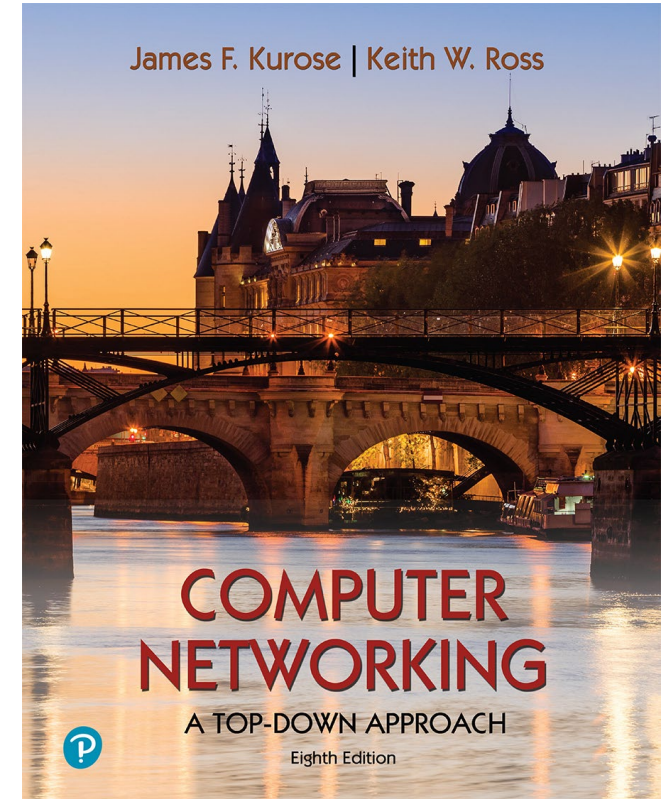


Network Layer: Control Plane

"Tell me and I forget. Show me and I remember. Involve me and I understand." Chinese proverb



Computer Networking: A Top-Down Approach

8th edition

Jim Kurose, Keith Ross
Pearson, 2020

Network layer control plane: our goals

- understand principles behind network control plane:
 - traditional routing algorithms
 - SDN controllers
 - network management, configuration
- instantiation, implementation in the Internet:
 - OSPF, BGP
 - OpenFlow, ODL and ONOS controllers
 - Internet Control Message Protocol: ICMP
 - SNMP, YANG/NETCONF

Network layer: “control plane” roadmap

- introduction
- routing protocols
 - link state
 - distance vector
 - hierarchical routing
- intra-ISP routing: OSPF
- routing among ISPs: BGP
- SDN control plane
- Internet Control Message Protocol



- network management, configuration
 - SNMP
 - NETCONF/YANG

Two key network-layer functions

network-layer functions:

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

analogy: taking a trip

- *forwarding*: process of getting through single interchange
- *routing*: process of planning trip from source to destination



forwarding



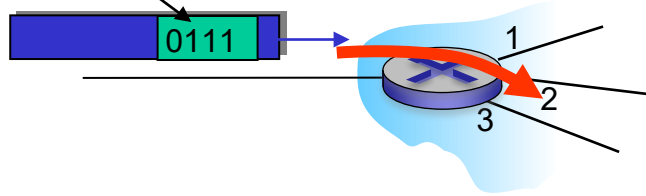
routing

Network layer: data plane, control plane

Data plane:

- *local*, per-router function
- determines how datagram arriving on router input port is forwarded to router output port

values in arriving
packet header

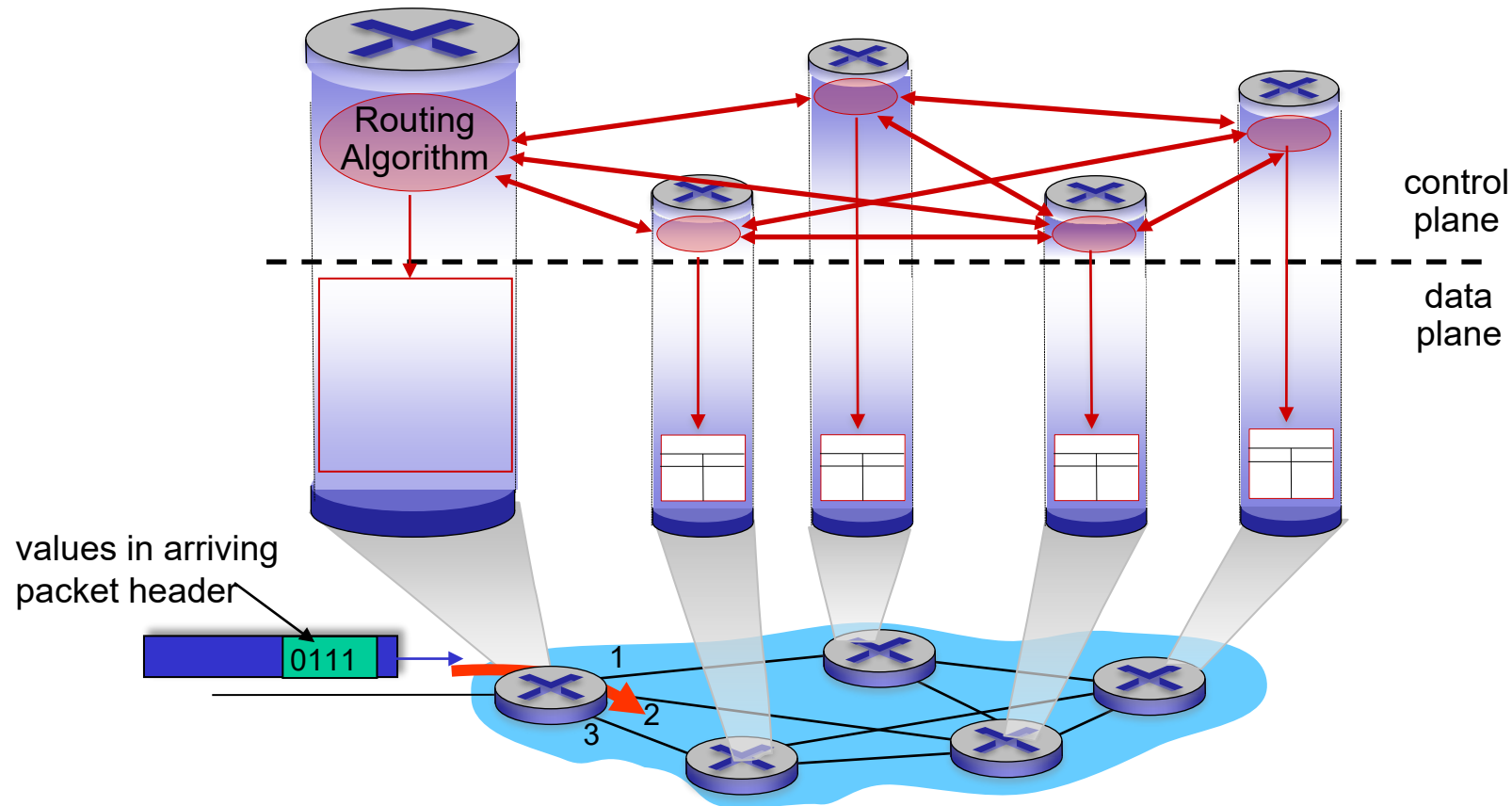


Control plane

- *network-wide* logic
- determines how datagram is routed among routers along end-end path from source host to destination host
- two control-plane approaches:
 - *traditional routing algorithms*: implemented in routers
 - *software-defined networking (SDN)*: implemented in (remote) servers

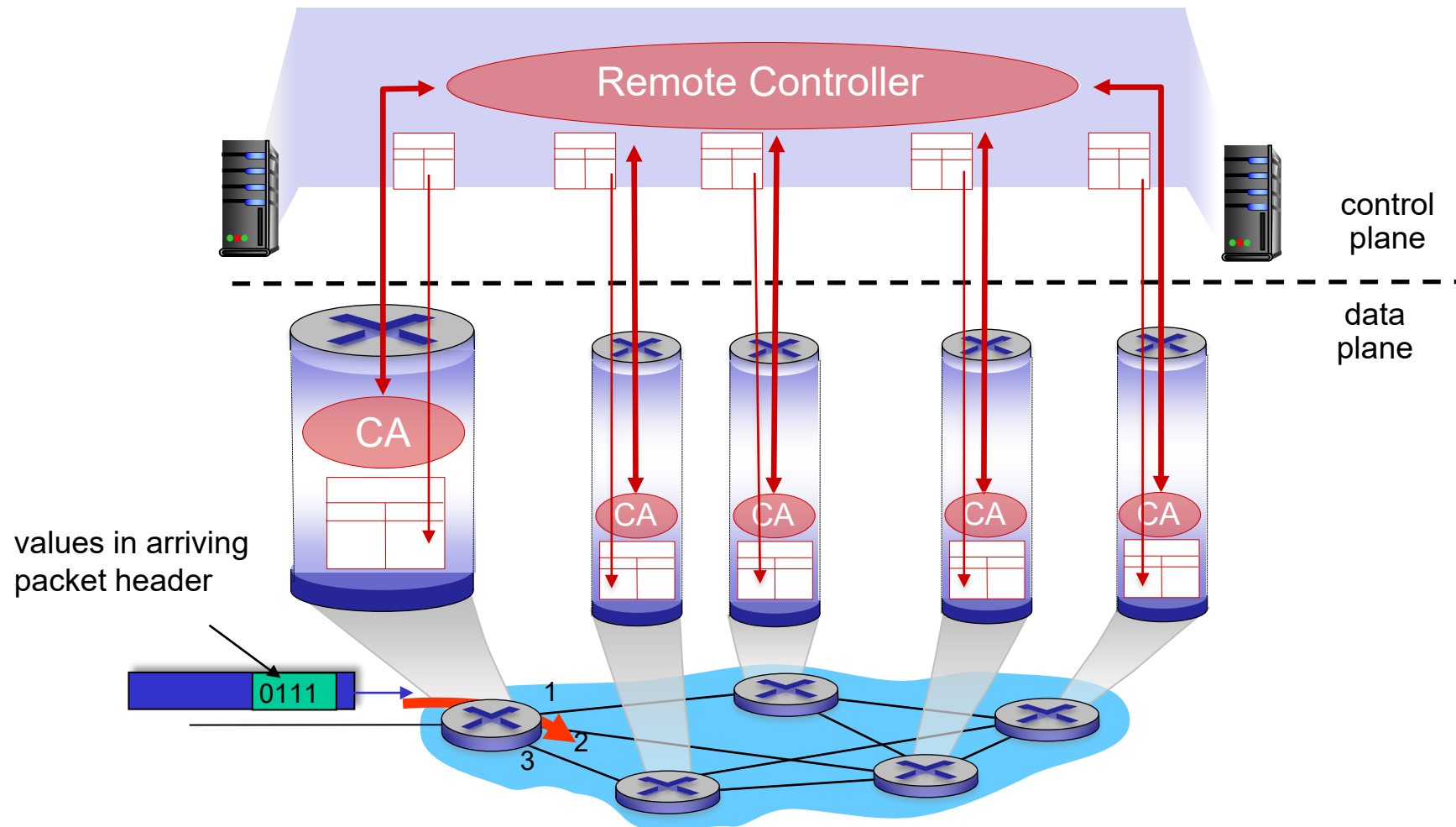
Per-router control plane

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

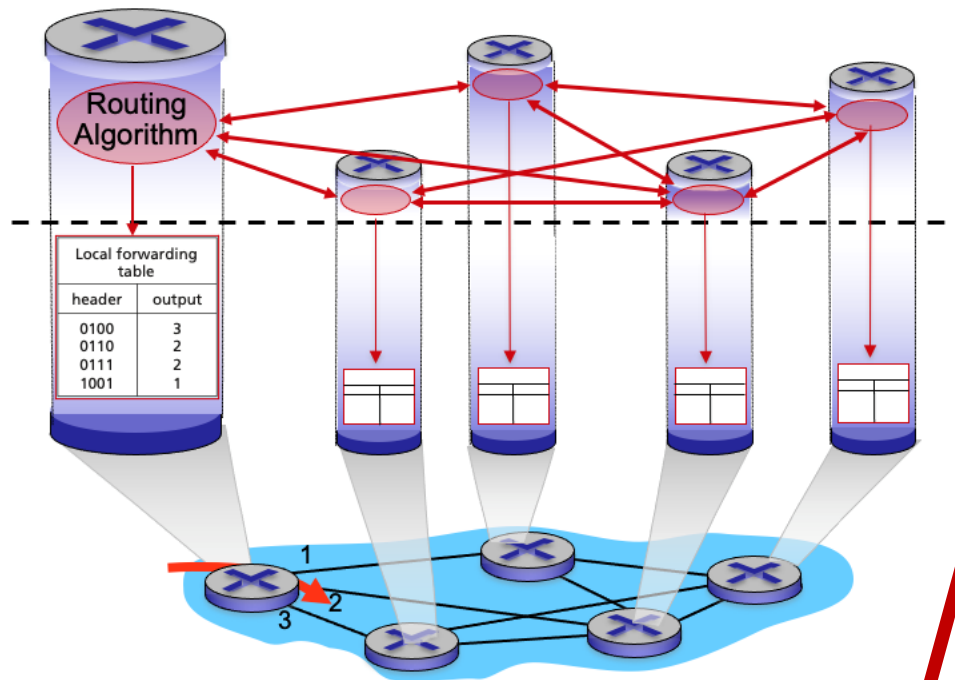


Software-Defined Networking (SDN) control plane

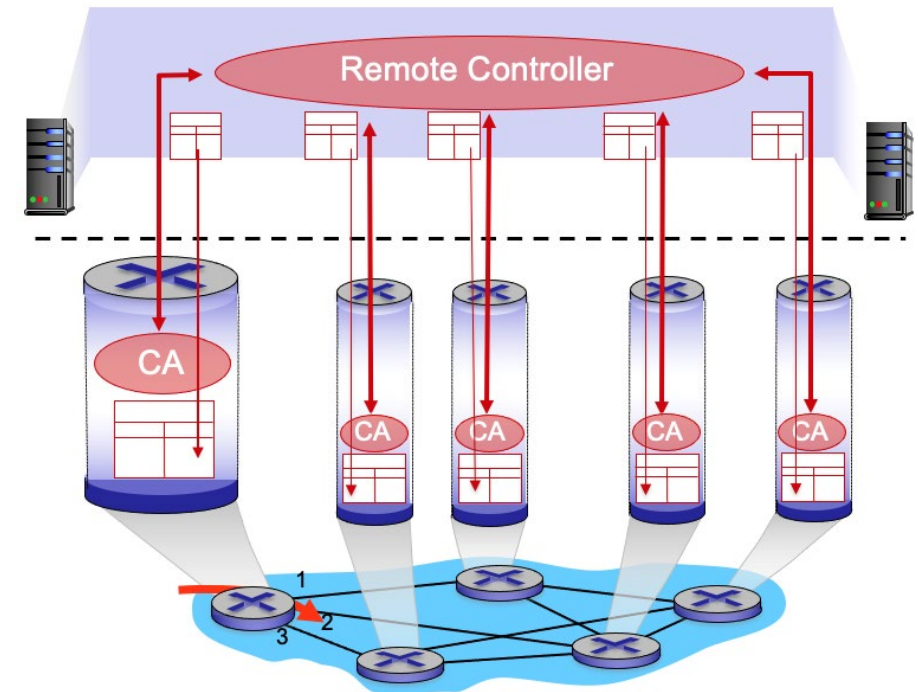
Remote controller computes, installs forwarding tables in routers



Per-router control plane



SDN control plane



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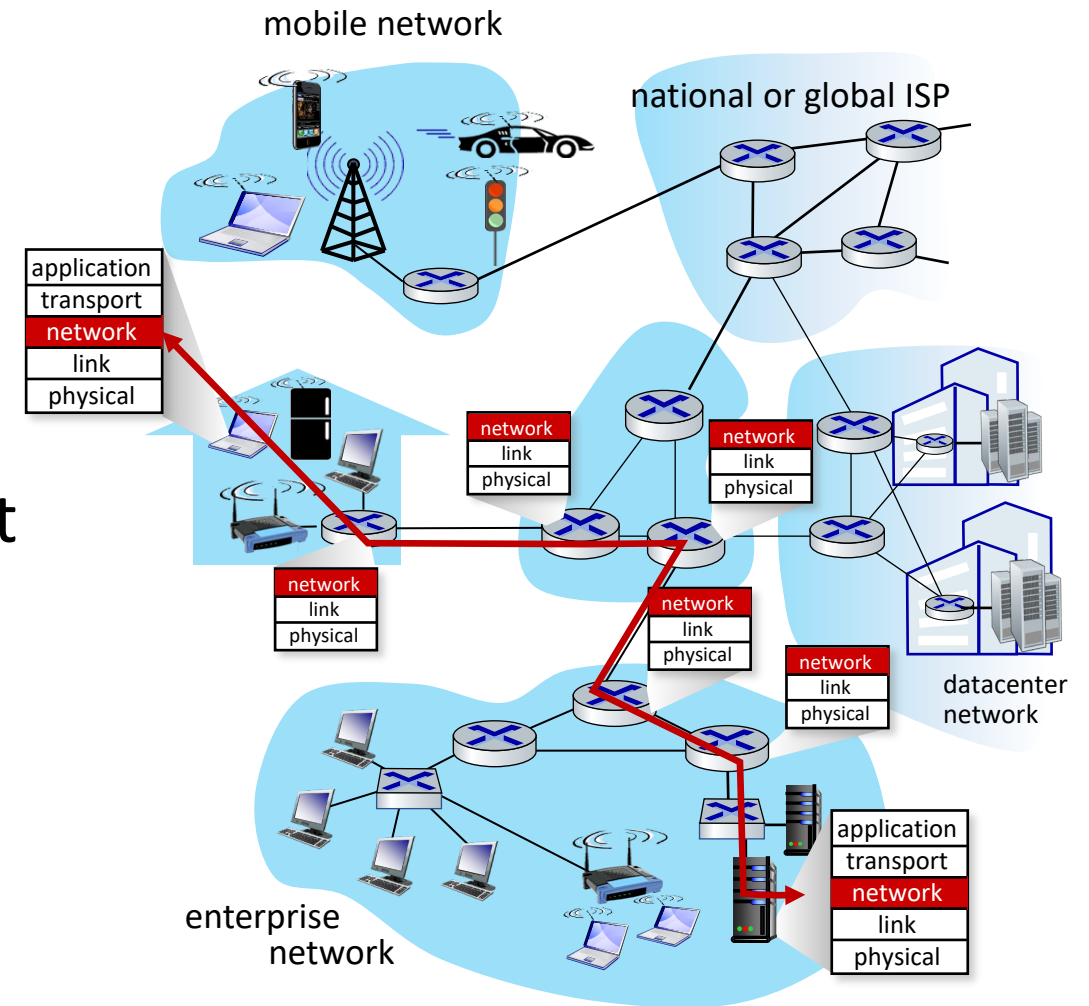


- network management, configuration
 - SNMP
 - NETCONF/YANG

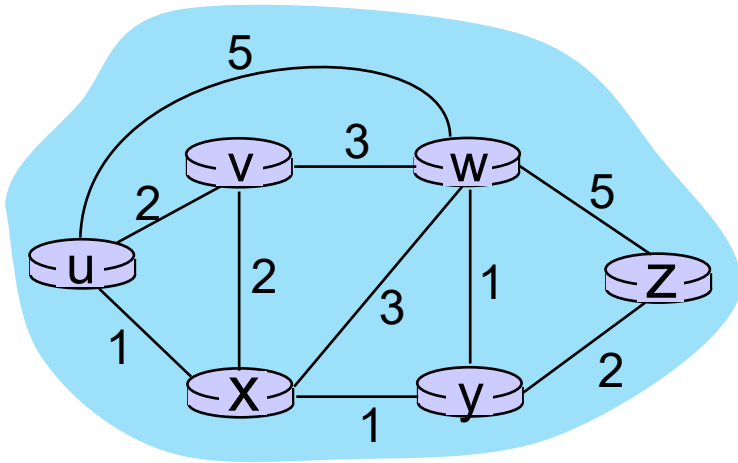
Routing protocols

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

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



Graph abstraction: link costs



$c_{a,b}$: cost of *direct* link connecting a and b

e.g., $c_{w,z} = 5$, $c_{u,z} = \infty$

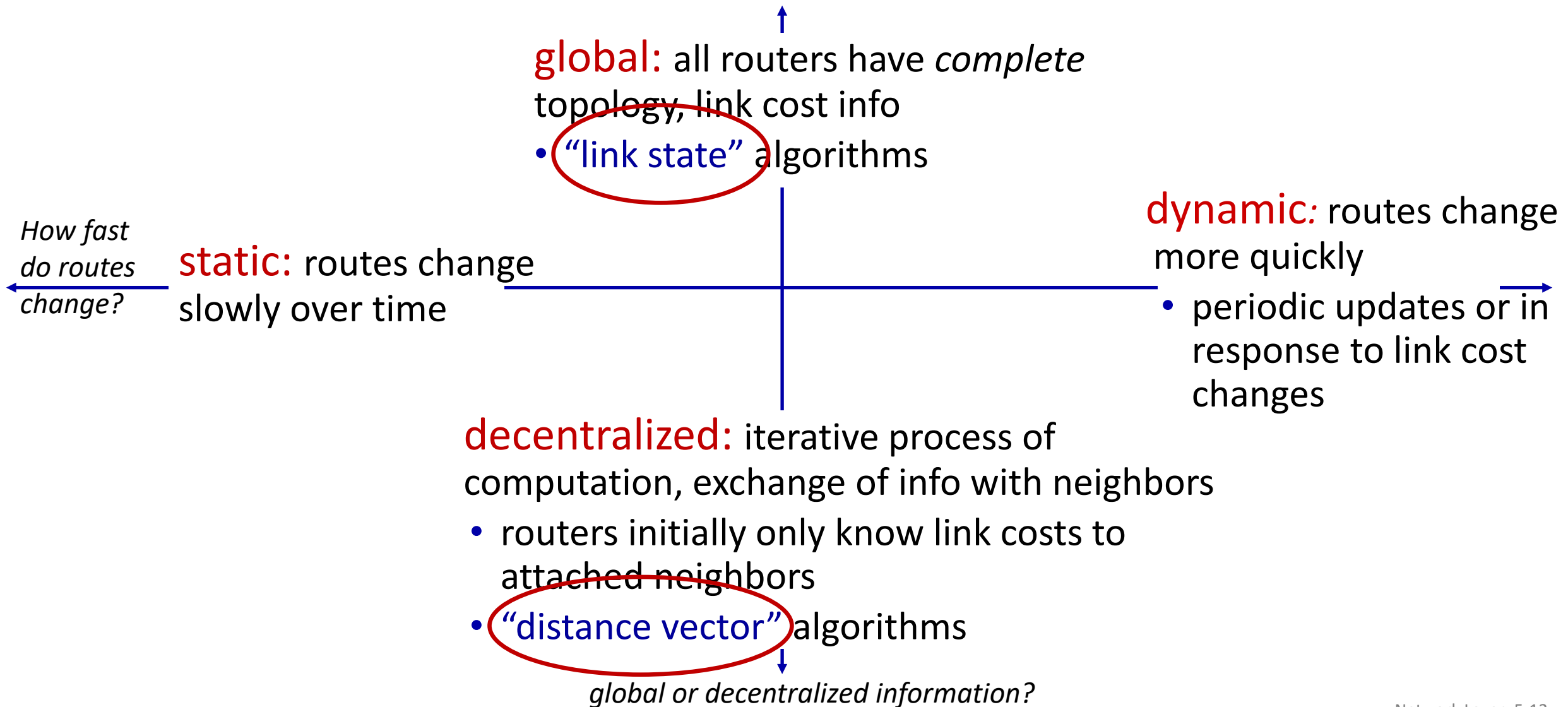
cost defined by network operator:
could always be 1, or inversely related
to bandwidth, or inversely related to
congestion

graph: $G = (N, E)$

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

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

Routing algorithm classification



Network layer: “control plane” roadmap

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Dijkstra's link-state routing algorithm

- **centralized:** network 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 destinations

notation

- $c_{x,y}$: direct link cost from node x to y ; $= \infty$ if not direct neighbors
- $D(v)$: *current* estimate of cost of least-cost-path from source to destination v
- $p(v)$: predecessor node along path from source to v
- N' : set of nodes whose least-cost-path *definitively* known

Dijkstra's link-state routing algorithm

1 *Initialization:*

2 $N' = \{u\}$ /* compute least cost path from u to all other nodes */

3 for all nodes v

4 if v adjacent to u /* u initially knows direct-path-cost only to direct neighbors */

5 then $D(v) = c_{u,v}$ /* but may not be *minimum* cost! */

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 **$D(v) = \min (D(v), D(w) + c_{w,v})$**

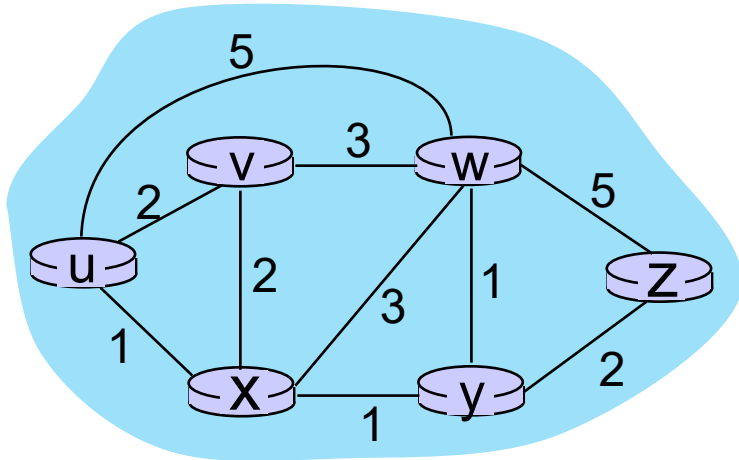
13 /* new least-path-cost to v is either old least-cost-path to v or known

14 least-cost-path to w plus direct-cost from w to v */

15 *until all nodes in N'*

Dijkstra's algorithm: an example

		v	w	x	y	z
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						
2						
3						
4						
5						

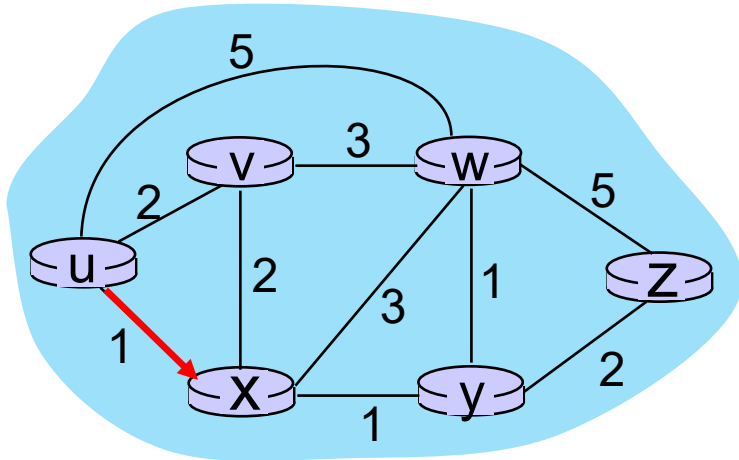


Initialization (step 0):

For all a : if a adjacent to u then $D(a) = c_{u,a}$

Dijkstra's algorithm: an 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						
3						
4						
5						



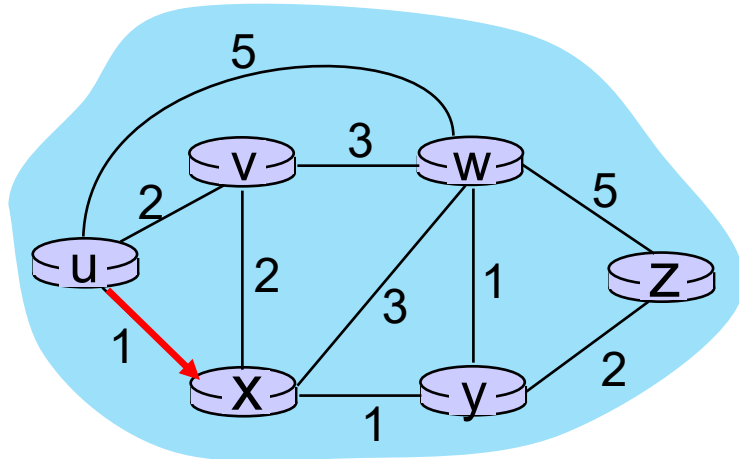
8 Loop

9 find a not in N' such that $D(a)$ is a minimum

10 add a to N'

Dijkstra's algorithm: an example

		v	w	x	y	z
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						
3						
4						
5						



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11 update $D(b)$ for all b adjacent to a and not in N' :

$$D(b) = \min (D(b), D(a) + c_{a,b})$$

$$D(v) = \min (D(v), D(x) + c_{x,v}) = \min(2, 1+2) = 2$$

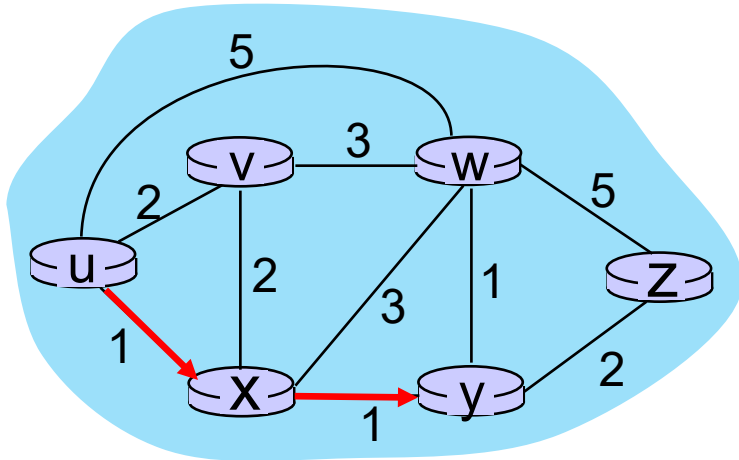
$$D(w) = \min (D(w), D(x) + c_{x,w}) = \min(5, 1+3) = 4$$

$$D(y) = \min (D(y), D(x) + c_{x,y}) = \min(\infty, 1+1) = 2$$



Dijkstra's algorithm: an example

		v	w	x	y	z
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					
3						
4						
5						



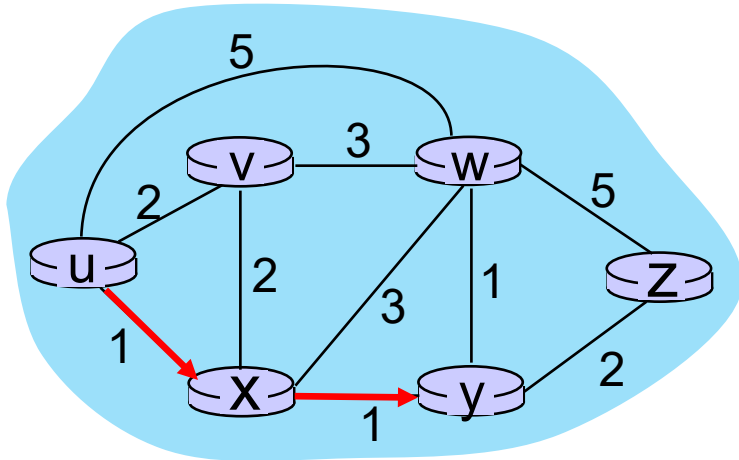
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Dijkstra's algorithm: an example

		v	w	x	y	z
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						
4						
5						



8 Loop

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11 update $D(b)$ for all b adjacent to a and not in N' :

$$D(b) = \min (D(b), D(a) + c_{a,b})$$

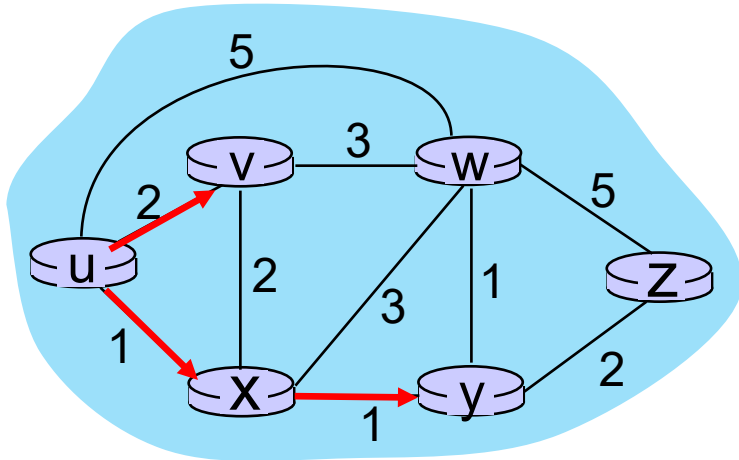
$$D(w) = \min (D(w), D(y) + c_{y,w}) = \min (4, 2+1) = 3$$

$$D(z) = \min (D(z), D(y) + c_{y,z}) = \min (\infty, 2+2) = 4$$

NEW!
NEW!

Dijkstra's algorithm: an 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					
4						
5						



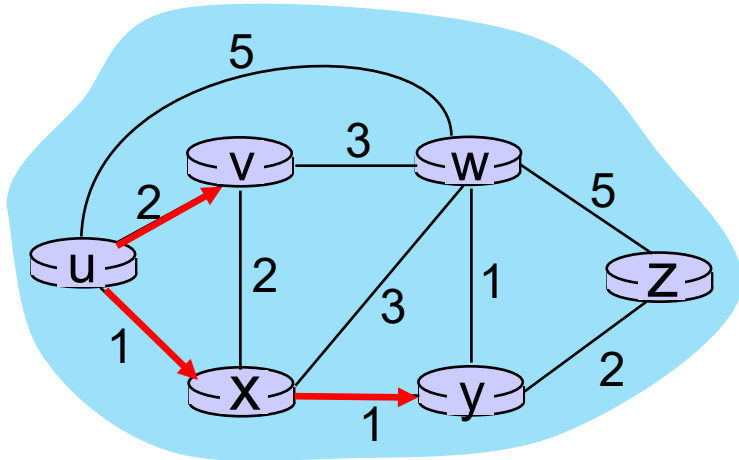
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Dijkstra's algorithm: an example

		v	w	x	y	z
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						
5						



8 *Loop*

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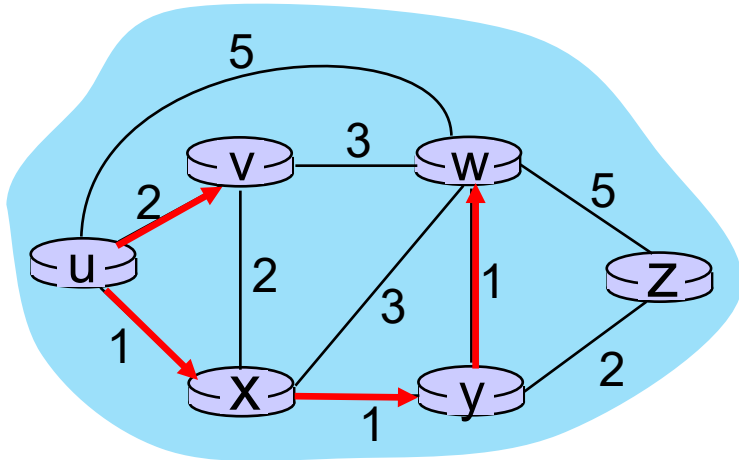
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$$D(b) = \min (D(b), D(a) + c_{a,b})$$

$$D(w) = \min (D(w), D(v) + c_{v,w}) = \min (3, 2+3) = 3$$

Dijkstra's algorithm: an 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	∞	∞	∞	∞	∞
5						



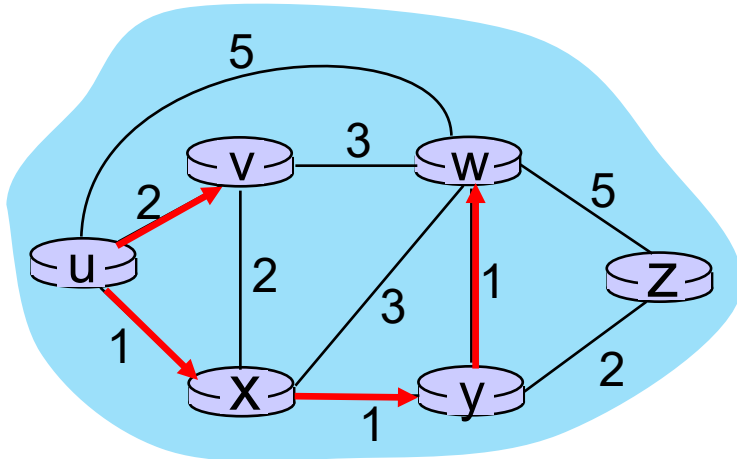
8 Loop

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10 add a to N'

Dijkstra's algorithm: an example

		v	w	x	y	z
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						



8 *Loop*

9 find a not in N' such that $D(a)$ is a minimum

10 add a to N'

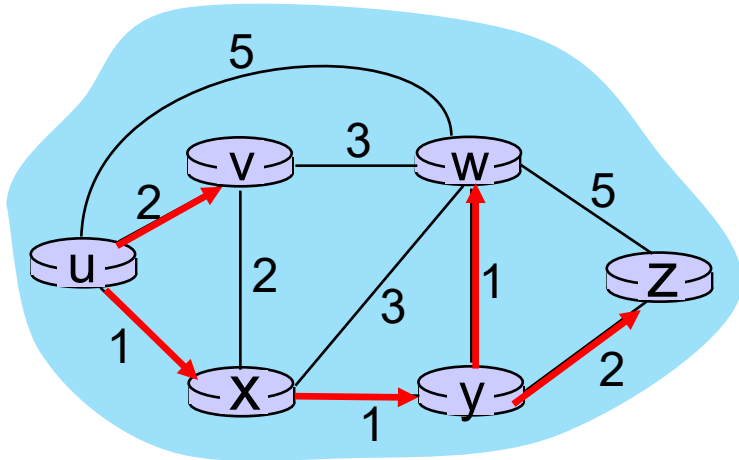
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Dijkstra's algorithm: an example

		v	w	x	y	z
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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					



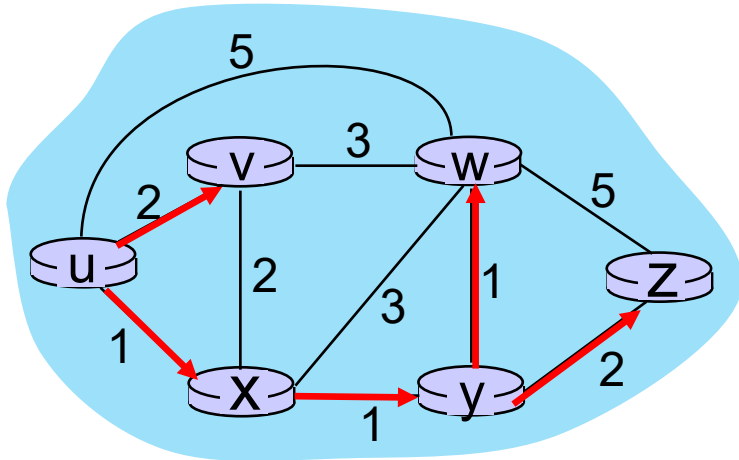
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Dijkstra's algorithm: an example

		v	w	x	y	z
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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					

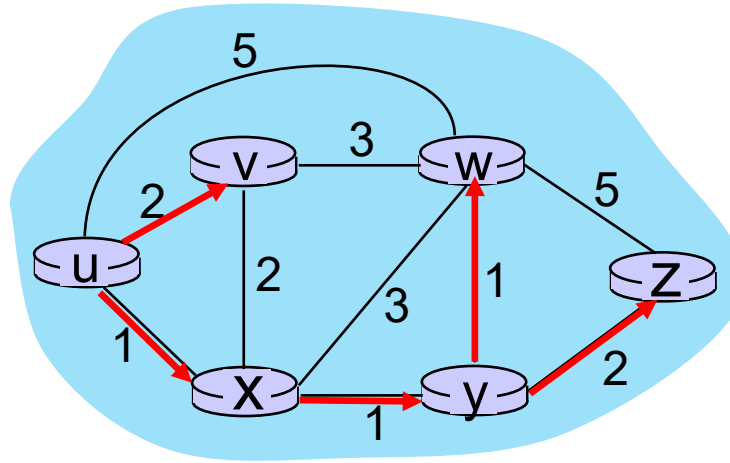


8 Loop

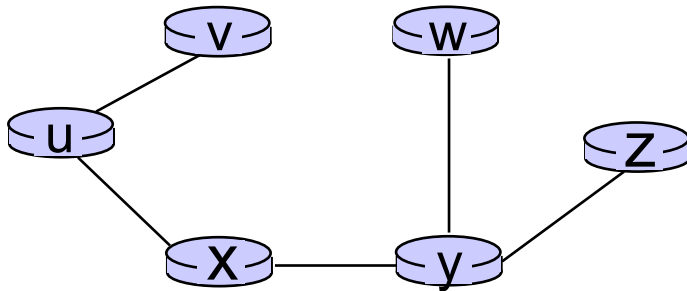
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- 11 update $D(b)$ for all b adjacent to a and not in N' :

$$D(b) = \min (D(b), D(a) + c_{a,b})$$

Dijkstra's algorithm: an example



resulting least-cost-path tree from u:



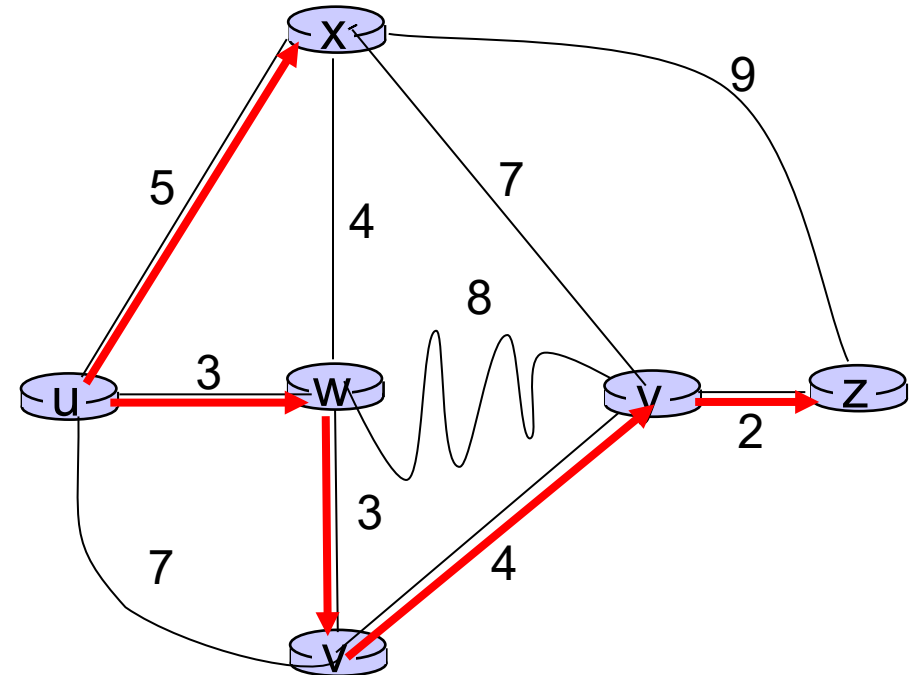
resulting forwarding table in u:

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

route from u to v directly
route from u to x directly
route from u to all other destinations via x

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	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 least-cost-path tree by tracing predecessor nodes
- ties can exist (can be broken arbitrarily)

Dijkstra's algorithm: discussion

algorithm complexity: n nodes

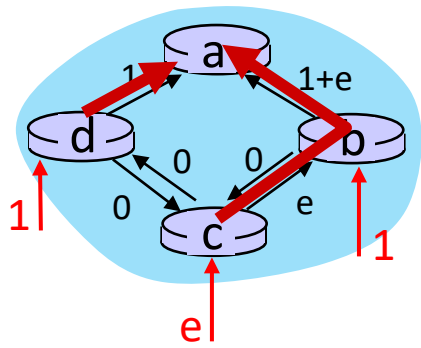
- each of n iteration: need to check all nodes, w , not in N
- $n(n+1)/2$ comparisons: $O(n^2)$ complexity
- more efficient implementations possible: $O(n \log n)$

message complexity:

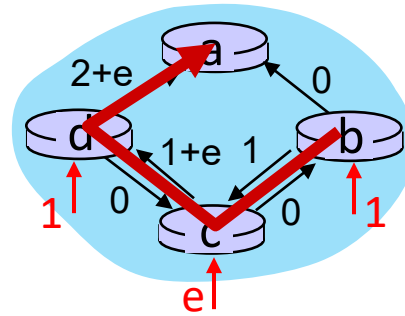
- each router must *broadcast* its link state information to other n routers
- efficient (and interesting!) broadcast algorithms: $O(n)$ link crossings to disseminate a broadcast message from one source
- each router's message crosses $O(n)$ links: overall message complexity: $O(n^2)$

Dijkstra's algorithm: oscillations possible

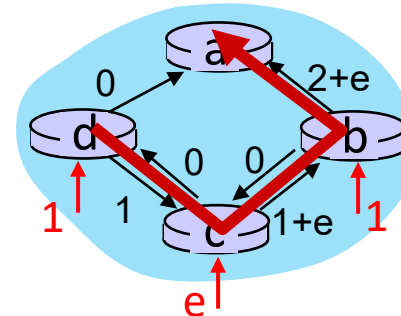
- when link costs depend on traffic volume, **route oscillations** possible
- sample scenario:
 - routing to destination a, traffic entering at d, c, e with rates 1, e (<1), 1
 - link costs are directional, and volume-dependent



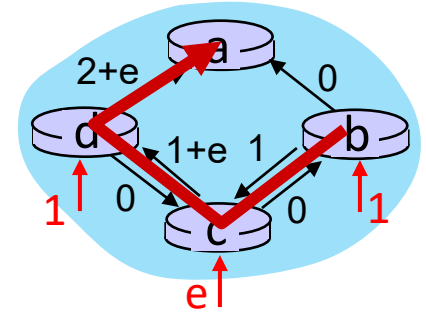
initially



given these costs,
find new routing....
resulting in new costs



given these costs,
find new routing....
resulting in new costs



given these costs,
find new routing....
resulting in new costs

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- network management, configuration
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 - NETCONF/YANG

Distance vector algorithm

Based on *Bellman-Ford* (BF) equation (dynamic programming):

Bellman-Ford equation

Let $D_x(y)$: cost of least-cost path from x to y .

Then:

$$D_x(y) = \min_v \{ c_{x,v} + D_v(y) \}$$

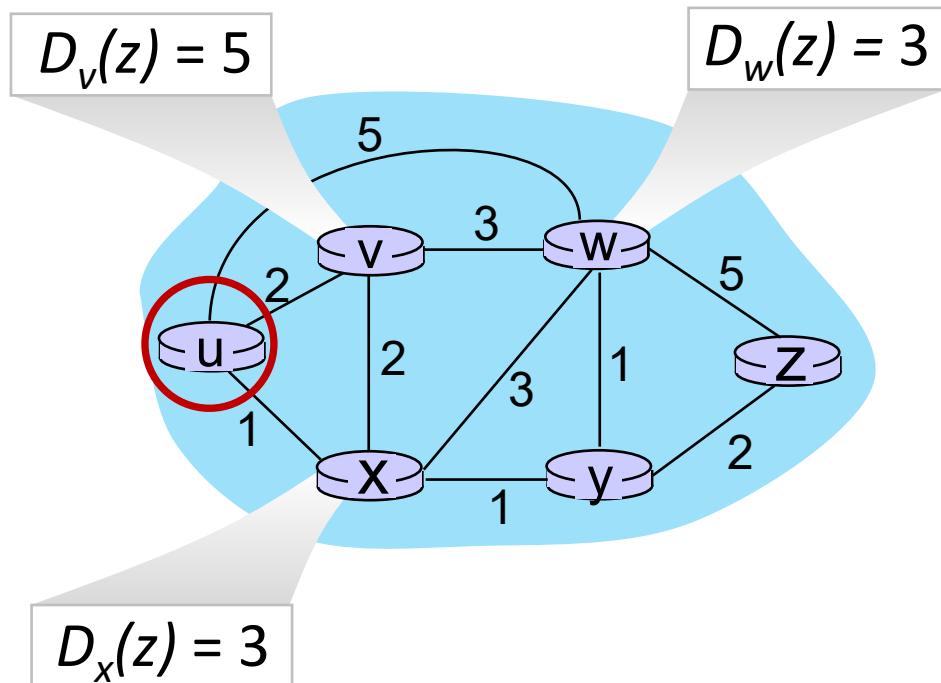
\min taken over all neighbors v of x

direct cost of link from x to v

v 's estimated least-cost-path cost to y

Bellman-Ford Example

Suppose that u 's neighboring nodes, x, v, w , know that for destination z :



Bellman-Ford 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 (x) is next hop on estimated least-cost path to destination (z)

Distance vector algorithm

key idea:

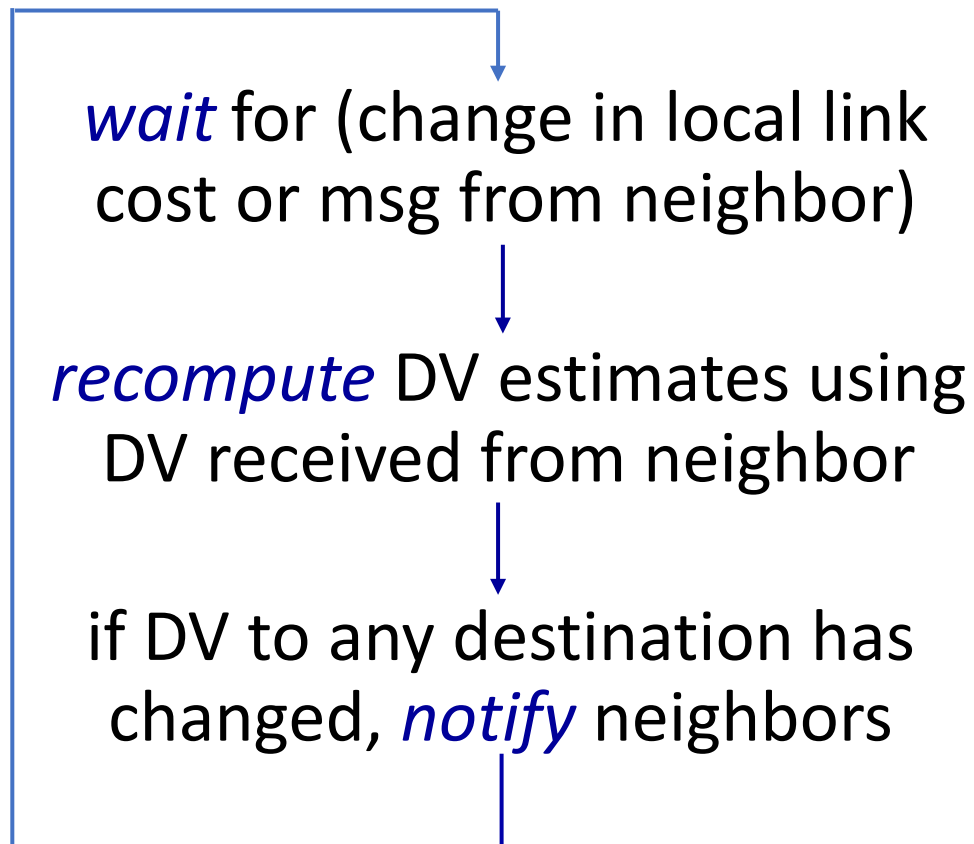
- from time-to-time, each node sends its own distance vector estimate to neighbors
- when x receives new DV estimate from any neighbor, it updates its own DV using B-F equation:

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

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

Distance vector algorithm:

each node:



iterative, asynchronous: each local iteration caused by:

- local link cost change
- DV update message from neighbor

distributed, self-stopping: each node notifies neighbors *only* when its DV changes

- neighbors then notify their neighbors – *only if necessary*
- no notification received, no actions taken!

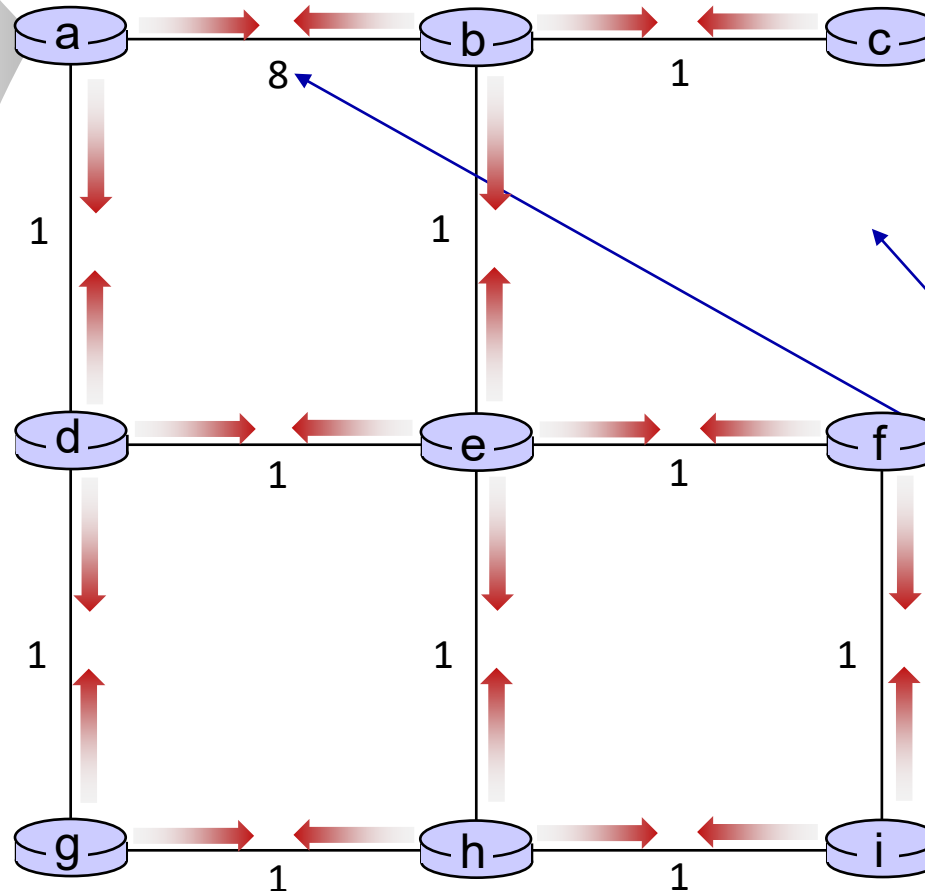
Distance vector: example



t=0

- All nodes have distance estimates to nearest neighbors (only)
- All nodes send their local distance vector to their neighbors

DV in a:
$D_a(a)=0$
$D_a(b)=8$
$D_a(c)=\infty$
$D_a(d)=1$
$D_a(e)=\infty$
$D_a(f)=\infty$
$D_a(g)=\infty$
$D_a(h)=\infty$
$D_a(i)=\infty$



A few asymmetries:
■ missing link
■ larger cost

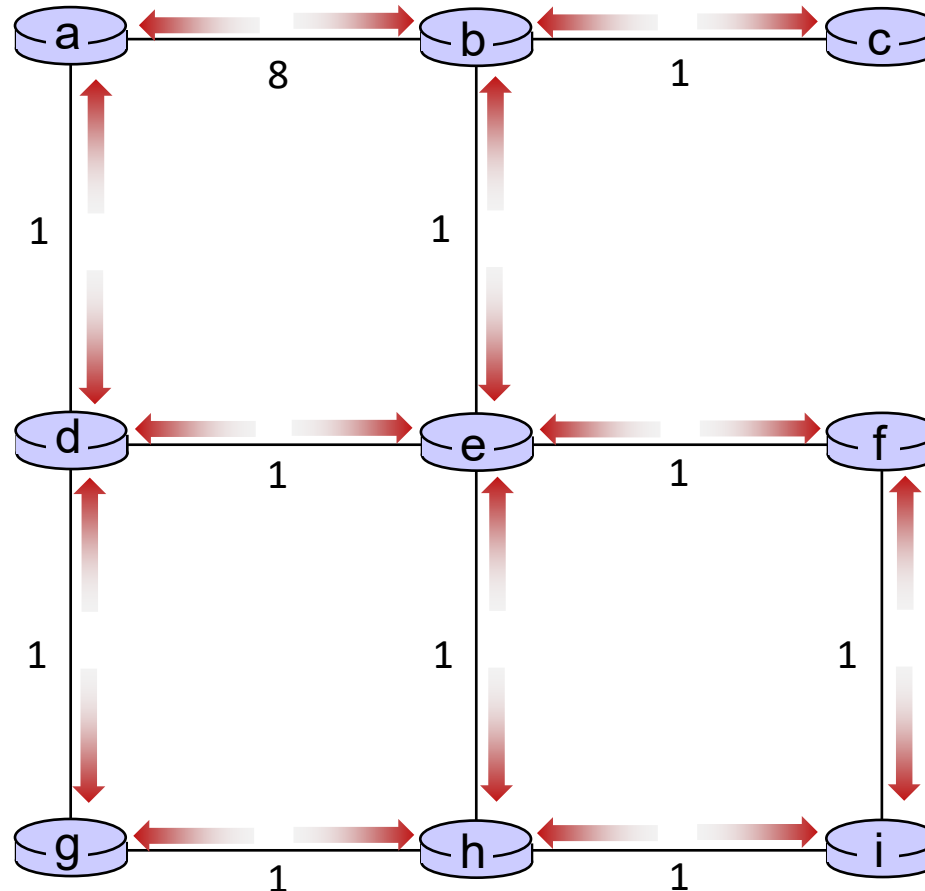
Distance vector example: iteration



t=1

All nodes:

- receive distance vectors from neighbors
- compute their new local distance vector
- send their new local distance vector to neighbors



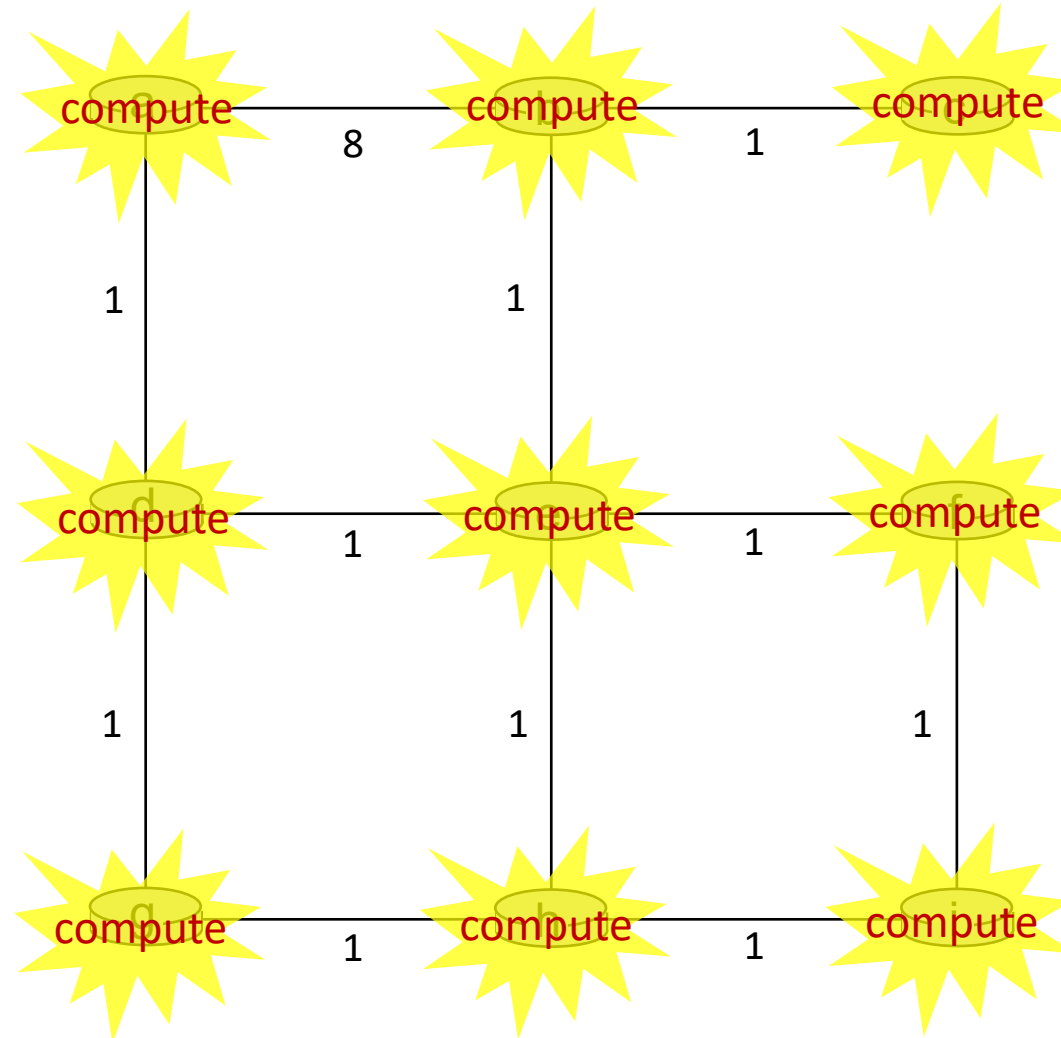
Distance vector example: iteration



t=1

All nodes:

- receive distance vectors from neighbors
- compute their new local distance vector
- send their new local distance vector to neighbors



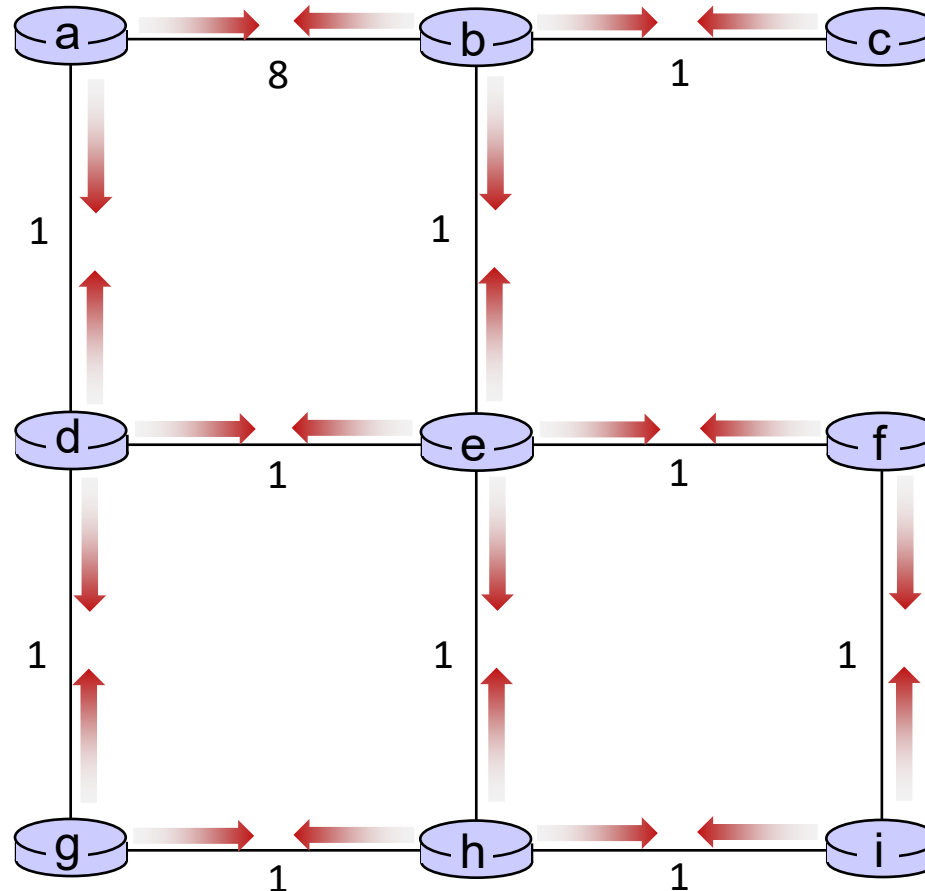
Distance vector example: iteration



t=1

All nodes:

- receive distance vectors from neighbors
- compute their new local distance vector
- send their new local distance vector to neighbors



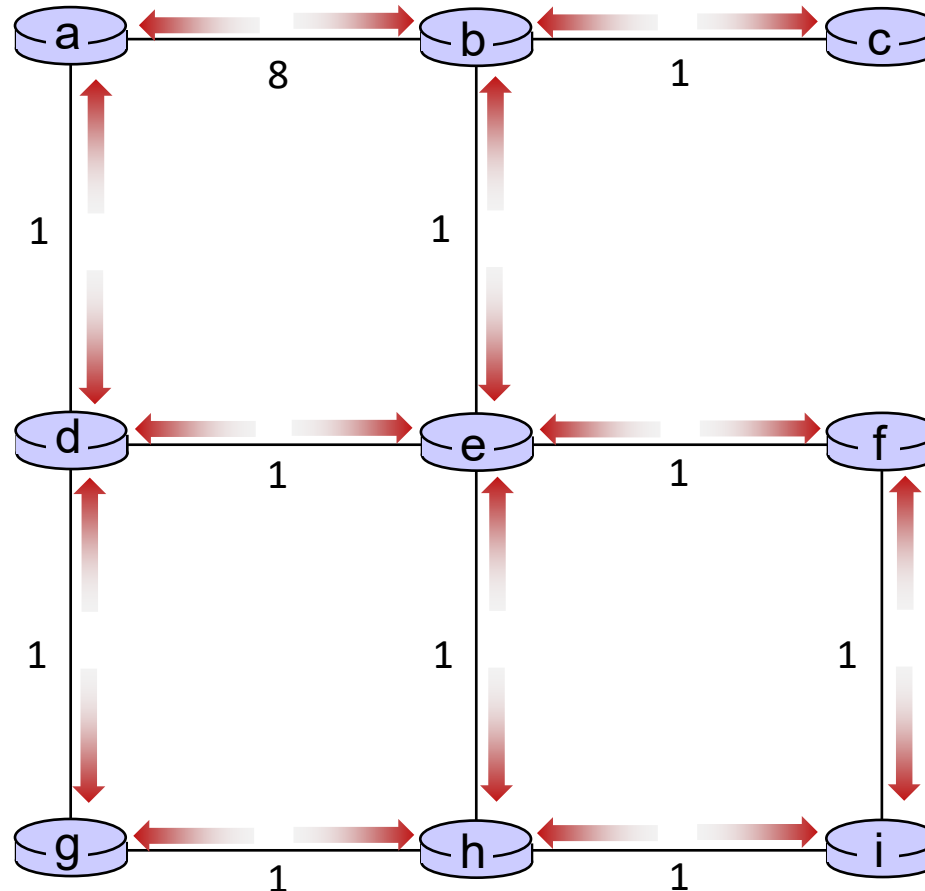
Distance vector example: iteration



t=2

All nodes:

- receive distance vectors from neighbors
- compute their new local distance vector
- send their new local distance vector to neighbors



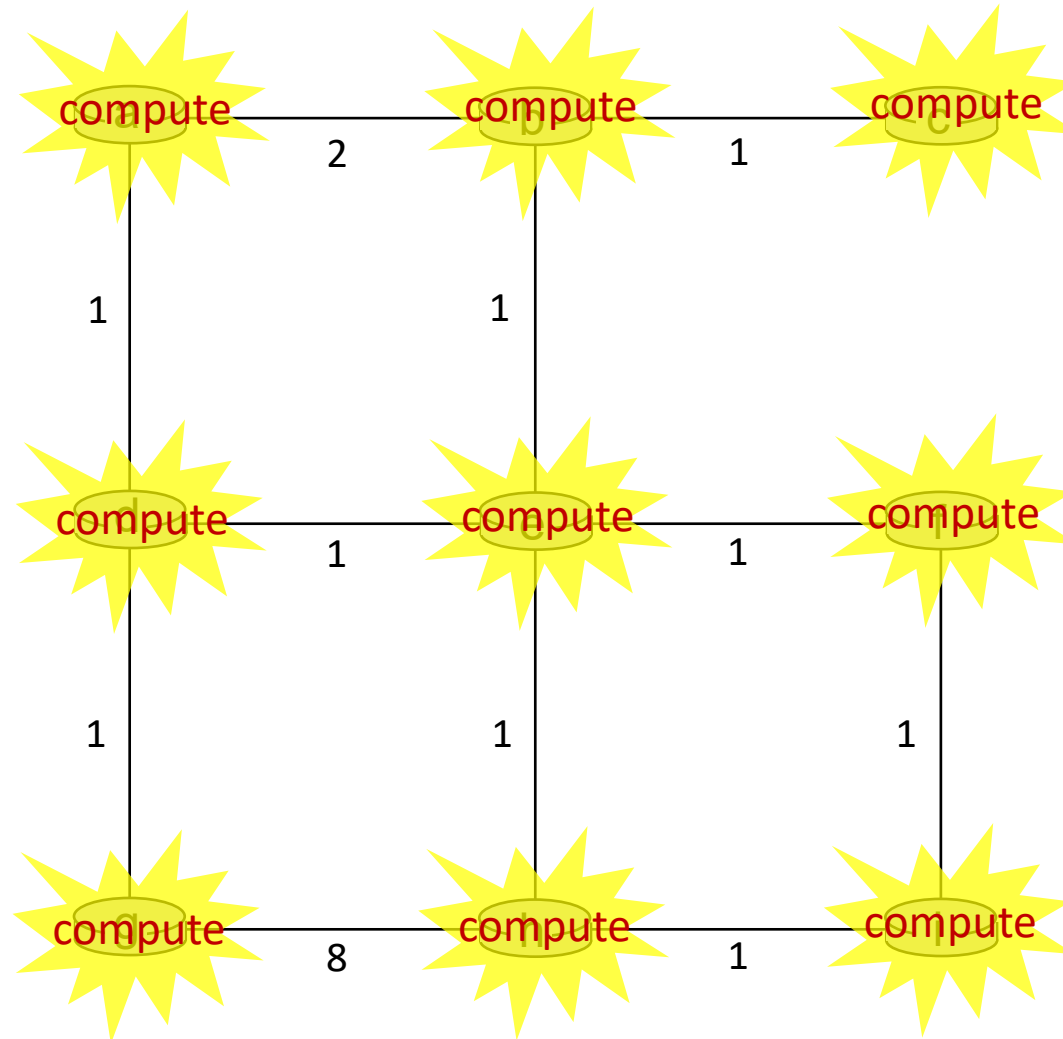
Distance vector example: iteration



t=2

All nodes:

- receive distance vectors from neighbors
- compute their new local distance vector
- send their new local distance vector to neighbors



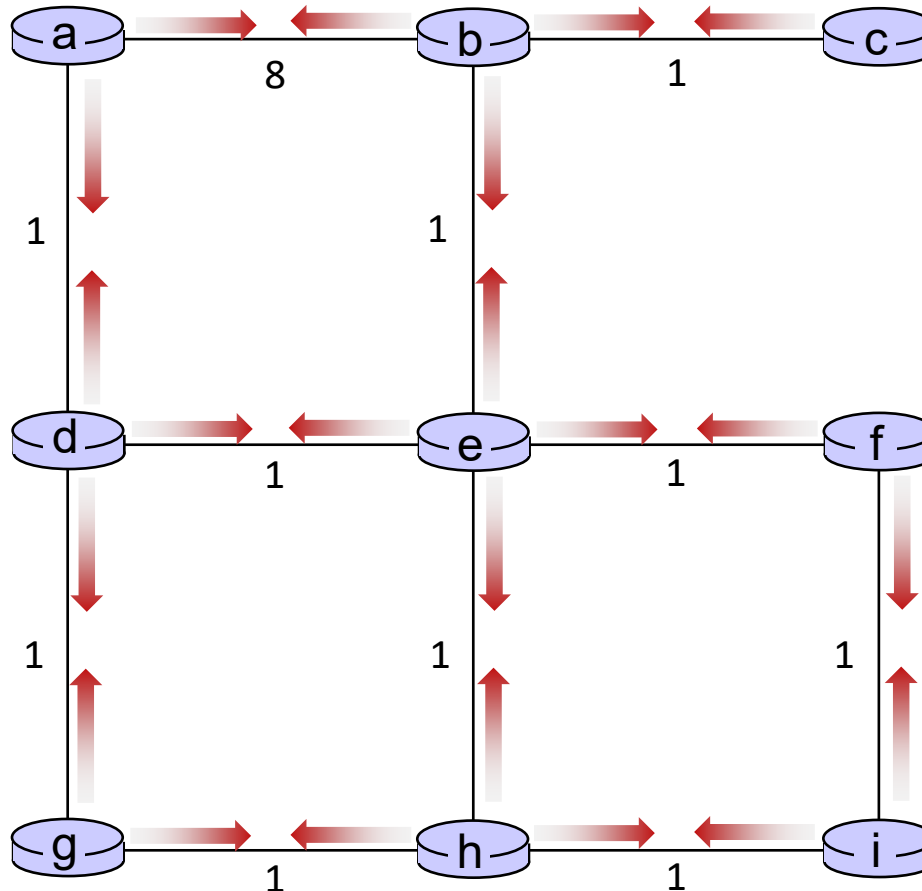
Distance vector example: iteration



t=2

All nodes:

- receive distance vectors from neighbors
- compute their new local distance vector
- send their new local distance vector to neighbors



Distance vector example: iteration

.... and so on

Let's next take a look at the iterative *computations* at nodes

Distance vector example:



t=1

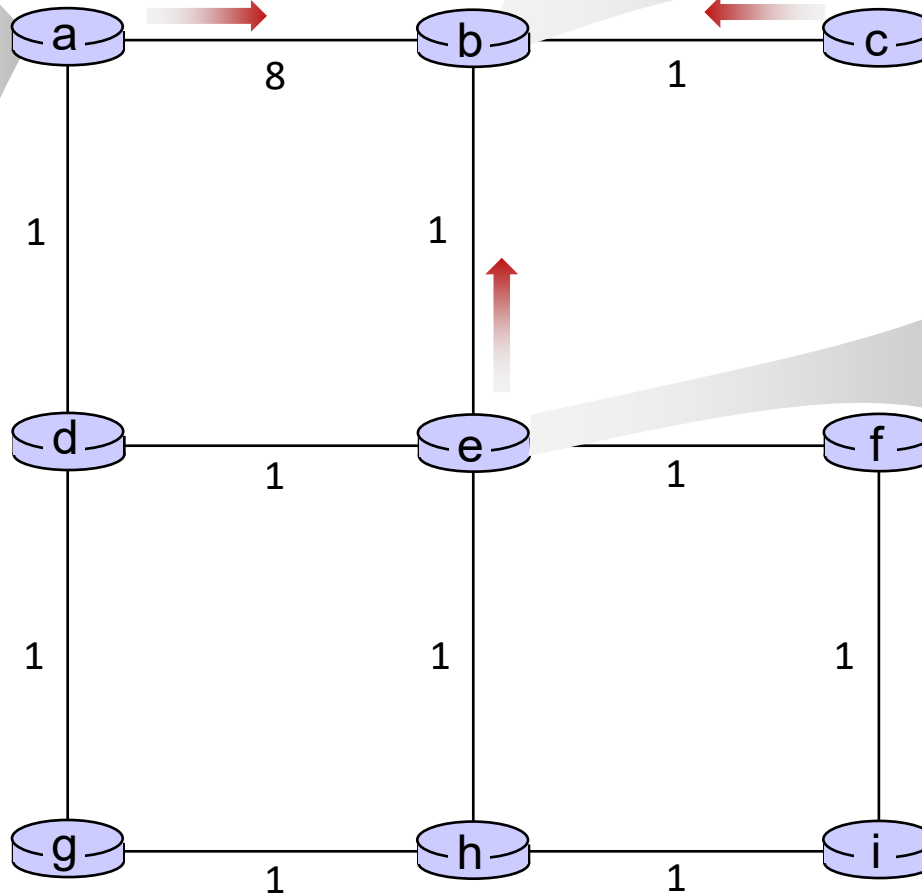
- b receives DVs from a, c, e

DV in a:
$D_a(a)=0$
$D_a(b)=8$
$D_a(c)=\infty$
$D_a(d)=1$
$D_a(e)=\infty$
$D_a(f)=\infty$
$D_a(g)=\infty$
$D_a(h)=\infty$
$D_a(i)=\infty$

DV in b:	
$D_b(a) = 8$	$D_b(f) = \infty$
$D_b(c) = 1$	$D_b(g) = \infty$
$D_b(d) = \infty$	$D_b(h) = \infty$
$D_b(e) = 1$	$D_b(i) = \infty$

DV in c:
$D_c(a)=\infty$
$D_c(b)=1$
$D_c(c)=0$
$D_c(d)=\infty$
$D_c(e)=\infty$
$D_c(f)=\infty$
$D_c(g)=\infty$
$D_c(h)=\infty$
$D_c(i)=\infty$

DV in e:
$D_e(a)=\infty$
$D_e(b)=1$
$D_e(c)=\infty$
$D_e(d)=1$
$D_e(e)=0$
$D_e(f)=1$
$D_e(g)=\infty$
$D_e(h)=1$
$D_e(i)=\infty$



Distance vector example:

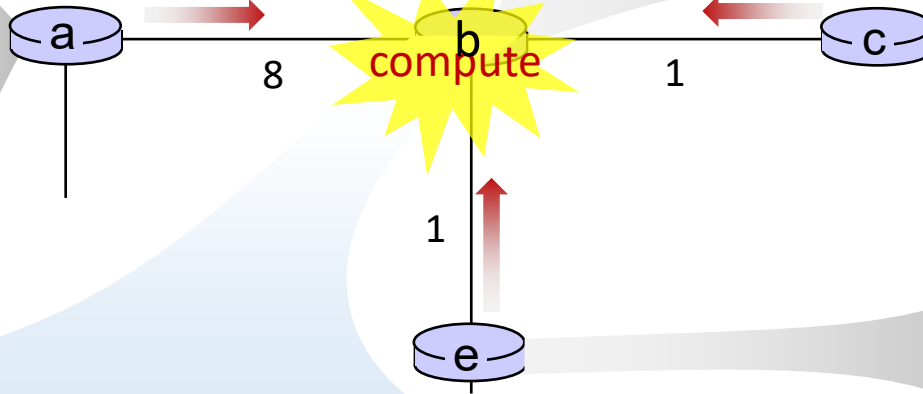


t=1

- b receives DVs from a, c, e, computes:

$$\begin{aligned}
 D_b(a) &= \min\{c_{b,a} + D_a(a), c_{b,c} + D_c(a), c_{b,e} + D_e(a)\} = \min\{8, \infty, \infty\} = 8 \\
 D_b(c) &= \min\{c_{b,a} + D_a(c), c_{b,c} + D_c(c), c_{b,e} + D_e(c)\} = \min\{\infty, 1, \infty\} = 1 \\
 D_b(d) &= \min\{c_{b,a} + D_a(d), c_{b,c} + D_c(d), c_{b,e} + D_e(d)\} = \min\{9, 2, \infty\} = 2 \\
 D_b(e) &= \min\{c_{b,a} + D_a(e), c_{b,c} + D_c(e), c_{b,e} + D_e(e)\} = \min\{\infty, \infty, 1\} = 1 \\
 D_b(f) &= \min\{c_{b,a} + D_a(f), c_{b,c} + D_c(f), c_{b,e} + D_e(f)\} = \min\{\infty, \infty, 2\} = 2 \\
 D_b(g) &= \min\{c_{b,a} + D_a(g), c_{b,c} + D_c(g), c_{b,e} + D_e(g)\} = \min\{\infty, \infty, \infty\} = \infty \\
 D_b(h) &= \min\{c_{b,a} + D_a(h), c_{b,c} + D_c(h), c_{b,e} + D_e(h)\} = \min\{\infty, \infty, 2\} = 2 \\
 D_b(i) &= \min\{c_{b,a} + D_a(i), c_{b,c} + D_c(i), c_{b,e} + D_e(i)\} = \min\{\infty, \infty, \infty\} = \infty
 \end{aligned}$$

DV in a:
$D_a(a) = 0$
$D_a(b) = 8$
$D_a(c) = \infty$
$D_a(d) = 1$
$D_a(e) = \infty$
$D_a(f) = \infty$
$D_a(g) = \infty$
$D_a(h) = \infty$
$D_a(i) = \infty$



DV in b:

$$D_b(a) = 8$$

$$D_b(c) = 1$$

$$D_b(d) = \infty$$

$$D_b(e) = 1$$

$$D_b(f) = \infty$$

$$D_b(g) = \infty$$

$$D_b(h) = \infty$$

$$D_b(i) = \infty$$

DV in c:
$D_c(a) = \infty$
$D_c(b) = 1$
$D_c(c) = 0$
$D_c(d) = \infty$
$D_c(e) = \infty$
$D_c(f) = \infty$
$D_c(g) = \infty$
$D_c(h) = \infty$
$D_c(i) = \infty$

DV in e:
$D_e(a) = \infty$
$D_e(b) = 1$
$D_e(c) = \infty$
$D_e(d) = 1$
$D_e(e) = 0$
$D_e(f) = 1$
$D_e(g) = \infty$
$D_e(h) = 1$
$D_e(i) = \infty$

DV in b:

$D_b(a) = 8$	$D_b(f) = 2$
$D_b(c) = 1$	$D_b(g) = \infty$
$D_b(d) = 2$	$D_b(h) = 2$
$D_b(e) = 1$	$D_b(i) = \infty$

Distance vector example:



t=1

- c receives DVs from b

DV in a:
$D_a(a) = 0$
$D_a(b) = 8$
$D_a(c) = \infty$
$D_a(d) = 1$
$D_a(e) = \infty$
$D_a(f) = \infty$
$D_a(g) = \infty$
$D_a(h) = \infty$
$D_a(i) = \infty$

DV in b:

$$D_b(a) = 8$$

$$D_b(c) = 1$$

$$D_b(d) = \infty$$

$$D_b(e) = 1$$

$$D_b(f) = \infty$$

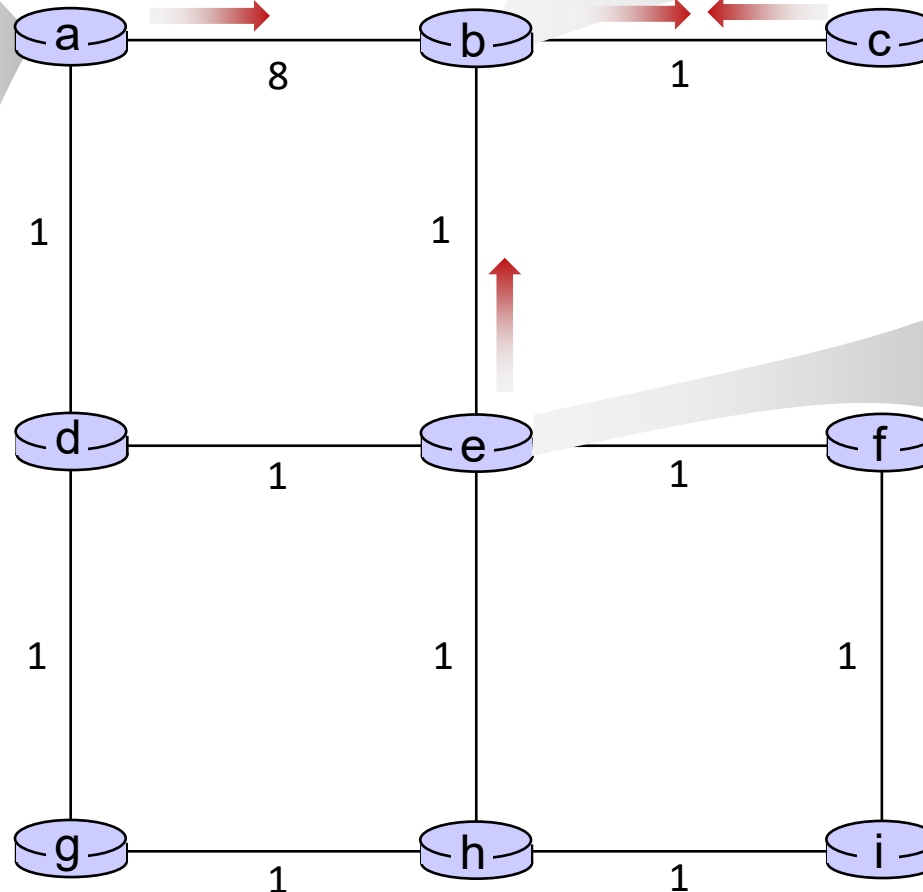
$$D_b(g) = \infty$$

$$D_b(h) = \infty$$

$$D_b(i) = \infty$$

DV in c:
$D_c(a) = \infty$
$D_c(b) = 1$
$D_c(c) = 0$
$D_c(d) = \infty$
$D_c(e) = \infty$
$D_c(f) = \infty$
$D_c(g) = \infty$
$D_c(h) = \infty$
$D_c(i) = \infty$

DV in e:
$D_e(a) = \infty$
$D_e(b) = 1$
$D_e(c) = \infty$
$D_e(d) = 1$
$D_e(e) = 0$
$D_e(f) = 1$
$D_e(g) = \infty$
$D_e(h) = 1$
$D_e(i) = \infty$



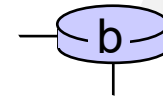
Distance vector example:



t=1

- c receives DVs from b computes:

$$\begin{aligned}D_c(a) &= \min\{c_{c,b} + D_b(a)\} = 1 + 8 = 9 \\D_c(b) &= \min\{c_{c,b} + D_b(b)\} = 1 + 0 = 1 \\D_c(d) &= \min\{c_{c,b} + D_b(d)\} = 1 + \infty = \infty \\D_c(e) &= \min\{c_{c,b} + D_b(e)\} = 1 + 1 = 2 \\D_c(f) &= \min\{c_{c,b} + D_b(f)\} = 1 + \infty = \infty \\D_c(g) &= \min\{c_{c,b} + D_b(g)\} = 1 + \infty = \infty \\D_c(h) &= \min\{c_{c,b} + D_b(h)\} = 1 + \infty = \infty \\D_c(i) &= \min\{c_{c,b} + D_b(i)\} = 1 + \infty = \infty\end{aligned}$$



1

compute

DV in b:

$D_b(a) = 8$	$D_b(f) = \infty$
$D_b(c) = 1$	$D_b(g) = \infty$
$D_b(d) = \infty$	$D_b(h) = \infty$
$D_b(e) = 1$	$D_b(i) = \infty$

DV in c:

$D_c(a) = \infty$
$D_c(b) = 1$
$D_c(c) = 0$
$D_c(d) = \infty$
$D_c(e) = \infty$
$D_c(f) = \infty$
$D_c(g) = \infty$
$D_c(h) = \infty$
$D_c(i) = \infty$

DV in c:

$D_c(a) = 9$
$D_c(b) = 1$
$D_c(c) = 0$
$D_c(d) = 2$
$D_c(e) = \infty$
$D_c(f) = \infty$
$D_c(g) = \infty$
$D_c(h) = \infty$
$D_c(i) = \infty$

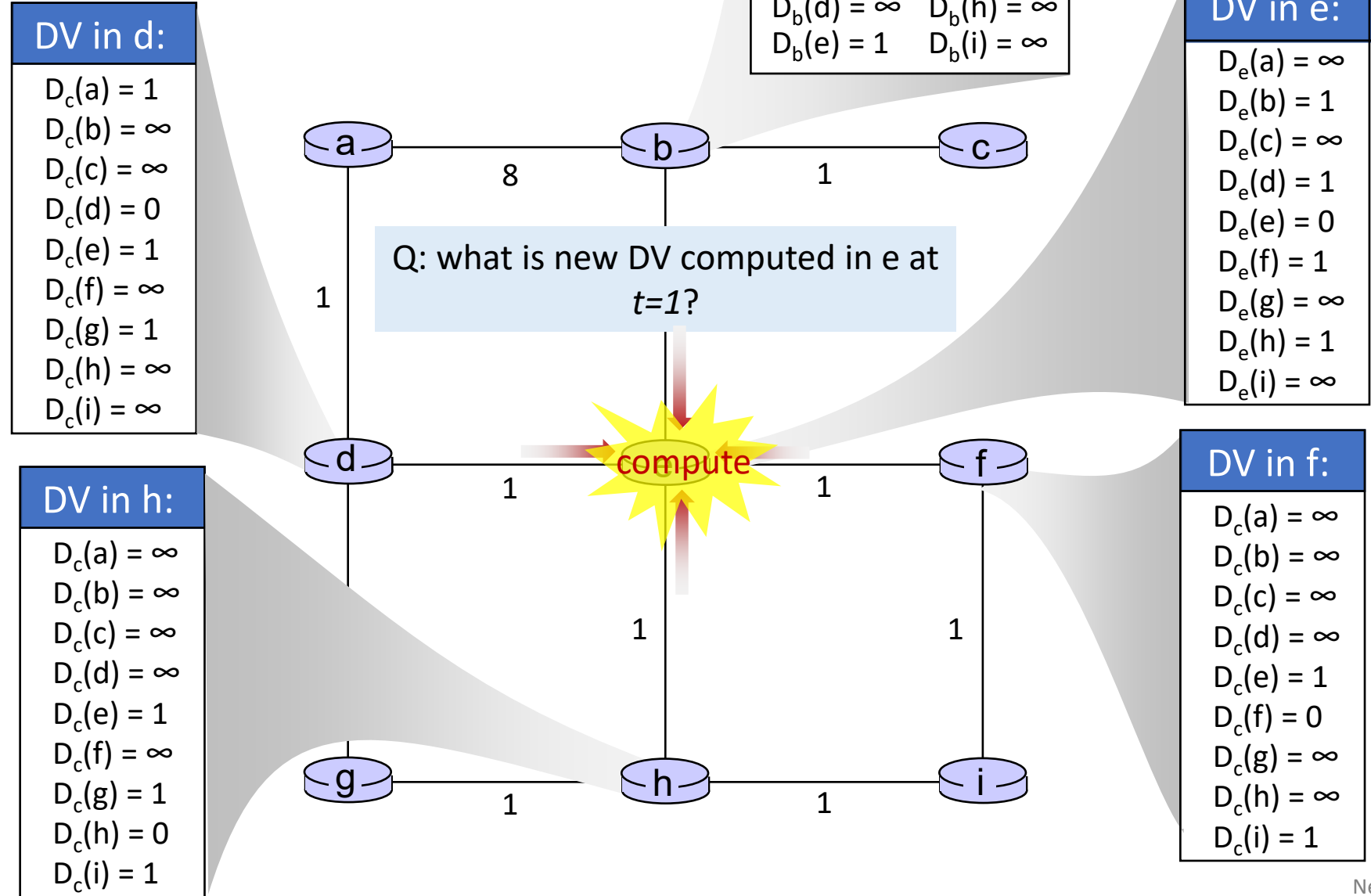
* Check out the online interactive exercises for more examples:
http://gaia.cs.umass.edu/kurose_ross/interactive/

Distance vector example:








t=1

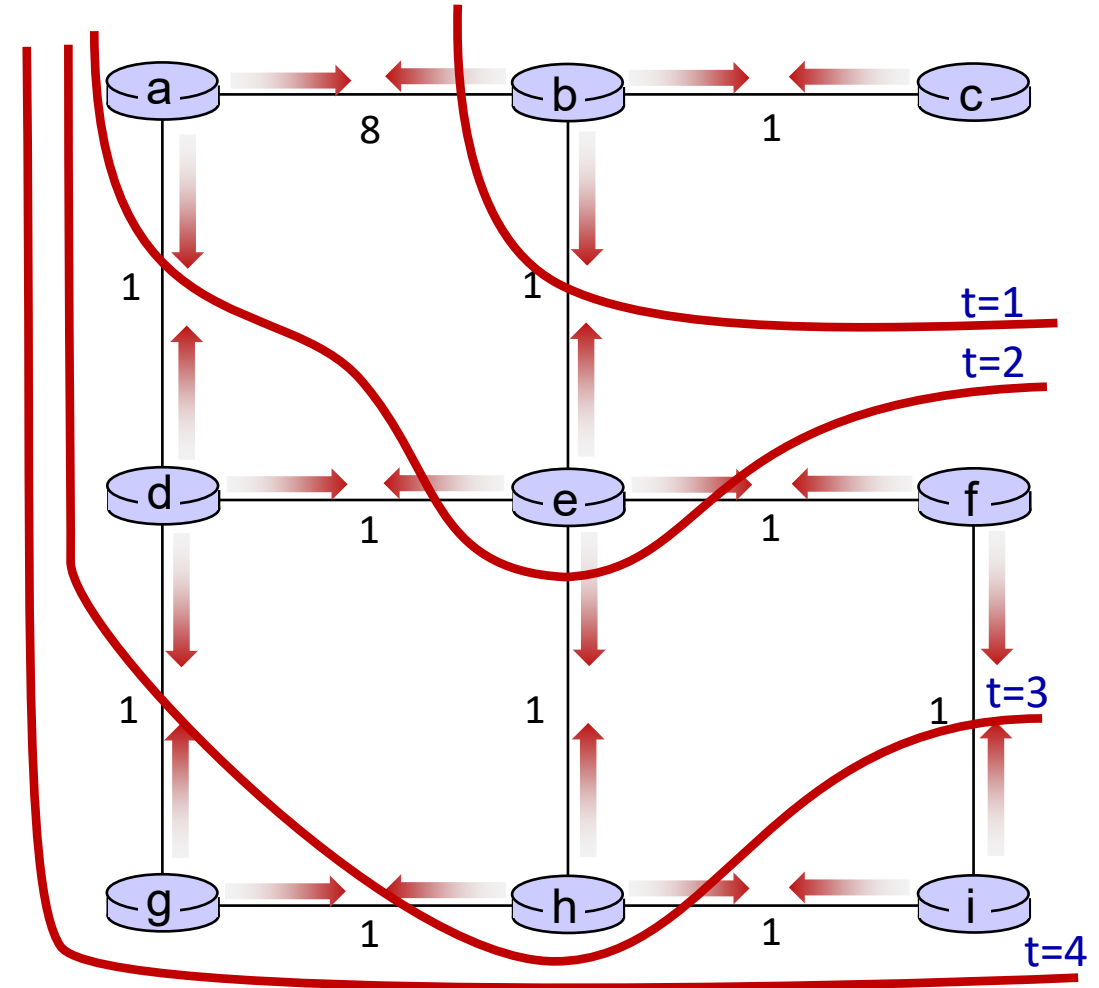
- e receives DVs from b, d, f, h



Distance vector: state information diffusion

Iterative communication, computation steps diffuses information through network:

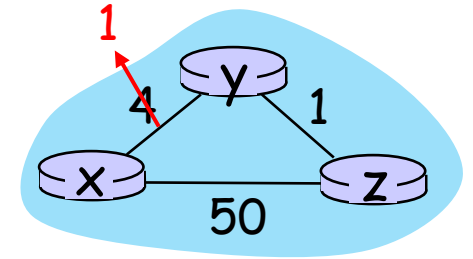
-  $t=0$ c's state at $t=0$ is at c only
-  $t=1$ c's state at $t=0$ has propagated to b, and may influence distance vector computations up to **1** hop away, i.e., at b
-  $t=2$ c's state at $t=0$ may now influence distance vector computations up to **2** hops away, i.e., at b and now at a, e as well
-  $t=3$ c's state at $t=0$ may influence distance vector computations up to **3** hops away, i.e., at d, f, h
-  $t=4$ c's state at $t=0$ may influence distance vector computations up to **4** hops away, i.e., at g, i



Distance vector: link cost changes

link cost changes:

- node detects local link cost change
- updates routing info, recalculates local DV
- if DV changes, notify neighbors



“good news
travels fast”

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

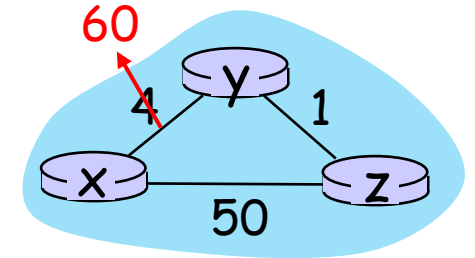
t_1 : z receives update from y, updates its DV, computes new least cost to x, sends its neighbors its DV.

t_2 : y receives z's update, updates its DV. 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:
 - y sees direct link to x has new cost 60, but z has said it has a path at cost of 5. So y computes “my new cost to x will be 6, via z); notifies z of new cost of 6 to x.
 - z learns that path to x via y has new cost 6, so z computes “my new cost to x will be 7 via y), notifies y of new cost of 7 to x.
 - y learns that path to x via z has new cost 7, so y computes “my new cost to x will be 8 via y), notifies z of new cost of 8 to x.
 - z learns that path to x via y has new cost 8, so z computes “my new cost to x will be 9 via y), notifies y of new cost of 9 to x.
 - ...

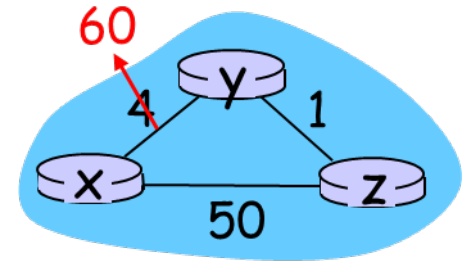


If there is no link between x and z and link cost of x-y changes to infinity, the algorithm will never converge, i.e. “count-to-infinity” problem!

Distance vector: link cost changes

link cost changes:

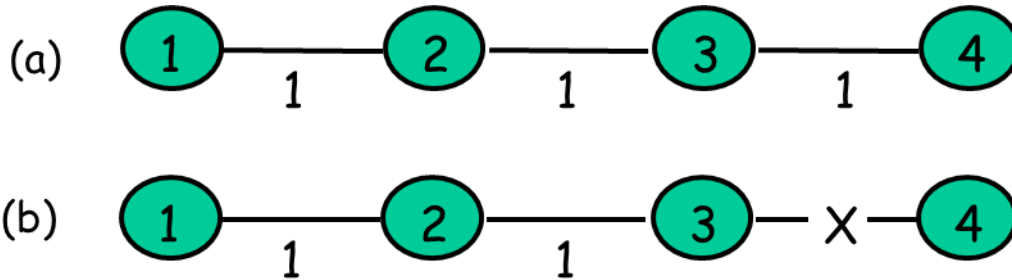
- ❖ node detects local link cost change
- ❖ *bad news travels slow* - “count to infinity” problem!
- ❖ more than 40 iterations before algorithm stabilizes: see next slide



split horizon with 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?

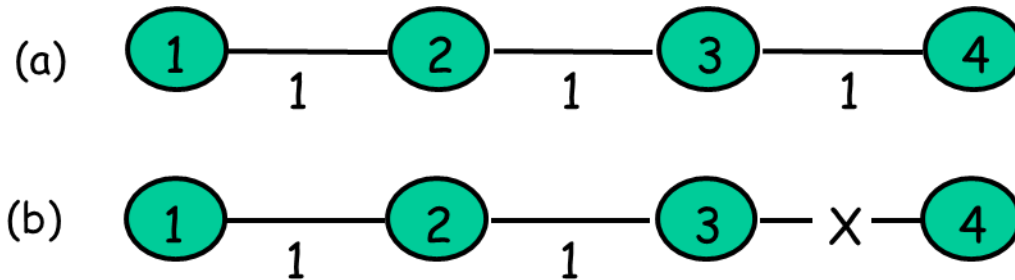
Counting to Infinity Problem



Nodes believe best path
is through each other
(Destination is node 4)

Update	Node 1	Node 2	Node 3
Before break	(2,3)	(3,2)	(4, 1)
After break	(2,3)	(3,2)	(2,3)
1	(2,3)	(3,4)	(2,3)
2	(2,5)	(3,4)	(2,5)
3	(2,5)	(3,6)	(2,5)
4	(2,7)	(3,6)	(2,7)
5	(2,7)	(3,8)	(2,7)
...

Split Horizon with Poison Reverse



Nodes believe best path is through each other

Update	Node 1	Node 2	Node 3	
Before break	(2, 3)	(3, 2)	(4, 1)	
After break	(2, 3)	(3, 2)	(-1, ∞)	Node 2 advertizes its route to 4 to node 3 as having distance infinity; node 3 finds there is no route to 4
1	(2, 3)	(-1, ∞)	(-1, ∞)	Node 1 advertizes its route to 4 to node 2 as having distance infinity; node 2 finds there is no route to 4
2	(-1, ∞)	(-1, ∞)	(-1, ∞)	Node 1 finds there is no route to 4

Comparison of LS and DV algorithms

message complexity

LS: n routers, $O(n^2)$ messages sent

DV: exchange between neighbors;
convergence time varies

speed of convergence

LS: $O(n^2)$ algorithm, $O(n^2)$ messages

- may have oscillations

DV: convergence time varies

- may have routing loops
- count-to-infinity problem

robustness: what happens if router malfunctions, or is compromised?

LS:

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

DV:

- DV router can advertise incorrect *path* cost (“I have a *really* low-cost path to everywhere”): *black-holing*
- each router’s DV is used by others: error propagate thru network

Network layer: “control plane” roadmap

- introduction
- routing protocols
 - link state
 - distance vector
 - hierarchical routing
- intra-ISP routing: OSPF
- routing among ISPs: BGP
- SDN control plane
- Internet Control Message Protocol



- network management, configuration
 - SNMP
 - NETCONF/YANG

Hierarchical routing

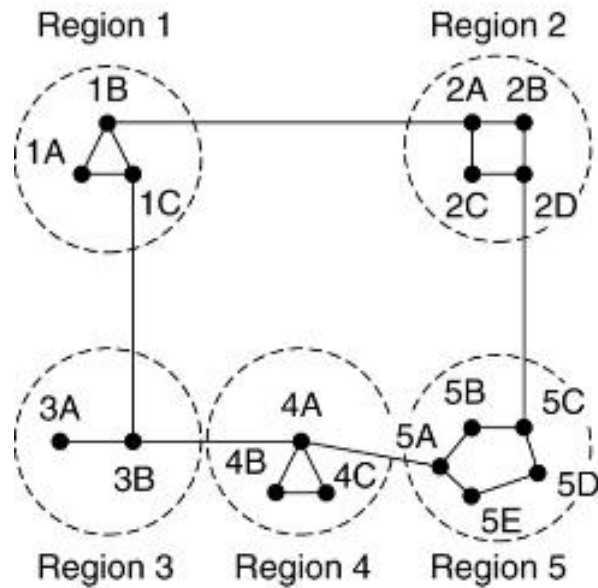
- Motivation: large networks need large routing tables
 - more computation to find shortest paths
 - more bandwidth wasted on exchanging DVs and LSPs
- Key idea
 - divide network into a set of domains/regions
 - gateways (or gateway routers) connect domains
 - routers only aware routers within domain but unaware of outside routers
 - gateways not only aware routers within domain but also only know about other gateways

Hierarchical routing (cont'd)

- Key idea (cont'd)

- each router knows the best path to the destination router which is in the same domain and know the best path to the domain of the destination router which is not in the same domain
- for even larger networks, domains may be grouped into clusters, clusters into zones, zones into groups, etc.

Hierarchical Routing



(a)

Full table for 1A

Dest.	Line	Hops
1A	—	—
1B	1B	1
1C	1C	1
2A	1B	2
2B	1B	3
2C	1B	3
2D	1B	4
3A	1C	3
3B	1C	2
4A	1C	3
4B	1C	4
4C	1C	4
5A	1C	4
5B	1C	5
5C	1B	5
5D	1C	6
5E	1C	5

(b)

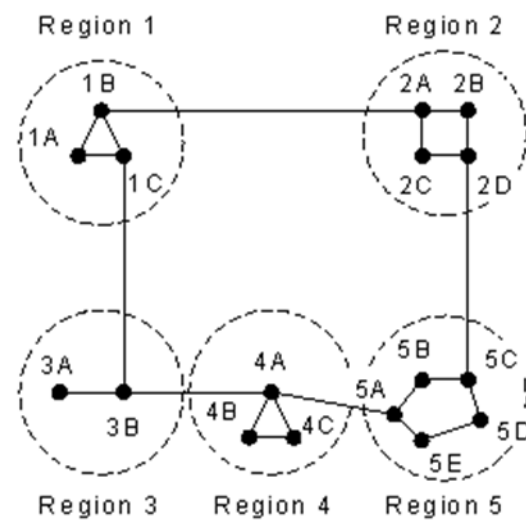
Hierarchical table for 1A

Dest.	Line	Hops
1A	—	—
1B	1B	1
1C	1C	1
2	1B	2
3	1C	2
4	1C	3
5	1C	4

(c)

Hierarchical Routing (Poll 1)

Disadvantages: Hierarchical routing may result in sub-optimal routing decisions.



Dest.	Line	Hops
1A	—	—
1B	1B	1
1C	1C	1
2	1B	2
3	1C	2
4	1C	3
5	1C	4

Routing from 1A to 5C

- Best route is 1A → Region2 → Region5
- Actual route will be 1A → Region3 → Region4 → Region5

Network layer: “control plane” roadmap

- introduction
- routing protocols
- **intra-ISP routing: OSPF**
- routing among ISPs: BGP
- SDN control plane
- Internet Control Message Protocol



- network management, configuration
 - SNMP
 - NETCONF/YANG

Making routing scalable - Hierarchical Routing

our routing study thus far - idealized

- all routers identical
- network “flat”

... not true in practice

scale: billions of destinations:

- can't store all destinations in routing tables!
- routing table exchange would swamp links!

administrative autonomy:

- Internet: a 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”)

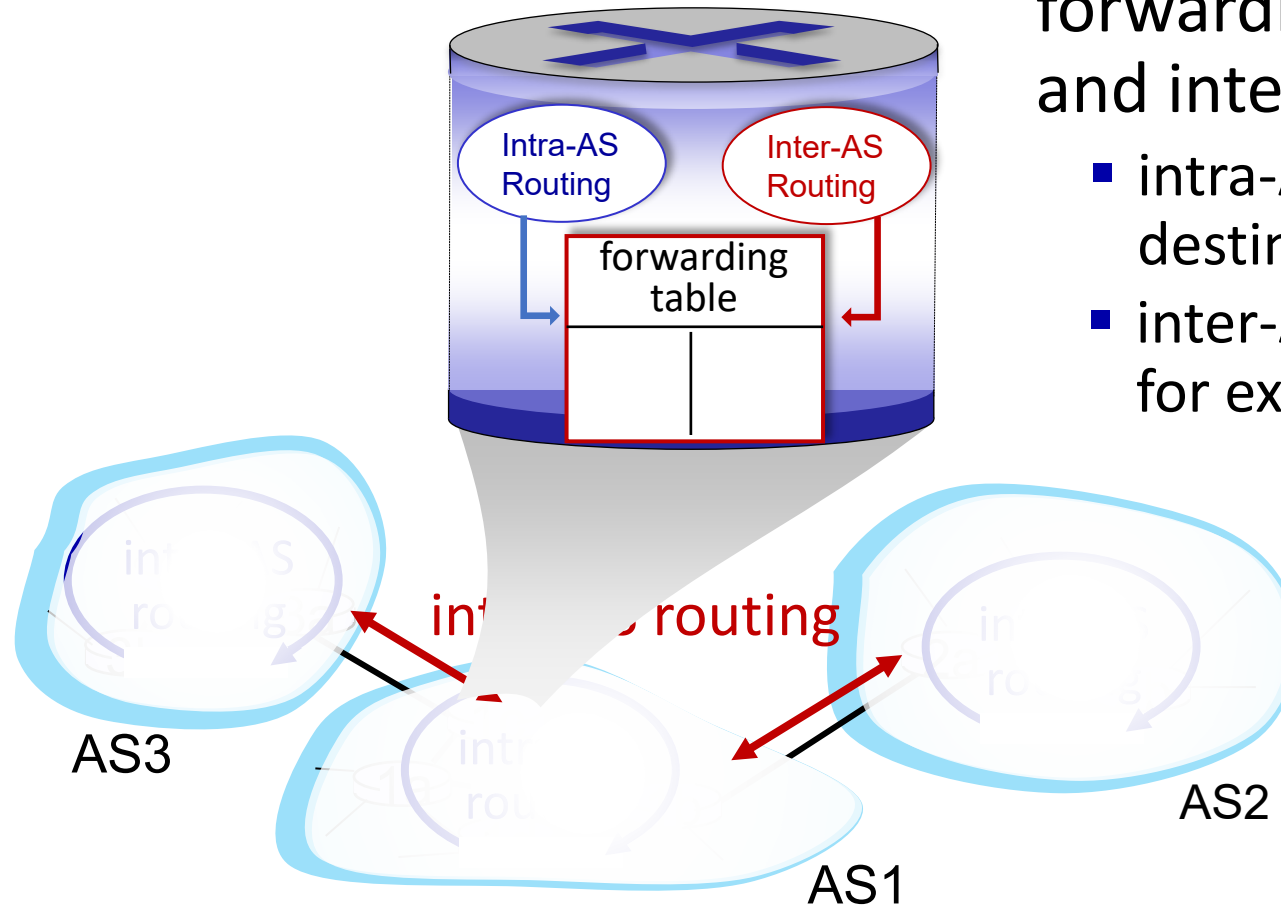
intra-AS (aka “intra-domain”):
routing among routers *within same AS (“network”)*

- all routers in AS must run same intra-domain protocol
- routers in different AS can run different intra-domain routing protocols
- **gateway router:** at “edge” of its own AS, has link(s) to router(s) in other AS'es

inter-AS (aka “inter-domain”):
routing *among* AS'es

- gateways perform inter-domain routing (as well as intra-domain routing)

Interconnected ASes



forwarding table configured by intra- and inter-AS routing algorithms

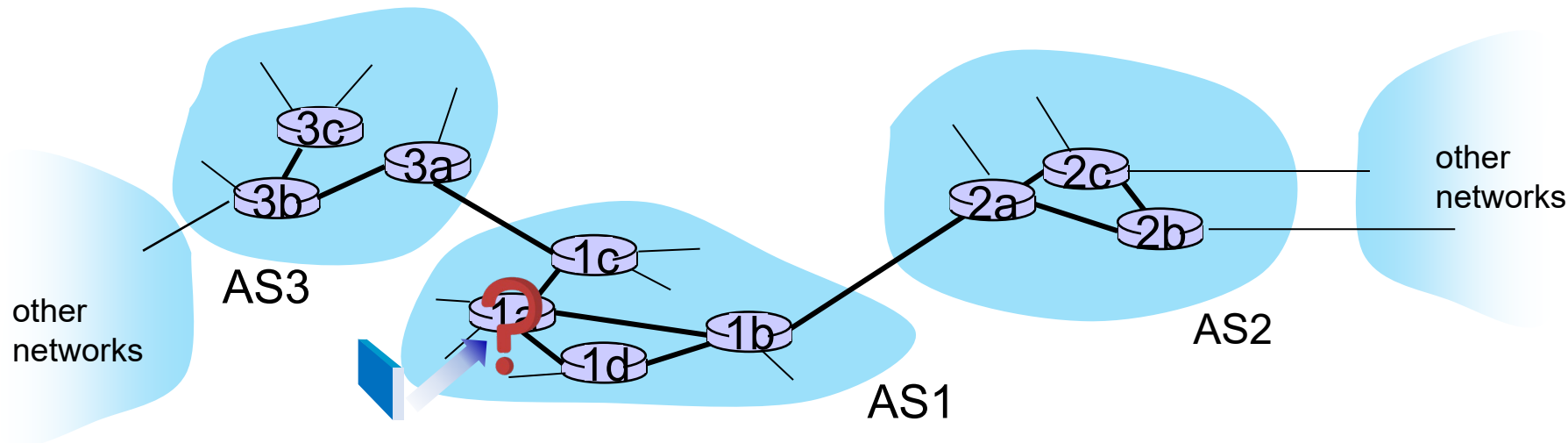
- intra-AS routing determine entries for destinations within AS
- inter-AS & intra-AS determine entries for external destinations

Inter-AS routing: a role in intradomain forwarding

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

AS1 inter-domain routing must:

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



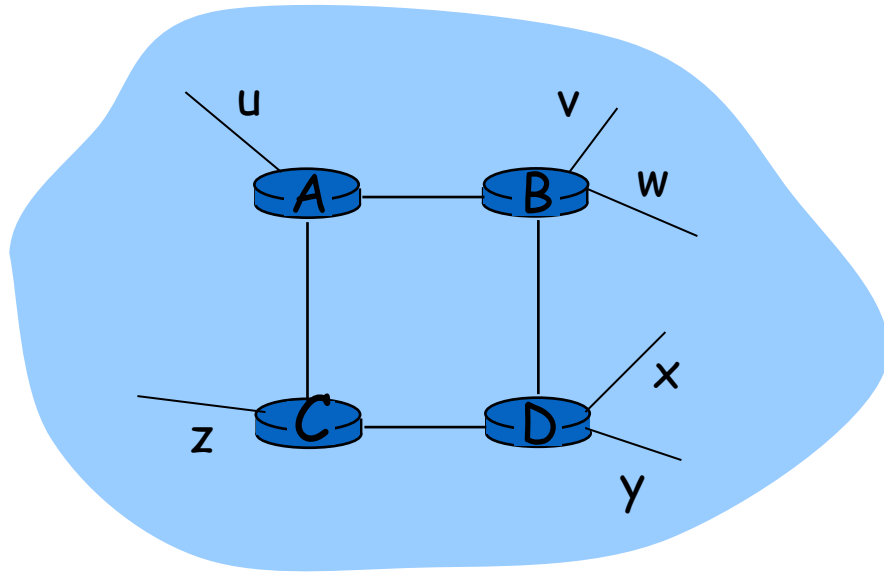
Intra-AS routing: routing within an AS

most common intra-AS routing protocols:

- **RIP: Routing Information Protocol** [RFC 1723]
 - classic DV: DVs exchanged every 30 secs
 - no longer widely used
- **EIGRP: Enhanced Interior Gateway Routing Protocol**
 - DV based
 - formerly Cisco-proprietary for decades (became open in 2013 [RFC 7868])
- **OSPF: Open Shortest Path First** [RFC 2328]
 - link-state routing
 - IS-IS protocol (ISO standard, not RFC standard) essentially same as OSPF

RIP (Routing Information Protocol)

- distance vector algorithm
- included in BSD-UNIX Distribution in 1982
- distance metric: # of hops (max = 15 hops)



From router A to subnets:

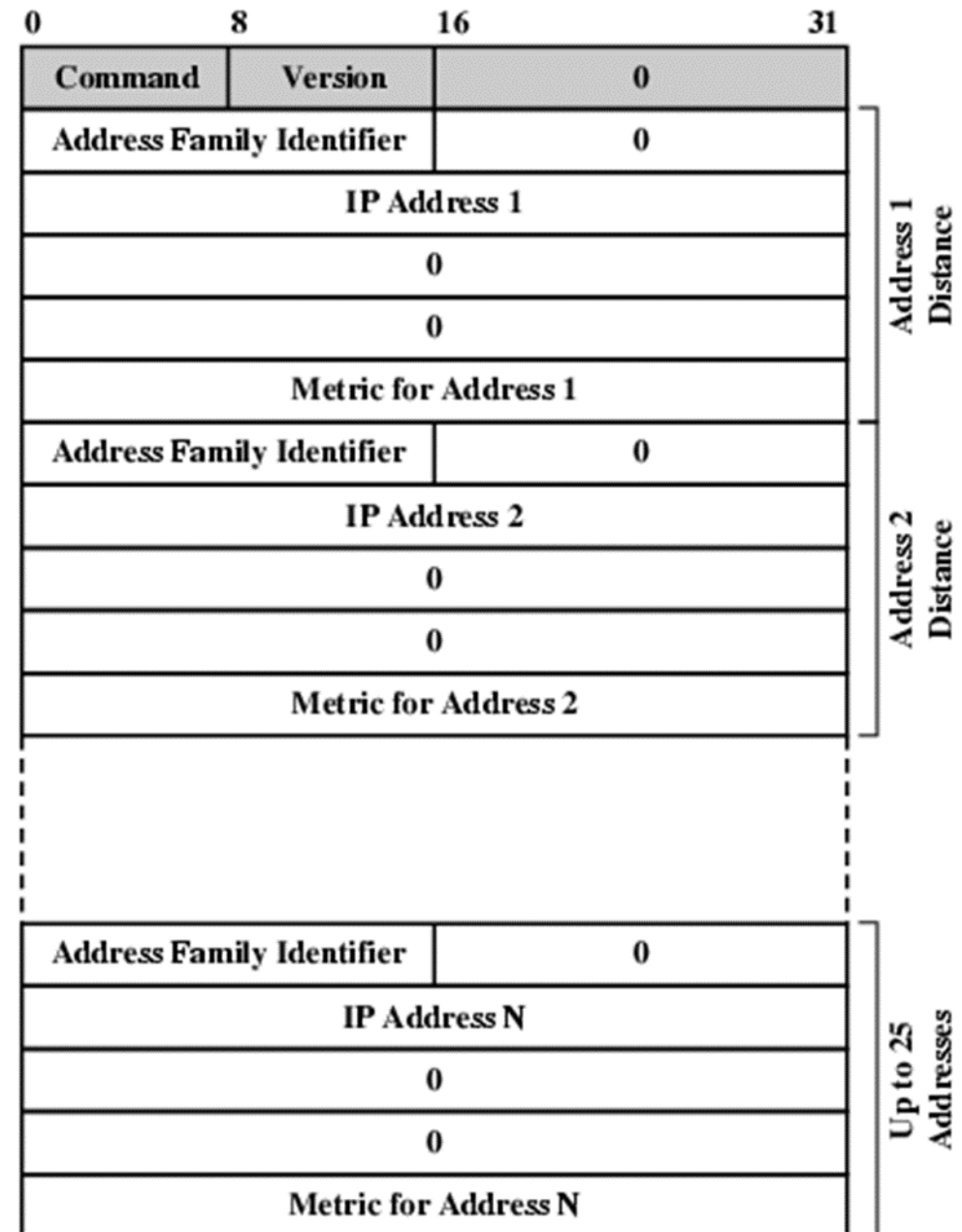
<u>destination</u>	<u>hops</u>
u	1
v	2
w	2
x	3
y	3
z	2

RIP advertisements

- distance vectors: exchanged among neighbors every 30 sec via Response Message (also called advertisement)
- each advertisement: list of up to 25 destination subnets within AS

RIP Packet Format

- **Command:** 1 = request, 2 = reply
 - Updates are replies whether asked for or not
 - Initializing node broadcasts request
 - Requests are replied to immediately
- **Version:** 1 or 2
- **Address family:** Always 2 for IP addresses
- **IP address:** non-zero network portion, zero host portion
 - Identifies particular network
- **Metric**
 - Path distance from this router to network
 - Typically 1, so metric is hop count



RIP: Link Failure and Recovery (Poll 3)

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)

EIGRP (Enhanced Interior Gateway Routing Protocol)

Roots of EIGRP: IGRP

- Developed in 1985 to overcome RIPv1's limited hop count
- Distance vector + link state routing protocol
- Classless
- Metrics used by EIGRP
 - bandwidth (used by default)
 - delay (used by default)
 - reliability
 - load

EIGRP (cont'd)

Diffusing Update Algorithm (DUAL)

- Purpose
 - EIGRP's primary method for preventing routing loops
- Advantage of using DUAL
 - Provides for fast convergence time by keeping a list of loop-free backup routes

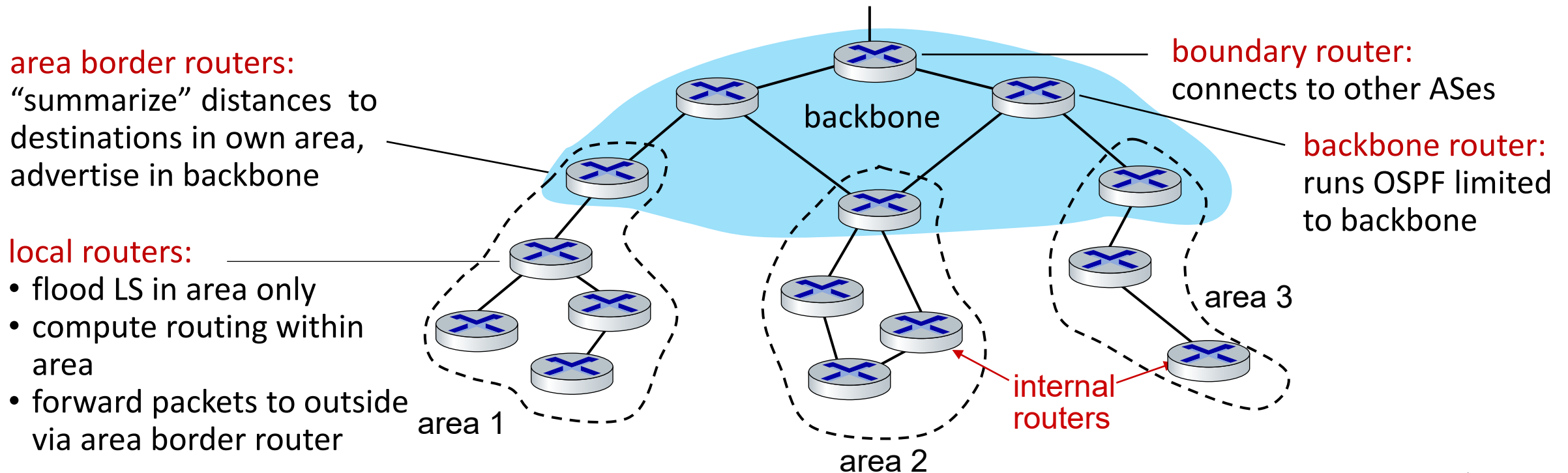
EIGRP Introduction: <https://youtu.be/OymtD3A-JbQ>

OSPF (Open Shortest Path First) routing

- “open”: publicly available
- classic link-state
 - each router floods OSPF link-state advertisements (directly over IP rather than using TCP/UDP) to all other routers in entire AS
 - multiple link costs metrics possible: bandwidth, delay
 - each router has full topology, uses Dijkstra’s algorithm to compute forwarding table
- *security*: all OSPF messages authenticated (to prevent malicious intrusion)

Hierarchical OSPF

- **two-level hierarchy:** local area, backbone.
 - link-state advertisements flooded only in area, or backbone
 - each node has detailed area topology; only knows direction to reach other destinations



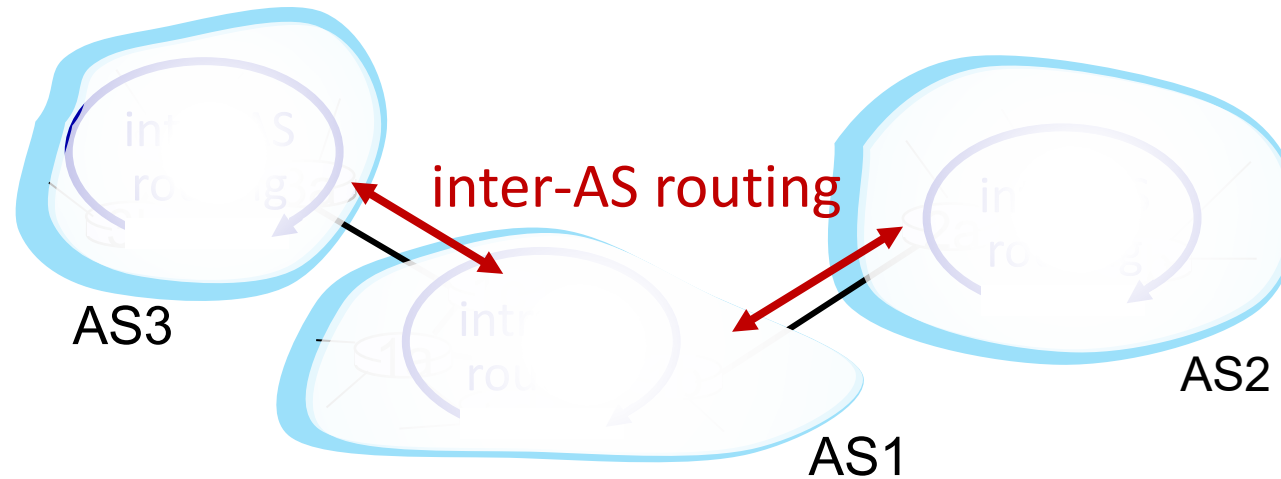
Network layer: “control plane” roadmap

- introduction
- routing protocols
- intra-ISP routing: OSPF
- **routing among ISPs: BGP**
- SDN control plane
- Internet Control Message Protocol



- network management, configuration
 - SNMP
 - NETCONF/YANG

Interconnected ASes

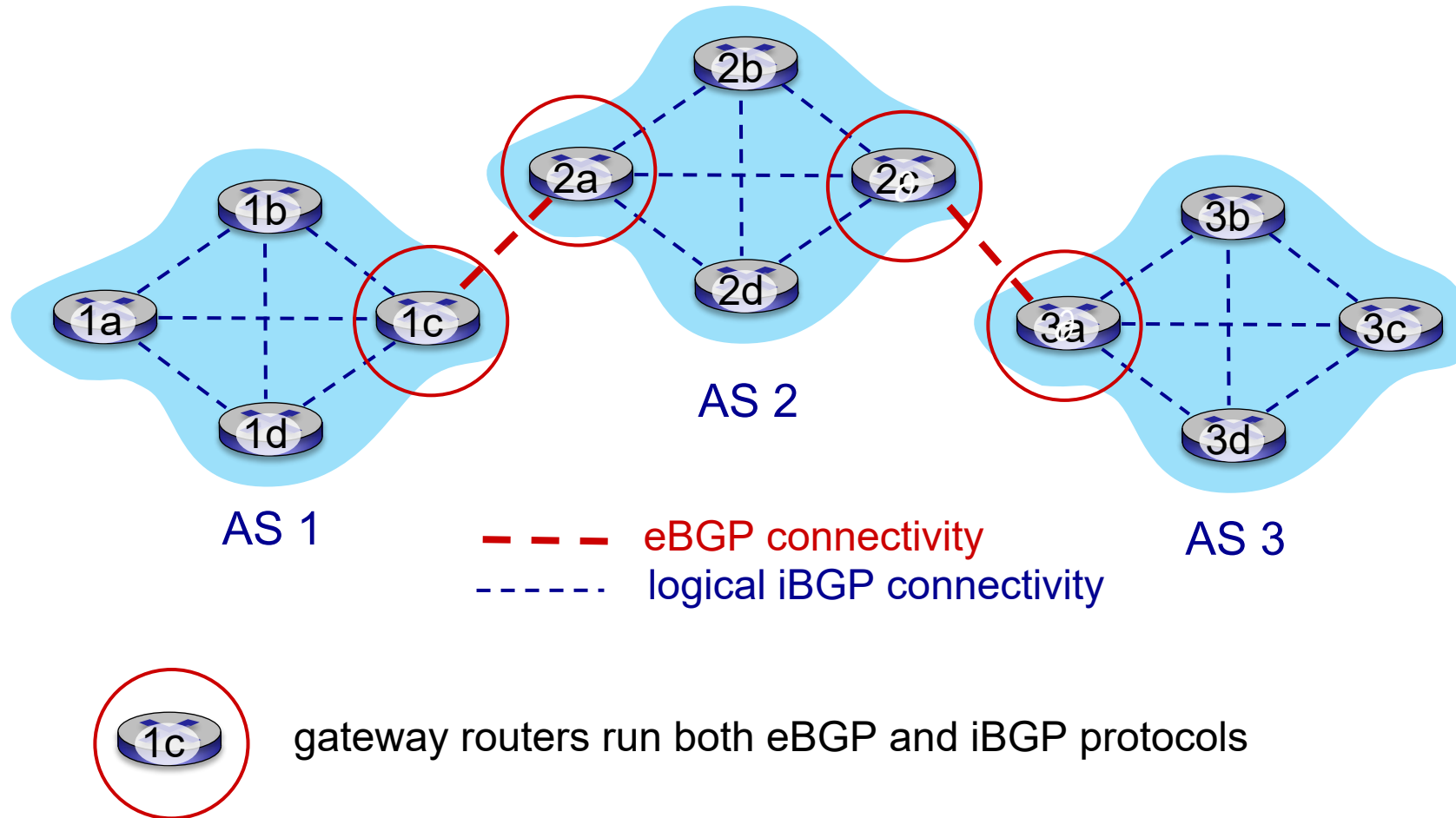


- ✓ **intra-AS (aka “intra-domain”)**: routing among routers *within same* AS (“*network*”)
- ➡ **inter-AS (aka “inter-domain”)**: routing *among* AS'es

Internet inter-AS routing: BGP

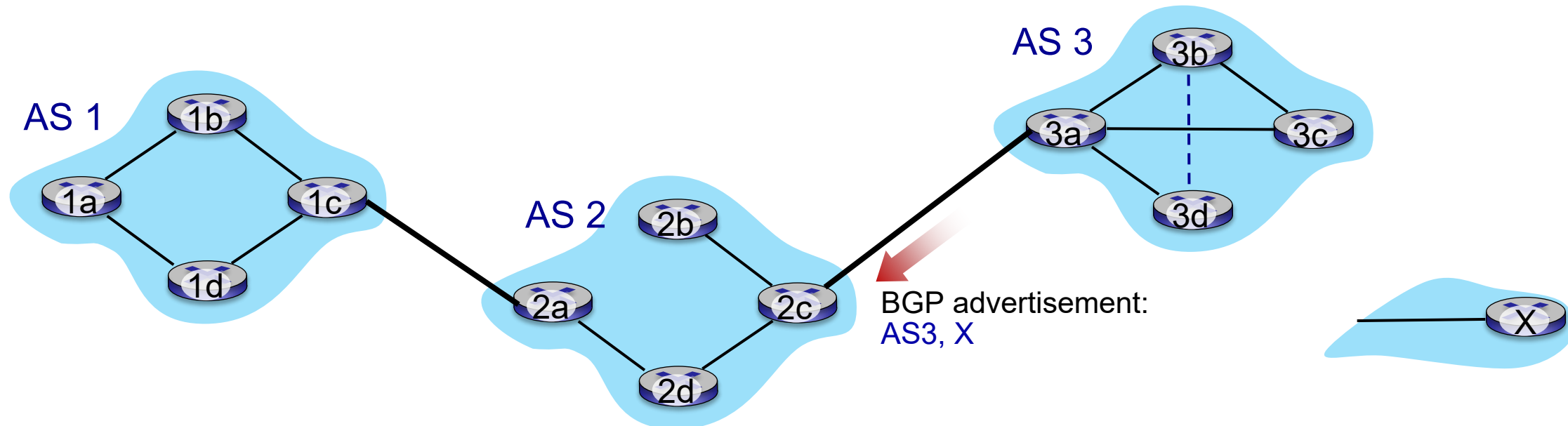
- **BGP (Border Gateway Protocol)**: *the* de facto inter-domain routing protocol
 - “glue that holds the Internet together”
- allows subnet to advertise its existence, and the destinations it can reach, to rest of Internet: *“I am here, here is who I can reach, and how”*
- BGP provides each AS a means to:
 - obtain destination network reachability info from neighboring ASes (**eBGP**)
 - determine routes to other networks based on reachability information and *policy*
 - propagate reachability information to all AS-internal routers (**iBGP**)
 - **advertise** (to neighboring networks) destination reachability info

eBGP, iBGP connections



BGP basics

- **BGP session:** 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 3a advertises *path AS3,X* to AS2 gateway 2c:
 - AS3 *promises* to AS2 it will forward datagrams towards X



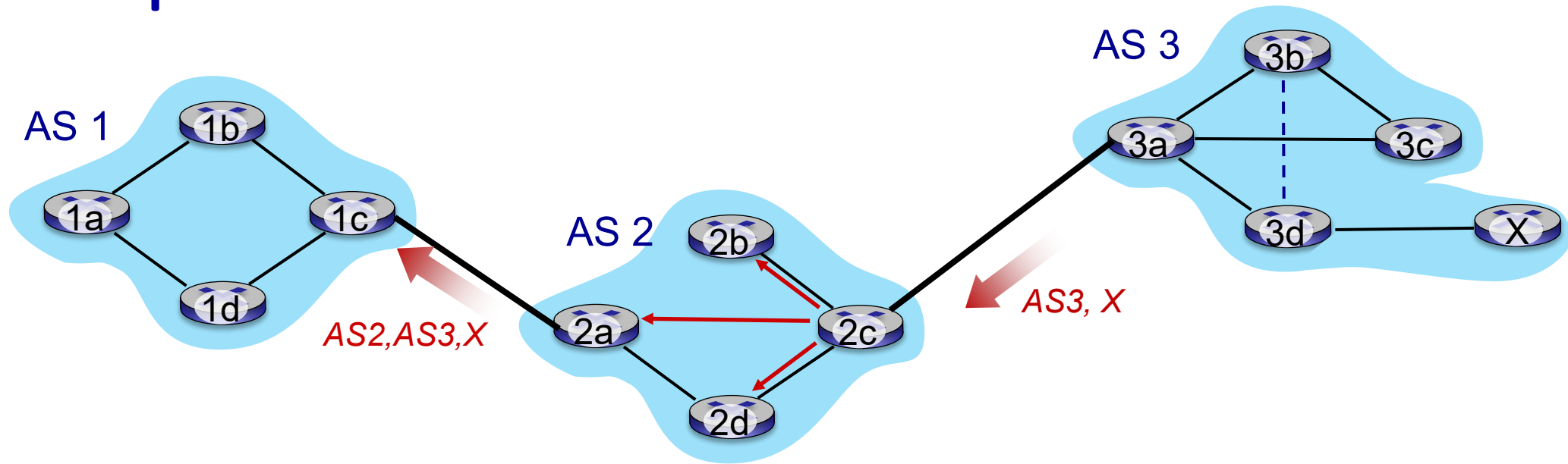
BGP protocol messages (Poll 4)

- BGP messages exchanged between peers over TCP connection
- BGP messages [RFC 4371]:
 - **OPEN**: opens TCP connection to remote BGP peer and authenticates sending BGP peer
 - **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

Path attributes and BGP routes

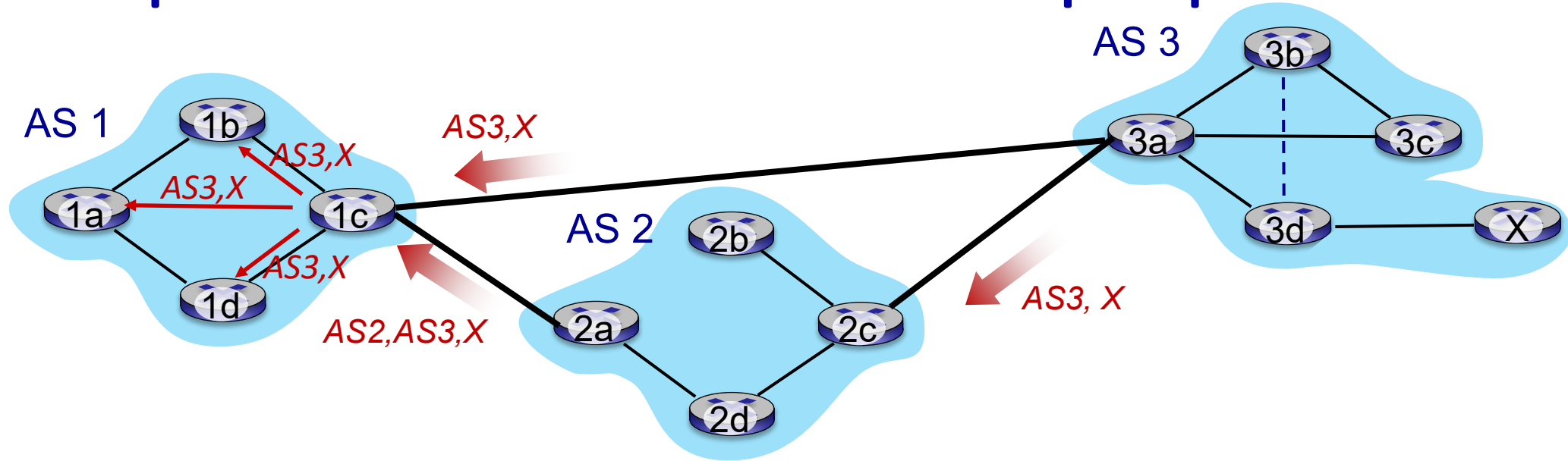
- BGP advertised route: prefix + attributes
 - prefix: destination being advertised
 - two important attributes:
 - **AS-PATH**: list of ASes through which prefix advertisement has passed
 - **NEXT-HOP**: indicates specific internal-AS router to next-hop AS
- **policy-based routing**:
 - gateway receiving route advertisement uses *import policy* to accept/decline path (e.g., never route through AS Y).
 - AS policy also determines whether to *advertise* path to other neighboring ASes

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

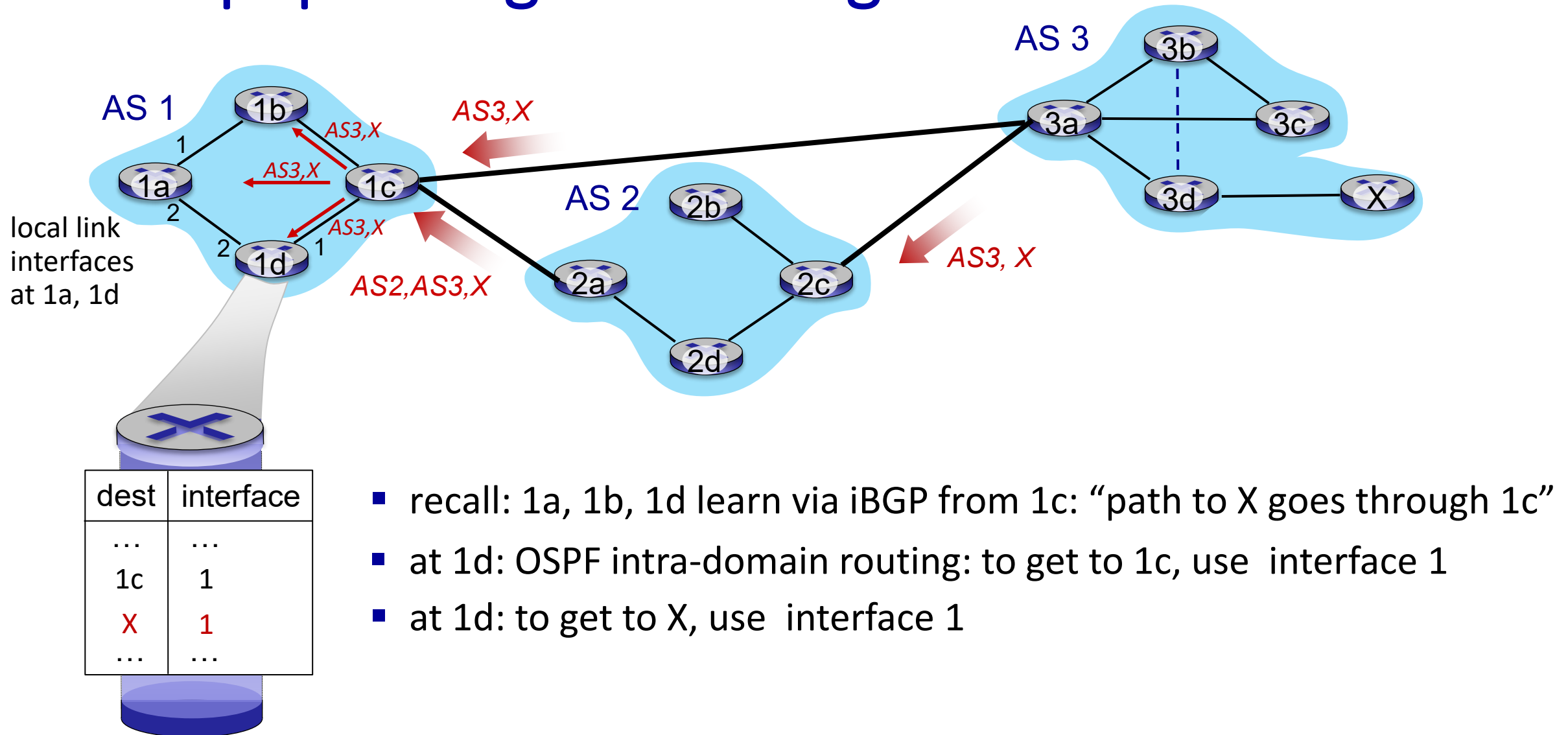
BGP path advertisement: multiple paths



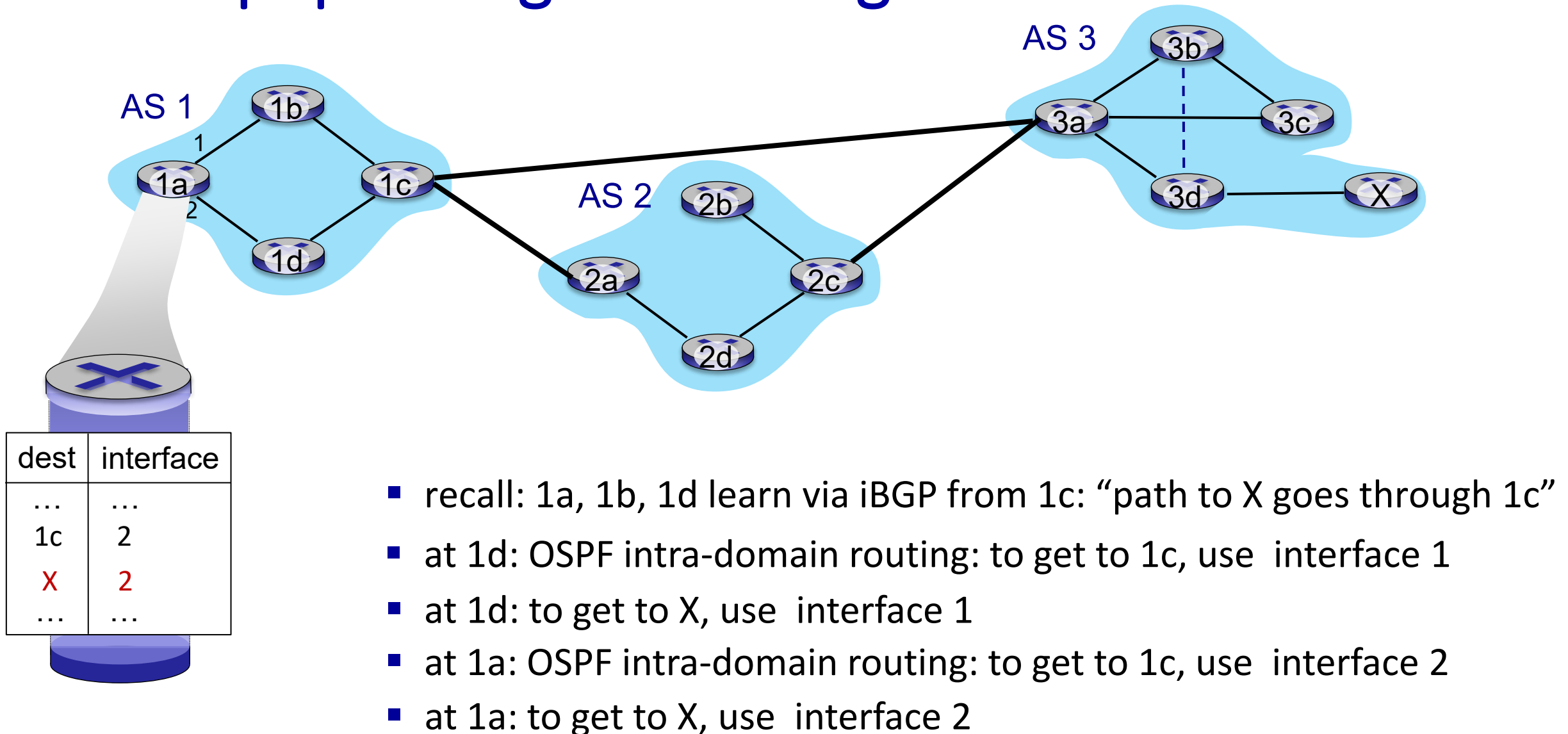
gateway router may learn about **multiple** paths to destination:

- AS1 gateway router 1c learns path **AS2,AS3,X** from 2a
- AS1 gateway router 1c learns path **AS3,X** from 3a
- based on **policy**, AS1 gateway router 1c chooses path **AS3,X** and advertises path within AS1 via iBGP

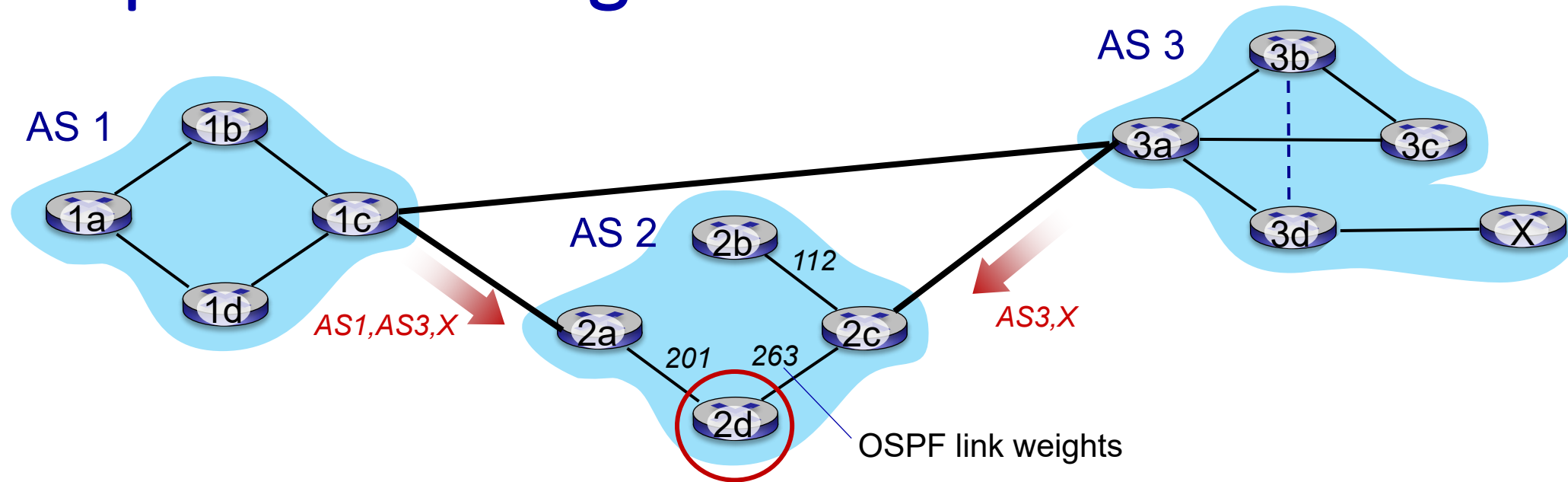
BGP: populating forwarding tables



BGP: populating forwarding tables

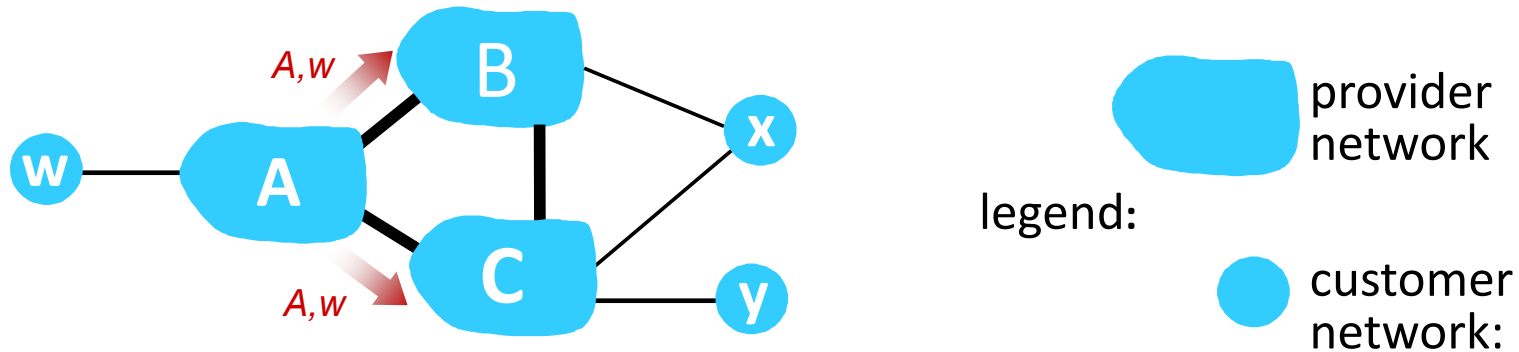


Hot potato routing



- 2d learns (via iBGP) it can route to X via 2a or 2c
- **hot potato routing**: choose local gateway that has least *intra-domain* cost (e.g., 2d chooses 2a, even though more AS hops to X): don't worry about inter-domain cost!

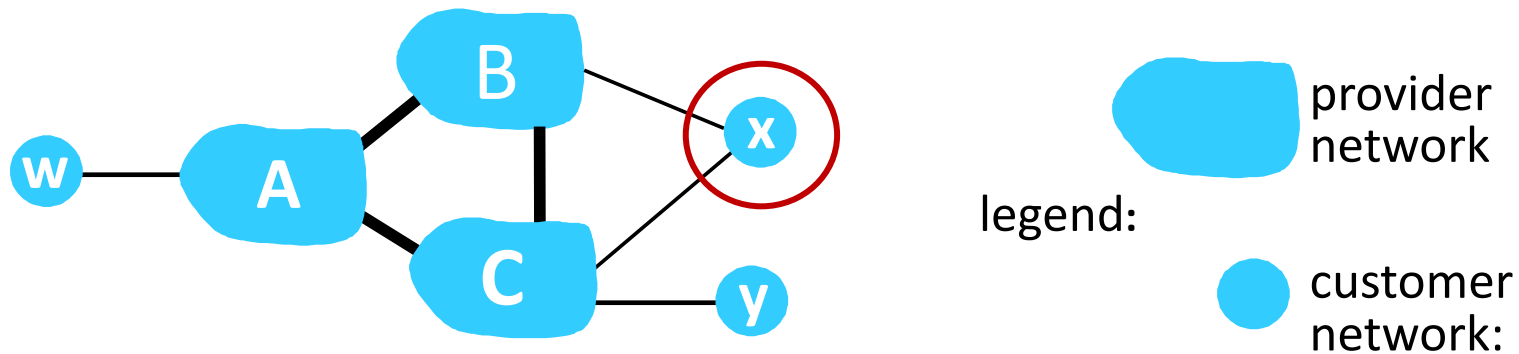
BGP: achieving policy via advertisements



ISP only wants to route traffic to/from its customer networks (does not want to carry transit traffic between other ISPs – a typical “real world” policy)

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

BGP: achieving policy via advertisements (more)



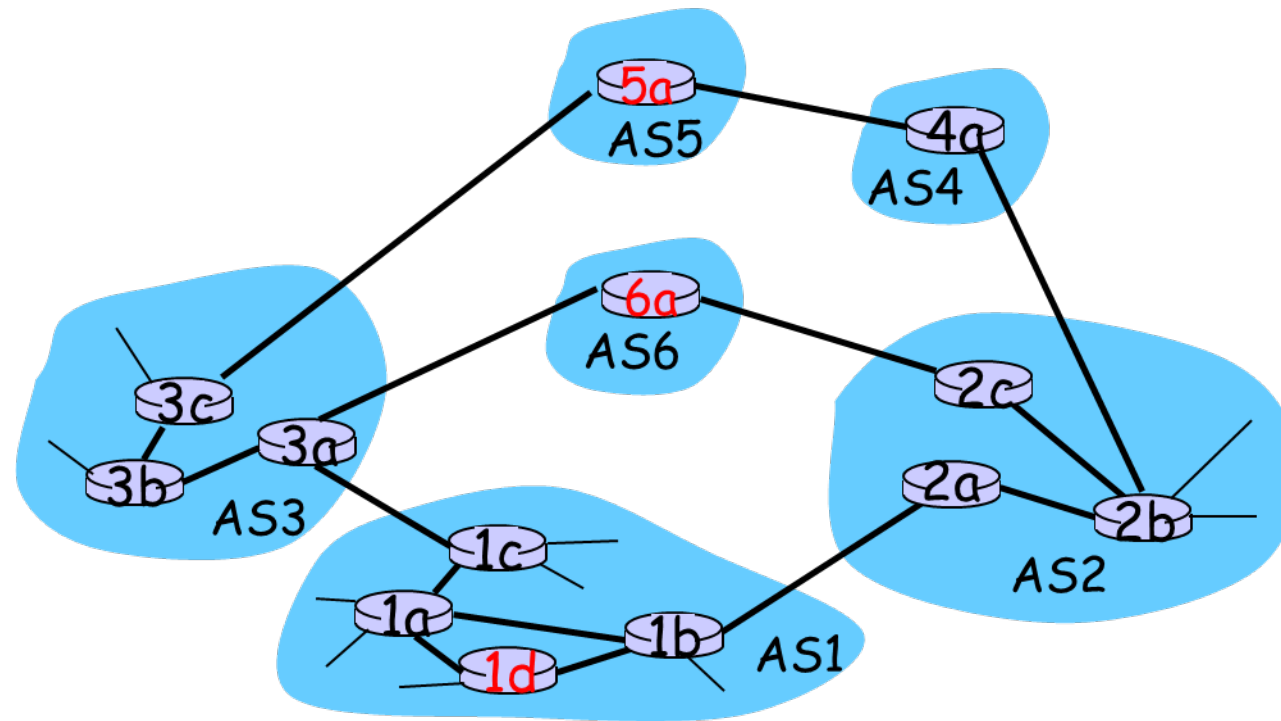
ISP only wants to route traffic to/from its customer networks (does not want to carry transit traffic between other ISPs – a typical “real world” policy)

- 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 route selection

- router may learn about more than one 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

Exercise for BGP route selection



Exercise for BGP route selection

- What is the path used (1) from 1d to 5a (2) from 1d to 6a, respectively, using the following routing algorithms?
 1. The shortest path routing
 2. The hot potato routing (with the shortest path routing outside AS1)
 3. BGP routing with the following preference:
 - i. shortest AS-PATH
 - ii. shortest path to NEXT-HOP

Suggested answers

(1) from 1d to 5a

1. 1d-1b-2a-2b-4a-5a
2. 1d-1b-2a-2b-4a-5a
3. 1d-1a-1c-3a-3b-3c-5a

(2) from 1d to 6a

1. 1d-1a-1c-3a-6a
2. 1d-1b-2a-2b-2c-6a
3. 1d-1b-2a-2b-2c-6a

Why different Intra-, Inter-AS routing ?

policy:

- inter-AS: admin wants control over how its traffic routed, who routes through its network
- intra-AS: single admin, so policy less of an issue

scale:

- hierarchical routing saves table size, reduced update traffic

performance:

- intra-AS: can focus on performance
- inter-AS: policy dominates over performance

Network layer: “control plane” roadmap

- introduction
- routing protocols
- intra-ISP routing: OSPF
- routing among ISPs: BGP
- **SDN control plane**
- Internet Control Message Protocol



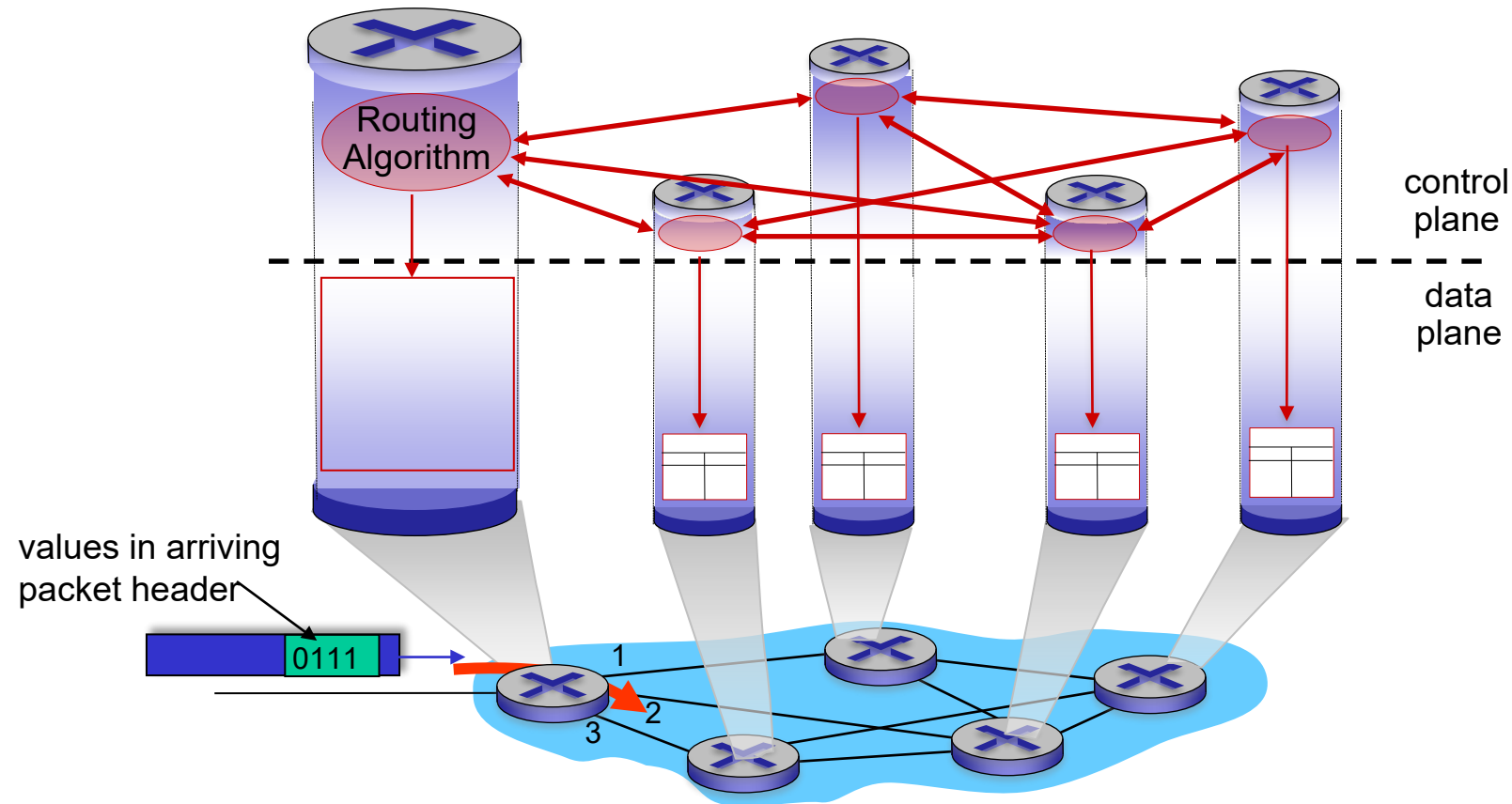
- network management, configuration
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Software defined networking (SDN)

- Internet network layer: historically implemented via distributed, per-router control approach:
 - *monolithic* router contains switching hardware, runs proprietary implementation of Internet standard protocols (IP, RIP, IS-IS, OSPF, BGP) in proprietary router OS (e.g., Cisco IOS)
 - different “middleboxes” for different network layer functions: firewalls, load balancers, NAT boxes, ..
- ~2005: renewed interest in rethinking network control plane

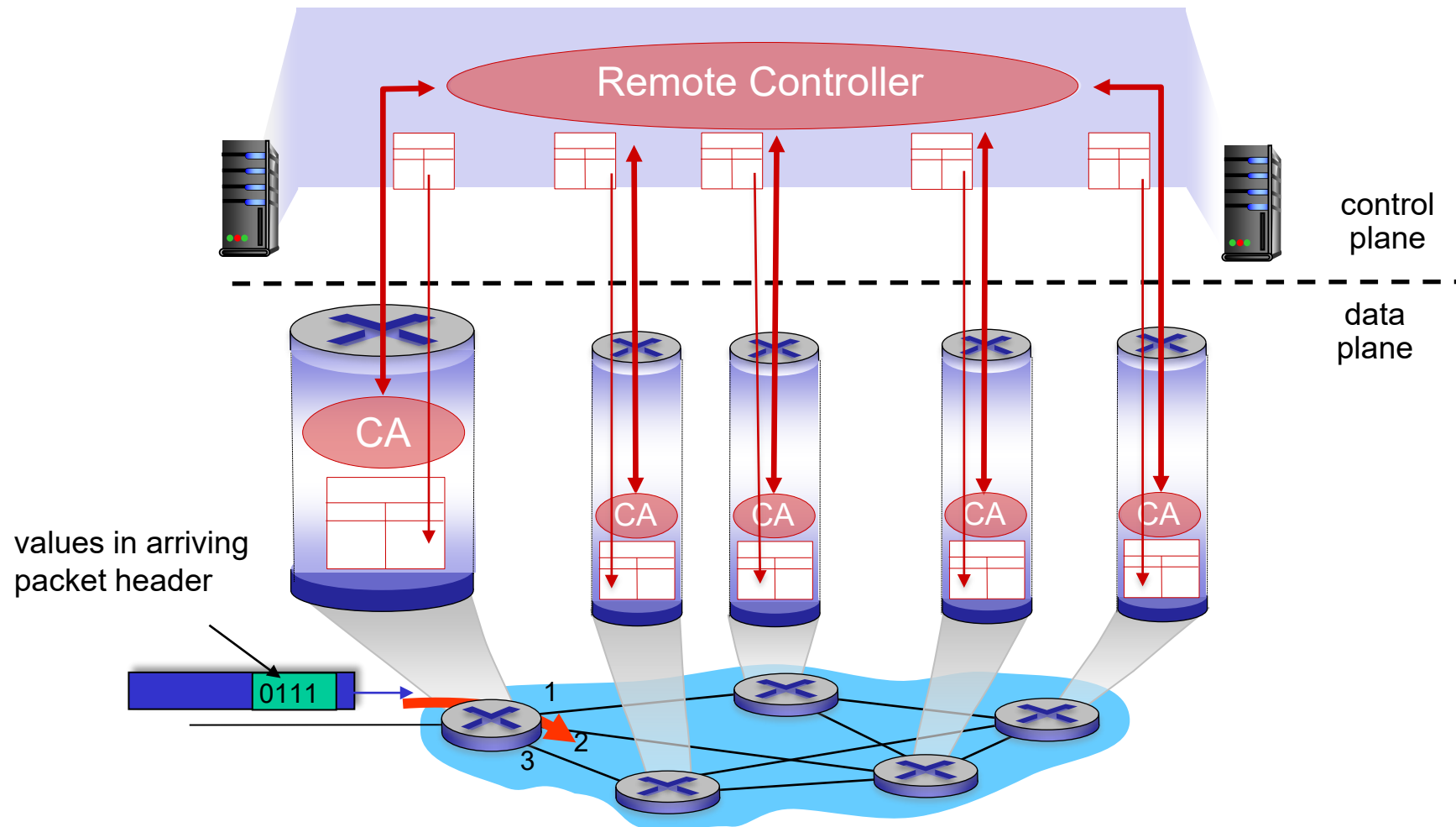
Per-router control plane

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



Software-Defined Networking (SDN) control plane

Remote controller computes, installs forwarding tables in routers

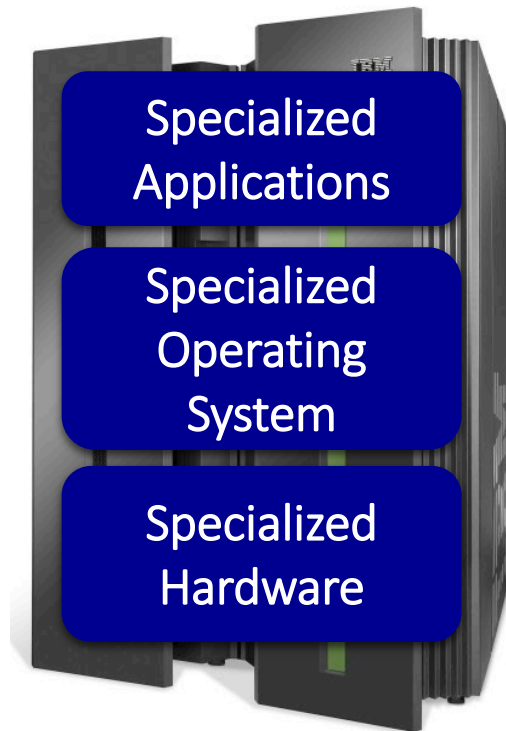


Software defined networking (SDN)

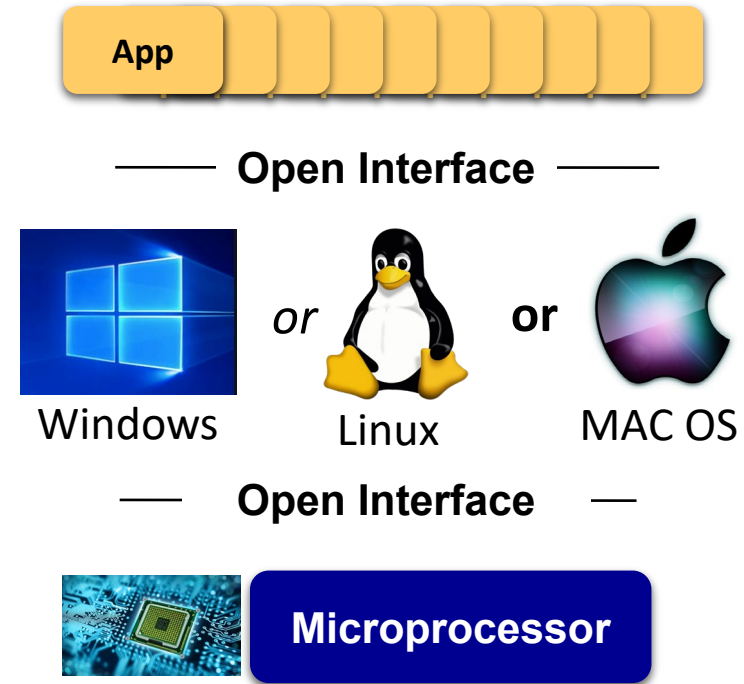
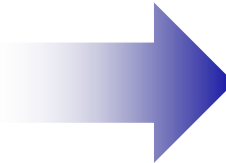
Why a *logically centralized* control plane?

- easier network management: avoid router misconfigurations, greater flexibility of traffic flows
- table-based forwarding (recall OpenFlow API) allows “programming” routers
 - centralized “programming” easier: compute tables centrally and distribute
 - distributed “programming” more difficult: compute tables as result of distributed algorithm (protocol) implemented in each-and-every router
- open (non-proprietary) implementation of control plane
 - foster innovation: let 1000 flowers bloom

SDN analogy: mainframe to PC revolution



Vertically integrated
Closed, proprietary
Slow innovation
Small industry



Horizontal
Open interfaces
Rapid innovation
Huge industry

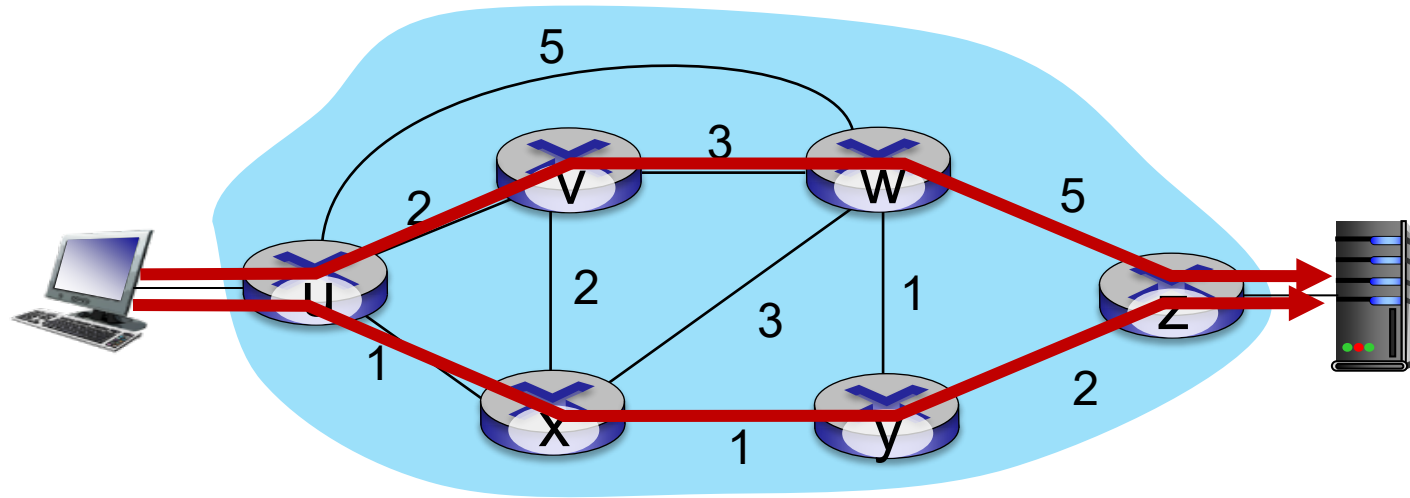
What is Traffic Engineering?

Traffic Engineering is how network operators deal with large amounts of data flowing through their networks. They reconfigure the network in response to changing traffic loads to achieve some operational goals, like:

- Traffic ratios in a peering relationship (aka "peering ratios")
- Relieve congestion
- Balance load more evenly

Software Defined Networking is used to make traffic engineering easier in both **data center networks** and **transit networks**.

Traffic engineering: difficult with traditional routing

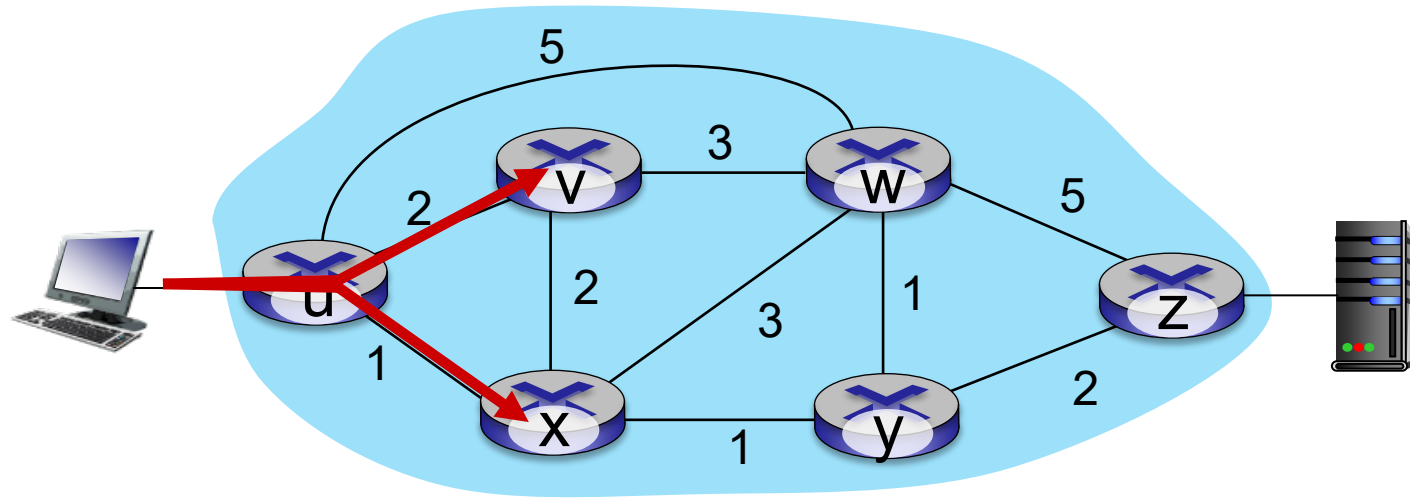


Q: what if network operator wants u-to-z traffic to flow along *uvwz*, rather than *uxyz*?

A: need to re-define link weights so traffic routing algorithm computes routes accordingly (or need a new routing algorithm)!

link weights are only control “knobs”: not much control!

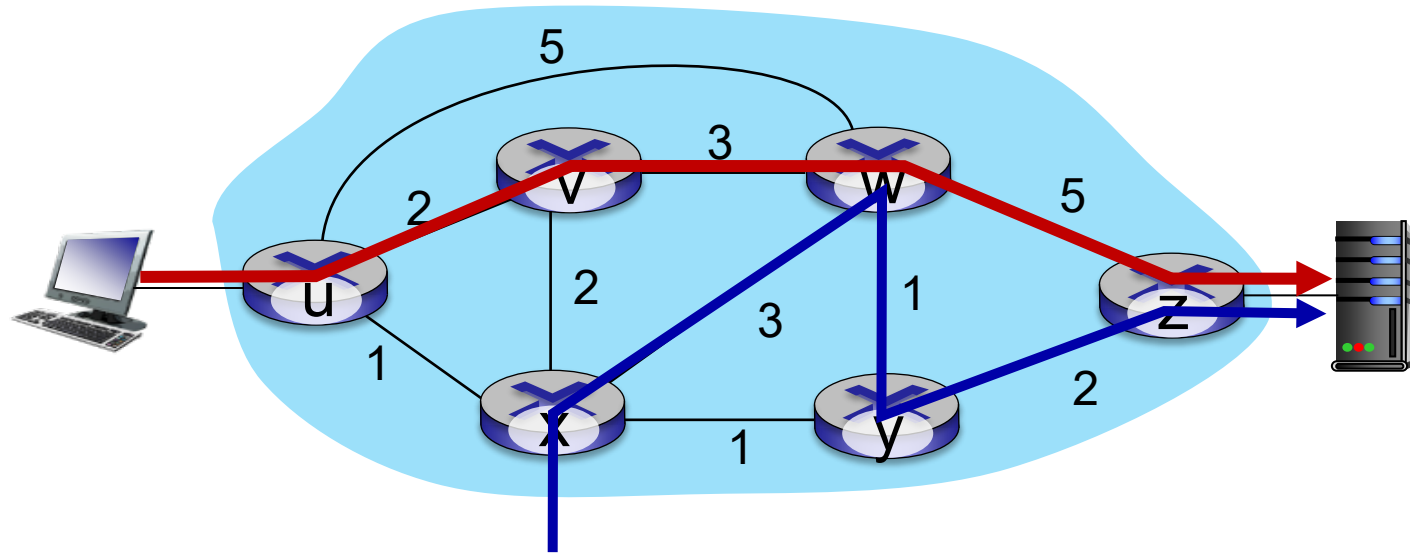
Traffic engineering: difficult with traditional routing



Q: what if network operator wants to split u-to-z traffic along uvwz *and* uxyz (load balancing)?

A: can't do it (or need a new routing algorithm)

Traffic engineering: difficult with traditional routing

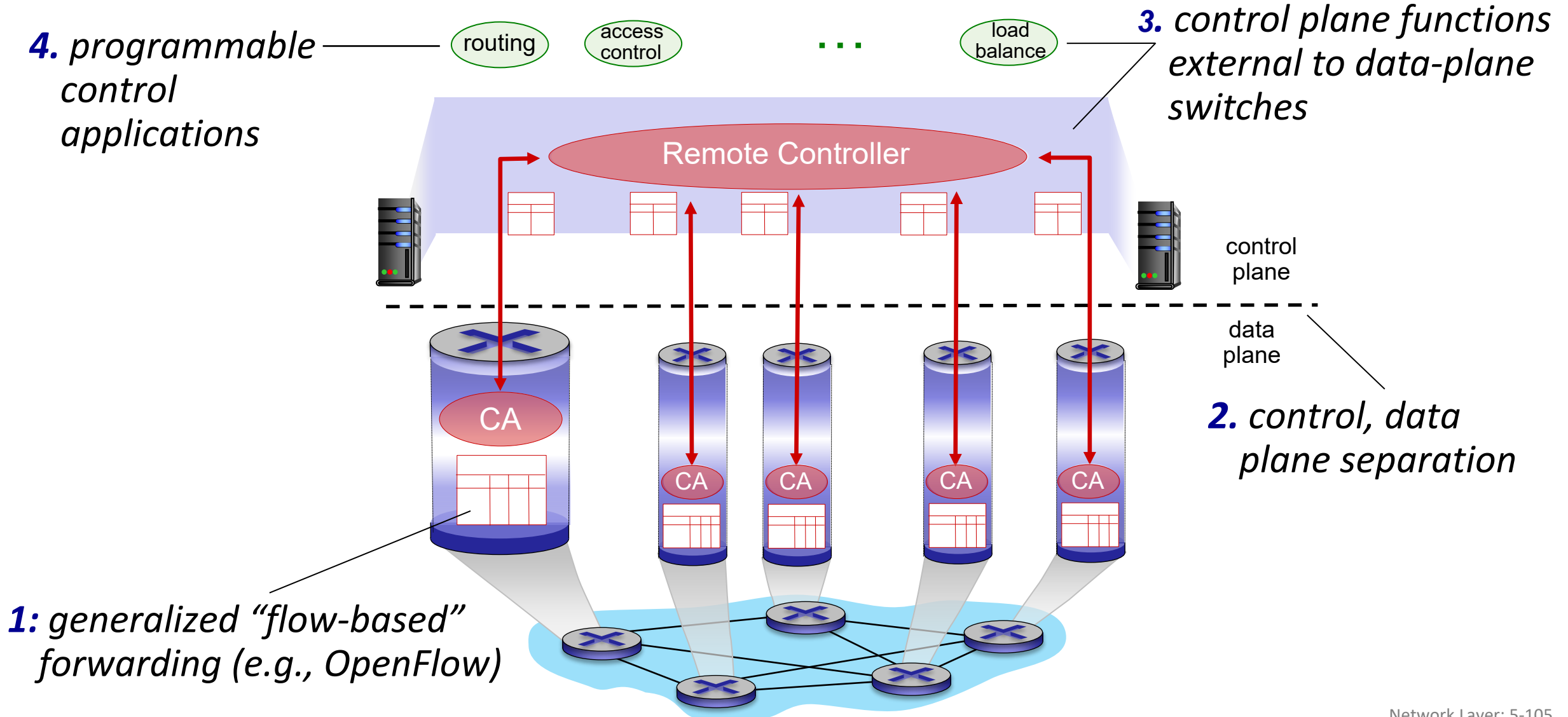


Q: what if w wants to route blue and red traffic differently from w to z?

A: can't do it (with destination-based forwarding, and LS, DV routing)

We learned that generalized forwarding and SDN can be used to achieve *any* routing desired

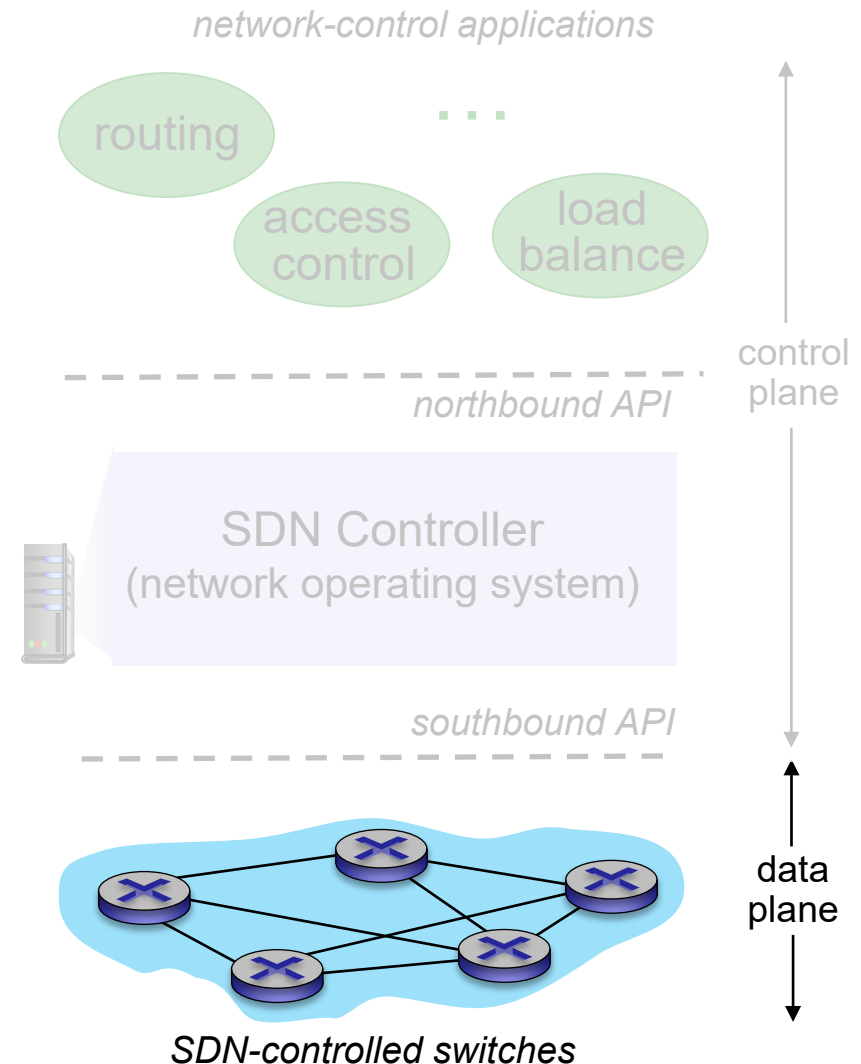
Software defined networking (SDN)



Software defined networking (SDN)

Data-plane switches:

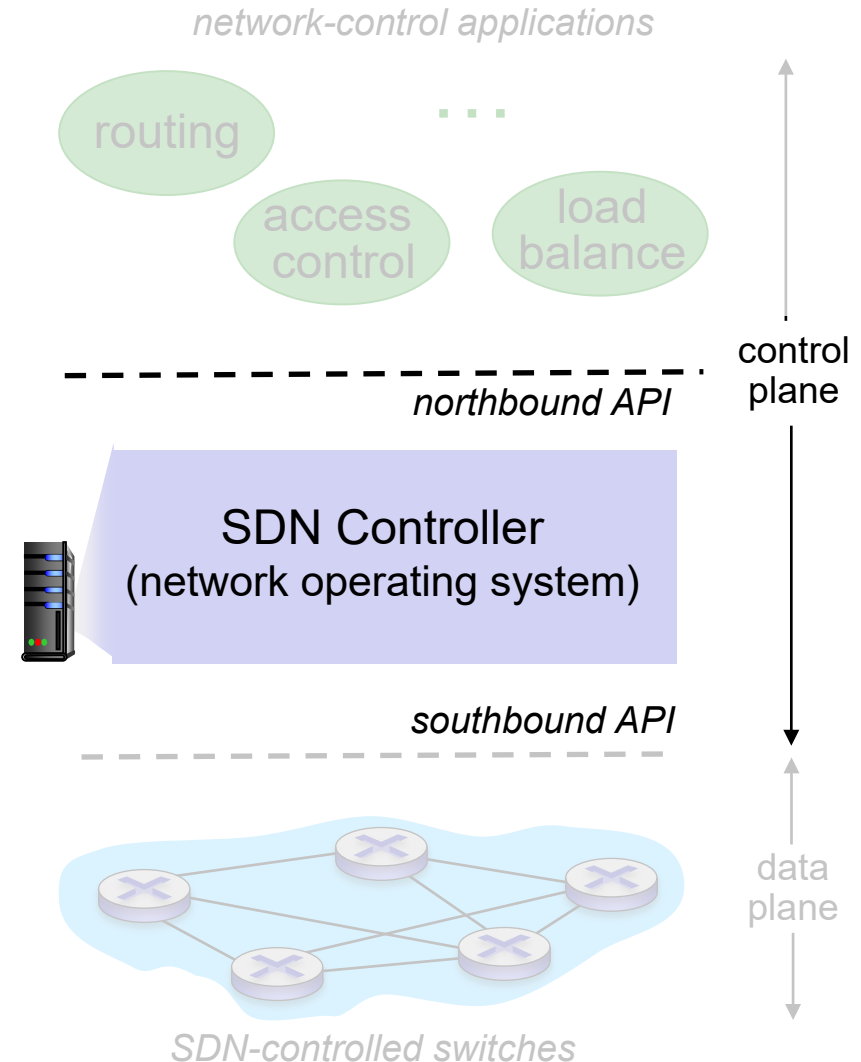
- fast, simple, commodity switches implementing generalized data-plane forwarding (Section 4.4) in hardware
- flow (forwarding) table computed, installed under controller supervision
- API for table-based switch control (e.g., OpenFlow)
 - defines what is controllable, what is not
- protocol for communicating with controller (e.g., OpenFlow)



Software defined networking (SDN)

SDN controller (network OS):

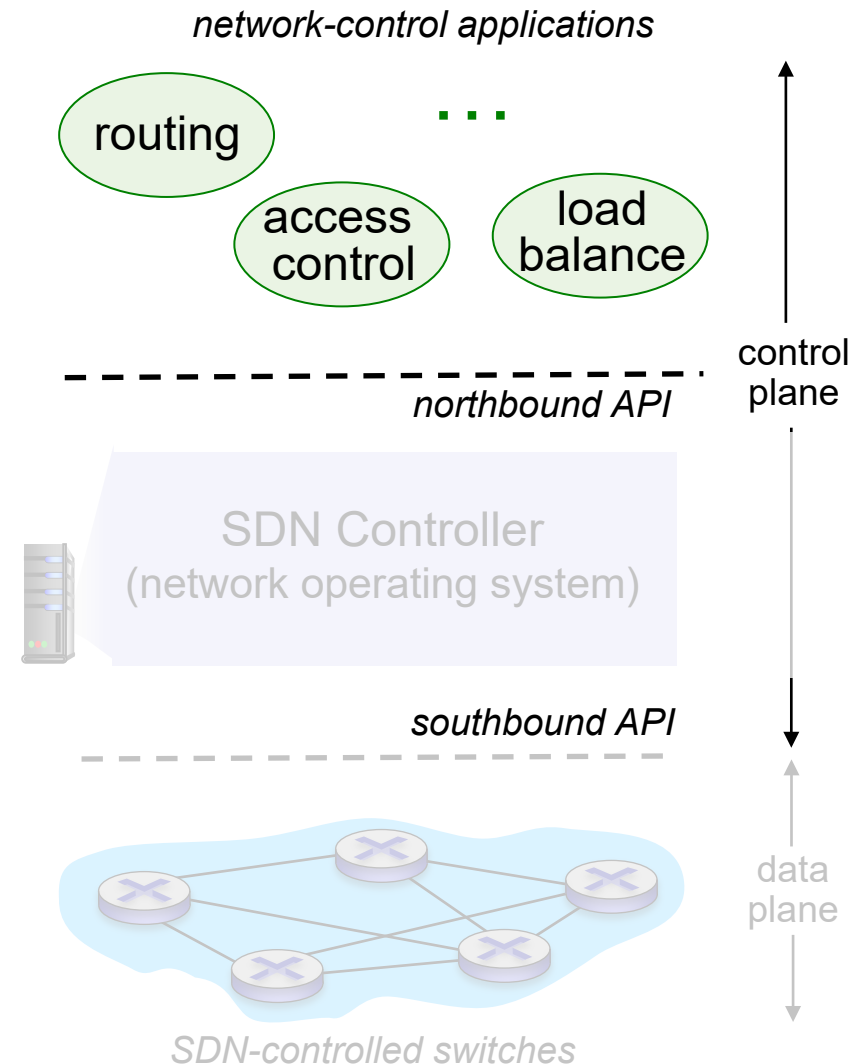
- maintain network state information
- interacts with network control applications “above” via northbound API
- interacts with network switches “below” via southbound API
- implemented as distributed system for performance, scalability, fault-tolerance, robustness



Software defined networking (SDN)

network-control apps:

- “brains” of control:
implement control functions
using lower-level services, API
provided by SDN controller
- *unbundled*: can be provided by
3rd party: distinct from routing
vendor, or SDN controller

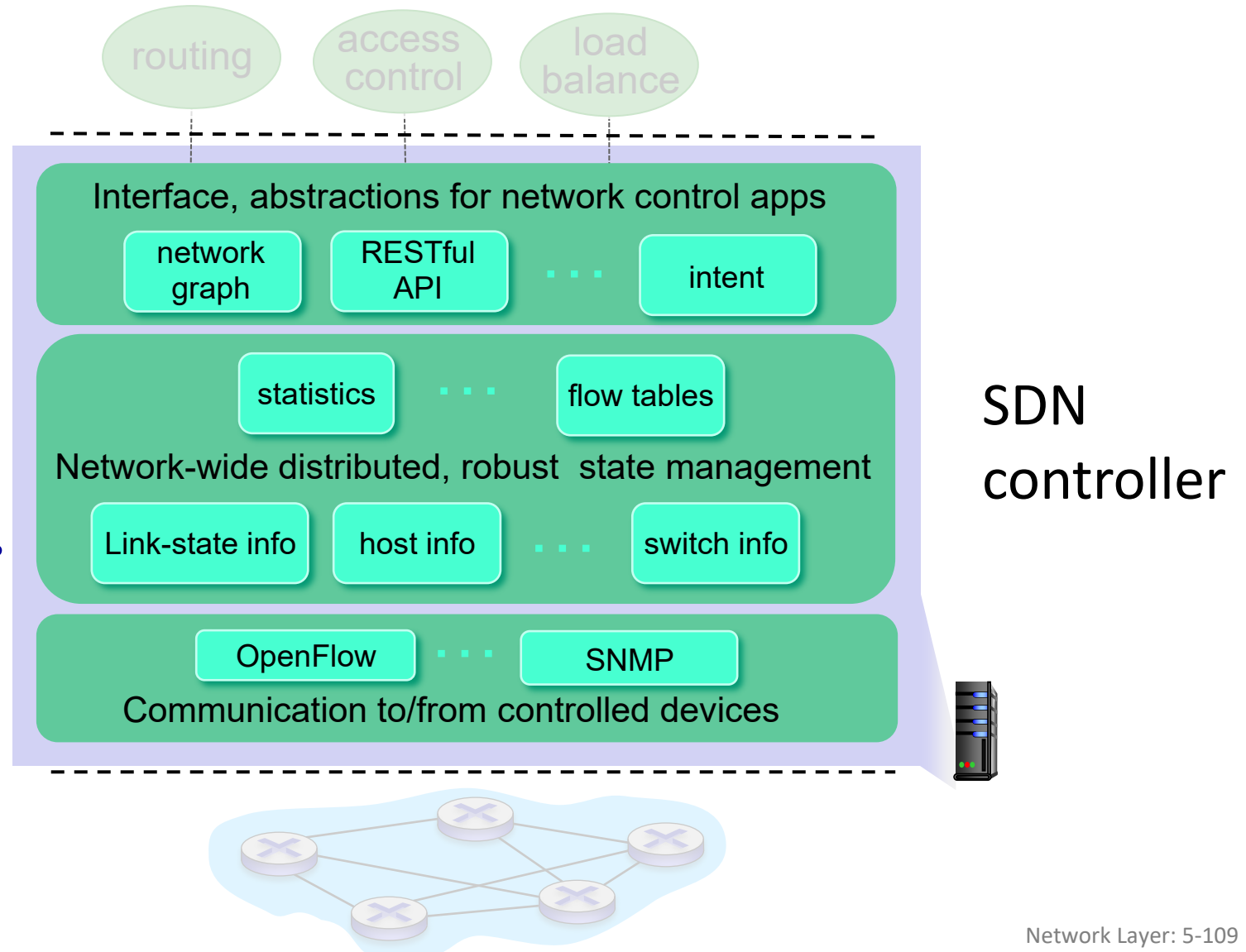


Components of SDN controller – Poll 2

interface layer to network control apps: abstractions API

network-wide state management : state of networks links, switches, services: a *distributed database*

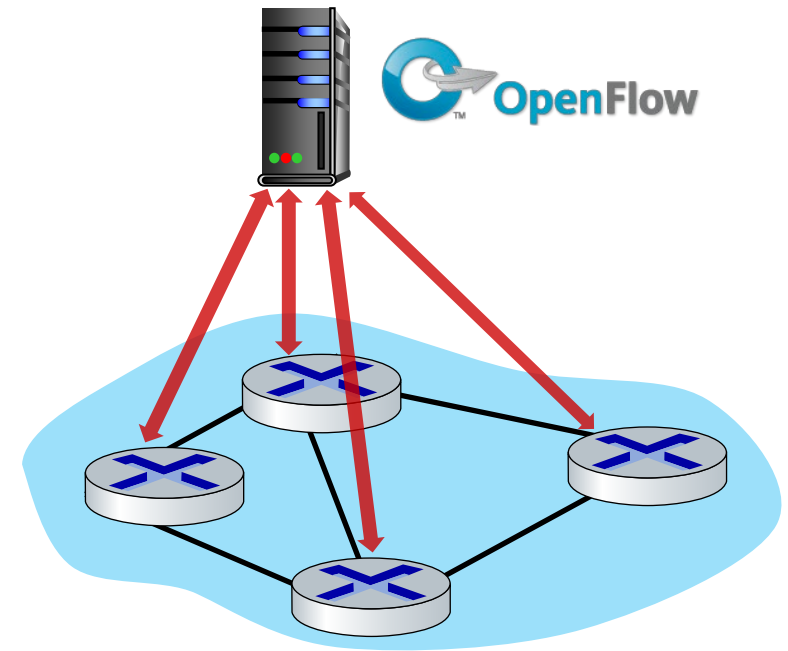
communication: communicate between SDN controller and controlled switches



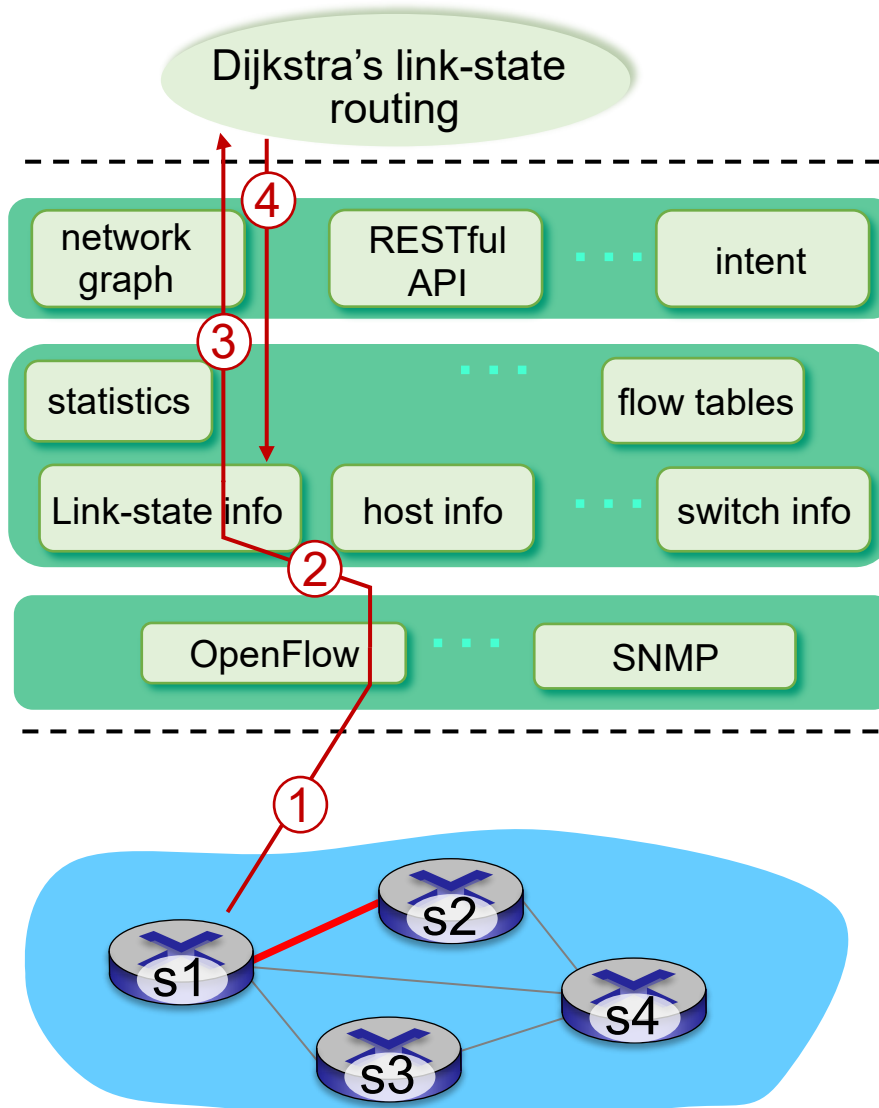
OpenFlow protocol – Poll 3

- operates between controller, switch
- TCP used to exchange messages
 - optional encryption
- three classes of OpenFlow messages:
 - controller-to-switch
 - asynchronous (switch to controller)
 - symmetric (misc.)
- distinct from OpenFlow API
 - API used to specify generalized forwarding actions

OpenFlow Controller

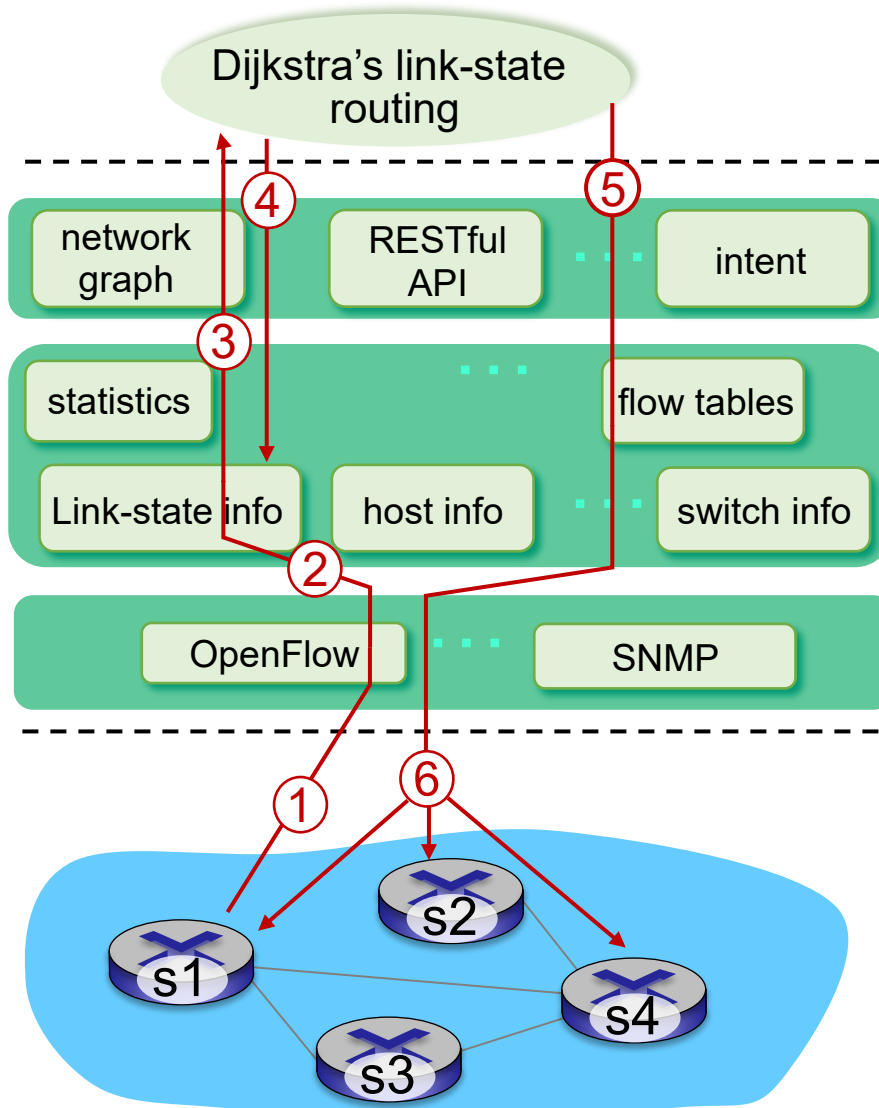


SDN: control/data plane interaction example



- ① S1, experiencing link failure uses OpenFlow port status message to notify controller
- ② SDN controller receives OpenFlow message, updates link status info
- ③ Dijkstra's routing algorithm application has previously registered to be called when ever link status changes. It is called.
- ④ Dijkstra's routing algorithm access network graph info, link state info in controller, computes new routes

SDN: control/data plane interaction example

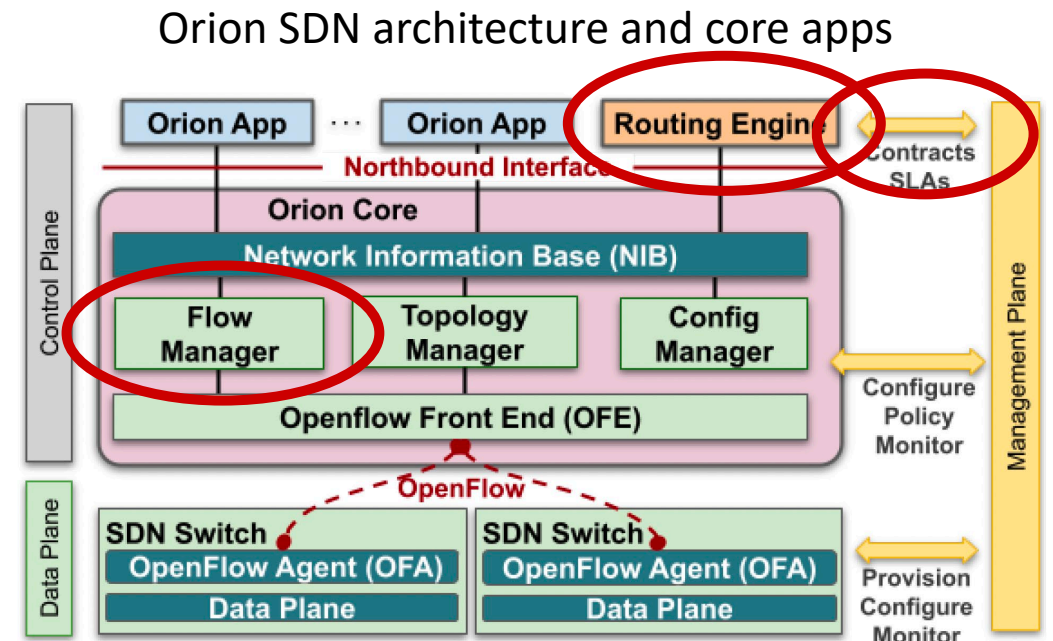


- ⑤ link state routing app interacts with flow-table-computation component in SDN controller, which computes new flow tables needed
- ⑥ controller uses OpenFlow to install new tables in switches that need updating

Google ORION SDN control plane

ORION: Google's SDN control plane (*NSDI'21*): control plane for Google's datacenter (Jupiter) and wide area (B4) networks

- **routing** (intradomain, iBGP), traffic engineering: implemented in *applications* on top of ORION core
- **edge-edge flow-based** controls (e.g., CoFlow scheduling) to meet contract SLAs
- **management:** pub-sub distributed microservices in Orion core, OpenFlow for switch signaling/monitoring



Note: ORION provides *intradomain* services within Google's network

SDN: selected challenges

- hardening the control plane: dependable, reliable, performance-scalable, secure distributed system
 - robustness to failures: leverage strong theory of reliable distributed system for control plane
 - dependability, security: “baked in” from day one?
- networks, protocols meeting mission-specific requirements
 - e.g., real-time, ultra-reliable, ultra-secure
- Internet-scaling: beyond a single AS
- SDN critical in 5G cellular networks

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- network management, configuration
 - SNMP
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ICMP: internet control message protocol – Poll 4

- used by hosts and routers to communicate network-level information
 - error reporting: unreachable host, network, port, protocol
 - echo request/reply (used by ping)
- network-layer “above” IP:
 - ICMP messages carried in IP datagrams
- *ICMP message*: type, code plus first 8 bytes of IP datagram causing error

<u>Type</u>	<u>Code</u>	<u>description</u>
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

Network layer: “control plane” roadmap

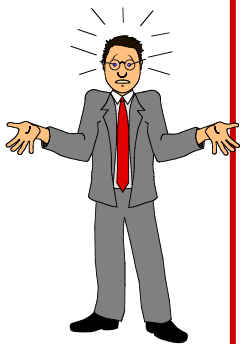
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- network management, configuration
 - SNMP
 - NETCONF/YANG

What is network management?

- autonomous systems (aka “network”): 1000s of interacting hardware/software components
- other complex systems requiring monitoring, configuration, control:
 - jet airplane, nuclear power plant, others?



"**Network management** includes the deployment, integration and coordination of the hardware, software, and human elements to monitor, test, poll, configure, analyze, evaluate, and control the network and element resources to meet the real-time, operational performance, and Quality of Service requirements at a reasonable cost."

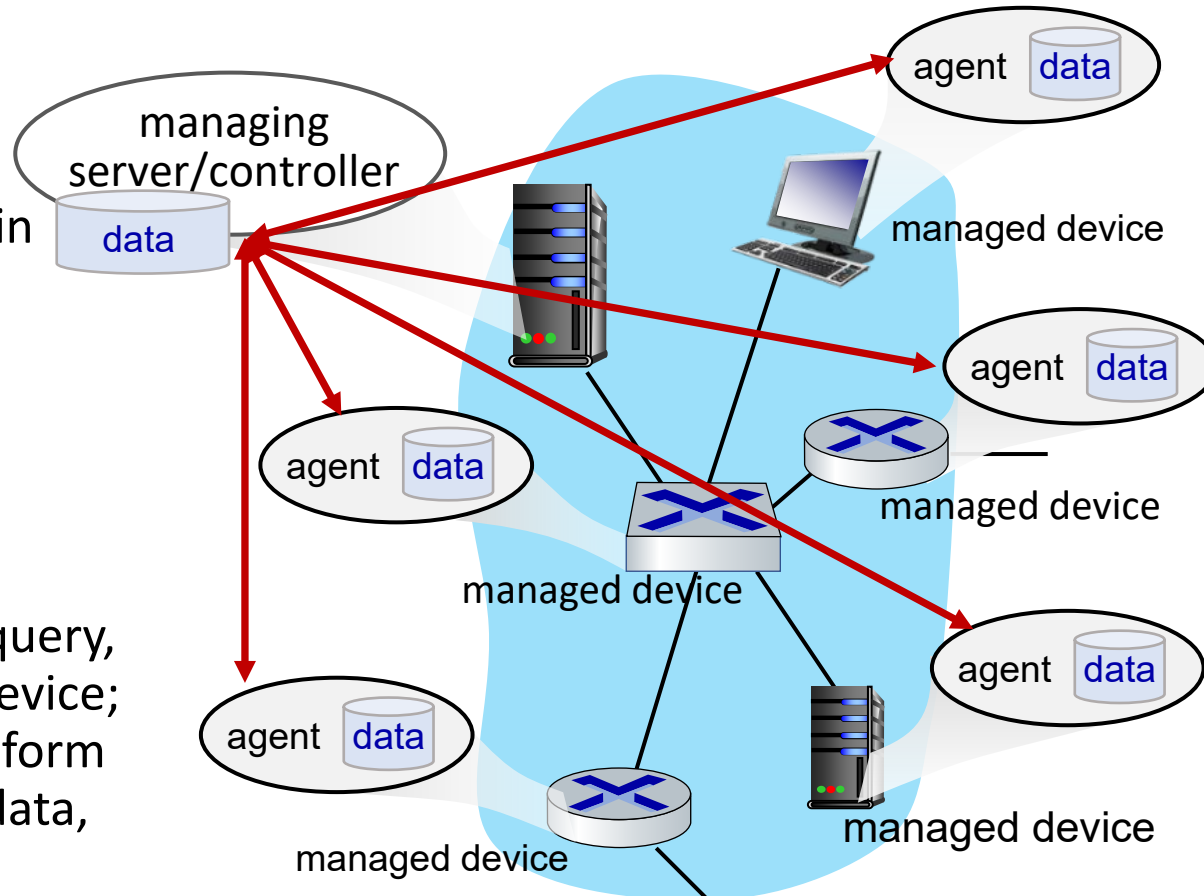
Components of network management

Managing server:

application, typically with network managers (humans) in the loop

Network management protocol:

used by managing server to query, configure, manage device; used by devices to inform managing server of data, events.



Managed device:

equipment with manageable, configurable hardware, software components

Data:

device “state”
configuration data,
operational data,
device statistics

Network layer: Summary

we've learned a lot!

- approaches to network control plane
 - per-router control (traditional)
 - logically centralized control (software defined networking)
- traditional routing algorithms
 - implementation in Internet: OSPF , BGP
- SDN controllers
 - implementation in practice: ODL, ONOS
- Internet Control Message Protocol
- network management

next stop: link layer!

Network layer, control plane: Done!

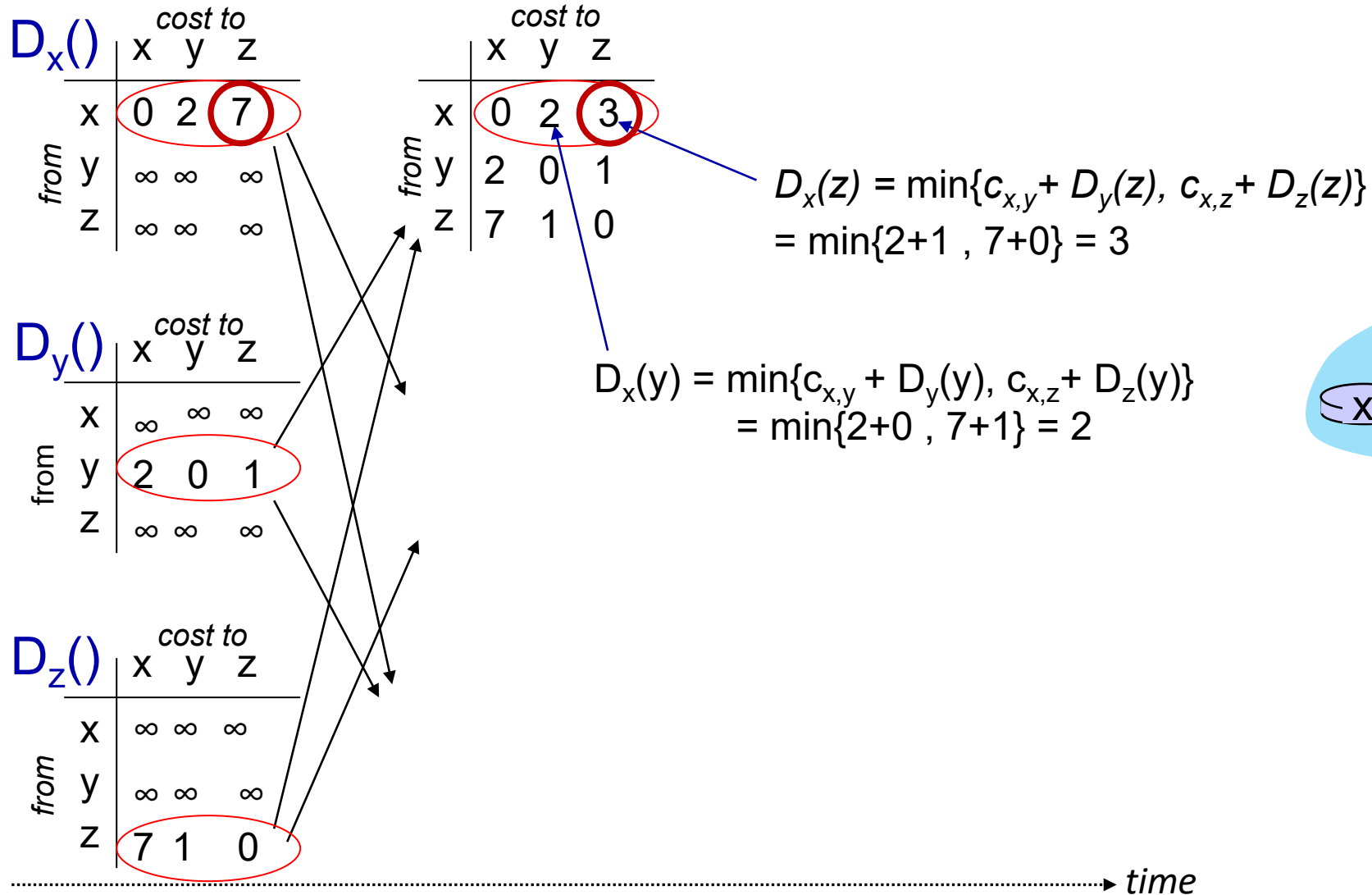
- introduction
- routing protocols
 - link state
 - distance vector
- intra-ISP routing: OSPF
- routing among ISPs: BGP
- SDN control plane
- Internet Control Message Protocol



- network management, configuration
 - SNMP
 - NETCONF/YANG

Additional Chapter 5 slides

Distance vector: another example



Distance vector: another example

