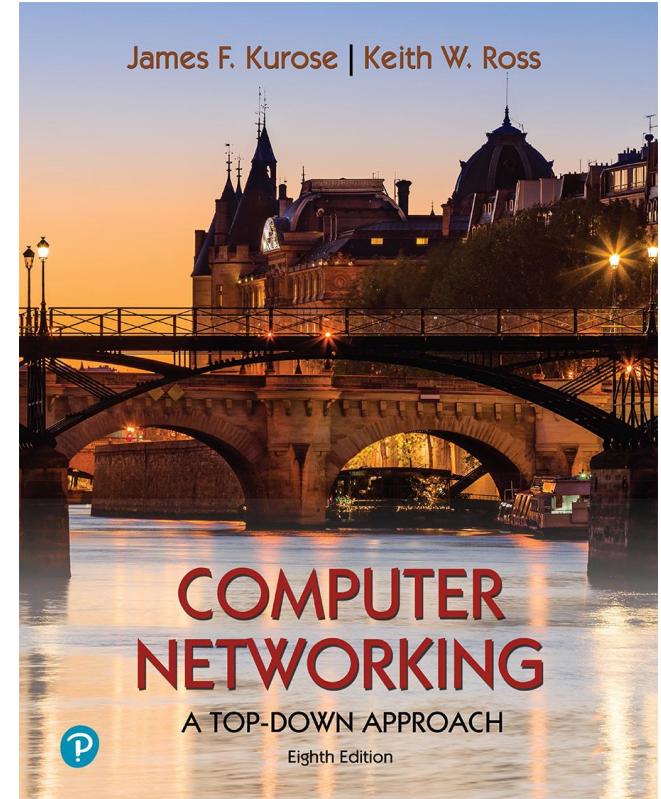


Chapter 5

Network Layer: Control Plane



*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 on 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

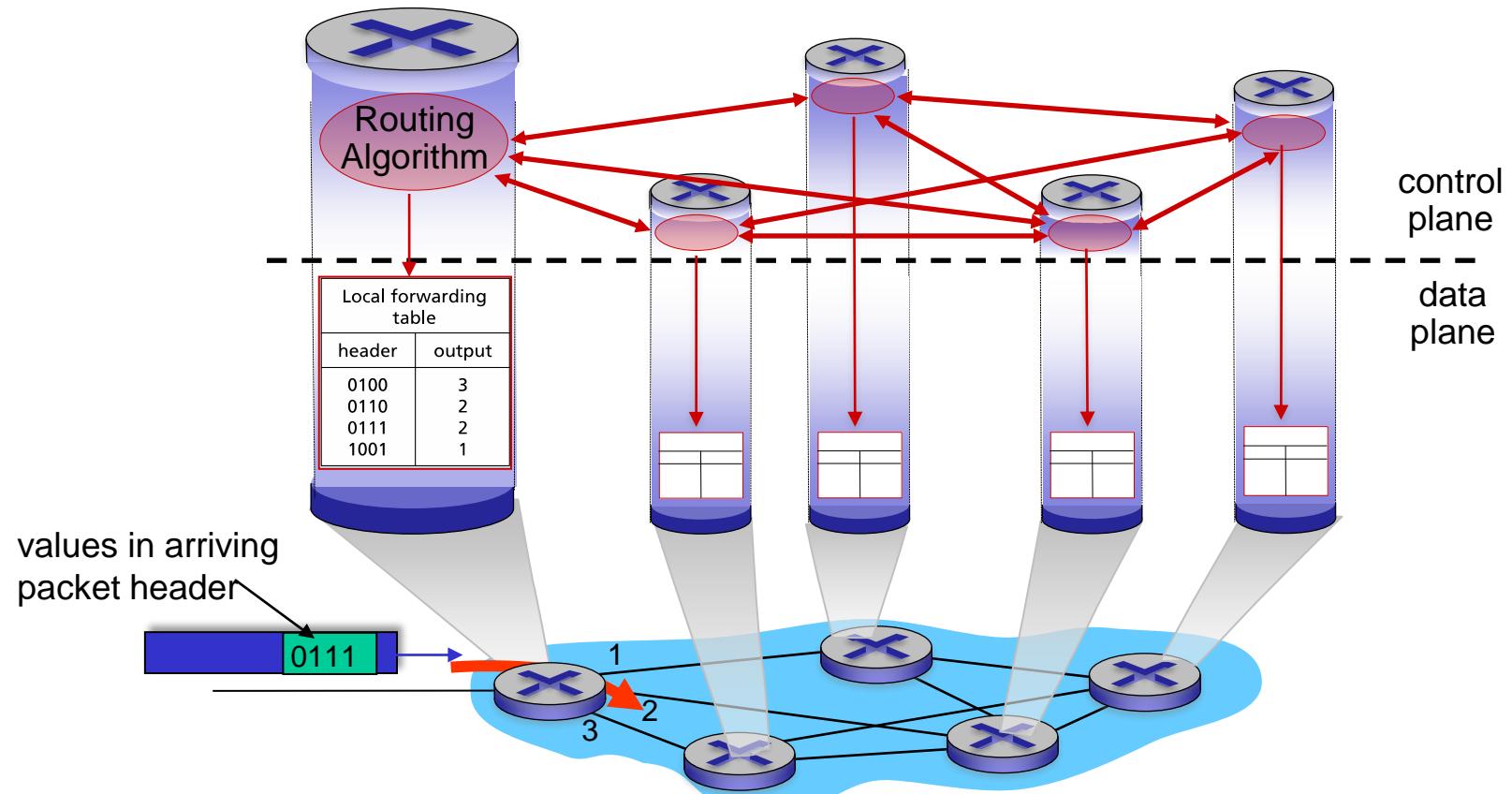
control plane

Two approaches to structuring network control plane:

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

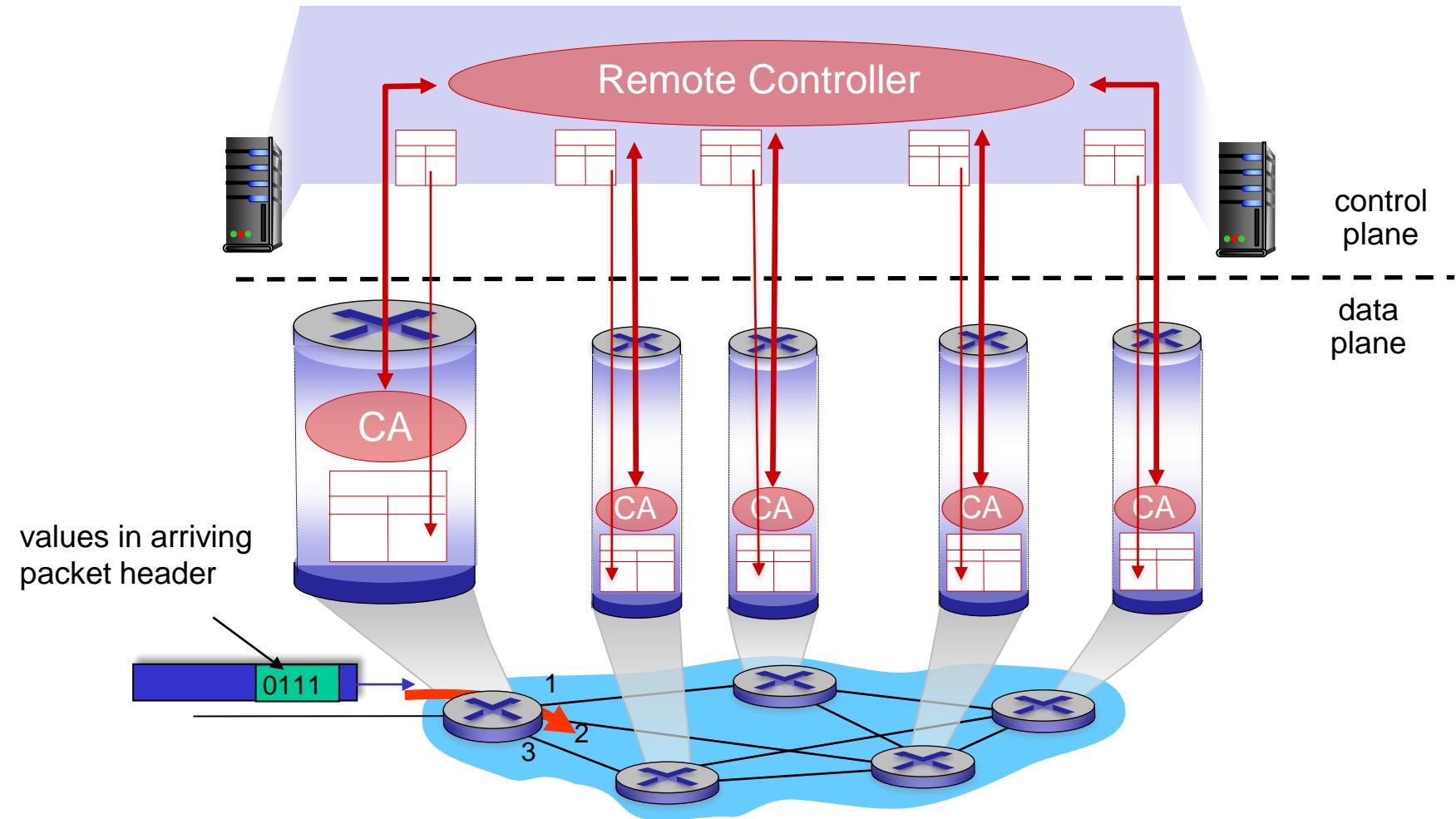
Per-router control plane

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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- **routing protocols**
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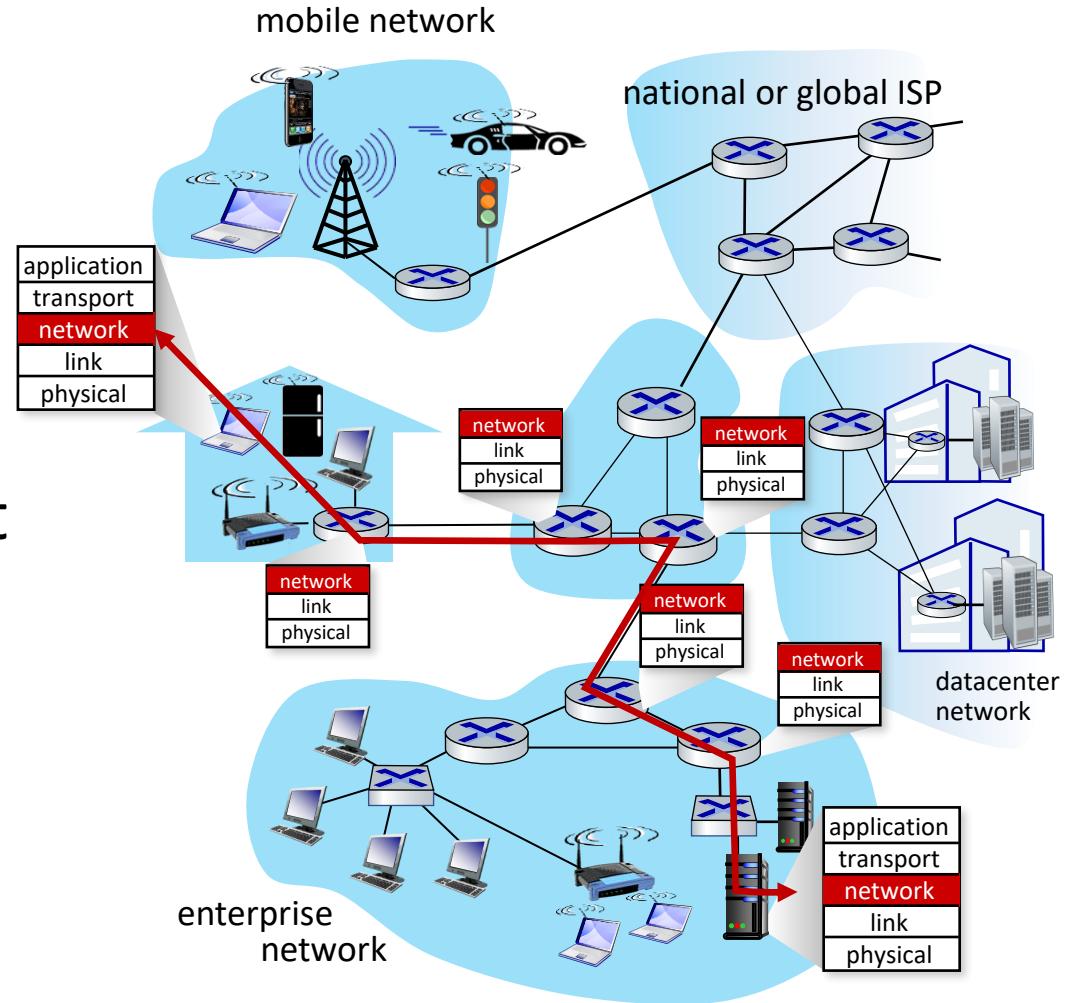


- network management, configuration
 - SNMP
 - NETCONF/YANG

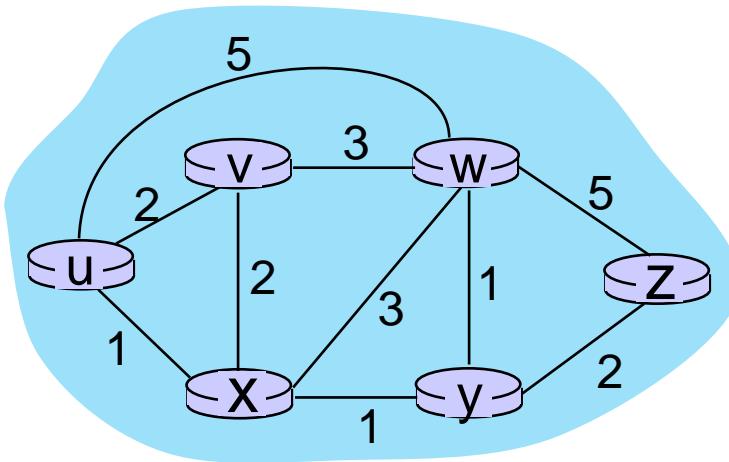
Routing protocols

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



graph: $G = (N, E)$

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

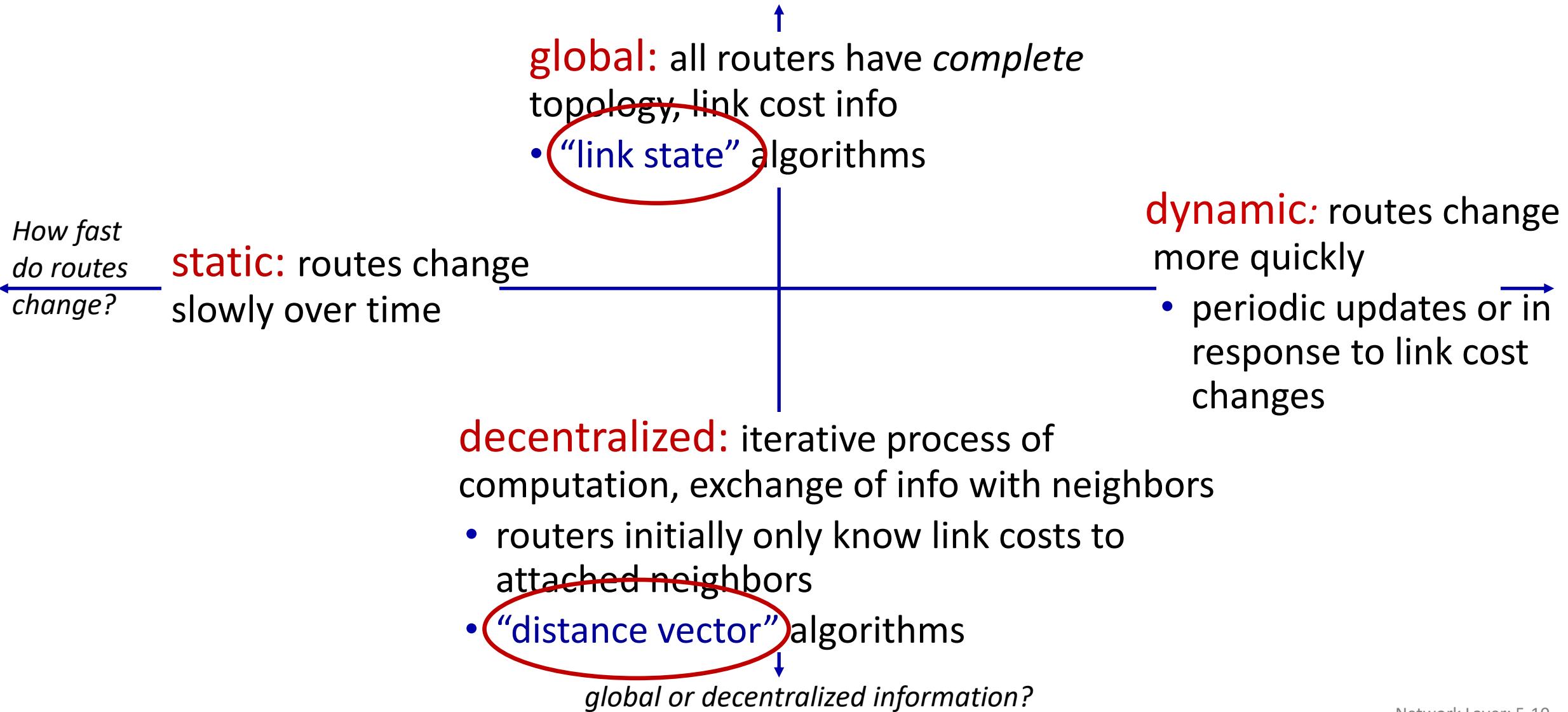
E : set of links = { $(u, v), (u, x), (v, x), (v, w), (x, w), (x, y), (w, y), (w, z), (y, z)$ }

$c_{a,b}$: 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

Routing algorithm classification



Network layer: “control plane” roadmap

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- network management, configuration
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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:

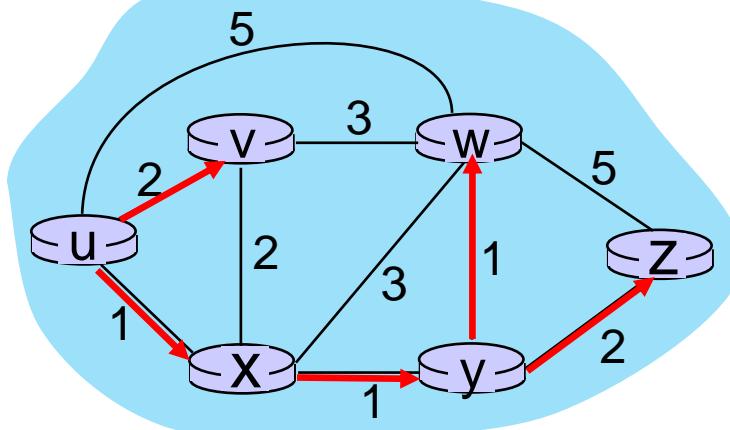
```
2  $N' = \{u\}$                                 /* compute least cost path from u to all other nodes */  
3 for all nodes  $v$   
4   if  $v$  adjacent to  $u$                   /*  $u$  initially knows direct-path-cost only to direct neighbors */  
5     then  $D(v) = c_{u,v}$                 /* 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

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	∞ , u	∞	∞
1	ux	2, u	4, x	∞ , x	∞	∞
2	uxy	2, u	3, y	∞	∞	4, y
3	uxyv		3, y	∞	∞	4, y
4	uxyvw			∞	∞	4, y
5	uxyvwz					4, y

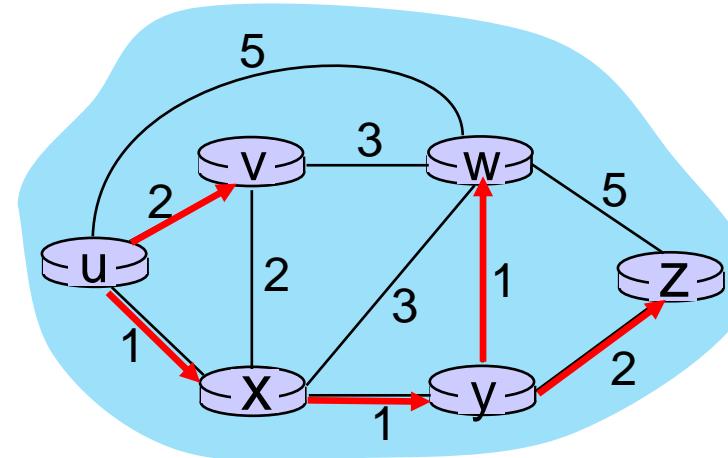


Initialization (step 0): For all a : if a adjacent to u then $D(a) = c_{u,a}$

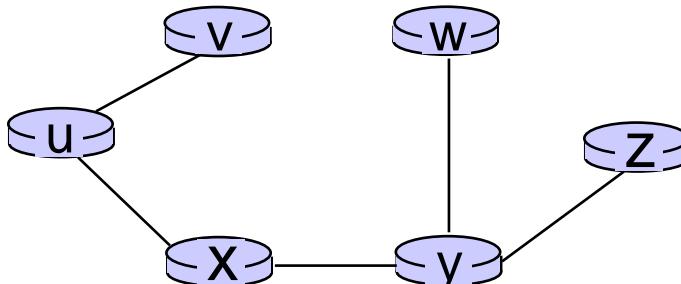
↓
 find a not in N' such that $D(a)$ is a minimum
 add a to N'
 update $D(b)$ for all b adjacent to a and not in N' :

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

Dijkstra's algorithm: an example



resulting *least-cost-path tree* from u:



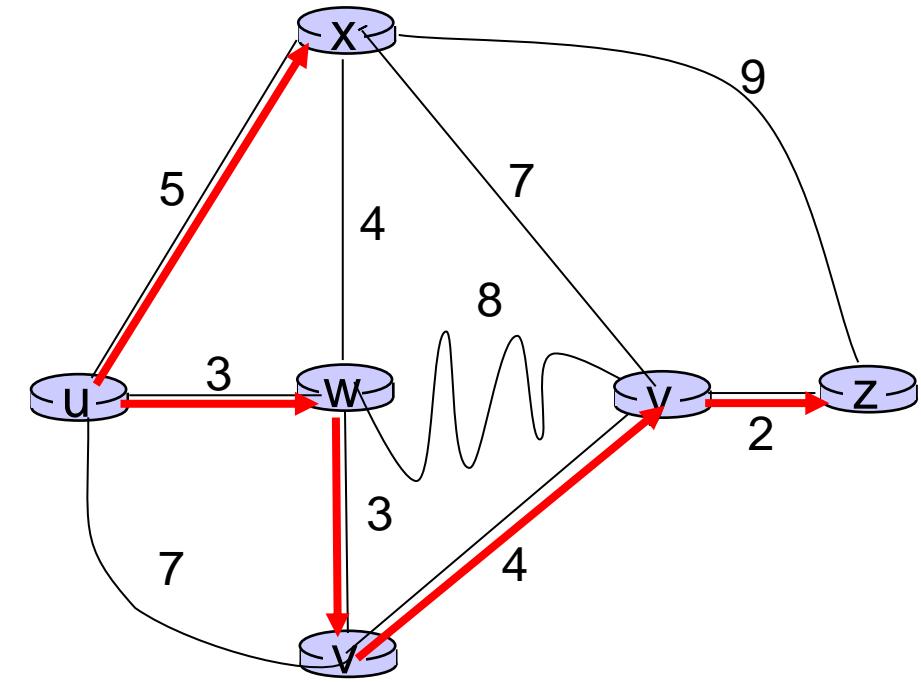
resulting *forwarding table* in u:

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

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

Dijkstra's algorithm: another example

Step	N'	v	w	x	y	z
0	u	$D(v), p(v)$	$D(w), p(w)$	$D(x), p(x)$	$D(y), p(y)$	$D(z), p(z)$
1	uw	$7, u$	$3, u$	$5, u$	∞	∞
2	uwx	$6, w$	$5, u$	$11, w$	8	
3	$uwxv$			$11, w$	$14, x$	
4	$uwxy$			$10, v$	$14, x$	
5	$uwxyz$				$12, y$	



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

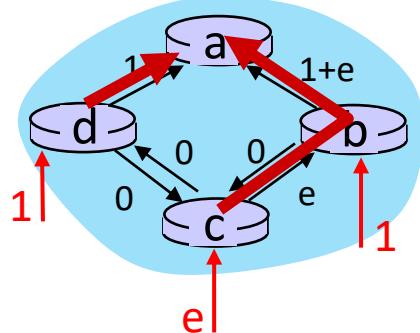
- each of n iteration: need to check all nodes, w , not in N
- $n(n+1)/2$ comparisons: $O(n^2)$ complexity
- more efficient implementations possible: $O(n \log n)$

message complexity:

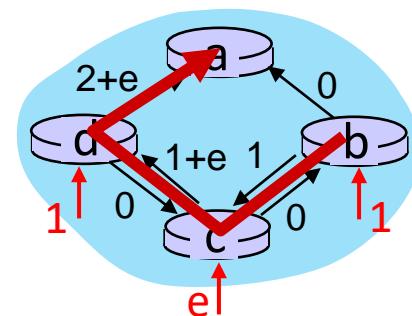
- each router must *broadcast* its link state information to other n routers
- efficient (and interesting!) broadcast algorithms: $O(n)$ link crossings to disseminate a broadcast message from one source
- each router's message crosses $O(n)$ links: overall message complexity: $O(n^2)$

Dijkstra's algorithm: oscillations possible

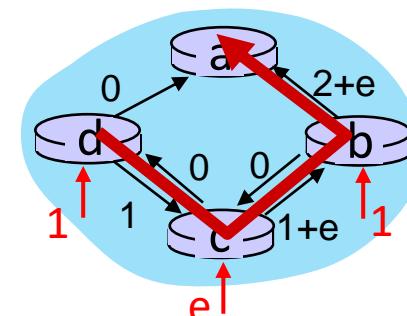
- when link costs depend on *traffic volume*, *route oscillations* possible
- sample scenario:
 - routing to destination a , traffic entering at d, c, b with rates $1, e < 1, 1$
 - link costs are *directional*, and *volume-dependent*



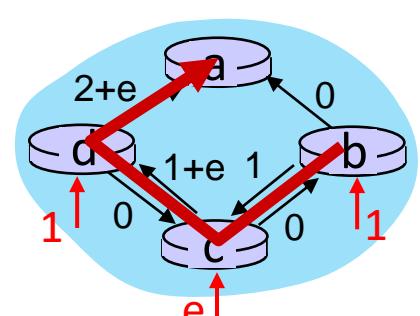
initially



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

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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:

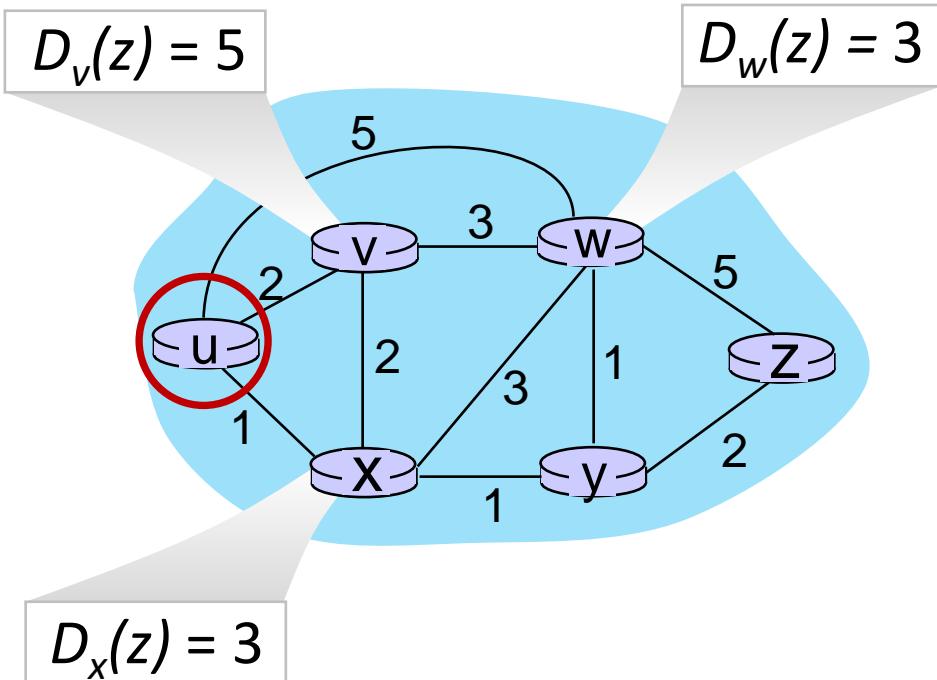
$$D_x(y) = \min_v \{ c_{x,v} + D_v(y) \}$$

\min taken over all neighbors v of x

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

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

recompute DV estimates using DV received from neighbor

if DV to any destination has changed, **notify** neighbors

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!

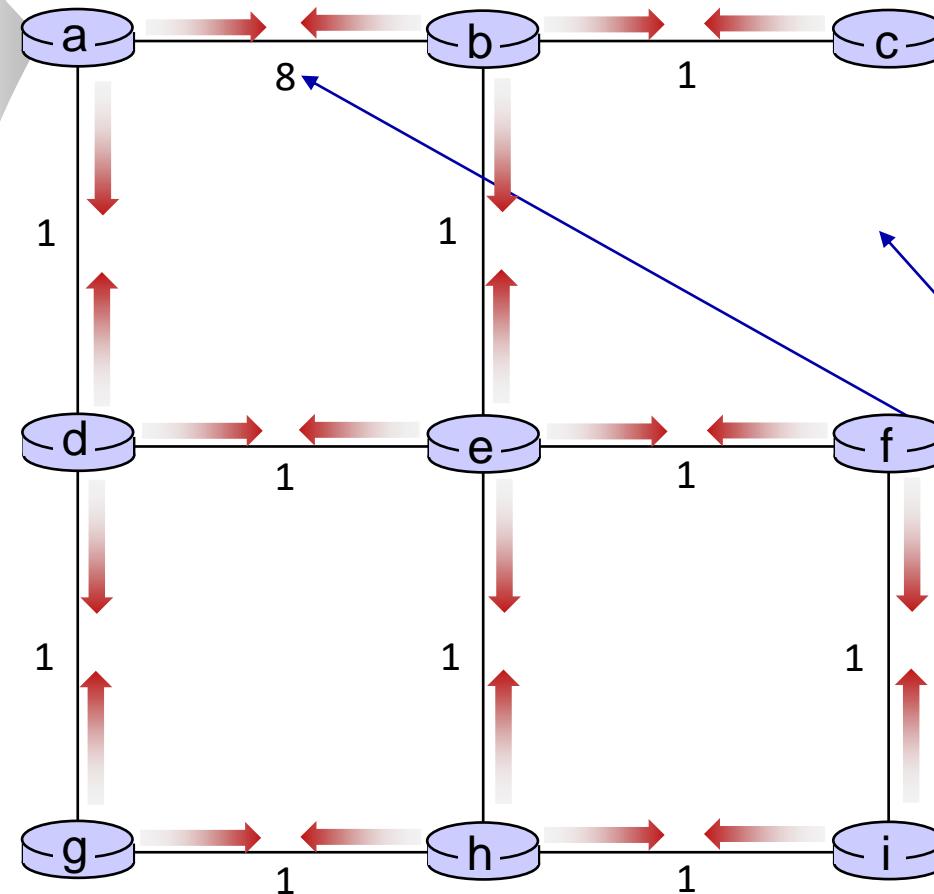
Distance vector: example



$t=0$

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

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



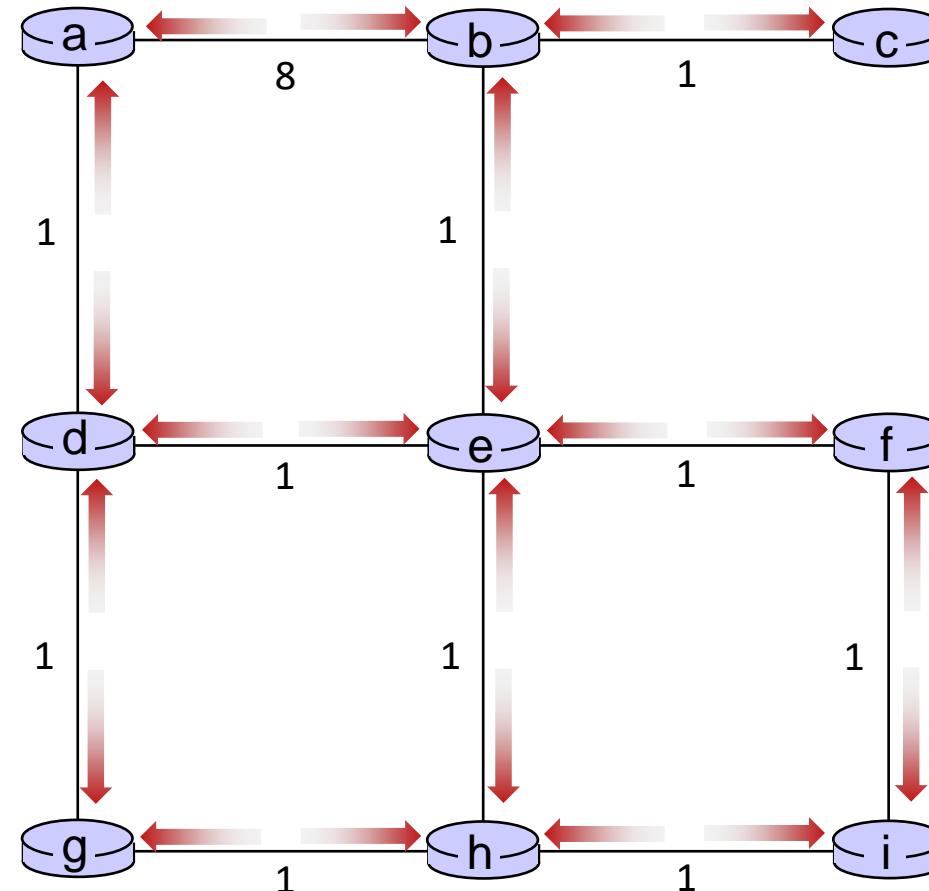
Distance vector example: iteration



$t=1$

All nodes:

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



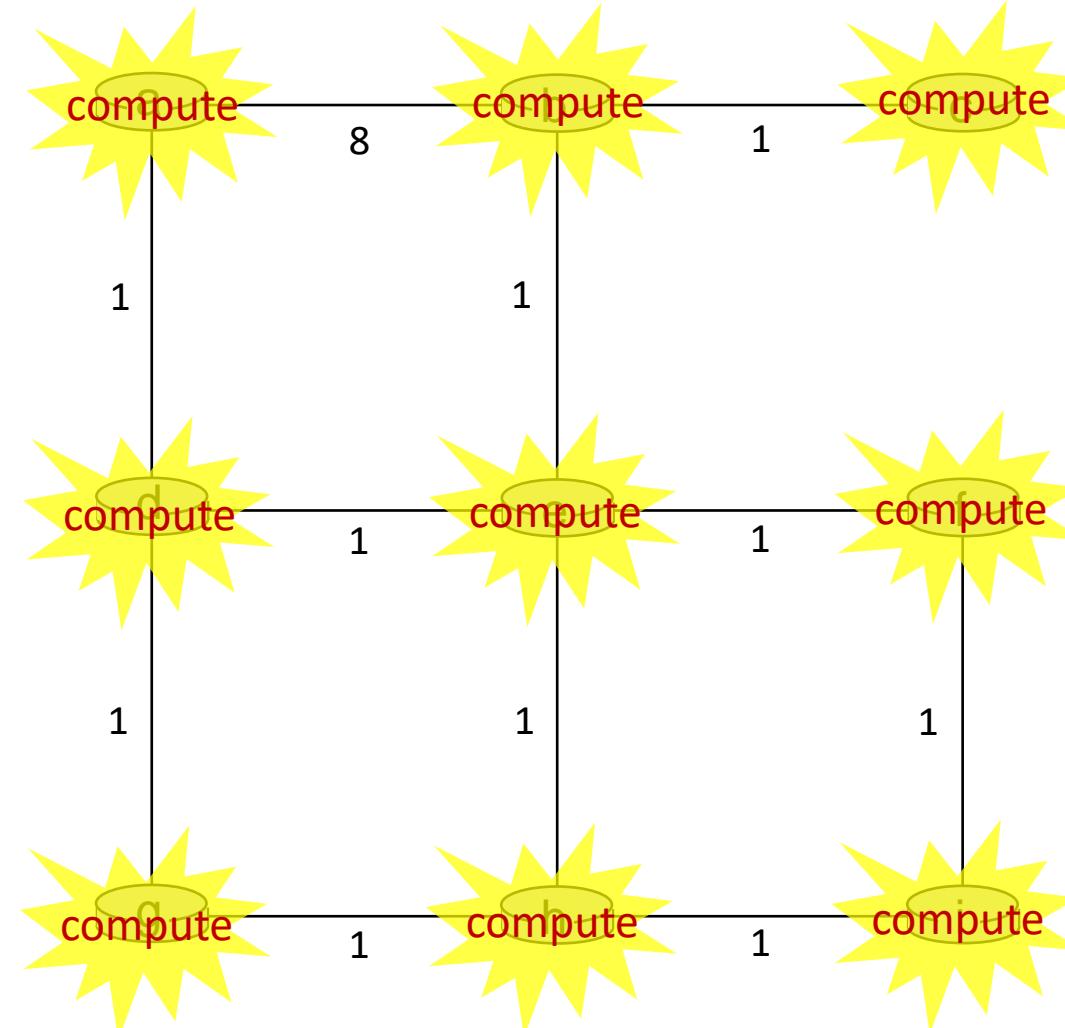
Distance vector example: iteration



$t=1$

All nodes:

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



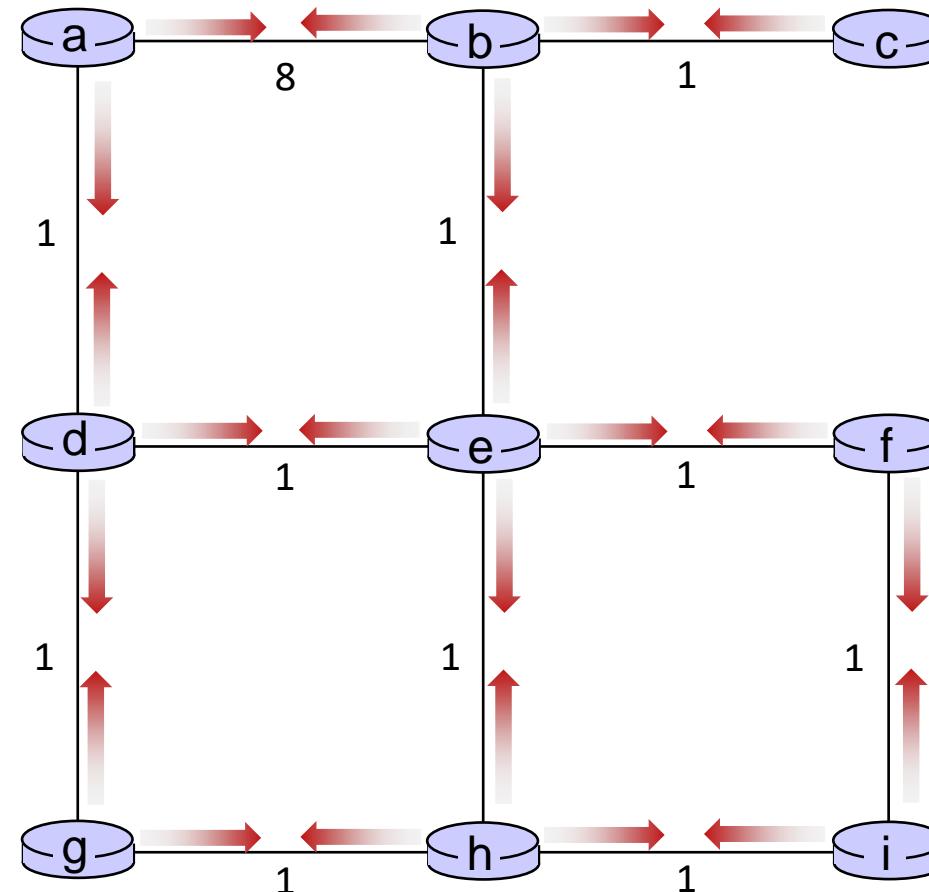
Distance vector example: iteration



$t=1$

All nodes:

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



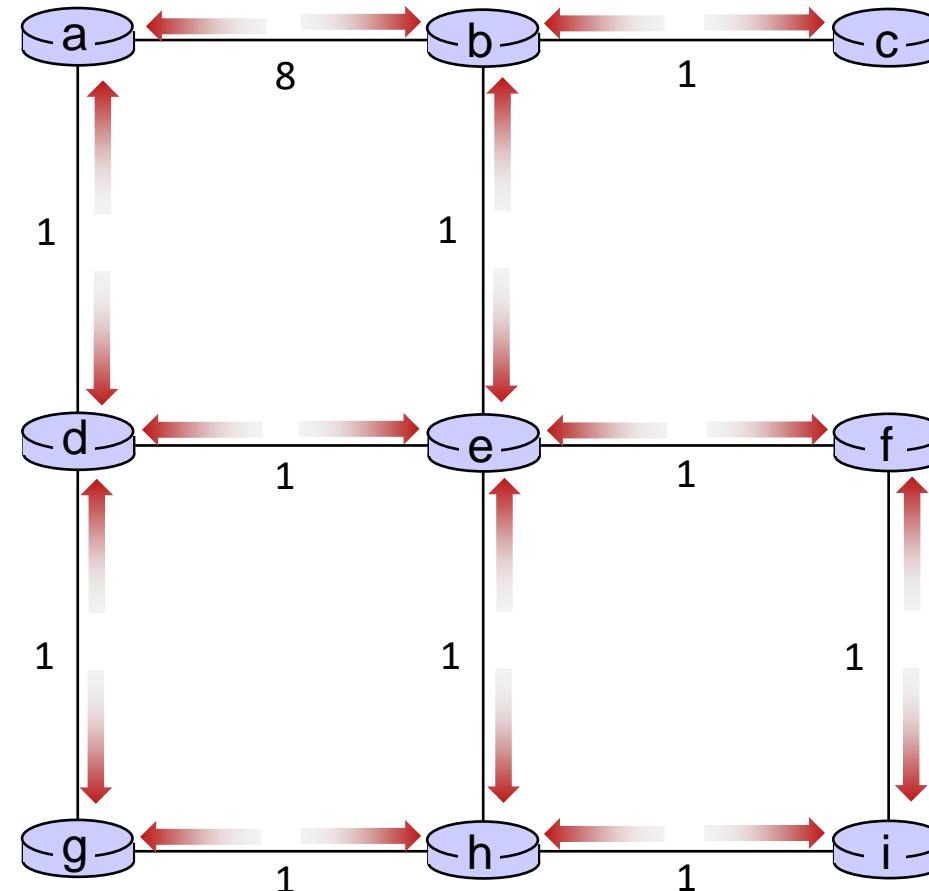
Distance vector example: iteration



$t=2$

All nodes:

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



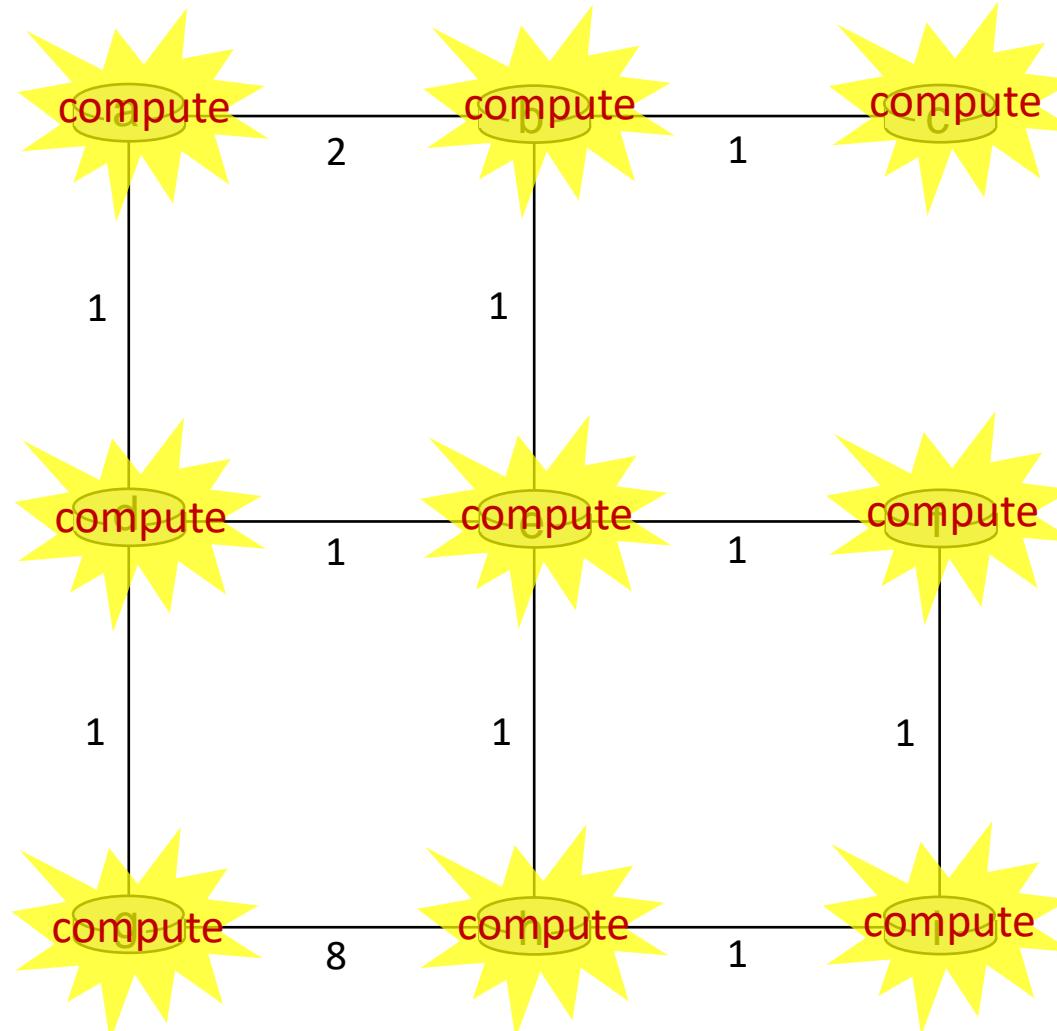
Distance vector example: iteration



$t=2$

All nodes:

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



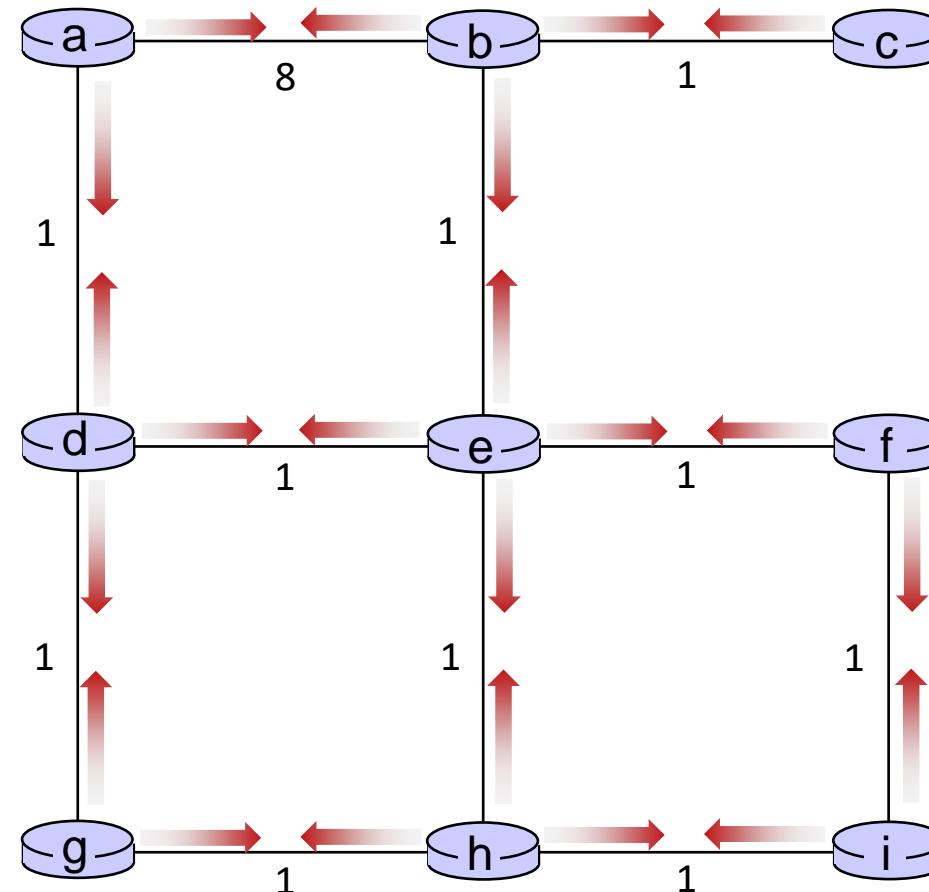
Distance vector example: iteration



$t=2$

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

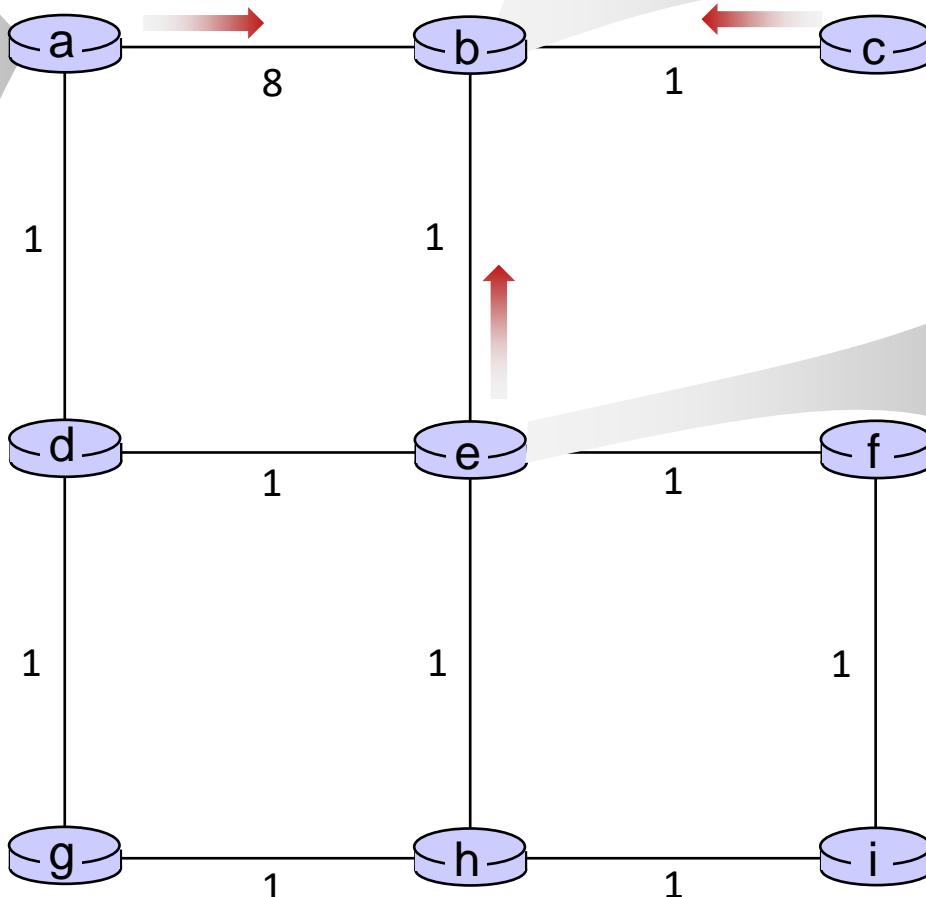
Distance vector example: t=1



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)

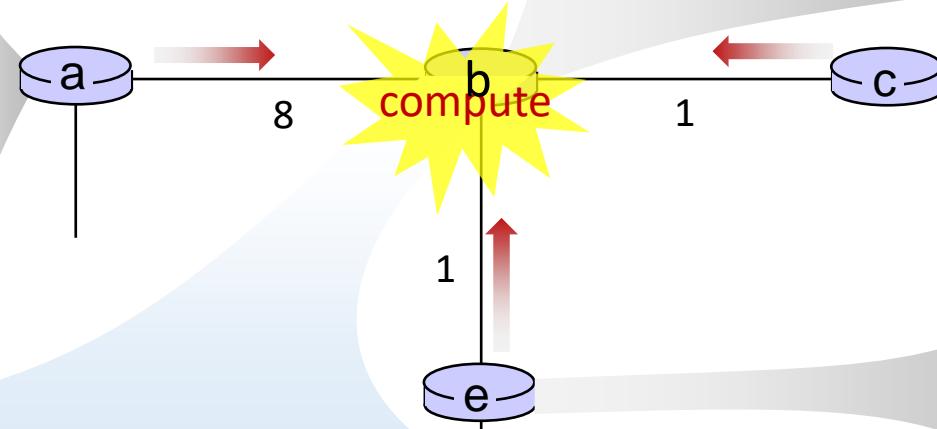


t=1

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

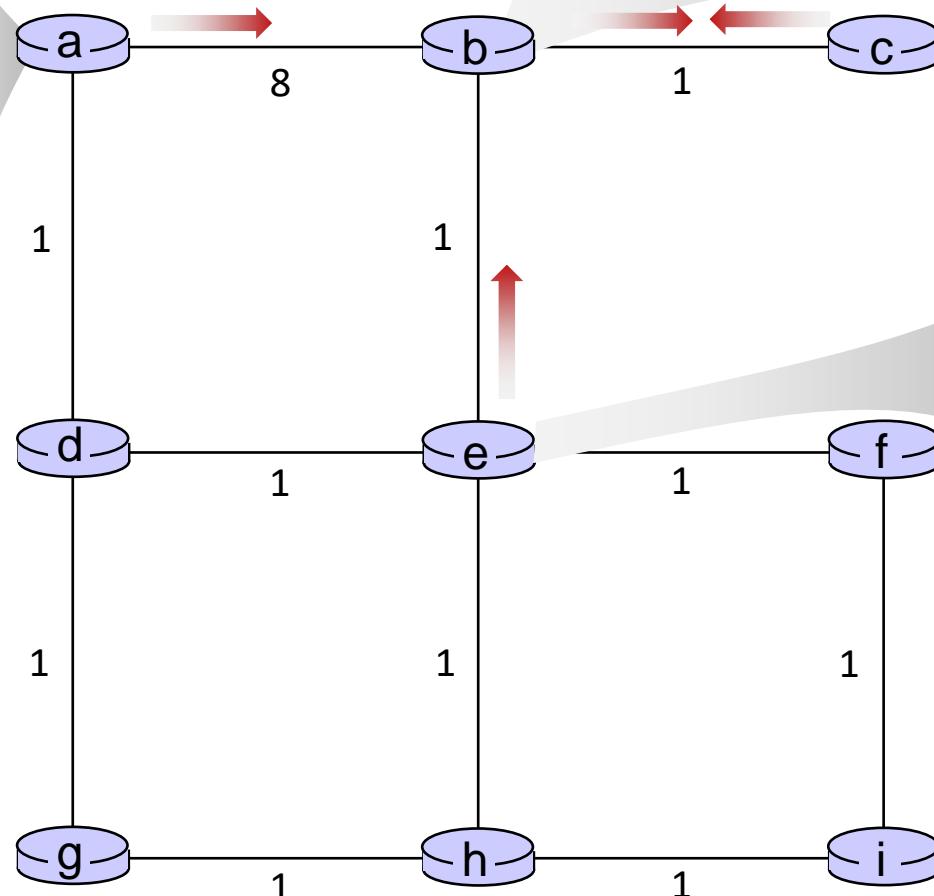
DV in b:	
$D_b(a) = 8$	$D_b(f) = 2$
$D_b(c) = 1$	$D_b(g) = \infty$
$D_b(d) = 2$	$D_b(h) = 2$
$D_b(e) = 1$	$D_b(i) = \infty$

Distance vector example: t=1



t=1

- c receives DVs from b



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

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

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

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

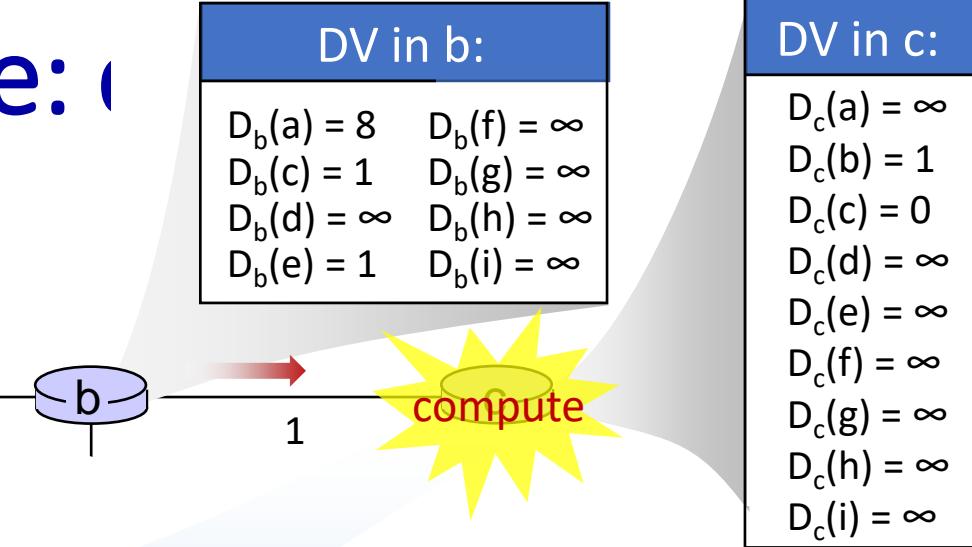
Distance vector example: (t=1)



t=1

- c receives DVs from b computes:

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



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

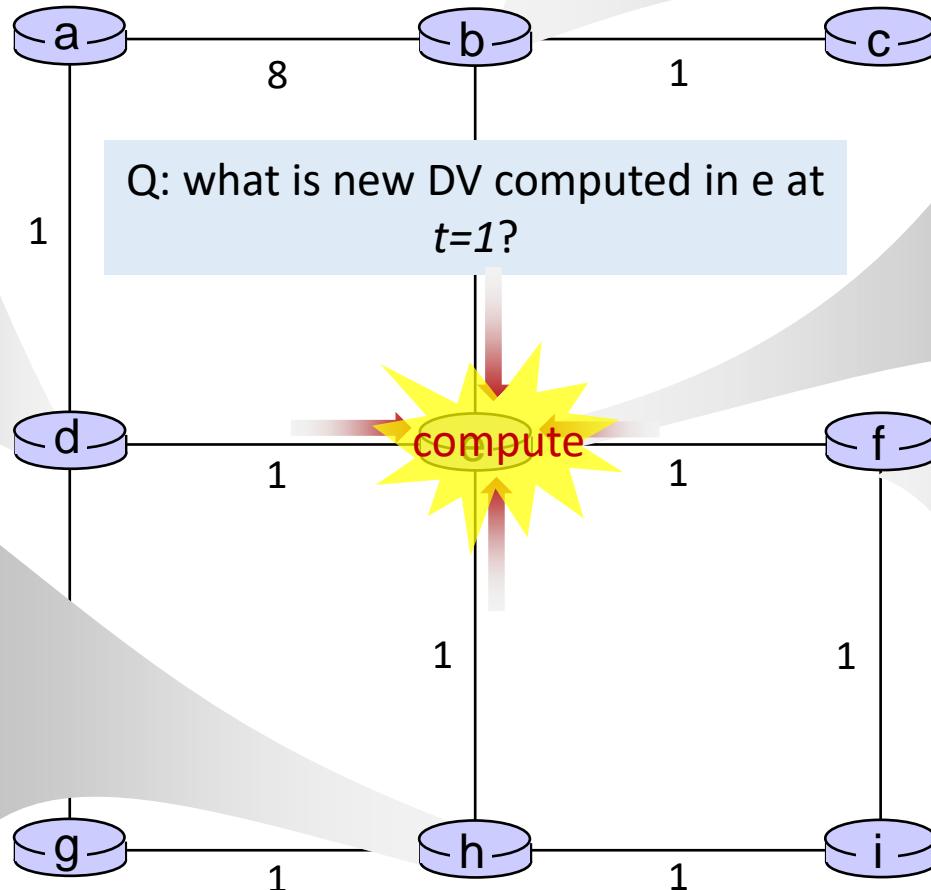


t=1

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

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

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



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

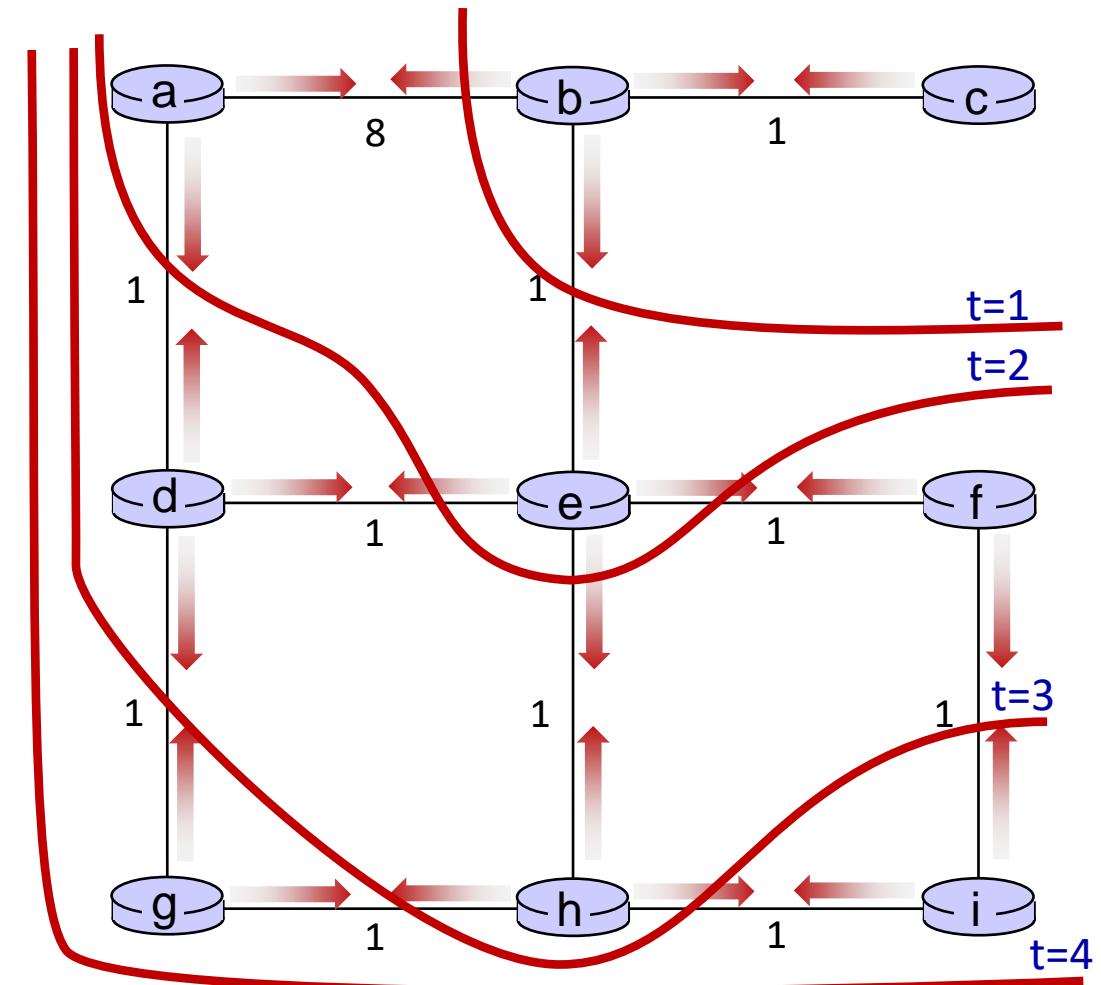
DV in e:
$D_e(a) = \infty$
$D_e(b) = 1$
$D_e(c) = \infty$
$D_e(d) = 1$
$D_e(e) = 0$
$D_e(f) = 1$
$D_e(g) = \infty$
$D_e(h) = 1$
$D_e(i) = \infty$

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

Distance vector: state information diffusion

Iterative communication, computation steps diffuses information through network:

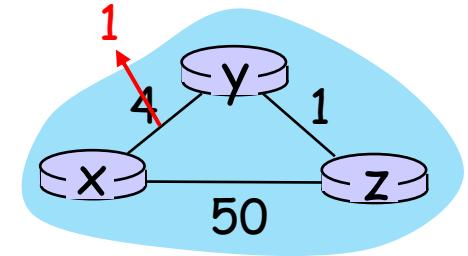
-  t=0 c's state at t=0 is at **c** only
-  t=1 c's state at t=0 has propagated to **b**, and may influence distance vector computations up to **1** hop away, i.e., at **b**
-  t=2 c's state at t=0 may now influence distance vector computations up to **2** hops away, i.e., at **b** and now at **a, e**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



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*



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

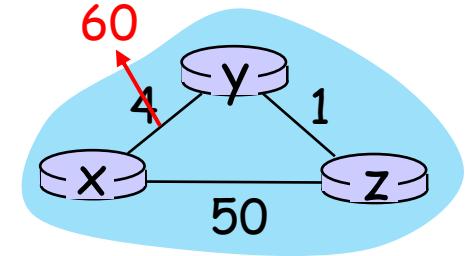
“good news travels fast” t_1 : **z** receives update from **y**, updates its table, computes new least cost to **x**, sends its neighbors its DV.

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

Distance vector: link cost changes

link cost changes:

- node detects *local link cost change*
- “bad news travels slow” – **count-to-infinity** problem:
 - **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 table 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”)

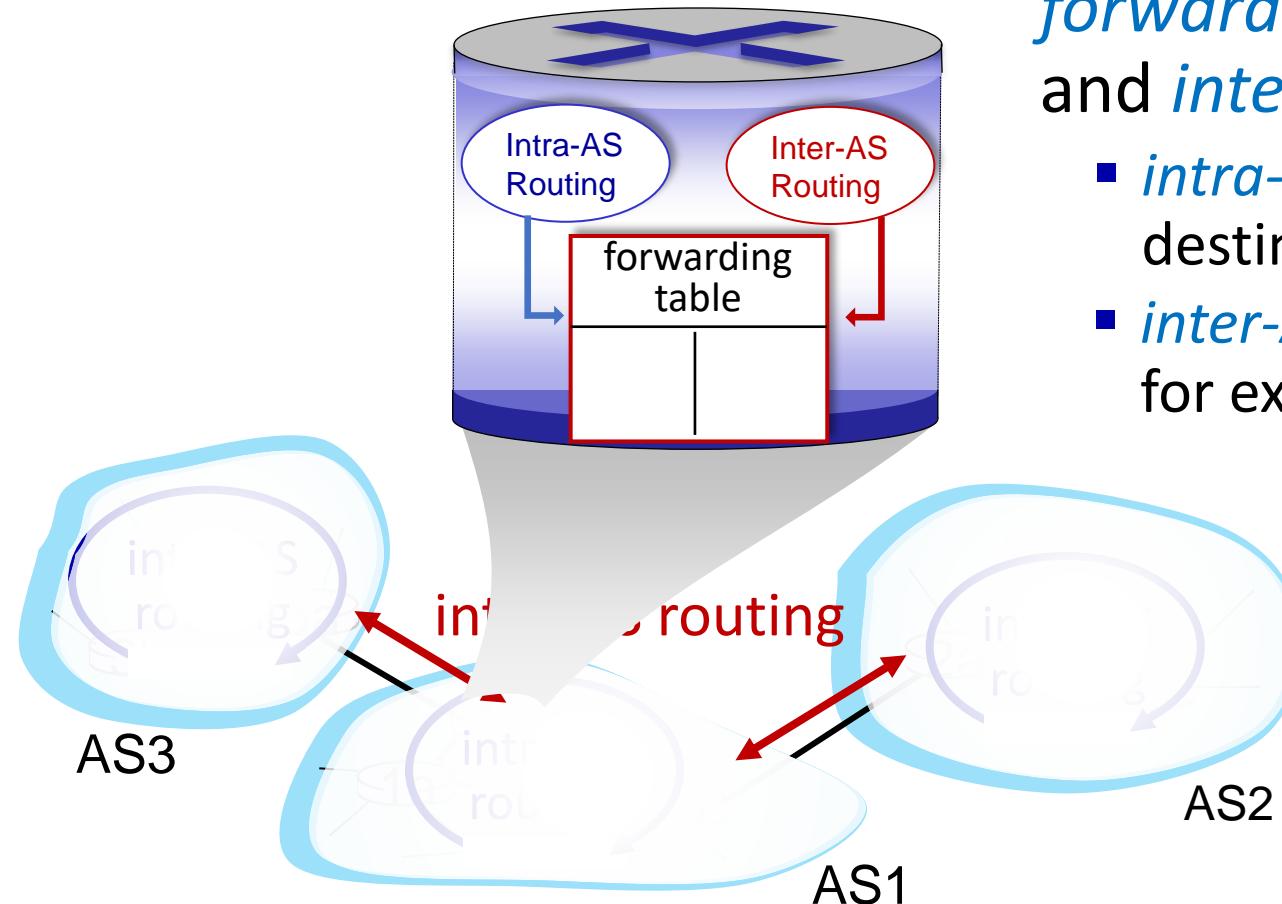
intra-AS (aka “intra-domain”):
routing among *within same AS*
 (“*network*”)

- 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

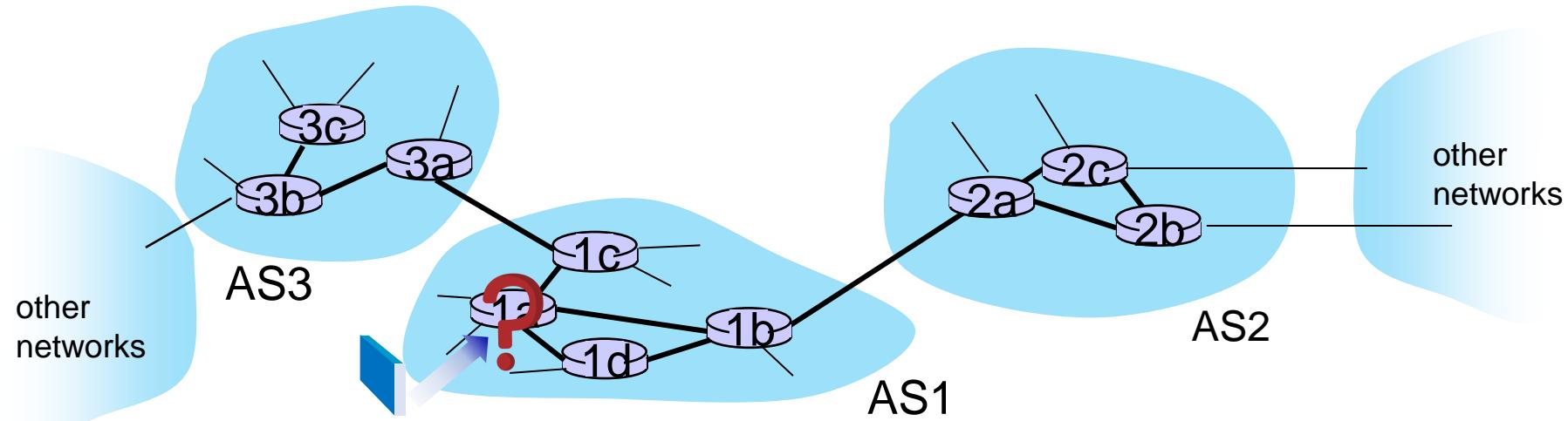
- *intra-AS routing* determine entries for destinations within AS
- *inter-AS & intra-AS* determine entries for external destinations

Inter-AS routing: a role in intradomain forwarding

- e.g., 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**



Inter-AS routing: routing within an AS

most common *intra-AS routing protocols*:

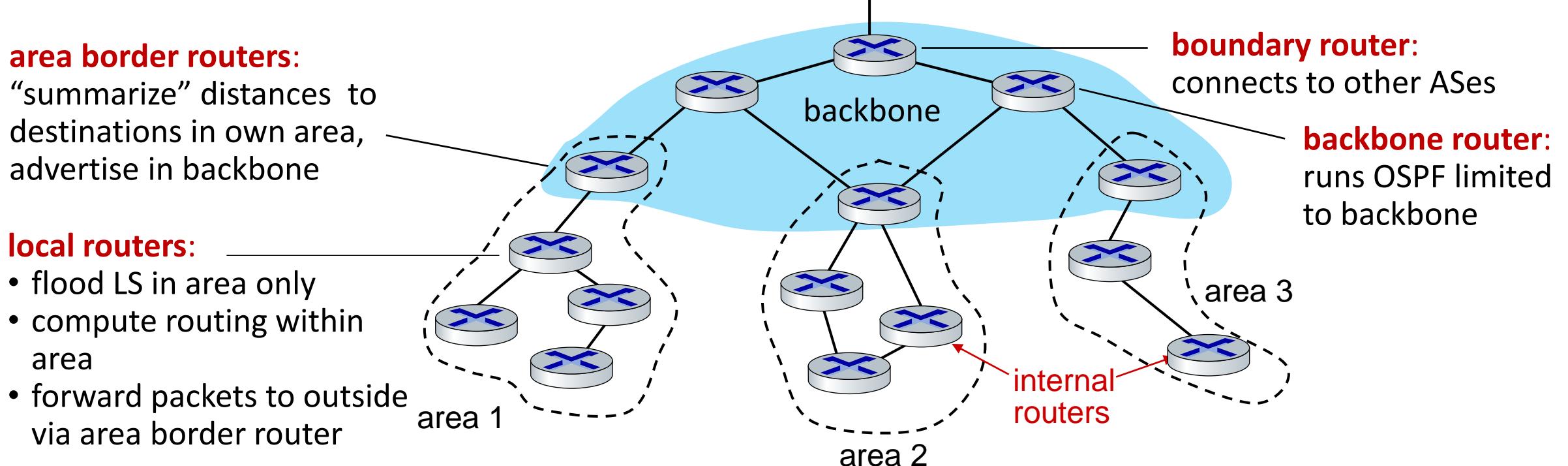
- RIP: Routing Information Protocol [RFC 1723]
 - classic DV: DVs exchanged every *30 secs*
 - *no longer widely used*
- EIGRP: Enhanced Interior Gateway Routing Protocol
 - DV based
 - formerly *Cisco-proprietary* for decades (became *open* in 2013 [RFC 7868])
- OSPF: Open Shortest Path First [RFC 2328]
 - *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

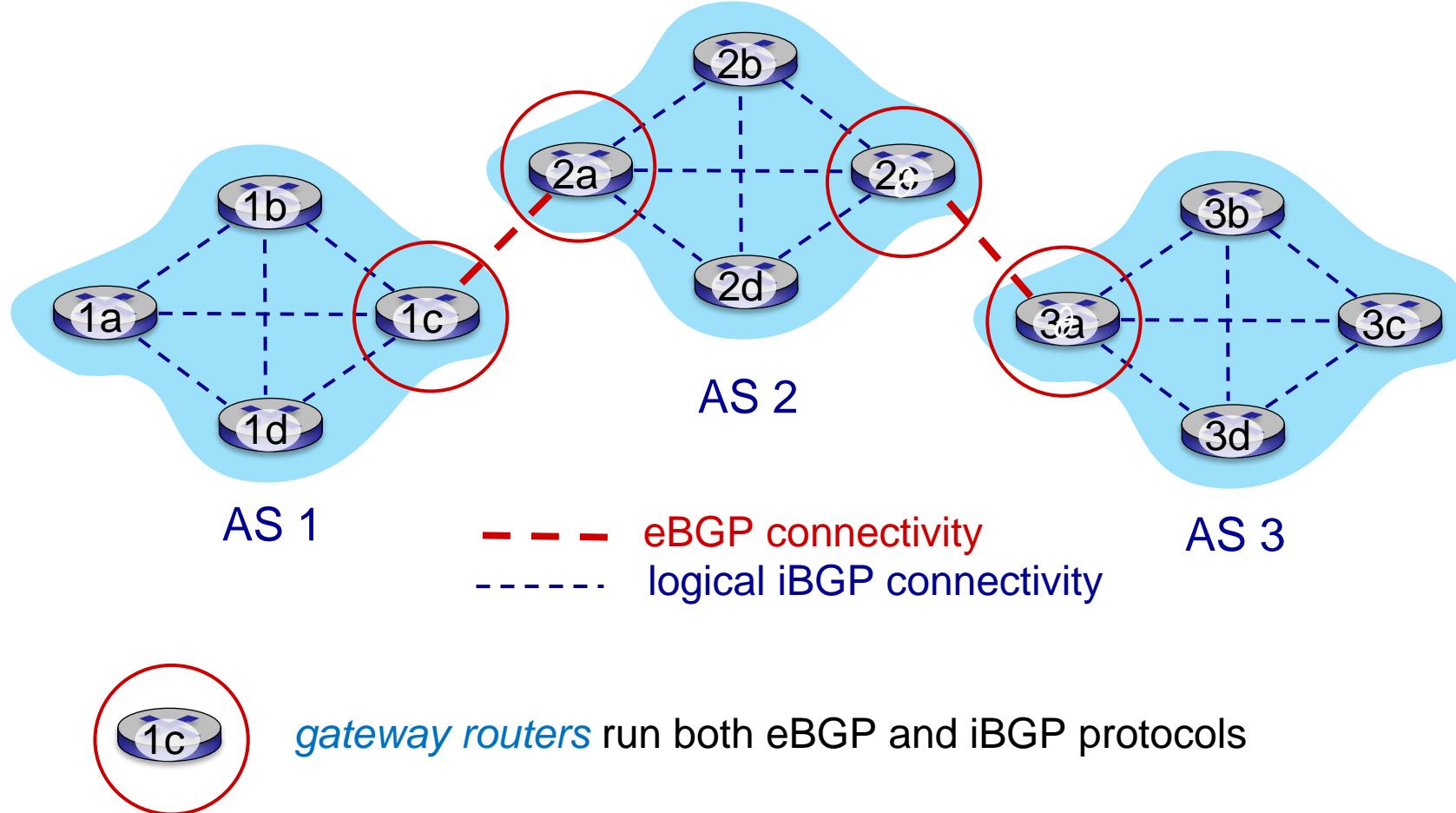


- network management, configuration
 - SNMP
 - NETCONF/YANG

Internet inter-AS routing: BGP

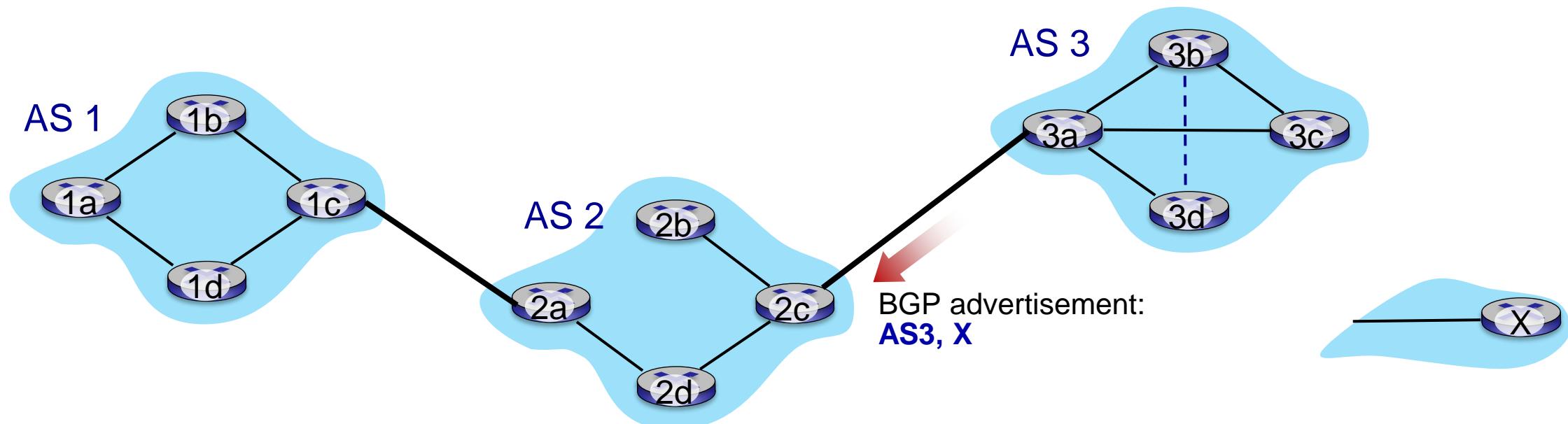
- BGP (Border Gateway Protocol): *the de facto* inter-domain routing protocol
 - “*glue* that holds the Internet together”
- allows *subnet* to advertise its existence, and the *destinations* it can reach, to rest of Internet: “*I am here, here is who I can reach, and how*”
- BGP provides each AS a means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

eBGP, iBGP connections



BGP basics

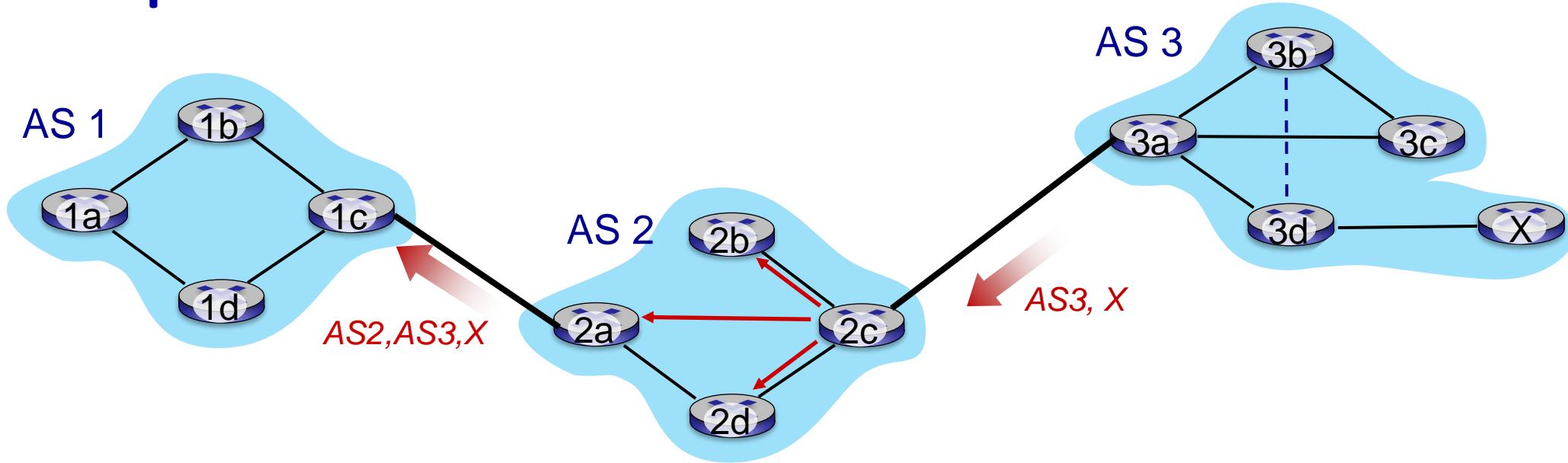
- BGP session: two BGP routers (“*peers*”) exchange *BGP messages* over *semi-permanent TCP connection*:
 - advertising *paths* to different destination network prefixes (BGP is a “*path vector*” protocol)
- e.g., when AS3 gateway 3a advertises **path AS3,X** to AS2 gateway 2c:
 - AS3 promises to AS2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



Path attributes and BGP routes

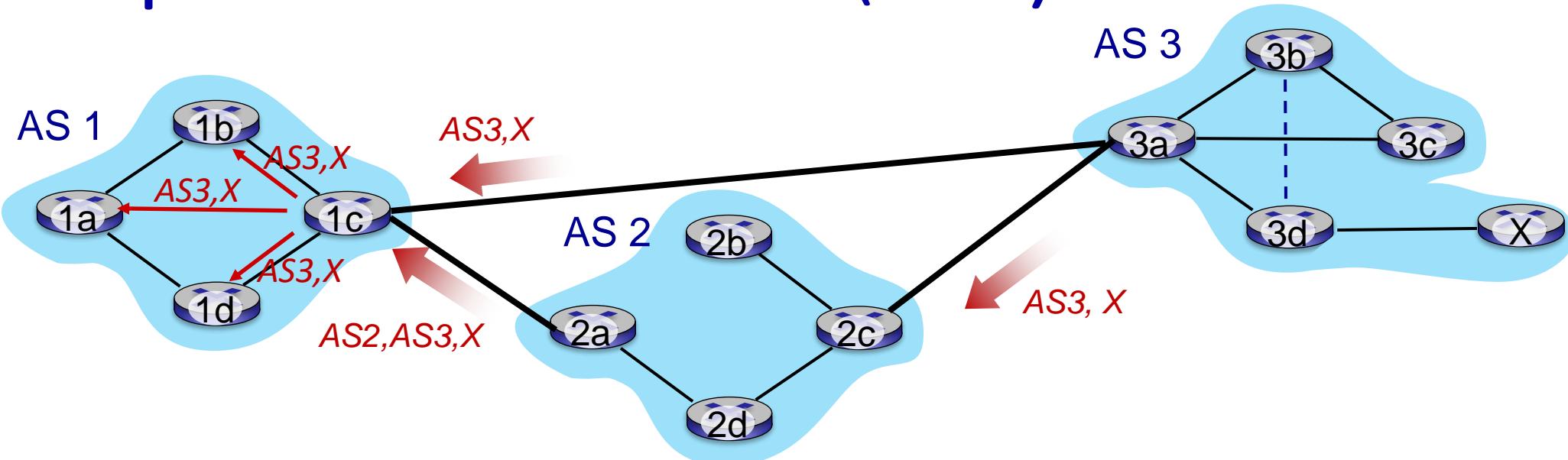
- BGP advertised **route** = **prefix** + **attributes**
 - *prefix*: destination being advertised
 - two important *attributes*:
 - **AS-PATH**: *list of ASes* through which prefix advertisement has passed
 - **NEXT-HOP**: indicates specific *internal-AS router* to next-hop AS
- **policy-based routing**: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



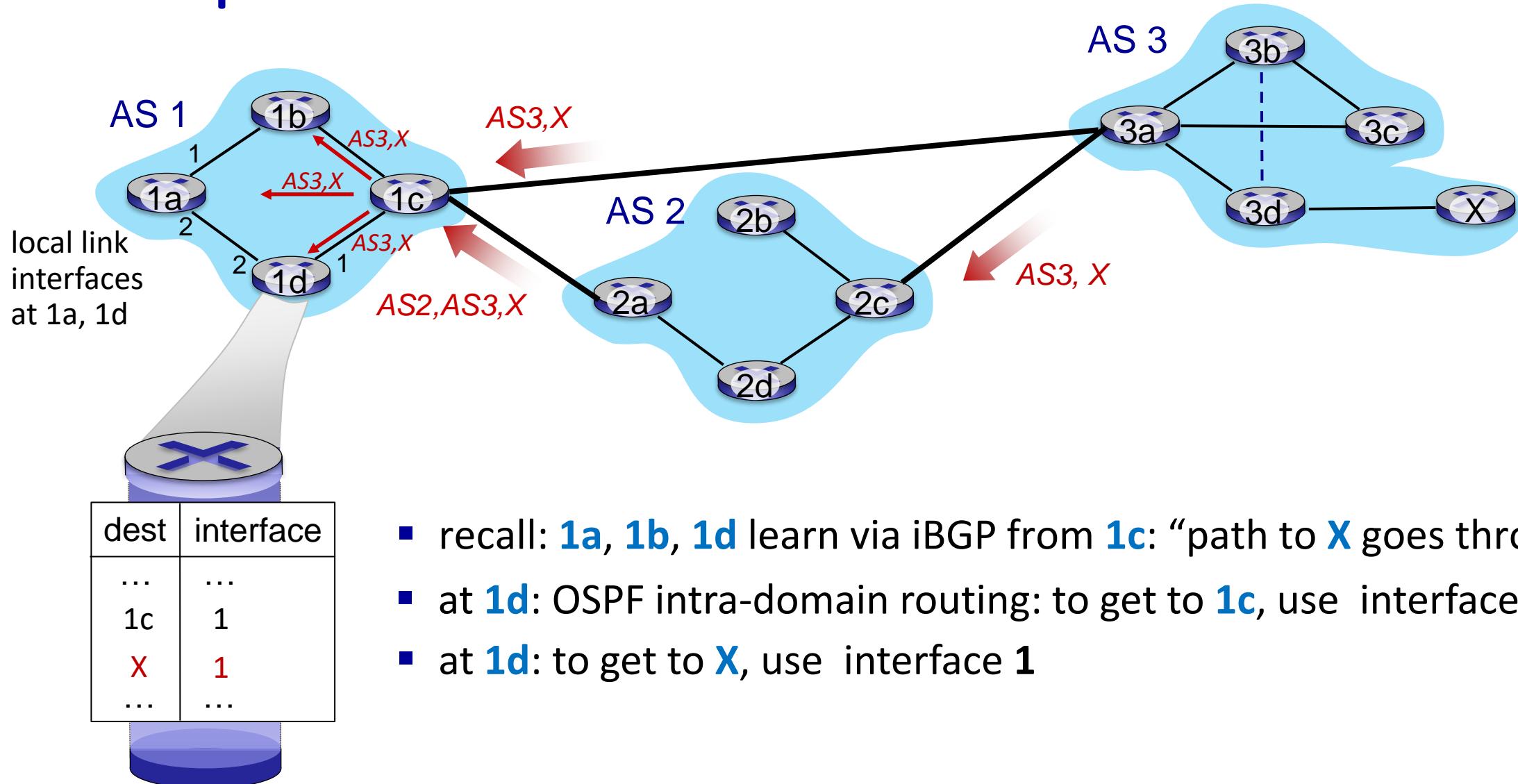
gateway router may learn about multiple paths to destination:

- **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 messages

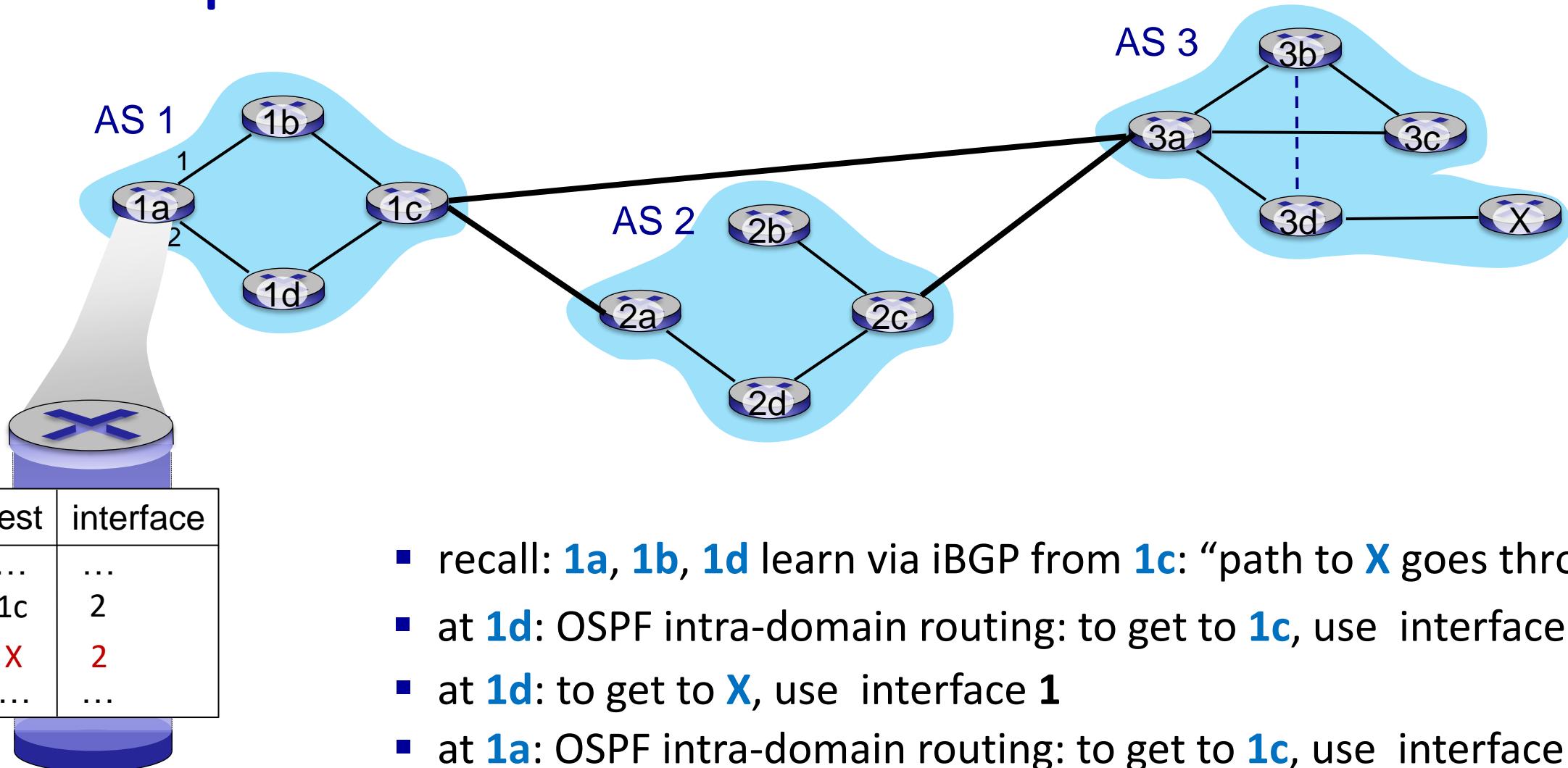
- *BGP messages* exchanged between peers over TCP connection
- *BGP messages*:
 - **OPEN**: opens TCP connection to remote BGP peer and authenticates sending BGP peer
 - **UPDATE**: advertises new path (or withdraws old)
 - **KEEPALIVE**: keeps connection alive in absence of UPDATES; also, ACKs OPEN request
 - **NOTIFICATION**: reports errors in previous msg; also, used to close connection

BGP path advertisement



- recall: **1a, 1b, 1d** learn via iBGP from **1c**: “path to **X** goes through **1c**”
- at **1d**: OSPF intra-domain routing: to get to **1c**, use interface **1**
- at **1d**: to get to **X**, use interface **1**

BGP path advertisement



- recall: **1a, 1b, 1d** learn via iBGP from **1c**: “path to **X** goes through **1c**”
- at **1d**: OSPF intra-domain routing: to get to **1c**, use interface **1**
- at **1d**: to get to **X**, use interface **1**
- at **1a**: OSPF intra-domain routing: to get to **1c**, use interface **2**
- at **1a**: to get to **X**, use interface **2**

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

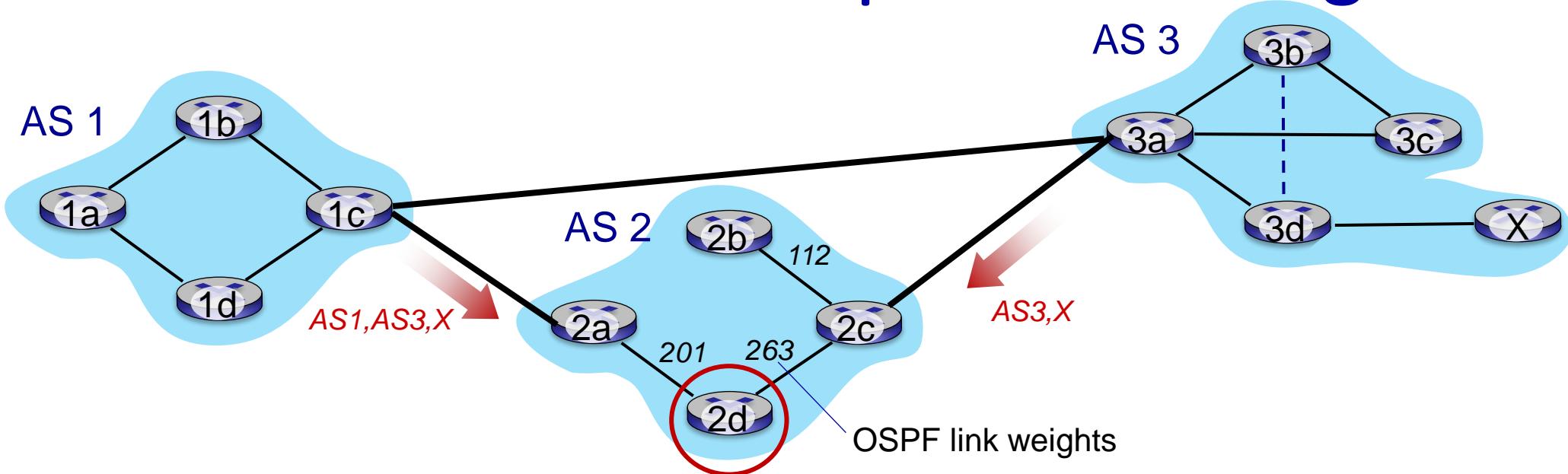
scale:

- *hierarchical routing* saves table size, reduced update traffic

performance:

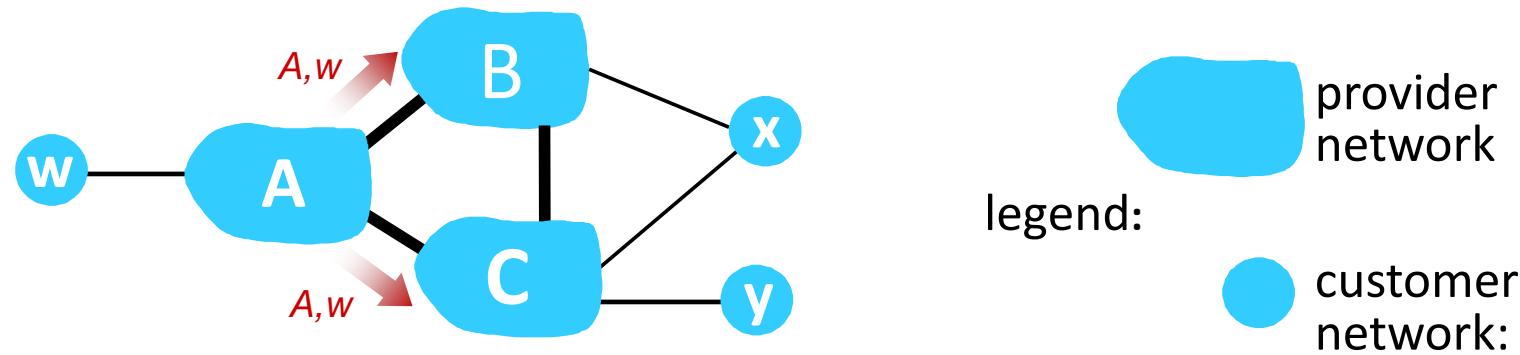
- *intra-AS*: can focus on *performance*
- *inter-AS*: *policy* dominates over performance

NEXT-HOP attribute: 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!

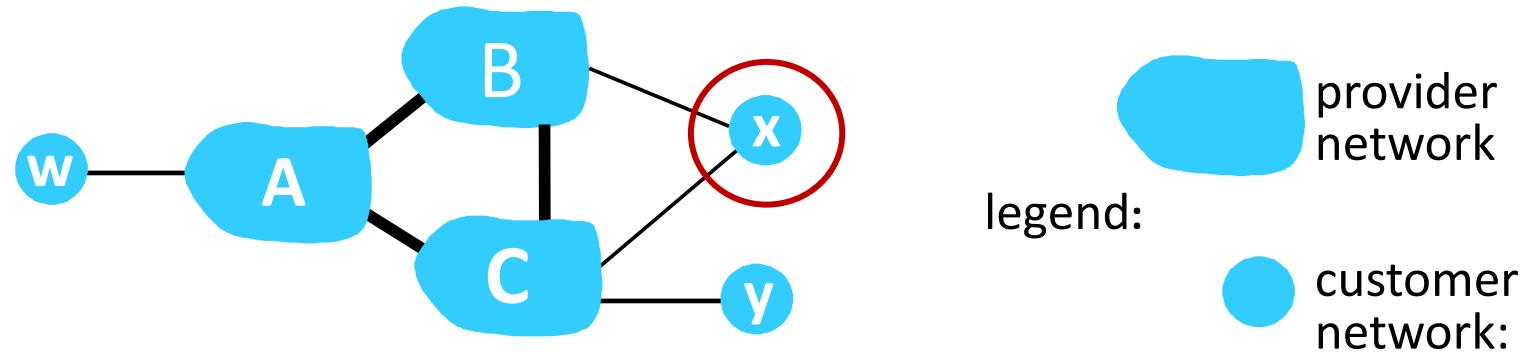
BGP: achieving policy via advertisements



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

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*

Network layer: “control plane” roadmap

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



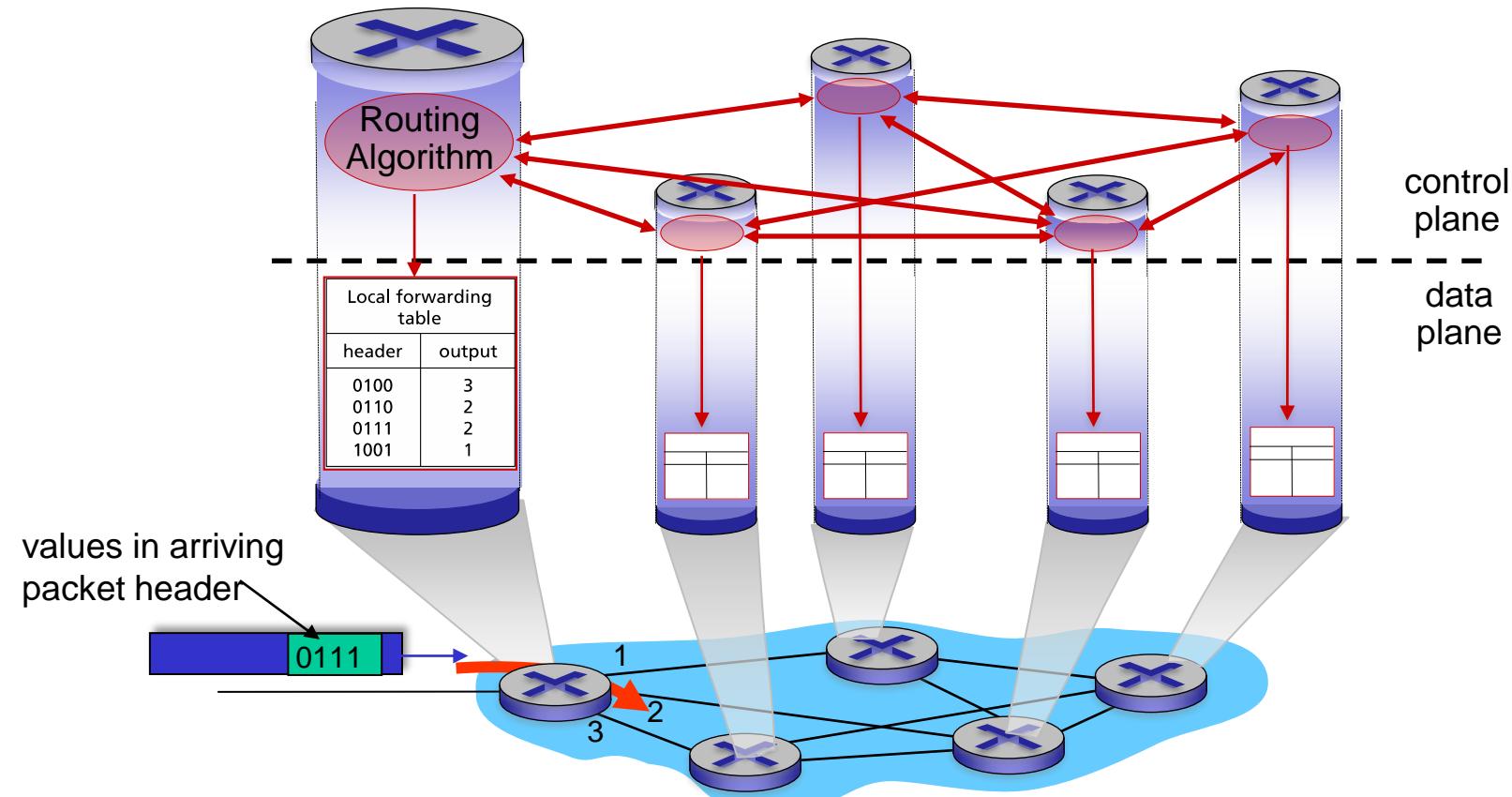
- network management, configuration
 - SNMP
 - NETCONF/YANG

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

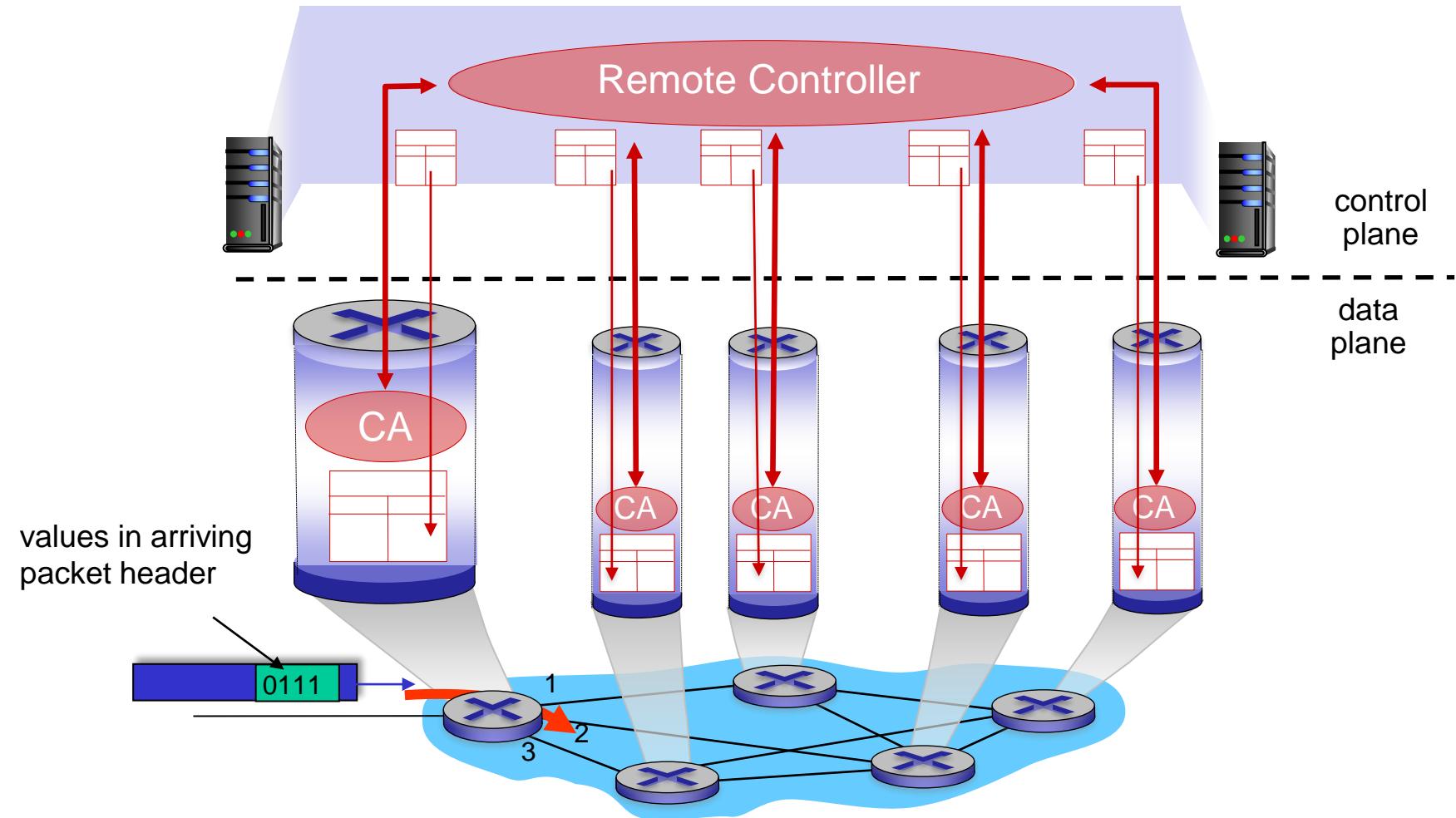
Per-router control plane

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

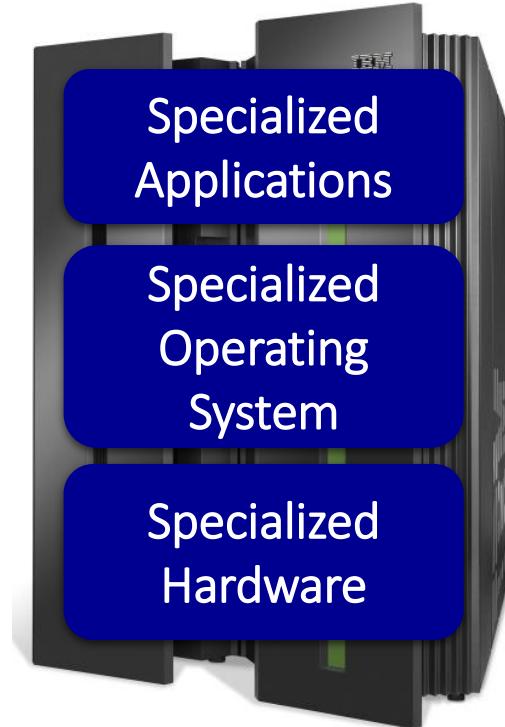


Software defined networking (SDN)

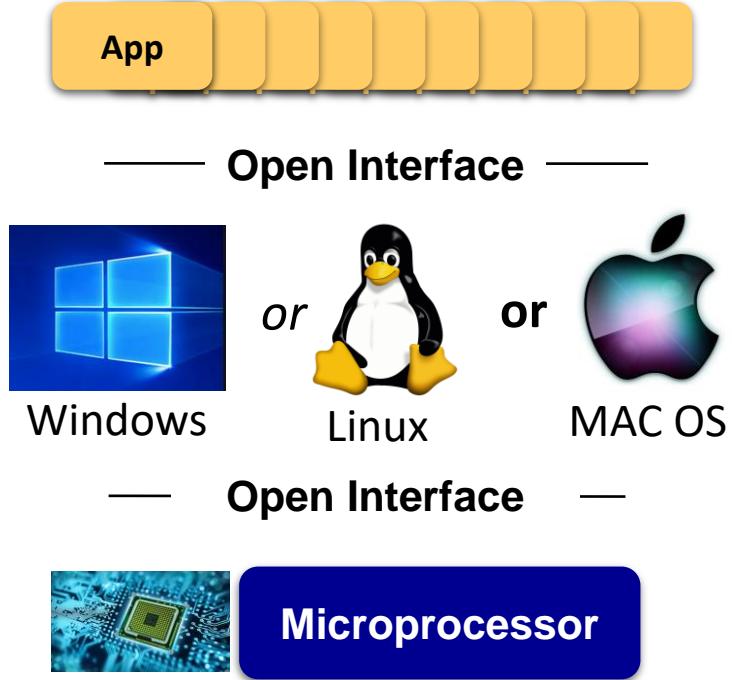
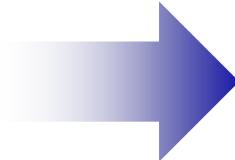
Why a logically centralized control plane?

- *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

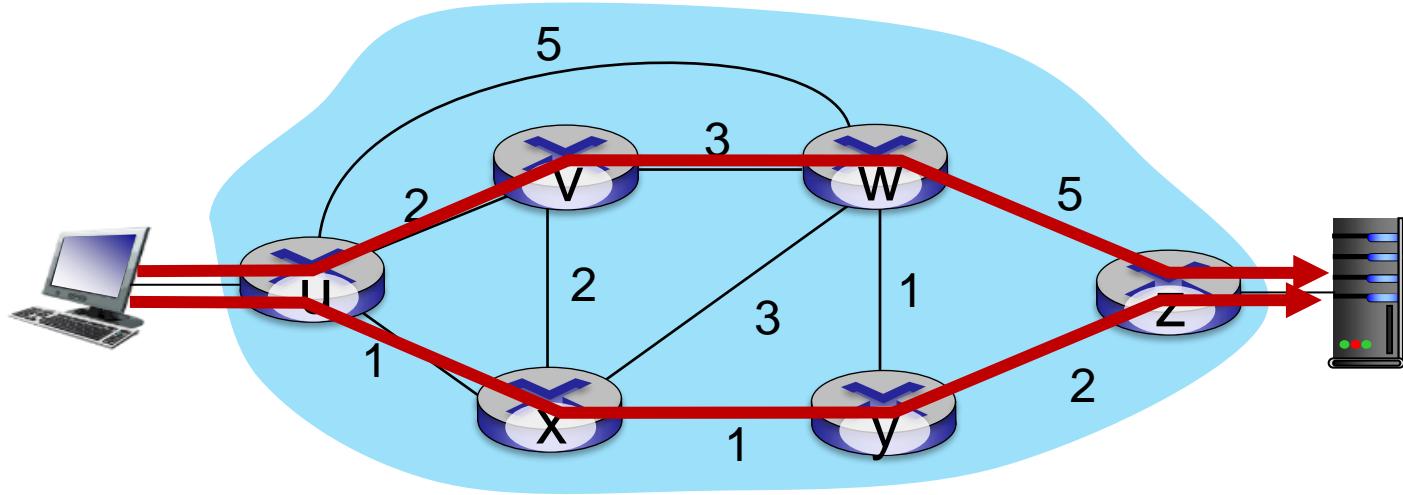


Vertically integrated
Closed, proprietary
Slow innovation
Small industry



*Horizontal
Open interfaces
Rapid innovation
Huge industry*

Traffic engineering: difficult with traditional routing

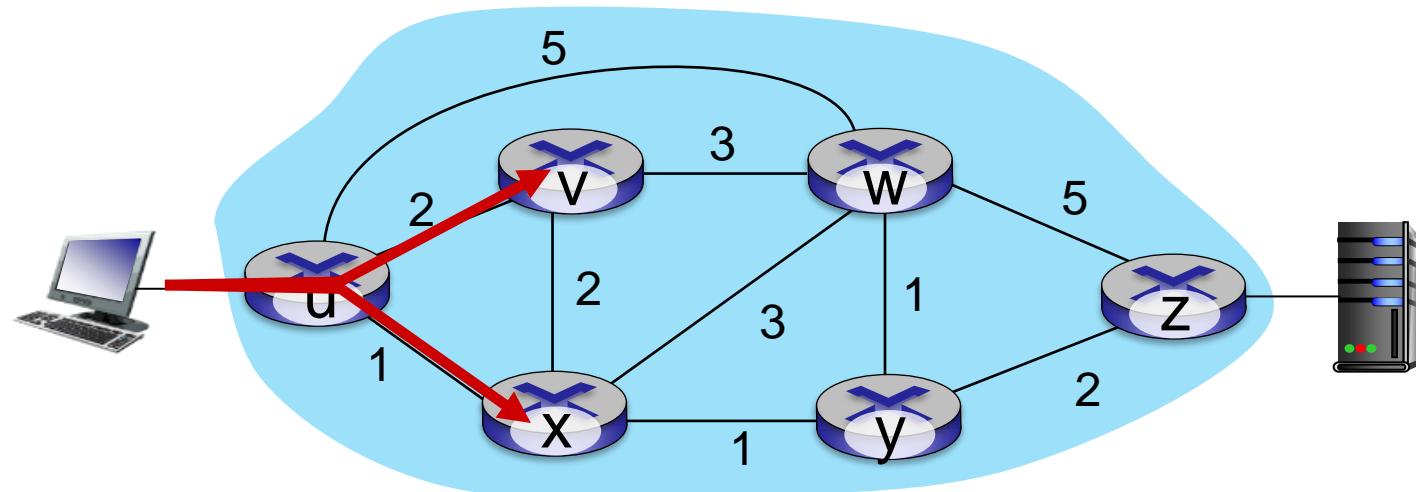


Q: what if network operator wants *u-to-z traffic* to *flow* along *uvwz*, rather than *uxyz*?

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!

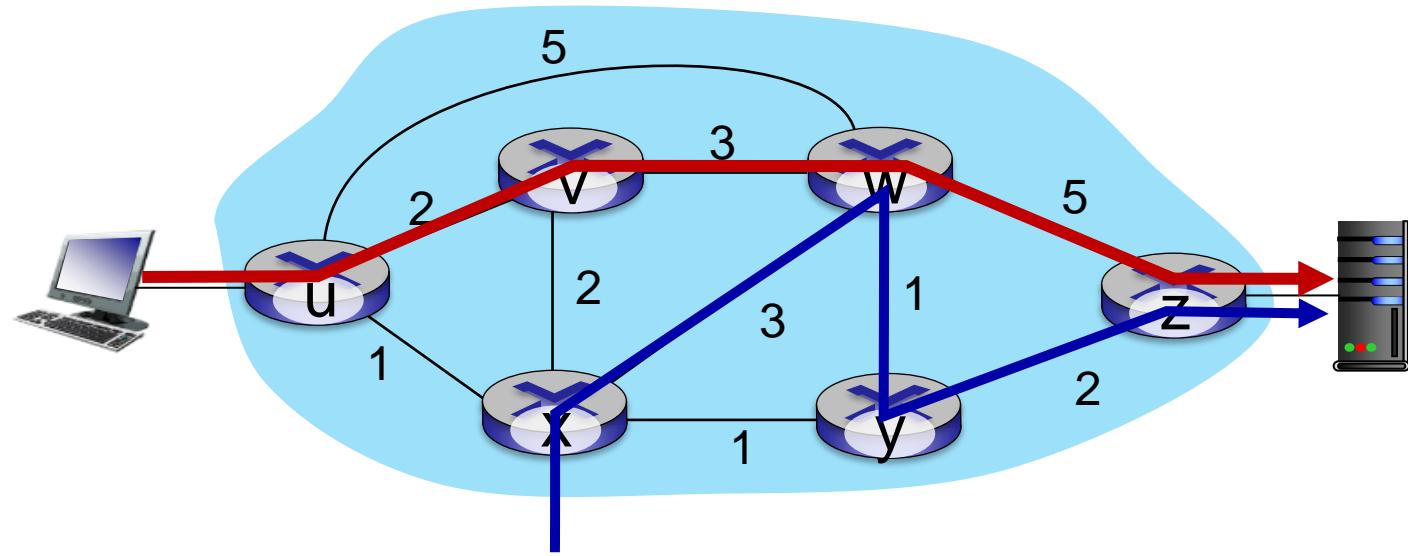
Traffic engineering: difficult with traditional routing



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)

4. programmable control applications

routing

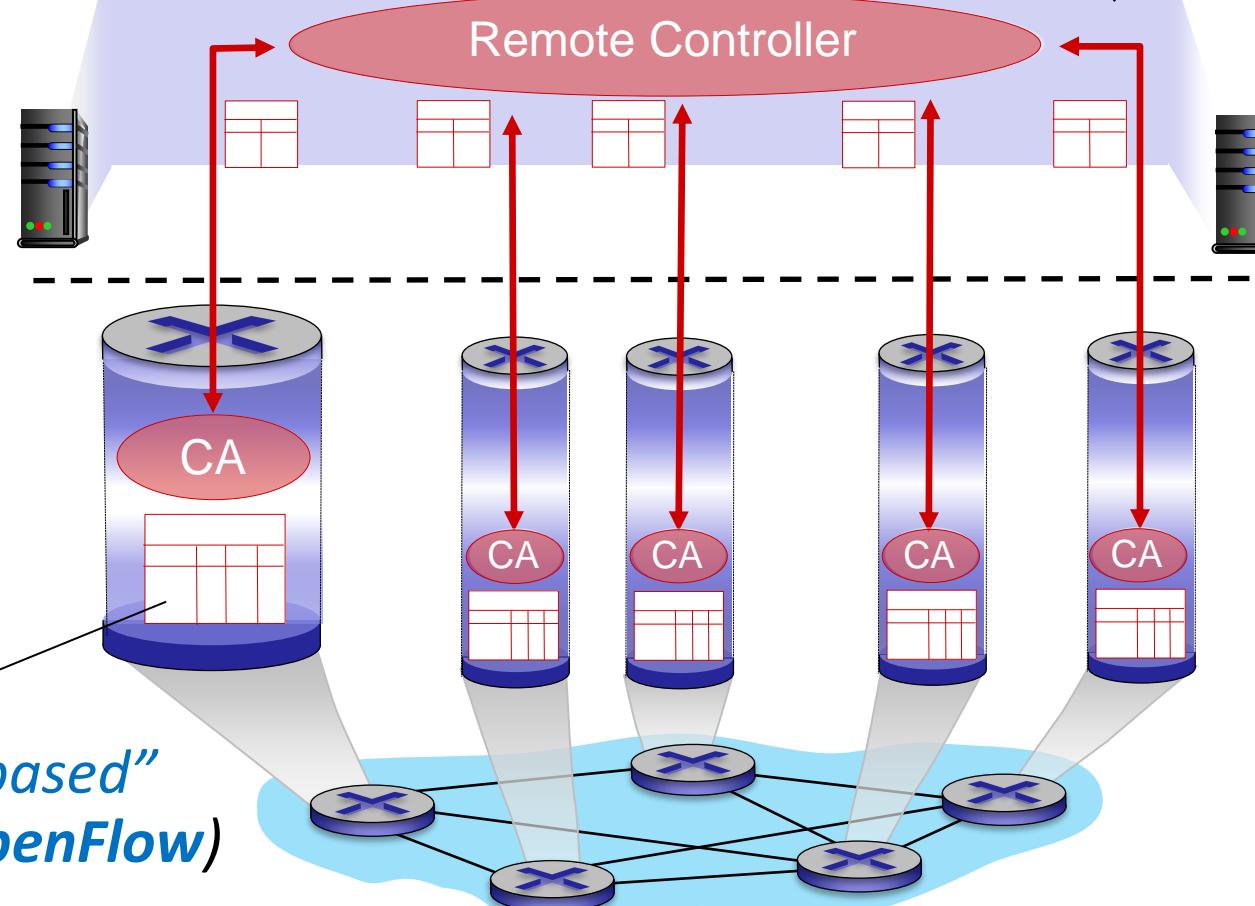
access control

...

load balance

3. control plane functions external to data-plane switches

1: generalized “flow-based” forwarding (e.g., OpenFlow)



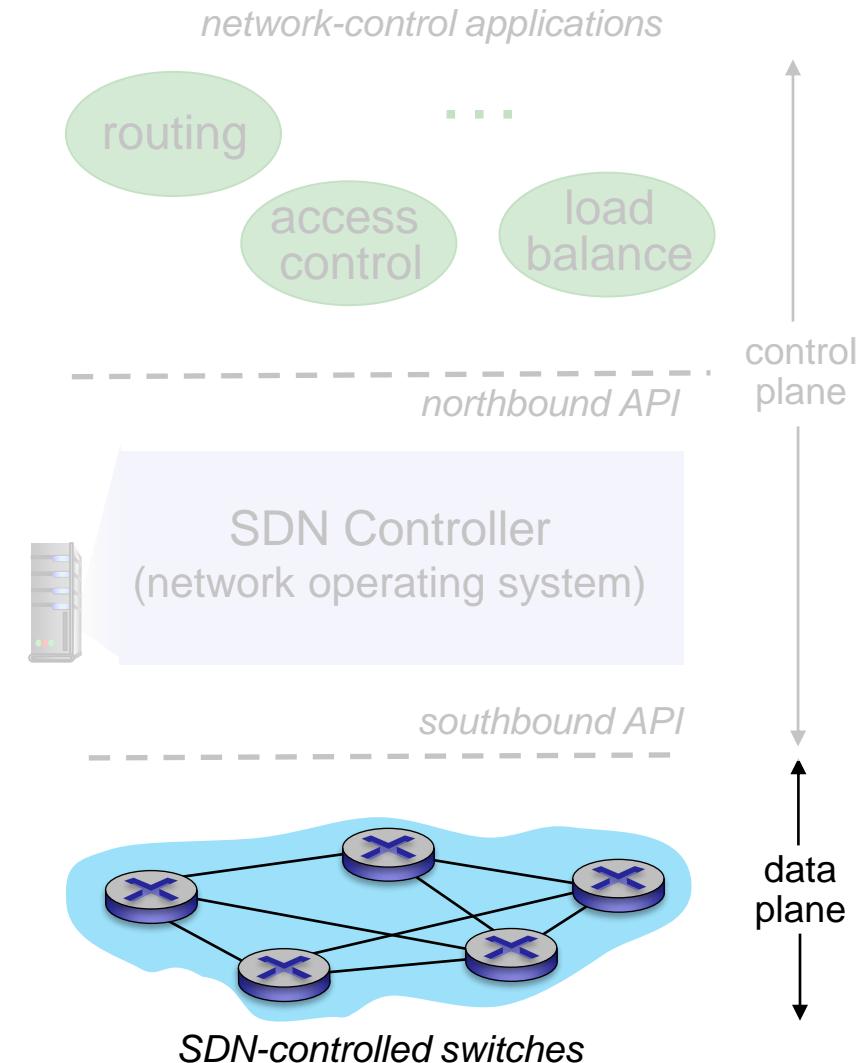
2. control, data plane separation

control plane
data plane

Software defined networking (SDN)

Data-plane switches:

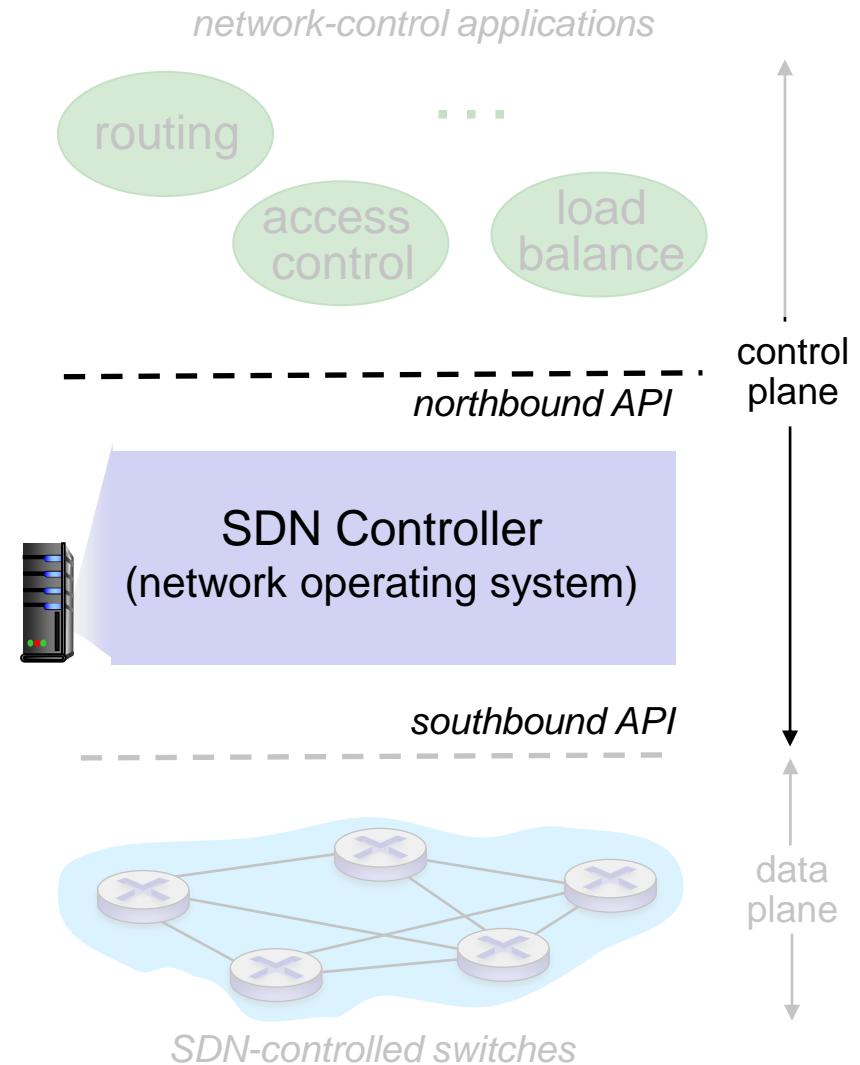
- fast, simple, *commodity switches* implementing generalized data-plane forwarding (Section 4.4) in *hardware*
- *flow* (forwarding) table computed, installed *under controller supervision*
- **API** for *table-based switch control* (e.g., **OpenFlow**)
 - defines what is controllable, what is not
-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



Software defined networking (SDN)

SDN controller (network OS):

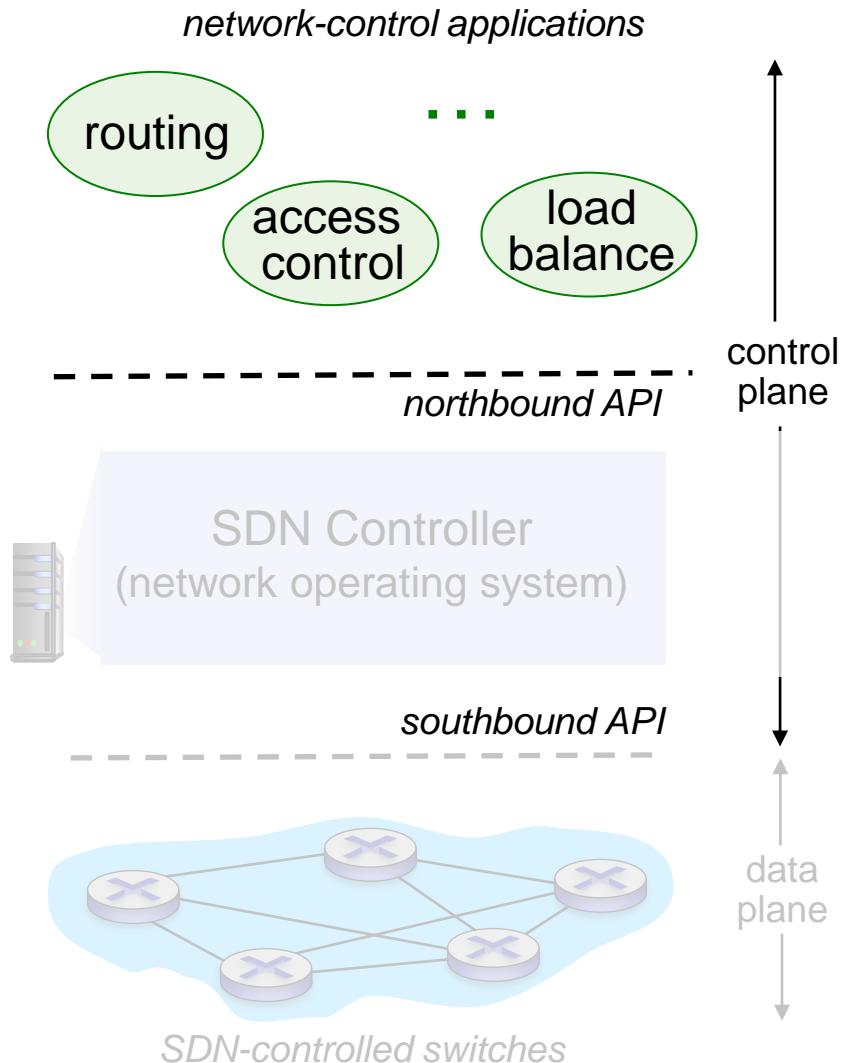
- maintain *network state information*
- interacts with *network control applications* “above” via *northbound API*
- interacts with *network switches* “below” via *southbound API*
- implemented as *distributed system* for performance, scalability, fault-tolerance, robustness



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

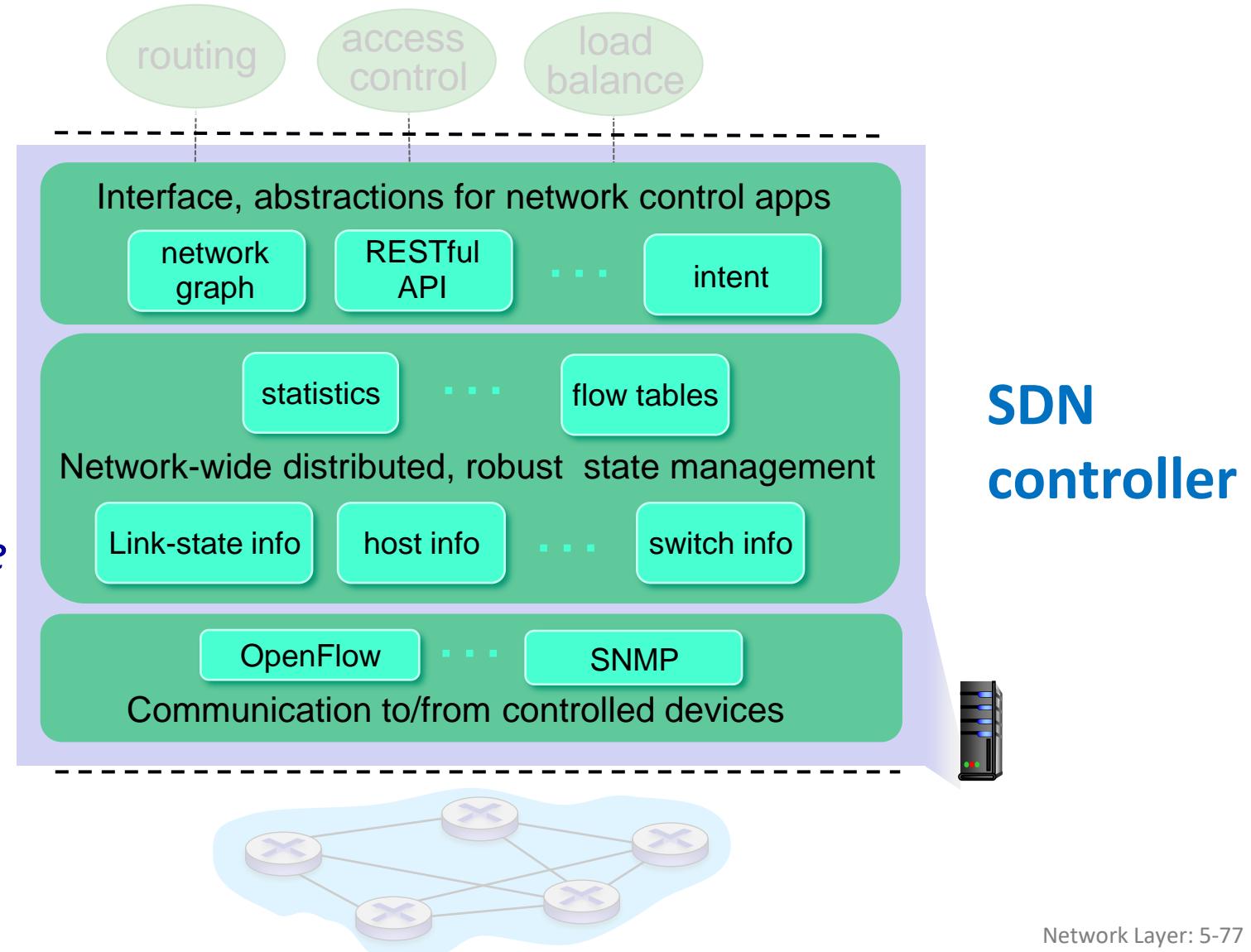


Components of SDN controller

interface layer to network control apps: abstractions API

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

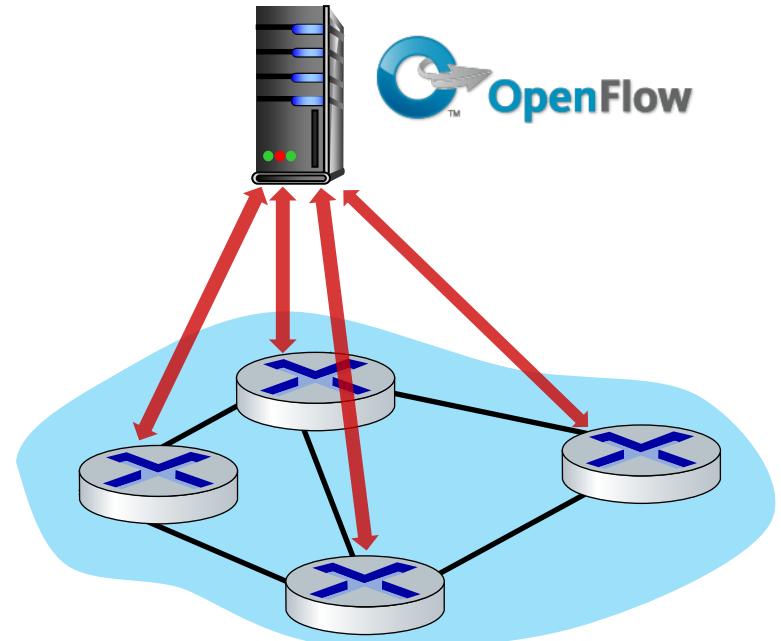
communication: communicate between SDN controller and controlled switches



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

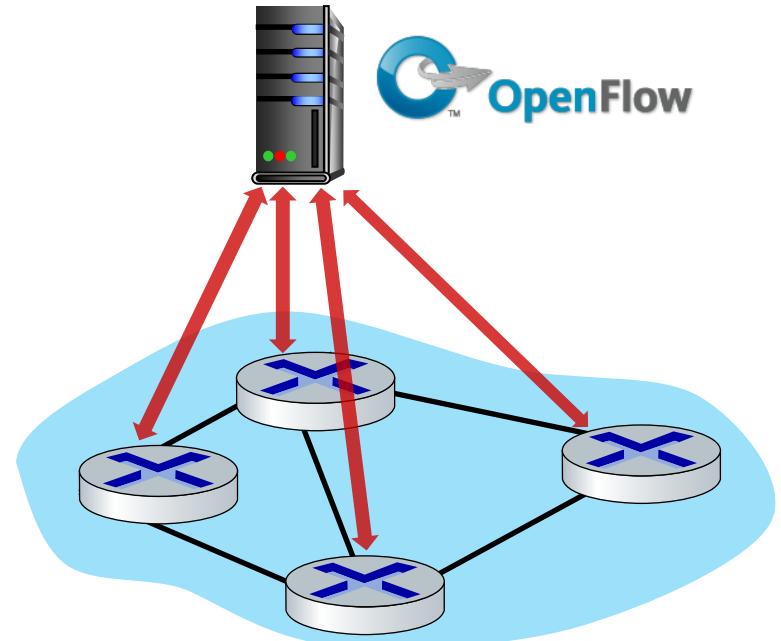


OpenFlow: controller-to-switch messages

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

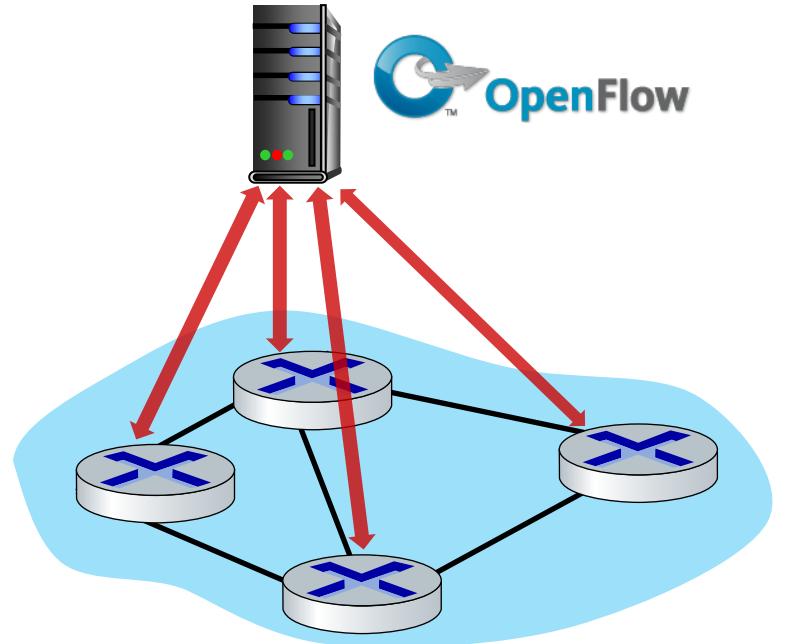


OpenFlow: switch-to-controller messages

Key switch-to-controller messages

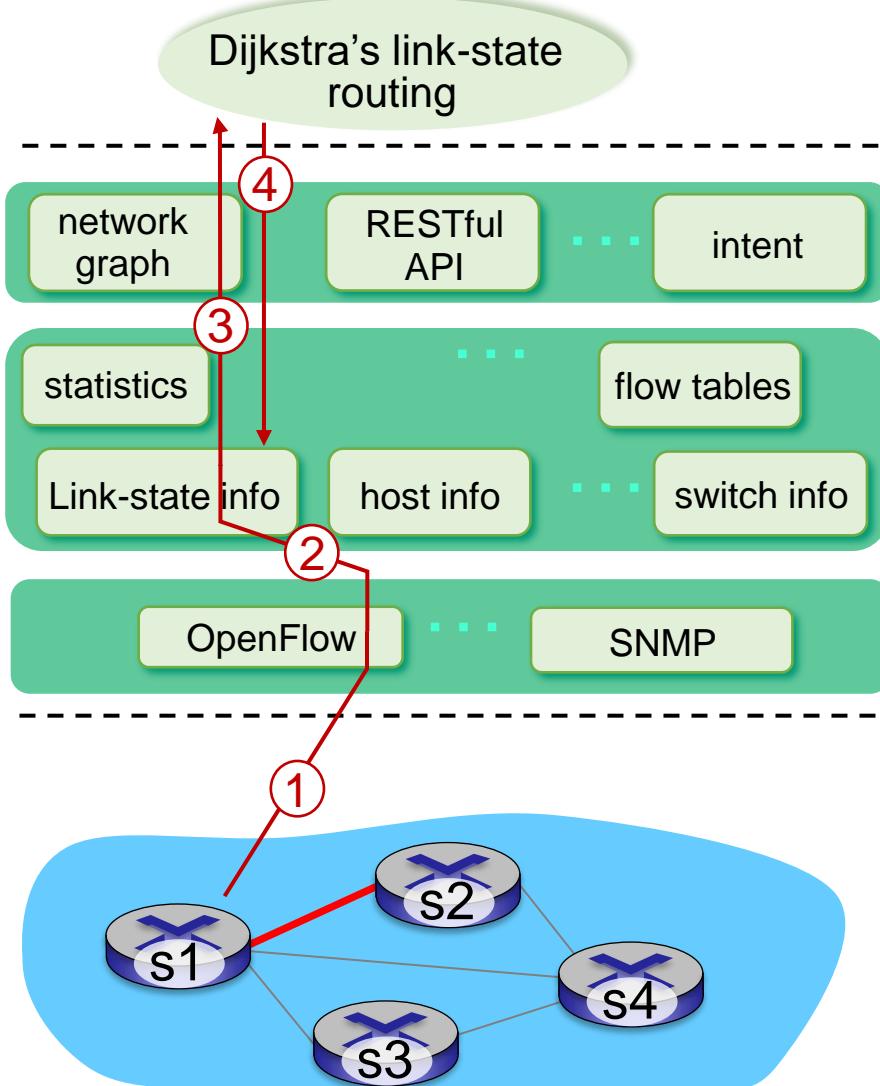
- *packet-in*: transfer packet (and its control) to controller. See packet-out message from controller
- *flow-removed*: flow table entry deleted at switch
- *port status*: inform controller of a change on a port.

OpenFlow Controller



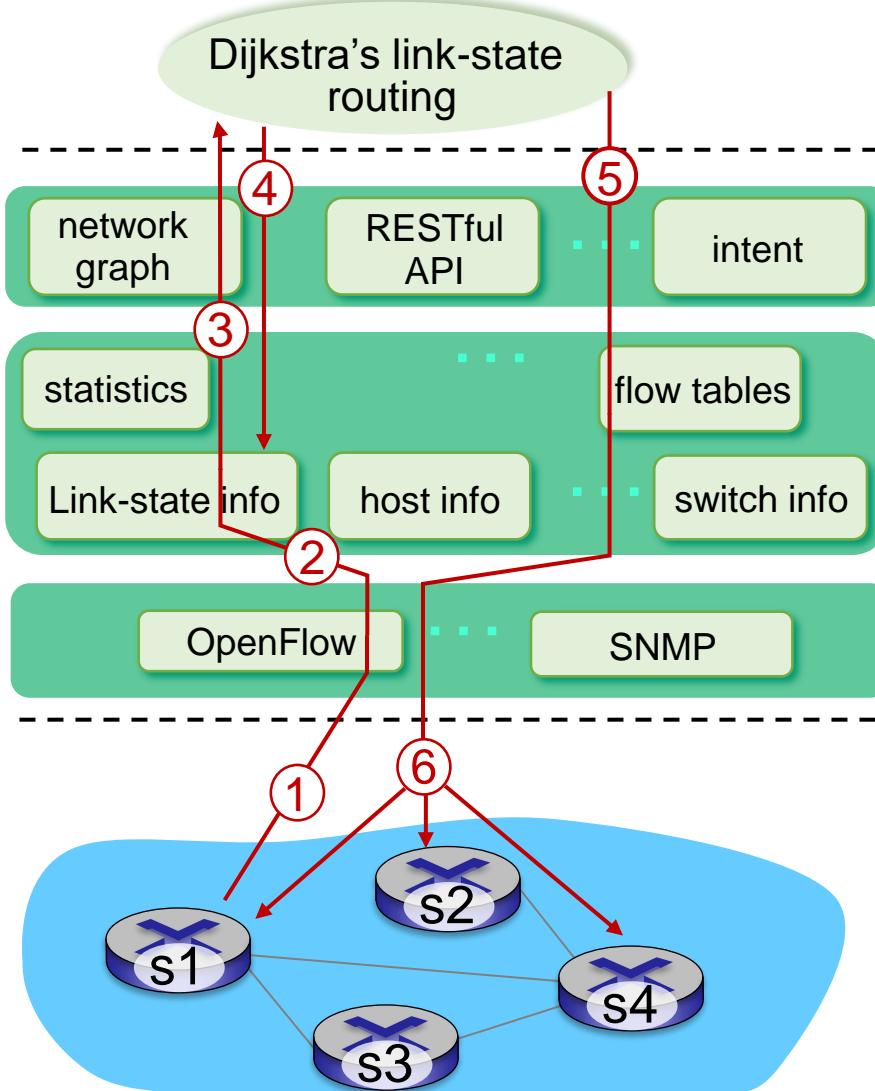
Fortunately, network operators don't "program" switches by creating/sending OpenFlow messages directly. Instead use ***higher-level abstraction at controller***

SDN: control/data plane interaction example



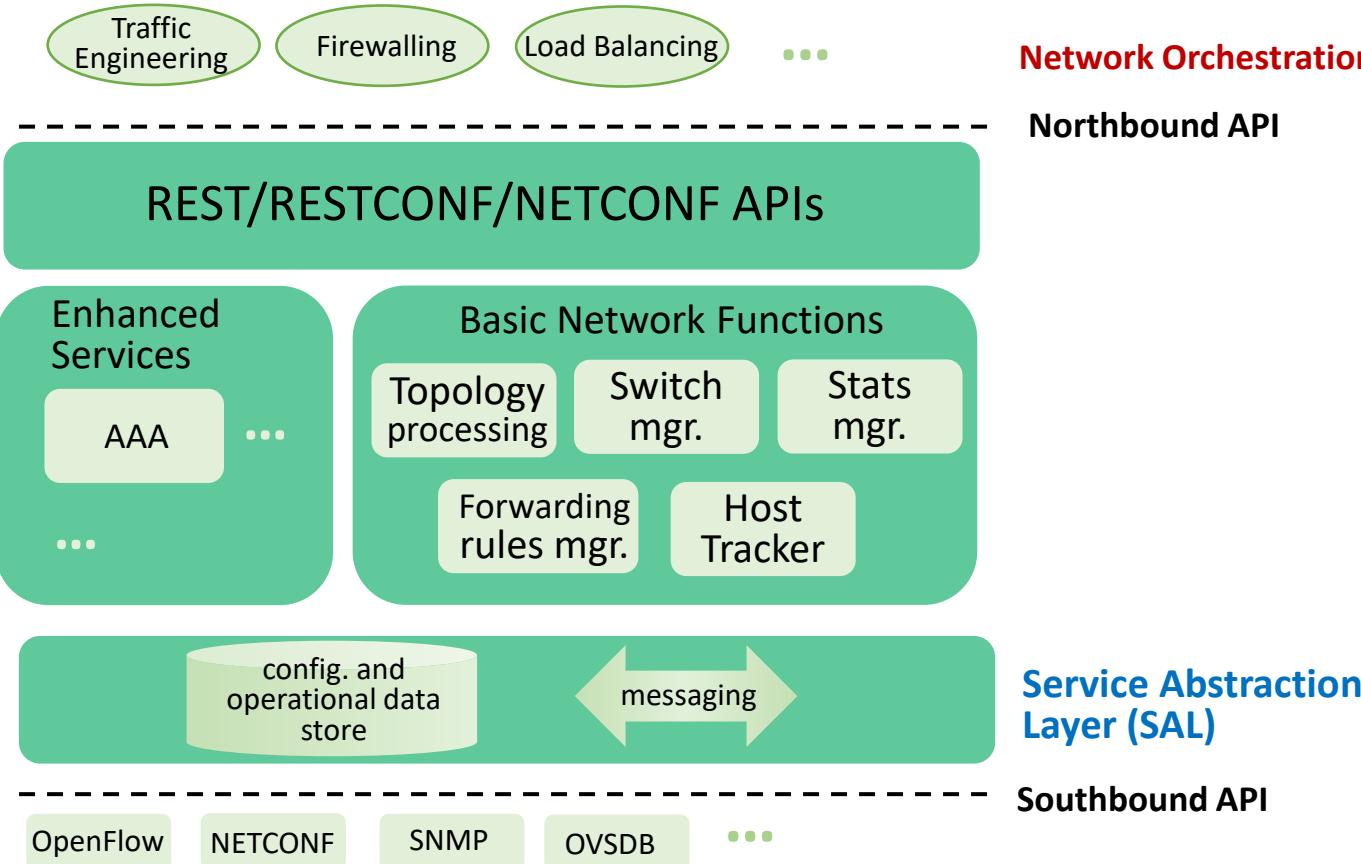
- ① **S1**, experiencing link failure uses OpenFlow *port status message* to notify controller
- ② **SDN controller** receives OpenFlow message, *updates link status info*
- ③ **Dijkstra's routing algorithm** application has previously registered to be called whenever link status changes. It is called.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

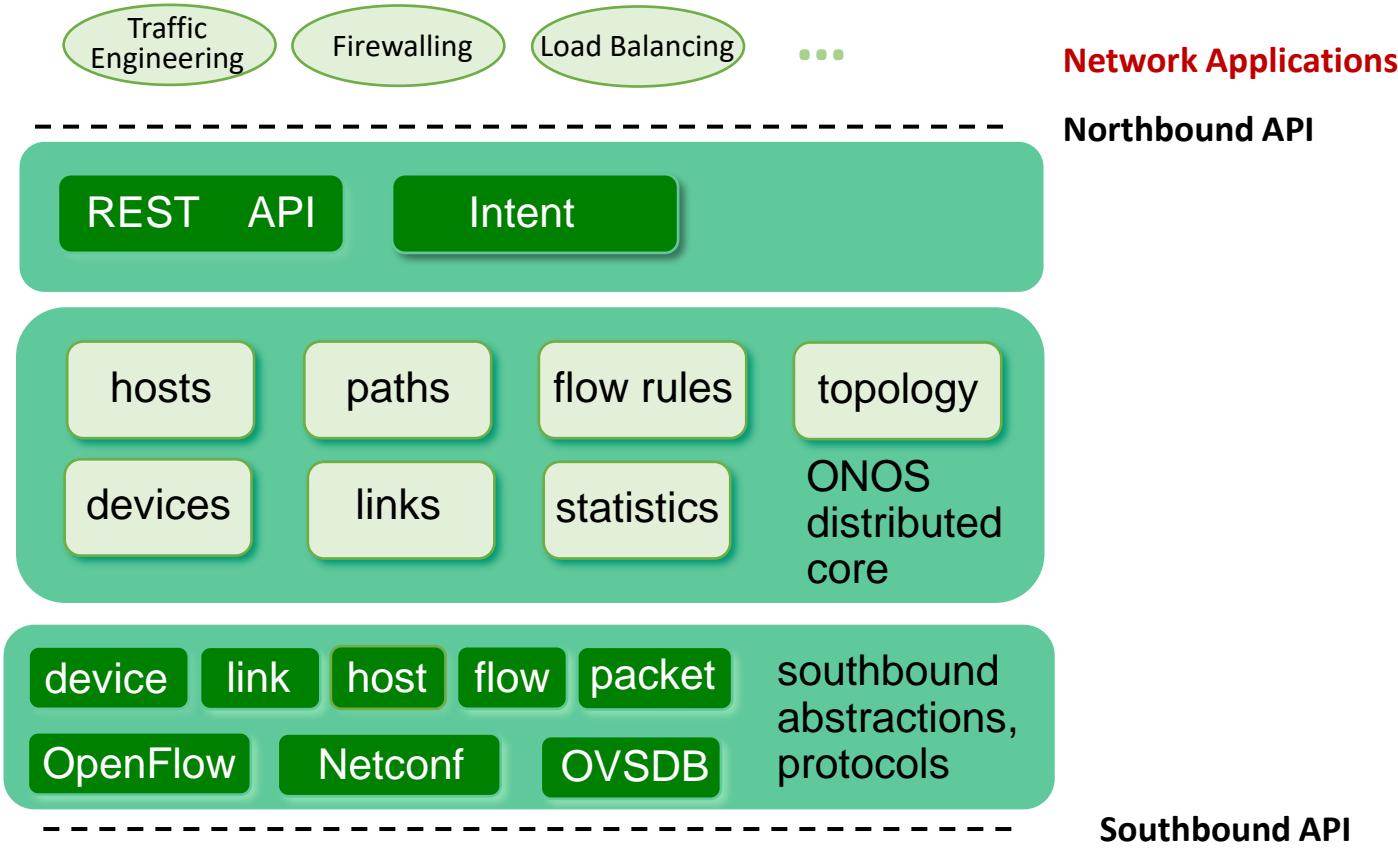
OpenDaylight (ODL) controller



Service Abstraction Layer:

- interconnects internal, external applications and services

ONOS 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

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*

SDN and the future of traditional network protocols

- *SDN-computed* versus *router-computed* forwarding tables:
 - just one example of *logically-centralized-computed* versus *protocol-computed*
- e.g., one could imagine *SDN-computed congestion control*:
 - controller sets sender rates based on router-reported (to controller) congestion levels



How will implementation of
network functionality (SDN
versus protocols) evolve?



Network layer: “control plane” roadmap

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



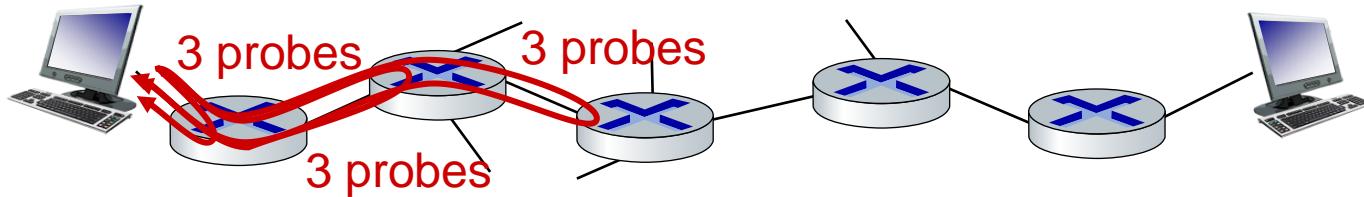
- network management, configuration
 - SNMP
 - NETCONF/YANG

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

Type	Code	description
0	0	echo reply (ping)
3	0	dest. network unreachable
3	1	dest host unreachable
3	2	dest protocol unreachable
3	3	dest port unreachable
3	6	dest network unknown
3	7	dest host unknown
4	0	source quench (congestion control - not used)
8	0	echo request (ping)
9	0	route advertisement
10	0	router discovery
11	0	TTL expired
12	0	bad IP header

Traceroute and ICMP



- *source* sends 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?

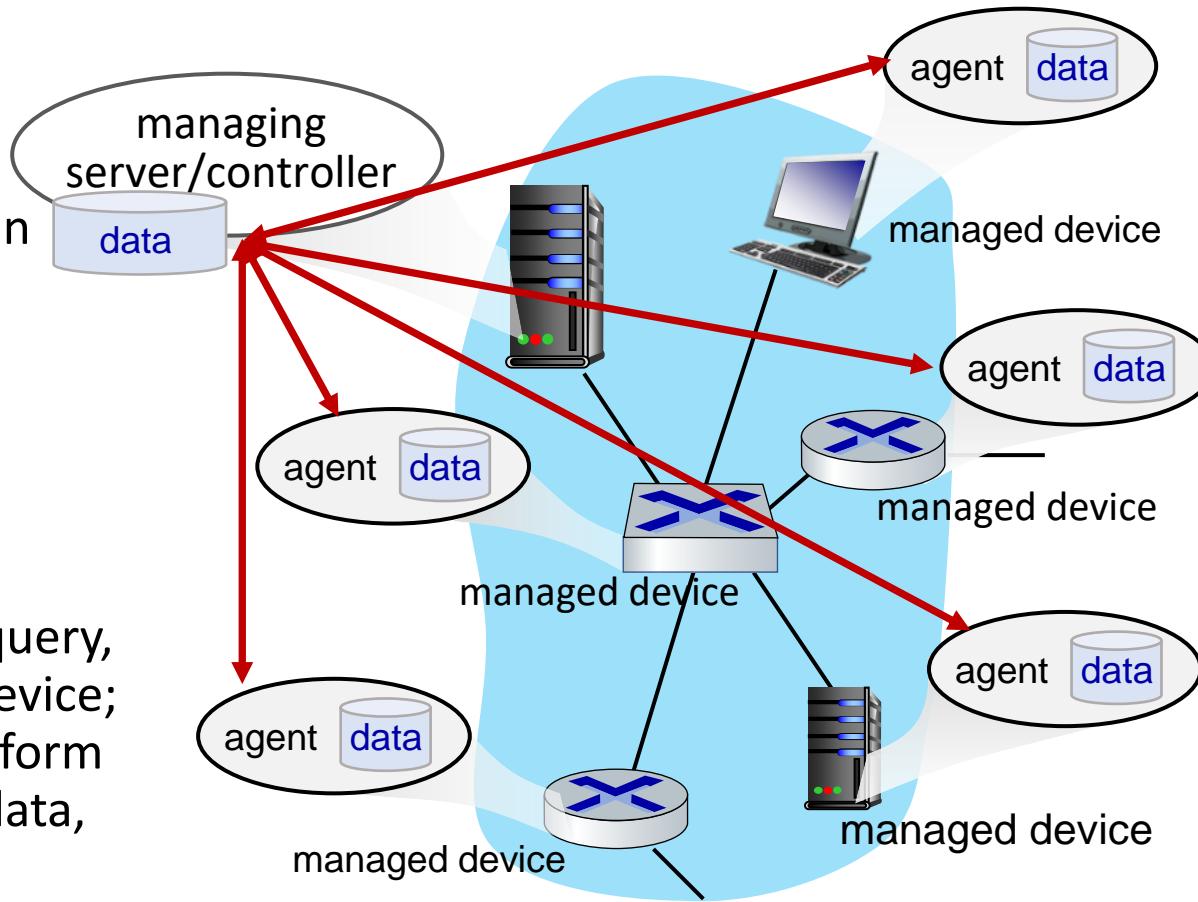


"Network management includes the deployment, integration and coordination of the hardware, software, and human elements to monitor, test, poll, configure, analyze, evaluate, and control the network and element resources to meet the real-time, operational performance, and Quality of Service requirements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

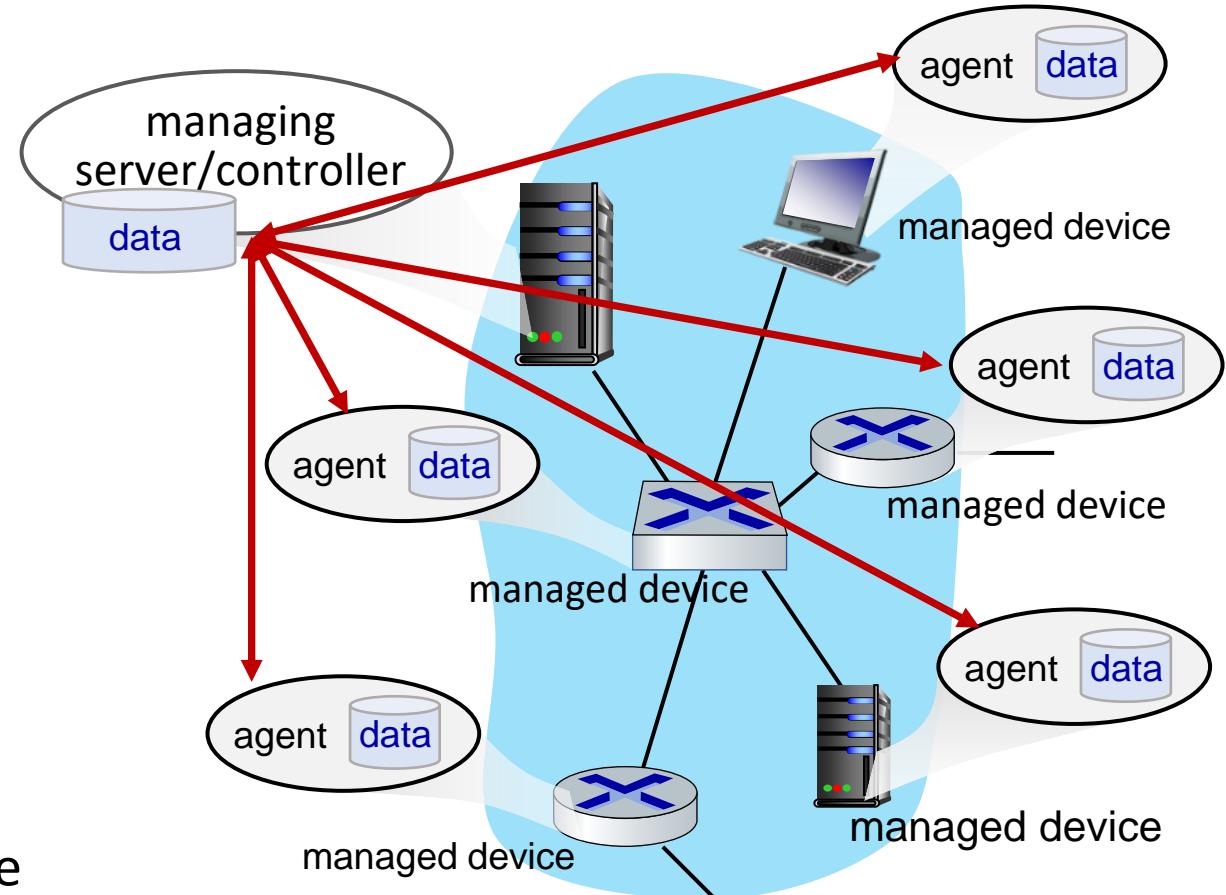
- operator issues (types, scripts) direct to individual devices (e.g., via ssh)

SNMP/MIB

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

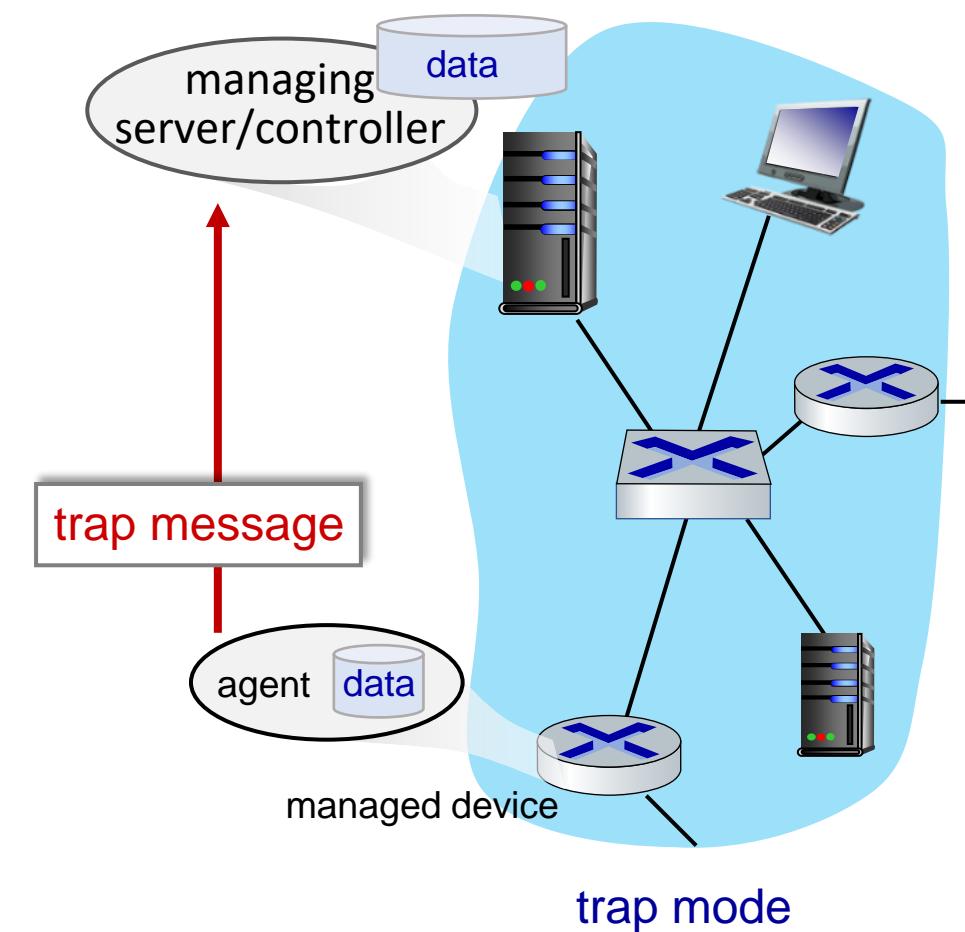
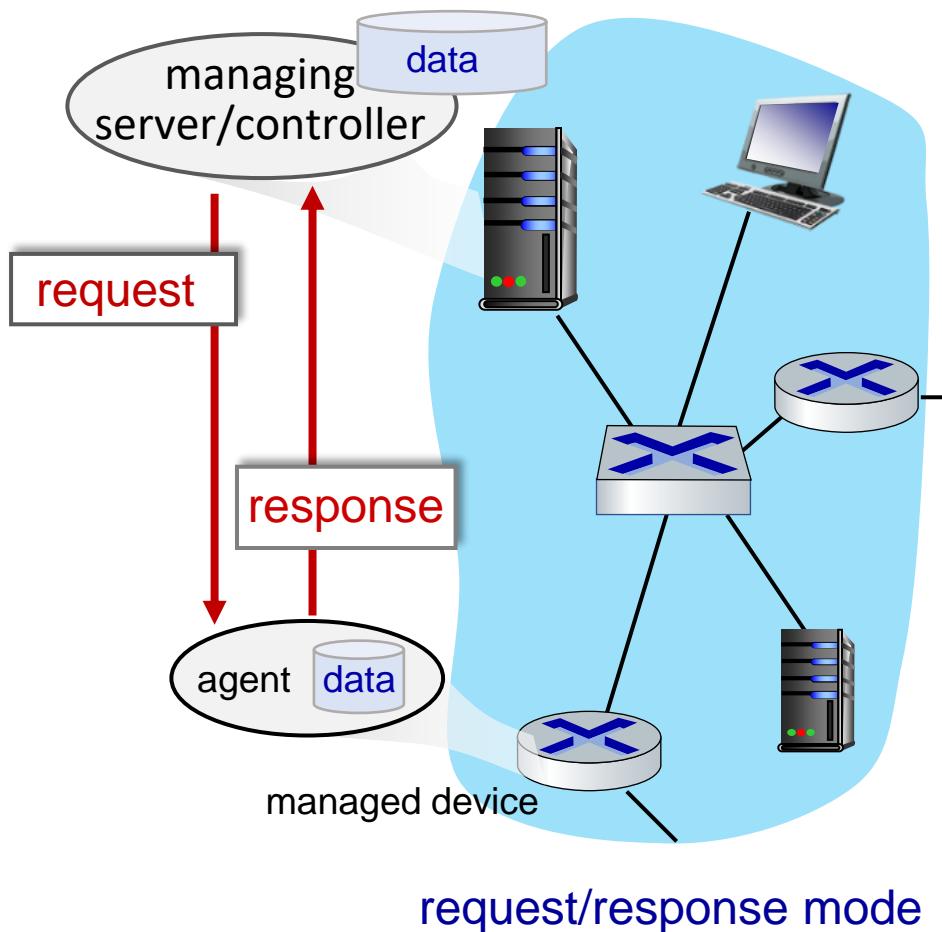
NETCONF/YANG

- 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

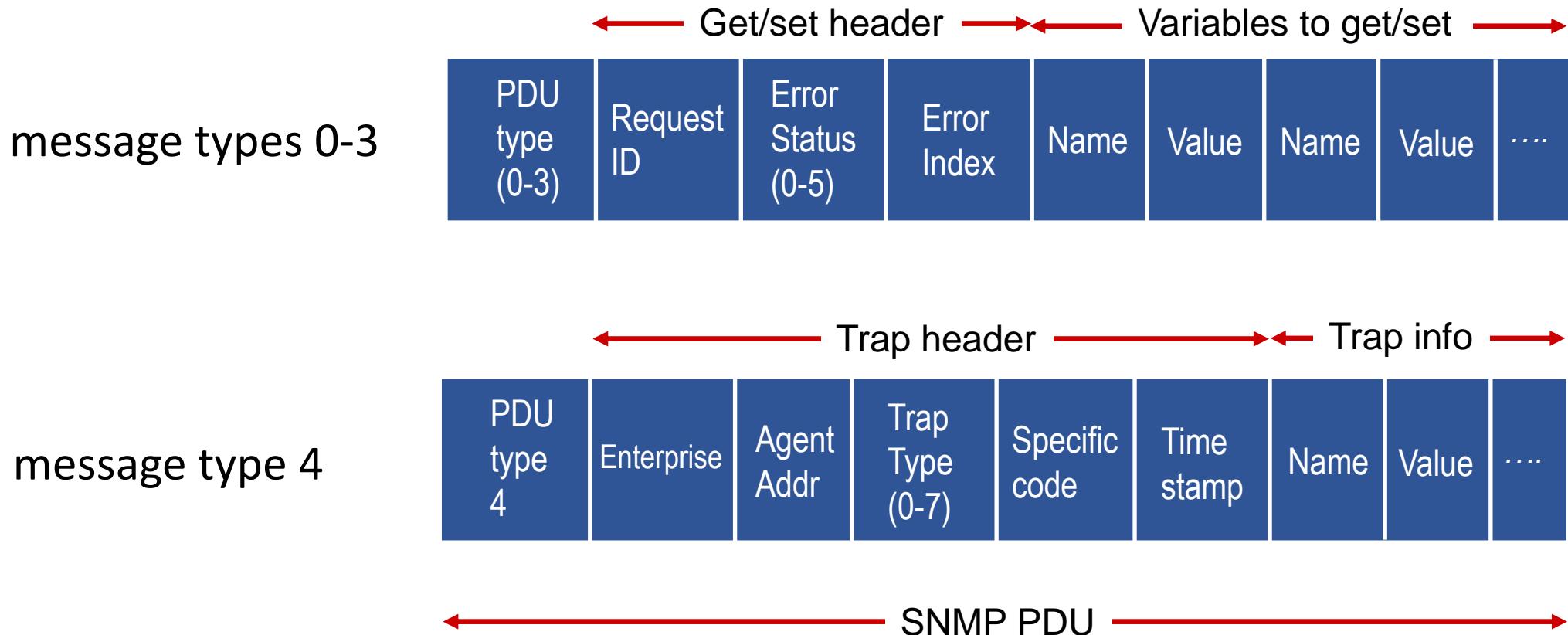
Two ways to convey MIB info, commands:



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 protocol: message formats



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:

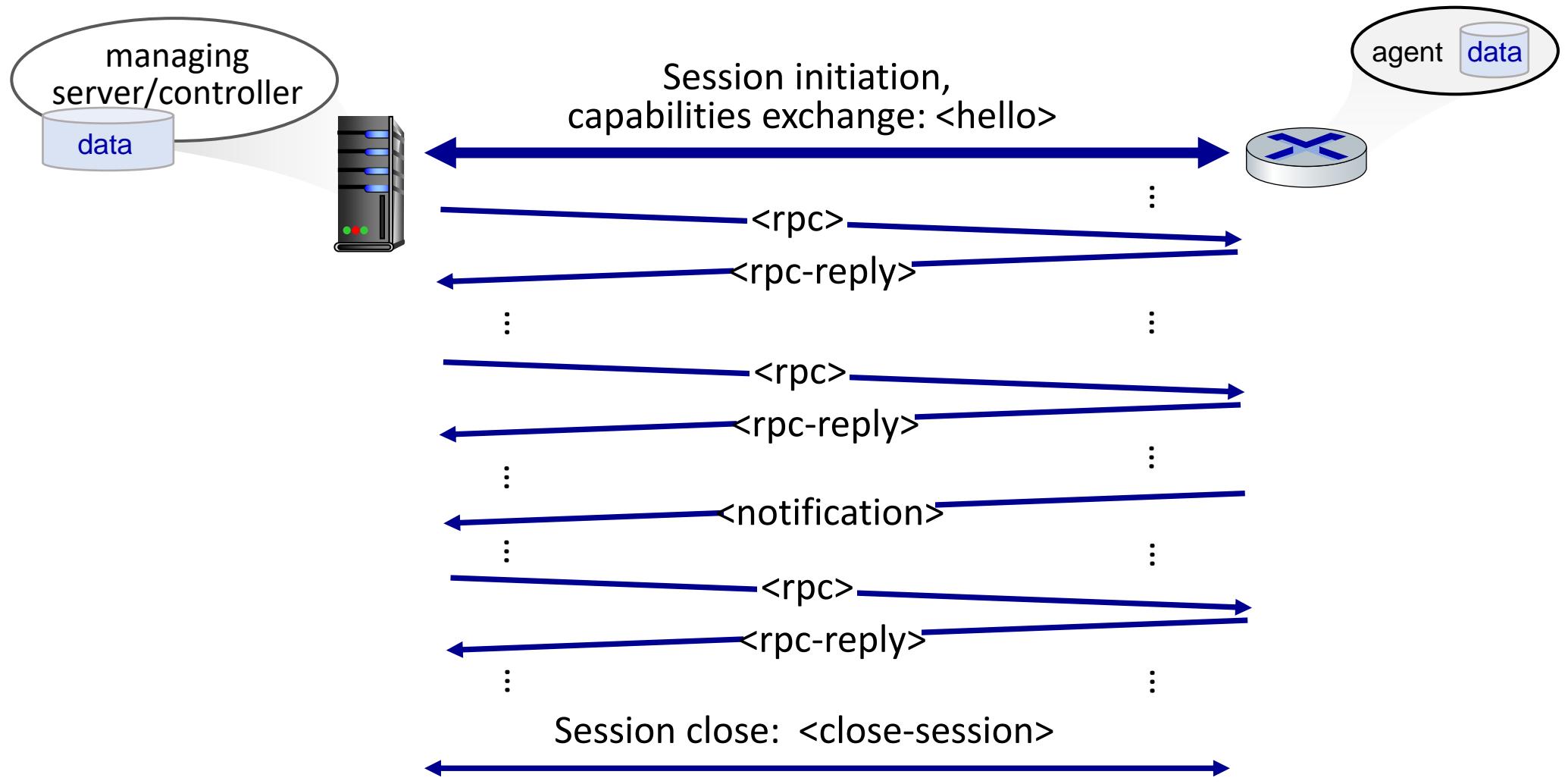


Object ID	Name	Type	Comments
1.3.6.1.2.1.7.1	UDPIInDatagrams	32-bit counter	total # datagrams delivered
1.3.6.1.2.1.7.2	UDPNoPorts	32-bit counter	# undeliverable datagrams (no application at port)
1.3.6.1.2.1.7.3	UDInErrors	32-bit counter	# undeliverable datagrams (all other reasons)
1.3.6.1.2.1.7.4	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

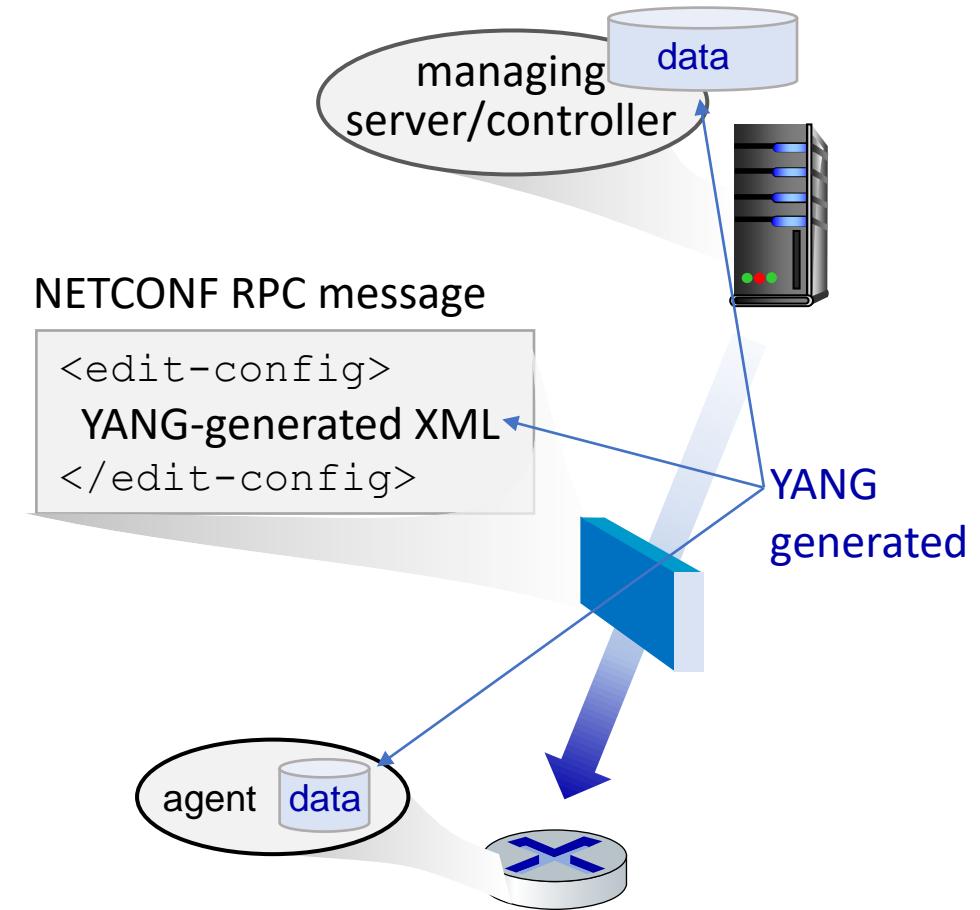
NETCONF	Operation Description
<get-config>	Retrieve all or part of a given configuration. A device may have multiple configurations.
<get>	Retrieve all or part of both configuration state and operational state data.
<edit-config>	Change specified (possibly running) configuration at managed device. Managed 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



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
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- network management, configuration
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Additional Chapter 5 slides

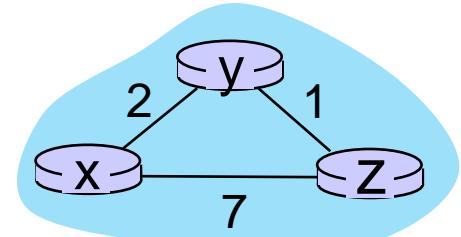
Distance vector: another example

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

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

$$\begin{aligned}D_x(z) &= \min\{c_{x,y} + D_y(z), c_{x,z} + D_z(z)\} \\&= \min\{2+1, 7+0\} = 3\end{aligned}$$

$$\begin{aligned}D_x(y) &= \min\{c_{x,y} + D_y(y), c_{x,z} + D_z(y)\} \\&= \min\{2+0, 7+1\} = 2\end{aligned}$$



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

time

Distance vector: another example

