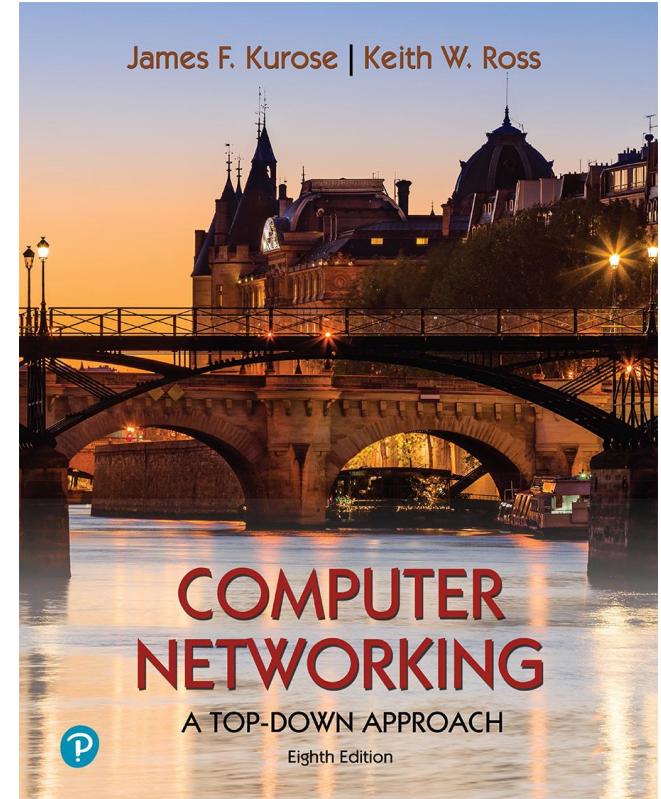


# Chapter 5

## Network Layer: Control Plane



*Computer Networking: A  
Top-Down Approach*  
8<sup>th</sup> 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
    - optimal path connection between ISP infrastructure, determine path from 1 isp infras to another infras
  - 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:

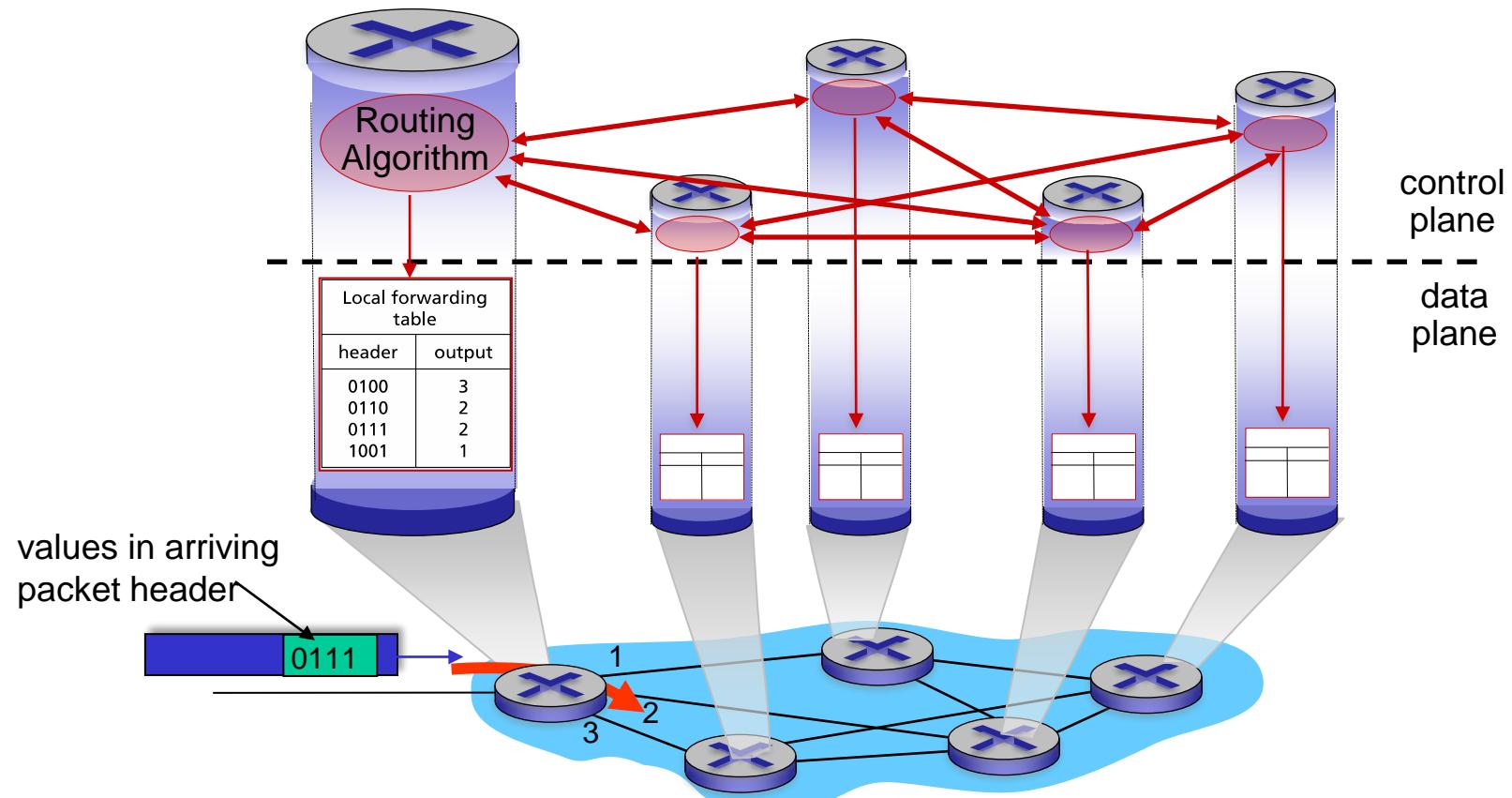
- per-router control (traditional)      router control
- logically centralized control (software defined networking)

controller control (centralize controller)

# Per-router control plane

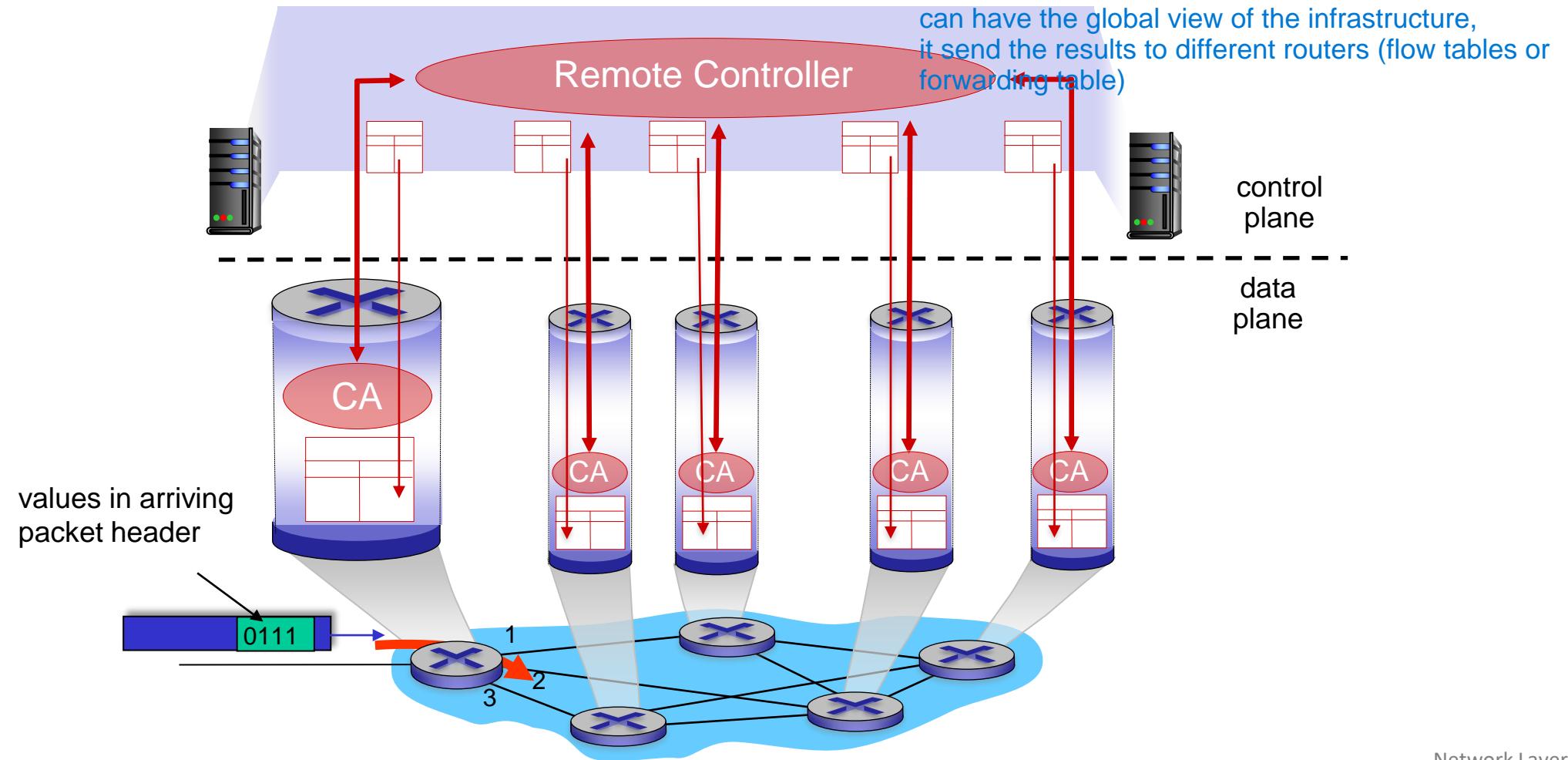
router implement both forwarding and routing

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

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



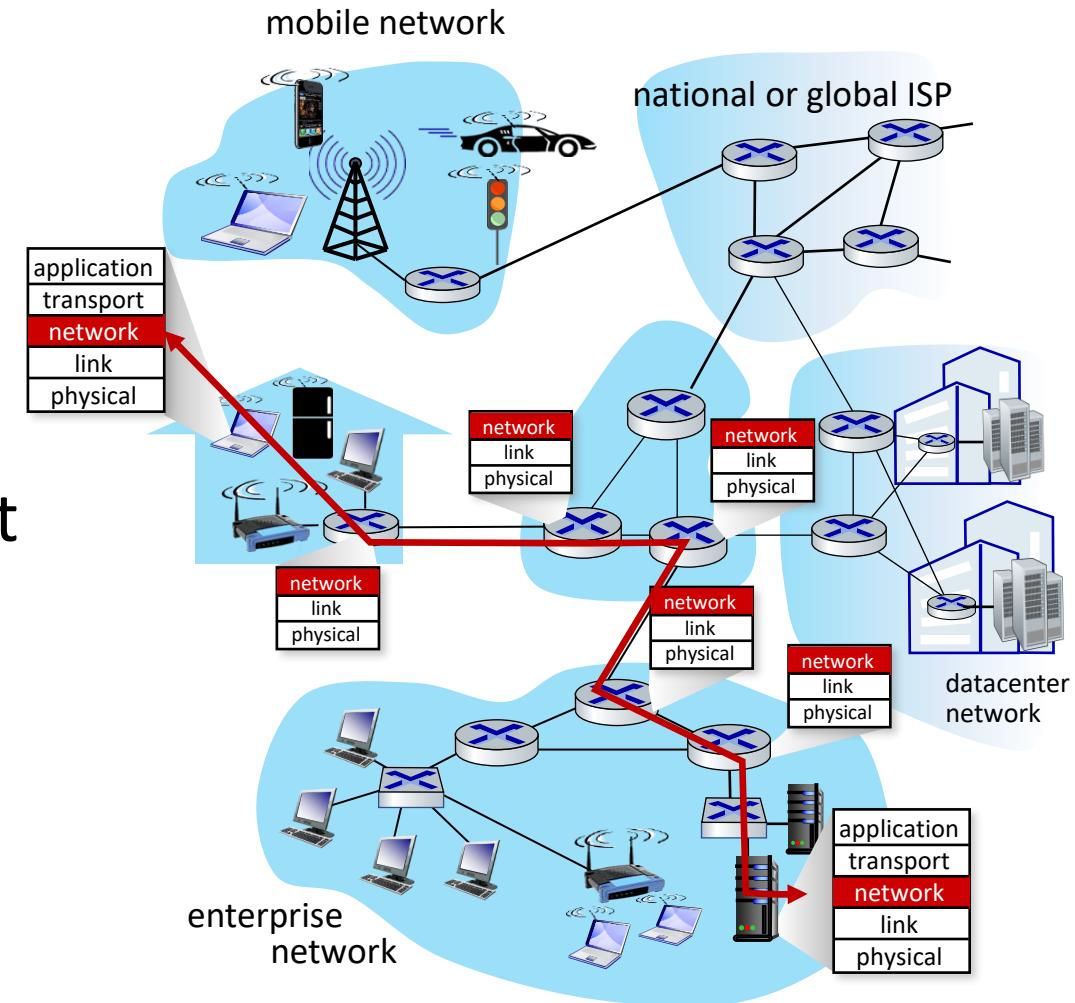
- network management, configuration
  - SNMP
  - NETCONF/YANG

# Routing protocols

routing algo is the algo which input are all information..., using routing protocols , output is the path, the router need the fowarding table, so the output must be transfer to the forwrding table

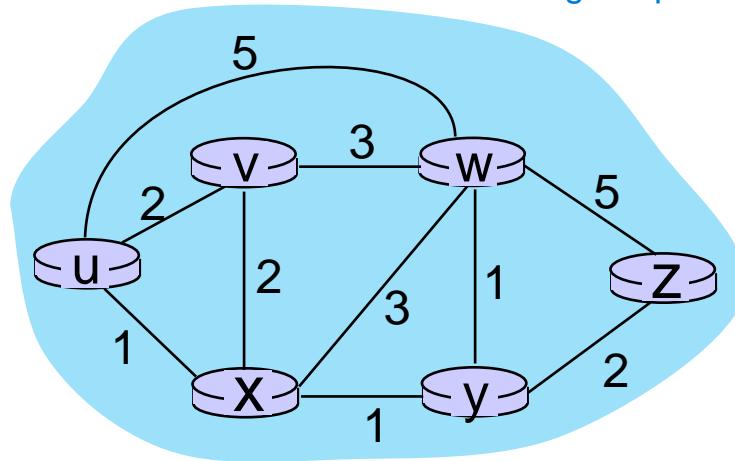
**Routing protocol goal:** determine “good” paths (equivalently, routes), from sending hosts to receiving host, through network of routers

- **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

good path : it can be the good interm of delay, distance or bandwidth



$c_{a,b}$ : 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:  $G = (N, E)$

nowadays, the link is very fast, \ -> we just "hop count": count number of the router

$N$ : 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

How fast  
do routes  
change?

**static:** routes change  
slowly over time

fix the path from 1 router to another router  
the determination is very fast,  
can be used for some network like  
homenetwork: we have just 1  
router at home , and this router has only 1 link to  
the isp -> routing is very expensive  
-> we should use static

**global:** all routers have *complete*  
topology, link cost info

- “link state” algorithms

each time there is a change in state, it will recompute

**dynamic:** routes change  
more quickly

- periodic updates or in  
response to link cost  
changes

**decentralized:** iterative process of  
computation, exchange of info with neighbors

- routers initially only know link costs to  
attached neighbors
- “distance vector” algorithms

global or decentralized information?

# Network layer: “control plane” roadmap

- introduction
- routing protocols
  - link state
  - distance vector
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# Dijkstra's link-state routing algorithm

find path with least hop in the graph

- 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  $\rightarrow$  cost
- $D(v)$ : 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:

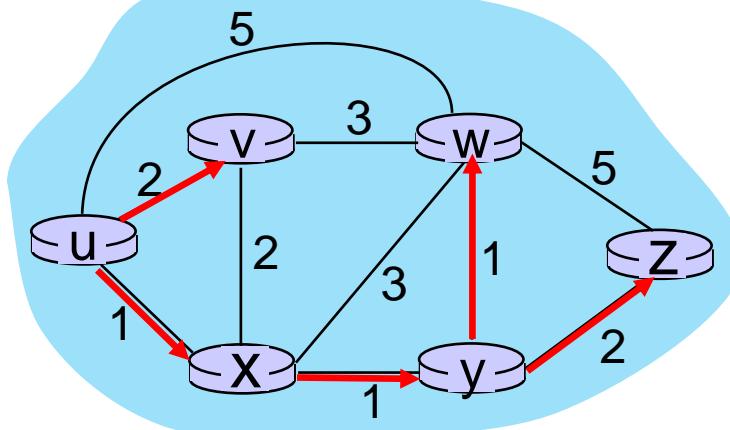
```
2  $N' = \{u\}$                                 /* compute least cost path from u to all other nodes */  
3 for all nodes  $v$   
4   if  $v$  adjacent to  $u$                   /*  $u$  initially knows direct-path-cost only to direct neighbors */  
5     then  $D(v) = c_{u,v}$                 /*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

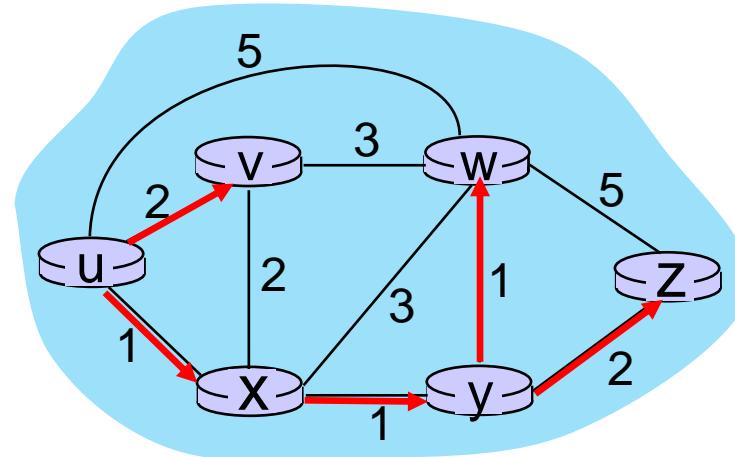


Initialization (step 0): For all  $a$ : if  $a$  adjacent to  $u$  then  $D(a) = c_{u,a}$

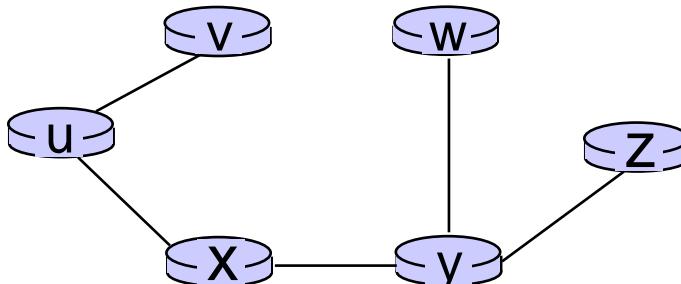
↓  
 find  $a$  not in  $N'$  such that  $D(a)$  is a minimum  
 add  $a$  to  $N'$   
 update  $D(b)$  for all  $b$  adjacent to  $a$  and not in  $N'$ :  

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

# Dijkstra's algorithm: an example



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



resulting *forwarding table* in u:

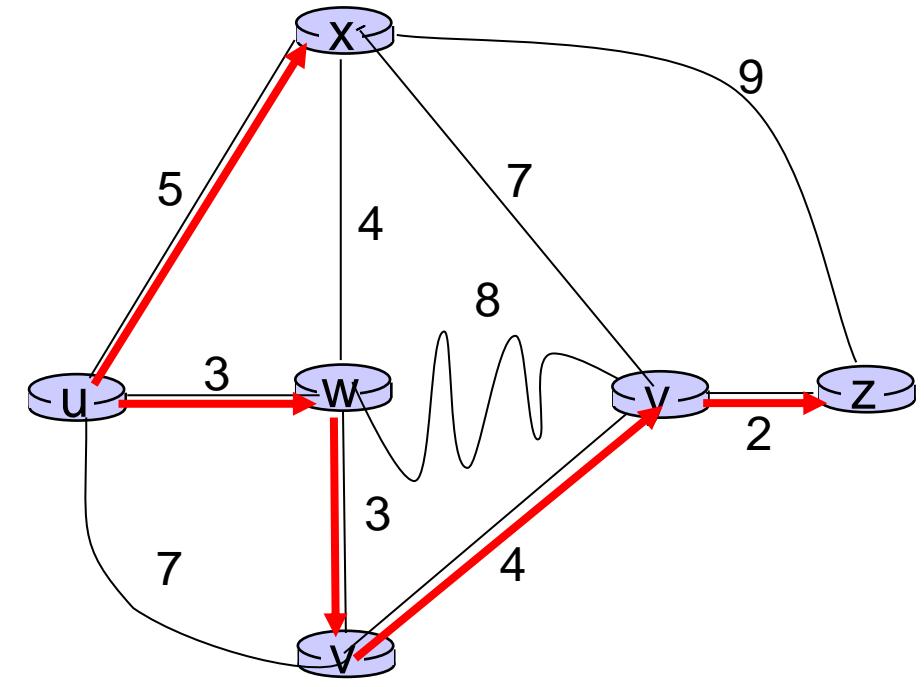
destination	outgoing link
v	(u,v)
x	(u,x)
y	(u,x)
w	(u,x)
z	(u,x)

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	$uw$	$7, u$	$3, u$	$5, u$	$\infty$	$\infty$
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

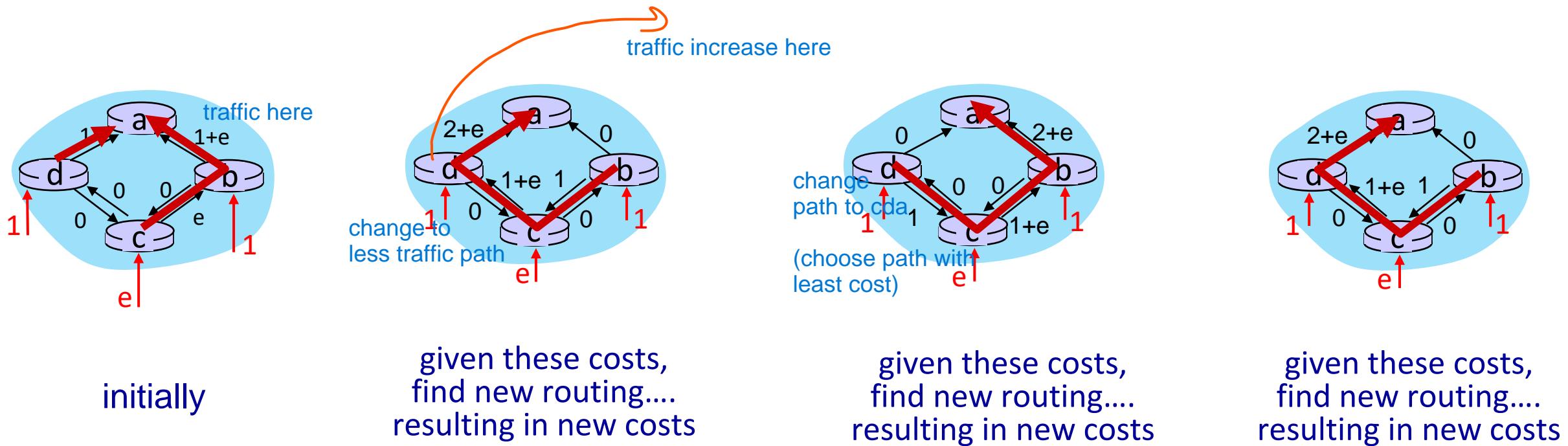
- each of  $n$  iteration: need to check all nodes,  $w$ , not in  $N$
- $n(n+1)/2$  comparisons:  $\underline{O(n^2)}$  complexity
- more efficient implementations possible:  $\cancel{O(n \log n)}$

## 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  
the metrics such as delay .... change over time
- 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*



# 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:

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

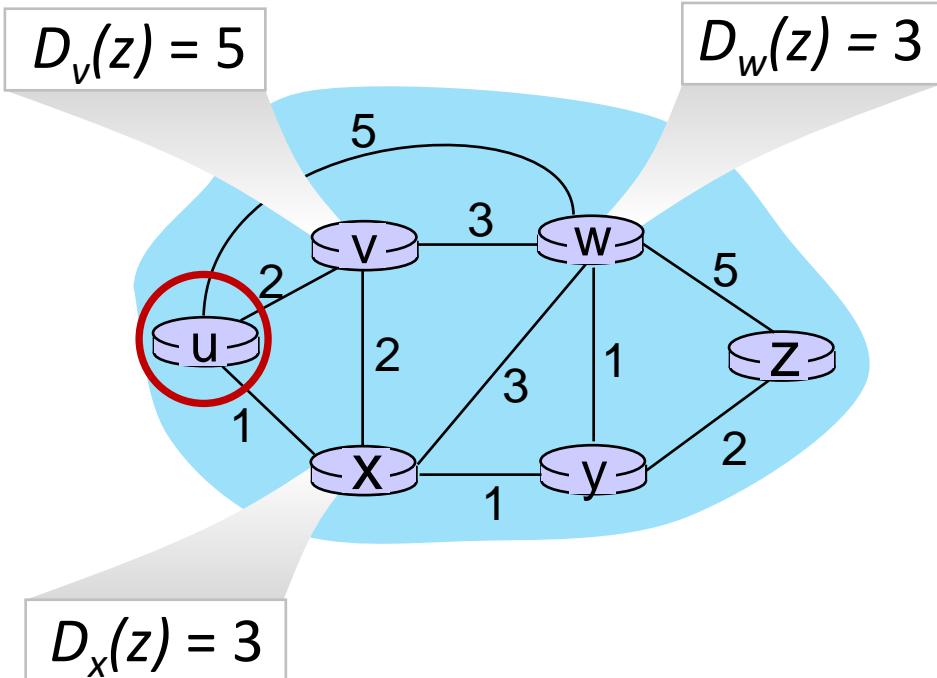
$\min$  taken over all neighbors  $v$  of  $x$

$v$ '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:

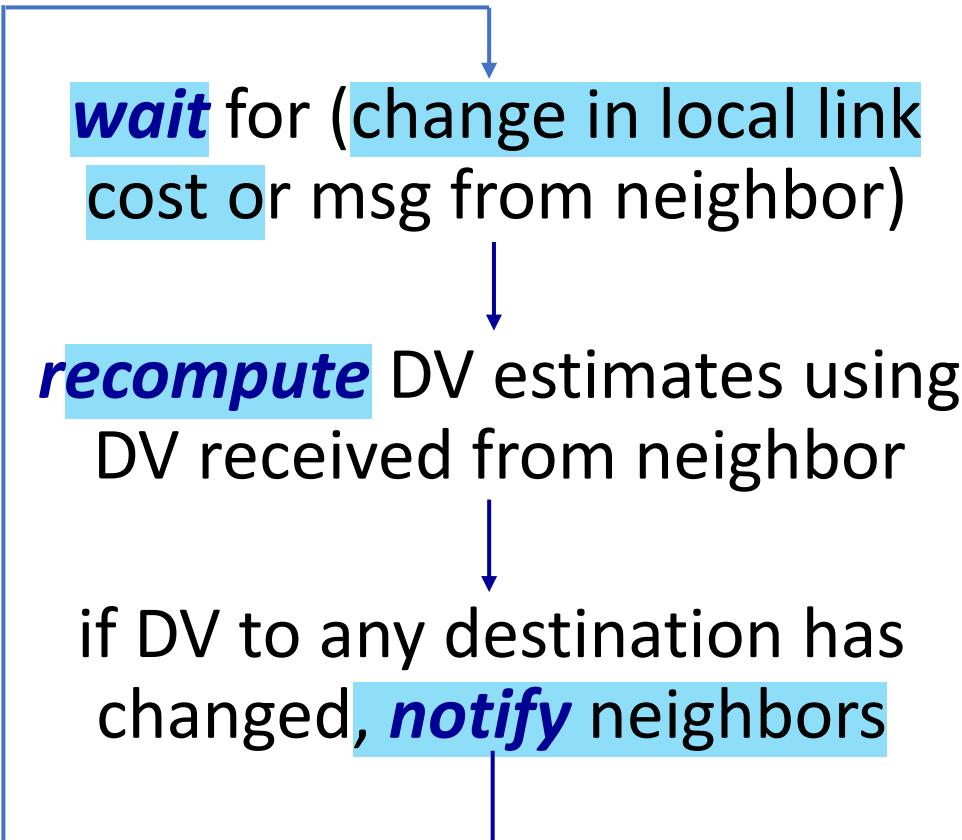
- from time-to-time, each node *sends* its own *distance vector estimate* to neighbors
- when  $x$  *receives* new DV estimate from any neighbor, it updates its own DV using B-F equation:

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

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

# Distance vector algorithm:

each node:



**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!

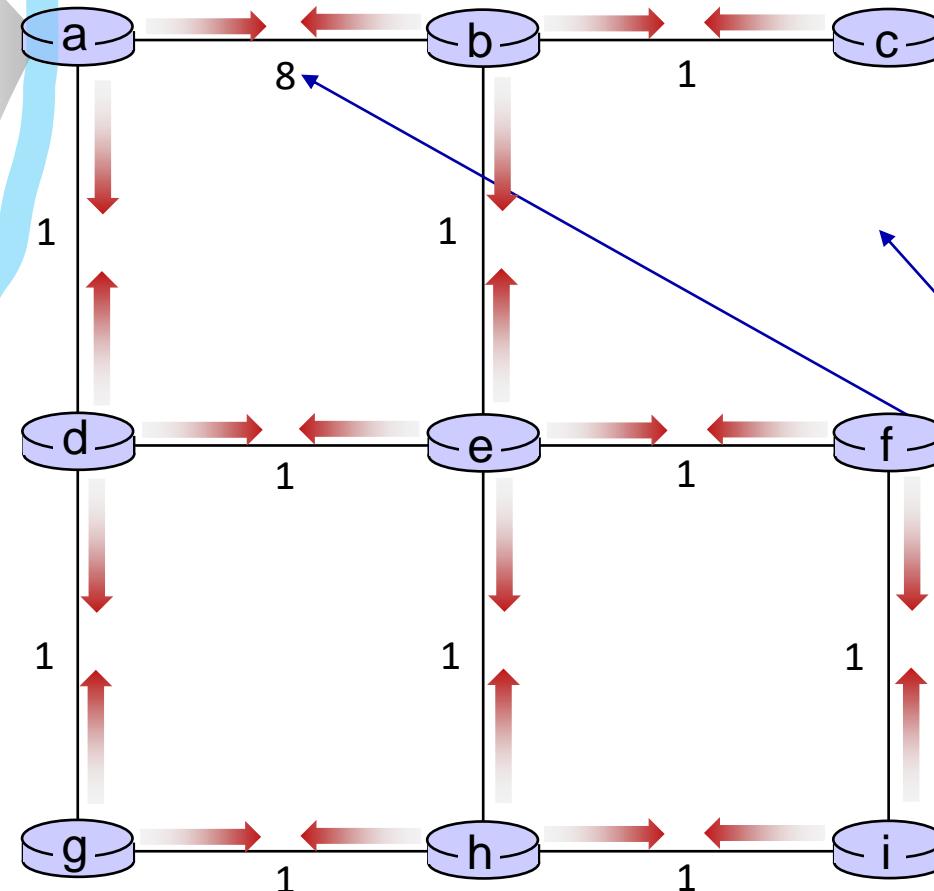
# Distance vector: example



$t=0$

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

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



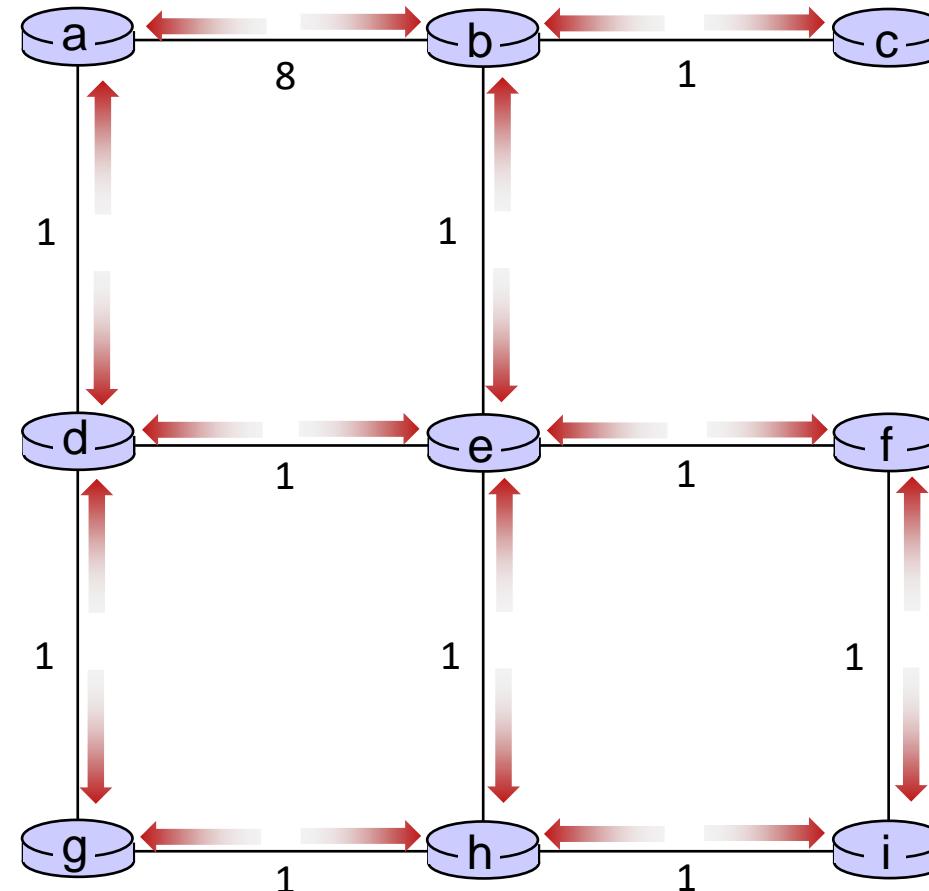
# Distance vector example: iteration



$t=1$

All nodes:

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



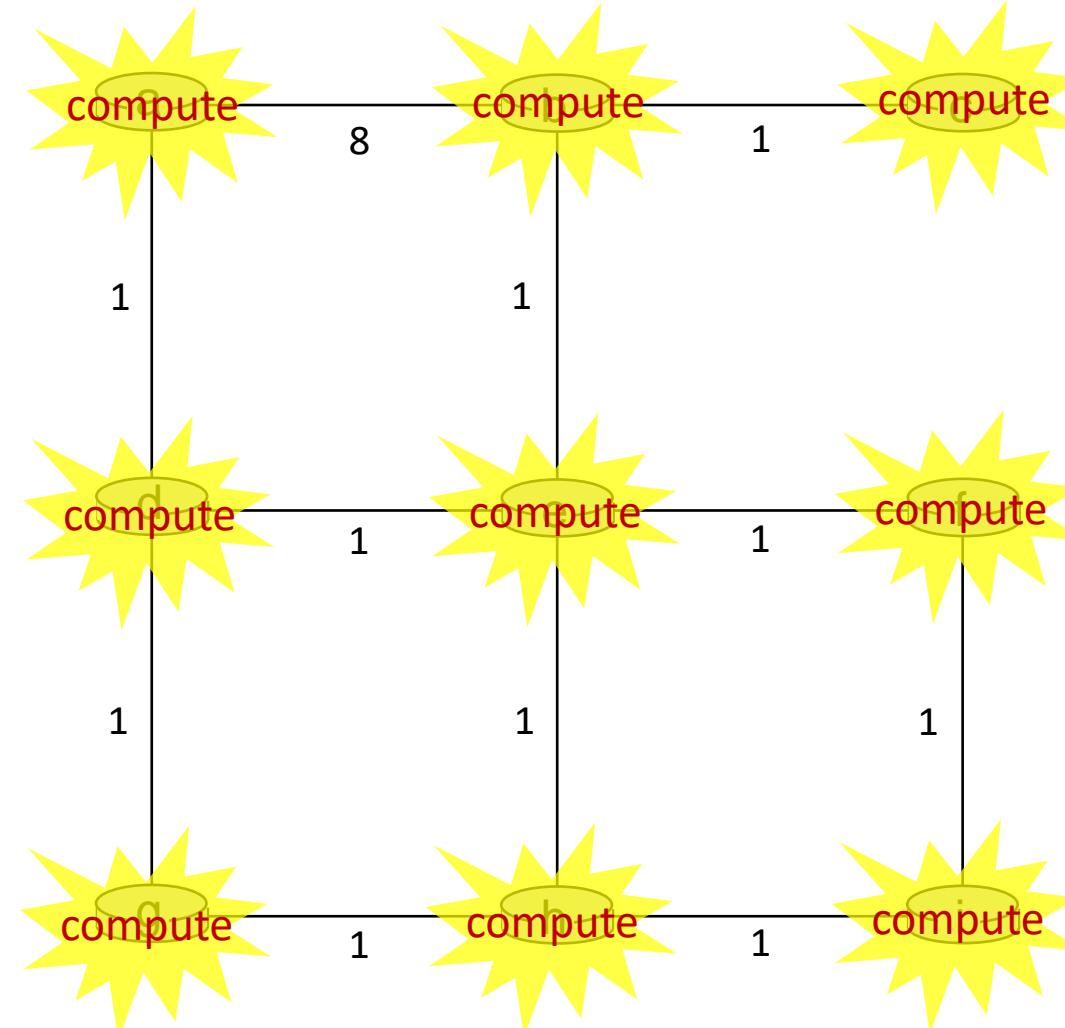
# Distance vector example: iteration



$t=1$

All nodes:

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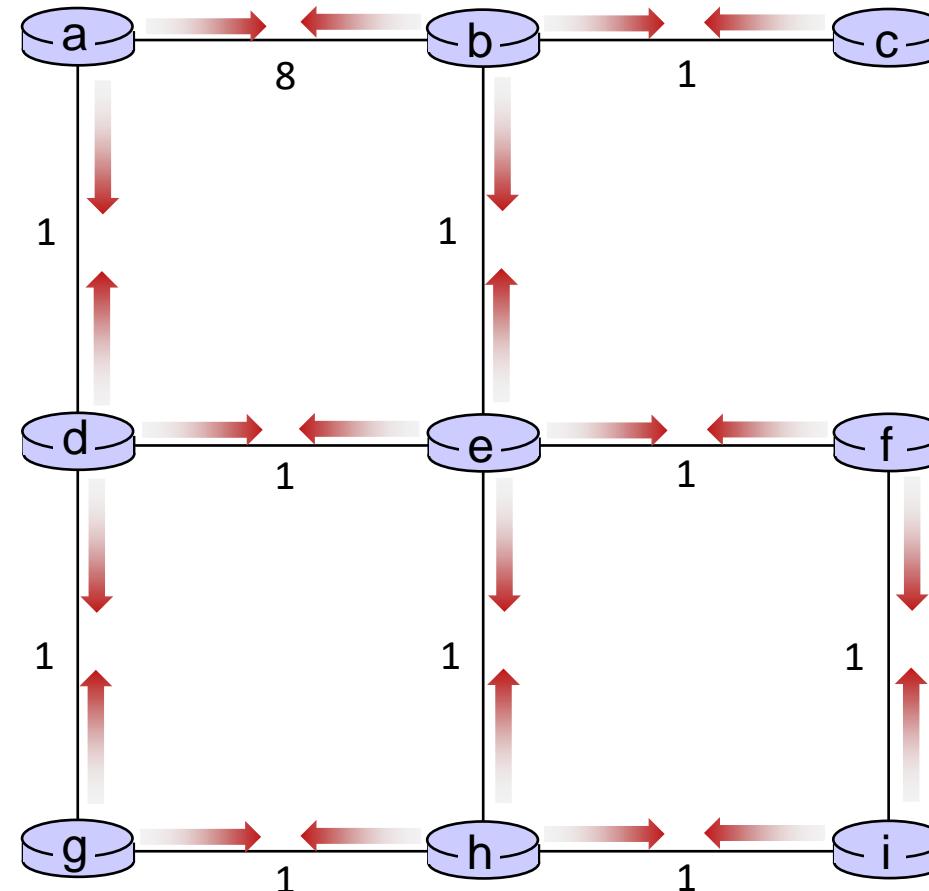
# Distance vector example: iteration



$t=1$

All nodes:

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



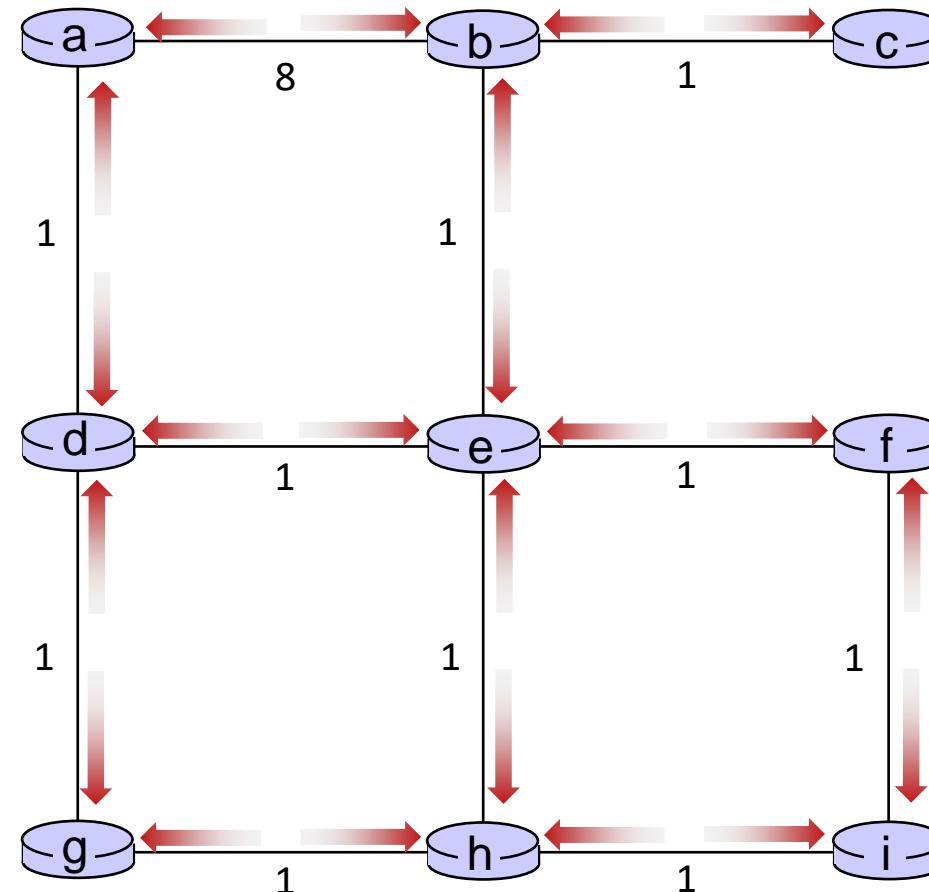
# Distance vector example: iteration



$t=2$

All nodes:

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



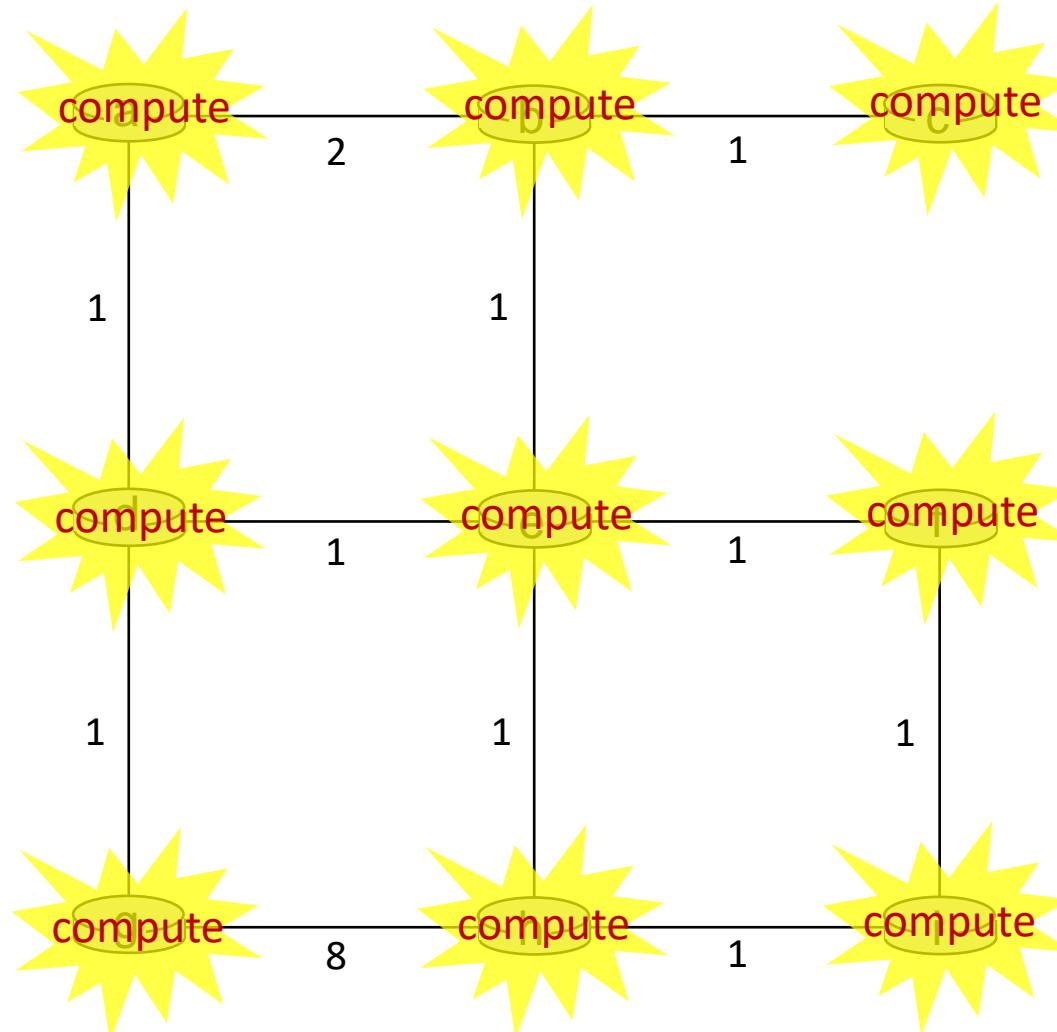
# Distance vector example: iteration



$t=2$

All nodes:

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



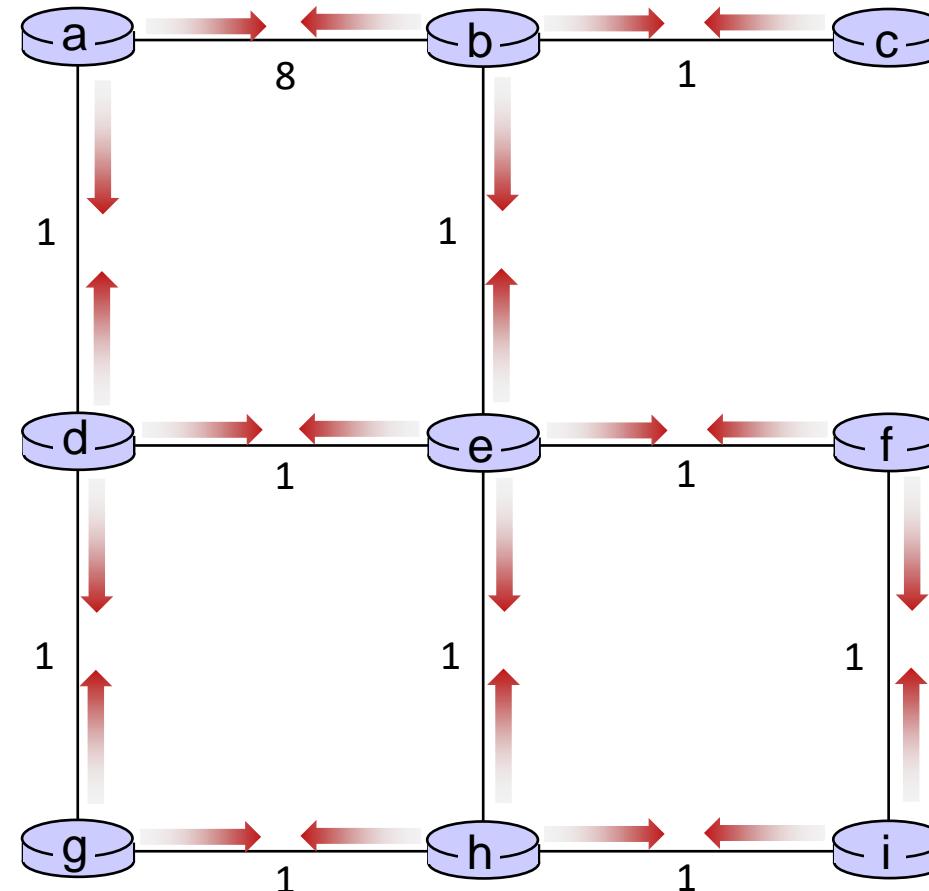
# Distance vector example: iteration



$t=2$

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

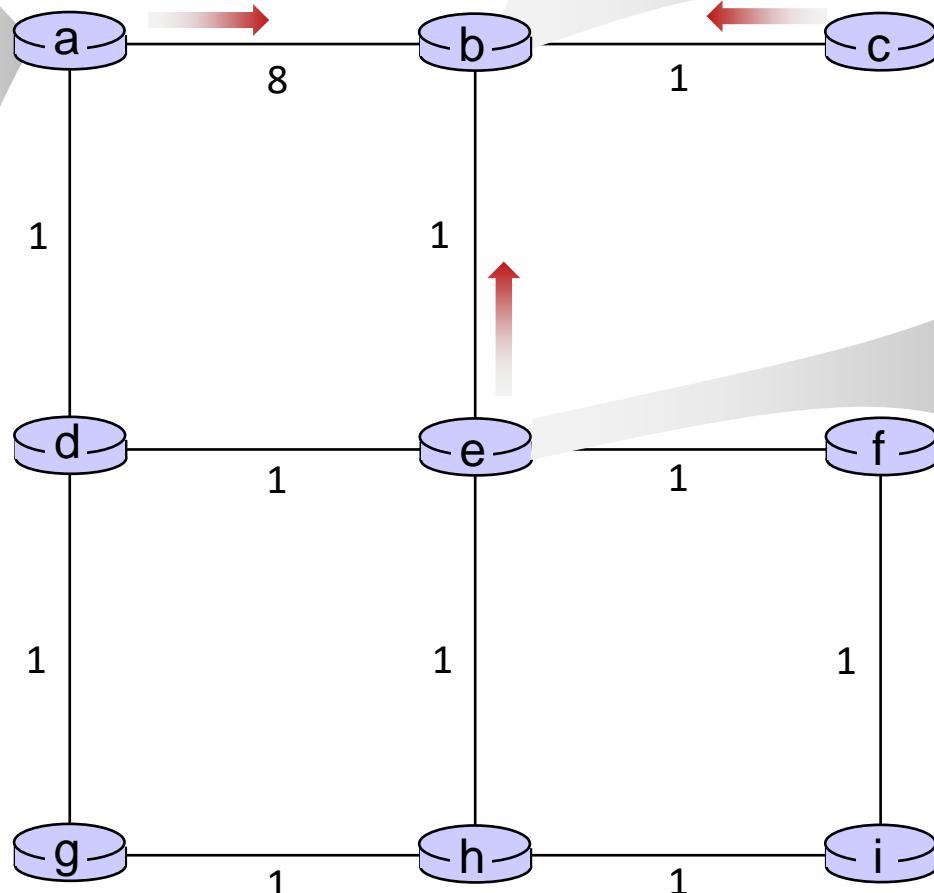
Let's next take a look at the *iterative computations* at nodes

# 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

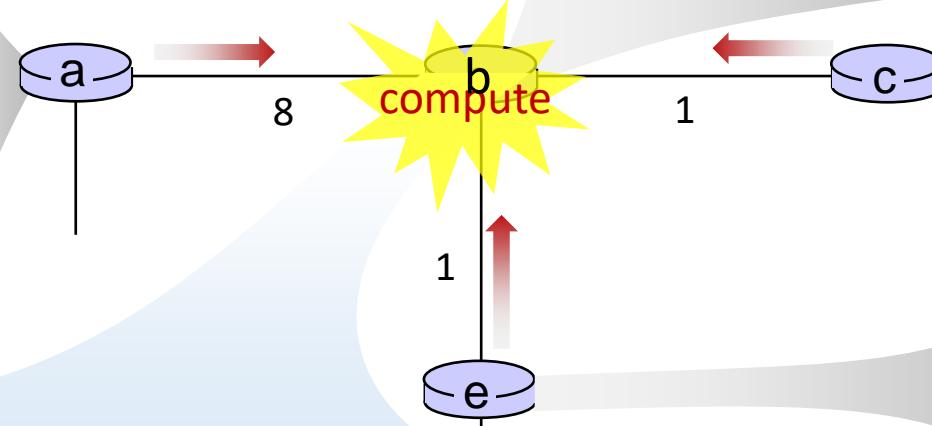


**t=1**

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

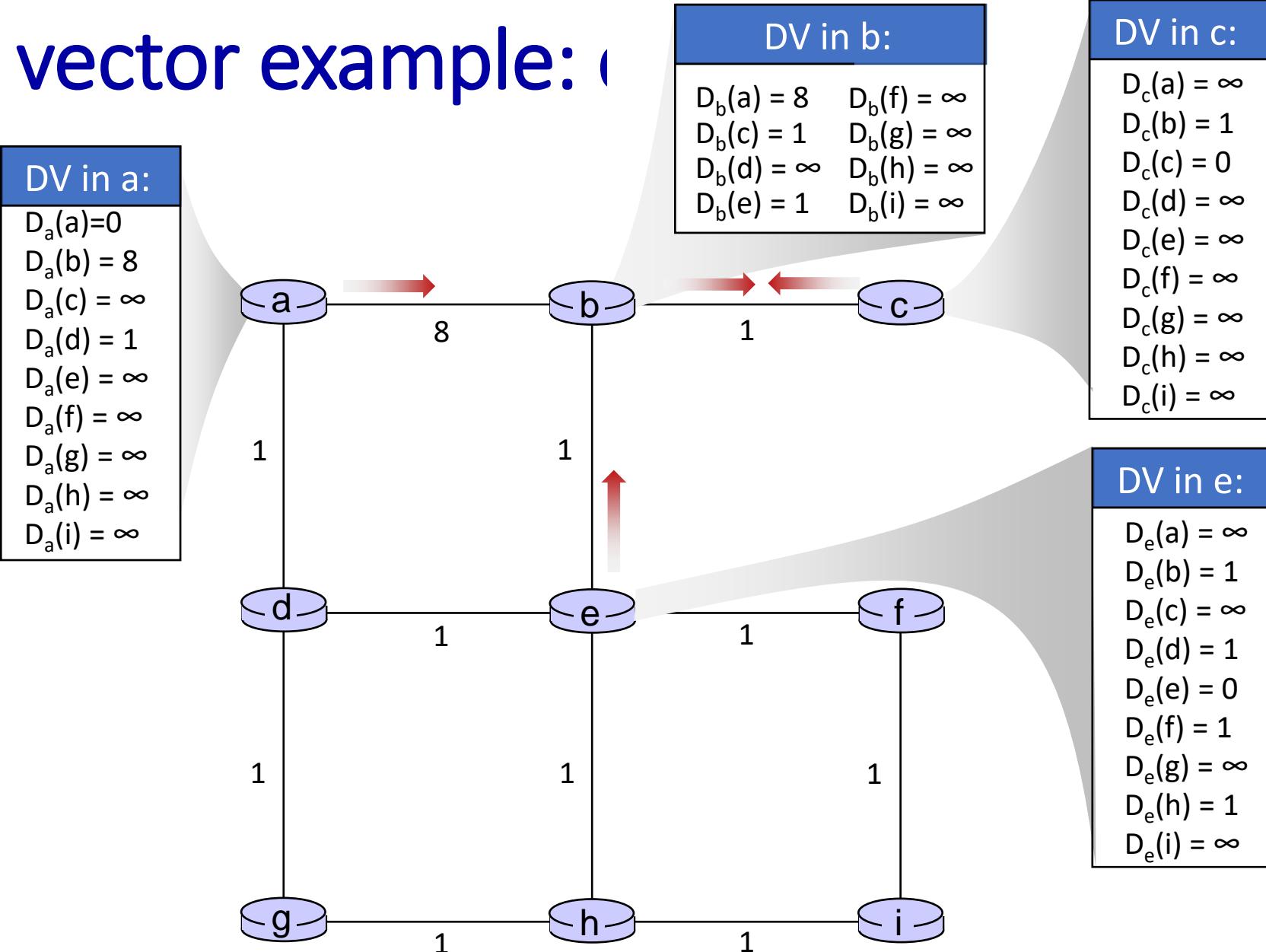
DV in b:	
$D_b(a) = 8$	$D_b(f) = 2$
$D_b(c) = 1$	$D_b(g) = \infty$
$D_b(d) = 2$	$D_b(h) = 2$
$D_b(e) = 1$	$D_b(i) = \infty$

# Distance vector example: t=1



**t=1**

- c receives DVs from b



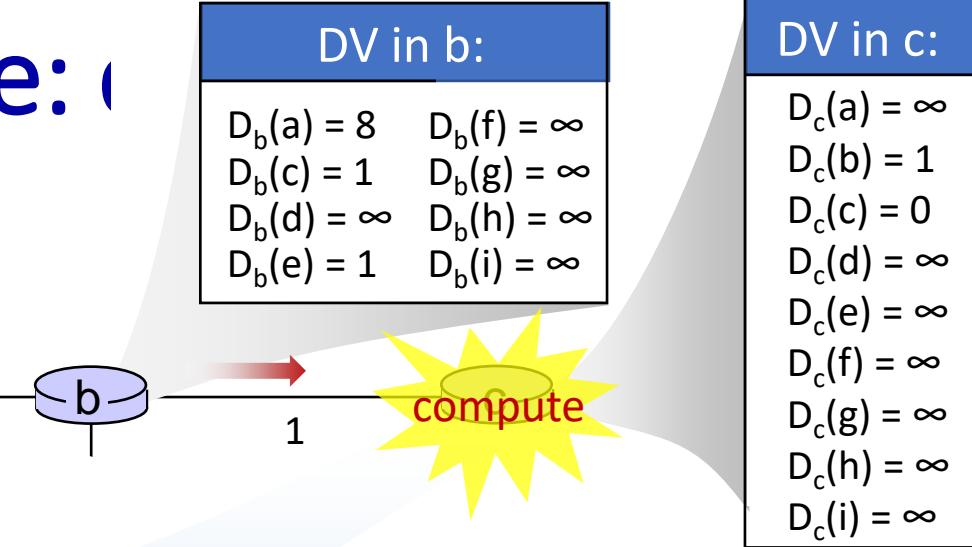
# Distance vector example: (t=1)



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/](http://gaia.cs.umass.edu/kurose_ross/interactive/)

# Distance vector example: t=1

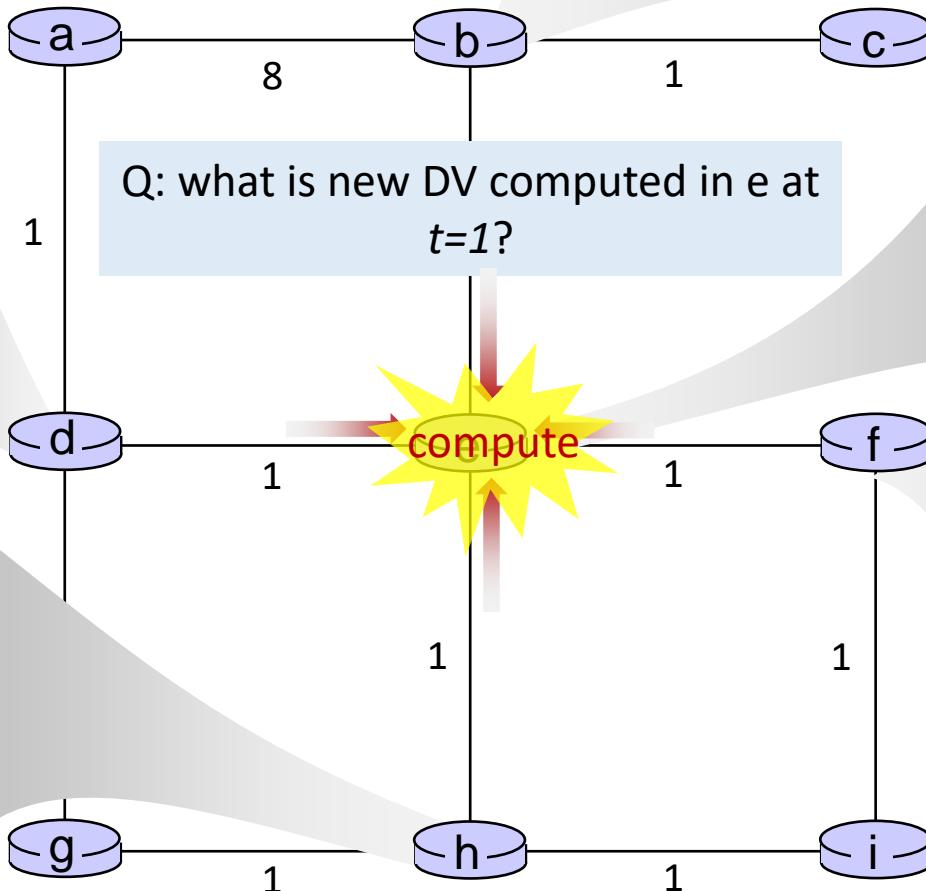


**t=1**

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

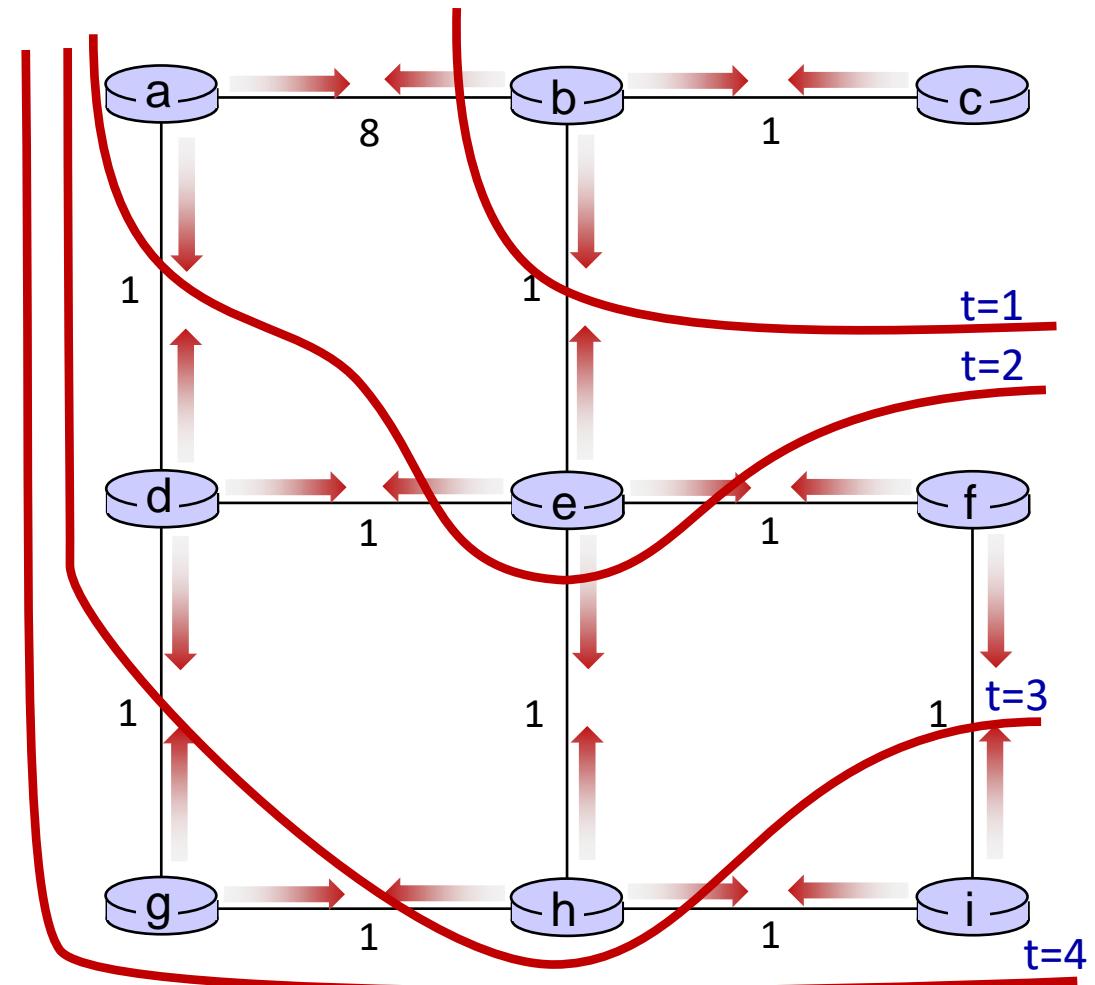
DV in e:
$D_e(a) = \infty$
$D_e(b) = 1$
$D_e(c) = \infty$
$D_e(d) = 1$
$D_e(e) = 0$
$D_e(f) = 1$
$D_e(g) = \infty$
$D_e(h) = 1$
$D_e(i) = \infty$

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:

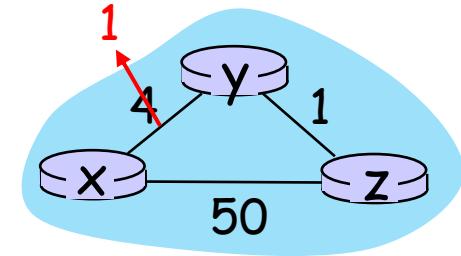
-  t=0    c's state at t=0 is at **c** only
-  t=1    c's state at t=0 has propagated to **b**, and may influence distance vector computations up to **1** hop away, i.e., at **b**
-  t=2    c's state at t=0 may now influence distance vector computations up to **2** hops away, i.e., at **b** and now at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

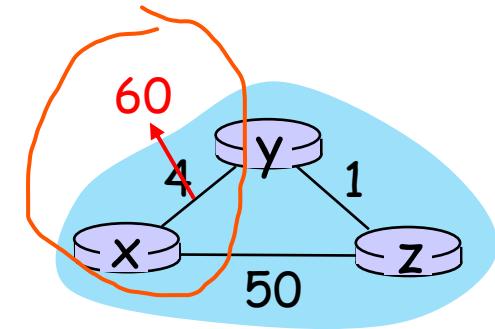
$t_2$ : **y** receives **z**'s update, updates its distance table. **y**'s least costs do *not* change, so **y** does *not* send a message to **z**.

# Distance vector: link cost changes

## link cost changes:

need more time to converge  
the algo can go to inf

- 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!*

divide internet into different domains

**administrative autonomy:**

- **Internet:** a network of networks
- each network admin may want to *control routing* in its own network

# Internet approach to scalable routing

in each AS, implement different routing protocols

*aggregate routers* into *regions* known as “autonomous systems” (**AS**) (a.k.a. “domains”)

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

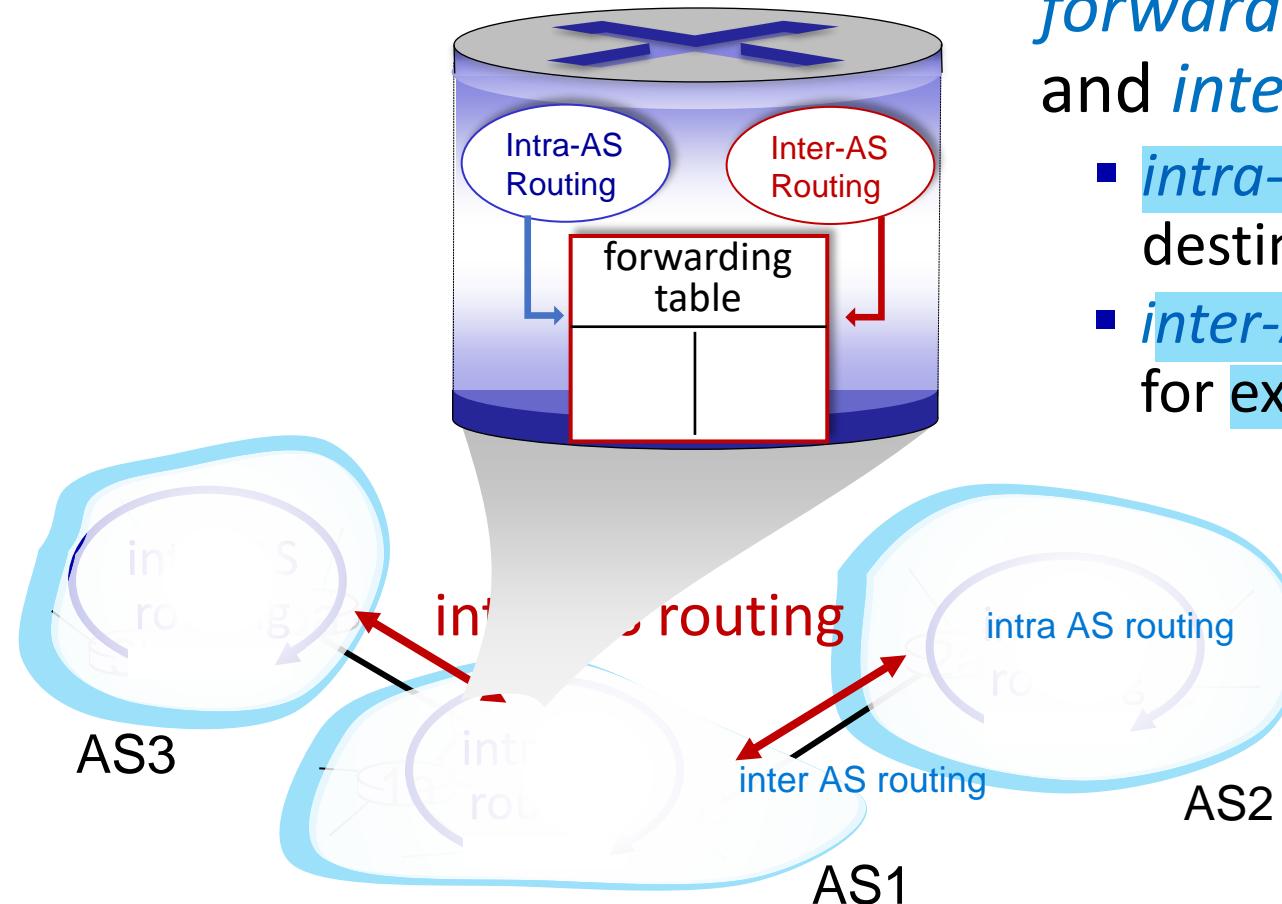
- all routers in AS must run *same intra-domain protocol*
  - routers in different AS can run different intra-domain routing protocols
- **gateway router:** at “edge” of its own AS, has link(s) to router(s) in other AS'es

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

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

need to run multiple protocols

# Interconnected ASes



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

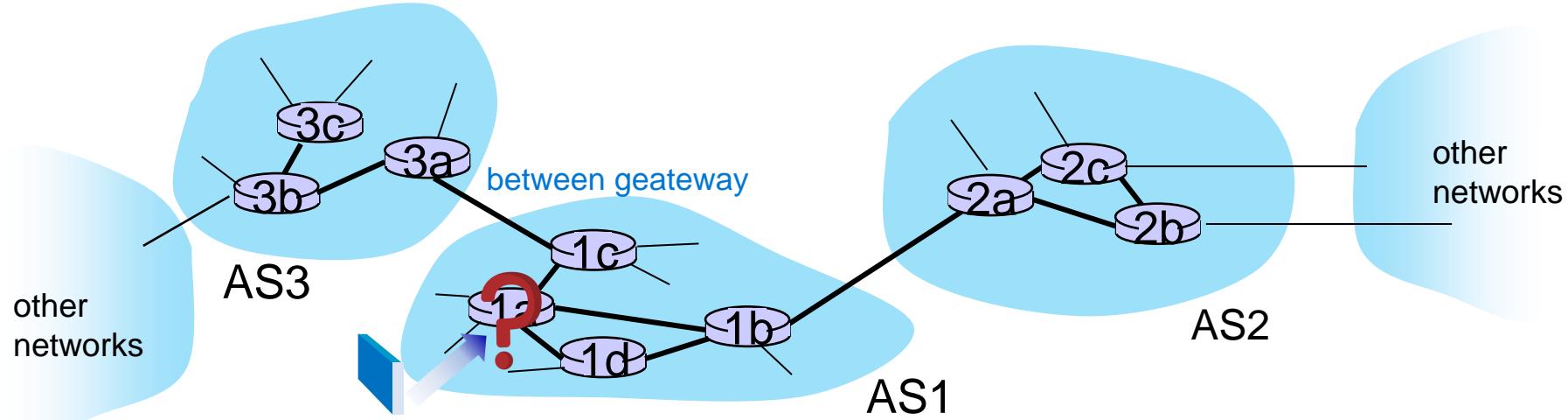
- *intra-AS routing* determine entries for destinations within AS
- *inter-AS & intra-AS* determine entries for external destinations

# 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:**

- learn which destinations reachable through **AS2**, which through **AS3**
- propagate this reachability info to all routers in **AS1**



# Inter-AS routing: routing within an AS

most common *intra-AS routing protocols*:

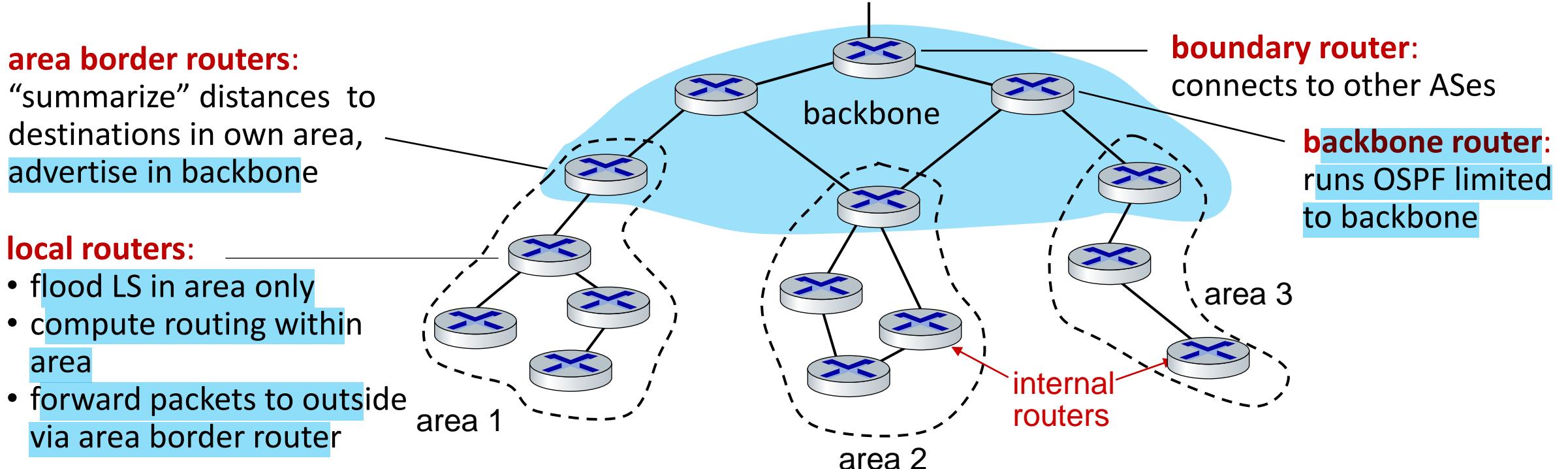
- RIP: Routing Information Protocol [RFC 1723]
  - classic DV: DVs exchanged every *30 secs*
  - *no longer widely used*
- EIGRP: Enhanced Interior Gateway Routing Protocol
  - DV based
  - formerly *Cisco-proprietary* for decades (became *open* in 2013 [RFC 7868])
- OSPF: Open Shortest Path First [RFC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

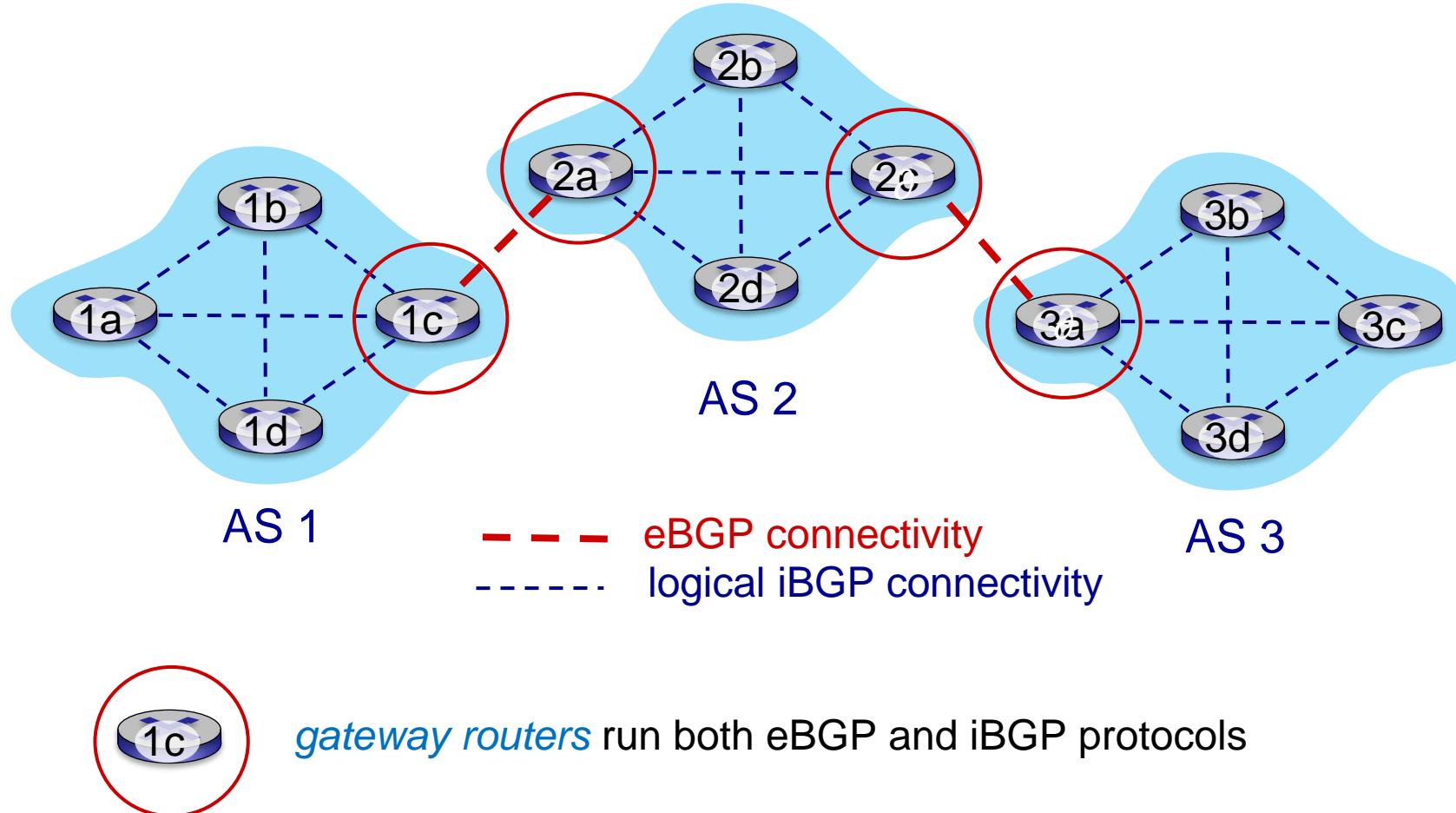


- network management, configuration
  - SNMP
  - NETCONF/YANG

# Internet inter-AS routing: BGP

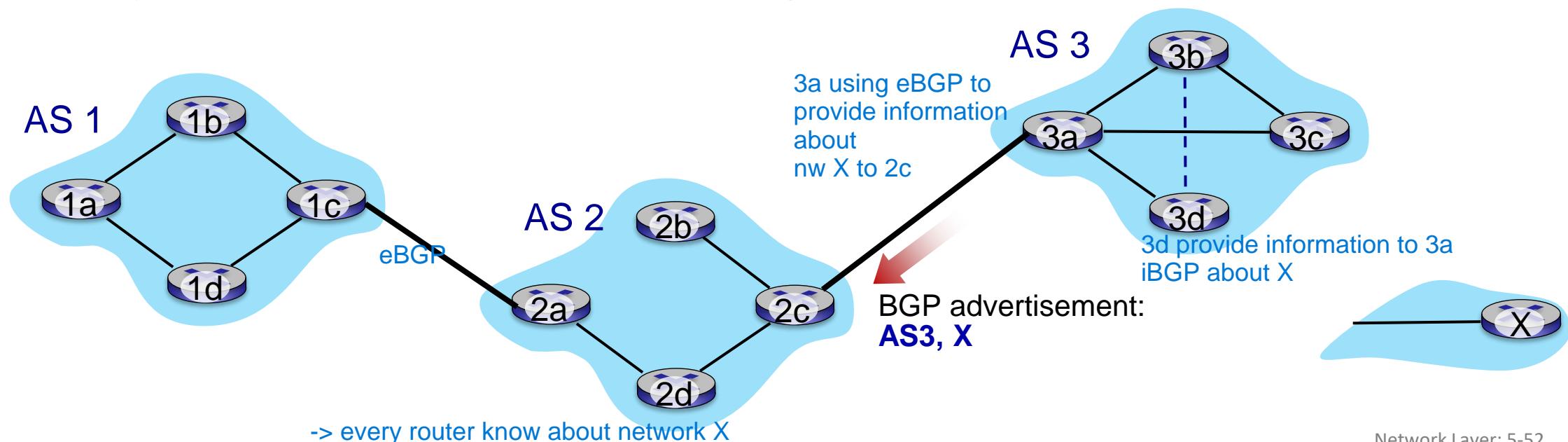
- BGP (Border Gateway Protocol): *the de facto* inter-domain routing protocol
  - “*glue* that holds the Internet together”
- allows *subnet* to advertise its existence, and the *destinations* it can reach, to rest of Internet: “*I am here, here is who I can reach, and how*”
- BGP provides each AS a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

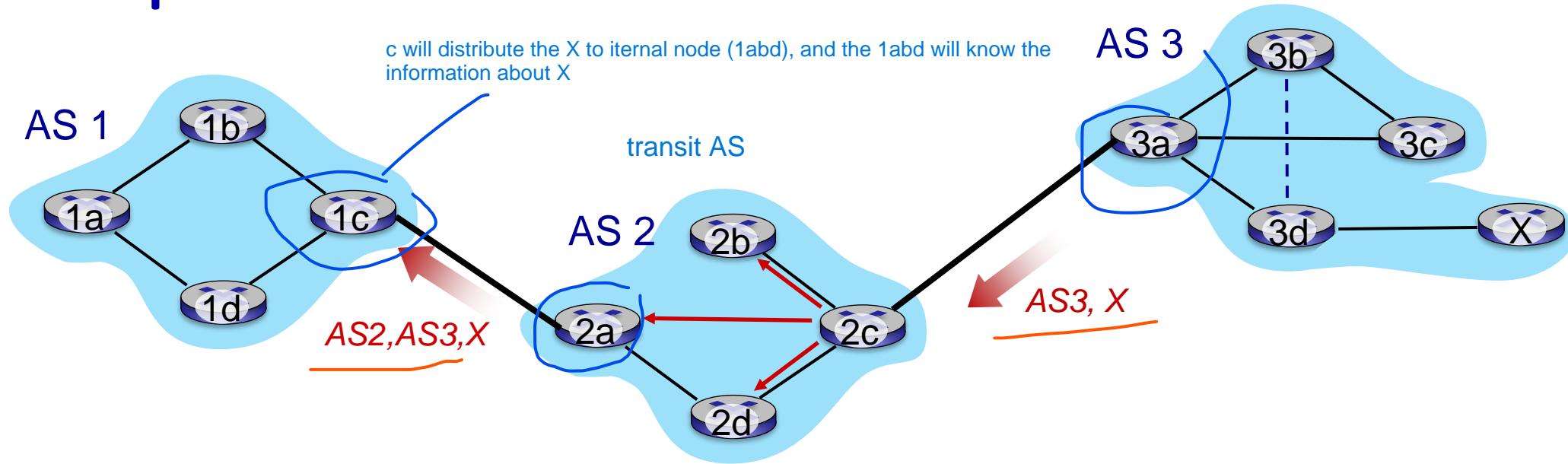
- BGP session: two BGP routers (“peers”) exchange *BGP messages* over *semi-permanent TCP connection*:
  - advertising **paths** to different destination network prefixes (BGP is a “*path vector*” protocol)
- e.g., when AS3 gateway 3a advertises **path AS3,X** to AS2 gateway 2c:
  - AS3 promises to AS2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



# Path attributes and BGP routes

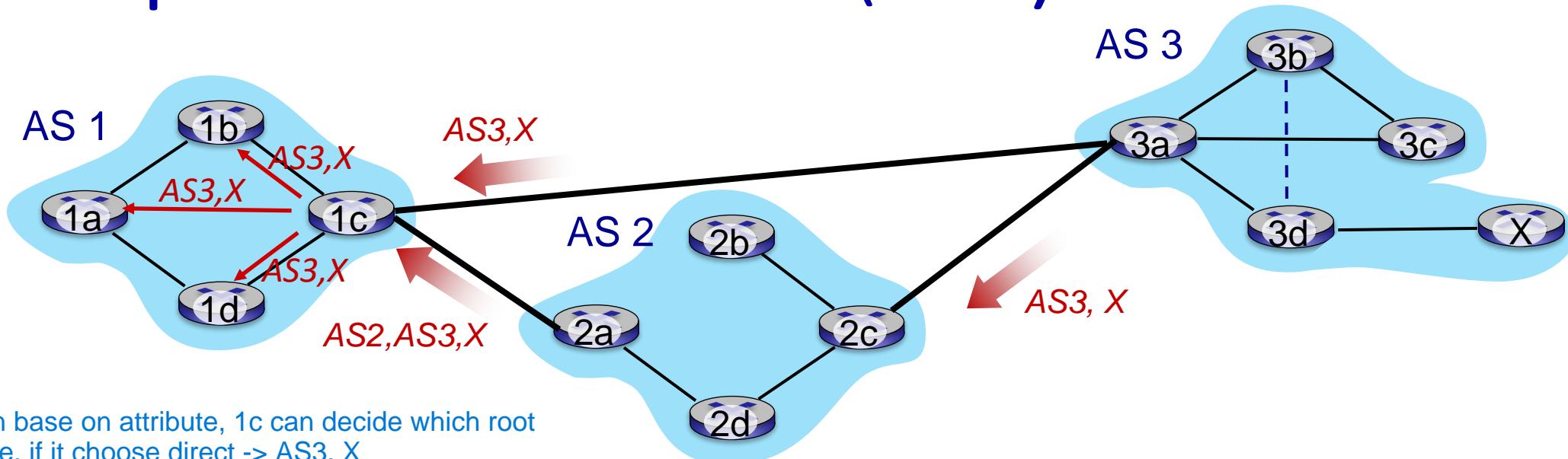
- BGP advertised **route = prefix + attributes**
  - *prefix*: destination being advertised
  - two important *attributes*:
    - **AS-PATH**: *list of ASes* through which prefix advertisement has passed
    - **NEXT-HOP**: indicates specific *internal-AS router* to next-hop AS
- **policy-based routing:**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



It can base on attribute, 1c can decide which root to use, if it choose direct -> AS3, X otherwise AS3, AS2, X attribute is involved in the 1c

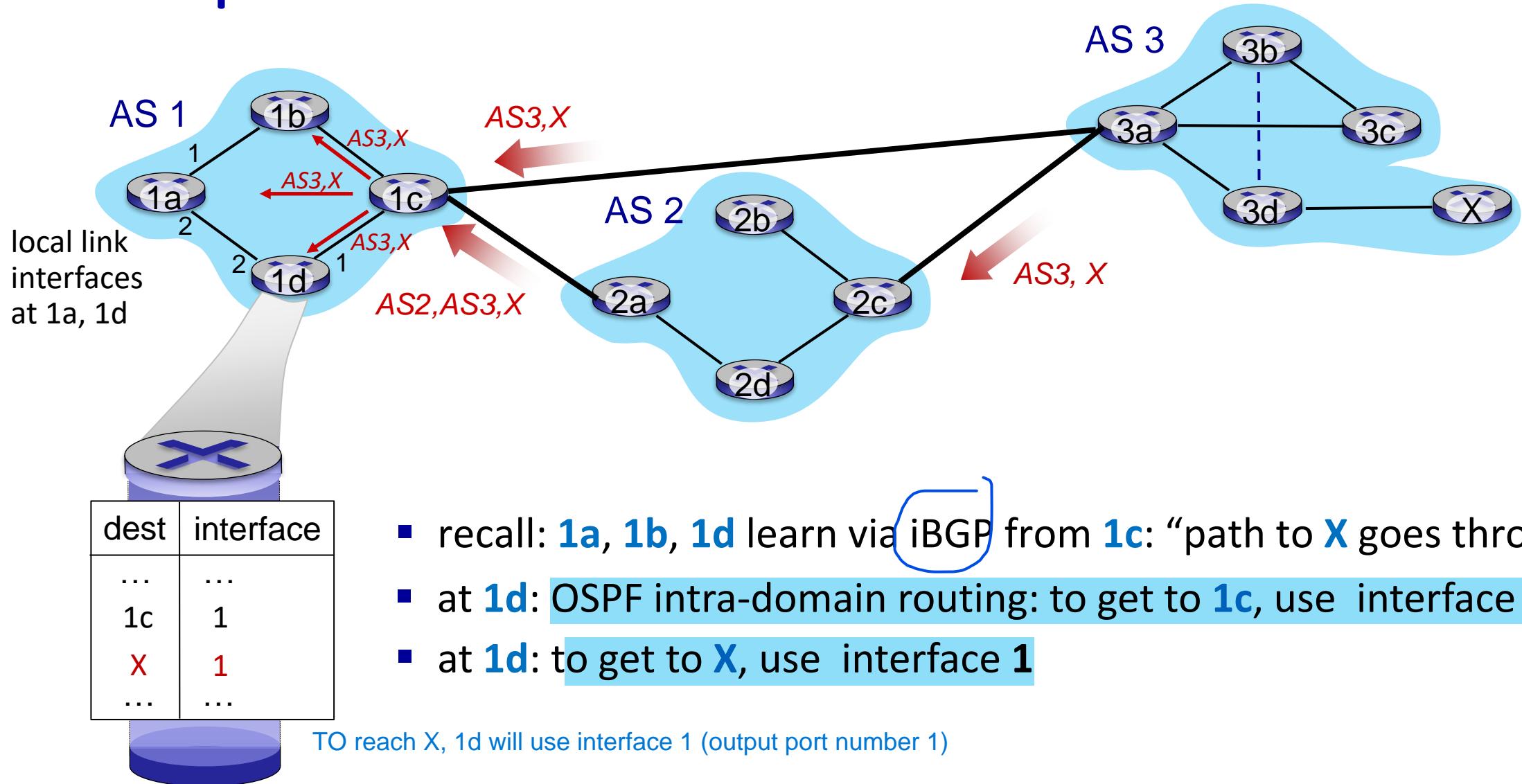
gateway router may learn about multiple paths to destination:

- 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

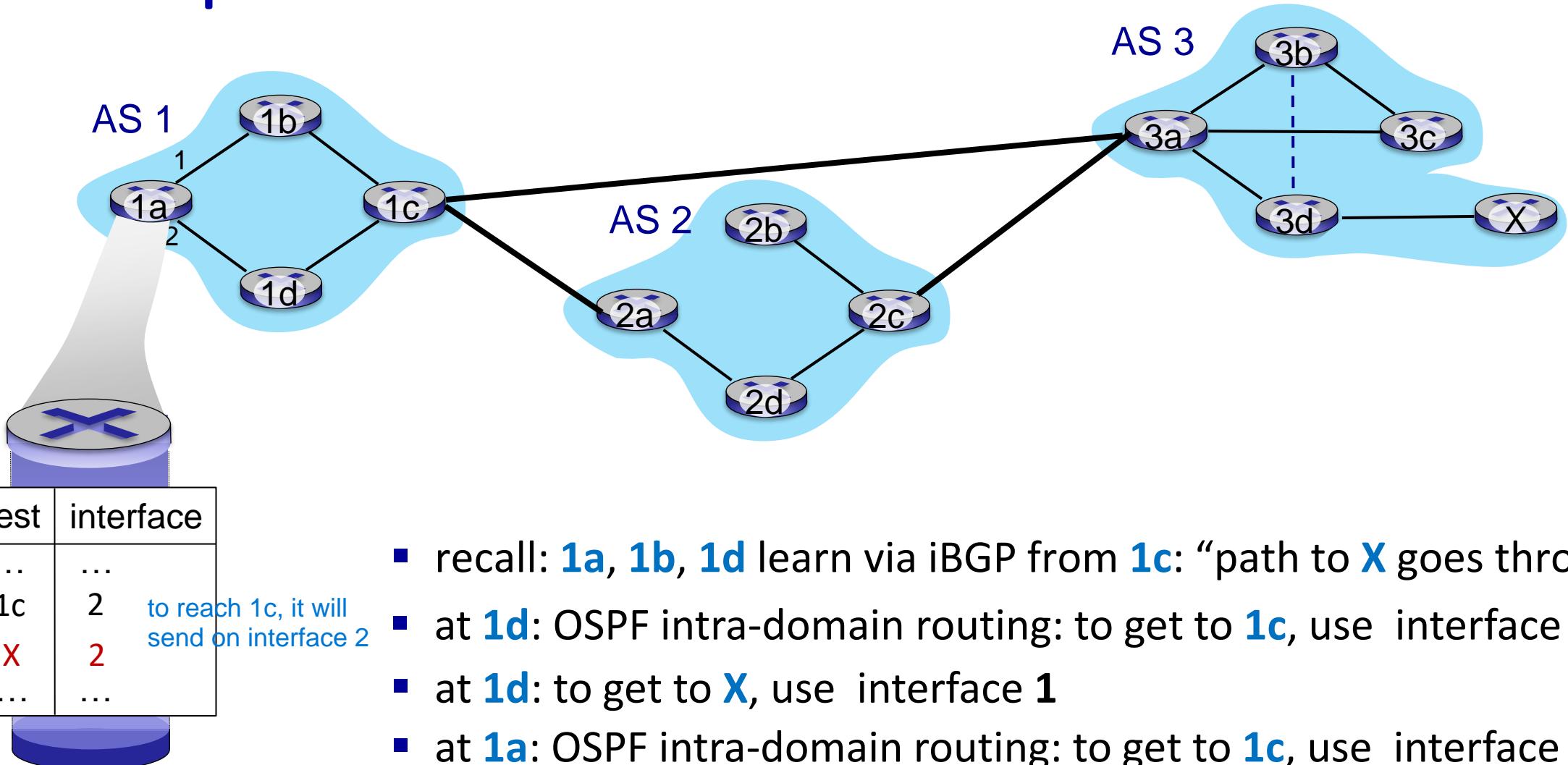
# BGP messages

- *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



# 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

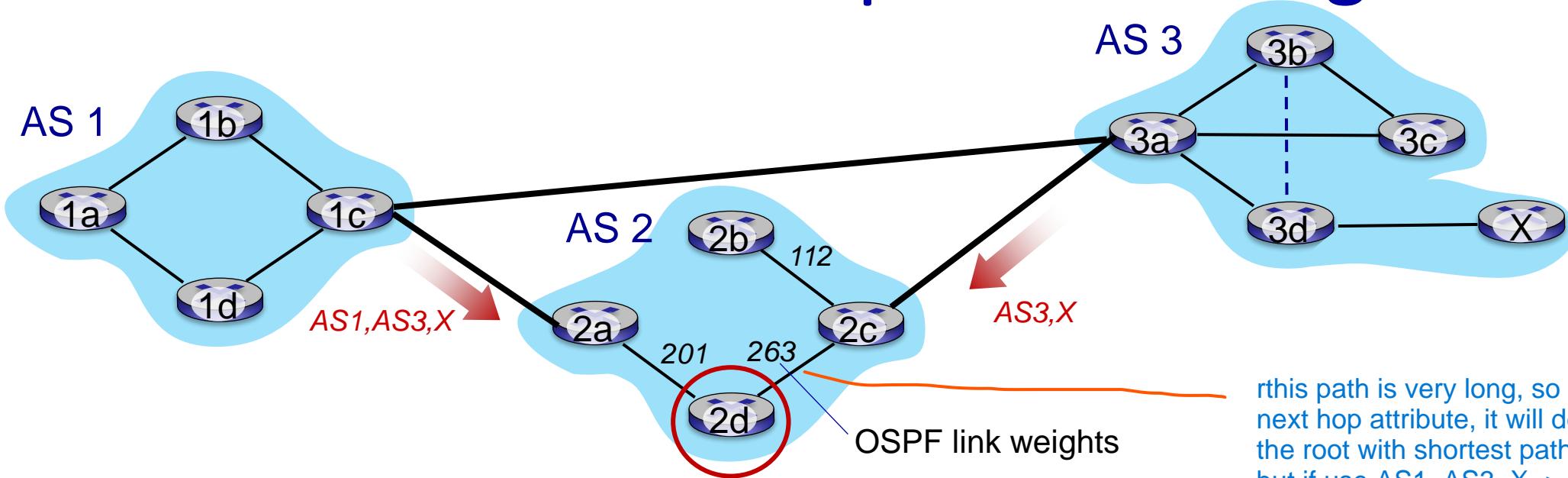
scale:

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

performance:

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

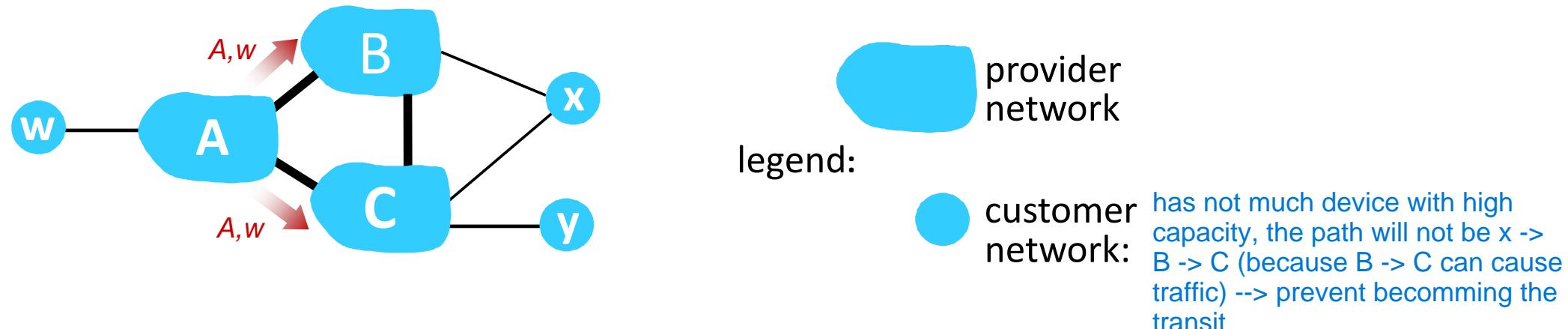
# NEXT-HOP attribute: Hot potato routing



this path is very long, so 2d adopt for next hop attribute, it will decide to use the root with shortest path within AD but if use AS1, AS3, X -> the root can be very long (through 2 ASes)  
--> choose the shortest one

- **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!

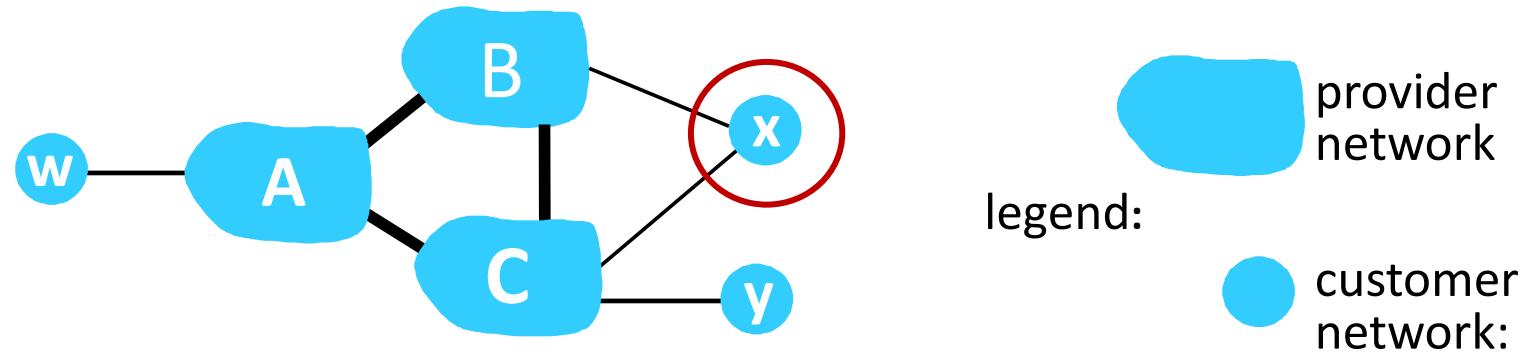
# BGP: achieving policy via advertisements



**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



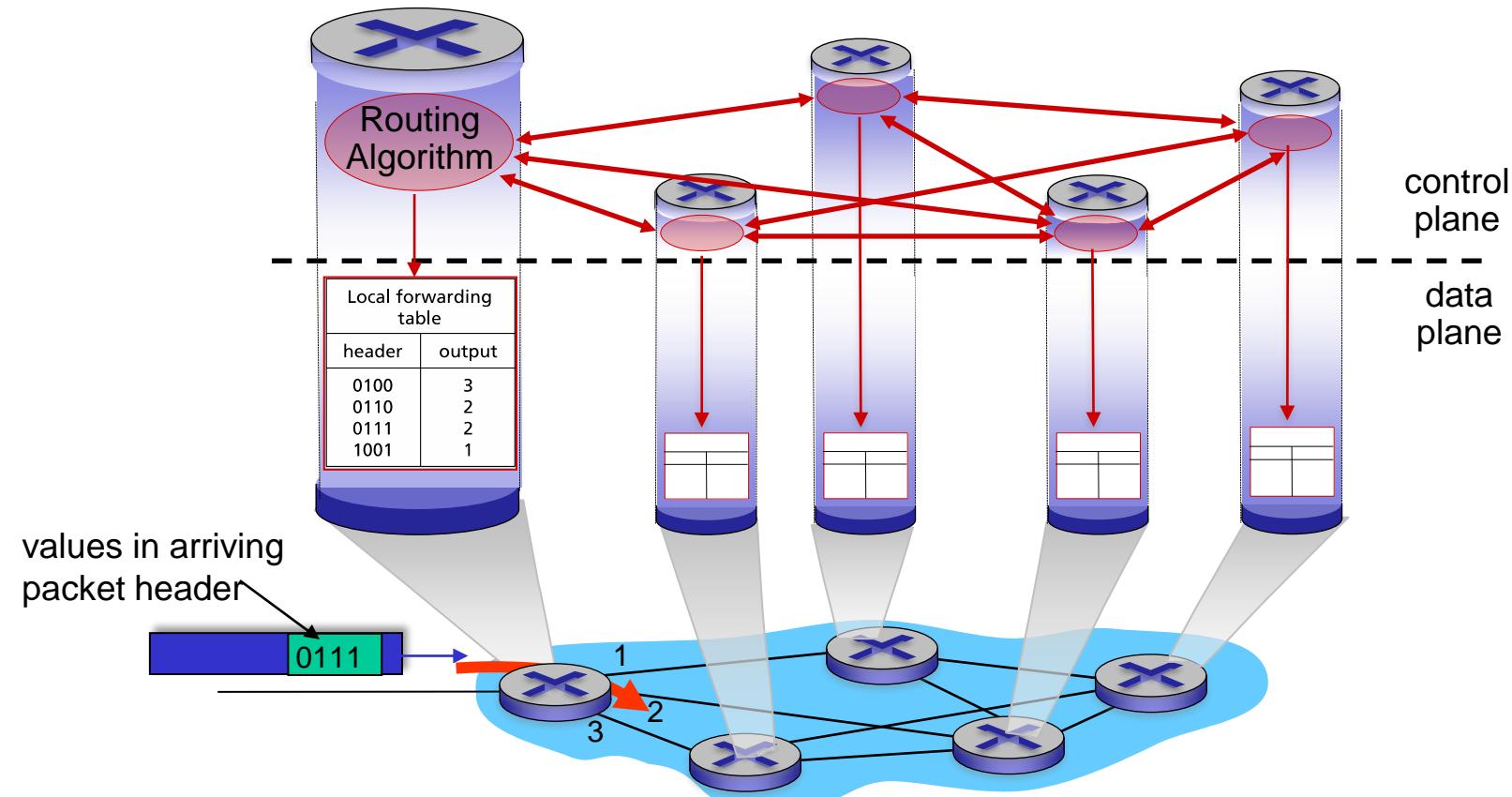
- network management, configuration
  - SNMP
  - NETCONF/YANG

# 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*, ..  
the router has 2 function: forwarding and routing, to add more function, we need middle box
- ~2005: renewed interest in rethinking network control plane

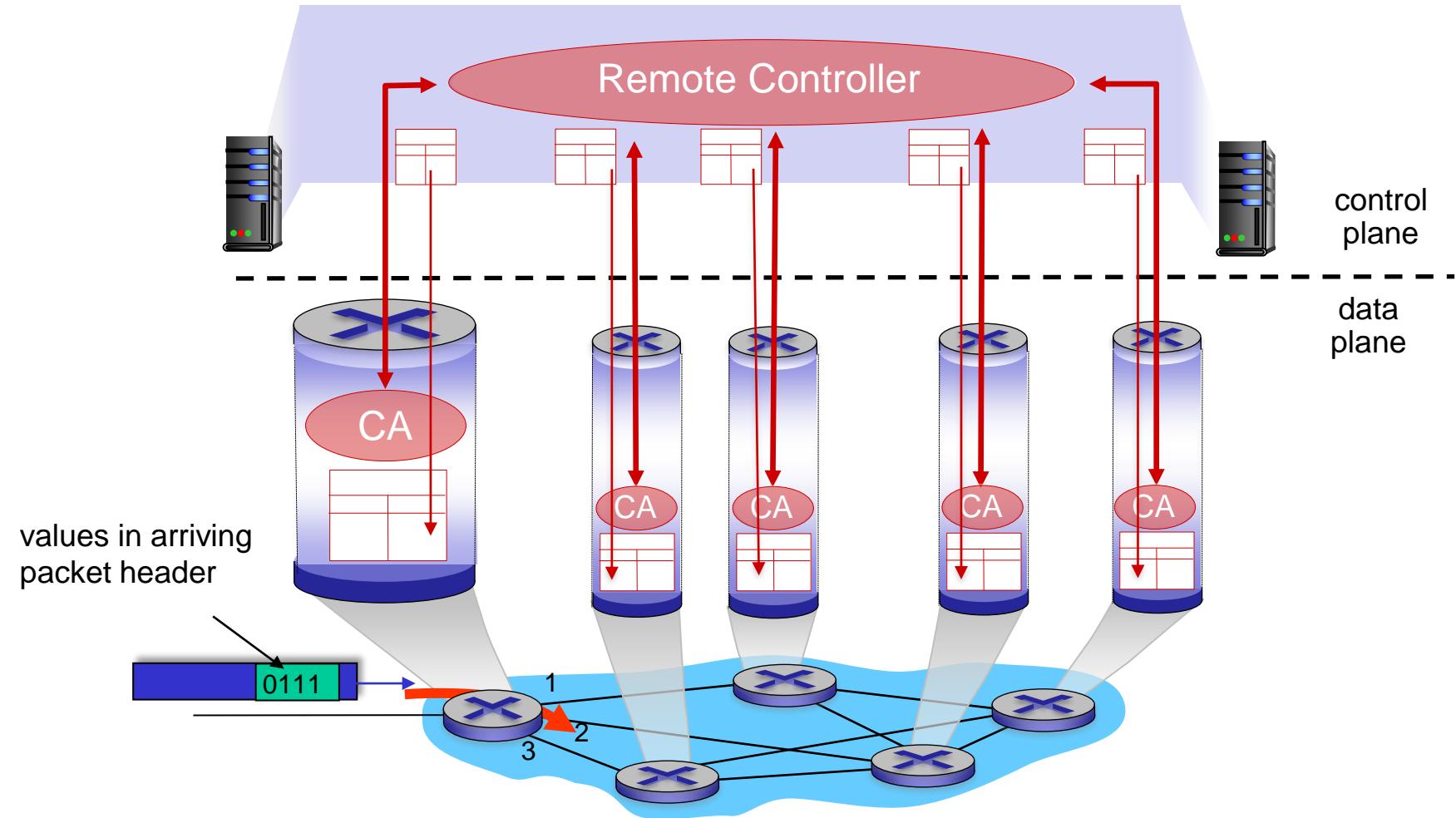
# Per-router control plane

*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

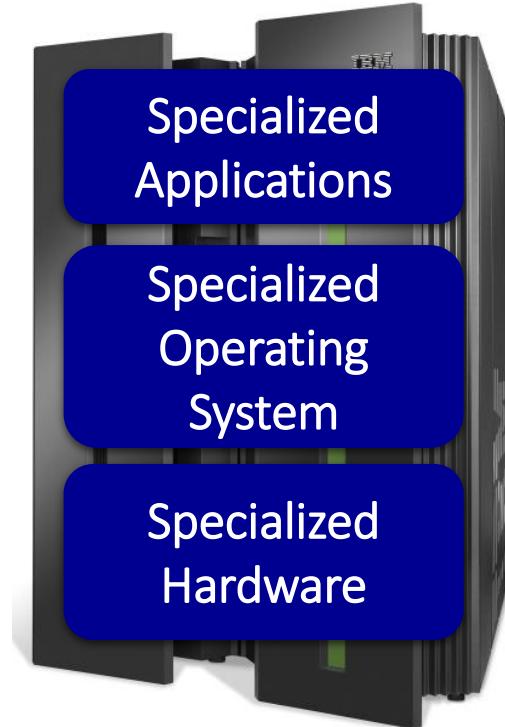


# Software defined networking (SDN)

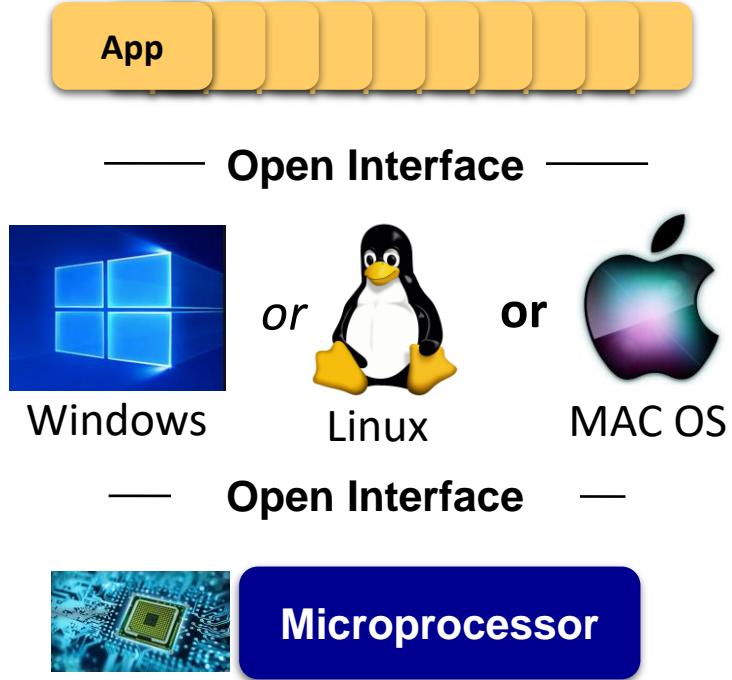
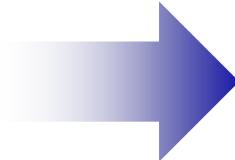
*Why* a *logically centralized* control plane?

- *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

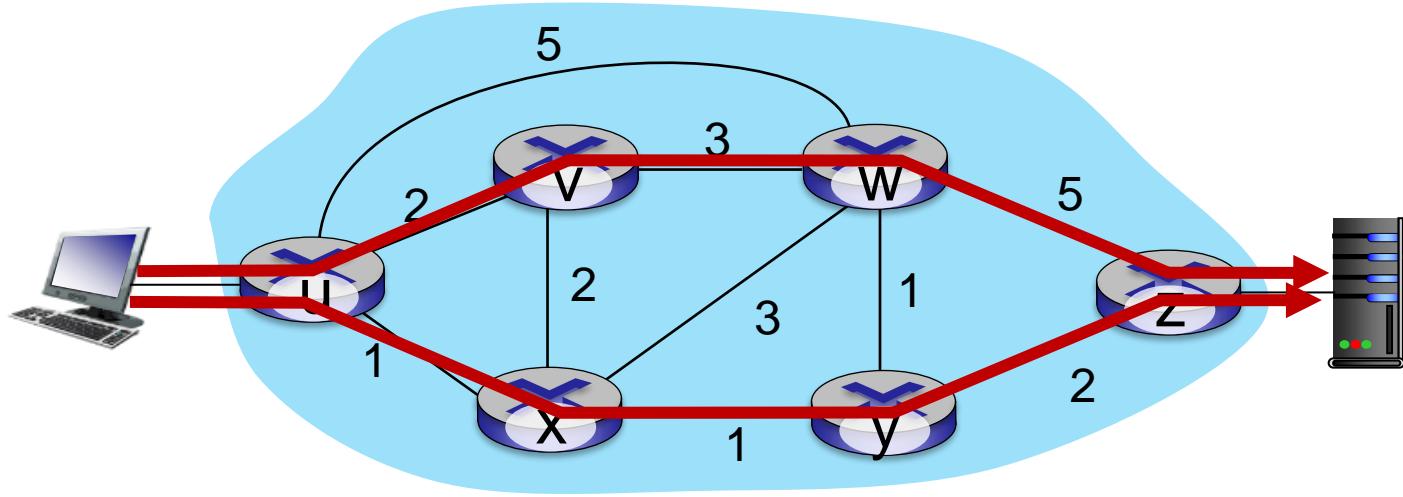


Vertically integrated  
Closed, proprietary  
Slow innovation  
Small industry



*Horizontal  
Open interfaces  
Rapid innovation  
Huge industry*

# Traffic engineering: difficult with traditional routing

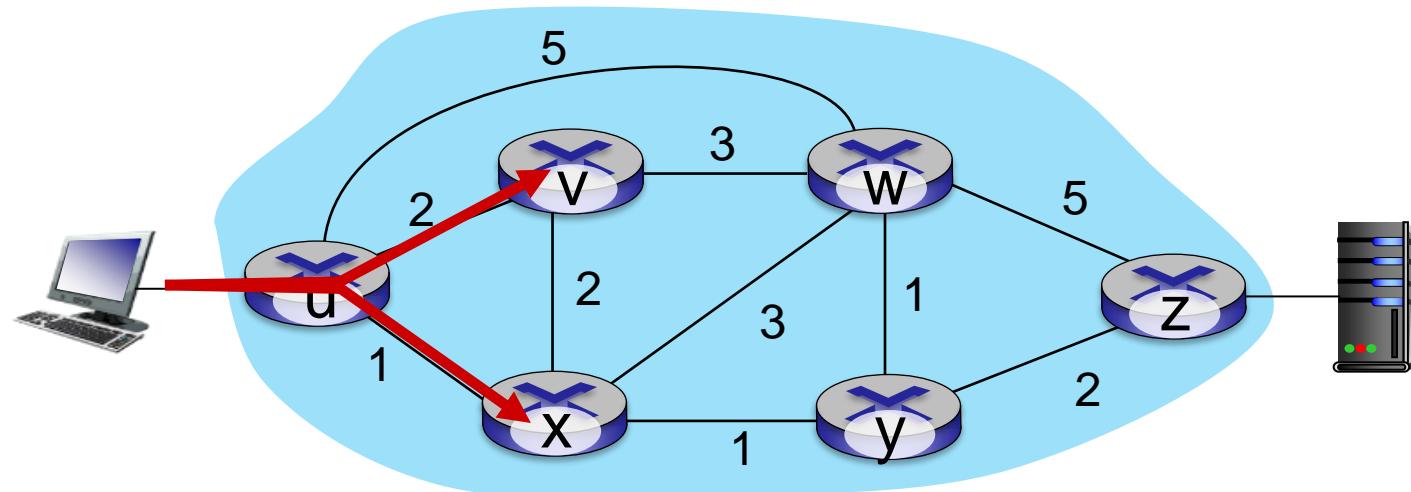


Q: what if network operator wants *u-to-z traffic* to *flow* along *uvwz*, rather than *uxyz*?

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!*

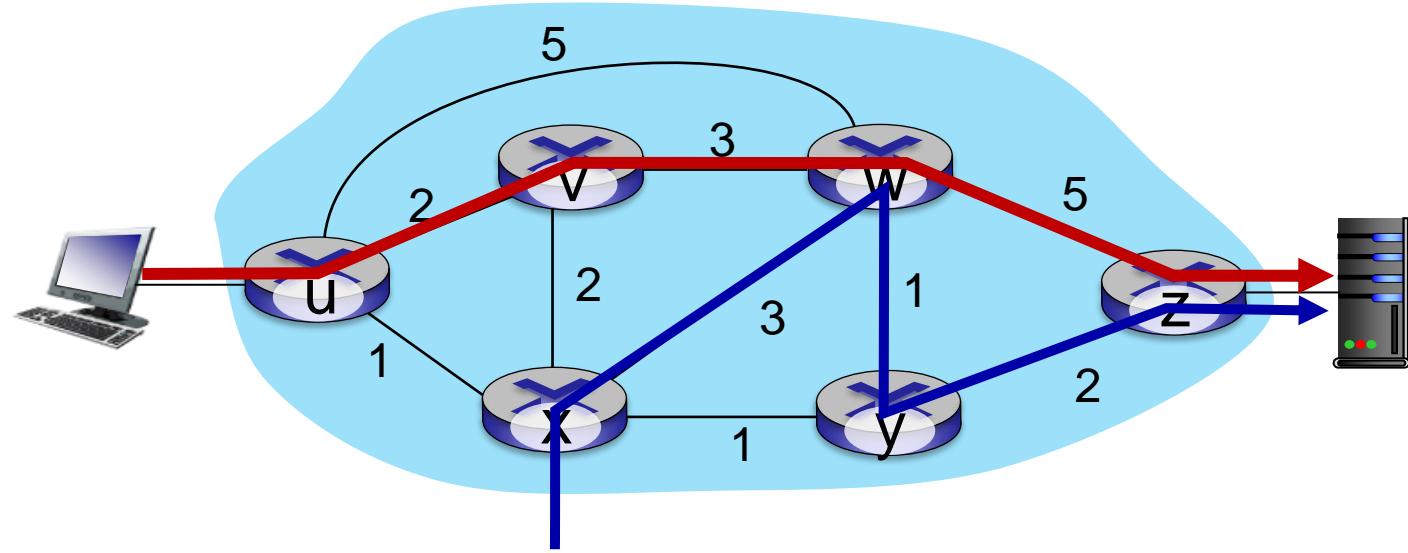
# Traffic engineering: difficult with traditional routing



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

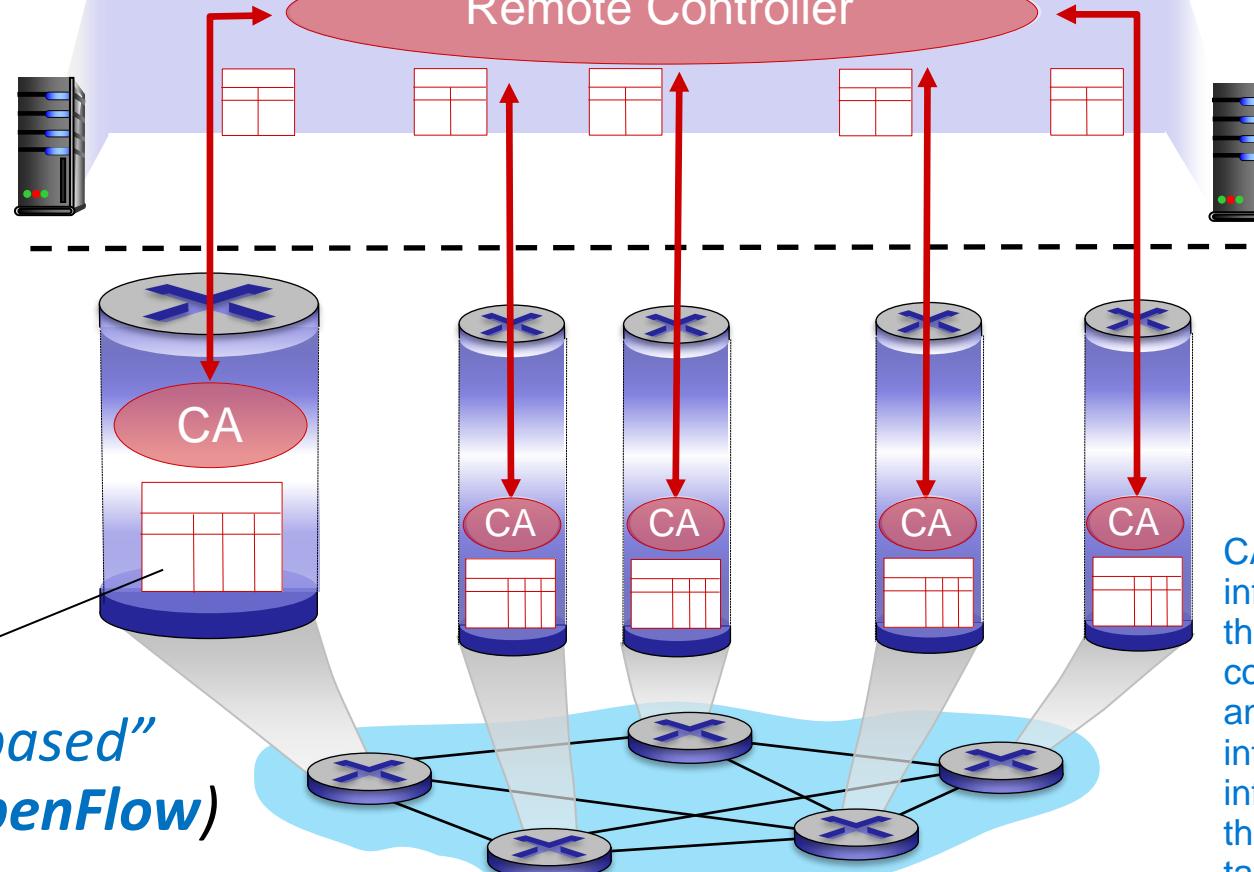
load balance

**3. control plane functions external to data-plane switches**

it can add load balancing, firewall ... the controller can expand the function using third party application

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



**2. control, data plane separation**

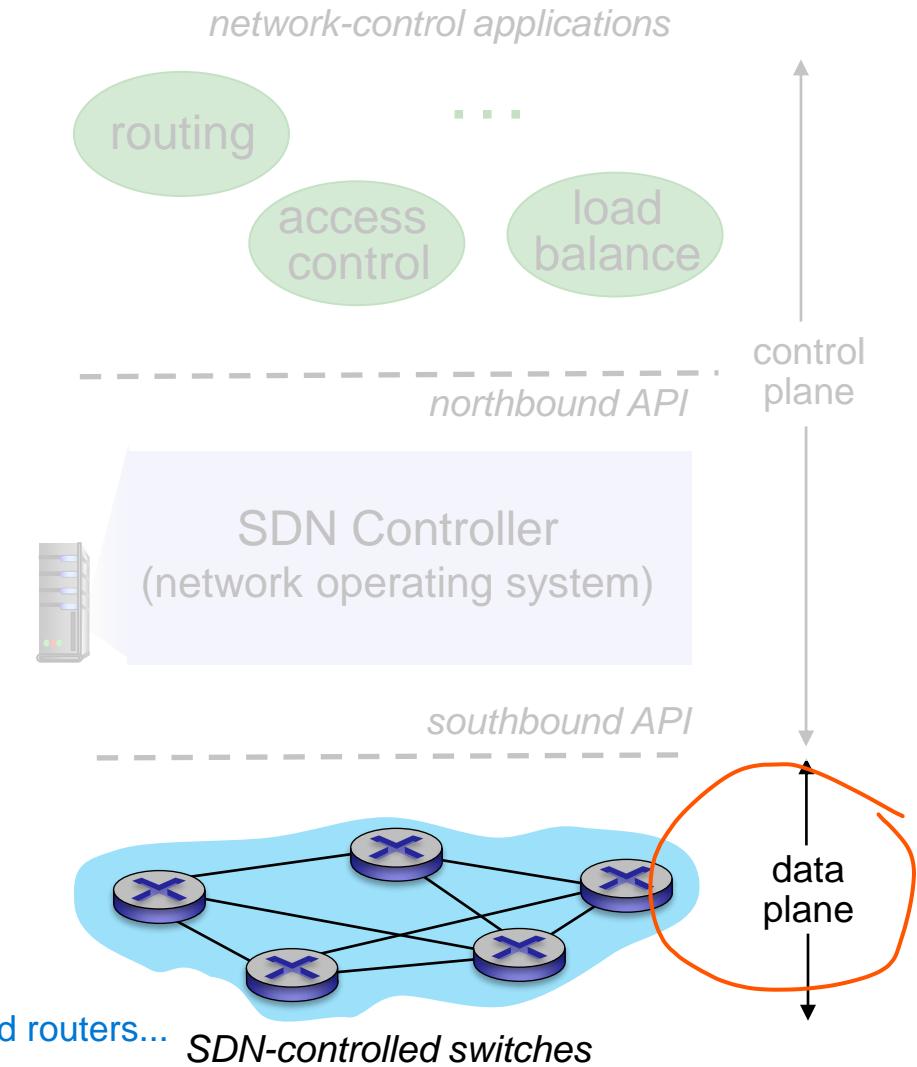
CA will report some information about the infrastructure (any link failed v.v) -> so that the controller will have the global view, compute shortest path from 1 port to another port ..., it will translate information into flow table for every router in the infrastructure, it can push the flow table to the router. Now the router use the flow table as forwarding table

# 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*)

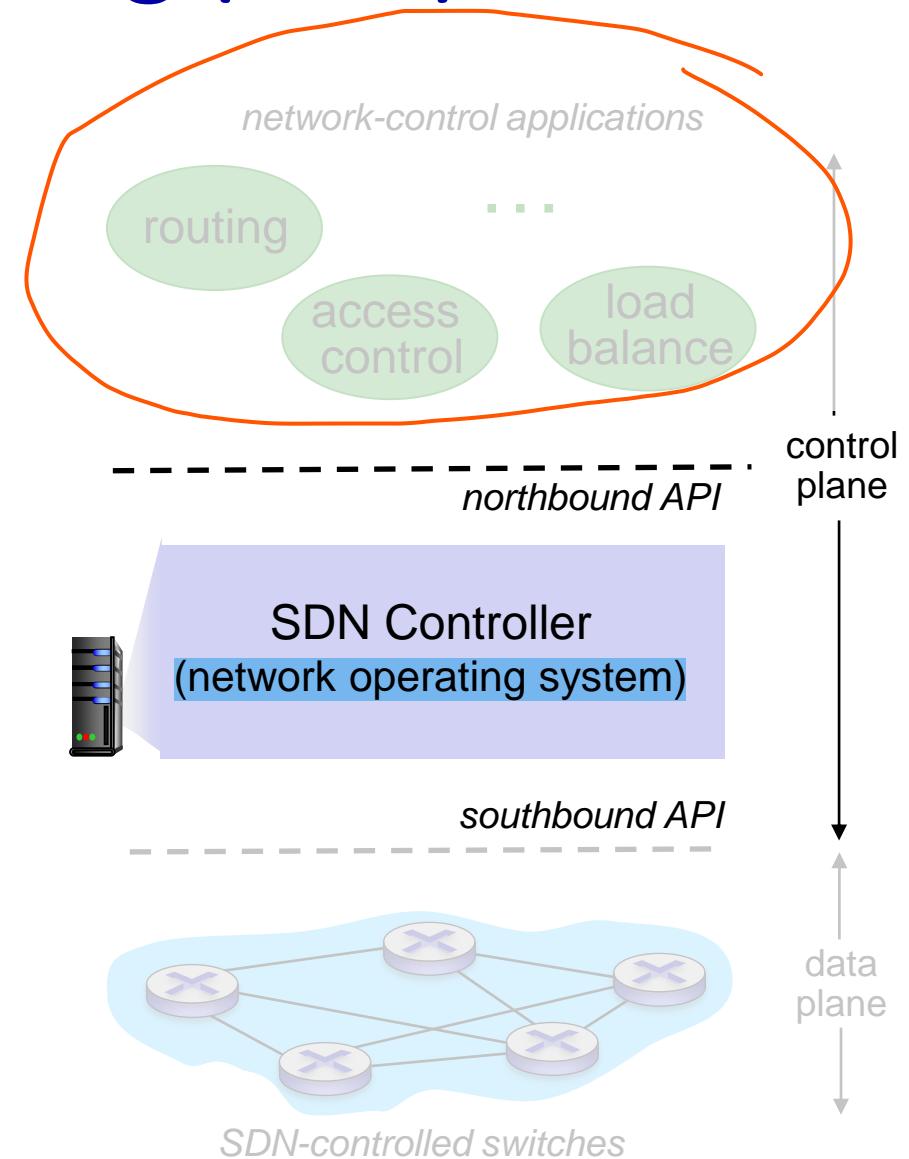
framework can be used to implement  
for communication between switches and routers...



# Software defined networking (SDN)

## SDN controller (network OS):

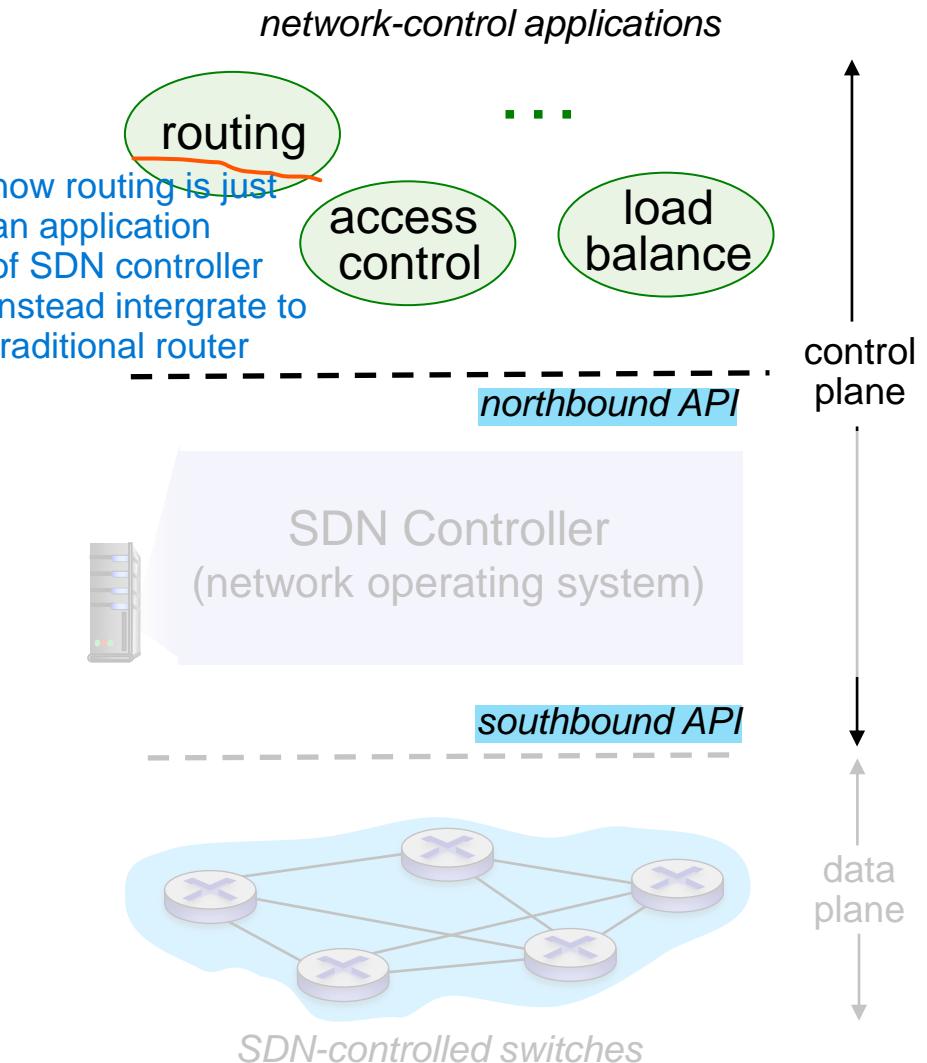
- maintain *network state information*
- interacts with *network control applications* “above” via *northbound API*
- interacts with *network switches* “below” via *southbound API*
- implemented as *distributed system* for performance, scalability, fault-tolerance, robustness



# 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 3<sup>rd</sup> party: *distinct from routing vendor*, or SDN controller

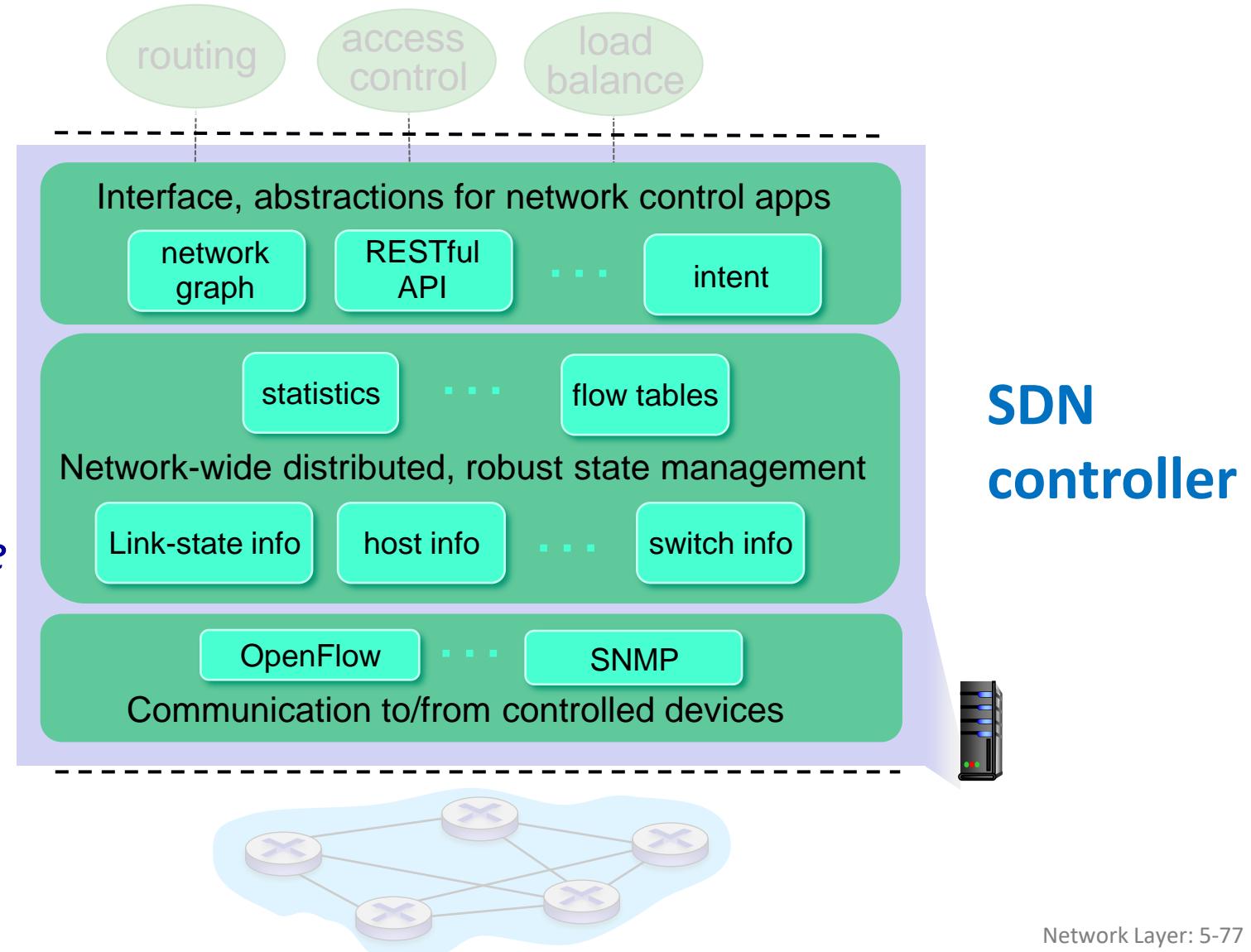


# Components of SDN controller

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

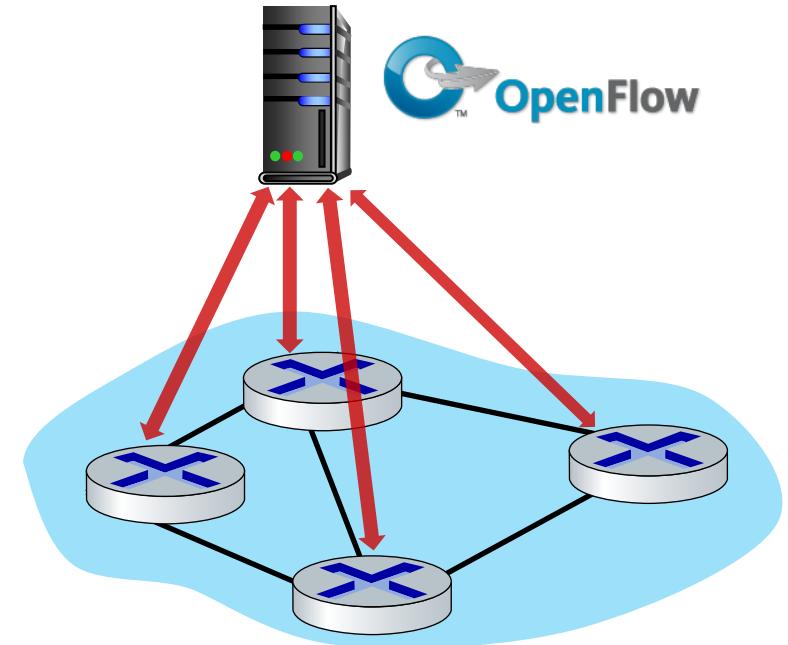


# OpenFlow protocol

- 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: for how to intergrate a switch to the network, how to build the controller, how to use protocol to communicate from the switch to the controller, specify on using TCP pro

## OpenFlow Controller

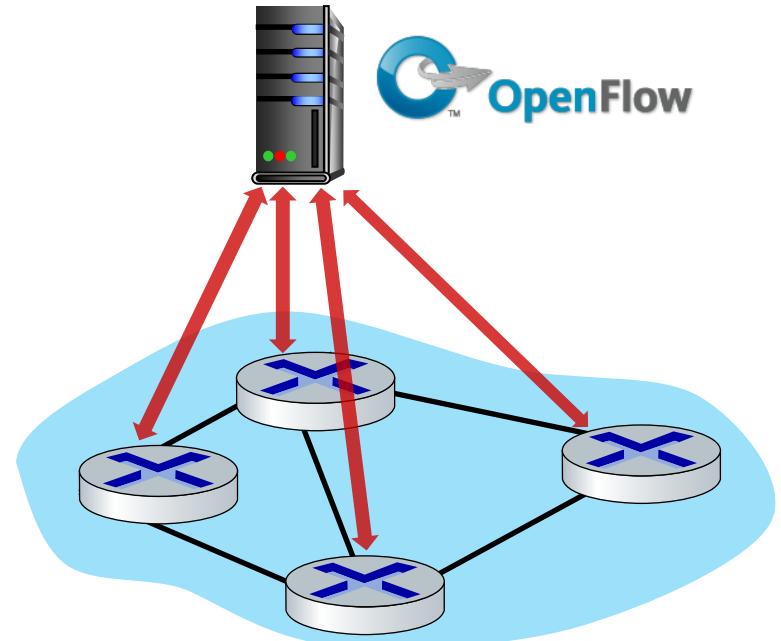


# OpenFlow: controller-to-switch messages

## 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

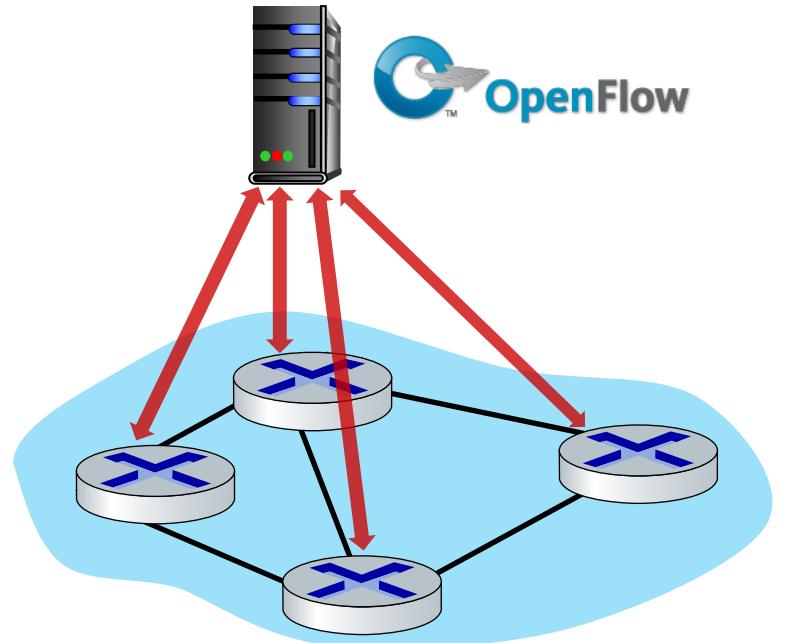


# OpenFlow: switch-to-controller messages

## Key switch-to-controller messages

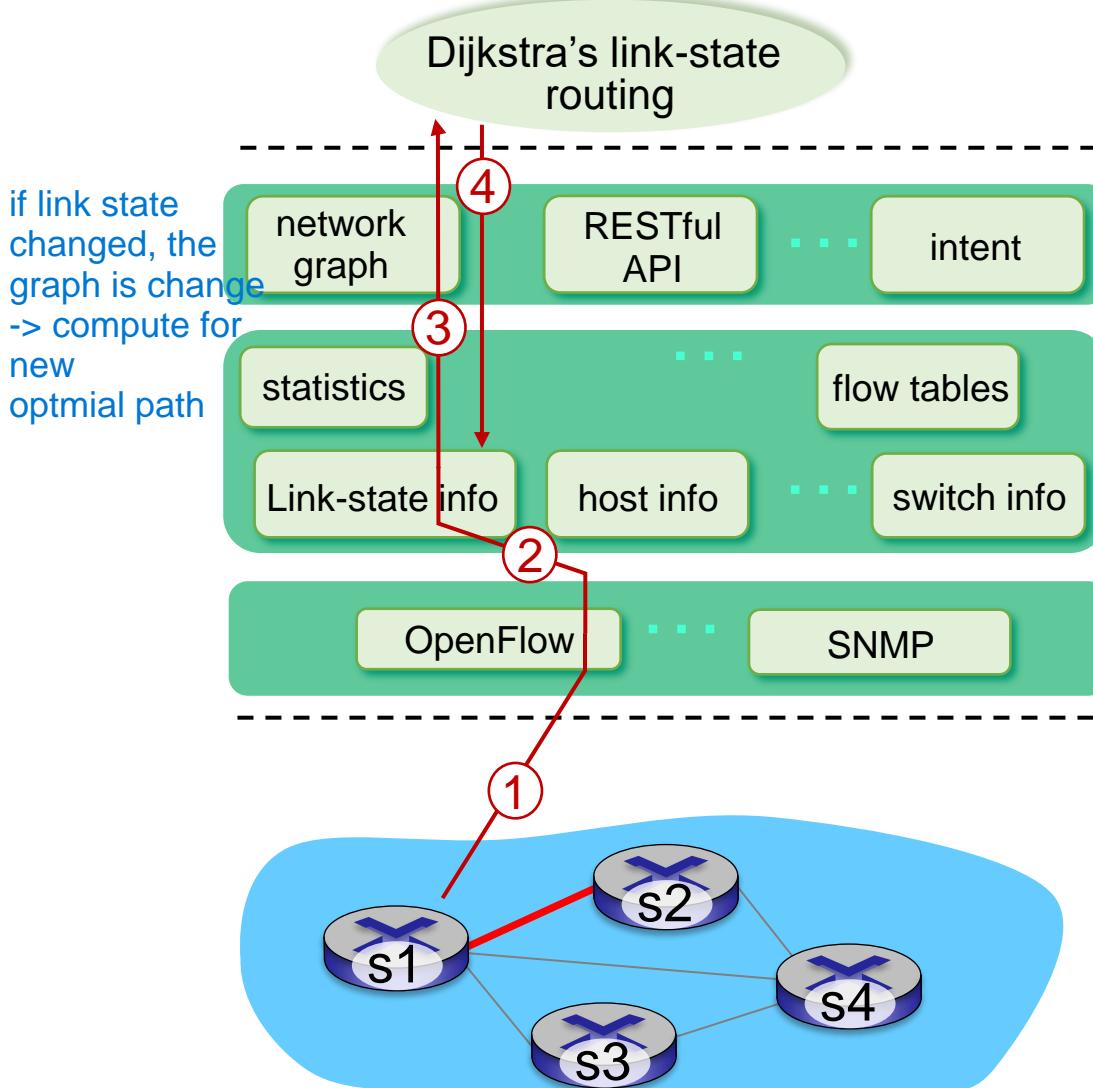
- ***packet-in***: transfer packet (and its control) to controller. See packet-out message from controller
- ***flow-removed***: flow table entry deleted at switch
- ***port status***: inform controller of a change on a port.

## OpenFlow Controller



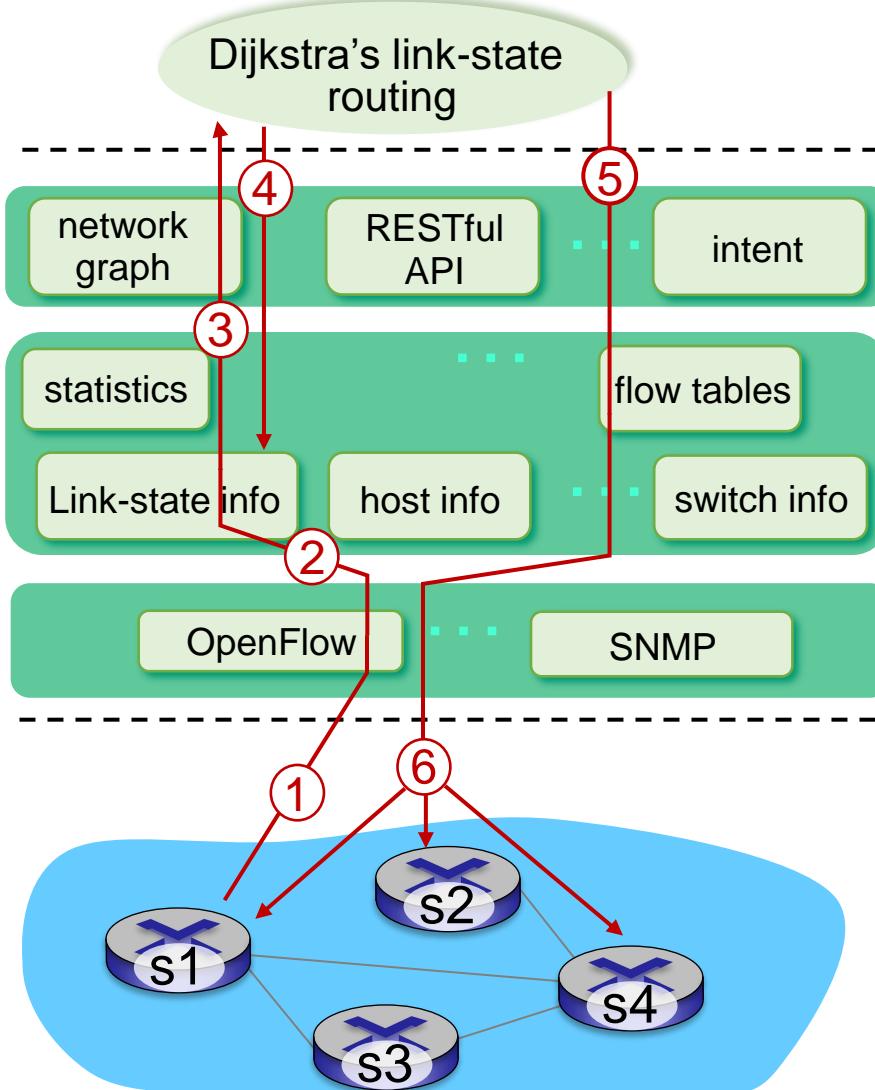
Fortunately, network operators don't "program" switches by creating/sending OpenFlow messages directly. Instead use ***higher-level abstraction at controller***

# SDN: control/data plane interaction example



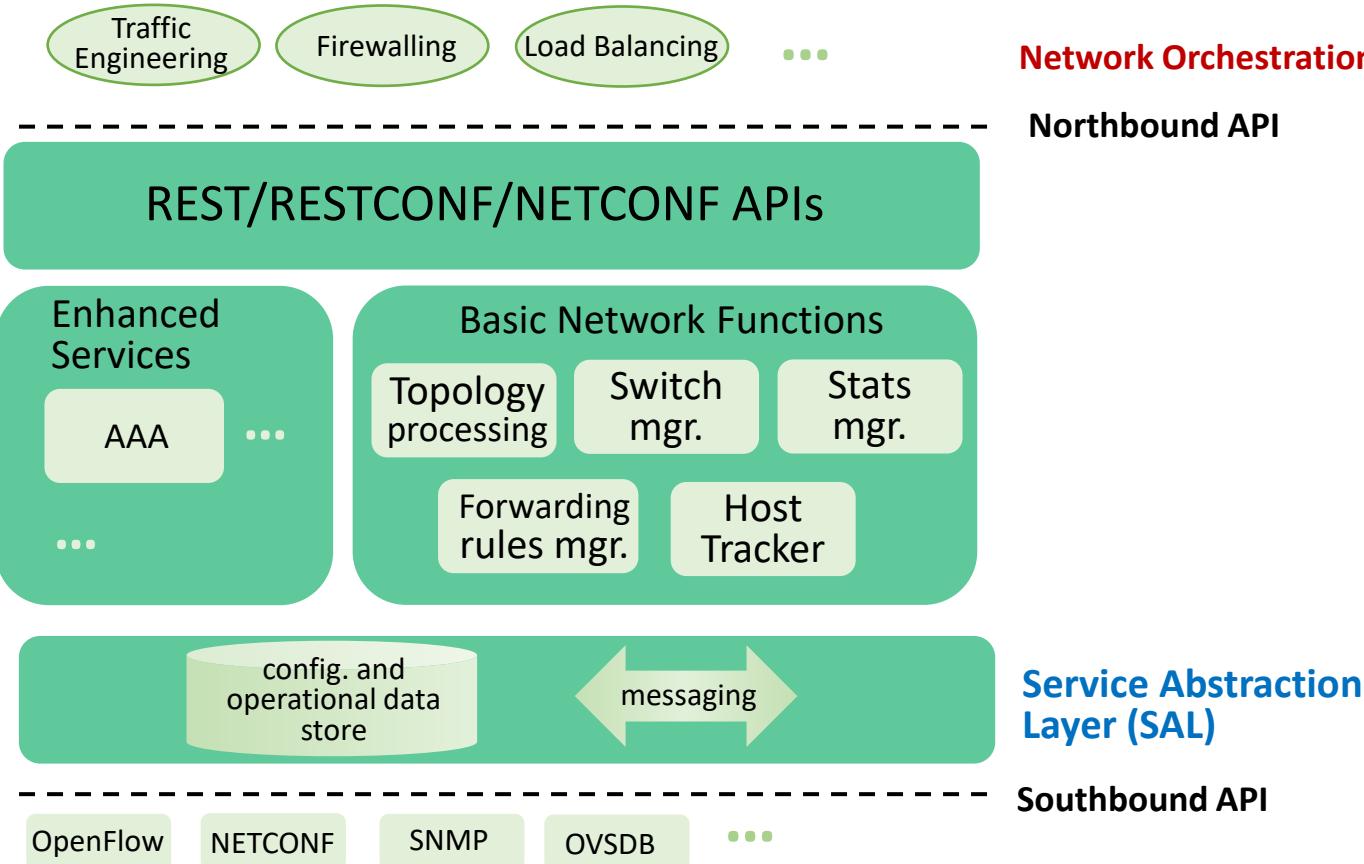
- ① **S1**, experiencing link failure uses OpenFlow *port status message* to notify controller
- ② **SDN controller** receives OpenFlow message, *updates link status info*
- ③ **Dijkstra's routing algorithm** application has previously registered to be called when ever link status changes. It is called.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

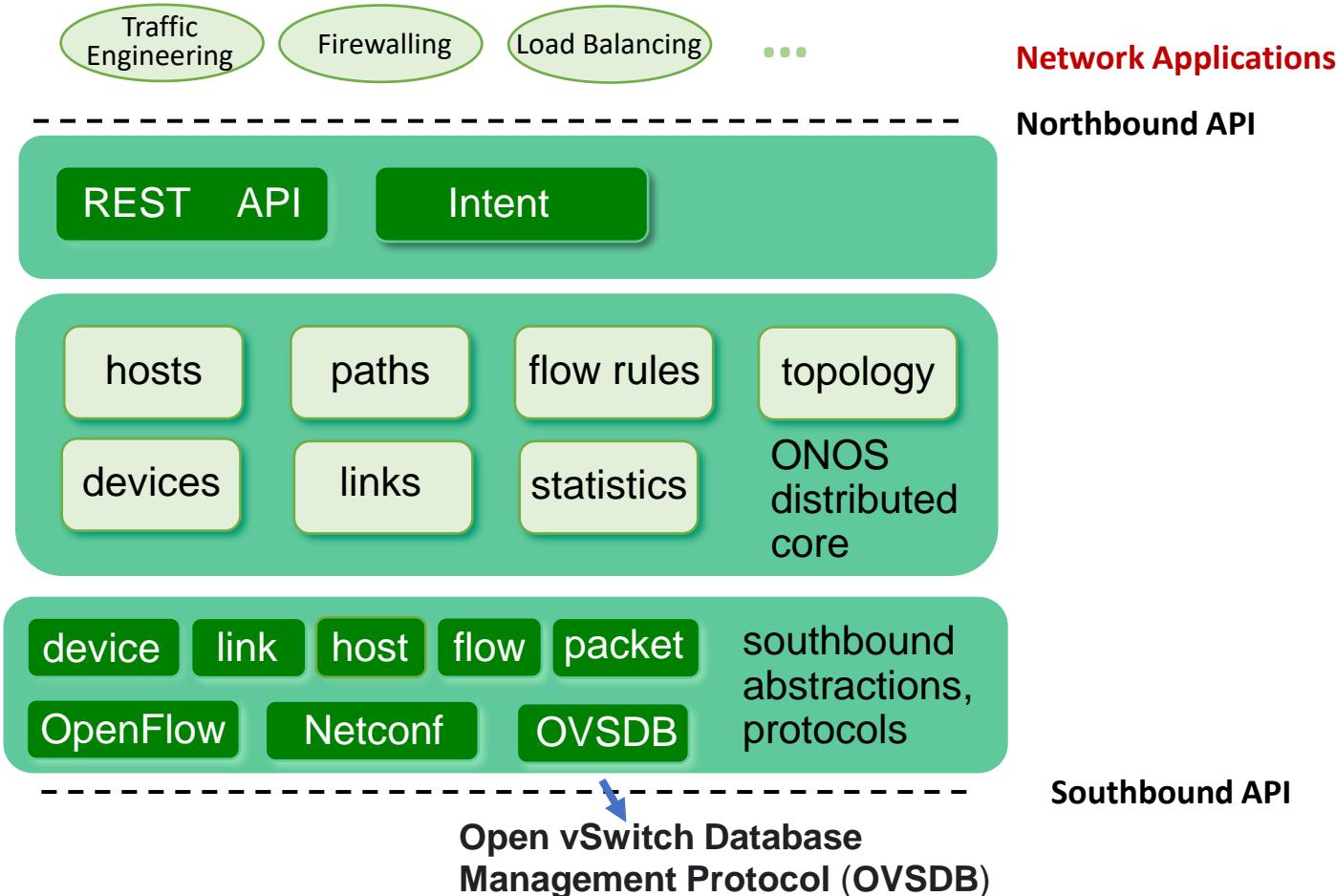
# OpenDaylight (ODL) controller



## 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**



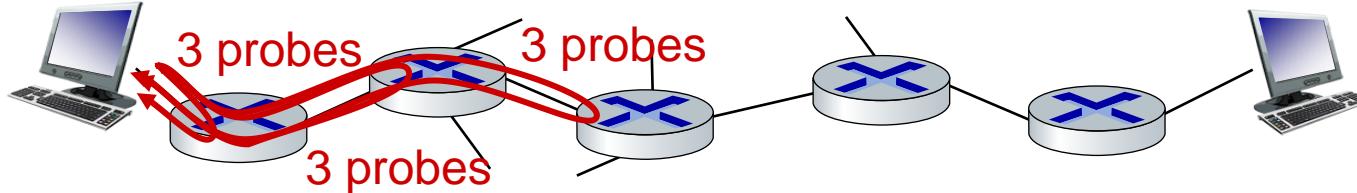
- network management, configuration
  - SNMP
  - NETCONF/YANG

# 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* in network layer , but IP datagrams will carry ICMP message
- **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*
  - 1<sup>st</sup> set has TTL =1, 2<sup>nd</sup> 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

- introduction
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- network management, configuration
  - SNMP
  - NETCONF/YANG

# What is network management?

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



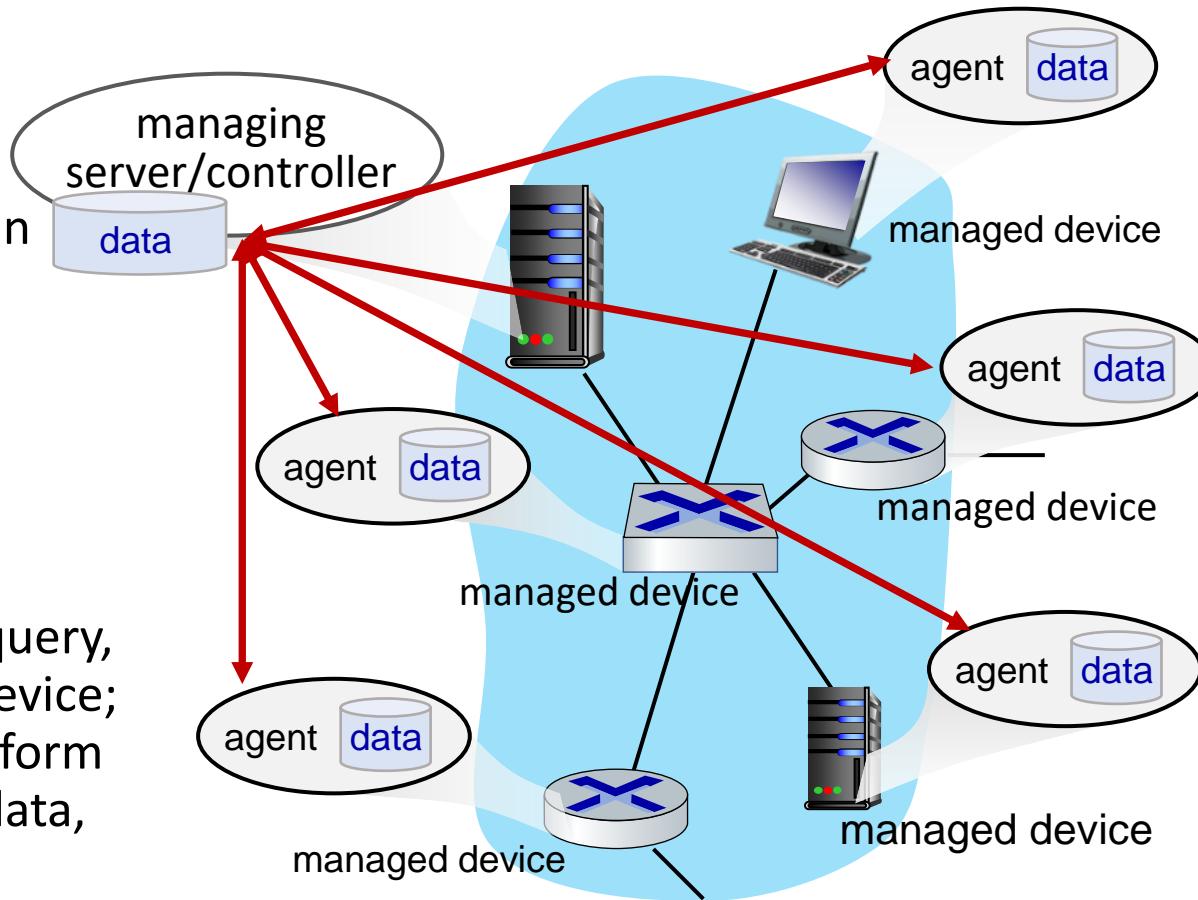
"Network management includes the *deployment, integration* and *coordination* of the *hardware, software*, and *human* elements to *monitor, test, poll, configure, analyze, evaluate*, and *control* the network and element resources to meet the real-time, operational performance, and Quality of Service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

# Components of network management

use to collect data from manage devices

**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)

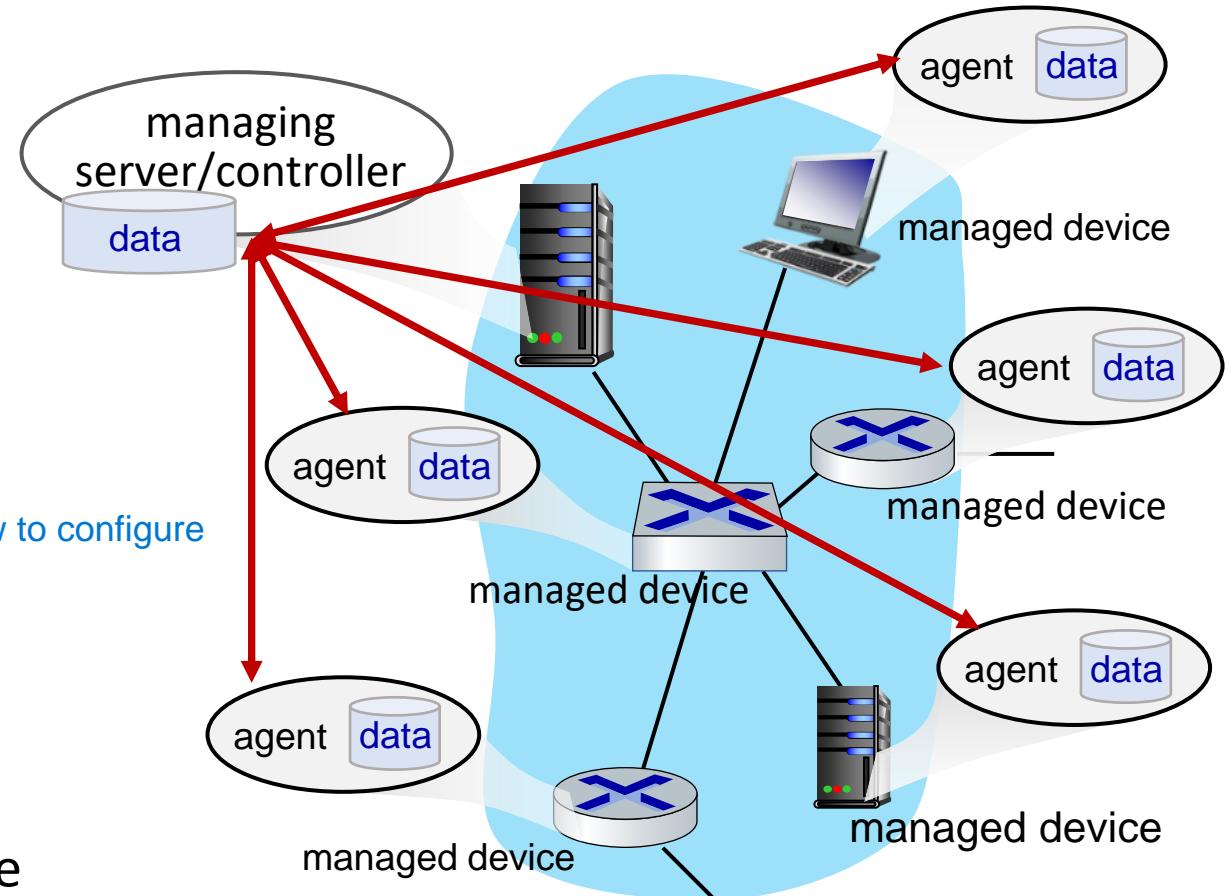
- operator issues (types, scripts) direct to individual devices (e.g., via ssh)

## SNMP/MIB

- operator queries/sets devices data (MIB) using Simple Network Management Protocol (SNMP)  
use in almost software in network connection

## NETCONF/YANG

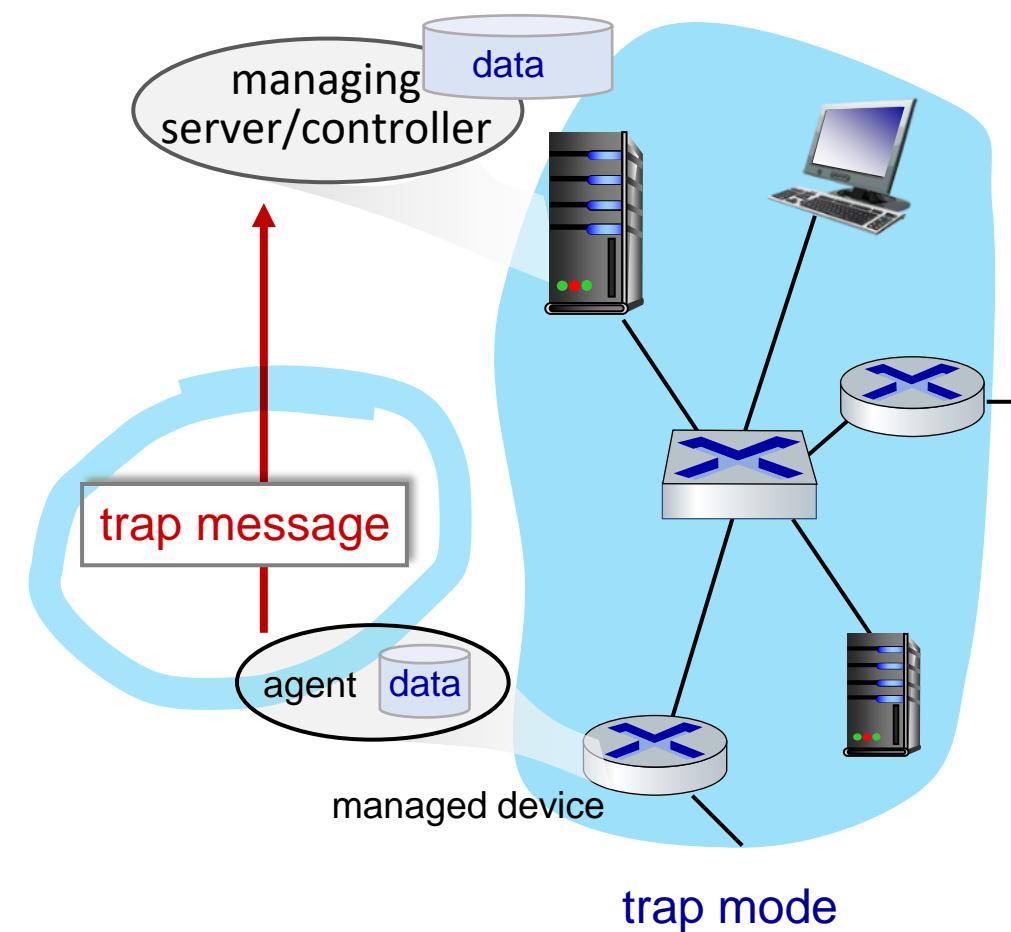
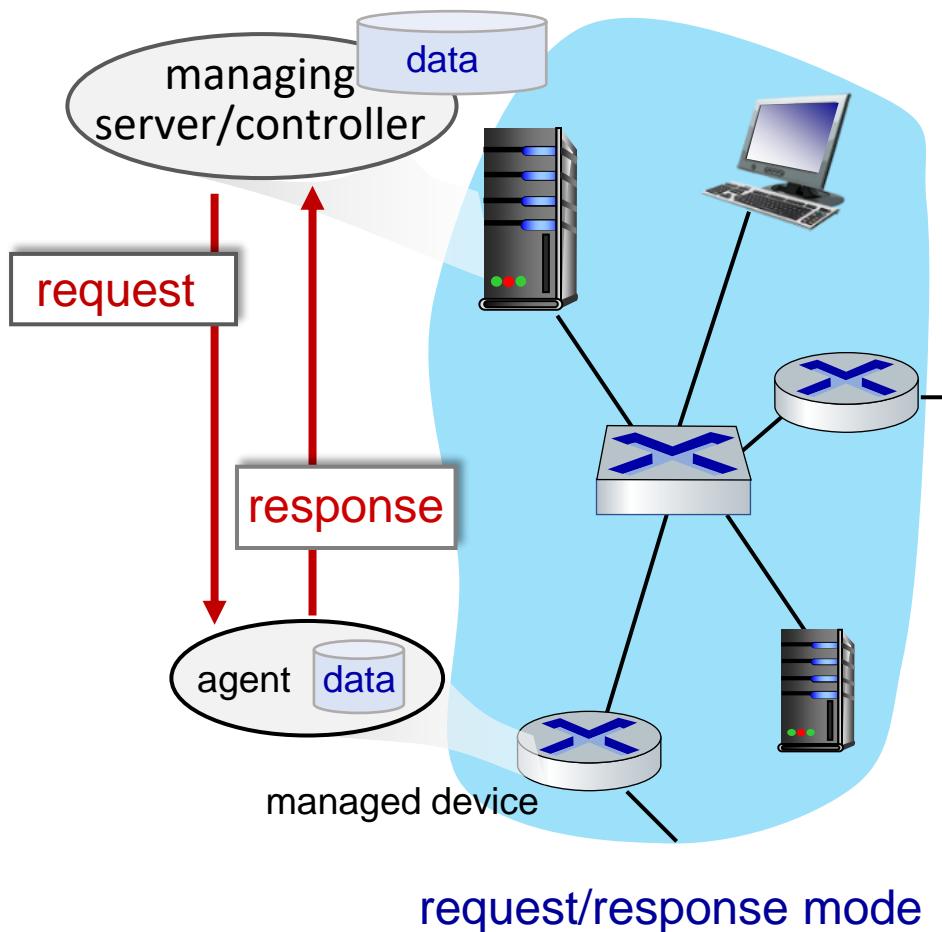
- more abstract, network-wide, holistic
- emphasis on multi-device configuration management.
- YANG: data modeling language
- NETCONF: communicate YANG-compatible actions/data to/from/among remote devices



# SNMP protocol

manager can send request to device, request for some information, and the information in MIB database, the device will provide information

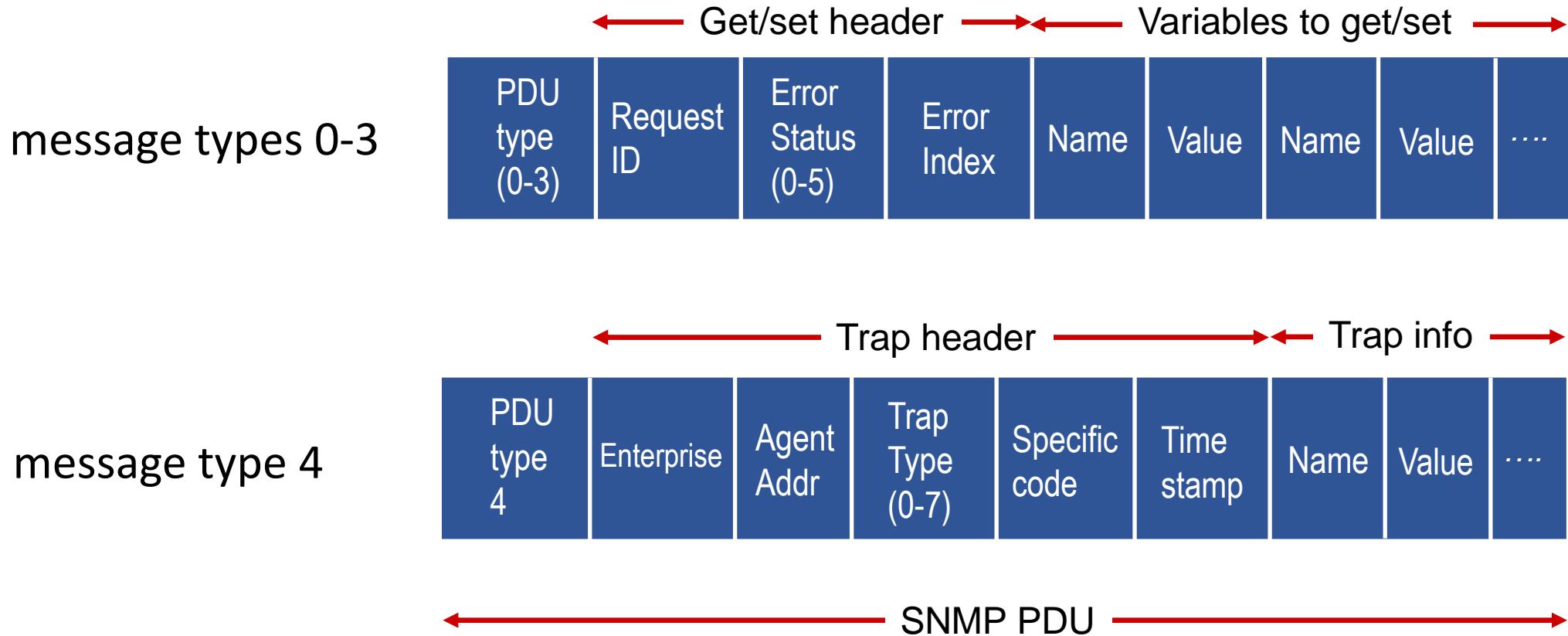
Two ways to convey MIB info, commands:



# 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:



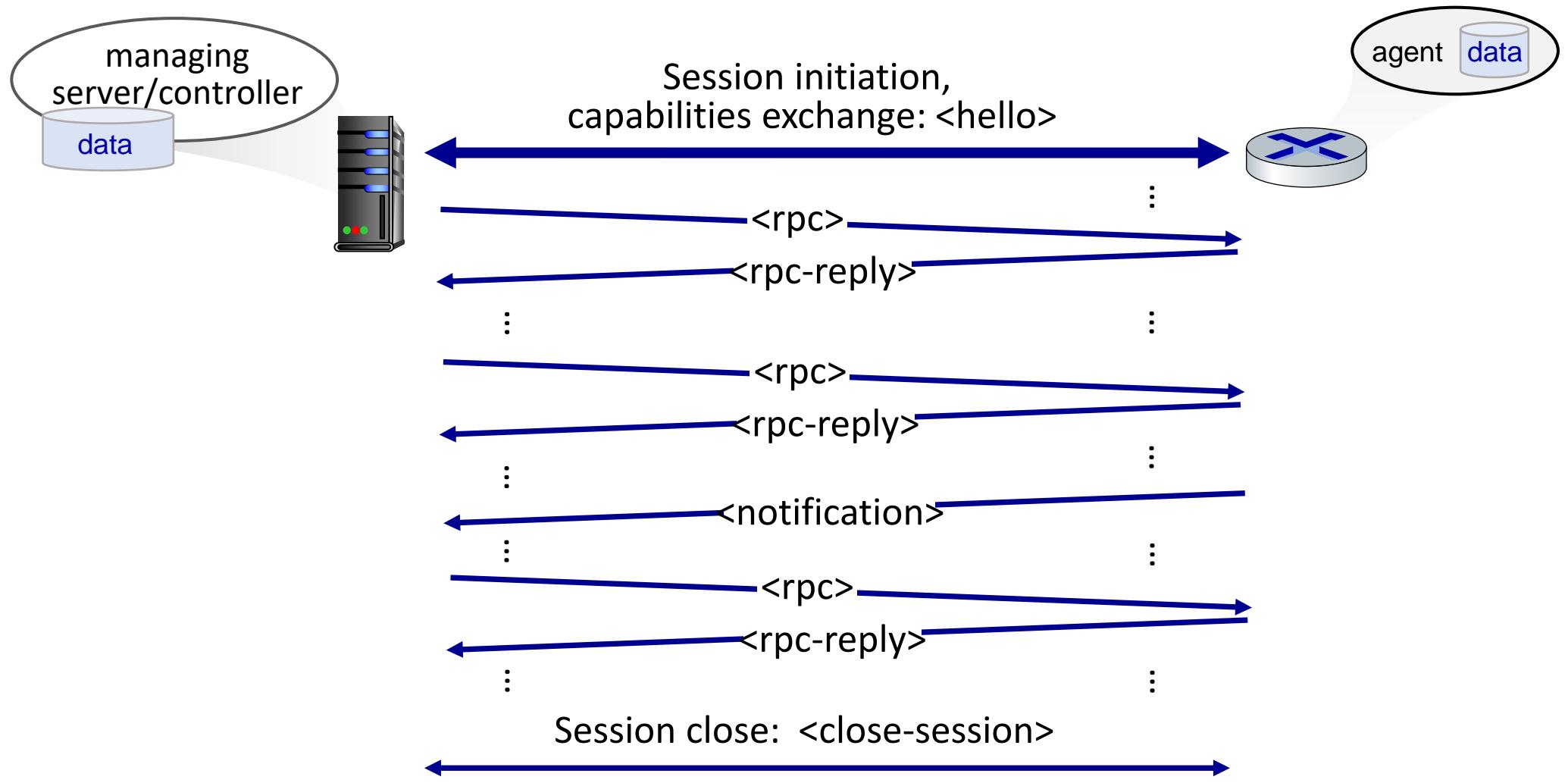
Object ID	Name	Type	Comments
1.3.6.1.2.1.7.1	UDPIInDatagrams	32-bit counter	total # datagrams delivered
1.3.6.1.2.1.7.2	UDPNoPorts	32-bit counter	# undeliverable datagrams (no application at port)
1.3.6.1.2.1.7.3	UDInErrors	32-bit counter	# undeliverable datagrams (all other reasons)
1.3.6.1.2.1.7.4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

next generation of network management

- **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



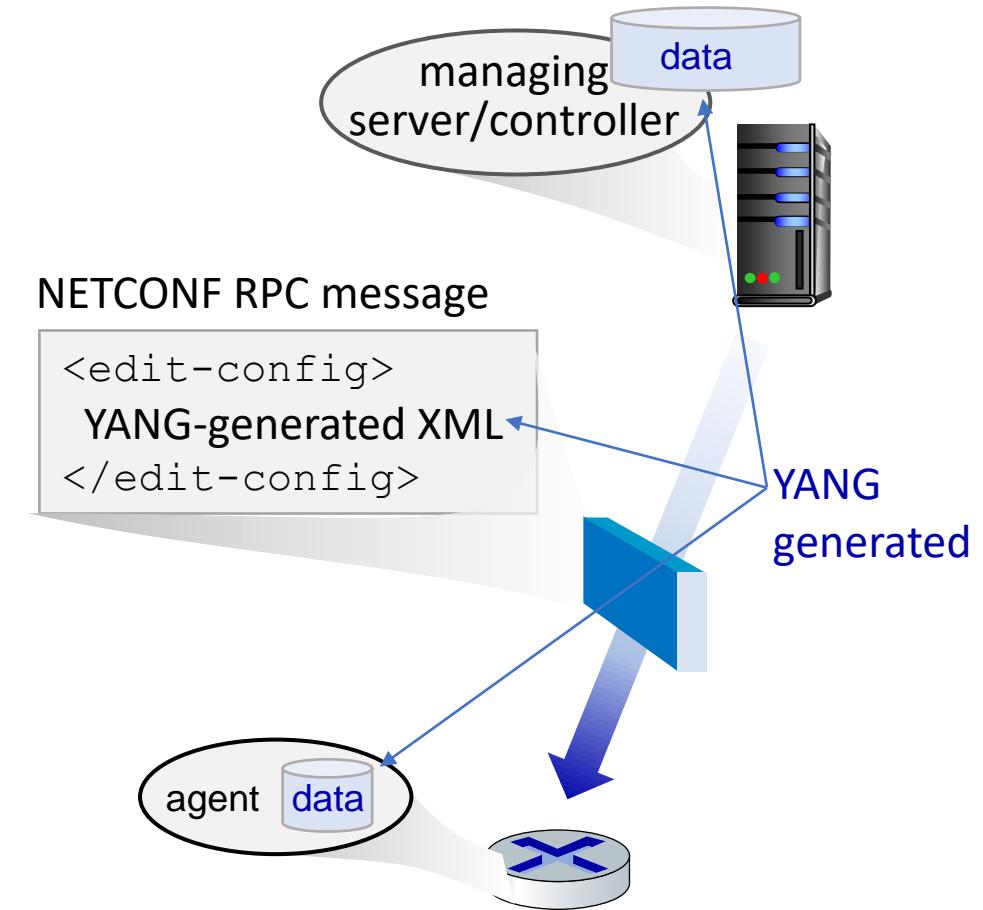
# Selected NETCONF Operations

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/
1.2/config">
10         <interface>
11           <name>Ethernet0/0</name> change MTU of Ethernet 0/0 interface to 1500
12           <mtu>1500</mtu>
13         </interface>
14       </top>
15     </config>
16   </edit-config>
17 </rpc>
```

- *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 (ICMP)
- network management (SNMP/SMI, NETCONF/YANG)

*next stop: link layer!*

# Network layer, control plane: Done!

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



- network management, configuration
  - SNMP
  - NETCONF/YANG

# Additional Chapter 5 slides

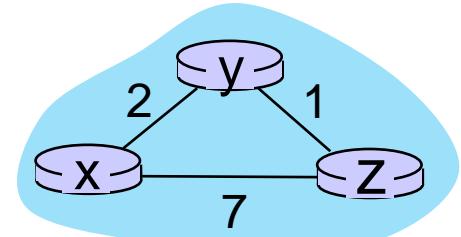
# Distance vector: another example

		cost to		
		x	y	z
from	x	0	2	7
	y	$\infty$	$\infty$	$\infty$
		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	$\infty$	$\infty$	$\infty$
	y	$\infty$	$\infty$	$\infty$
		7	1	0

time

# Distance vector: another example

