Network Layer

MODULE 4

Chapter 4: outline

4.1 introduction

4.2 virtual circuit and datagram networks

4.4 IP: Internet Protocol
  - datagram format
  - IPv4 addressing
 - ICMP
  - IPv6

4.5 routing algorithms
  - link state
  - distance vector

4.6 routing in the Internet
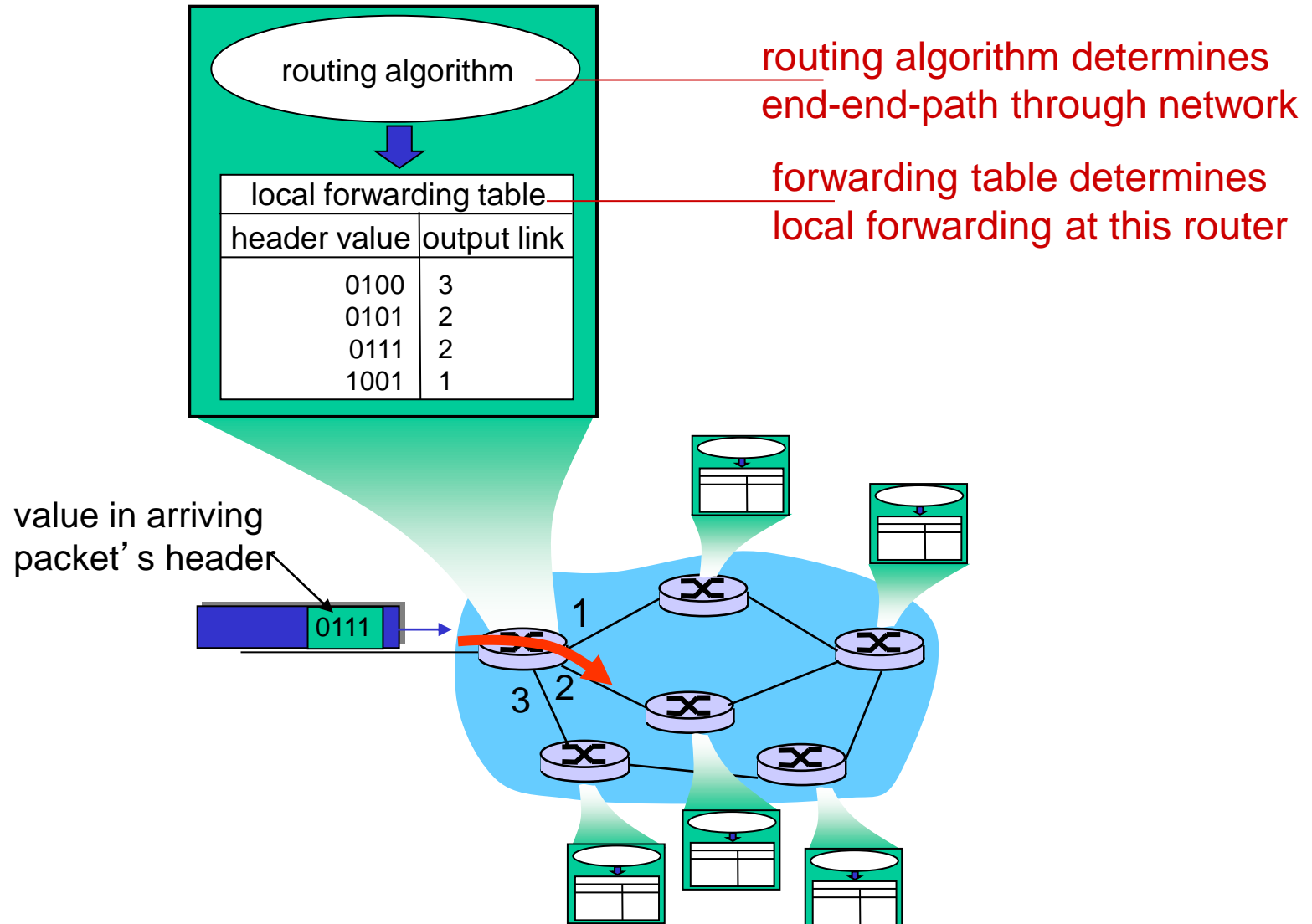 - RIP
  - OSPF
  - BGP

Network layer

❖ **transport segment from sending to receiving host**

❖ **on sending side encapsulates segments into datagrams**

❖ **on receiving side, delivers segments to transport layer**

❖ **network layer protocols in *every* host, router**

❖ **router examines header fields in all IP datagrams passing through it**
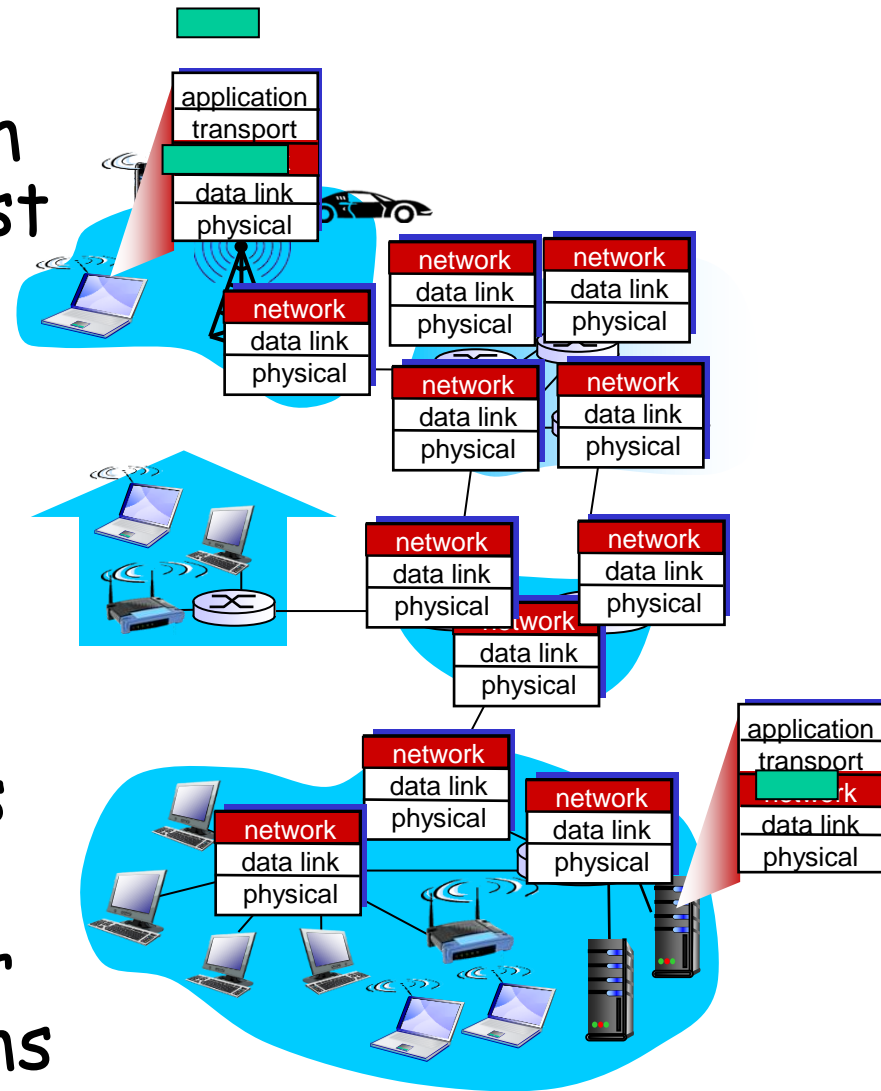
Two key network-layer functions

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

❖ *routing:* determine route taken by packets from source to dest.

  ▪ *routing algorithms*

Interplay between routing and forwarding

routing algorithm

local forwarding table

header value	output link
0100	3
0101	2
0111	2
1001	1

routing algorithm determines
end-end-path through network

forwarding table determines
local forwarding at this router

value in arriving
packet's header

0111

1

3   2

Connection setup

❖ 3rd important function in *some* network architectures:
  - ATM, frame relay, X.25
❖ before datagrams flow, two end hosts *and* intervening routers establish virtual connection
  - routers get involved
❖ network vs transport layer connection service:
  - *network:* between two hosts (may also involve intervening routers in case of VCs)
  - *transport:* between two processes

Network service model

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

example services for individual datagrams:

❖ guaranteed delivery
❖ guaranteed delivery with less than 40 msec (bounded)delay

example services for a flow of datagrams:

❖ in-order datagram delivery
❖ guaranteed minimum bandwidth to flow.
❖ Security services

Network layer service models:

Network Architecture	Service Model	Bandwidth Guarantee	No-Loss Guarantee	Ordering	Timing	Congestion Indication
Internet	Best Effort	None	None	Any order possible	Not maintained	None
ATM	CBR	Guaranteed constant rate	Yes	In order	Maintained	Congestion will not occur
ATM	ABR	Guaranteed minimum	None	In order	Not maintained	Congestion indication provided

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- link state
- distance vector
- hierarchical routing

4.6 routing in the Internet
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4.7 broadcast and multicast routing

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4.7 broadcast and multicast routing

Connection, connection-less service

❖ *datagram* network provides network-layer *connectionless* service

❖ *virtual-circuit* network provides network-layer *connection* service

❖ analogous to TCP/UDP connecton-oriented / connectionless transport-layer services, but:

  ▪ *service:* host-to-host

  ▪ *no choice:* network provides one or the other

  ▪ *implementation:* in network core

Virtual circuits

"source-to-dest path behaves much like telephone circuit"

- performance-wise
- network actions along source-to-dest path

❖ call setup, teardown for each call *before* data can flow
❖ each packet carries VC identifier (not destination host address)
❖ *every* router on source-dest path maintains "state" for each passing connection
❖ link, router resources (bandwidth, buffers) may be *allocated* to VC (dedicated resources = predictable service)

# VC implementation

a VC consists of:

    1. *path* from source to destination
    2. *VC numbers*, one number for each link along path
    3. *entries in forwarding tables* in routers along path

❖ packet belonging to VC carries VC number (rather than dest address)

❖ VC number can be changed on each link.

    ▪ new VC number comes from forwarding table

VC forwarding table

VC number
interface number

forwarding table in northwest router:
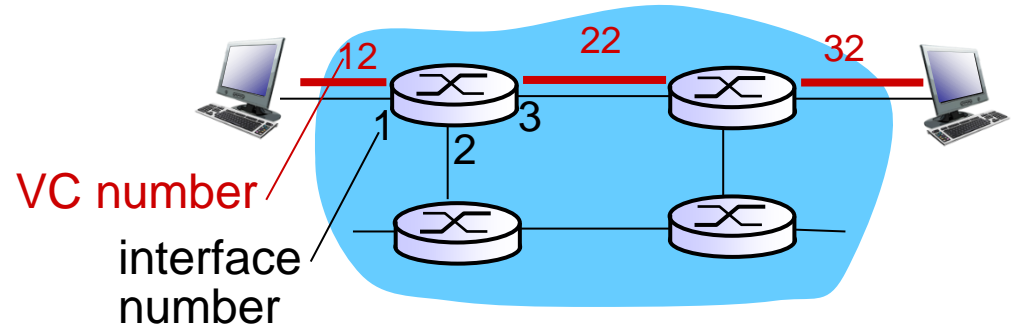
Incoming interface	Incoming VC #	Outgoing interface	Outgoing VC #
1	12	3	22
2	63	1	18
3	7	2	17
1	97	3	87
…	…	…	…

VC routers maintain connection state information!

Virtual circuits: signaling protocols

- ❖ used to setup, maintain teardown VC
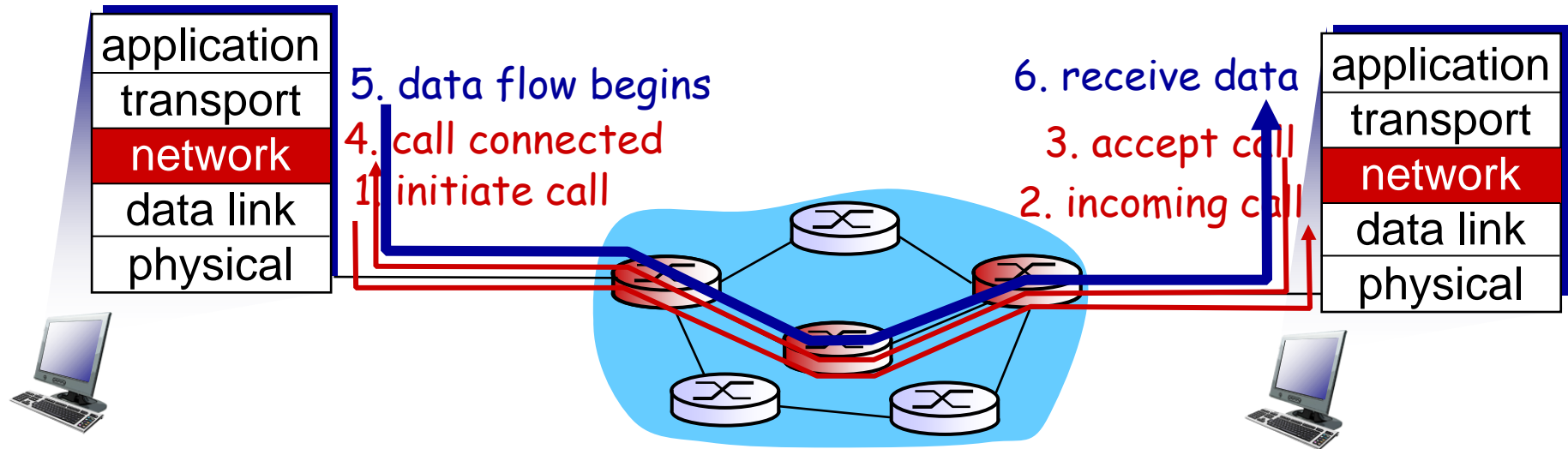- ❖ used in ATM, frame-relay, X.25
- ❖ not used in today's Internet

application
transport
network
data link
physical

5. data flow begins
4. call connected
1. initiate call

6. receive data
3. accept call
2. incoming call

application
transport
network
data link
physical

Figure 4.6: Forwarding process in a router when used in a virtual circuit network

Forwarding table

Incoming		Outgoing	
Port	Label	Port	Label
1	**L1**	2	**L2**
⋮	⋮	⋮	⋮

L1 | SA | DA | Data

L2 | SA | DA | Data

1   2
3   4

Incoming label

Outgoing label

4.16
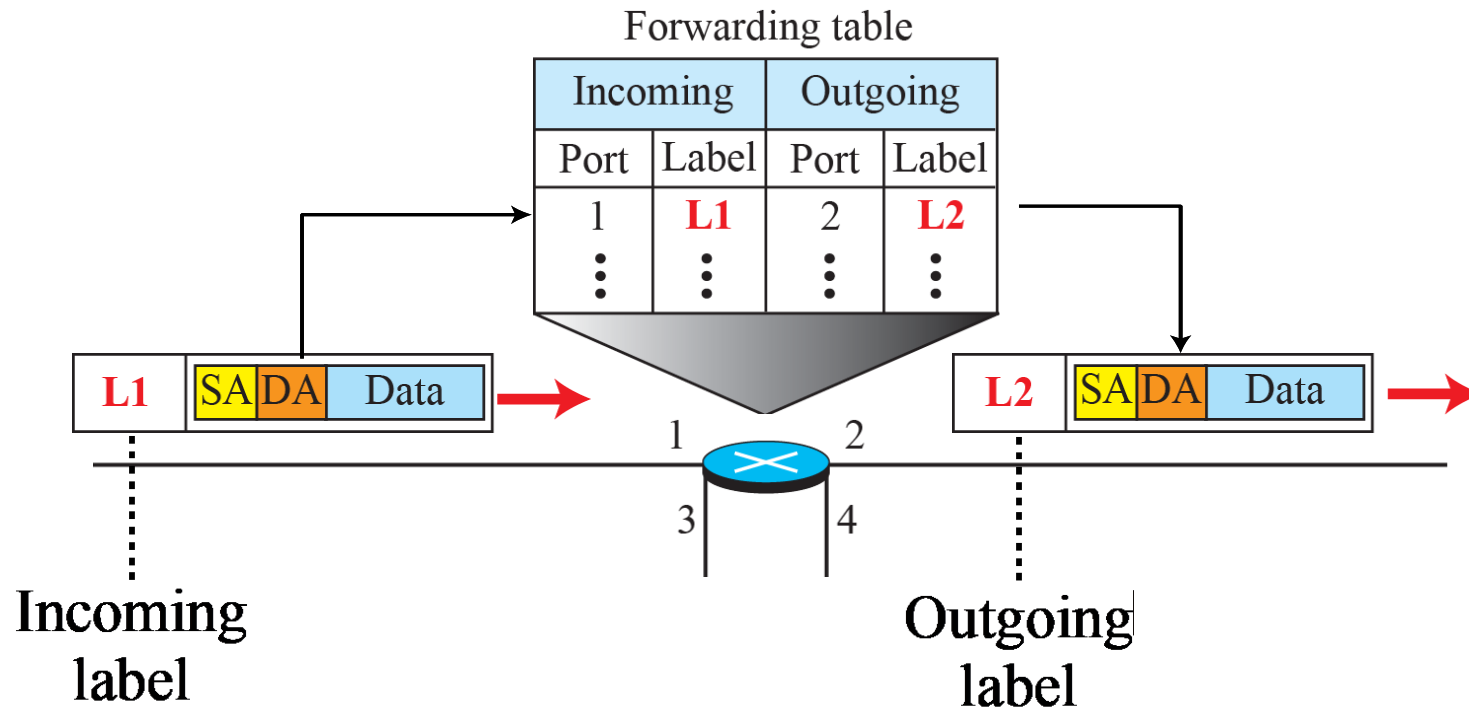
Figure 4.7: Sending request packet in a virtual-circuit network

A to B

Incoming		Outgoing	
Port	Label	Port	Label
1	14	3	

Legend

A to B	Request packet
▬▬▬	Virtual circuit

A to B

Incoming		Outgoing	
Port	Label	Port	Label
1	66	3	

A to B

Incoming		Outgoing	
Port	Label	Port	Label
1	22	4	

A to B

1.17

4.17
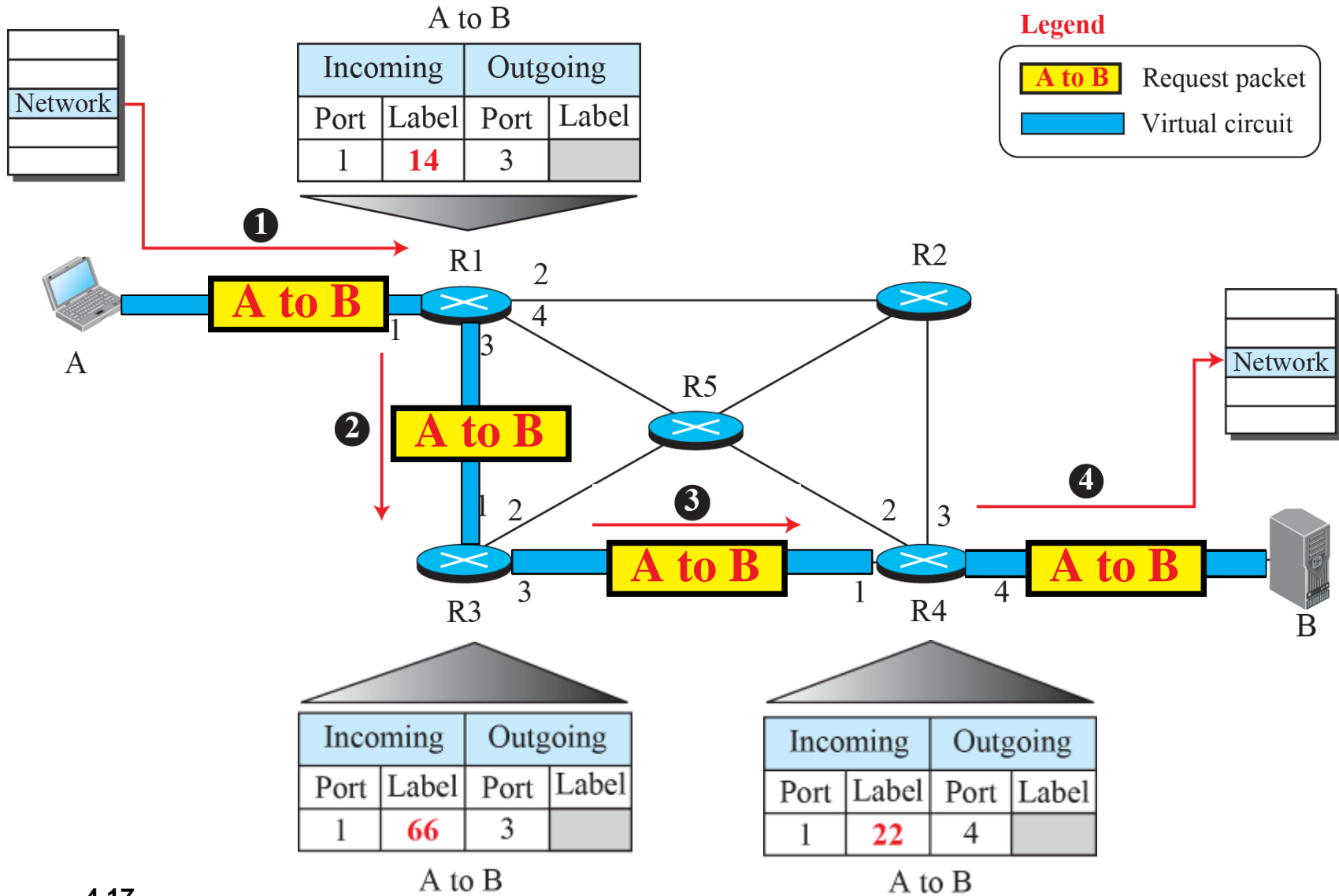
Figure 4.8: Sending acknowledgments in a virtual-circuit network

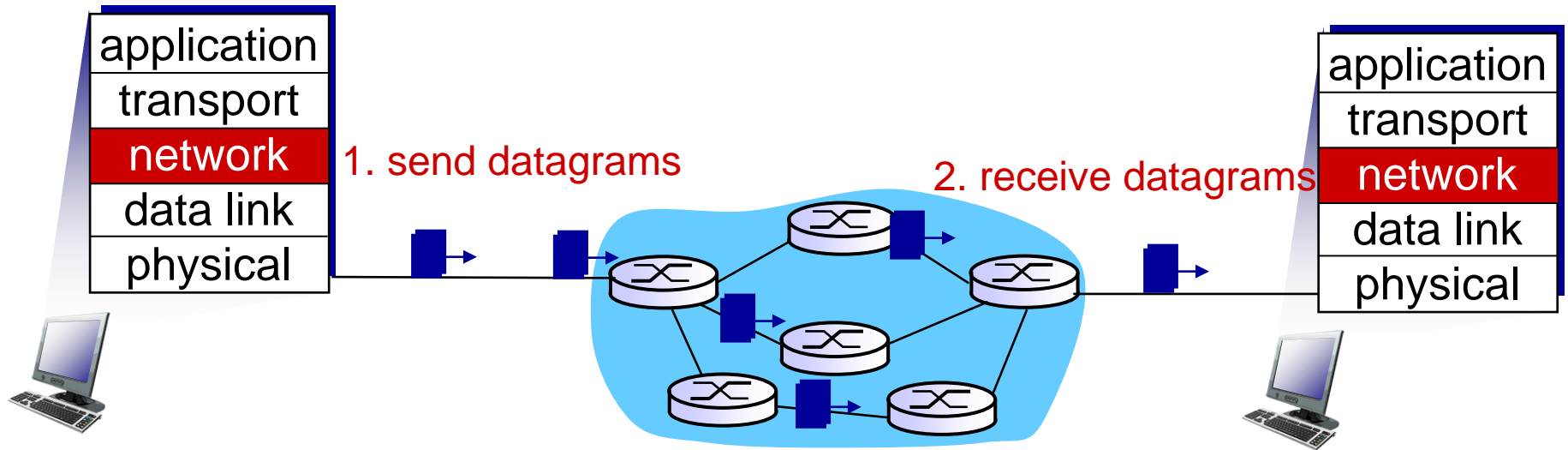# Figure 4.8: *Sending acknowledgments in a virtual-circuit network*

4.19
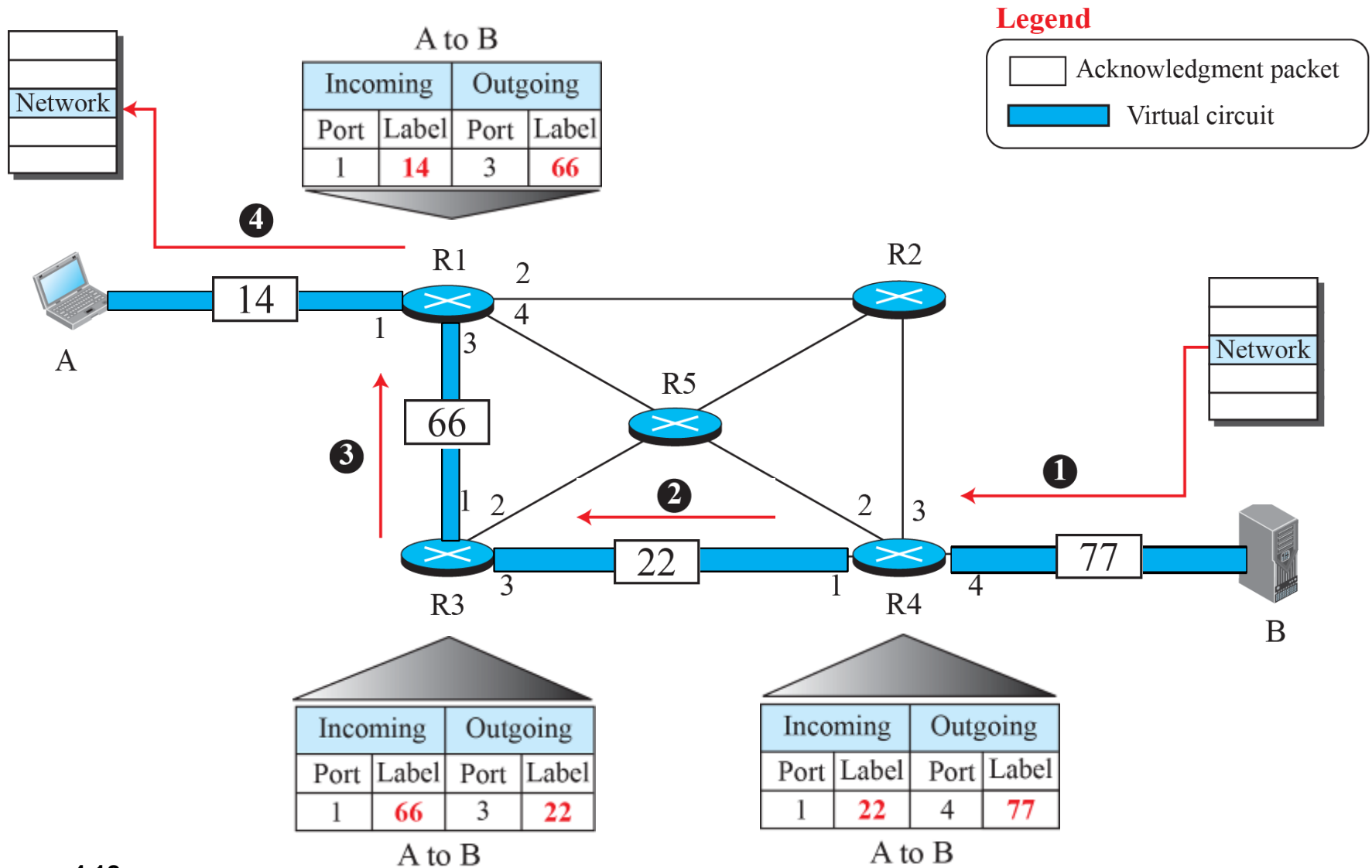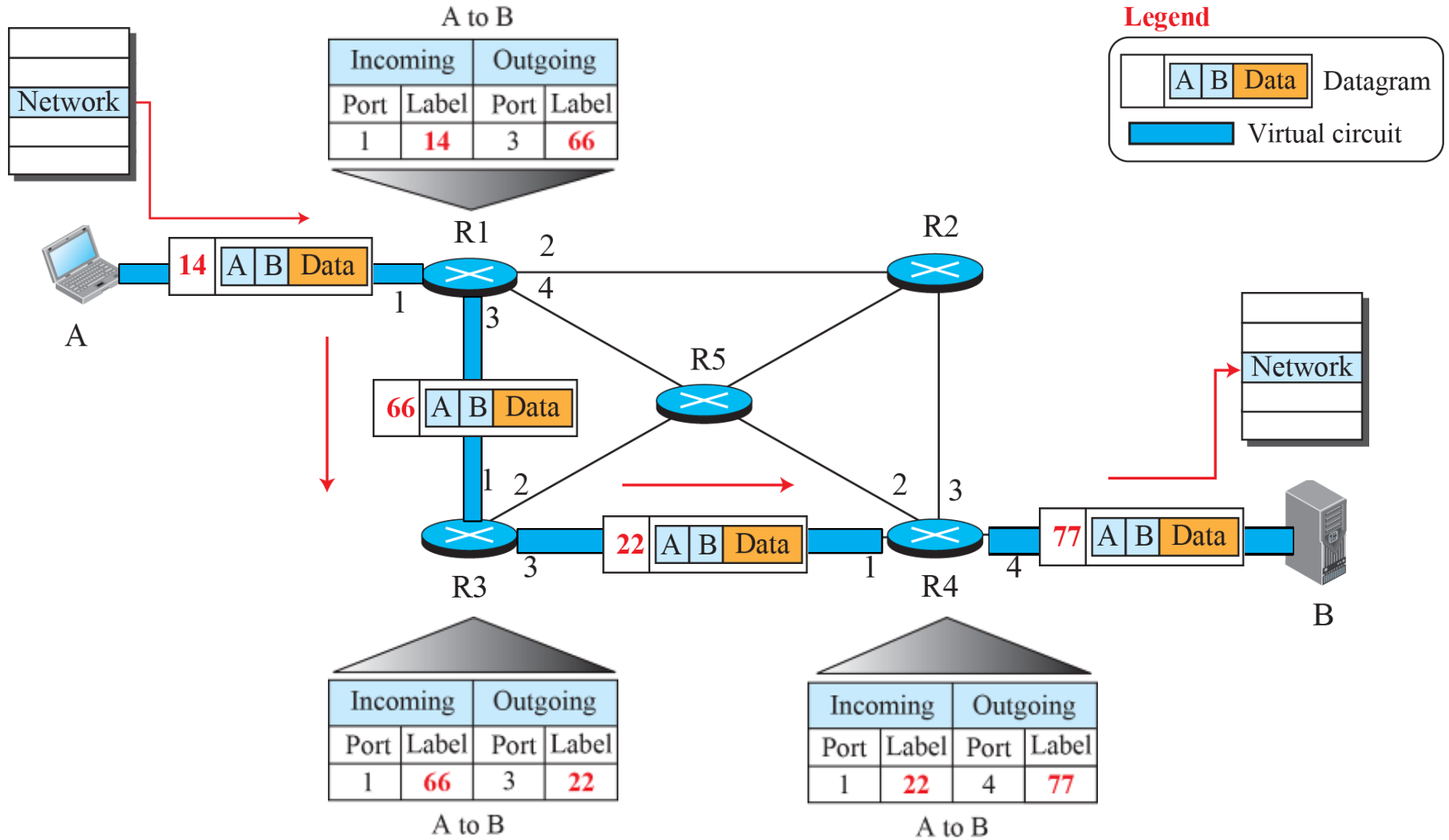
Datagram networks

❖ no call setup at network layer
❖ routers: no state about end-to-end connections
  ▪ no network-level concept of "connection"
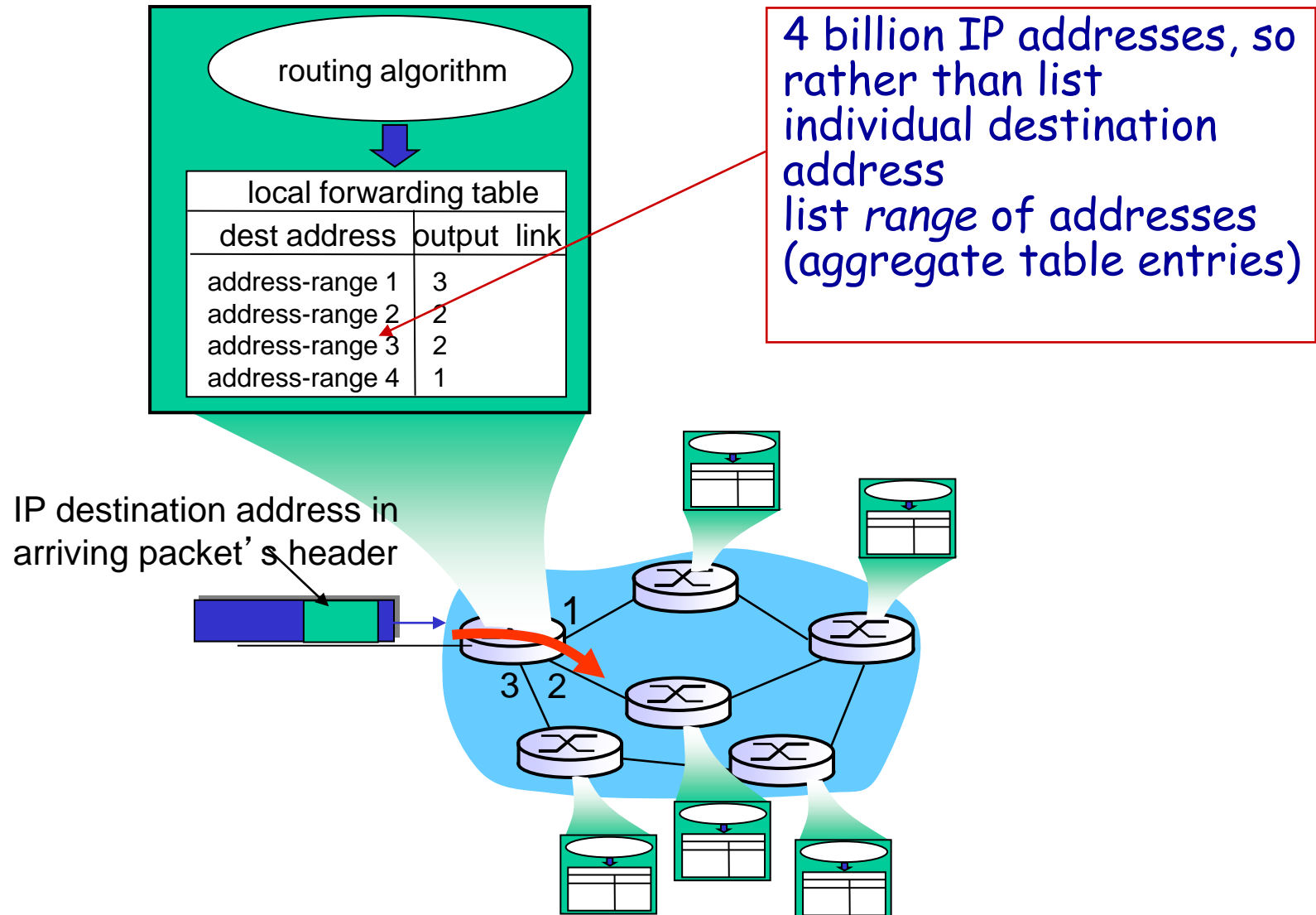❖ packets forwarded using destination host address

| application |
| transport |
| **network** |
| data link |
| physical |

1. send datagrams

2. receive datagrams

| application |
| transport |
| **network** |
| data link |
| physical |

Datagram forwarding table

routing algorithm

local forwarding table	
dest address	output link
address-range 1	3
address-range 2	2
address-range 3	2
address-range 4	1

4 billion IP addresses, so rather than list individual destination address
list *range* of addresses (aggregate table entries)

IP destination address in arriving packet's header

Figure 4.3: A connectionless packet-switched network
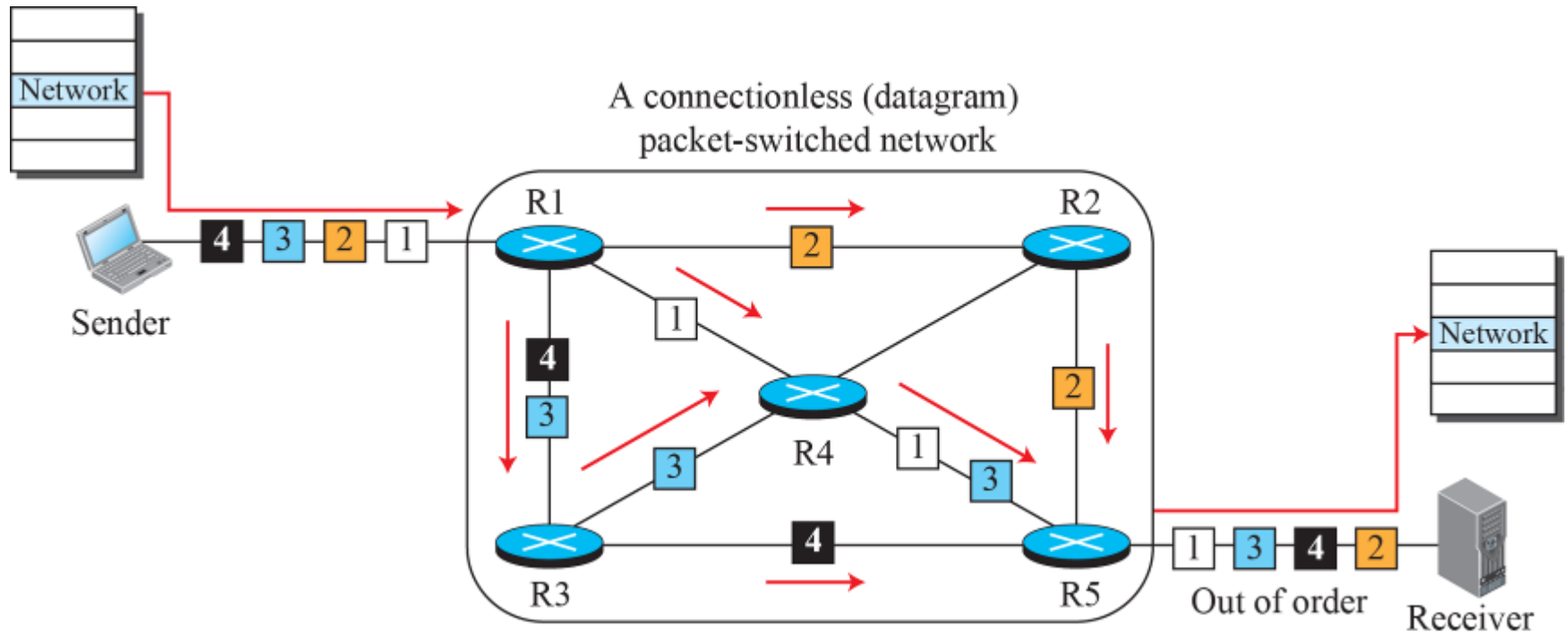
Figure 4.4: *Forwarding process in a router when used in a connectionless network*
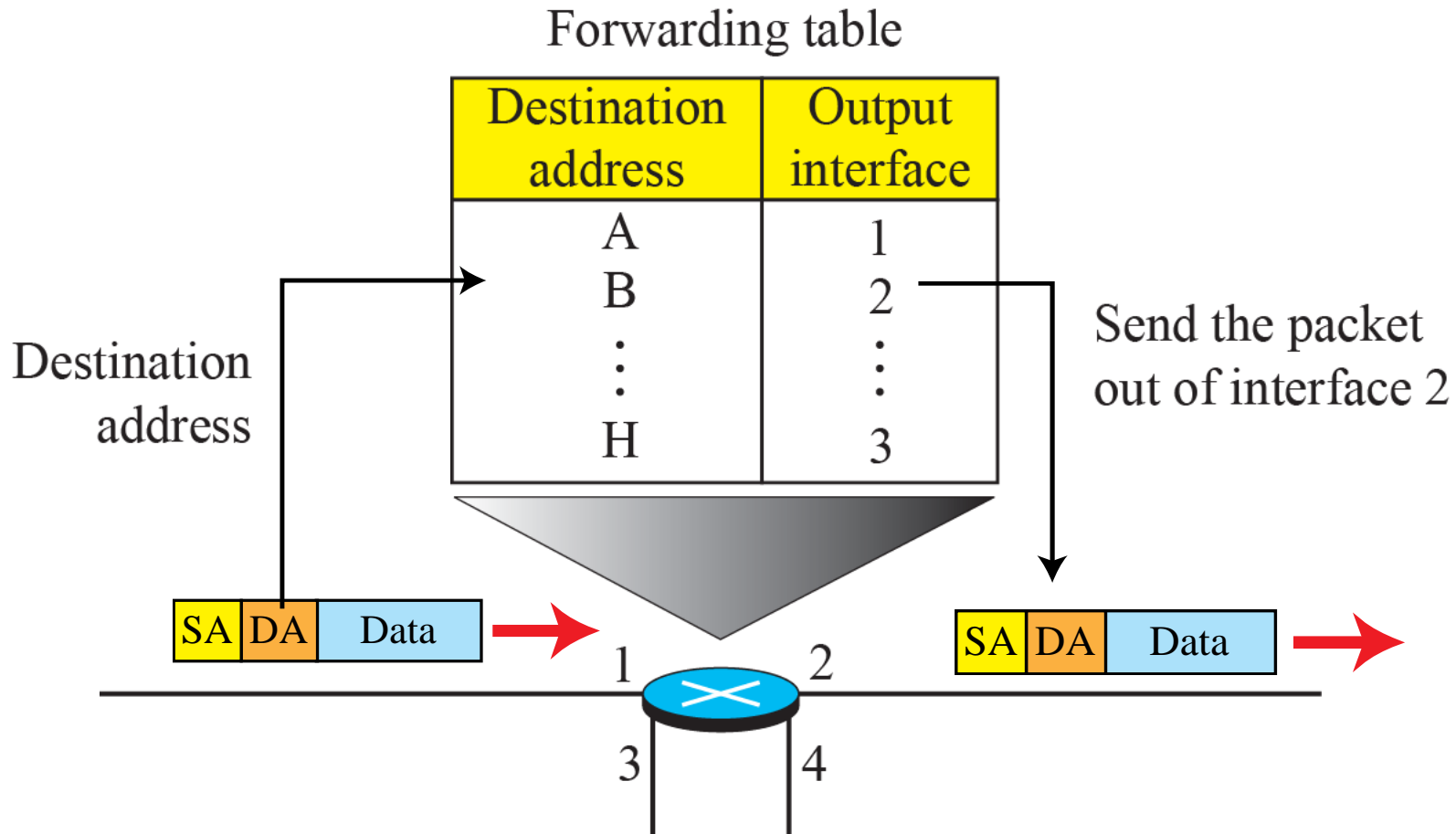
Datagram forwarding table

Destination Address Range	Link Interface
11001000 00010111 00010000 00000000 through 11001000 00010111 00010111 11111111	0
11001000 00010111 00011000 00000000 through 11001000 00010111 00011000 11111111	1
11001000 00010111 00011001 00000000 through 11001000 00010111 00011111 11111111	2
otherwise	3

Q: but what happens if ranges don't divide up so nicely?

Longest prefix matching

longest prefix 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?

Datagram or VC network: why?

Internet (datagram)

- ❖ data exchange among computers
  - ▪ "elastic" service, no strict timing req.
- ❖ many link types
  - ▪ different characteristics
  - ▪ uniform service difficult
- ❖ "smart" end systems (computers)
  - ▪ can adapt, perform control, error recovery
  - ▪ *simple inside network, complexity at "edge"*

ATM (VC)

- ❖ evolved from telephony
- ❖ human conversation:
  - ▪ strict timing, reliability requirements
  - ▪ need for guaranteed service
- ❖ "dumb" end systems
  - ▪ telephones
  - ▪ *complexity inside network*

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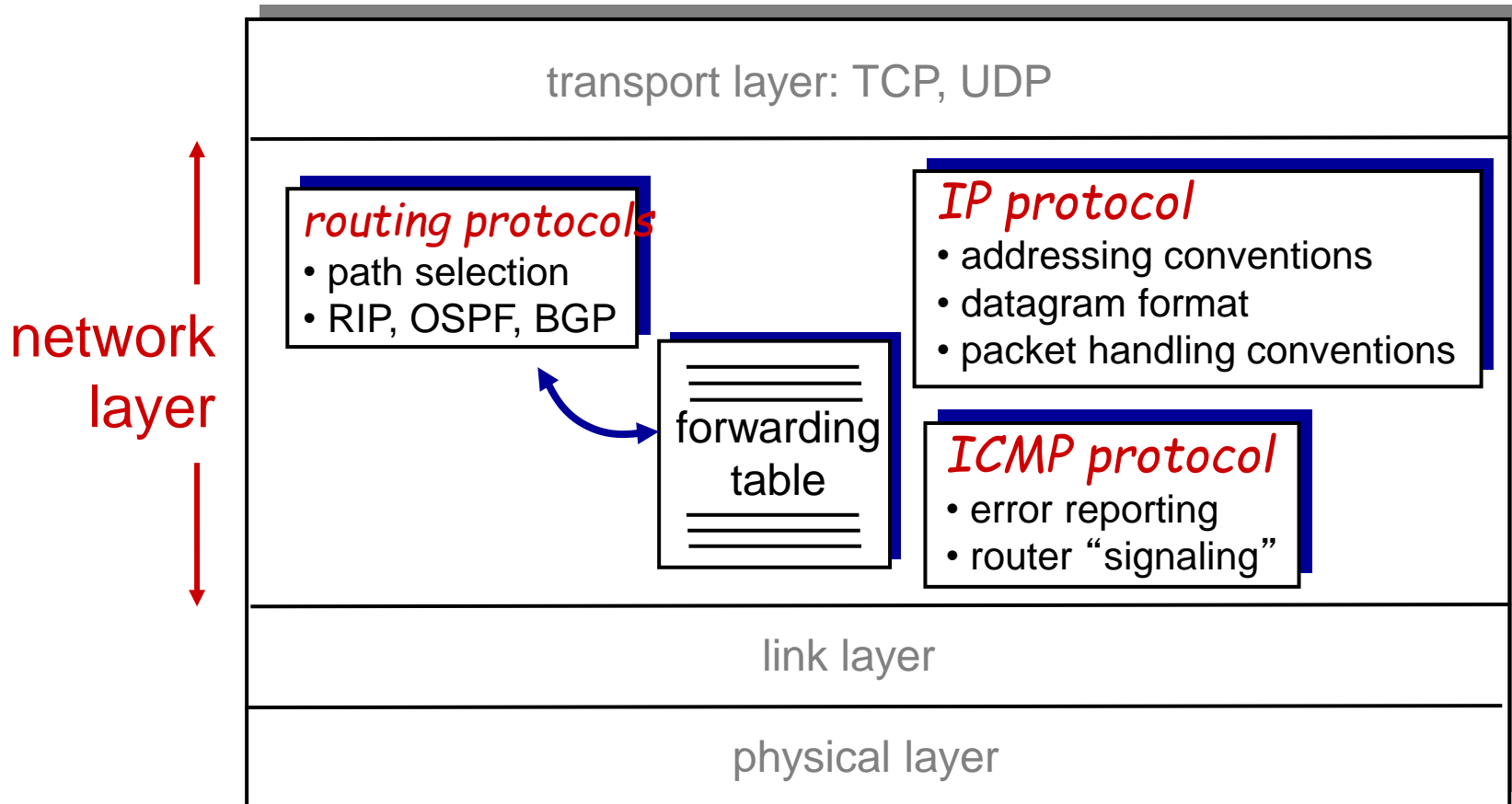- distance vector
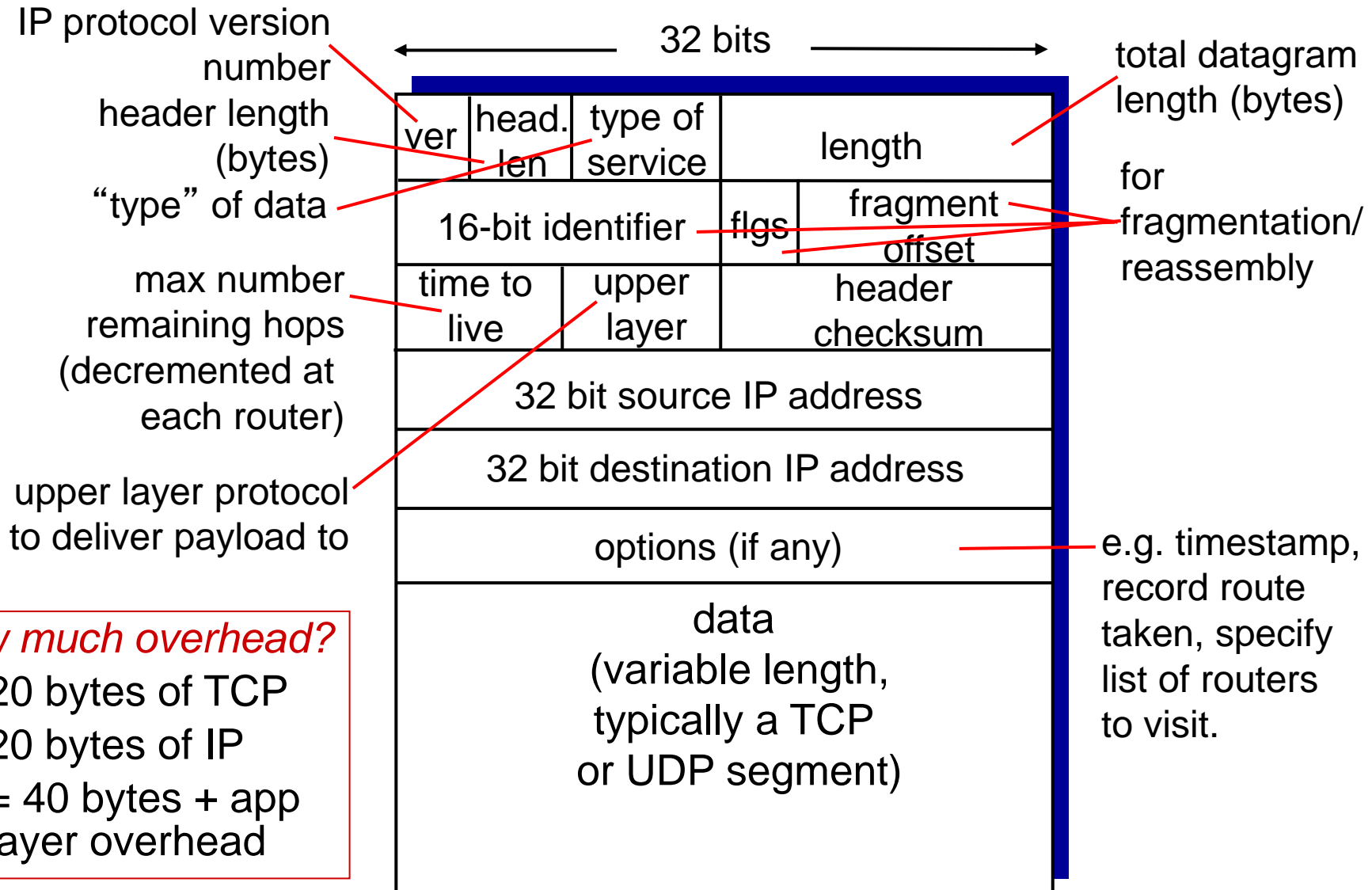- hierarchical routing

4.6 routing in the Internet
- RIP
- OSPF
- BGP

4.7 broadcast and multicast routing

The Internet network layer

host, router network layer functions:

network layer

transport layer: TCP, UDP	

routing protocols
- path selection
- RIP, OSPF, BGP

forwarding table

IP protocol
- addressing conventions
- datagram format
- packet handling conventions

ICMP protocol
- error reporting
- router "signaling"

link layer

physical layer

IP datagram format

IP protocol version number

header length (bytes)

"type" of data

max number remaining hops (decremented at each router)

upper layer protocol to deliver payload to

32 bits

ver	head. len	type of service	length
16-bit identifier	flgs	fragment offset
time to live	upper layer	header checksum
32 bit source IP address
32 bit destination IP address
options (if any)
data (variable length, typically a TCP or UDP segment)

total datagram length (bytes)

for fragmentation/ reassembly

e.g. timestamp, record route taken, specify list of routers to visit.

how much overhead?
- ❖ 20 bytes of TCP
- ❖ 20 bytes of IP
- ❖ = 40 bytes + app layer overhead

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

fragmentation:
in: one large datagram
out: 3 smaller datagrams
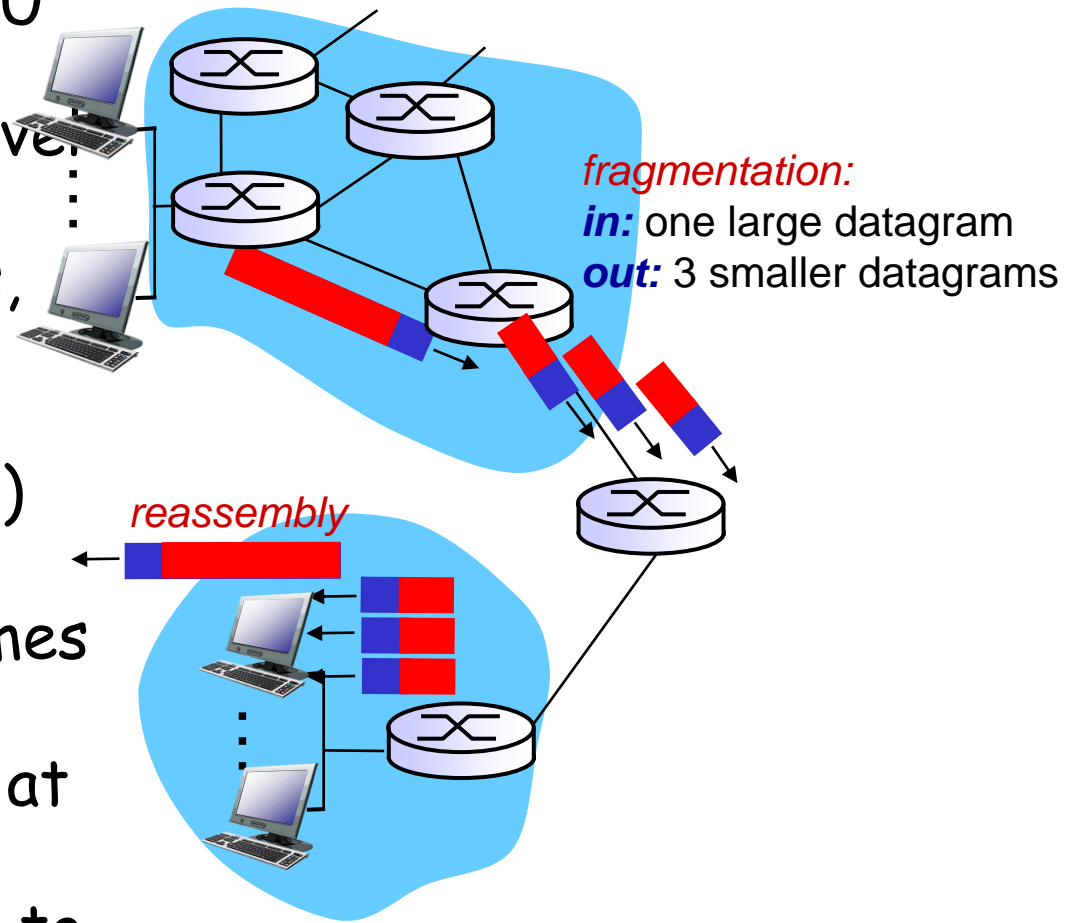
reassembly

IP fragmentation, reassembly

example:

❖ 4000 byte datagram
❖ MTU = 1500 bytes

	length =4000	ID =x	fragflag =0	offset =0	

one large datagram becomes several smaller datagrams

1480 bytes in data field

offset = 1480/8

	length =1500	ID =x	fragflag =1	offset =0	

	length =1500	ID =x	fragflag =1	offset =185	

	length =1040	ID =x	fragflag =0	offset =370	

Total data length=?

Figure 4.27: *Fragmentation example*

Offset = 0000/8 = 0

Byte 0000   Byte 3999

Offset = 0000/8 = 0
0000   1399

Offset = 1400/8 = 175
1400   2799

Offset = 2800/8 = 350
2800   3999

4.32
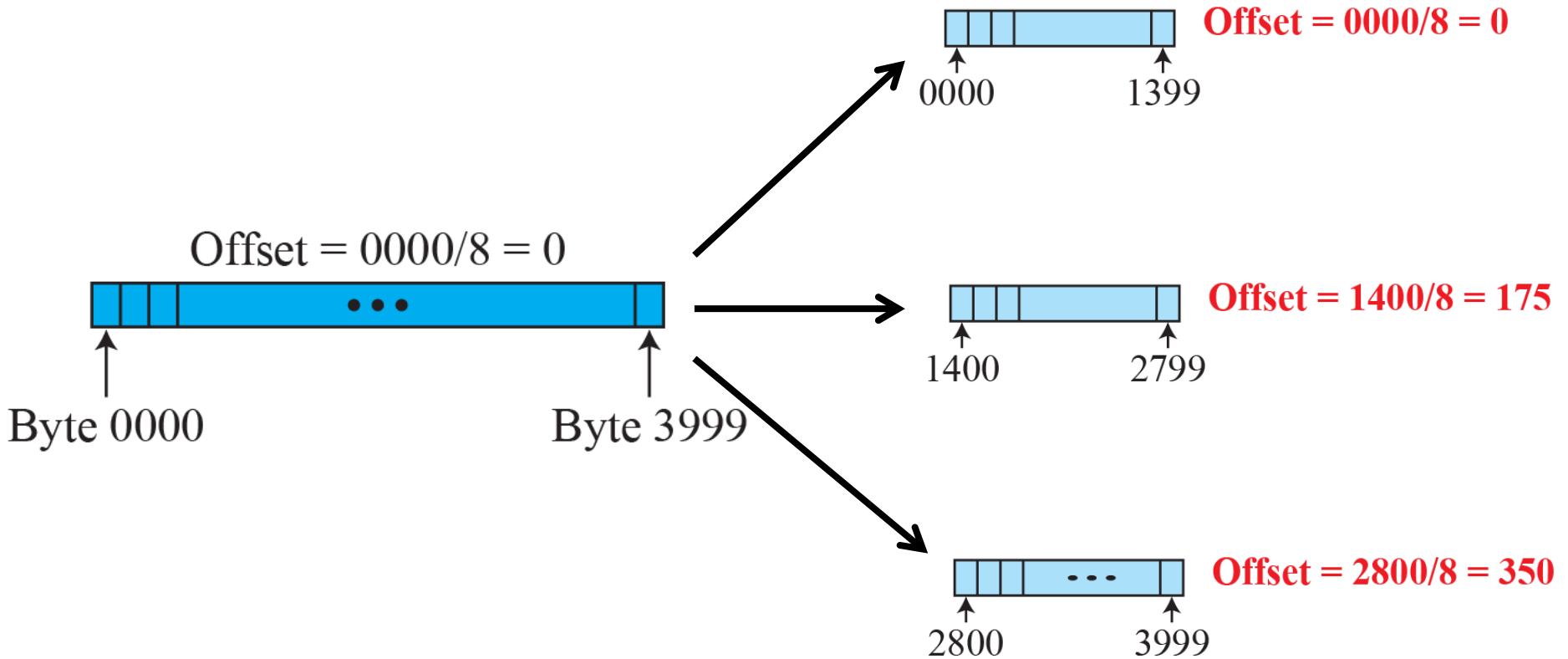
Figure 4.28: Detailed fragmentation example
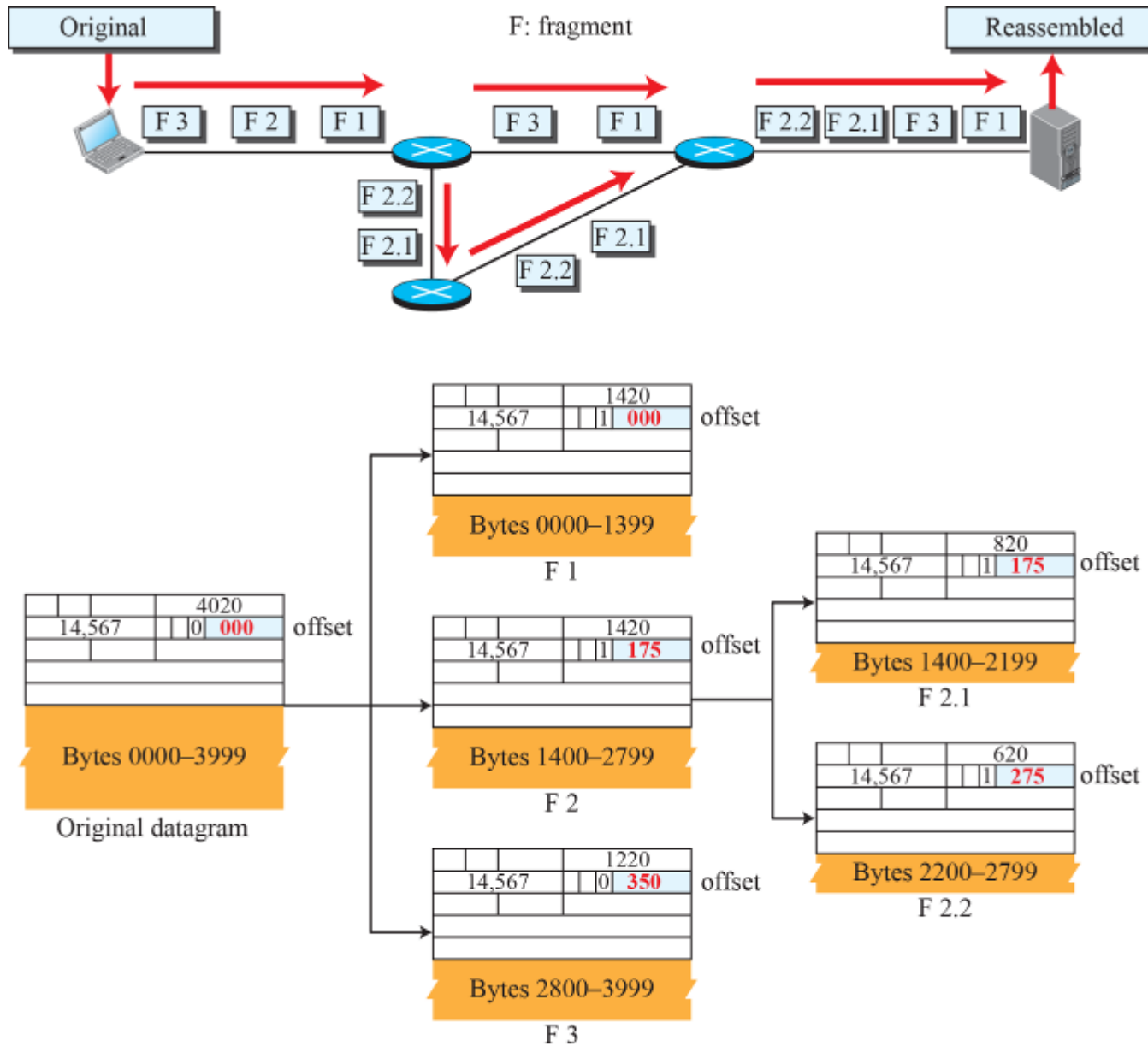
Reassemble the original datagram

❖ Identify first fragment :
 offset=0
❖ Divide the length of first fragment by 8 :
   second fragment offset
❖ Divide the length of first and second :
    fragment by 8 : Third fragment offset
❖ Continue the process until last fragment :
   M bit=0

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- distance vector
- hierarchical routing

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The identifier used in the IP layer.

Identifies the connection of each device to the Internet is called the Internet address or IP address.

An IPv4 address is a 32-bit address

The IP address is the address of the connection, not the host or the router, because if the device is moved to another network, the IP address may be changed.

4.36

❑ Address Space

❑ Notation

❑ Hierarchy in Addressing

❑ Classful Addressing

❖ Address Depletion
❖ Subnetting and Supernetting
❖ Advantage of Classful Addressing

4.37

❑   Classless Addressing

❖ Prefix Length: Slash Notation
❖ Extracting information from an address
❖ Address Mask
❖ Network Address
❖ Block Allocation
❖ Subnetting
❖ Address Aggregation
❖ Special Addresses

4.38

IP addressing: introduction

❖ *IP address:* 32-bit identifier for host, router *interface*

❖ *interface:* connection between host/router and physical link
  ▪ routers typically have multiple interfaces
  ▪ host typically has one active interface (e.g., wired Ethernet, wireless 802.11)

❖ *one IP address associated with each interface*

223.1.1.1
223.1.1.2
223.1.1.4   223.1.2.9
223.1.1.3
223.1.3.27
223.1.2.1
223.1.2.2
223.1.3.1   223.1.3.2
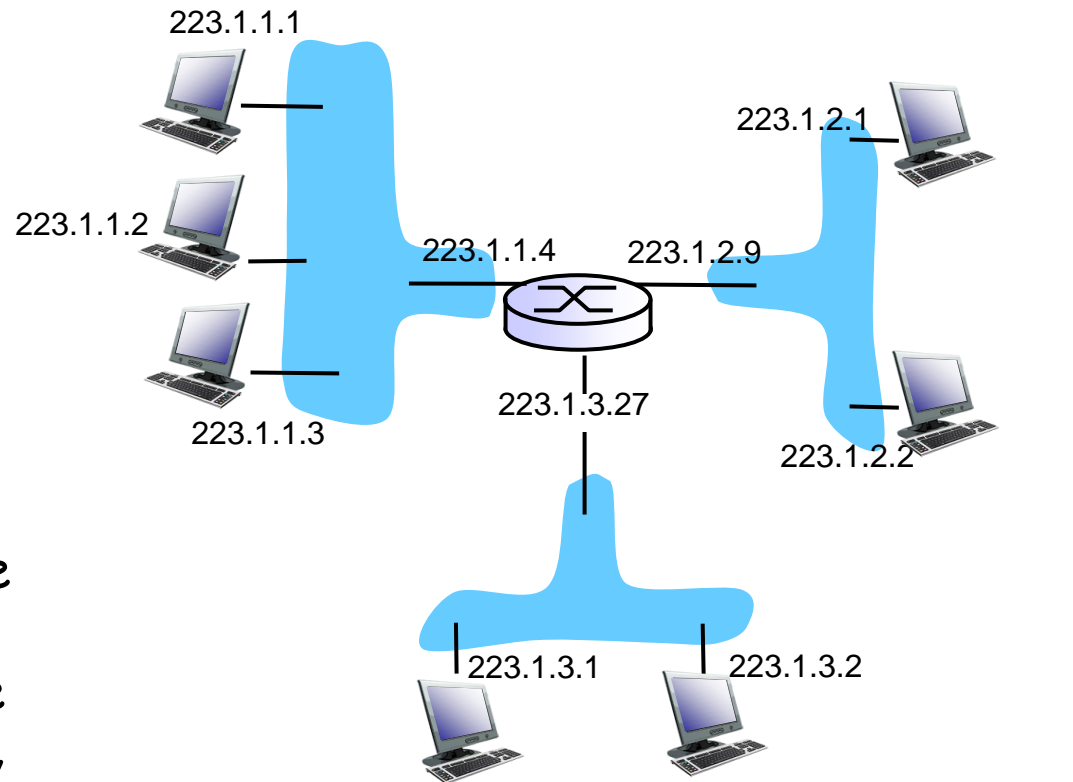
223.1.1.1 = 11011111 00000001 00000001 00000001

| 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)

223.1.1.1

223.1.2.1

223.1.1.2

223.1.1.4

223.1.2.9

223.1.1.3

223.1.3.27

223.1.2.2

223.1.3.1

223.1.3.2
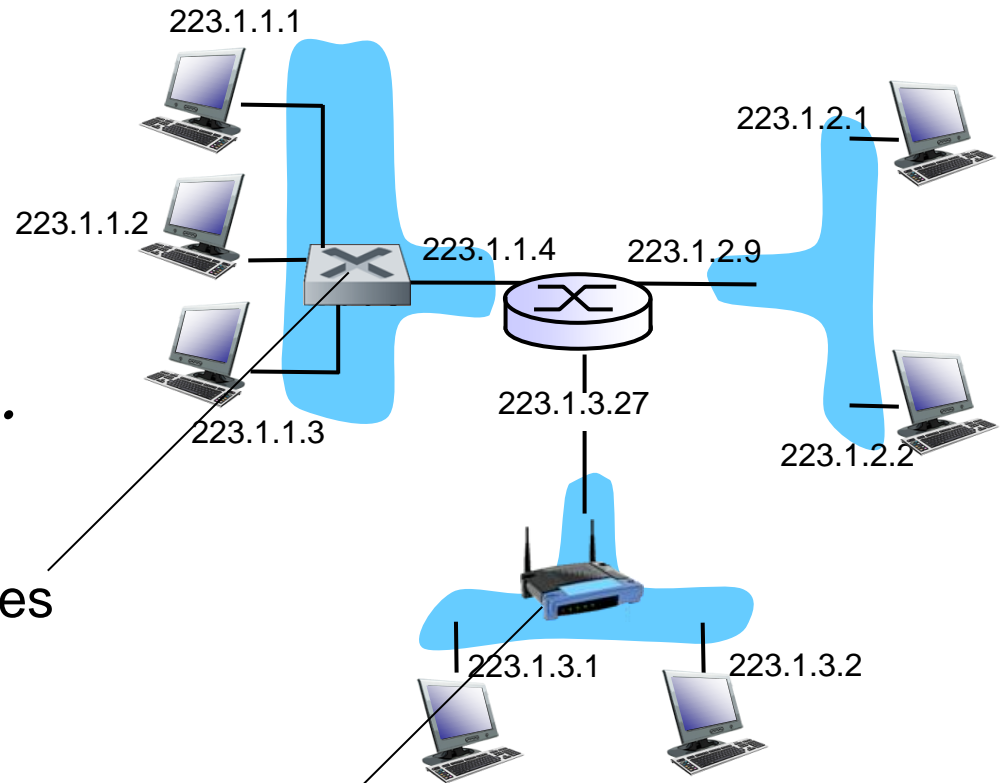
A: wireless WiFi interfaces connected by WiFi base station

Figure 4.29: *Three different notations in IPv4 addressing*

Binary: 10000000 00001011 00000011 00011111

Dotted decimal: 128 . 11 . 3 . 31

Hexadecimal: 80 0B 03 1F

4.41
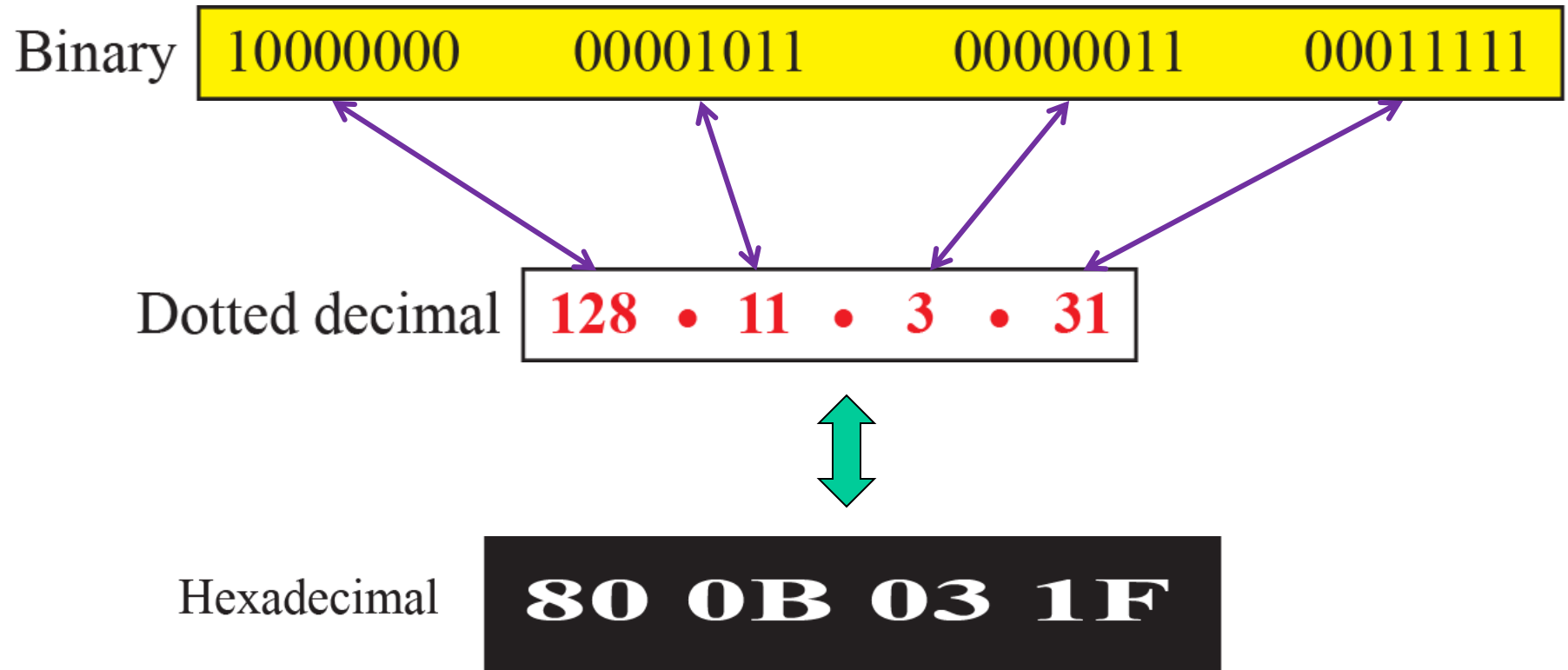
Figure 4.30: *Hierarchy in addressing*
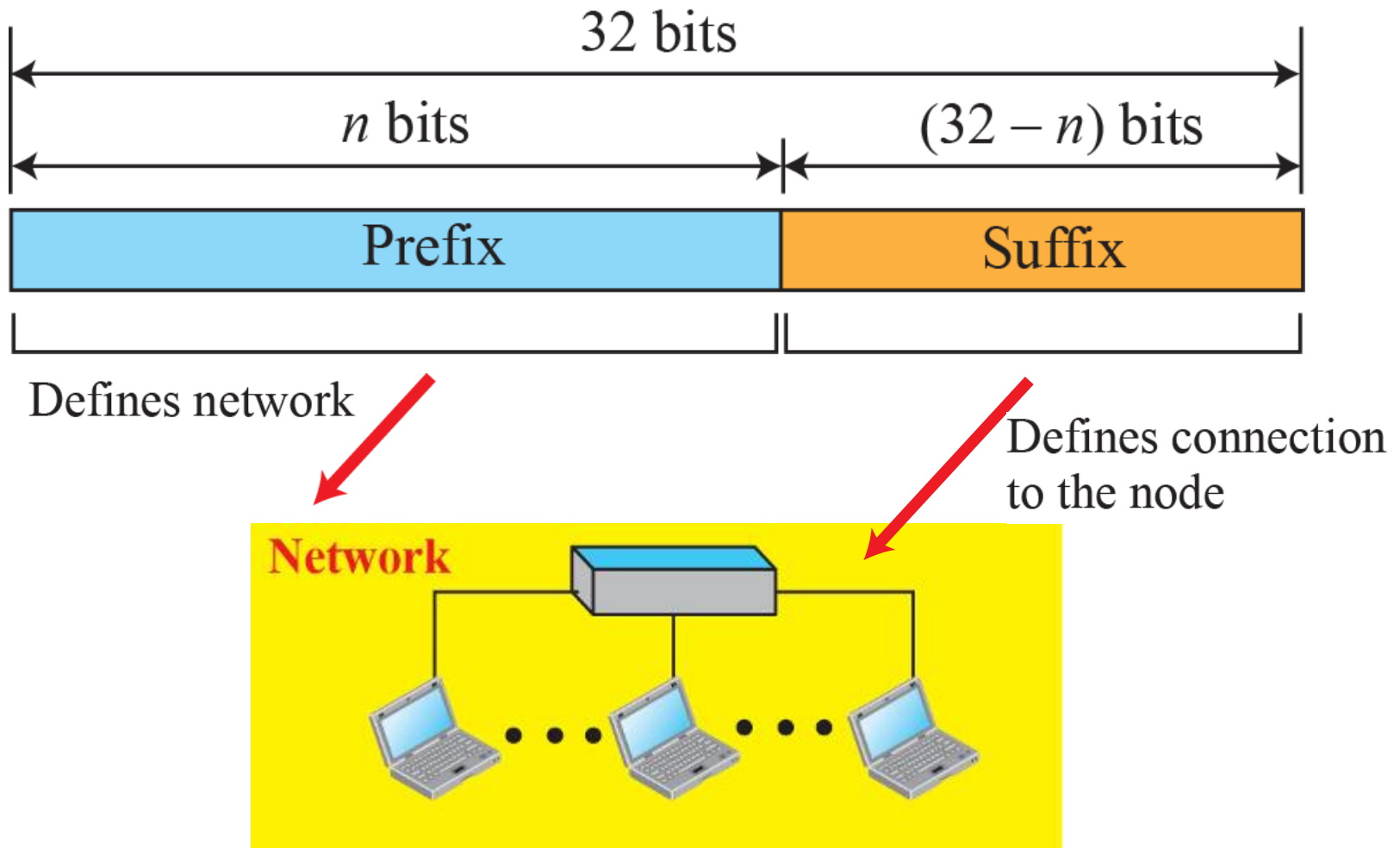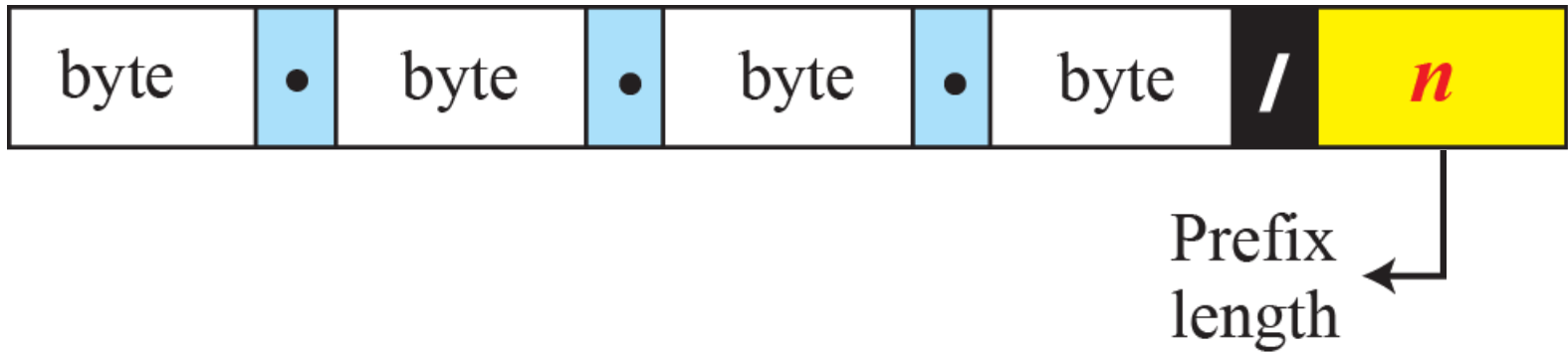
Figure 4.31: Occupation of the address space in classful addressing

Address space: 4,294,967,296 addresses

A	B	C	D	E
50%	25%	12.5%	6.25%	6.25%

8 bits　8 bits　8 bits　8 bits

Class A | 0 Prefix | Suffix
Class B | 10 Prefix | Suffix
Class C | 110 Prefix | Suffix
Class D | 1110 Multicast addresses
Class E | 1111 Reserved for future use
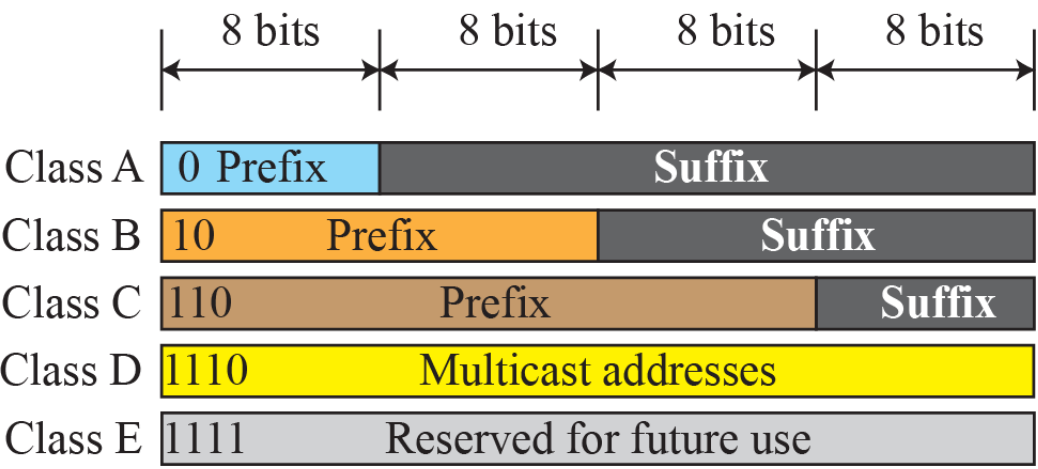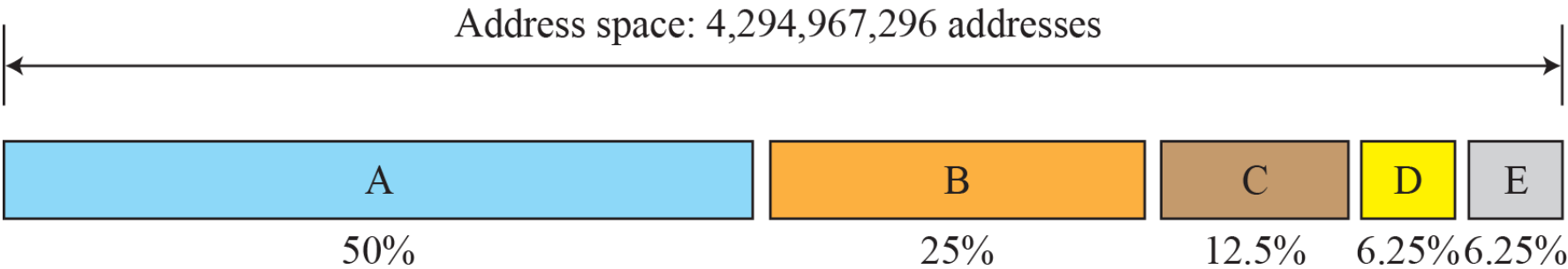
Class	Prefixes	First byte
A	$n = 8$ bits	0 to 127
B	$n = 16$ bits	128 to 191
C	$n = 24$ bits	192 to 223
D	Not applicable	224 to 239
E	Not applicable	240 to 255

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Figure 4.32:   Variable-length blocks in classless addressing

Block 1 | Block 2 | • • • | Block i | • • • | Block (m − 1) | Block m

Address space

Slash notation (CIDR)

| byte | • | byte | • | byte | • | byte | **/** | **n** |

Prefix length
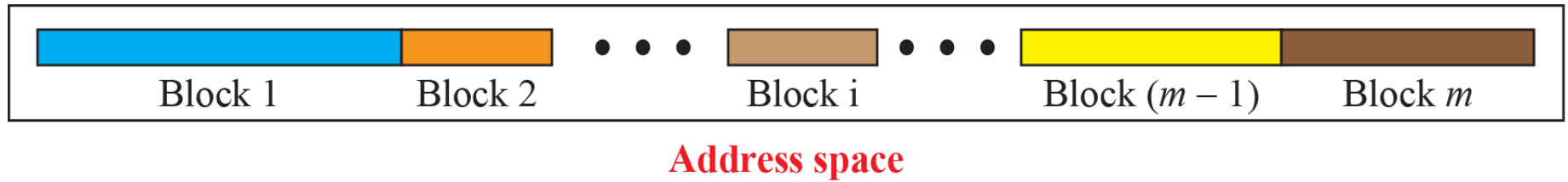
Examples:

12.24.76.8/**8**

23.14.67.92/**12**

220.8.24.255/**25**

4.45

1.45

Figure 4.34: *Information extraction in classless addressing*

Any address

n bits | $(32 - n)$ bits

| Prefix | Suffix |

Number of addresses:
$$N = 2^{32 - n}$$

| Prefix | 000 ... 0 |

First address

Set all suffix bits to 0s

| Prefix | 111 ... 1 |

Last address

Set all suffix bits to 1s

4.46

Example 4.1
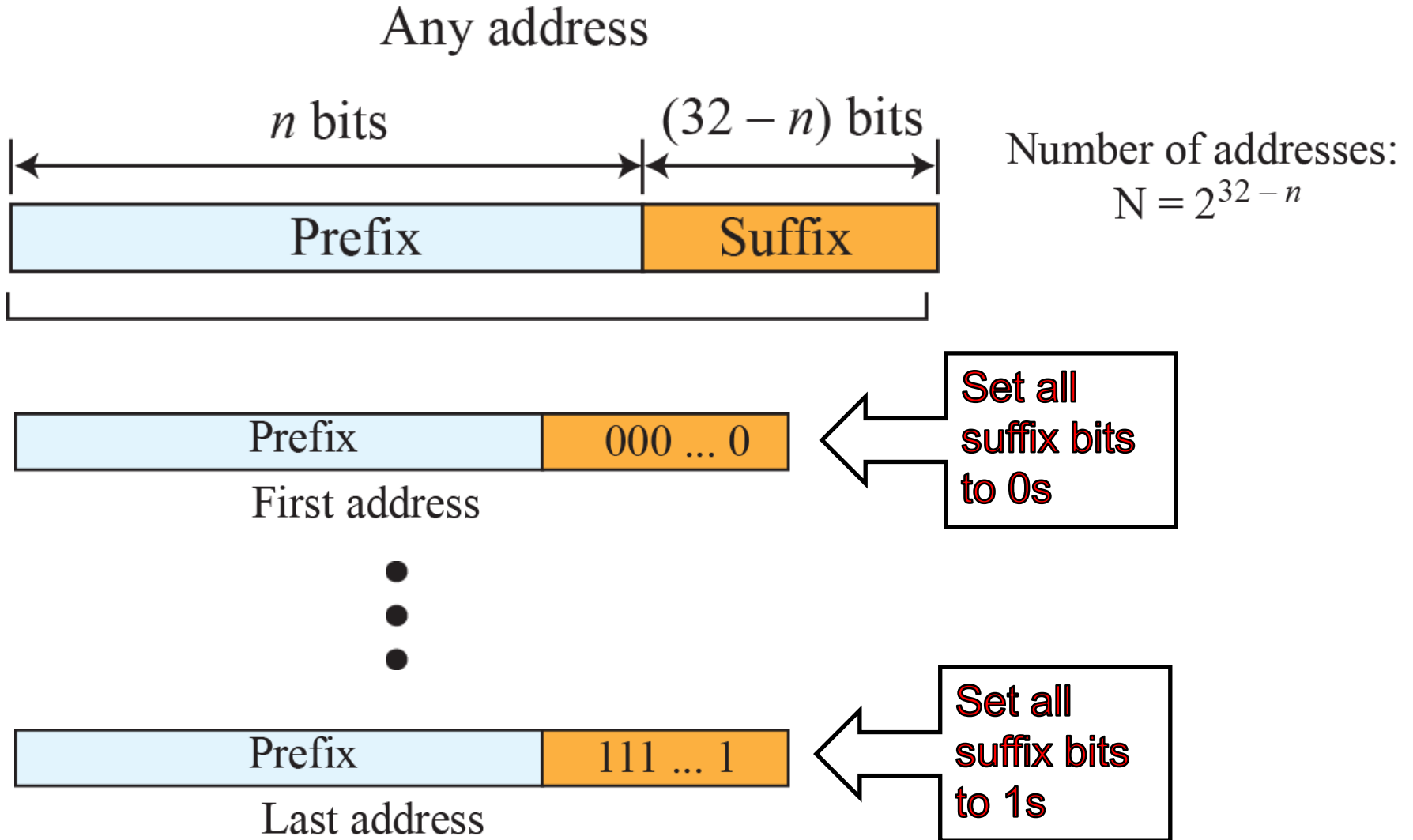
A classless address is given as 167.199.170.82/27. We can find the above three pieces of information as follows. The number of addresses in the network is $2^{32-n} = 2^5 = 32$ addresses. The first address can be found by keeping the first 27 bits and changing the rest of the bits to 0s.

Address: 167.199.170.82/**27**	10100111 11000111 10101010 01010010
First address: 167.199.170.64/**27**	10100111 11000111 10101010 01000000

The last address can be found by keeping the first 27 bits and changing the rest of the bits to 1s.

Address: 167.199.170.82/**27**	10100111 11000111 10101010 01011111
Last address: 167.199.170.95/**27**	10100111 11000111 10101010 01011111

4.47

Example 4.2

We repeat Example 4.1 using the mask. The mask in dotted-decimal notation is 255.255.255.224 The AND, OR, and NOT operations can be applied to individual bytes using calculators and applets at the book website.

Number of addresses in the block:	N = **NOT** (mask) + 1= 0.0.0.31 + 1 = 32 addresses
First address:	First = (address) **AND** (mask)
Last address:	Last = (address) **OR** (**NOT** mask)

Example 4.3

In classless addressing, an address cannot per se define the block the address belongs to. For example, the address 230.8.24.56 can belong to many blocks. Some of them are shown below with the value of the prefix associated with that block.

Prefix length:16	→	Block:	230.8.0.0	to	230.8.255.255
Prefix length:20	→	Block:	230.8.16.0	to	230.8.31.255
Prefix length:26	→	Block:	230.8.24.0	to	230.8.24.63
Prefix length:27	→	Block:	230.8.24.32	to	230.8.24.63
Prefix length:29	→	Block:	230.8.24.56	to	230.8.24.63
Prefix length:31	→	Block:	230.8.24.56	to	230.8.24.57

Figure 4.35: *Network address*

Network 1   Network 2   • • •   Network m

1   2   m

Router

Routing Process

Forwarding table

Network address	Interface
$b_1 \cdot c_1 \cdot d_1 \cdot e_1$	1
$b_2 \cdot c_2 \cdot d_2 \cdot e_2$	2
• • •	...
$b_m \cdot c_m \cdot d_m \cdot e_m$	m

Destination address → Find network address → Interface number

4.50
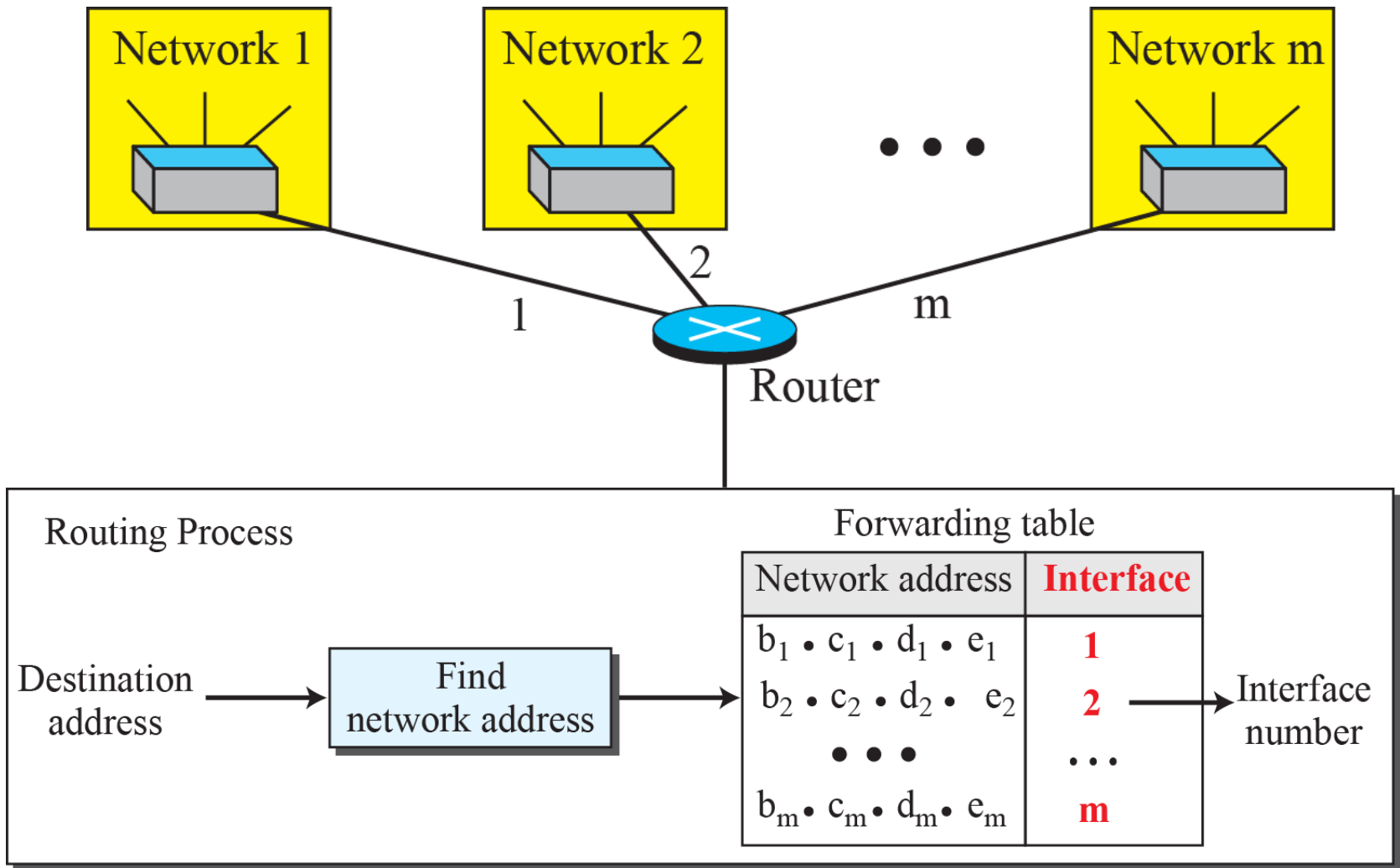
By ICANN (Internet Corporation for Assigned Names & Numbers)
1. No of addresses N: power of 2, n to be an int.
2. Contiguous block . But selection such that first address needs to be divisible by N. (I address : suffix zero, i.e 32-n zeros. The decimal value then equal to the decimal equivalent of prefix with suffix all zeros.

i.e FA= prefix * 2^{32-n} = prefix in decimal X N

An ISP has requested a block of 1000 addresses. Since 1000 is not a power of 2, 1024 addresses are granted. The prefix length is calculated as $n = 32 - \log_2 1024 = 22$. An available block, 18.14.12.0**/22**, is granted to the ISP. It can be seen that the first address in decimal is 302,910,464, which is divisible by 1024.

Subnetting

❖ Divide range into several subranges & assign each one to different subnetwork.

❖ Subnetwork -- into several sub-subnetwork.

❖ Design: to enable routing.

❖ Let Total no of addresses is N with prefix n.

❖ Total no of addresses is Nsub with prefix n_{sub}.

Rule: 1. Nsub is power of 2

2. n_{sub}= 32-$\log_2$ Nsub

3. FA in each subnet sould be divisible by Nsub.

An organization is granted a block of addresses with the beginning address 14.24.74.0**/24**. The organization needs to have 3 subblocks of addresses to use in its three subnets: one subblock of 10 addresses, one subblock of 60 addresses, and one subblock of 120 addresses. Design the subblocks.

Solution

There are $2^{32-24} = 256$ addresses in this block. The first address is 14.24.74.0**/24**; the last address is 14.24.74.255**/24**. To satisfy the third requirement, we assign addresses to subblocks, starting with the largest and ending with the smallest one.

Example 4.5 (continued)

a. The number of addresses in the largest subblock, which requires 120 addresses, is not a power of 2. We allocate 128 addresses. The subnet mask for this subnet can be found as $n_1 = 32 - \log_2 128 = 25$. The first address in this block is 14.24.74.0**/25**; the last address is 14.24.74.127**/25**.
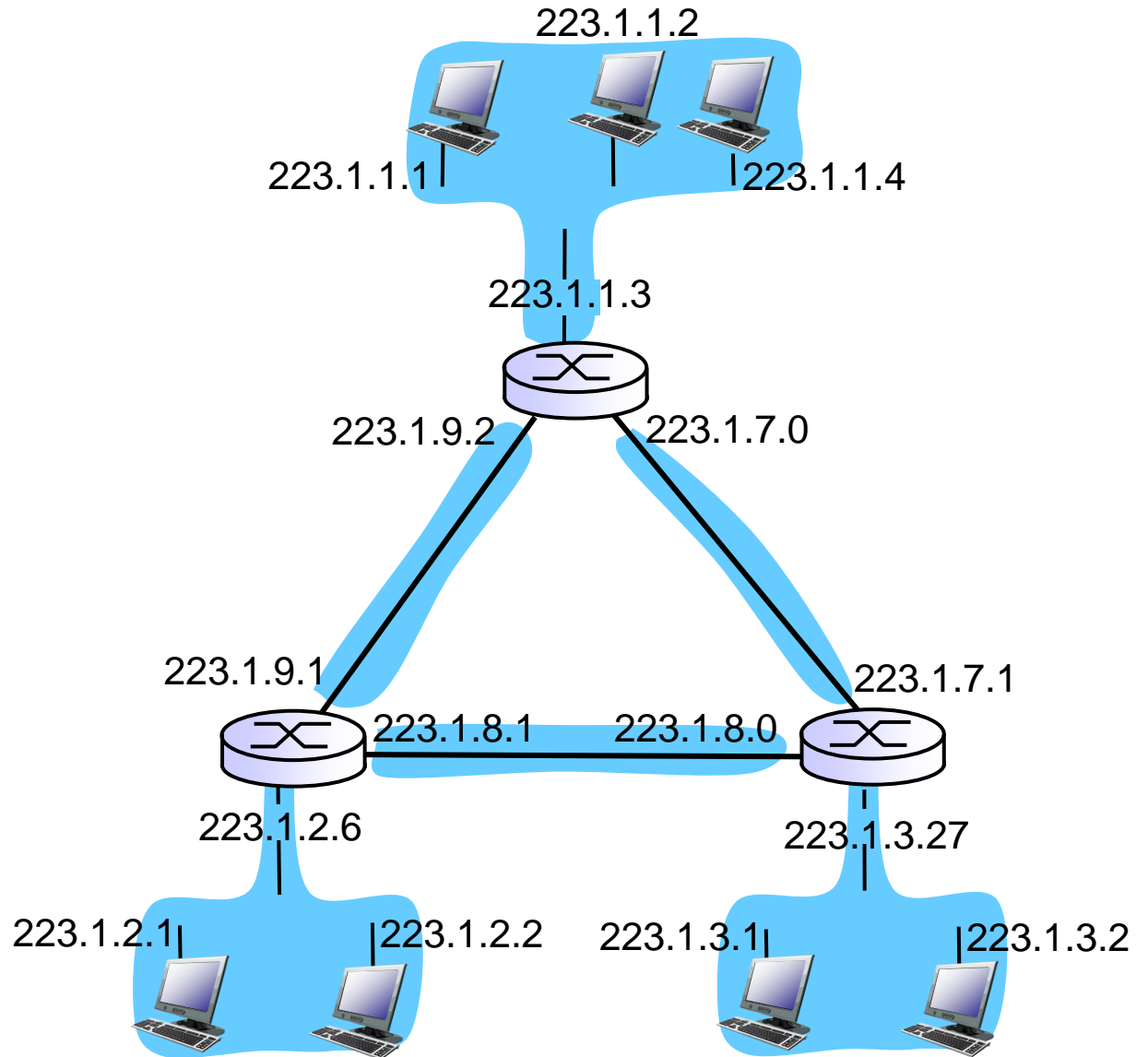
b. The number of addresses in the second largest subblock, which requires 60 addresses, is not a power of 2 either. We allocate 64 addresses. The subnet mask for this subnet can be found as $n_2 = 32 - \log_2 64 = 26$. The first address in this block is 14.24.74.128**/26**; the last address is 14.24.74.191**/26**.

Example 4.5 (continued)

c. The number of addresses in the smallest subblock, which requires 10 addresses, is not a power of 2. We allocate 16 addresses. The subnet mask for this subnet can be found as $n_1 = 32 - \log_2 16 = 28$. The first address in this block is 14.24.74.192**/28**; the last address is 14.24.74.207**/28**.

If we add all addresses in the previous subblocks, the result is 208 addresses, which means 48 addresses are left in reserve. The first address in this range is 14.24.74.208. The last address is 14.24.74.255. We don't know about the prefix length yet. Figure 4.36 shows the configuration of blocks. We have shown the first address in each block.

Figure 4.36: Solution to Example 4.5

N = 256 addresses

n = 24

14.24.74.0/24
First address

a. Original block

14.24.74.255/24
Last address

N = 128   64   16   48

n = 25   n = 26   28   Unused

14.24.74.0/25

14.24.74.128/26   14.24.192.0/28

b. Subblocks

4.56

Subnets

how many?

223.1.1.2

223.1.1.1

223.1.1.4

223.1.1.3

223.1.9.2   223.1.7.0

223.1.9.1   223.1.7.1

223.1.8.1   223.1.8.0

223.1.2.6   223.1.3.27

223.1.2.1   223.1.2.2   223.1.3.1   223.1.3.2
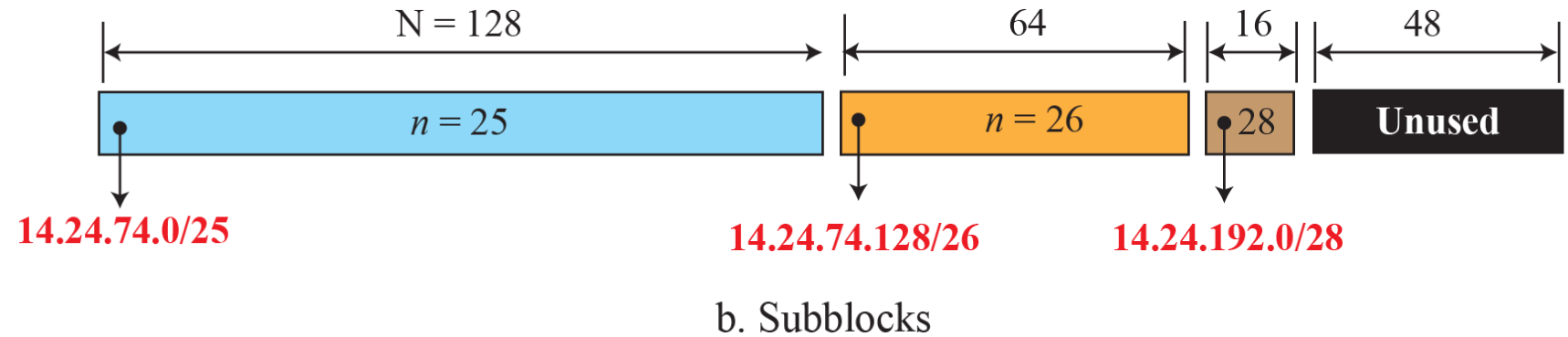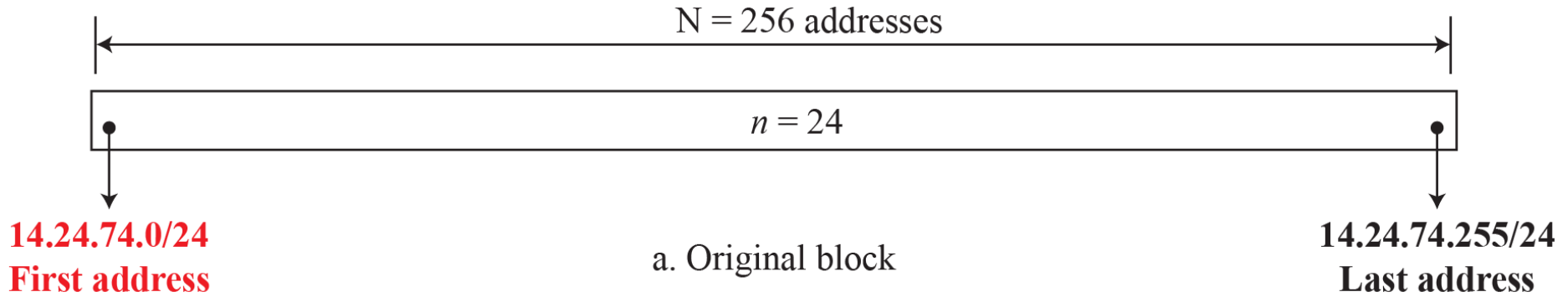
IP addressing: CIDR

CIDR: Classless InterDomain Routing
- subnet portion of address of arbitrary length
- address format: a.b.c.d/x, where x is # bits in subnet portion of address

```
         ←———————— subnet ————————→  ←—— host ——→
                   part                   part
  11001000  00010111  00010000  00000000

                 200.23.16.0/23
```
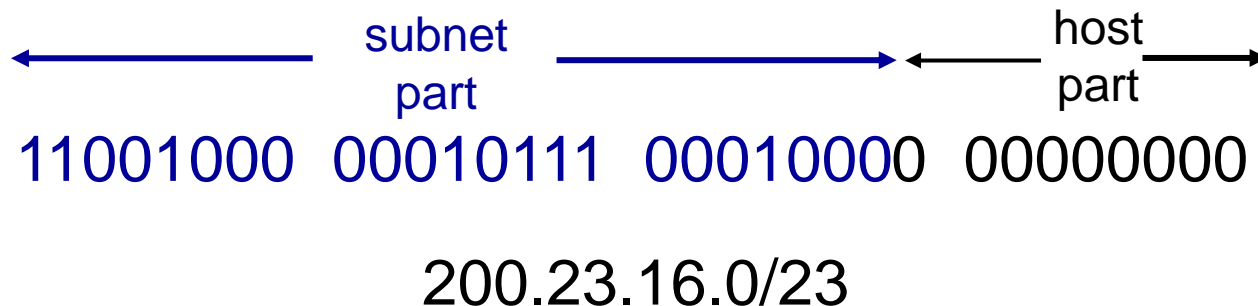
Hierarchical addressing: route aggregation

hierarchical addressing allows efficient advertisement of routing information:

Organization 0
200.23.16.0/23

Organization 1
200.23.18.0/23

Organization 2
200.23.20.0/23

Organization 7
200.23.30.0/23

Fly-By-Night-ISP

ISPs-R-Us

"Send me anything with addresses beginning 200.23.16.0/20"

"Send me anything with addresses beginning 199.31.0.0/16"

Internet
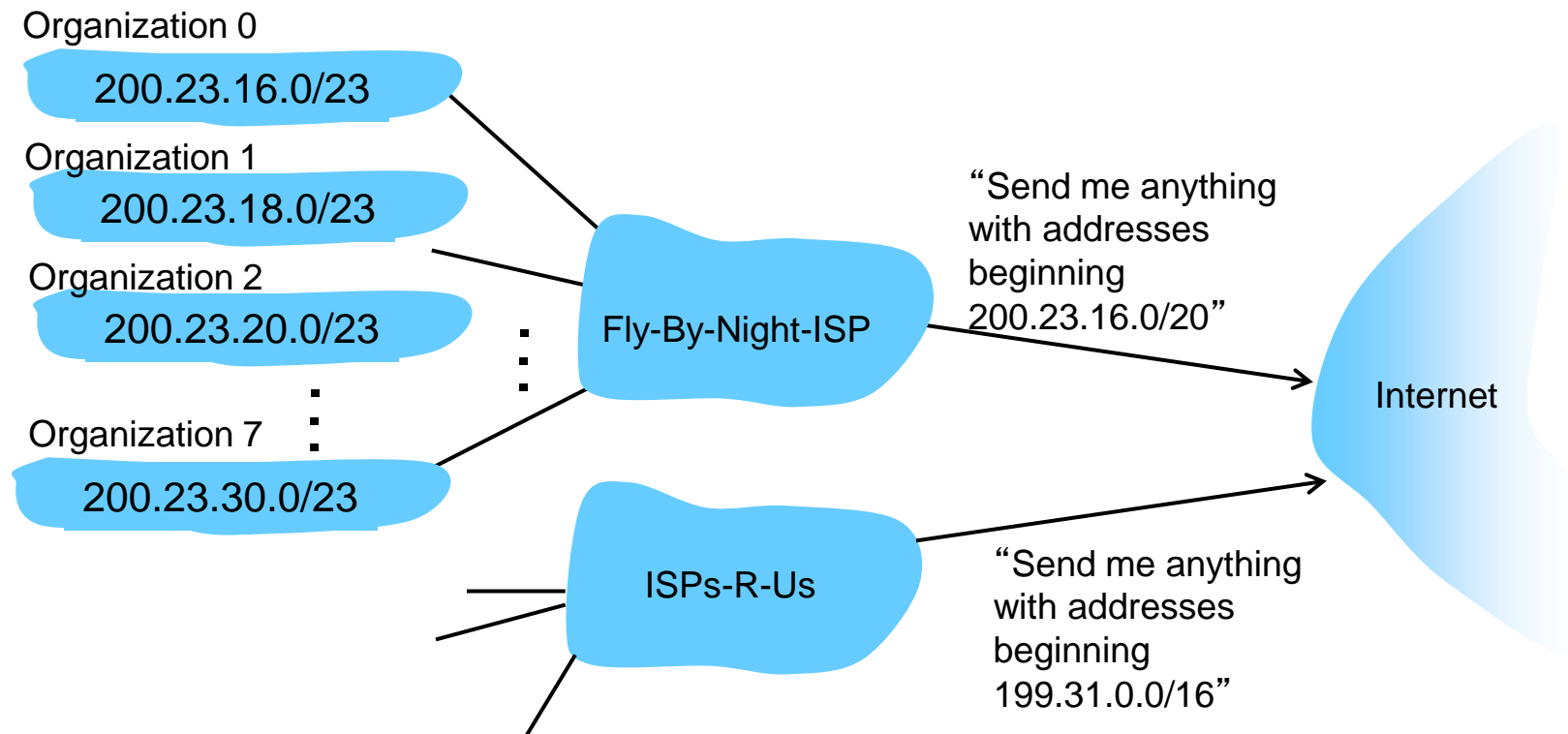
Hierarchical addressing: more specific routes

ISPs-R-Us has a more specific route to Organization 1

Organization 0
200.23.16.0/23

Organization 2
200.23.20.0/23

Organization 7
200.23.30.0/23

Fly-By-Night-ISP

"Send me anything with addresses beginning 200.23.16.0/20"

Internet

ISPs-R-Us

Organization 1
200.23.18.0/23

"Send me anything with addresses beginning 199.31.0.0/16 or 200.23.18.0/23"
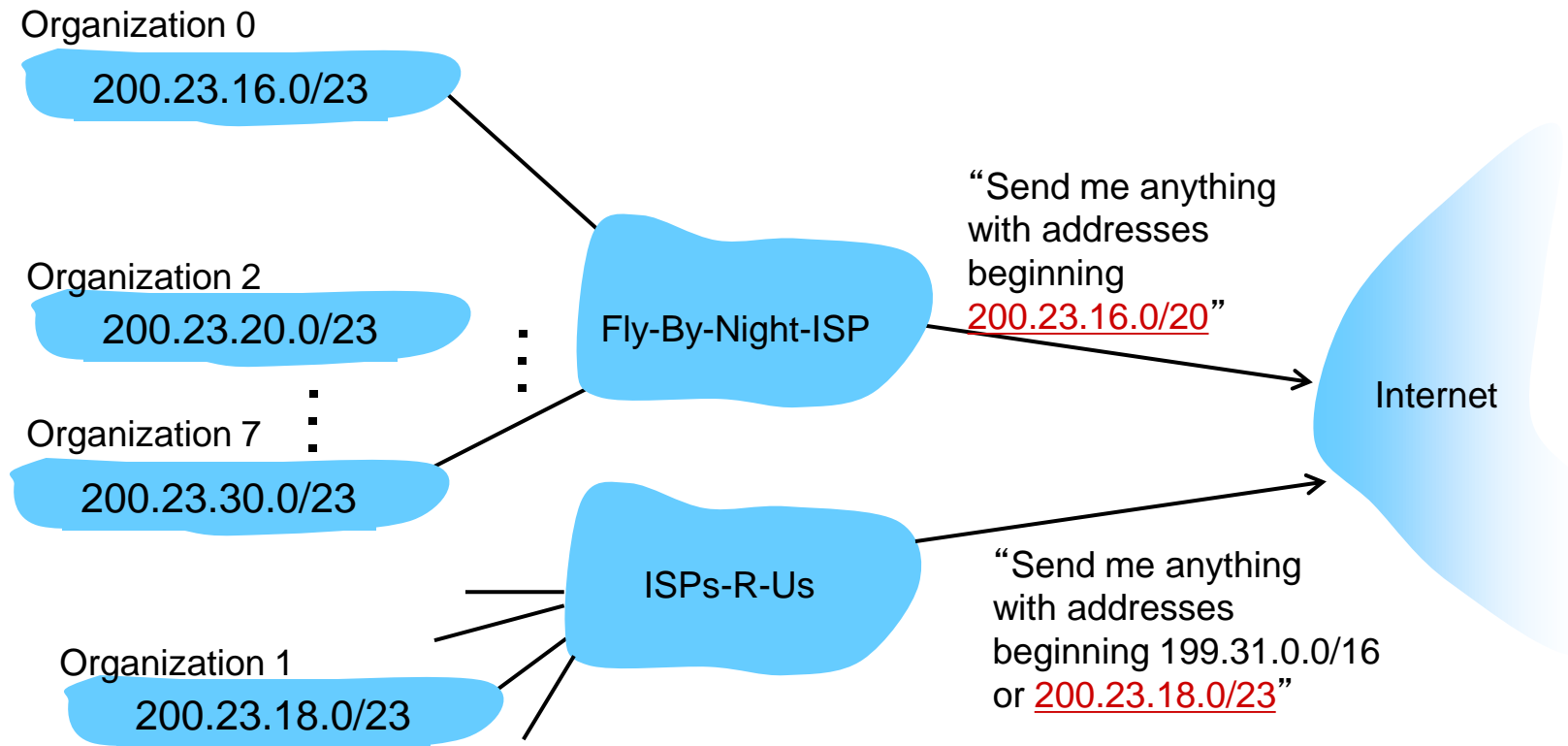
Special Addresses

❖ 1. This host Address: 0.0.0.0

❖ 2. Limited broadcast address: 255.255.255.255, all hosts in a network

❖ 3. Loopback address: 127.0.0.0/8.

❖ Packet in the same host. Software testing

❖ 4. Private address: 4 Blocks

❖ 17.16.0.0/12, 10.0.0.0/8, 169.254.0.0/16, 192.168.0.0/16

IP addressing: how to get a block?

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, resolves disputes

IP addresses: how to get one?

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: 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

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

223.1.1.0/24

223.1.1.1

223.1.1.2

223.1.1.4   223.1.2.9

223.1.1.3   223.1.3.27

DHCP
server

223.1.2.1

*arriving DHCP
client needs
address in this
network*

223.1.2.2

223.1.2.0/24

223.1.3.1   223.1.3.2

223.1.3.0/24
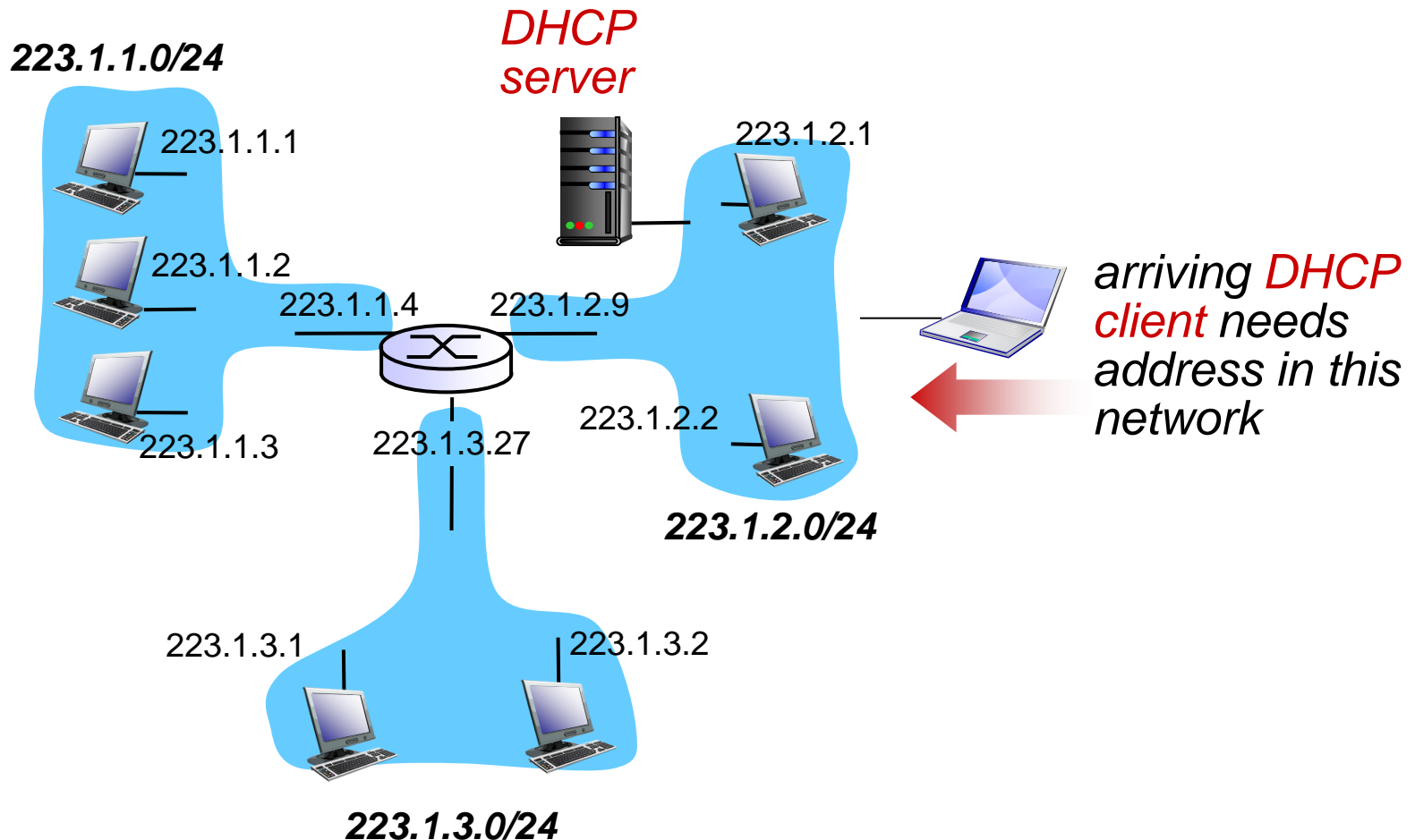
DHCP client-server scenario

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

arriving client

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

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

DHCP: more than IP addresses

DHCP returns:

- IP address
- 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

router with DHCP server built into router
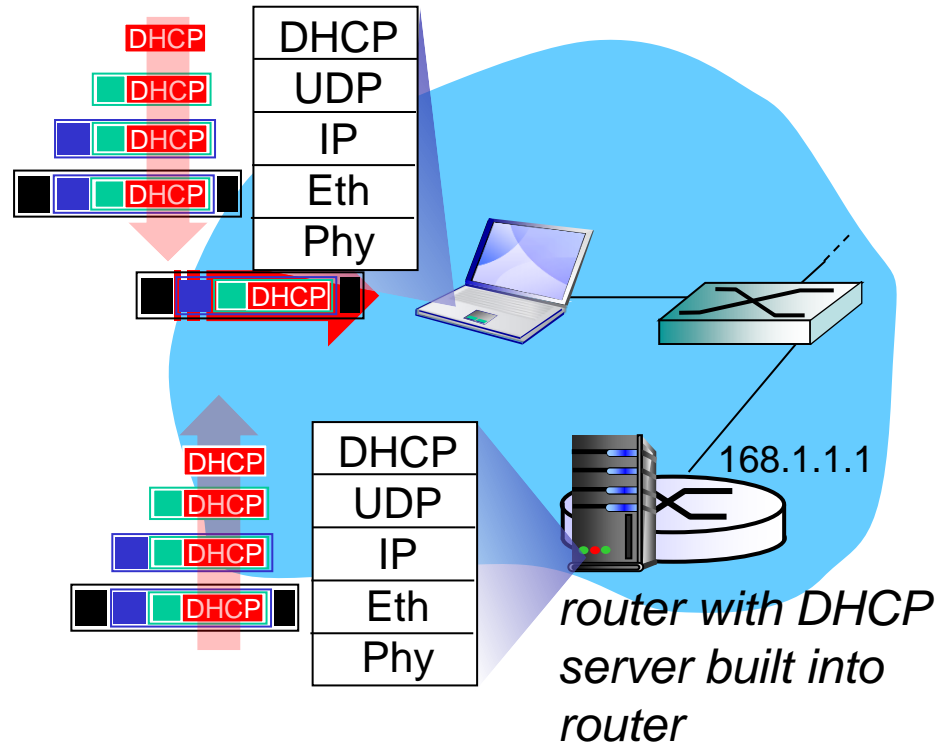
❖ connecting laptop needs its IP address, addr of first-hop router, addr of DNS server: use DHCP

❖ DHCP request encapsulated in UDP, encapsulated in IP, encapsulated in 802.3 Ethernet

❖ Ethernet frame broadcast (dest: FFFFFFFFFFFF) on LAN, received at router running DHCP server

❖ Ethernet demuxed to IP demuxed, UDP demuxed to DHCP

DHCP: example

DHCP
UDP
IP
Eth
Phy

DHCP
UDP
IP
Eth
Phy

router with DHCP server built into router
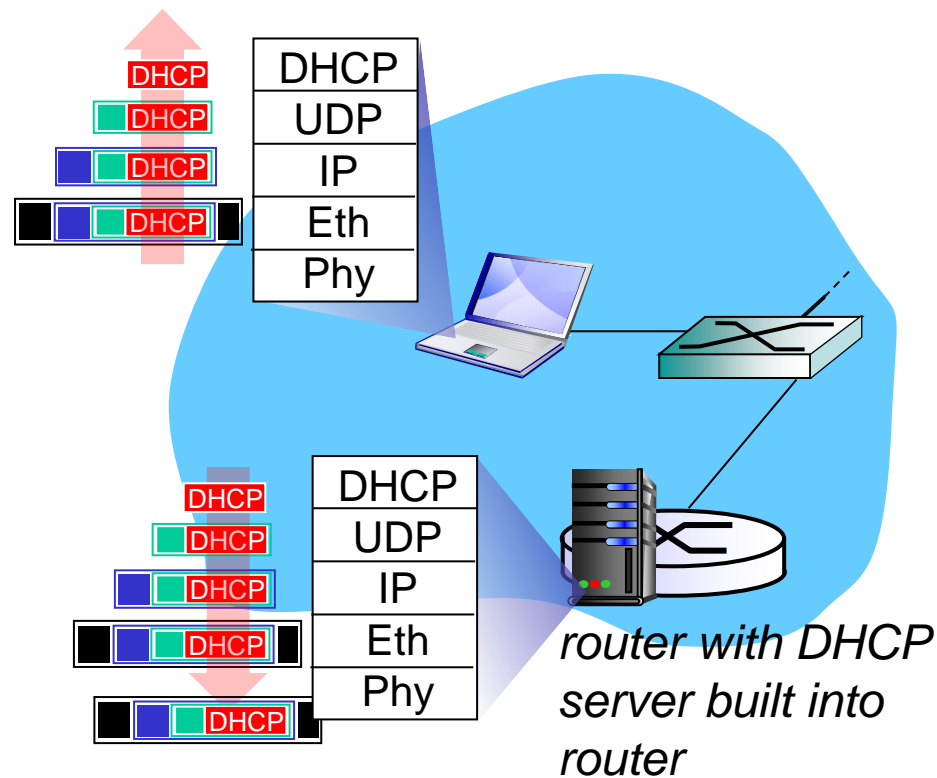
- ❖ DHCP server formulates DHCP ACK containing client's IP address, IP address of first-hop router for client, name & IP address of DNS server

- ❖ encapsulation of DHCP server, frame 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

DHCP: Wireshark output (home LAN)

Message type: **Boot Request (1)**
Hardware type: Ethernet
Hardware address length: 6
Hops: 0   request
Transaction ID: 0x6b3a11b7
Seconds elapsed: 0
Bootp flags: 0x0000 (Unicast)
Client IP address: 0.0.0.0 (0.0.0.0)
Your (client) IP address: 0.0.0.0 (0.0.0.0)
Next server IP address: 0.0.0.0 (0.0.0.0)
Relay agent IP address: 0.0.0.0 (0.0.0.0)
Client MAC address: Wistron_23:68:8a (00:16:d3:23:68:8a)
Server host name not given
Boot file name not given
Magic cookie: (OK)
Option: (t=53,l=1) **DHCP Message Type = DHCP Request**
Option: (61) Client identifier
    Length: 7; Value: 010016D323688A;
    Hardware type: Ethernet
    Client MAC address: Wistron_23:68:8a (00:16:d3:23:68:8a)
Option: (t=50,l=4) Requested IP Address = 192.168.1.101
Option: (t=12,l=5) Host Name = "nomad"
Option: (55) Parameter Request List
    Length: 11; Value: 010F03062C2E2F1F21F92B
    1 = Subnet Mask; 15 = Domain Name
    3 = Router; 6 = Domain Name Server
    44 = NetBIOS over TCP/IP Name Server
    ……

reply

Message type: **Boot Reply (2)**
Hardware type: Ethernet
Hardware address length: 6
Hops: 0
Transaction ID: 0x6b3a11b7
Seconds elapsed: 0
Bootp flags: 0x0000 (Unicast)
Client IP address: 192.168.1.101 (192.168.1.101)
Your (client) IP address: 0.0.0.0 (0.0.0.0)
Next server IP address: 192.168.1.1 (192.168.1.1)
Relay agent IP address: 0.0.0.0 (0.0.0.0)
Client MAC address: Wistron_23:68:8a (00:16:d3:23:68:8a)
Server host name not given
Boot file name not given
Magic cookie: (OK)
Option: (t=53,l=1) DHCP Message Type = DHCP ACK
Option: (t=54,l=4) Server Identifier = 192.168.1.1
Option: (t=1,l=4) Subnet Mask = 255.255.255.0
Option: (t=3,l=4) Router = 192.168.1.1
Option: (6) Domain Name Server
    Length: 12; Value: 445747E2445749F244574092;
    IP Address: 68.87.71.226;
    IP Address: 68.87.73.242;
    IP Address: 68.87.64.146
Option: (t=15,l=20) Domain Name = "hsd1.ma.comcast.net."

NAT: network address translation

rest of Internet

local network (e.g., home network) 10.0.0/24

10.0.0.1

10.0.0.2

10.0.0.3

10.0.0.4
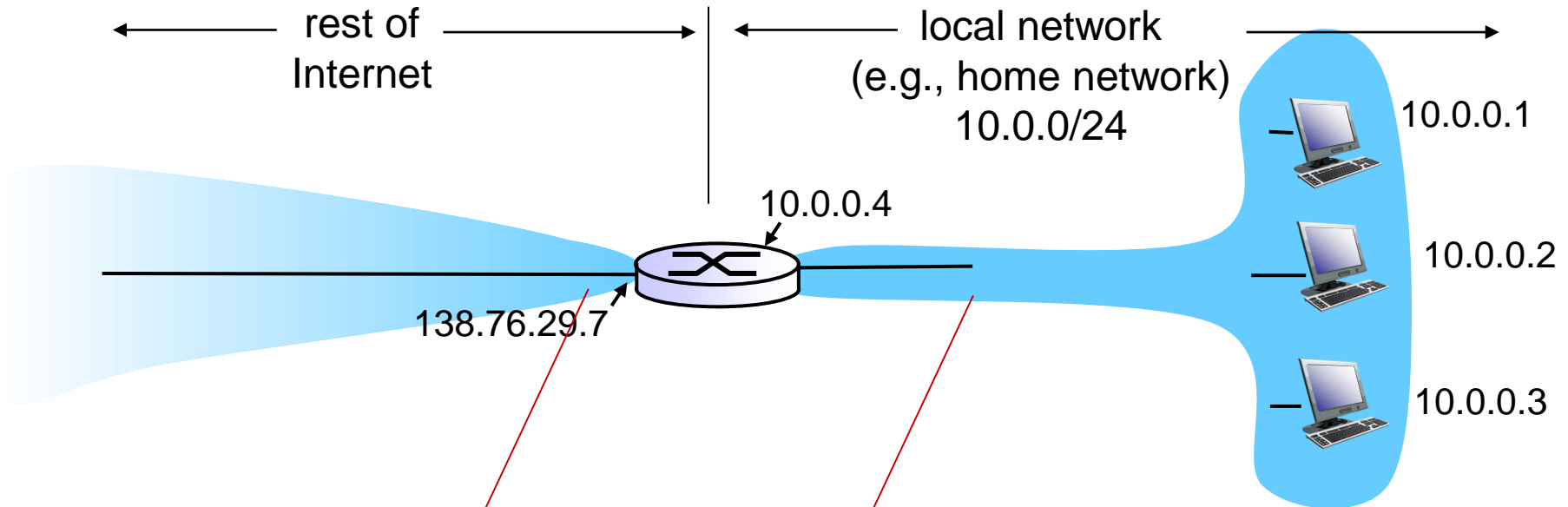
138.76.29.7

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 as far as outside world is concerned:

- range of addresses not needed from ISP: 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 net 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

COMPUTER NETWORKS SURPRISE ASSIGNMENT INSTRUCTIONS
- Be seated According to Roll Nos
- Date- 29/9/2022 (Thursday)
- Timing-1.30 Pm to 1.50 pm (20 Minutes)
- All students should have their own handwritten note books
- Exchange of handwritten note books not allowed

Malpractice Warnings

- Discussions and talking with other classmates during Assignment timings is a malpractice.

- Possession/Usage of any electronic gadget including Mobile phone, Smart watches, I pads , Programmable calculator etc. is a malpractice.

- Possession/Usage of any Text books, Printed materials, chits etc. related to CN subject is a malpractice.

- Looking/Peeping into other classmates assignment question paper and answers is malpractice.

NAT: network address translation

2: NAT router changes datagram source addr from 10.0.0.1, 3345 to 138.76.29.7, 5001, updates table

NAT translation table	
WAN side addr	LAN side addr
138.76.29.7, 5001	10.0.0.1, 3345
……	……

1: host 10.0.0.1 sends datagram to 128.119.40.186, 80

S: 10.0.0.1, 3345
D: 128.119.40.186, 80

1

10.0.0.1

S: 138.76.29.7, 5001
D: 128.119.40.186, 80

2

10.0.0.4

10.0.0.2

138.76.29.7

S: 128.119.40.186, 80
D: 10.0.0.1, 3345

4

S: 128.119.40.186, 80
D: 138.76.29.7, 5001

3

10.0.0.3

3: reply arrives dest. address: 138.76.29.7, 5001

4: NAT router changes datagram dest addr from 138.76.29.7, 5001 to 10.0.0.1, 3345

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
  ▪ address shortage should instead be solved by IPv6

NAT traversal problem

❖ **client wants to connect to server with address 10.0.0.1**

  ▪ server address 10.0.0.1 local to LAN (client can't use it as destination addr)

  ▪ only one externally visible NATed address: 138.76.29.7

❖ *solution1:* statically configure NAT to forward incoming connection requests at given port to server

  ▪ e.g., (123.76.29.7, port 25000) always forwarded to 10.0.0.1 port 25000

client

?

138.76.29.7

NAT router

10.0.0.1

10.0.0.4
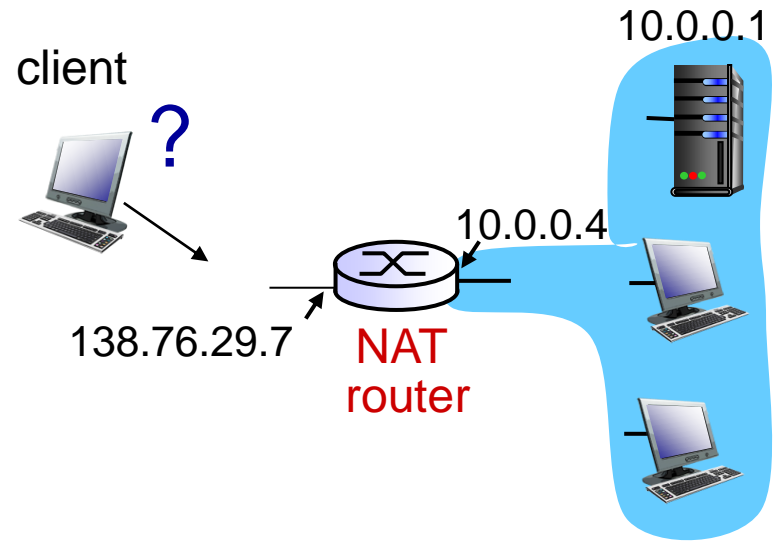
NAT traversal problem

❖ *solution 2:* Universal Plug and Play (UPnP) Internet Gateway Device (IGD) Protocol. Allows NATed host to:
  ❖ learn public IP address (138.76.29.7)
  ❖ add/remove port mappings (with lease times)

  i.e., automate static NAT port map configuration
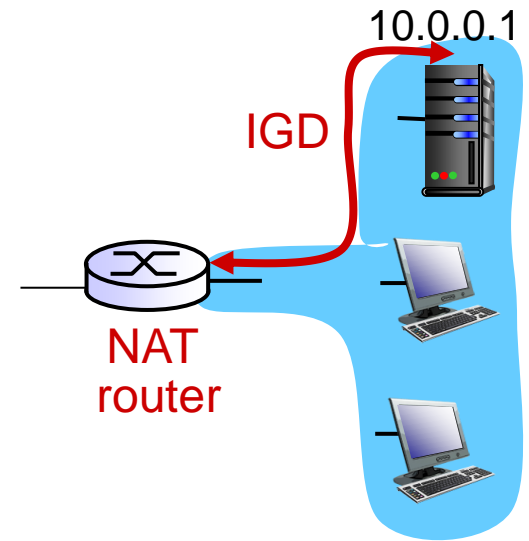
10.0.0.1

IGD

NAT router

Chapter 4: outline

4.1 introduction

4.2 virtual circuit and datagram networks

4.3 what's inside a router

4.4 IP: Internet Protocol
- datagram format
- IPv4 addressing
- ICMP
- IPv6

4.5 routing algorithms
- link state
- distance vector
- hierarchical routing

4.6 routing in the Internet
- RIP
- OSPF
- BGP

4.7 broadcast and multicast routing

ICMP: internet control message protocol

❖ **used by hosts & routers to communicate network-level information**
  - error reporting: unreachable host, network, port, protocol
  - echo request/reply (used by ping)

❖ **network-layer "above" IP:**
  - ICMP msgs carried in IP datagrams

❖ **ICMP message:** type, code plus first 8 bytes of IP datagram causing error
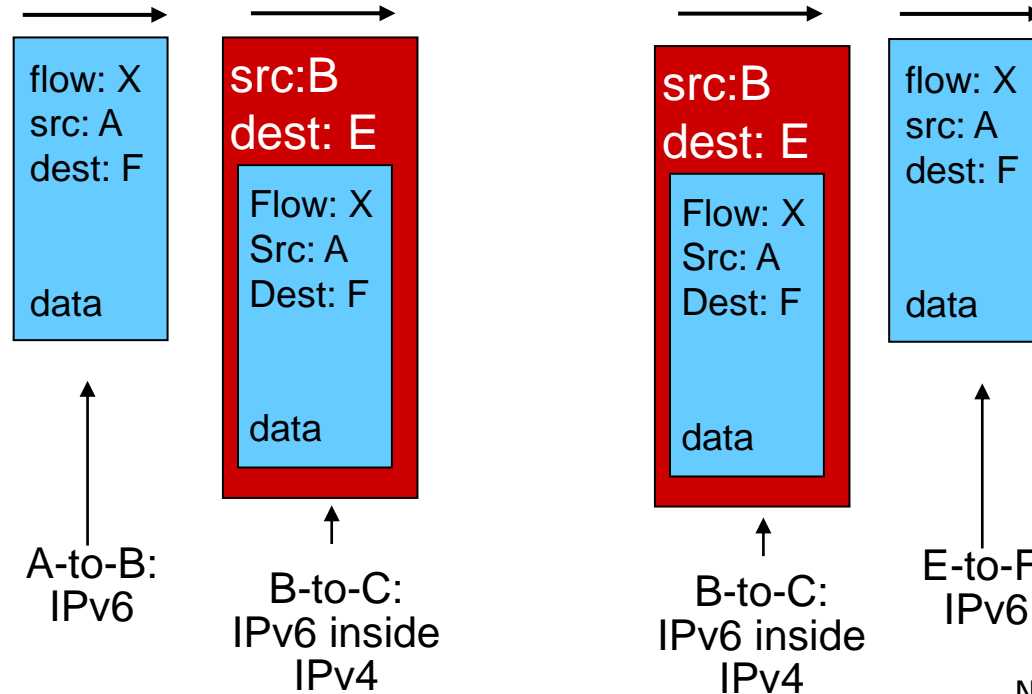
Type	Code	description
0	0	echo reply (ping)
3	0	dest. network unreachable
3	1	dest host unreachable
3	2	dest protocol unreachable
3	3	dest port unreachable
3	6	dest network unknown
3	7	dest host unknown
4	0	source quench (congestion control - not used)
8	0	echo request (ping)
9	0	route advertisement
10	0	router discovery
11	0	TTL expired
12	0	bad IP header

Traceroute and ICMP

- source sends series of UDP segments to dest
  - first set has TTL =1
  - second set has TTL=2, etc.
  - unlikely port number
- when *n*th set of datagrams arrives to nth router:
  - router discards datagrams
  - and sends source ICMP messages (type 11, code 0)
  - ICMP messages includes name of router & IP address

- when ICMP messages arrives, source records RTTs

stopping criteria:
- UDP segment eventually arrives at destination host
- destination returns ICMP "port unreachable" message (type 3, code 3)
- source stops

3 probes 3 probes

3 probes
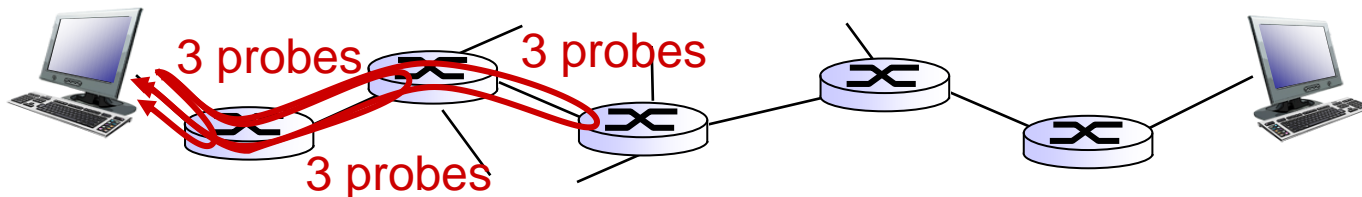
Figure 4.55: *Example of traceroute program*

Message types

🟧	Traceroute
⬜	Time-exceeded
⬛	Destination-unreachable

TTL: 1

1

TTL: 2

2

TTL: 3

3

TTL: 4

4

4.83

1.83
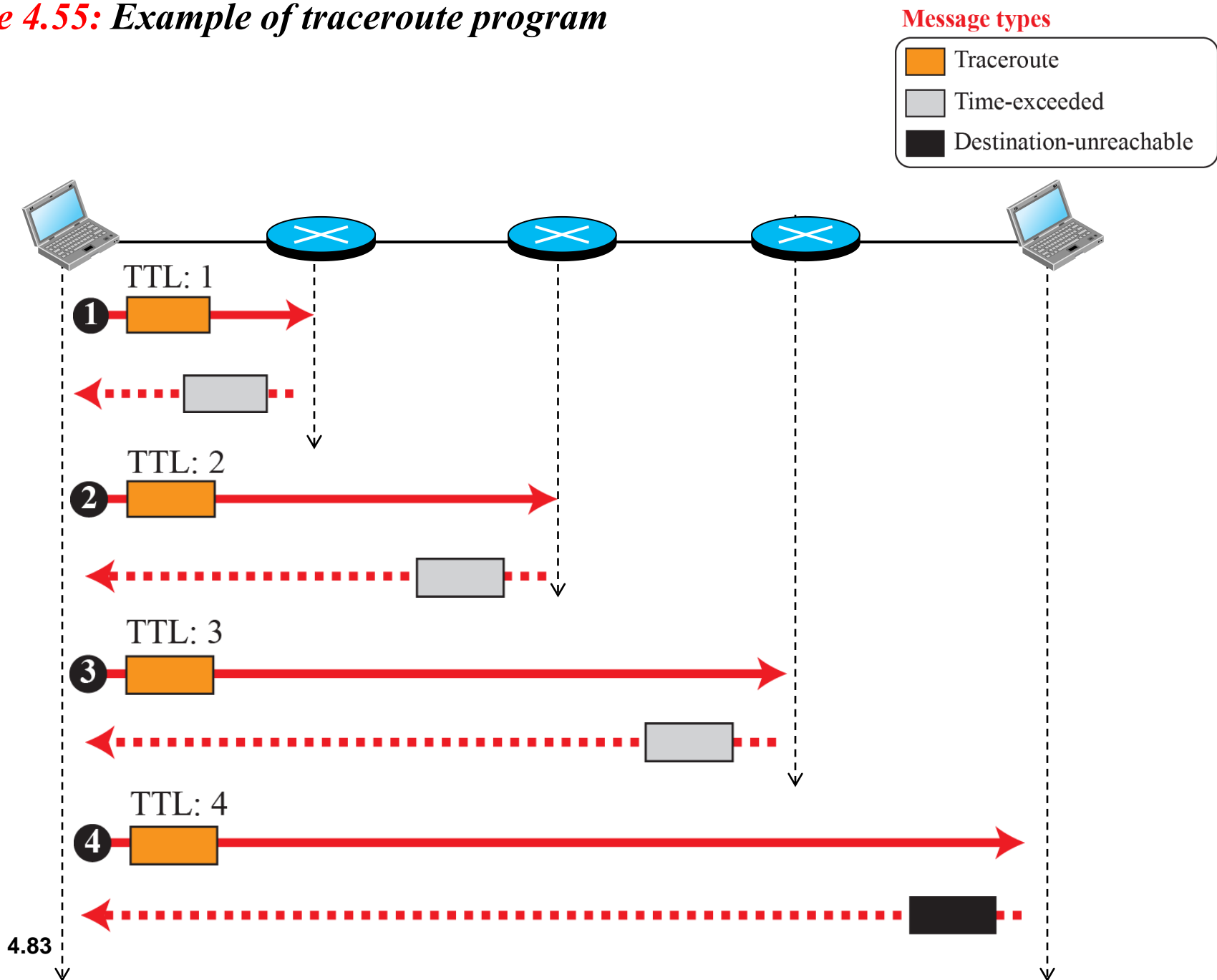
IPv6: motivation

❖ *initial motivation:* 32-bit address space soon to be completely allocated.
❖ additional motivation:
  ▪ header format helps speed processing/forwarding
  ▪ header changes to facilitate QoS

IPv6 datagram format:
  ▪ fixed-length 40 byte header
  ▪ no fragmentation allowed

IPv6 datagram format

priority: identify priority among datagrams in flow
flow Label: identify datagrams in same "flow."
next header: identify upper layer protocol for data

ver	Trafficclass	flow label		
payload len			next hdr	hop limit
source address (128 bits)				
destination address (128 bits)				
data				

←————————— 32 bits —————————→
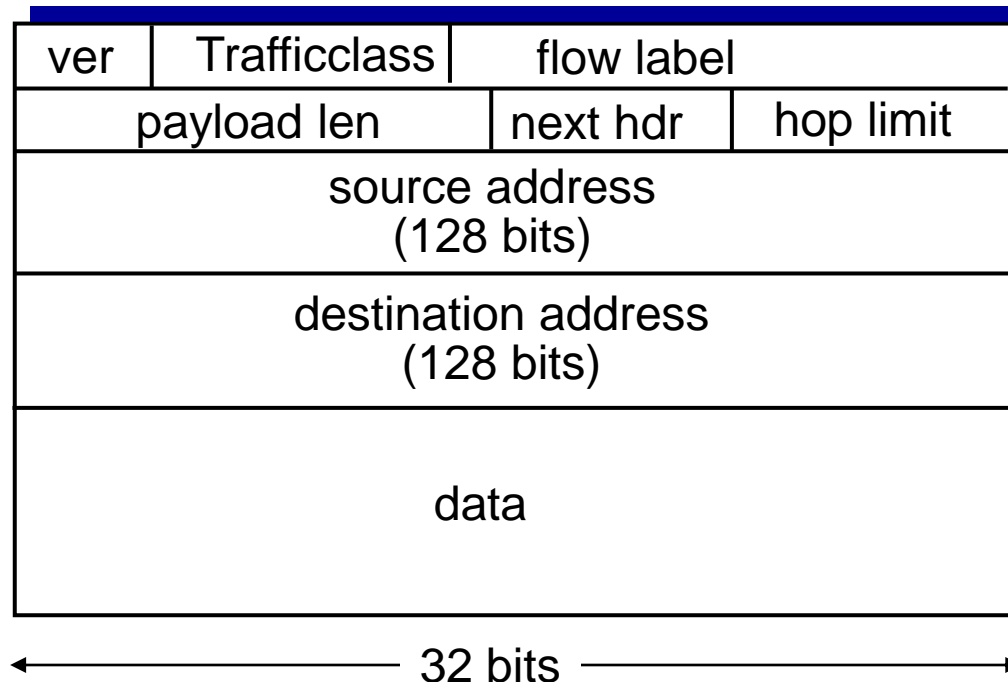
Other changes from IPv4

❖ *checksum*: removed entirely to reduce processing time at each hop

❖ *options:* allowed, but outside of header, indicated by "Next Header" field

❖ *ICMPv6:* new version of ICMP
  ▪ additional message types, e.g. "Packet Too Big"
  ▪ multicast group management functions

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
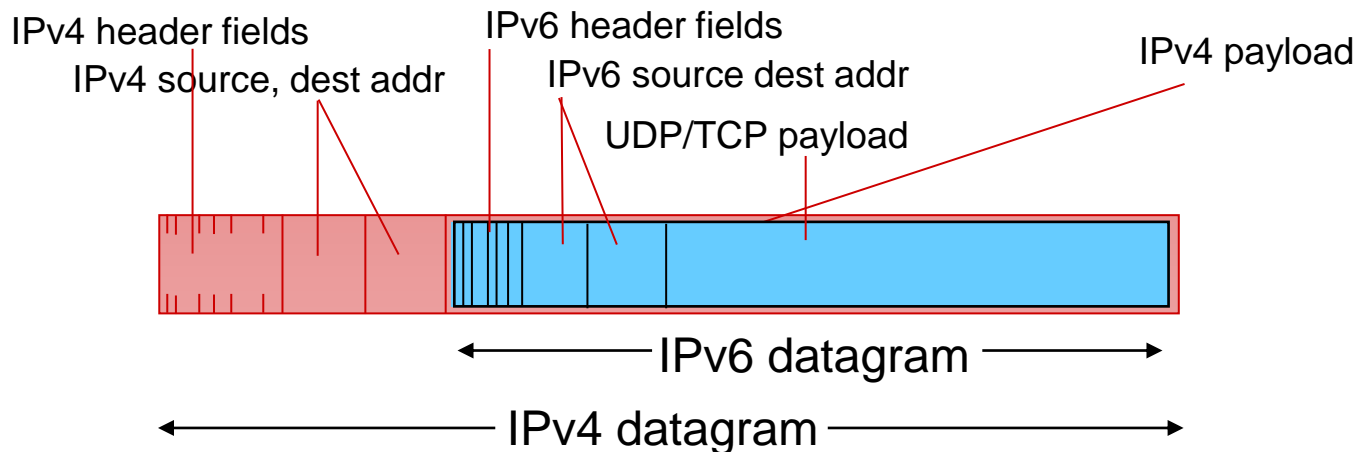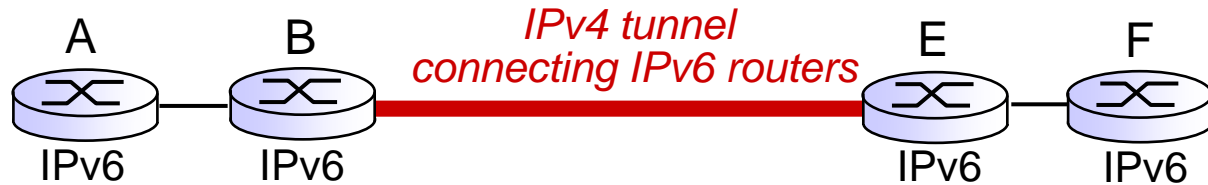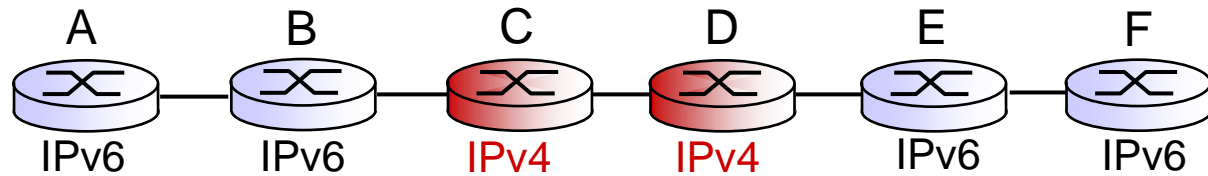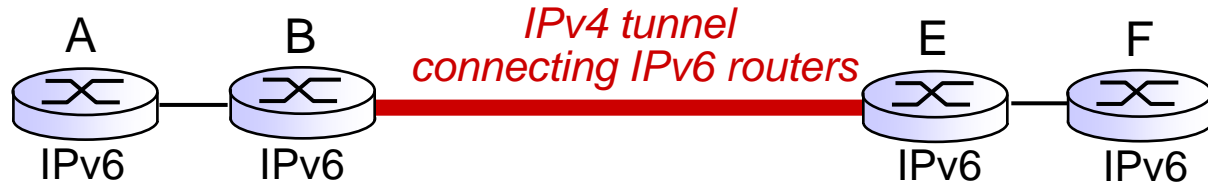
IPv4 header fields
IPv4 source, dest addr

IPv6 header fields
IPv6 source dest addr

IPv4 payload

UDP/TCP payload

◄—— IPv6 datagram ——►

◄—————— IPv4 datagram ——————►

Tunneling

logical view:

A
IPv6

B
IPv6

*IPv4 tunnel
connecting IPv6 routers*

E
IPv6

F
IPv6

physical view:

A
IPv6

B
IPv6

C
IPv4

D
IPv4

E
IPv6

F
IPv6

Tunneling

logical view:

A   B   *IPv4 tunnel*   E   F
connecting IPv6 routers

IPv6   IPv6   IPv6   IPv6

physical view:

A   B   C   D   E   F

IPv6   IPv6   IPv4   IPv4   IPv6   IPv6

| flow: X
src: A
dest: F

data | src:B
dest: E

Flow: X
Src: A
Dest: F

data | src:B
dest: E

Flow: X
Src: A
Dest: F

data | flow: X
src: A
dest: F

data |

A-to-B:
IPv6

B-to-C:
IPv6 inside
IPv4

B-to-C:
IPv6 inside
IPv4

E-to-F:
IPv6

Chapter 4: outline

4.1 introduction

4.2 virtual circuit and datagram networks

4.3 what's inside a router

4.4 IP: Internet Protocol
- datagram format
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- ICMP
- IPv6

4.5 routing algorithms
- link state
- distance vector
- hierarchical routing

4.6 routing in the Internet
- RIP
- OSPF
- BGP
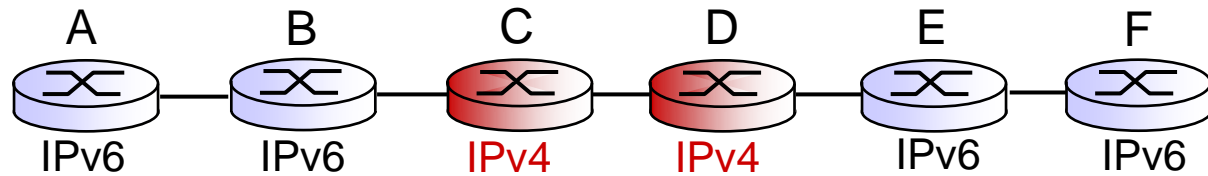
4.7 broadcast and multicast routing

Interplay between routing, forwarding

routing algorithm

routing algorithm

routing algorithm determines
end-end-path through network

forwarding table determines
local forwarding at this router

local forwarding table	
dest address	output link
address-range 1	3
address-range 2	2
address-range 3	2
address-range 4	1

IP destination address in
arriving packet's header

1

3 2
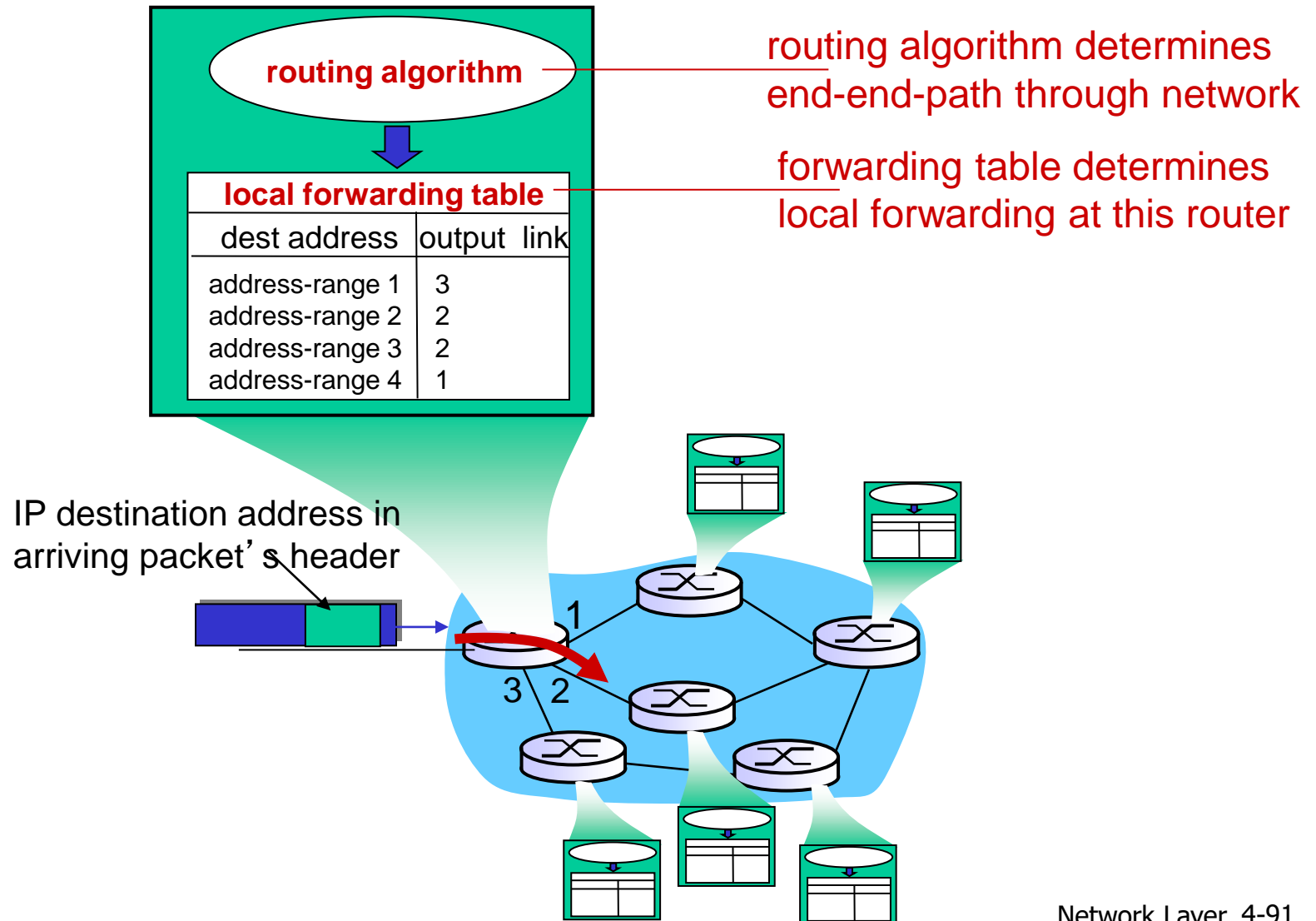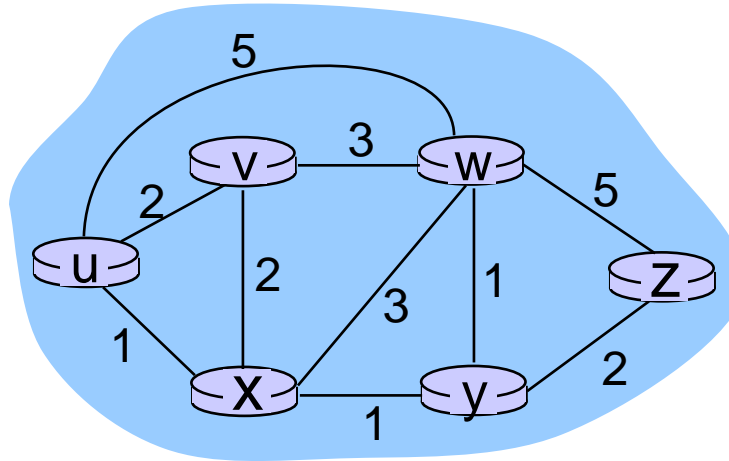
Graph abstraction

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) }

aside: graph abstraction is useful in other network contexts, e.g., P2P, where *N* is set of peers and *E* is set of TCP connections

Graph abstraction: costs
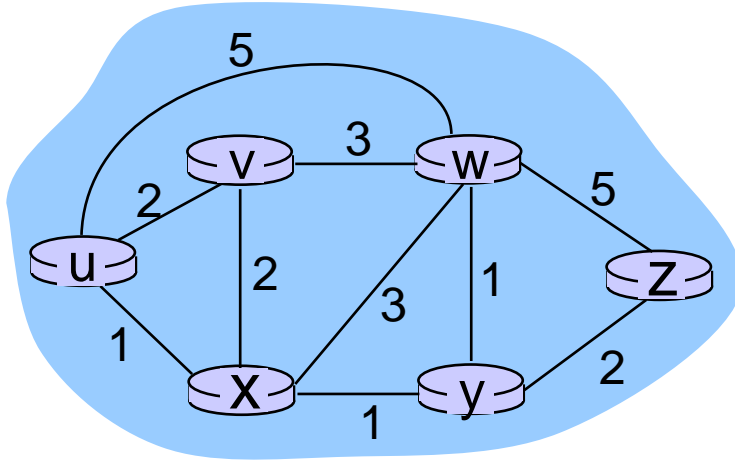
$c(x,x') = $ cost of link (x,x')
    e.g., $c(w,z) = 5$

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

Chapter 4: outline

A Link-State Routing Algorithm

Dijkstra's algorithm

- ❖ net topology, link costs known to all nodes
  - accomplished via "link state broadcast"
  - all nodes have same info
- ❖ computes least cost paths from one node ('source") to all other nodes
  - gives *forwarding table* for that node
- ❖ iterative: after k iterations, know least cost path to k dest.'s

notation:

- ❖ $c(x,y)$: link cost from node x to y; = ∞ if not direct neighbors
- ❖ $D(v)$: current value of cost of path from source to dest. v
- ❖ $p(v)$: predecessor node along path from source to v
- ❖ N': set of nodes whose least cost path definitively known

Dijsktra's Algorithm

```
1  Initialization:
2    N' = {u}
3   for all nodes v
4     if v adjacent to u
5        then D(v) = c(u,v)
6     else D(v) = ∞
7
8   Loop
9     find w not in N' such that D(w) is a minimum
10    add w to N'
11    update D(v) for all v adjacent to w and not in N' :
12      D(v) = min( D(v), D(w) + c(w,v) )
13    /* new cost to v is either old cost to v or known
14      shortest path cost to w plus cost from w to v */
15  until all nodes in N'
```

Chapter 4: outline

4.1 introduction

4.2 virtual circuit and datagram networks

4.3 what's inside a router

4.4 IP: Internet Protocol
  - datagram format
  - IPv4 addressing
  - ICMP
  - IPv6

4.5 routing algorithms
  - link state
  - distance vector
  - hierarchical routing

4.6 routing in the Internet
  - RIP
  - OSPF
  - BGP

4.7 broadcast and multicast routing

Distance vector algorithm

Bellman-Ford equation (dynamic programming)

let

$d_x(y) :=$ cost of least-cost path from x to y

then

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

cost from neighbor v to destination

cost to neighbor v

min taken over all neighbors v of x

Bellman-Ford example
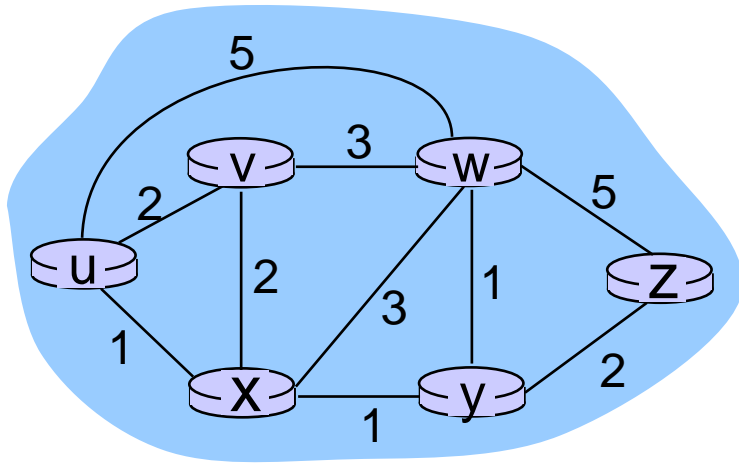
clearly, $d_v(z) = 5$, $d_x(z) = 3$, $d_w(z) = 3$

B-F equation says:

$$d_u(z) = \min \{ c(u,v) + d_v(z),$$
$$c(u,x) + d_x(z),$$
$$c(u,w) + d_w(z) \}$$
$$= \min \{2 + 5,$$
$$1 + 3,$$
$$5 + 3\} \ = 4$$

node achieving minimum is next
hop in shortest path, used in forwarding table

Distance vector algorithm

* $D_x(y)$ = estimate of least cost from x to y
  * x maintains distance vector $\mathbf{D_x}$ = [$D_x(y)$: y ϵ N]
* node x:
  * knows cost to each neighbor v: c(x,v)
  * maintains its neighbors' distance vectors. For each neighbor v, x maintains $\mathbf{D_v}$ = [$D_v(y)$: y ϵ N]

Distance vector algorithm

key idea:

- ❖ from time-to-time, each node sends its own distance vector estimate to neighbors
- ❖ when x receives new DV estimate from neighbor, it updates its own DV using B-F equation:

$$D_x(y) \leftarrow min_v\{c(x,v) + D_v(y)\} \quad \text{for each node } y \in N$$

- ❖ under minor, natural conditions, the estimate $D_x(y)$ converge to the actual least cost $d_x(y)$

Distance vector algorithm

iterative, asynchronous: each local iteration caused by:

❖ local link cost change
❖ DV update message from neighbor

distributed:

❖ each node notifies neighbors *only* when its DV changes
  ▪ neighbors then notify their neighbors if necessary

each node:

wait for (change in local link cost or msg from neighbor)

↓

recompute estimates

↓

if DV to any dest has changed, *notify* neighbors
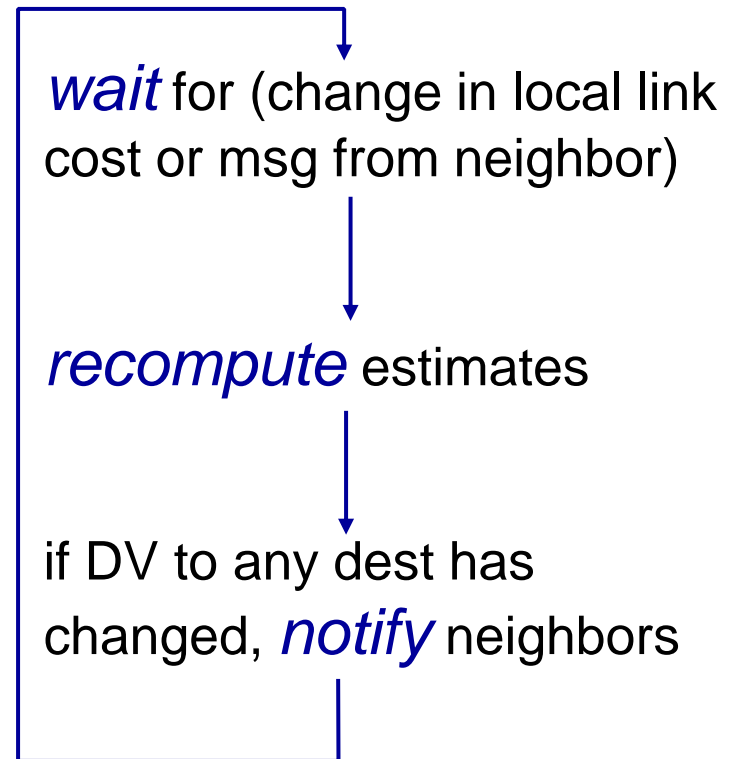
Distance-Vector (DV) Algorithm

At each node, x:

```
1   Initialization:
2      for all destinations y in N:
3         D_x(y) = c(x,y)    /* if y is not a neighbor then c(x,y) = ∞ */
4      for each neighbor w
5         D_w(y) = ? for all destinations y in N
6      for each neighbor w
7         send distance vector D̄_x = [D_x(y): y in N] to w
8
```

```
9  loop
10    wait (until I see a link cost change to some neighbor w or
11          until I receive a distance vector from some neighbor w)
12
13    for each y in N:
14       D_x(y) = min_v{c(x,v) + D_v(y)}
15
16    if D_x(y) changed for any destination y
17       send distance vector D_x = [D_x(y): y in N] to all neighbors
18
19 forever
```

Summary

❖ Each node create its own least cost tree with the help of its immediate neighbours.

❖ Incomplete tree exchanged with immediate neighbours to make tree more and more complete.

❖ i.e router continuously tell about what it knows about internet.

❖ Uses Bellman –Ford equation & distance vector.

Figure 4.58: *Graphical idea behind Bellman-Ford equation*
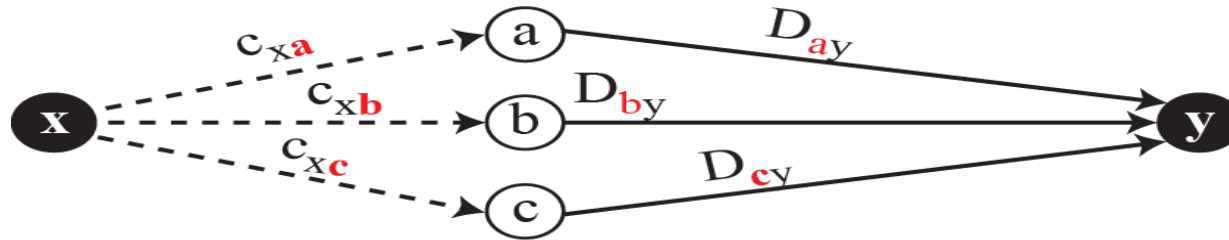
a. General case with three intermediate nodes

$Dxy = min\{(Cxa+Day), (Cxb+Dby), (Cxc+Dcy)....\}$
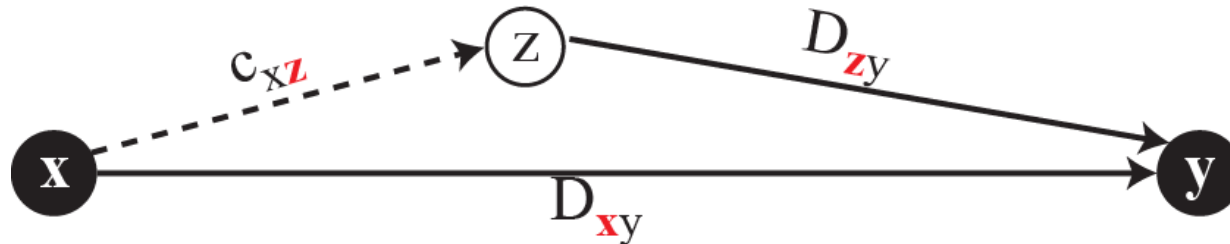
b. Updating a path with a new route

$Dxy = min\{ Dxy, (Cxz+Dzy)\}$

4.107

1.107

Figure 4.59: *The distance vector corresponding to a tree*
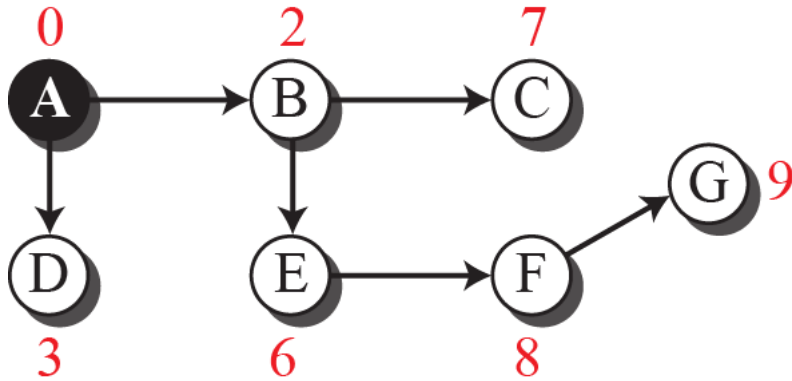
a. Tree for node A

	A
A	0
B	2
C	7
D	3
E	6
F	8
G	9

b. Distance vector for node A

4.108

Figure 4.60: The first distance vector for an internet
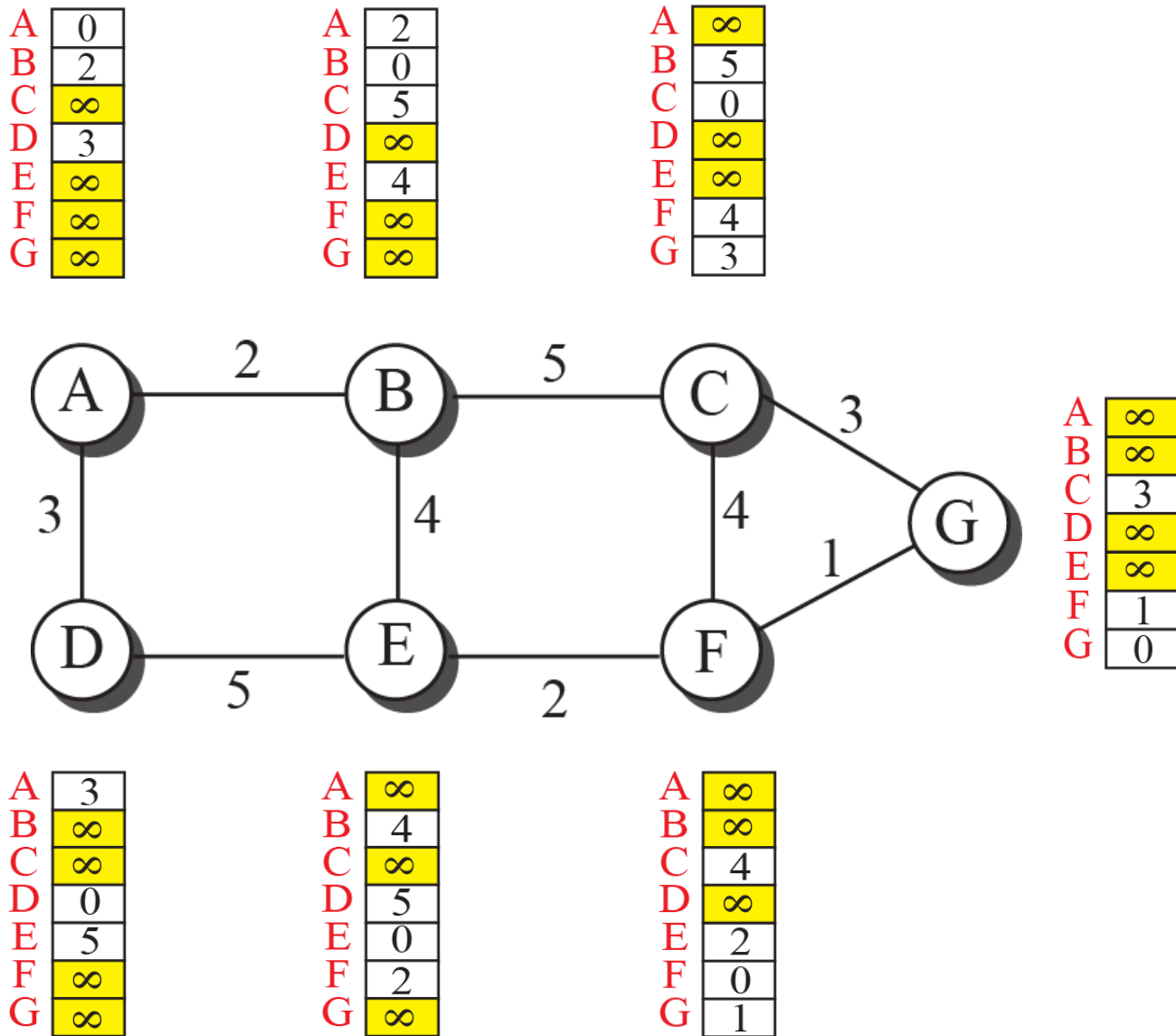
Figure 4.61: *Updating distance vectors*

a. First event: B receives a copy of A's vector.

Note:
X[ ]: the whole vector

$$B[\ ] = \min\ (B[\ ],\ 2 + A[\ ])$$

$$B[\ ] = \min\ (B[\ ],\ 4 + E[\ ])$$

b. Second event: B receives a copy of E's vector.

4.110

Distance vector: link cost changes

link cost changes:

* ❖ node detects local link cost change
* ❖ updates routing info, recalculates distance vector
* ❖ if DV changes, notify neighbors
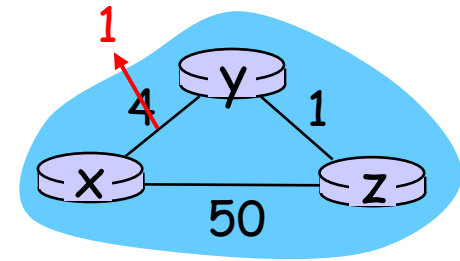
"good news travels fast"

t_0: *y* detects link-cost change, updates its DV, informs its neighbors.

t_1: *z* receives update from *y*, updates its table, computes new least cost to *x* , sends its neighbors its DV.

t_2: *y* receives *z*'s update, updates its distance table. *y*'s least costs do *not* change, so *y* does *not* send a message to *z*.

Distance vector: link cost changes

link cost changes:

❖ node detects local link cost change

❖ *bad news travels slow* - "count to infinity" problem!

❖ 44 iterations before algorithm stabilizes:

poisoned reverse:

❖ If Z routes through Y to get to X :

  ▪ Z tells Y its (Z's) distance to X is infinite (so Y won't route to X via Z)

❖ will this completely solve count to infinity problem?
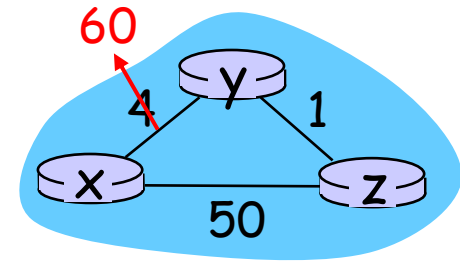
Comparison of LS and DV algorithms

message complexity
- **LS:** with n nodes, E links, O(nE) msgs sent
- **DV:** exchange between neighbors only
  - convergence time varies

speed of convergence
- **LS:** O(n²) algorithm requires O(nE) msgs
  - may have oscillations
- **DV:** convergence time varies
  - may be routing loops
  - count-to-infinity problem

robustness: what happens if router malfunctions?

LS:
- node can advertise incorrect *link* cost
- each node computes only its *own* table

DV:
- DV node can advertise incorrect *path* cost
- each node's table used by others
  - ❿ error propagate thru network

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4.5 routing algorithms
- link state
- distance vector
- hierarchical routing

4.6 routing in the Internet
- RIP
- OSPF
- BGP

Hierarchical routing

our routing study thus far - idealization
- ❖ all routers identical
- ❖ network "flat"

… *not* true in practice

scale: with 600 million destinations:
- ❖ can't store all dest's in routing tables!
- ❖ routing table exchange would swamp links!

administrative autonomy
- ❖ internet = network of networks
- ❖ each network admin may want to control routing in its own network

Hierarchical routing

❖ aggregate routers into regions, "autonomous systems" (AS)

❖ routers in same AS run same routing protocol

  ▪ "intra-AS" routing protocol

  ▪ routers in different AS can run different intra-AS routing protocol

gateway router:

❖ at "edge" of its own AS

❖ has link to router in another AS

Interconnected ASes
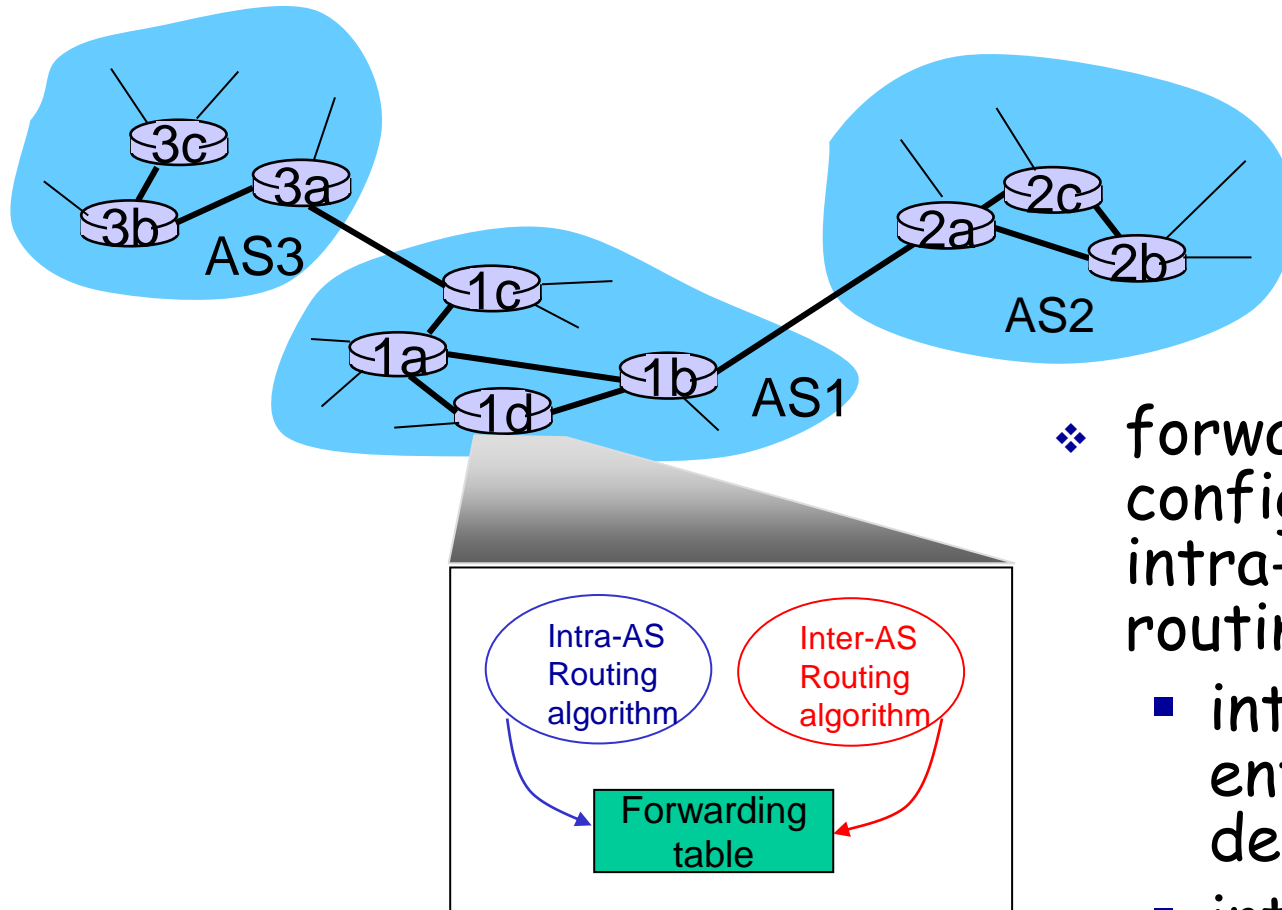
- ❖ **forwarding table configured by both intra- and inter-AS routing algorithm**
  - ▪ intra-AS sets entries for internal dests
  - ▪ inter-AS & intra-AS sets entries for external dests

Inter-AS tasks

❖ suppose router in AS1 receives datagram destined outside of AS1:

  ▪ router should forward packet to gateway router, but which one?

AS1 must:

1. learn which dests are reachable through AS2, which through AS3

2. propagate this reachability info to all routers in AS1

job of inter-AS routing!
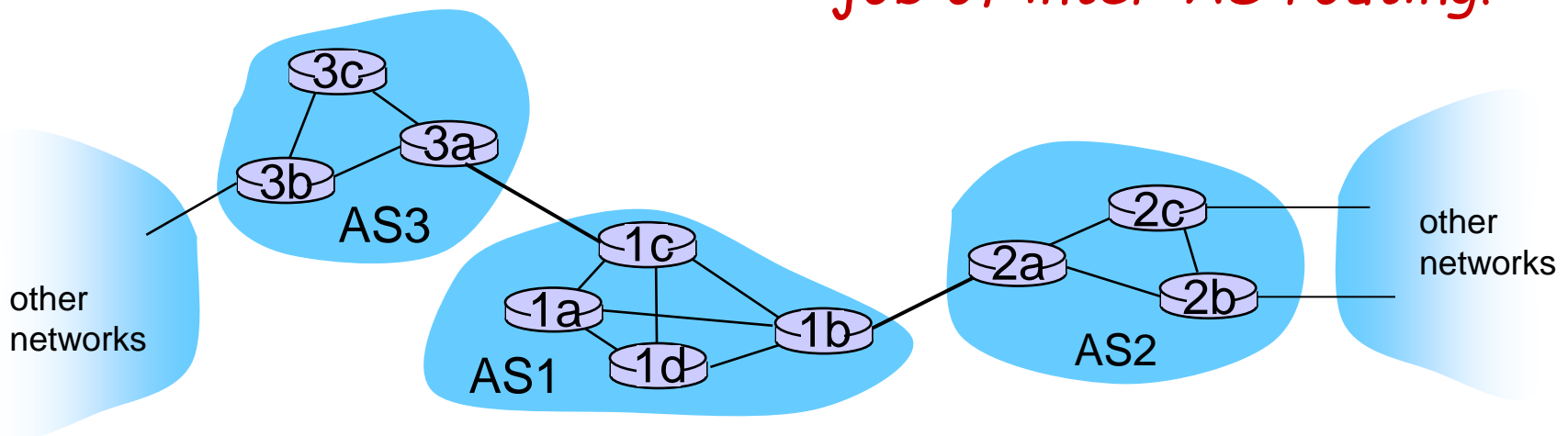
Example: setting forwarding table in router 1d

❖ suppose AS1 learns (via inter-AS protocol) that subnet *x* reachable via AS3 (gateway 1c), but not via AS2
  - inter-AS protocol propagates reachability info to all internal routers
❖ router 1d determines from intra-AS routing info that its interface *I* is on the least cost path to 1c
  - installs forwarding table entry *(x,I)*
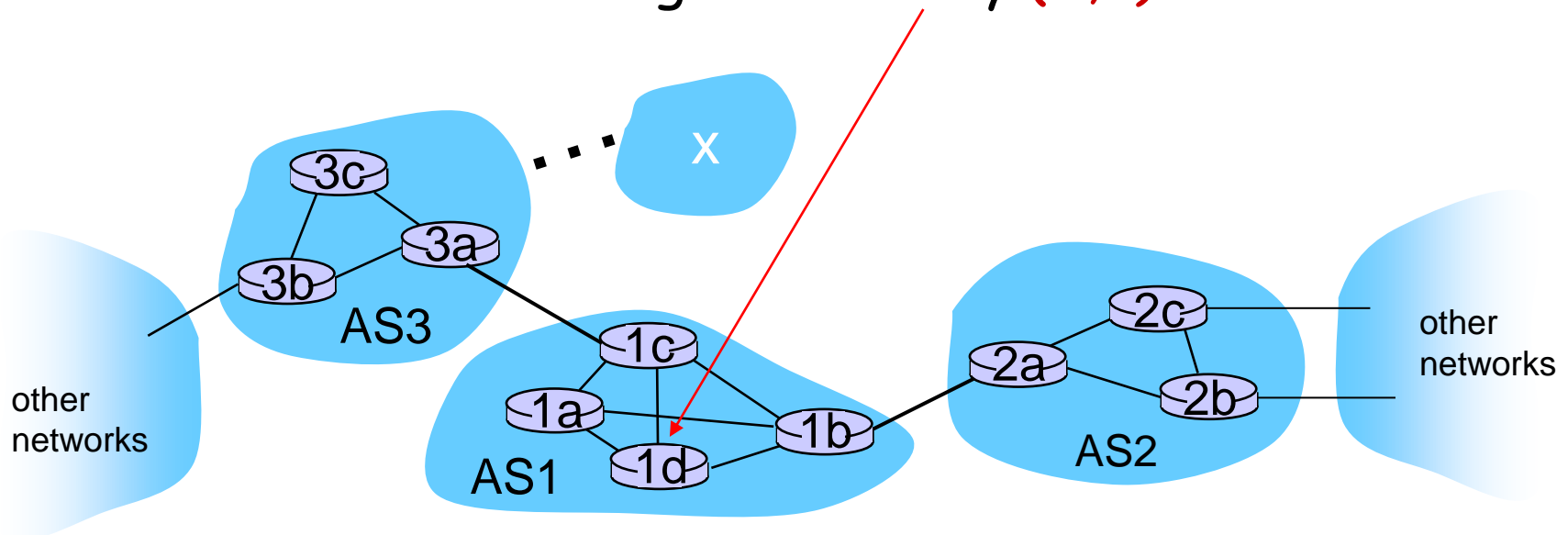
Example: choosing among multiple ASes

❖ now suppose AS1 learns from inter-AS protocol that subnet *x* is reachable from AS3 *and* from AS2.

❖ to configure forwarding table, router 1d must determine towards which gateway it should forward packets for dest *x*

  ▪ this is also job of inter-AS routing protocol!
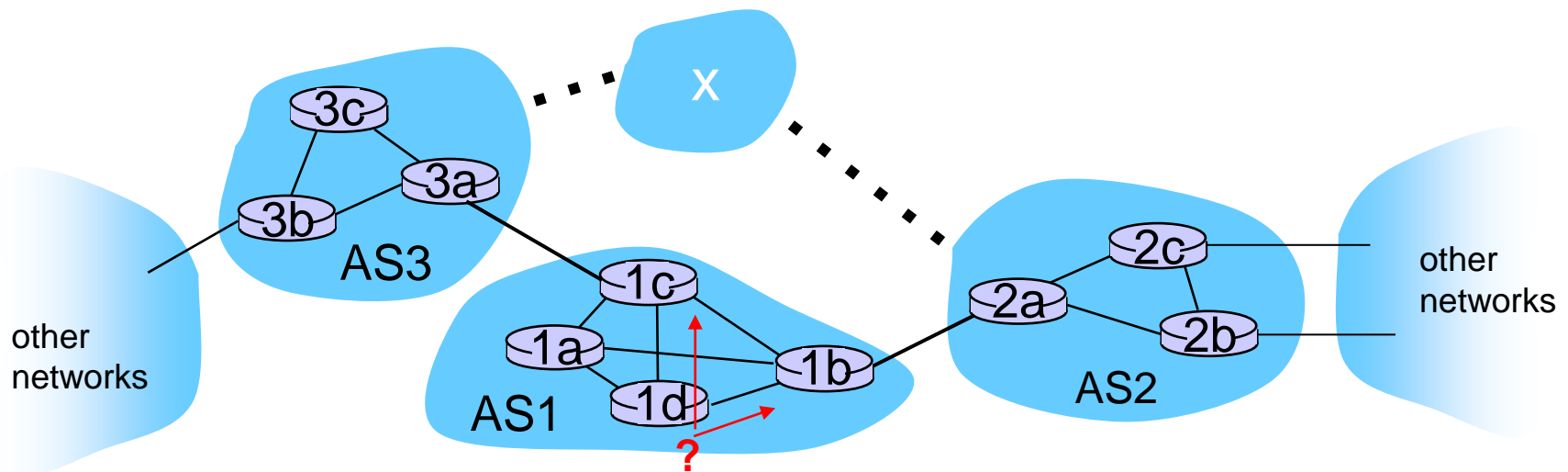
Example: choosing among multiple ASes

❖ now suppose AS1 learns from inter-AS protocol that subnet *x* is reachable from AS3 *and* from AS2.

❖ to configure forwarding table, router 1d must determine towards which gateway it should forward packets for dest *x*
  ▪ this is also job of inter-AS routing protocol!

❖ *hot potato routing: send* packet towards closest of two routers.
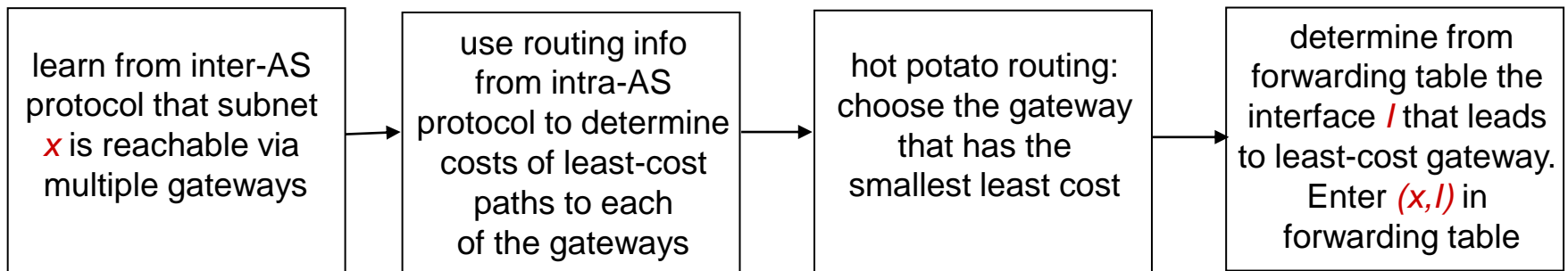
learn from inter-AS protocol that subnet *x* is reachable via multiple gateways	→	use routing info from intra-AS protocol to determine costs of least-cost paths to each of the gateways	→	hot potato routing: choose the gateway that has the smallest least cost	→	determine from forwarding table the interface *I* that leads to least-cost gateway. Enter *(x,I)* in forwarding table

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- distance vector
- hierarchical routing

4.6 routing in the Internet
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- OSPF
- BGP

4.7 broadcast and multicast routing

Intra-AS Routing

❖ also known as *interior gateway protocols (IGP)*

❖ most common intra-AS routing protocols:

  ▪ RIP: Routing Information Protocol

  ▪ OSPF: Open Shortest Path First

  ▪ IGRP: Interior Gateway Routing Protocol (Cisco proprietary)

RIP (Routing Information Protocol)

❖ included in BSD-UNIX distribution in 1982

❖ distance vector algorithm

- distance metric: # hops (max = 15 hops), each link has cost 1
- DVs exchanged with neighbors every 30 sec in response message (aka advertisement)
- each advertisement: list of up to 25 destination *subnets* (in IP addressing sense)
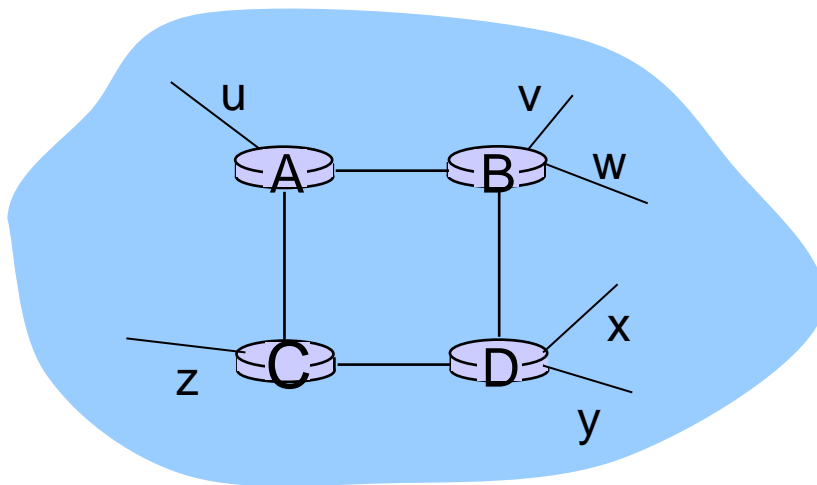
from router A to destination *subnets:*

subnet	hops
u	1
v	2
w	2
x	3
y	3
z	2

RIP: link failure, recovery

RIP-Request, Response msg.

if no advertisement heard after 180 sec --> neighbor/link declared dead

- routes via neighbor invalidated
- new advertisements sent to neighbors
- neighbors in turn send out new advertisements (if tables changed)
- link failure info quickly (?) propagates to entire net

RIP table processing

❖ RIP routing tables managed by *application-level* process called route-d (daemon)

❖ advertisements sent in UDP packets port no 520, periodically repeated

```
      routed                              routed


transport                                          transprt
(UDP)                                              (UDP)

network        forwarding          forwarding      network
(IP)             table               table         (IP)

link                                               link

physical                                           physical
```
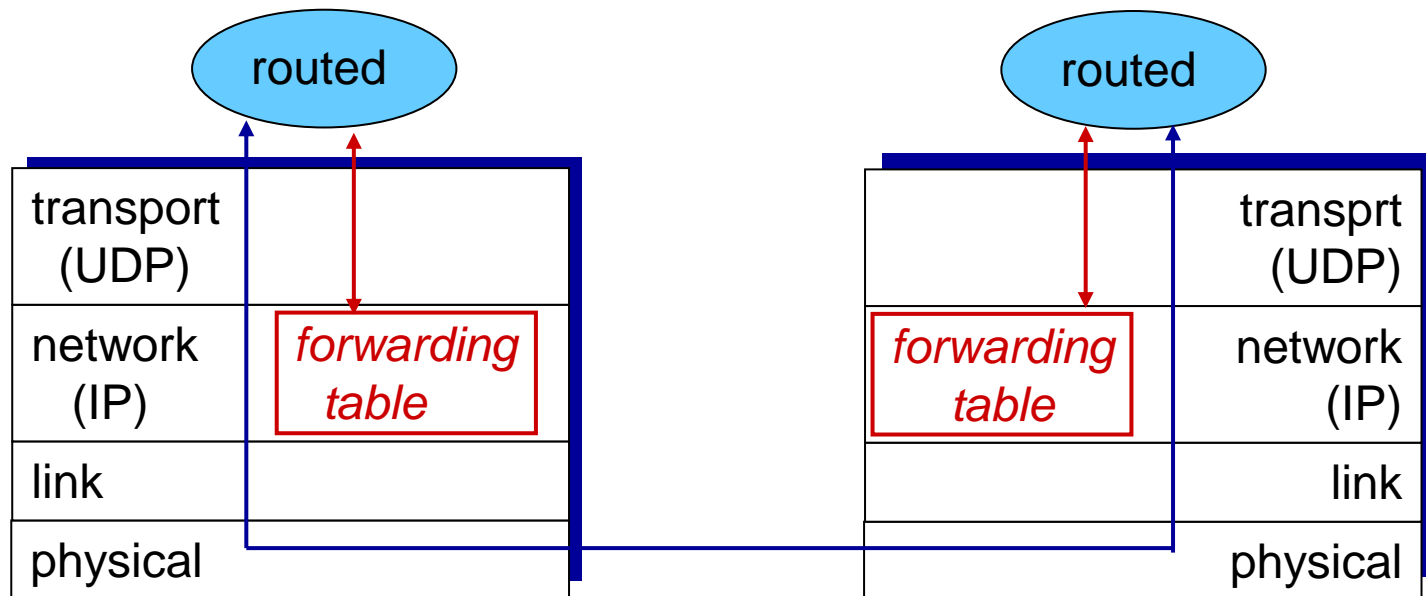
OSPF (Open Shortest Path First)

❖ "open": publicly available
❖ uses link state algorithm
   ▪ LS packet dissemination
   ▪ topology map at each node
   ▪ route computation using Dijkstra's algorithm
❖ OSPF advertisement carries one entry per neighbor
❖ advertisements flooded to *entire* AS
   ▪ carried in OSPF messages directly over IP (rather than TCP or UDP
❖ *IS-IS routing* protocol: nearly identical to OSPF
❖ RIP- lower tier ISPs; OSPF-upper tier ISP

OSPF "advanced" features (not in RIP)

- *security:* all OSPF messages authenticated (to prevent malicious intrusion)
- multiple same-cost paths allowed (only one path in RIP)
- for each link, multiple cost metrics for different TOS (e.g., satellite link cost set "low" for best effort ToS; high for real time ToS)
- integrated uni- and multicast support:
  - Multicast OSPF (MOSPF) uses same topology data base as OSPF
- hierarchical OSPF in large domains.

Hierarchical OSPF

boundary router

backbone router

backbone

area border routers

internal routers

area 1

area 2

area 3
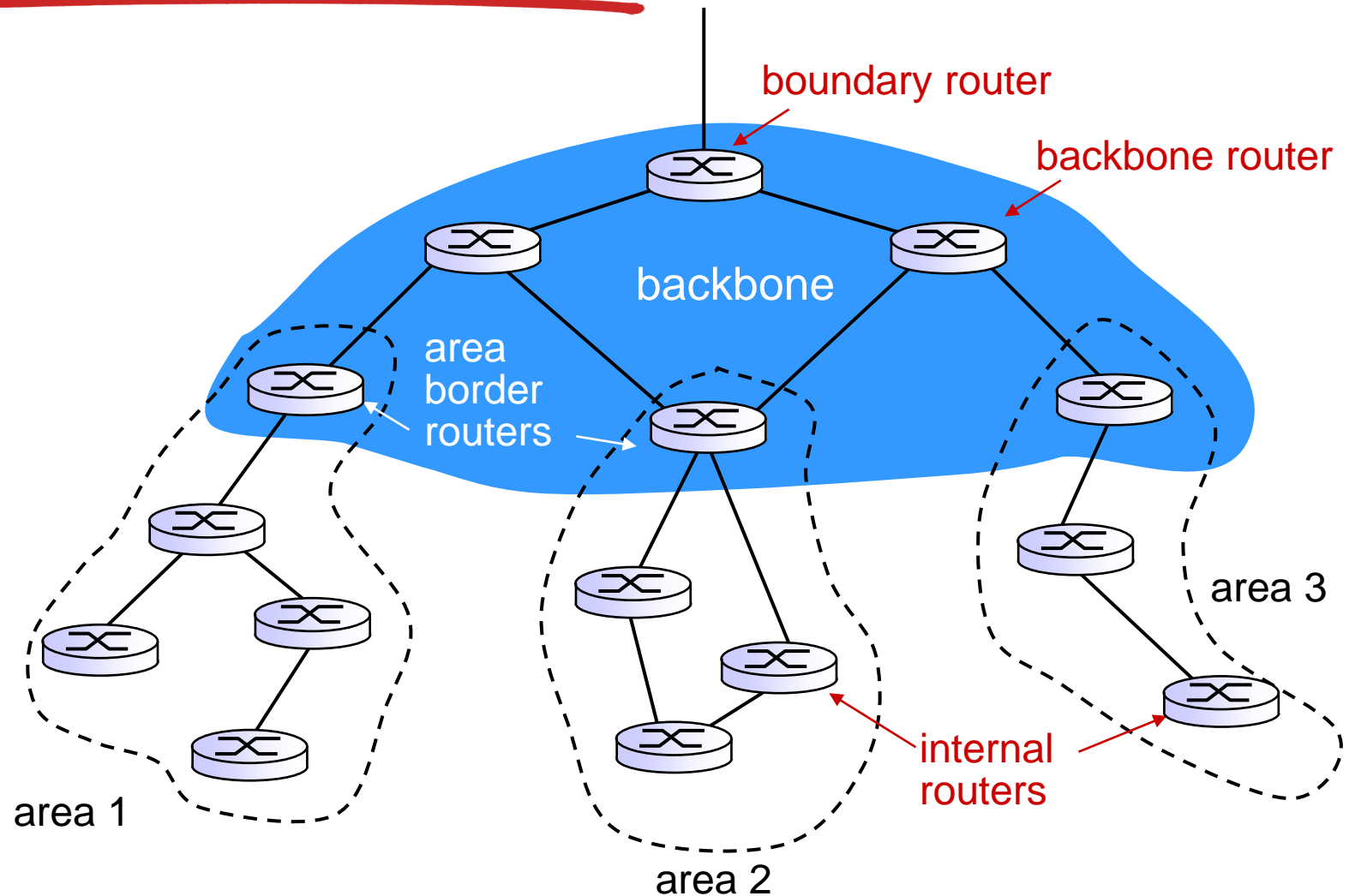
Hierarchical OSPF

❖ *two-level hierarchy:* local area, backbone.
  ▪ link-state advertisements only in area
  ▪ each nodes has detailed area topology; only know direction (shortest path) to nets in other areas.

❖ *area border routers:* "summarize" distances to nets in own area, advertise to other Area Border routers.

❖ *backbone routers:* run OSPF routing limited to backbone.

❖ *boundary routers:* connect to other AS's.

Internet inter-AS routing: BGP

❖ BGP (Border Gateway Protocol): *the* de facto standard inter-domain routing protocol

  ▪ "glue that holds the Internet together"

❖ BGP provides each AS a means to:

  ▪ eBGP: obtain subnet reachability information from neighboring ASs.

  ▪ iBGP: propagate reachability information to all AS-internal routers.

  ▪ determine "good" routes to other networks based on reachability information and policy.

❖ allows subnet to advertise its existence to rest of Internet: *"I am here"*

BGP basics

❖ **BGP session:** two BGP routers ("peers") exchange BGP messages:
  ▪ advertising *paths* to different destination network prefixes ("path vector" protocol)
  ▪ exchanged over semi-permanent TCP connections

❖ when AS3 advertises a prefix to AS1:
  ▪ AS3 *promises* it will forward datagrams towards that prefix
  ▪ AS3 can aggregate prefixes in its advertisement
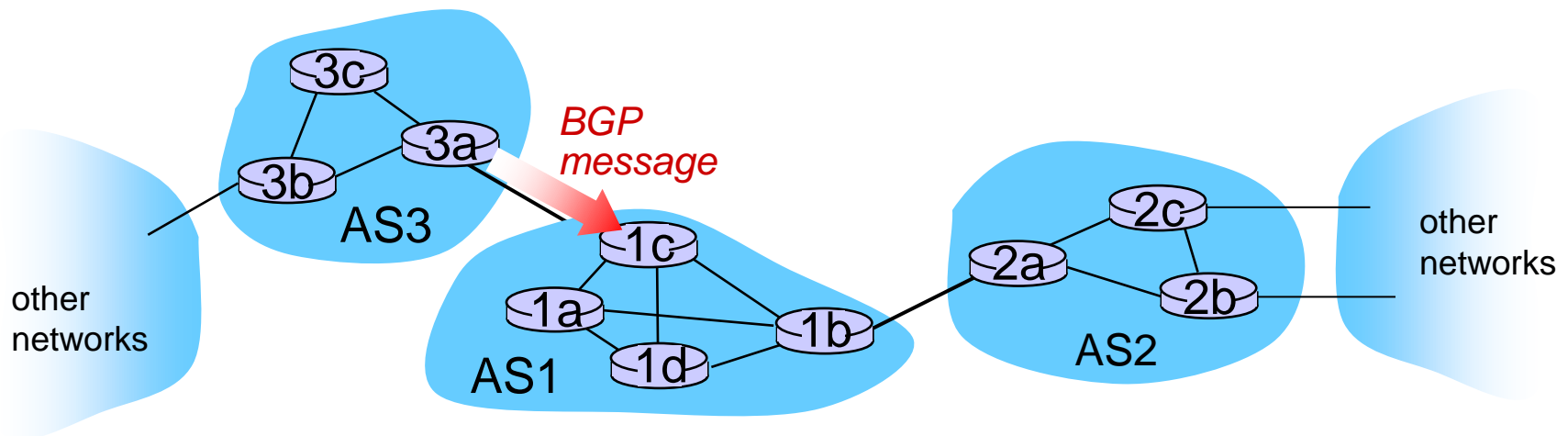
BGP basics: distributing path information

- ❖ using eBGP session between 3a and 1c, AS3 sends prefix reachability info to AS1.
  - 1c can then use iBGP do distribute new prefix info to all routers in AS1
  - 1b can then re-advertise new reachability info to AS2 over 1b-to-2a eBGP session
- ❖ when router learns of new prefix, it creates entry for prefix in its forwarding table.
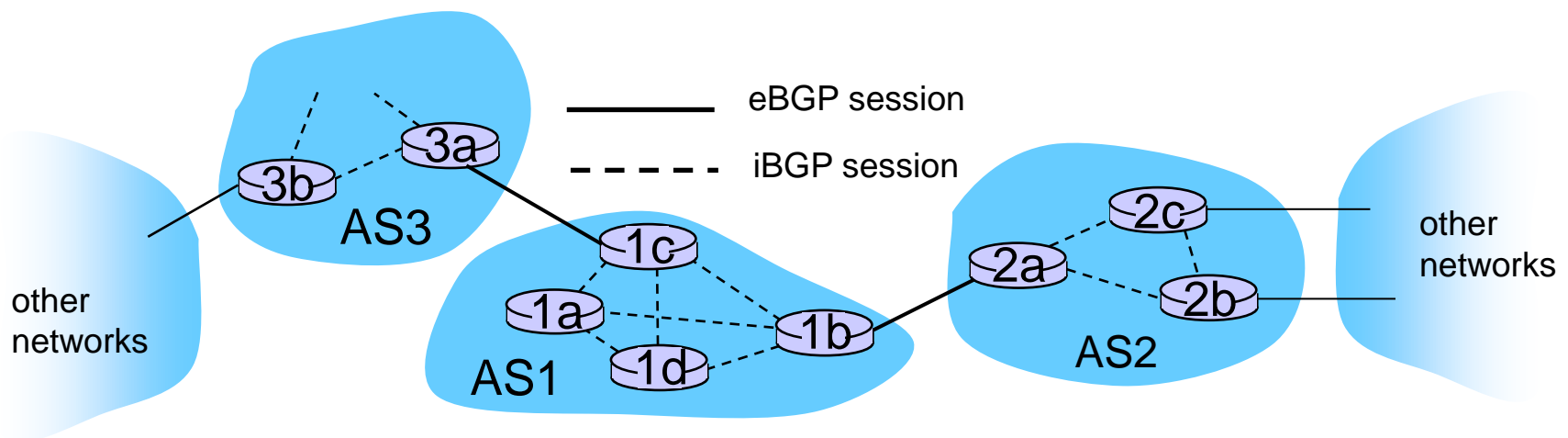
Path attributes and BGP routes

❖ advertised prefix includes BGP attributes
  ▪ prefix + attributes = "route"
❖ two important attributes:
  ▪ AS-PATH: contains ASs through which prefix advertisement has passed: e.g., AS 67, AS 17
  ▪ NEXT-HOP: indicates specific internal-AS router to next-hop AS. (may be multiple links from current AS to next-hop-AS)
❖ gateway router receiving route advertisement uses import policy to accept/decline
  ▪ e.g., never route through AS x
  ▪ *policy-based* routing

BGP route selection

❖ router may learn about more than 1 route to destination AS, selects route based on:

1. local preference value attribute: policy decision
2. shortest AS-PATH
3. closest NEXT-HOP router: hot potato routing
4. additional criteria

BGP messages

❖ BGP messages exchanged between peers over TCP connection

❖ BGP messages:
  ▪ OPEN: opens TCP connection to peer and authenticates sender
  ▪ UPDATE: advertises new path (or withdraws old)
  ▪ KEEPALIVE: keeps connection alive in absence of UPDATES; also ACKs OPEN request
  ▪ NOTIFICATION: reports errors in previous msg; also used to close connection

Putting it Altogether:
How Does an Entry Get Into a Router's Forwarding Table?

- ❖ Answer is complicated!

- ❖ Ties together hierarchical routing (Section 4.5.3) with BGP (4.6.3) and OSPF (4.6.2).

- ❖ Provides nice overview of BGP!

How does entry get in forwarding table?

routing algorithms

local forwarding table

prefix	output port
138.16.64/22	3
124.12/16	2
212/8	4
……………	…

entry

Assume prefix is in another AS.

Dest IP

1

3 2
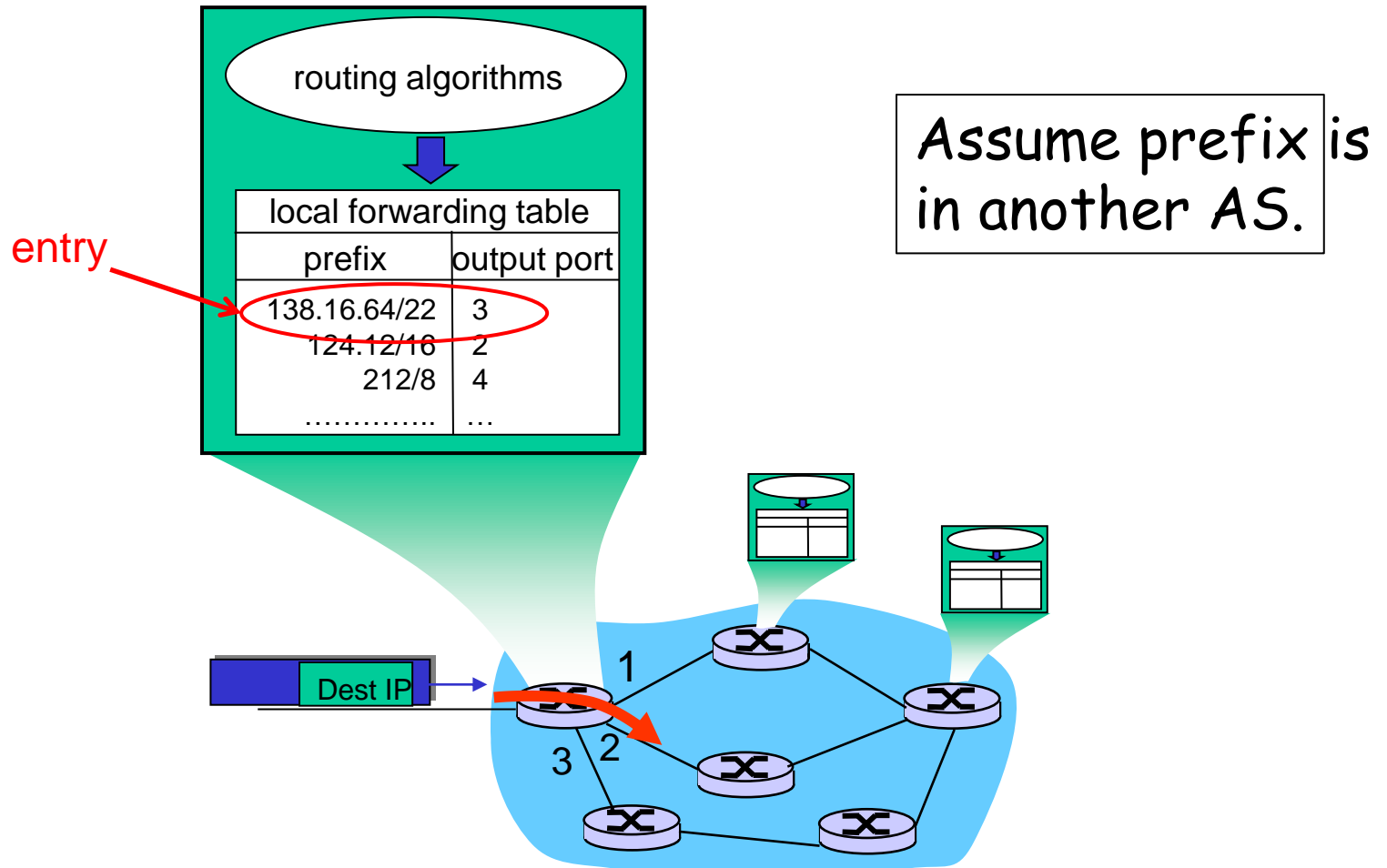
How does entry get in forwarding table?

High-level overview

1. Router becomes aware of prefix
2. Router determines output port for prefix
3. Router enters prefix-port in forwarding table

Router becomes aware of prefix
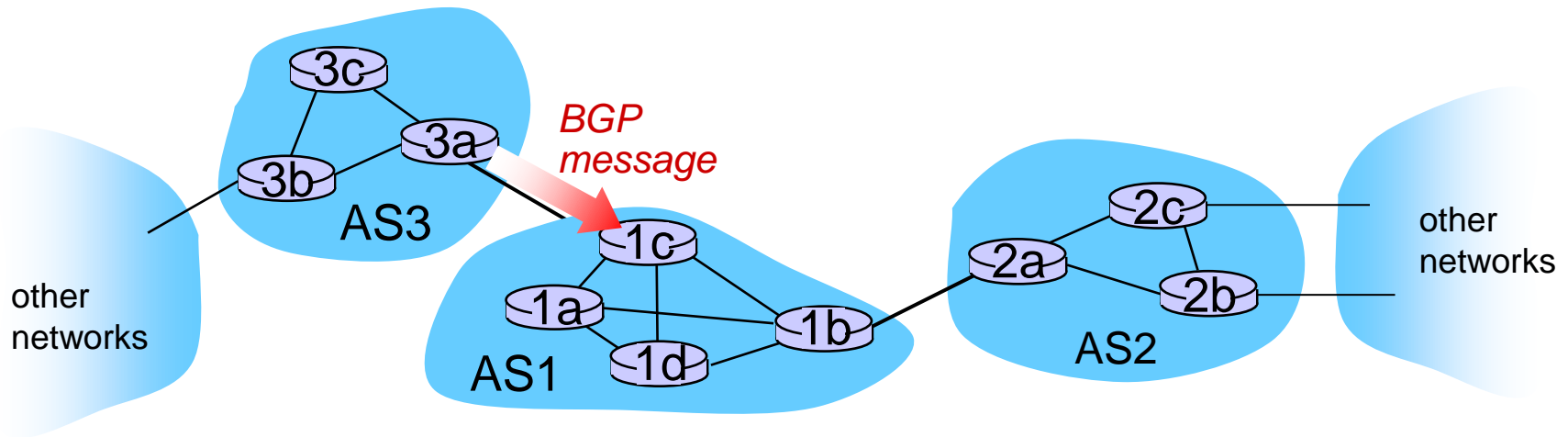
- ❖ BGP message contains "routes"
- ❖ "route" is a prefix and attributes: AS-PATH, NEXT-HOP,…
- ❖ Example: route:
  - ❖ Prefix:138.16.64/22 ; AS-PATH: AS3 AS131 ; NEXT-HOP: 201.44.13.125

Router may receive multiple routes
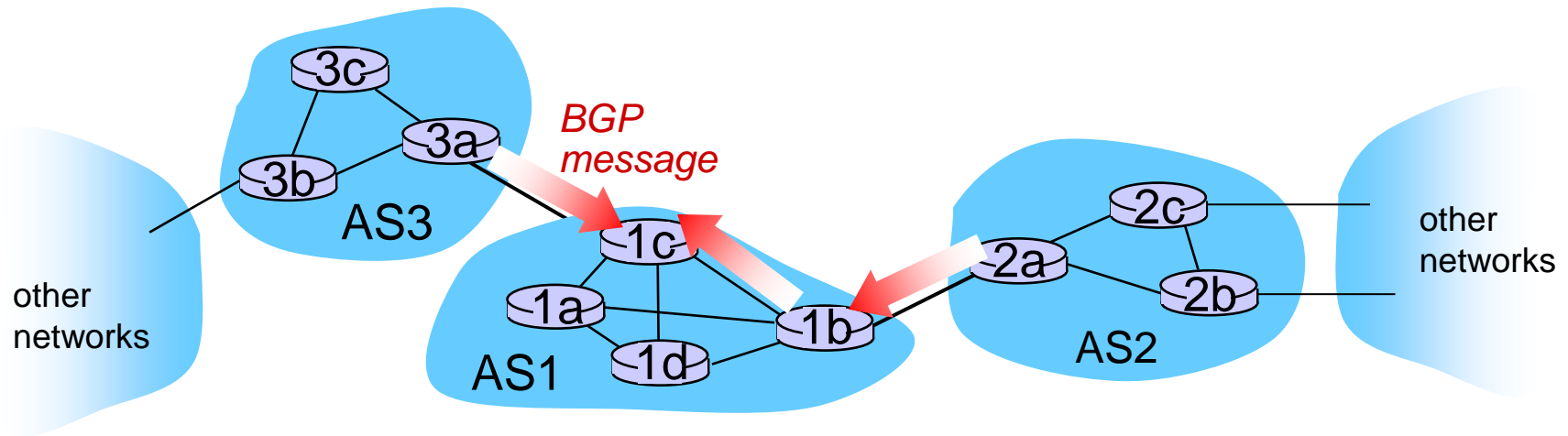
- Router may receive multiple routes for <u>same</u> prefix
- Has to select one route

Select best BGP route to prefix

❖ Router selects route based on shortest AS-PATH

❖ Example:

select

❖ AS2 AS17 to 138.16.64/22
❖ AS3 AS131 AS201 to 138.16.64/22

Find best intra-route to BGP route

- ❖ Use selected route's NEXT-HOP attribute
  - ▪ Route's NEXT-HOP attribute is the IP address of the router interface that begins the AS PATH.
- ❖ Example:
  - ❖ AS-PATH: AS2 AS17 ; NEXT-HOP: 111.99.86.55
- ❖ Router uses OSPF to find shortest path from 1c to 111.99.86.55
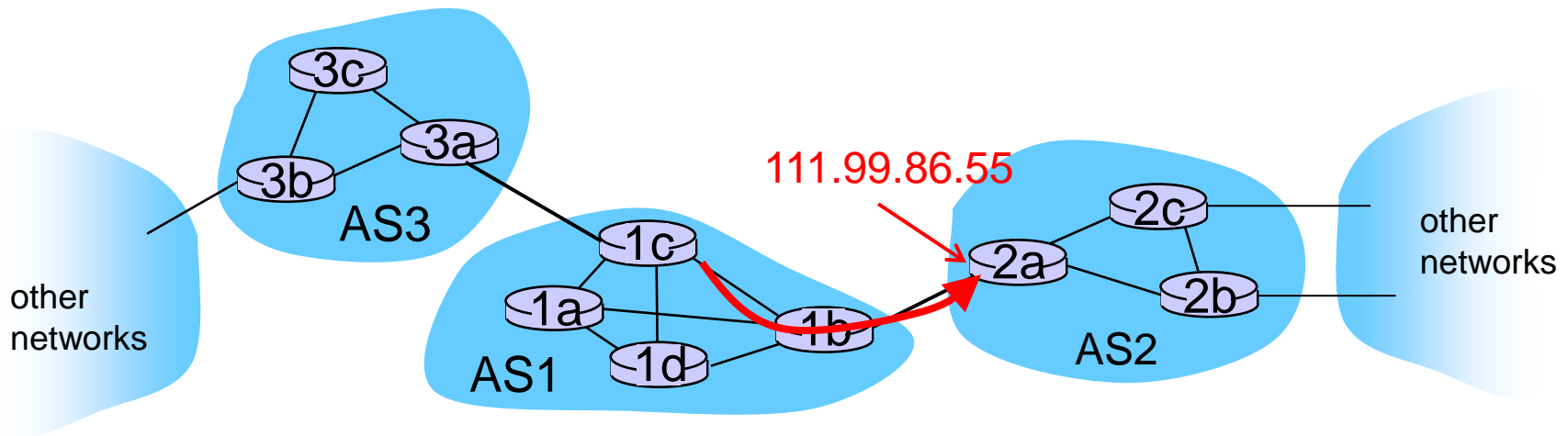
Router identifies port for route

- Identifies port along the OSPF shortest path
- Adds prefix-port entry to its forwarding table:
  - (138.16.64/22 , port 4)
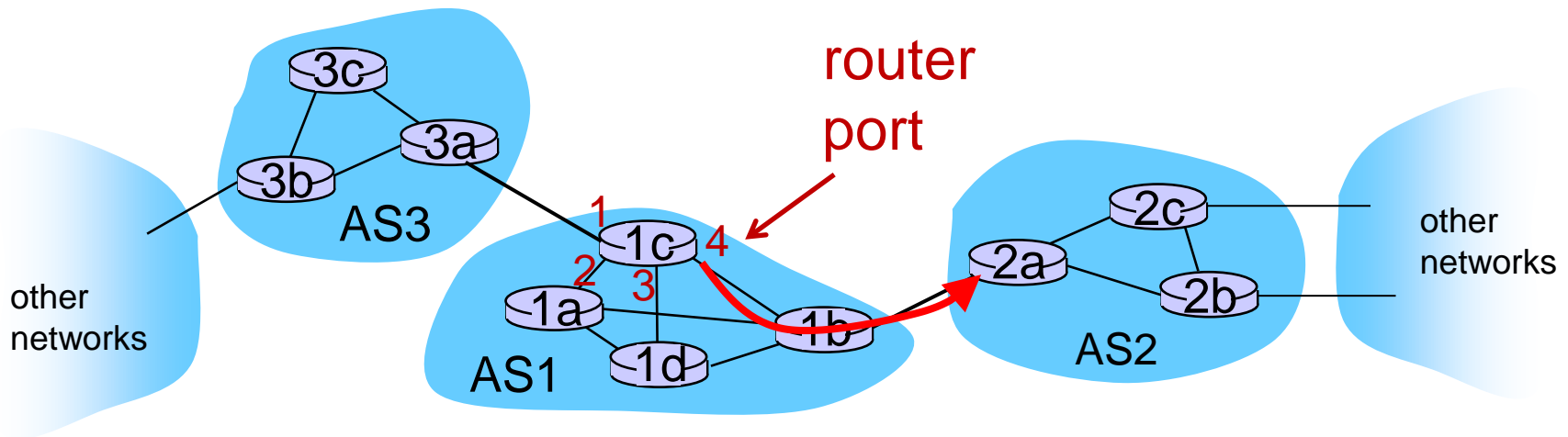
Hot Potato Routing

❖ Suppose there two or more best inter-routes.
❖ Then choose route with closest NEXT-HOP
- Use OSPF to determine which gateway is closest
- Q: From 1c, chose AS3 AS131 or AS2 AS17?
- A: route AS3 AS201 since it is closer
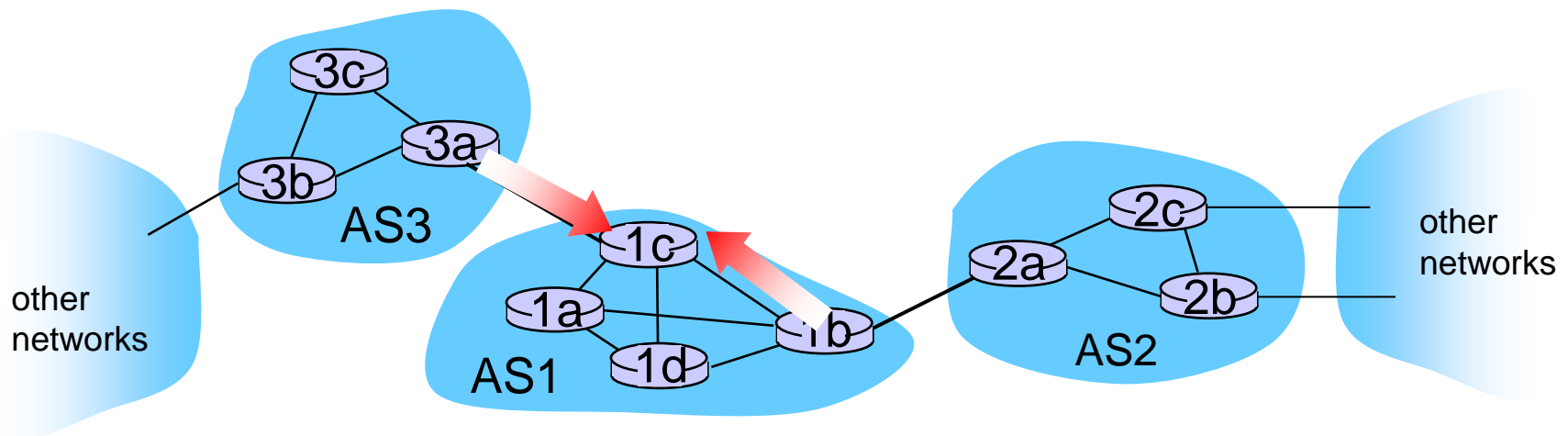
How does entry get in forwarding table?

Summary

1. Router becomes aware of prefix
   - via BGP route advertisements from other routers
2. Determine router output port for prefix
   - Use BGP route selection to find best inter-AS route
   - Use OSPF to find best intra-AS route leading to best inter-AS route
   - Router identifies router port for that best route
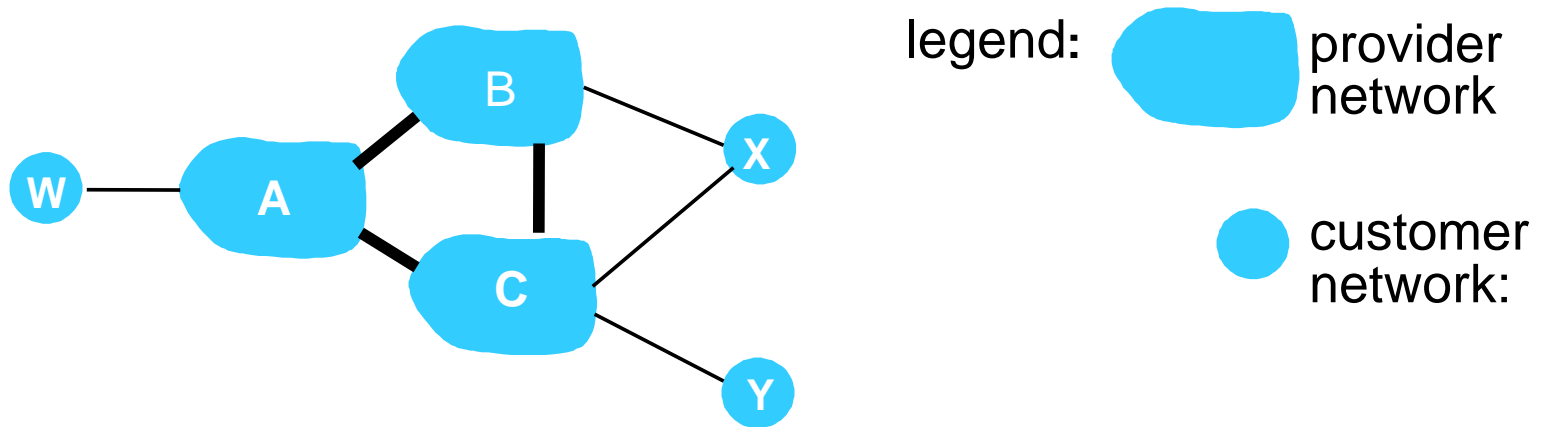3. Enter prefix-port entry in forwarding table

BGP routing policy
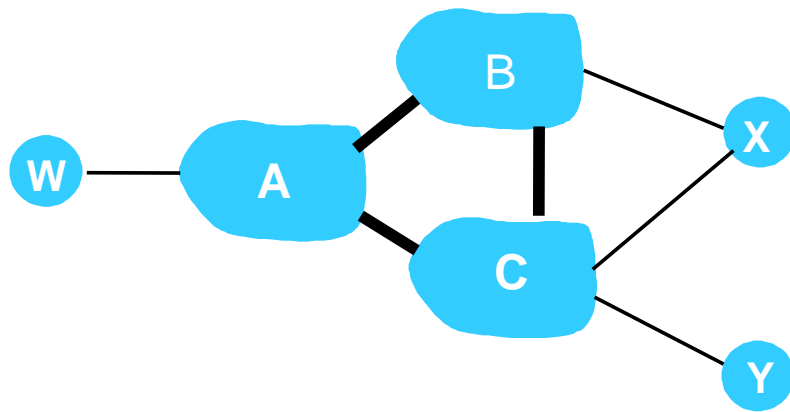
legend: provider network

customer network:

- ❖ A,B,C are *provider networks*
- ❖ X,W,Y are customer (of provider networks)
- ❖ X is *dual-homed:* attached to two networks
  - ▪ X does not want to route from B via X to C
  - ▪ .. so X will not advertise to B a route to C

BGP routing policy (2)

legend:

provider network

customer network:

- ❖ A advertises path AW to B
- ❖ B advertises path BAW to X
- ❖ Should B advertise path BAW to C?
  - No way! B gets no "revenue" for routing CBAW since neither W nor C are B's customers
  - B wants to force C to route to w via A
  - B wants to route *only* to/from its customers!

Why different Intra-, Inter-AS routing ?

policy:

❖ inter-AS: admin wants control over how its traffic routed, who routes through its net.
❖ intra-AS: single admin, so no policy decisions needed

scale:

❖ hierarchical routing saves table size, reduced update traffic

performance:

❖ intra-AS: can focus on performance
❖ inter-AS: policy may dominate over performance

Chapter 4: *done!*

4.1 introduction

4.2 virtual circuit and datagram networks

4.3 what's inside a router

4.4 IP: Internet Protocol
- datagram format, IPv4 addressing, ICMP, IPv6

4.5 routing algorithms
- link state, distance vector, hierarchical routing

4.6 routing in the Internet
- RIP, OSPF, BGP

❖ understand principles behind network layer services:

- network layer service models, forwarding versus routing how a router works, routing (path selection), broadcast, multicast

❖ instantiation, implementation in the Internet