COMP 3331/9331: Computer Networks and Applications

Week 7

Network Layer: Data Plane

Reading Guide: Chapter 4: Sections 4.1, 4.3

Network Layer: outline

Our goals:

- understand principles behind network layer services, focusing on data plane:
  - network layer service models
  - forwarding versus routing
  - addressing
- instantiation, implementation in the Internet
  - IP, NAT, ICMP

Network Layer, data plane: outline

4.1 Overview of Network layer
- data plane
- control plane

4.2 What's inside a router
-- **Not Covered**

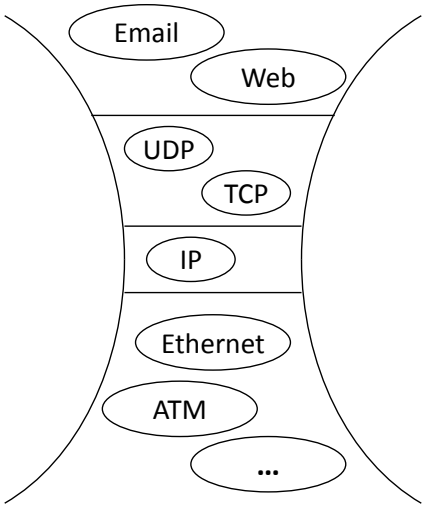
4.3 IP: Internet Protocol
- datagram format
- fragmentation
- IPv4 addressing
- network address translation
- IPv6

4.4 Generalized forwarding and Software Defined Networking (SDN)
- **Not Covered**

Some Background

- 1968: DARPAnet/ARPAnet (precursor to Internet)
  - (Defense) Advanced Research Projects Agency Network
- Mid 1970's: new networks emerge
  - SATNet, Packet Radio, Ethernet
  - All "islands" to themselves – didn't work together
- Big question: How to connect these networks?

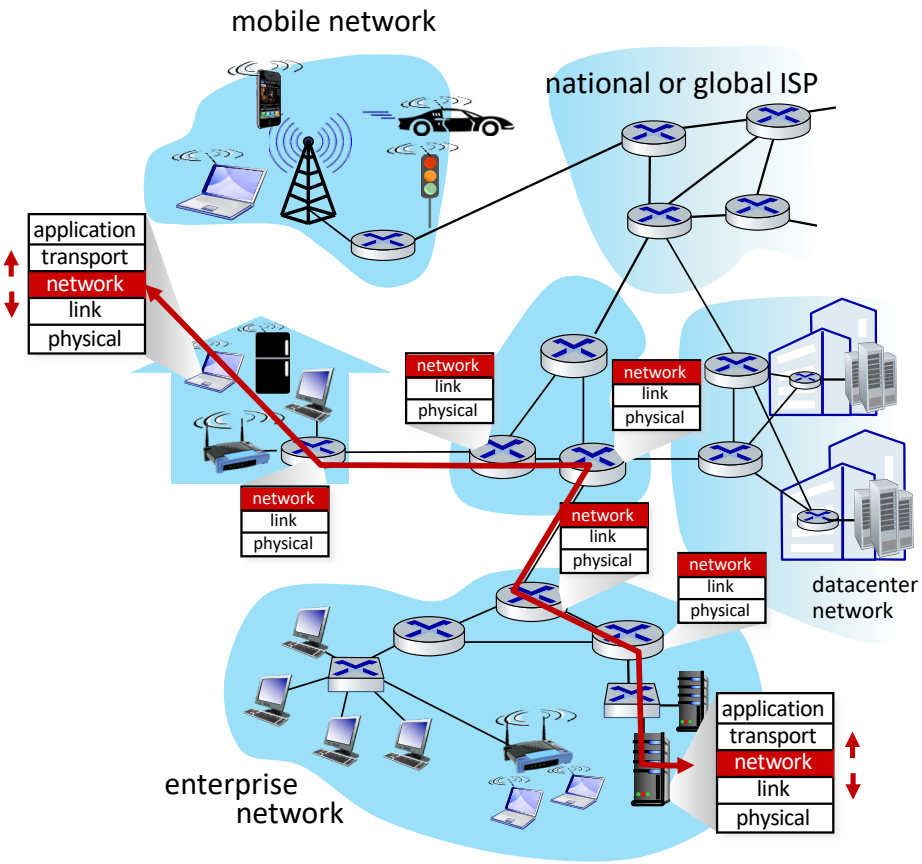
Internetworking



- Cerf & Kahn in 1974,
  - "A Protocol for Packet Network Intercommunication"
  - Foundation for the modern Internet
- **Routers** forward **packets** from source to destination
  - May cross many separate networks along the way
- All packets use a common **Internet Protocol**
  - Any underlying data link protocol
  - Any higher layer transport protocol

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*

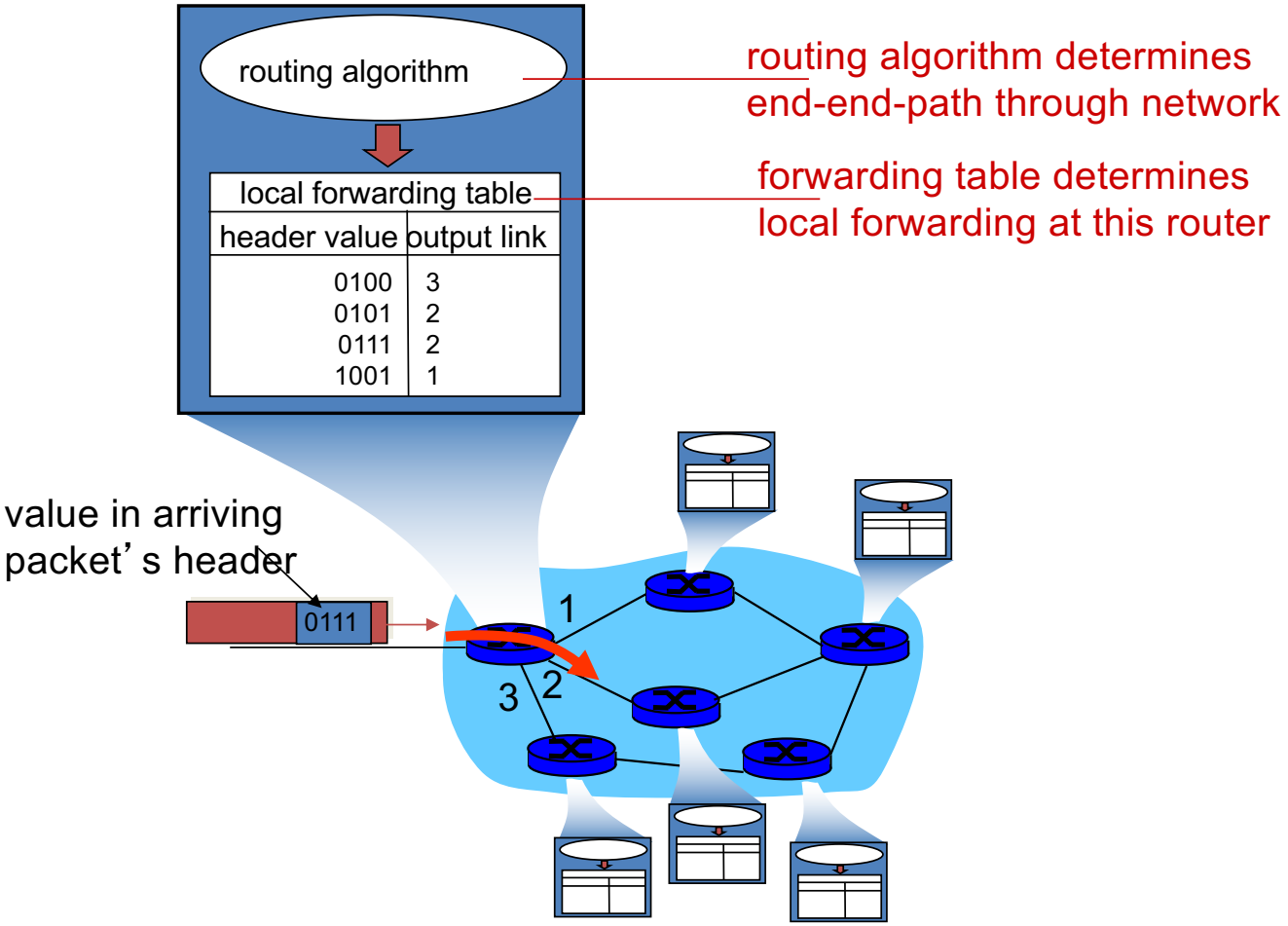
analogy: taking a trip

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

forwarding

routing

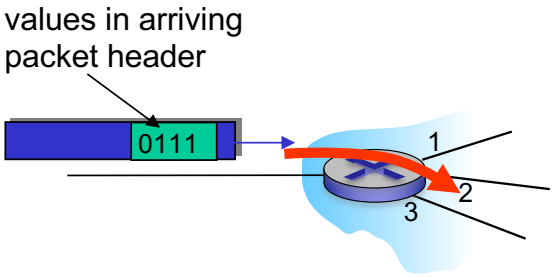
Interplay between routing and forwarding



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

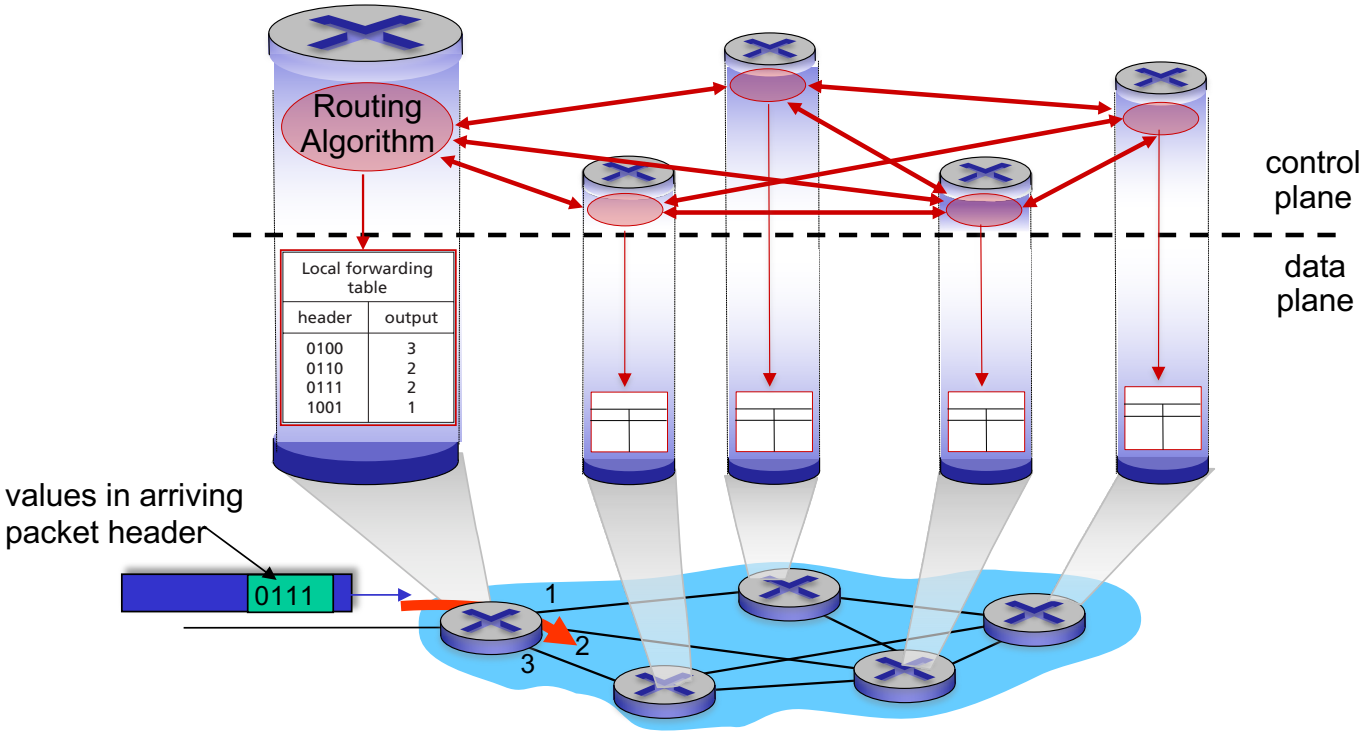


Control plane

- *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

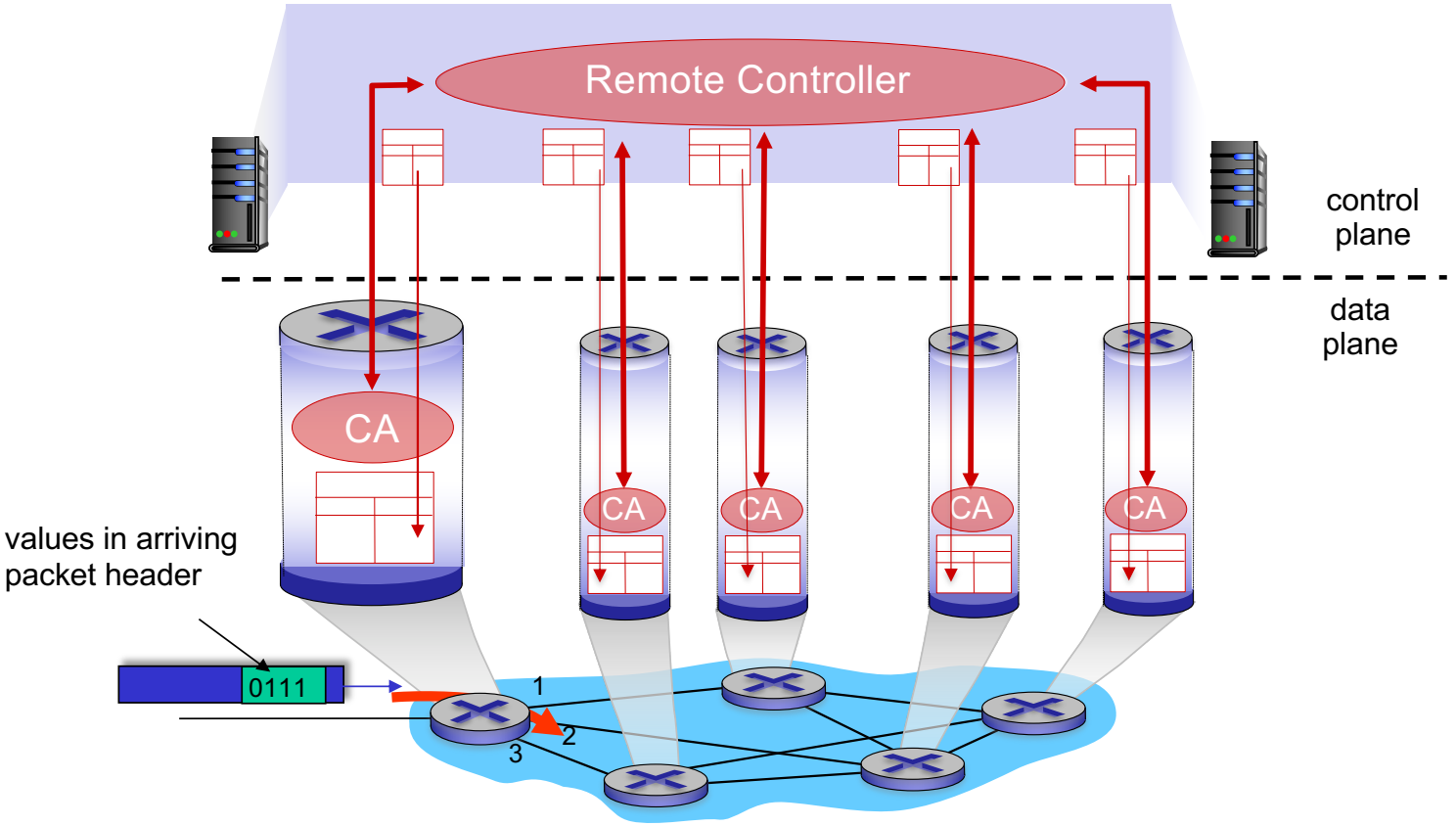
Individual routing algorithm components *in each and every router* interact in the control plane



Software-Defined Networking (SDN) control plane

Remote controller computes, installs forwarding tables in routers

NOT ON EXAM



Network Layer: service model

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

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

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: outline

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-- **Not Covered**

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4.4 Generalized forwarding and Software Defined Networking (SDN)
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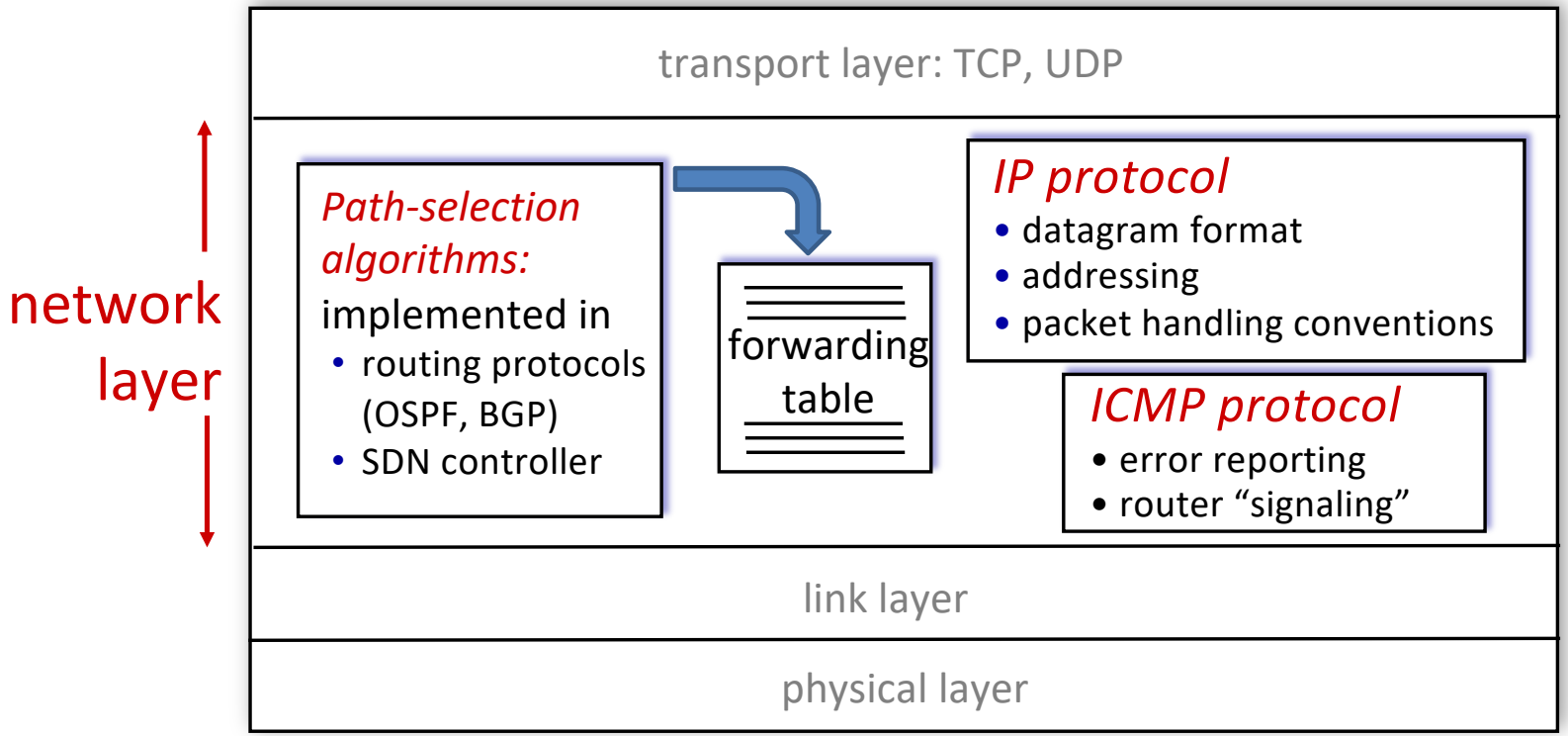
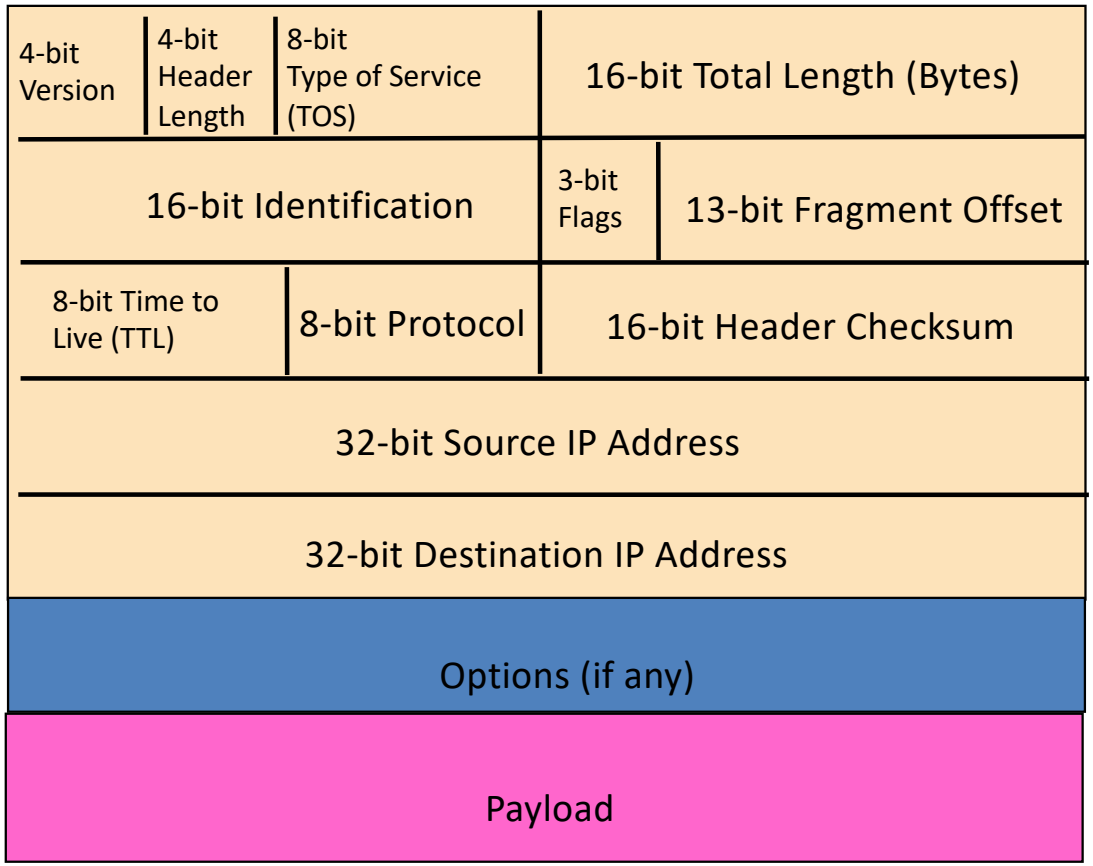
Network Layer: Internet

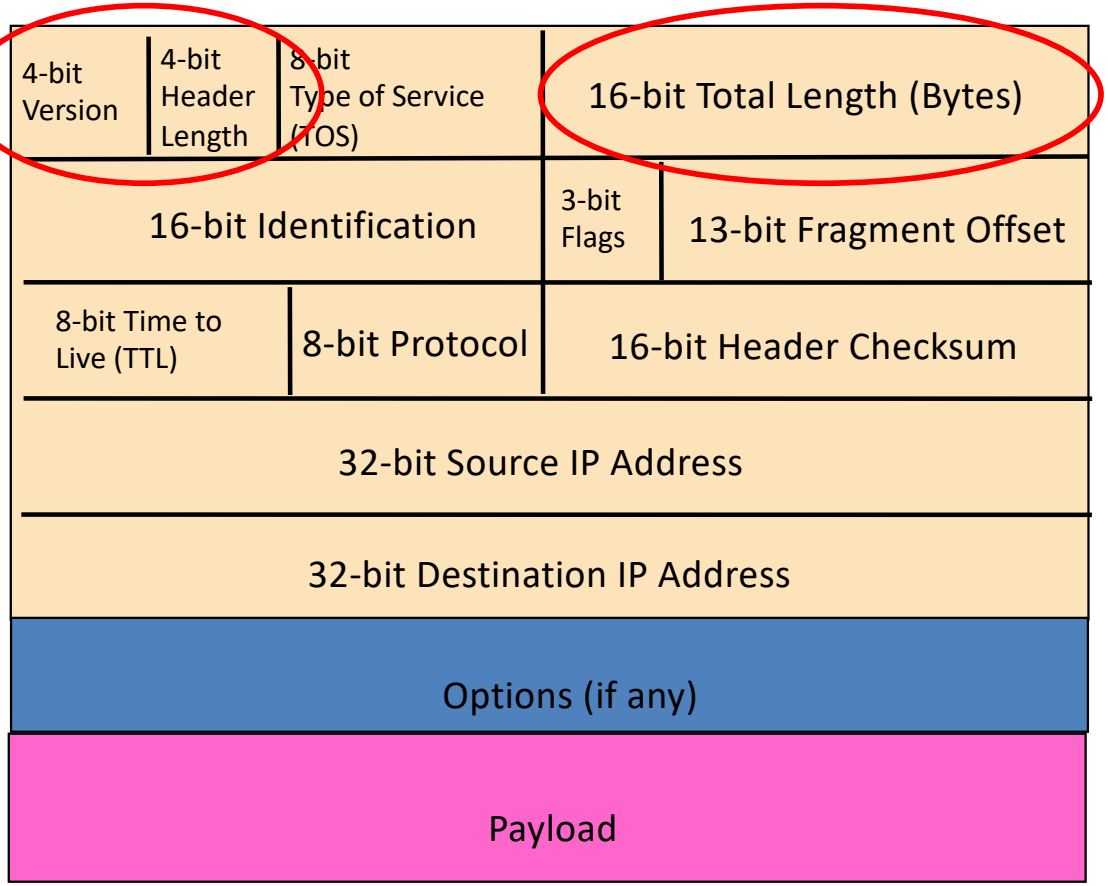
host, router network layer functions:



IP Datagram Format



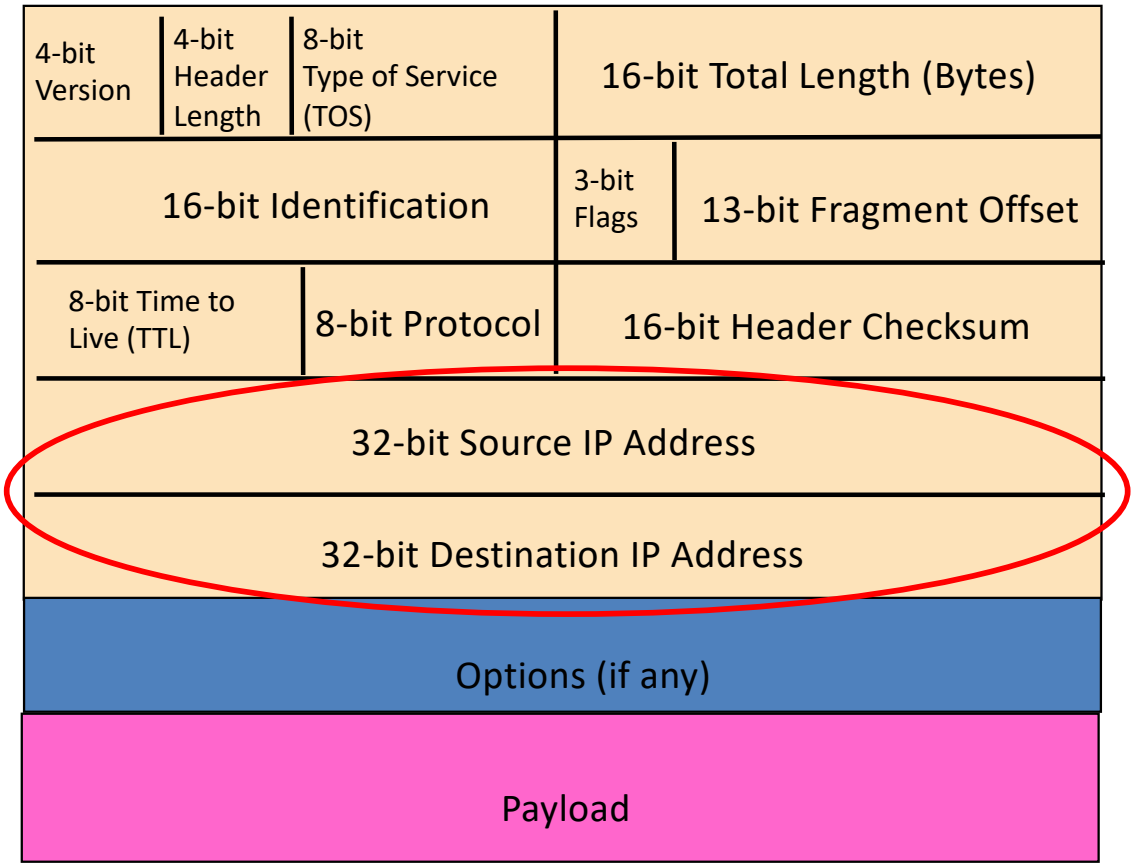
Fields for Reading Packet Correctly



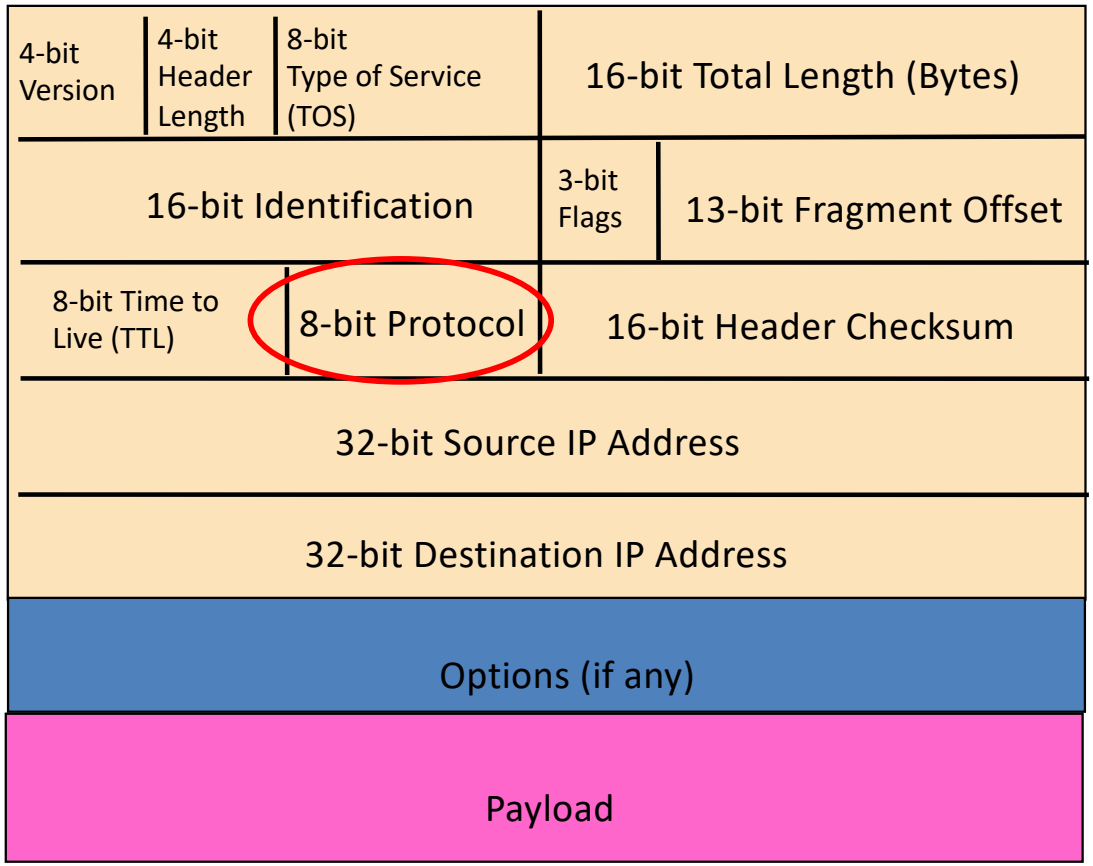
Reading Packet Correctly

- Version number (4 bits)
  - Indicates the version of the IP protocol
  - Necessary to know what other fields to expect
  - Typically, “4” (for IPv4)
- Header length (4 bits)
  - Number of 32-bit words in the header
  - Typically, “5” (for a 20-byte IPv4 header)
  - Can be more when IP options are used
- Total length (16 bits)
  - Number of bytes in the packet
  - Maximum size is 65,535 bytes (2^{16} -1)
  - … though link layer protocols may impose smaller limits

Fields for Reaching Destination and Back

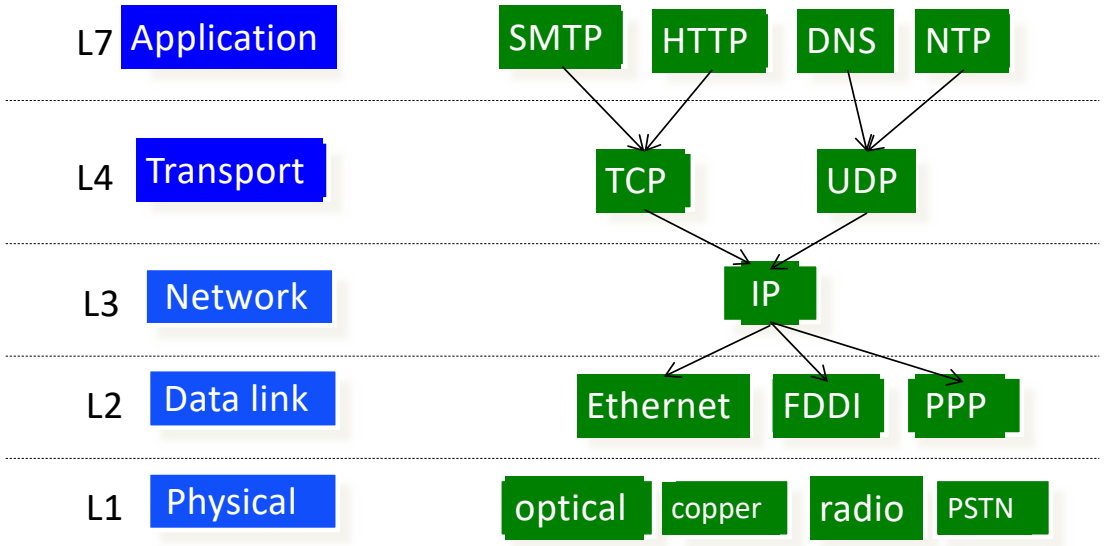


Telling End-Host How to Handle Packet

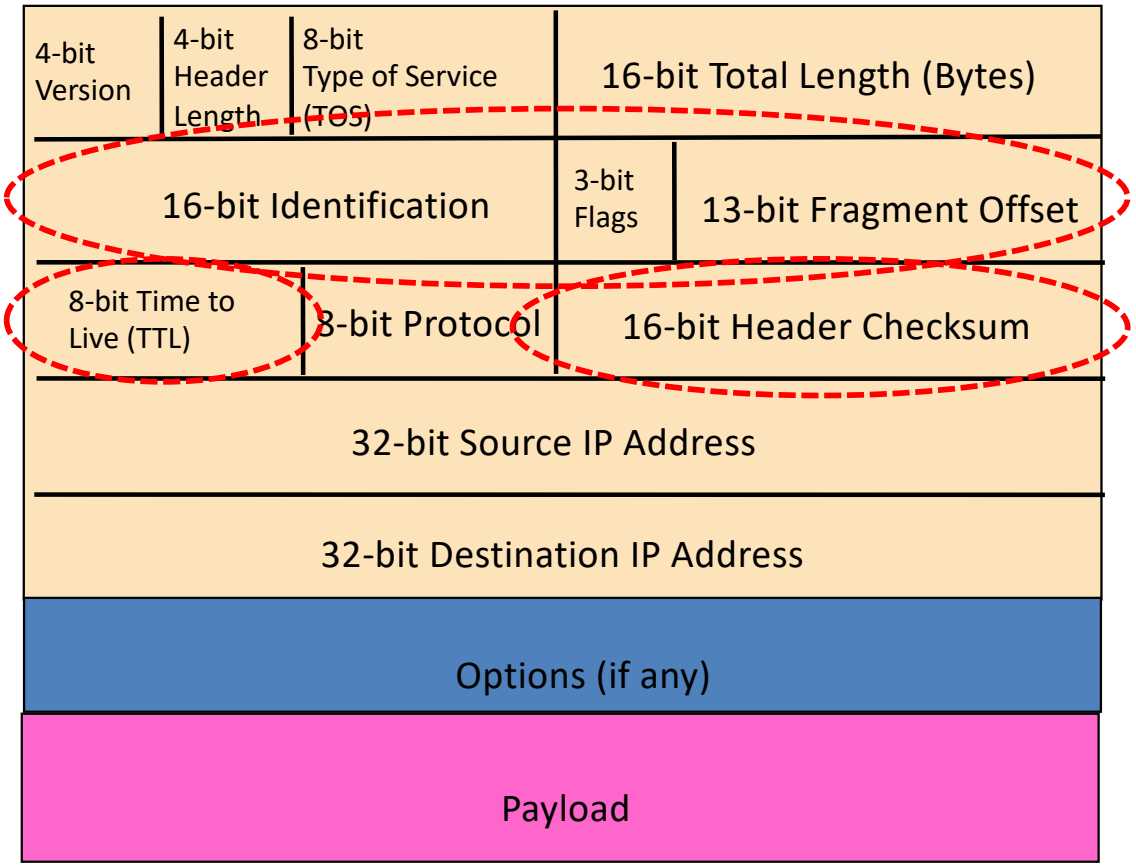


Telling End-Host How to Handle Packet

- Protocol (8 bits)
  - Identifies the higher-level protocol
  - Important for **demultiplexing** at receiving host



Checksum, TTL and Fragmentation Fields

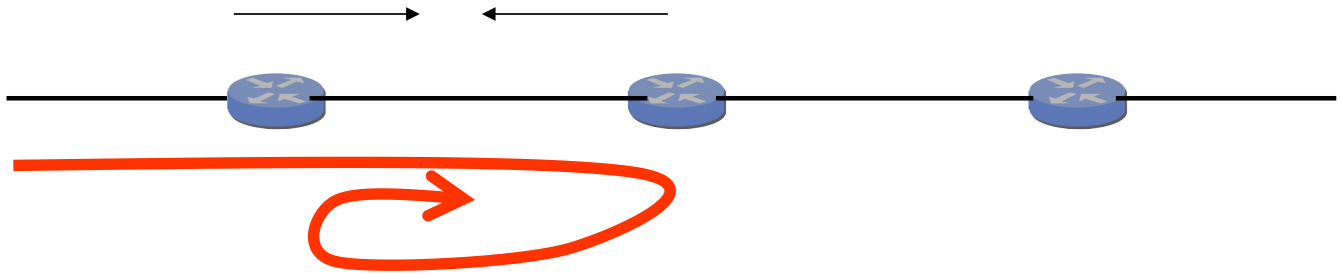


Potential Problems

- Loop: **TTL**
- Header Corrupted: **Checksum**
- Packet too large: **Fragmentation**

Preventing Loops (TTL)

- Forwarding loops cause packets to cycle for a long time
  - As these accumulate, eventually consume **all** capacity



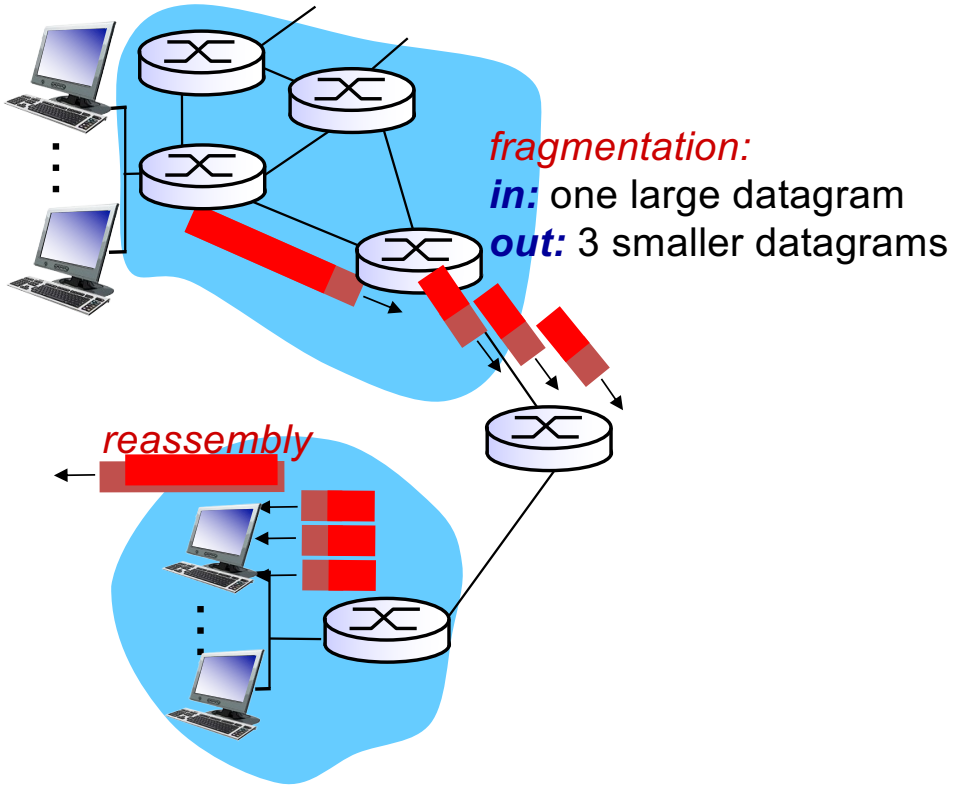
- Time-to-Live (TTL) Field (8 bits)
  - Decremented at each hop, packet discarded if reaches 0
  - …and “time exceeded” message is sent to the source
  - Recommended default value is 64

Header Corruption (Checksum)

- Checksum (16 bits)
  - Only computed over packet header, method is same as UDP/TCP checksum
- If not correct, router discards packets
  - So, it doesn't act on bogus information
- Checksum recalculated at every router
  - **Why?**
  - **Why include TTL?**
  - **Why only header?**

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

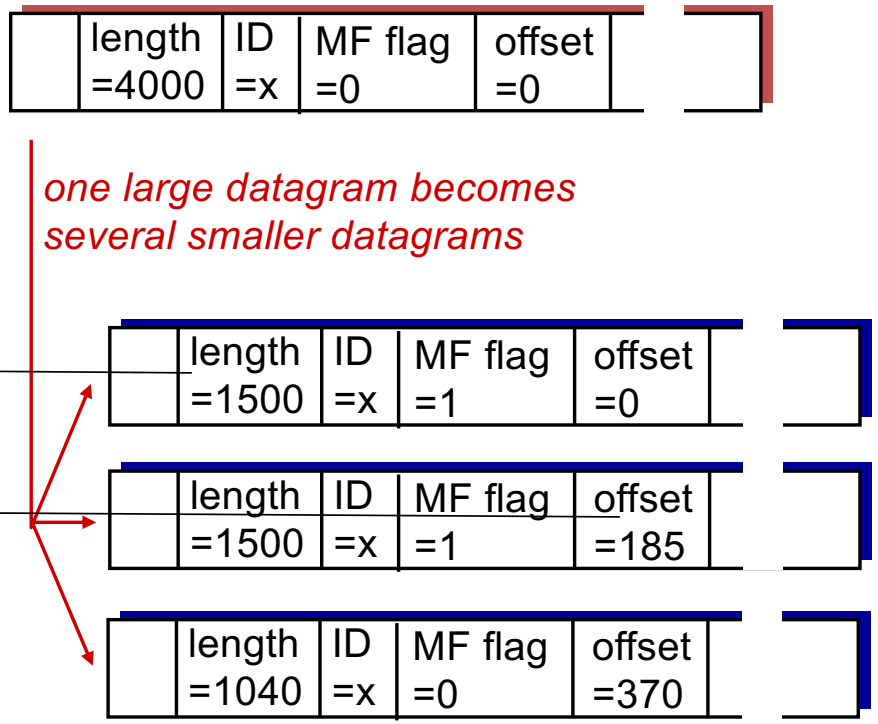


IP fragmentation, reassembly

Note: Offset is expressed as multiple of 8 bytes

example:

- 4000-byte datagram
- MTU = 1500 bytes



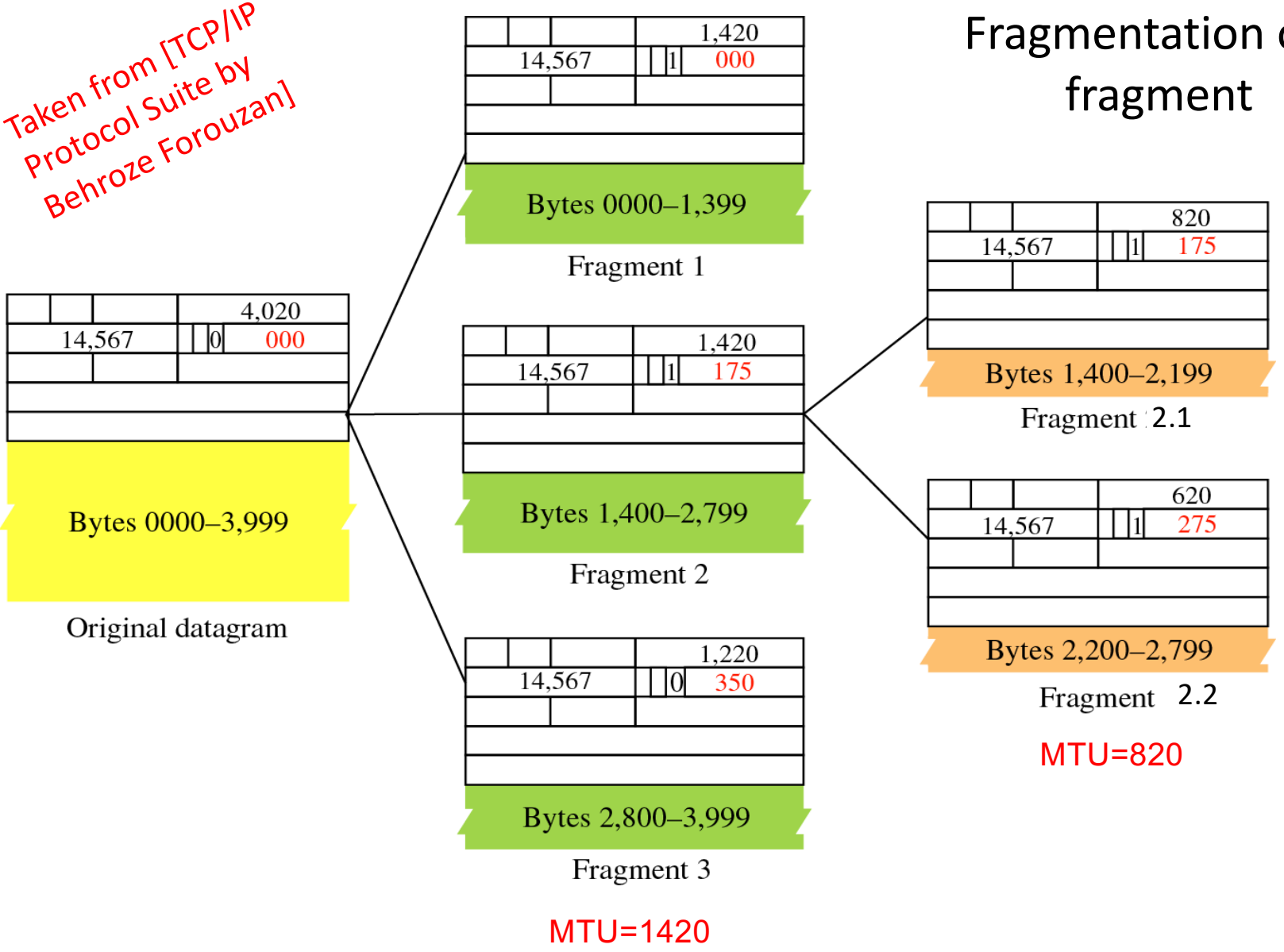
Data = 4000 – 20 (IP header)
=3980
F1=1480
F2=1480
F3=1020

IPv4 fragmentation procedure

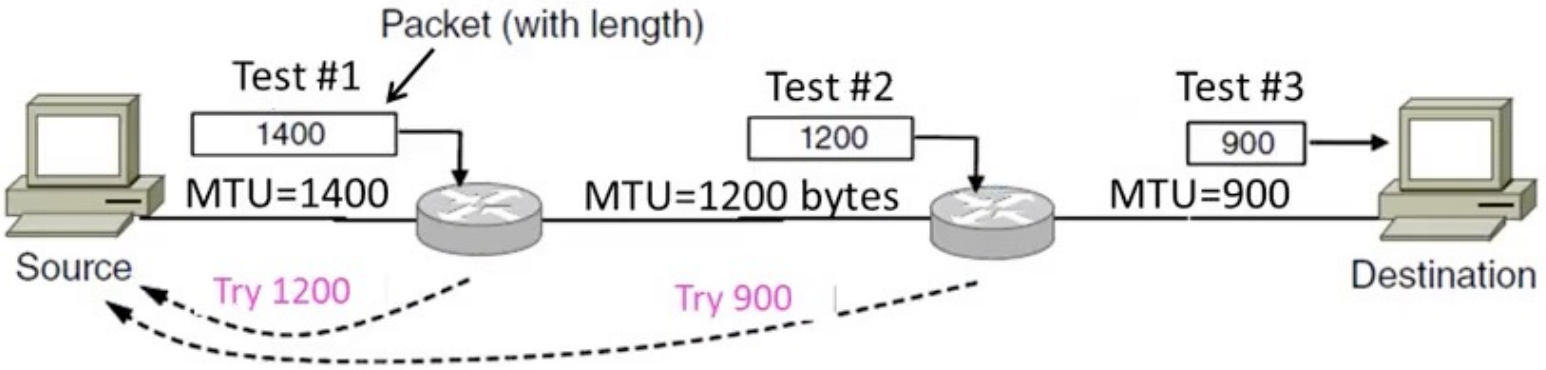
- Fragmentation
  - Router breaks up datagram in size that output link can support
  - Copies IP header to pieces
  - Adjust length on pieces
  - Set offset to indicate position
  - Set MF (More fragments) flag on pieces except the last
  - Re-compute checksum
- Re-assembly
  - Receiving host uses identification field with MF and offsets to complete the datagram.
- Fragmentation of fragments also supported

Fragmentation of a fragment

Taken from [TCP/IP Protocol Suite by Behroze Forouzan]

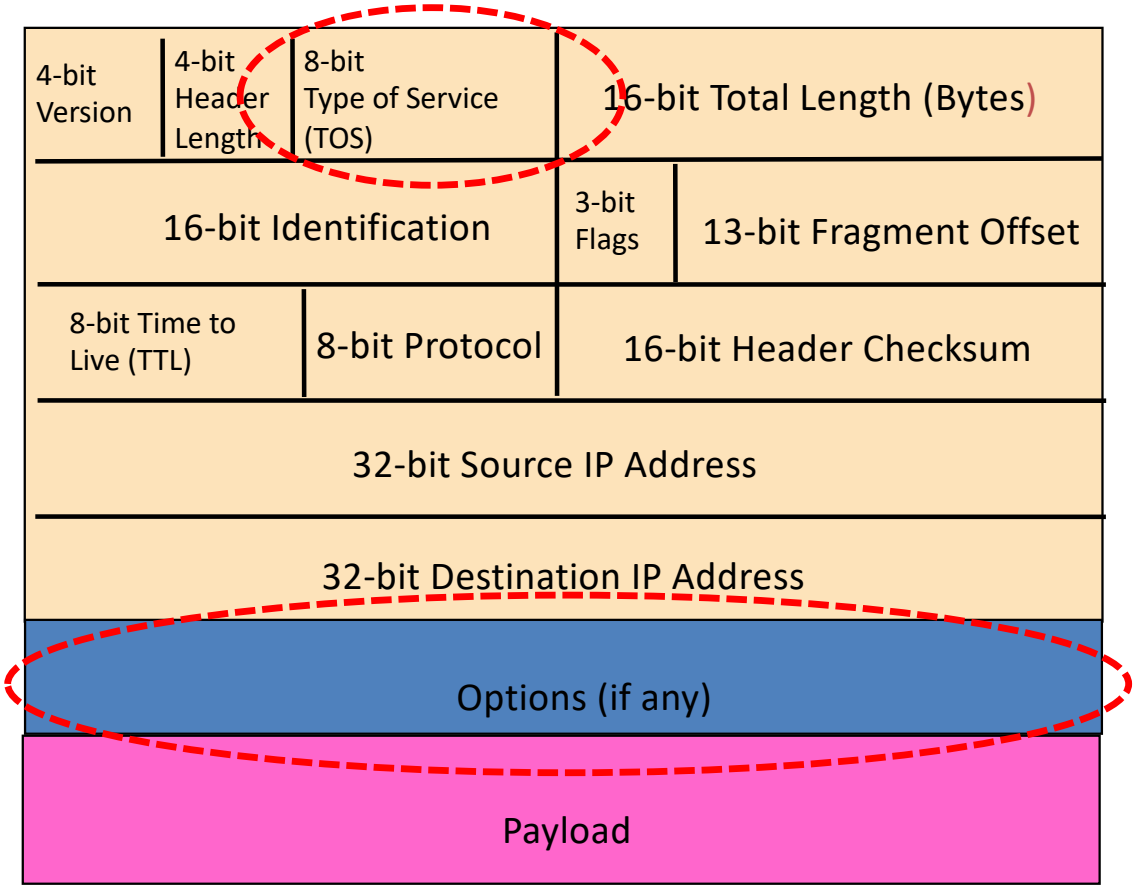


Path MTU Discovery procedure



- Host
  - Sends a big packet to test whether all routers in path to the destination can support or not
  - Set DF (Do not fragment) flag
- Routers
  - Drops the packet if it is too large (as DF is set)
  - Provides feedback to Host with ICMP message telling the maximum supported size

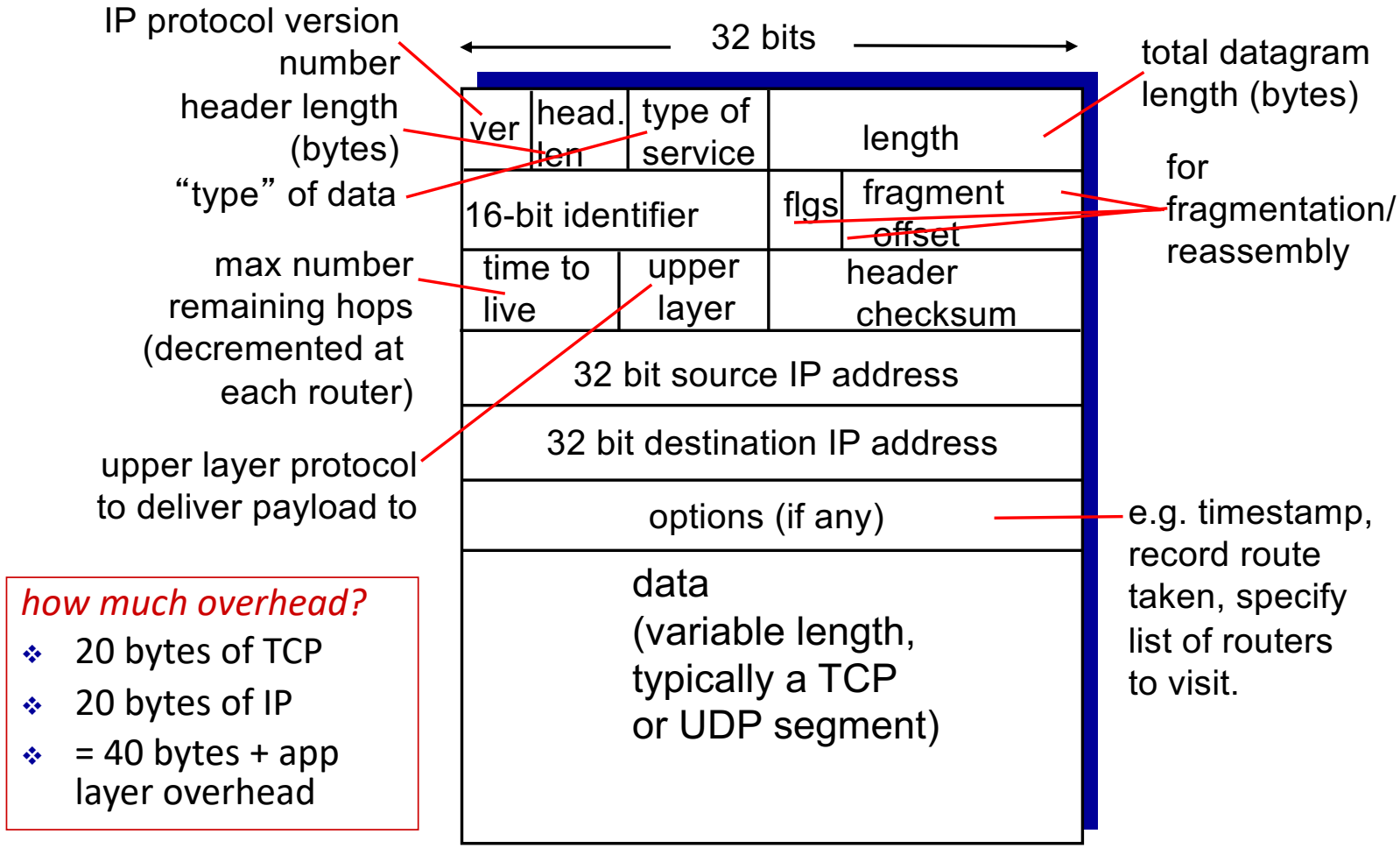
Fields for Special Handling



Special Handling

- “Type of Service”, or “Differentiated Services Code Point (DSCP)” (8 bits)
  - Allow packets to be treated differently based on needs
  - E.g., low delay for audio, high bandwidth for bulk transfer
  - Has been redefined several times
  - Not widely used
- Options (not often used)

RECAP: IP datagram format



how much overhead?

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

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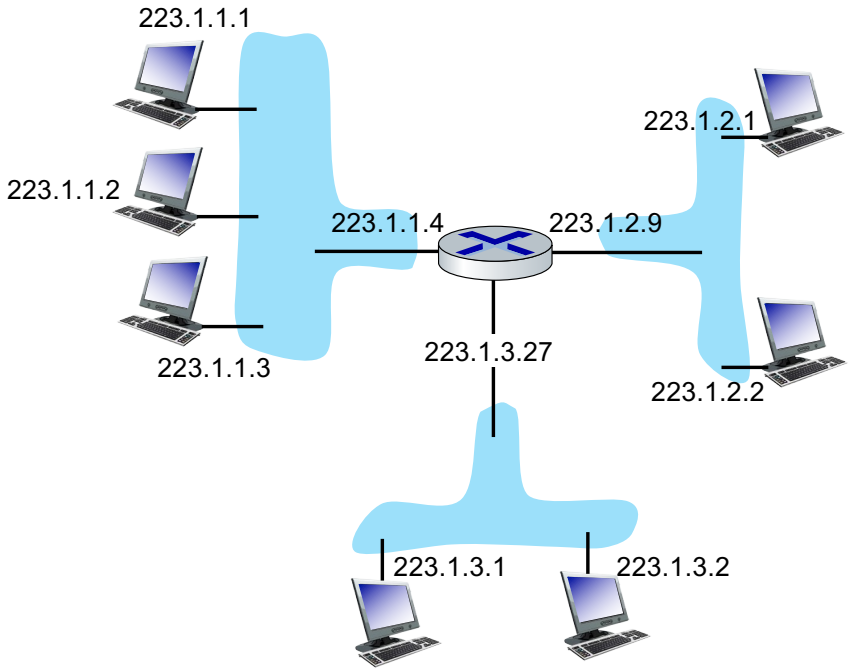
- IPv6

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

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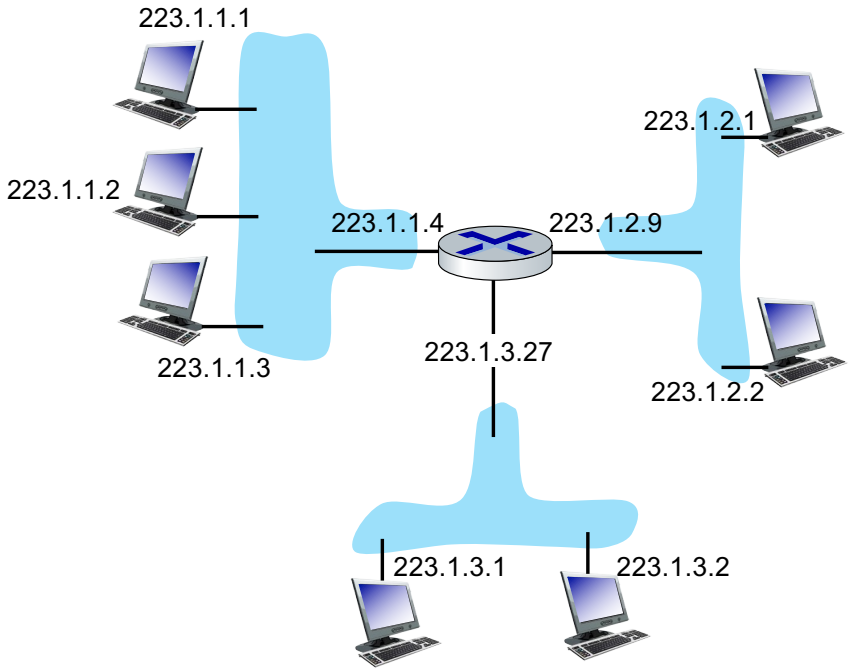


dotted-decimal IP address notation:

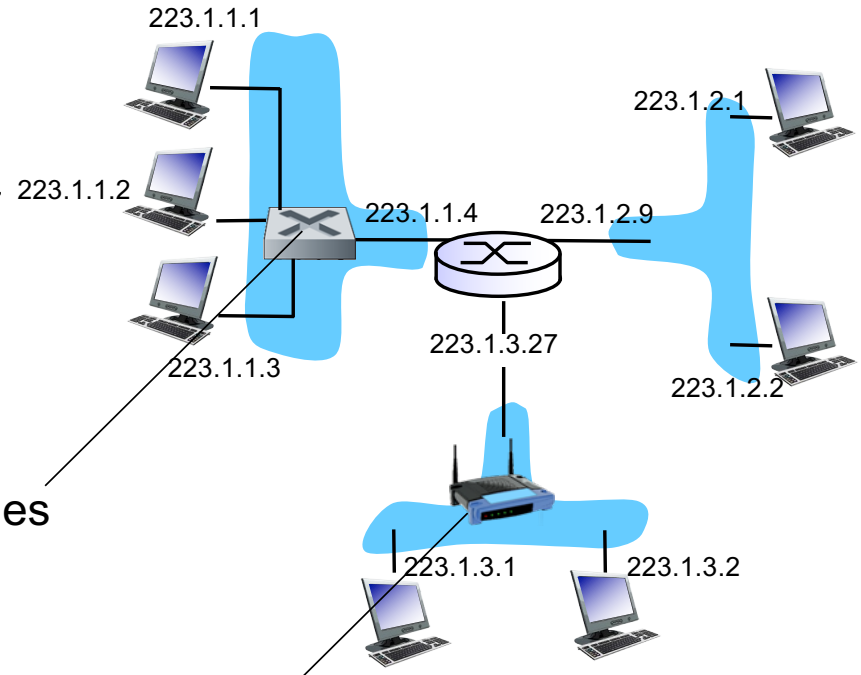
223.1.1.1 = 11011111 00000001 00000001 00000001

223 1 1 1

IP addressing: introduction

Q: how are interfaces actually connected?

A: we'll learn about that in the link layer

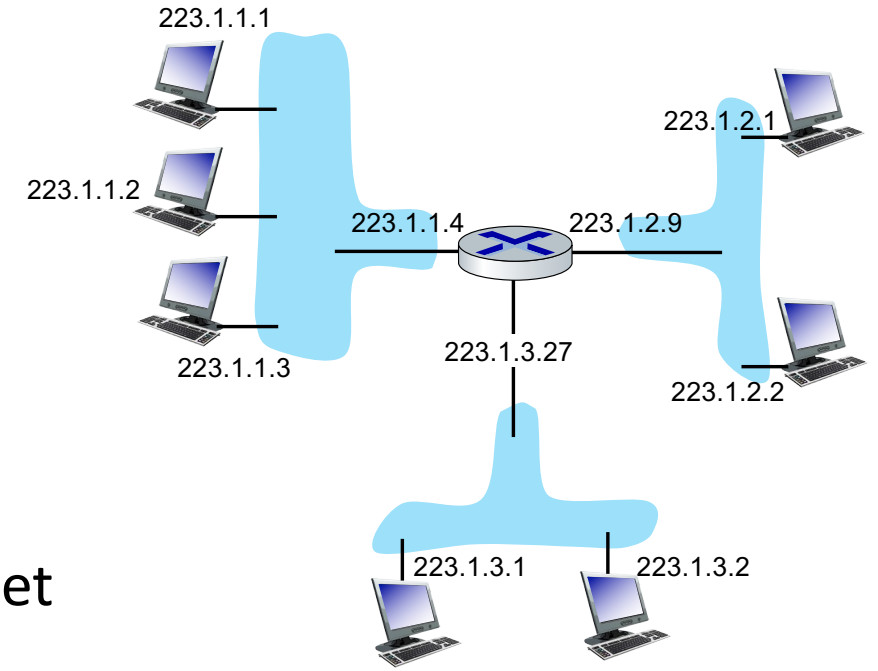


A: wired Ethernet interfaces connected by Ethernet switches

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

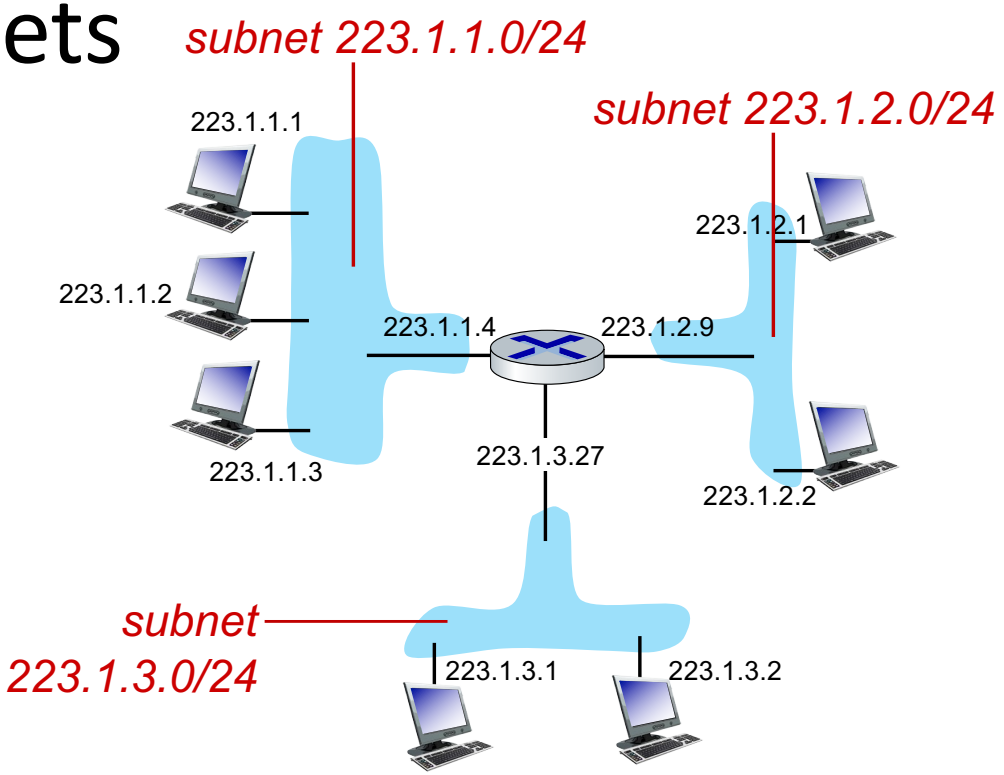


network consisting of 3 subnets

Subnets

Recipe for defining subnets:

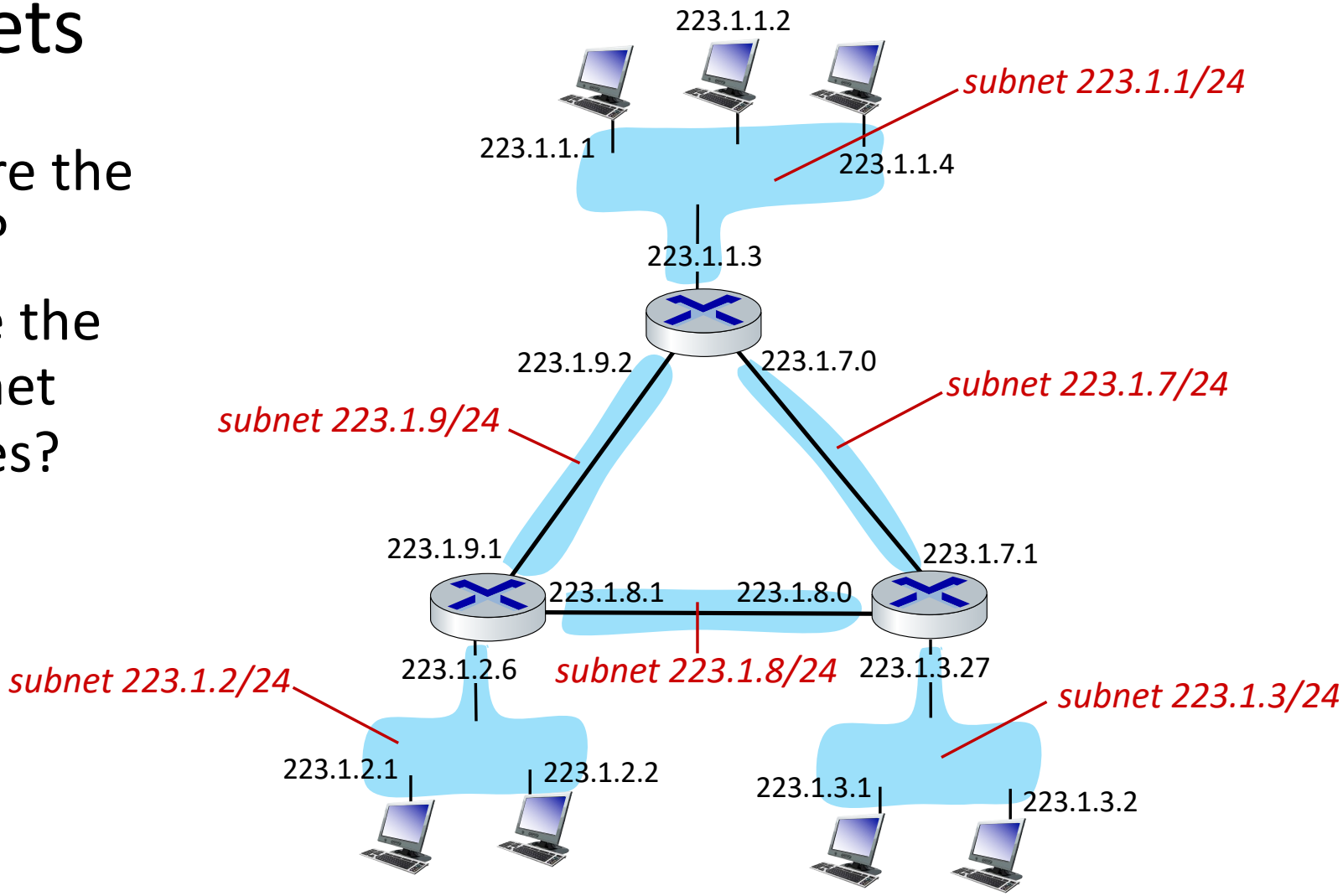
- detach each interface from its host or router, creating "islands" of isolated networks
- each isolated network is called a *subnet*



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

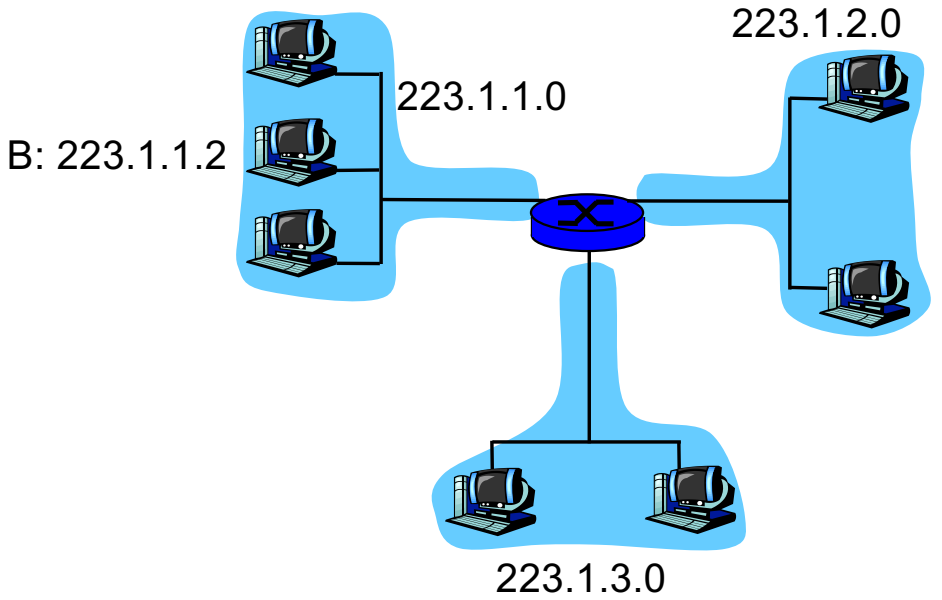
Subnets

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



Network Mask

- Mask
  - Used in conjunction with the network address to indicate how many higher order bits are used for the network part of the address
    - Bit-wise AND
  - 223.1.1.0 with mask 255.255.255.0
- Broadcast Address
  - host part is all 111's
  - E.g., 223.1.1.255
- Network Address
  - Host part is all 0000's
  - E.g., 223.1.1.0
- Both are typically not assigned to any host



Host B	Dot-decimal address	Binary
IP address	223.1.1.2	11011111.00000001.00000001.00000010
Mask	255.255.255.0	11111111.11111111.11111111.00000000
Network Part	223.1.1.0	11011111.00000001.00000001.00000000
Host Part	0.0.0.2	00000000.00000000.00000000.00000010

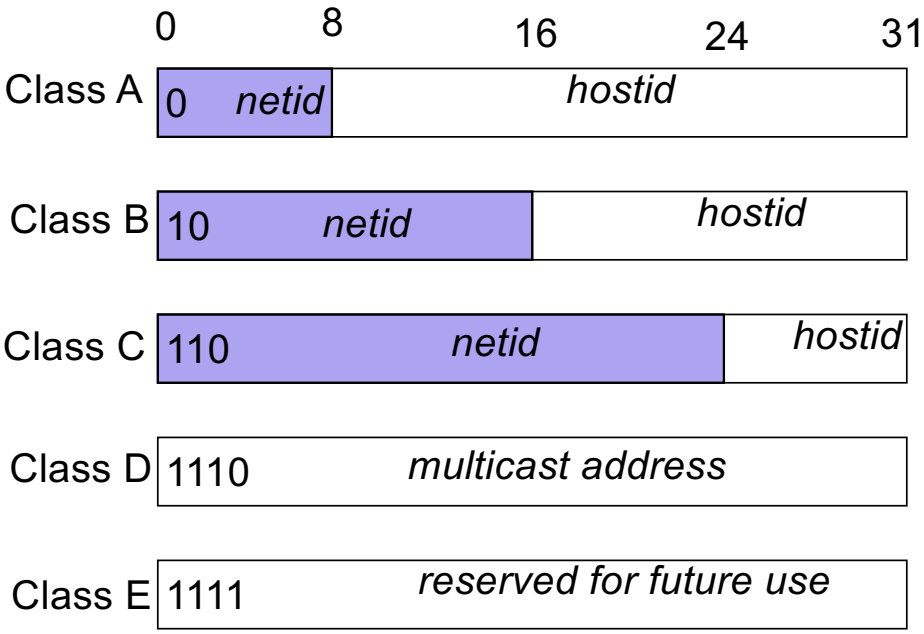
Original Internet Addresses

- First eight bits: network address (/8)
- Last 24 bits: host address, ~16.7 million

Assumed 256 networks were more than enough!

Next design: Class-ful Addresses

Used till the introduction of CIDR 1993



2^7 nets, 2^{24}hosts

1.0.0.0 to 127.255.255.255

2^{14} nets, 2^{16} hosts

128.0.0.0 to 191.255.255.255

2^{21} nets, 2^8 hosts

192.0.0.0 to 223.255.255.255

224.0.0.0 to 239.255.255.255

240.0.0.0 to 255.255.255.255

Problem: Networks only come in three sizes!

What are the issues?

- An organization requires 6 nets each of size 30. Does it have to buy 6 class C address blocks?

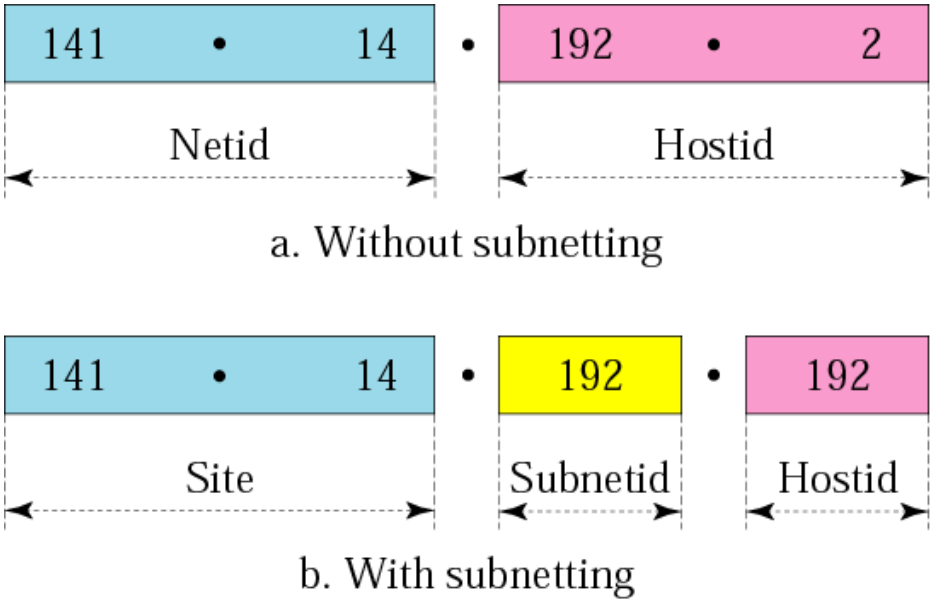
- An organization requires 512 addresses? How many IP addresses should it buy?

Subnetting

- Subnetting is the process of dividing the class A, B or C network into more manageable chunks that are suited to your network's size and structure.
- Subnetting allows 3 levels of hierarchy
  - netid, subnetid, hostid
- Original netid remains the same and designates the site
- Subnetting remains transparent outside the site

Subnetting

- The process of subnetting simply extends the point where the 1's of Mask stop and 0's start
- You are sacrificing some host ID bits to gain Network ID bits



Class B Network

Quiz?

A company is granted the site address 201.70.64.0 (class C). The company needs six subnets. Design the subnets.

The company needs six subnets. 6 is not a power of 2. The next number that is a power of 2 is 8 (2^3). We need 3 more 1s in the subnet mask. The total number of 1s in the subnet mask is 27 (24 + 3). The mask is

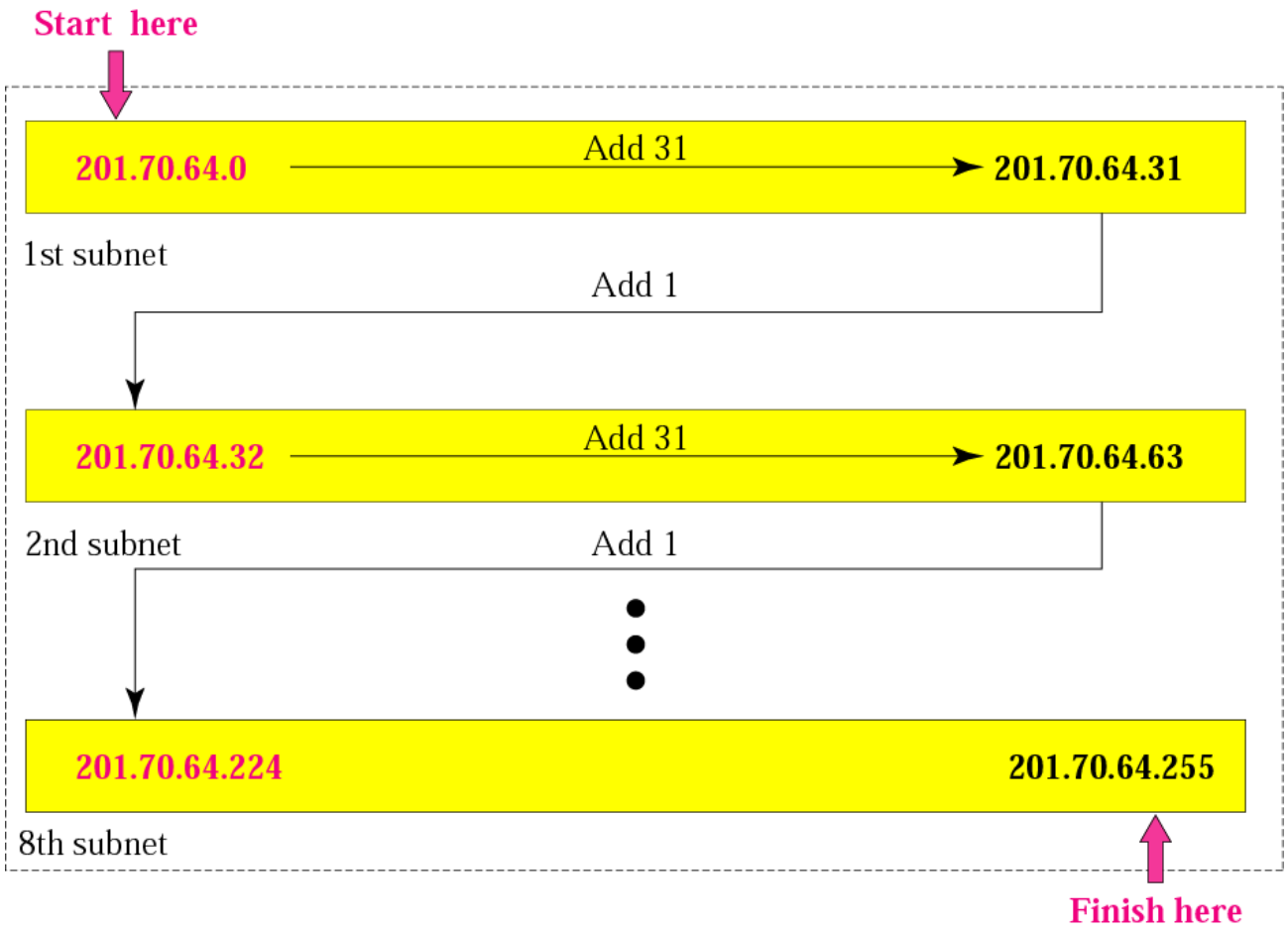
11111111 11111111 11111111 11100000

or 255.255.255.224

Number of addresses in each subnet = 2^5

= 32

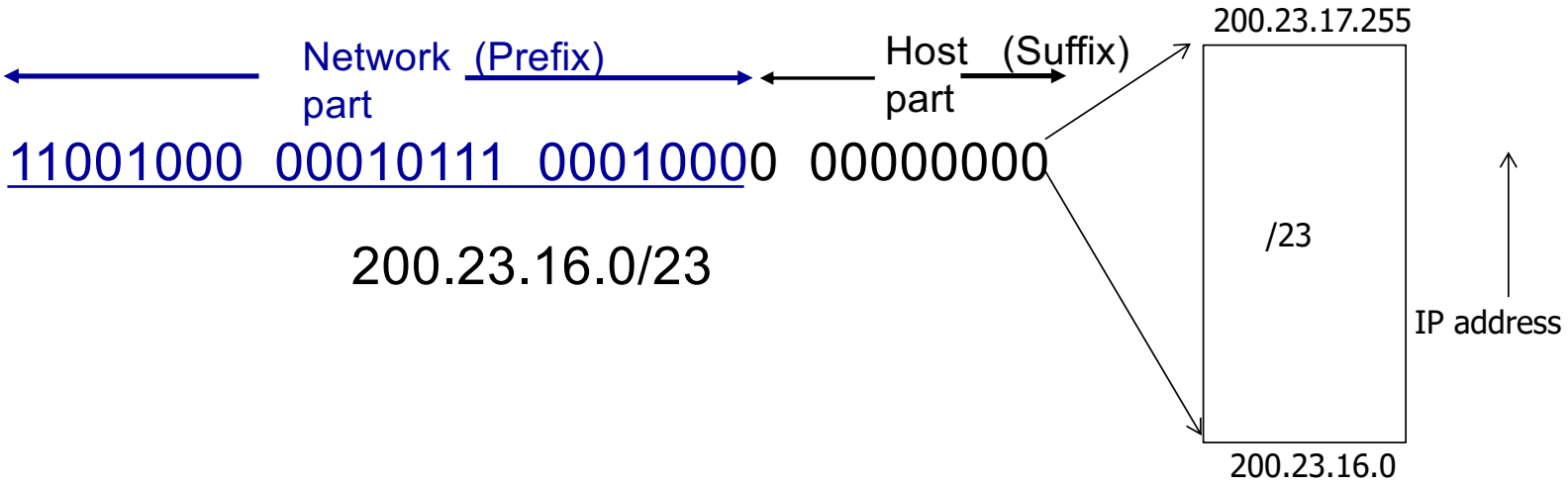
The number of addresses in each subnet is 2^5 or 32.



Today's addressing: CIDR

CIDR: Classless InterDomain Routing

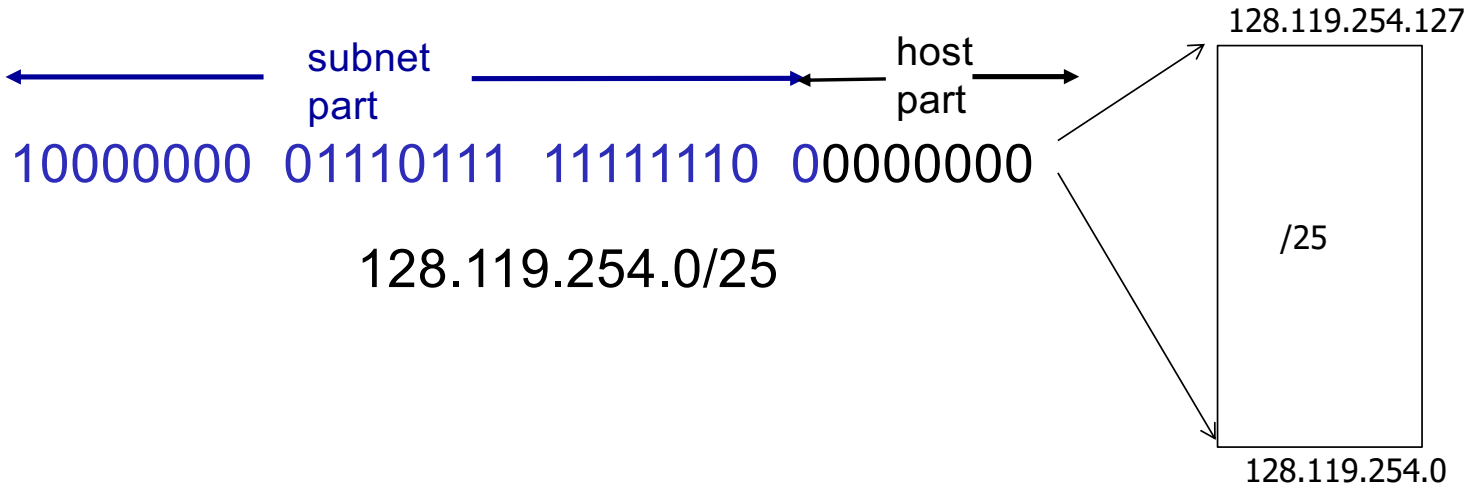
- network portion of address of arbitrary length
- address format: a.b.c.d/x, where x is # bits in network portion of address



Quiz: IP Addressing

- How many IP addresses belong to the subnet 128.119.254.0/25 ? What are the IP addresses at the two end-points of this range ?

Answer: 2^7 = 128 addresses (126 are usable)



Quiz: IP Addressing

How many IP addresses belong to the subnet 134.45.22.0/23?

www.pollev.com/salil

A) 32

B) 64

C) 128

D) 256

E) 512

Answer: E (2^9 = 512)

Quiz: IP Addressing

An ISP is granted a block of addresses starting with 190.100.0.0/16 (Class B). The ISP needs to distribute these addresses to three groups of customers as follows:

1. The first group has 64 customers; each needs 256 addresses.
2. The second group has 128 customers; each needs 128 addresses.
3. The third group has 128 customers; each needs 64 addresses.

Design the sub-blocks and give the slash notation for each sub-block. Find out how many addresses are still available after these allocations.

Group 1

For this group, each customer needs 256 addresses. This means the suffix length is 8 ($2^8 = 256$). The prefix length is then $32 - 8 = 24$.

01: 190.100.0.0/24 ➔ 190.100.0.255/24

02: 190.100.1.0/24 ➔ 190.100.1.255/24

……

64: 190.100.63.0/24 ➔ 190.100.63.255/24

Total = $64 \times 256 = 16{,}384$

Group 2

For this group, each customer needs 128 addresses. This means the suffix length is 7 ($2^7 = 128$). The prefix length is then $32 - 7 = 25$. The addresses are:

001: 190.100.64.0/25 ➔ 190.100.64.127/25

002: 190.100.64.128/25 ➔ 190.100.64.255/25

.....

128: 190.100.127.128/25 ➔ 190.100.127.255/25

Total = $128 \times 128 = 16{,}384$

Group 3

For this group, each customer needs 64 addresses. This means the suffix length is 6 ($2^6 = 64$). The prefix length is then 32 – 6 = 26.

001:190.100.128.0/26 ➔ 190.100.128.63/26

002:190.100.128.64/26 ➔ 190.100.128.127/26

……

128:190.100.159.192/26 ➔ 190.100.159.255/26

Total = 128 × 64 = 8,192

Number of granted addresses: $65,536$

Number of allocated addresses: $40,960$

Number of available addresses: $24,576$

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

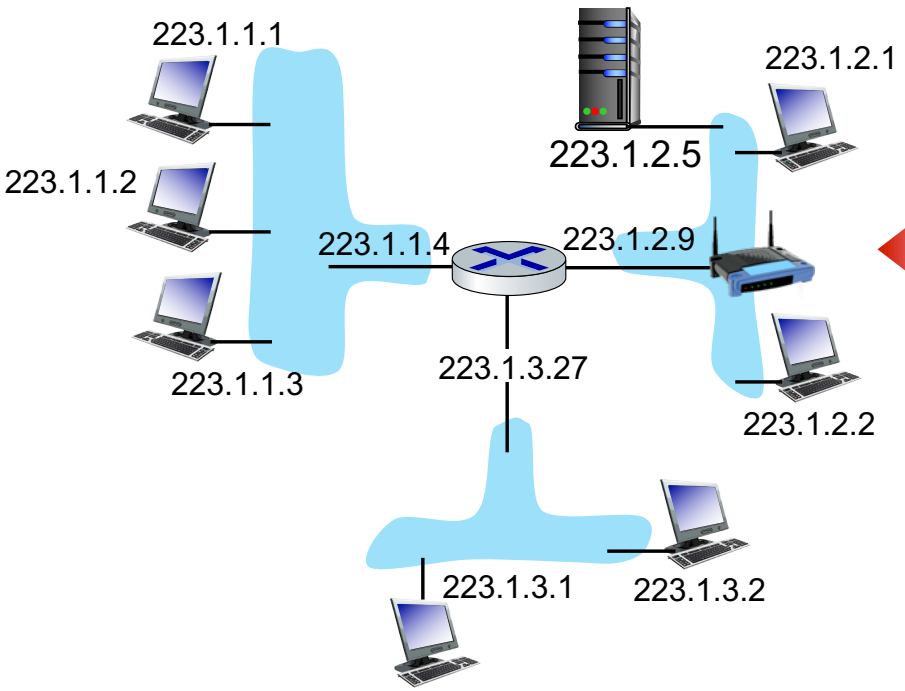
goal: host *dynamically* obtains IP address from network server when it "joins" network

- 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

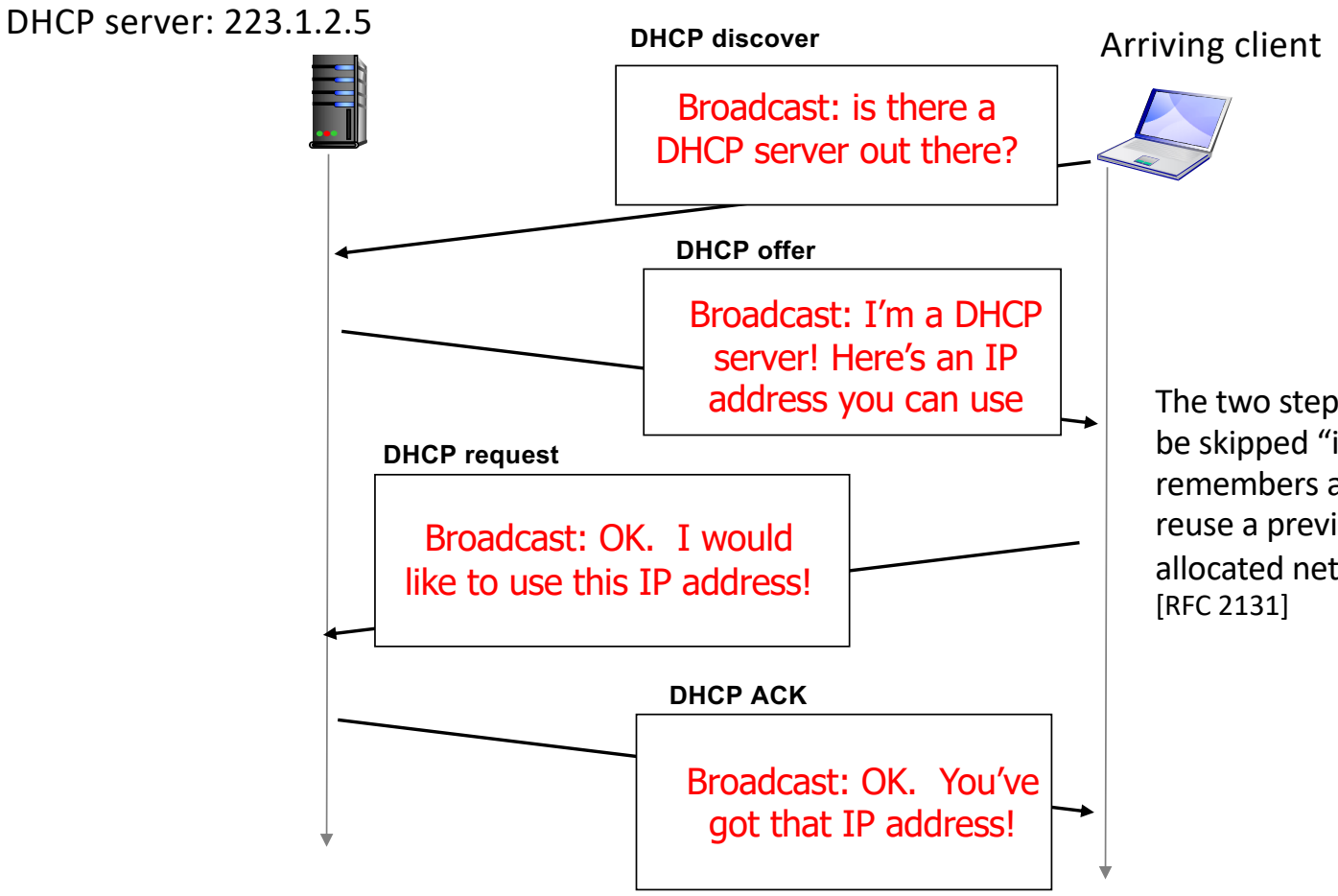
DHCP client-server scenario



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



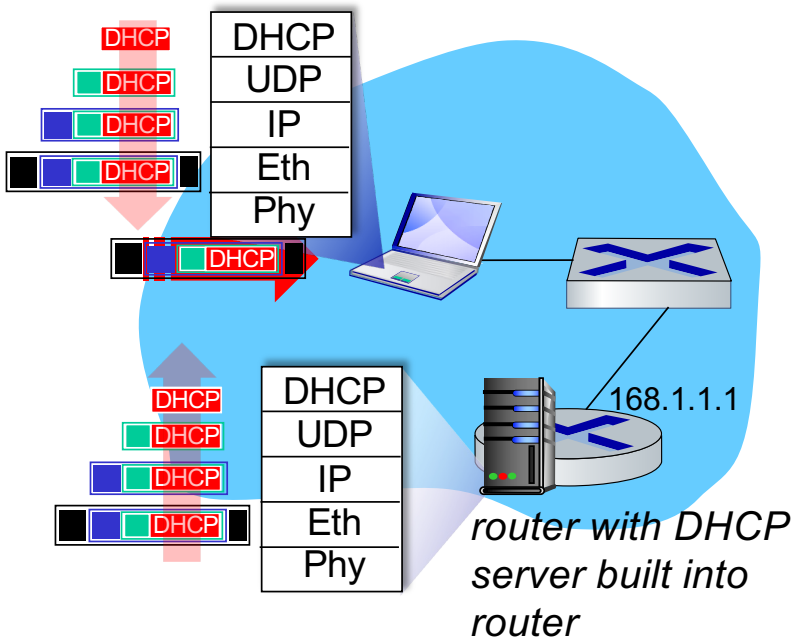
The two steps above can be skipped "if a client remembers and wishes to reuse a previously allocated network address" [RFC 2131]

DHCP: more than IP addresses

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

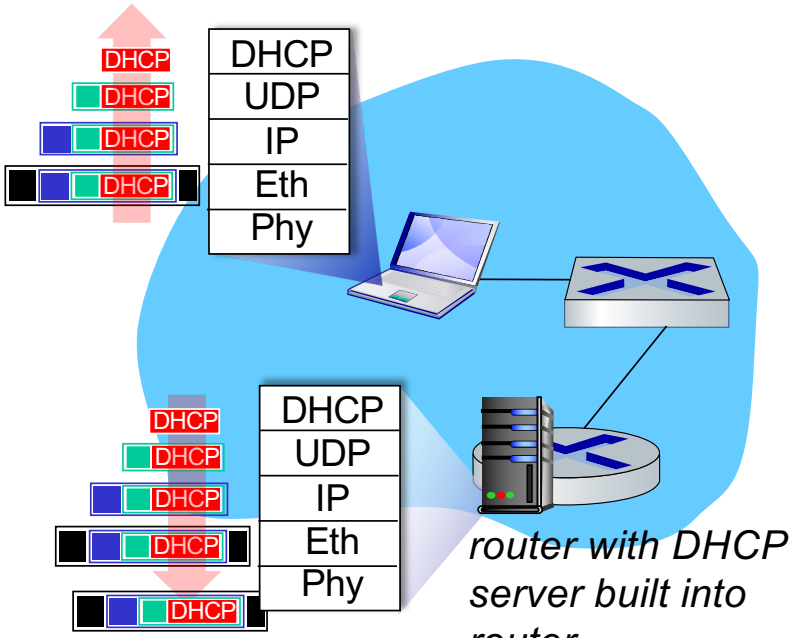
- address of first-hop router for client
- name and IP address of DNS sever
- network mask (indicating network versus host portion of address)

DHCP: 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

Note: Only last 2 steps of the 4-way message exchange are shown

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

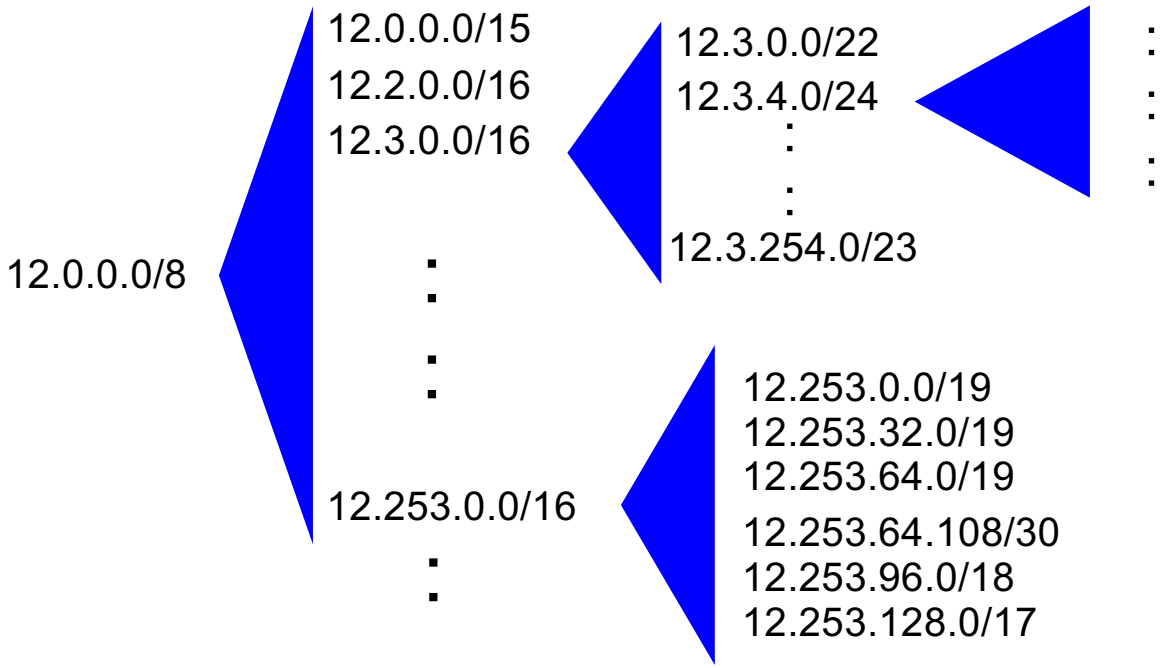
ISP's block	11001000 00010111 00010000 00000000	200.23.16.0/20

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

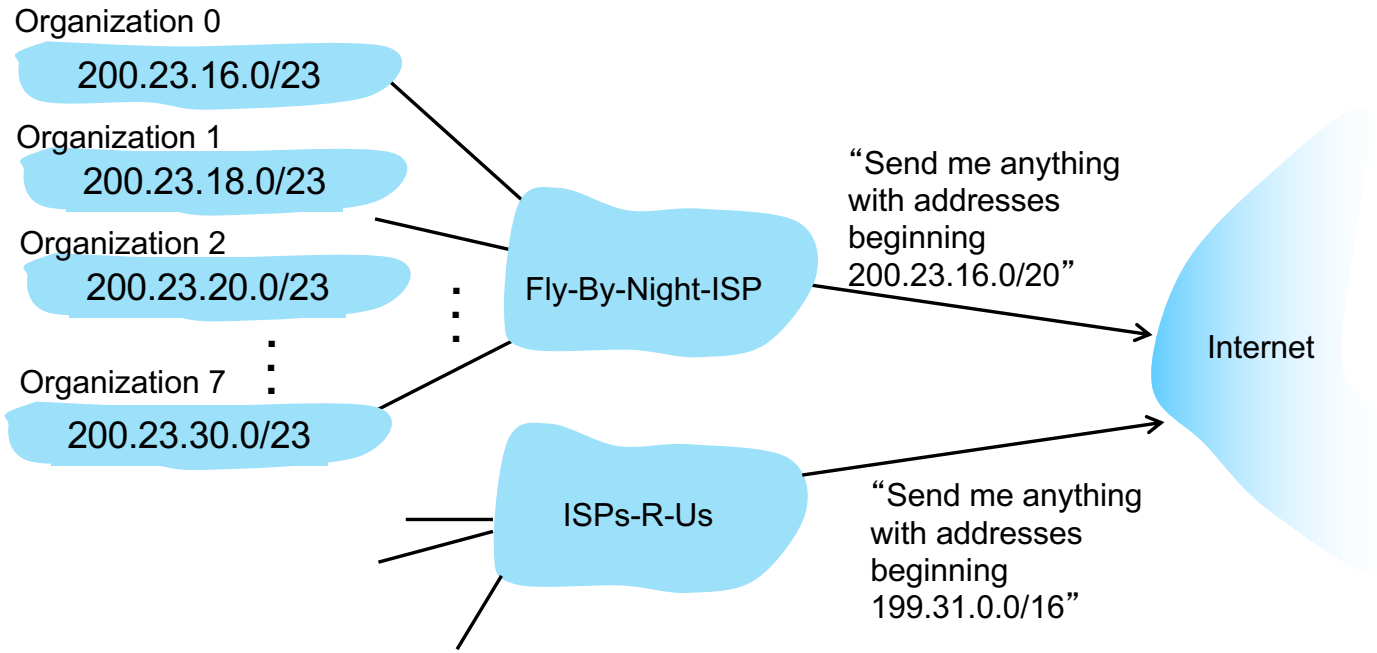
CIDR: Addresses allocated in contiguous prefix chunks

Recursively break down chunks as get closer to host



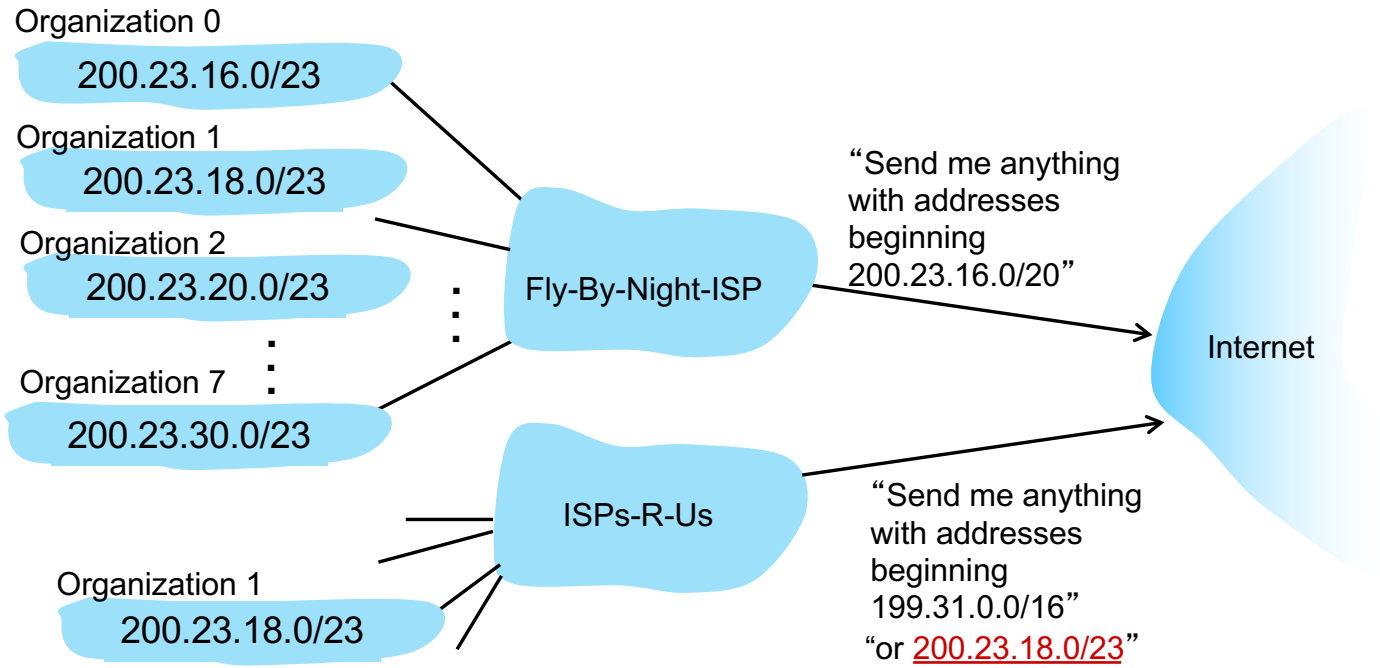
Hierarchical addressing: route aggregation

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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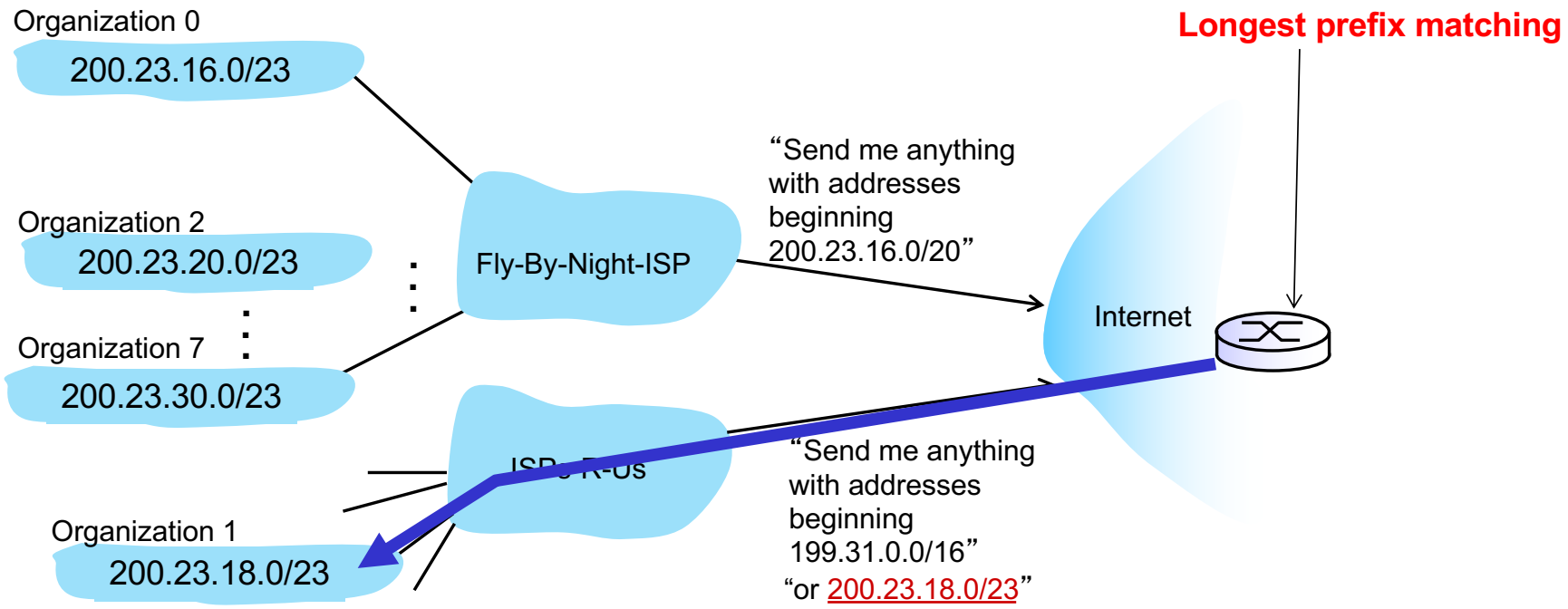
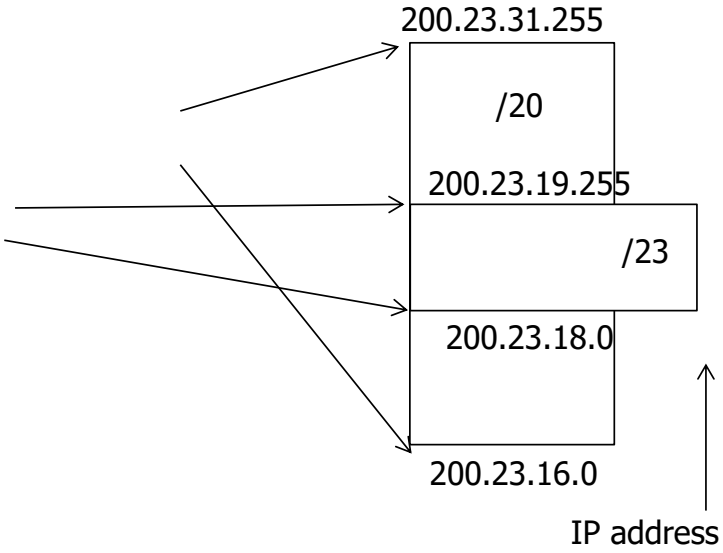


Example: continued

- But how will this work?
- Routers in the Internet will have two entries in their tables
  - 200.23.16.0/20 (Fly-by-Night-ISP)
  - 200.23.18.0/23 (ISPs-R-Us)
- Longest prefix match



Longest prefix matching

longest prefix matching

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:

DA: 11001000 00010111 00010110 10100001 which interface?

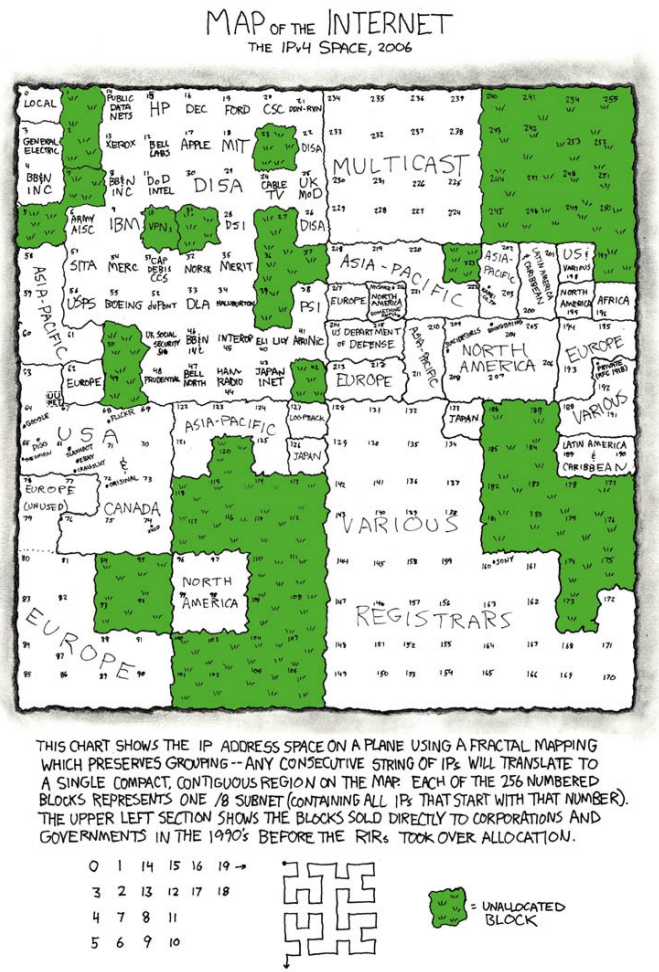
DA: 11001000 00010111 00011000 10101010 which interface?

More on IP addresses

- IP addresses are allocated as blocks and have geographical significance
- It is possible to determine the geographical location of an IP address

http://www.geobytes.com/IpLocator.htm

Source: www.xkcd.com



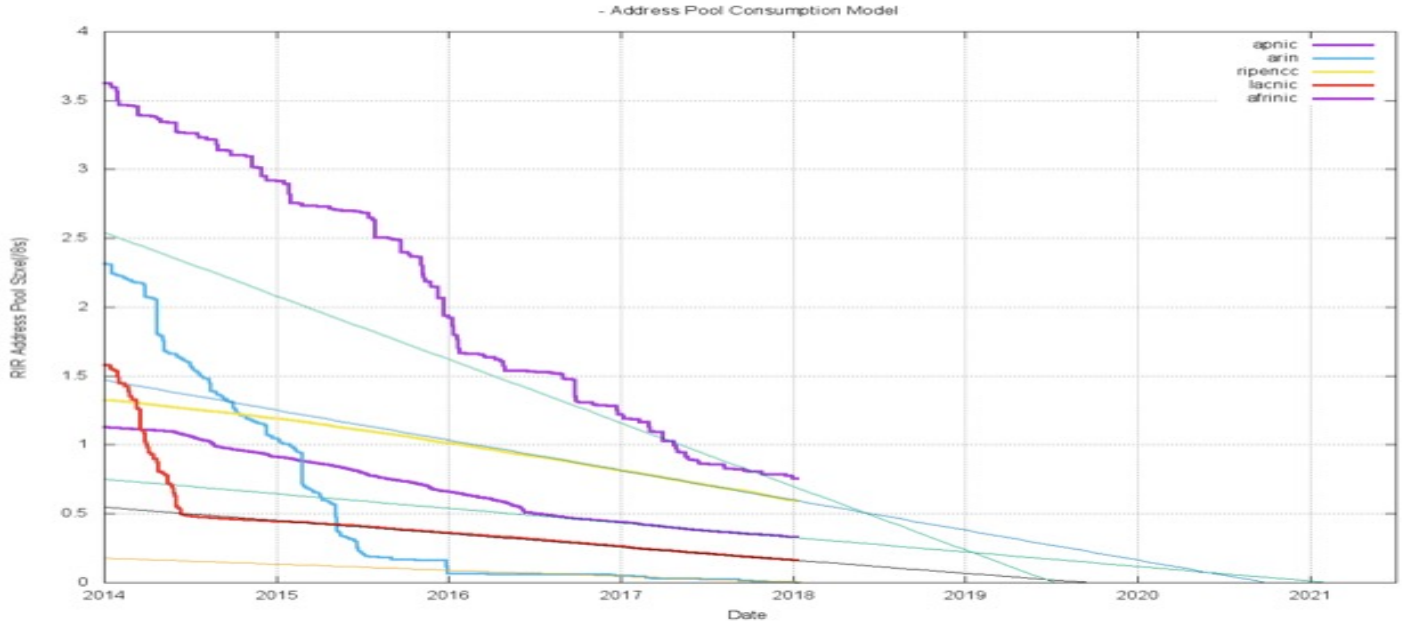
IP Addressing: the last word...

Q: How does an ISP get block of addresses?

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

IANA works through Regional Internet Registries (RIRs):

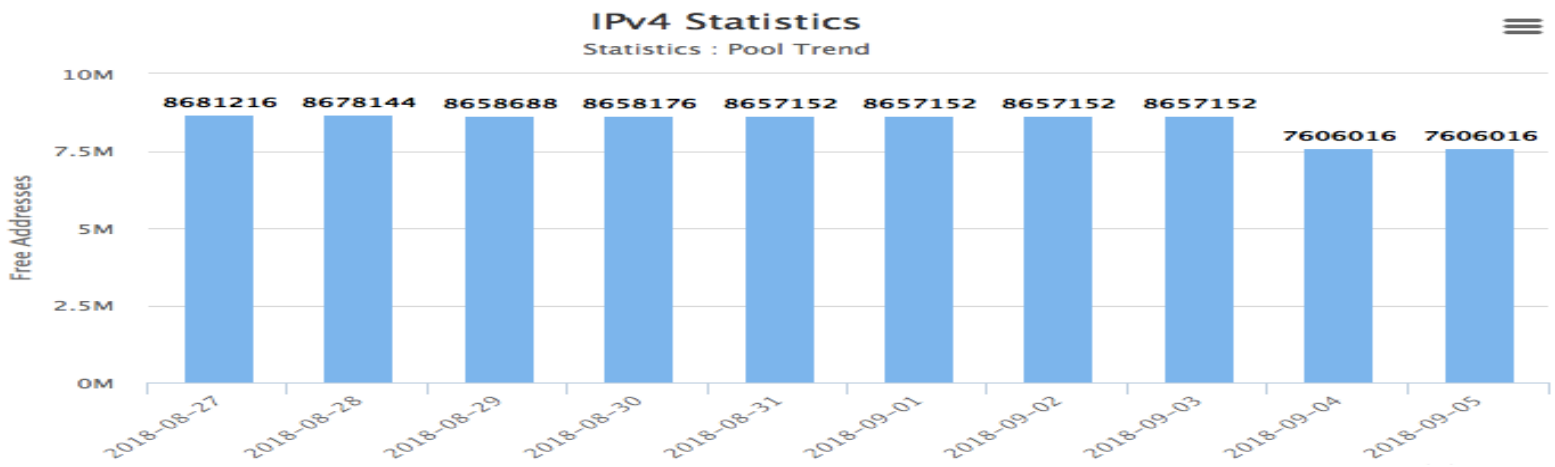
- ARIN — American Registry for Internet Numbers
- LACNIC — Latin America and Caribbean Network Information Centre
- RIPE NCC — IRéseaux IP Européens Network Coordination Centre
- APNIC — Asia-Pacific Network Information Center
- AfriNIC — African Network Information Centre



IPv4 Exhaustion

In this section you can find statistics for IPv4 pool in the AfriNIC region.

IPv4 Usage per IANA allocation | IPv4 available space over time | IPv4 availability by prefix size



Made-up Example

- ICANN gives APNIC several /8s
- APNIC gives Telstra one /8, **129/8**
  - Network Prefix**: 10000001**
- Telstra gives UNSW a /16, **129.94/16**
  - Network Prefix**: 1000000101011110**
- UNSW gives CSE a /24, **129.94.242/24**
  - Network Prefix**: 100000010101111011110010**
- CSE gives me a specific address **129.94.242.51**
  - Address: **10000001010111101111001000110011**