CS 305: Computer Networks

Fall 2022

Lecture 10: Network Layer – The Data Plane

Ming Tang

Department of Computer Science and Engineering
Southern University of Science and Technology (SUSTech)

Chapter 4: outline

4.1 Overview of Network layer
- data plane
- control plane

4.2 What's inside a router

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

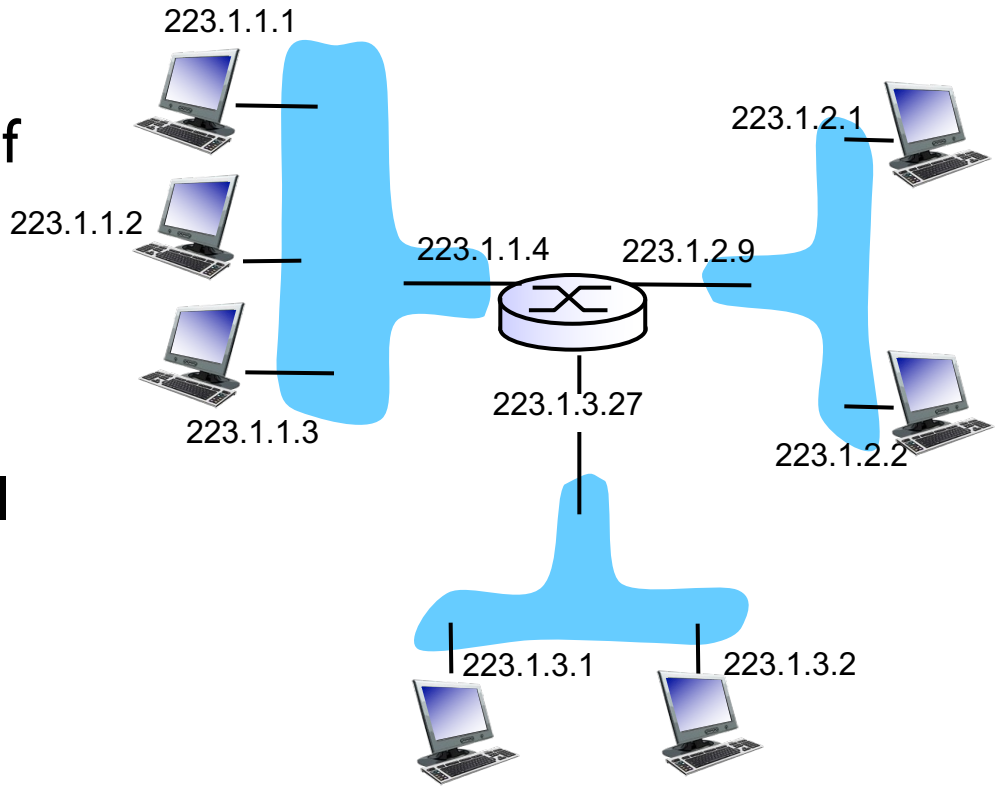
4.4 Generalized Forward and SDN
- match
- action
- OpenFlow examples of match-plus-action in action

Overview

- IP addressing
- Subnet
- How to assign/obtain IP address?

IP addressing: introduction

- *IP address:* 32-bit identifier for interface of hosts and routers
- *interface:* (network interface card) connection between host/router and physical link
  - router's typically have multiple interfaces
  - host typically has one or two interfaces (e.g., wired Ethernet, wireless 802.11)
- *IP addresses associated with each interface*



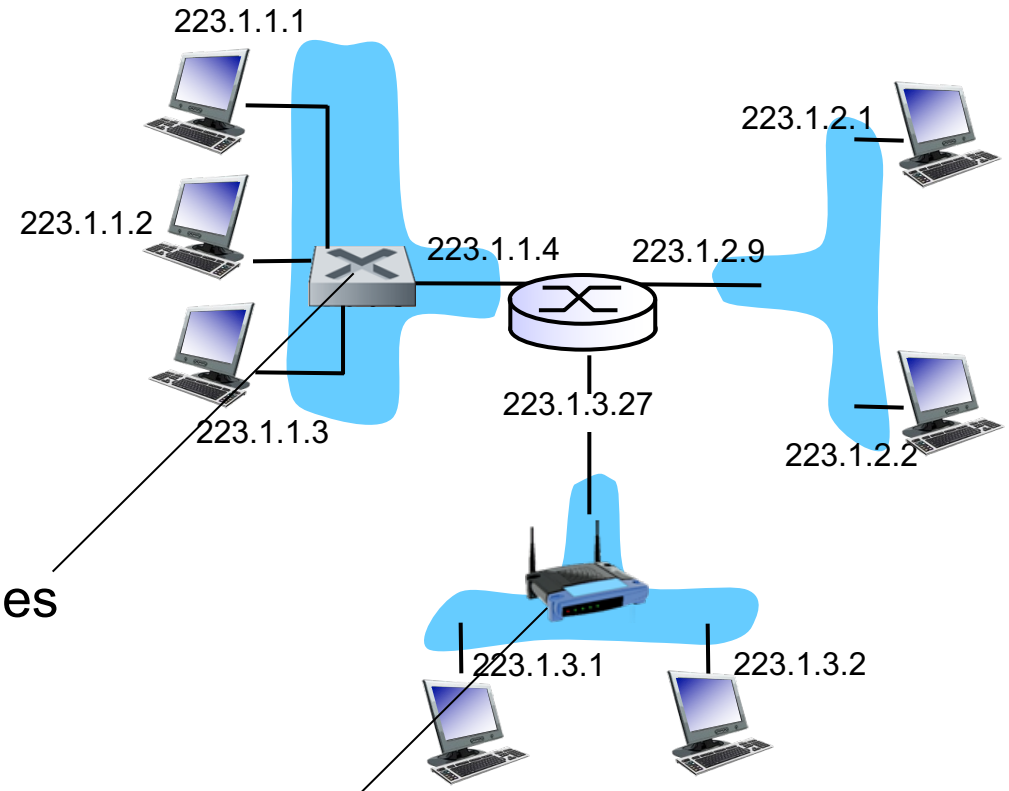
223.1.1.1 = 11011111 00000001 00000001 00000001

223 1 1 1

IP addressing: introduction

Q: how are interfaces actually connected?

A: we'll learn about that in chapter 5, 6.



A: wired Ethernet interfaces connected by Ethernet switches

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

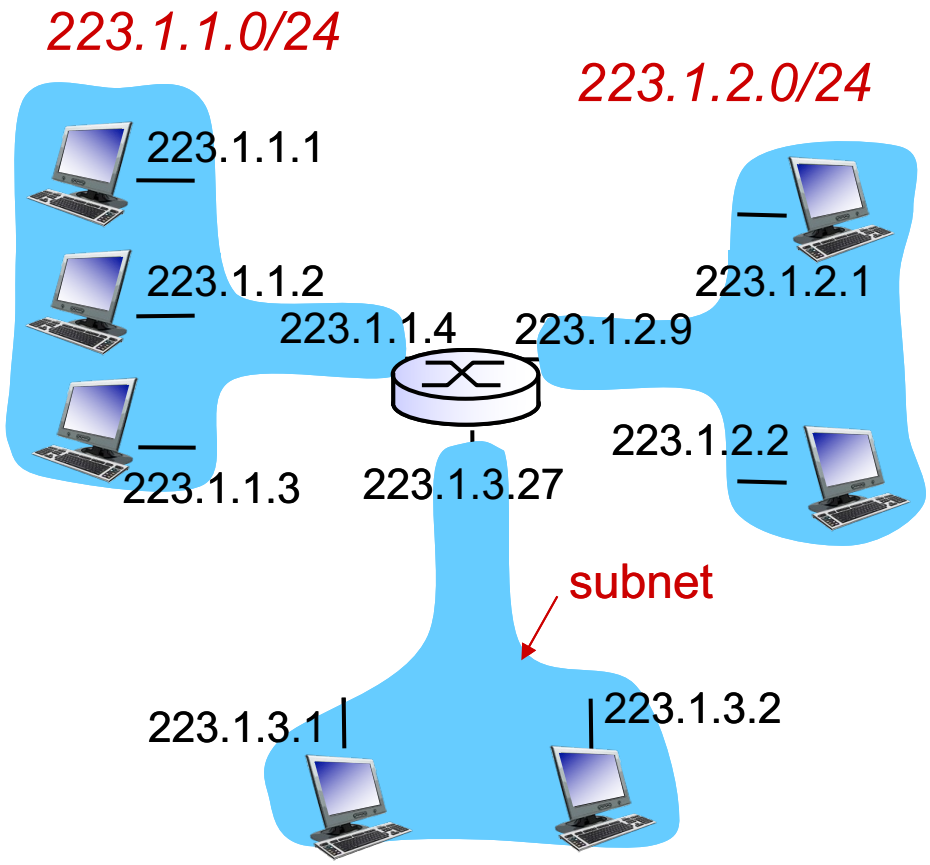
A: wireless WiFi interfaces connected by WiFi base station

Overview

- IP addressing
- Subnet
- How to assign/obtain IP address?

Subnets

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



network consisting of 3 subnets

223.1.3.0/24

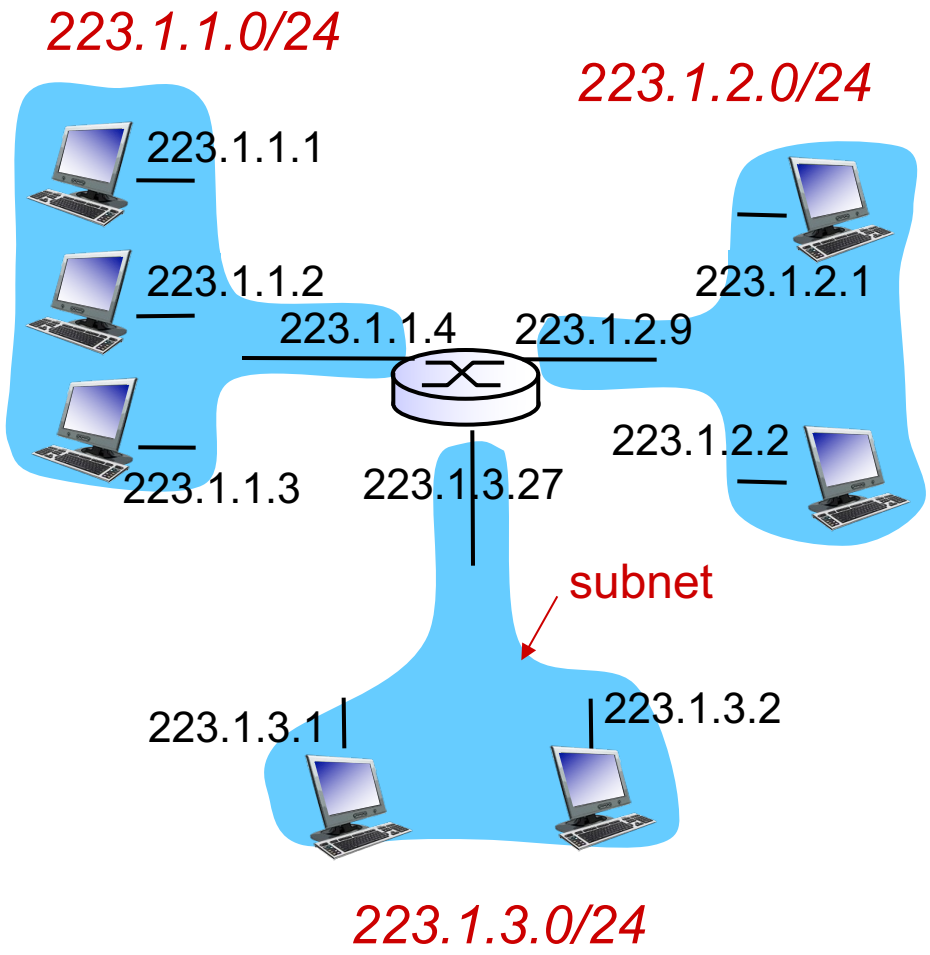
subnet mask: /24

255.255.255.0

Subnets

recipe

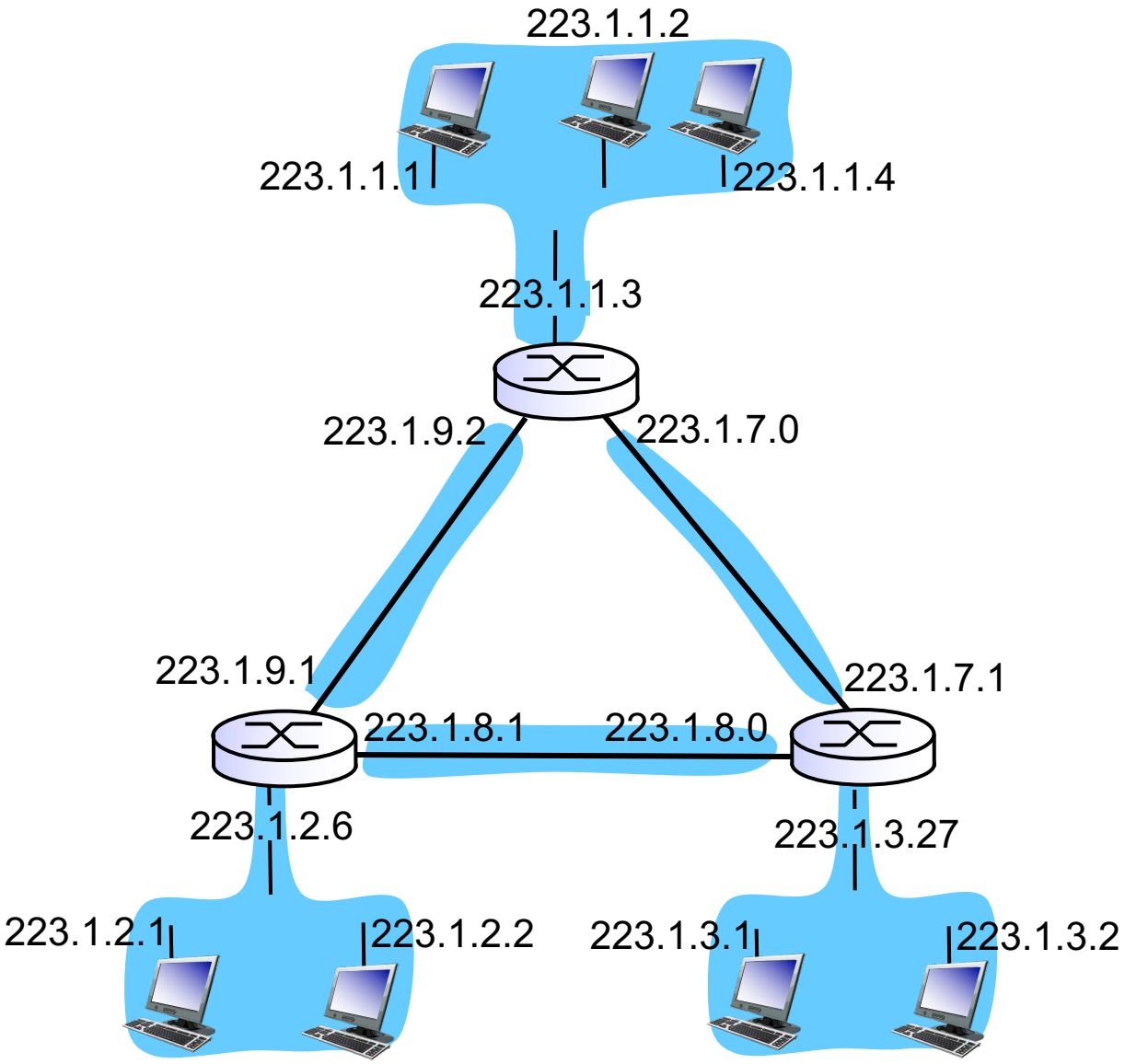
- to determine the subnets, detach each interface from its host or router, creating islands of isolated networks
- each isolated network is called a *subnet*



subnet mask: /24
255.255.255.0

Subnets

how many?



subnet mask: /24

255.255.255.0

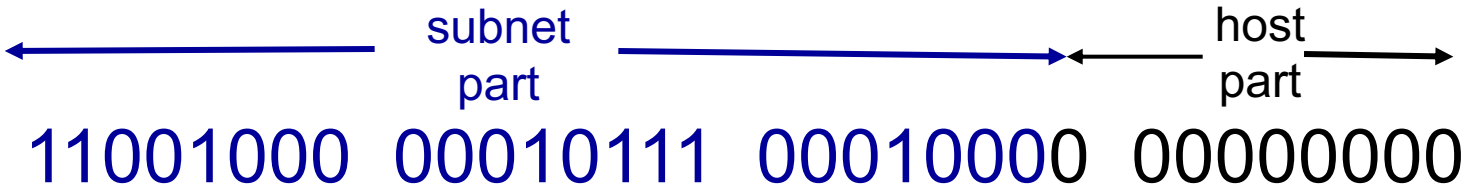
Overview

- IP addressing
- Subnet
- How to assign/obtain IP address?

Subnet addressing: CIDR

CIDR: Classless InterDomain Routing

- A method to assign blocks of IP address
- subnet portion of address of arbitrary length
- Subnet address format: a.b.c.d/x, where x is number of bits in subnet portion of address



- Subnet mask: 255.255.254.0
- Subnet address/block of addresses: 200.23.16.0/23
- Available IP addresses in this subnet?

Overview

- How does an ISP get a block of addresses?
- How does a subnet get a block of addresses?
- How does a host get an IP?

How does an ISP get block of addresses?

Q: how does an ISP get block of addresses?

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

- allocates addresses
- manages DNS
- assigns domain names

How does a subnet get block of addresses?

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

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

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

How does a subnet get block of addresses?

Suppose all of the interfaces in each of these three subnets are required to have the prefix 166.4.20.128/25.

- Subnet 1 is required to support at least 62 interfaces
- Subnet 2 is required to support at least 30 interfaces
- Subnet 3 is required to support at least 28 interfaces

Provide three network addresses (of the form a.b.c.d/x) that satisfy these constraints.

How does a subnet get block of addresses?

Block of addresses: 166.4.20.128/25. Subnet 1: at least 62 interfaces; Subnet 2: at least 30 interfaces; Subnet 3: at least 28 interfaces

This block of IP addresses can be written as

10100110 00000100 00010100 10000000

Subnet 1: since $2^6 = 64 > 62$, we can assign the following block

10100110 00000100 00010100 10000000

which can be represented as 166.4.20.128/26.

Subnet 2: since $2^5 = 32 > 30$, we can assign the following block

10100110 00000100 00010100 11000000

which can be represented as 166.4.20.192/27.

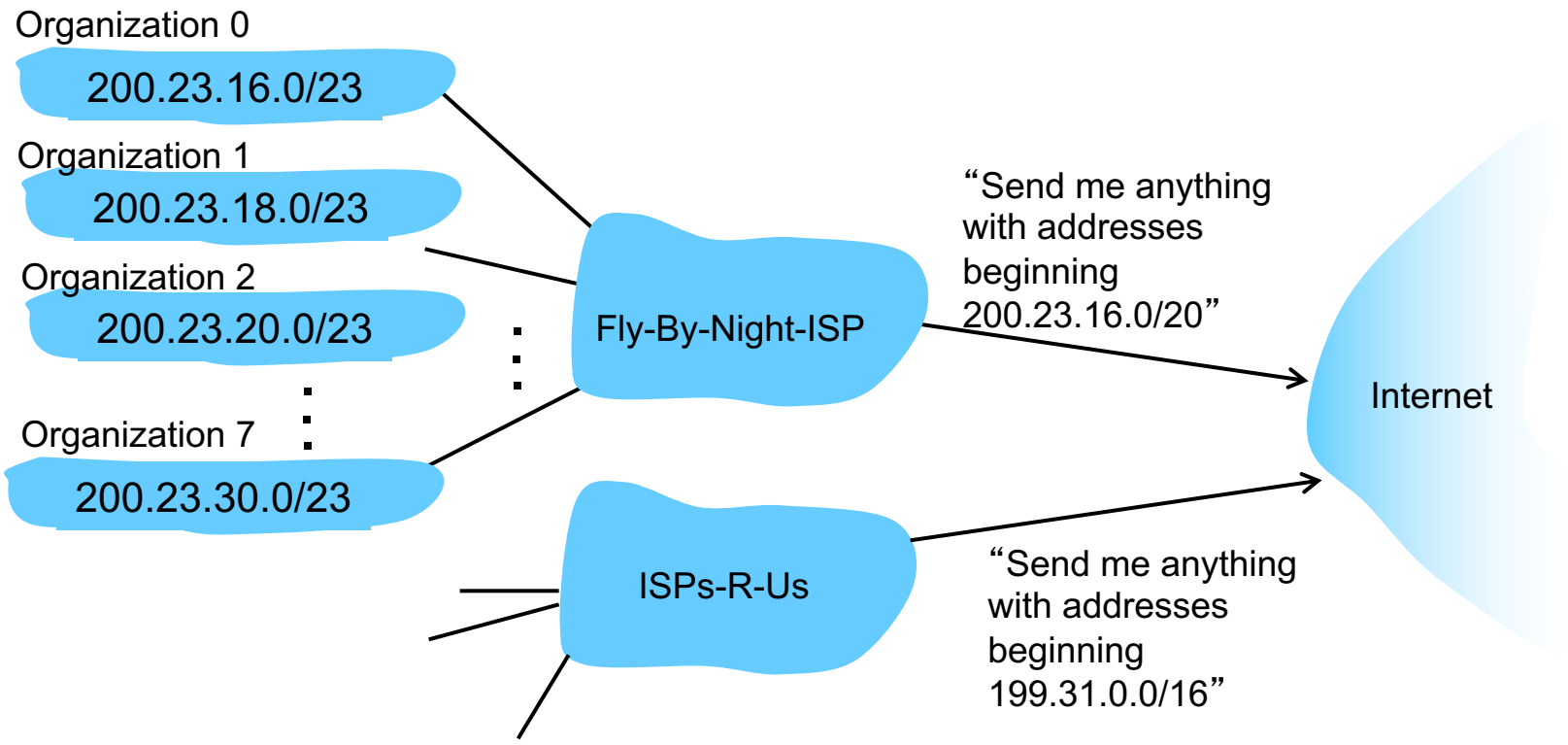
Subnet 3: since $2^5 = 32 > 38$, we can assign the following block

10100110 00000100 00010100 11100000

which can be represented as 166.4.20.224/27.

Hierarchical addressing: route aggregation

hierarchical addressing allows efficient advertisement of routing information:

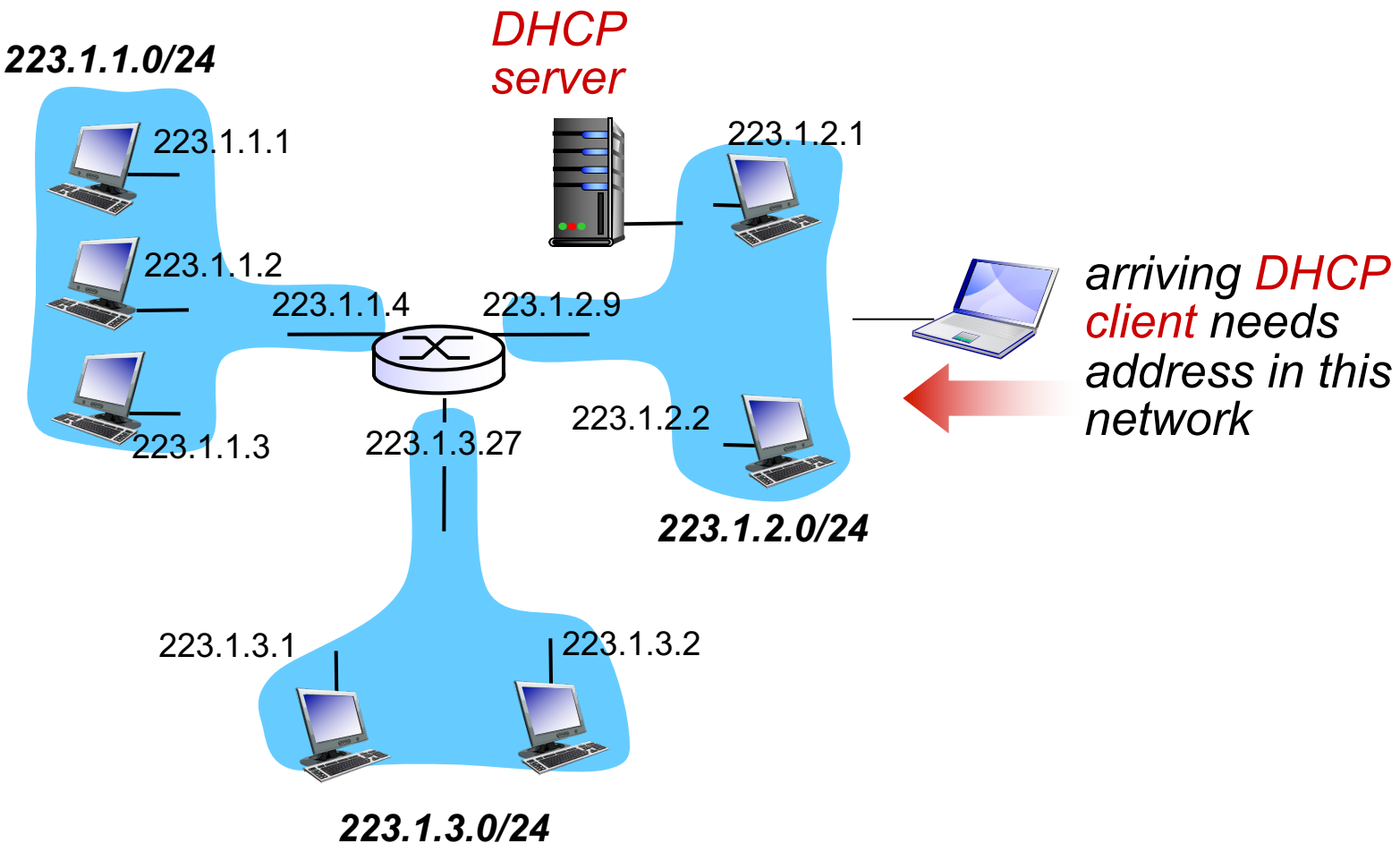


How does a host get an IP?

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

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

DHCP client-server scenario



DHCP: Dynamic Host Configuration Protocol

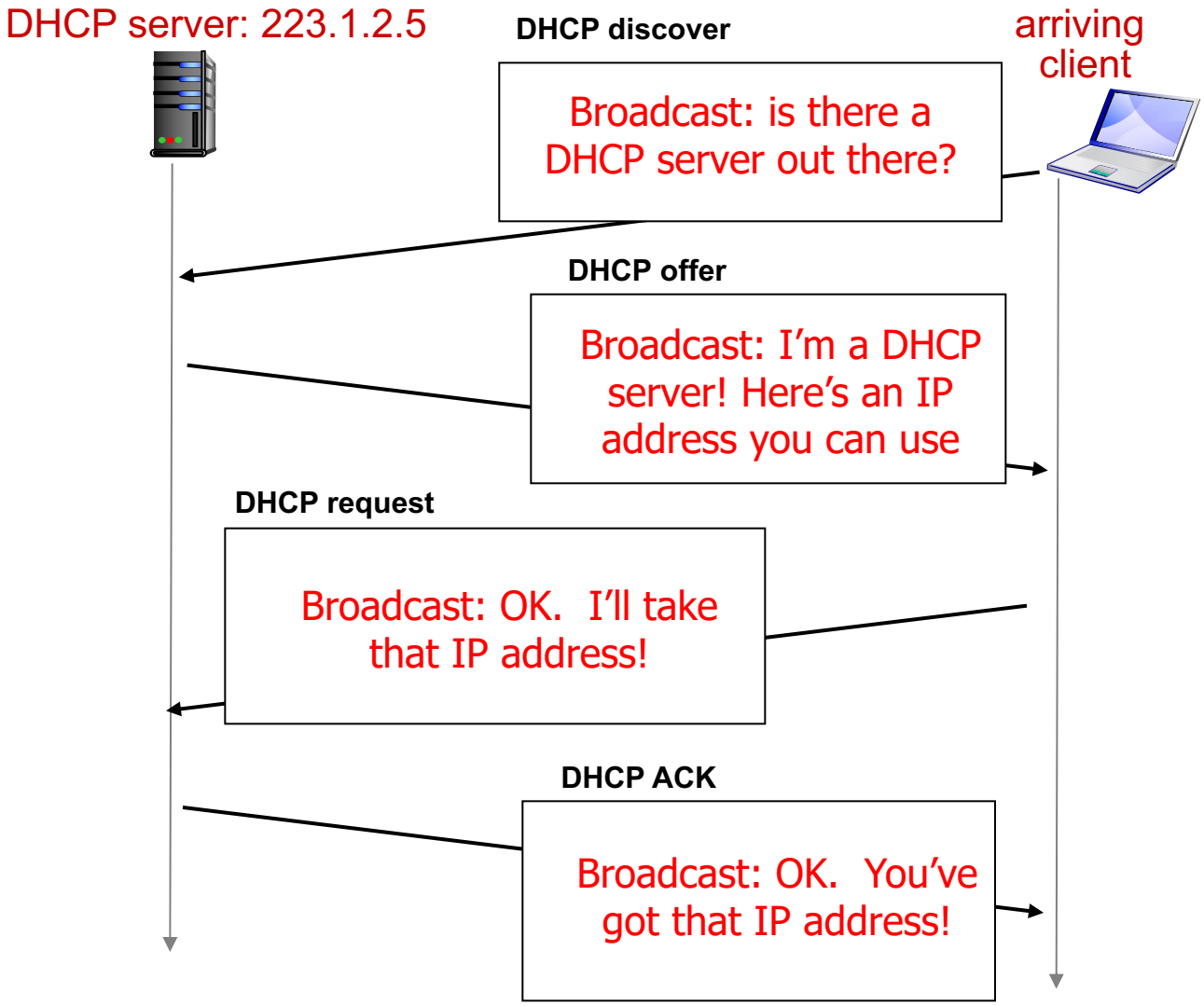
goal: allow host to *dynamically* obtain its IP address from network server when it joins network

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

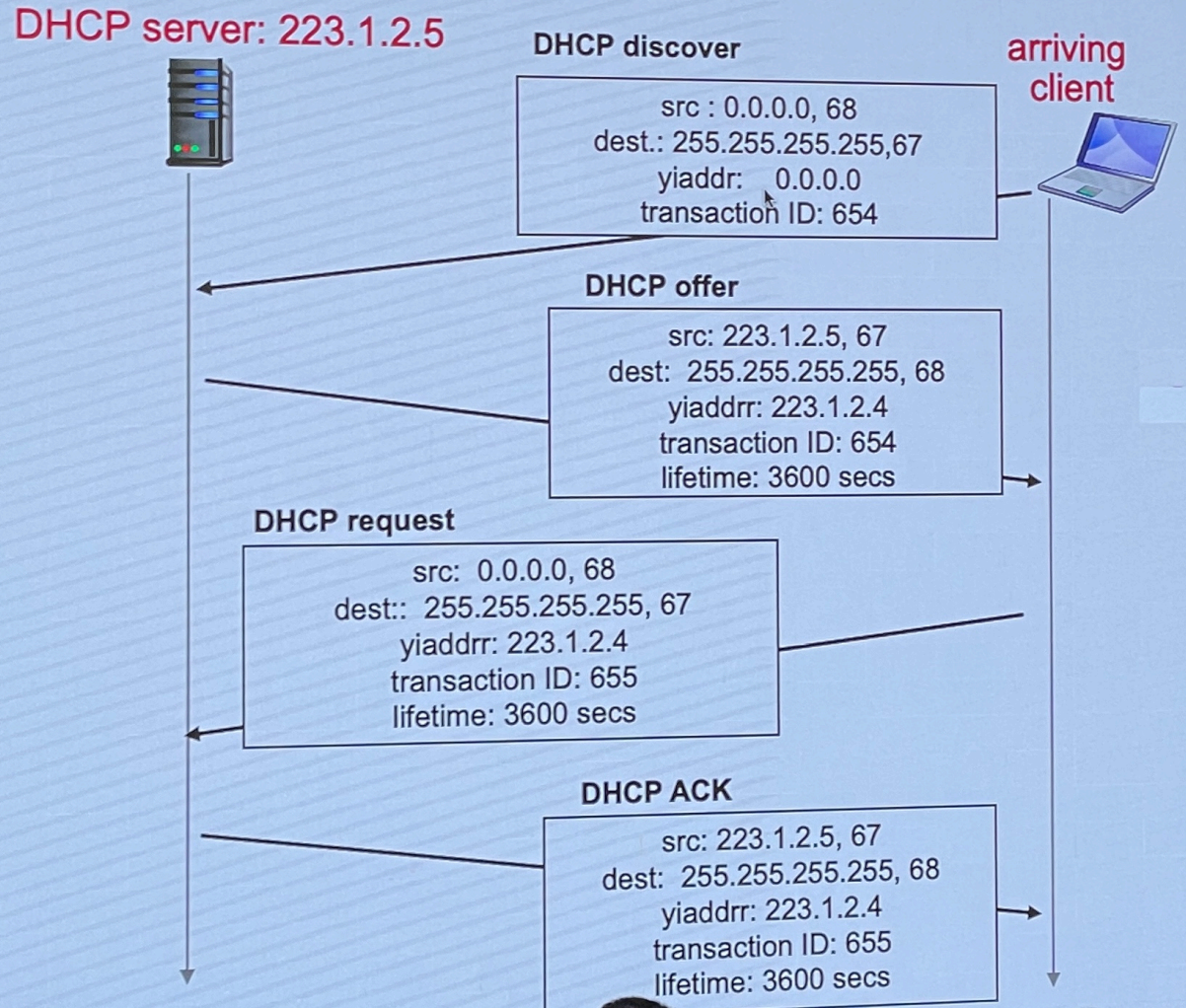
DHCP overview:

- host broadcasts "DHCP discover" msg
- DHCP server responds with "DHCP offer" msg
- host requests IP address: "DHCP request" msg
- DHCP server sends address: "DHCP ack" msg

DHCP client-server scenario



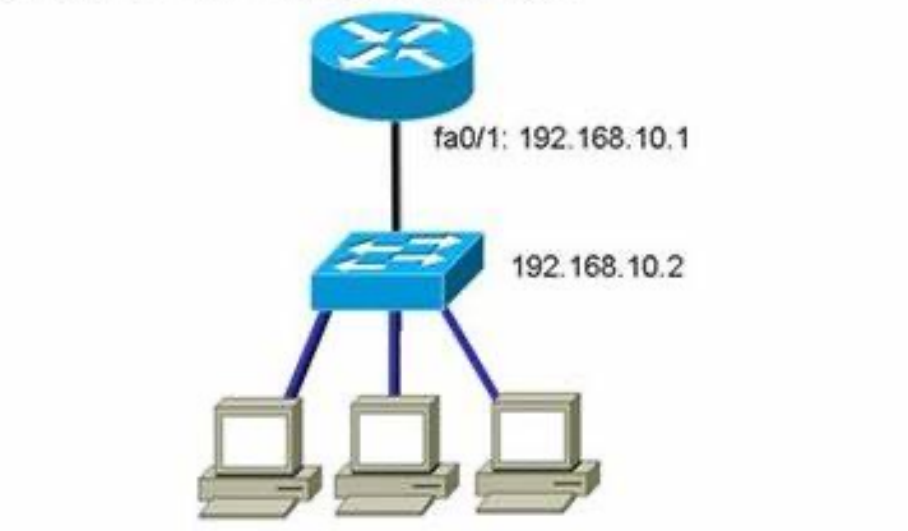
DHCP client-server scenario



DHCP: more than IP addresses

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

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



Both the hosts and the switch would use a default gateway address of 192.168.10.1

Chapter 4: outline

4.1 Overview of Network layer
- data plane
- control plane

4.2 What's inside a router

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

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

NAT: network address translation

Local area networks (LANs):

- E.g., a residence, school, laboratory, university campus or office building
- a range of addresses would need to be allocated by the ISP to cover all of the LAN's IP devices
- If the subnet grew bigger, a larger block of addresses would have to be allocated.
- Huge number of LAN …

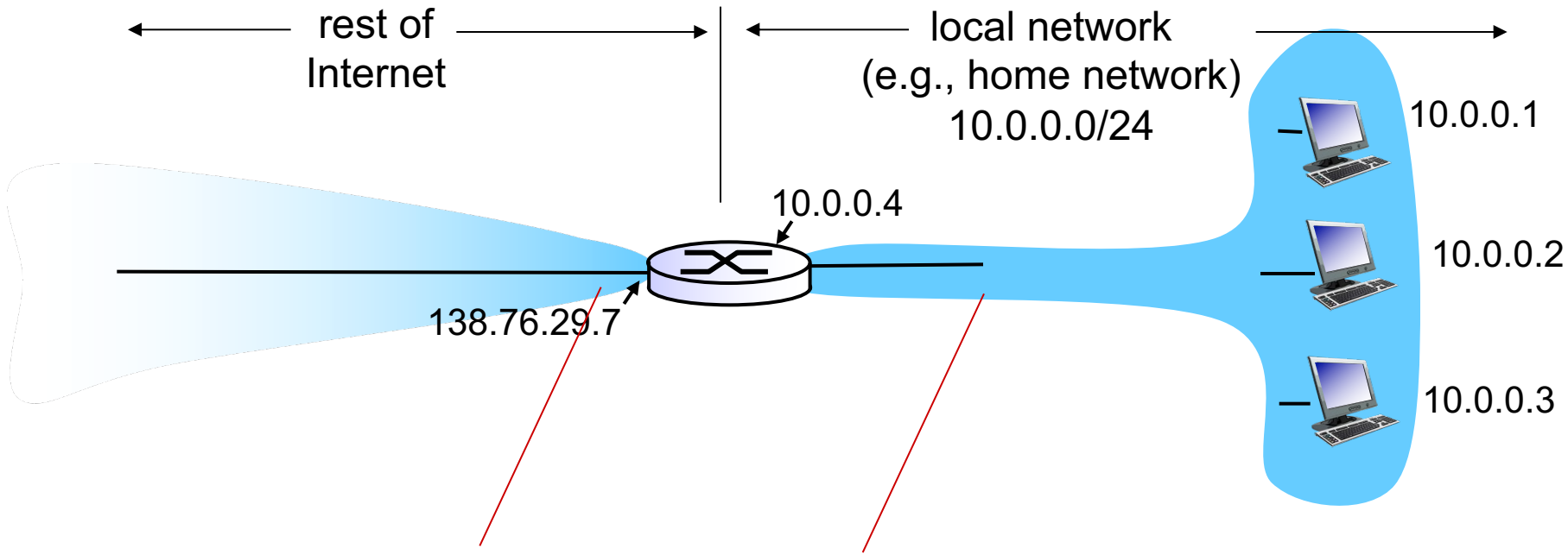
NAT: network address translation

NAT: reserve blocks of IP addresses for LANs

- Private network; private IP address

RFC 1918 name	IP address range	Number of addresses	Largest CIDR block (subnet mask)	Host ID size	Mask bits	*Classful* description[Note 1]
24-bit block	10.0.0.0 – 10.255.255.255	16 777 216	10.0.0.0/8 (255.0.0.0)	24 bits	8 bits	single class A network
20-bit block	172.16.0.0 – 172.31.255.255	1 048 576	172.16.0.0/12 (255.240.0.0)	20 bits	12 bits	16 contiguous class B networks
16-bit block	192.168.0.0 – 192.168.255.255	65 536	192.168.0.0/16 (255.255.0.0)	16 bits	16 bits	256 contiguous class C networks

NAT: network address translation



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

datagrams with source or destination in this network have 10.0.0/24 address for source, destination (as usual)

NAT: network address translation

motivation: local network uses just one IP address (e.g., 138.76.29.7 in the example) as far as outside world is concerned:

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

NAT: network address translation

implementation: NAT router must:

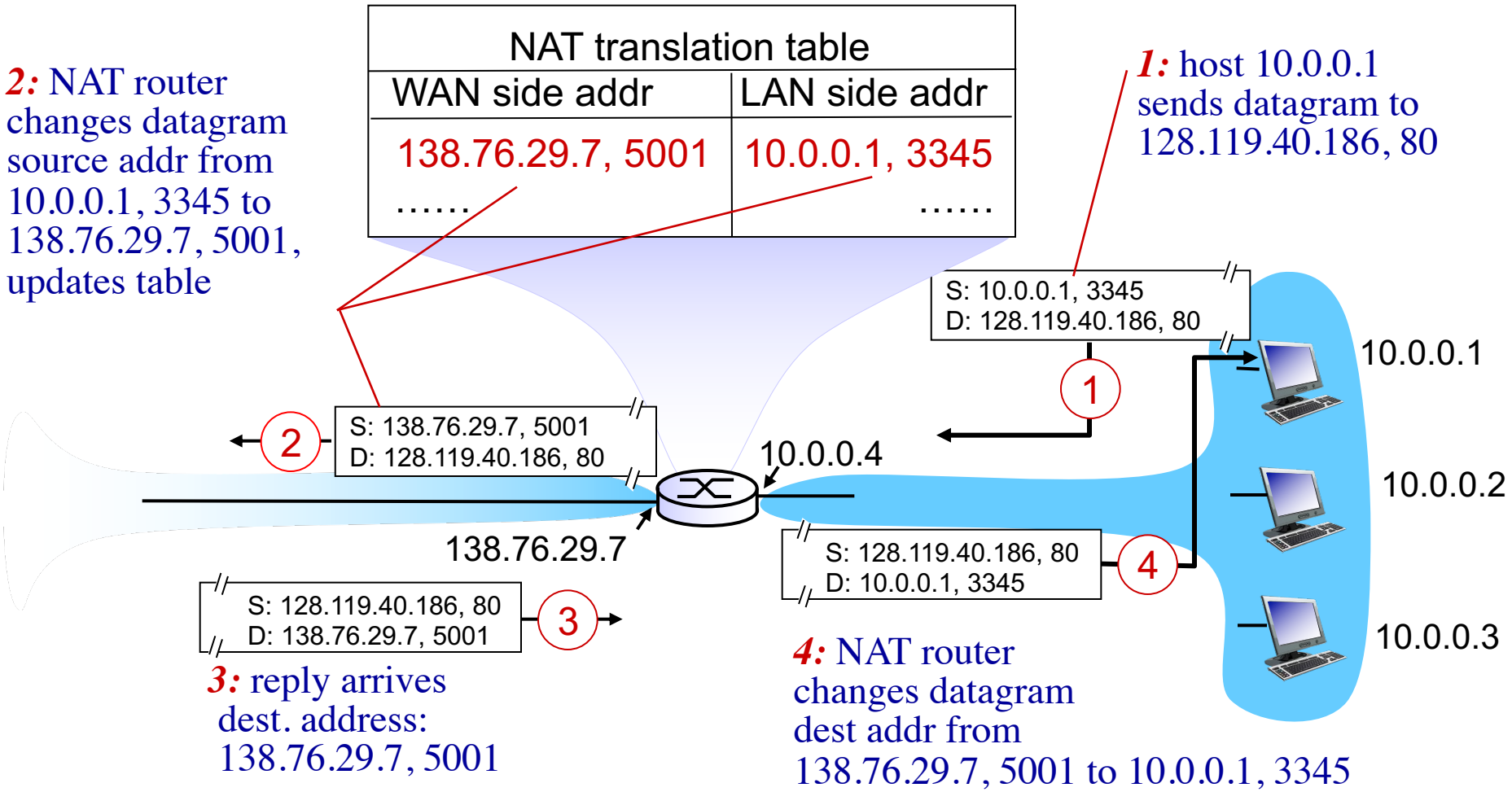
- *outgoing datagrams: replace* (source IP address, port #) of every outgoing datagram to (NAT IP address, new port #)

  . . . remote clients/servers will respond using (NAT IP address, new port #) as destination addr

- *remember (in NAT translation table)* every (source IP address, port #) to (NAT IP address, new port #) translation pair

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

NAT: network address translation



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

NAT: network address translation

- 16-bit port-number field:
  - 60,000 simultaneous connections with a single LAN-side address!
- NAT is controversial:
  - routers should only process up to layer 3
  - violates end-to-end argument
    - NAT possibility must be taken into account by app designers, e.g., P2P applications, server processes
    - Well-known port number

Chapter 4: outline

4.1 Overview of Network layer
- data plane
- control plane

4.2 What's inside a router

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

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

IPv6: motivation

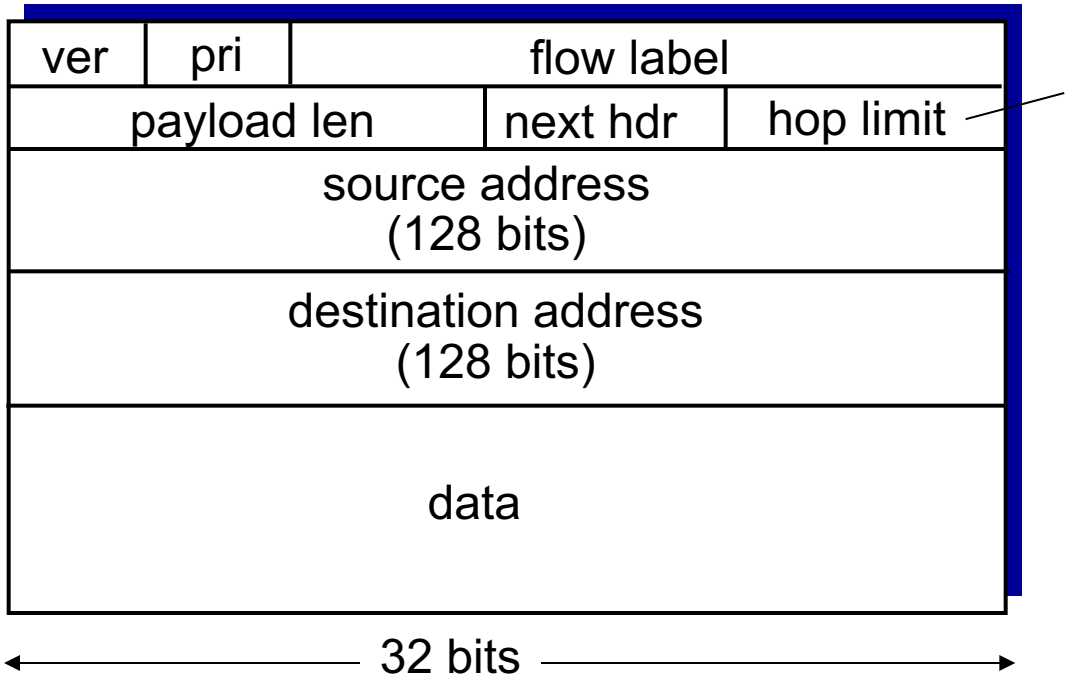
- *initial motivation:* 32-bit address space soon to be completely allocated.
- additional motivation:
  - header format helps to speed up processing/forwarding

IPv6 datagram format:

- 128-bit address space: why?
- fixed-length 40 byte header; why?
- no fragmentation allowed; why?

IPv6 datagram format

priority: identify priority among datagrams in flow
flow Label: identify datagrams in same "flow."
(concept of"flow" not well defined).
next header: identify upper layer protocol for data (for example, to TCP or UDP).



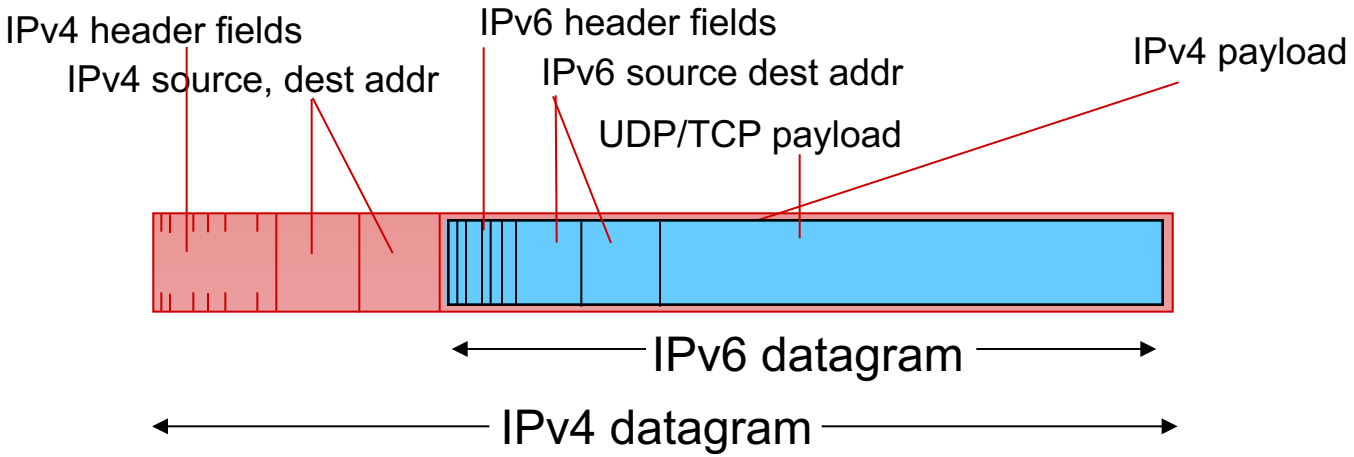
decremented by one by each router that forwards the Datagram; if reaches zero, the datagram is discarded.

Other changes from IPv4

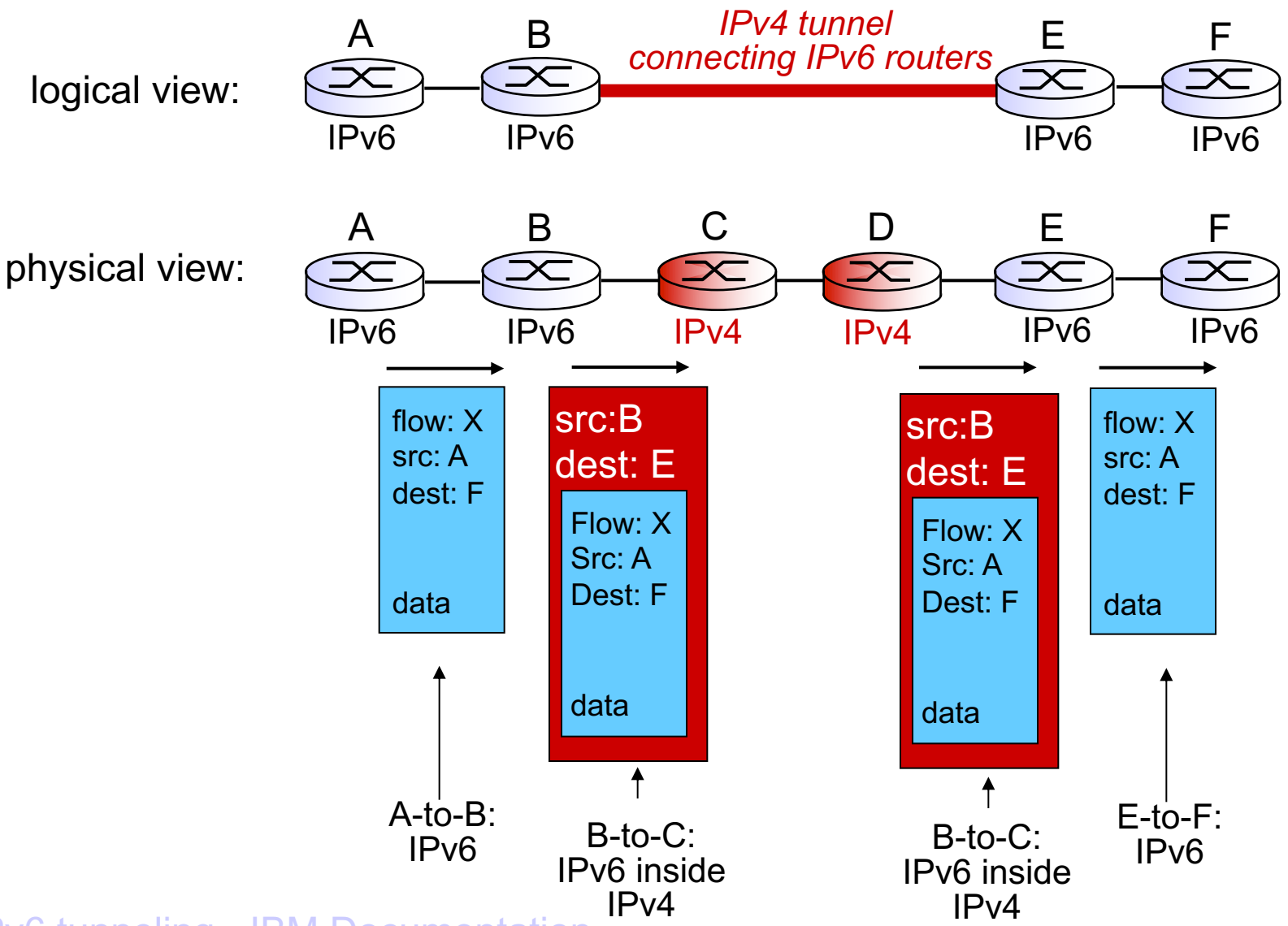
- *checksum*: removed entirely to reduce processing time at each hop; why?
- *options:* allowed, but outside of header, indicated by "Next Header" field
- *no fragmentation:*
  - too large to be forwarded over the outgoing link
  - the router simply drops the datagram and sends a "Packet Too Big" ICMP error message

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



Tunneling



IPv6 tunneling - IBM Documentation

IPv6: adoption

- Google: 8% of clients access services via IPv6
- NIST: 1/3 of all US government domains are IPv6 capable

- *Long (long!) time for deployment, use*
  - 20 years and counting!
  - think of application-level changes in last 20 years: WWW, Facebook, streaming media, Skype, …
  - *Why?*

Chapter 4: outline

4.1 Overview of Network layer
- data plane
- control plane

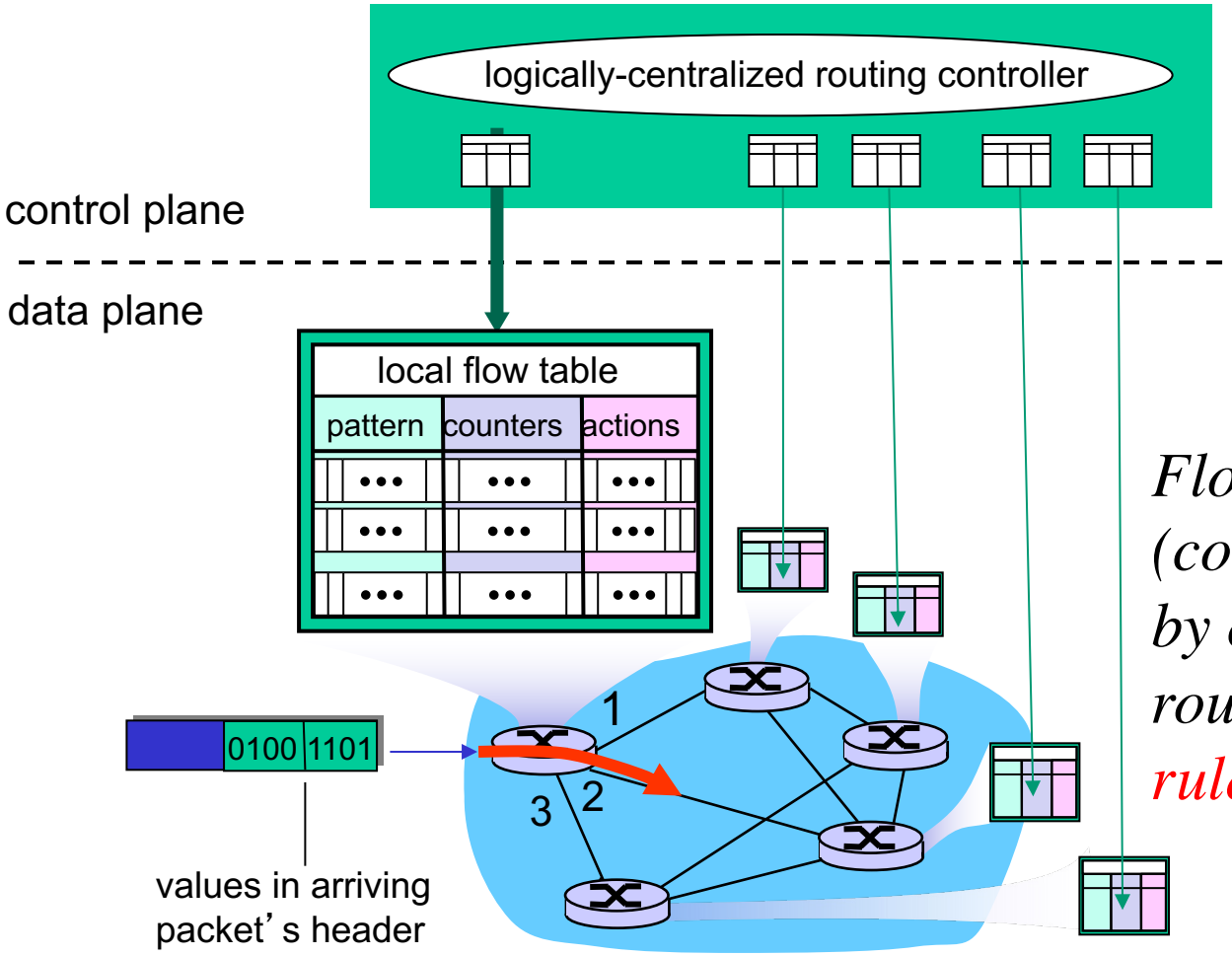
4.2 What's inside a router

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

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

Generalized Forwarding and SDN

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

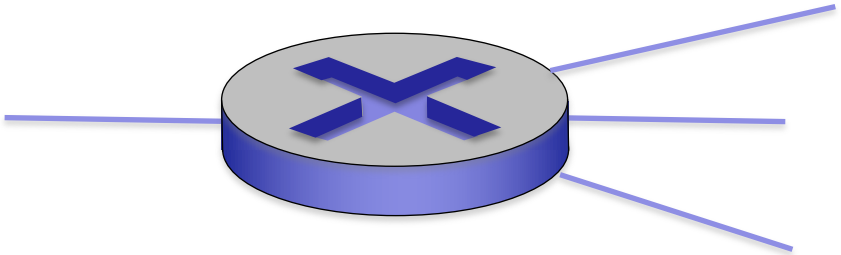


Flow table in a router (computed and distributed by controller) define router's match+action rules

OpenFlow data plane abstraction

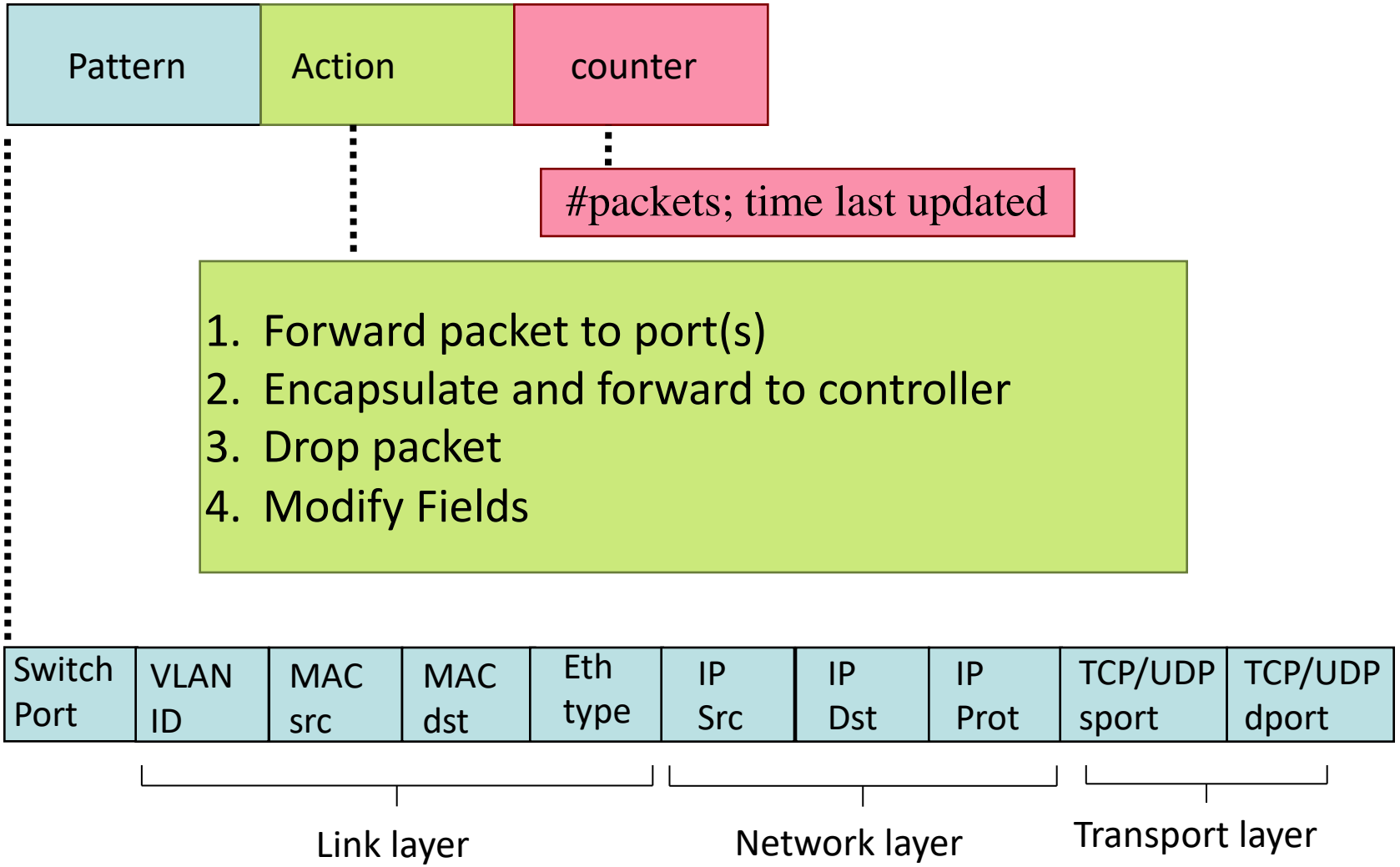
Generalized forwarding: simple packet-handling rules

- *Pattern:* match values in packet header fields
- *Actions: for matched packet:* drop, forward, modify, matched packet or send matched packet to controller
- *Priority*: disambiguate overlapping patterns
- *Counters:* #packets; time last updated



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

OpenFlow: Flow Table Entries



Destination-based forwarding:

Destination-based forwarding:

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP/UDP sport	TCP/UDP dport	Action
*	*	*	*	*	*	51.6.0.8	*	*	*	port6

IP datagrams destined to IP address 51.6.0.8 should be forwarded to router output port 6

Destination-based layer 2 (switch) forwarding:

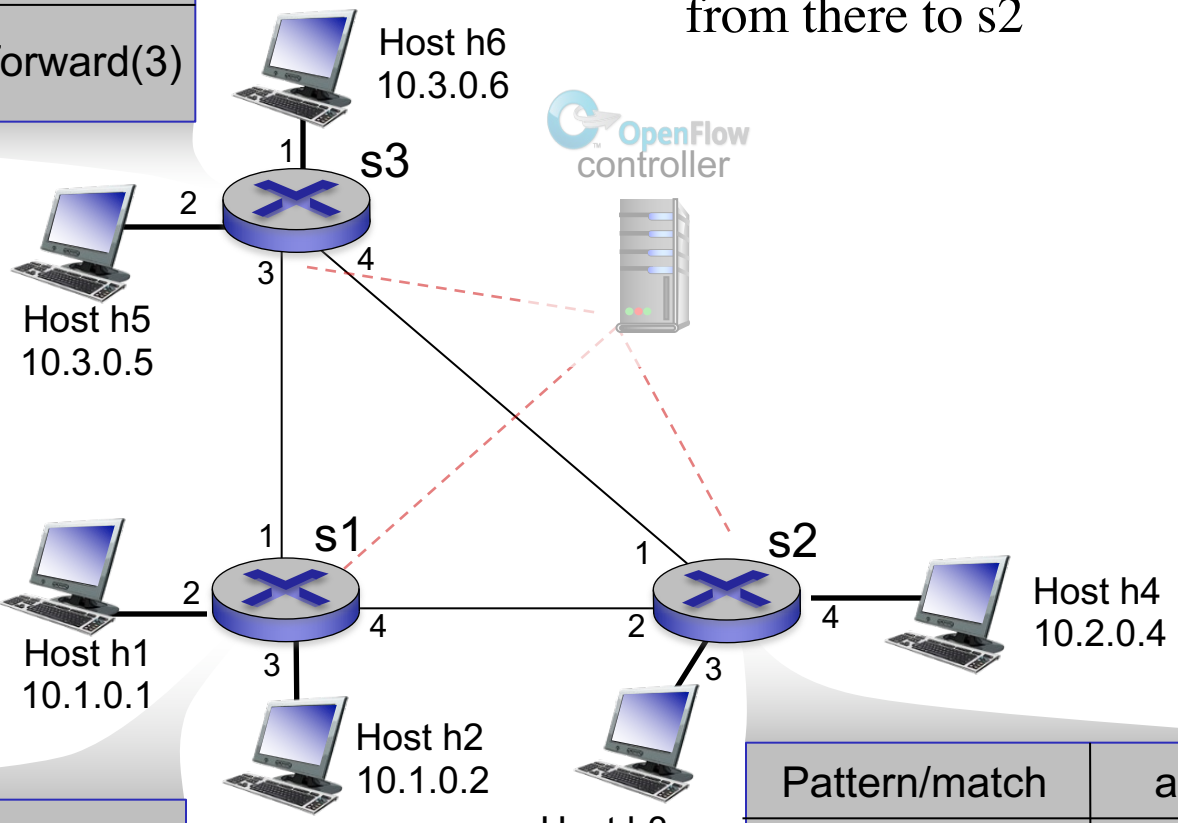
Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP/UDP sport	TCP/UDP dport	Action
*	22:A7:23:11:E1:02	*	*	*	*	*	*	*	*	port3

layer 2 frames from MAC address 22:A7:23:11:E1:02 should be forwarded to output port 6

OpenFlow example

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

Pattern/match	action
IP Src = 10.3.*.* IP Dst = 10.2.*.*	forward(3)



Pattern/match	action
ingress port = 1 IP Src = 10.3.*.* IP Dst = 10.2.*.*	forward(4)

Pattern/match	action
ingress port = 2 IP Dst = 10.2.0.3	forward(3)
ingress port = 2 IP Dst = 10.2.0.4	forward(4)

Firewall

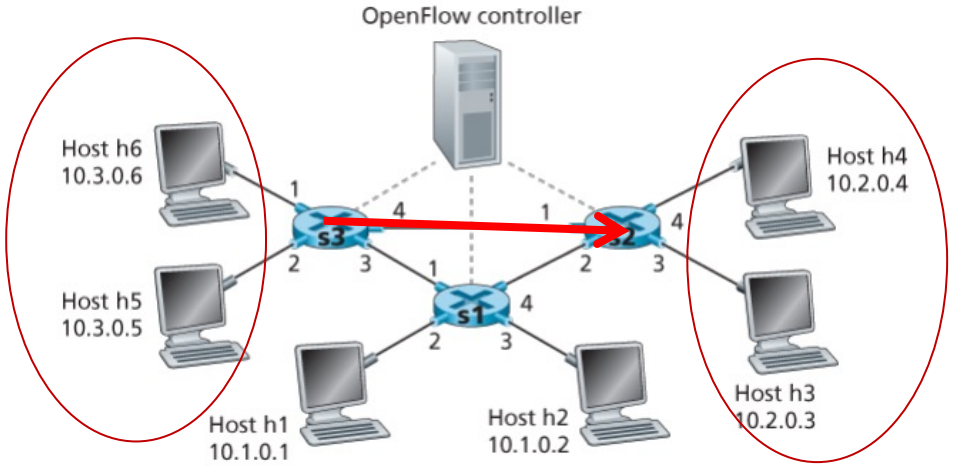
Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP/UDP dport	TCP/UDP dport	Forward
*	*	*	*	*	*	*	*	*	22	drop

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

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP/UDP dport	TCP/UDP dport	Forward
*	*	*	*	*	128.119.1.1	*	*	*	*	drop

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

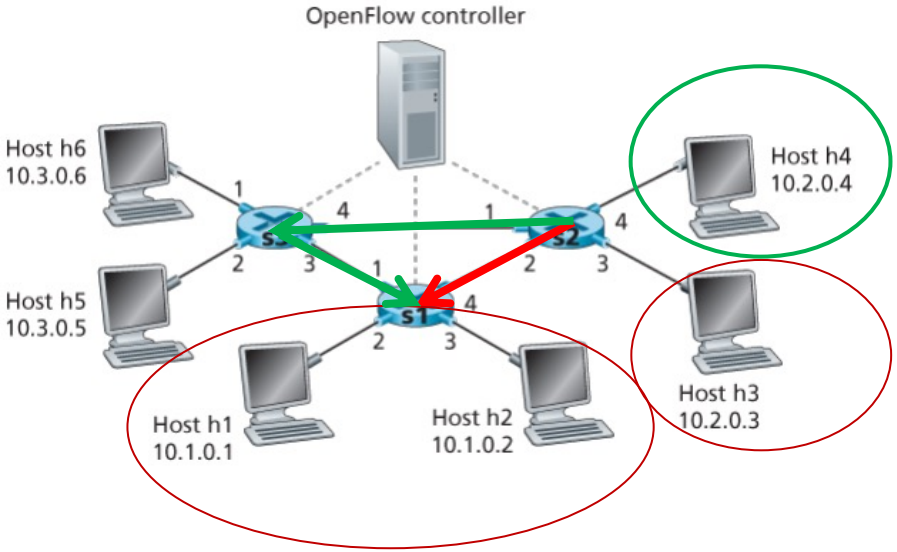
Firewall



s2 Flow Table (Example 3)	
Match	Action
IP Src = 10.3.*.* IP Dst = 10.2.0.3	Forward(3)
IP Src = 10.3.*.* IP Dst = 10.2.0.4	Forward(4)

there were no other entries in s2's flow table

Load Balancing



s2 Flow Table (Example 2)	
Match	Action
Ingress port = 3; IP Dst = 10.1.*.*	Forward(2)
Ingress port = 4; IP Dst = 10.1.*.*	Forward(1)
…	…

OpenFlow abstraction

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

- Router
  - *match:* longest destination IP prefix
  - *action:* forward out a link
- Switch
  - *match:* destination MAC address
  - *action:* forward

- Firewall
  - *match*: IP addresses and TCP/UDP port numbers
  - *action:* permit or deny
- NAT
  - *match:* IP address and port
  - *action:* rewrite address and port

Chapter 4: *done!*

4.1 Overview of Network layer: data plane and control plane

4.2 What's inside a router

4.3 IP: Internet Protocol

- datagram format
- fragmentation
- IPv4 addressing
- NAT
- IPv6

4.4 Generalized Forward and SDN

- match plus action
- OpenFlow example

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

Answer: by the control plane (next chapter)

Chapter 5: network layer control plane

chapter goals: understand principles behind network control plane

- traditional routing algorithms
- SDN controllers
- Internet Control Message Protocol
- network management

and their instantiation, implementation in the Internet:

- OSPF, BGP, OpenFlow, ICMP, SNMP

Chapter 5: outline

5.1 introduction

5.2 routing protocols

- link state
- distance vector

5.3 intra-AS routing in the Internet: OSPF

5.4 routing among the ISPs: BGP

5.5 The SDN control plane

5.6 ICMP: The Internet Control Message Protocol

5.7 Network management and SNMP

Network-layer functions

Recall: two network-layer functions:

- *forwarding:* move packets from router's input to appropriate router output

data plane

- *routing:* determine route taken by packets from source to destination

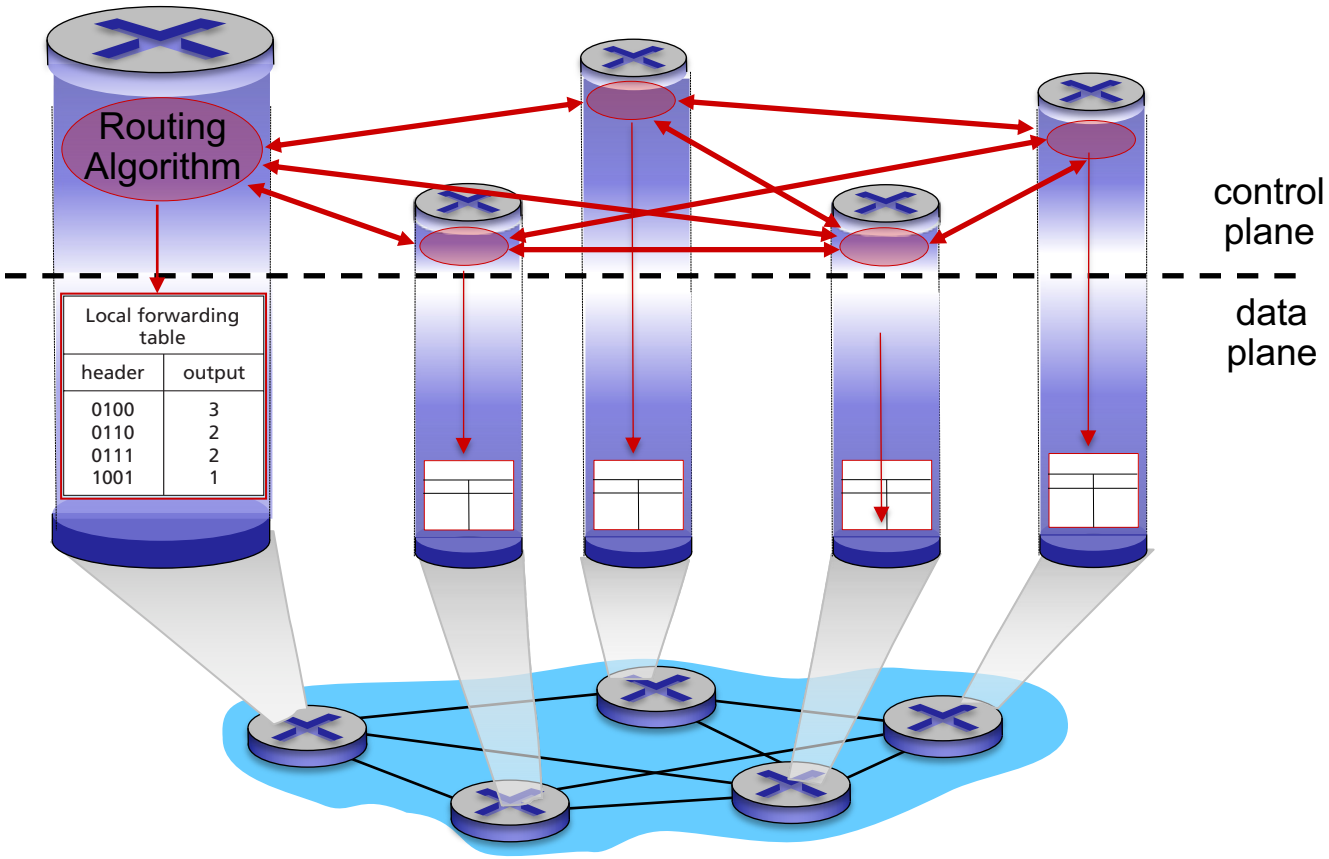
control plane

Two approaches to structuring network control plane:

- per-router control (traditional)
- logically centralized control (software defined networking)

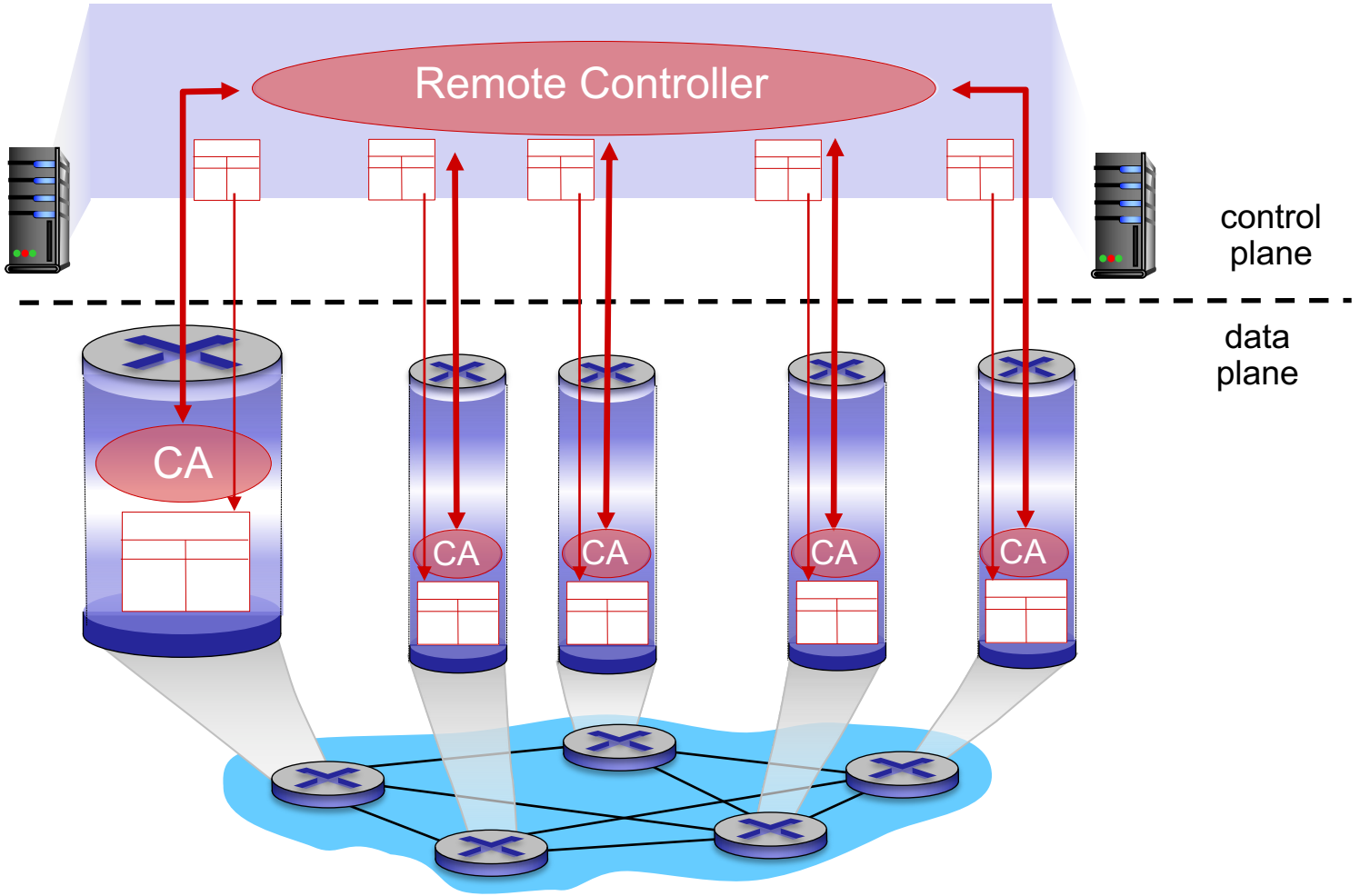
Per-router control plane

Individual routing algorithm components *in each and every router* interact with each other in control plane to compute forwarding tables



Logically centralized control plane

A distinct (typically remote) controller interacts with local control agents (CAs) in routers to compute forwarding tables



Chapter 5: outline

5.1 introduction

5.2 routing protocols

- link state
- distance vector

5.3 intra-AS routing in the Internet: OSPF

5.4 routing among the ISPs: BGP

5.5 The SDN control plane

5.6 ICMP: The Internet Control Message Protocol

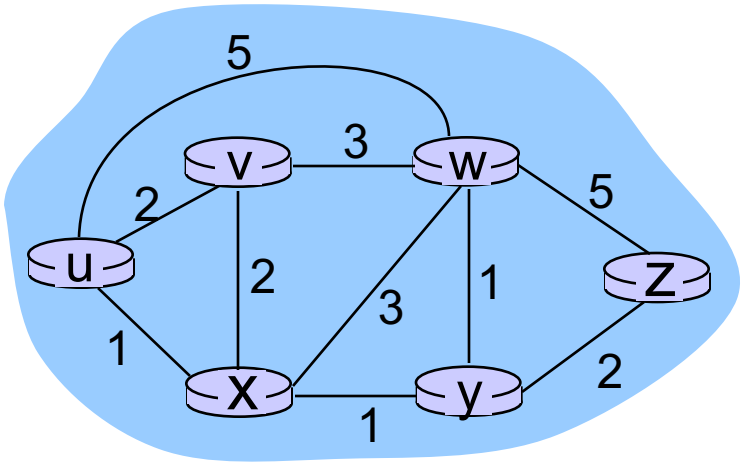
5.7 Network management and SNMP

Routing protocols

Routing protocol goal: determine "good" paths (equivalently, routes), from sending hosts to receiving host, through network of routers

- path: sequence of routers packets will traverse in going from given initial source host to given final destination host
- "good": least "cost", "fastest", "least congested"
- routing: a "top-10" networking challenge!

Graph abstraction of the network



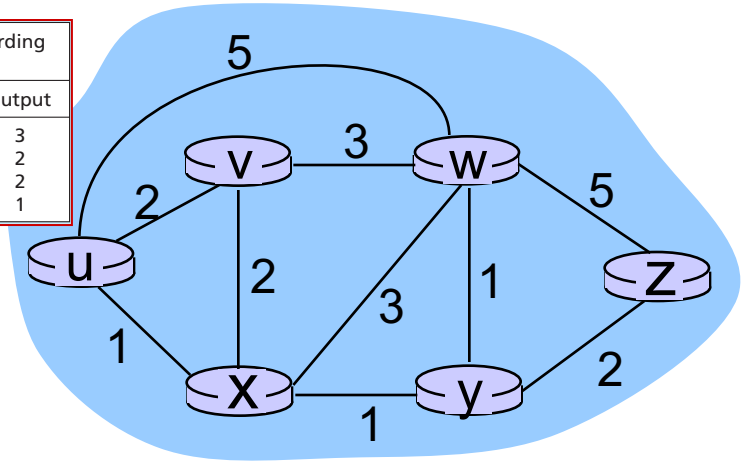
graph: G = (N,E)

N = set of routers = { u, v, w, x, y, z }

E = set of links ={ (u,v), (u,x), (v,x), (v,w), (x,w), (x,y), (w,y), (w,z), (y,z) }

Graph abstraction: costs

Local forwarding table	
header	output
0100	3
0110	2
0111	2
1001	1



c(x,x’) = cost of link (x,x’)
e.g., c(w,z) = 5

cost could always be 1, or inversely related to bandwidth, or inversely related to congestion

cost of path $(x_1, x_2, x_3, \ldots, x_p) = c(x_1,x_2) + c(x_2,x_3) + \ldots + c(x_{p-1},x_p)$

key question: what is the least-cost path between u and z ?
routing algorithm: algorithm that finds that least cost path

Routing algorithm classification

Q: global or decentralized information?

global:

- all routers have complete topology, link cost info
- "link state" algorithms

decentralized:

- router knows physically-connected neighbors, link costs to neighbors
- iterative process of computation, exchange of info with neighbors
- "distance vector" algorithms

Q: static or dynamic?

static:

- routes change slowly over time

dynamic:

- routes change more quickly
  - periodic update
  - in response to link cost changes

Routing algorithm classification

Q: load-sensitive or load insensitive?

Load-sensitive:

- Link costs vary dynamically to reflect the current level of congestion

Load-insensitive

- A link's cost does not explicitly reflect its current level of congestion

Chapter 5: outline

5.1 introduction

5.2 routing protocols

- link state (global)
- distance vector (decentralized)

5.3 intra-AS routing in the Internet: OSPF

5.4 routing among the ISPs: BGP

5.5 The SDN control plane

5.6 ICMP: The Internet Control Message Protocol

5.7 Network management and SNMP