

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

- IPv6

4.5 routing algorithms

- link state
- distance vector
- hierarchical routing

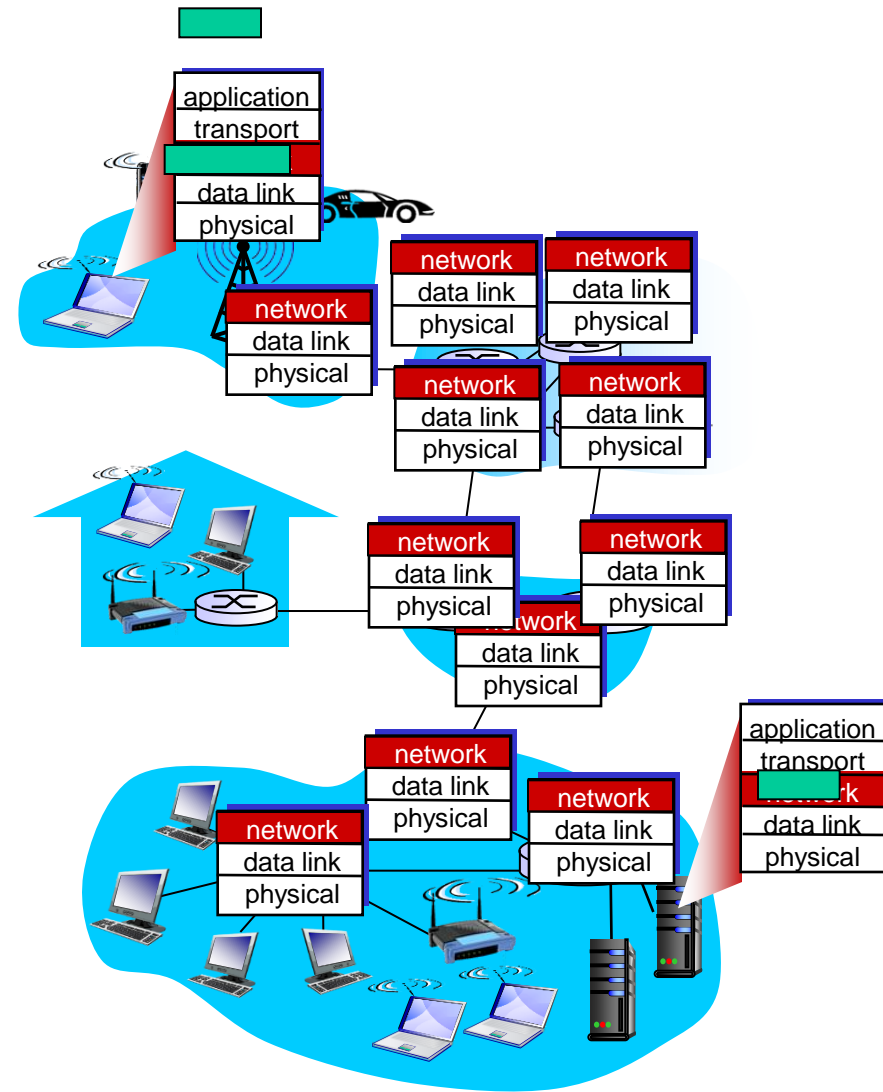
4.6 routing in the Internet

- RIP
- OSPF
- BGP

4.7 broadcast and multicast routing

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.

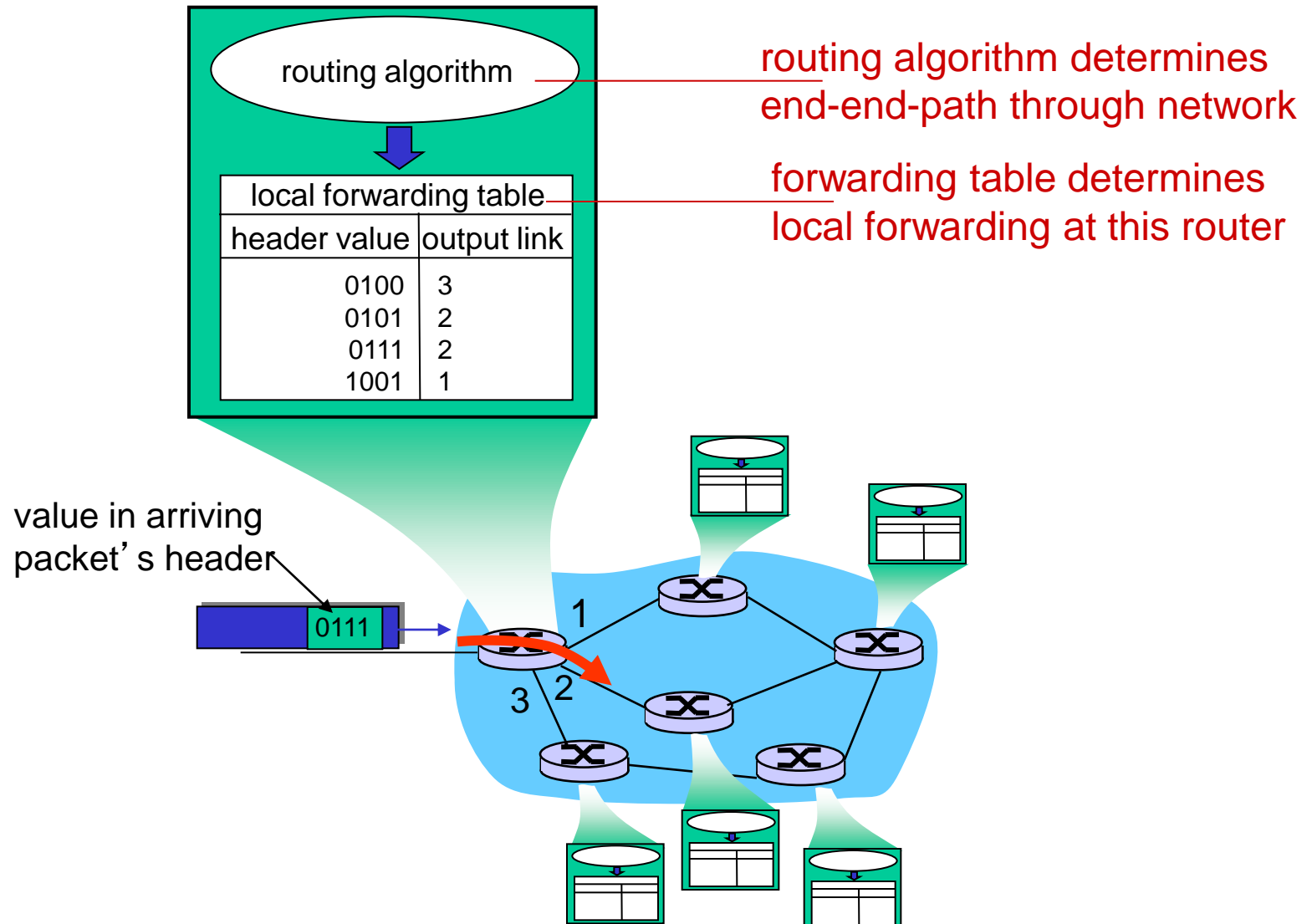
 - *routing algorithms*

analogy:

- ❖ *routing*: process of planning trip from source to dest

- ❖ *forwarding*: process of getting through single interchange

Interplay between routing and forwarding



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

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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datagram networks

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4.6 routing in the Internet

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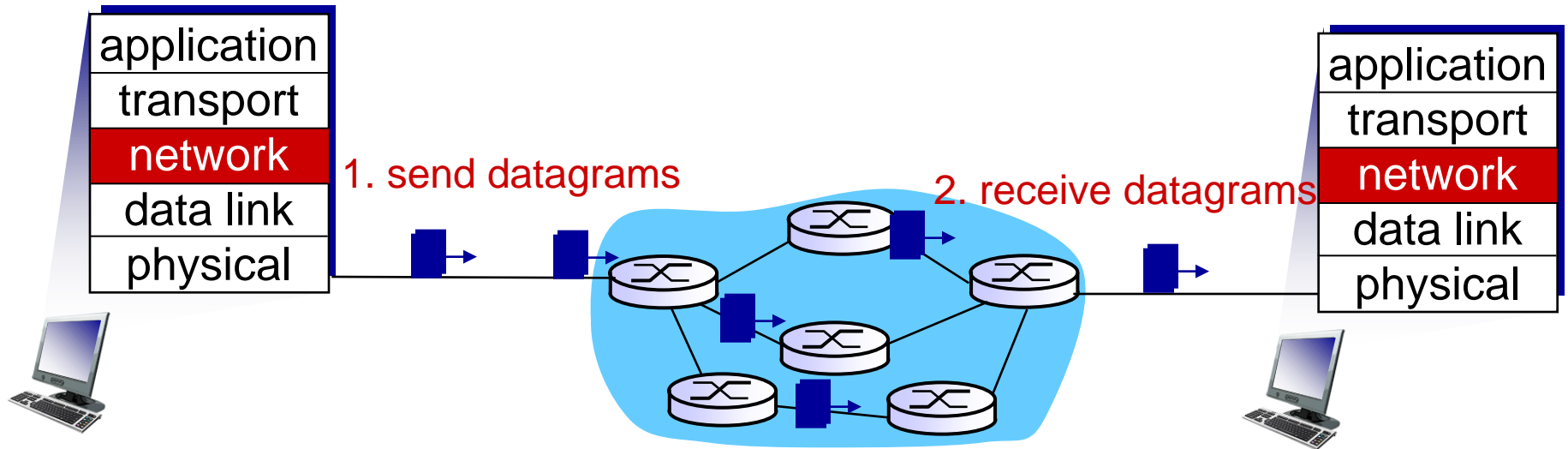
4.7 broadcast and multicast
routing

Connection, connection-less service

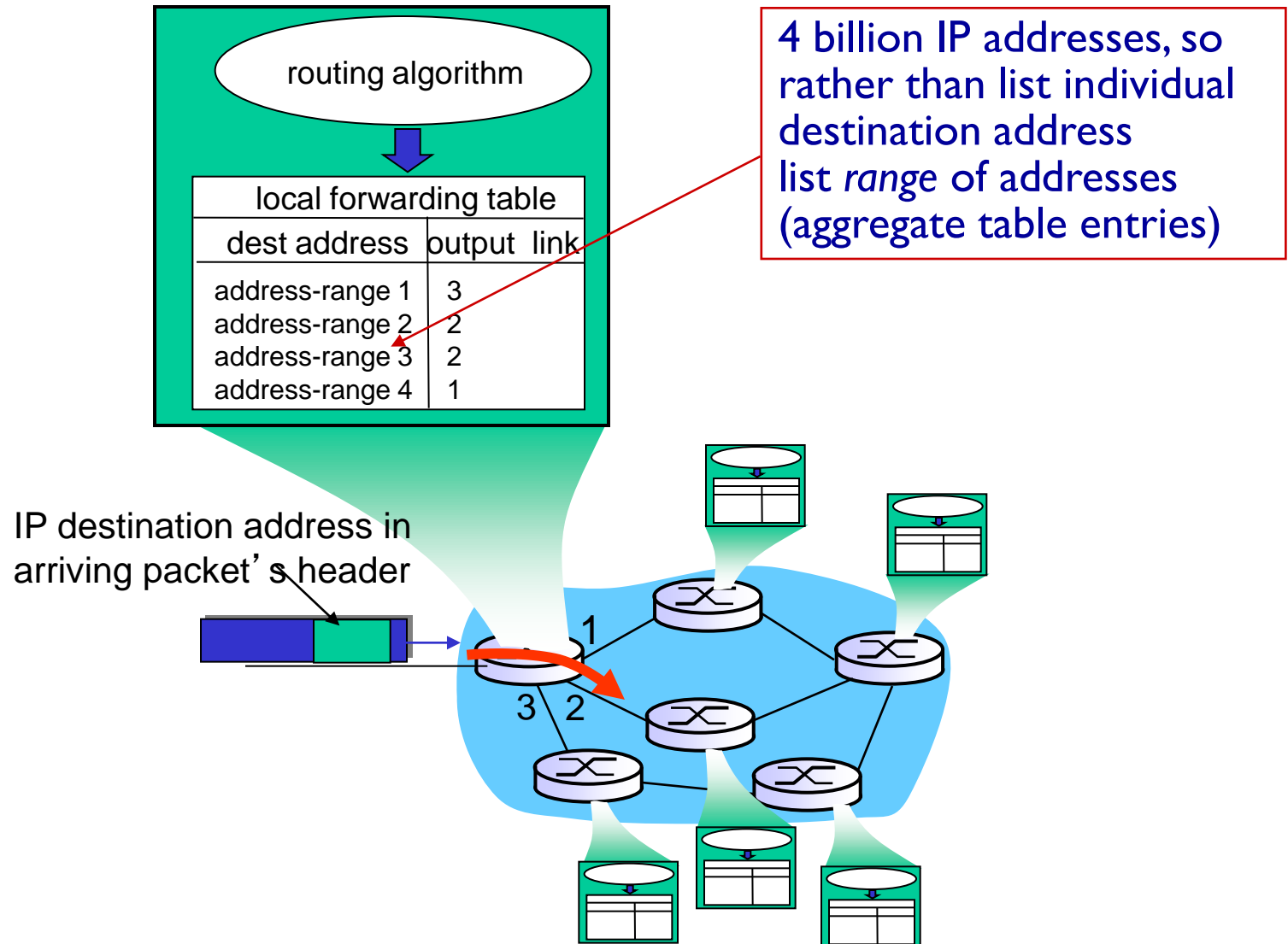
- ❖ *datagram* network provides network-layer *connectionless* service
- ❖ *virtual-circuit* network provides network-layer *connection* service
- ❖ analogous to TCP/UDP connection-oriented / connectionless transport-layer services, but:
 - *service*: host-to-host
 - *no choice*: network provides one or the other
 - *implementation*: in network core

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



Datagram forwarding table



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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4.1 introduction

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- IPv4 addressing
- ICMP
- IPv6

4.5 routing algorithms

- link state
- distance vector
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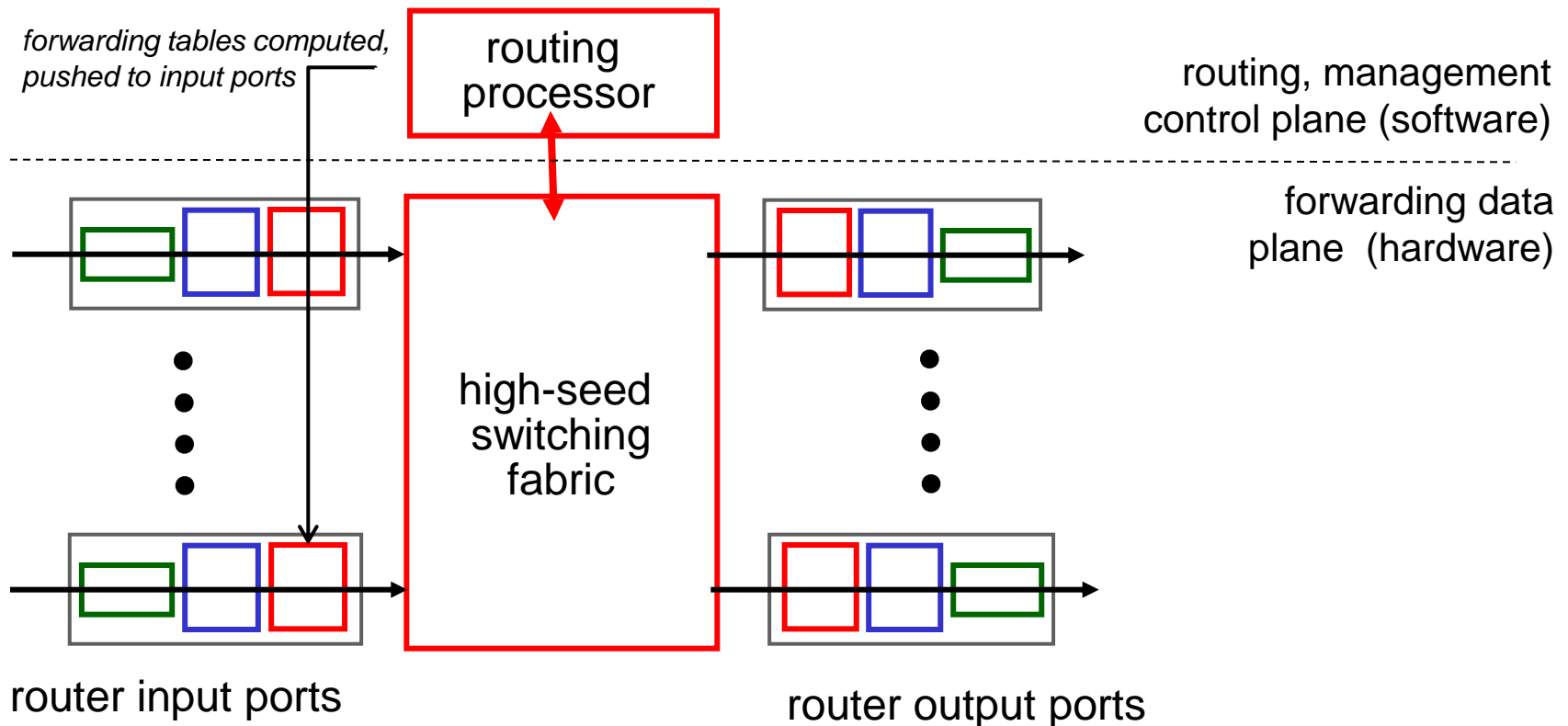
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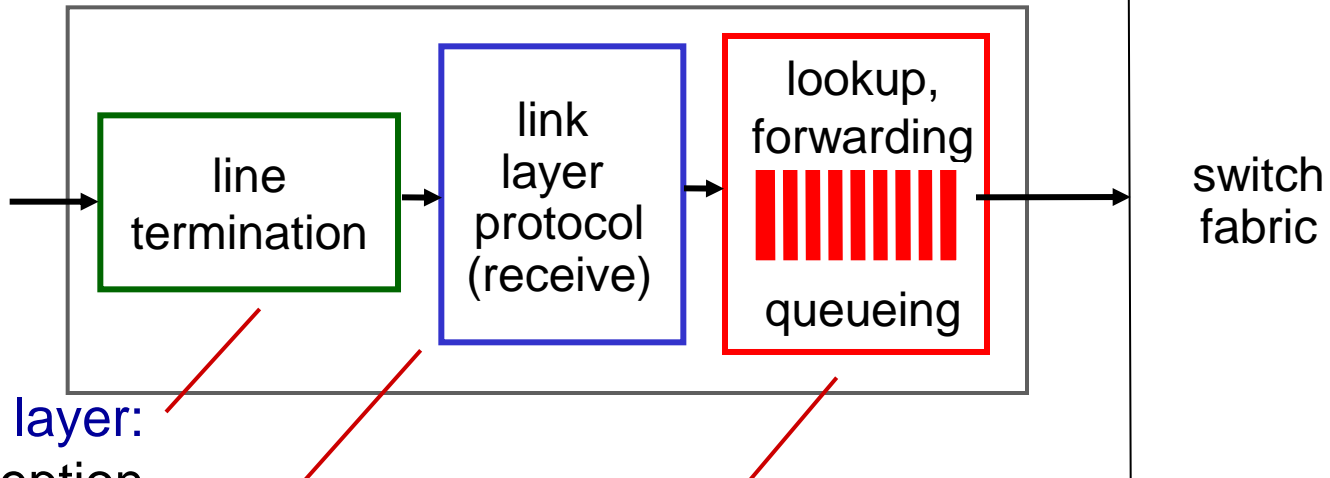
Router architecture overview

two key router functions:

- ❖ run routing algorithms/protocol (RIP, OSPF, BGP)
- ❖ *forwarding* datagrams from incoming to outgoing link



Input port functions



physical layer:
bit-level reception

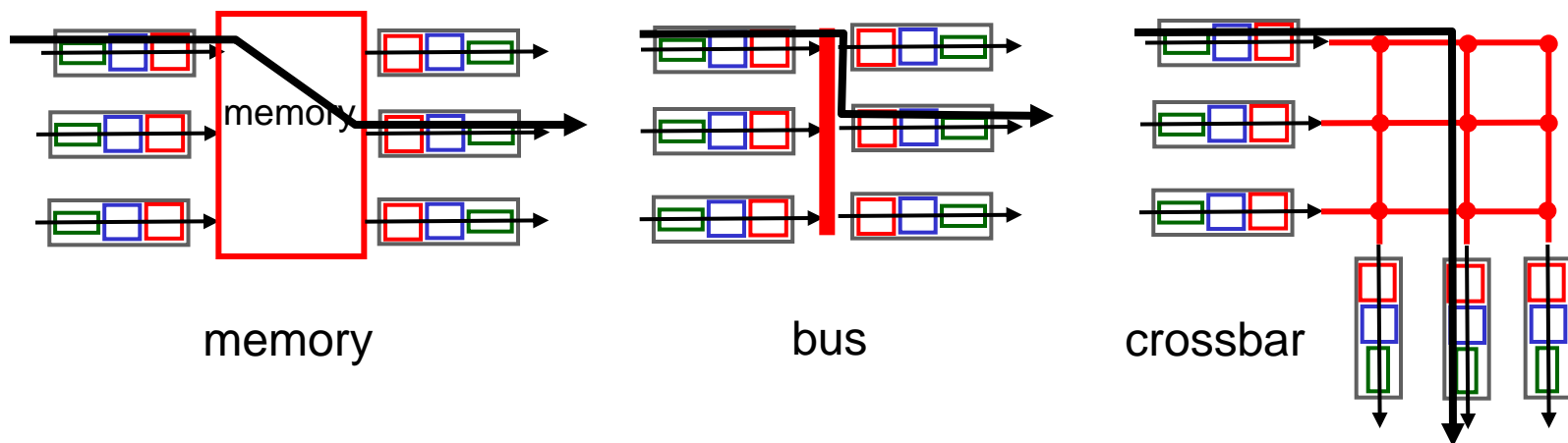
data link layer:
e.g., Ethernet
see chapter 5

decentralized switching:

- ❖ given datagram dest., 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

Switching fabrics

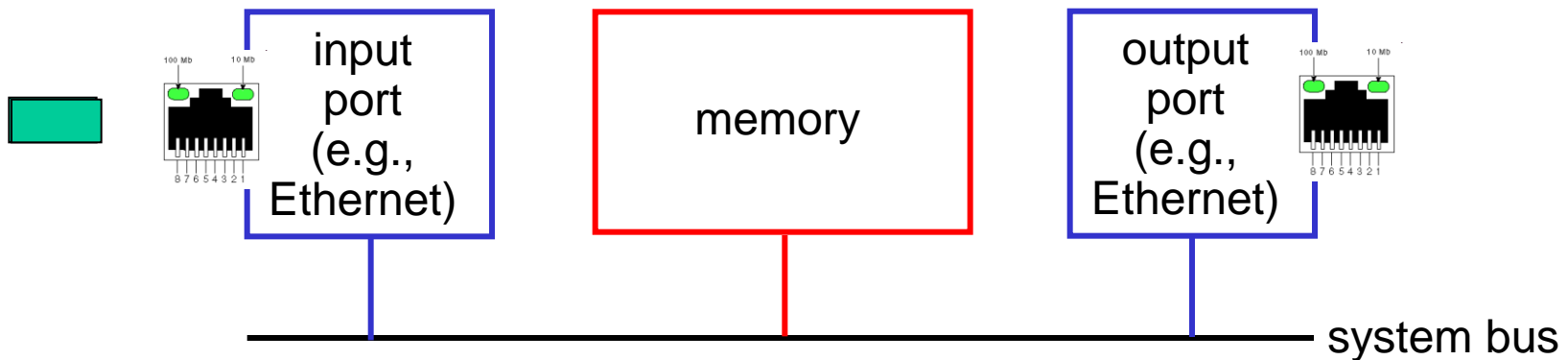
- ❖ transfer packet from input buffer to appropriate output buffer
- ❖ switching rate: rate at which packets can be transfer from inputs to outputs
 - often measured as multiple of input/output line rate
 - N inputs: switching rate N times line rate desirable
- ❖ three types of switching fabrics



Switching via memory

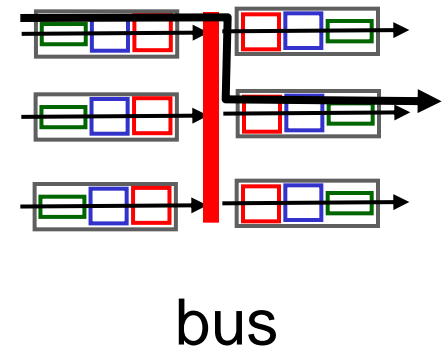
first generation routers:

- ❖ traditional computers with switching under direct control of CPU
- ❖ packet copied to system's memory
- ❖ speed limited by memory bandwidth (2 bus crossings per datagram)



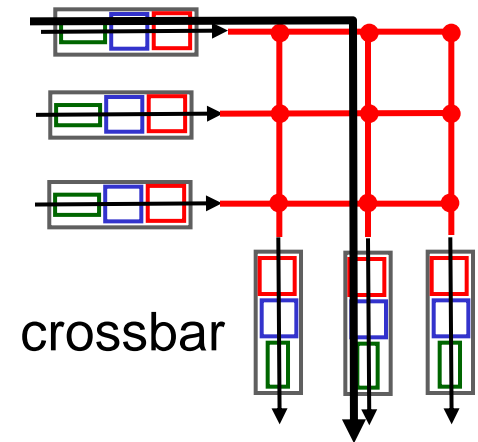
Switching via a bus

- ❖ datagram from input port memory to output port memory via a shared bus
- ❖ *bus contention*: switching speed limited by bus bandwidth
- ❖ 32 Gbps bus, Cisco 5600: sufficient speed for access and enterprise routers

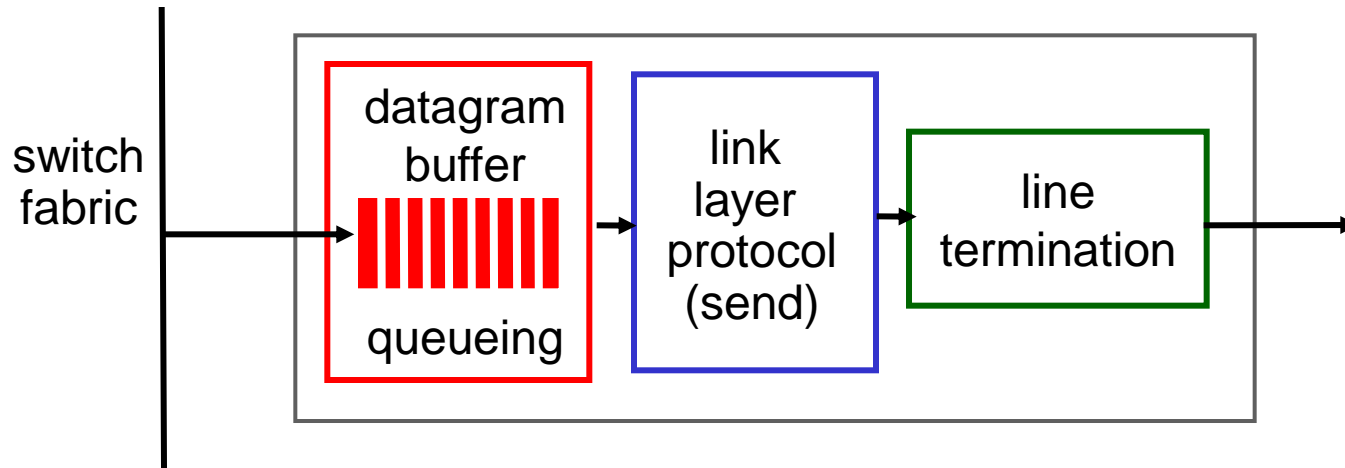


Switching via interconnection network

- ❖ overcome bus bandwidth limitations
- ❖ banyan networks, crossbar, other interconnection nets initially developed to connect processors in multiprocessor
- ❖ advanced design: fragmenting datagram into fixed length cells, switch cells through the fabric.
- ❖ Cisco I2000: switches 60 Gbps through the interconnection network

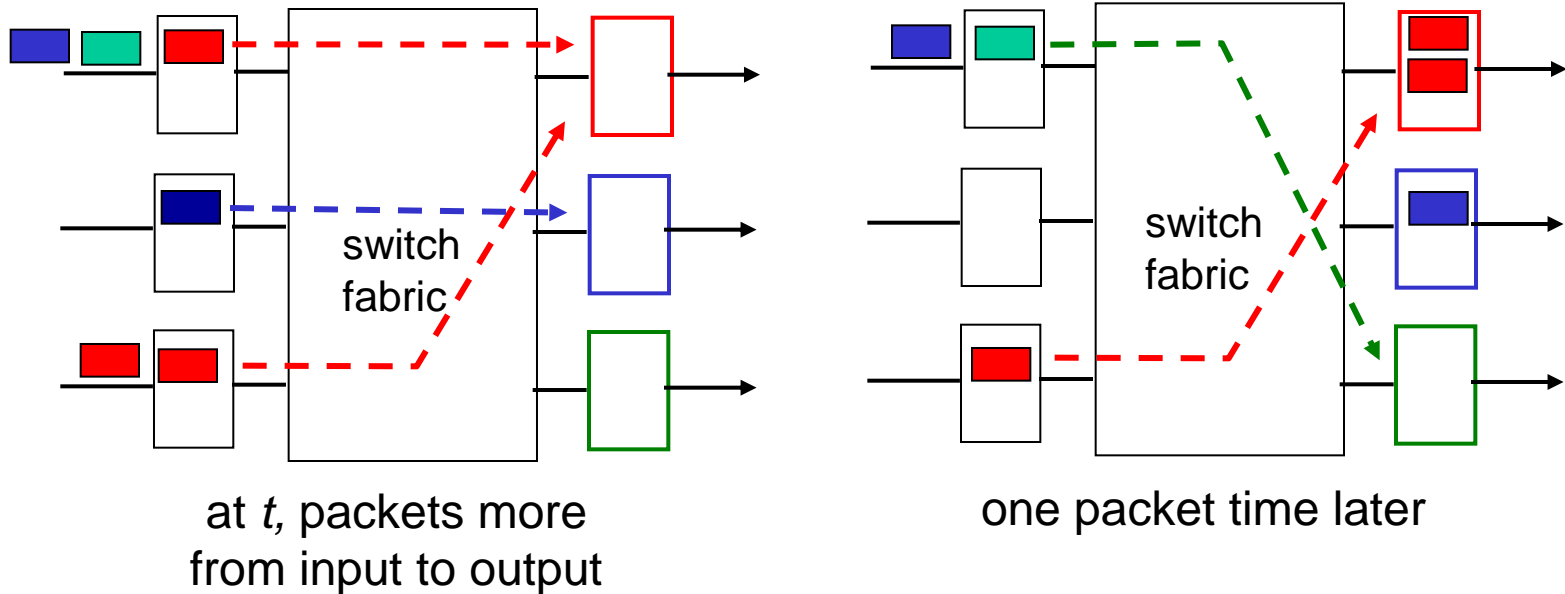


Output ports



- ❖ *buffering* required when datagrams arrive from fabric faster than the transmission rate
- ❖ *scheduling discipline* chooses among queued datagrams for transmission

Output port queueing



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

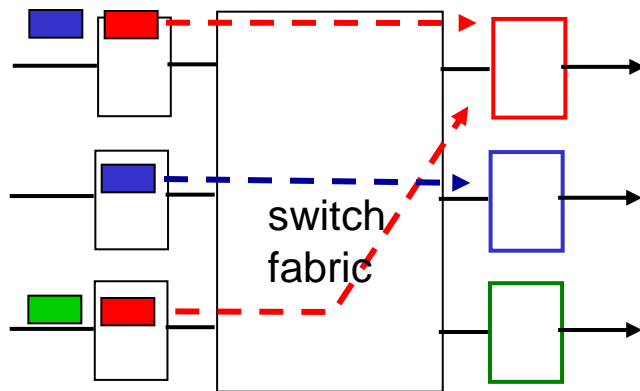
How much buffering?

- ❖ RFC 3439 rule of thumb: average buffering equal to “typical” RTT (say 250 msec) times link capacity C
 - e.g., $C = 10$ Gpbs link: 2.5 Gbit buffer
- ❖ recent recommendation: with N flows, buffering equal to

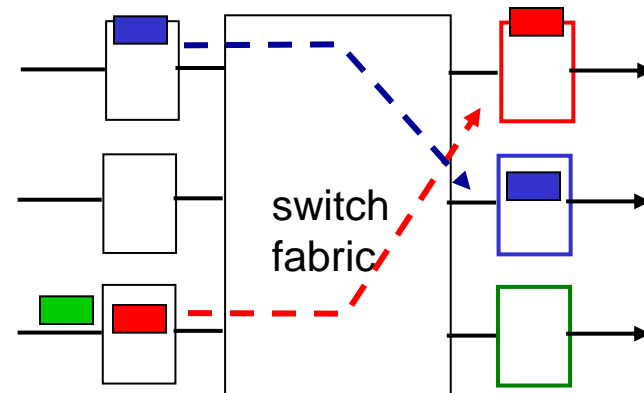
$$\frac{RTT \cdot C}{\sqrt{N}}$$

Input port queuing

- ❖ fabric slower than input ports combined -> queueing may occur at input queues
 - *queueing delay and loss due to input buffer overflow!*
- ❖ **Head-of-the-Line (HOL) blocking:** queued datagram at front of queue prevents others in queue from moving forward



output port contention:
only one red datagram can be
transferred.
lower red packet is blocked



one packet time later:
green packet
experiences HOL
blocking

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- IPv6

4.5 routing algorithms

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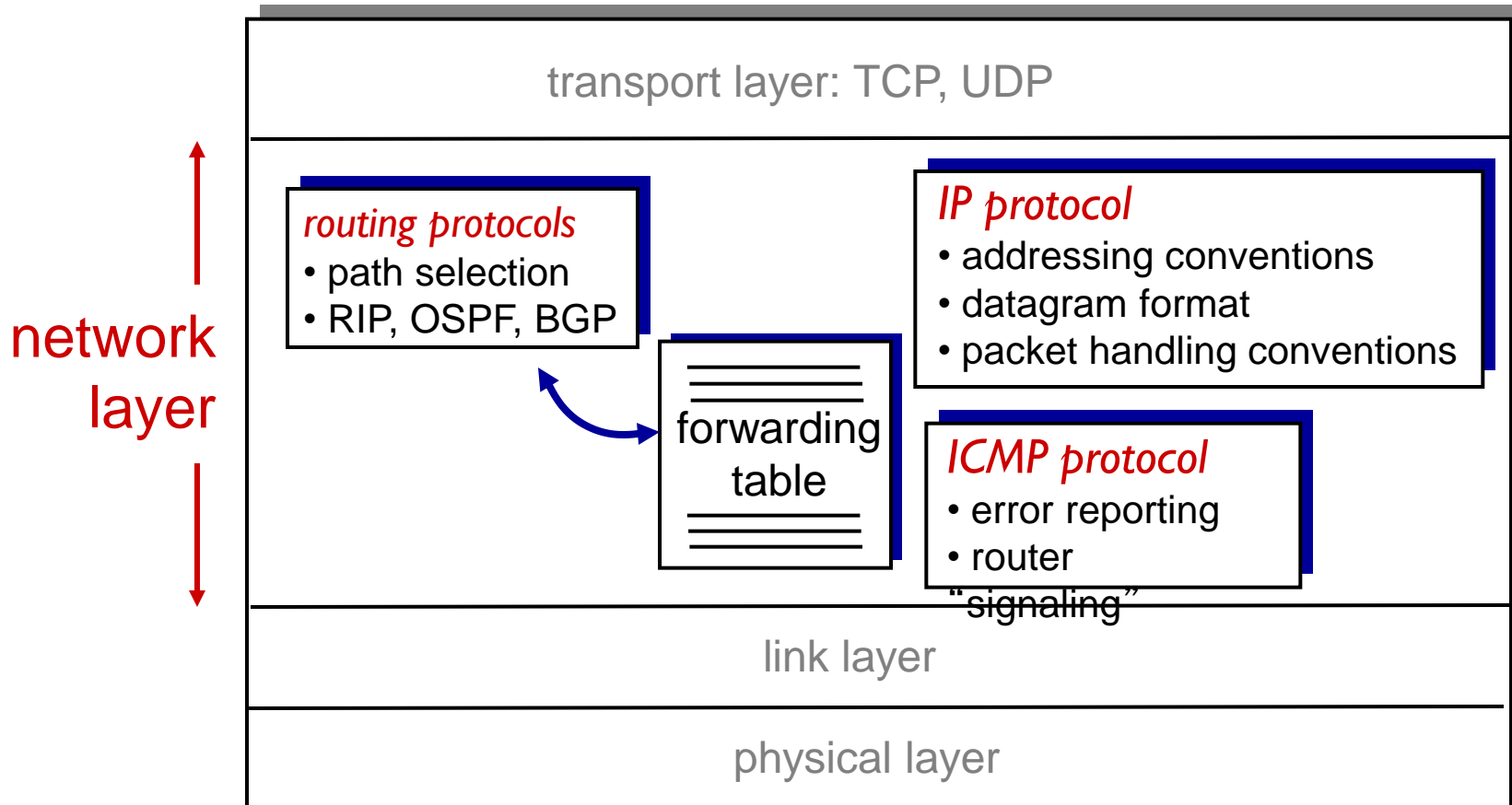
4.6 routing in the Internet

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4.7 broadcast and multicast
routing

The Internet network layer

host, router network layer functions:



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4.2 virtual circuit and
datagram networks

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- IPv6

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- link state
- distance vector
- hierarchical routing

4.6 routing in the Internet

- RIP
- OSPF
- BGP

4.7 broadcast and multicast
routing

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

- IPv6

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- RIP
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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

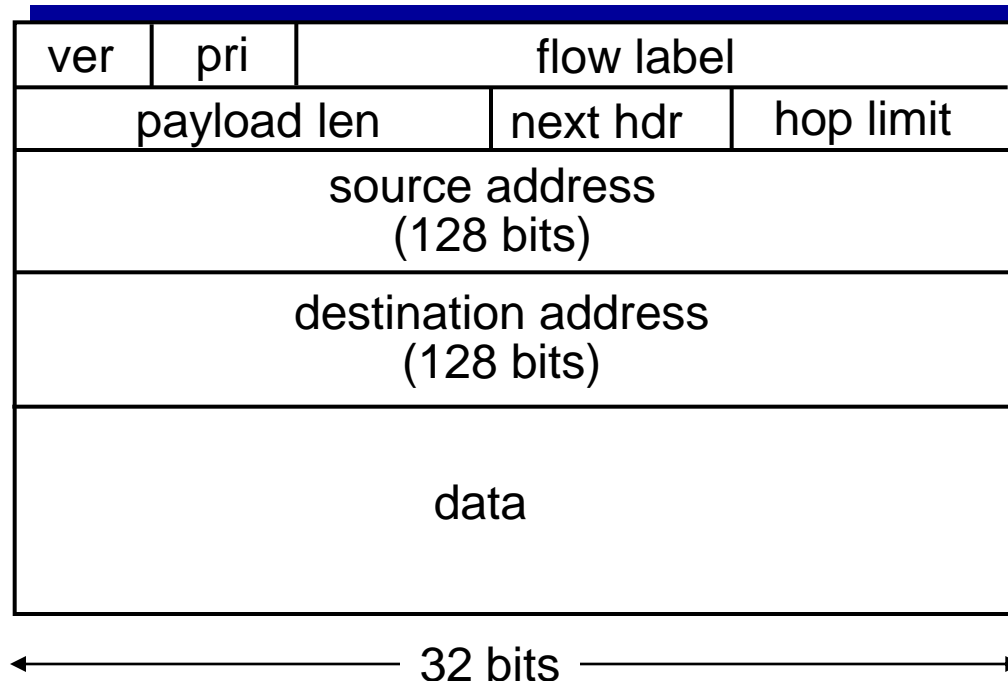
IPv6 datagram format

priority: identify priority among datagrams in flow

flow Label: identify datagrams in same “flow.”

(concept of “flow” not well defined).

next header: identify upper layer protocol for data

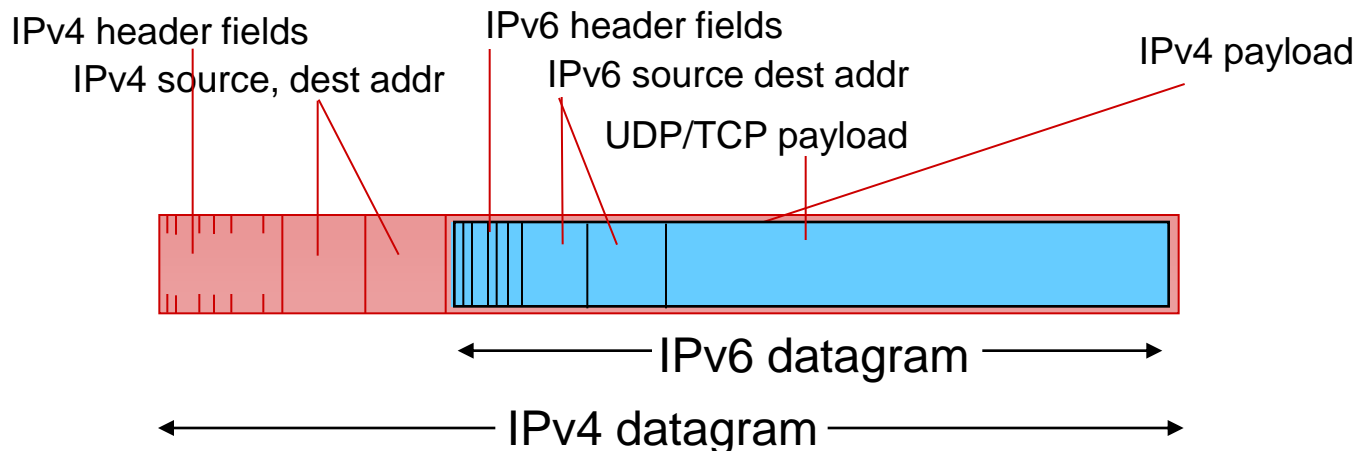


Other changes from IPv4

- ❖ *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

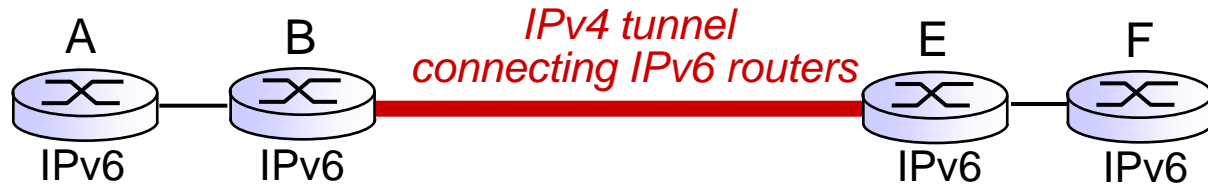
Transition from IPv4 to IPv6

- ❖ 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

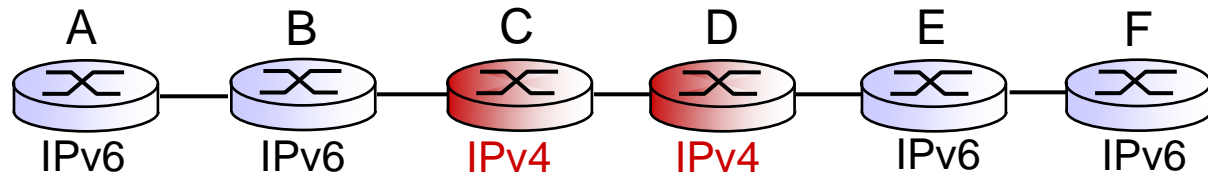


Tunneling

logical view:

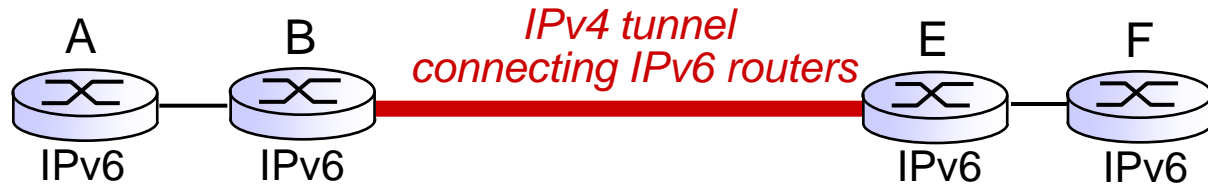


physical view:

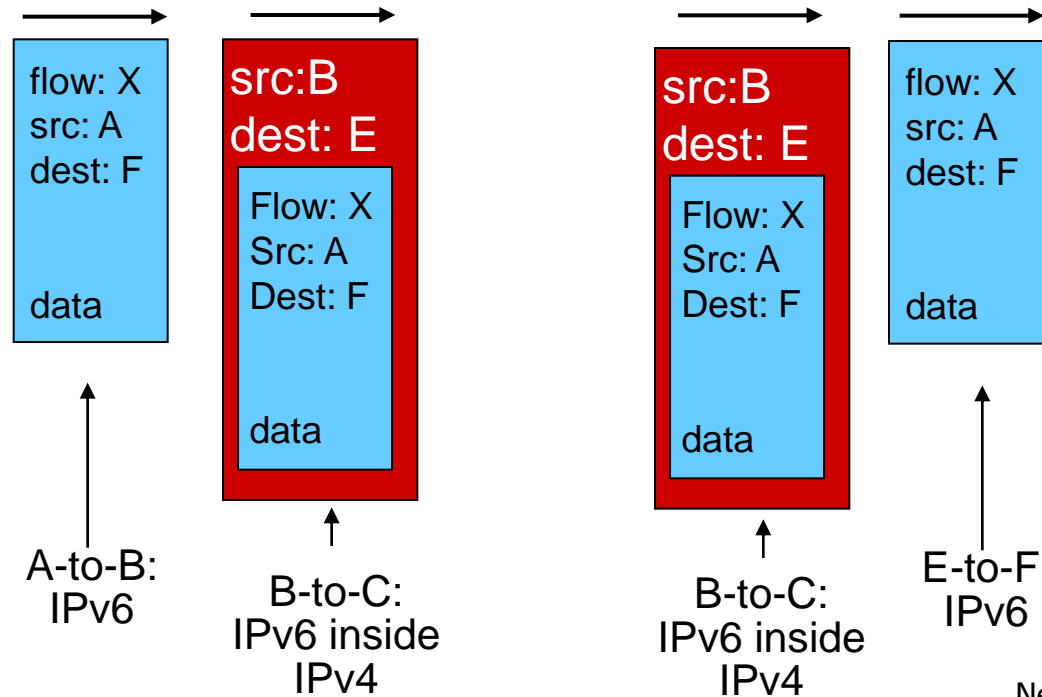
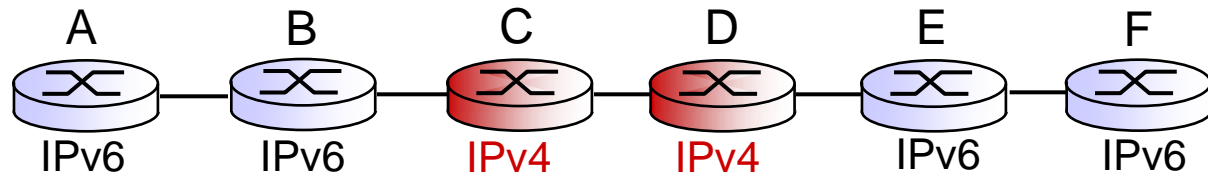


Tunneling

logical view:



physical view:



Chapter 4: outline

4.1 introduction

4.2 virtual circuit and datagram networks

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- ICMP
- IPv6

4.5 routing algorithms

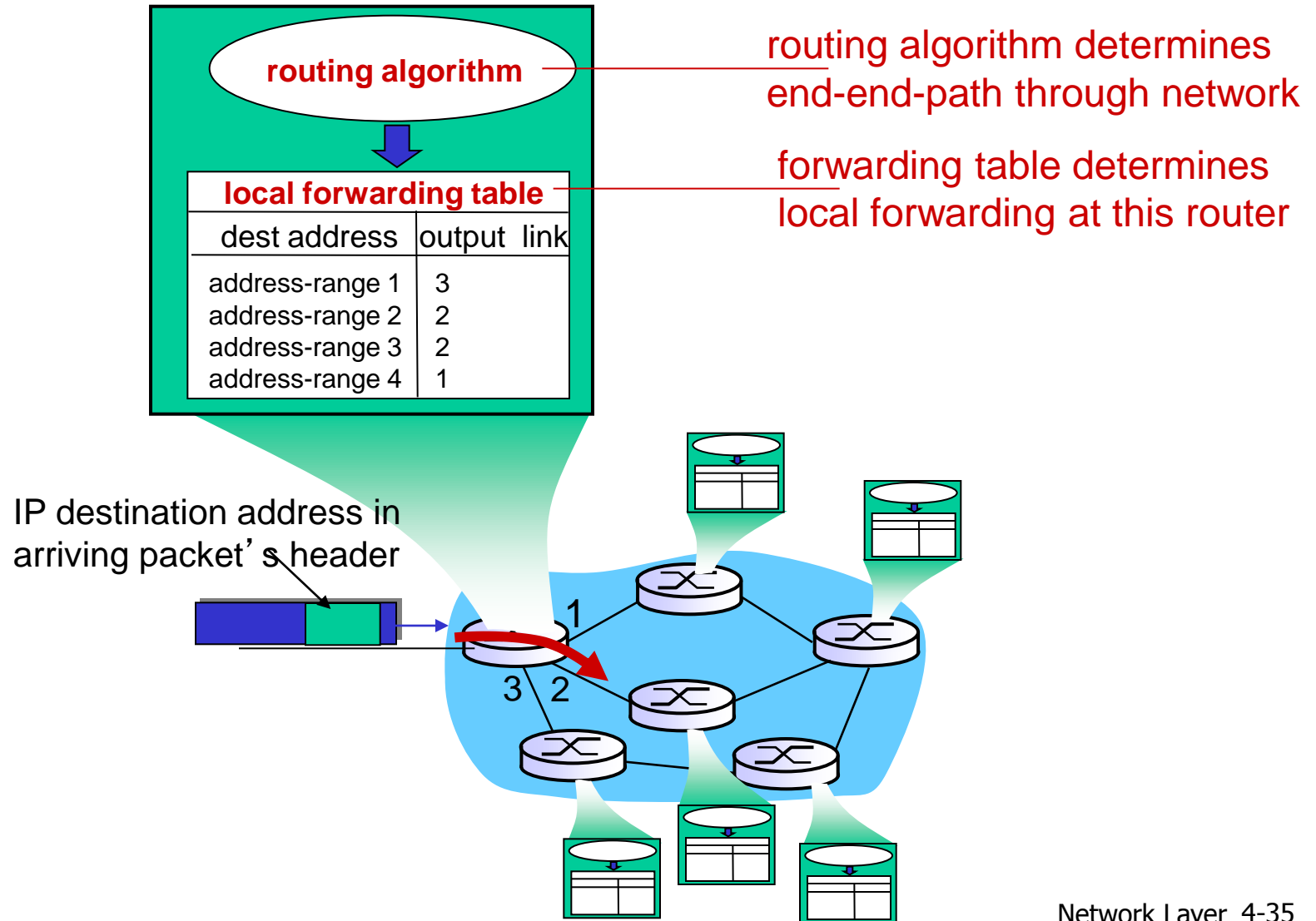
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4.6 routing in the Internet

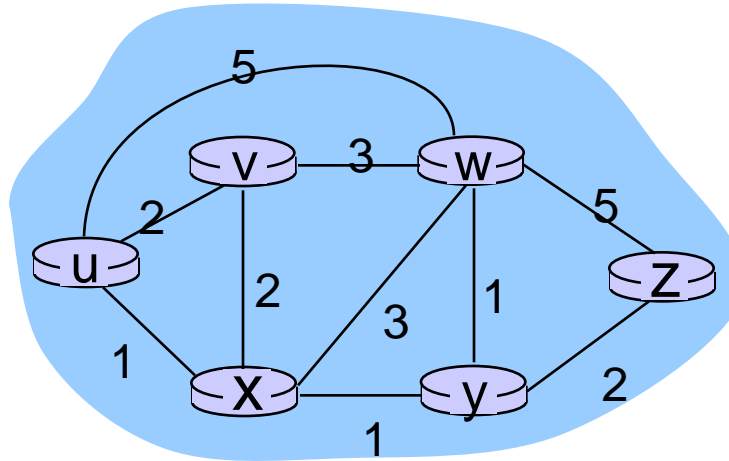
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4.7 broadcast and multicast routing

Interplay between routing, forwarding



Graph abstraction



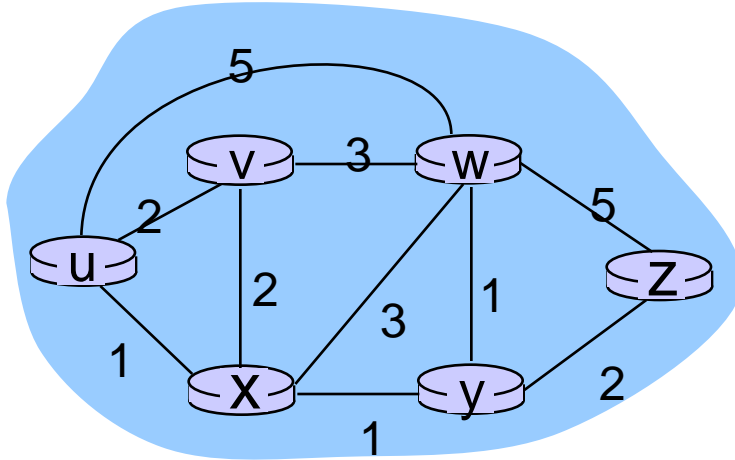
graph: $G = (N, E)$

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



$c(x, x') = \text{cost of link } (x, x')$
e.g., $c(w, z) = 5$

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

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

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

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4.7 broadcast and multicast routing

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 ; $= \infty$ 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

Dijkstra'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 $D(v) = \infty$

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 */

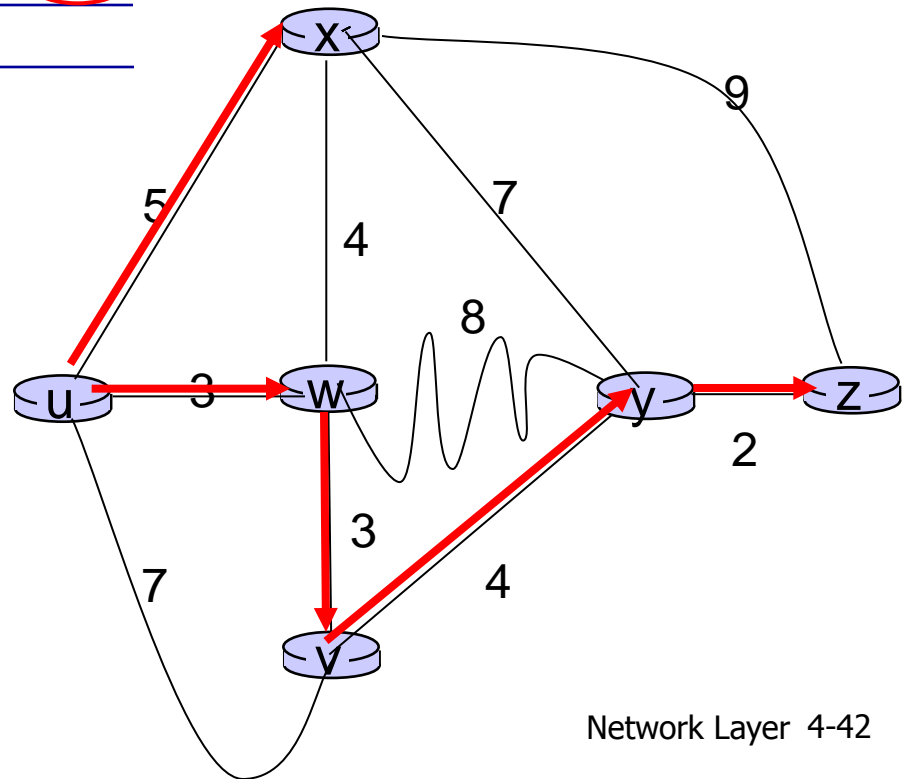
15 **until all nodes in N'**

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					

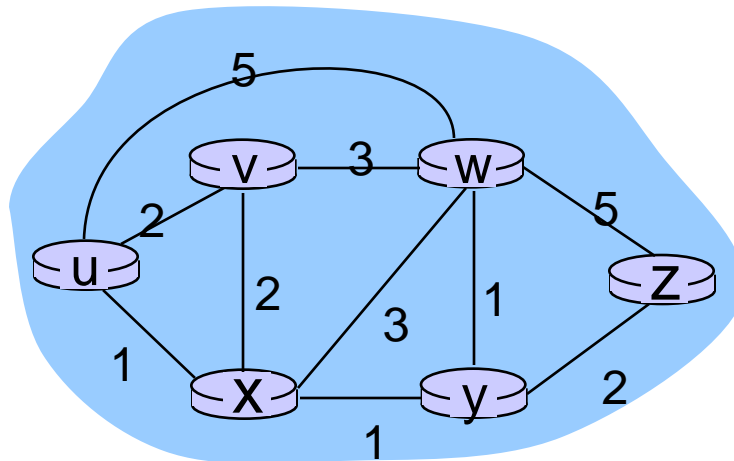
notes:

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



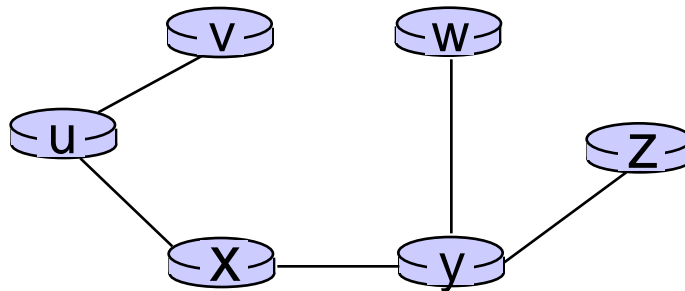
Dijkstra's algorithm: another example

Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					4,y
5	uxyvwz					



Dijkstra's algorithm: example (2)

resulting shortest-path tree from u:



resulting forwarding table in u:

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

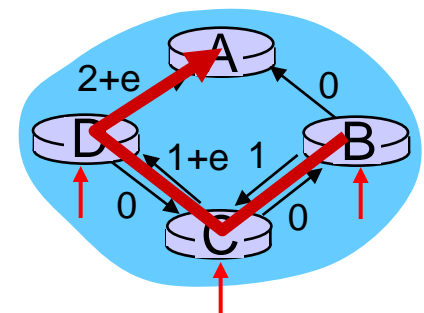
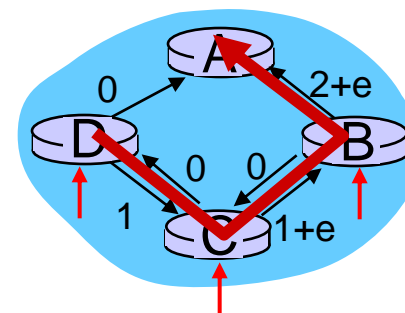
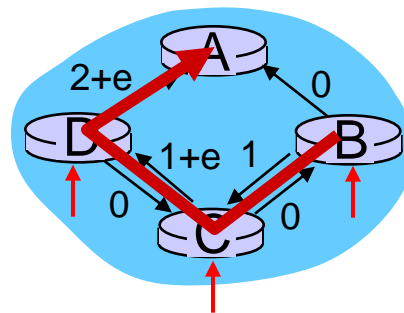
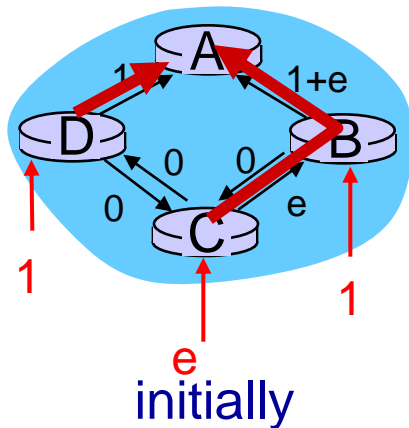
Dijkstra's algorithm, discussion

algorithm complexity: n nodes

- ❖ each iteration: need to check all nodes, w, not in N
- ❖ $n(n+1)/2$ comparisons: $O(n^2)$
- ❖ more efficient implementations possible: $O(n \log n)$

oscillations possible:

- ❖ e.g., support link cost equals amount of carried traffic:



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- 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

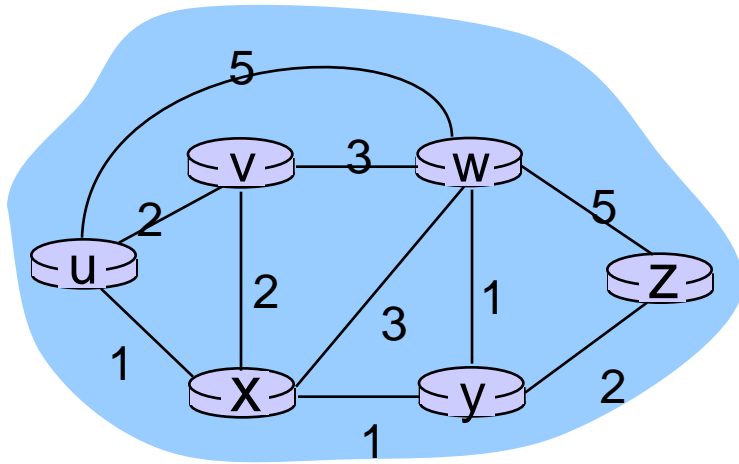
$$d_x(y) = \min_v \{ c(x,v) + d_v(y) \}$$

cost from neighbor v to destination 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:

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

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 $\mathbf{D}_x = [D_x(y): y \in N]$
- ❖ node x :
 - knows cost to each neighbor v : $c(x,v)$
 - maintains its neighbors' distance vectors. For each neighbor v , x maintains $\mathbf{D}_v = [D_v(y): y \in N]$

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:

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

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

Distance vector algorithm

iterative, asynchronous:

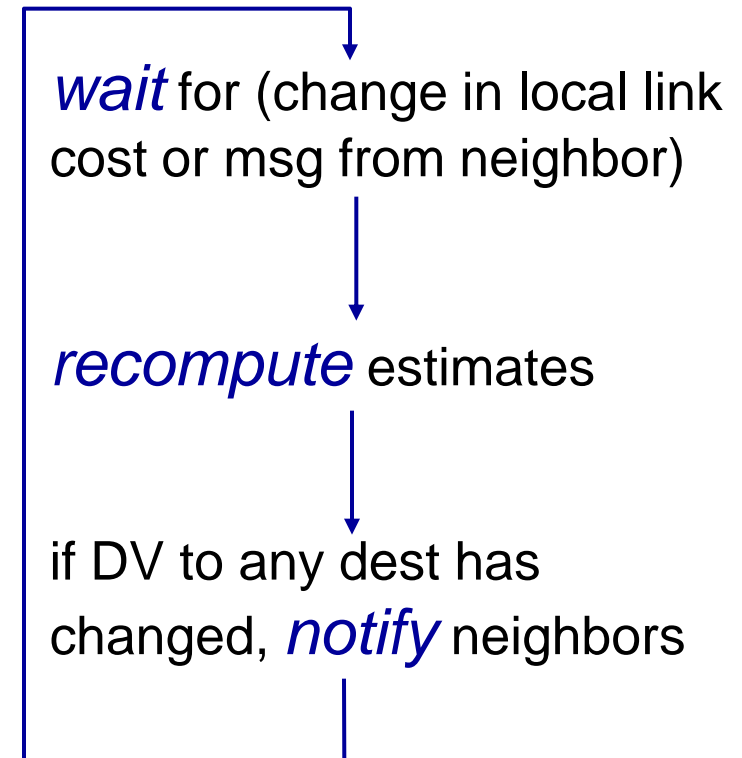
each local iteration
caused by:

- ❖ 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:



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

$$= \min\{2+0, 7+1\} = 2$$

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

$$= \min\{2+1, 7+0\} = 3$$

**node x
table**

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

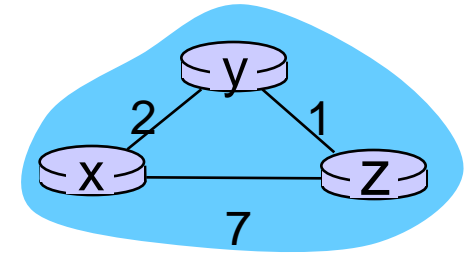
		cost to		
		x	y	z
from	x	0	2	3
	y	2	0	1
	z	7	1	0

**node y
table**

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

**node z
table**

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



time

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

$$= \min\{2+0, 7+1\} = 2$$

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

$$= \min\{2+1, 7+0\} = 3$$

**node x
table**

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

**node y
table**

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

**node z
table**

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

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

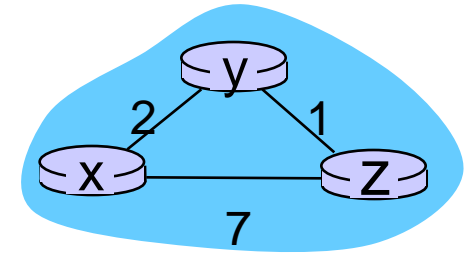
		cost to		
		x	y	z
from	x	0	2	7
	y	2	0	1
	z	7	1	0

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

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

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

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

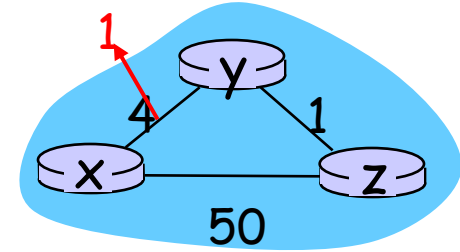


time →

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.

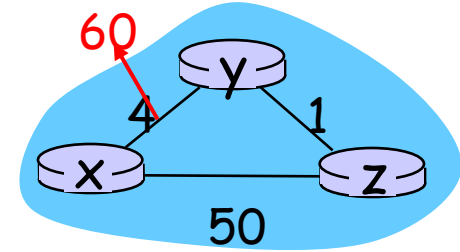
t_1 : z receives update from y , updates its table, computes new least cost to x , sends its neighbors its DV.

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: see text



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:** $O(n^2)$ 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
 - error propagate thru network

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

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

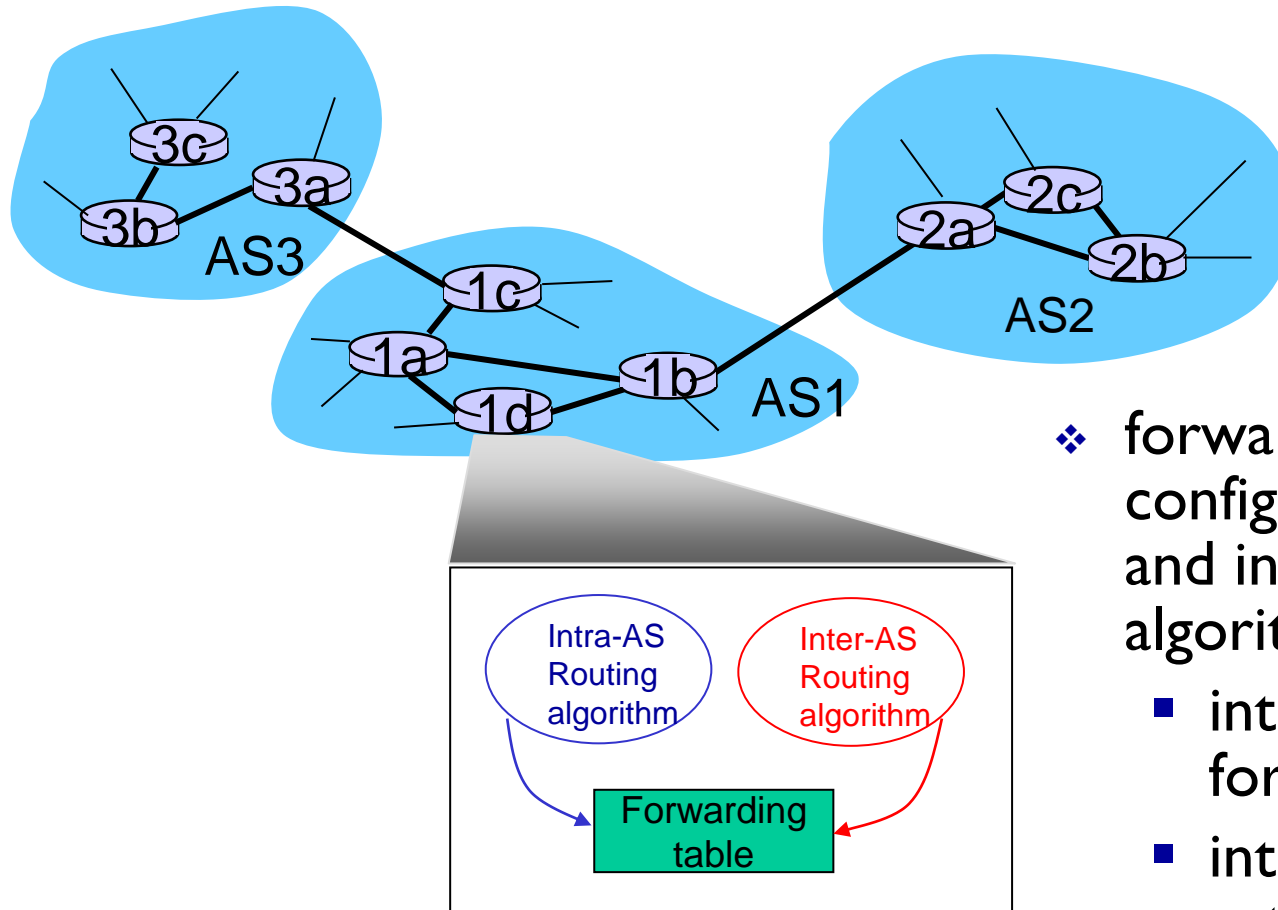
Hierarchical routing

- ❖ 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

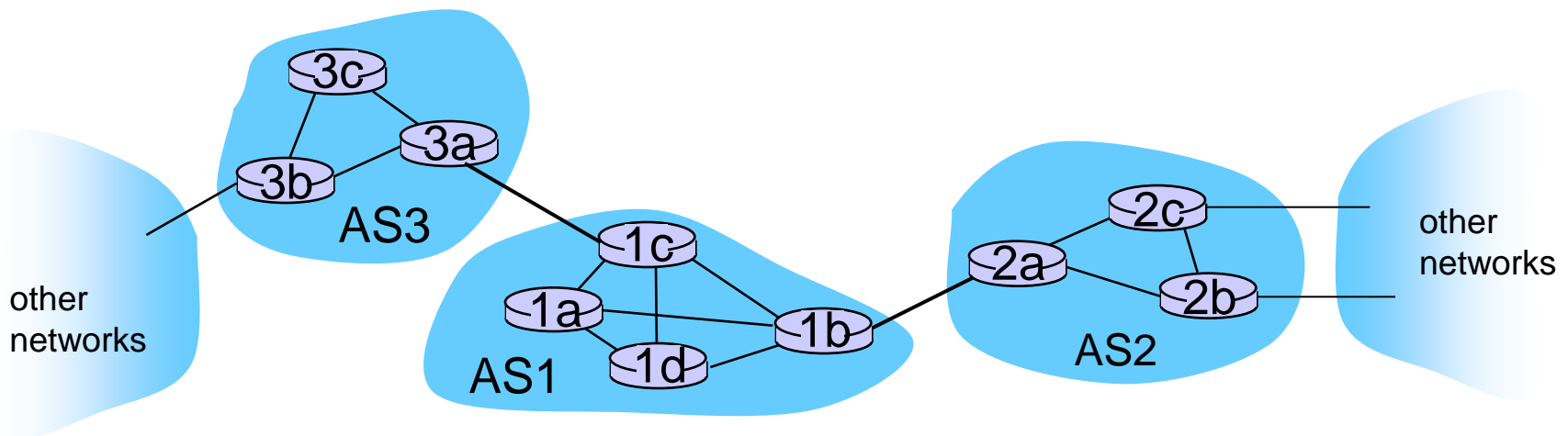
Inter-AS tasks

- ❖ suppose router in AS1 receives datagram destined outside of AS1:
 - router should forward packet to gateway router, but which one?

AS1 must:

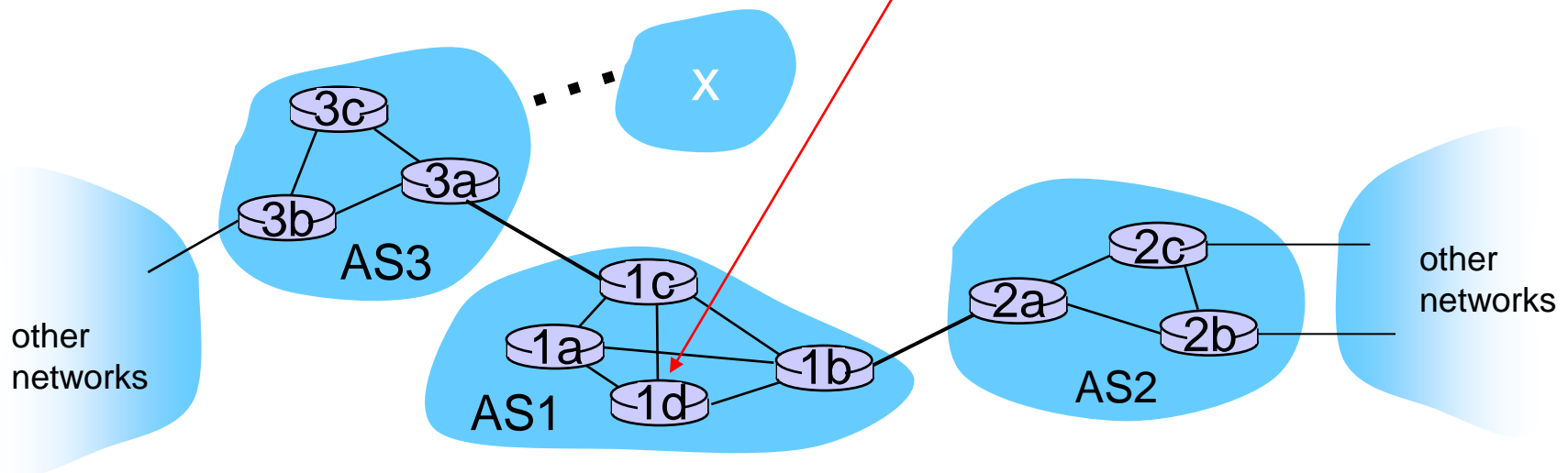
1. learn which destds are reachable through AS2, which through AS3
2. propagate this reachability info to all routers in AS1

job of inter-AS routing!



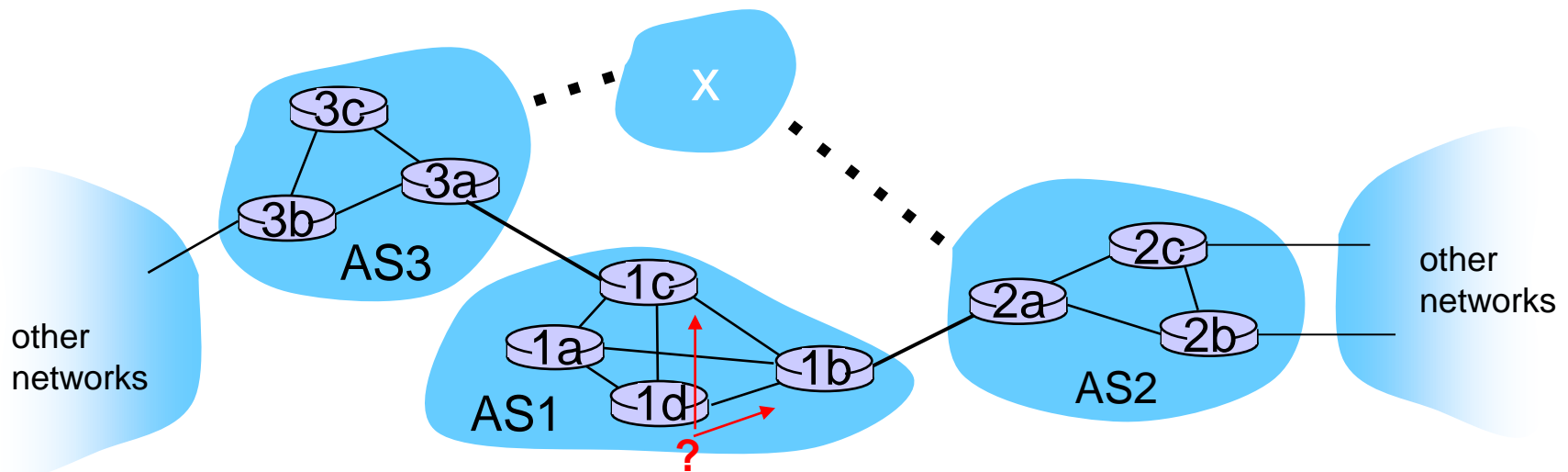
Example: setting forwarding table in router 1d

- ❖ 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 **l** is on the least cost path to 1c
 - installs forwarding table entry **(x,l)**



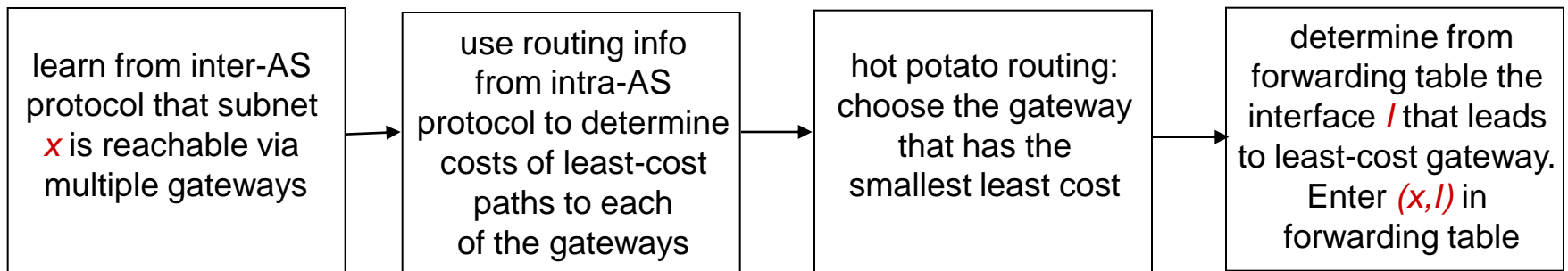
Example: choosing among multiple ASes

- ❖ 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 which gateway it should forward packets towards 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.



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- distance vector
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- OSPF
- BGP

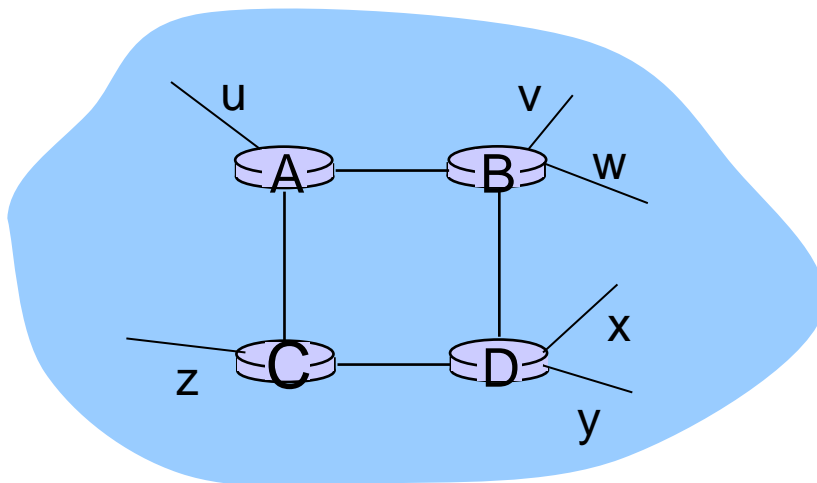
4.7 broadcast and multicast routing

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)

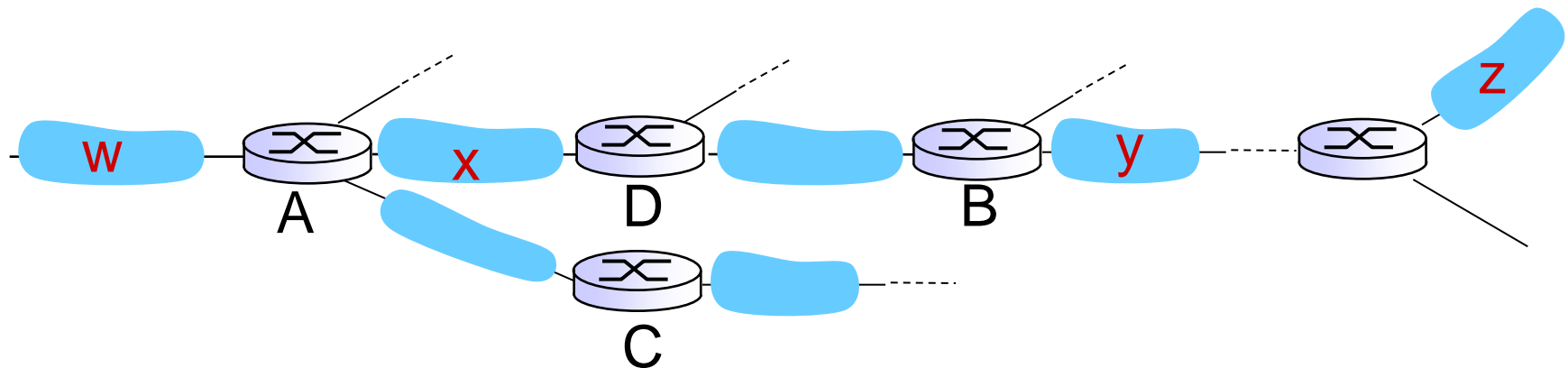
- ❖ included in BSD-UNIX distribution in 1982
- ❖ distance vector algorithm
 - distance metric: # hops (max = 15 hops), each link has cost 1
 - DVs exchanged with neighbors every 30 sec in response message (aka **advertisement**)
 - each advertisement: list of up to 25 destination **subnets** (in IP addressing sense)



from router A to destination **subnets**:

<u>subnet</u>	<u>hops</u>
u	1
v	2
w	2
x	3
y	3
z	2

RIP: example



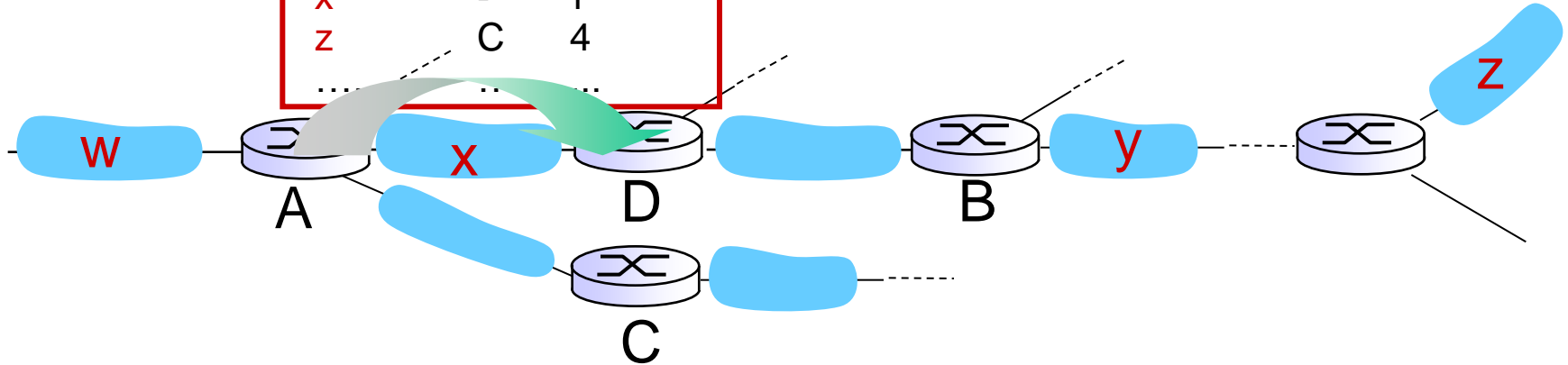
routing table in router D

destination subnet	next router	# hops to dest
W	A	2
y	B	2
z	B	7
x	--	1
....

RIP: example

A-to-D advertisement

dest	next	hops
W	-	1
X	-	1
Z	C	4
...



routing table in router D

destination subnet	next router	# hops to dest
W	A	2
y	B	2
Z	B → A	7 → 5
X	--	1
....

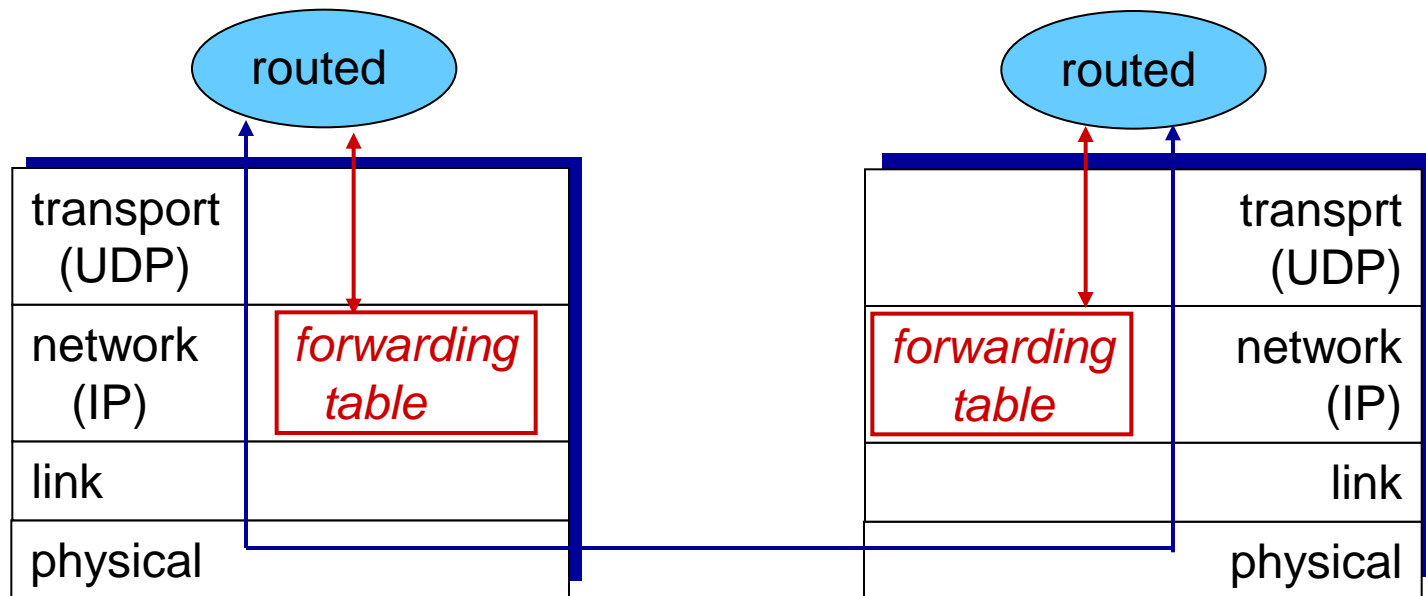
RIP: link failure, recovery

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
- *poison reverse* used to prevent ping-pong loops (infinite distance = 16 hops)

RIP table processing

- ❖ RIP routing tables managed by *application-level* process called route-d (daemon)
- ❖ advertisements sent in UDP packets, periodically repeated



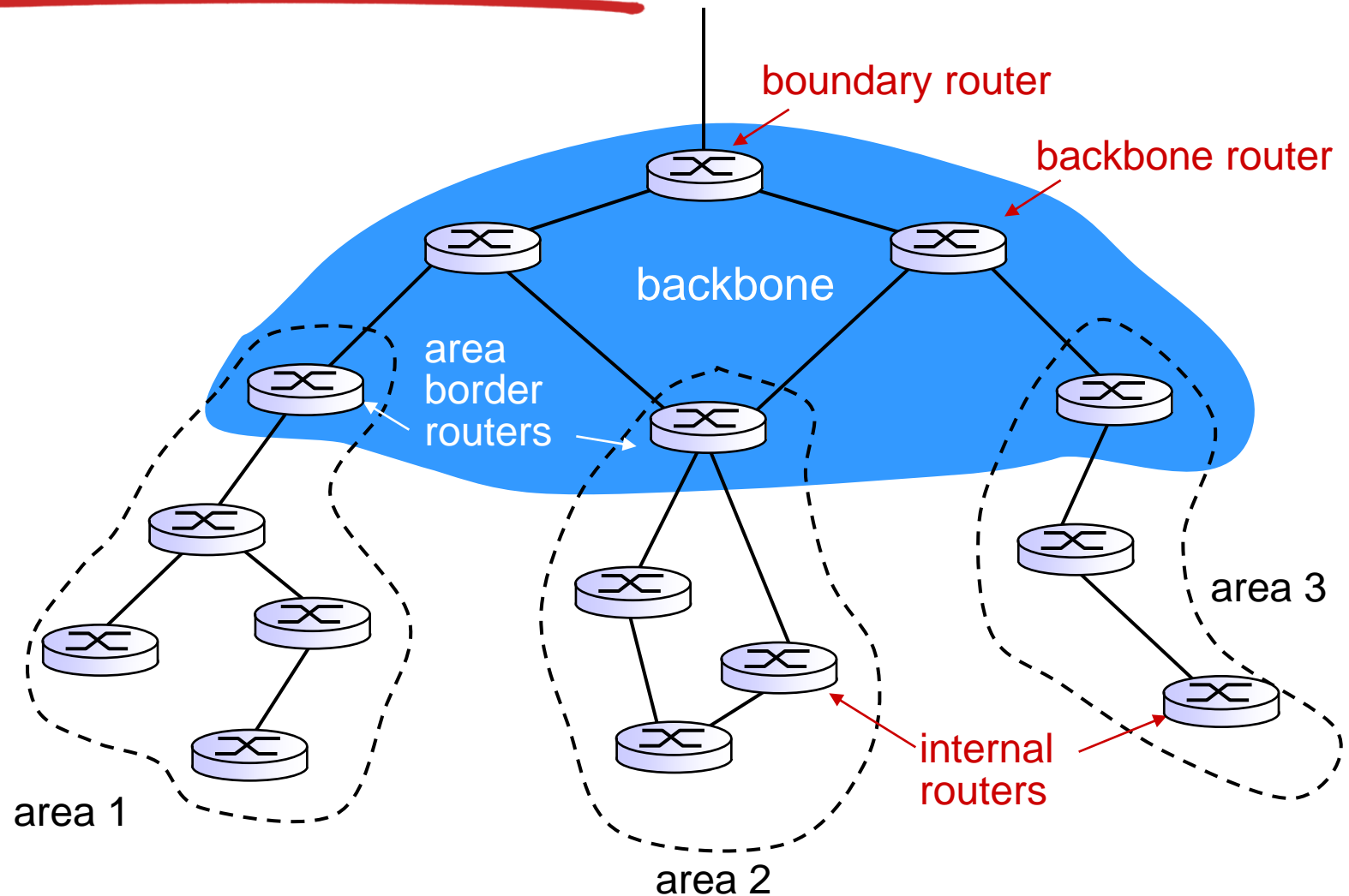
OSPF (Open Shortest Path First)

- ❖ “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

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



Hierarchical OSPF

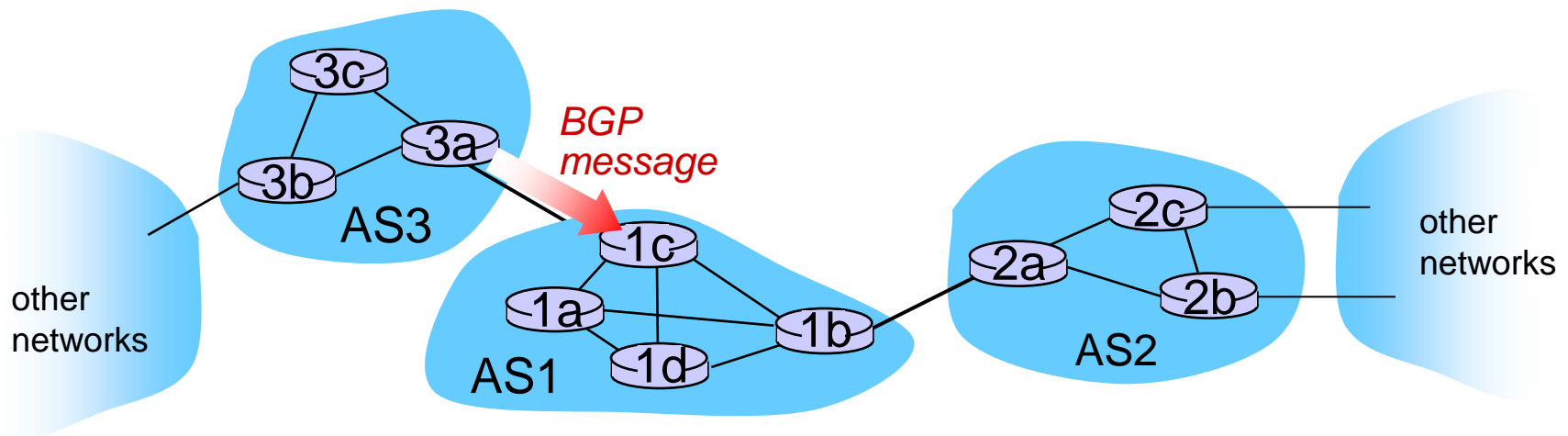
- ❖ *two-level hierarchy*: local area, backbone.
 - link-state advertisements only in area
 - each nodes has detailed area topology; only know direction (shortest path) to nets in other areas.
- ❖ *area border routers*: “summarize” distances to nets in own area, advertise to other Area Border routers.
- ❖ *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 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*”

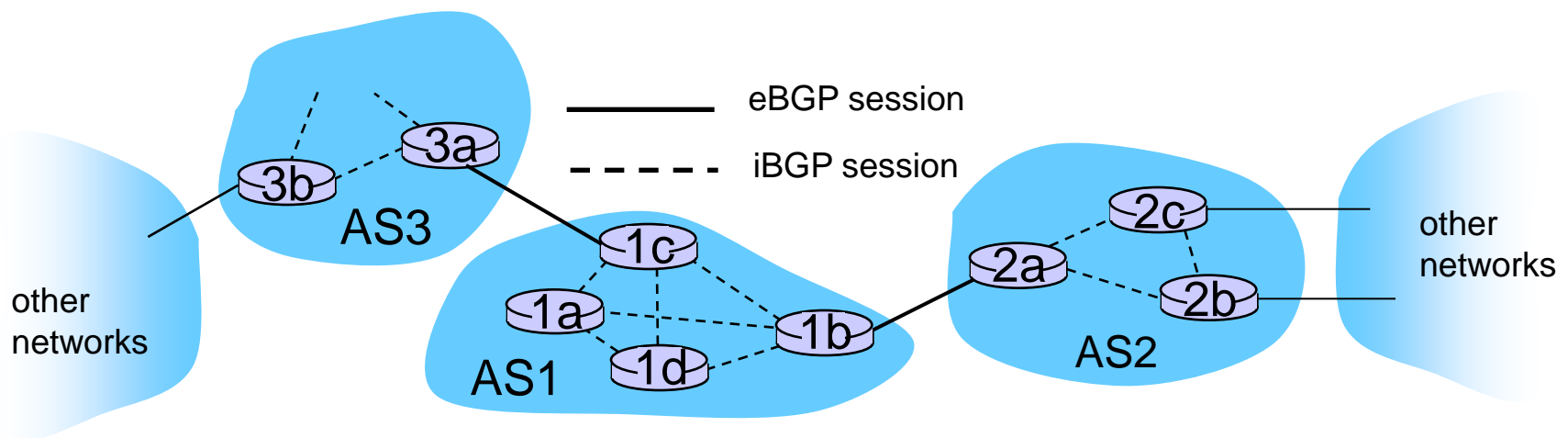
BGP basics

- ❖ **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 to 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

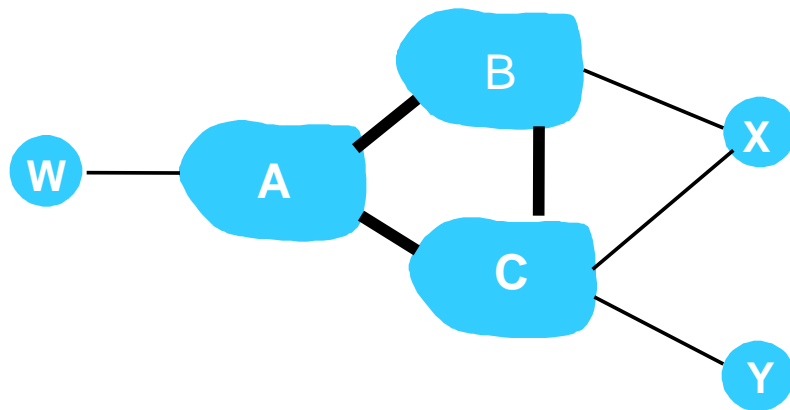
BGP route selection



- ❖ 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

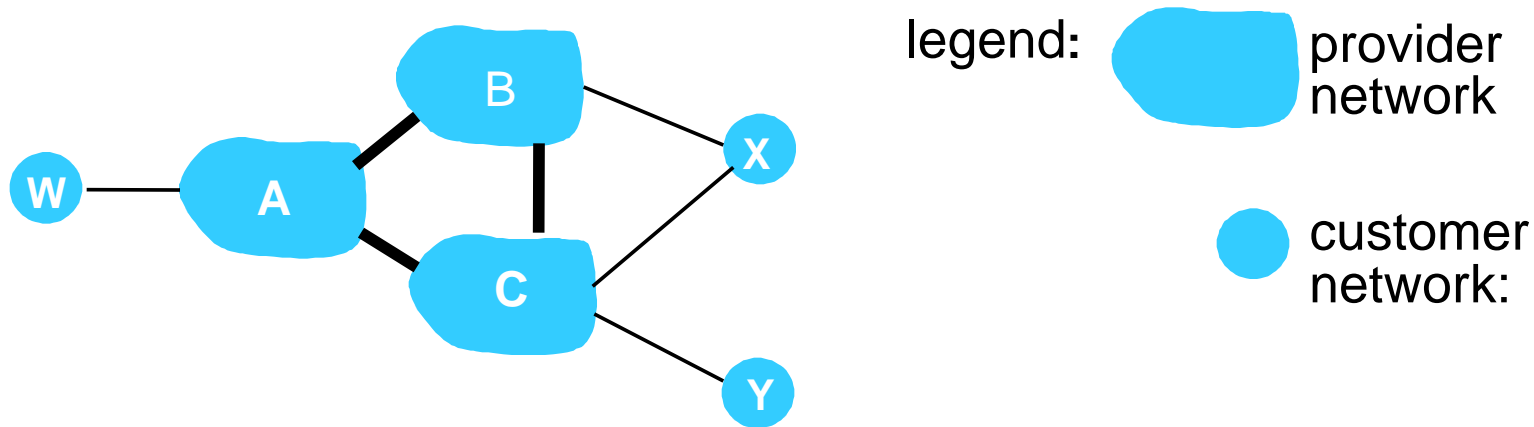
BGP routing policy



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)



- ❖ 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