

Chapter 5

Network Layer: Control Plane

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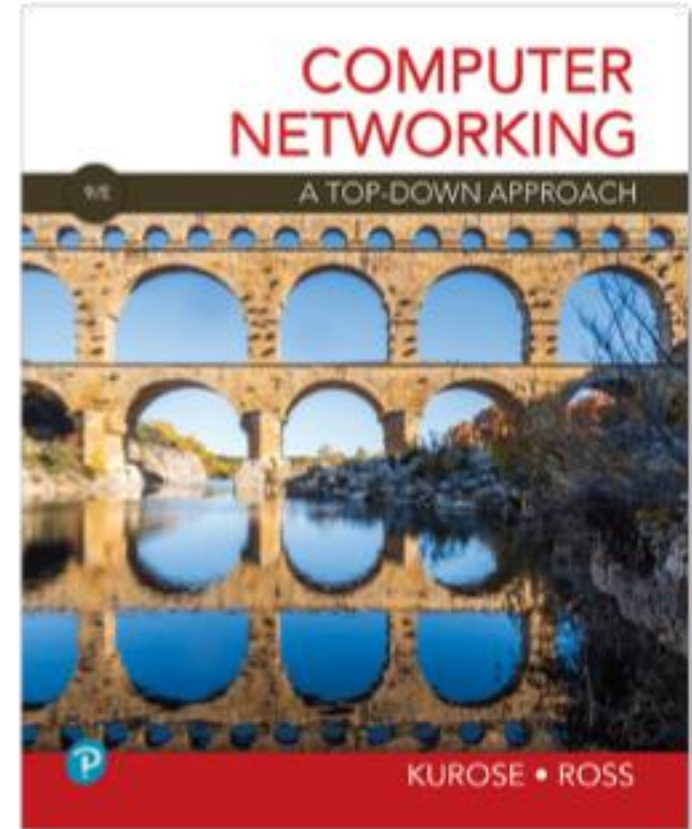
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*Computer Networking: A
Top-Down Approach*

9th edition

Jim Kurose, Keith Ross
Pearson, 2025

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



- network management, configuration
 - SNMP
 - NETCONF/YANG

Network-layer functions

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

data plane

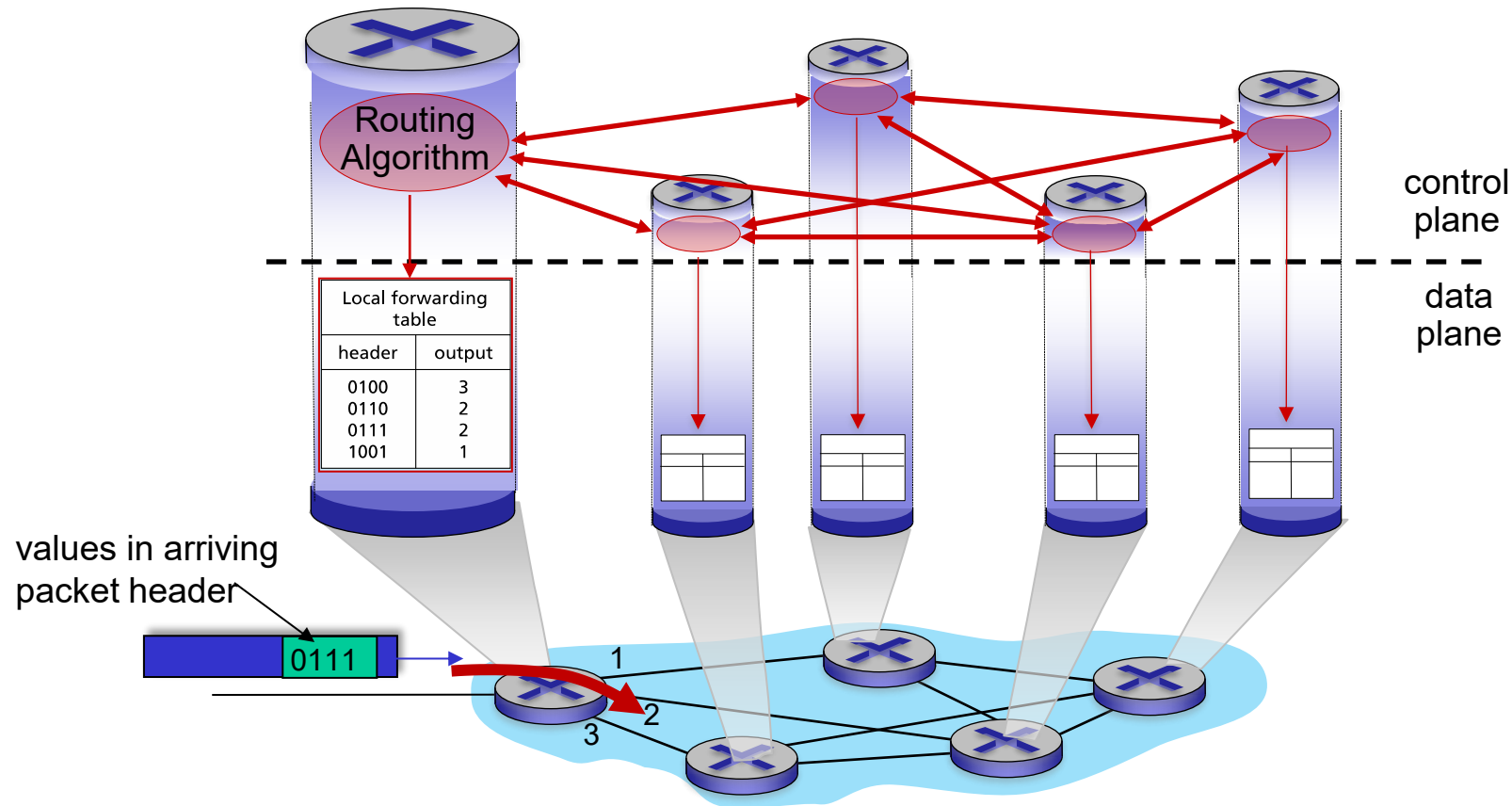
control plane

Two approaches to structuring network control plane:

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

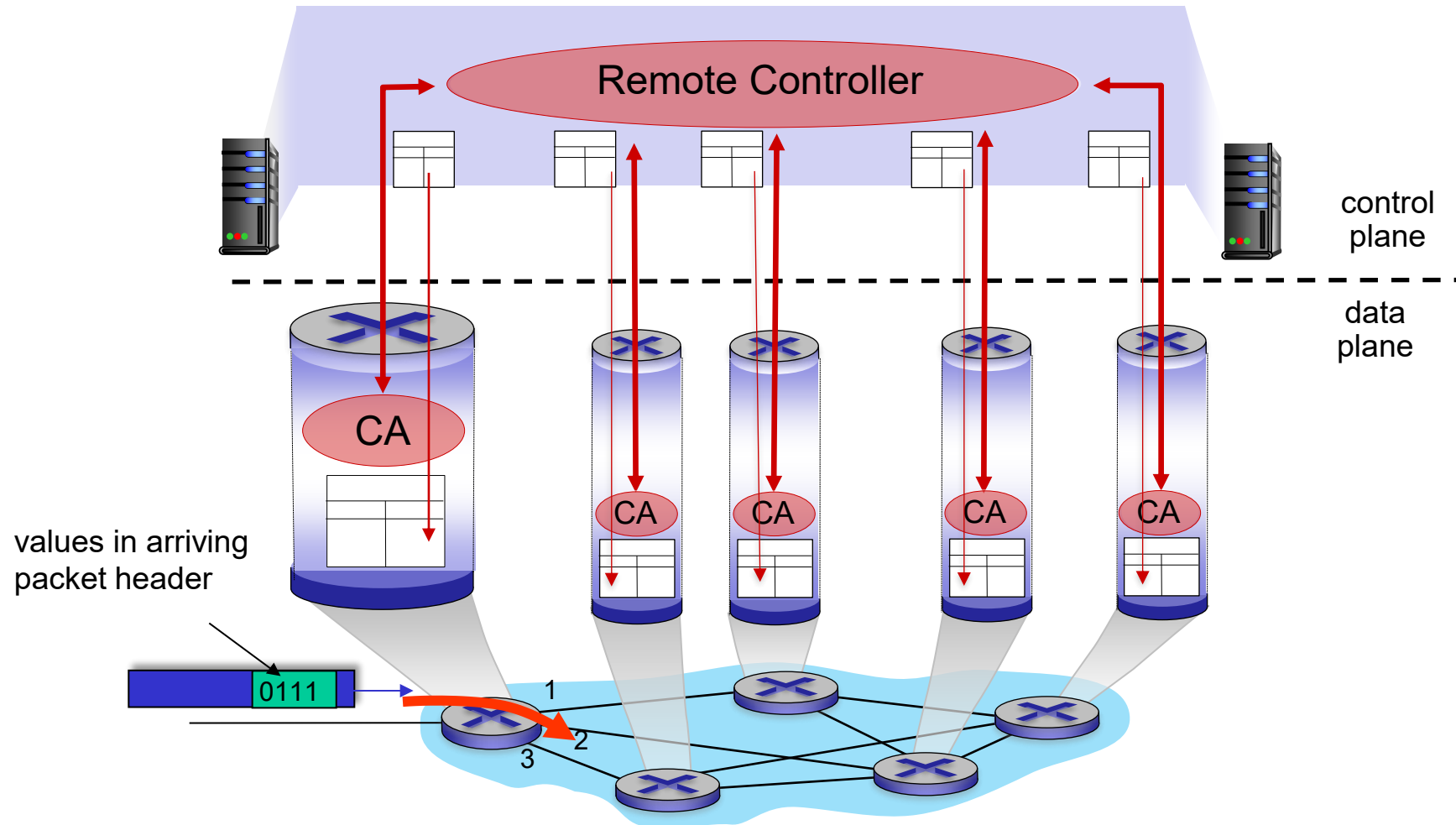
Per-router control plane

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



Software-Defined Networking (SDN) control plane

Remote controller computes, installs forwarding tables in routers



Network layer: “control plane” roadmap

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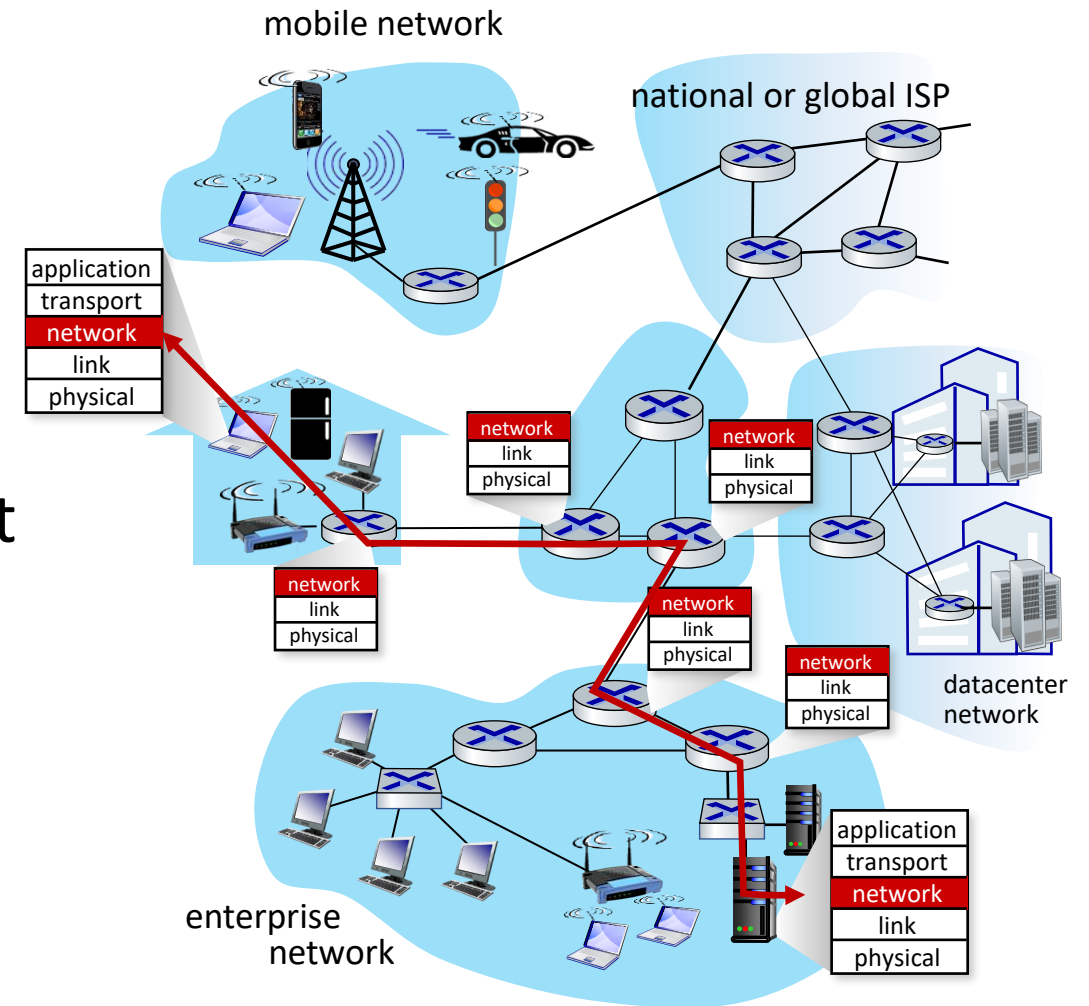


- network management, configuration
 - SNMP
 - NETCONF/YANG

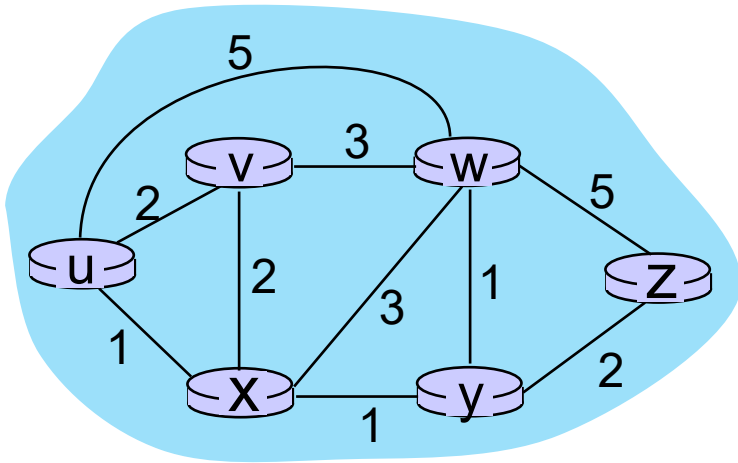
Routing protocols

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

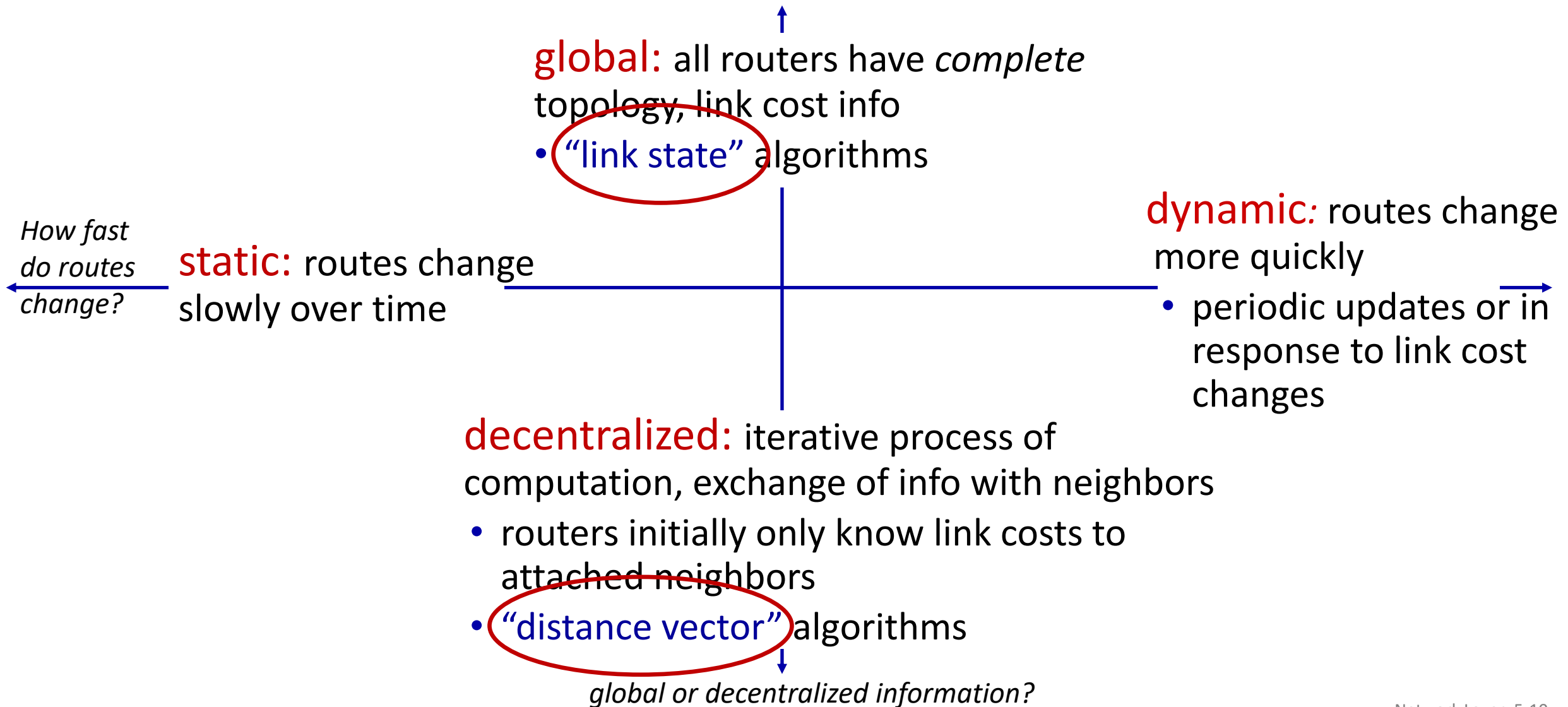
cost defined by network operator:
could always be 1, or inversely related
to bandwidth, or inversely related to
congestion

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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- network management, configuration
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 - NETCONF/YANG

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

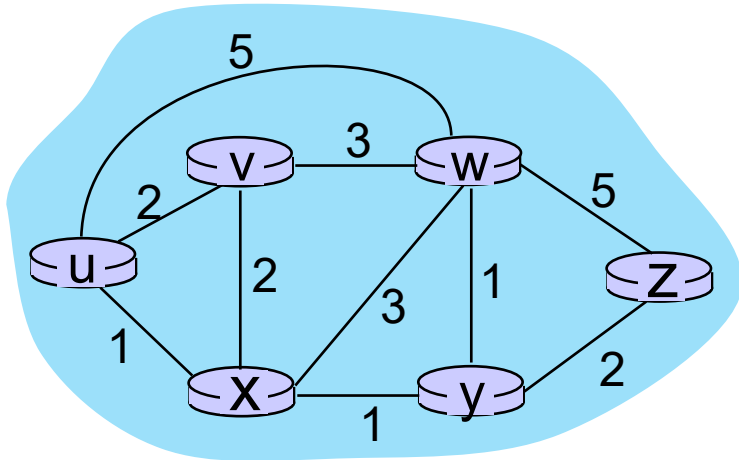
13 /* new least-path-cost to v is either old least-cost-path to v or known

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						

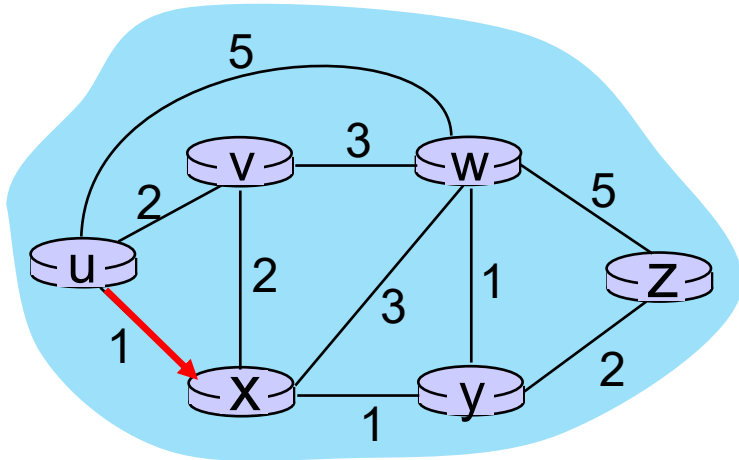


Initialization (step 0):

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						



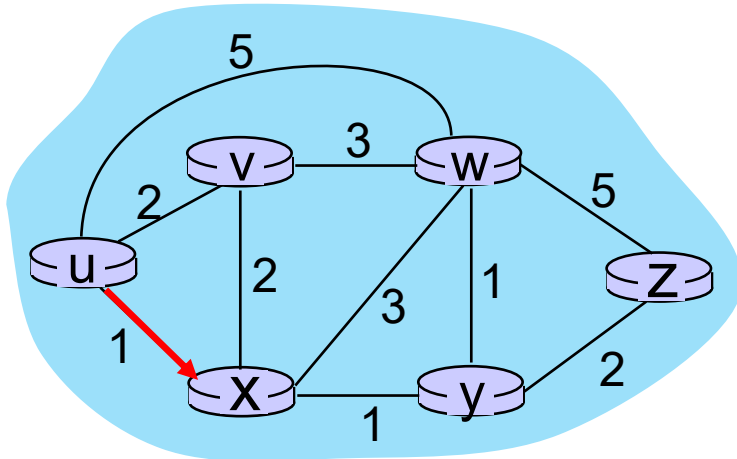
8 Loop

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						



8 Loop

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

10 add a to N'

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

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

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

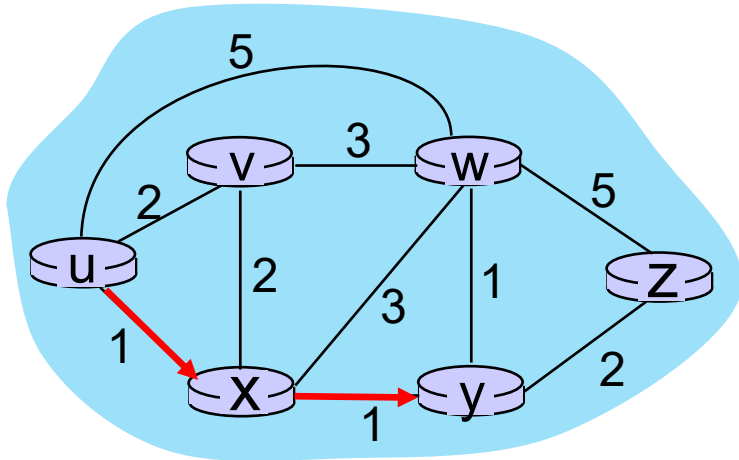
$$D(w) = \min (D(w), D(x) + c_{x,w}) = \min(5, 1+3) = 4$$

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



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						



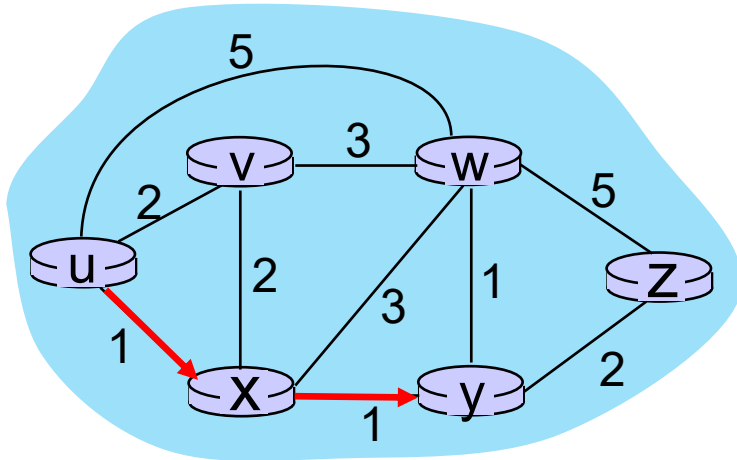
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Dijkstra's algorithm: an example

		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

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

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

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

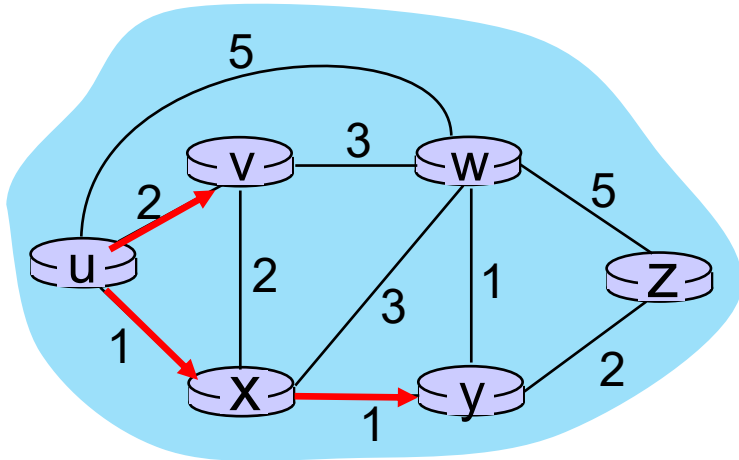
$$D(w) = \min (D(w), D(y) + c_{y,w}) = \min (4, 2+1) = 3$$

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

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						



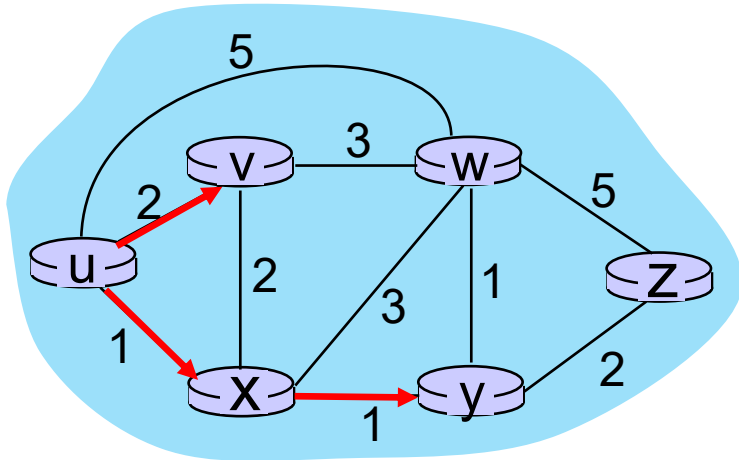
8 Loop

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	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4						
5						



8 *Loop*

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

10 add a to N'

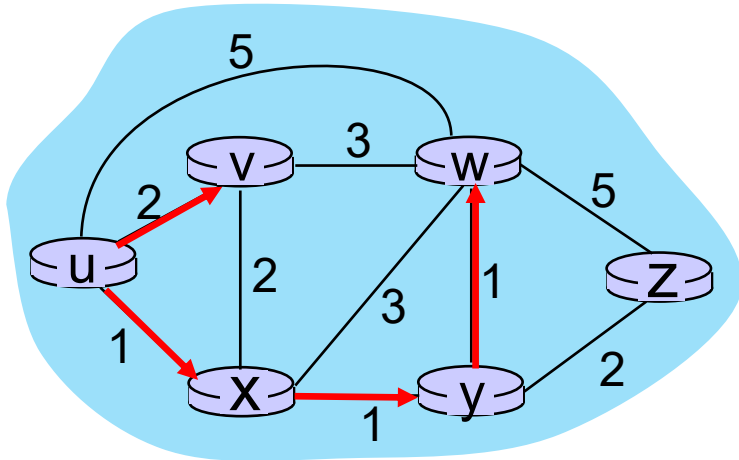
11 update $D(b)$ for all b adjacent to a and not in N' :

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

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

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	5, y	∞	∞
4	uxyvw	4, v	5, v	6, v	3, y	5, y
5	uxyvwz	5, z	6, z	7, z	4, y	5, y



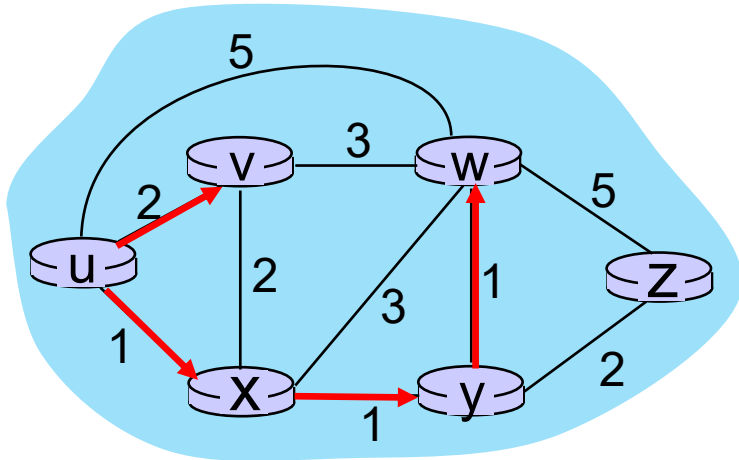
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Dijkstra's algorithm: an example

		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						



8 *Loop*

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

10 add a to N'

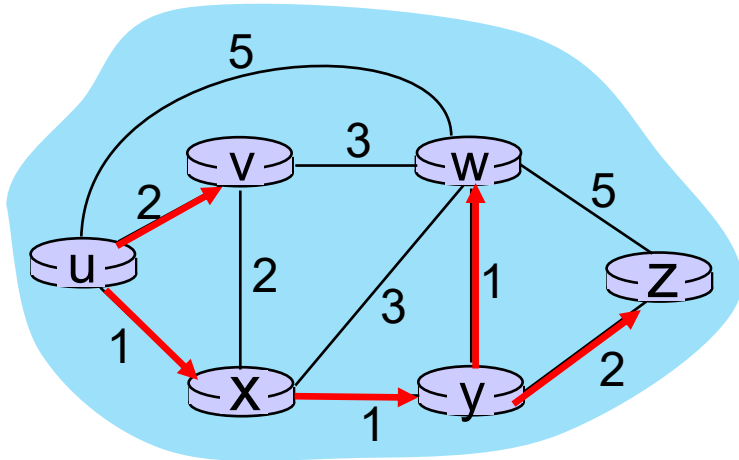
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$$D(z) = \min (D(z), D(w) + c_{w,z}) = \min (4, 3+5) = 4$$

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					4, y
5	uxyvwz					



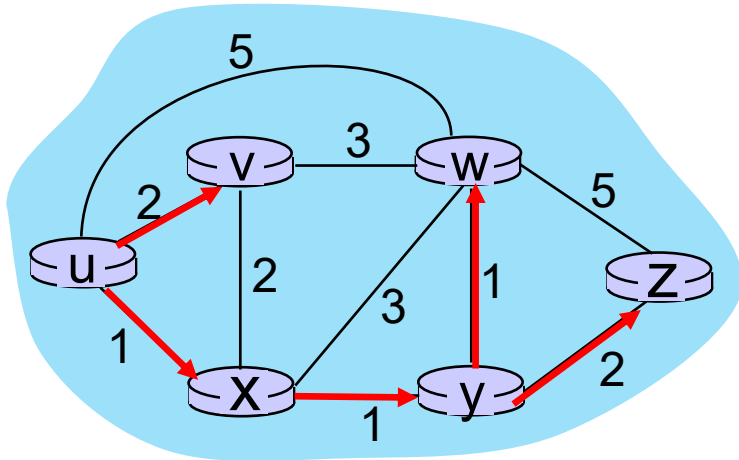
8 Loop

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

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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	uxyvw					4,y
5	uxyvwz					

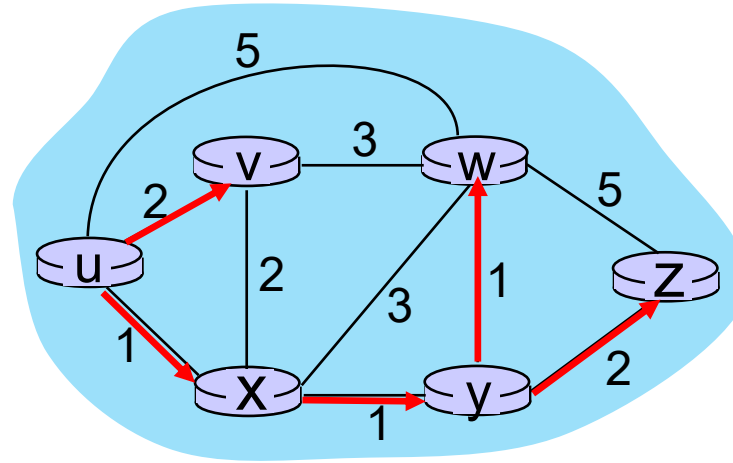


8 Loop

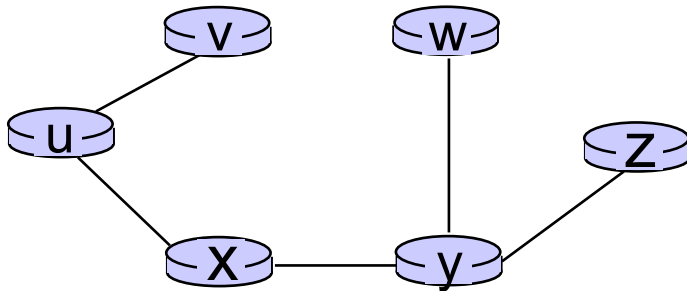
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$$D(b) = \min (D(b), D(a) + c_{a,b})$$

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)
x	(u,x)

route from u to v directly

route from u to all other destinations via x

Dijkstra's algorithm: discussion

algorithm complexity: n nodes

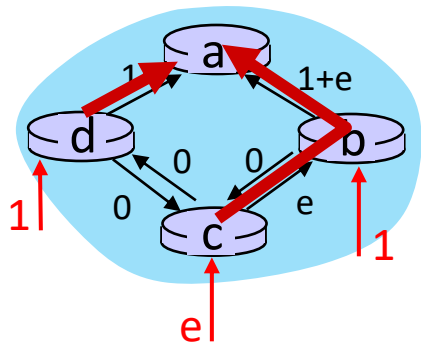
- each of n iteration: need to check all nodes, w , not in N
- $n(n+1)/2$ comparisons: $O(n^2)$ complexity
- more efficient implementations possible: $O(n \log n)$

message complexity:

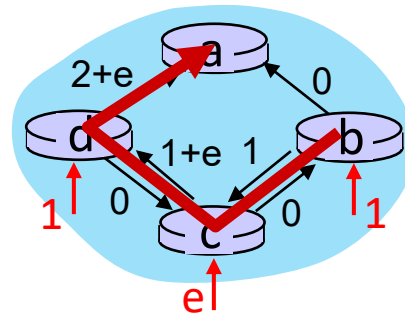
- each router must *broadcast* its link state information to other n routers
- efficient (and interesting!) broadcast algorithms: $O(n)$ link crossings to disseminate a broadcast message from one source
- each router's message crosses $O(n)$ links: overall message complexity: $O(n^2)$

Dijkstra's algorithm: oscillations possible

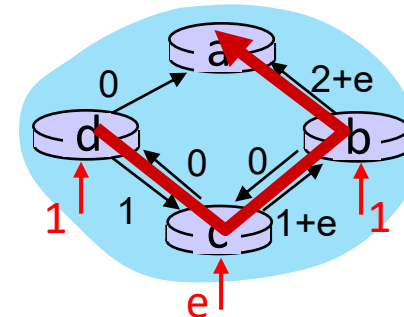
- when link costs depend on traffic volume, **route oscillations** possible
- sample scenario:
 - routing to destination a, traffic entering at d, c, e with rates 1, e (<1), 1
 - link costs are directional, and volume-dependent



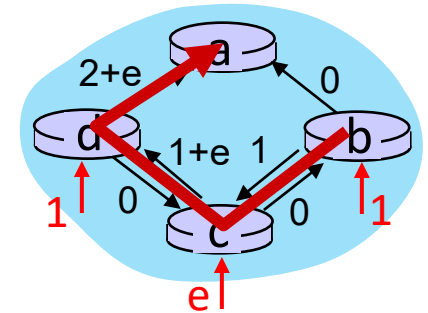
initially



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

Network layer: “control plane” roadmap

- 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

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:

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

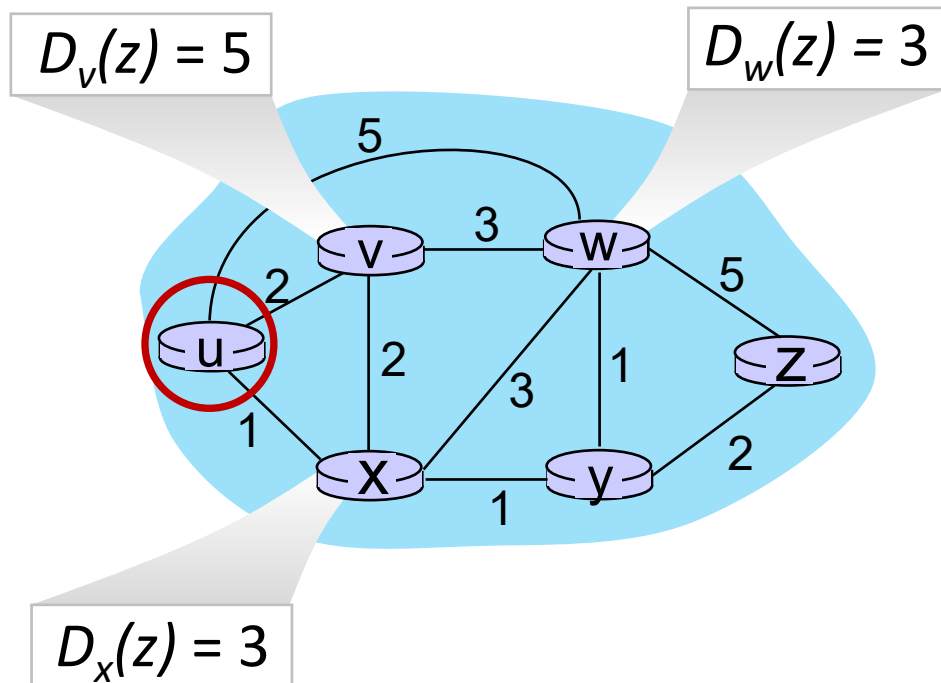
v 's estimated least-cost-path cost to y

\min taken over all neighbors v of x

direct cost of link from x to v

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:

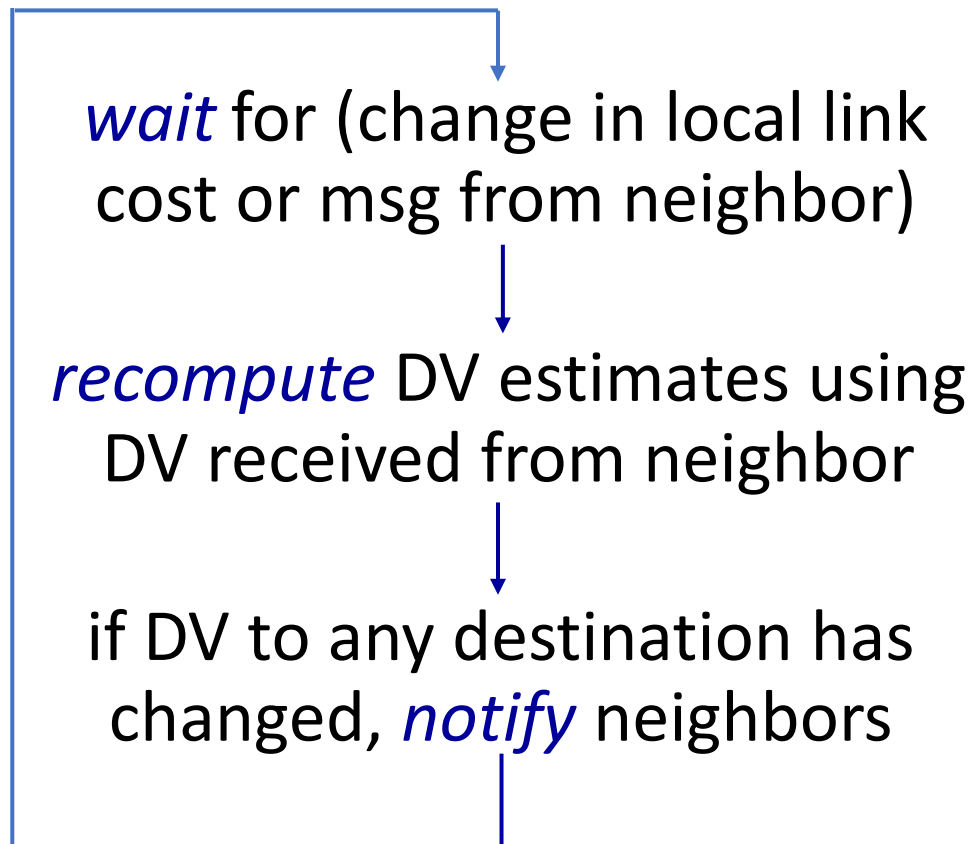
- from time-to-time, each node sends its own distance vector estimate to neighbors
- when x receives new DV estimate from any neighbor, it updates its own DV using B-F equation:

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

- 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!

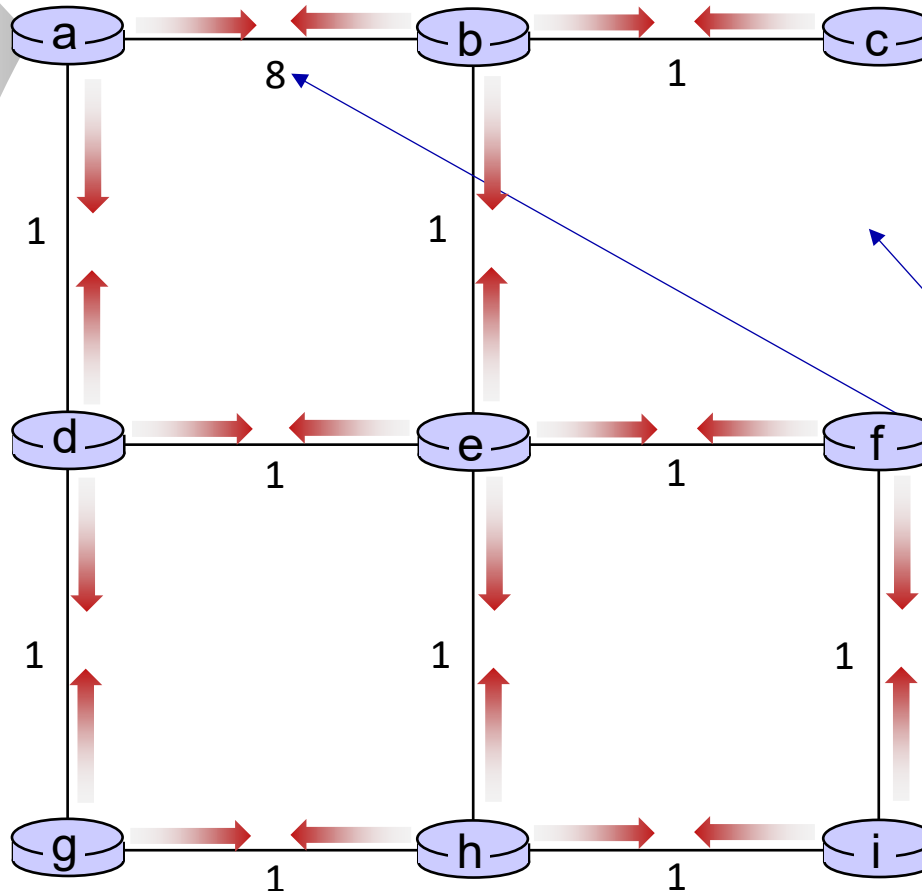
Distance vector: example



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

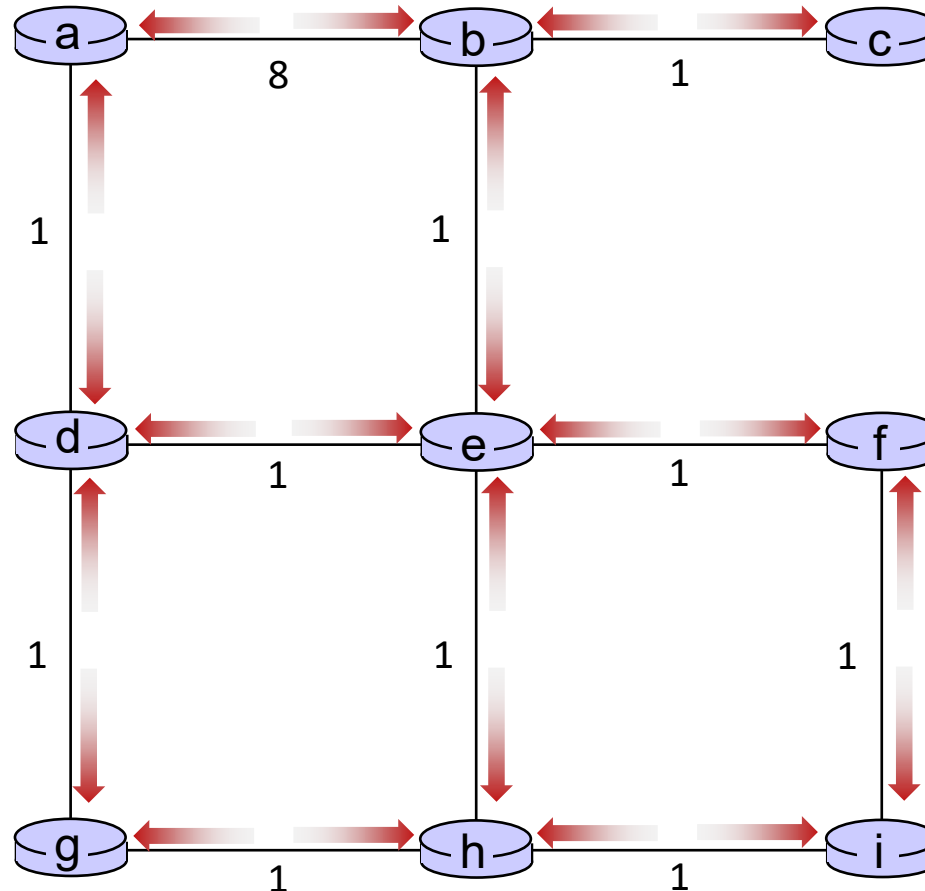
Distance vector example: iteration



$t=1$

All nodes:

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



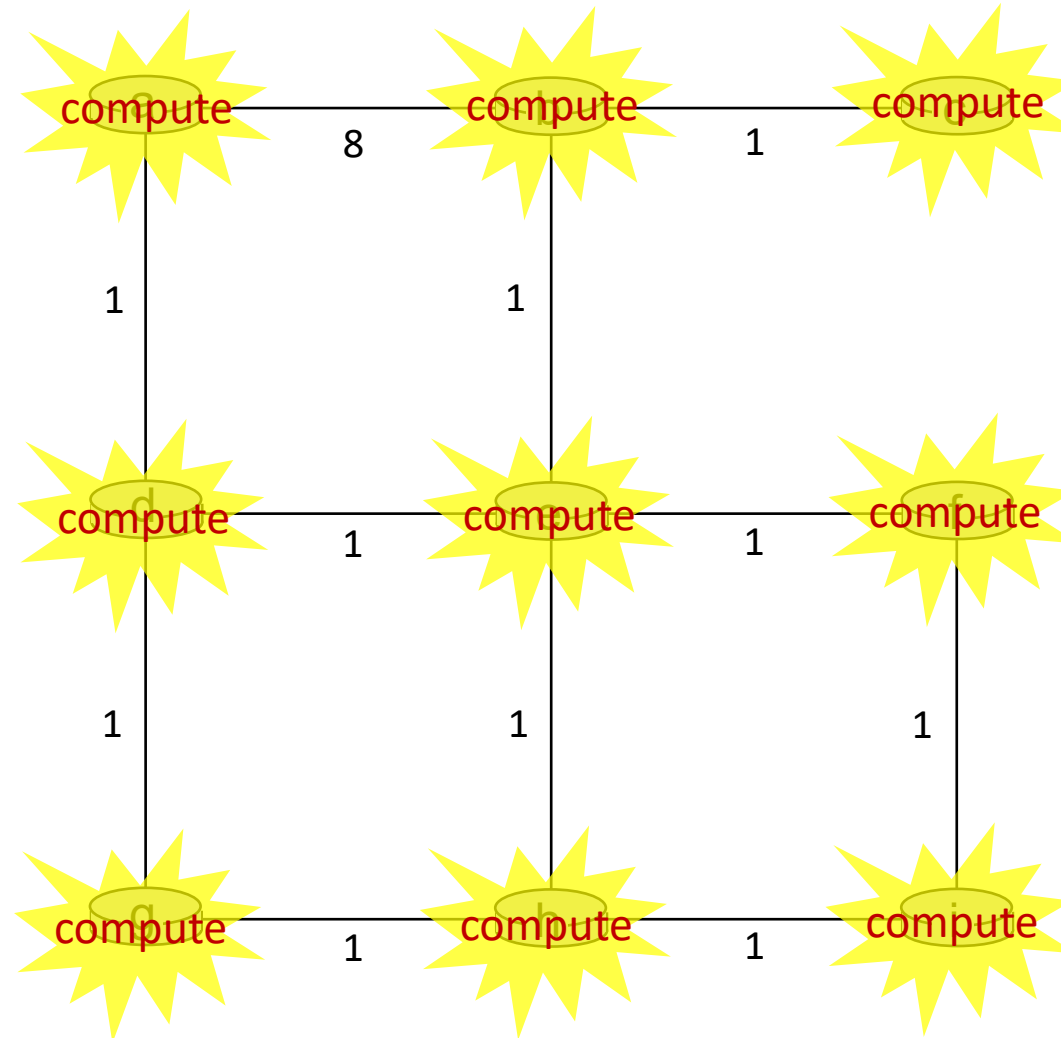
Distance vector example: iteration



$t=1$

All nodes:

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



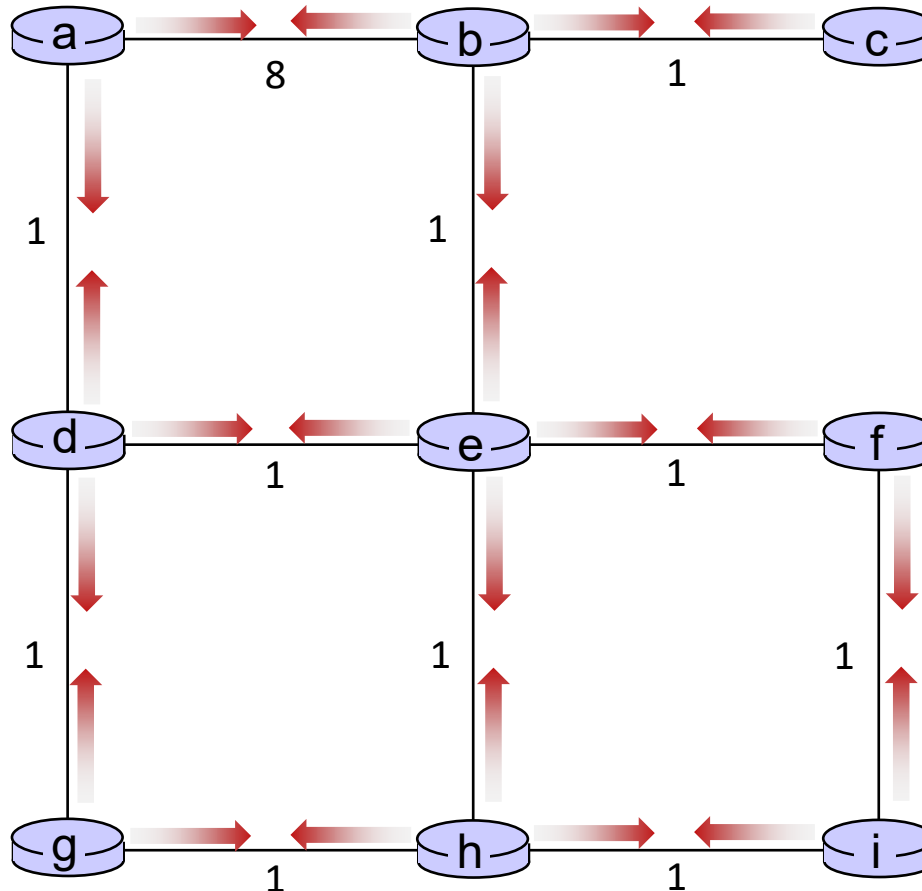
Distance vector example: iteration



t=1

All nodes:

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



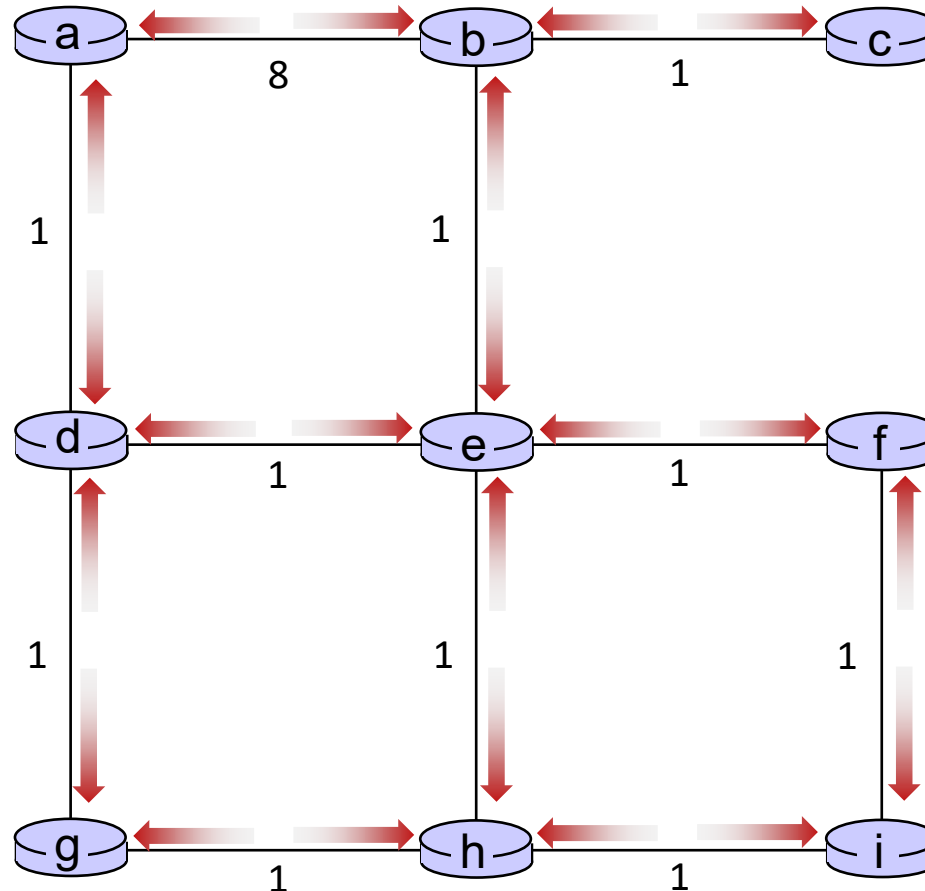
Distance vector example: iteration



$t=2$

All nodes:

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



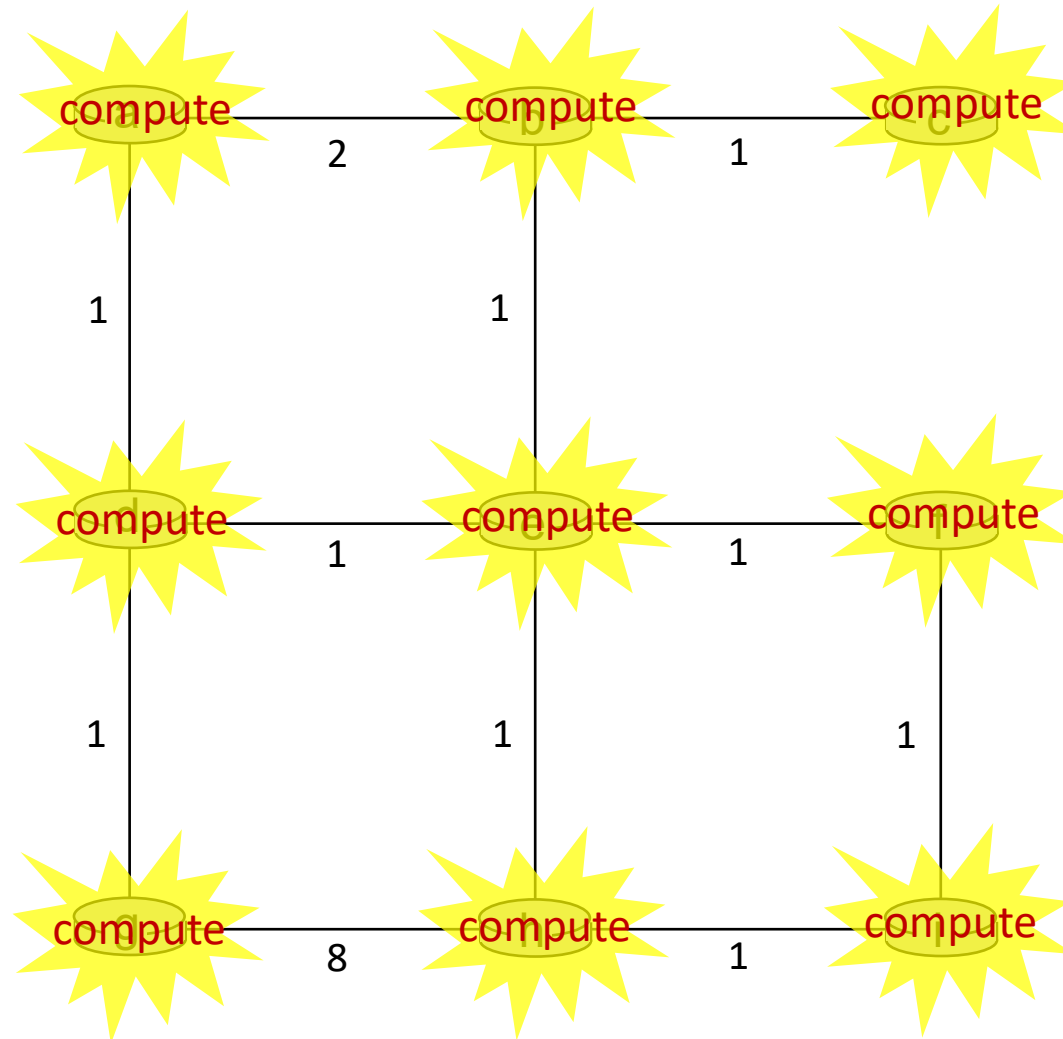
Distance vector example: iteration



t=2

All nodes:

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



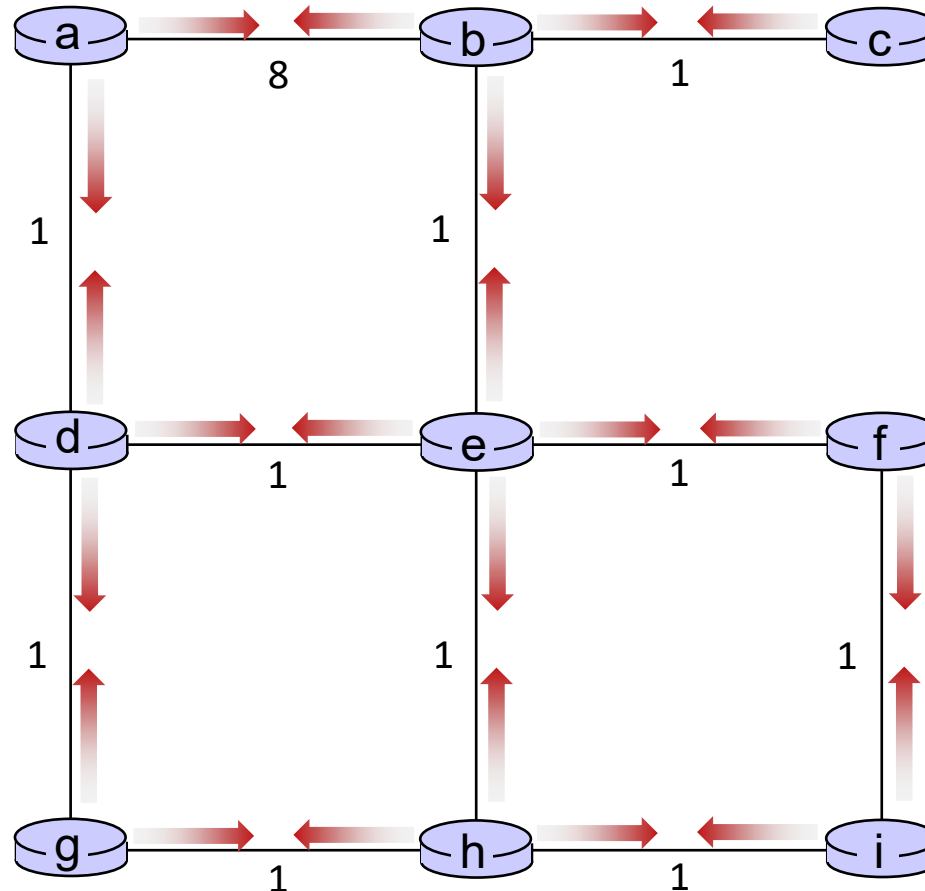
Distance vector example: iteration



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:

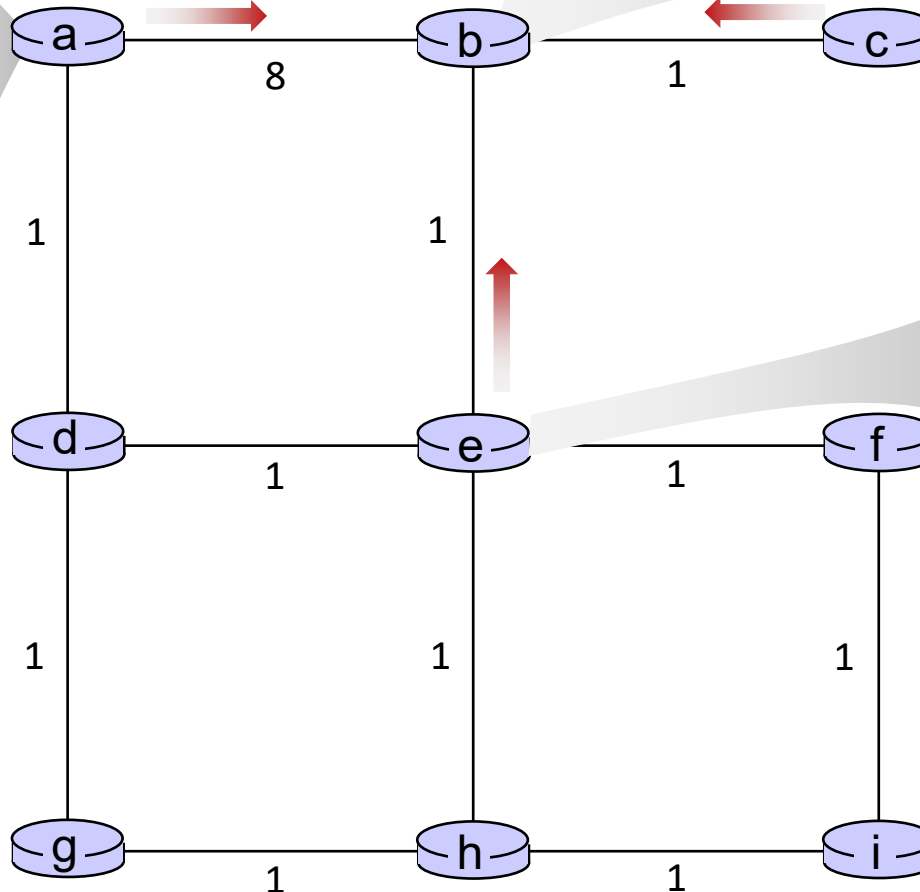
$D_b(a)=8$ $D_b(f)=\infty$
 $D_b(c)=1$ $D_b(g)=\infty$
 $D_b(d)=\infty$ $D_b(h)=\infty$
 $D_b(e)=1$ $D_b(i)=\infty$

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:

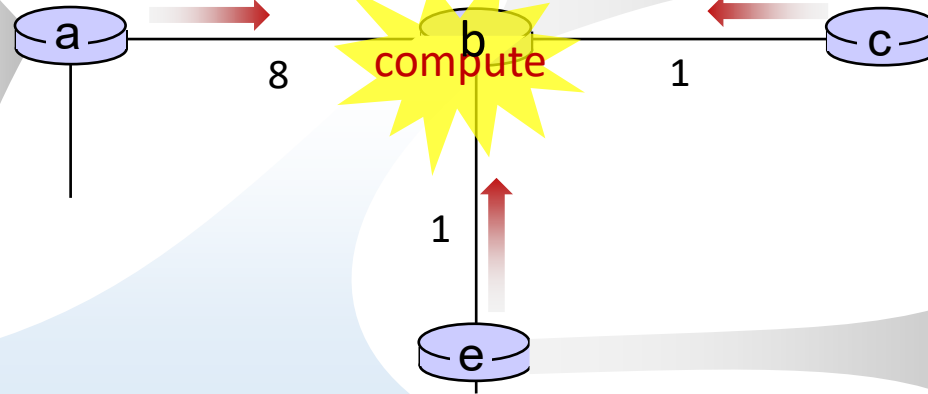


t=1

- 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:

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

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

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:

$$D_b(a) = 8$$

$$D_b(c) = 1$$

$$D_b(d) = \infty$$

$$D_b(e) = 1$$

$$D_b(f) = \infty$$

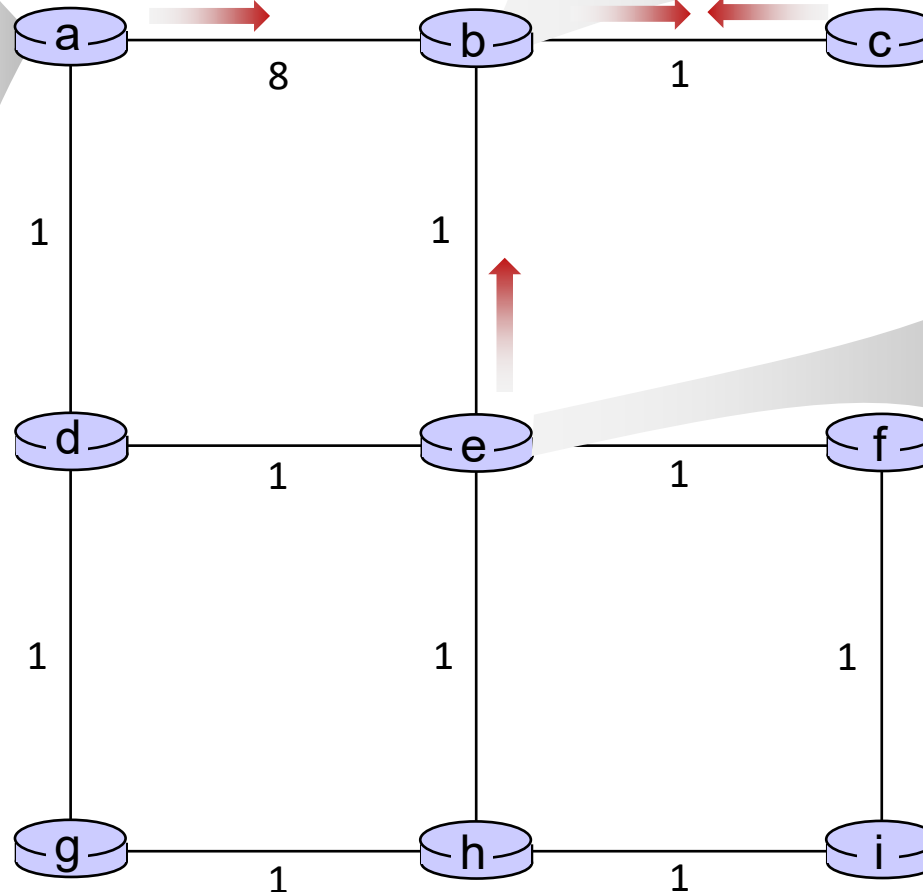
$$D_b(g) = \infty$$

$$D_b(h) = \infty$$

$$D_b(i) = \infty$$

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



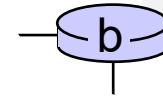
Distance vector example:



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:

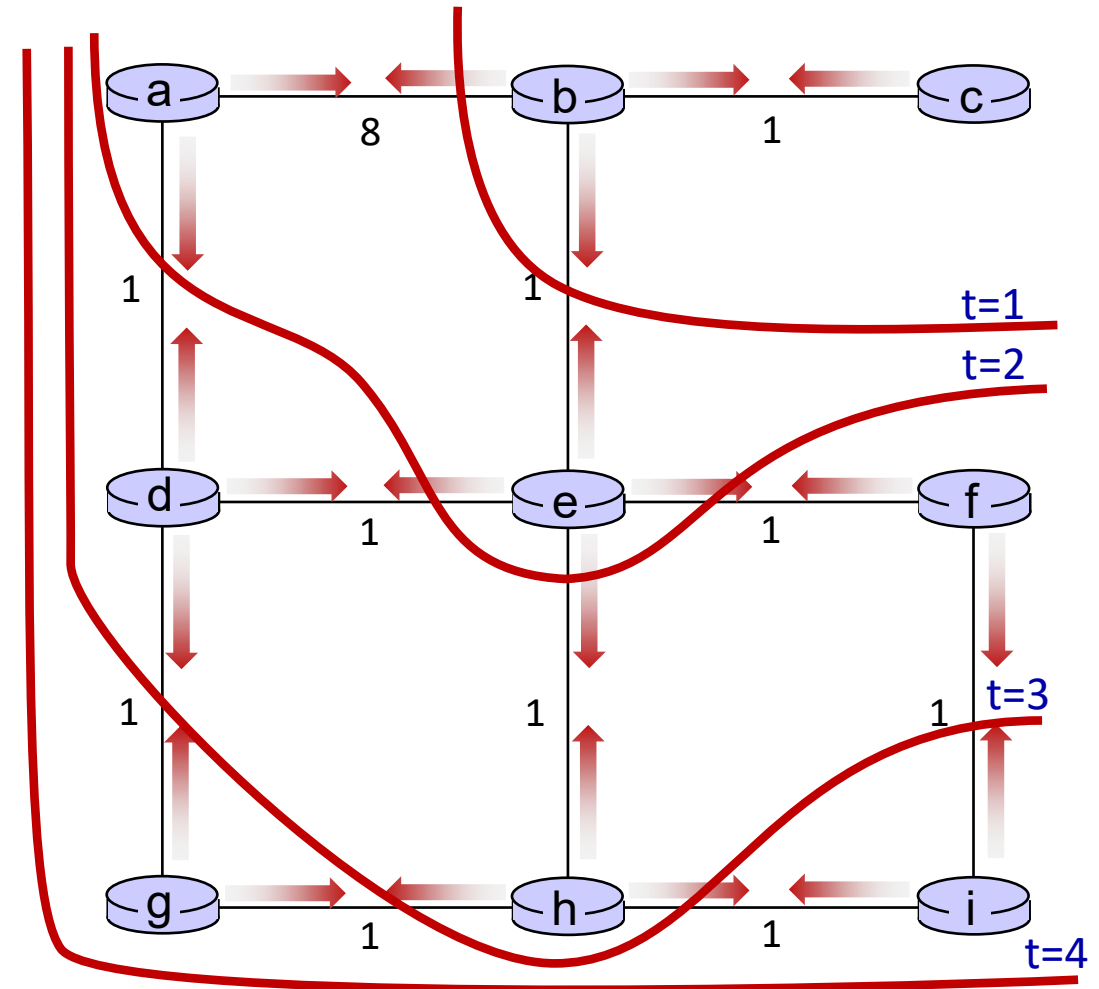
$D_c(a) = 9$
$D_c(b) = 1$
$D_c(c) = 0$
$D_c(d) = 2$
$D_c(e) = \infty$
$D_c(f) = \infty$
$D_c(g) = \infty$
$D_c(h) = \infty$
$D_c(i) = \infty$

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

Distance vector: state information diffusion

Iterative communication, computation steps diffuses information through network:

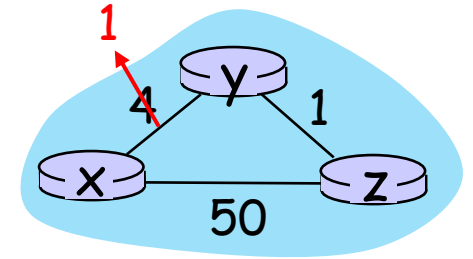
-  $t=0$ c's state at $t=0$ is at c only
-  $t=1$ c's state at $t=0$ has propagated to b, and may influence distance vector computations up to **1** hop away, i.e., at b
-  $t=2$ c's state at $t=0$ may now influence distance vector computations up to **2** hops away, i.e., at b and now at a, e as well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

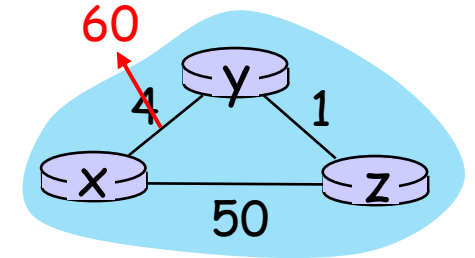
t_1 : z receives update from y, updates its DV, computes new least cost to x, sends its neighbors its DV.

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.
 - ...
- see text for solutions. *Distributed algorithms are tricky!*



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 through network

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

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”)

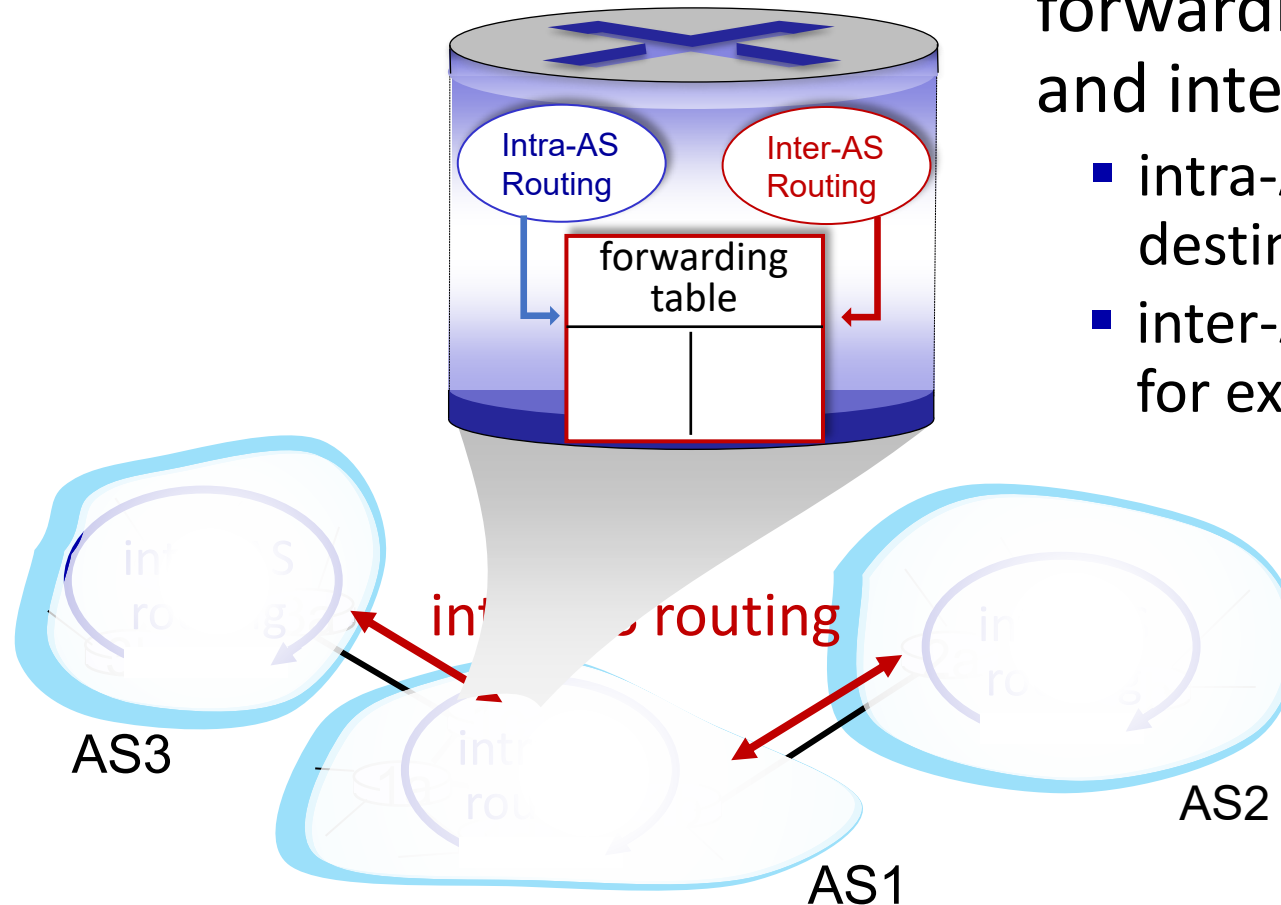
intra-AS (aka “intra-domain”):
routing among routers *within same AS (“network”)*

- 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

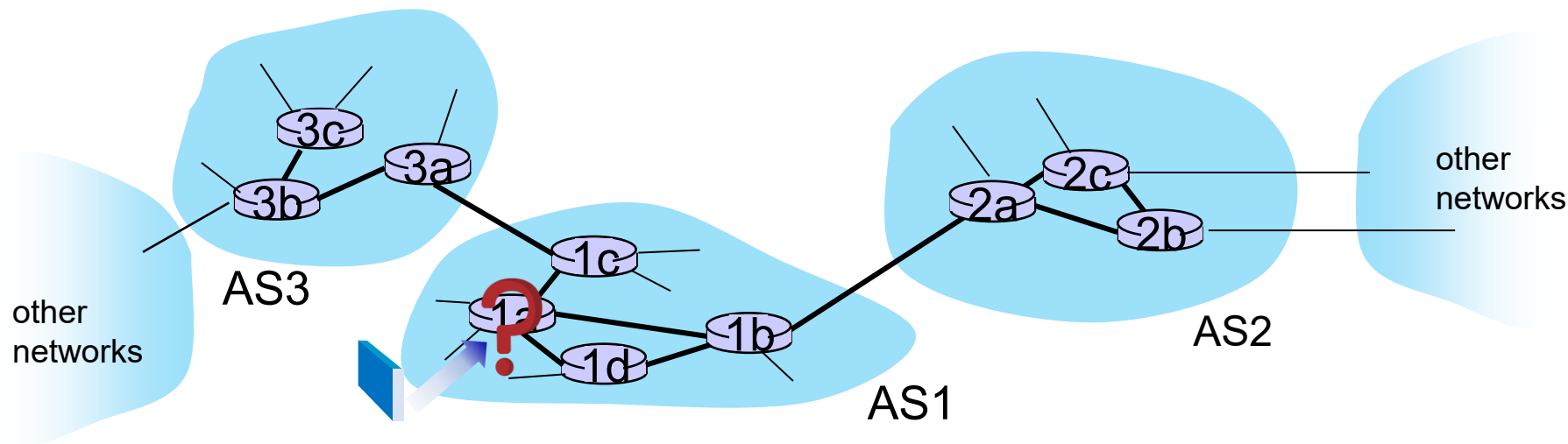
Inter-AS routing: a role in intradomain forwarding

- 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:

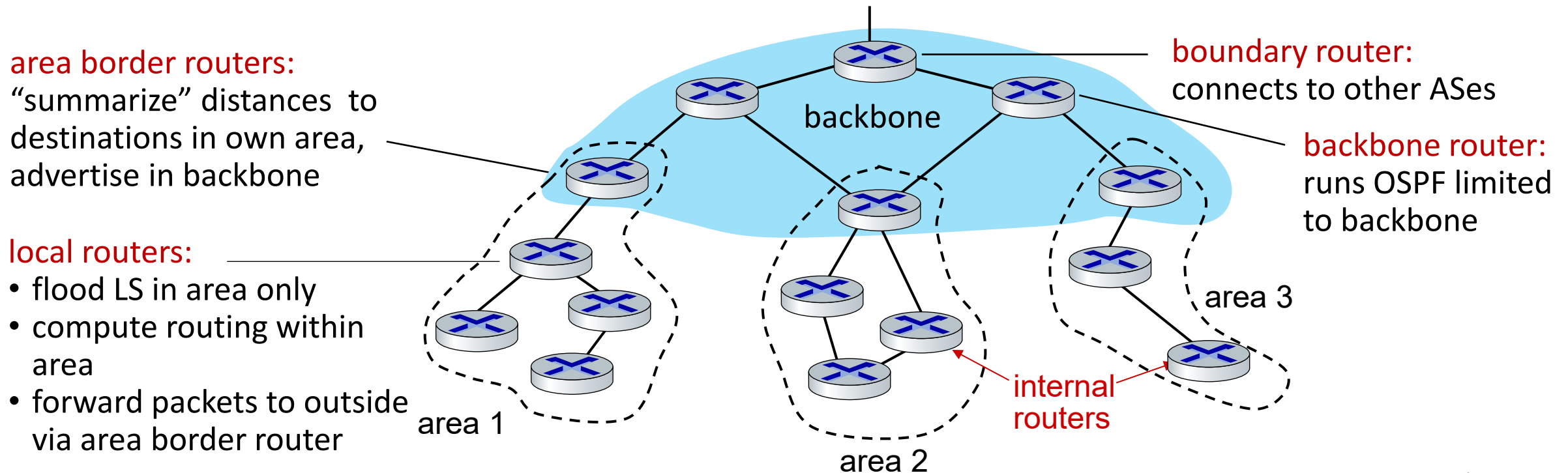
- **RIP: Routing Information Protocol** [RFC 1723]
 - classic DV: DVs exchanged every 30 secs
 - no longer widely used
- **EIGRP: Enhanced Interior Gateway Routing Protocol**
 - DV based
 - formerly Cisco-proprietary for decades (became open in 2013 [RFC 7868])
- **OSPF: Open Shortest Path First** [RFC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

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

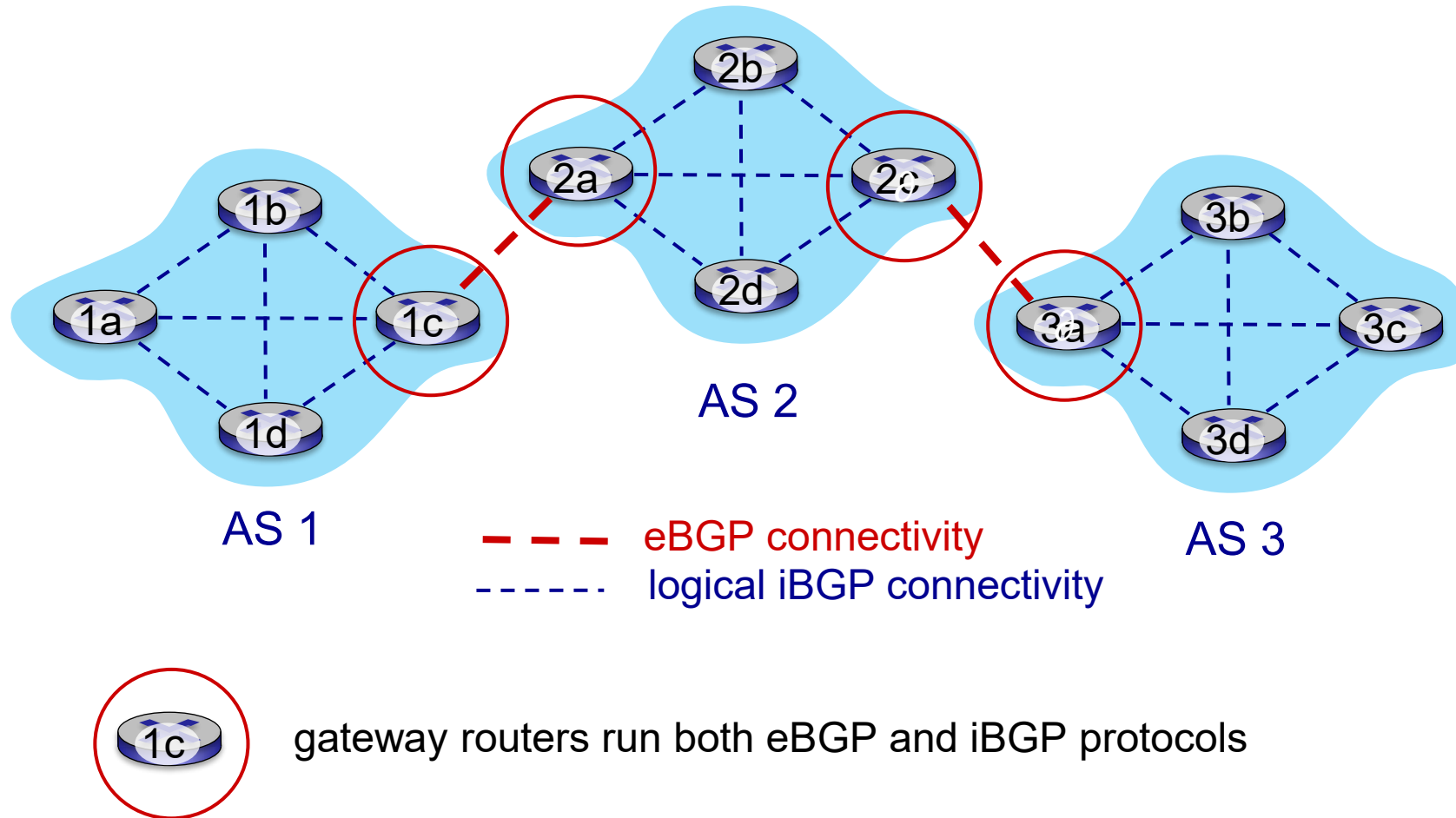


- network management, configuration
 - SNMP
 - NETCONF/YANG

Internet inter-AS routing: BGP

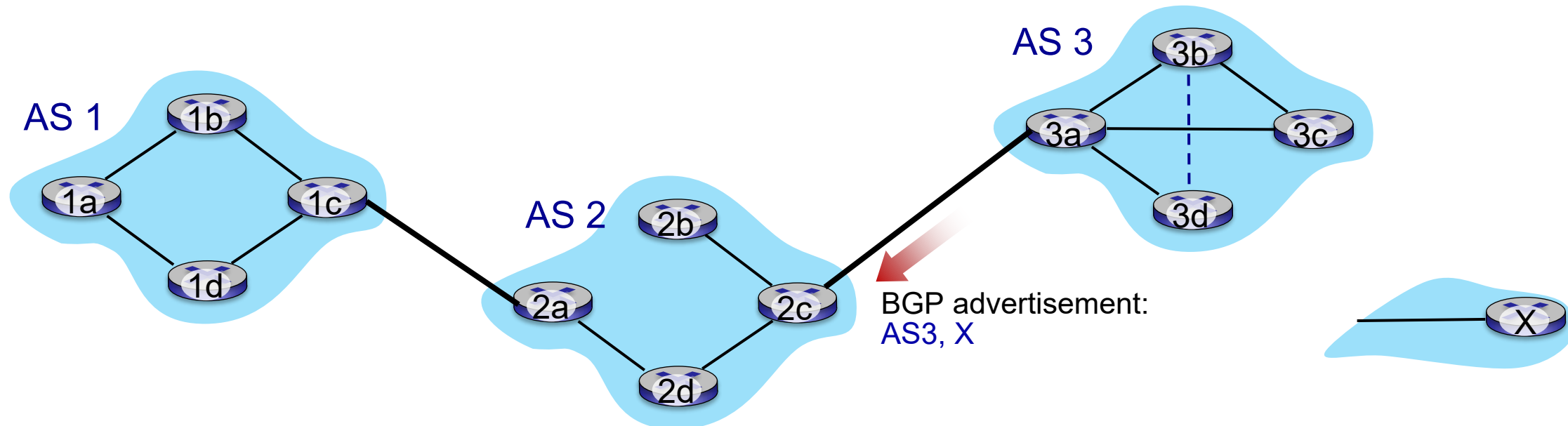
- **BGP (Border Gateway Protocol)**: *the* de facto inter-domain routing protocol
 - “glue that holds the Internet together”
- allows subnet to advertise its existence, and the destinations it can reach, to rest of Internet: *“I am here, here is who I can reach, and how”*
- BGP provides each AS a means 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



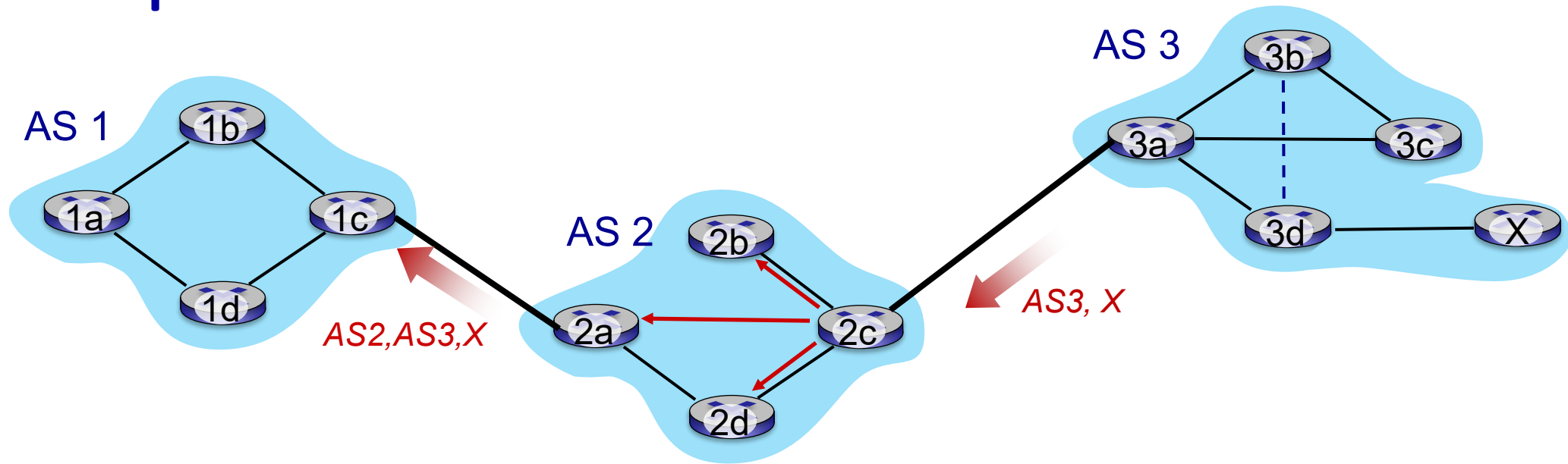
BGP protocol messages

- 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

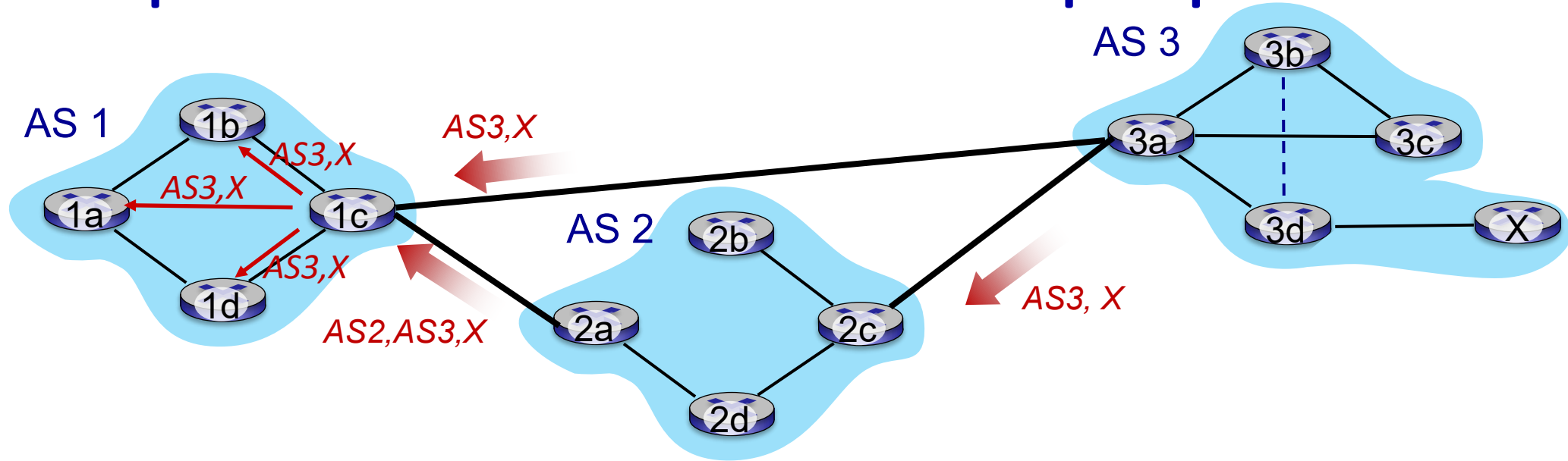
- BGP advertised route: prefix + attributes
 - prefix: destination being advertised
 - two important attributes:
 - **AS-PATH**: list of ASes through which prefix advertisement has passed
 - **NEXT-HOP**: indicates specific internal-AS router to next-hop AS
- **policy-based routing**:
 - gateway receiving 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

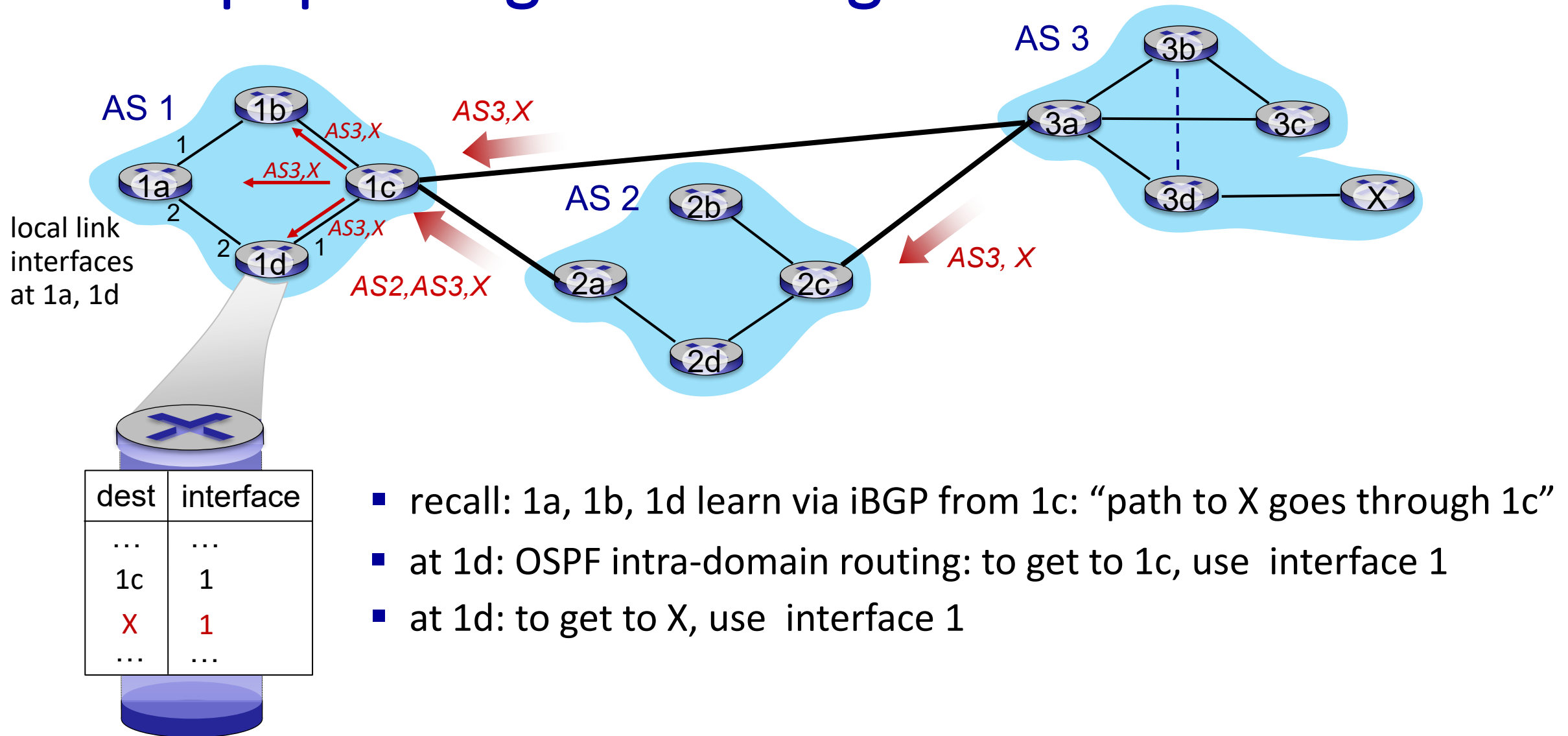
BGP path advertisement: multiple paths



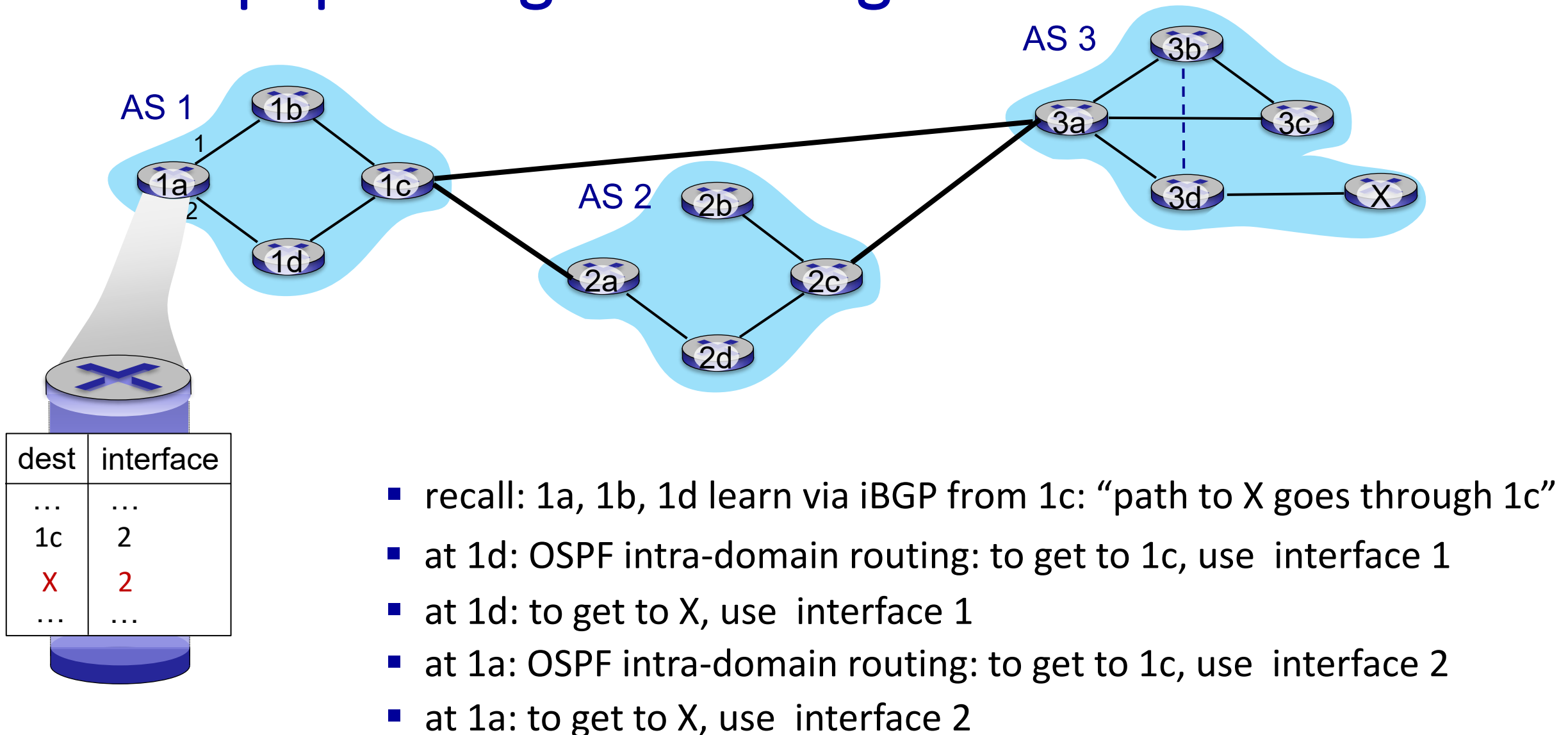
gateway router may learn about **multiple** paths to destination:

- 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

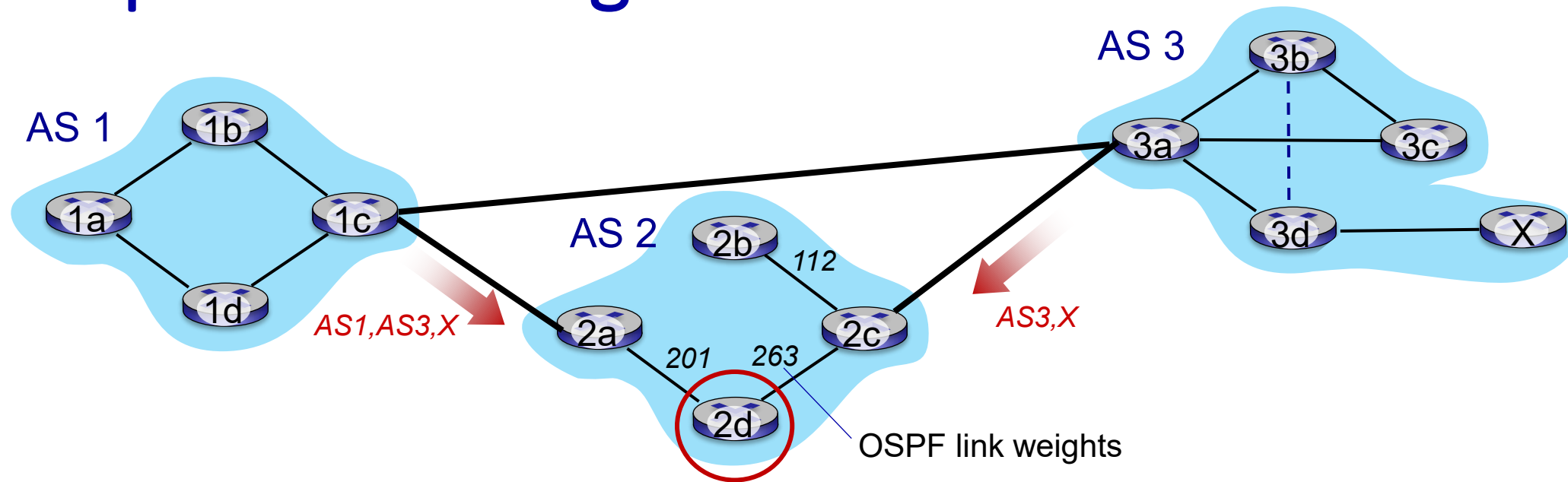
BGP: populating forwarding tables



BGP: populating forwarding tables

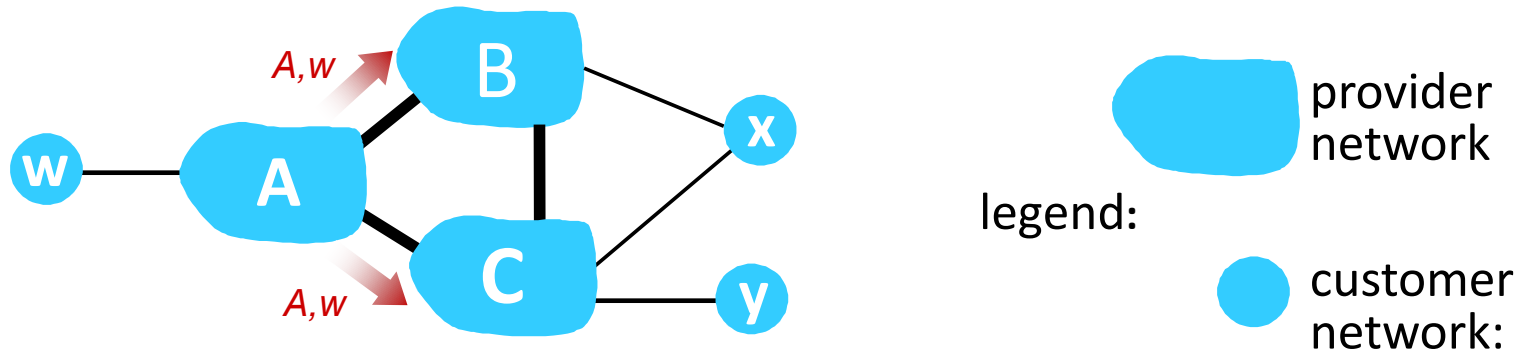


Hot potato routing



- 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!

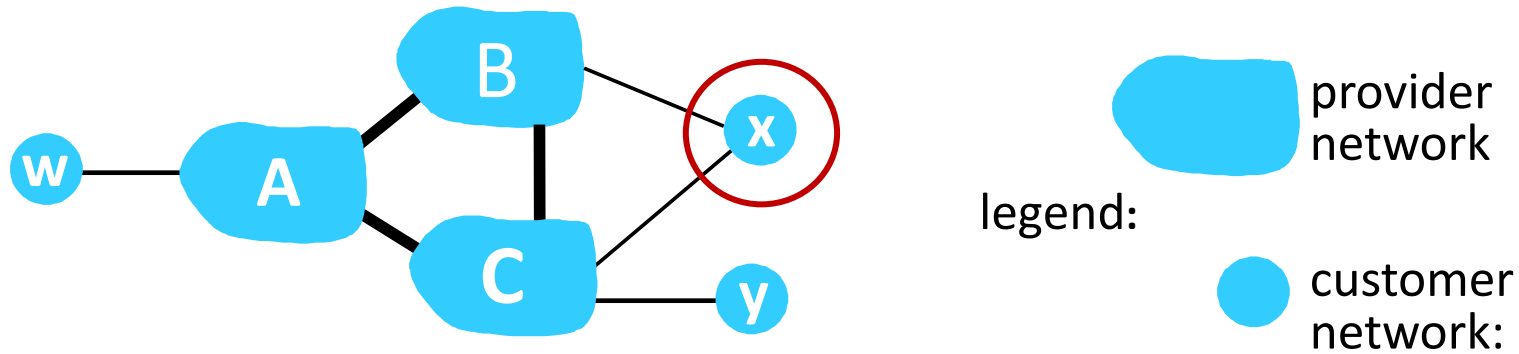
BGP: achieving policy via advertisements



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

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

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



- network management, configuration
 - SNMP
 - NETCONF/YANG

Software defined networking (SDN)

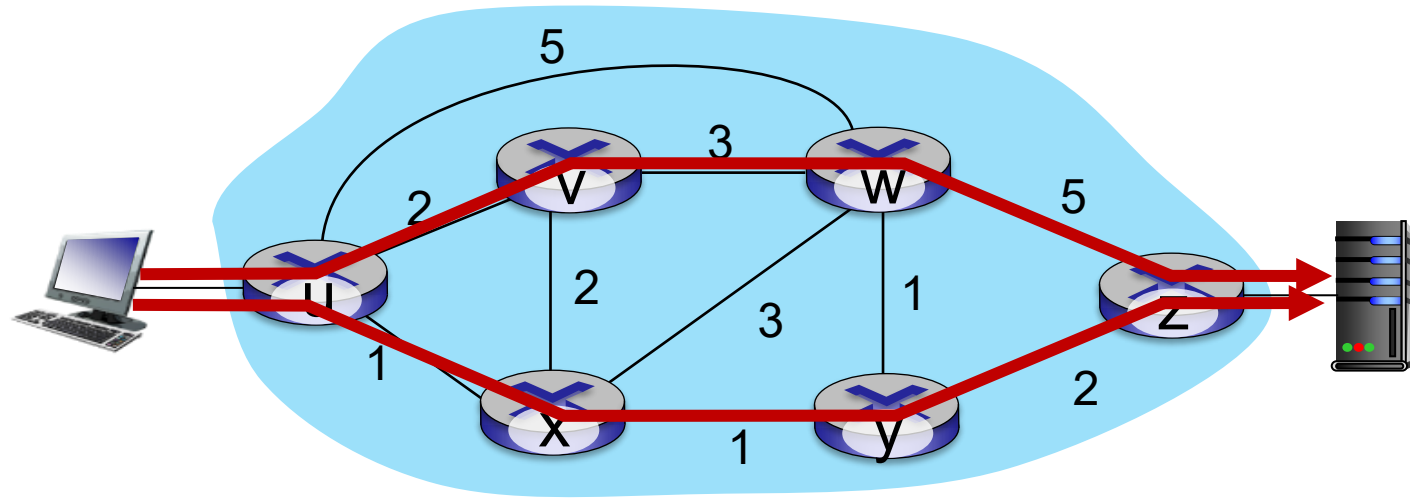
- Internet network layer: historically implemented via distributed, per-router control approach:
 - *monolithic* router contains switching hardware, runs proprietary implementation of Internet standard protocols (IP, RIP, IS-IS, OSPF, BGP) in proprietary router OS (e.g., Cisco IOS)
 - different “middleboxes”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

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

Traffic engineering: difficult with traditional routing

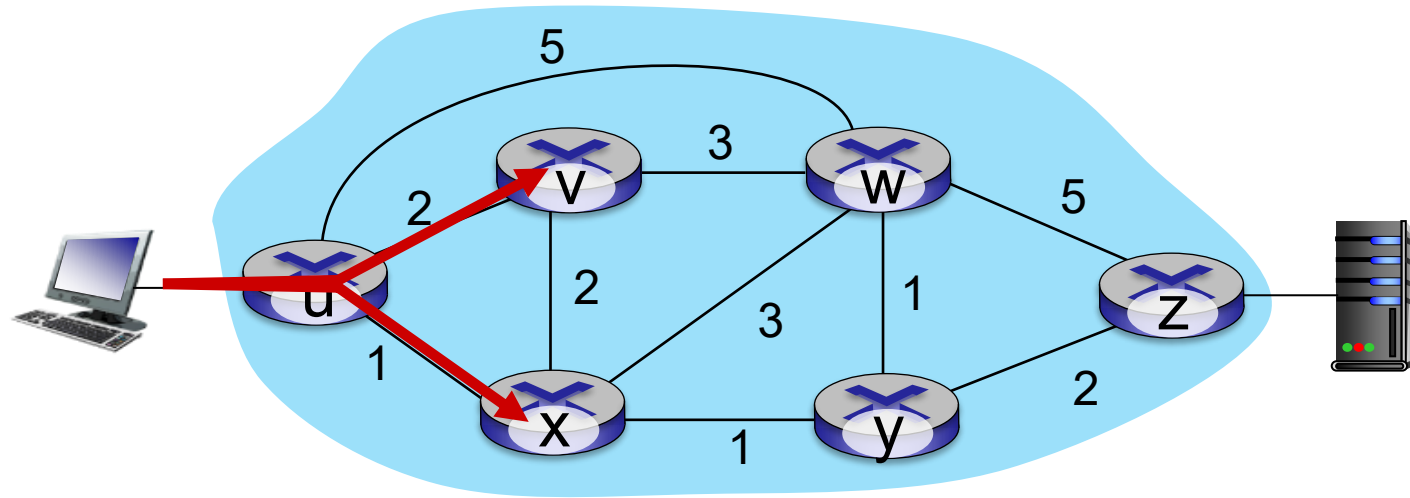


Q: what if network operator wants u-to-z traffic to flow along *uvwz*, rather than *uxyz*?

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!

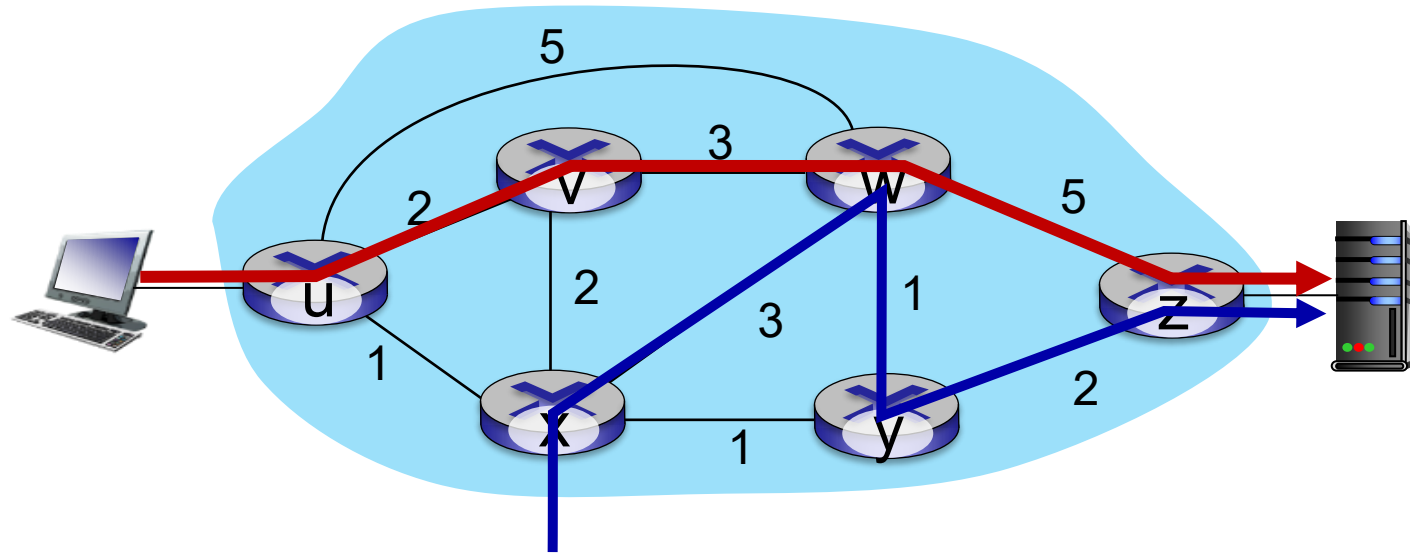
Traffic engineering: difficult with traditional routing



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

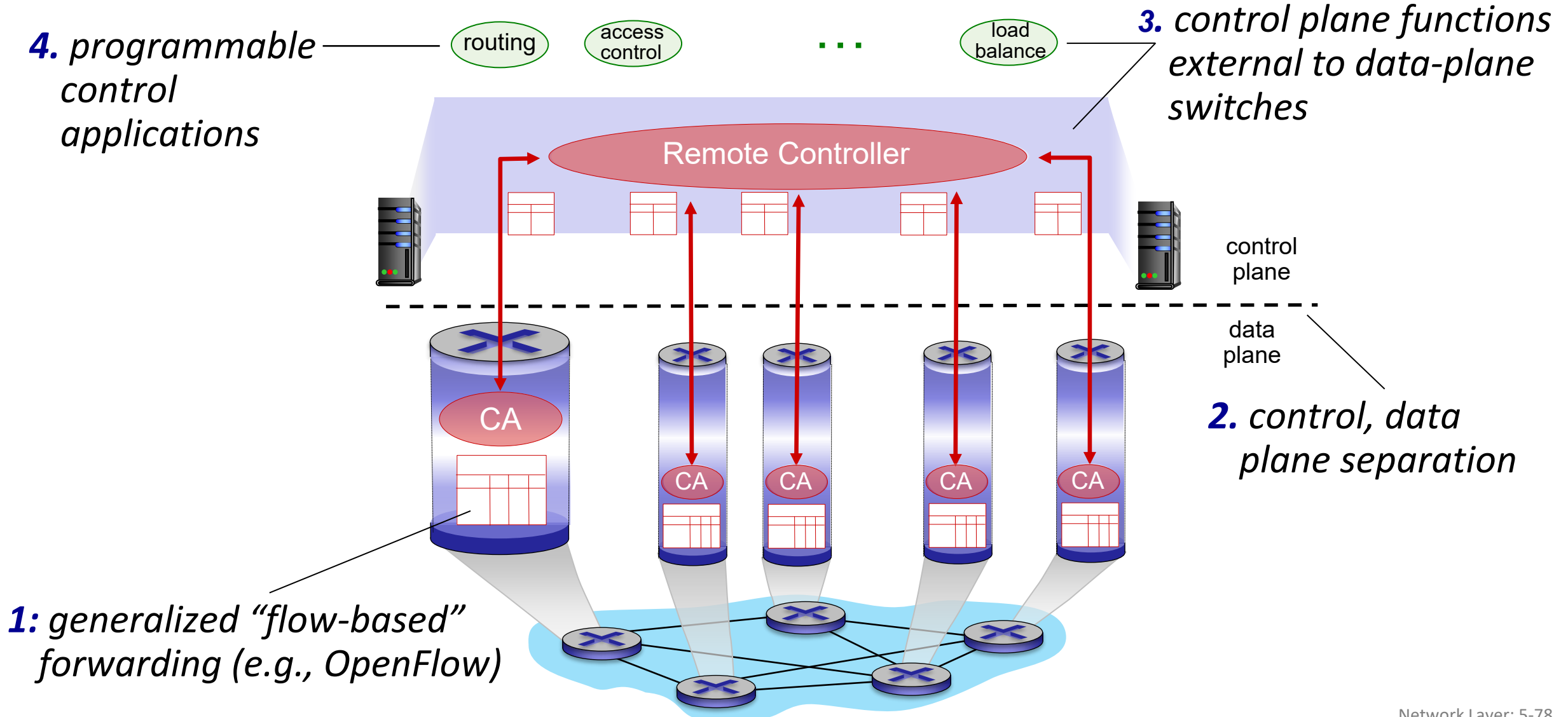


Q: what if w wants to route blue and red traffic differently from w to z?

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

We learned in Chapter 4 that generalized forwarding and SDN can be used to achieve *any* routing desired

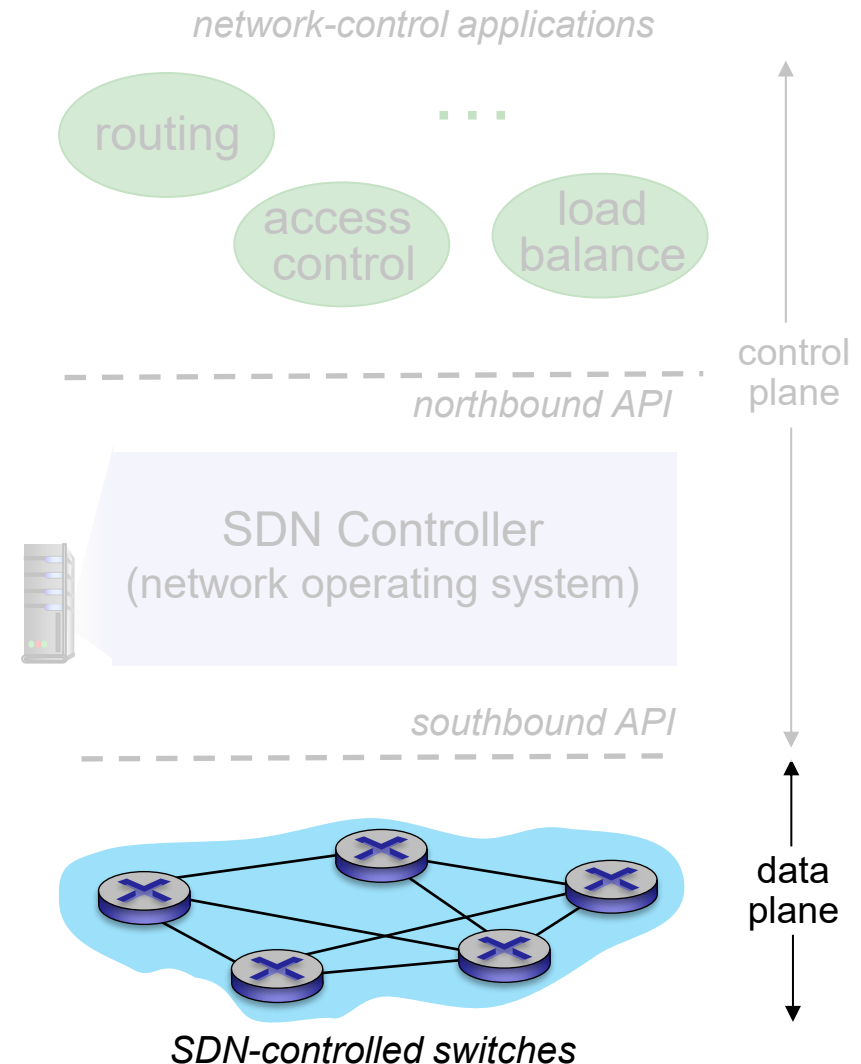
Software defined networking (SDN)



Software defined networking (SDN)

Data-plane switches:

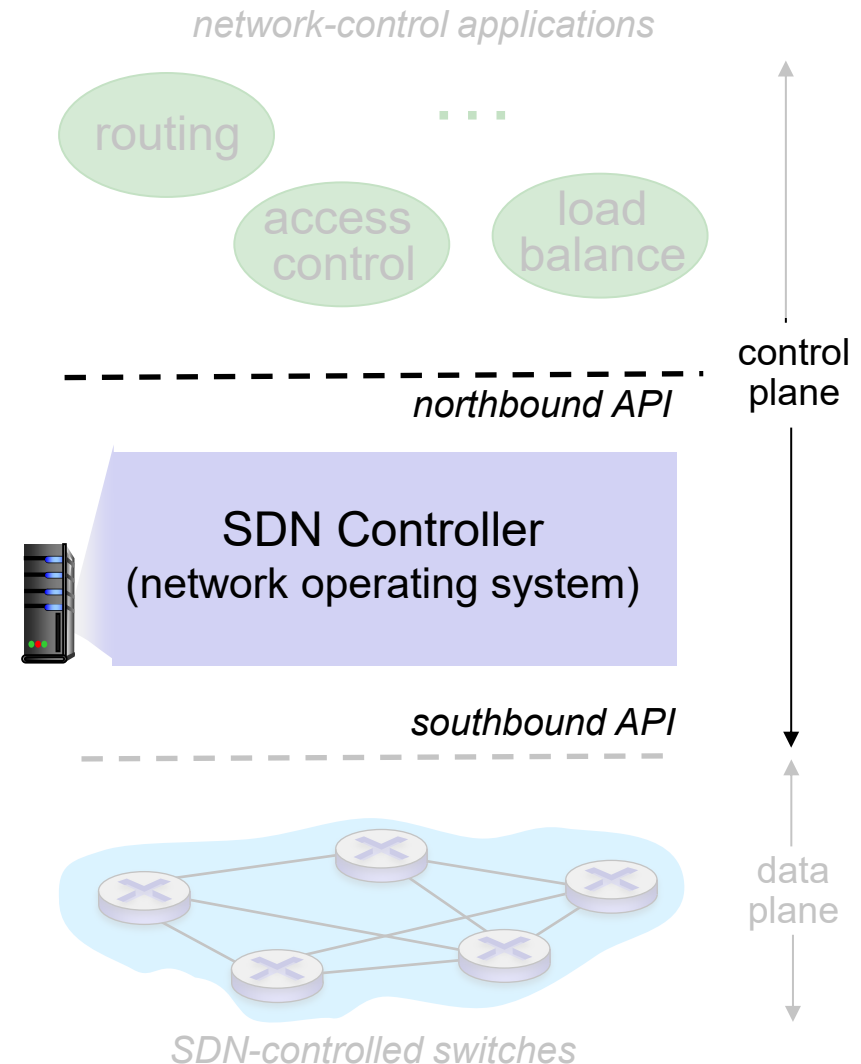
- fast, simple, commodity switches implementing generalized data-plane forwarding (Section 4.4) in hardware
- flow (forwarding) table computed, installed under controller supervision
- API for table-based switch control (e.g., OpenFlow)
 - defines what is controllable, what is not
- protocol for communicating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



Software defined networking (SDN)

SDN controller (network OS):

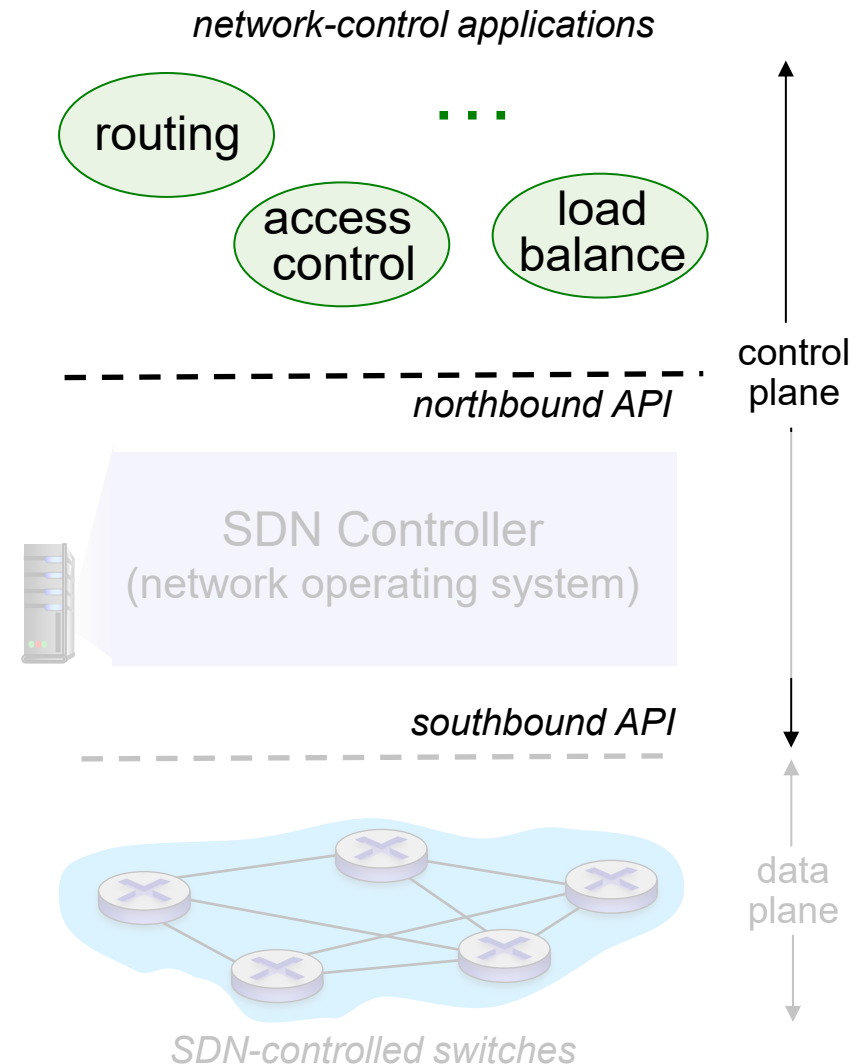
- maintain network state information
- interacts with network control applications “above” via northbound API
- interacts with network switches “below” via southbound API
- implemented as distributed system for performance, scalability, fault-tolerance, robustness



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

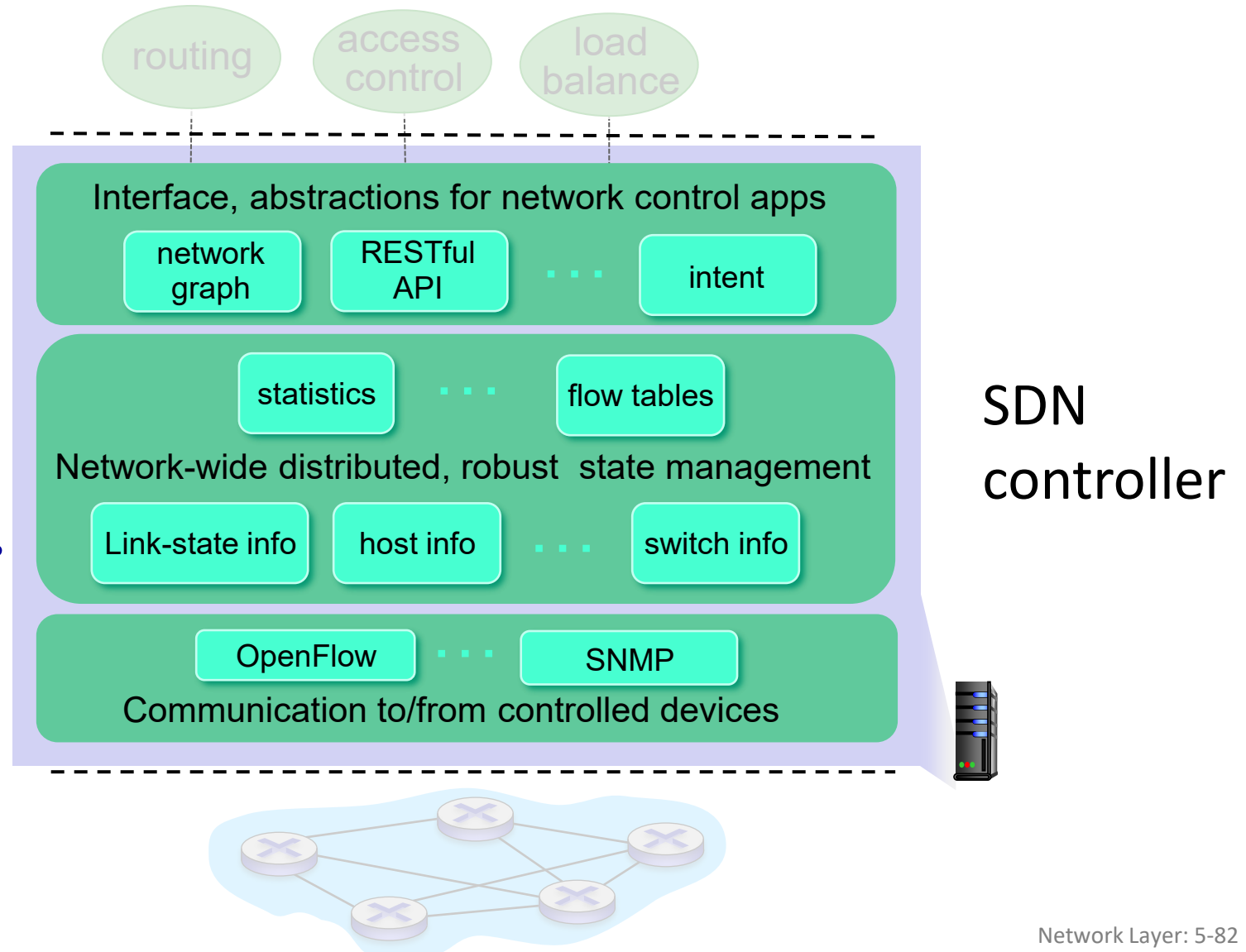


Components of SDN controller

interface layer to network
control apps: abstractions API

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

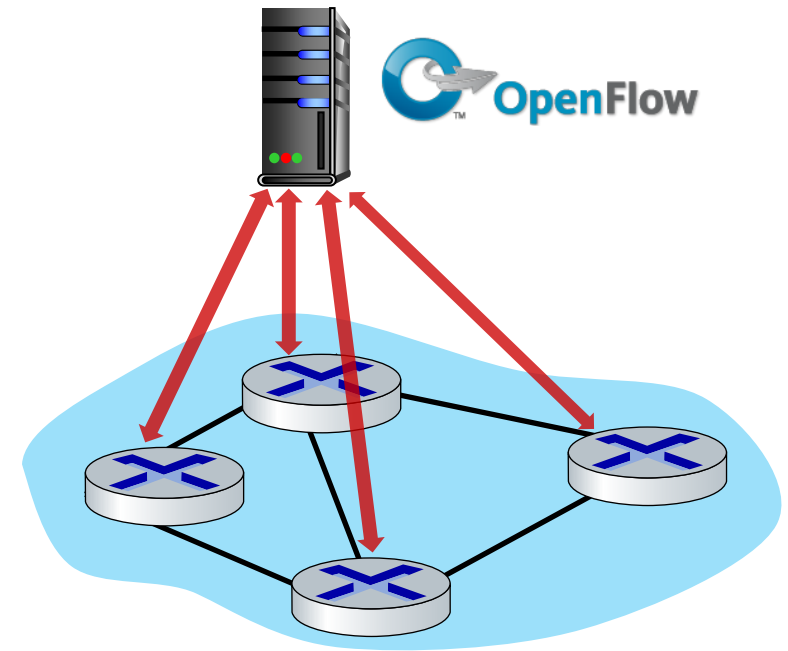
communication: communicate
between SDN controller and
controlled switches



OpenFlow protocol

- 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

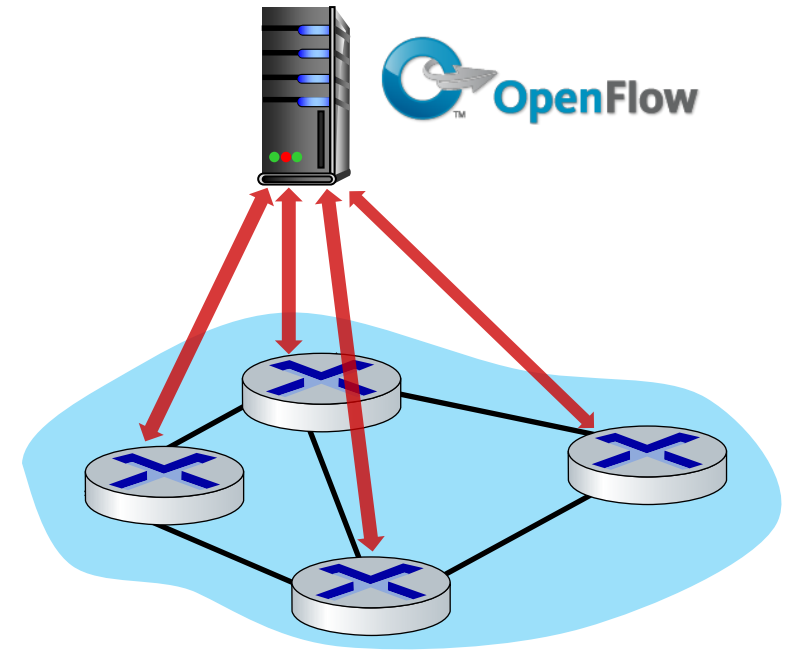


OpenFlow: controller-to-switch messages

Key controller-to-switch messages

- *features*: controller queries switch features, switch replies
- *configure*: controller queries/sets switch configuration parameters
- *modify-state*: add, delete, modify flow entries in the OpenFlow tables
- *packet-out*: controller can send this packet out of specific switch port

OpenFlow Controller

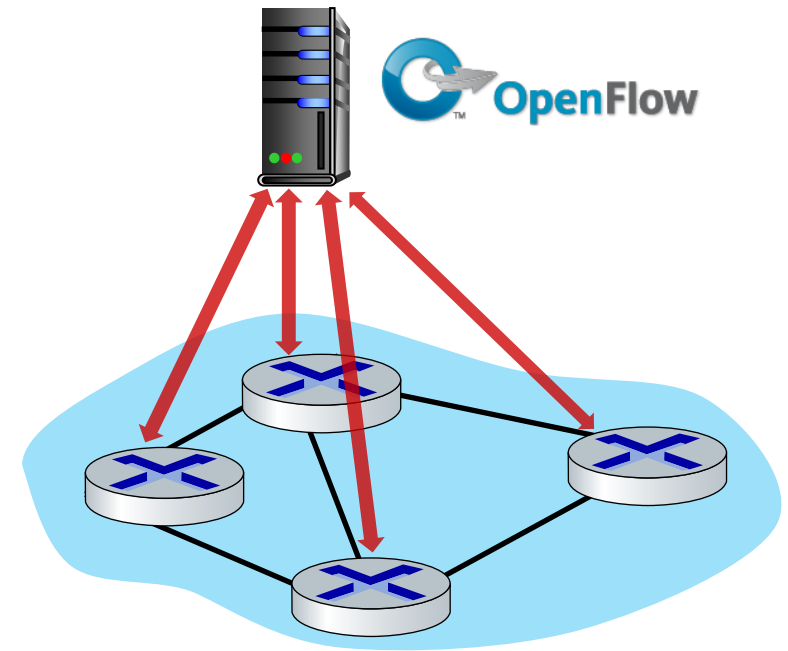


OpenFlow: switch-to-controller messages

Key switch-to-controller messages

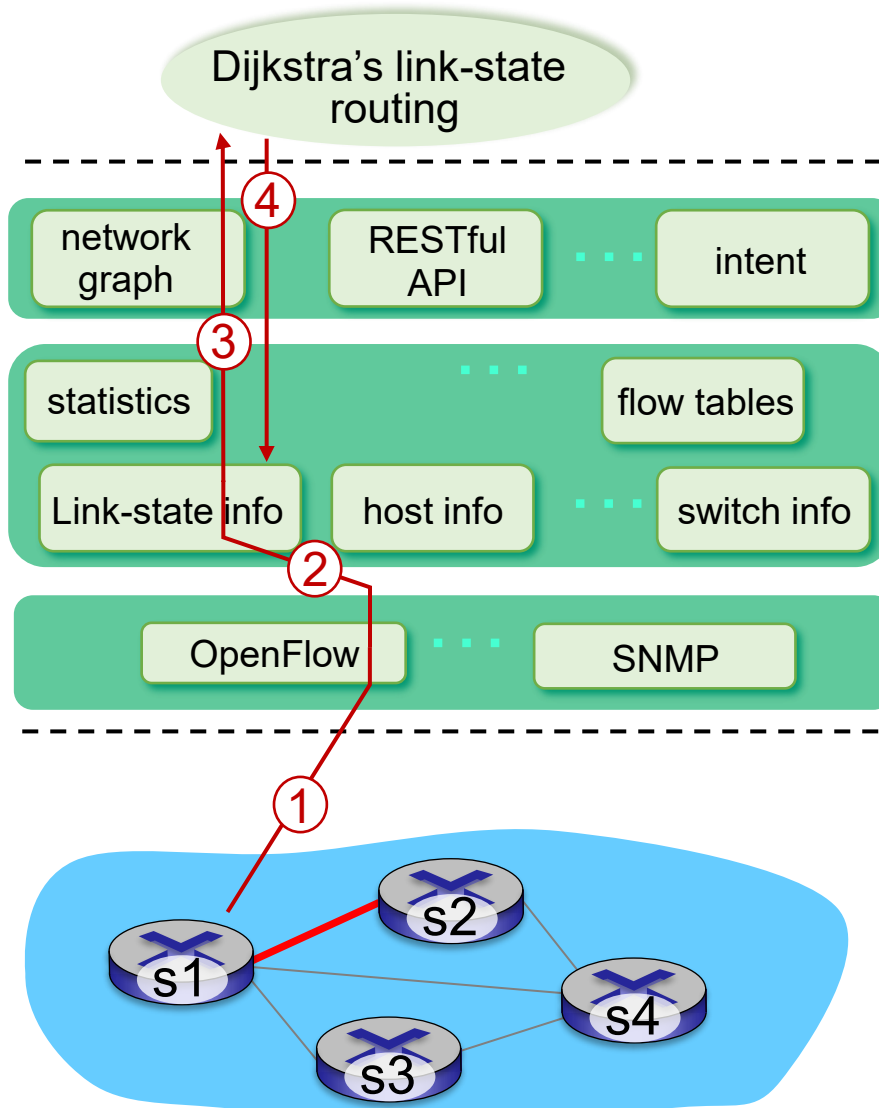
- *packet-in*: transfer packet (and its control) to controller. See packet-out message from controller
- *flow-removed*: flow table entry deleted at switch
- *port status*: inform controller of a change on a port.

OpenFlow Controller



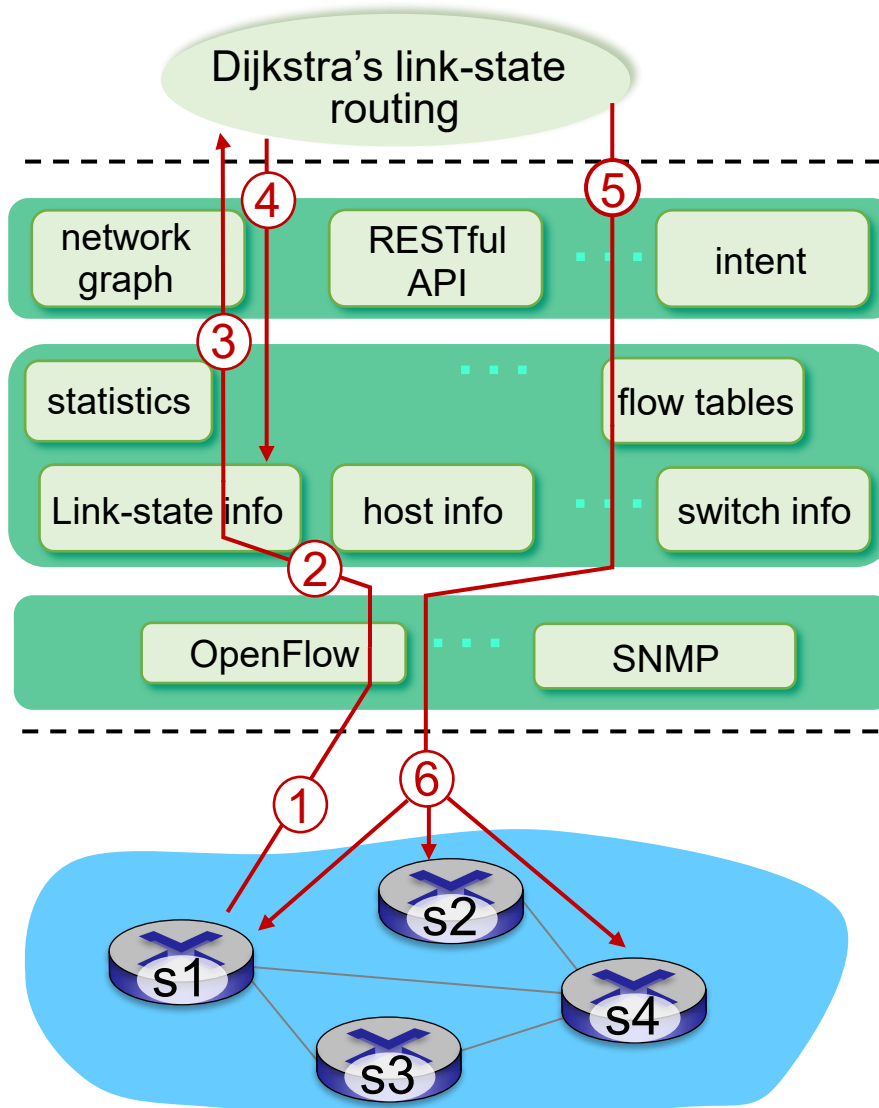
Fortunately, network operators don't "program" switches by creating/sending OpenFlow messages directly. Instead use higher-level abstraction at controller

SDN: control/data plane interaction example



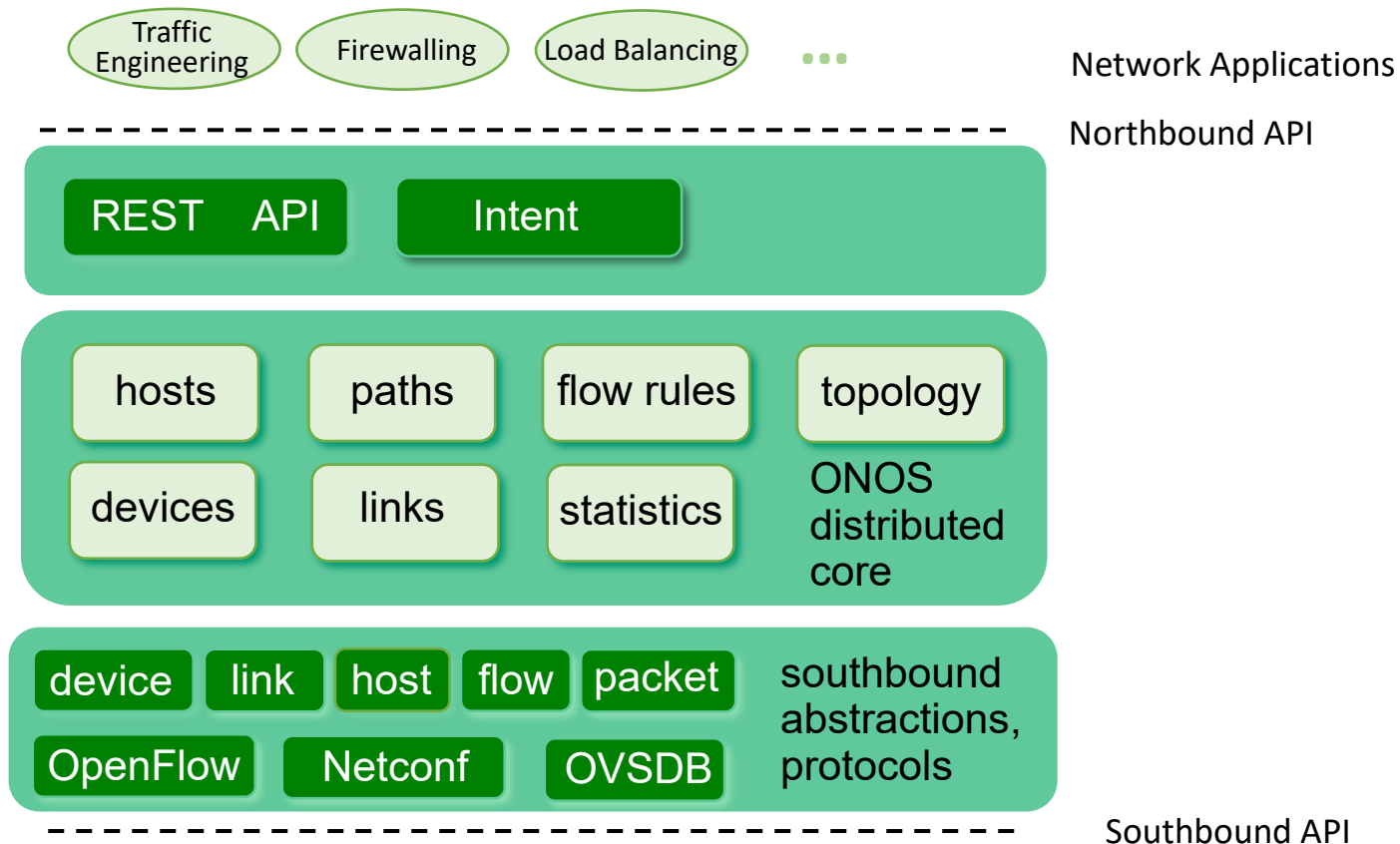
- ① S1, experiencing link failure uses OpenFlow port status message to notify controller
- ② SDN controller receives OpenFlow message, updates link status info
- ③ Dijkstra's routing algorithm application has previously registered to be called when ever link status changes. It is called.
- ④ Dijkstra's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

ONOS SDN controller



- control apps separate from controller
- intent framework: high-level specification of service: what rather than how
- considerable emphasis on distributed core: service reliability, replication performance scaling

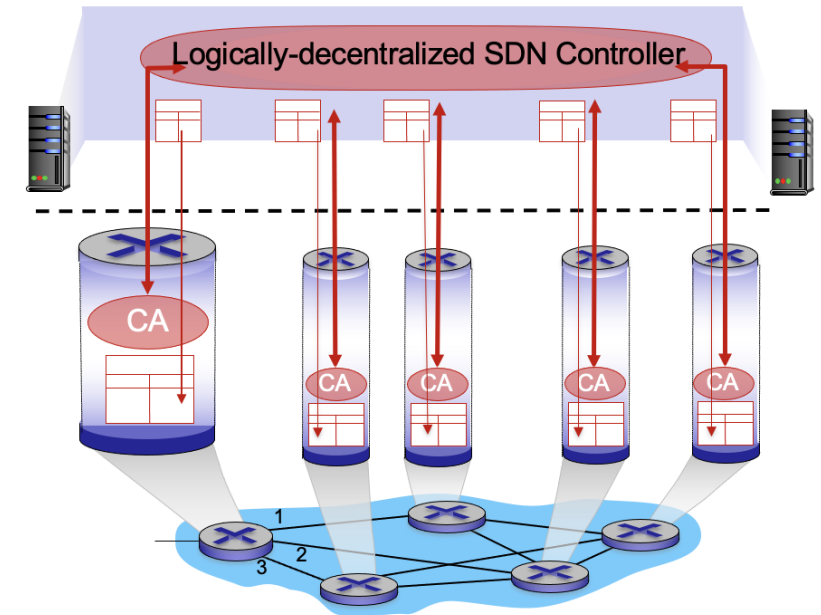
ONOS: early, influential open-source SDN controller

Google, SDN: the value of a logically-centralized abstraction

- new opportunities to more formally, intentionally manage configuration

“... in a single building or even across a private global WAN such that we[Google] were designing, the location and role of every network element is known ahead of time. So - rather than allowing a node to boot, exchange messages with neighbors, and learn its role in the global network, we knew we could configure the role of all network elements into a logically centralized controller that could then inform all relevant elements of new and changing configurations. *This shifted the problem of network management from managing the configuration of individual network elements to managing the configuration of a logical network, dramatically simplifying the problem* both from a technical perspective but also from the perspective of the cognitive load on network managers.”

https://www.youtube.com/watch?v=qn7d_iK92TI



Amin Vahdat, Engineering Fellow, VP for the Machine Learning, Systems, and Cloud AI team



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

Network layer: “control plane” roadmap

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



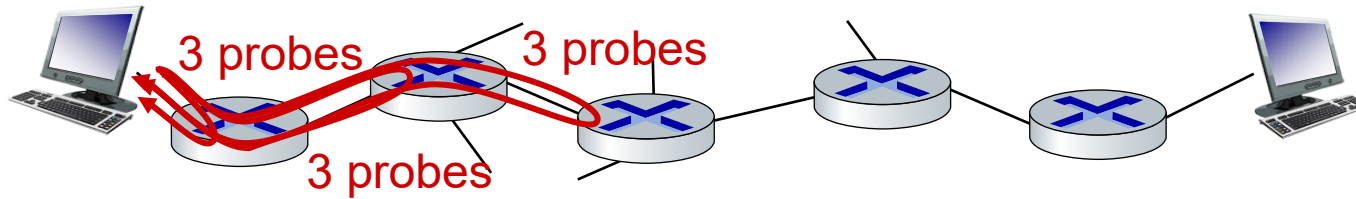
- network management, configuration
 - SNMP
 - NETCONF/YANG

ICMP: internet control message protocol

- 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

Traceroute and ICMP



- source sends sets of UDP segments to destination
 - 1st set has TTL =1, 2nd set has TTL=2, etc.
- datagram in n th set arrives to n th router:
 - router discards datagram and sends source ICMP message (type 11, code 0)
 - ICMP message possibly includes name of router & IP address
- when ICMP message arrives at source: record RTTs

stopping criteria:

- UDP segment eventually arrives at destination host
- destination returns ICMP “port unreachable” message (type 3, code 3)
- source stops

Network layer: “control plane” roadmap

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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."

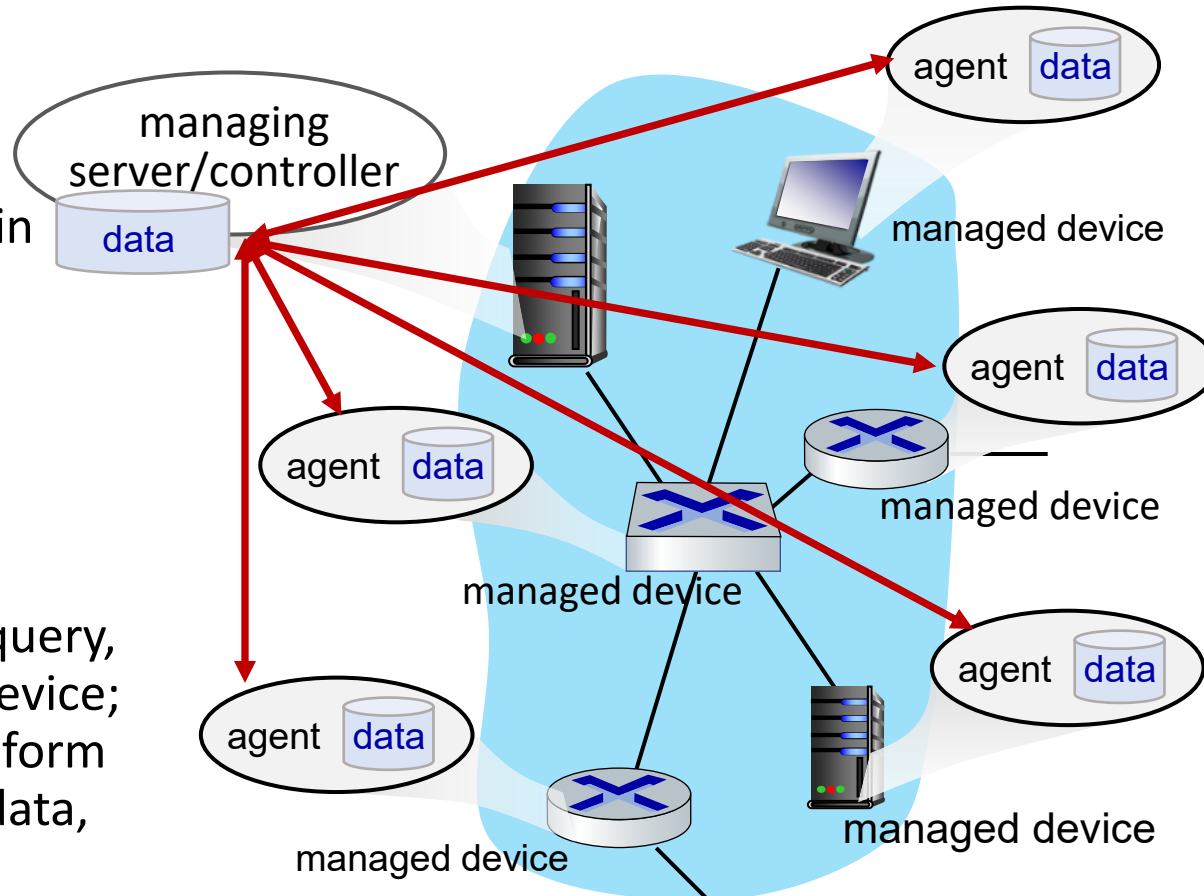
Components of network management

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 operator approaches to management

CLI (Command Line Interface)

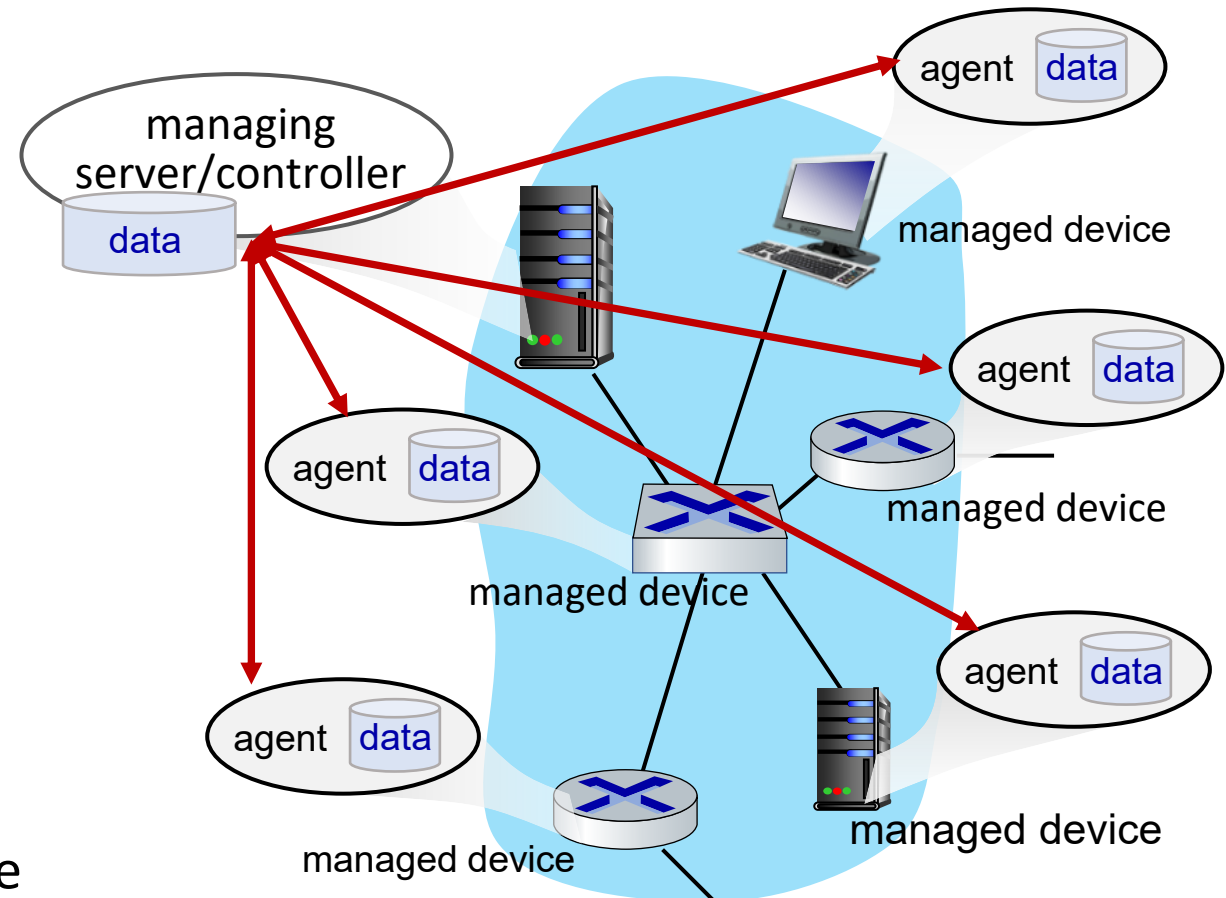
- operator issues (types, scripts) direct to individual devices (e.g., vis ssh)

SNMP/MIB

- operator queries/sets devices data (MIB) using Simple Network Management Protocol (SNMP)

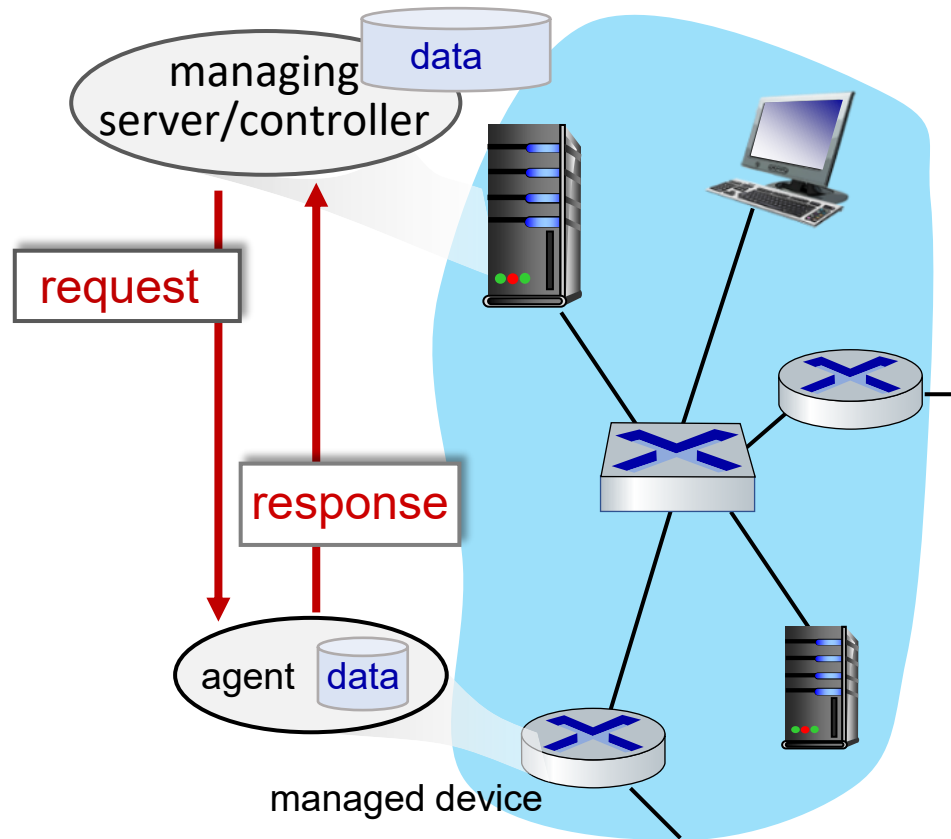
NETCONF/YANG

- more abstract, network-wide, holistic
- emphasis on multi-device configuration management.
- YANG: data modeling language
- NETCONF: communicate YANG-compatible actions/data to/from/among remote devices

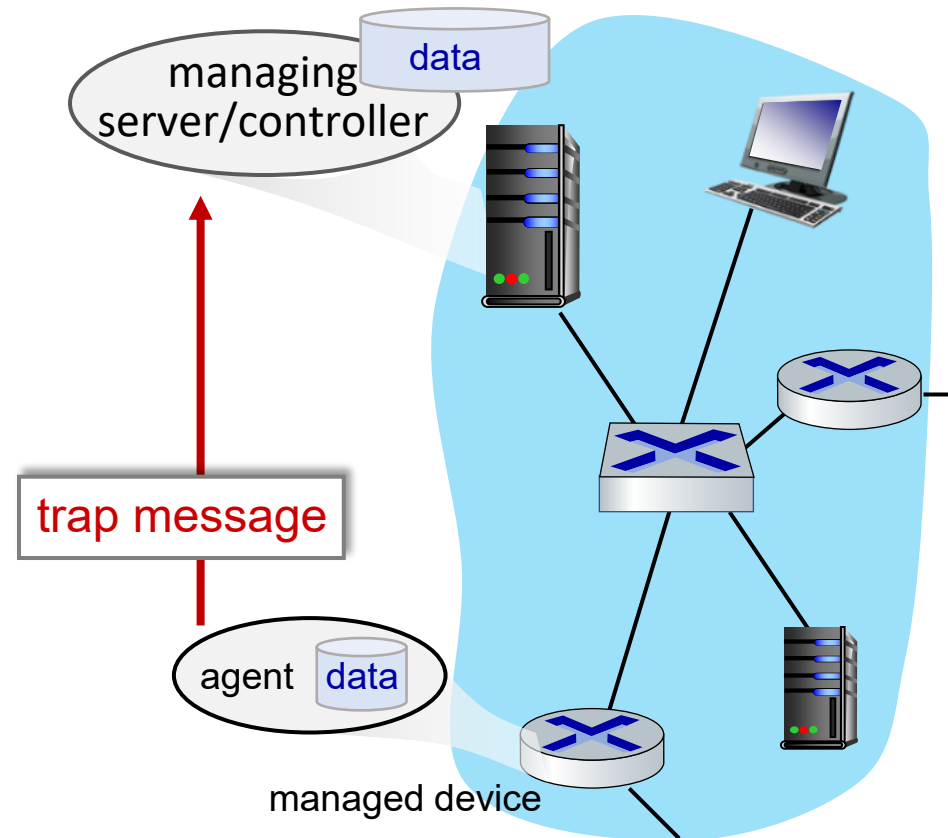


SNMP protocol

Two ways to convey MIB info, commands:



request/response mode



trap mode

SNMP protocol: message types

Message type	Function
GetRequest GetNextRequest GetBulkRequest	manager-to-agent: “get me data” (data instance, next data in list, block of data).
SetRequest	manager-to-agent: set MIB value
Response	Agent-to-manager: value, response to Request
Trap	Agent-to-manager: inform manager of exceptional event

SNMP: Management Information Base (MIB)

- managed device's operational (and some configuration) data
- gathered into device **MIB module**
 - 400 MIB modules defined in RFC's; many more vendor-specific MIBs
- **Structure of Management Information (SMI):** data definition language
- example MIB variables for UDP protocol:

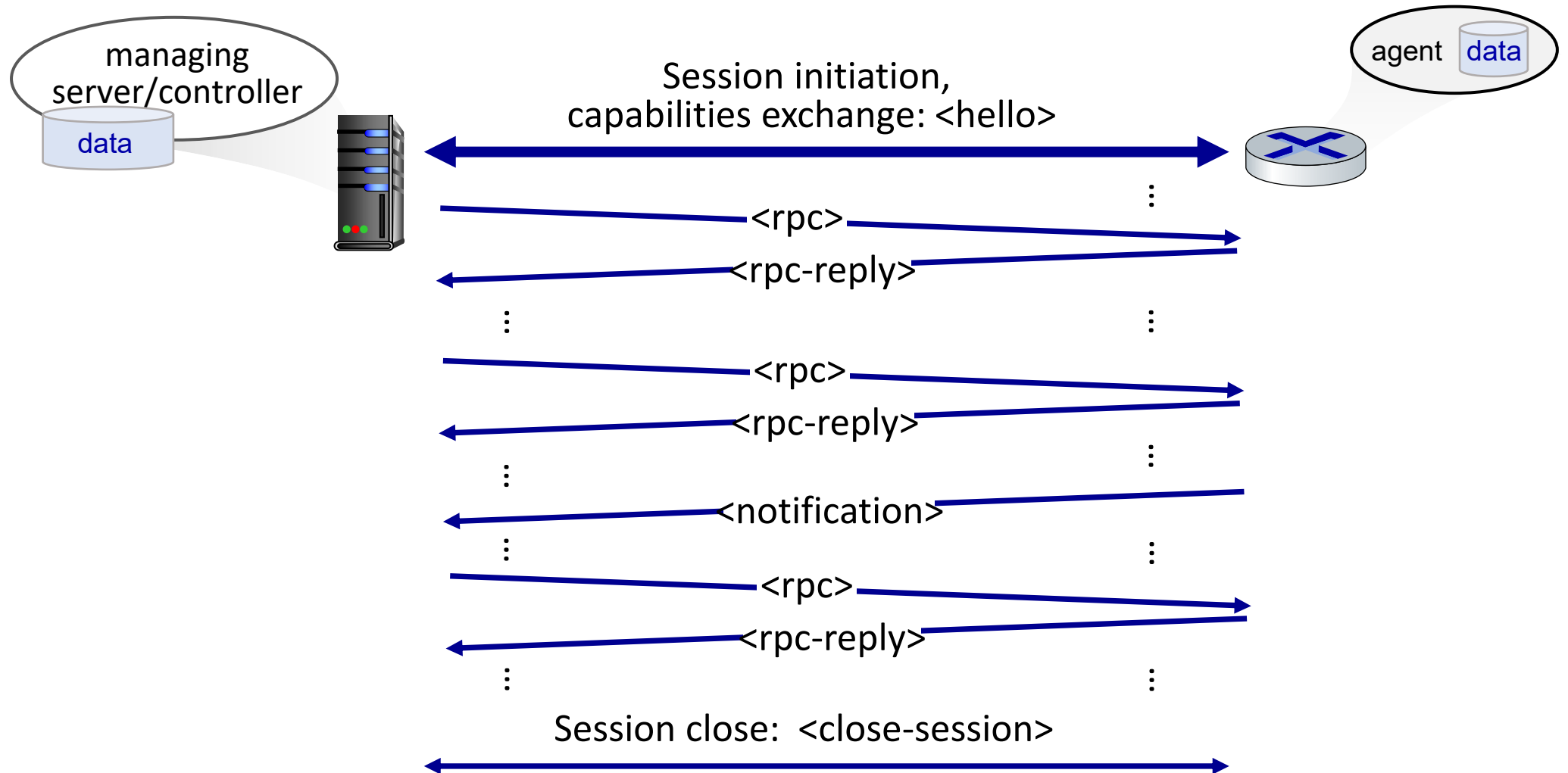


Object ID	Name	Type	Comments
1.3.6.1.2.1.7.1	UDPInDatagrams	32-bit counter	total # datagrams delivered
1.3.6.1.2.1.7.2	UDPNoPorts	32-bit counter	# undeliverable datagrams (no application at port)
1.3.6.1.2.1.7.3	UDInErrors	32-bit counter	# undeliverable datagrams (all other reasons)
1.3.6.1.2.1.7.4	UDPOutDatagrams	32-bit counter	total # datagrams sent
1.3.6.1.2.1.7.5	udpTable	SEQUENCE	one entry for each port currently in use

NETCONF overview

- **goal:** actively manage/**configure** devices network-wide
- operates between managing server and managed network devices
 - actions: retrieve, set, modify, activate configurations
 - **atomic-commit** actions over multiple devices
 - query operational data and statistics
 - subscribe to notifications from devices
- remote procedure call (RPC) paradigm
 - NETCONF protocol messages encoded in XML
 - exchanged over secure, reliable transport (e.g., TLS) protocol

NETCONF initialization, exchange, close



Selected NETCONF Operations

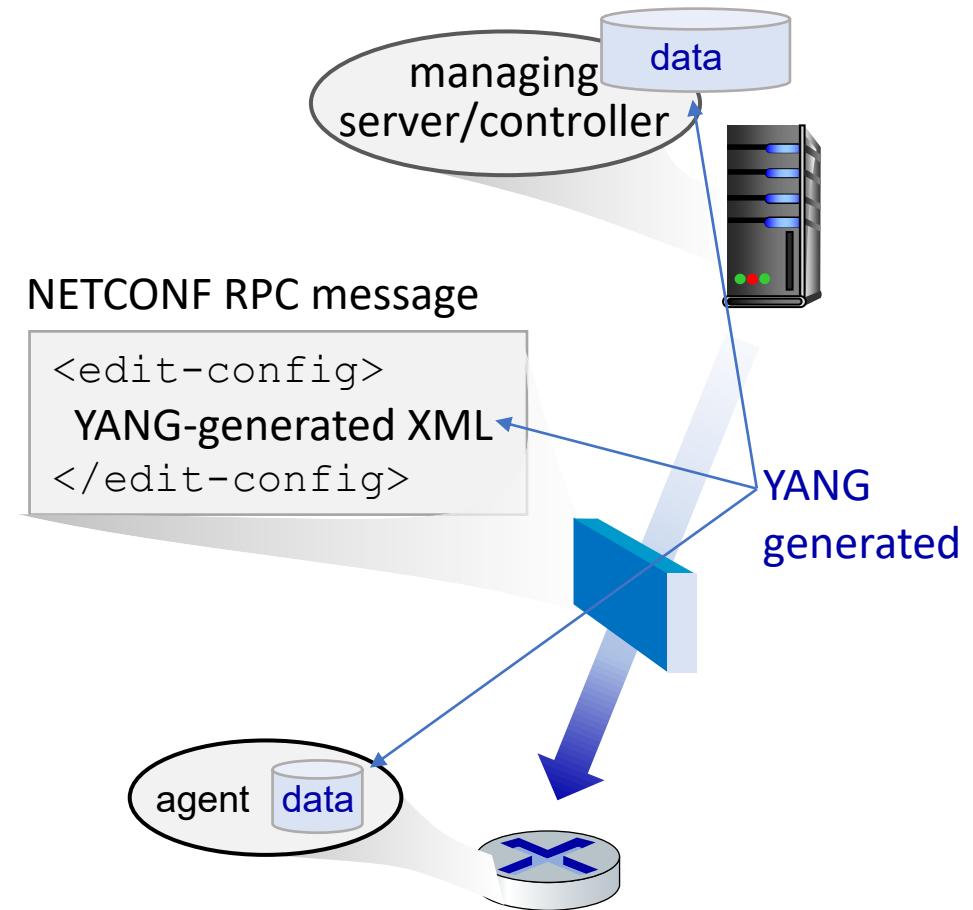
NETCONF	Operation Description
<get-config>	Retrieve all or part of a given configuration. A device may have multiple configurations.
<get>	Retrieve all or part of both configuration state and operational state data.
<edit-config>	Change specified (possibly running) configuration at managed device. Managed device <rpc-reply> contains <ok> or <rpcerror> with rollback.
<lock>, <unlock>	Lock (unlock) configuration datastore at managed device (to lock out NETCONF, SNMP, or CLIs commands from other sources).
<create-subscription>, <notification>	Enable event notification subscription from managed device

Sample NETCONF RPC message

```
01 <?xml version="1.0" encoding="UTF-8"?>
02 <rpc message-id="101"  note message id
03   xmlns="urn:ietf:params:xml:ns:netconf:base:1.0">
04   <edit-config>      change a configuration
05     <target>
06       <running/>  change the running configuration
07     </target>
08     <config>
09       <top xmlns="http://example.com/schema/
10         1.2/config">
11         <interface>
12           <name>Ethernet0/0</name>  change MTU of Ethernet 0/0 interface to 1500
13           <mtu>1500</mtu>
14         </interface>
15       </top>
16     </config>
17   </edit-config>
18 </rpc>
```


YANG

- data modeling language used to specify structure, syntax, semantics of NETCONF network management data
 - built-in data types, like SMI
- XML document describing device, capabilities can be generated from YANG description
- can express constraints among data that must be satisfied by a valid NETCONF configuration
 - ensure NETCONF configurations satisfy correctness, consistency constraints



Chapter 5: security implications (1 of 2)

- Routing is distributed; easy to disrupt
 - Misconfiguration is as dangerous as attacks
 - Example: routing metrics that change due to routing (load)
- Impact of malicious actors on routing protocols?
- Link state: very low
 - Worst case: bad actor attracts nearby traffic
- Distance vector: very high
 - Worst case: bad actor becomes black hole
- Path vector: quite high
 - Filtering may help, otherwise like distance vector

Chapter 5: security implications (2 of 2)

- Is SDN more or less secure than classic IP?
- Classic IP is quite resilient
 - It is distributed, after all
 - You need to bring down many nodes
- In SDN the controller is the target
 - You bring the controller down, the network is dead
 - Hence the need for “hardening”
 - But (say) controller replication is expensive
- Network management is a security mess
 - SNMP is a relic, NETCONF is a great step forward

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
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