CS2105

An Αωεσομε Introduction to Computer Networks

Lectures 6&7: The Network Layer

NUS National University of Singapore | Department of Computer Science
School of Computing

Lectures 6&7: The Network Layer

After this class, you are expected to understand:

- the basic services network layer provides.
- the purpose of DHCP and how it works.
- IP address, subnet, subnet mask and address allocation.
- how longest prefix forwarding in a router works.
- the purpose of routing protocols on the Internet.
- the principle of Bellman-Ford equation.
- the workings of distance vector algorithm.
- the purpose of NAT and how it works.
- the Internet Protocol (IP) and how datagram fragmentation works.

Lectures 6&7: Roadmap

4.1 Overview of Network Layer

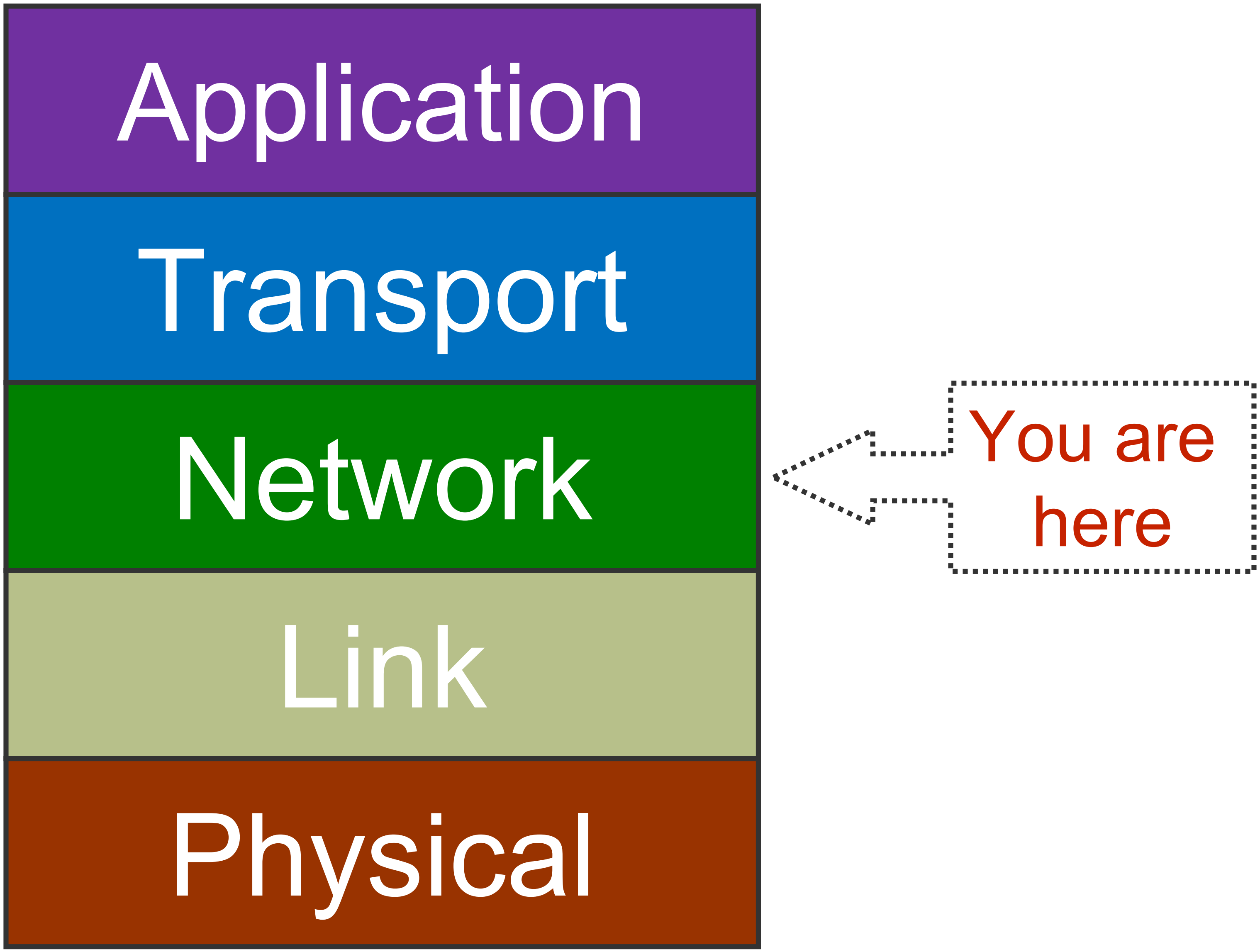
4.2 What's Inside a Router

4.3 The Internet Protocol (IP)

5.2 Routing Algorithms

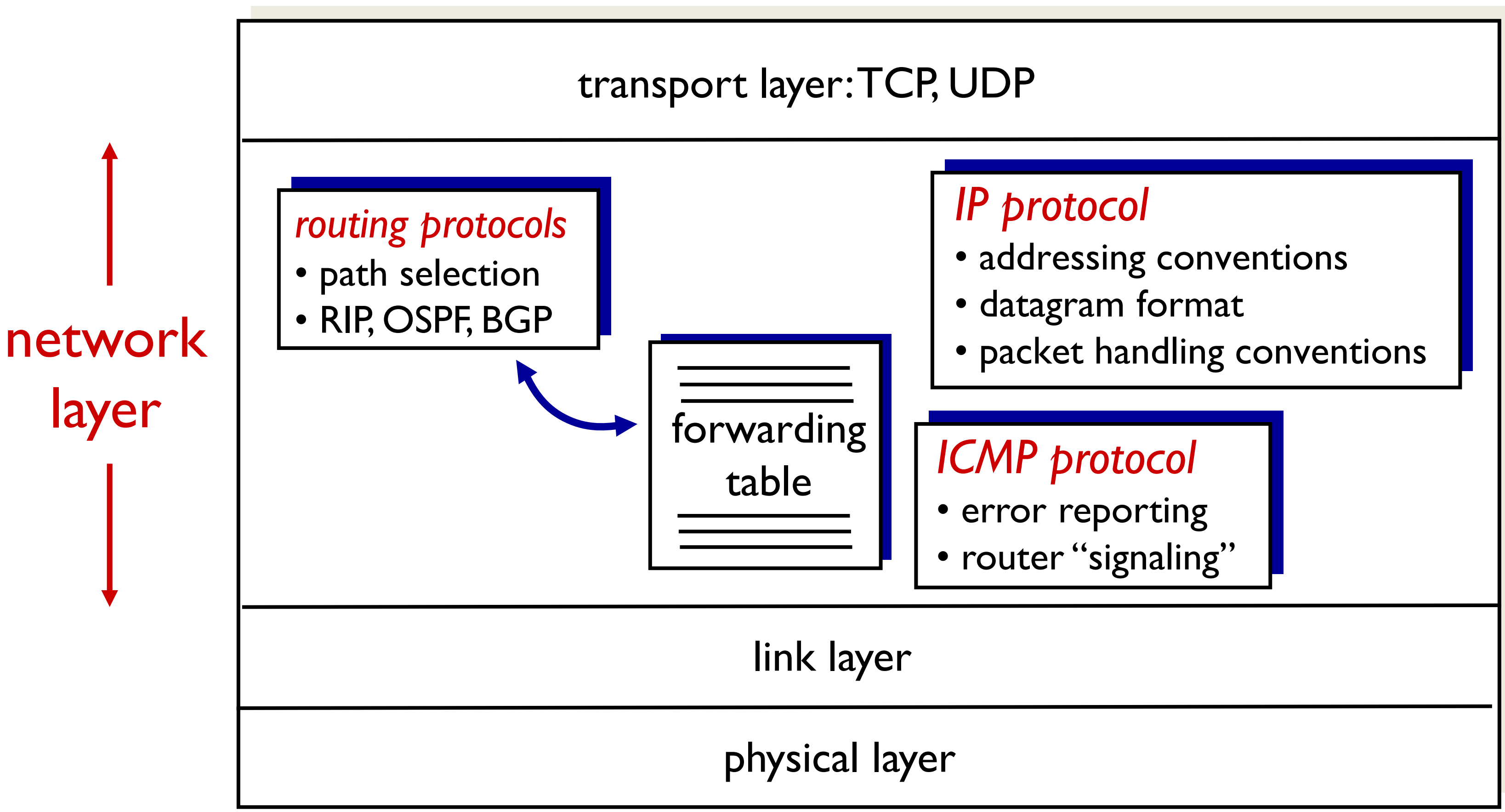
5.6 ICMP

Kurose Textbook, Chapters 4&5
(Some slides are taken from the book)


Application
Transport
Network
Link
Physical
You are here

Network Layer Services

- Network layer delivers packets to receiving hosts.
  - Routers examine header fields of IP datagrams passing it.



Lectures 6&7: Roadmap

4.1 Overview of Network Layer

4.2 What’s Inside a Router

- 4.2.1 Destination-Based Forwarding

4.3 The Internet Protocol (IP)

- 4.3.3 IPv4 Addressing

5.2 Routing Algorithms

5.6 ICMP

IP Address

- IP address is used to identify a host (or a router).
  - A 32-bit integer expressed in either binary or decimal

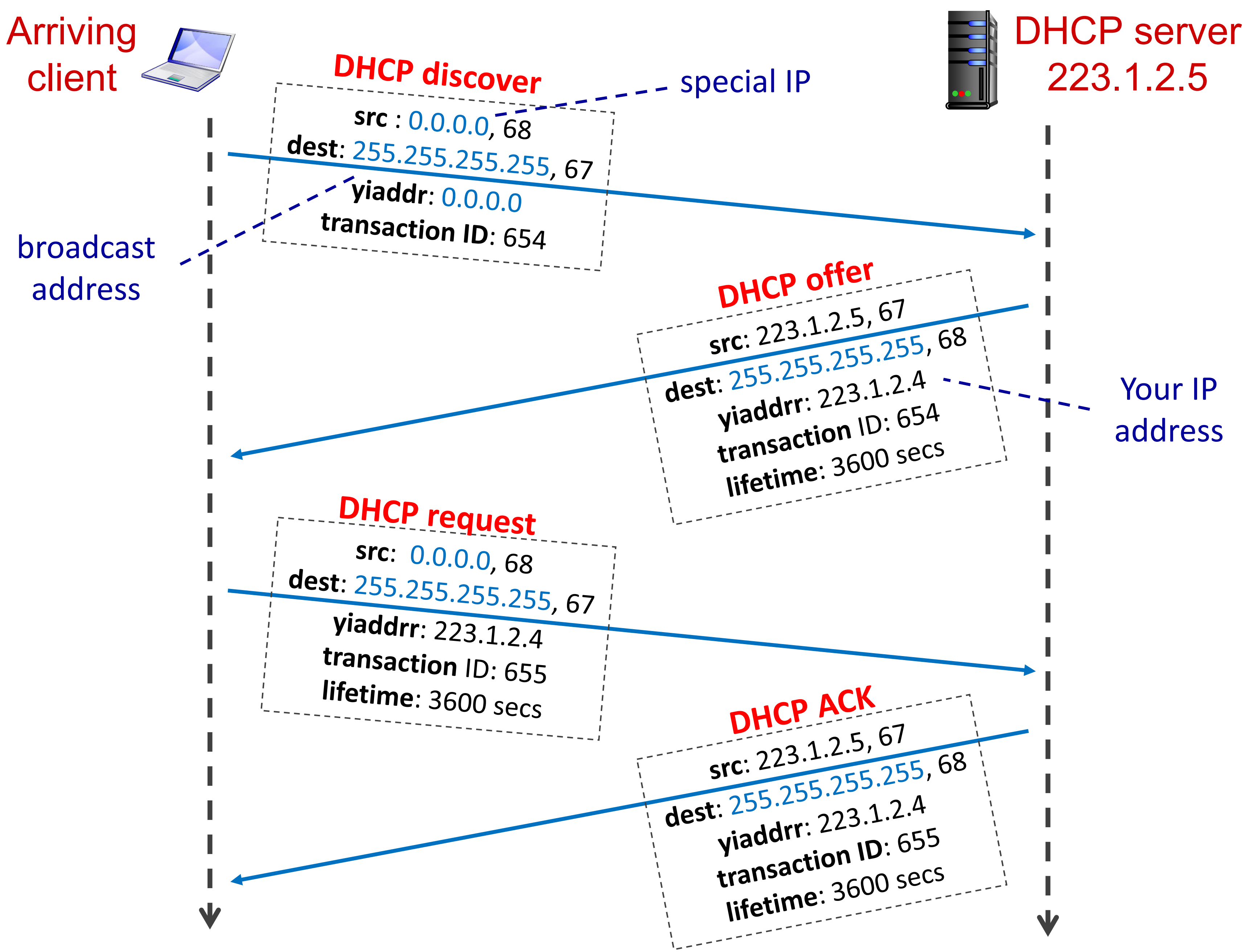
Binary:	**00000001**	**00000010**	**00000011**	**10000001**
Decimal:	1	2	3	129

- How does a host get an IP address?
  - manually configured by system administrator, or
  - automatically assigned by a DHCP (Dynamic Host Configuration Protocol) server.

Dynamic Host Configuration Protocol

- DHCP allows a host to dynamically obtain its IP address from DHCP server when it joins network.
  - IP address is renewable
  - allow reuse of addresses (only hold address while connected)
  - support mobile users who want to join network.

- DHCP: 4-step process:
  1) Host broadcasts "DHCP discover" message
  2) DHCP server responds with "DHCP offer" message
  3) Host requests IP address: "DHCP request" message
  4) DHCP server sends address: "DHCP ACK" message


Arriving client
DHCP server 223.1.2.5
DHCP discover
src : 0.0.0.0, 68
dest: 255.255.255.255, 67
yiaddr: 0.0.0.0
transaction ID: 654
special IP
broadcast address
DHCP offer
src: 223.1.2.5, 67
dest: 255.255.255.255, 68
yiaddrr: 223.1.2.4
transaction ID: 654
lifetime: 3600 secs
Your IP address
DHCP request
src: 0.0.0.0, 68
dest: 255.255.255.255, 67
yiaddrr: 223.1.2.4
transaction ID: 655
lifetime: 3600 secs
DHCP ACK
src: 223.1.2.5, 67
dest: 255.255.255.255, 68
yiaddrr: 223.1.2.4
transaction ID: 655
lifetime: 3600 secs

More on DHCP

- In addition to host IP address assignment, DHCP may also provide a host additional network information:
  - IP address of first-hop router
  - IP address of local DNS server
  - Network mask (indicating network prefix versus host ID of an IP address)

- DHCP runs over UDP
  - DHCP server port number: 67
  - DHCP client port number: 68

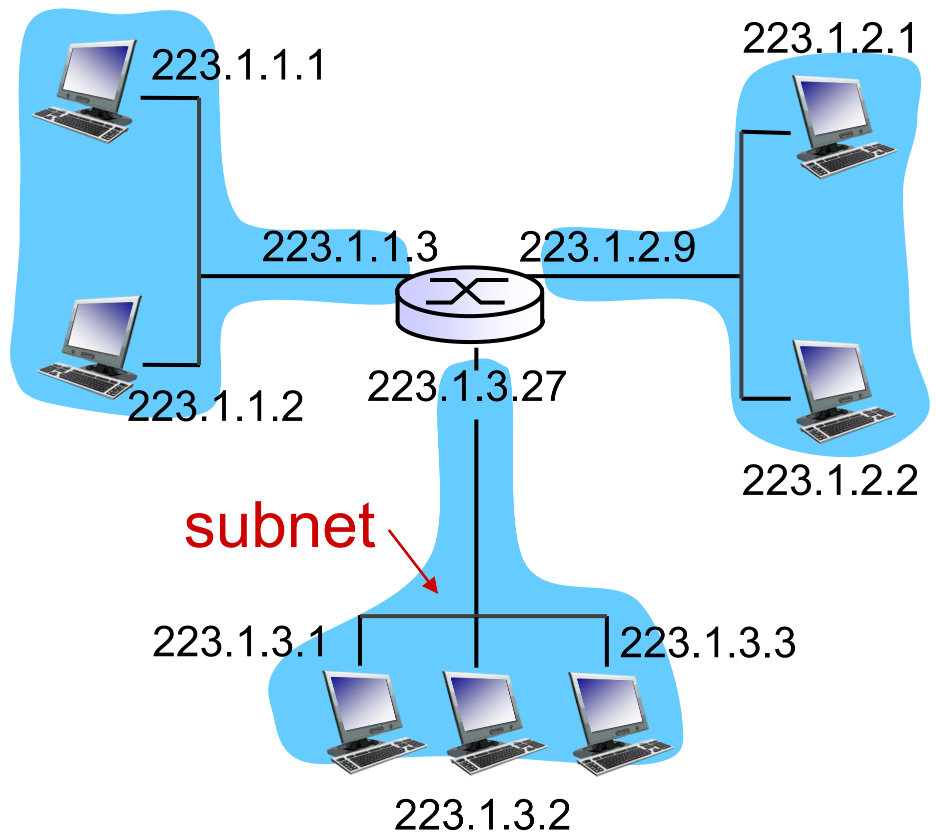
Some Special IP Addresses

Special Addresses	Present Use
0.0.0.0/8	Non-routable meta-address for special use
127.0.0.0/8	Loopback address. A datagram sent to an address within this block loops back inside the host. This is ordinarily implemented using only 127.0.0.1/32.
10.0.0.0/8 172.16.0.0/12 192.168.0.0/16	Private addresses, can be used without any coordination with IANA or an Internet registry.
255.255.255.255/32	Broadcast address. All hosts on the same subnet receive a datagram with such a destination address.

The full list of special IP addresses can be found in RFC5735:
https://tools.ietf.org/rfc/rfc5735.txt

IP Address and Network Interface

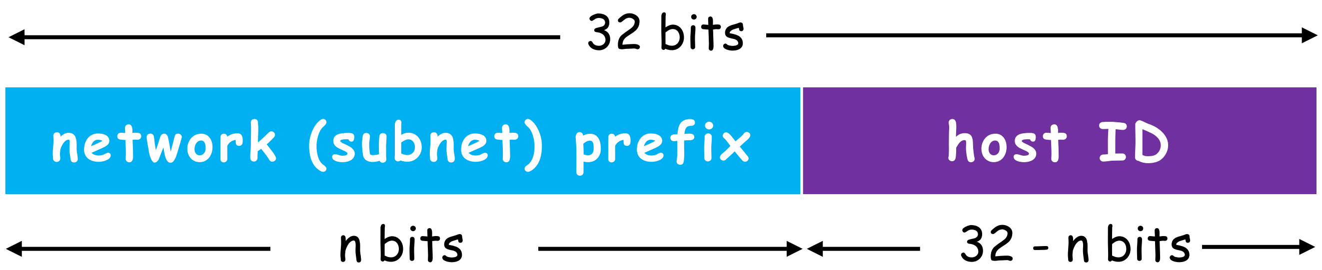
- An IP address is associated with a network interface.
  - A host usually has one or two network interfaces (e.g. wired Ethernet and WiFi).
  - A router typically has multiple interfaces.



A network consisting of 3 subnets
(first 24 bits of IP addr. are network prefix)

IP Address and Subnet

- An IP address logically comprises two parts:



- Subnet is a network formed by a group of “directly” interconnected hosts.
  - Hosts in the same subnet have the same network prefix of IP address.
  - Hosts in the same subnet can physically reach each other without intervening router.
  - They connect to the outside world through a router.

IP Address: CIDR

- The Internet's IP address assignment strategy is known as Classless Inter-domain Routing (CIDR).
  - Subnet prefix of IP address is of arbitrary length.
  - Address format: **a.b.c.d/x**, where **x** is the number of bits in subnet prefix of IP address.

← subnet prefix →← host ID →

11001000 00010111 00010000 00101010

this subnet contains 2^9 IP addresses
subnet prefix: 200.23.16.42/23

/23 indicates the no. of bits of subnet prefix

Subnet Mask

- Subnet mask is used to determine which subnet an IP address belongs to.
  - made by setting all subnet prefix bits to "1"s and host ID bits to "0"s.
- Example: for IP address 200.23.16.42/23:

	← subnet prefix →			← host ID →
IP address in binary	11001000	00010111	00010000	00101010
Subnet mask	11111111	11111111	11111110	00000000
Subnet mask in decimal	255.255.254.0			

Quiz

- For the following 4 IP addresses, which one is in a different subnet from the rest 3?

  a. 172.26.185.128/26

  b. 172.26.185.130/26

  c. 172.26.185.160/26

  d. 172.26.185.192/26

IP Address Allocation

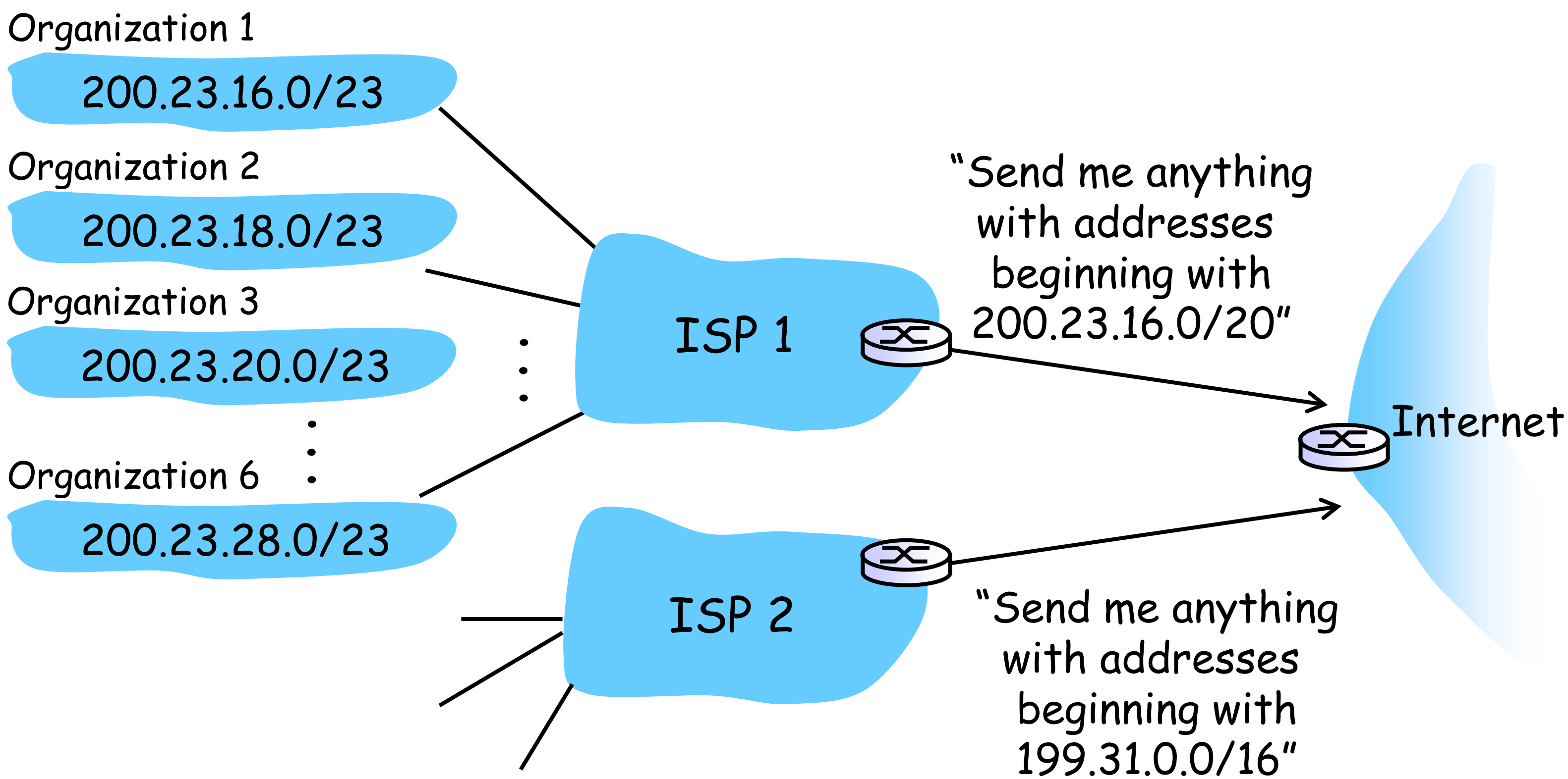
- Q: How does an organization obtain a block of IP addresses?
- A: Buy from registry or rent from ISP's address space.

	Binary Address	Decimal Address
ISP's block	11001000 00010111 0001 000 0 00000000	200.23.16.0/20
Organization 1	11001000 00010111 0001 000 0 00000000	200.23.16.0/23
Organization 2	11001000 00010111 0001 001 0 00000000	200.23.18.0/23
Organization 3	11001000 00010111 0001 010 0 00000000	200.23.20.0/23
...	...	...
Organization 6	11001000 00010111 0001 101 0 00000000	200.23.28.0/23

use 3 more bits to differentiate 6 organizations

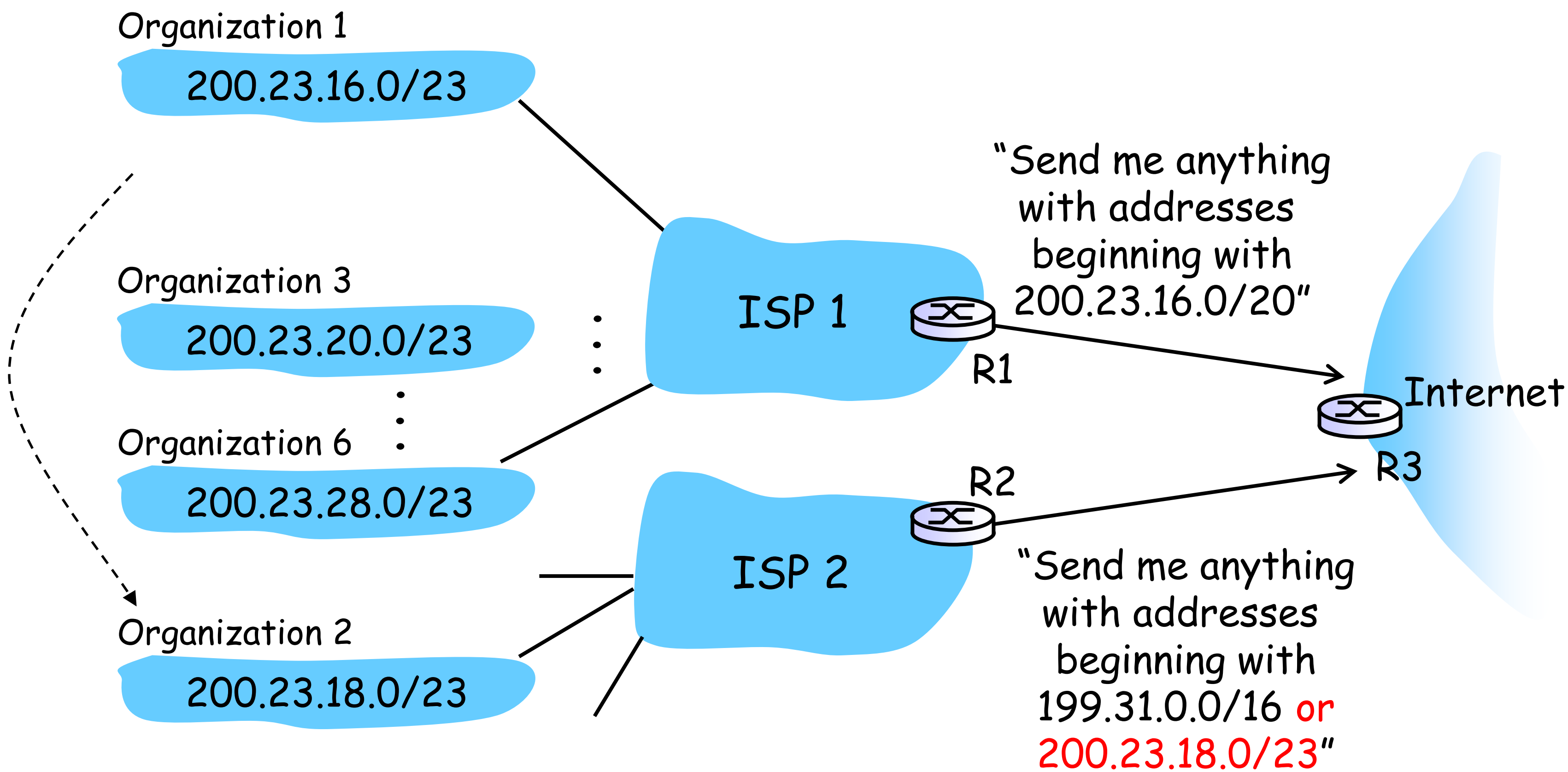
Hierarchical Addressing

Hierarchical addressing allows efficient advertisement of routing information:



Hierarchical Addressing

Suppose Organization 2 now switches to ISP 2, but doesn't want to renumber all of its routers and hosts.

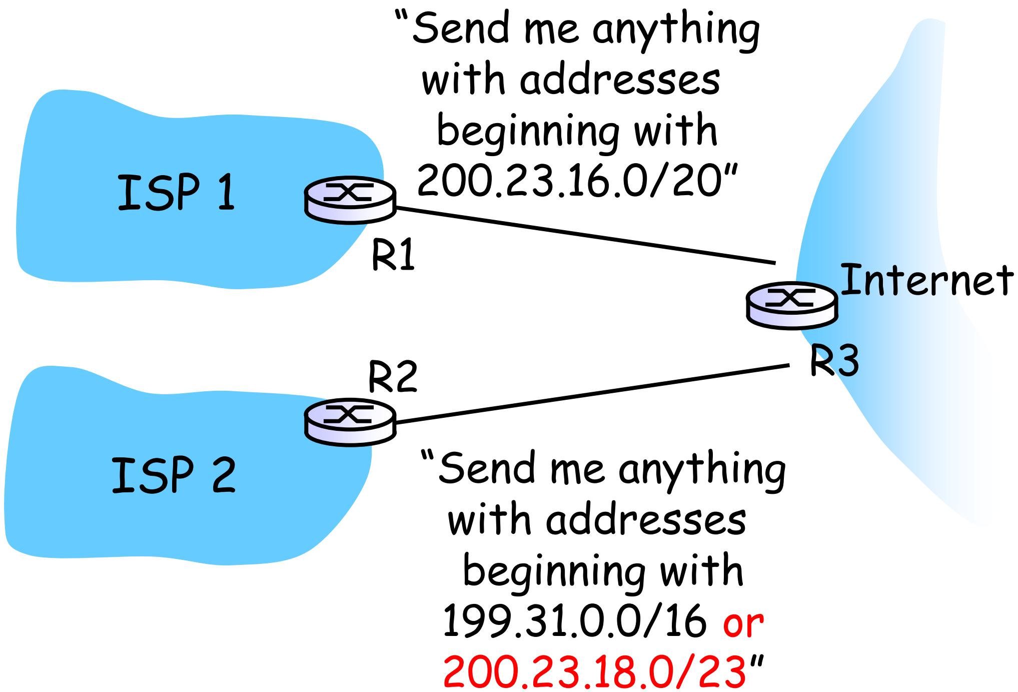


Longest Prefix Match (1/2)

- Question: which router to deliver to,
  - if a packet has destination IP 200.23.20.2?
  - if a packet has destination IP 200.23.19.3?

Forwarding Table at R3

Net mask	Next hop
200.23.16.0/20	R1
200.23.18.0/23	R2
199.31.0.0/16	R2
…	…



Longest Prefix Match (2/2)

- Packet with destination IP 200.23.20.2 ⇨ R1
  - (Binary: 11001000 00010111 00010100 00000010)
- Packet with destination IP 200.23.19.3 ⇨ R2
  - (Binary: 11001000 00010111 00010011 00000011)

match the longest prefix

Forwarding Table at R3

Net mask	Net mask in binary	Next hop
200.23.16.0/20	11001000 00010111 00010000 00000000	R1
200.23.18.0/23	11001000 00010111 00010010 00000000	R2
199.31.0.0/16	11000111 00011111 00000000 00000000	R2
…		…

More on IP Address Allocation

- Q1: How does an organization obtain a block of IP addresses?
- A1: Buy from registry or rent from ISP's address space.

- Q2: How does an ISP get a block of addresses?
- A2: ICANN: Internet Corporation for Assigned Names and Numbers
  - Allocates addresses
  - Manages DNS
  - Assigns domain names, resolves disputes

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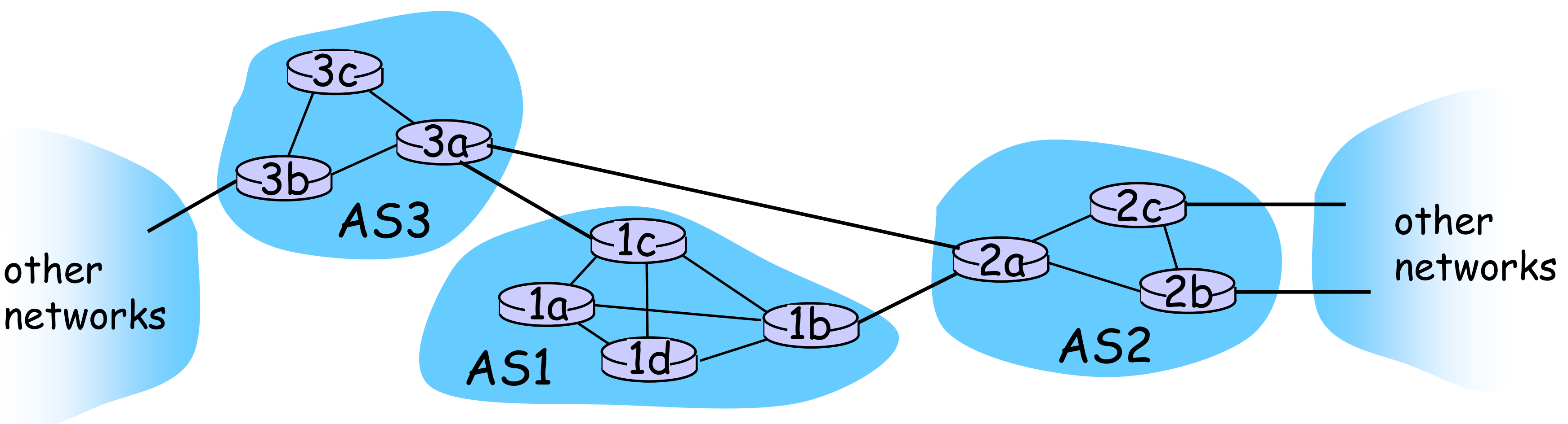
5.2 Routing Algorithms

- 5.2.2 The Distance Vector Routing Algorithm

5.6 ICMP

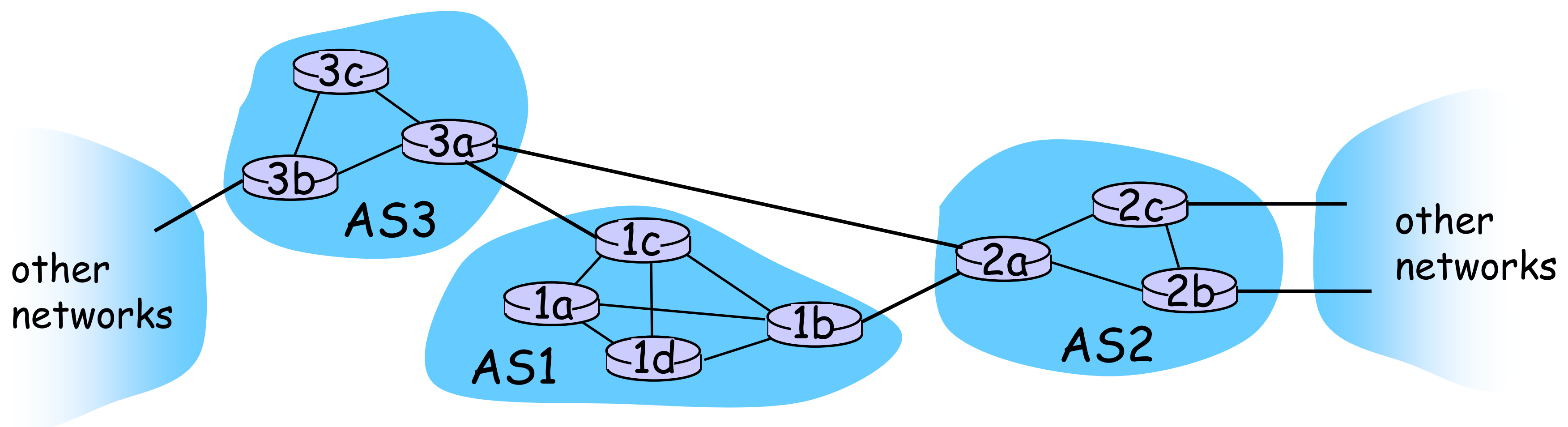
Internet: Network of Networks

- The Internet is a "network-of-networks".
  - A hierarchy of Autonomous Systems (AS), e.g., ISPs, each owns routers and links.
- Due to the size of the Internet and the decentralized administration of the Internet, routing on the Internet is done hierarchically.



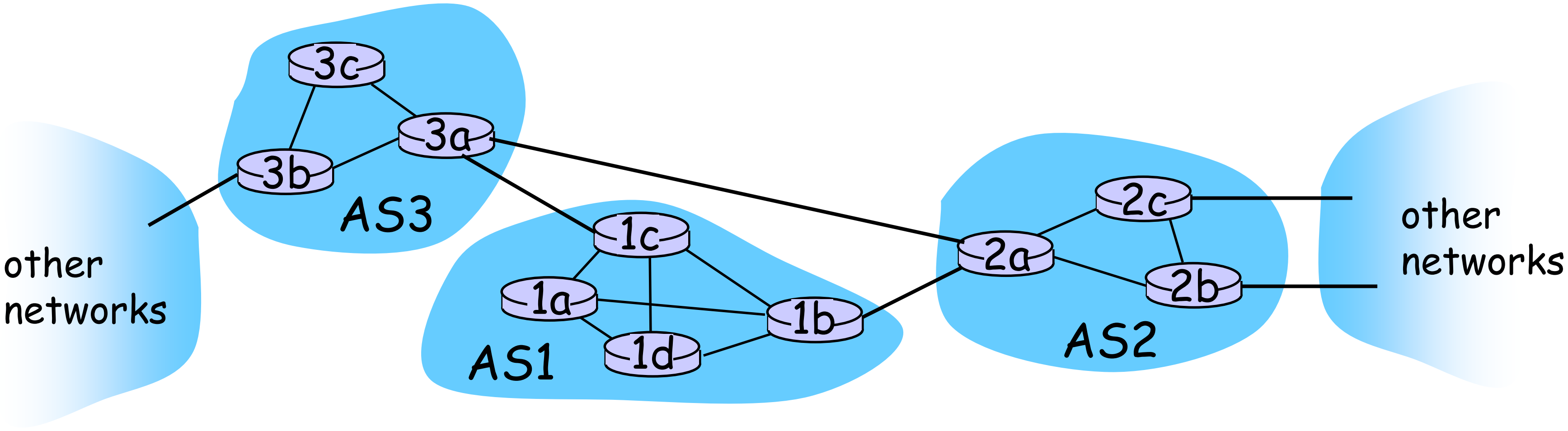
Routing in The Internet

- Intra-AS routing
  - Finds a good path between two routers within an AS.
  - Commonly used protocols: **RIP**, **OSPF**
- Inter-AS routing (not covered)
  - Handles the interfaces between ASs.
  - The de facto standard protocol: **BGP**

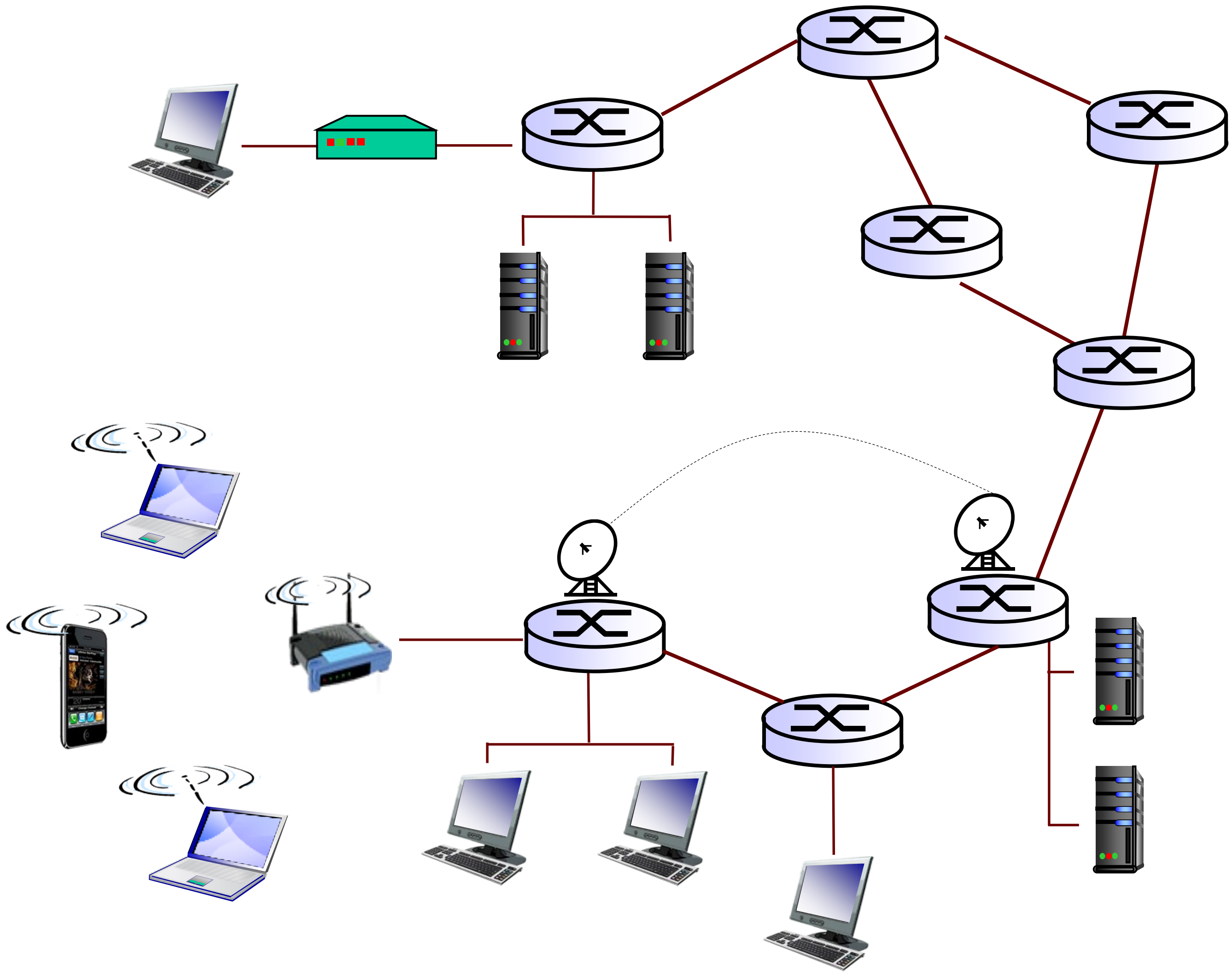


Routing in The Internet

- Intra-AS routing
  - Single admin, so no policy decisions are needed.
  - Routing mostly focus on performance.
- Inter-AS routing (not covered)
  - Admin often wants to control over how its traffic is routed, who routes through its net, etc.
  - Policy may dominate over performance.

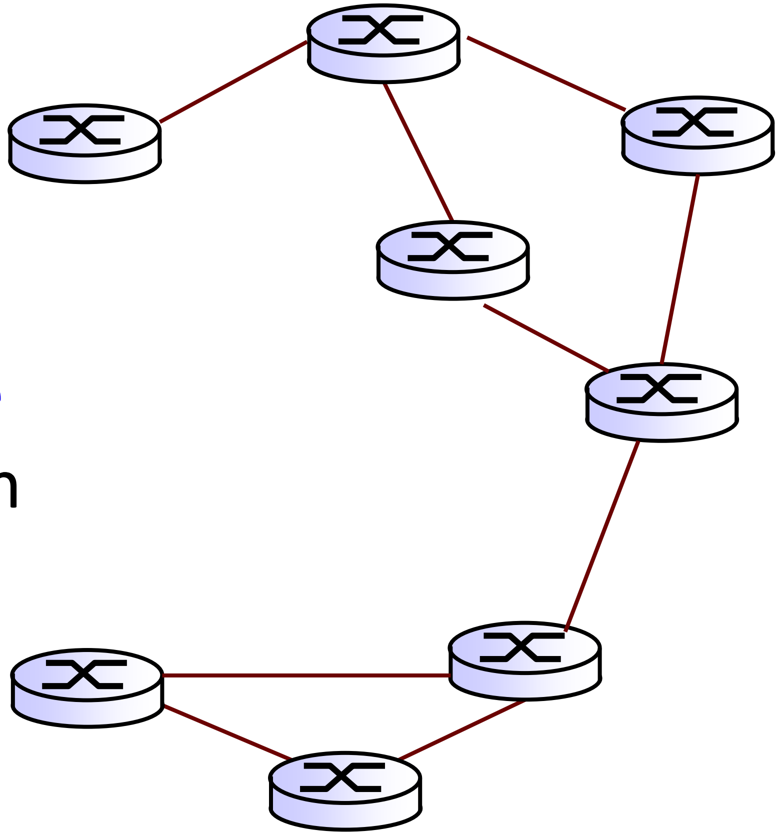


Abstract View of Intra-AS Routing



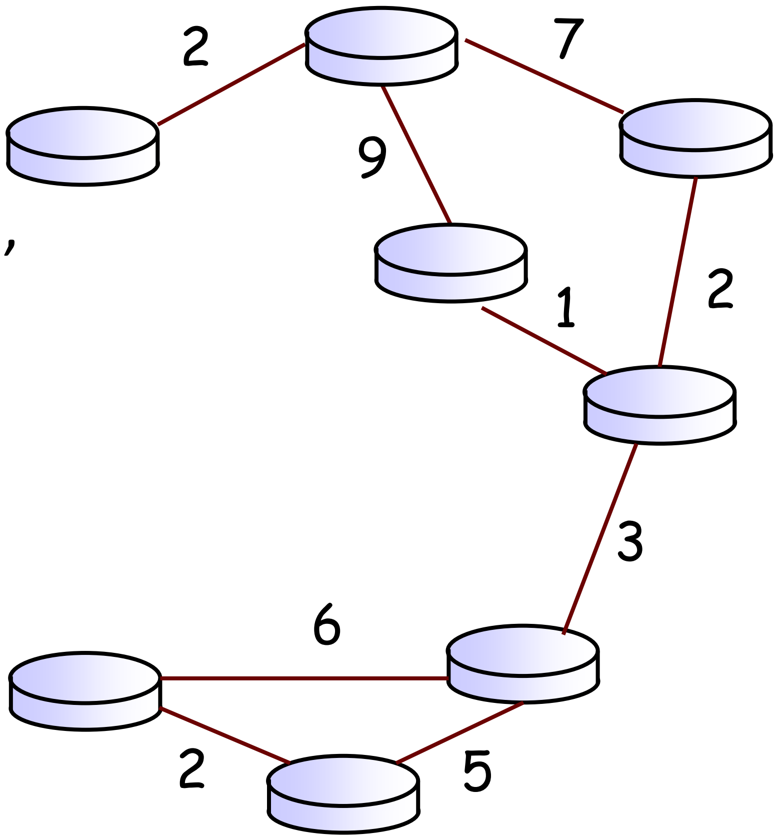
Abstract View of Intra-AS Routing

- We can abstractly view a network of routers as a graph, where vertices are routers and edges are physical links between routers.



Abstract View of Intra-AS Routing

- We can associate a cost to each link.
  - cost could always be 1, or inversely related to bandwidth, or related to congestion.

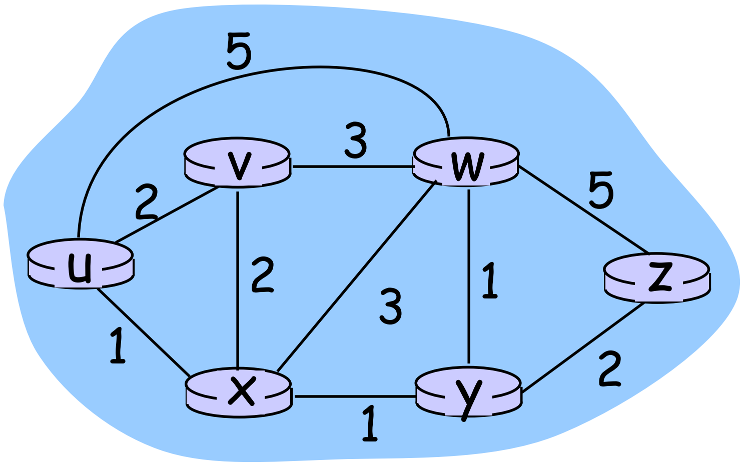


Routing: finding a least cost path between two vertices in a graph

Routing Algorithms Classification

"link state" algorithms

- All routers have the complete knowledge of network topology and link cost.
  - Routers periodically broadcast link costs to each other.
- Use Dijkstra algorithm to compute least cost path locally (using global map).
- Non-examinable ☺

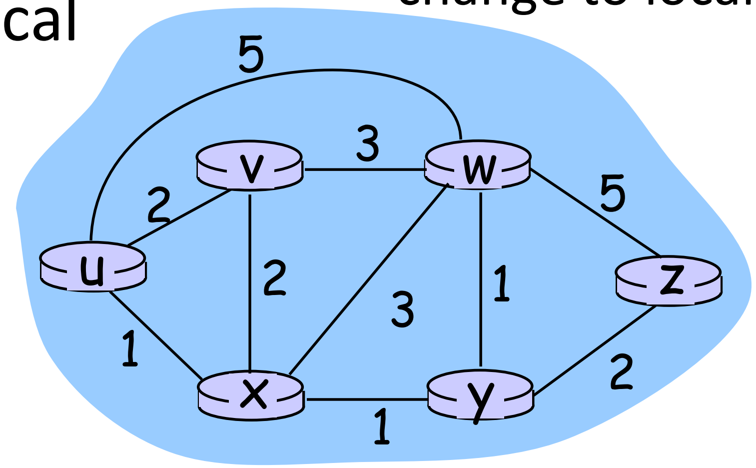


Routing Algorithms Classification

"distance vector" algorithms

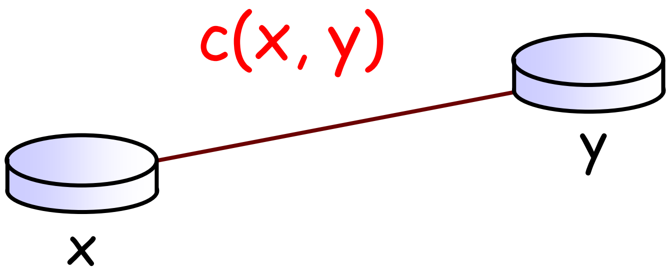
- Routers know physically-connected neighbors and link costs to neighbors.
- Routers exchange "local views" with neighbors and update own "local views" (based on neighbors' view).

- Iterative process of computation
  1. Swap local view with <u>direct</u> neighbours.
  2. Update own's local view.
  3. Repeat 1 - 2 till no more change to local view.

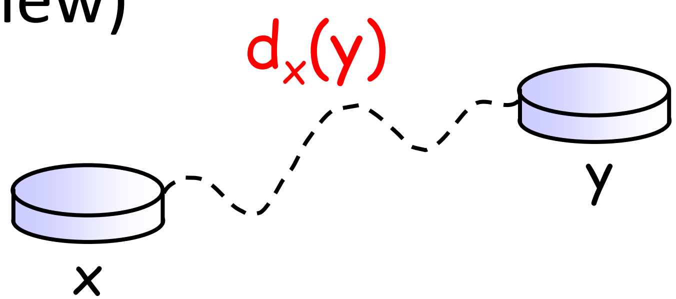


Some Graph Notations

- $c(x, y)$: the cost of link between routers x and y
  - = ∞ if x and y are not direct neighbours



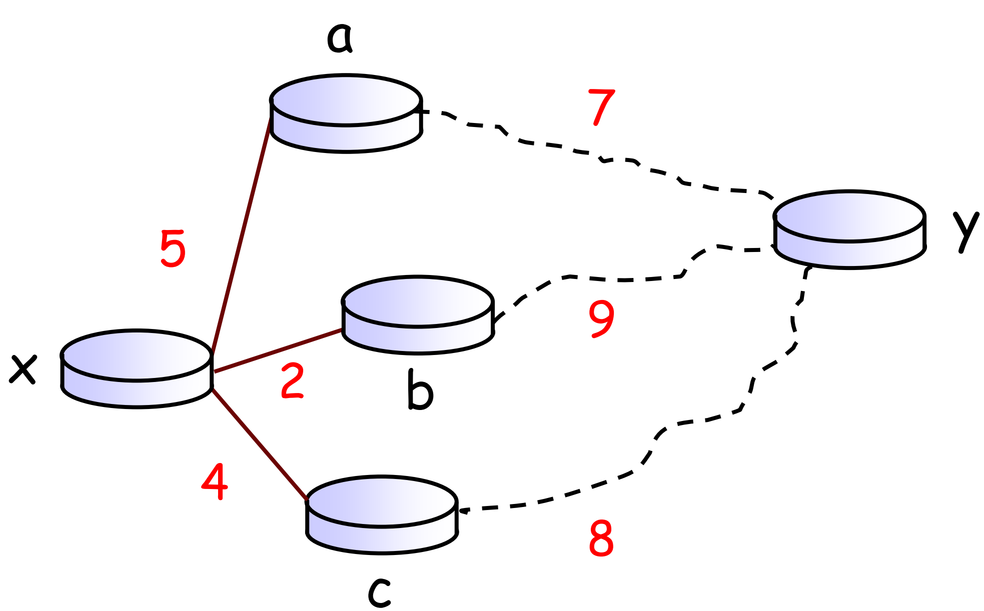
- $d_x(y)$: the cost of the least-cost path from x to y (from x's view)



Bellman-Ford Equation

$$d_x(y) = min_v\,\{c(x,v) + d_v(y)\}$$

where min is taken over all direct neighbors v of x

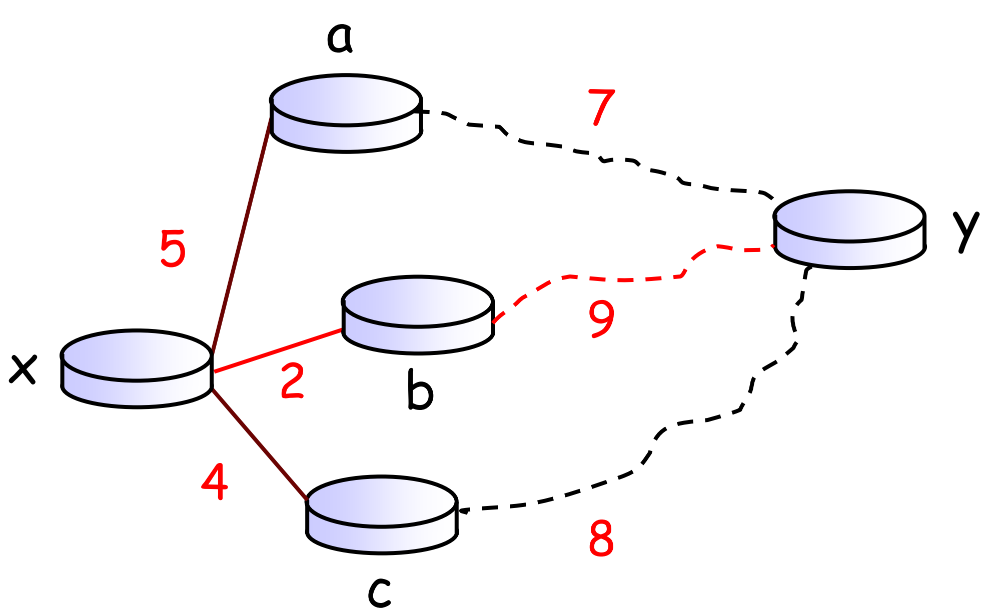


$$\begin{aligned} d_x(y) = min_v\,\{\, & c(x,a) + d_a(y), \\ & c(x,b) + d_b(y), \\ & c(x,c) + d_c(y)\,\} \end{aligned}$$

$$= min\,\{12, 11, 12\} = 11$$

Bellman-Ford Equation

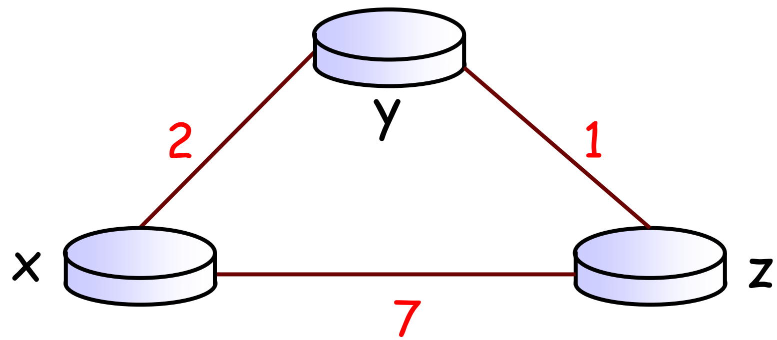
- To find the least cost path, x needs to know the cost from each of its direct neighbour to y.
- Each neighbour v sends its distance vector (y, k) to x, telling x that the cost from v to y is k.



Now x knows, to reach y, packet should be forward to b and the total cost would be 11.

Bellman-Ford Example

$$d_x(y) = min_v\{c(x,v) + d_v(y)\}$$



cost to

from

	x	y	z
x			
y			
z			

x' view

cost to

from

	x	y	z
x			
y			
z			

y' view

cost to

from

	x	y	z
x			
y			
z			

z' view

Distance Vector Algorithm

- Every router, **x**, **y**, **z**, sends its distance vectors to its directly connected neighbors.
- When **x** finds out that **y** is advertising a path to **z** that is cheaper than **x** currently knows,
  - **x** will update its distance vector to **z** accordingly.
  - In addition, **x** will note down that all packets for **z** should be sent to **y**. This info will be used to create forwarding table of **x**.
- After every router has exchanged several rounds of updates with its direct neighbors, all routers will know the least-cost paths to all the other routers.

RIP

- RIP (Routing Information Protocol) implements the DV algorithm. It uses hop count as the cost metric (i.e., insensitive to network congestion).
- Exchange routing table every 30 seconds over UDP port 520.
- "Self-repair": if no update from a neighbour router for 3 minutes, assume neighbour has failed.

Lectures 6&7: Roadmap

4.1 Overview of Network Layer

4.2 What's Inside a Router

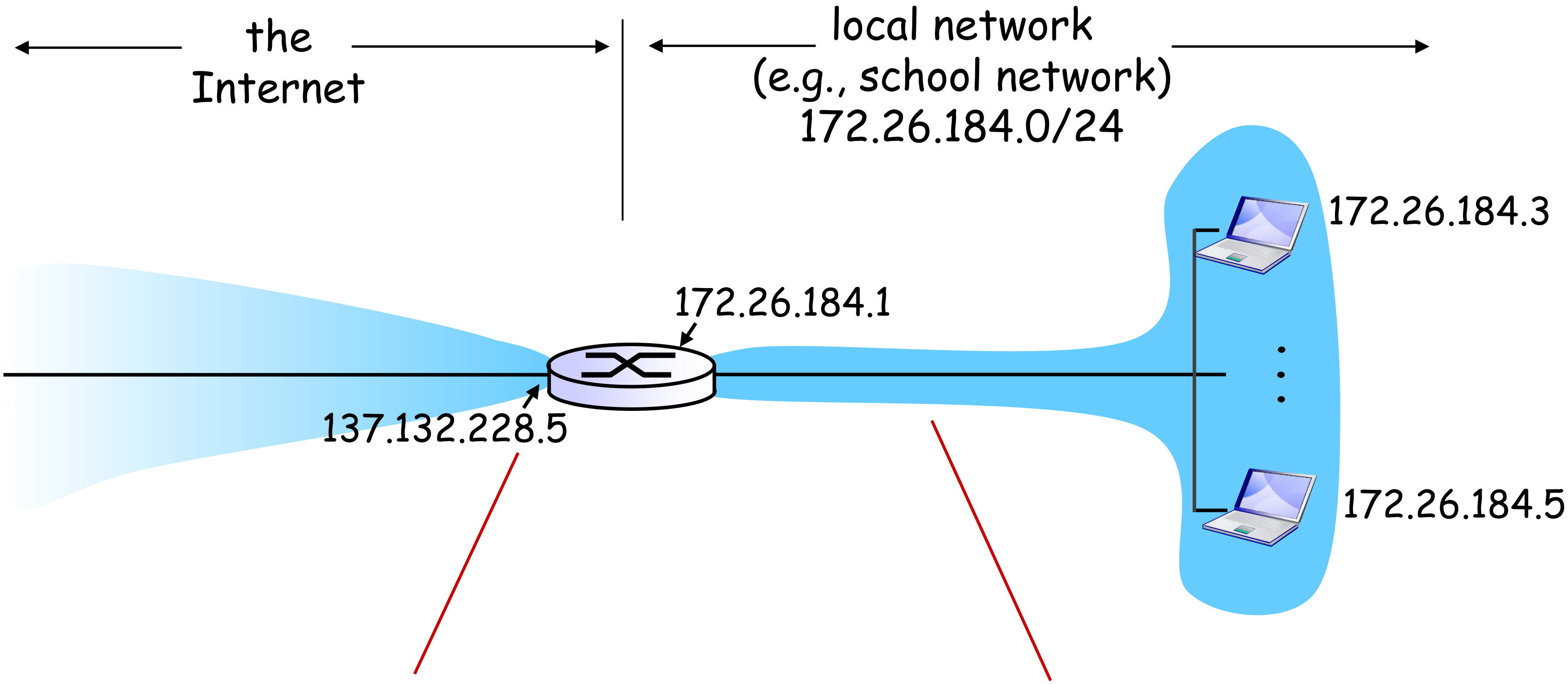
4.3 The Internet Protocol (IP)

- 4.3.4 Network Address Translation

5.2 Routing Algorithms

5.6 ICMP

NAT: Network Address Translation



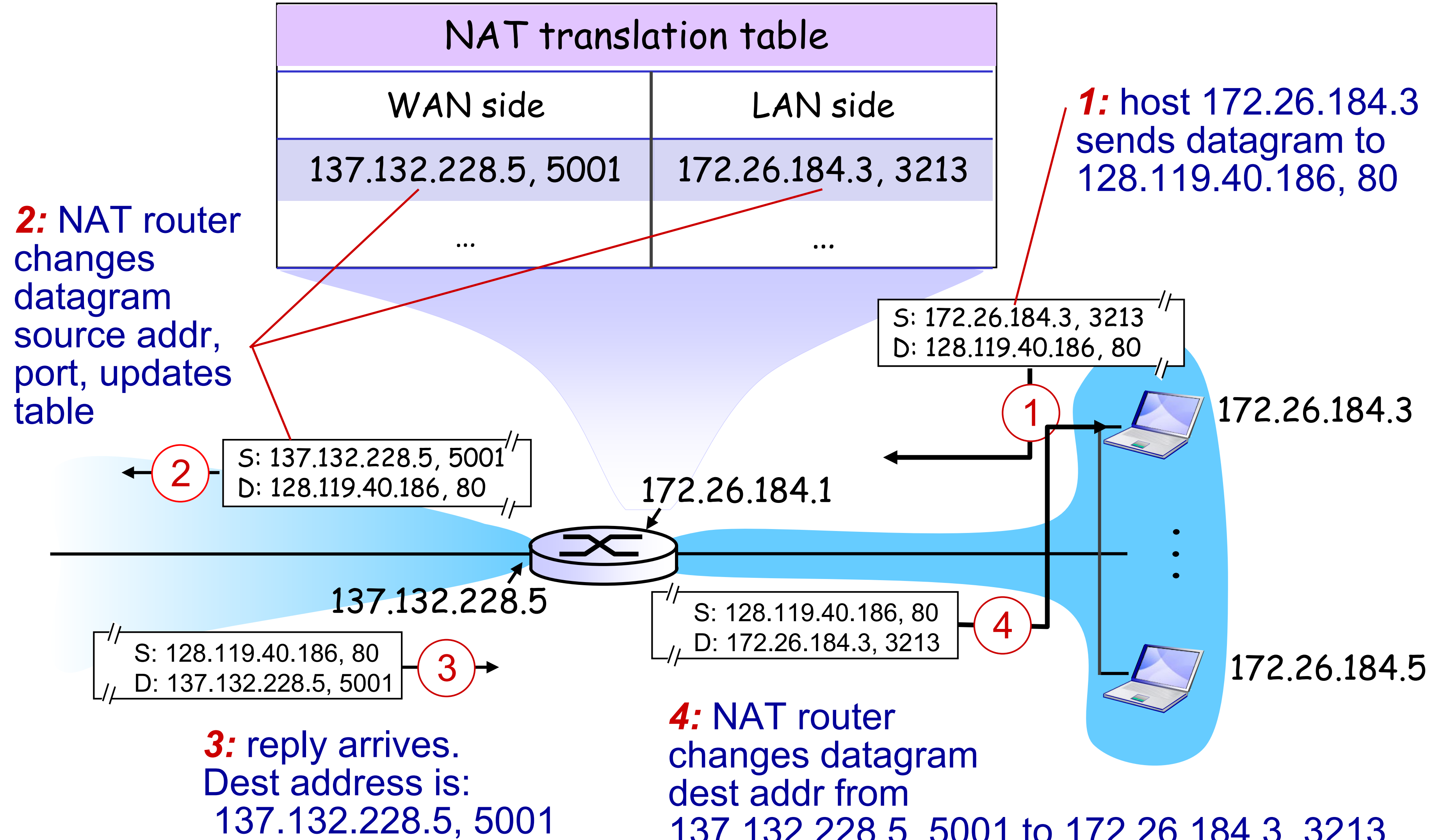
all datagrams *leaving* local network have the *same* source NAT IP address: 137.132.228.5

Within local network, hosts use private IP addresses 172.26.184.* for communication

NAT: Implementation

- NAT routers must:
  - Replace (source IP address, port #) of every outgoing datagram to (NAT IP address, new port #).
  - Remember (in NAT translation table) the mapping from (source IP address, port #) to (NAT IP address, new port #).
  - Replace (NAT IP address, new port #) in destination fields of every incoming datagram with corresponding (source IP address, port #) stored in NAT translation table.

NAT: Illustration



NAT translation table

WAN side	LAN side
137.132.228.5, 5001	172.26.184.3, 3213
…	…

NAT: Motivation and Benefits

- No need to rent a range of public IP addresses from ISP: just one public IP for the NAT router.
- All hosts use private IP addresses. Can change addresses of hosts in local network without notifying the outside world.
- Can change ISP without changing addresses of hosts in local network.
- Hosts inside local network are not explicitly addressable and visible by outside world (a security plus).

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- 4.3.1 IPv4 Datagram Format
- 4.3.2 IPv4 Datagram Fragmentation
- 4.3.5 IPv6 (non-examinable)

5.2 Routing Algorithms

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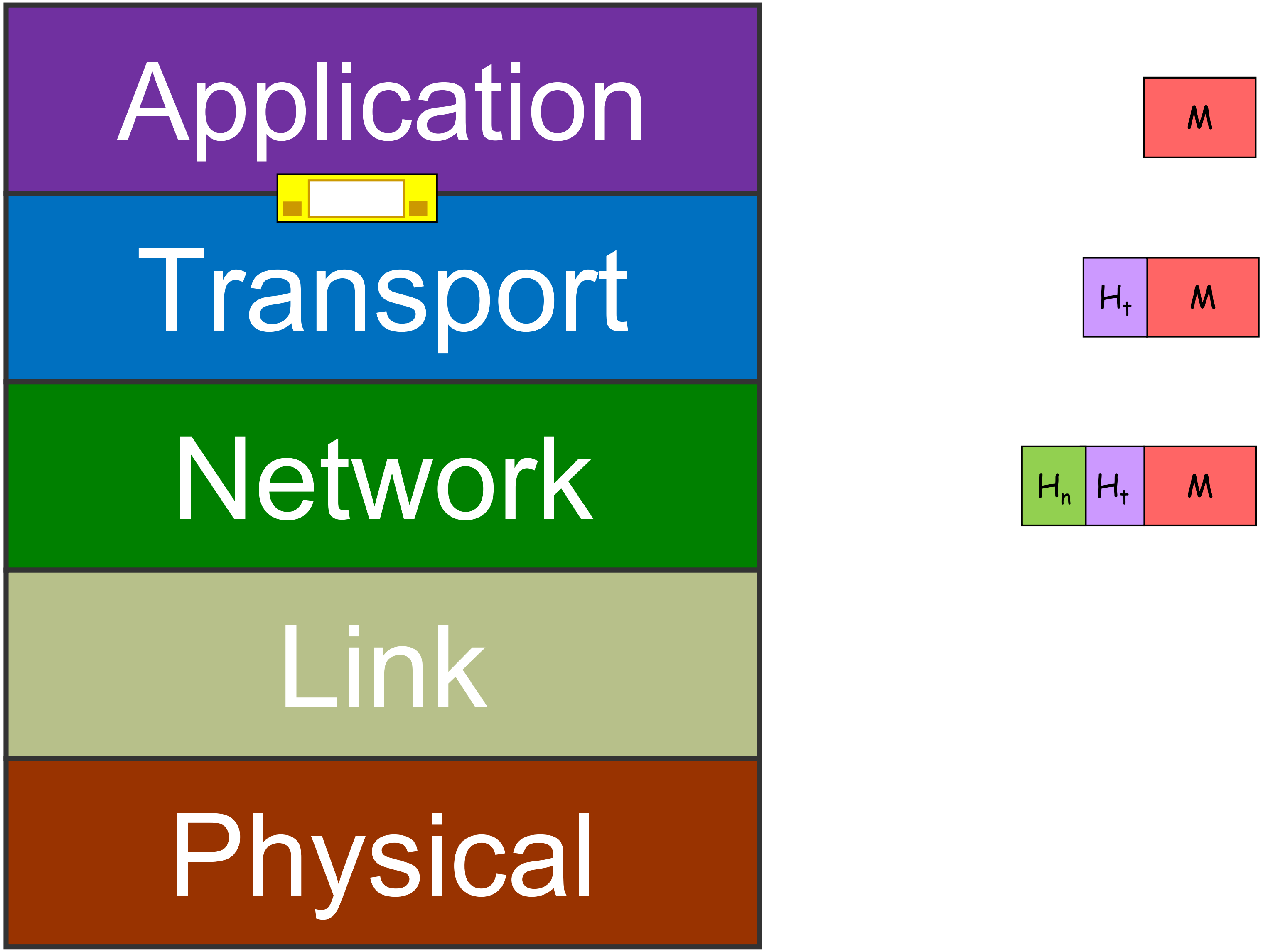
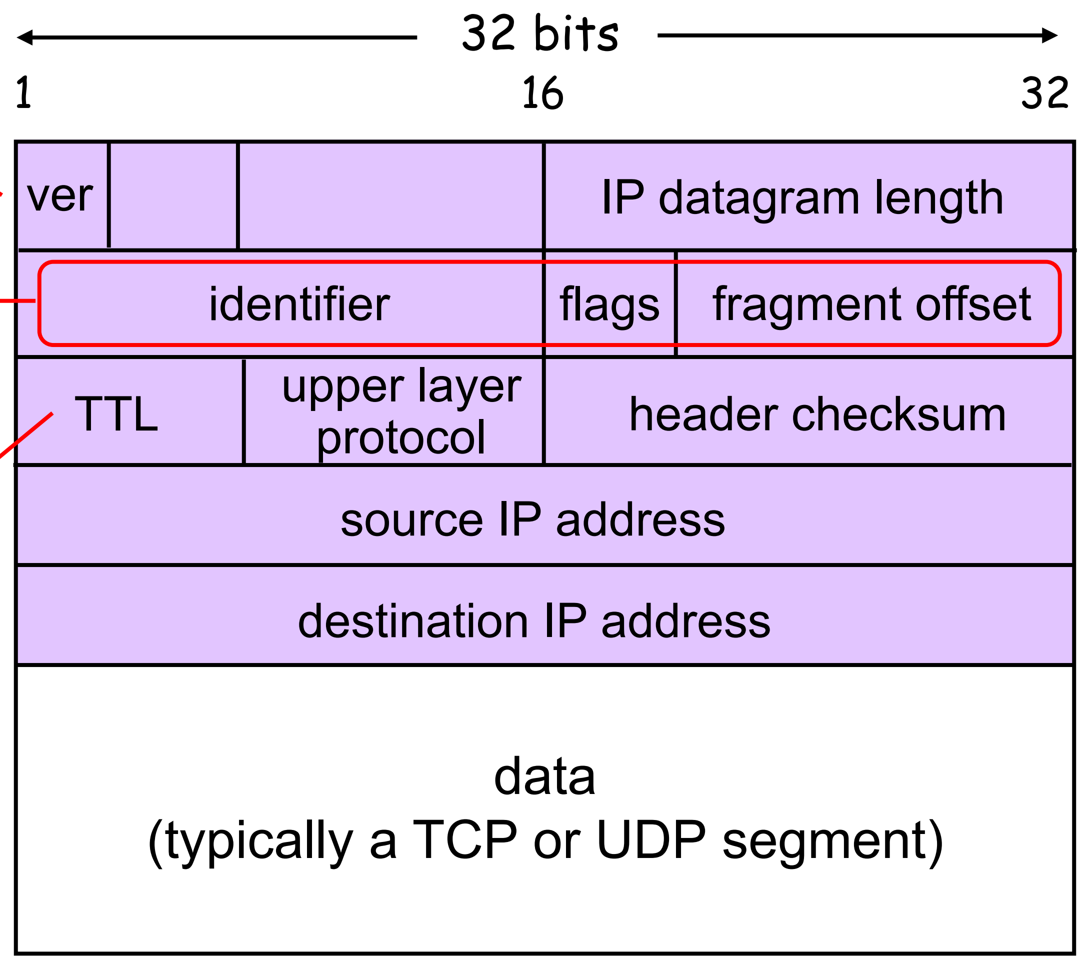


Application
Transport
Network
Link
Physical
M
H_t
M
H_n
H_t
M

IPv4 Datagram Format

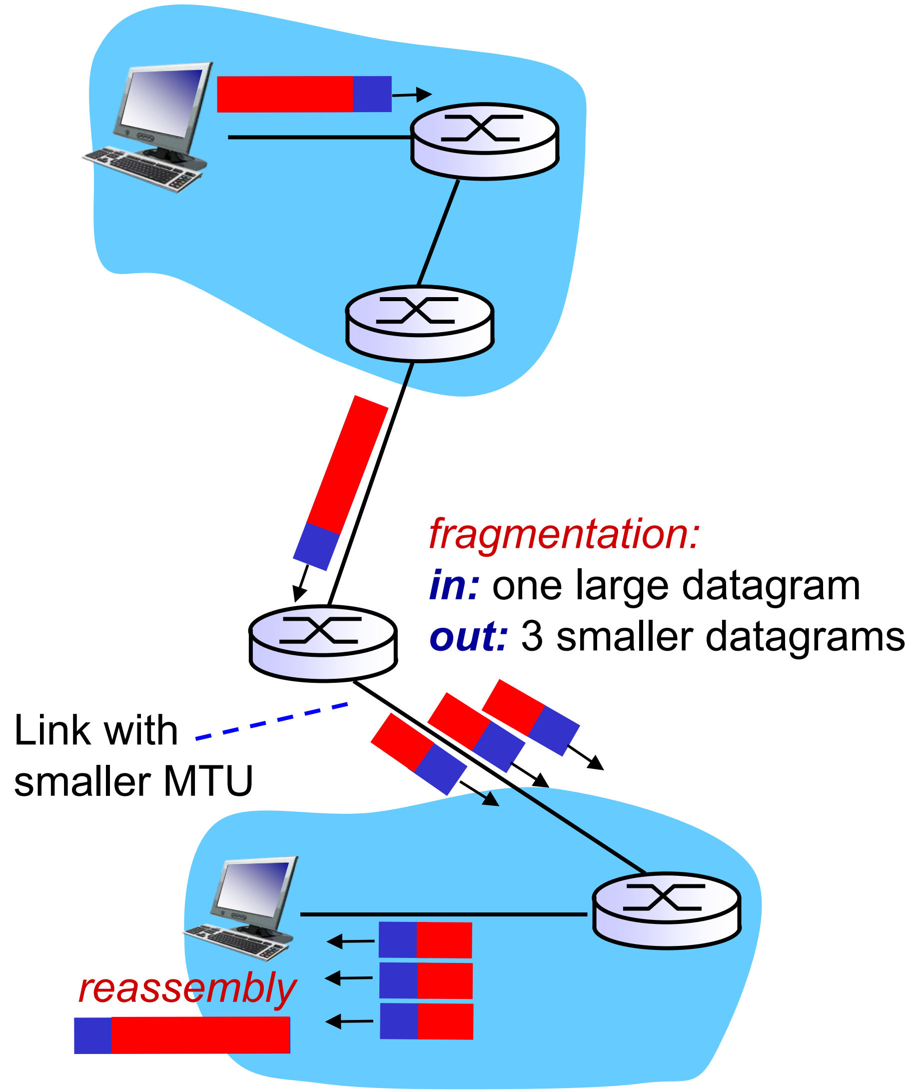


- IP header
  - 20 bytes

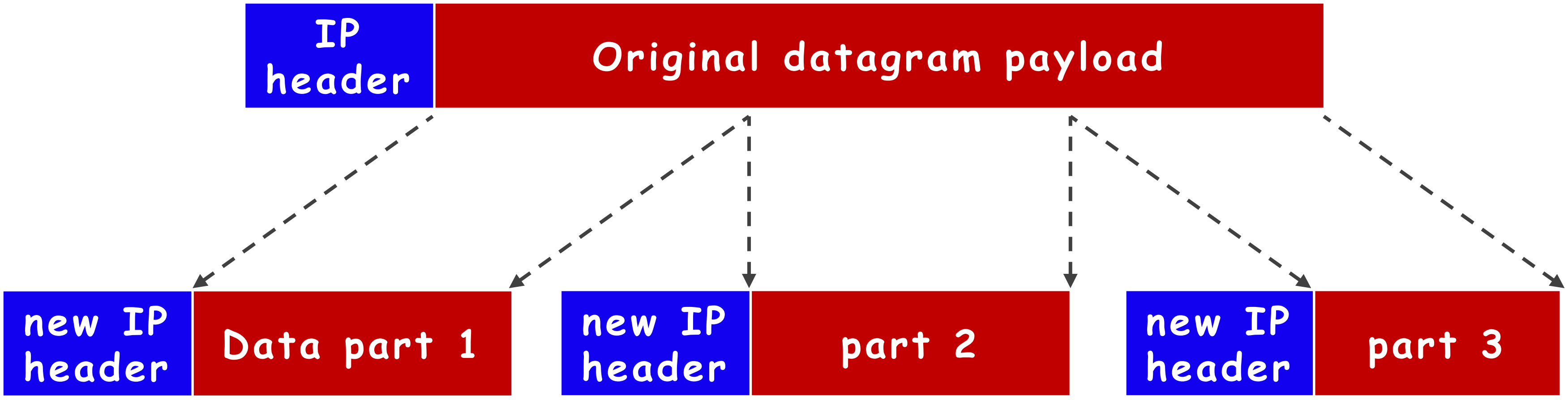
(some fields are not shown)

IP Fragmentation & Reassembly

- Different links may have different MTU (Max Transfer Unit) – the maximum amount of data a link-level frame can carry.
- "Too large" IP datagrams may be fragmented by routers.

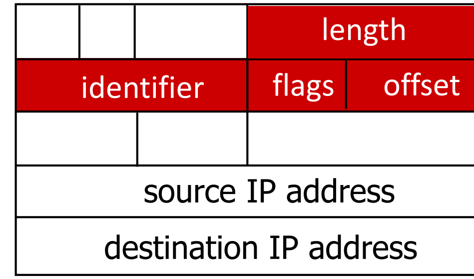


IP Fragmentation Illustration

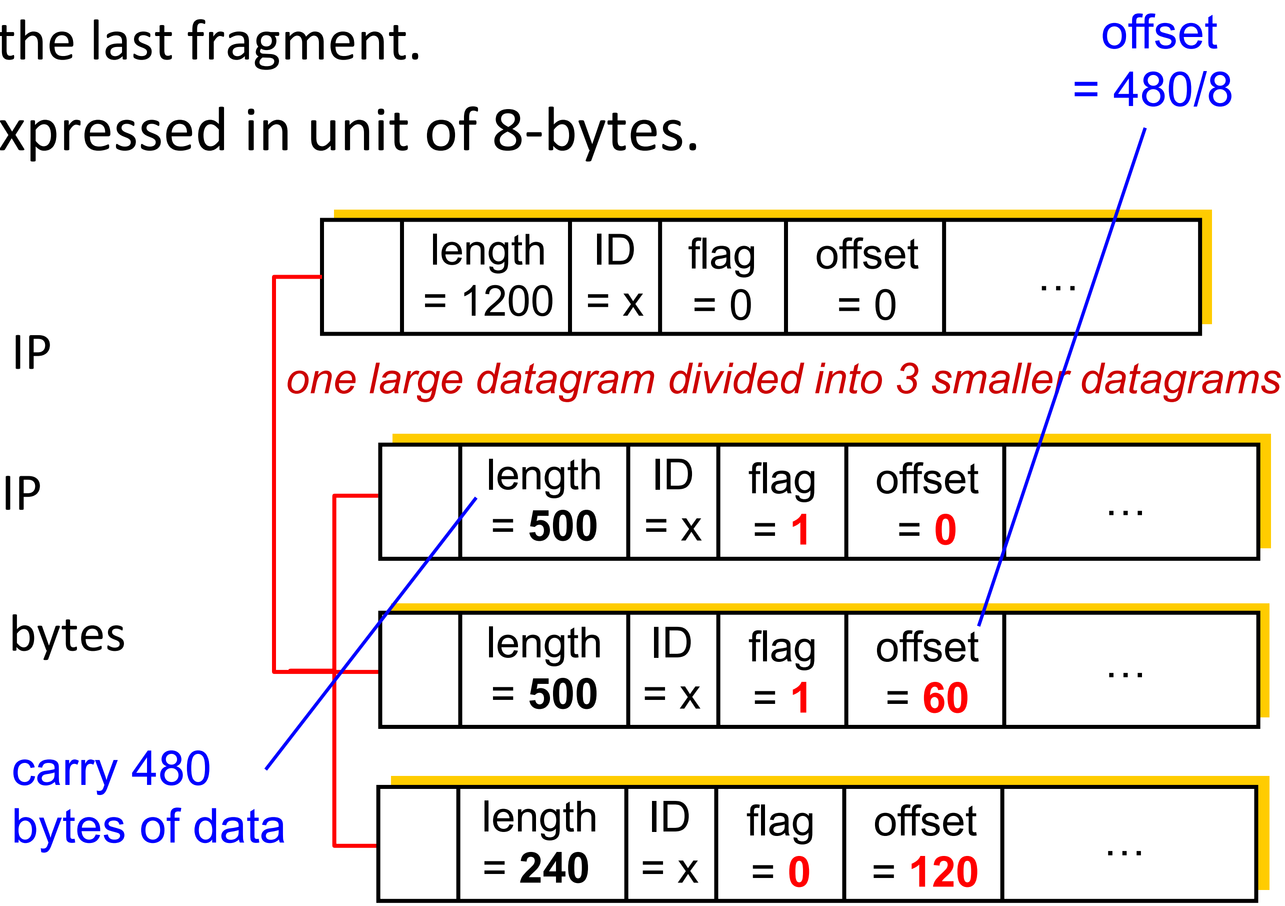


- Destination host will reassemble the packet.
- IP header fields are used to identify fragments and their relative order.

IP Fragmentation



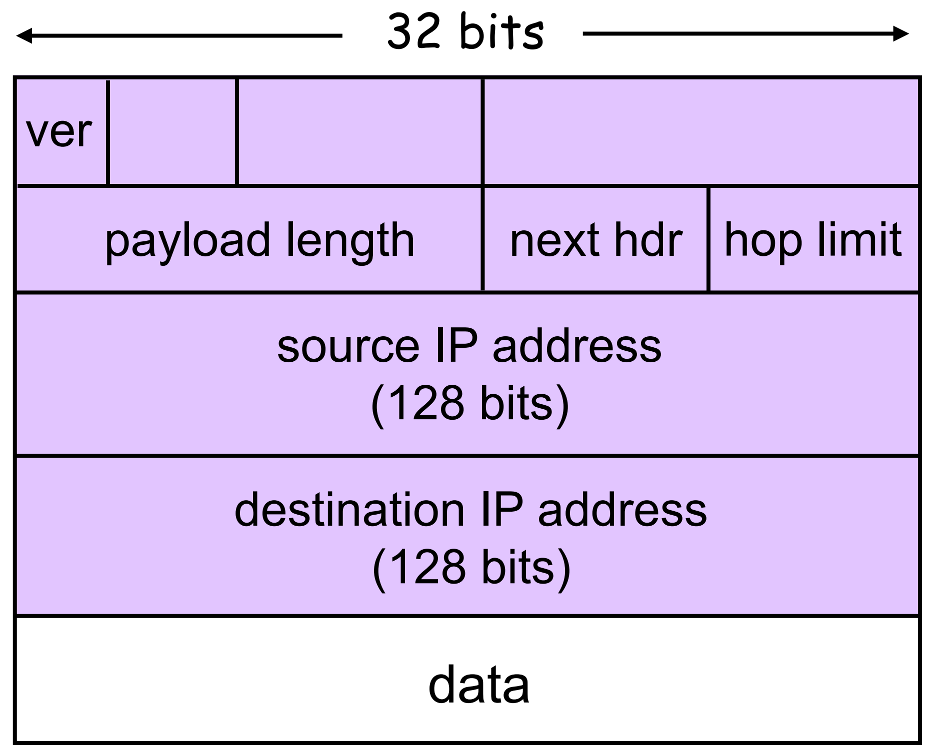
- Flag (frag flag) is set to
  - 1 if there is next fragment from the same segment.
  - 0 if this is the last fragment.
- Offset is in expressed in unit of 8-bytes.
- Example
  - 20 bytes of IP header
  - 1,200 byte IP datagram
  - MTU = 500 bytes



IPv6

Non-examinable

- IPv6 is designed to replace IPv4.
- Primary motivation: 32-bit IPv4 address space is soon to be completely allocated.
- IPv6 datagram:
  - 40 byte header



(some fields are not shown)

Example IPv6 address (in hexadecimal):

2001:0db8:85a3:0042:1000:8a2e:0370:7334

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ICMP

- ICMP (Internet Control Message Protocol) is used by hosts & routers to communicate network-level information.
  - Error reporting: unreachable host / network / port / protocol
  - Echo request/reply (used by *ping*)

- ICMP messages are carried in IP datagrams.
  - ICMP header starts after IP header.

ICMP Type and Code

- ICMP header: Type + Code + Checksum + others.

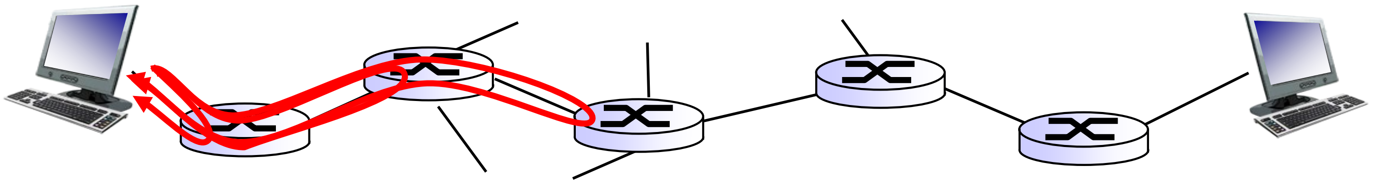
Type	Code	Description
8	0	echo request (ping)
0	0	echo reply (ping)
3	1	dest host unreachable
3	3	dest port unreachable
11	0	TTL expired
12	0	bad IP header

Selected ICMP Type and subtype (Code)

Examples: *ping* and *traceroute*

- The command ping sees if a remote host will respond to us – do we have a connection?

- The command traceroute sends a series of small packets across a network, and attempts to display the route (or path) that the messages would take to get to a remote host.



Lectures 6&7: Summary

- An IP address is associated with a network interface. A device may have multiple network interfaces, thus multiple IP addresses.
- DHCP automates the assignment of IP addresses in an organization's network.
- On TCP/IP networks, subnets are defined as all devices whose IP addresses have the same network (subnet) prefix.
- Subnet mask is useful in checking if two hosts are on the same subnet.

Lectures 6&7: Summary

- Routing is the process of selecting best paths in a network.
- NAT maps one IP addresses space into another.
  - Commonly used to hide an entire private IP address space behind a single public IP address.
  - NAT router uses stateful translation tables to remember the mapping.
- ICMP is used by routers to send error messages.
  - E.g. when TTL is 0, a packet is discarded and an ICMP error message is sent to the datagram's source address.