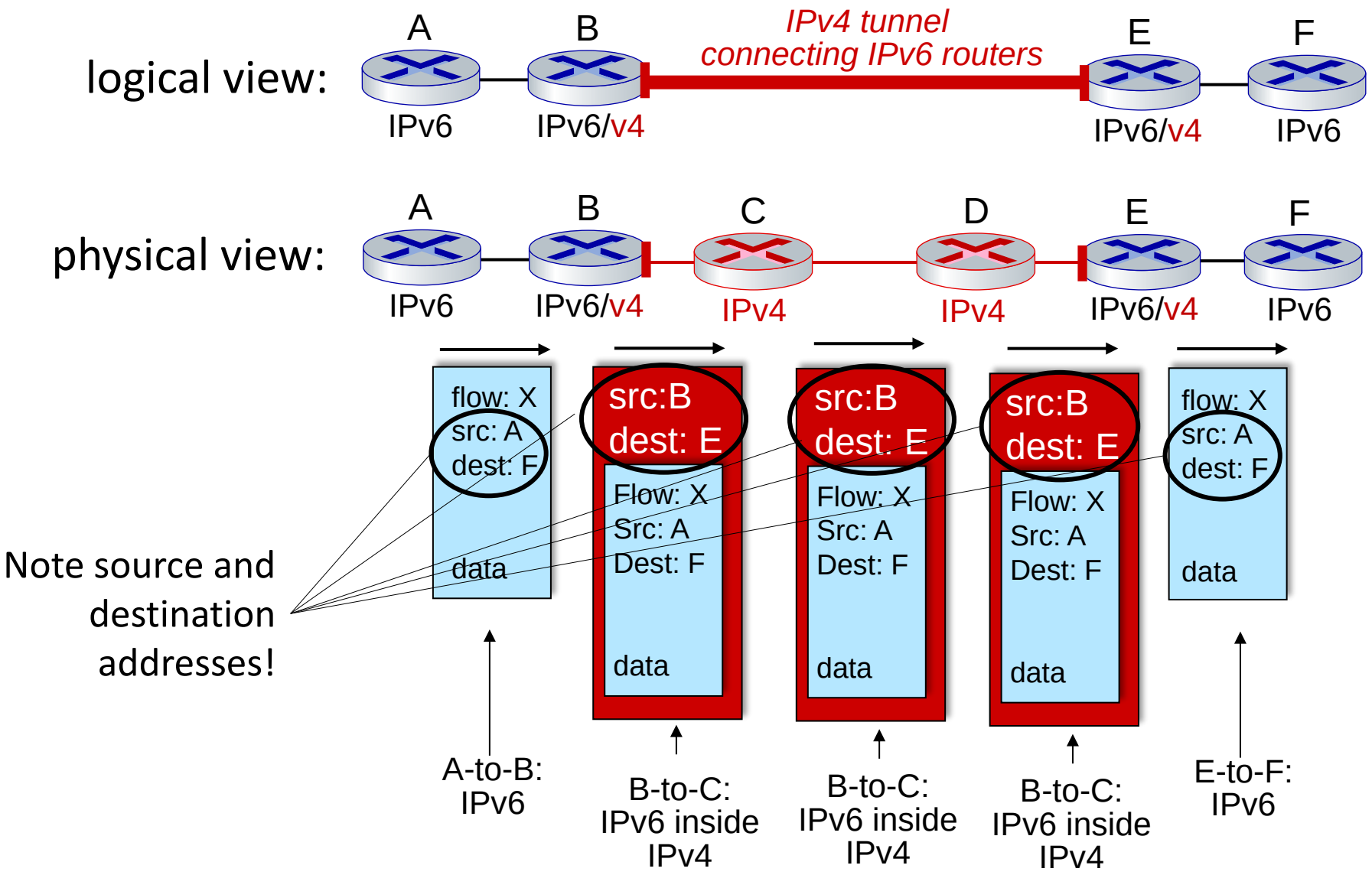


IPv4 tunnel connecting two IPv6 routers

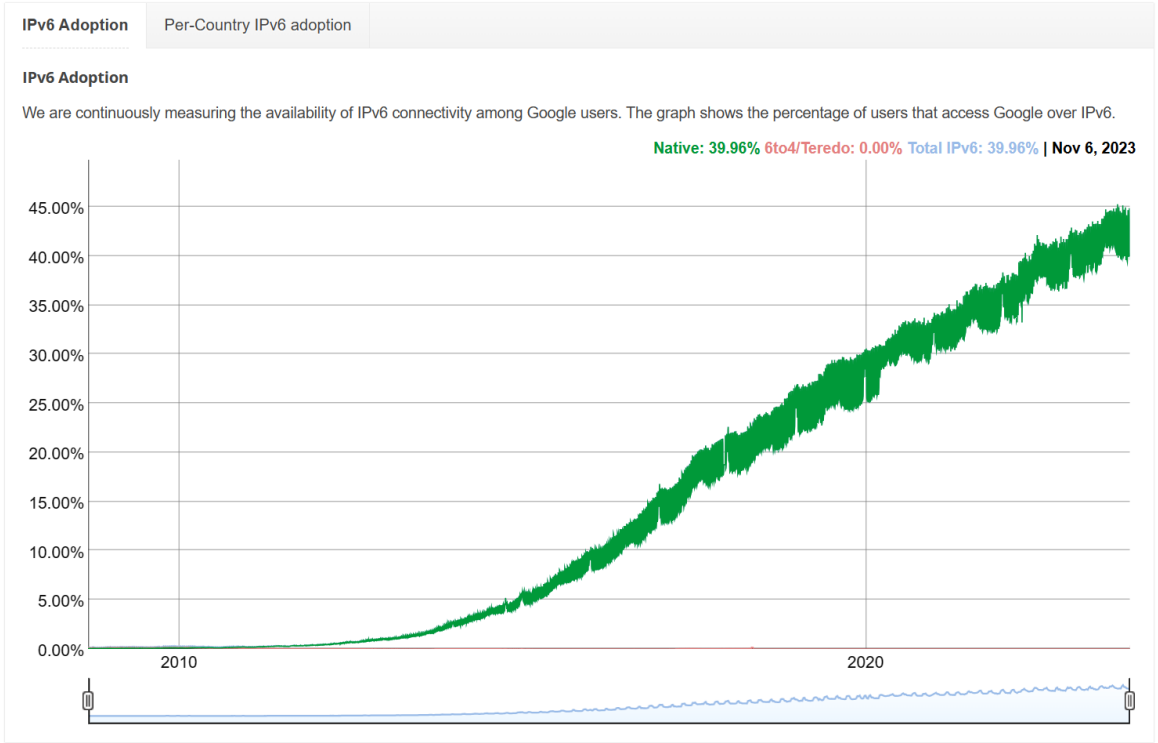


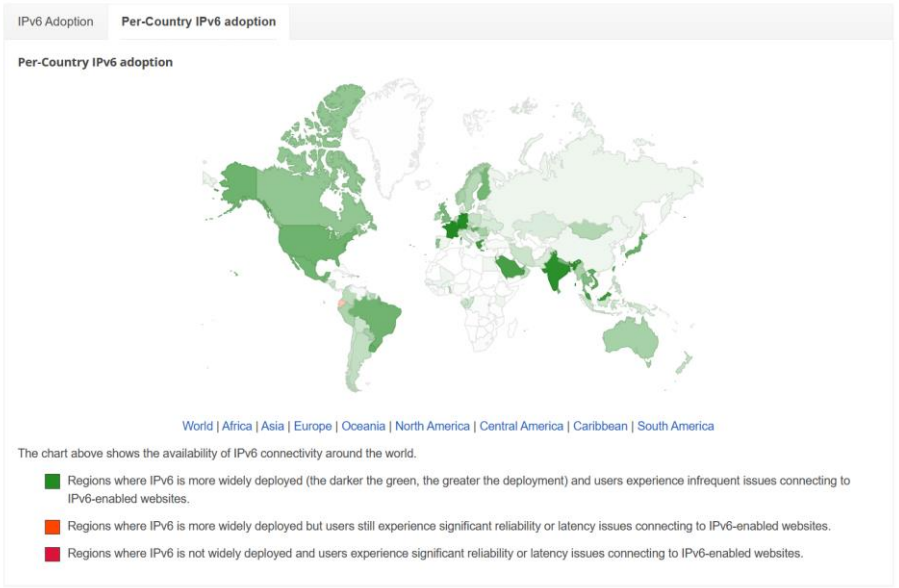
Tunneling


logical view:
A
B
IPv4 tunnel
connecting IPv6 routers
E
F
IPv6
IPv6/v4
IPv6/v4
IPv6
physical view:
A
B
C
D
E
F
IPv6
IPv6/v4
IPv4
IPv4
IPv6/v4
IPv6
Note source and
destination
addresses!
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
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
B-to-C:
IPv6 inside
IPv4
E-to-F:
IPv6

IPv6: adoption

- Google[1]: ~ 40-45% of clients access services via IPv6



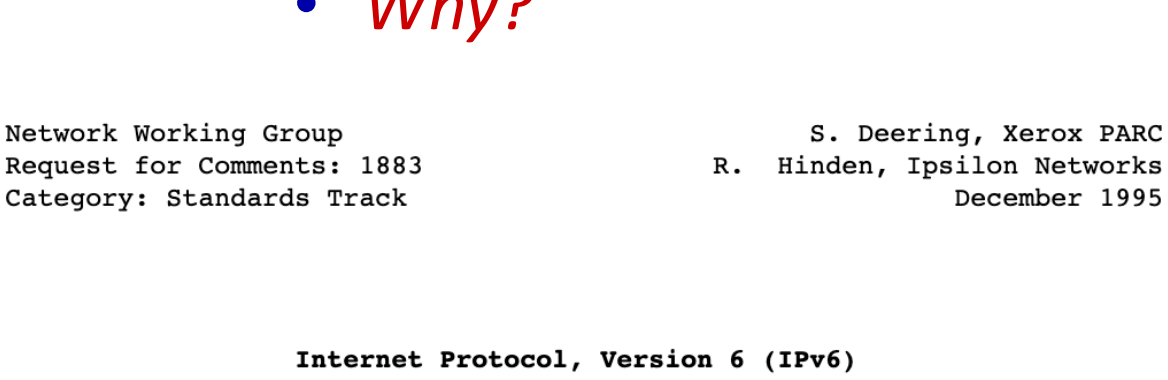


1

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

IPv6: adoption

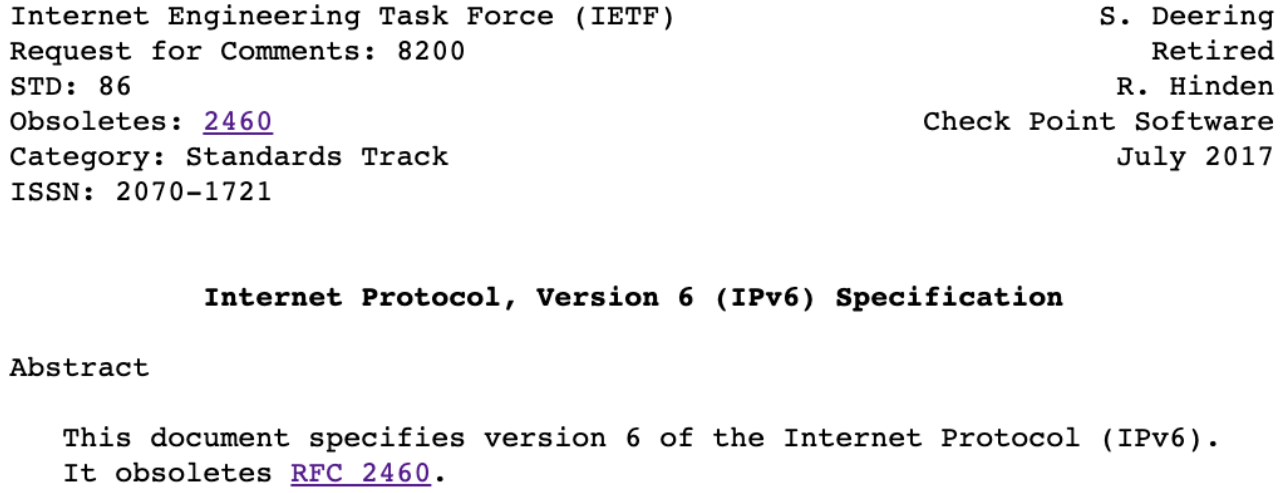
- Google: ~ 40-45% of clients access services via IPv6
- NIST: 1/3 of all US government domains are IPv6 capable
- Long (long!) time for deployment, use
  - 26 years and counting!
  - think of application-level changes in last 26 years: WWW, social media, streaming media, gaming, telepresence, …
  - *Why?*



Network Working Group
Request for Comments: 1883
Category: Standards Track

S. Deering, Xerox PARC
R. Hinden, Ipsilon Networks
December 1995

Internet Protocol, Version 6 (IPv6) Specification



Internet Engineering Task Force (IETF)
Request for Comments: 8200
STD: 86
Obsoletes: 2460
Category: Standards Track
ISSN: 2070-1721

S. Deering
Retired
R. Hinden
Check Point Software
July 2017

Internet Protocol, Version 6 (IPv6) Specification

Abstract

This document specifies version 6 of the Internet Protocol (IPv6). It obsoletes RFC 2460.