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**

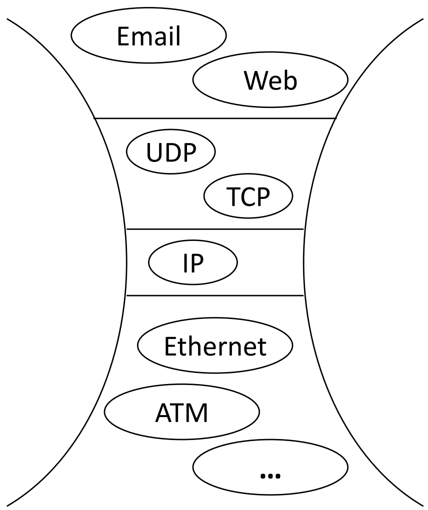
4.3 IP: Internet Protocol
- datagram format
- fragmentation
- IPv4 addressing
- network address translation
- IPv6

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?

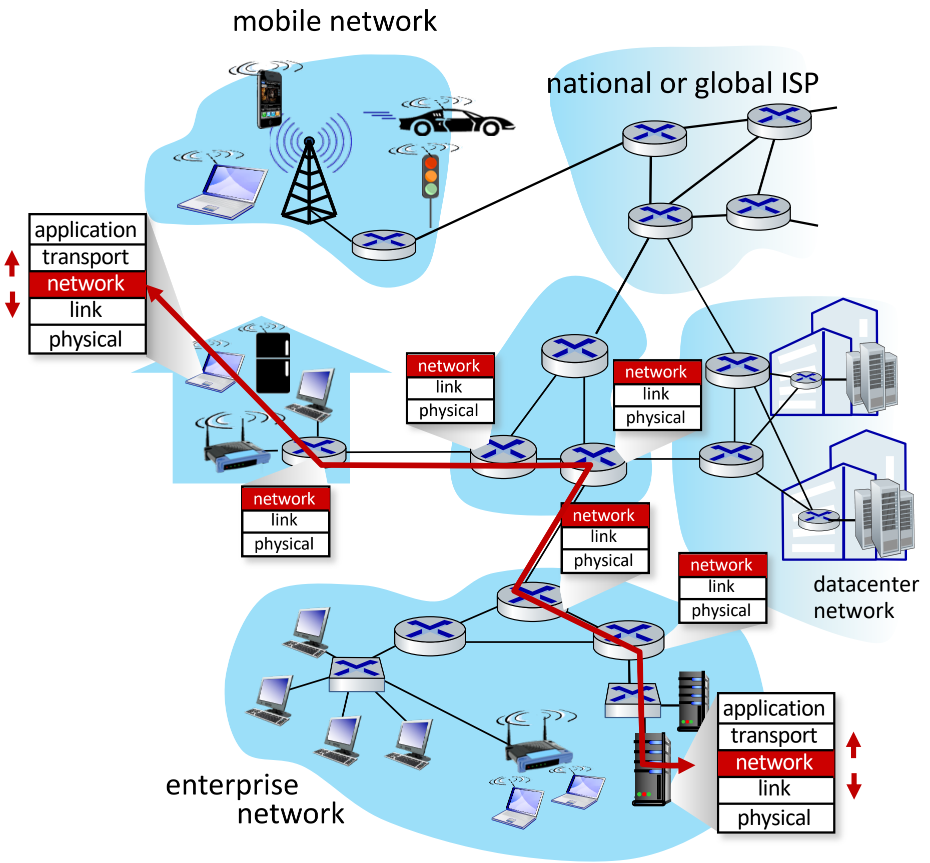
Internetworking



- 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*

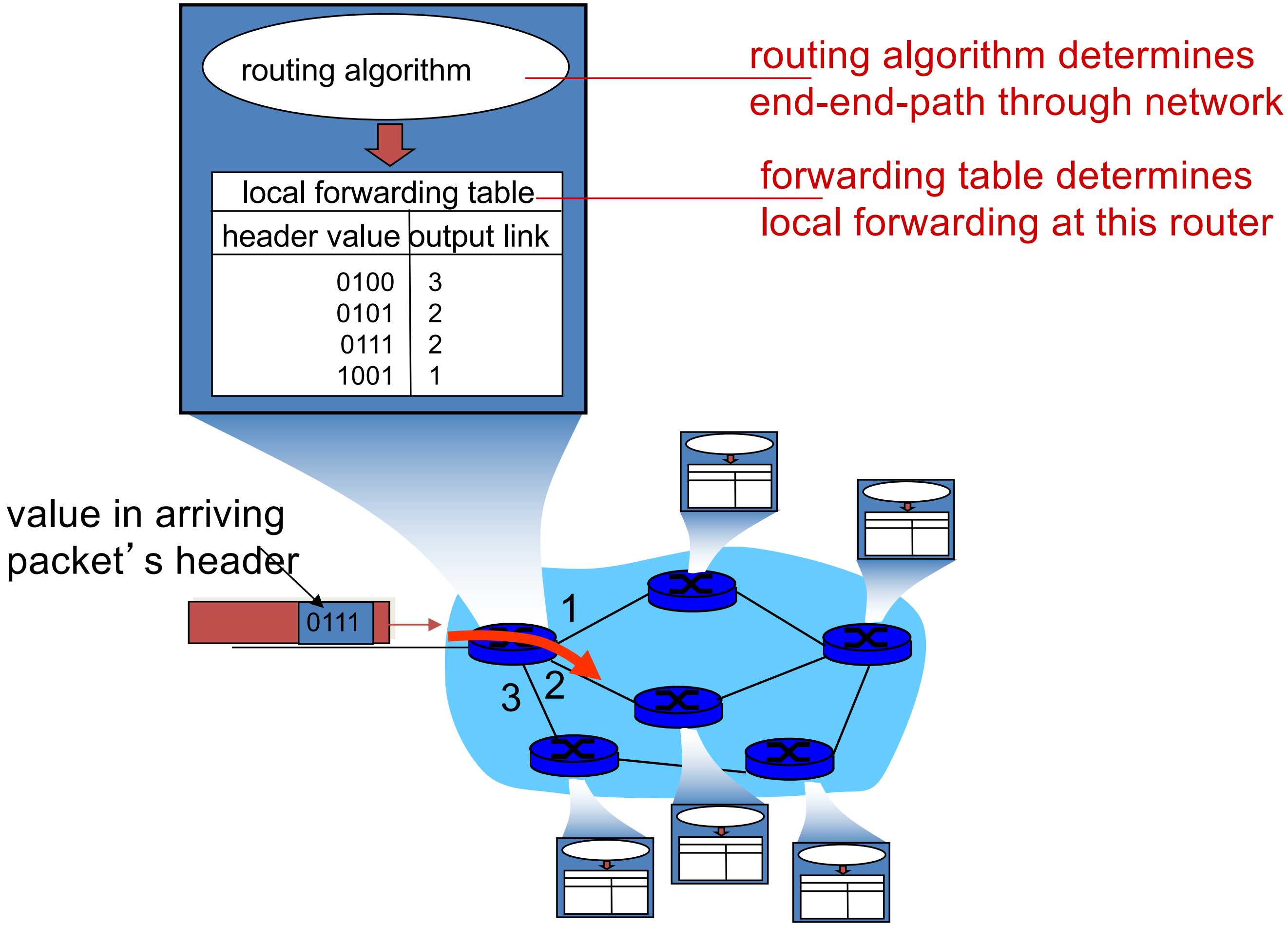
analogy: taking a trip

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

forwarding

routing

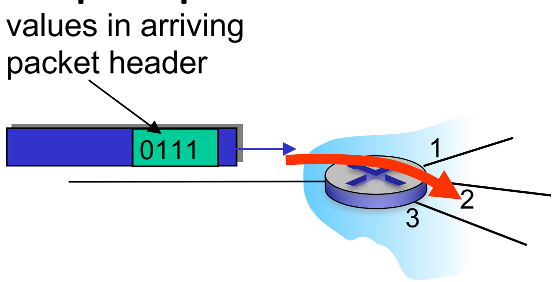
Interplay between routing and forwarding



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

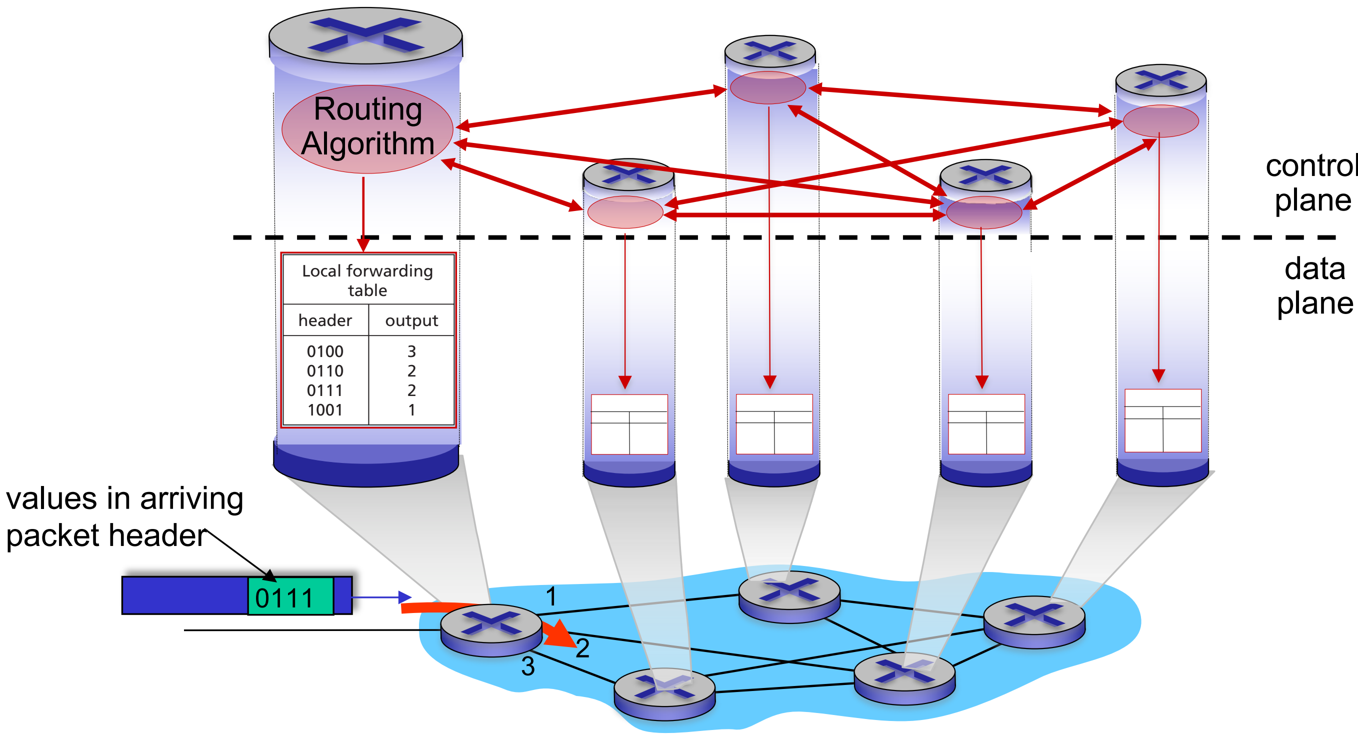


Control plane

- *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

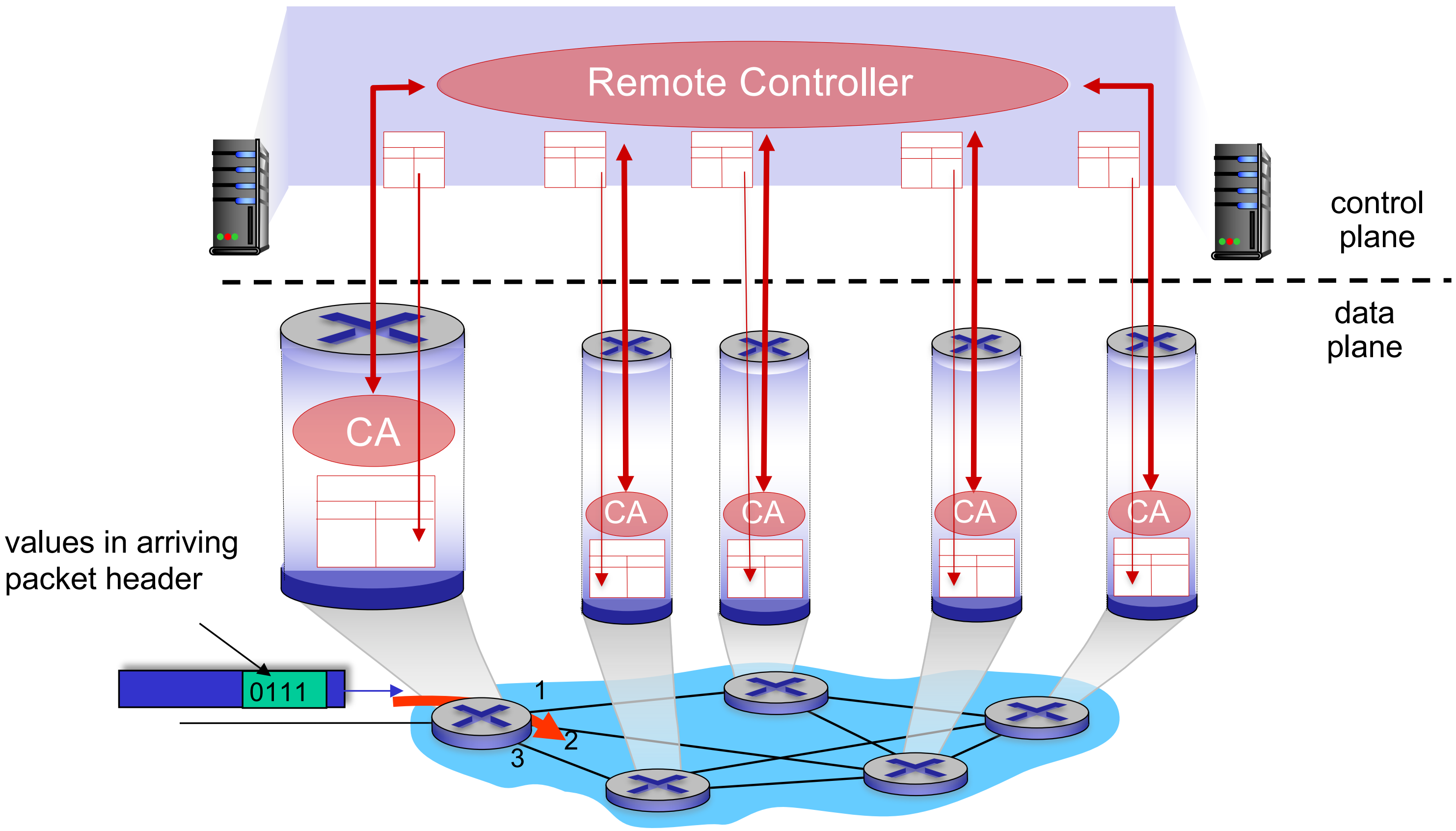
Per-router control plane

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



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

4.1 Overview of Network layer
- data plane
- control plane

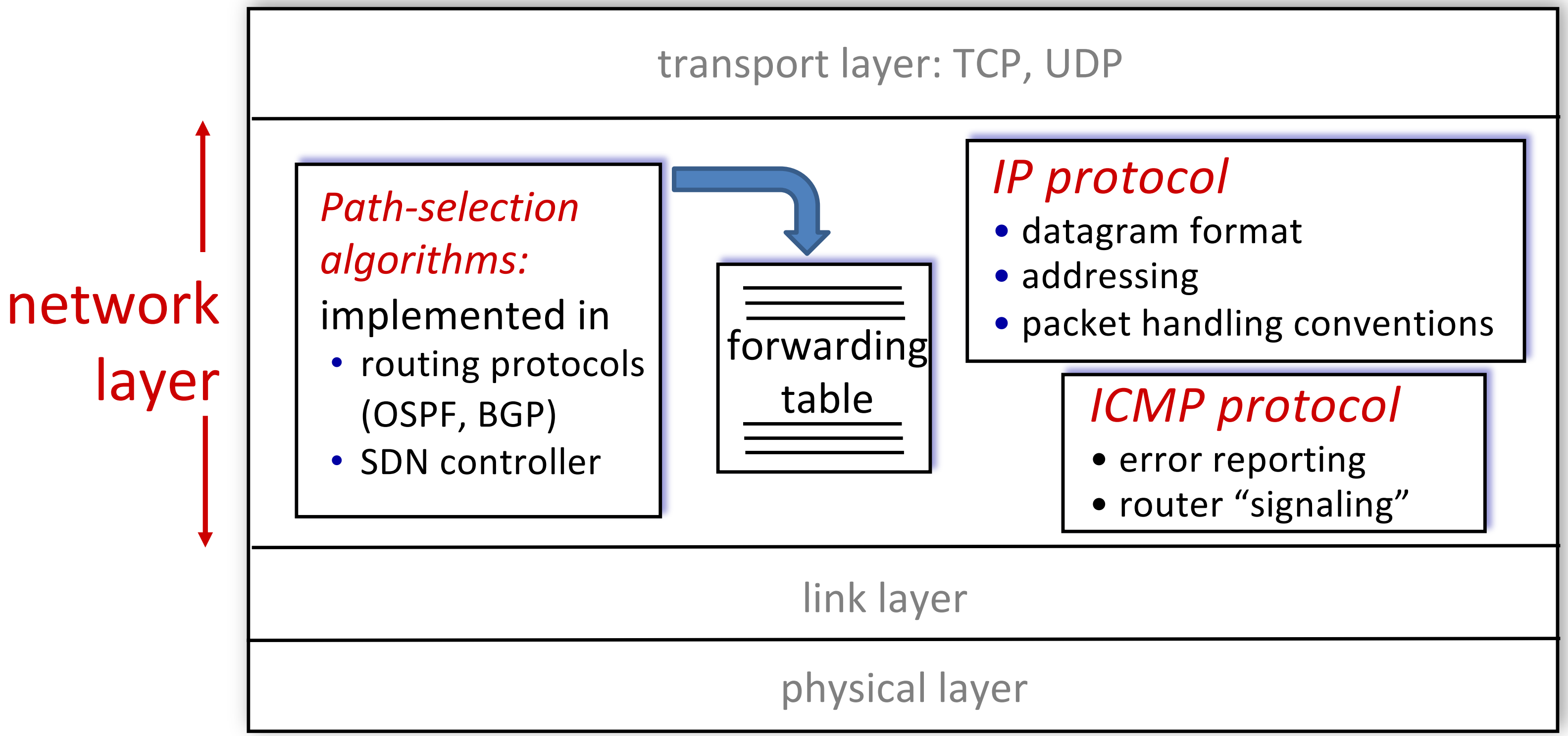
4.2 What's inside a router
-- **Not Covered**

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

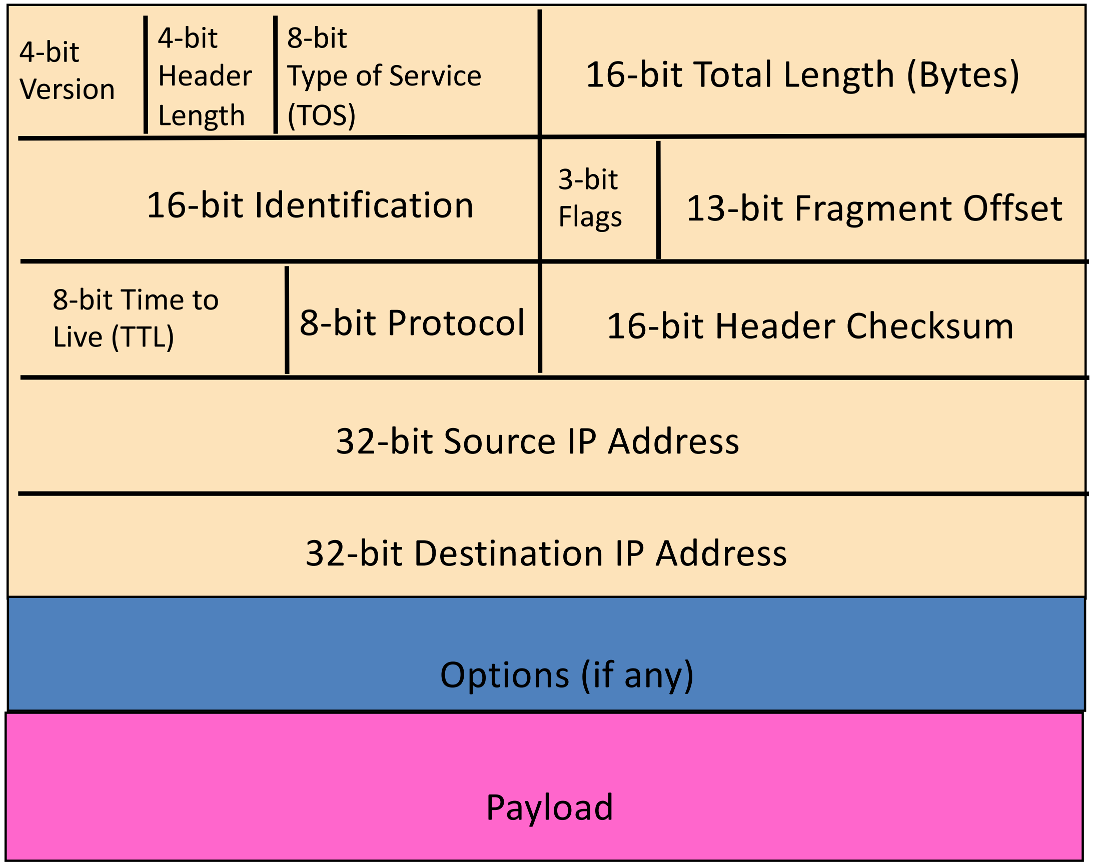
4.4 Generalized forwarding and Software Defined Networking (SDN)
- **Not Covered**

Network Layer: Internet

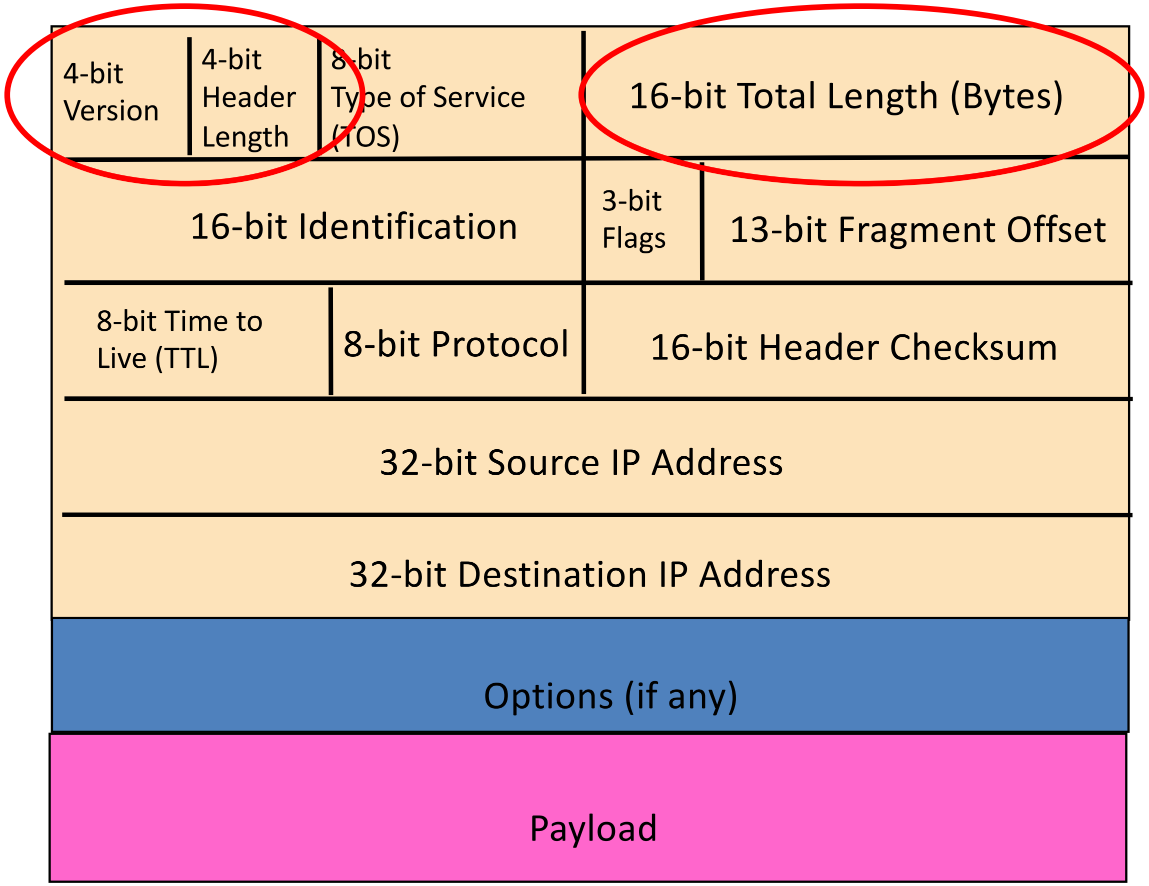
host, router network layer functions:



IP Datagram Format



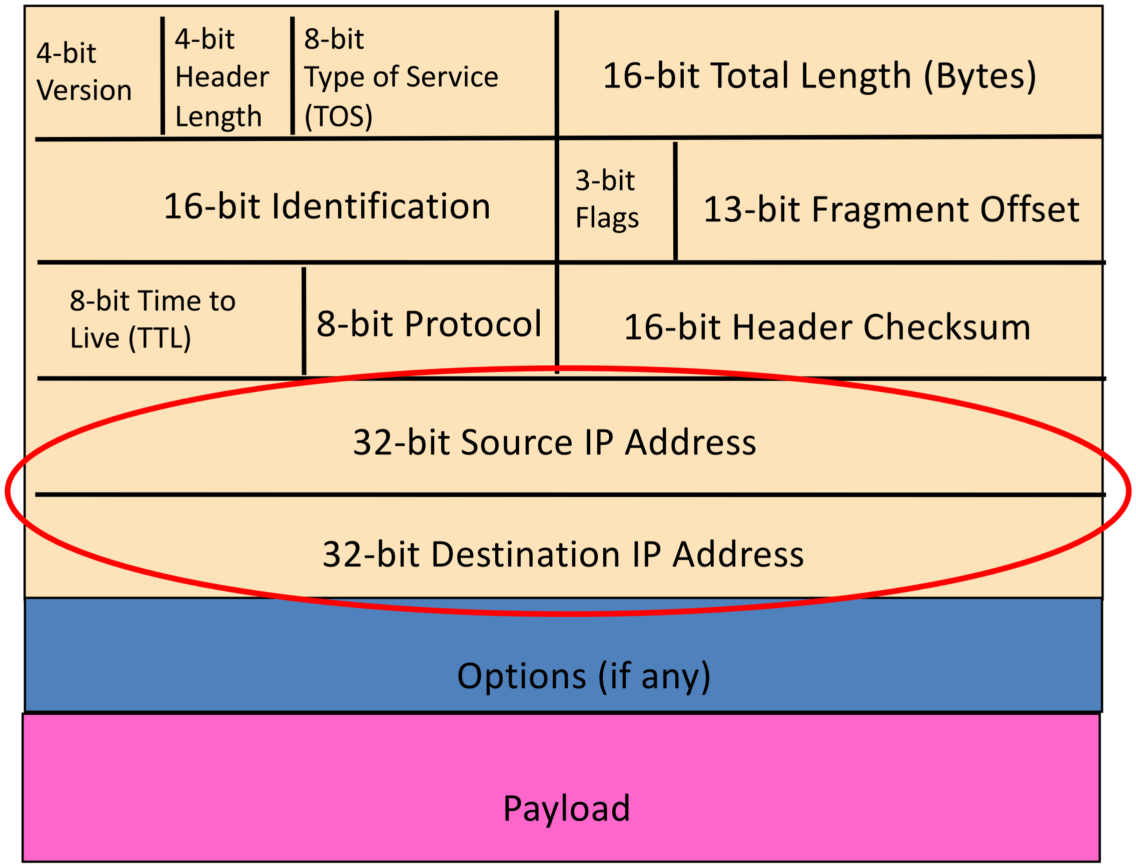
Fields for Reading Packet Correctly



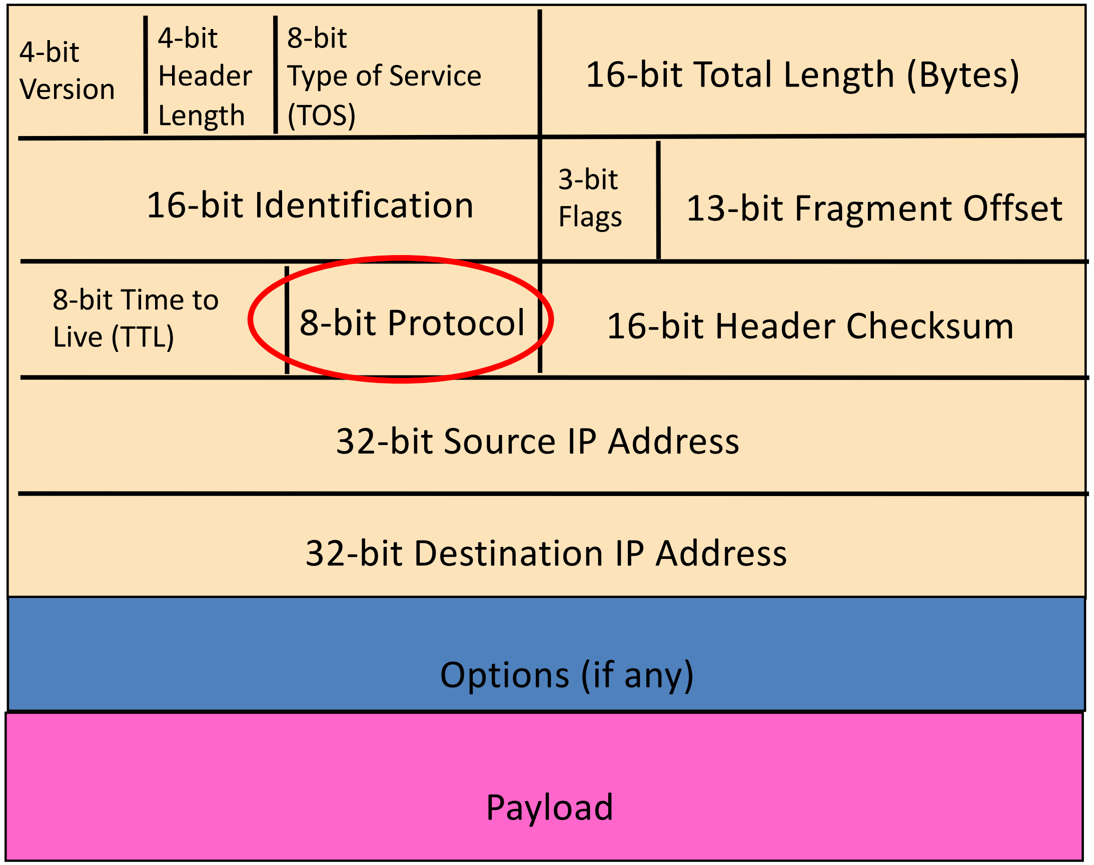
Reading Packet Correctly

- 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

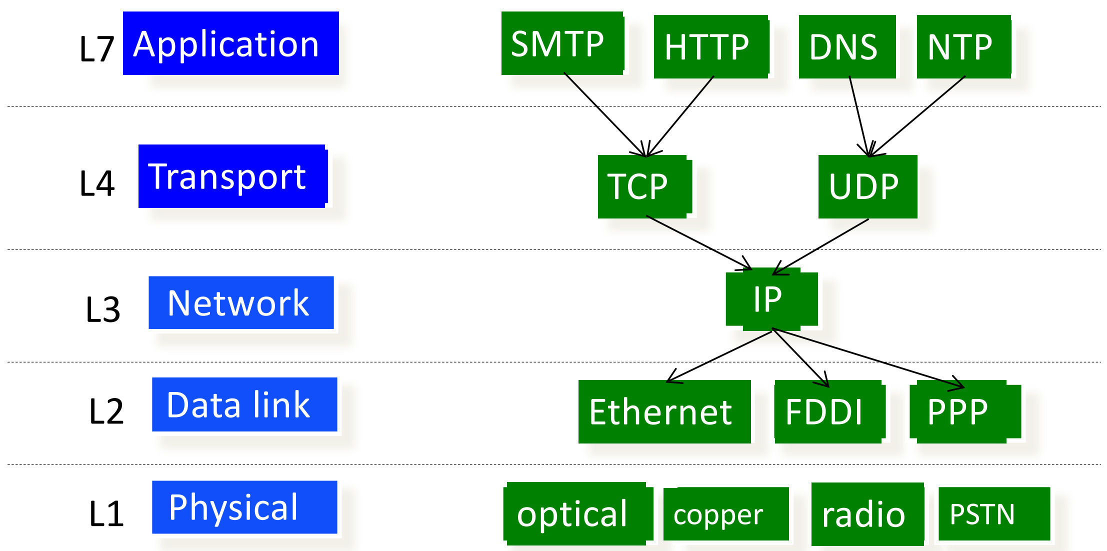


Telling End-Host How to Handle Packet

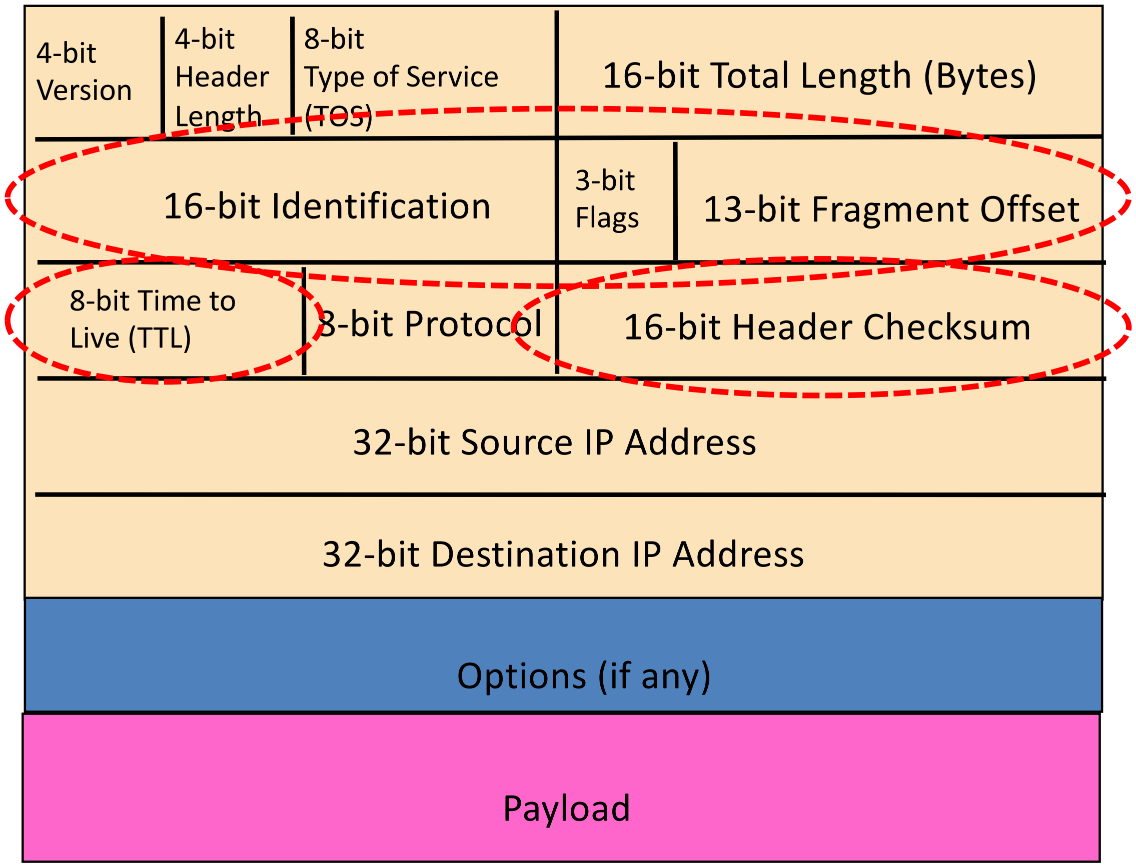


Telling End-Host How to Handle Packet

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



Checksum, TTL and Fragmentation Fields

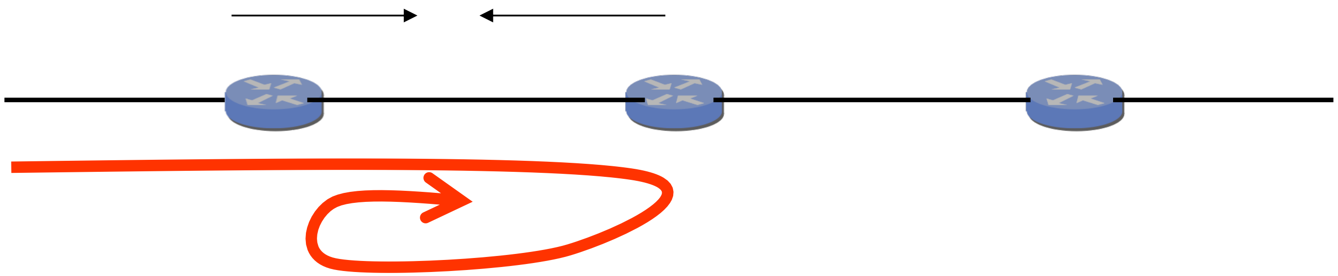


Potential Problems

- 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



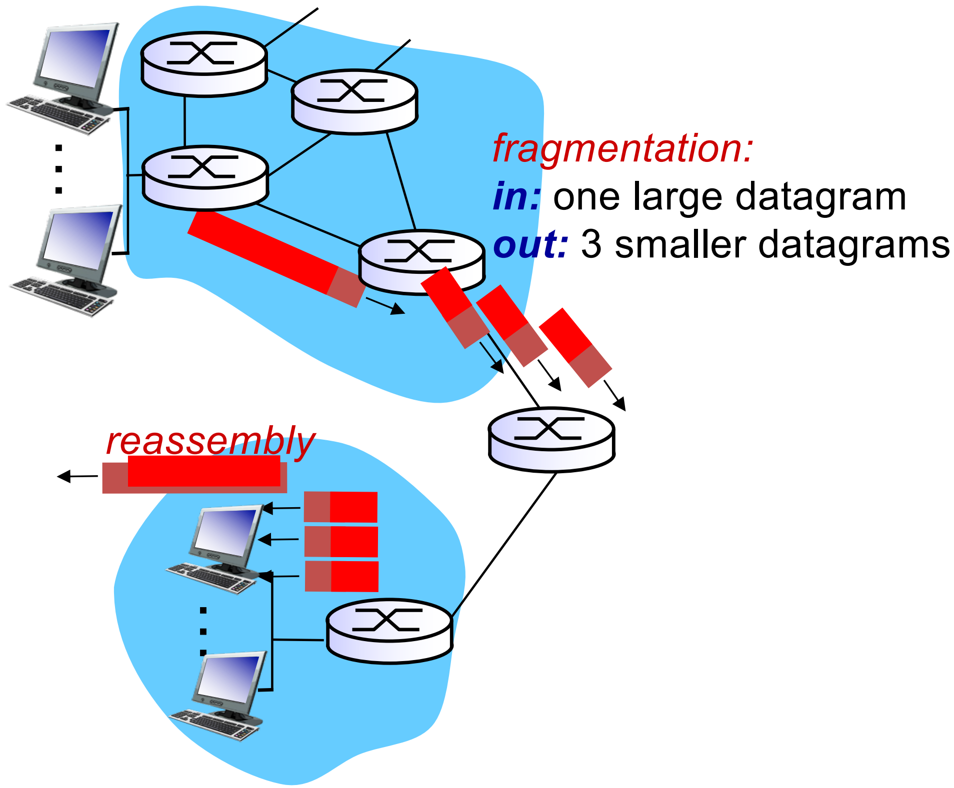
- Time-to-Live (TTL) Field (8 bits)
  - Decremented at each hop, packet discarded if reaches 0
  - …and “time exceeded” message is sent to the source
  - Recommended default value is 64

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

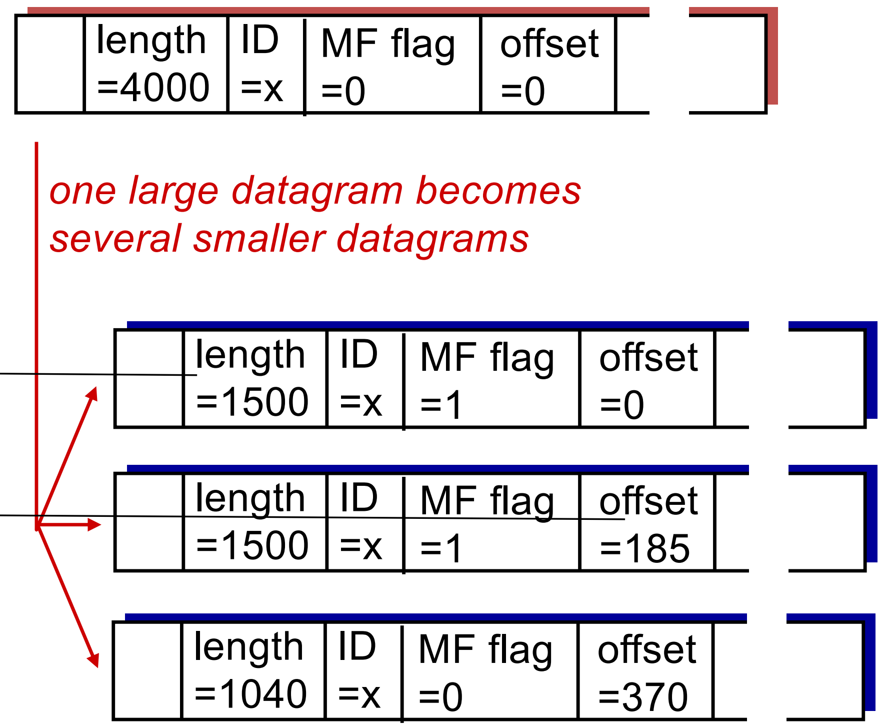
example:

- 4000-byte datagram
- MTU = 1500 bytes

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

1480 bytes in data field

offset = 1480/8

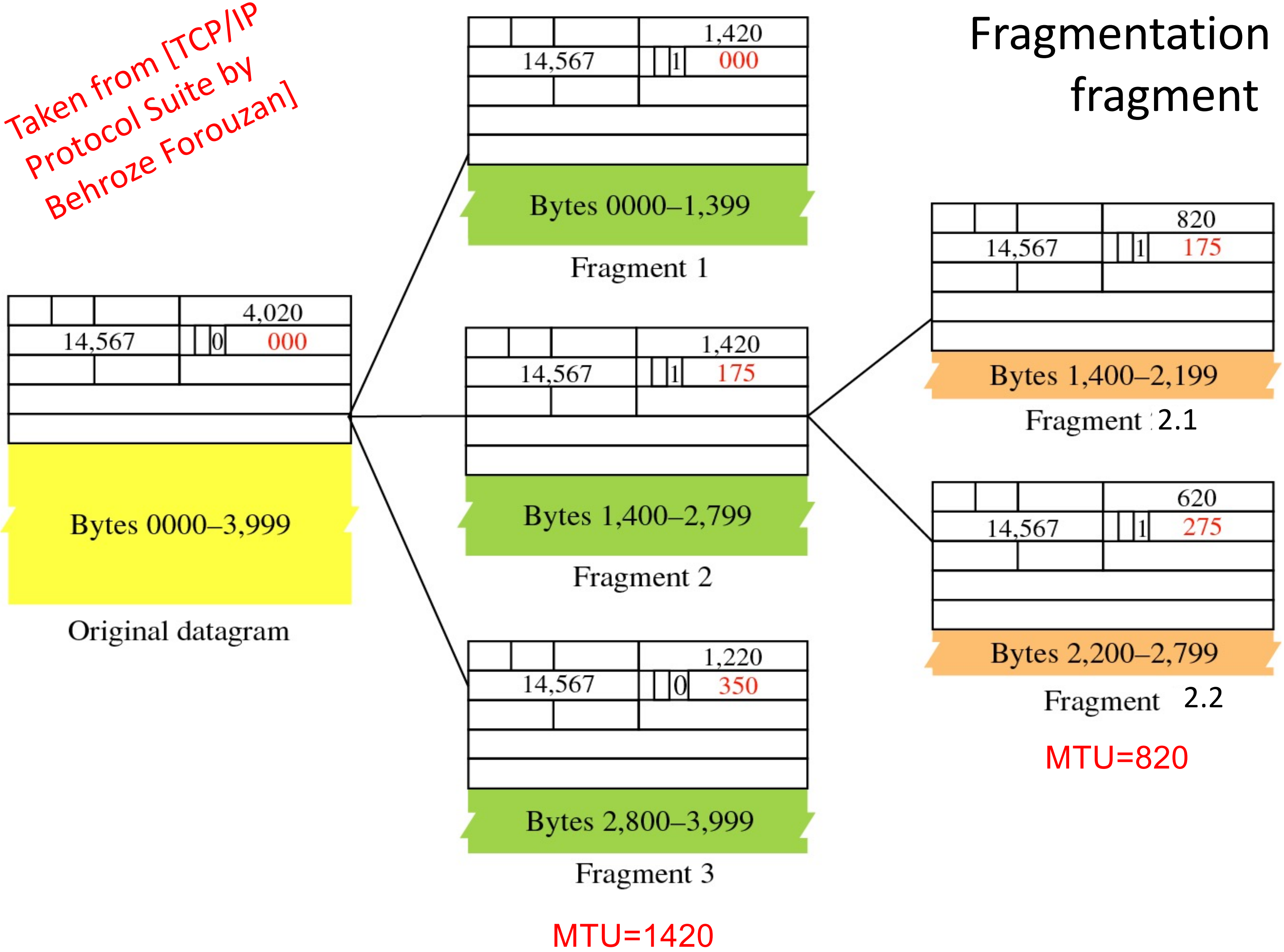


IPv4 fragmentation procedure

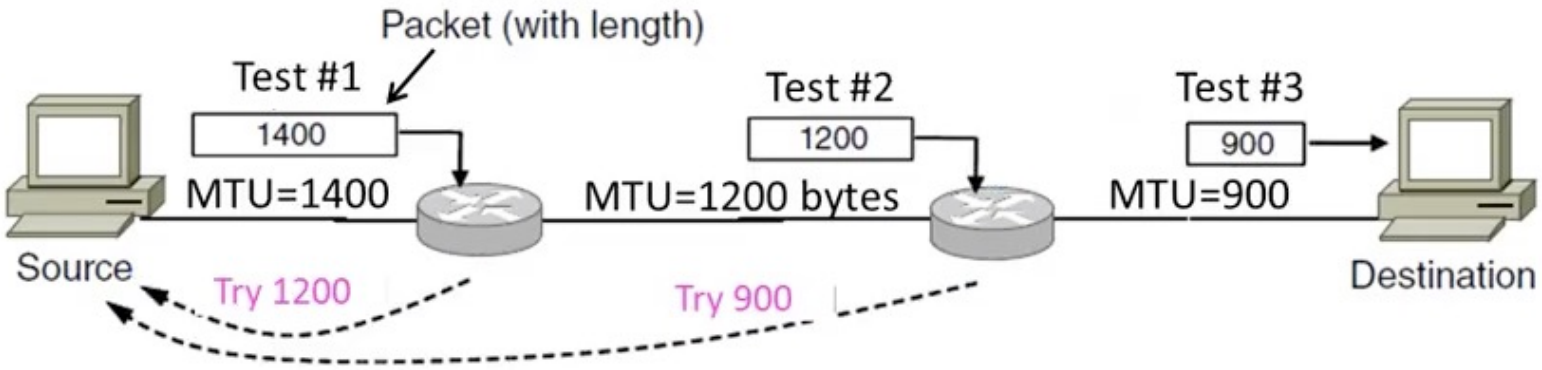
- Fragmentation
  - Router breaks up datagram in size that output link can support
  - Copies IP header to pieces
  - Adjust length on pieces
  - Set offset to indicate position
  - Set MF (More fragments) flag on pieces except the last
  - Re-compute checksum
- Re-assembly
  - Receiving host uses identification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

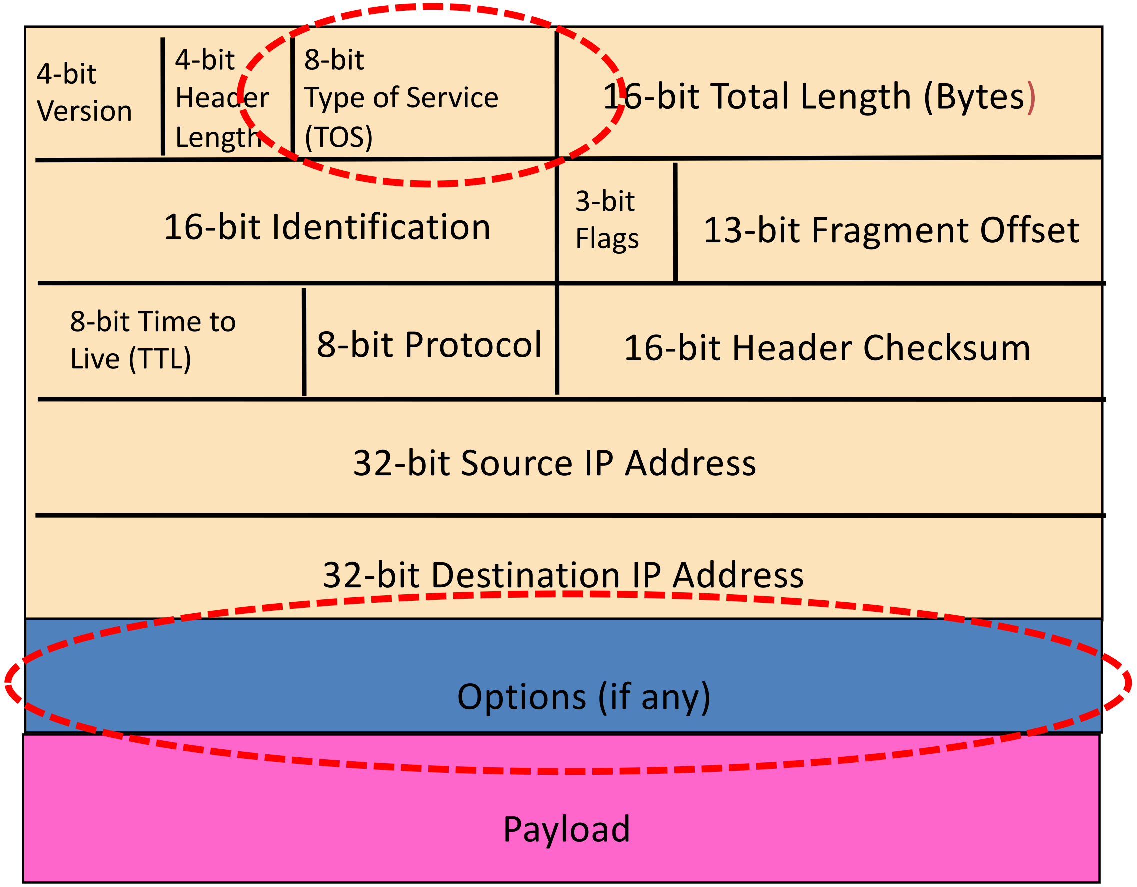


Path MTU Discovery procedure



- 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

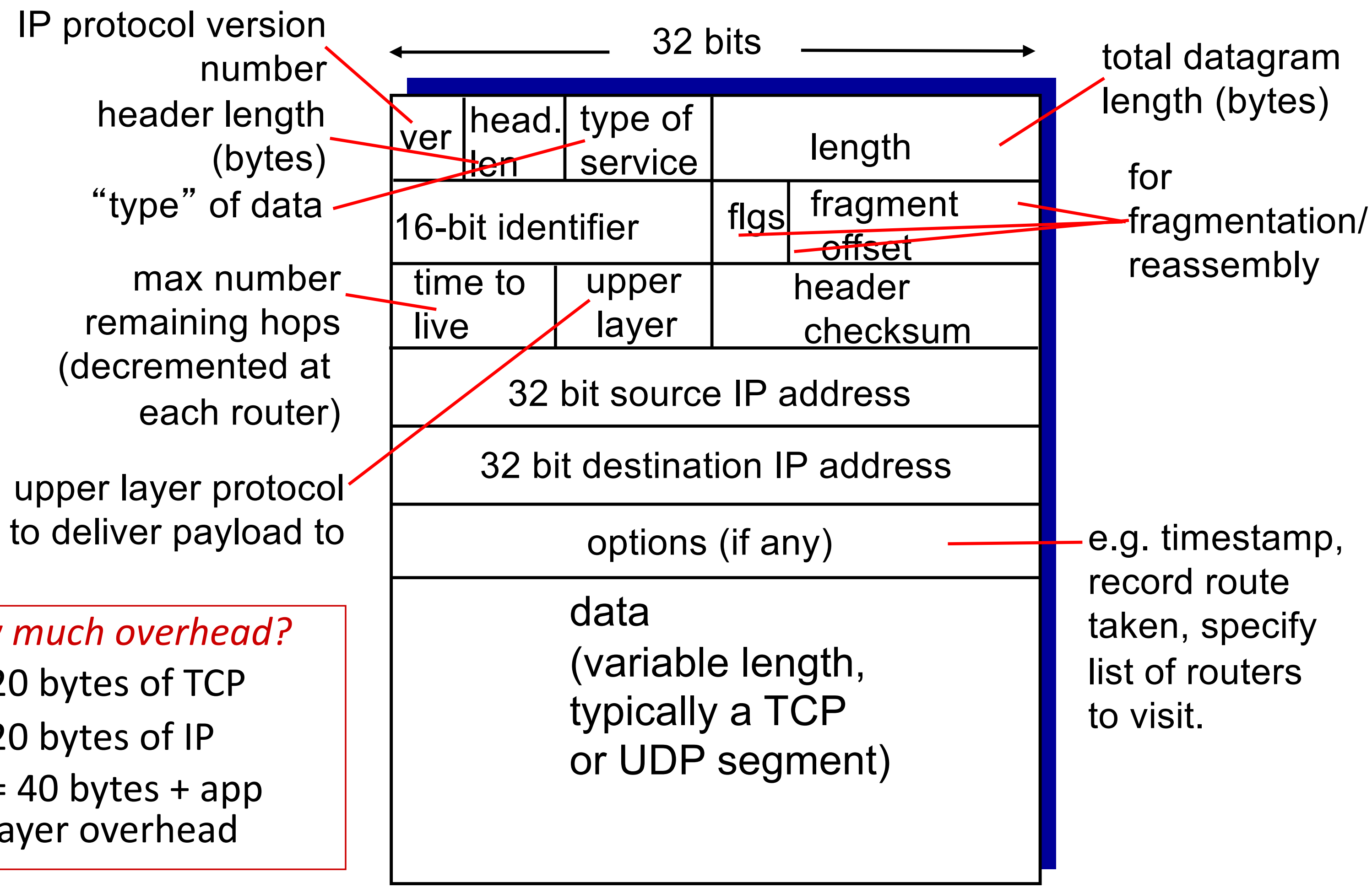


Special Handling

- “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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- datagram format
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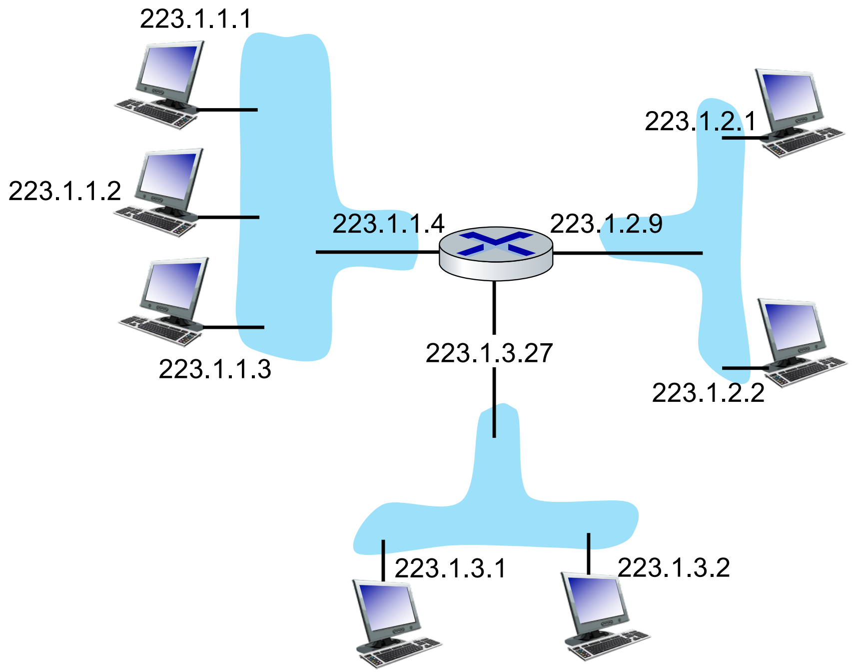
IP addressing: introduction

- 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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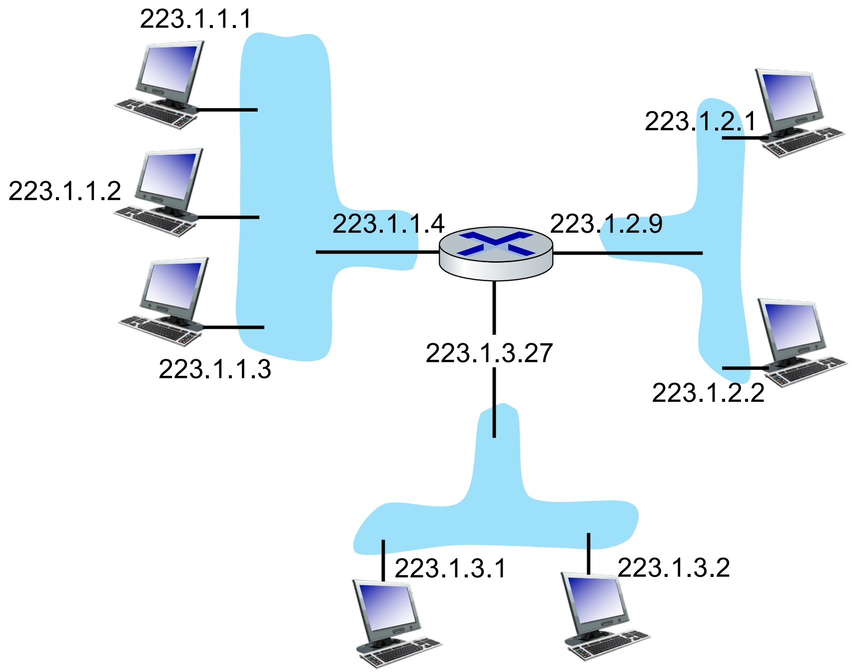


dotted-decimal IP address notation:

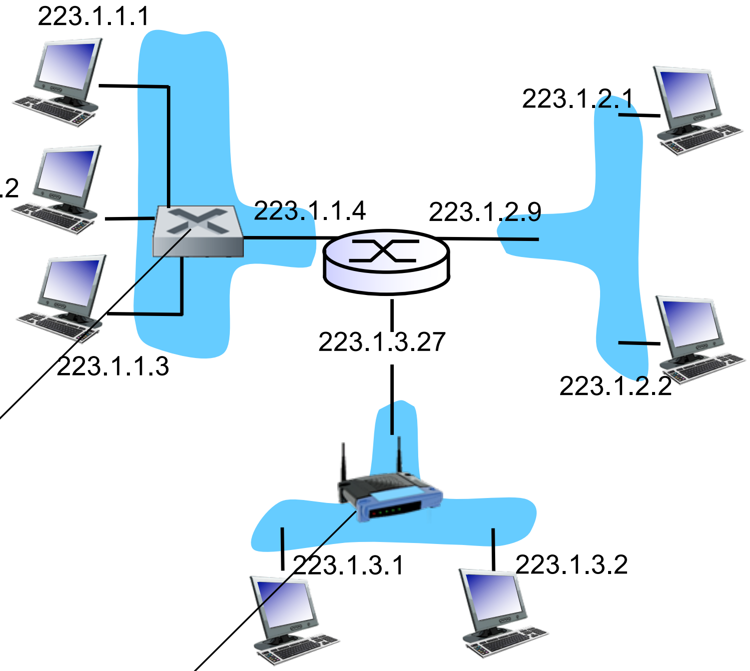
223.1.1.1 = 11011111 00000001 00000001 00000001

223 1 1 1

IP addressing: introduction

Q: how are interfaces actually connected?

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

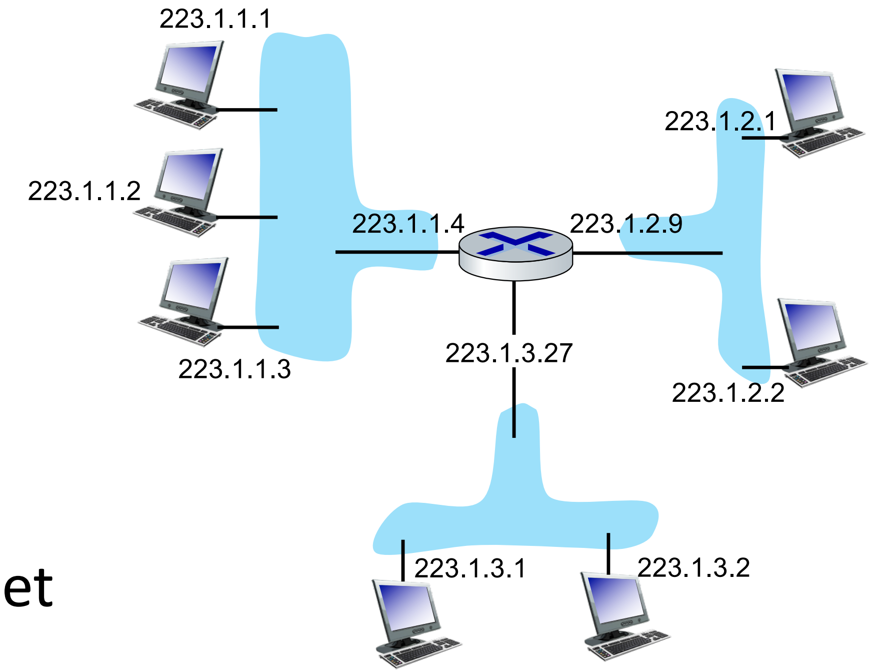


A: wired Ethernet interfaces connected by Ethernet switches

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

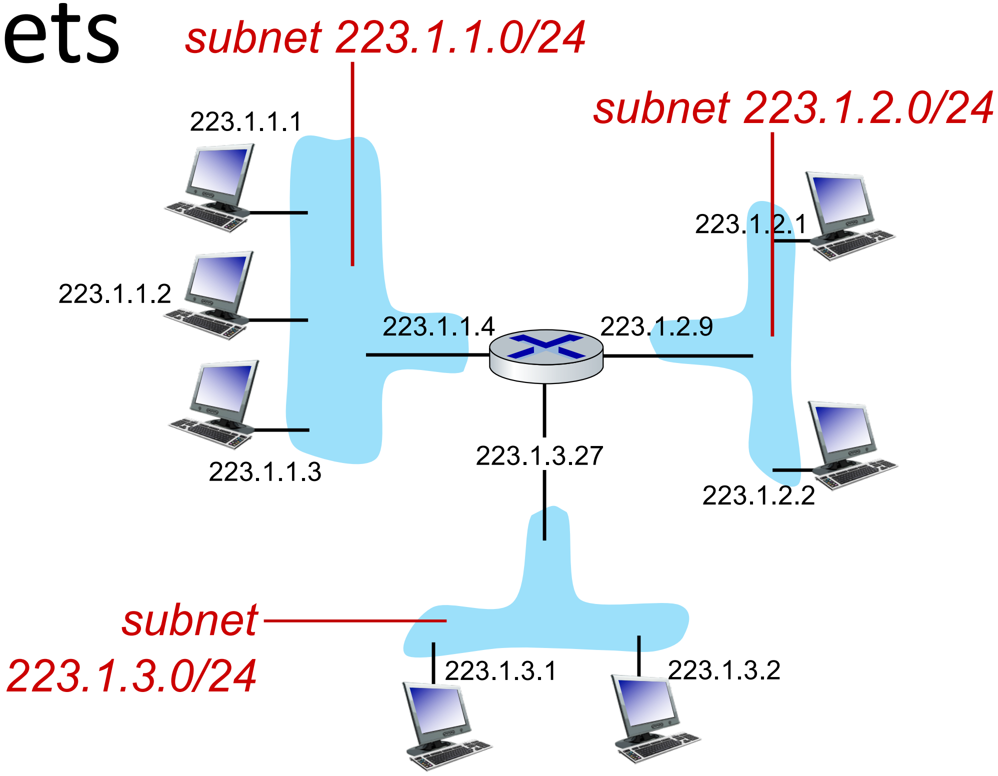


network consisting of 3 subnets

Subnets

Recipe for defining subnets:

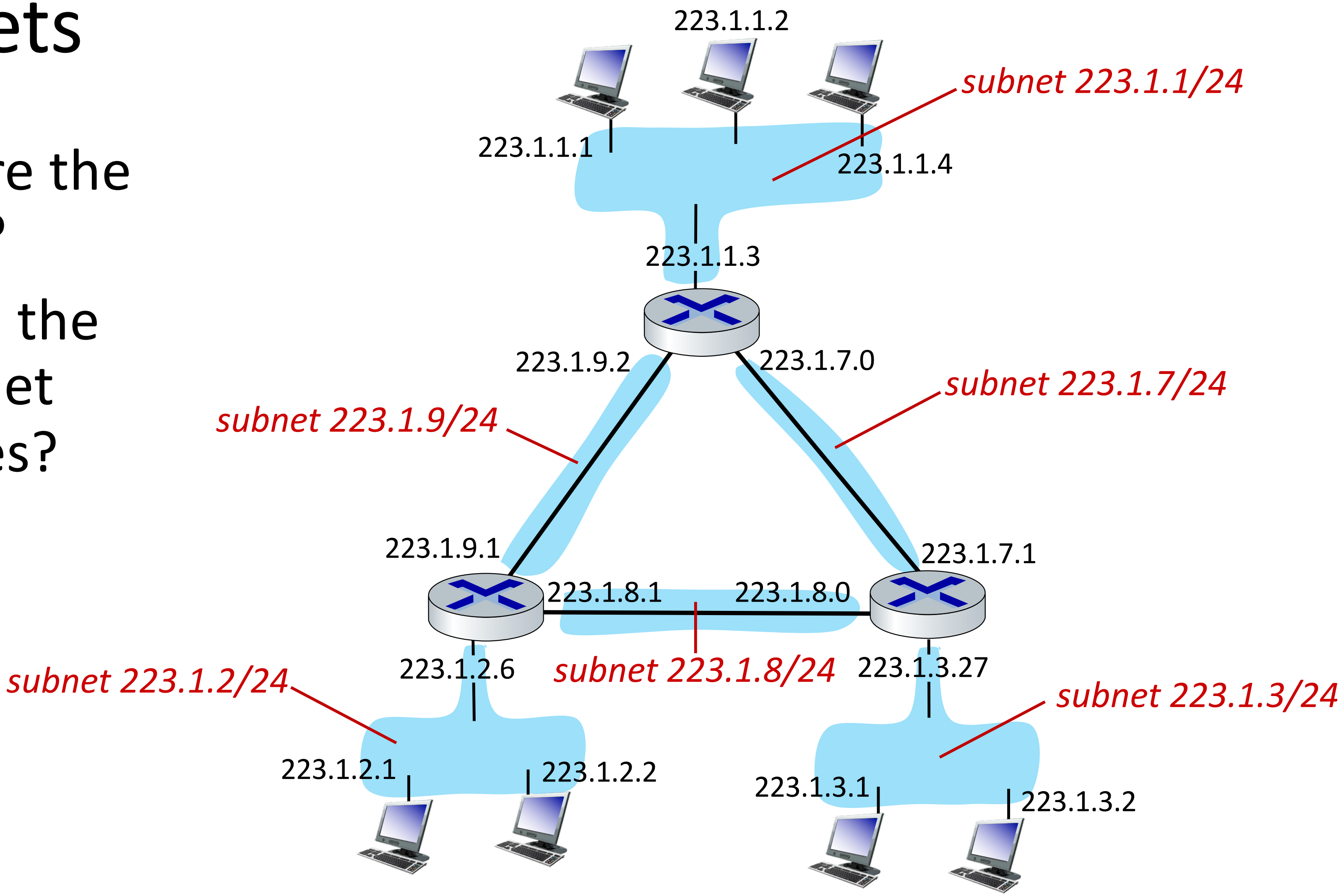
- detach each interface from its host or router, creating "islands" of isolated networks
- each isolated network is called a *subnet*



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

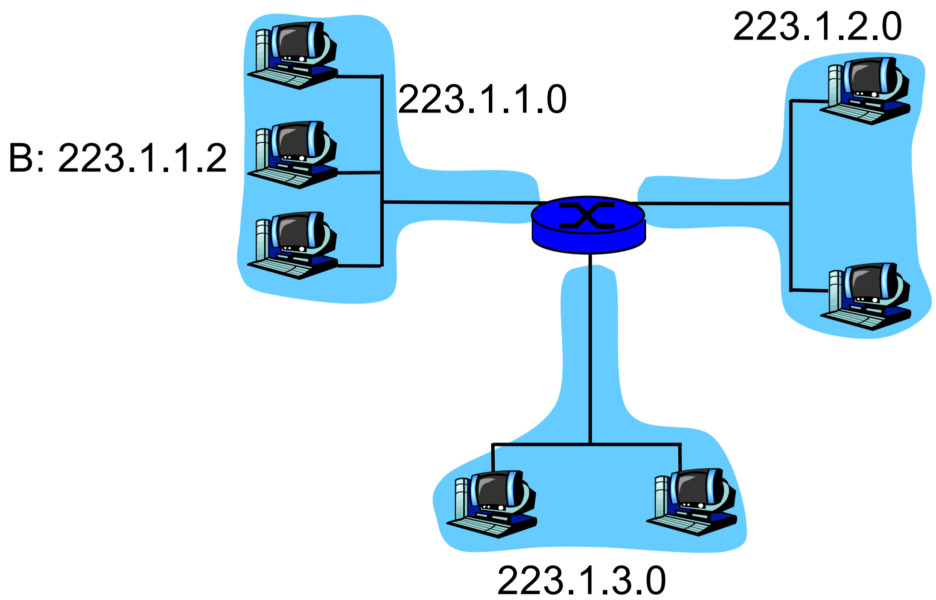
Subnets

- 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!

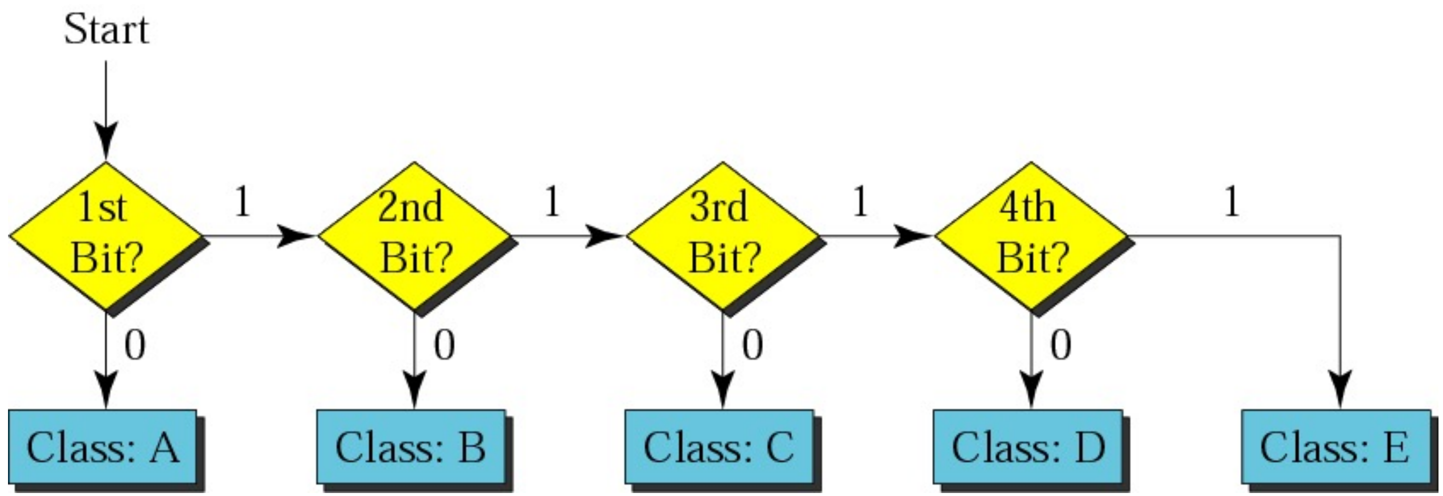
Next design: Class-ful Addresses

Used till the introduction of CIDR 1993

	0, 8, 16, 24, 31		
Class A	0 *netid* (bits 0–7) | *hostid*	2^7 nets, 2^{24} hosts	1.0.0.0 to 127.255.255.255
Class B	10 *netid* (bits 0–15) | *hostid*	2^{14} nets, 2^{16} hosts	128.0.0.0 to 191.255.255.255
Class C	110 *netid* (bits 0–23) | *hostid*	2^{21} nets, 2^8 hosts	192.0.0.0 to 223.255.255.255
Class D	1110 *multicast address*		224.0.0.0 to 239.255.255.255
Class E	1111 *reserved for future use*		240.0.0.0 to 255.255.255.255

Problem: Networks only come in three sizes!

Finding the address class



What are the issues?

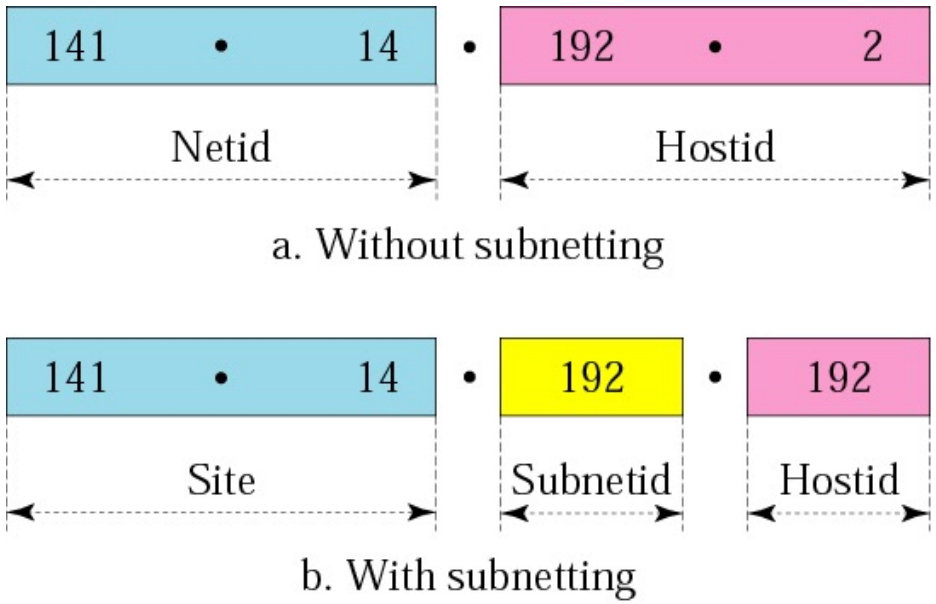
- An organization requires 6 nets each of size 30. Does it have to buy 6 class C address blocks?
- An organization requires 512 addresses? How many IP addresses should it buy?

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

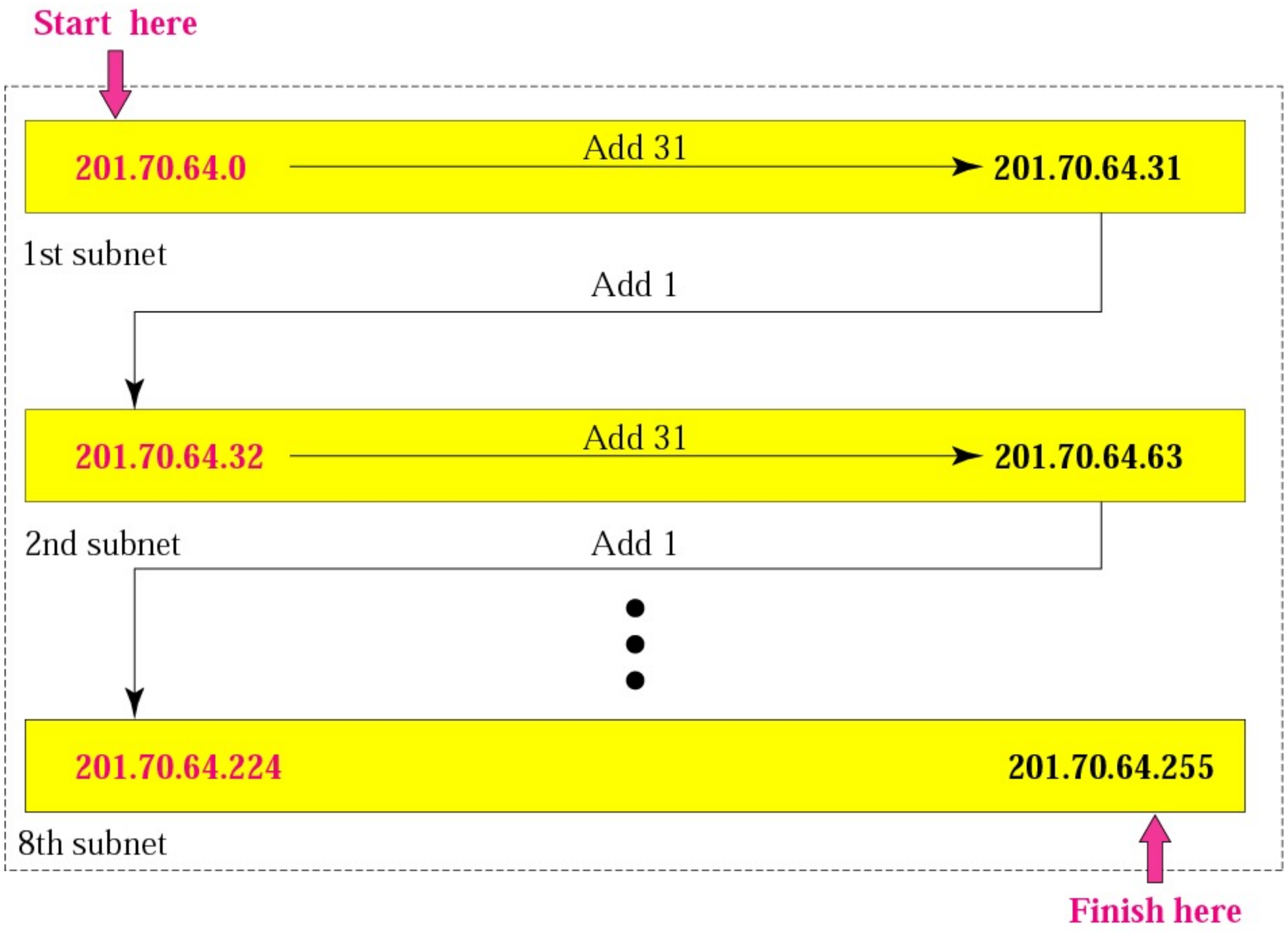
11111111 11111111 11111111 11100000

or 255.255.255.224

Number of addresses in each subnet = 2^5

= 32

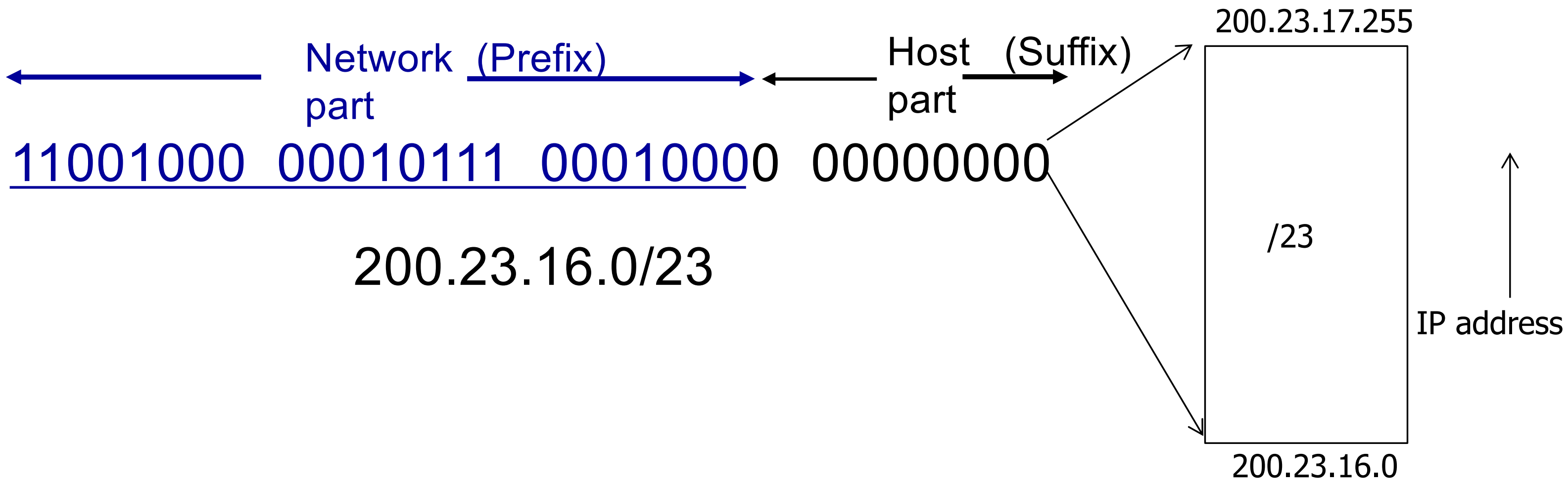
The number of addresses in each subnet is 2^5 or 32.



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

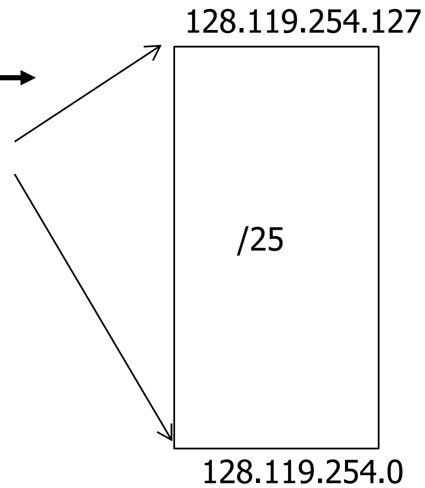
- How many IP addresses belong to the subnet 128.119.254.0/25 ? What are the IP addresses at the two end-points of this range ?

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

subnet part | host part

10000000 01110111 11111110 00000000

128.119.254.0/25



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 × 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 = $128 \times 64 = 8,192$

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

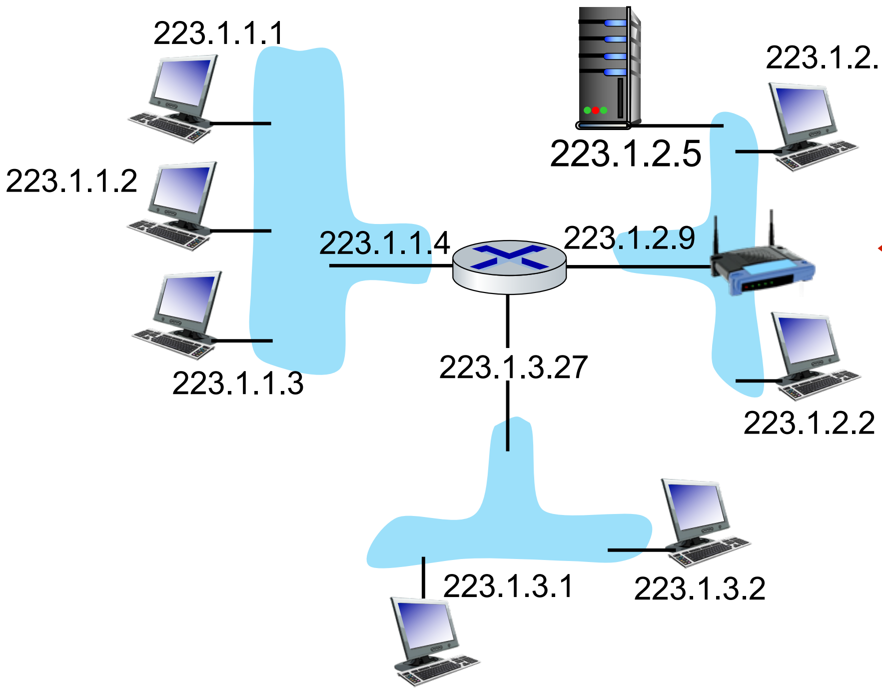
goal: host *dynamically* obtains IP address from network server when it "joins" network

- 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

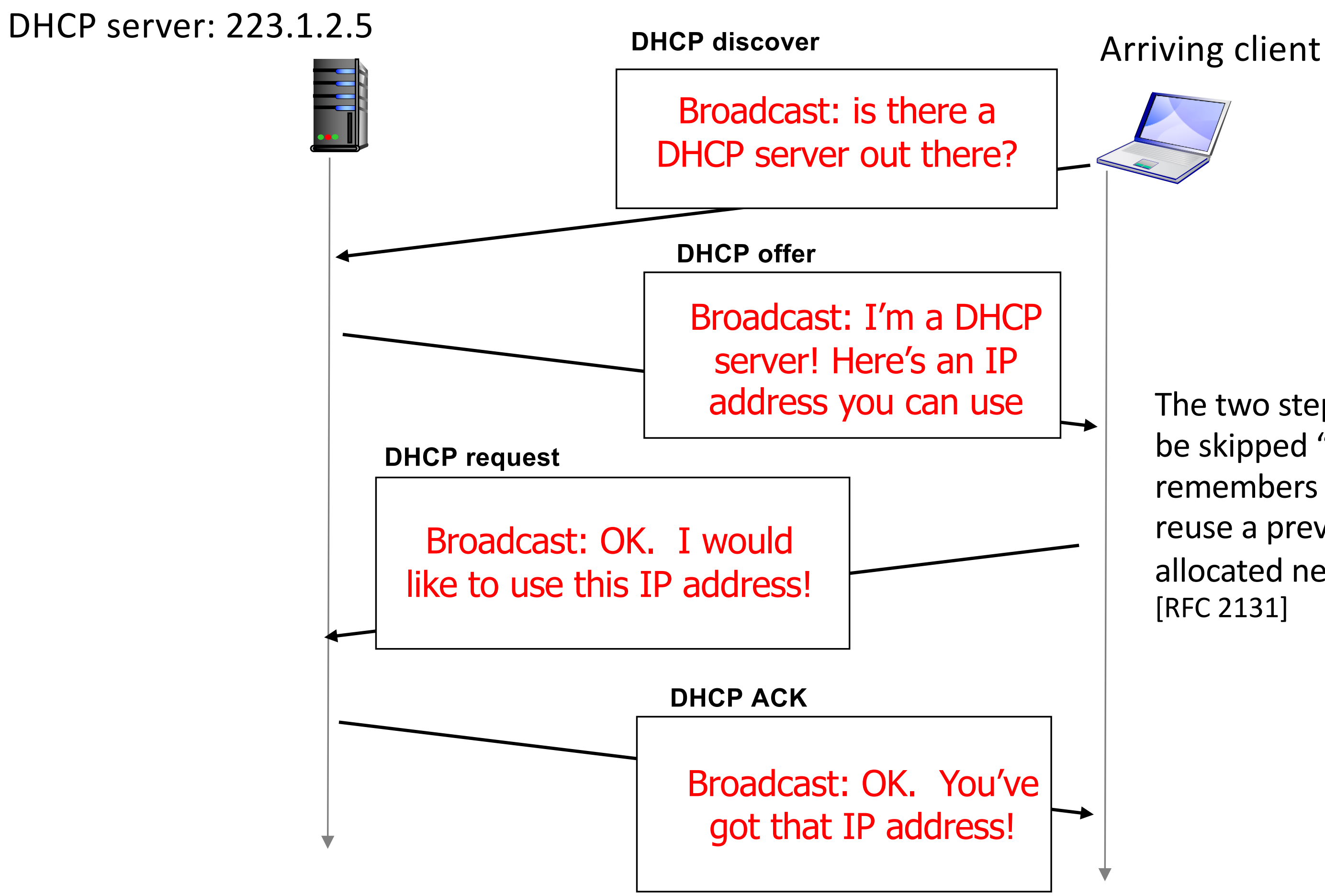
DHCP client-server scenario



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



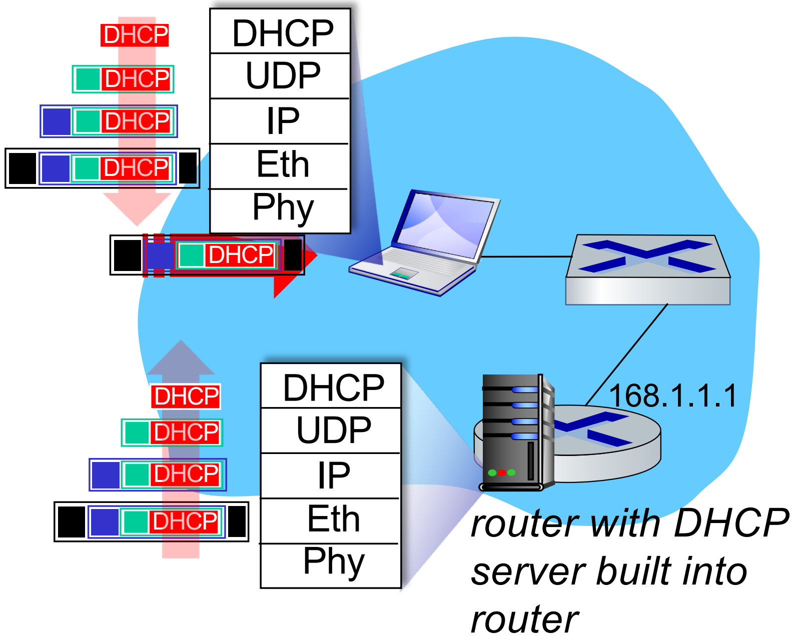
The two steps above can be skipped "if a client remembers and wishes to reuse a previously allocated network address" [RFC 2131]

DHCP: more than IP addresses

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

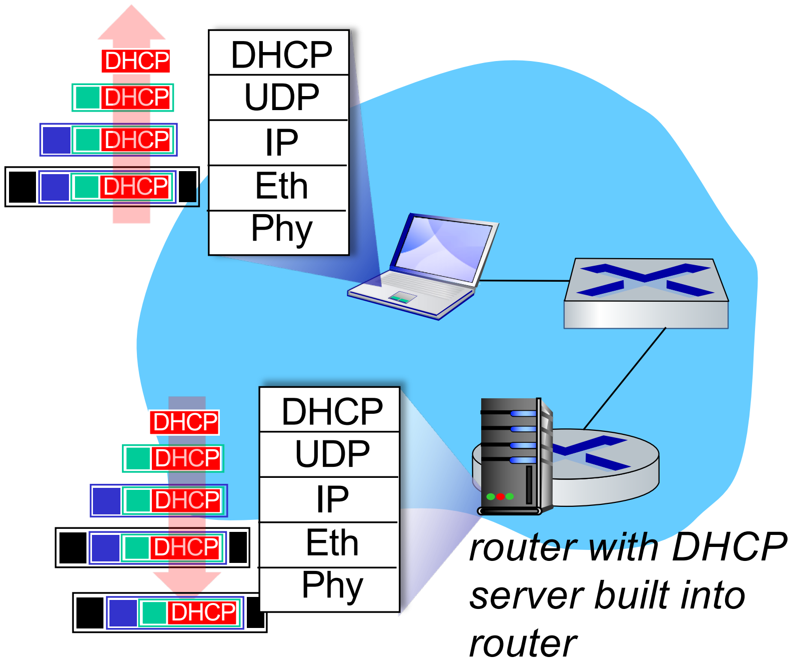
- address of first-hop router for client
- name and IP address of DNS sever
- network mask (indicating network versus host portion of address)

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

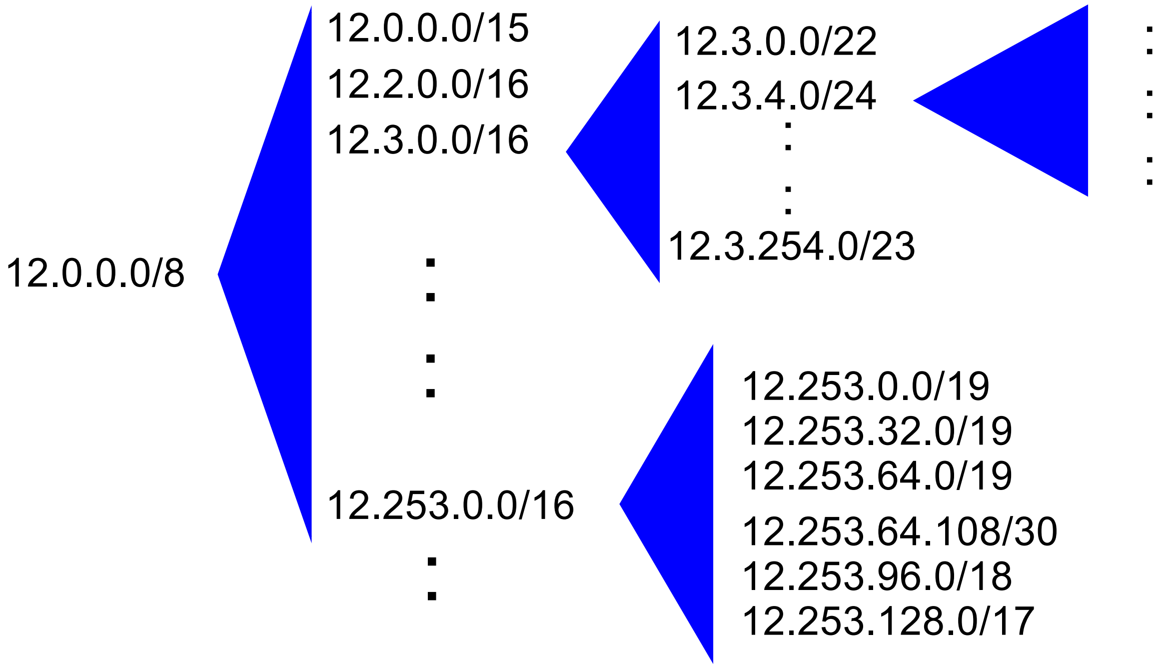
ISP's block	11001000 00010111 00010000 00000000	200.23.16.0/20

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

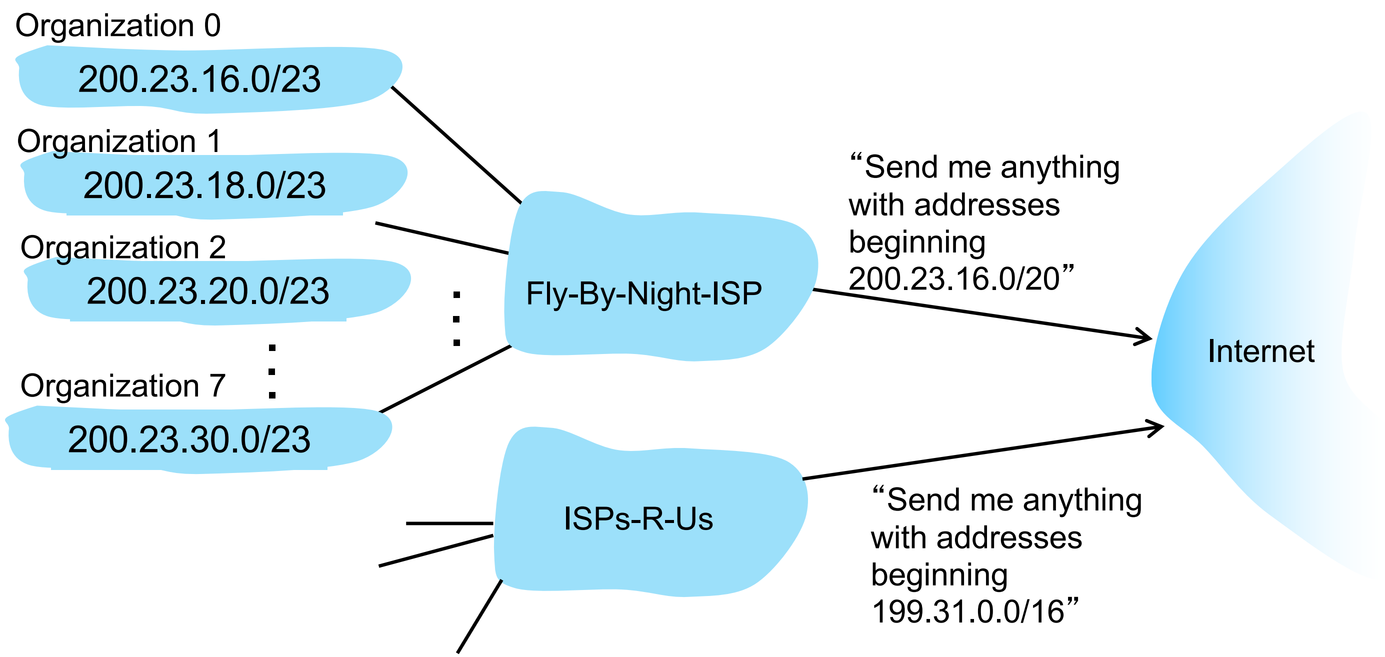
CIDR: Addresses allocated in contiguous prefix chunks

Recursively break down chunks as get closer to host



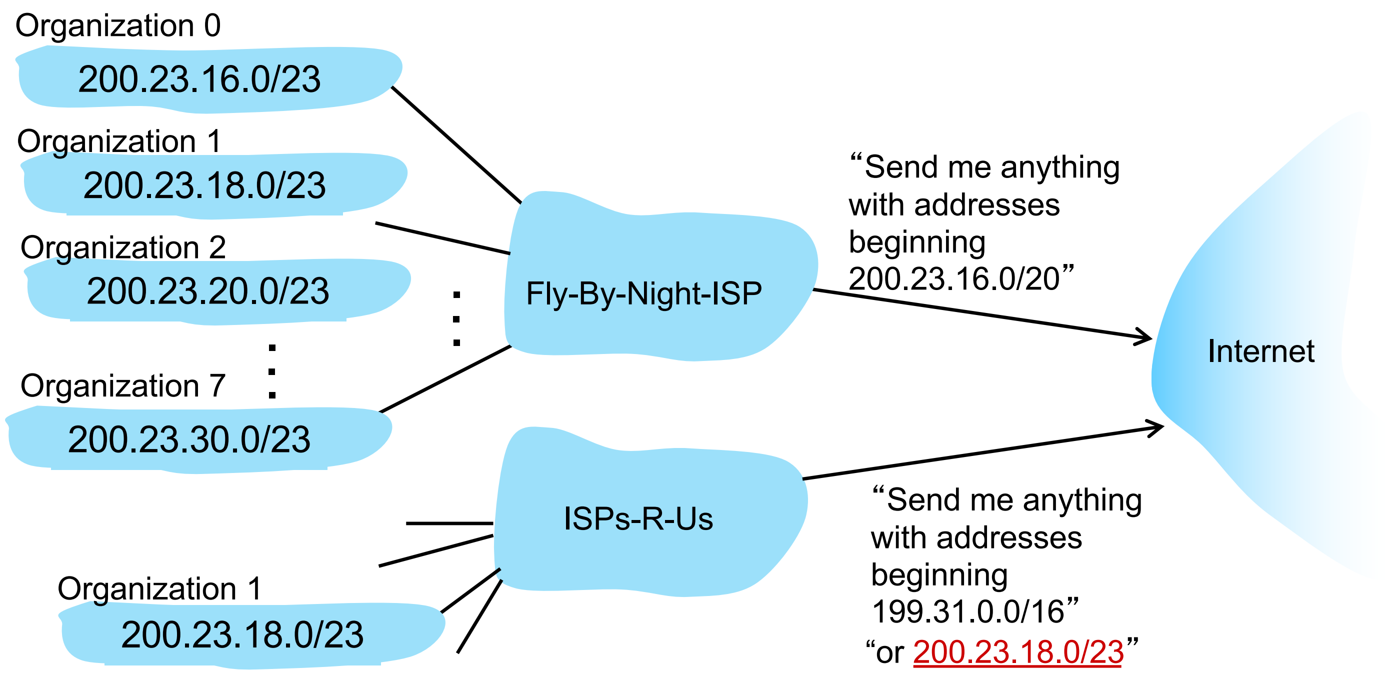
Hierarchical addressing: route aggregation

hierarchical addressing allows efficient advertisement of routing information:



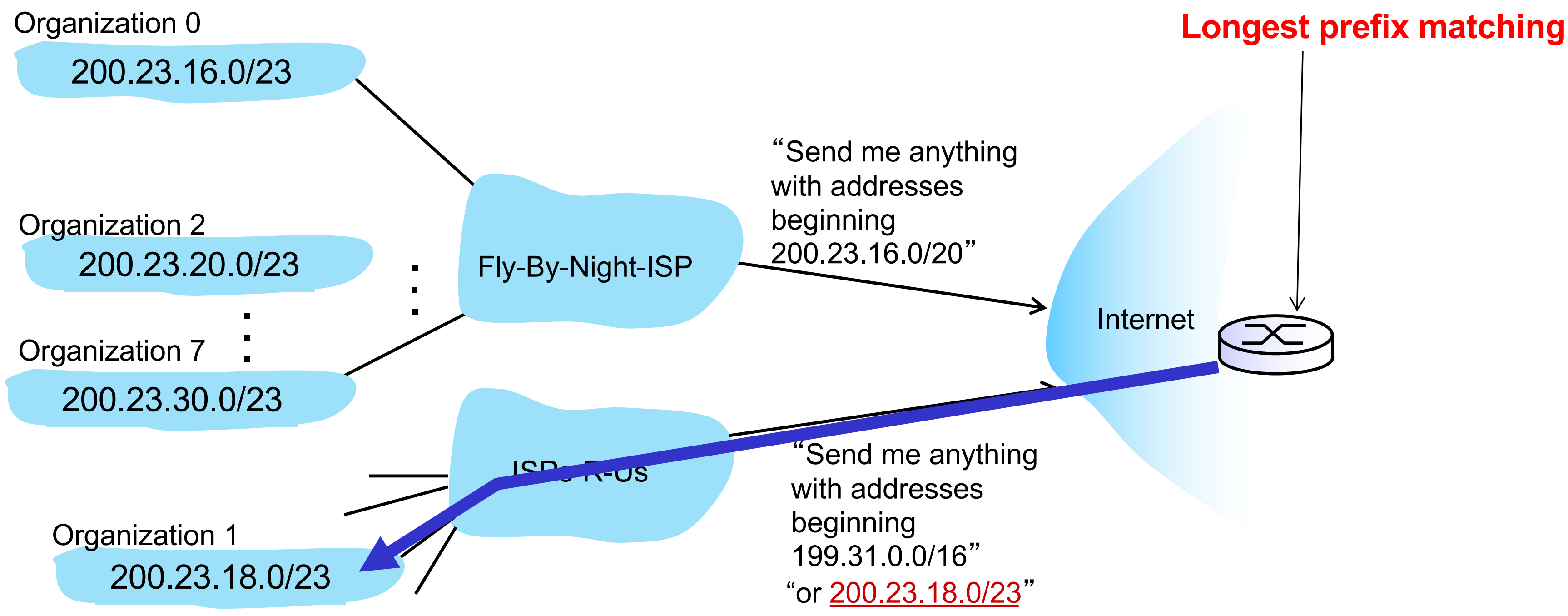
Hierarchical addressing: more specific routes

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



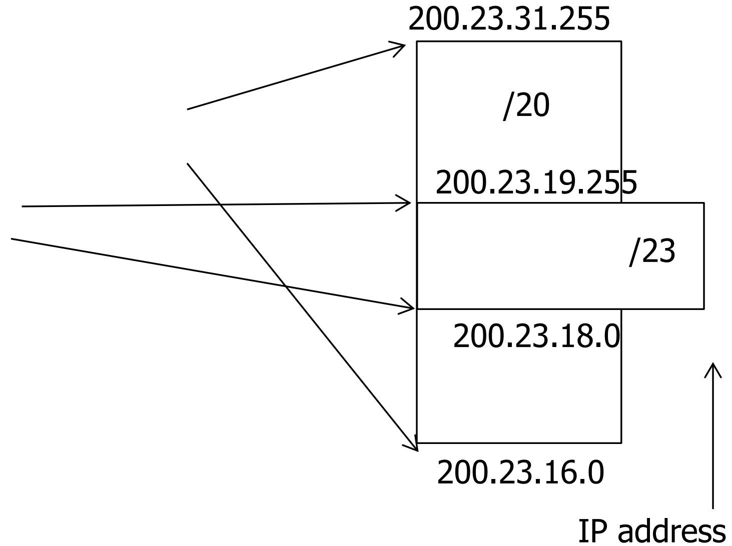
Hierarchical addressing: more specific routes

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



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

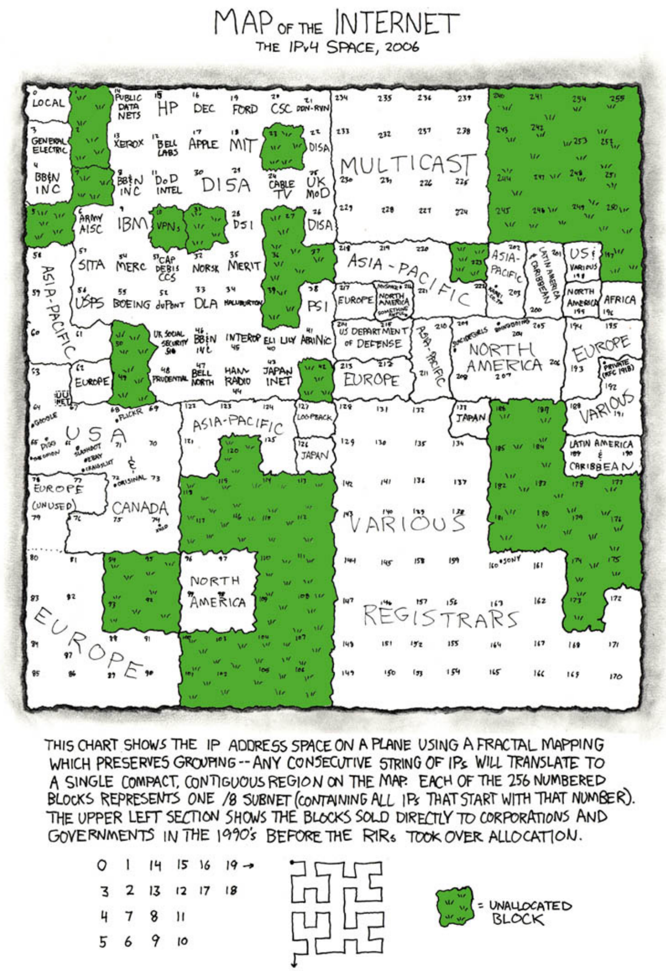
examples:

DA: 11001000 00010111 00010110 10100001 which interface?

DA: 11001000 00010111 00011000 10101010 which interface?

More on IP addresses

Source: www.xkcd.com



- 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

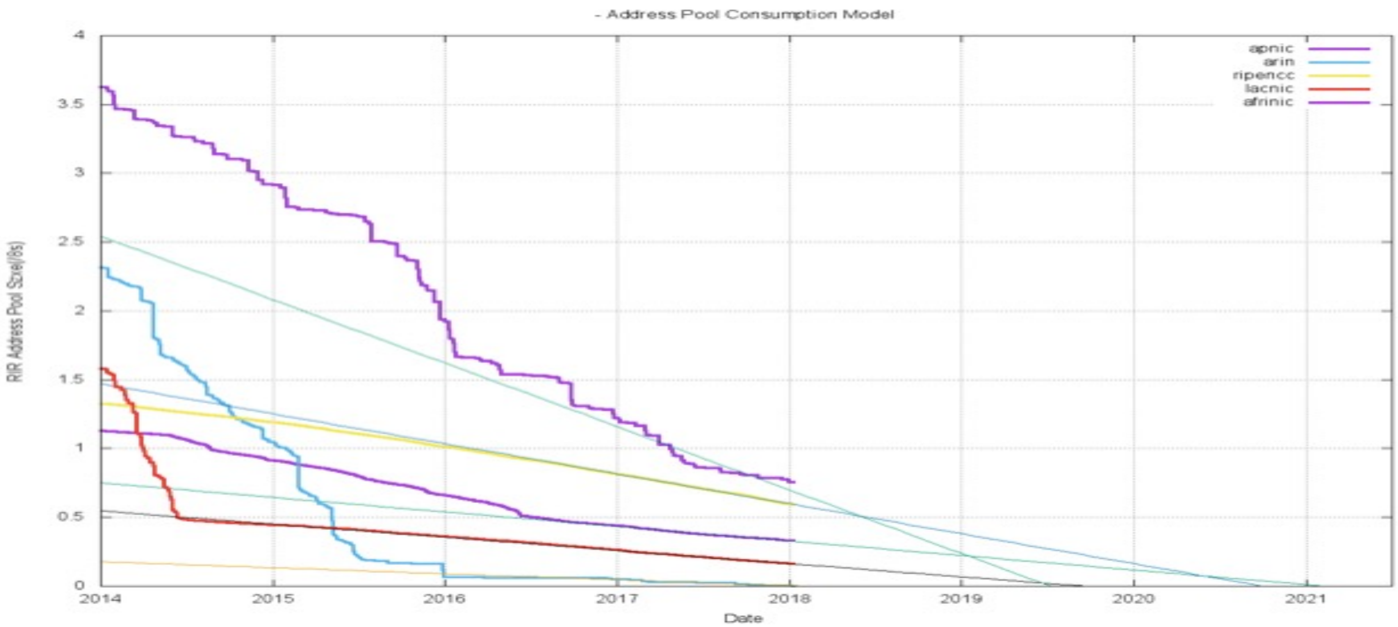
IP Addressing: the last word...

Q: How does an ISP get block of addresses?

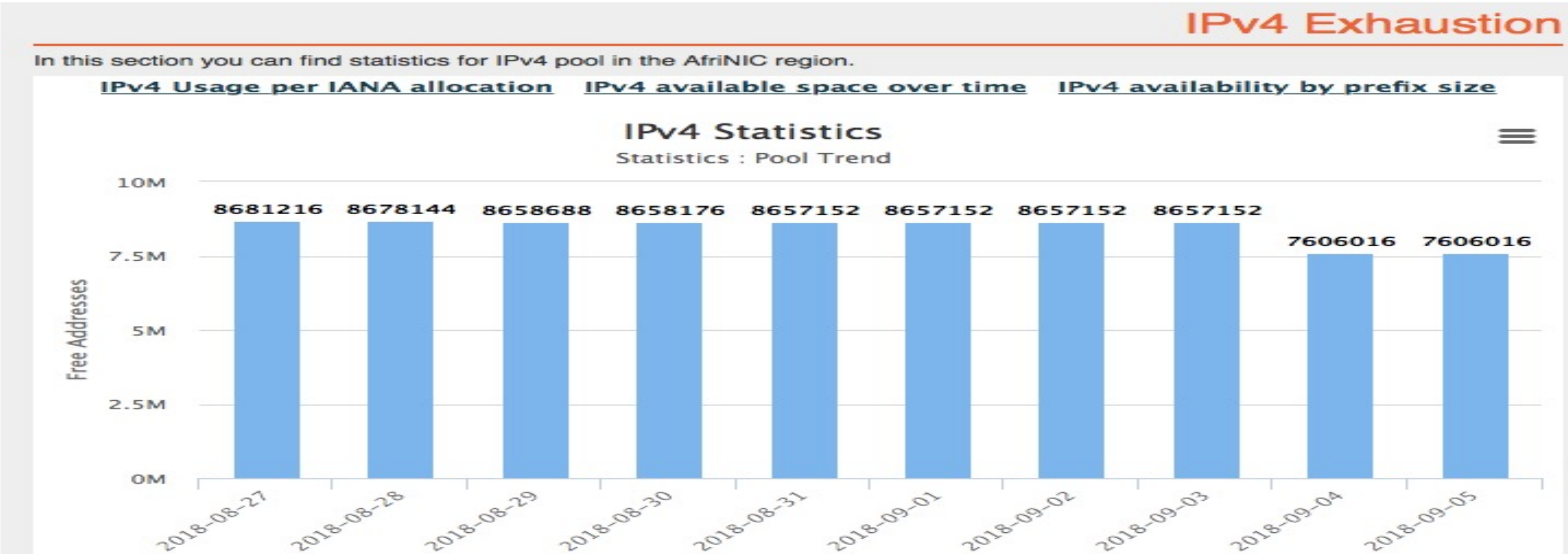
A: ICANN: Internet Corporation for Assigned Names and Numbers http://www.icann.org/

iana — 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



- Address Pool Consumption Model
apnic
arin
ripencc
lacnic
afrinic
RIR Address Pool Size(/8s)
Date
2014
2015
2016
2017
2018
2019
2020
2021



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
IPv4 Statistics
Statistics : Pool Trend
Free Addresses
10M
7.5M
5M
2.5M
0M
8681216
8678144
8658688
8658176
8657152
8657152
8657152
8657152
7606016
7606016
2018-08-27
2018-08-28
2018-08-29
2018-08-30
2018-08-31
2018-09-01
2018-09-02
2018-09-03
2018-09-04
2018-09-05

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**