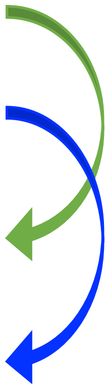
Network Layer

CMPS 4750/6750: Computer Networks

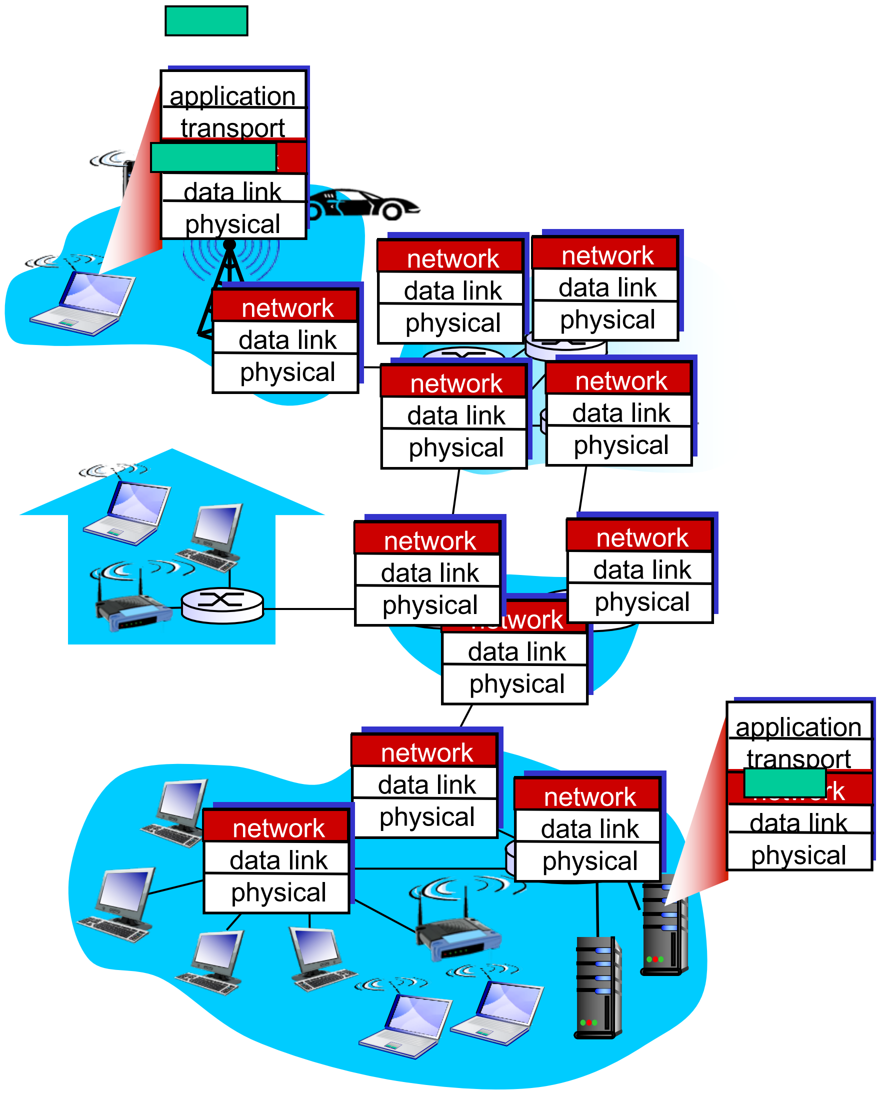
Outline

- Overview of network layer
- Forwarding (data plane)
- Routing (control plane)
- The Internet Protocol (IP): IPv4, DHCP, NAT, IPv6
- Routing in the Internet: 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



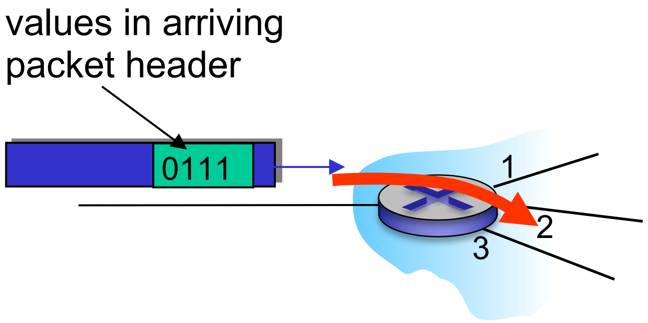
Two key network-layer functions

- *forwarding:* move packets from router's input to appropriate router output
- *routing:* determine route taken by packets from source to destination
  - *routing algorithms*

Network layer: data plane, control plane

Data plane

- local, per-router function
  - forwarding
  - dropping
  - modify field
  - …

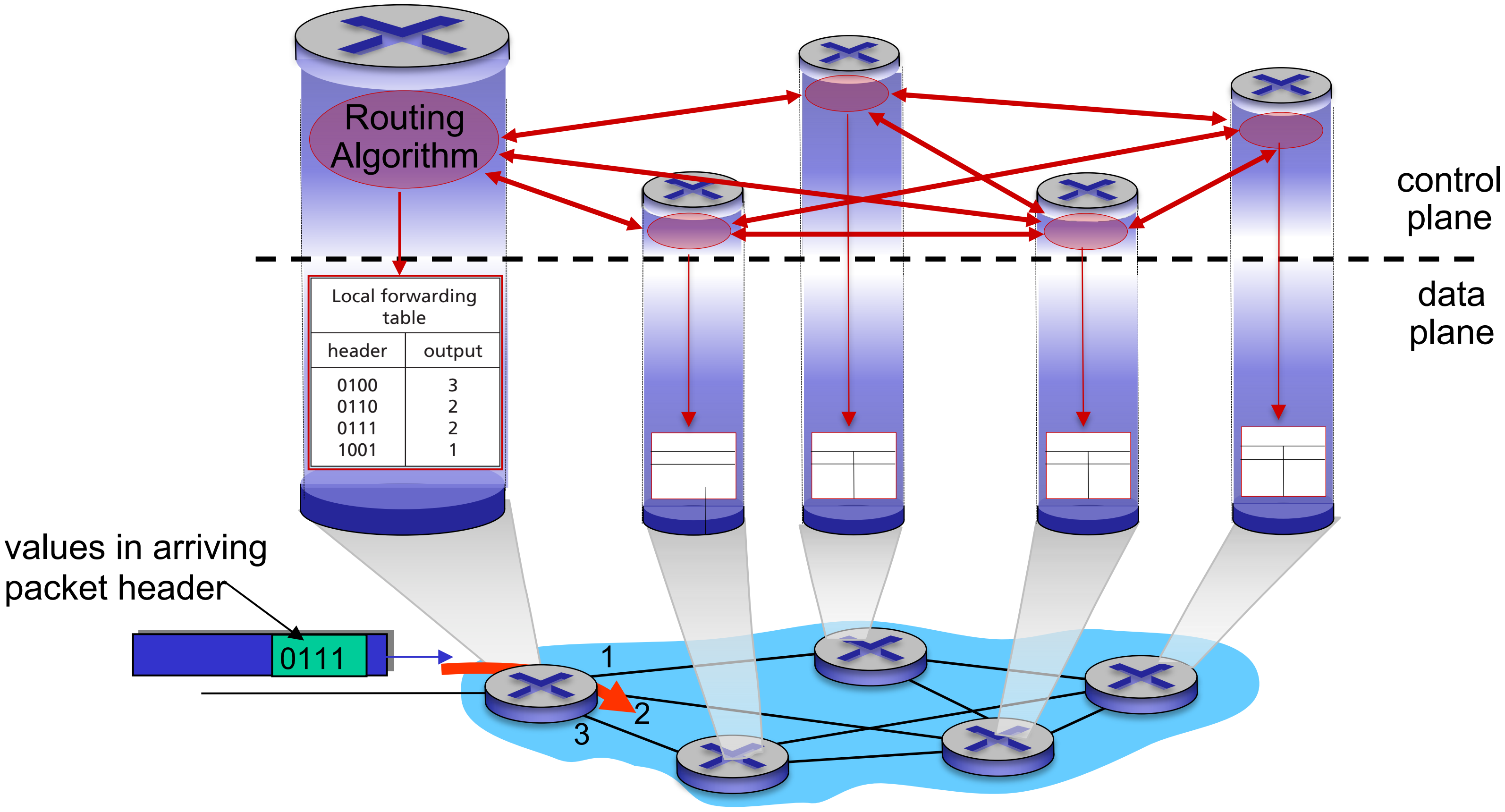


Control plane

- network-wide logic
  - routing
  - access control
  - load balancing
  - …
- two control-plane approaches:
  - *traditional routing algorithms:* implemented in routers
  - *software-defined networking (SDN)*: implemented in (remote) servers

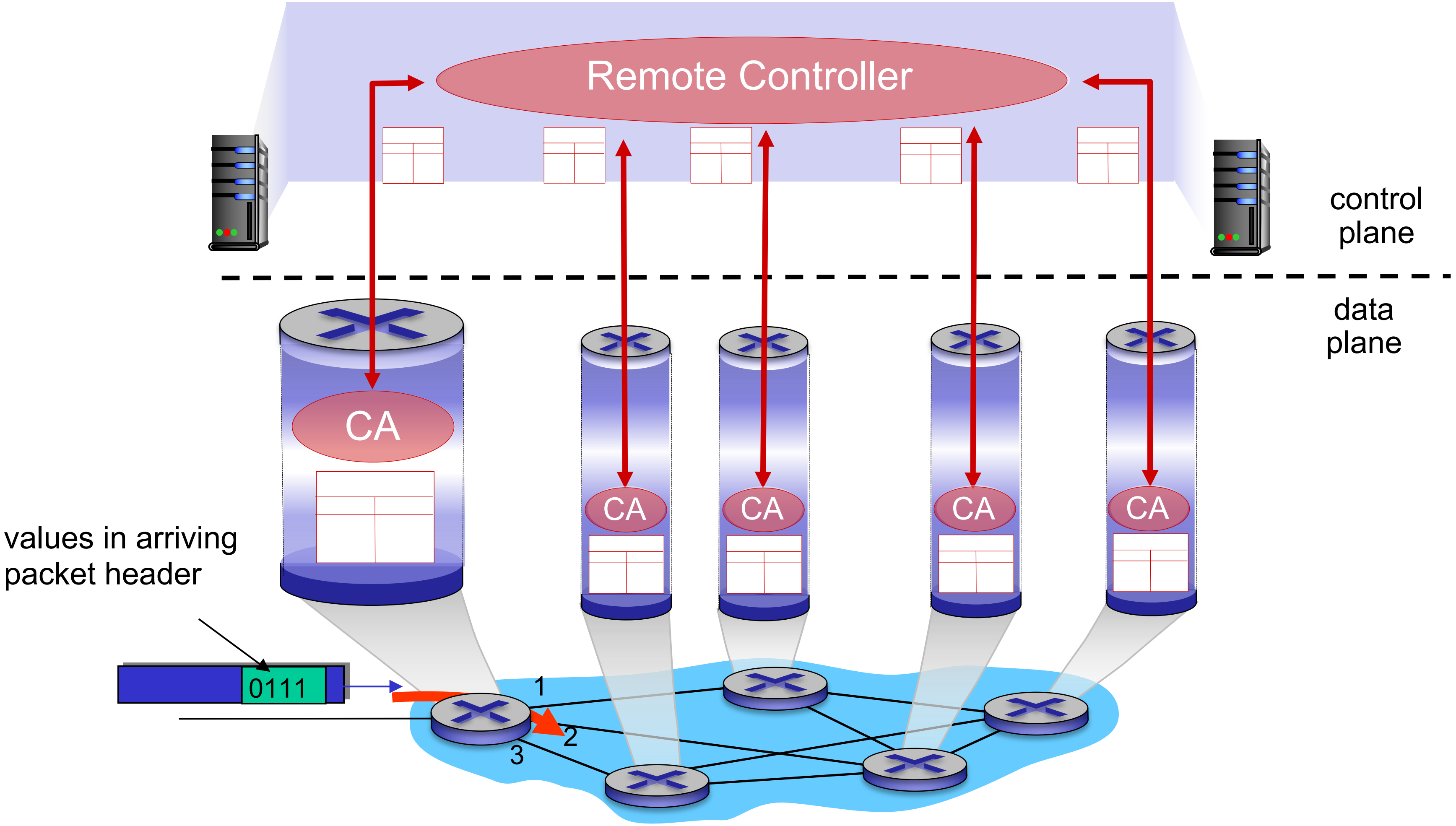
Per-router control plane

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



Logically centralized control plane

- A distinct (typically remote) controller interacts with local control agents (CAs)



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 delay

The Internet's network layer provides "best-effort" service

example services for a flow of datagrams:

- in-order datagram delivery
- guaranteed minimum bandwidth to flow
- restrictions on changes in inter-packet spacing

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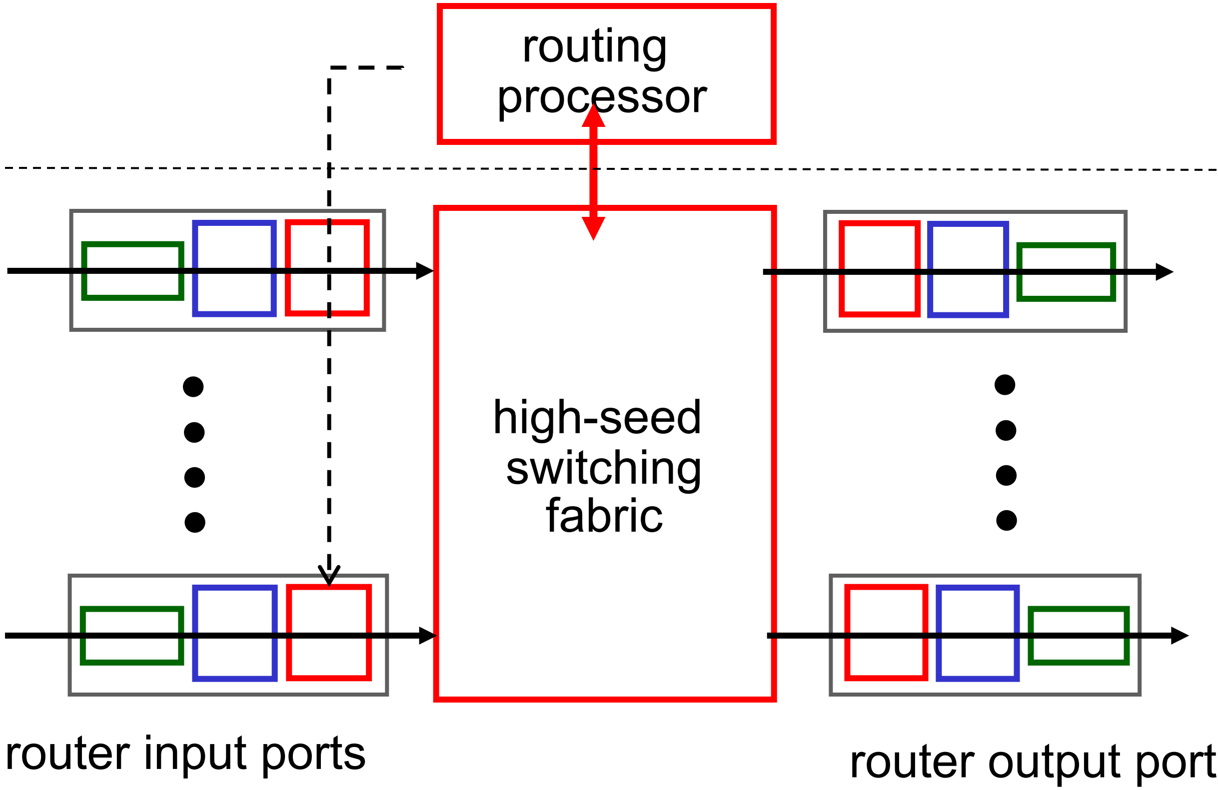
Router architecture overview



routing processor

high-seed switching fabric

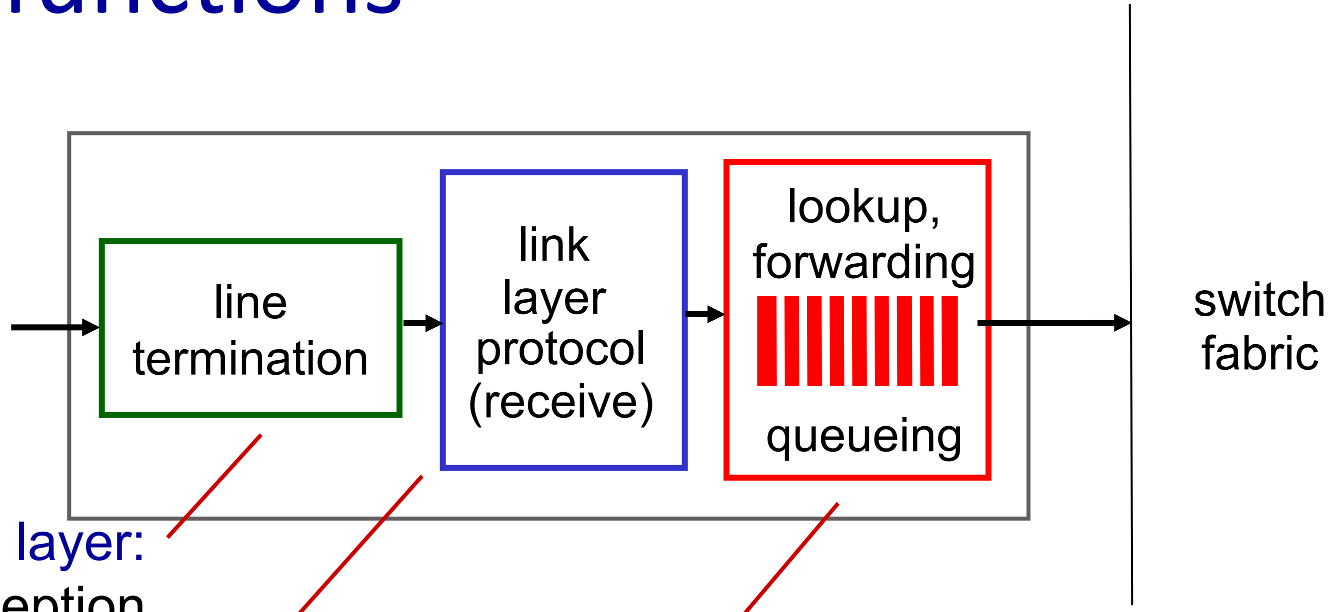
router input ports

router output ports

routing, management
control plane (software)
operates in millisecond
time frame

forwarding data plane
(hardware) operates
in nanosecond
timeframe

Input port functions



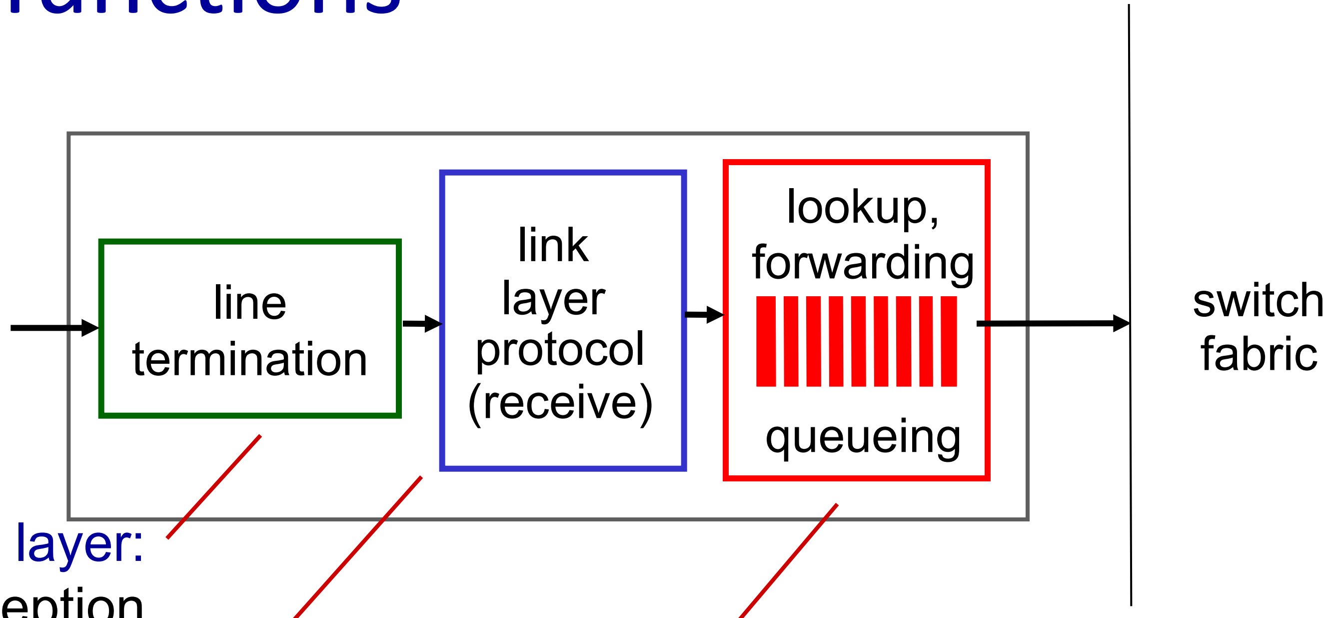
physical layer:
bit-level reception

data link layer:
e.g., Ethernet
see chapter 5

decentralized switching:

- using header field values, lookup output port using forwarding table in input port memory *("match plus action")*
- goal: complete input port processing at 'line speed'
- queuing: if datagrams arrive faster than forwarding rate into switch fabric

Input port functions



physical layer:
bit-level reception

data link layer:
e.g., Ethernet
see chapter 5

decentralized switching:

- using header field values, lookup output port using forwarding table in input port memory *("match plus action")*
- *destination-based forwarding:* forward based only on destination IP address (traditional)
- *generalized forwarding:* forward based on any set of header field values

Destination-based forwarding

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

Destination-based forwarding

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

Longest prefix matching

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? 0

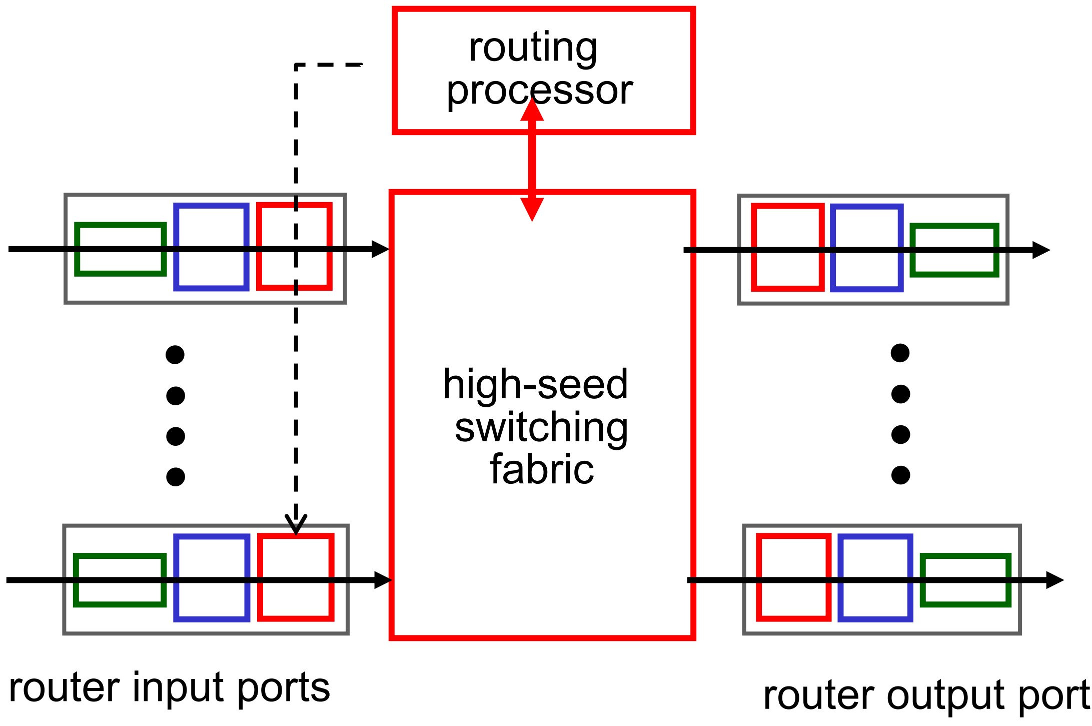
DA: 11001000 00010111 00011000 10101010 which interface? 1

longest prefix matching

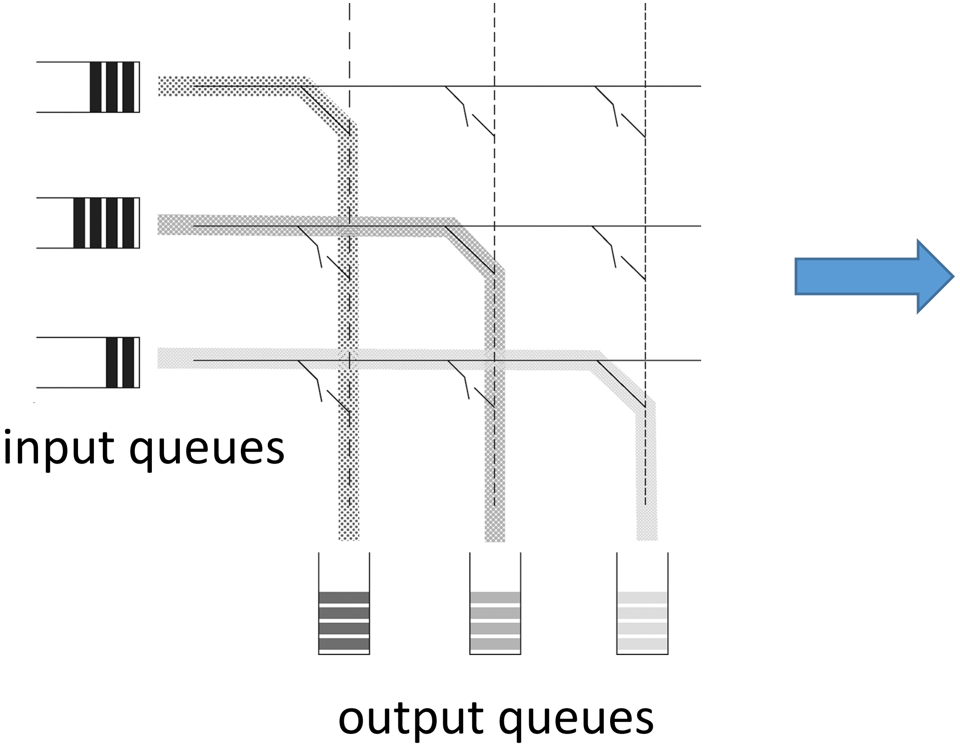
when looking for forwarding table entry for given destination address, use *longest* address prefix that matches destination address.

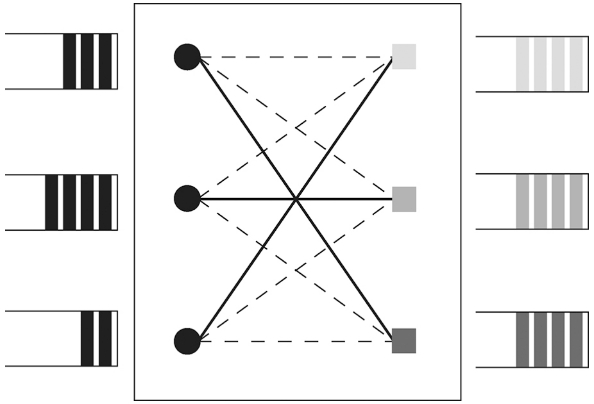
Switching fabrics

- transfer packets from input buffer to appropriate output buffer
- switching rate: rate at which packets can be transfer from inputs to outputs
  - often measured as multiple of input/output line rate
  - N inputs: switching rate N times line rate desirable



Crossbar switches



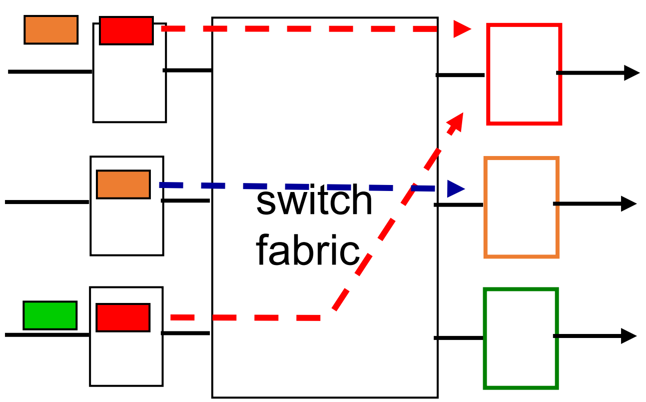


Bipartite graph representation

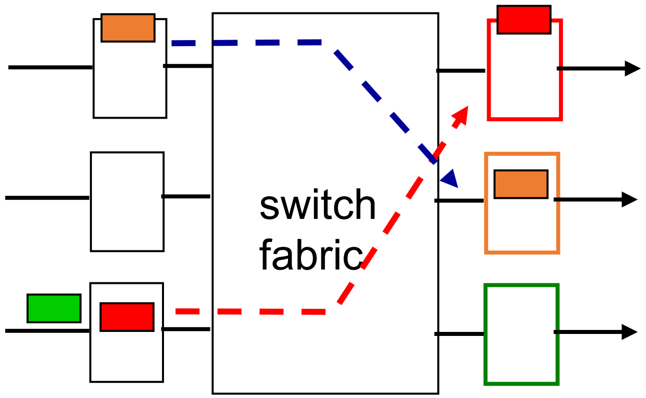
- at any time, one input point can be connected to at most one output port, and vice versa
- a schedule in a crossbar switch corresponds to a matching in the corresponding bipartite graph

Input port queuing

- fabric slower than input ports combined -> queueing may occur at input queues
  - *queueing delay and loss due to input buffer overflow!*



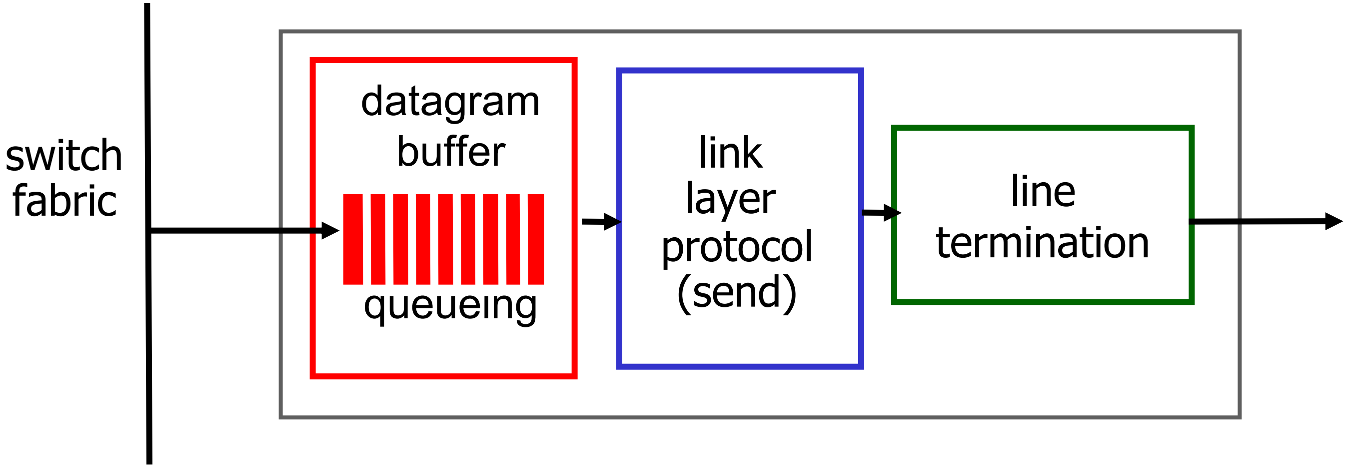
output port contention: *lower red packet is blocked*



assuming FCFS, green packet experiences HOL blocking

- Head-of-the-Line (HOL) blocking: queued datagram at front of queue prevents others in queue from moving forward

Output ports



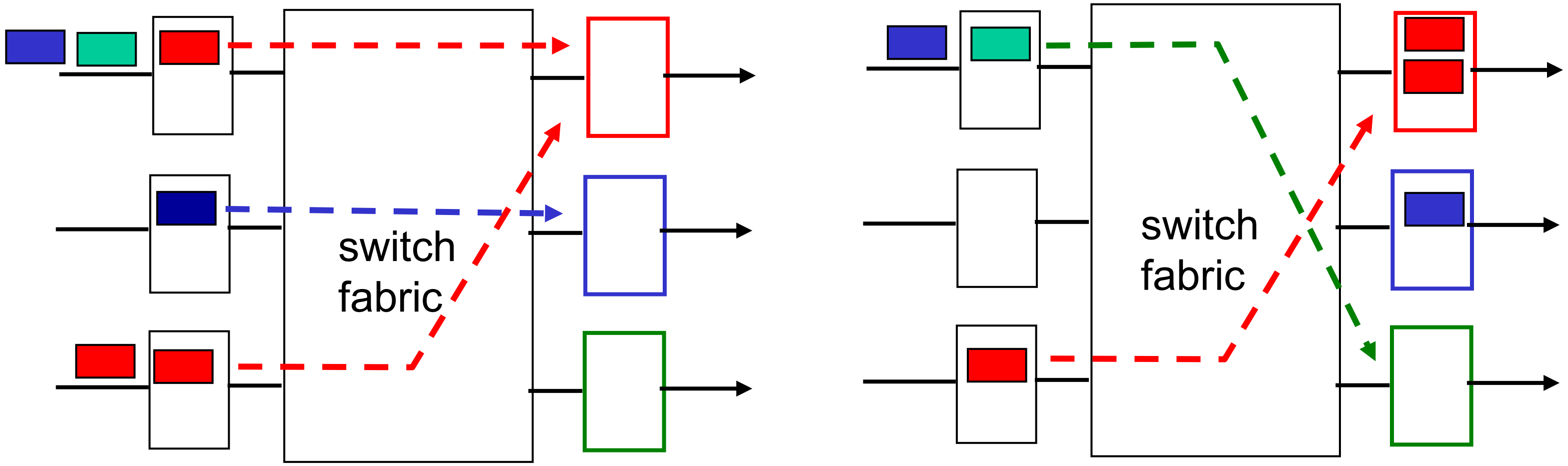
- *buffering* required
  fabric faster than t

Datagram (packets) can be lost due to congestion, lack of buffers

- *scheduling*
  datagrams

Priority scheduling – who gets best performance, network neutrality

Output port queueing



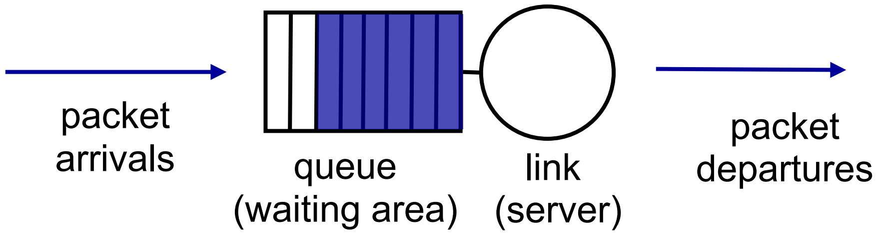
at *t,* packets more from input to output

one packet time later (assume switch operates at three times the line speed)

- buffering when arrival rate via switch exceeds output line speed
- *queueing (delay) and loss due to output port buffer overflow!*

Scheduling mechanisms

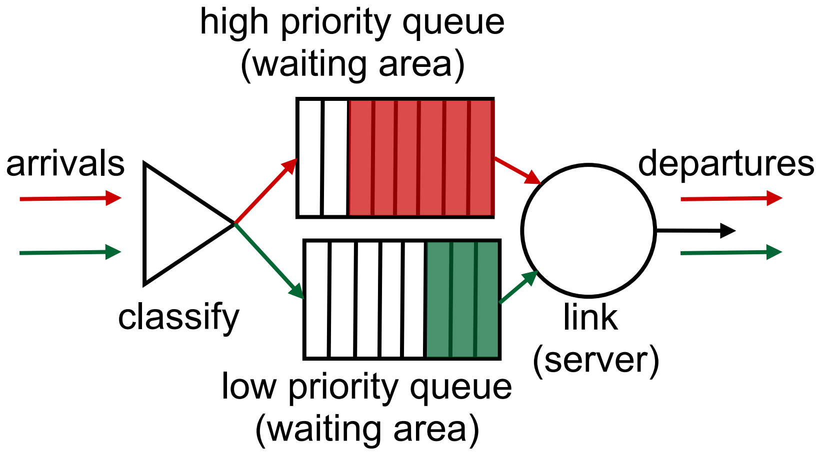
- *scheduling:* choose next packet to send on link

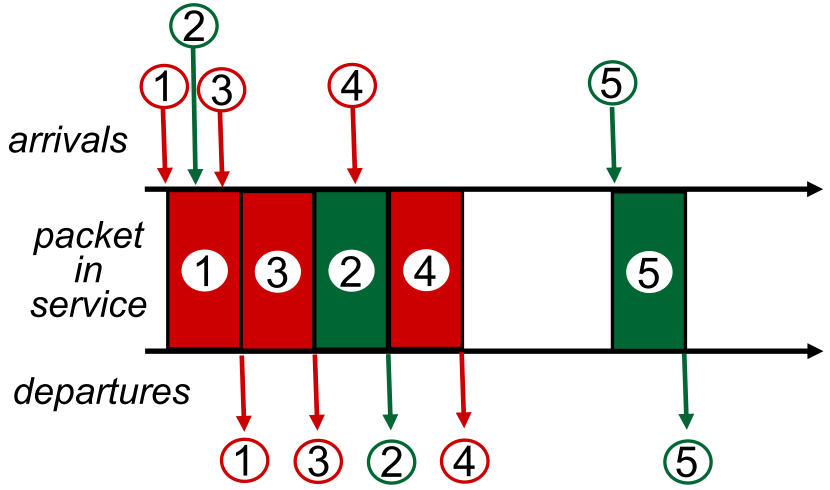


- *FCFS (first-come-first-served) scheduling:* send in order of arrival to queue
  - Also known as *first-in-first-out, FIFO*
  - real-world example?
  - *discard policy:* if packet arrives to full queue: who to discard?
    - *tail drop:* drop arriving packet
    - *priority:* drop/remove on priority basis
    - *random:* drop/remove randomly

Scheduling policies: priority

- *priority scheduling:* send highest priority queued packet
- multiple *classes*, with different priorities
  - class may depend on marking or other header info, e.g. IP source/dest, port numbers, etc.
  - real world example?

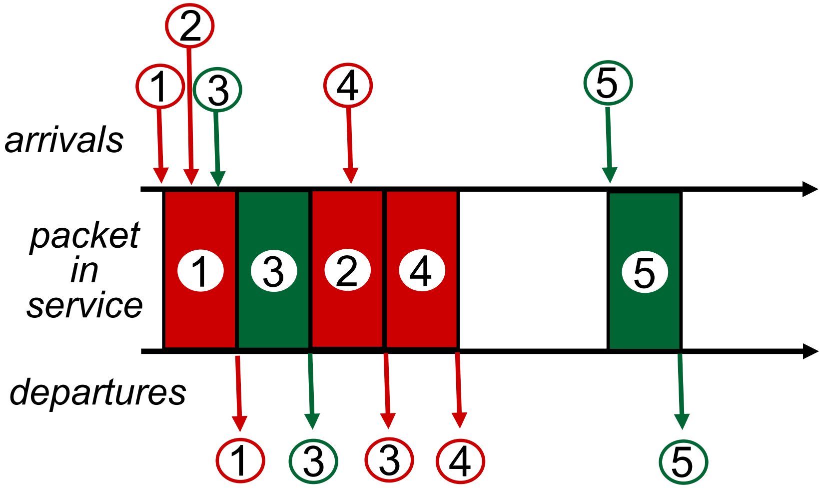




Scheduling policies: still more

Round Robin (RR) scheduling:

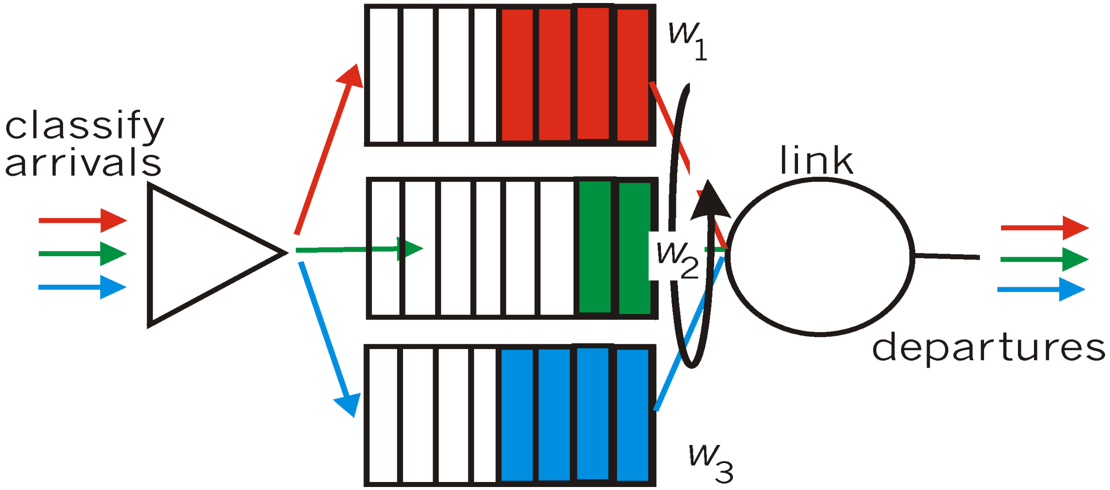
- multiple classes
- cyclically scan class queues, sending one complete packet from each class (if available)



Scheduling policies: still more

Weighted Fair Queuing (WFQ):

- generalized Round Robin
- each class gets weighted amount of service in each cycle



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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:

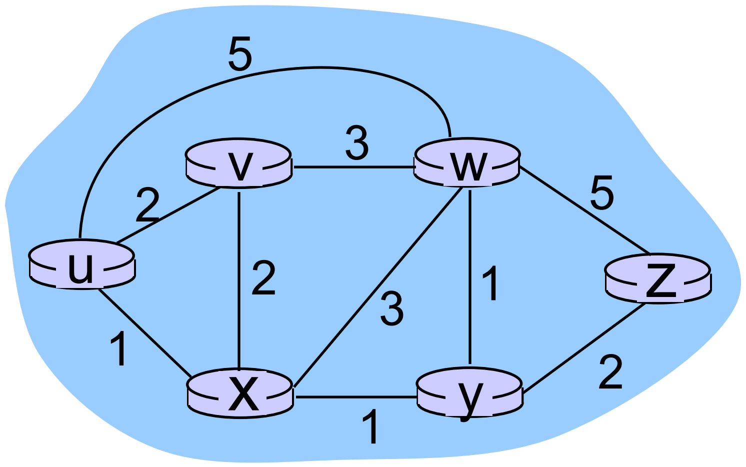
- per-router control (traditional)
- logically centralized control (software defined networking)

Routing protocols

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



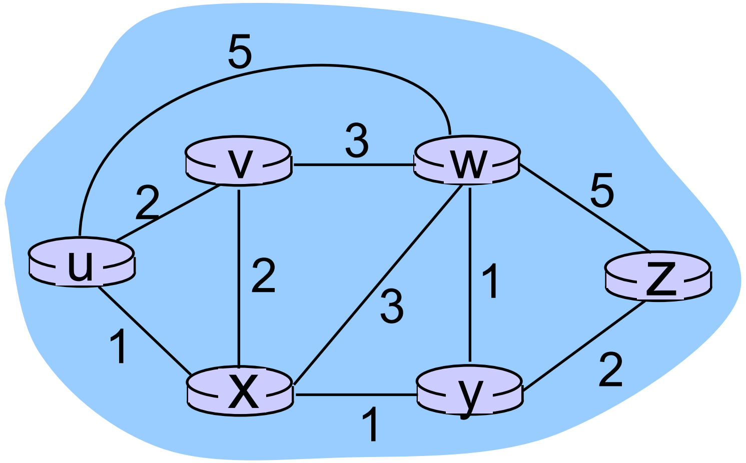
graph: G = (N,E)

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) }

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 related to congestion or delay

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

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

```
Initialization:
  N' = {u}
  for all nodes v
    if v adjacent to u
      then D(v) = c(u,v)
    else D(v) = ∞

Loop
  find w not in N' such that D(w) is a minimum
  add w to N'
  for all v adjacent to w and not in N' :
     D(v) = min( D(v), D(w) + c(w,v) )
until all nodes in N'
```

new cost to v is either old cost to v or known shortest path cost to w plus cost from w to v

Dijkstra’s algorithm: example

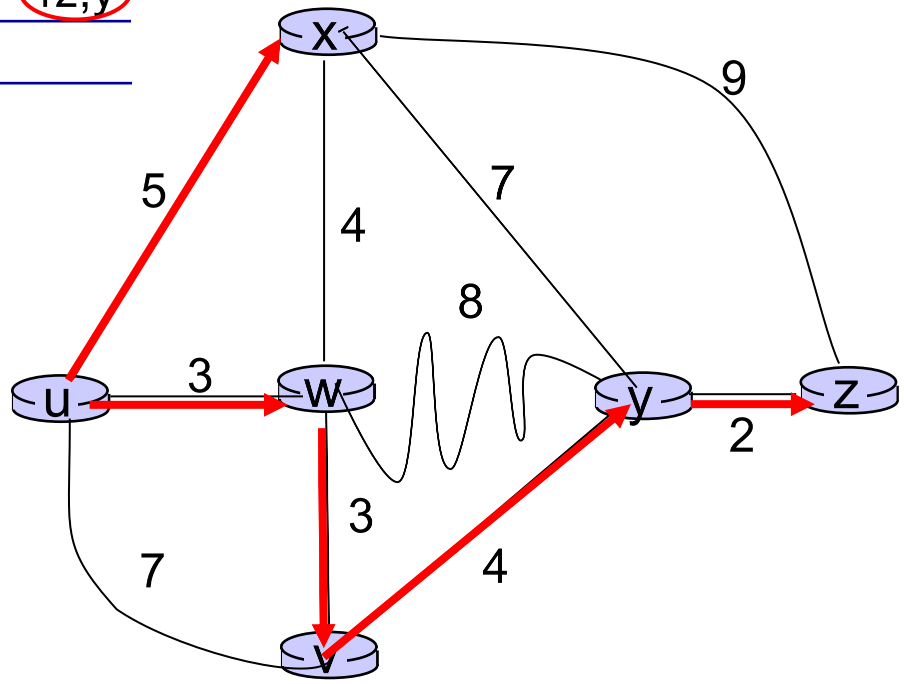
Step	N'	D(v) p(v)	D(w) p(w)	D(x) p(x)	D(y) p(y)	D(z) p(z)
0	u	7,u	3,u	5,u	∞	∞
1	uw	6,w		5,u	11,w	∞
2	uwx	6,w			11,w	14,x
3	uwxv				10,v	14,x
4	uwxvy					12,y
5	uwxvyz					

resulting forwarding table in u:

destination	link
v	(u,w)
w	(u,w)
x	(u,x)
y	(u,w)
z	(u,w)

notes:

- construct shortest path tree by tracing predecessor nodes
- ties can exist (can be broken arbitrarily)



Complexity of Dijkstra’s algorithm

For a given network $G(N, E)$

- each iteration: need to check all nodes not in N’ and edges adjacent to w
- $|N|(|N| + 1)/2$ comparisons + $O(|E|)$ updates: $O(|N|^2)$
- more efficient implementations possible: $O(|N| \log|N| + |E|)$

Distance vector algorithm

Bellman-Ford equation (dynamic programming)

let

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

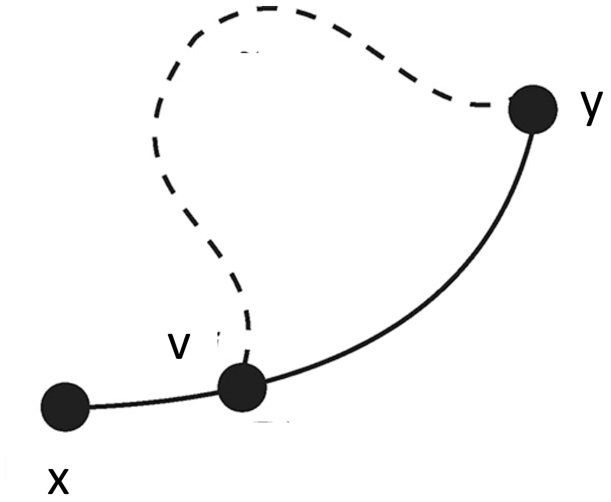
then

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

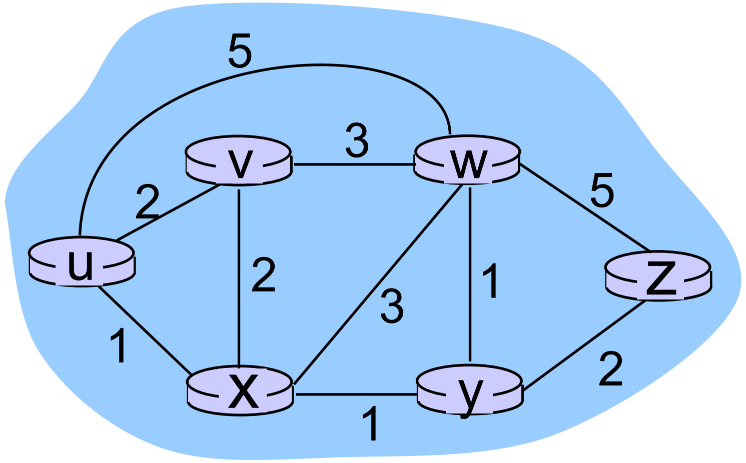
cost from neighbor v to destination y

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:

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

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

Distance vector algorithm

- node x:
  - knows cost to each neighbor v: $c(x,v)$
  - x maintains distance vector $\mathbf{D}_x = [D_x(y): y \in N]$
    - $D_x(y)$ = estimate of least cost from x to y
  - maintains its neighbors' distance vectors
    - From each neighbor v, x receives $\mathbf{D}_v = [D_v(y): y \in N]$

Distance vector algorithm

key idea:

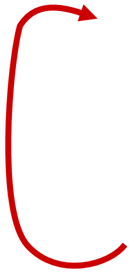
- from time-to-time, each node sends its own distance vector estimate to neighbors
- when x receives new DV estimate from neighbor, it updates its own DV using B-F equation:

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

Distance vector algorithm

Each node x

- start with known costs to neighbors
- calculate initial estimate of $D_x = \{D_x(y), y \in N\}$
- send distance vector to neighbors

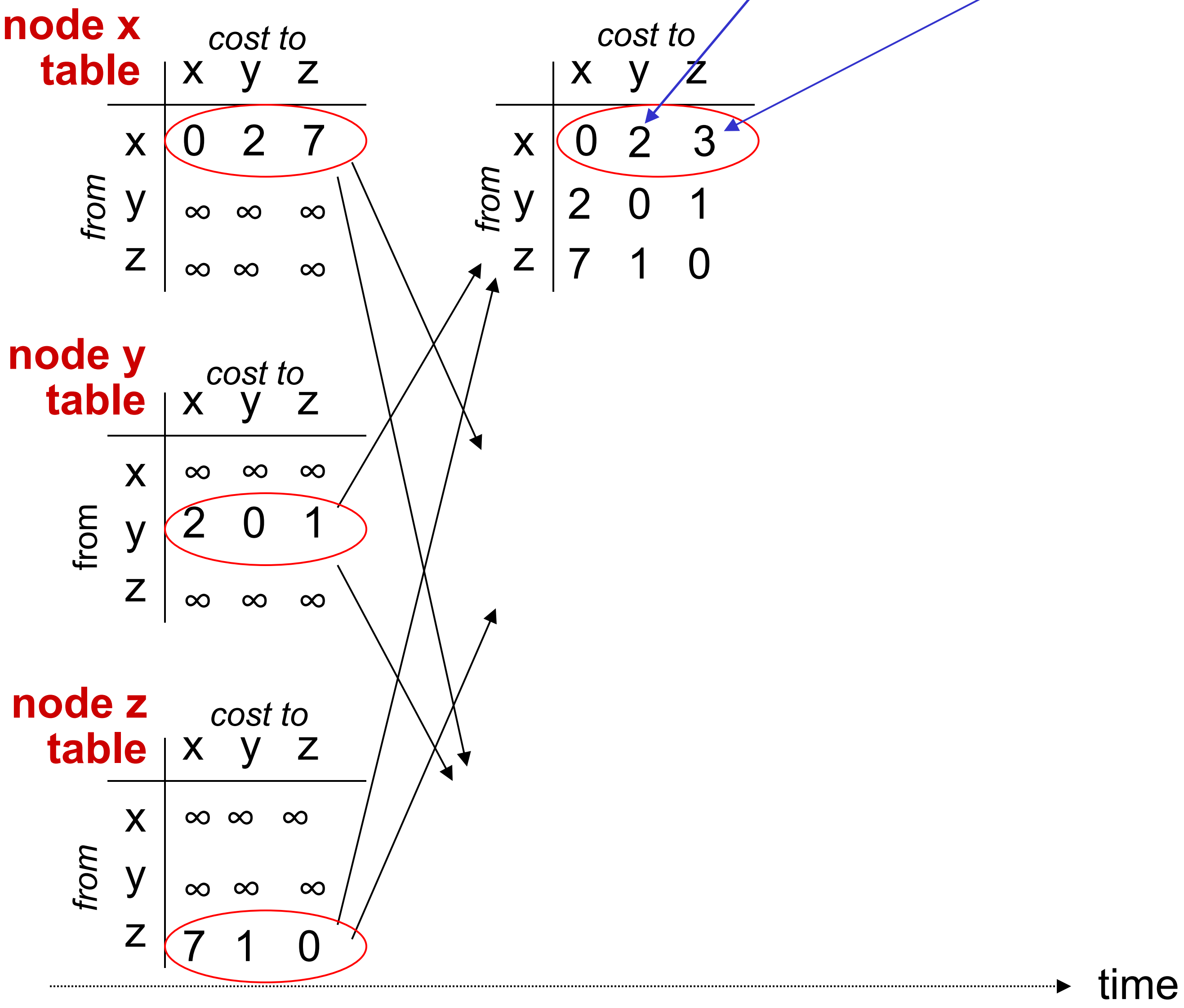


- *wait* for change in local link cost or msg from neighbor
- *recompute* D_x using Bellman-Ford equation
- if $D_x(y)$ changed for any y, *notify* neighbors

- **distributed**, **asynchronous** algorithm
- under minor, natural conditions, the estimate $D_x(y)$ *converge to the actual least cost* $d_x(y)$

$$D_x(y) = \min\{c(x,y) + D_y(y), c(x,z) + D_z(y)\}$$
$$= \min\{2+0, 7+1\} = 2$$

$$D_x(z) = \min\{c(x,y) + D_y(z), c(x,z) + D_z(z)\}$$
$$= \min\{2+1, 7+0\} = 3$$



node x table

from \ cost to	x	y	z
x	0	2	7
y	∞	∞	∞
z	∞	∞	∞

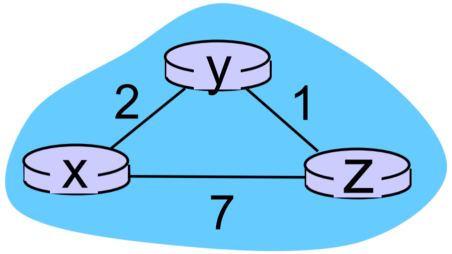
from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	7	1	0

node y table

from \ cost to	x	y	z
x	∞	∞	∞
y	2	0	1
z	∞	∞	∞

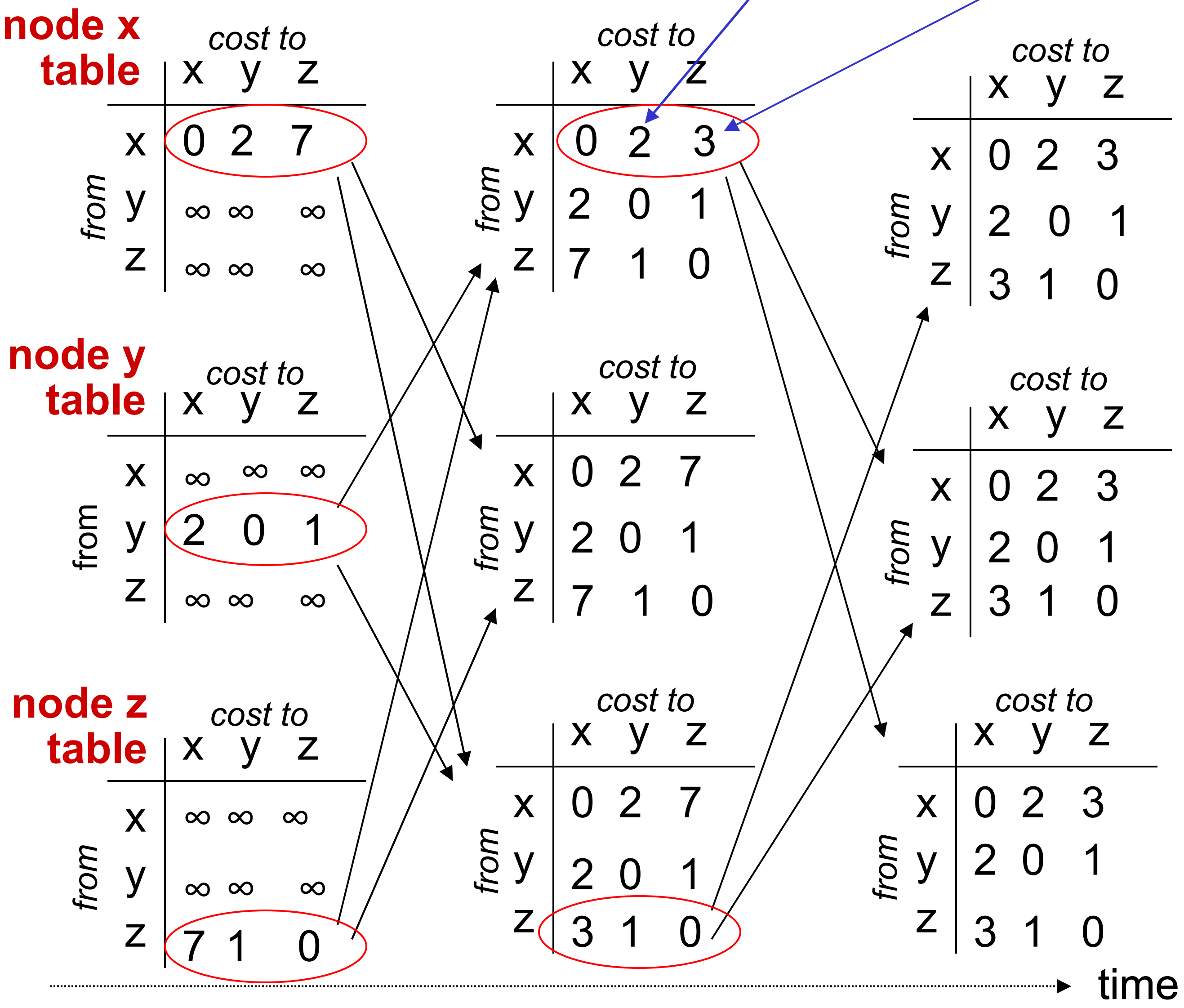
node z table

from \ cost to	x	y	z
x	∞	∞	∞
y	∞	∞	∞
z	7	1	0



$$D_x(y) = \min\{c(x,y) + D_y(y),\ c(x,z) + D_z(y)\}$$
$$= \min\{2+0\ ,\ 7+1\} = 2$$

$$D_x(z) = \min\{c(x,y) + D_y(z),\ c(x,z) + D_z(z)\}$$
$$= \min\{2+1\ ,\ 7+0\} = 3$$



node x table

	cost to		
from	x	y	z
x	0	2	7
y	∞	∞	∞
z	∞	∞	∞

	cost to		
from	x	y	z
x	0	2	3
y	2	0	1
z	7	1	0

	cost to		
from	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

node y table

	cost to		
from	x	y	z
x	∞	∞	∞
y	2	0	1
z	∞	∞	∞

	cost to		
from	x	y	z
x	0	2	7
y	2	0	1
z	7	1	0

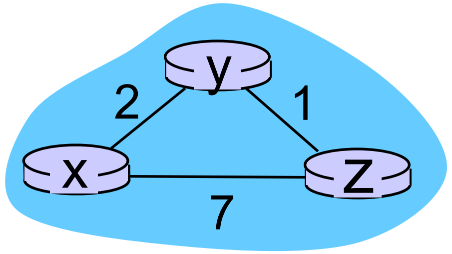
	cost to		
from	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

node z table

	cost to		
from	x	y	z
x	∞	∞	∞
y	∞	∞	∞
z	7	1	0

	cost to		
from	x	y	z
x	0	2	7
y	2	0	1
z	3	1	0

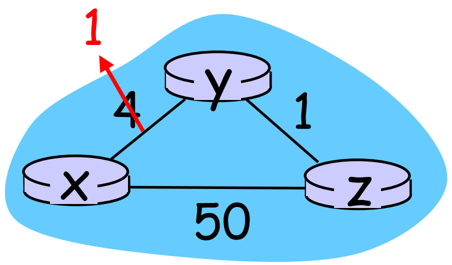
	cost to		
from	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0



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.

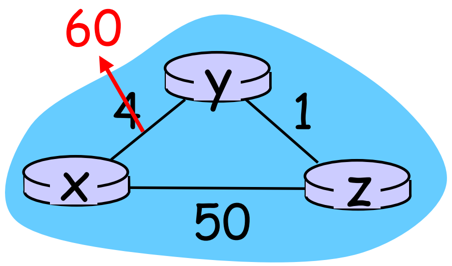
t_1 : *z* receives update from *y*, updates its table, computes new least cost to *x* , sends its neighbors its DV.

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
- may have routing loops during convergence
- *bad news travels slow* - “count-to-infinity” problem!



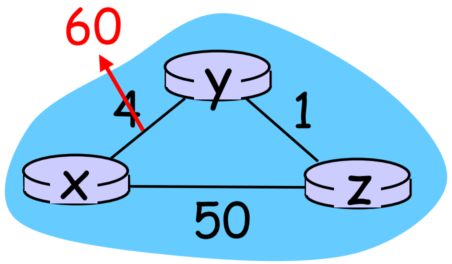
y detect link cost change

t	$D_y(x)$	$D_z(x)$
0	4	5
1	$\min(60+0,1+5)=6$	5
2	6	$\min(50+0,1+6)=7$
3	$\min(60+0,1+7)=8$	7
4	8	$\min(50+0,1+8)=9$
…	…	…
46	50	$\min(50+0,1+50)=50$
47	$\min(60+0,1+50)=51$	50
48	51	$\min(50+0,1+51)=50$

Distance vector: link cost changes

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?



y detect link cost change → 1

t	$D_y(x)$	$D_z(x)$
0	4	5
1	$\min(60+0, 1+\infty) = 60$	5
2	60	$\min(50+0, 1+60) = 50$
3	$\min(60+0, 1+50) = 51$	50
4	51	$\min(50+0, 1+\infty) = 50$

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(n^2) algorithm requires O(nE) msgs
- ***DV:*** convergence time varies
  - may be routing loops
  - count-to-infinity problem

robustness: what happens if router malfunctions?

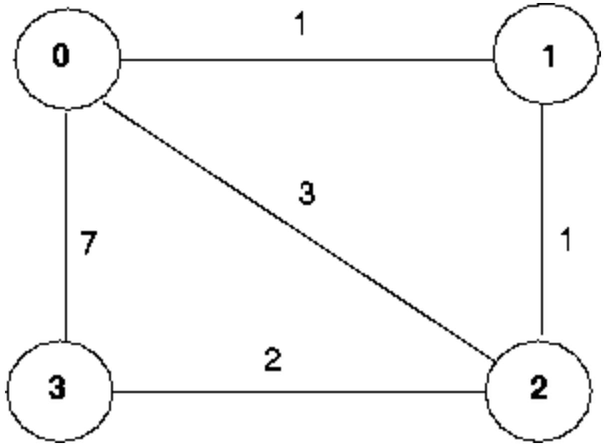
LS:

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

DV:

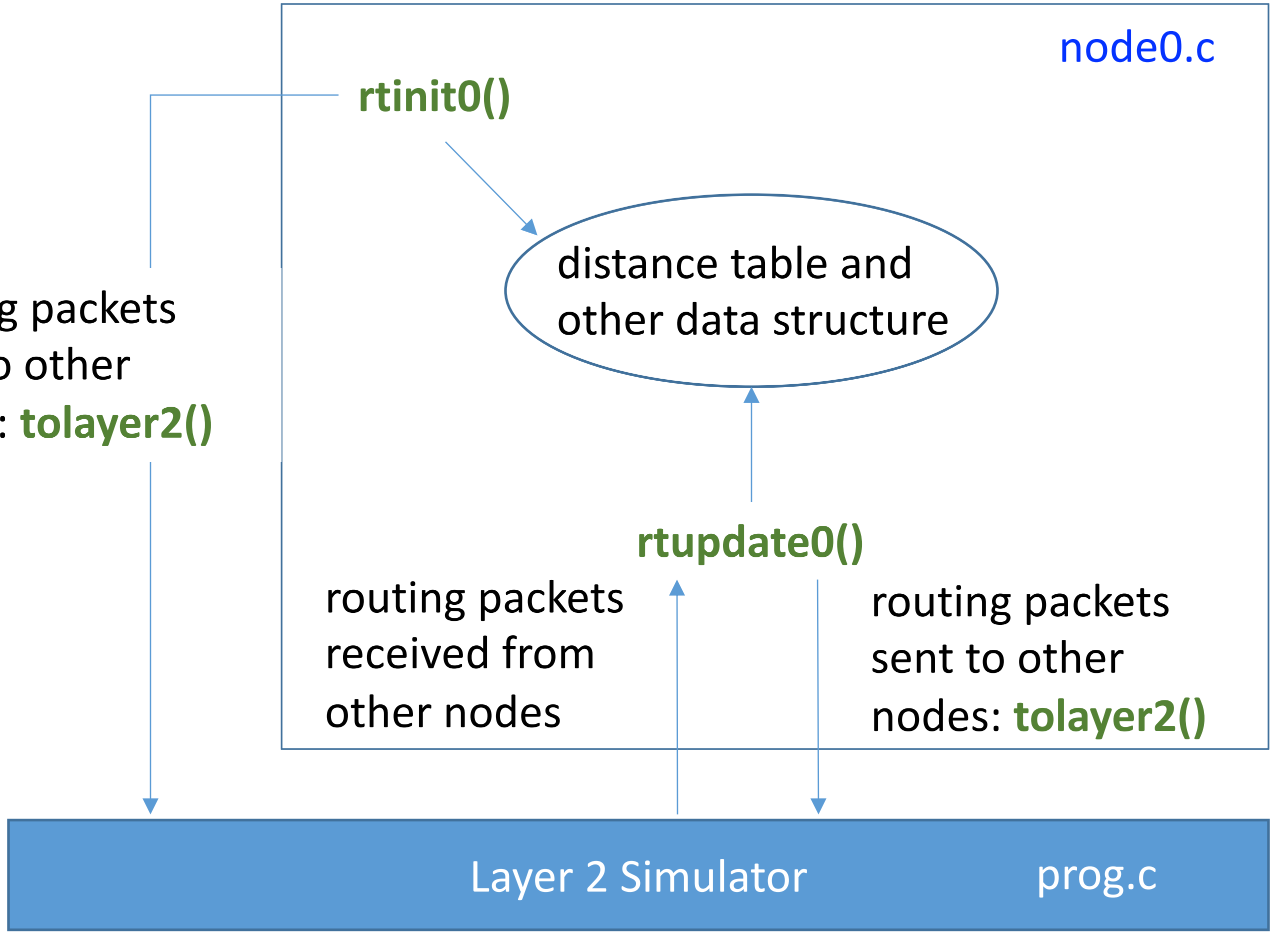
- DV node can advertise incorrect *path* cost
- each node's table used by others
  - error propagate thru network

Lab 2: Distance Vector Routing



distance table at node 0

- **dt.costs[4][4]**: 4-by-4 array of int’s
- **printdt0()**: print distance table



node0.c

rtinit0()

distance table and other data structure

routing packets sent to other nodes: **tolayer2()**

rtupdate0()

routing packets received from other nodes

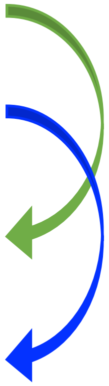
routing packets sent to other nodes: **tolayer2()**

Layer 2 Simulator

prog.c

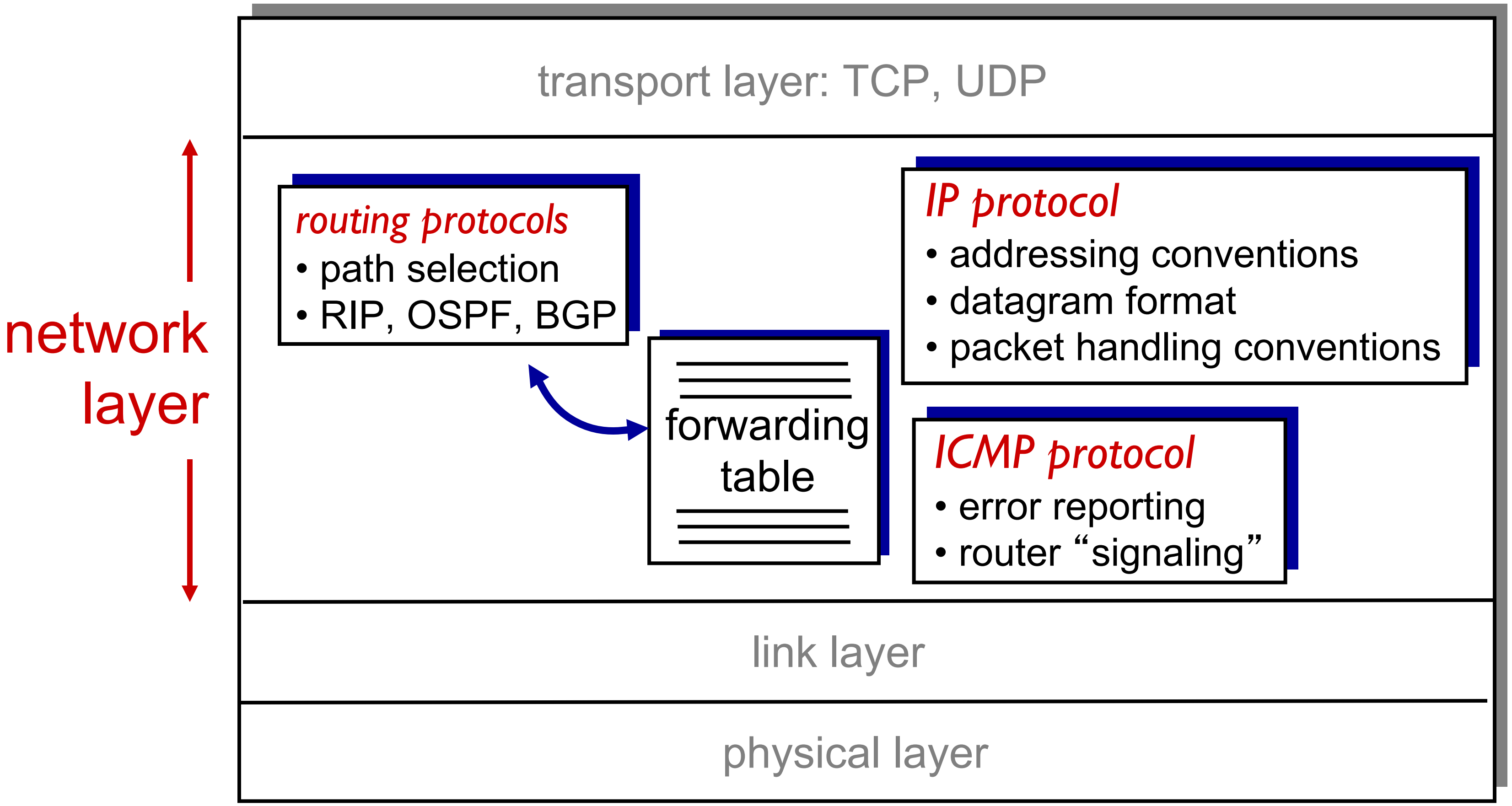
Outline

- Overview of network layer
- Forwarding (data plane)
- Routing (control plane)
- The Internet Protocol (IP): IPv4, DHCP, NAT, IPv6
- Routing in the Internet: OSPF, BGP

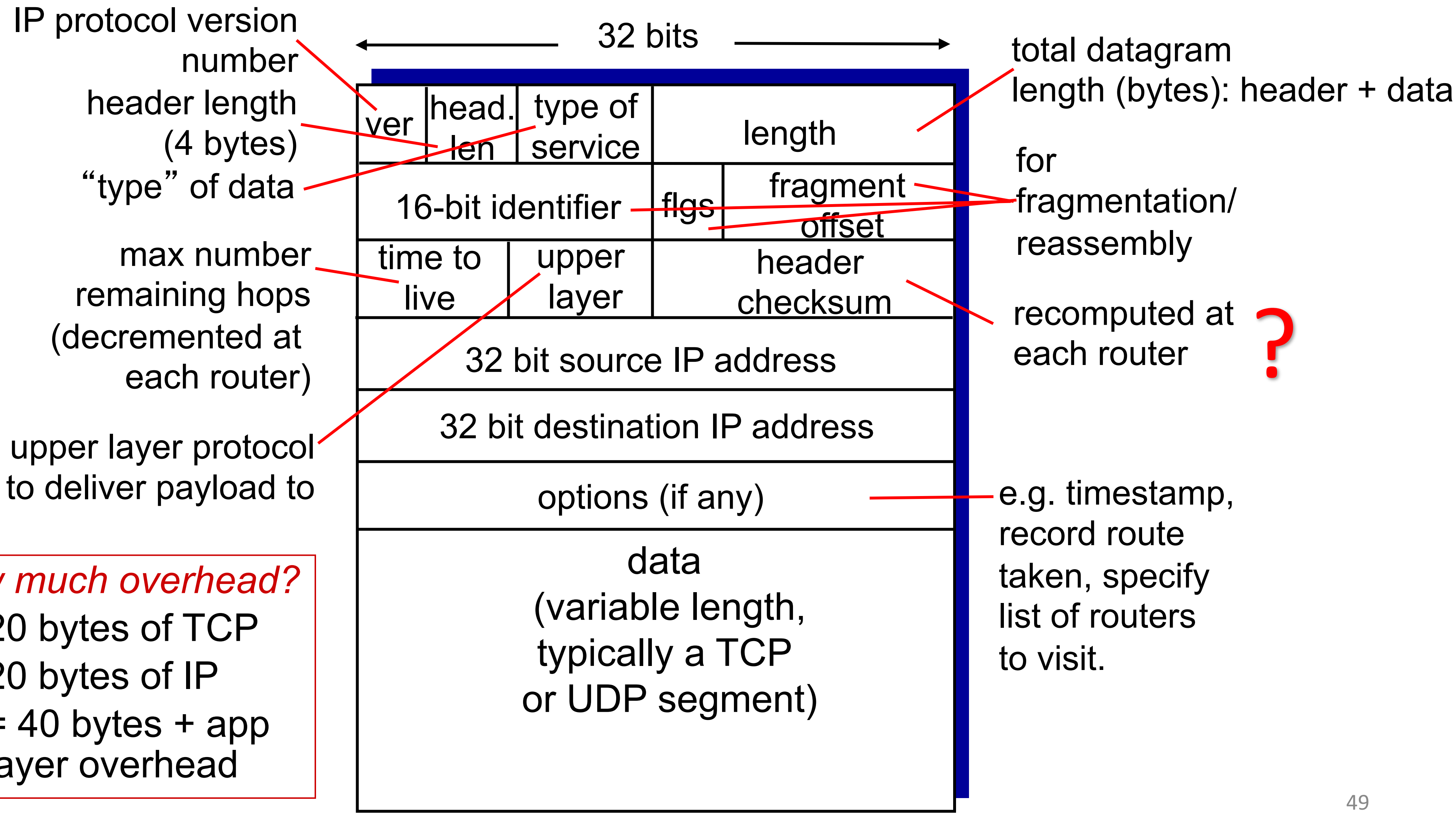


The Internet network layer

host, router network layer functions:



IPv4 datagram format



IP protocol version number

header length (4 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): header + data

for fragmentation/ reassembly

recomputed at each router ?

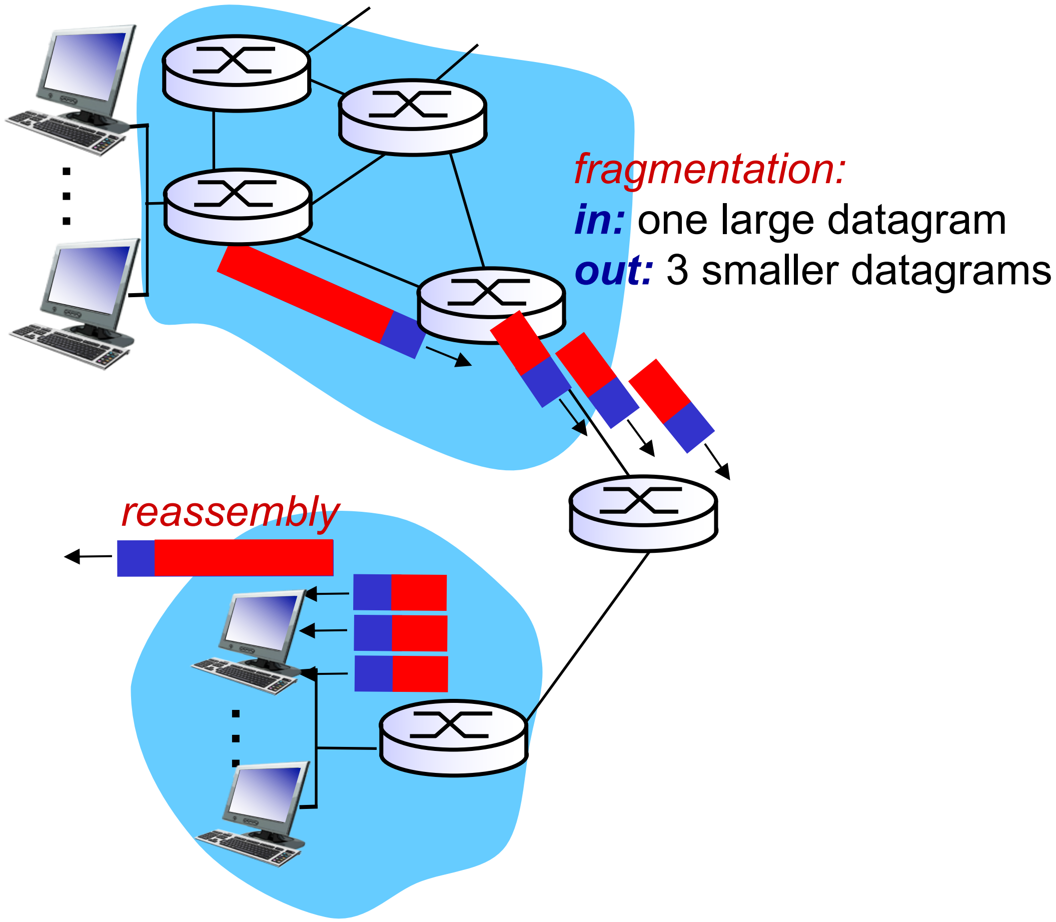
e.g. timestamp, record route taken, specify list of routers to visit.

how much overhead?

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

IP fragmentation, reassembly

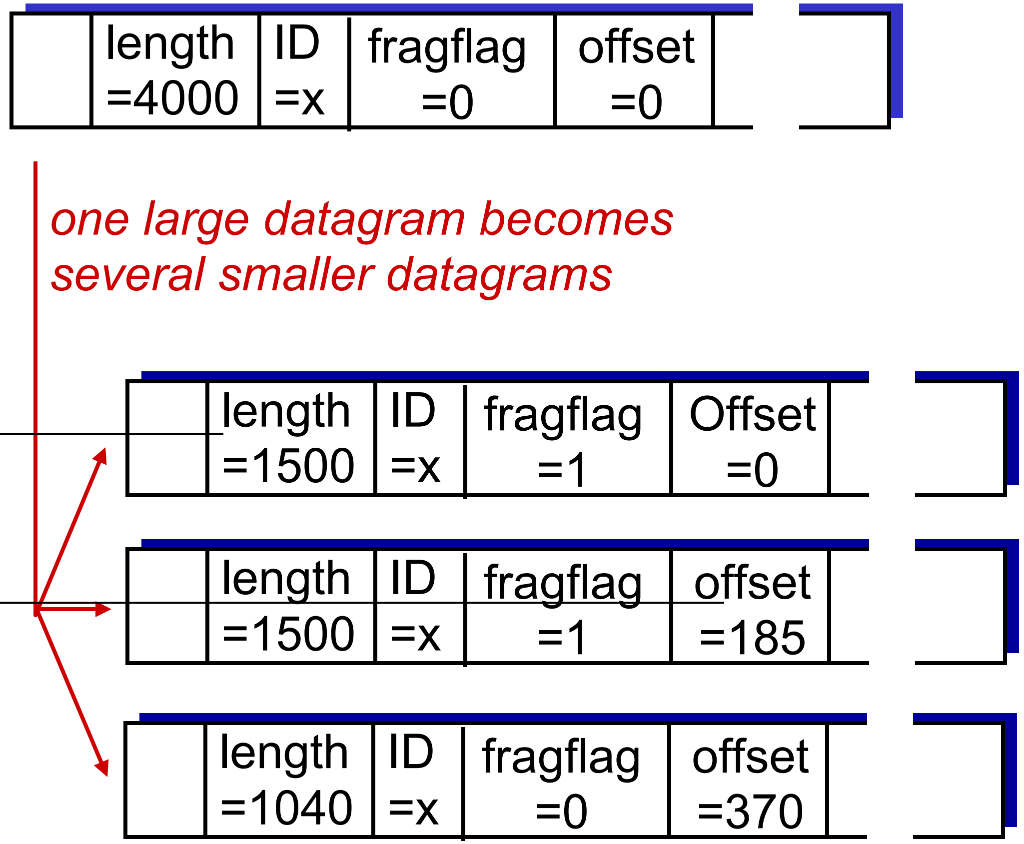
- network links have MTU (maximum transmission unit) - largest possible link-level frame
  - different link types, different MTUs
- large IP datagram divided ("fragmented") within net
  - one datagram becomes several datagrams
  - "reassembled" only at final destination
  - IP header bits used to identify, order related fragments



IP fragmentation, reassembly

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

length =1500 | ID =x | fragflag =1 | Offset =0

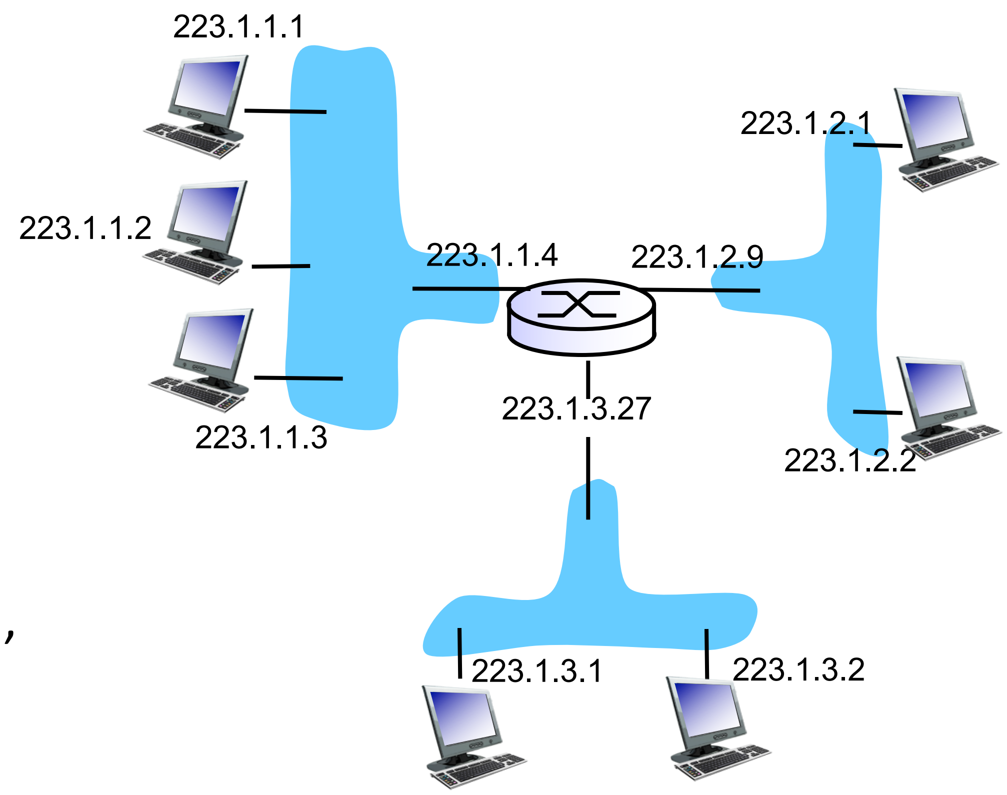
offset = 1480/8

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

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

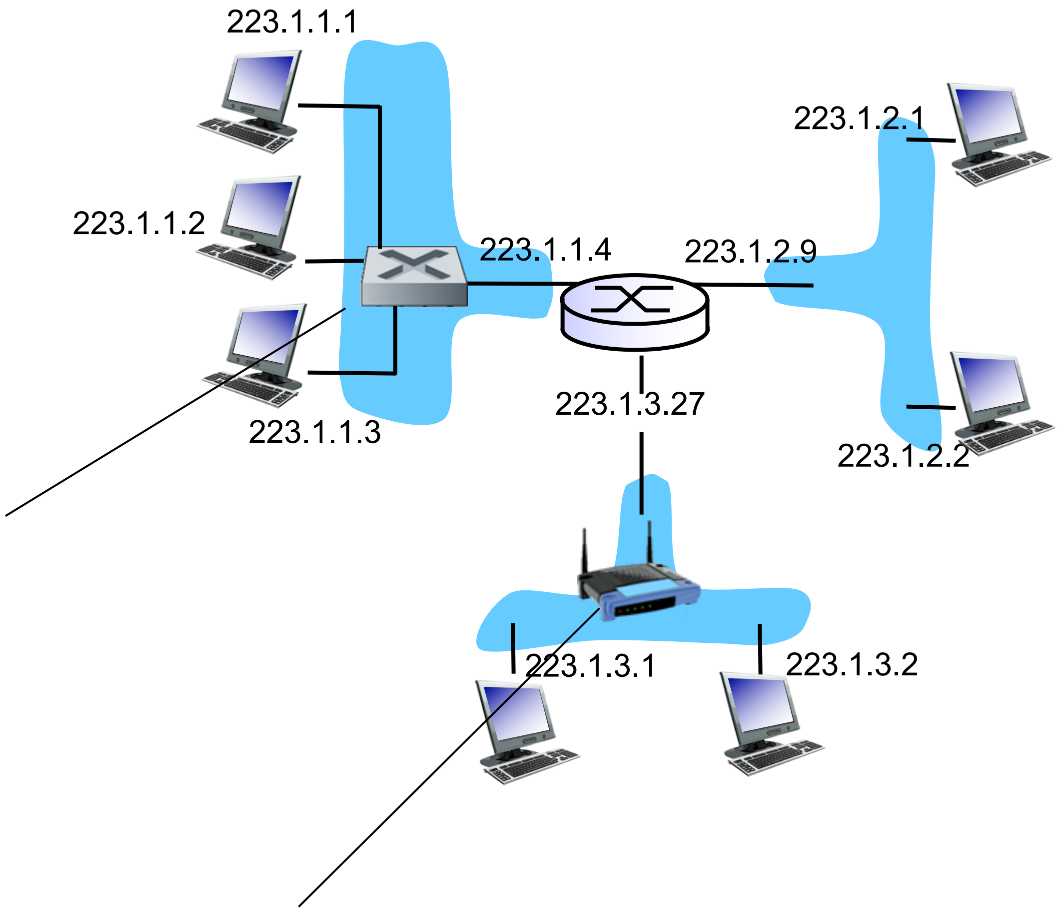
IP addressing: introduction

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



$$223.1.1.1 = \underbrace{11011111}_{223}\ \underbrace{00000001}_{1}\ \underbrace{00000001}_{1}\ \underbrace{00000001}_{1}$$

IP addressing: introduction

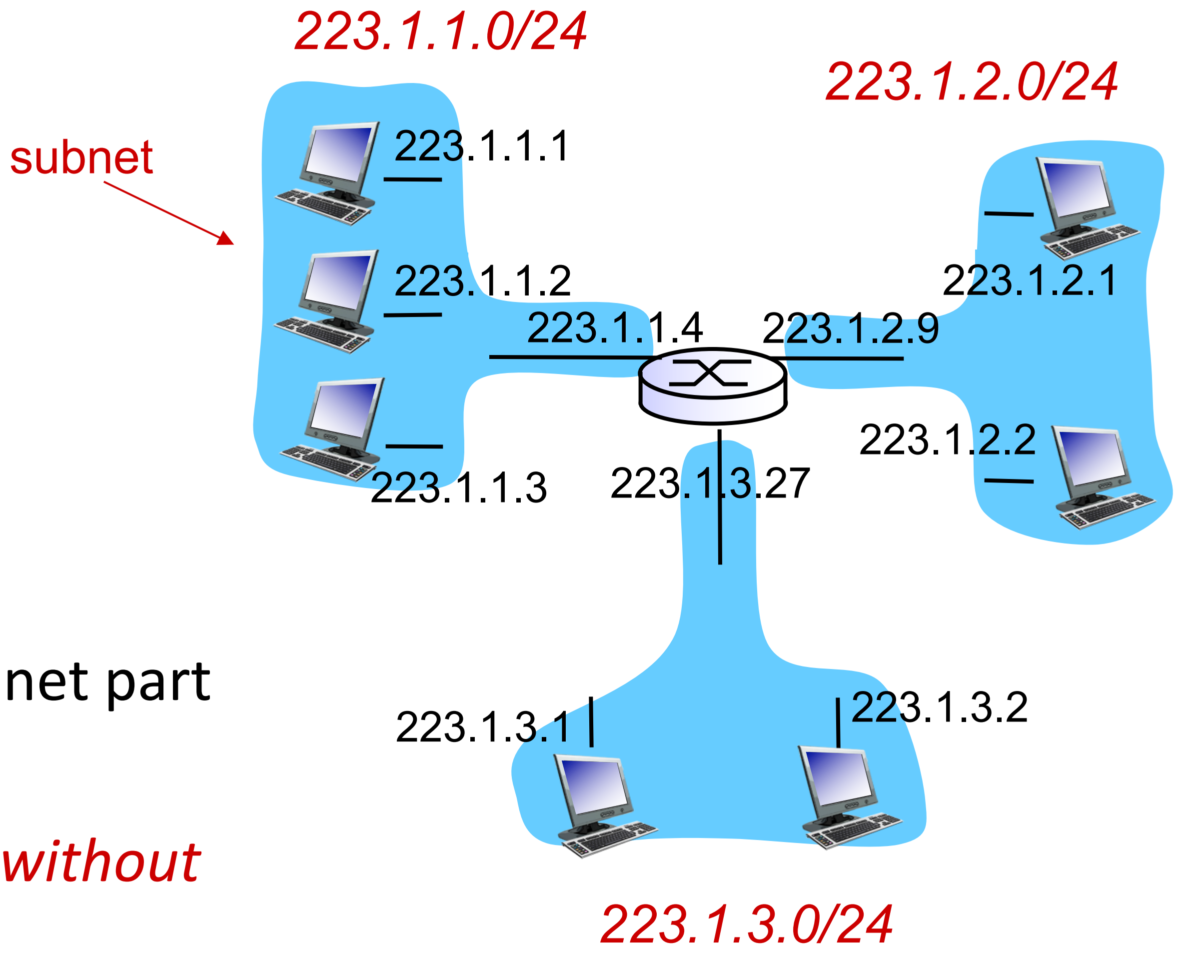


wired Ethernet interfaces connected by Ethernet switches

wireless WiFi interfaces connected by WiFi base station

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*

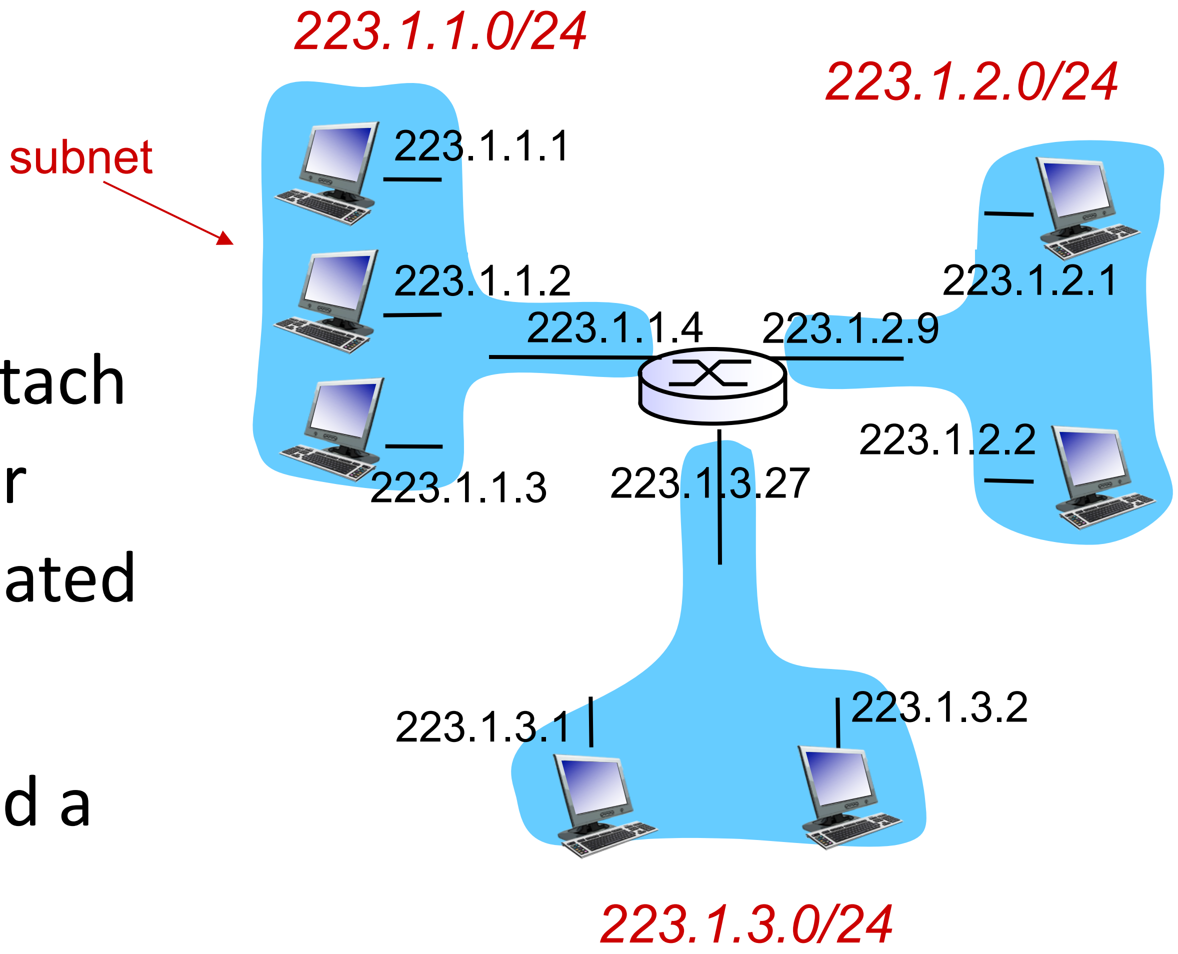


subnet mask: /24

Subnets

recipe

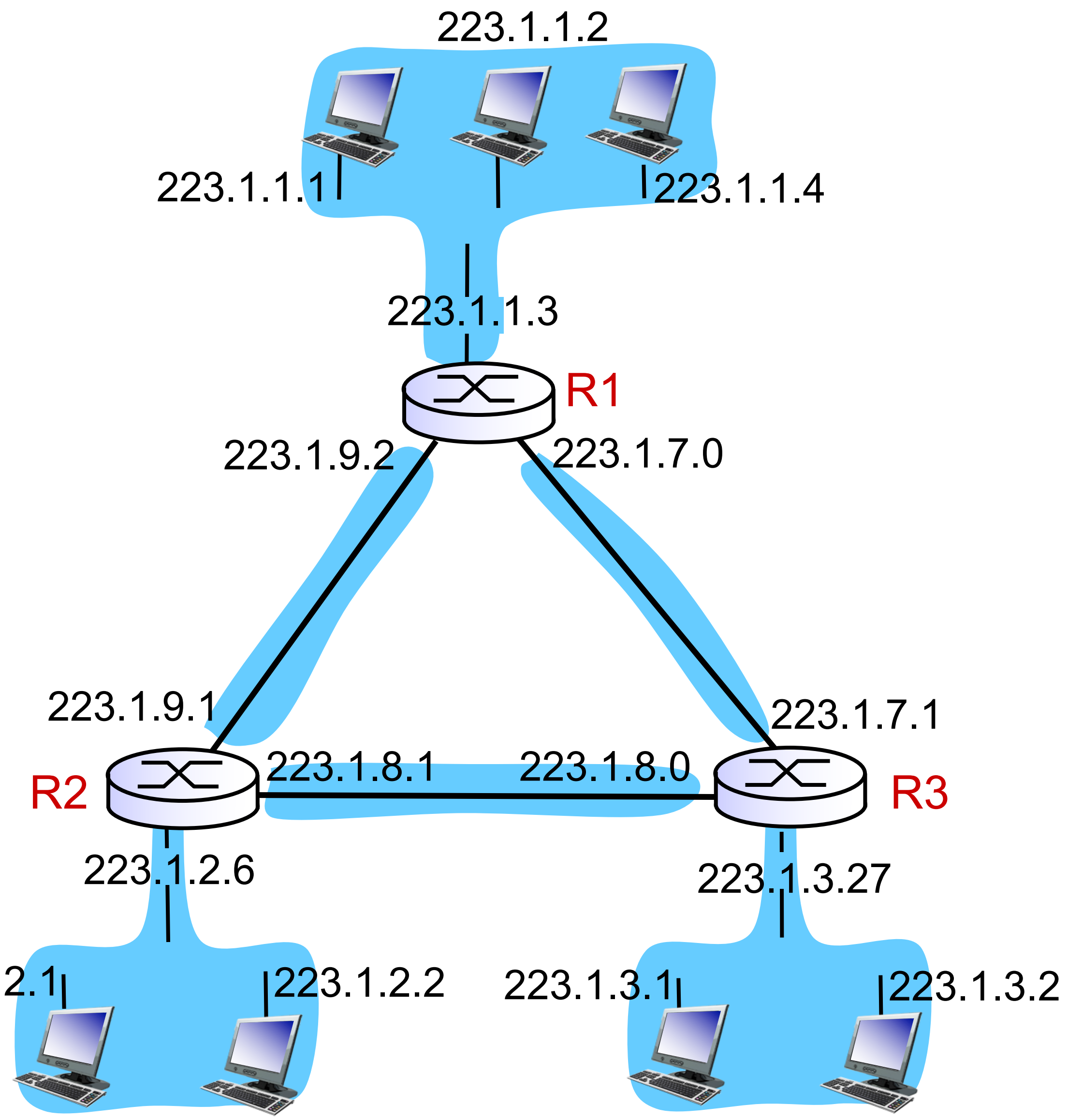
- to determine the subnets, detach each interface from its host or router, creating islands of isolated networks
- each isolated network is called a *subnet*



subnet mask: /24

Subnets

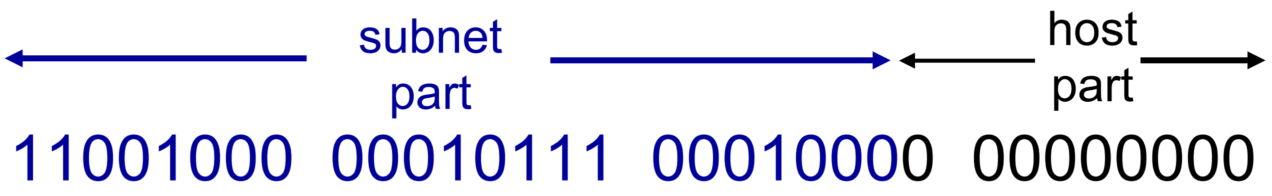
how many subnets?



IP addressing: CIDR

CIDR: Classless InterDomain Routing

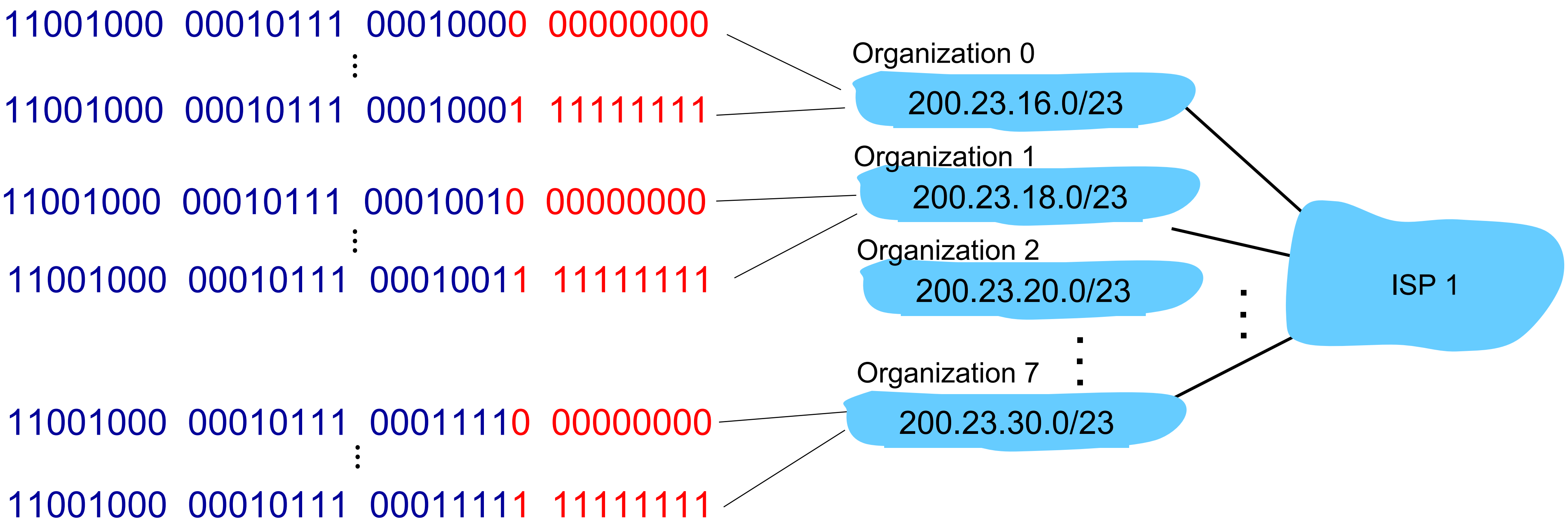
- subnet portion of address of arbitrary length
- address format: a.b.c.d/x, where x is # bits in subnet portion of address



200.23.16.0/23

Hierarchical addressing: route aggregation

hierarchical addressing allows efficient advertisement of routing information:



11001000 00010111 00010000 00000000
⋮
11001000 00010111 00010001 11111111

11001000 00010111 00010010 00000000
⋮
11001000 00010111 00010011 11111111

11001000 00010111 00011110 00000000
⋮
11001000 00010111 00011111 11111111

Organization 0
200.23.16.0/23

Organization 1
200.23.18.0/23

Organization 2
200.23.20.0/23

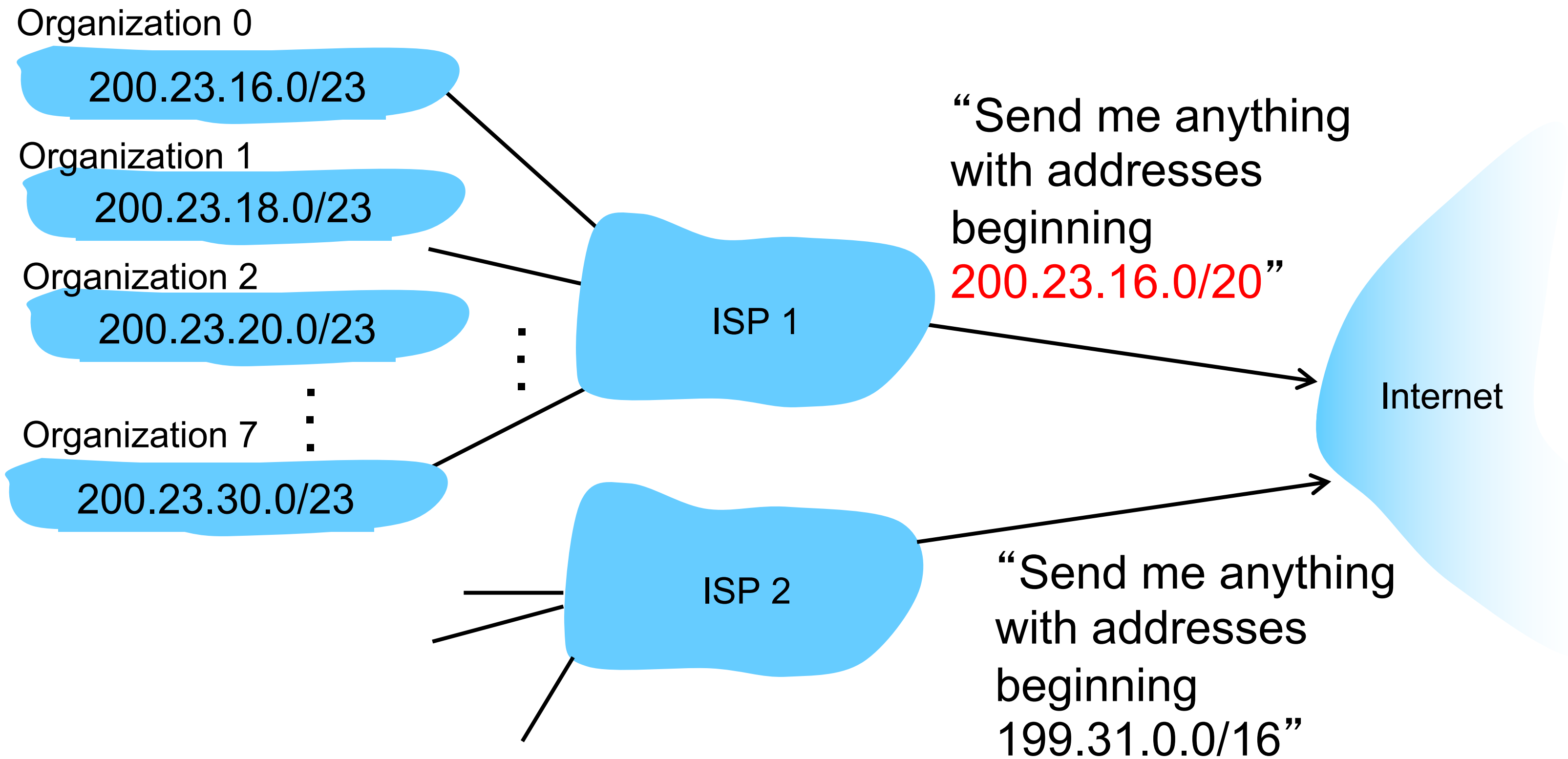
Organization 7
200.23.30.0/23

ISP 1

200.23.16.0/20

Hierarchical addressing: route aggregation

hierarchical addressing allows efficient advertisement of routing information:

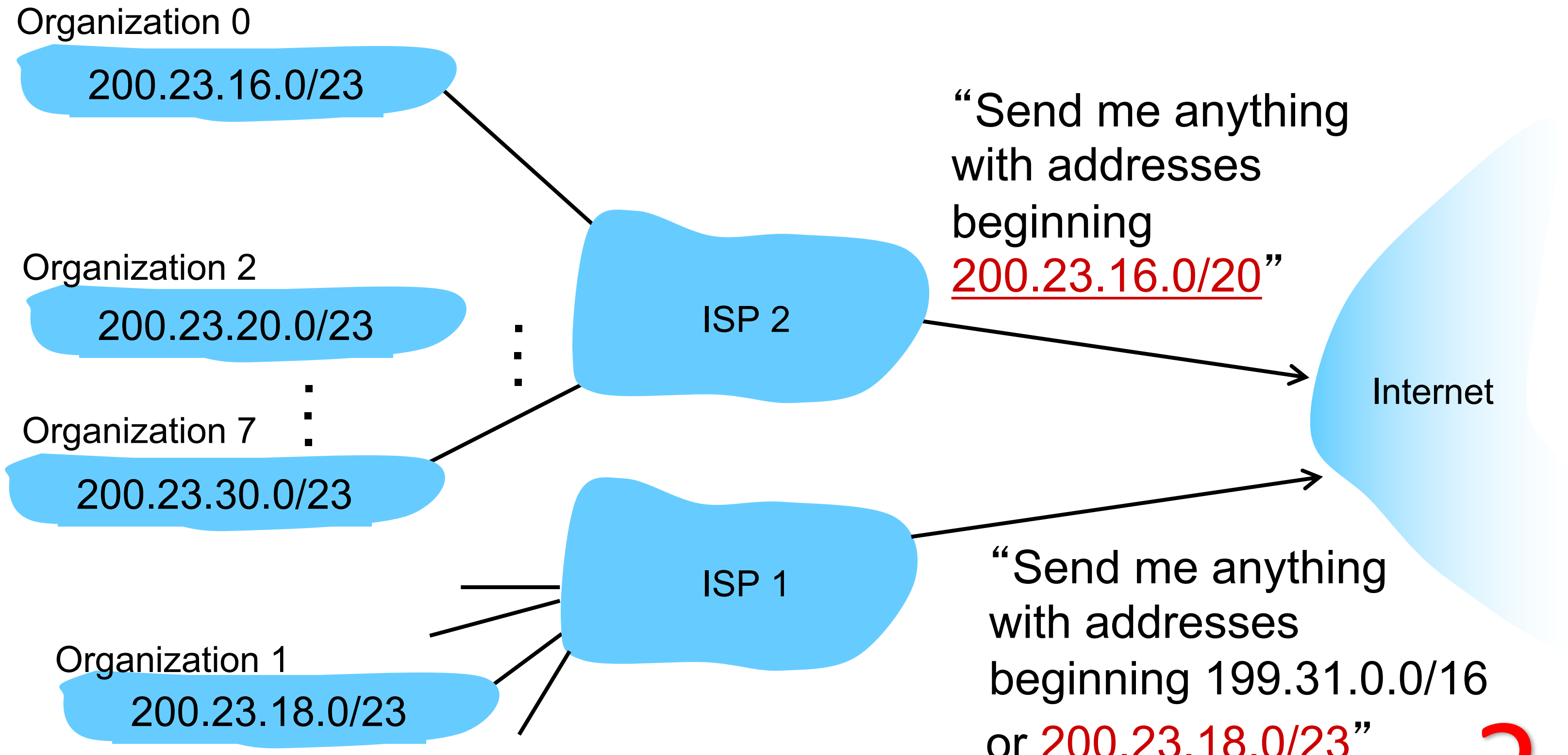


"Send me anything with addresses beginning 200.23.16.0/20"

"Send me anything with addresses beginning 199.31.0.0/16"

Hierarchical addressing: route aggregation

ISP 2 has a more specific route to Organization 1



"Send me anything with addresses beginning 200.23.16.0/20"

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

? Longest prefix matching

IP addresses: how to get one?

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

Q: how does an ISP get block of addresses?

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

IP addresses: how to get one?

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

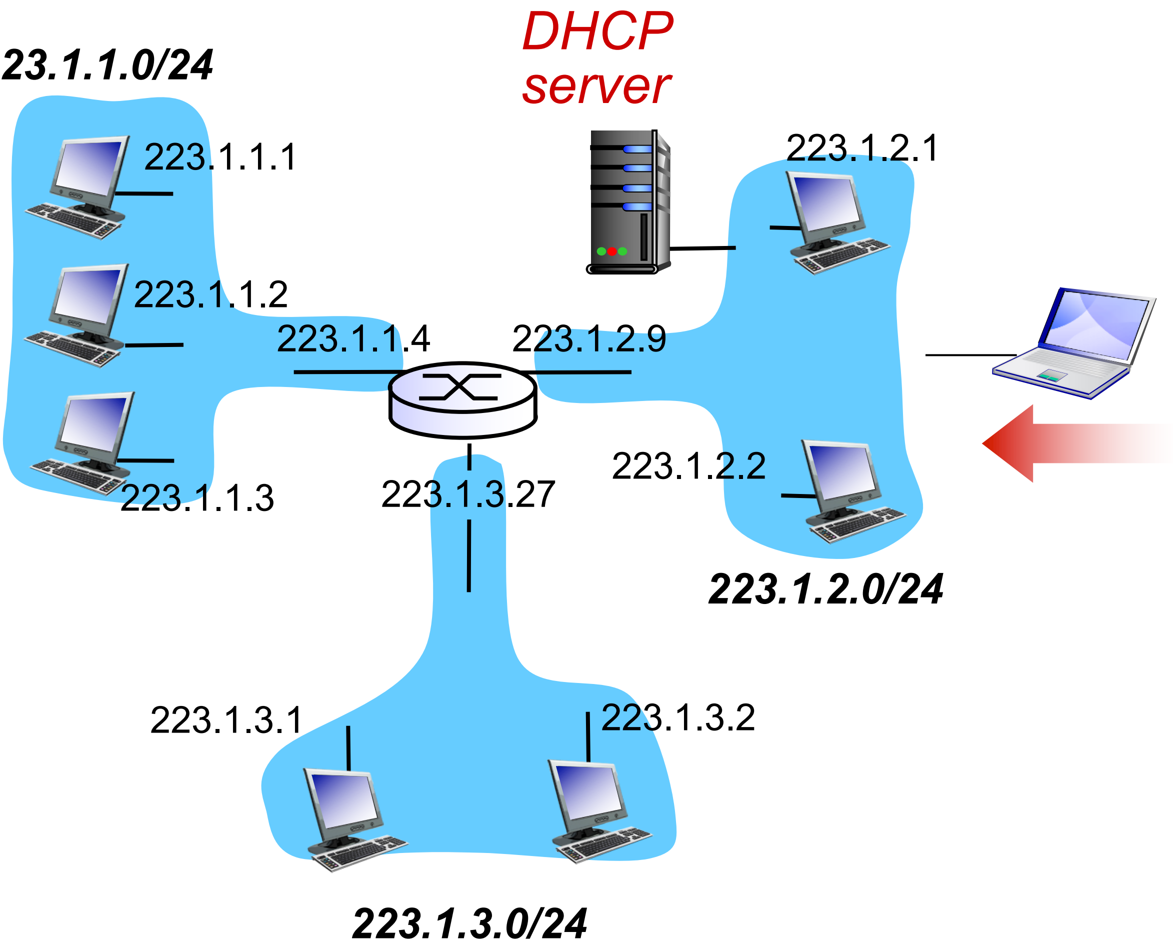
- hard-coded by system admin in a file
  - Windows: control-panel->network->configuration->tcp/ip->properties
  - UNIX: /etc/rc.config
- DHCP: Dynamic Host Configuration Protocol: dynamically get address from a server
  - “plug-and-play”

DHCP: Dynamic Host Configuration Protocol

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

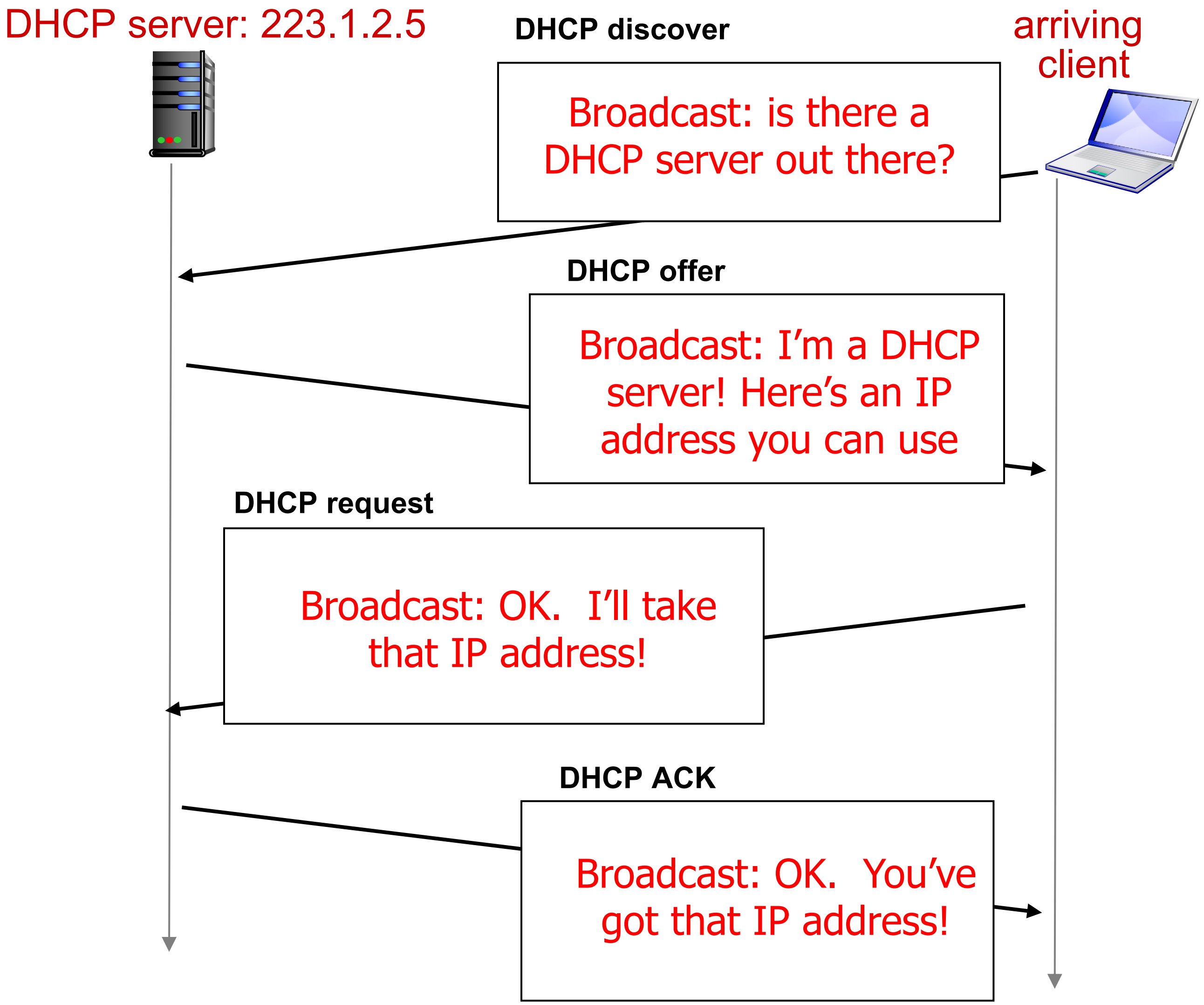
- can renew its lease on address in use
- allows reuse of addresses (only hold address while connected/“on”)
- support for mobile users who want to join network (more shortly)

DHCP client-server scenario



arriving DHCP client needs address in this network

DHCP client-server scenario



- DHCP messages exchanged through UDP
- 255.255.255.255 - IP broadcast address: message delivered to all hosts on the same subnet

DHCP: Dynamic Host Configuration Protocol

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

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

NAT: network address translation

- IPv4 has ~4.3 billion IP addresses, but we have
  - ~7.6 billion people in 2018, each with multiple devices
  - ~30 billion Internet of Things (IoT) devices in 2020

- *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
  - devices inside local net not explicitly addressable, visible by outside world (a security plus)

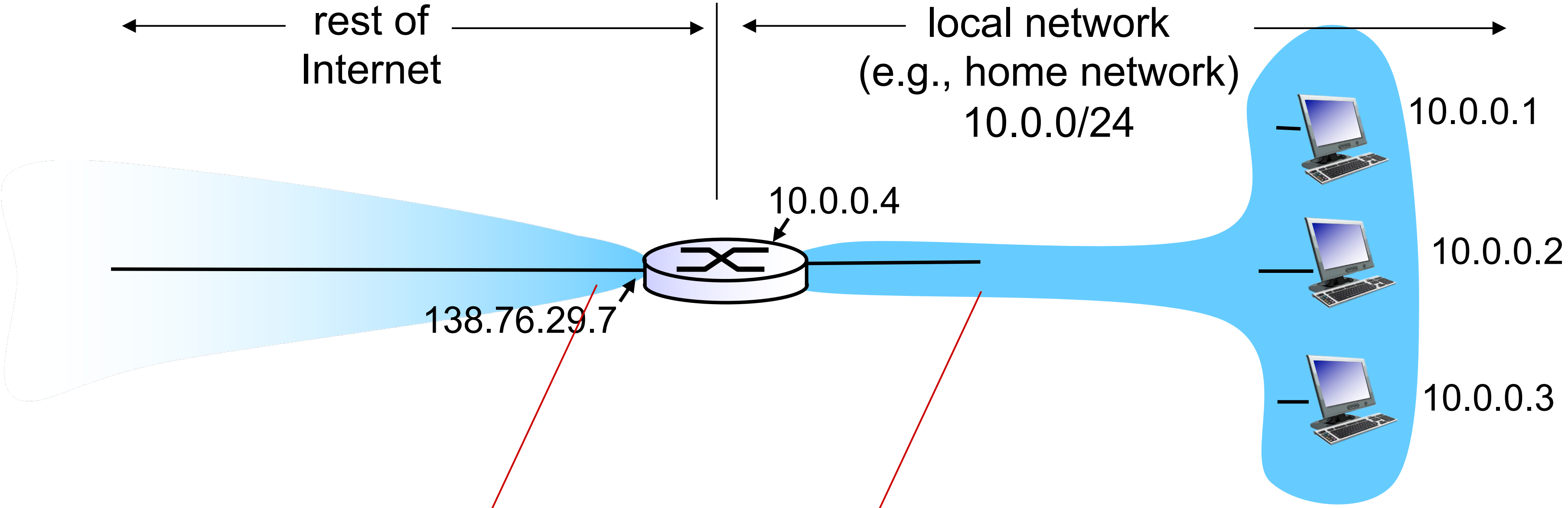
NAT: network address translation

Private IP addresses:

10.x.x.x

192.168.x.x

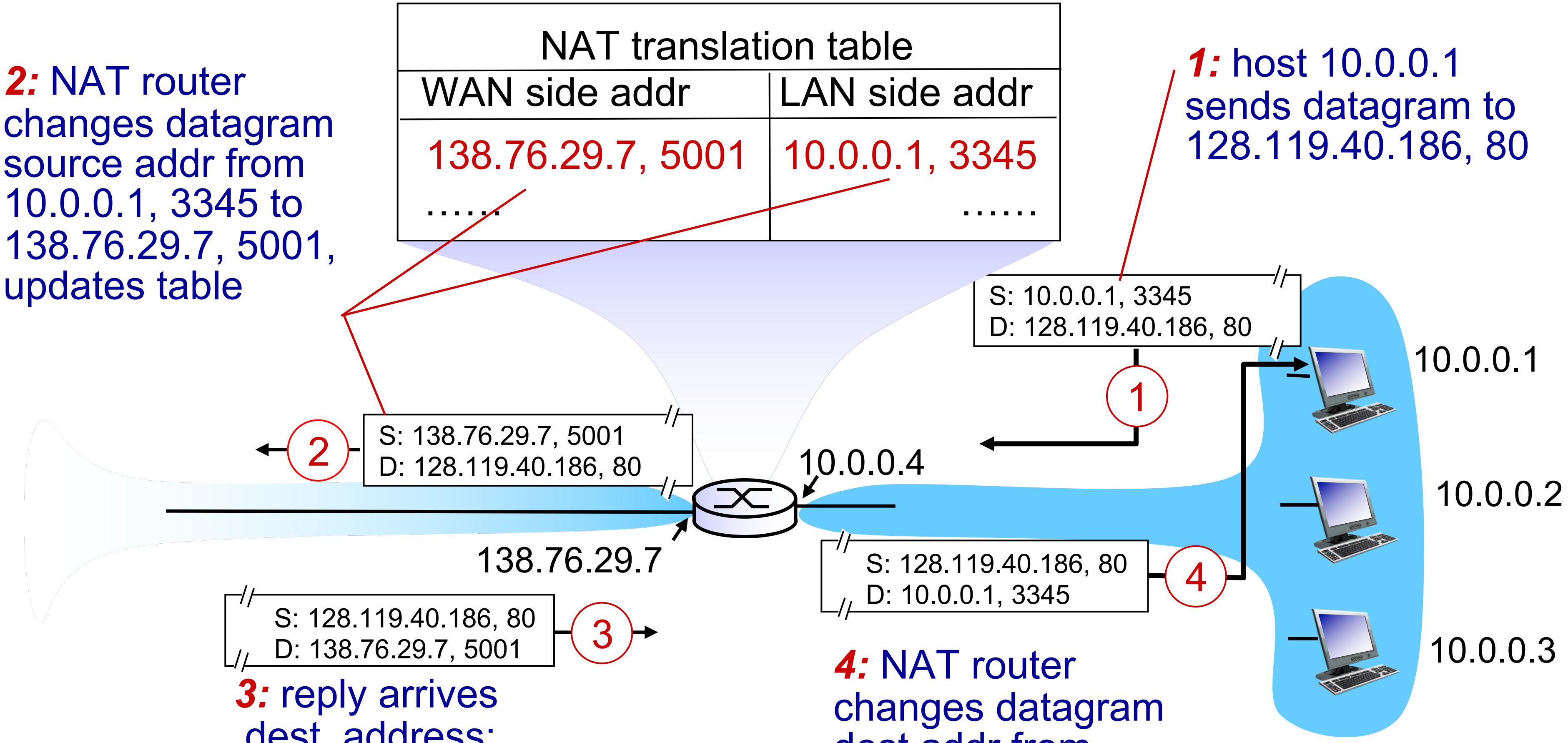
172.16.0.0 – 172.31.255.255



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



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

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

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
  - address shortage should be solved by IPv6
  - NAT traversal: what if client wants to connect to server behind NAT?

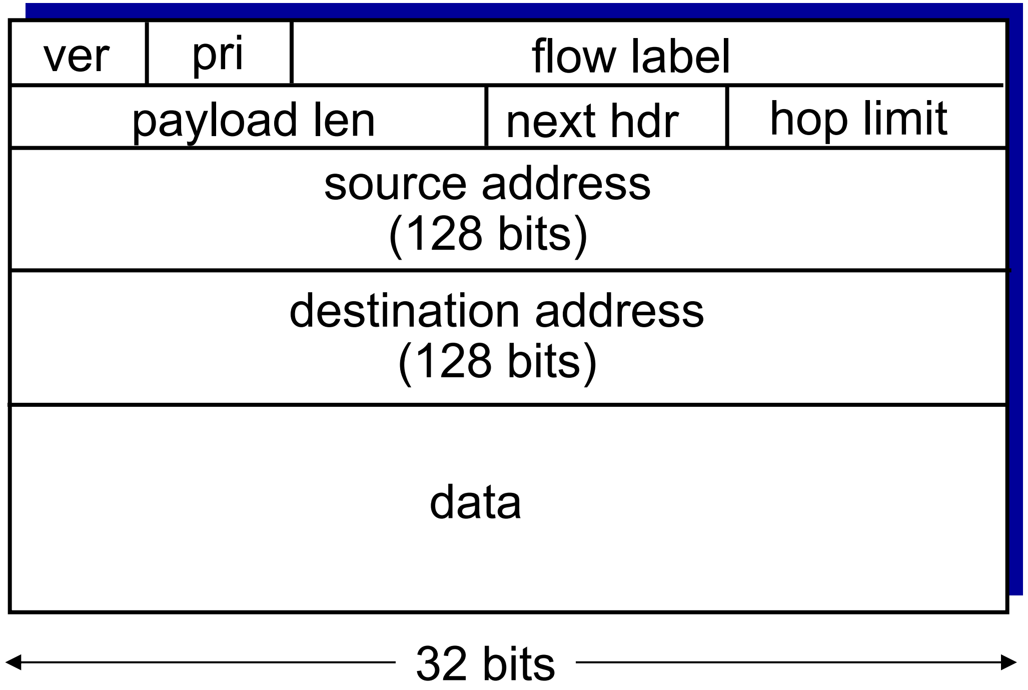
IPv6: motivation

- *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

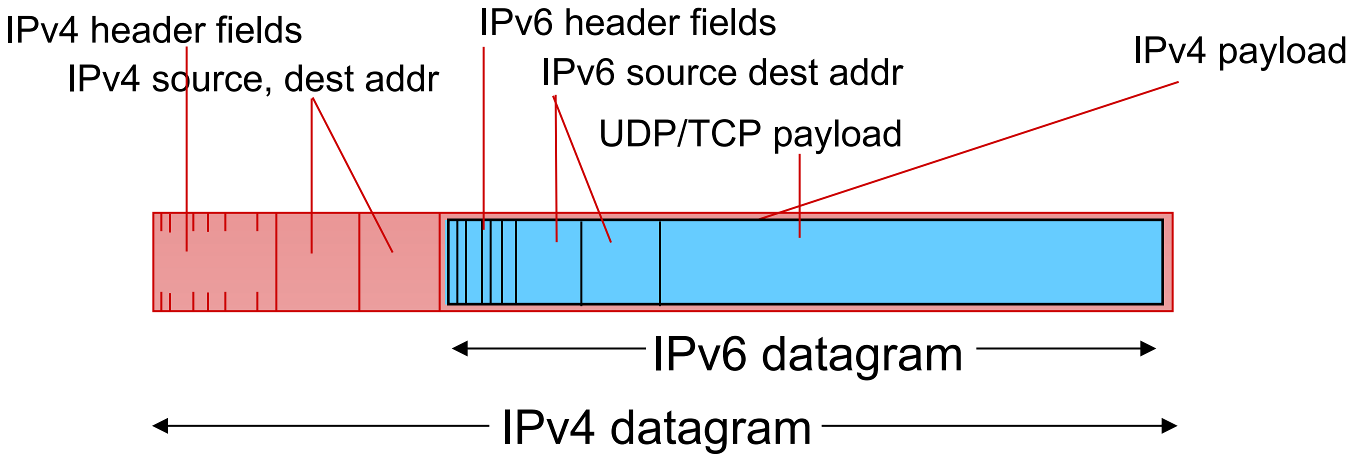


Fragmentation/reassembly: handled by source and destination

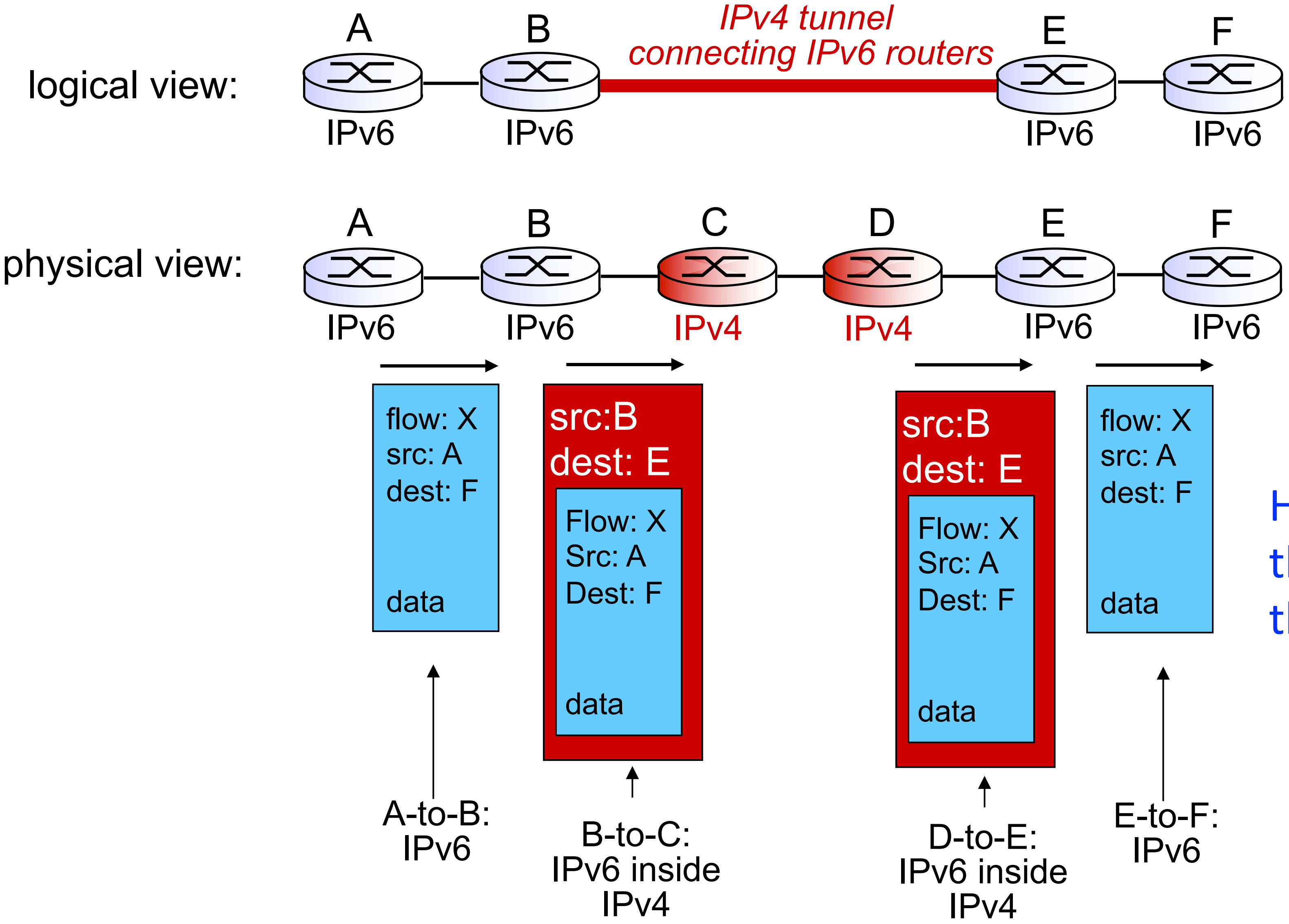
- *Priority (traffic class):* identify priority among datagrams in flow
- *flow Label:* identify datagrams in same "flow"
- *next header:* identify upper layer protocol for data
- *header checksum*: removed entirely to reduce processing time at each hop
- *options:* allowed, but outside of header, indicated by "Next Header" field

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



How does E recognize the IPv6 payload inside the IPv4 packet?

Outline

- Overview of network layer
- Forwarding (data plane)
- Routing (control plane)
- The Internet Protocol (IP)
- Routing in the Internet: OSPF, BGP

Making routing scalable

our routing study thus far - idealized

- all routers identical
- network "flat"

… *not* true in practice

scale: with billions of destinations:

- can't store all destinations 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

Internet approach to scalable routing

aggregate routers into regions known as "autonomous systems" (AS) (a.k.a. "domains")

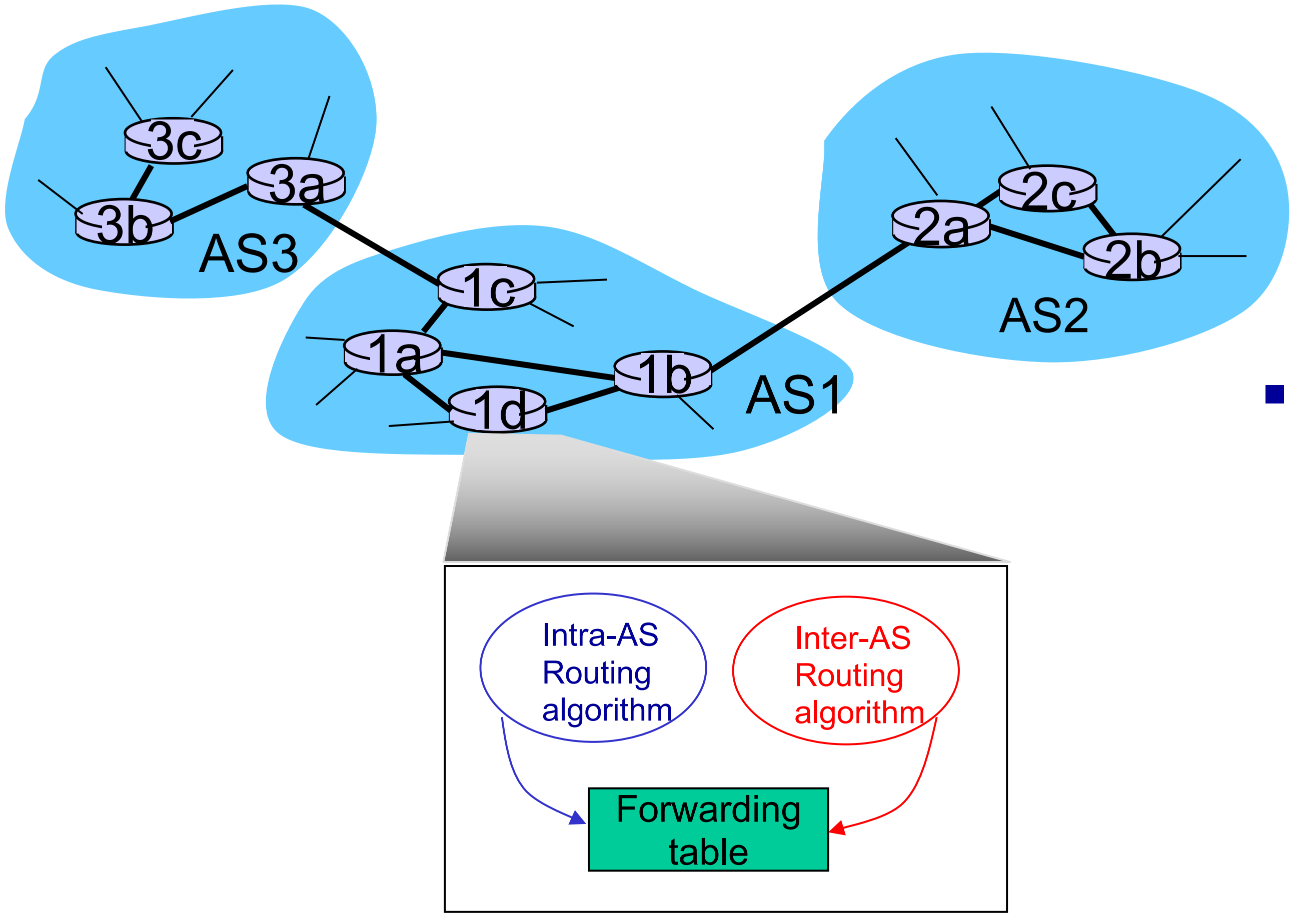
intra-AS routing

- routing among hosts, routers in same AS ("network")
- all routers in AS must run *same* intra-domain protocol
- routers in *different* AS can run *different* intra-domain routing protocol

inter-AS routing

- routing among AS'es
- gateway router: at "edge" of its own AS, has link(s) to router(s) in other AS'es
- gateways perform inter-domain routing (as well as intra-domain routing)

Interconnected ASes



- forwarding table configured by both intra- and inter-AS routing algorithm
  - intra-AS routing determine entries for destinations within AS
  - inter-AS & intra-AS determine entries for external destinations

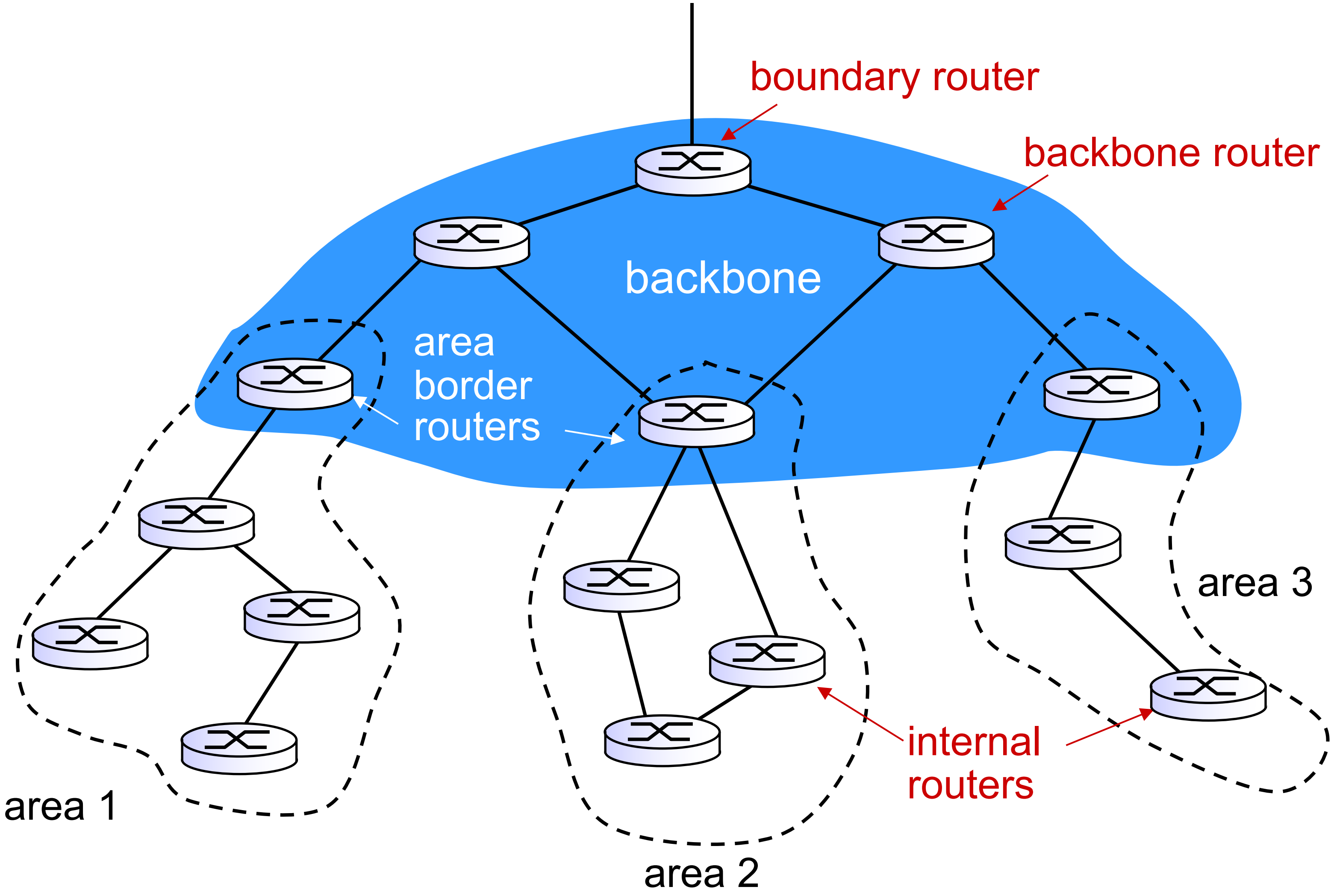
Intra-AS Routing

- also known as *interior gateway protocols (IGP)*
- most common intra-AS routing protocols:
  - RIP: Routing Information Protocol (distance vector)
  - OSPF: Open Shortest Path First (link state)
  - IGRP: Interior Gateway Routing Protocol (distance vector; Cisco proprietary for decades, until 2016)

OSPF (Open Shortest Path First)

- “open”: publicly available
- uses link-state algorithm
  - link state packet dissemination
  - topology map at each node
  - route computation using Dijkstra’s algorithm
- router floods OSPF link-state advertisements to all other routers in *entire* AS
  - carried in OSPF messages directly over IP (rather than TCP or UDP)
- “advanced” features: *security, multiple same-cost paths*, etc.

Hierarchical OSPF



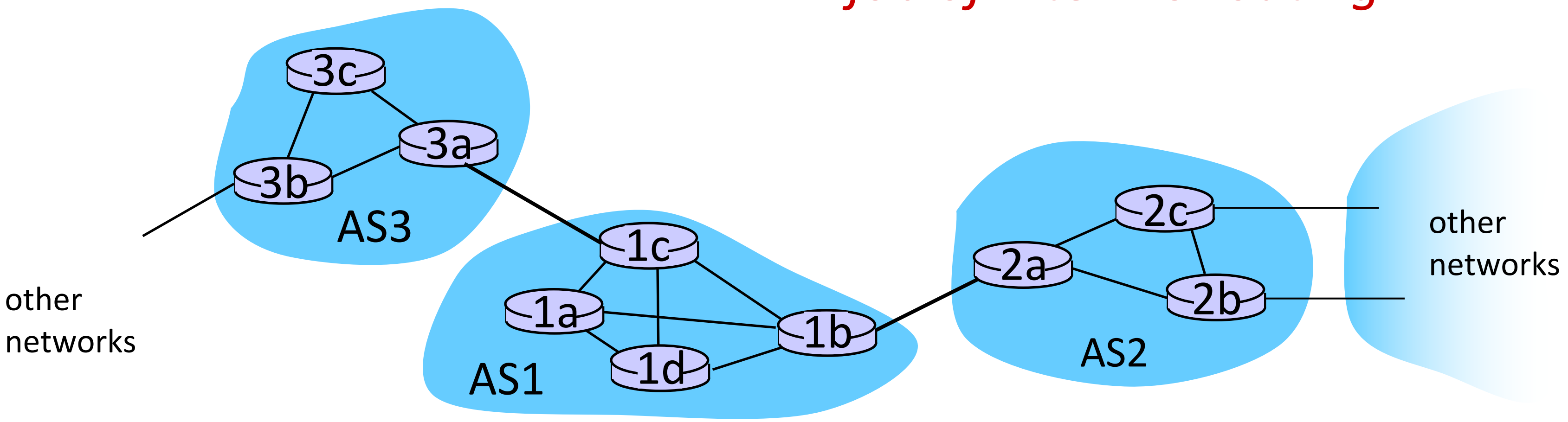
Inter-AS tasks

- 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!

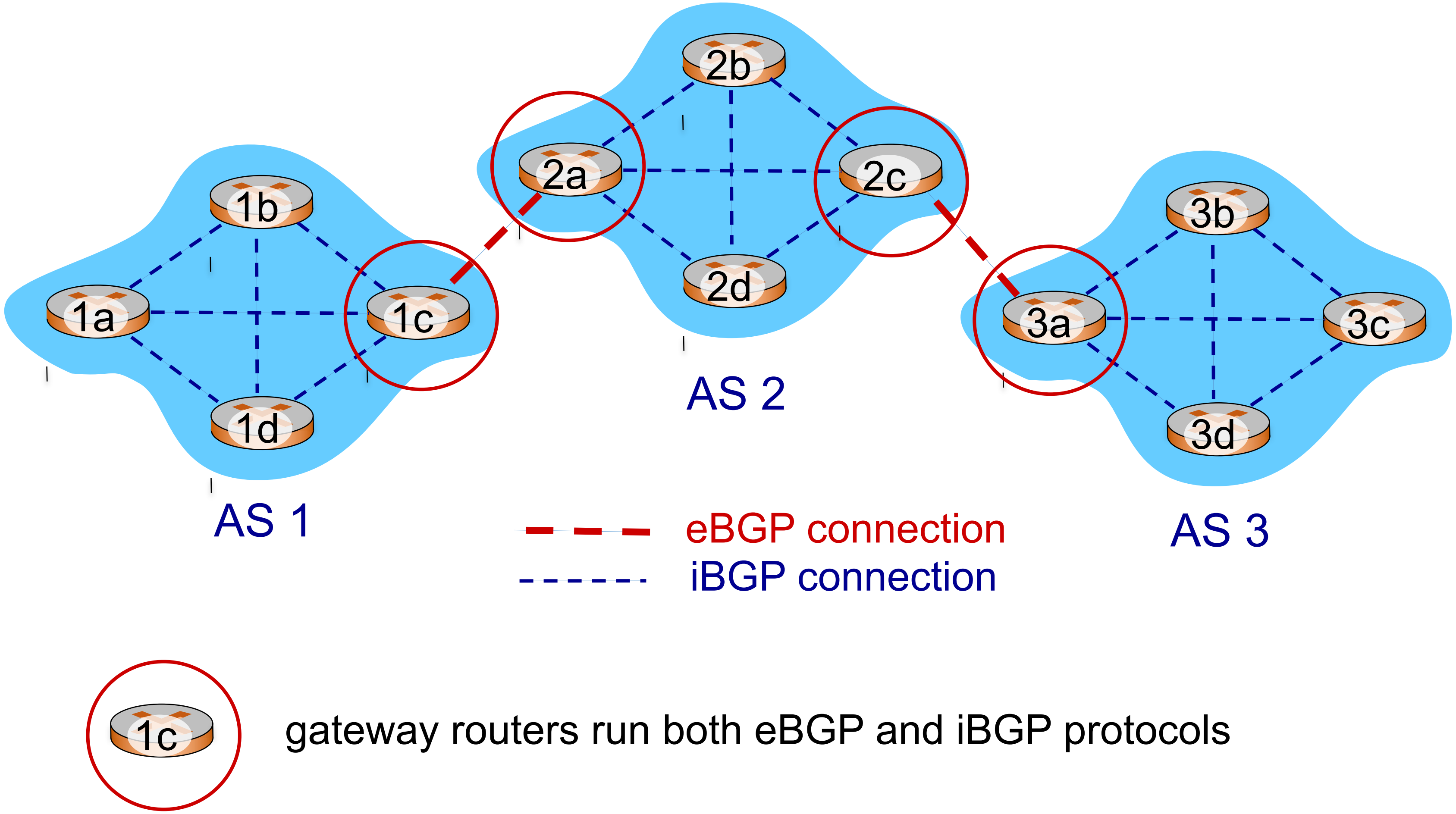


Internet inter-AS routing: BGP

- BGP (Border Gateway Protocol): *the* de facto inter-domain routing protocol
  - "glue that holds the Internet together"
- BGP provides each AS a means to:
  - allows subnet to advertise its existence to rest of Internet: *"I am here"*
  - obtain subnet reachability information from neighboring ASes
  - propagate reachability information to all AS-internal routers.
  - determine "good" routes to other networks based on reachability information and *policy*

BGP connections

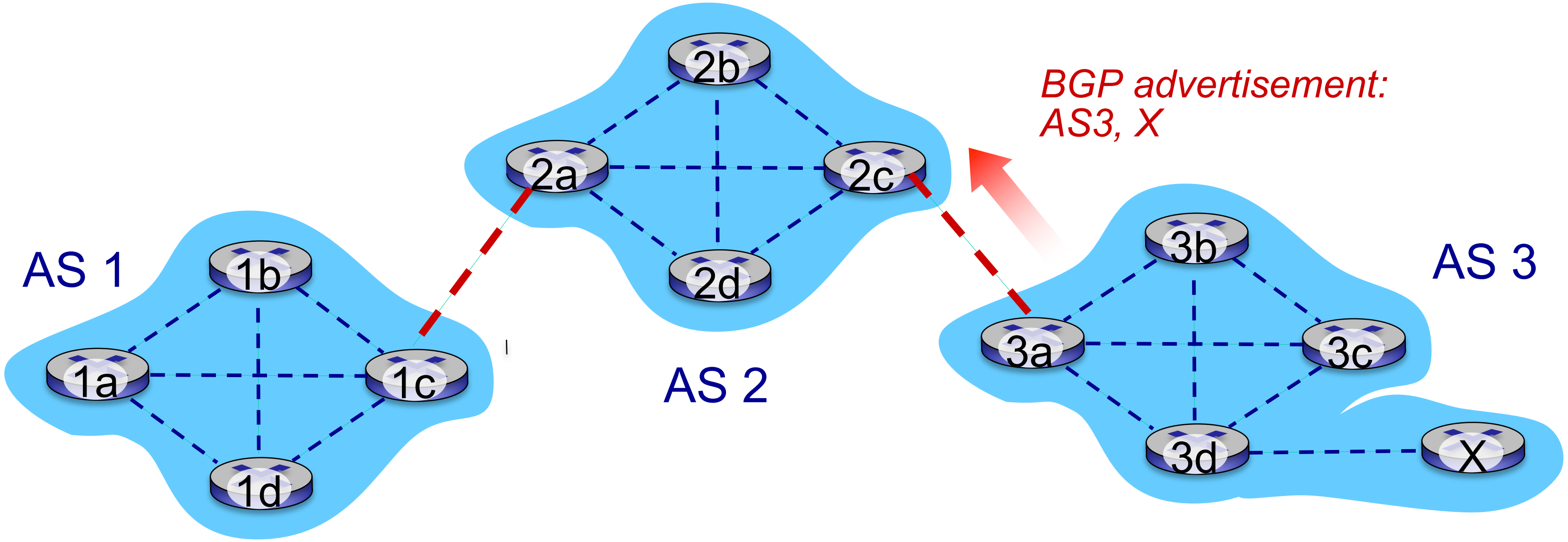
- BGP connection: two BGP routers ("peers") exchange BGP messages over semi-permanent TCP connection



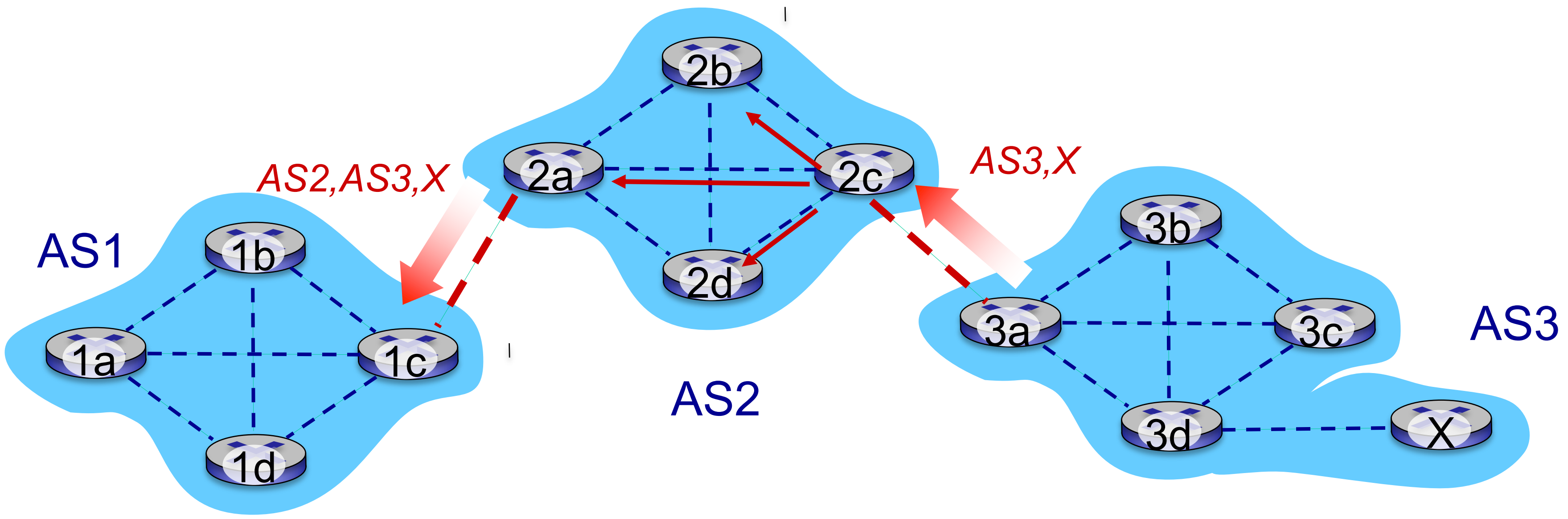
gateway routers run both eBGP and iBGP protocols

BGP basics

- BGP connection: two BGP routers ("peers") exchange BGP messages over semi-permanent TCP connection:
  - advertising *paths* to different destination network prefixes (BGP is a "path vector" protocol)
  - when AS3 gateway router 3a advertises path AS3,X to AS2 gateway router 2c:
    - AS3 *promises* to AS2 it will forward datagrams towards X

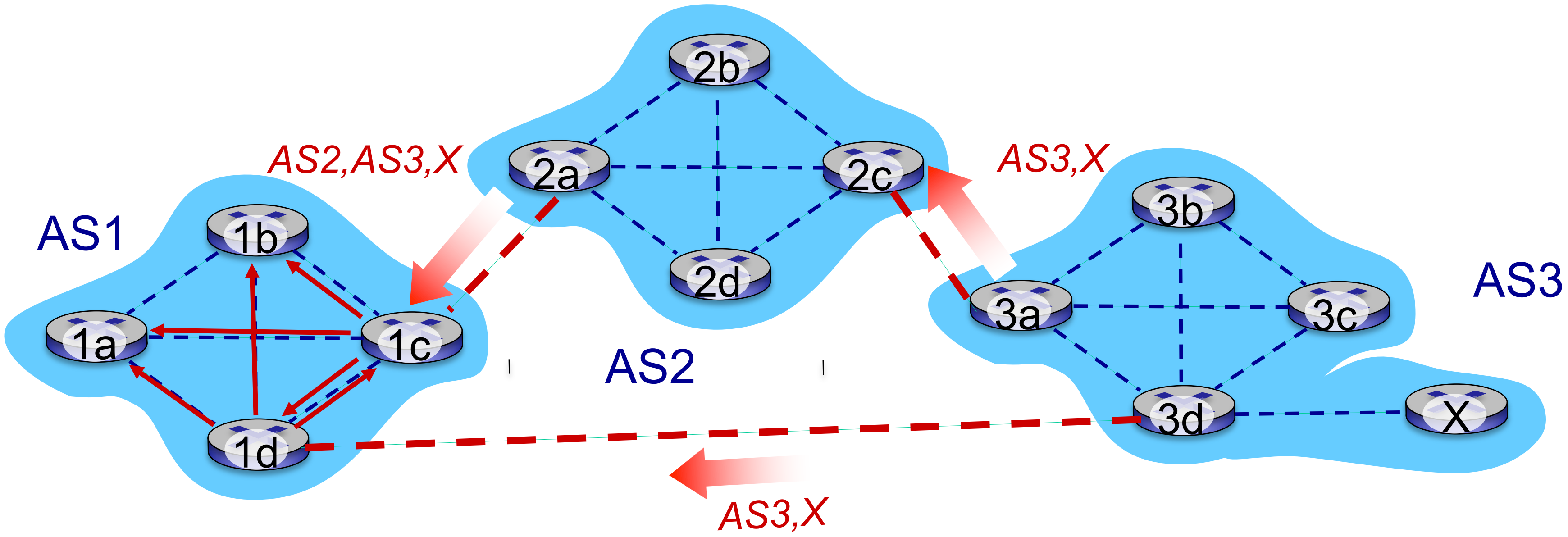


BGP path advertisement



- AS2 router 2c receives path advertisement AS3,X (via eBGP) from AS3 router 3a
- Based on AS2 policy, AS2 router 2c accepts path AS3,X, propagates (via iBGP) to all AS2 routers
- Based on AS2 policy, AS2 router 2a advertises (via eBGP) path AS2, AS3, X to AS1 router 1c

BGP path advertisement



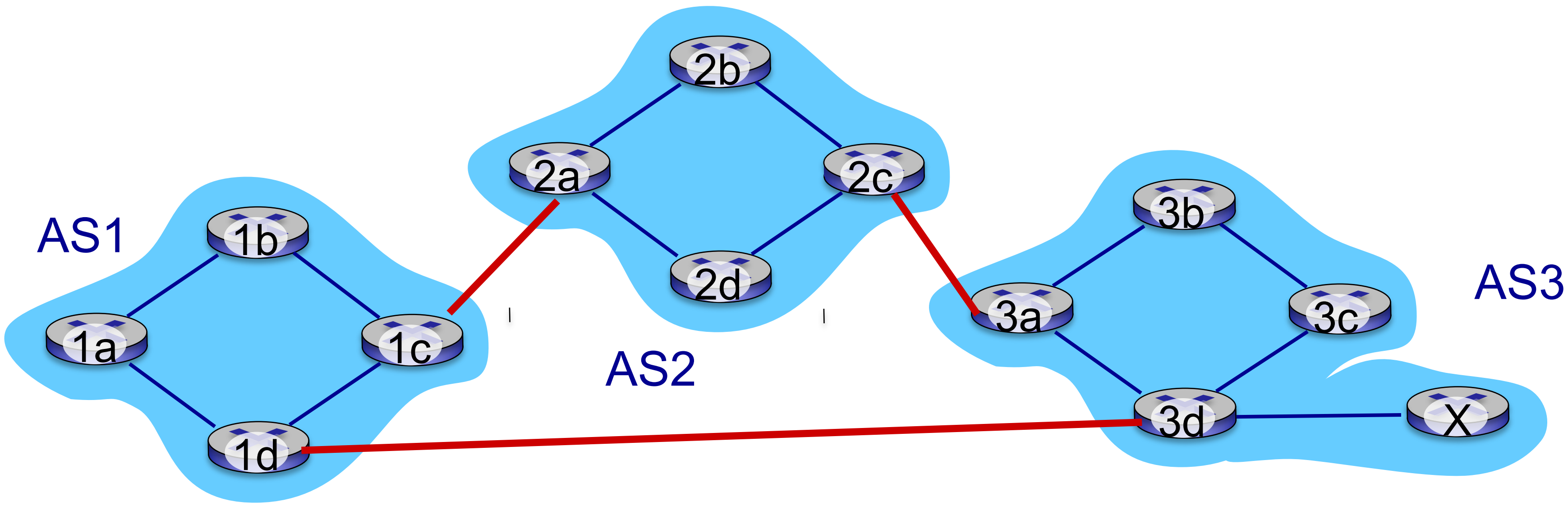
gateway router may learn about multiple paths to destination:

- AS1 gateway router 1c learns path *AS2,AS3,X* from 2a
- AS1 gateway router 1d learns path *AS3,X* from 3d

Path attributes and BGP routes

- advertised prefix includes BGP attributes
  - prefix + attributes = "route"
- two important attributes:
  - AS-PATH: list of ASes through which prefix advertisement has passed
  - NEXT-HOP: indicates specific internal-AS router to next-hop AS

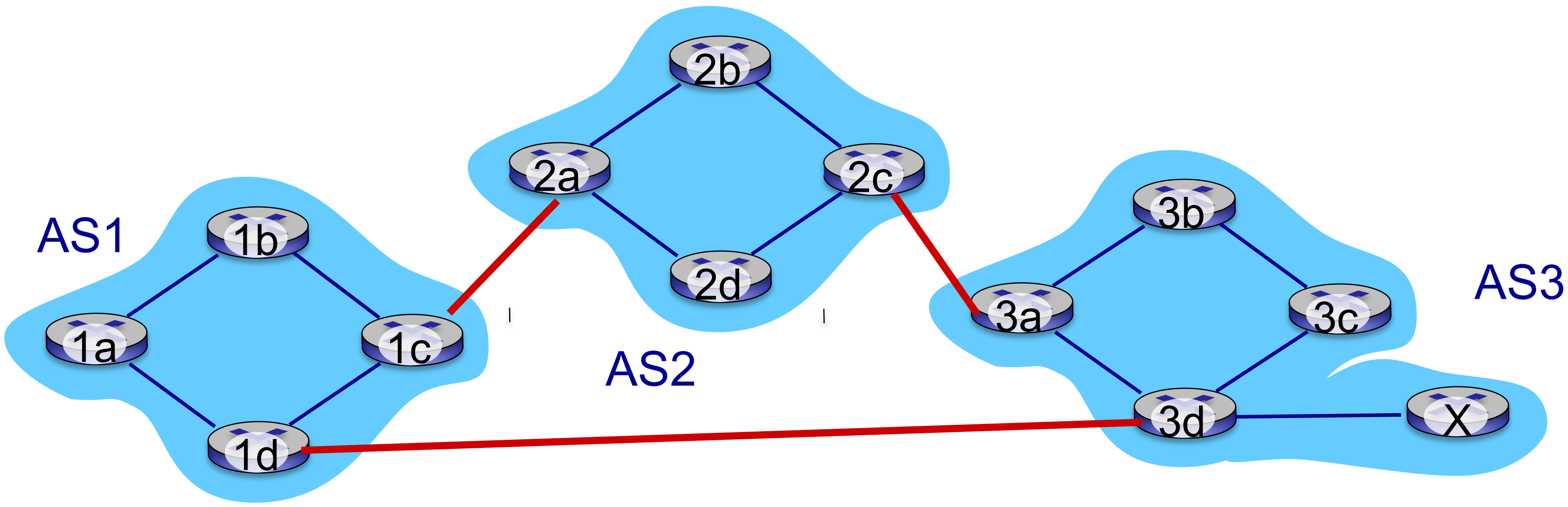
Path attributes and BGP routes



NEXT-HOP AS-PATH

- IP address of leftmost interface for router 2a; *AS2,AS3;X*
- IP address of leftmost interface for router 3d; *AS3;X*

Hot Potato Routing

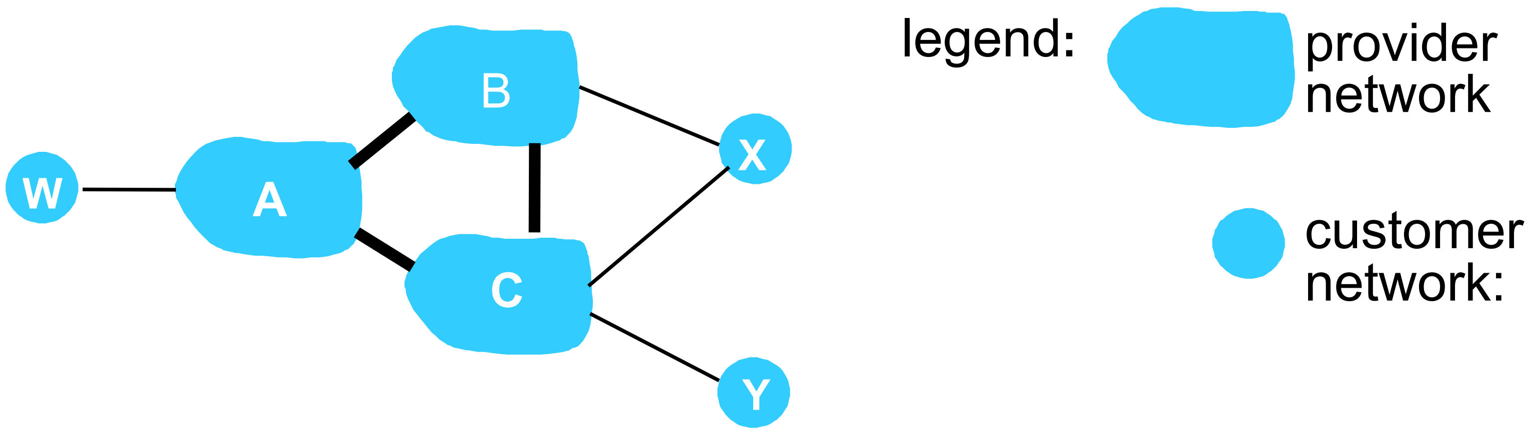


- 1b learns (via iBGP) it can route to X via 2a or 3d
- *hot potato routing:* choose route with the least cost to NEXT-HOP router: get packets out of its AS as quickly as possible!
- 1b and 1d may choose different AS paths to the same prefix

BGP route selection

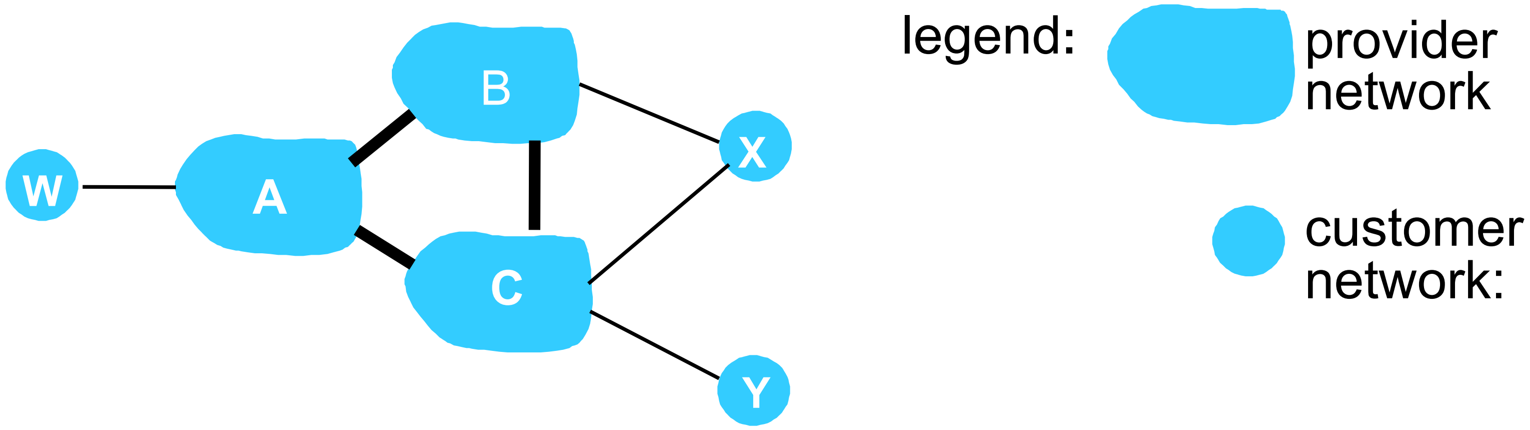
- router may learn about more than one route to destination AS, selects route based on:
  1. local preference value attribute: policy decision
     - e.g., never route through AS Y
     - AS policy also determines whether to *advertise* path to other other neighboring ASes
  2. shortest AS-PATH (DV algorithm)
  3. closest NEXT-HOP router: hot potato routing
  4. additional criteria

BGP: achieving policy via advertisements



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

BGP: achieving policy via advertisements



- A advertises path Aw to B and to C
- B *chooses not to advertise* BAw to C:
  - B gets no “revenue” for routing CBAw, since none of C, A, w are B’s customers
  - C does not learn about CBAw path
- C will route CAw (not using B) to get to w

Usually, an ISP only wants to route traffic to/from its customer networks (does not want to carry transit traffic between other ISPs)

Why different Intra-, Inter-AS routing ?

policy:

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

scale:

- hierarchical routing saves table size, reduced update traffic

performance:

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