

# Chapter 5

## Network Layer:

# Control Plane

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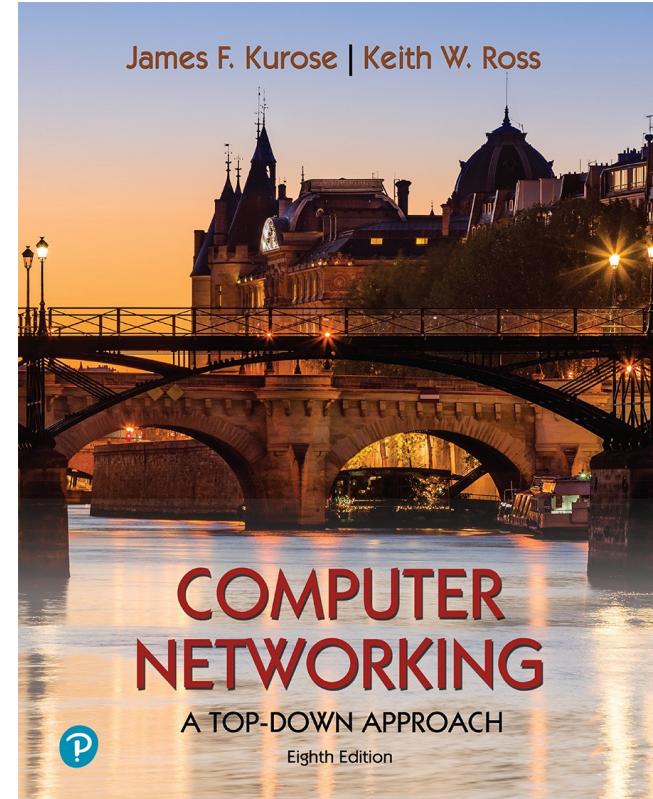
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**Computer Networking: A  
Top-Down Approach**  
8<sup>th</sup> edition  
Jim Kurose, Keith Ross  
Pearson, 2020

# Network layer: “control plane” roadmap

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



# Network-layer functions

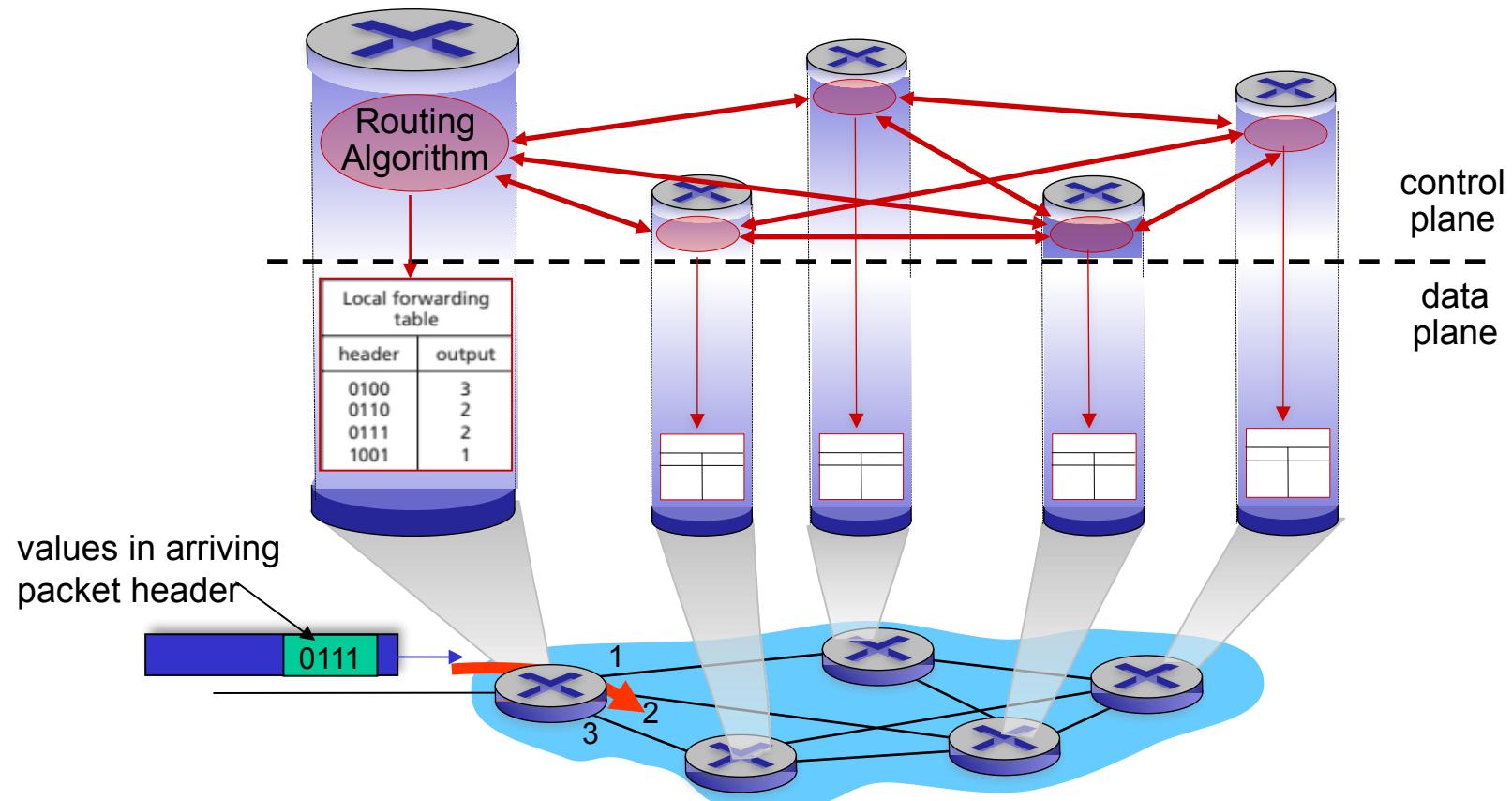
- **forwarding:** move packets from router's input to appropriate router output *data plane*
- **routing:** determine route taken by packets from source to destination *control plane*

Two approaches to structuring network control plane:

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

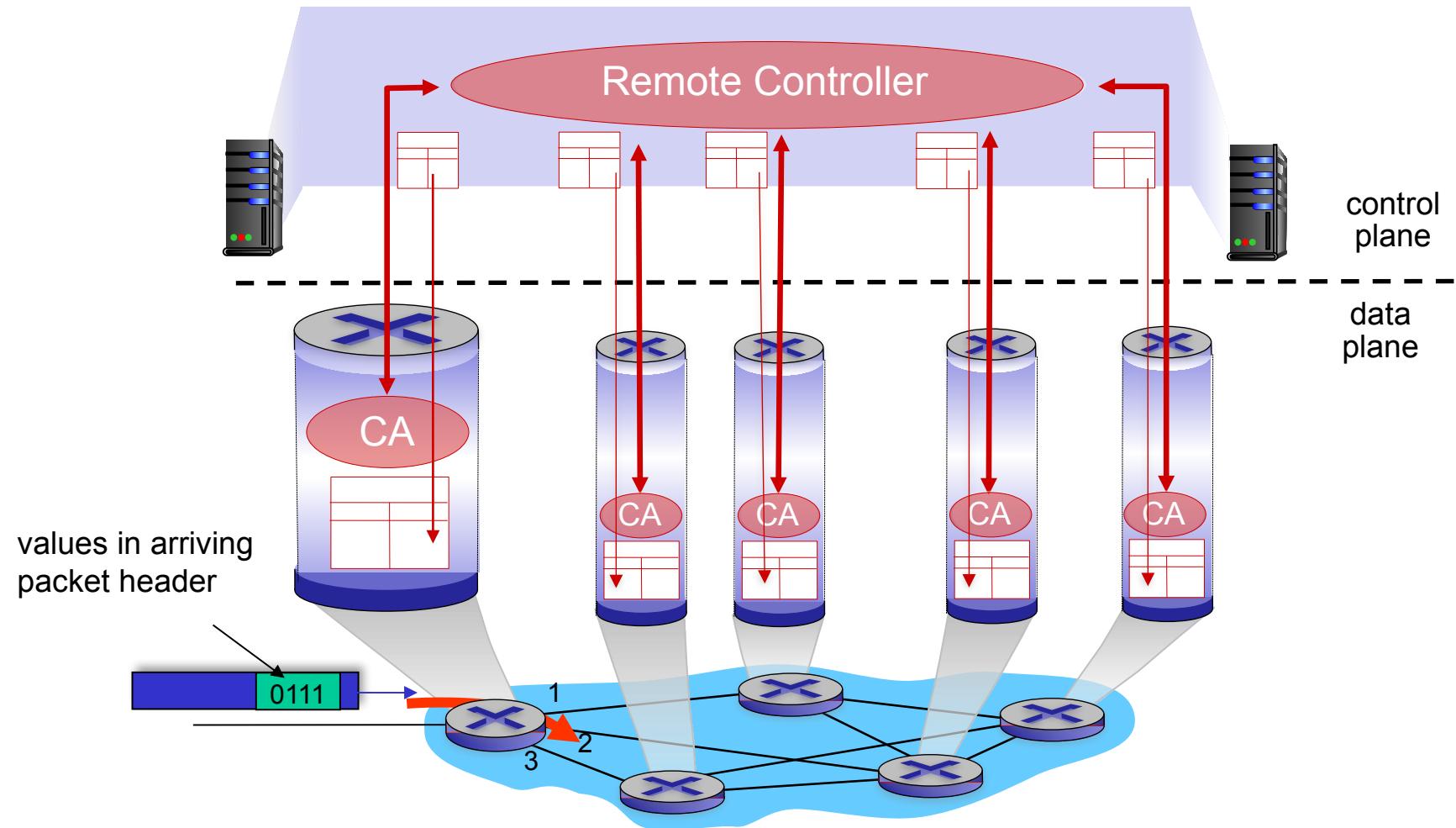
# Per-router control plane

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

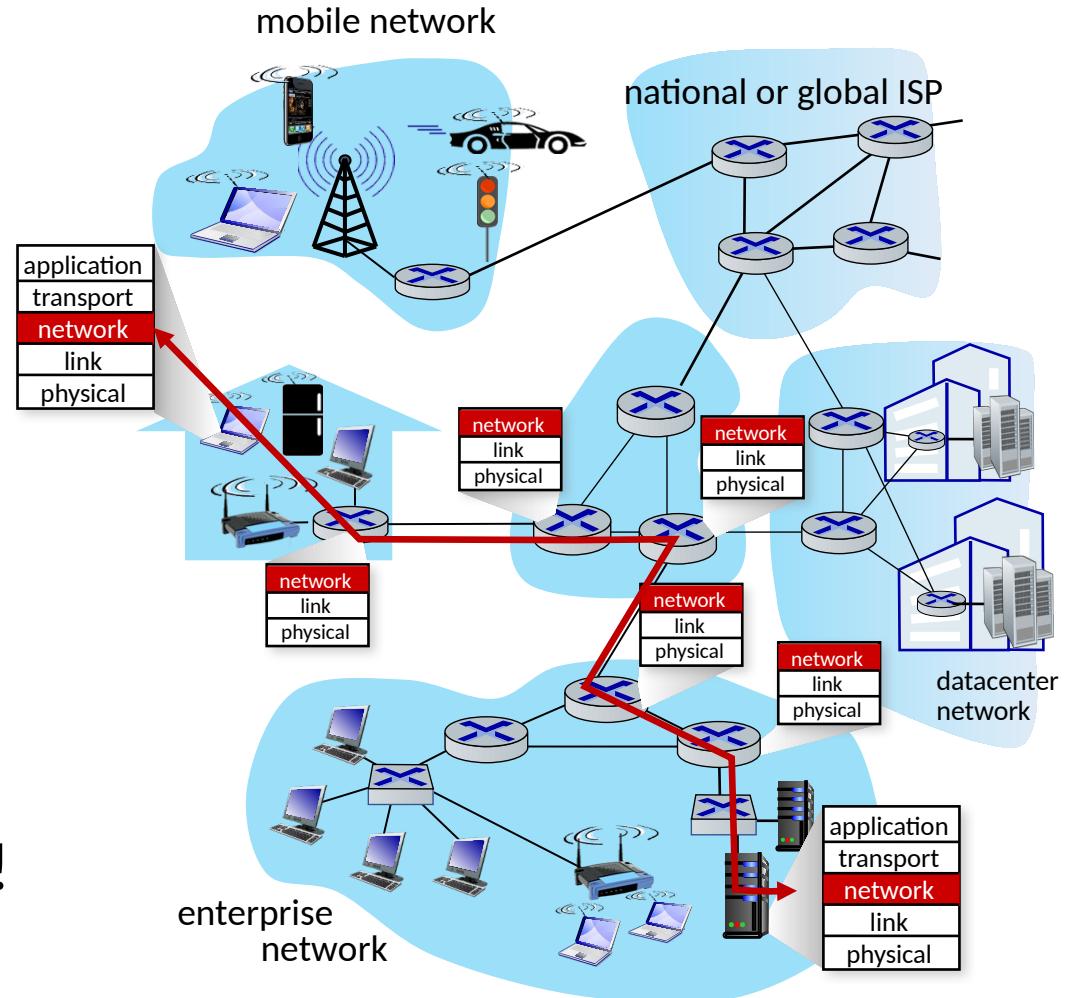
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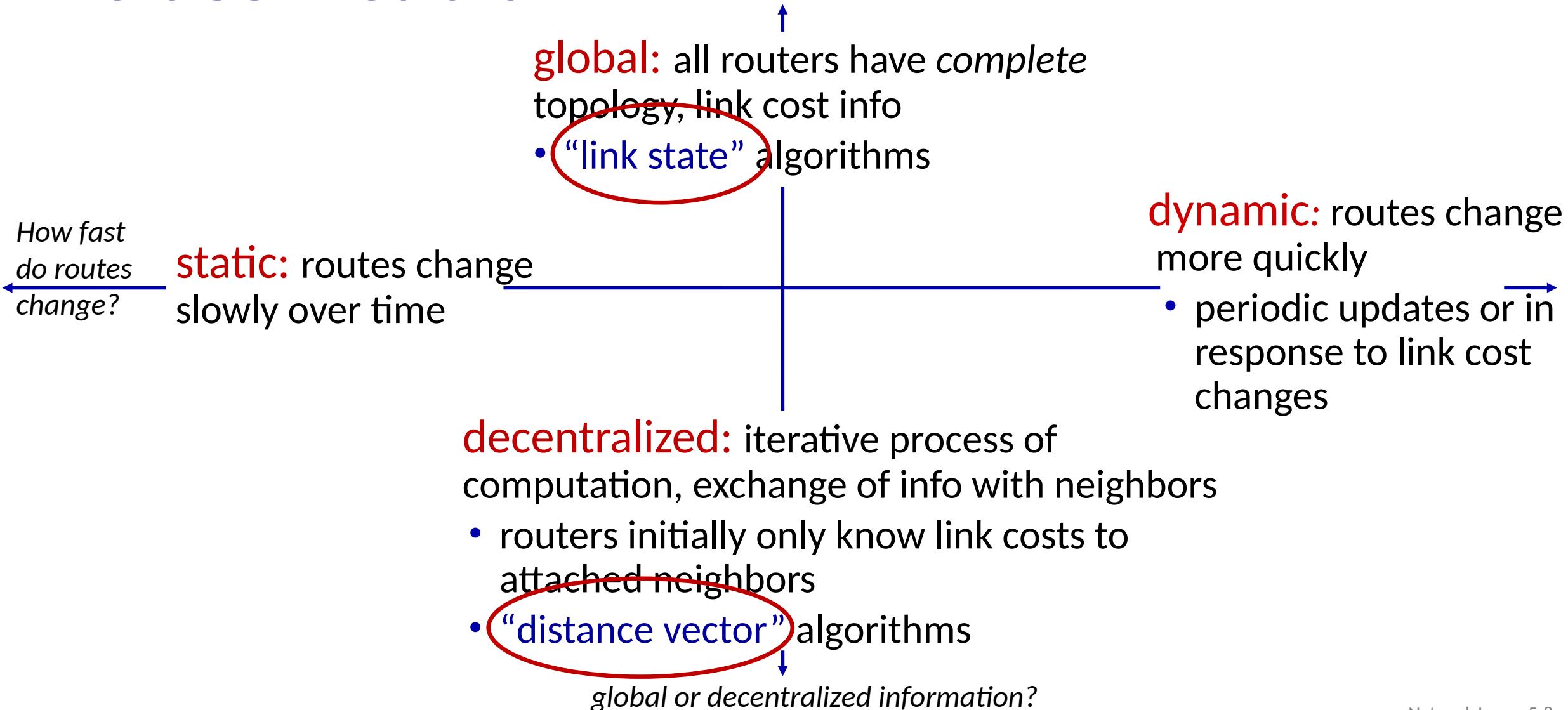
# Routing protocols

**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!



# Routing algorithm classification



# Classification of Dynamic Routing Protocols

## ■ Distance Vector Protocols

- Distance to destination
- Direction to reach destination
- Each router sends the neighboring router information about destination that it knows how to reach
- Does not have the knowledge of complete path
- Prone to Routing Loops

## ■ Link State Protocols

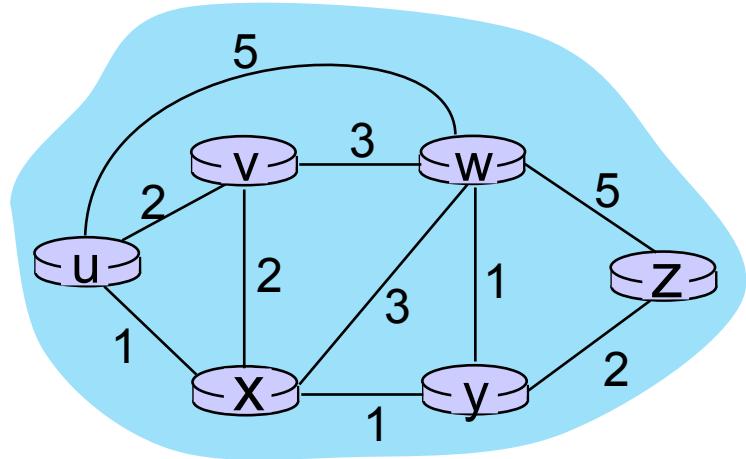
- Router does not provide information about the destination
- Provides information of the network topology
- Whether the link is active or not
- This information is flooded throughout the network
- No Routing Loops

# Network layer: “control plane” roadmap

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# 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

# Dijkstra's link-state routing algorithm

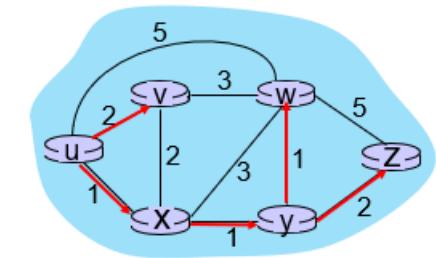
- **centralized:** network topology, link costs known to *all* nodes
  - accomplished via “link state broadcast”
  - all nodes have same info
- computes least cost paths from one node (“source”) to all other nodes
  - gives *forwarding table* for that node
- **iterative:** after  $k$  iterations, know 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

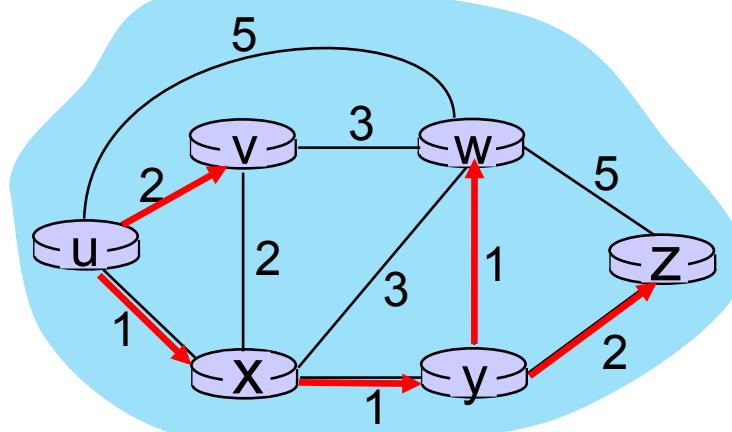
# Dijkstra's link-state routing algorithm

```
1 Initialization:
2    $N' = \{u\}$                                 /* compute least cost path from u to all other nodes */
3   for all nodes  $a$ 
4     if  $a$  adjacent to  $u$                   /*  $u$  initially knows direct-path-cost only to direct neighbors */
5       then  $D(a) = c_{u,a}$                   /* but may not be minimum cost! */ 
6     else  $D(a) = \infty$ 
7
8 Loop
9   find  $a$  not in  $N'$  such that  $D(a)$  is a minimum
10  add  $a$  to  $N'$ 
11  update  $D(b)$  for all  $b$  adjacent to  $a$  and not in  $N'$ :
12     $D(b) = \min(D(b), D(a) + c_{a,b})$ 
13  /* new least-path-cost to  $b$  is either old least-cost-path to  $b$  or known
14  least-cost-path to  $a$  plus direct-cost from  $a$  to  $b$  */
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	1, u	$\infty$	$\infty$
1	ux	2, u	4, x	2, x	$\infty$	$\infty$
2	uxy	2, u	3, y	4, y	4, y	4, y
3	uxyv	3, y	3, y	4, y	4, y	4, y
4	uxyvw					
5	uxyvwz					

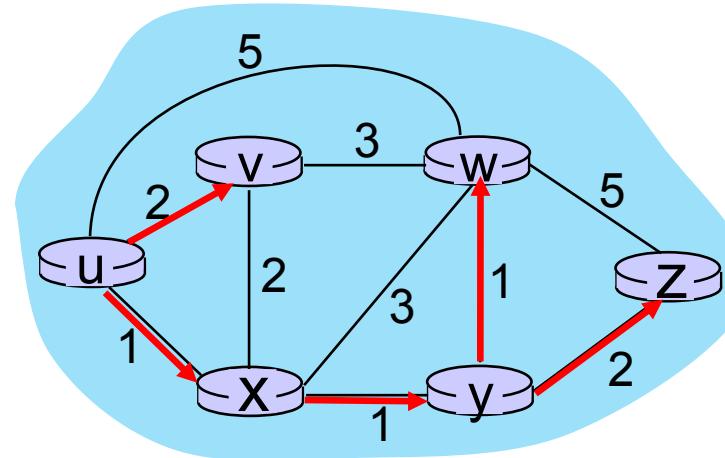


Initialization (step 0): For all  $a$ : if  $a$  adjacent to  $u$  then  $D(a) = c_{u,a}$

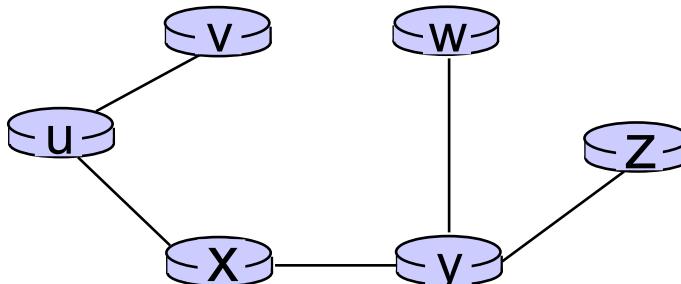
find  $a$  not in  $N'$  such that  $D(a)$  is a minimum  
 add  $a$  to  $N'$   
 update  $D(b)$  for all  $b$  adjacent to  $a$  and not in  $N'$  :  

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

# Dijkstra's algorithm: an example



resulting least-cost-path tree from u:



resulting forwarding table in u:

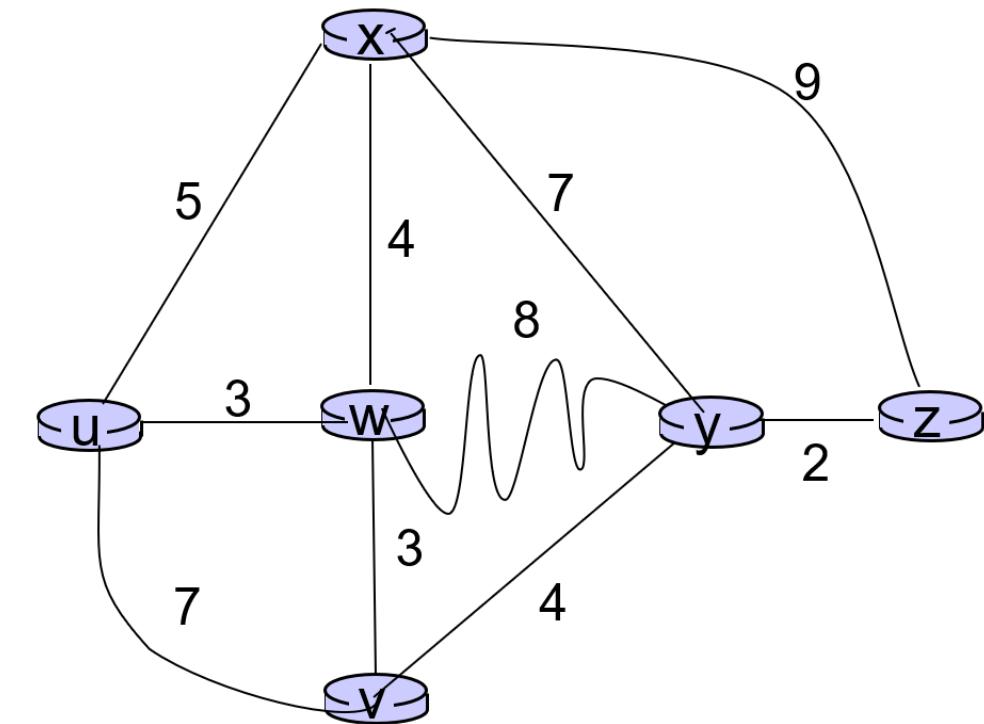
destination	outgoing link
v	(u,v)
x	(u,x)
y	(u,x)
w	(u,x)
x	(u,x)

route from  $u$  to  $v$  directly

route from  $u$  to all other destinations via  $x$

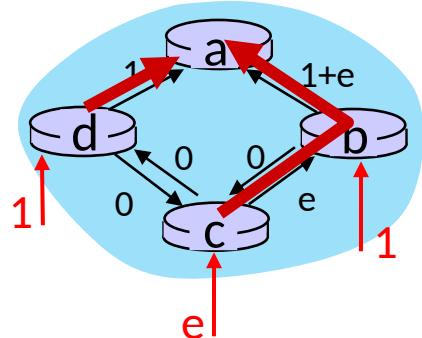
# Dijkstra's algorithm: another example

Step	$N'$	$v$ $D(v), p(v)$	$w$ $D(w), p(w)$	$x$ $D(x), p(x)$	$y$ $D(y), p(y)$	$z$ $D(z), p(z)$
0	$u$					
1						
2						
3						
4						
5						

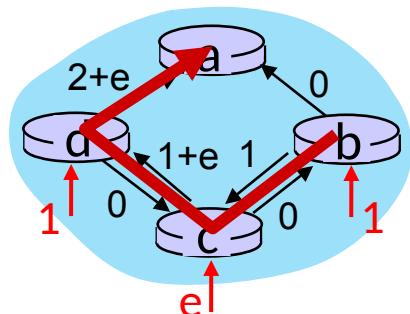


# Dijkstra's algorithm: oscillations possible

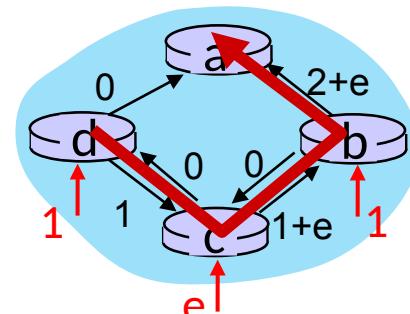
- when link costs depend on traffic volume, **route oscillations** possible
  - sample scenario:
    - routing to destination a, traffic entering at d, c, e with rates 1, e (<1), 1
    - link costs are directional, and volume-dependent



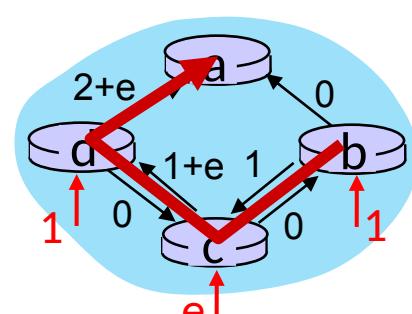
initially



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



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



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

# Network layer: “control plane” roadmap

- introduction
- routing protocols
  - link state
  - **distance vector**
- intra-ISP routing: OSPF
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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:

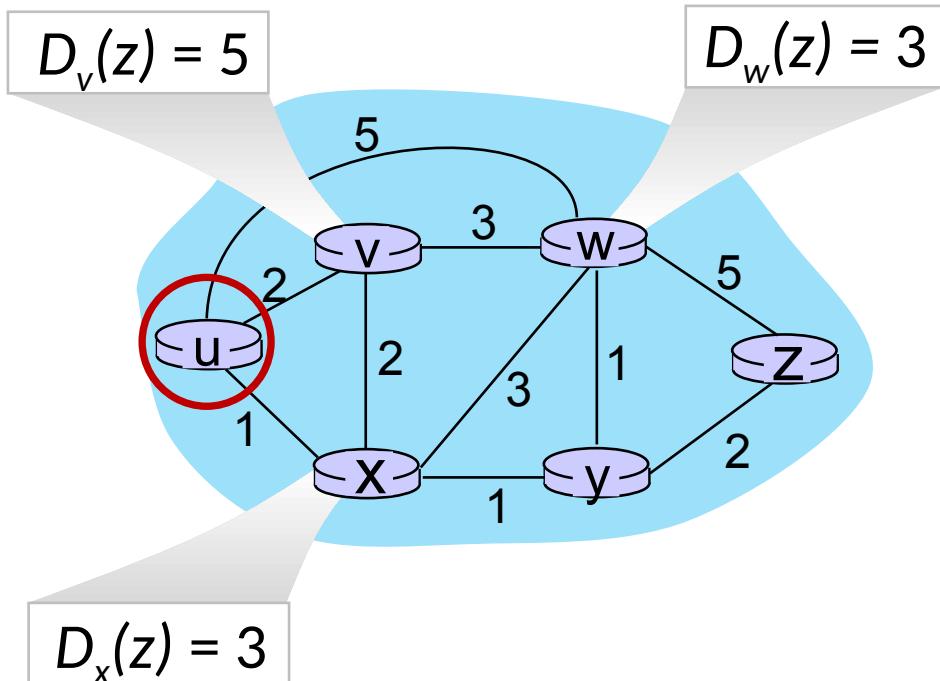
$$D_x(y) = \min_v \{ c_{x,v} + D_v(y) \}$$

*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:

$$\begin{aligned} D_u(z) &= \min \{ c_{u,v} + D_v(z), \\ &\quad c_{u,w} + D_w(z), \\ &\quad c_{u,x} + D_x(z) \} \\ &= \min \{ 2 + 5, \\ &\quad 1 + 3, \\ &\quad 5 + 3 \} = 4 \end{aligned}$$

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

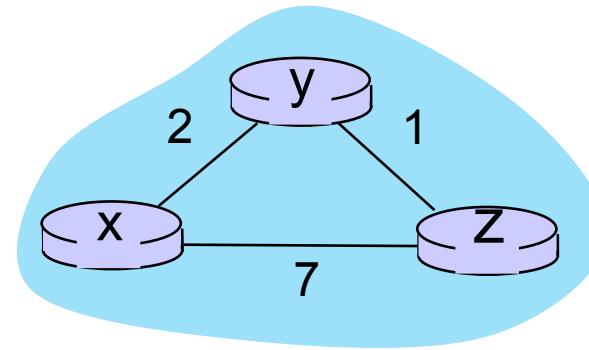
**iterative, asynchronous:** each local iteration caused by:

- local link cost change
- DV update message from neighbor

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

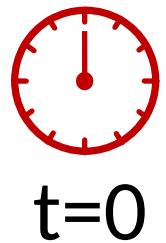
- neighbors then notify their neighbors – *only if necessary*
- no notification received, no actions taken!

# Distance vector: Example



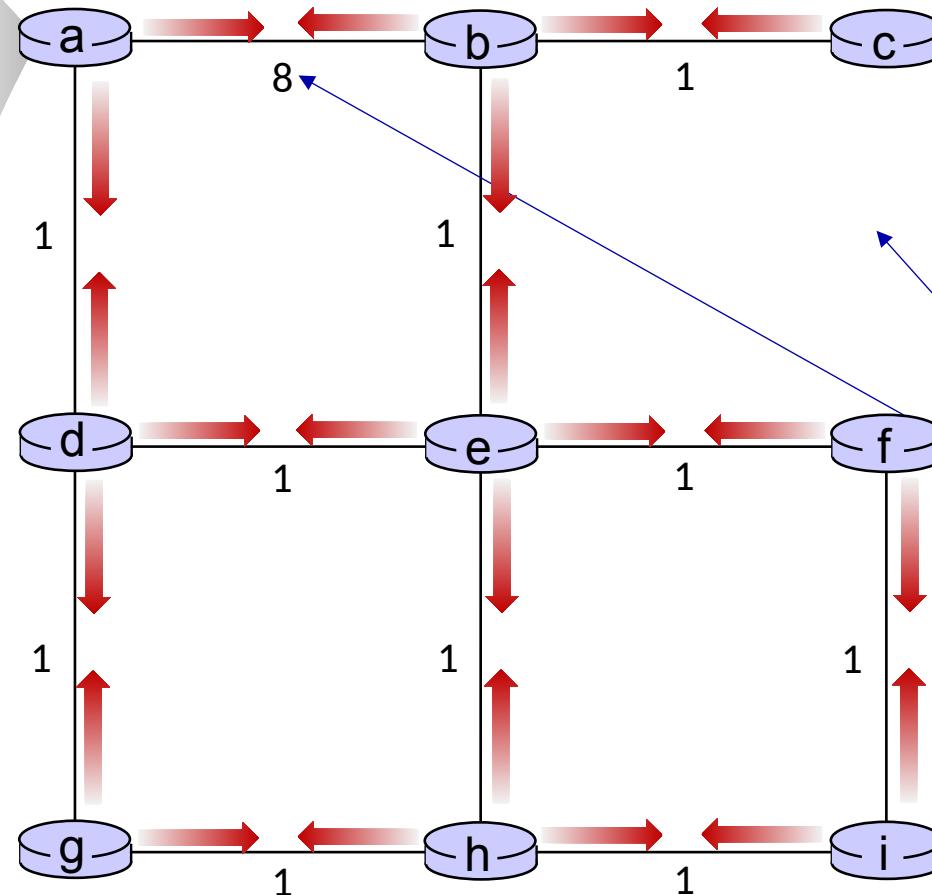
*time*

# Distance vector: example



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

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



- A few asymmetries:
  - missing link
  - larger cost

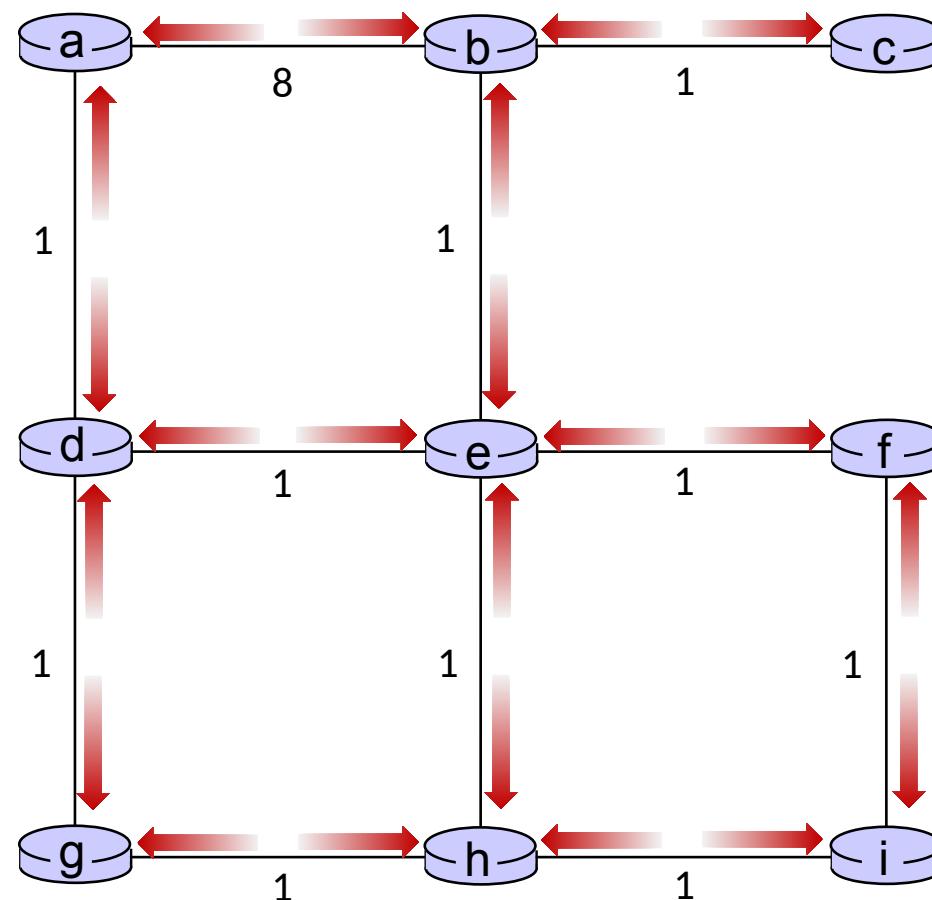
# Distance vector example: iteration



$t=1$

All nodes:

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



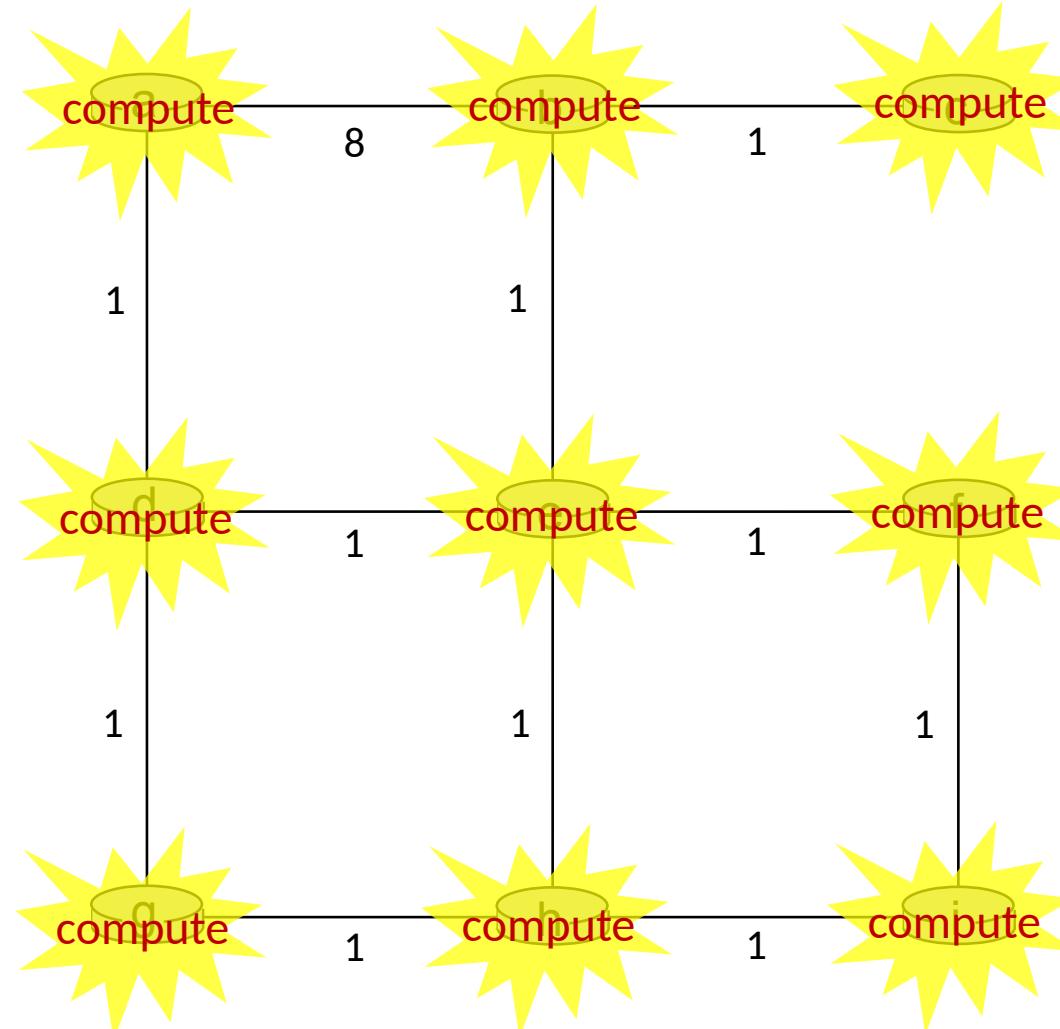
# Distance vector example: iteration



$t=1$

All nodes:

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



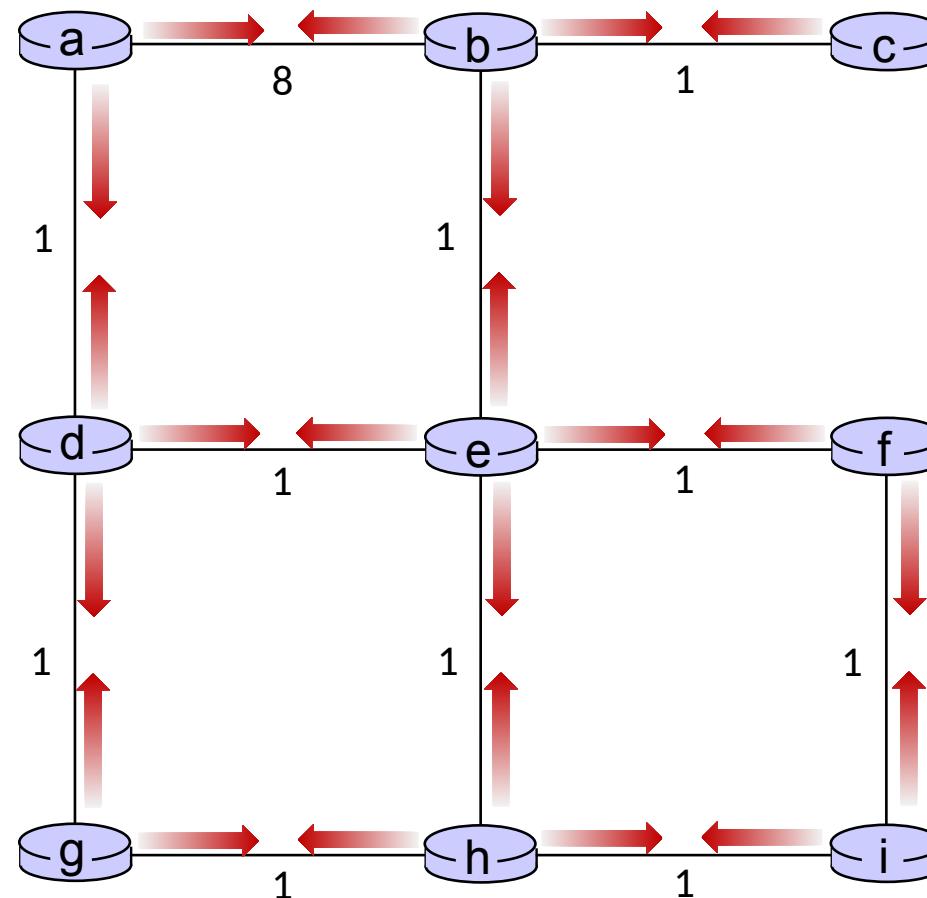
# Distance vector example: iteration



$t=1$

All nodes:

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



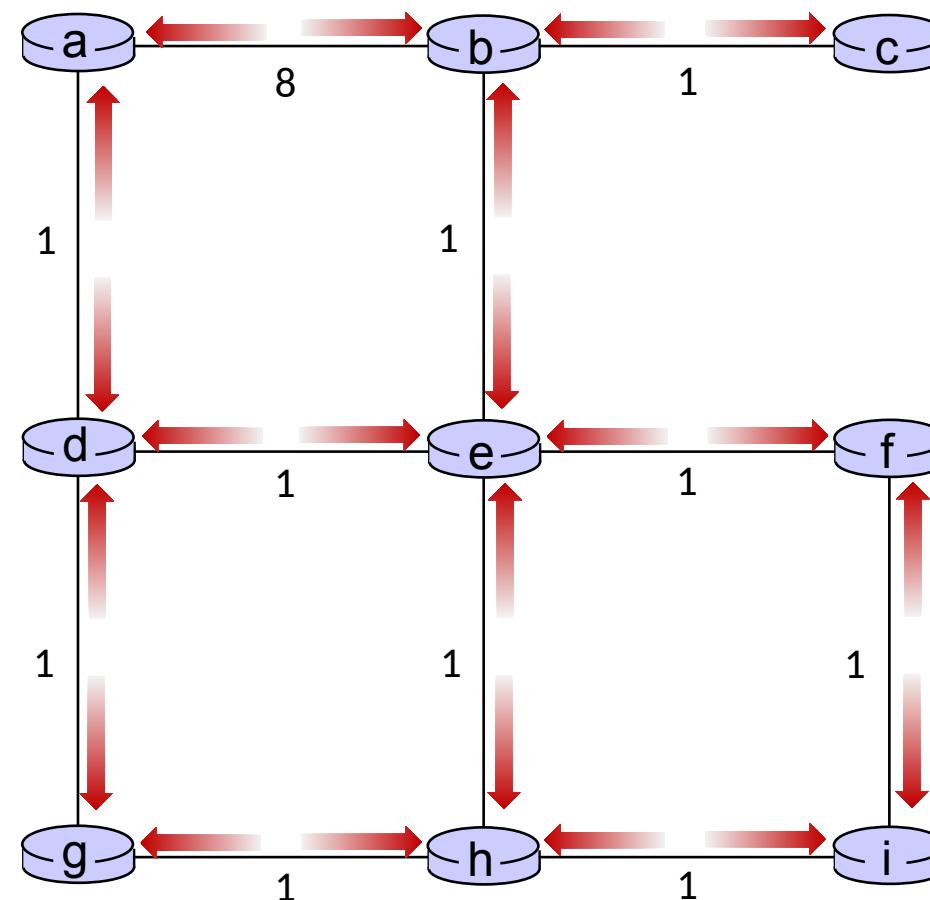
# Distance vector example: iteration



$t=2$

All nodes:

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



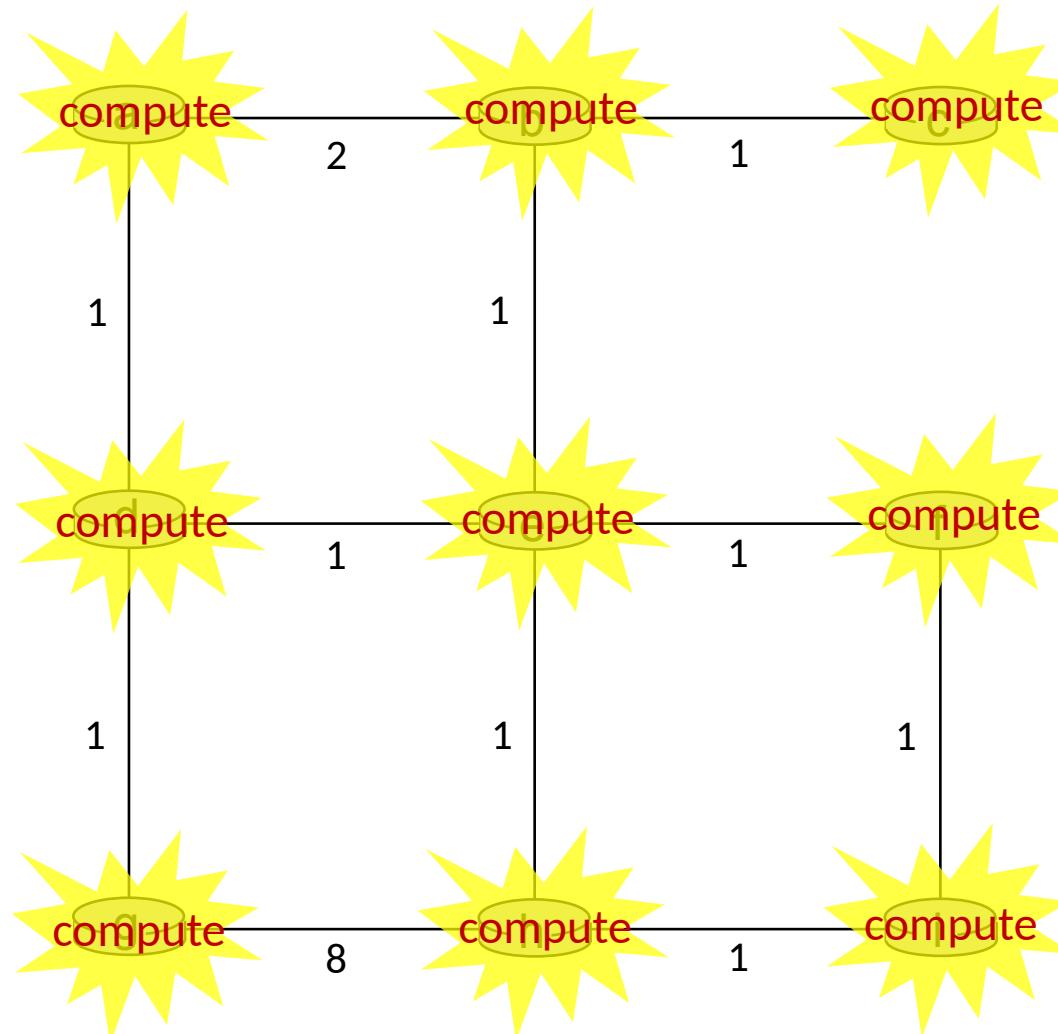
# Distance vector example: iteration



$t=2$

All nodes:

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



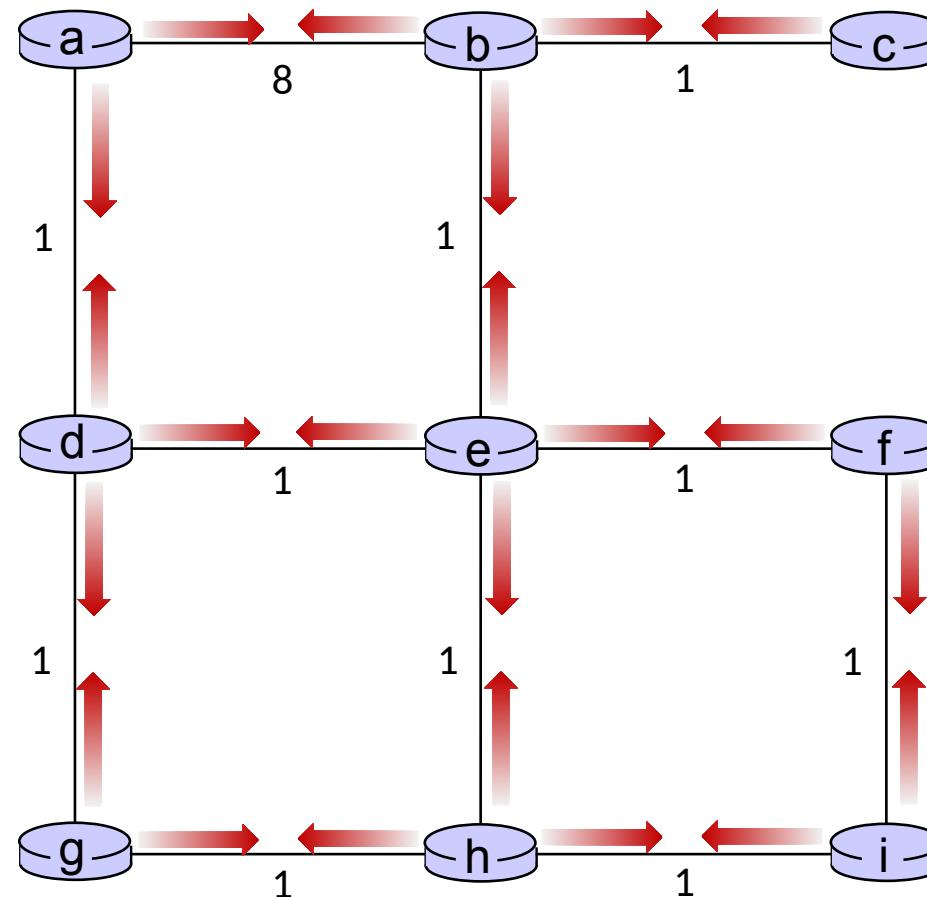
# Distance vector example: iteration



$t=2$

All nodes:

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



# Distance vector example: iteration

.... and so on

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

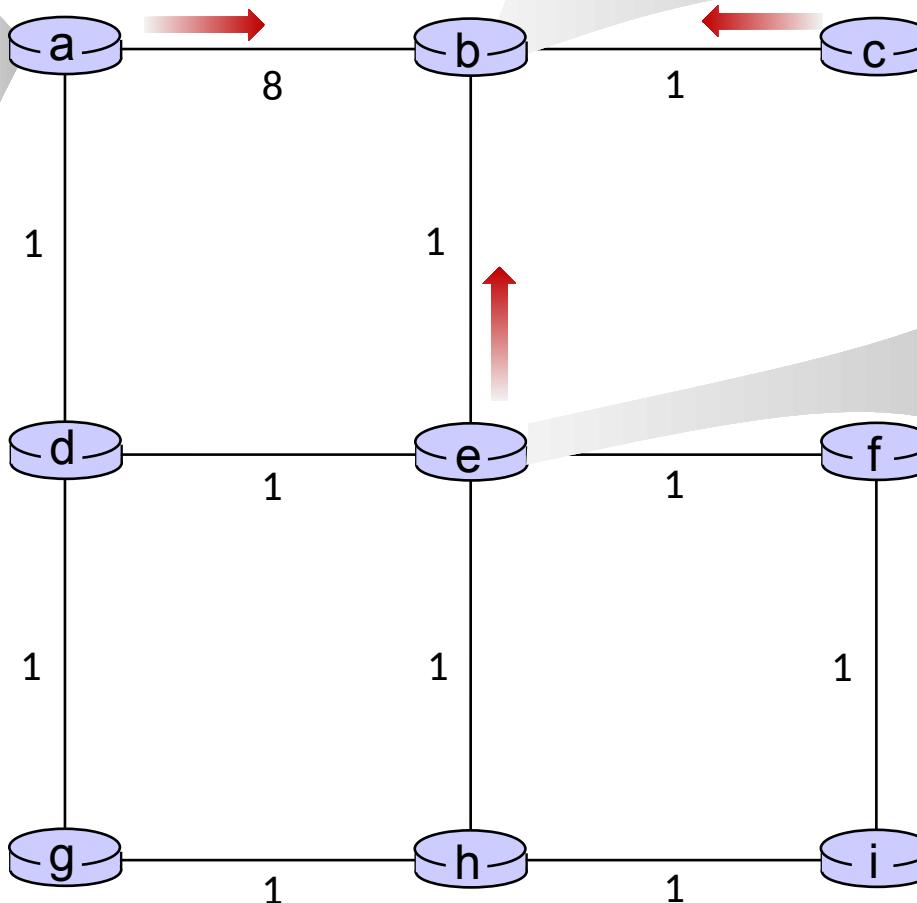
# Distance vector example: computation



$t=1$

- 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: computation

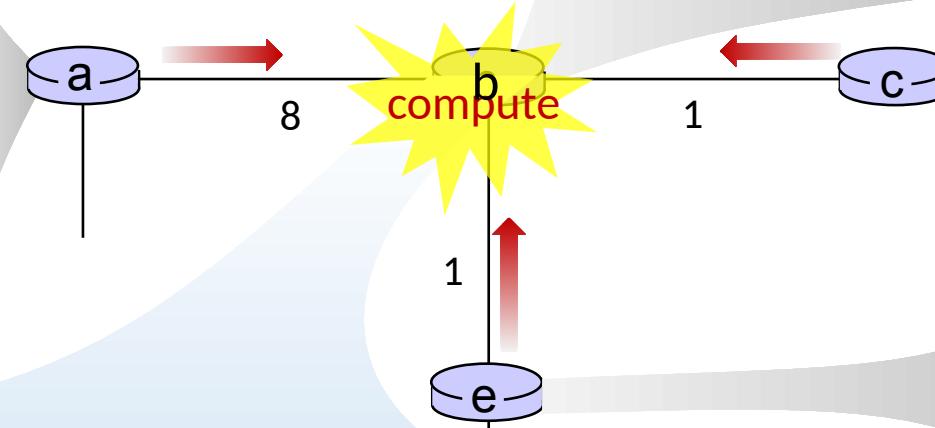


$t=1$

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

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

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



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

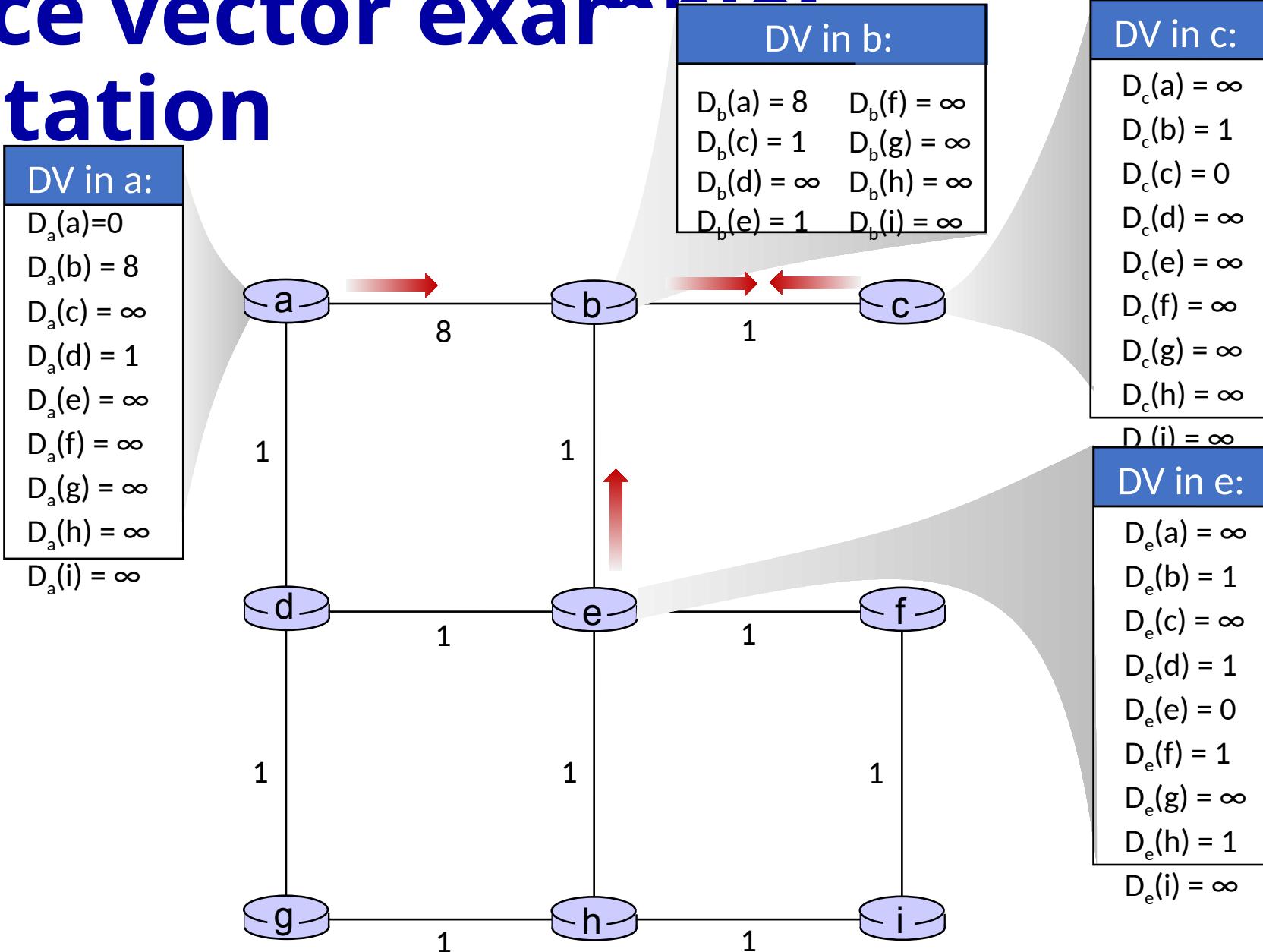
DV in b:	
$D_b(a) = 8$	$D_b(f) = 2$
$D_b(c) = 1$	$D_b(g) = \infty$
$D_b(d) = 2$	$D_b(h) = 2$
$D_b(e) = 1$	$D_b(i) = \infty$

# Distance vector example: computation



$t=1$

- c receives DVs from b



# Distance vector example: computation

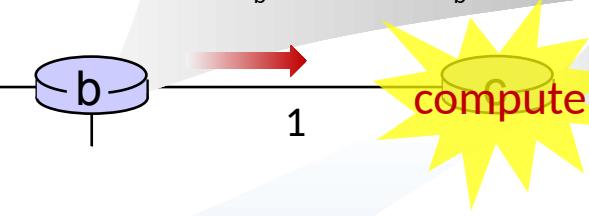


t=1

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



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

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

\* Check out the online interactive exercises for more examples:  
[http://gaia.cs.umass.edu/kurose\\_ross/interactive/](http://gaia.cs.umass.edu/kurose_ross/interactive/)

# Distance vector example: computation

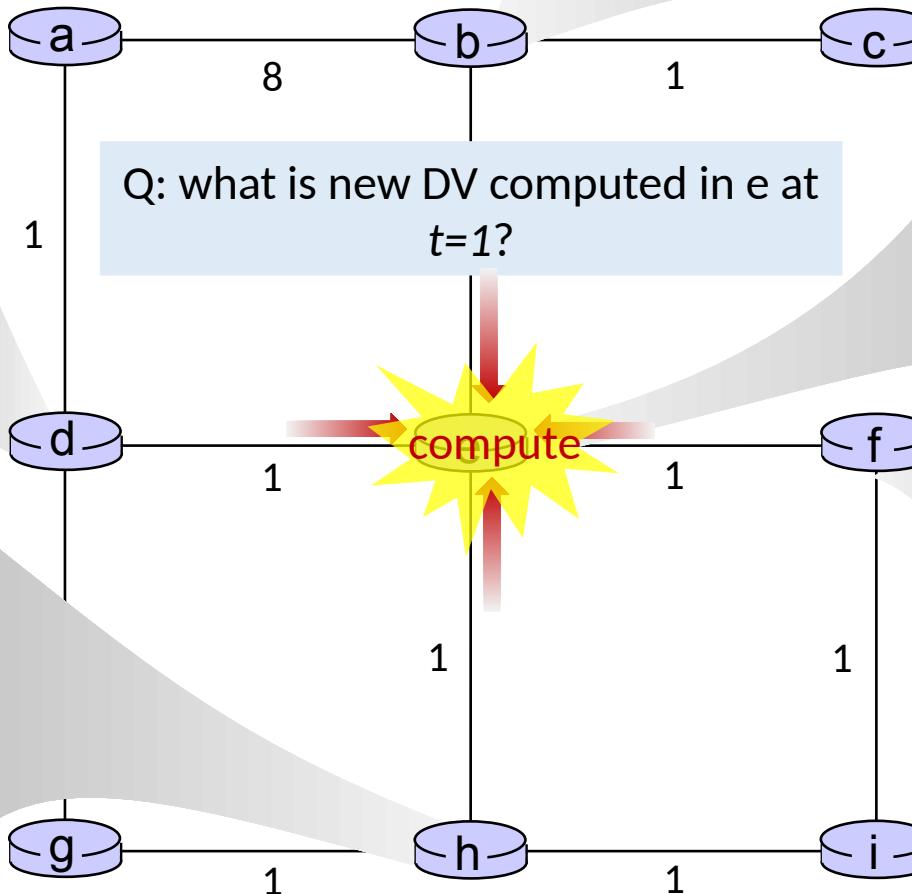


$t=1$

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

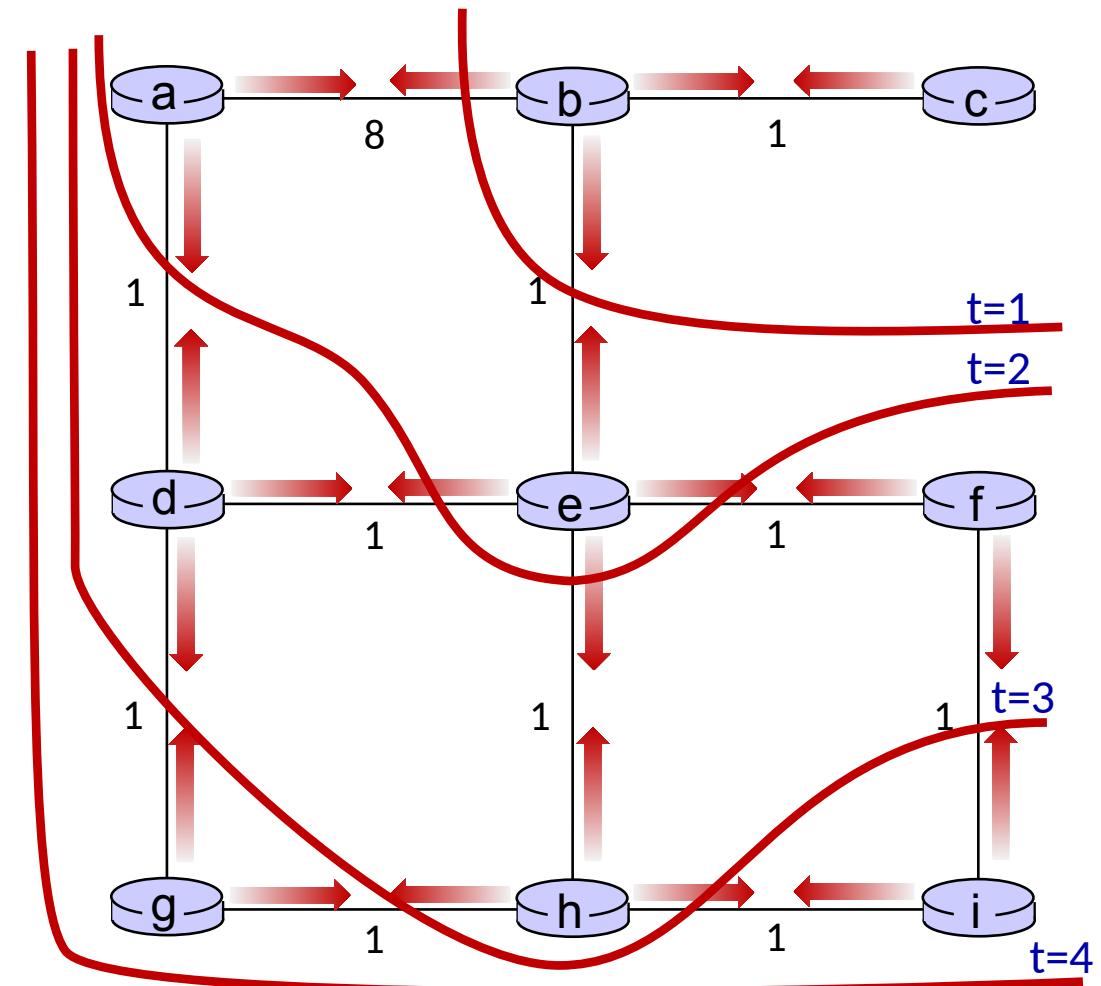
DV in e:
$D_e(a) = \infty$
$D_e(b) = 1$
$D_e(c) = \infty$
$D_e(d) = 1$
$D_e(e) = 0$
$D_e(f) = 1$
$D_e(g) = \infty$
$D_e(h) = 1$
$D_e(i) = \infty$

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:

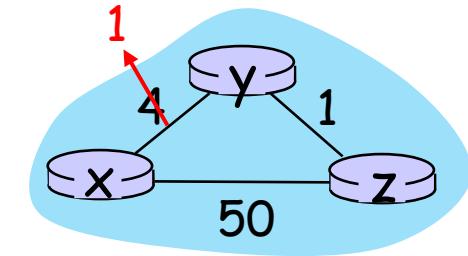
-  t=0 c's state at t=0 is at c only
-  t=1 c's state at t=0 has propagated to b, and may influence distance vector computations up to **1** hop away, i.e., at b
-  t=2 c's state at t=0 may now influence distance vector computations up to **2** hops away, i.e., at b and now at a, e as well
-  t=3 c's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

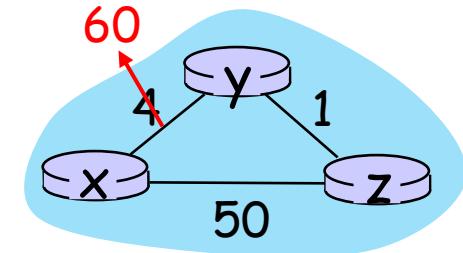
**“good news travels fast”**       $t_1$ : z receives update from y, updates its table, computes new least cost to x , sends its neighbors its DV.

$t_2$ : 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!*

# Network layer: “control plane” roadmap

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



# 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”)*

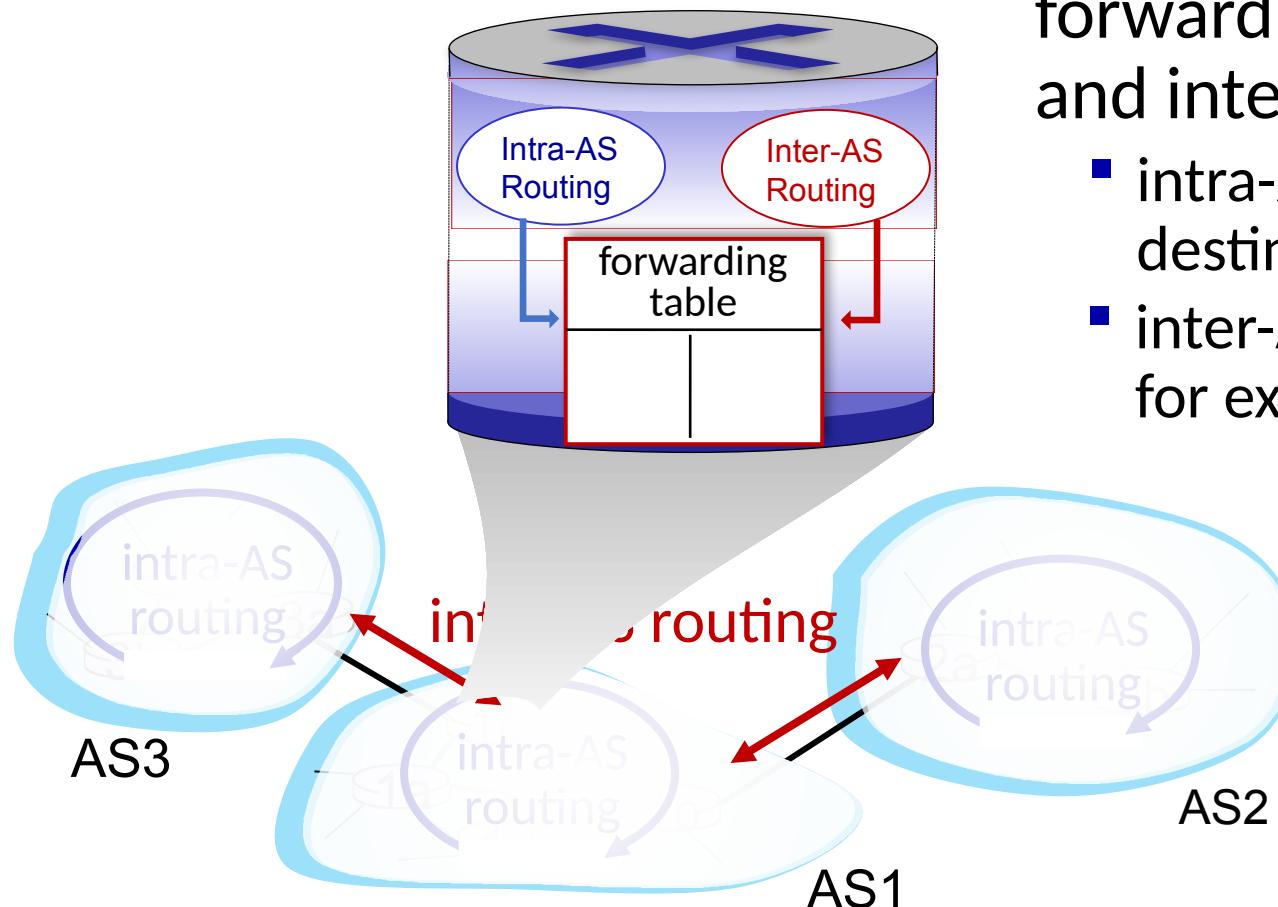
- all routers in AS must run same intra-domain protocol
- routers in different AS can run different intra-domain routing protocols
- **gateway router:** at “edge” of its own AS, has link(s) to router(s) in other AS'es

**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

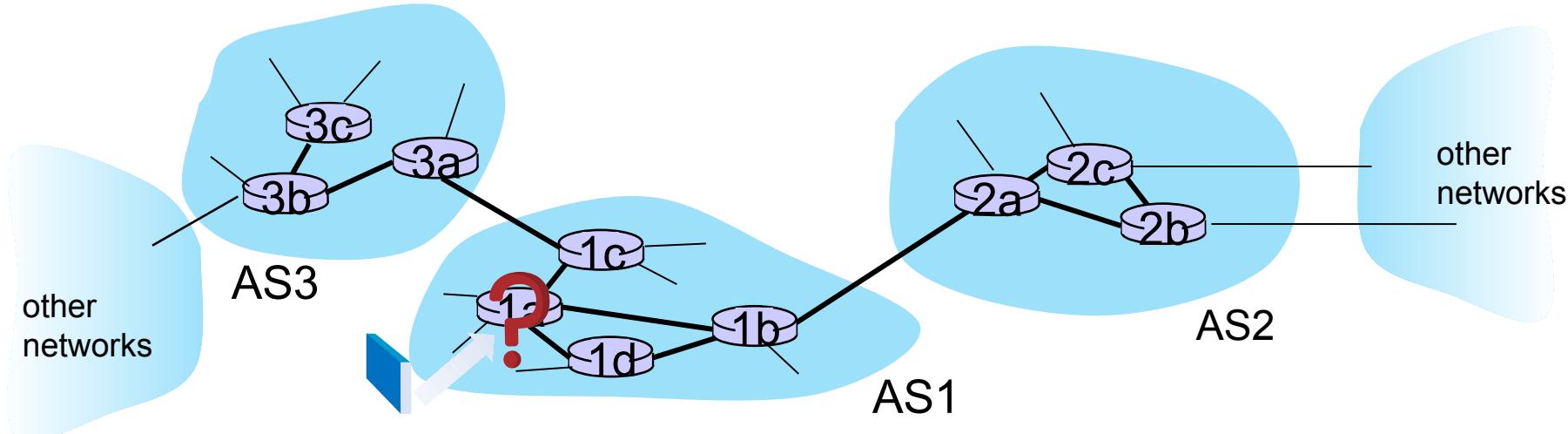
- intra-AS routing determine entries for destinations within AS
- inter-AS & intra-AS determine entries for external destinations

# Inter-AS routing: a role in intradomain forwarding

- 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:

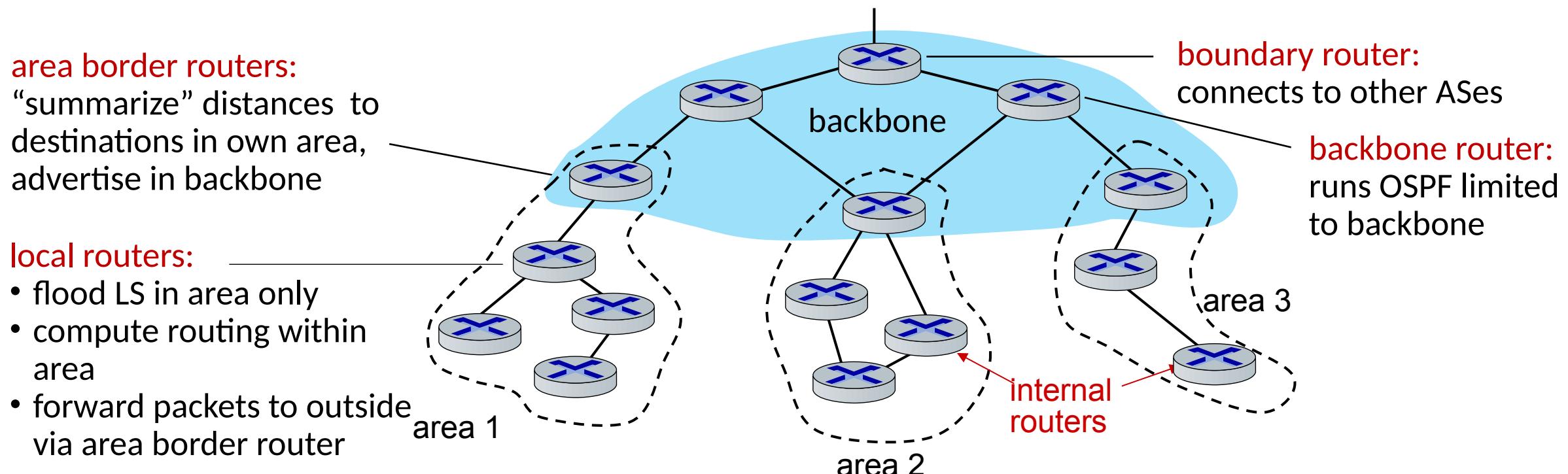
- **RIP: Routing Information Protocol [RFC 1723]**
  - classic DV: DVs exchanged every 30 secs
  - no longer widely used
- **EIGRP: Enhanced Interior Gateway Routing Protocol**
  - DV based
  - formerly Cisco-proprietary for decades (became open in 2013 [RFC 7868])
- **OSPF: Open Shortest Path First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

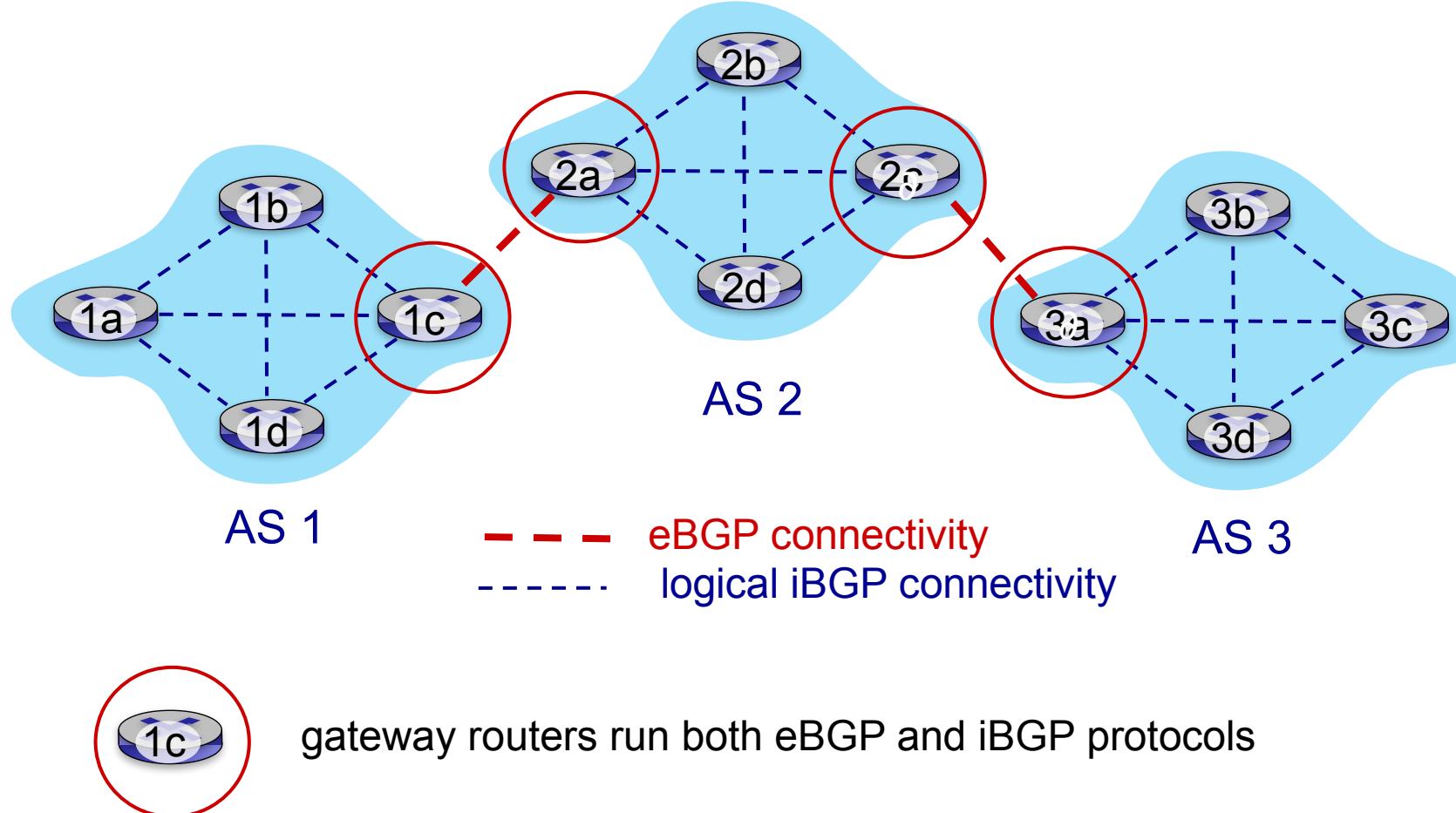
- introduction
- routing protocols
- intra-ISP routing: OSPF
- **routing among ISPs: BGP**
- Internet Control Message Protocol



# Internet inter-AS routing: BGP

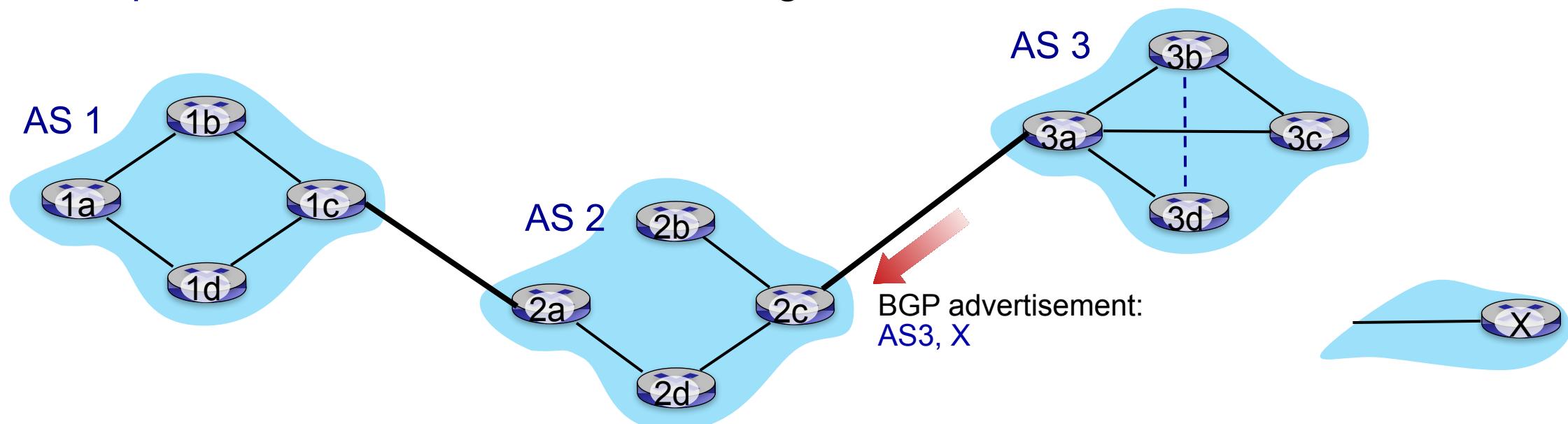
- BGP (Border Gateway Protocol): *the de facto inter-domain routing protocol*
  - “glue that holds the Internet together”
- allows subnet to advertise its existence, and the destinations it can reach, to rest of Internet: *“I am here, here is who I can reach, and how”*
- BGP provides each AS a means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

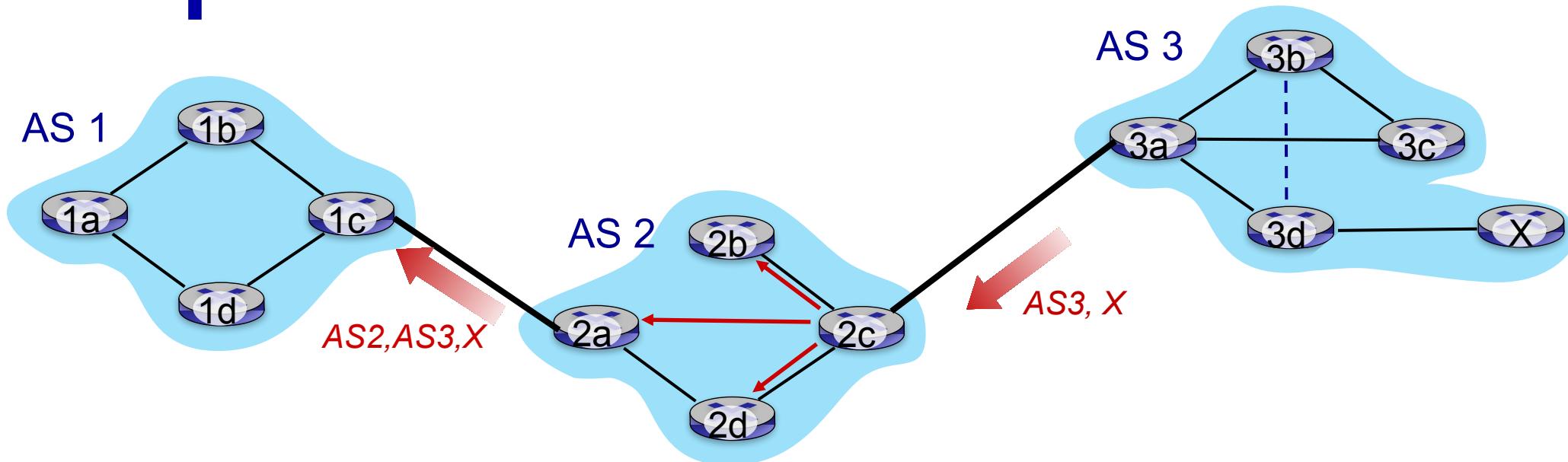
- **BGP session:** two BGP routers (“peers”) exchange BGP messages over semi-permanent TCP connection:
  - advertising *paths* to different destination network prefixes (BGP is a “path vector” protocol)
- when AS3 gateway 3a advertises **path AS3,X** to AS2 gateway 2c:
  - AS3 *promises* to AS2 it will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



# Path attributes and BGP routes

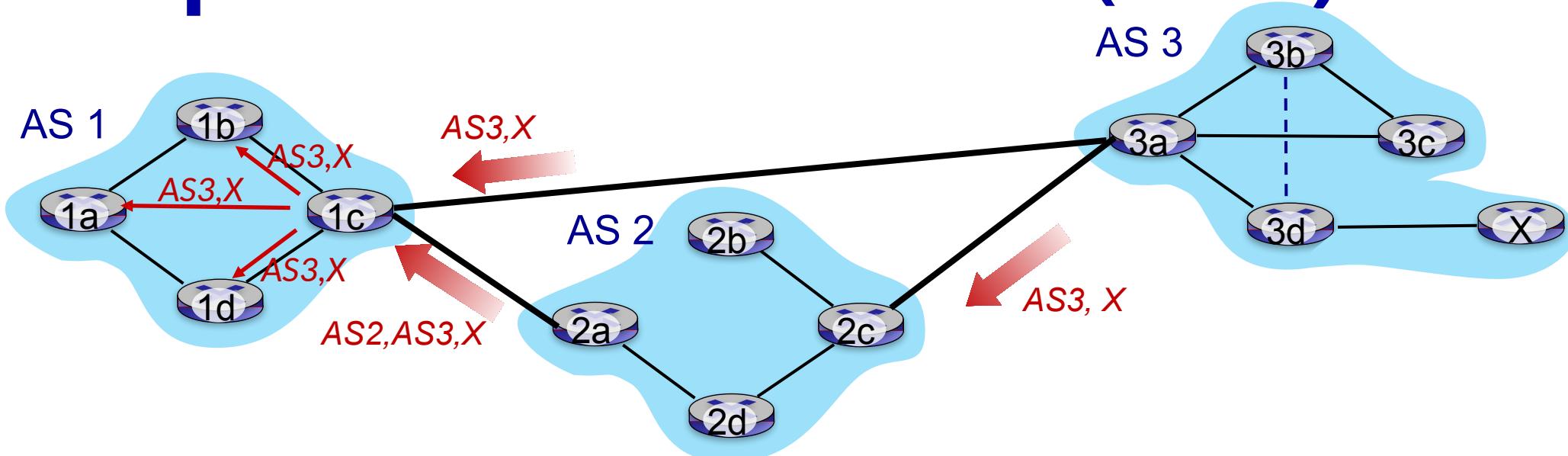
- BGP advertised route: prefix + attributes
  - prefix: destination being advertised
  - two important attributes:
    - AS-PATH: list of ASes through which prefix advertisement has passed
    - NEXT-HOP: indicates specific internal-AS router to next-hop AS
- policy-based routing:
  - gateway receiving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

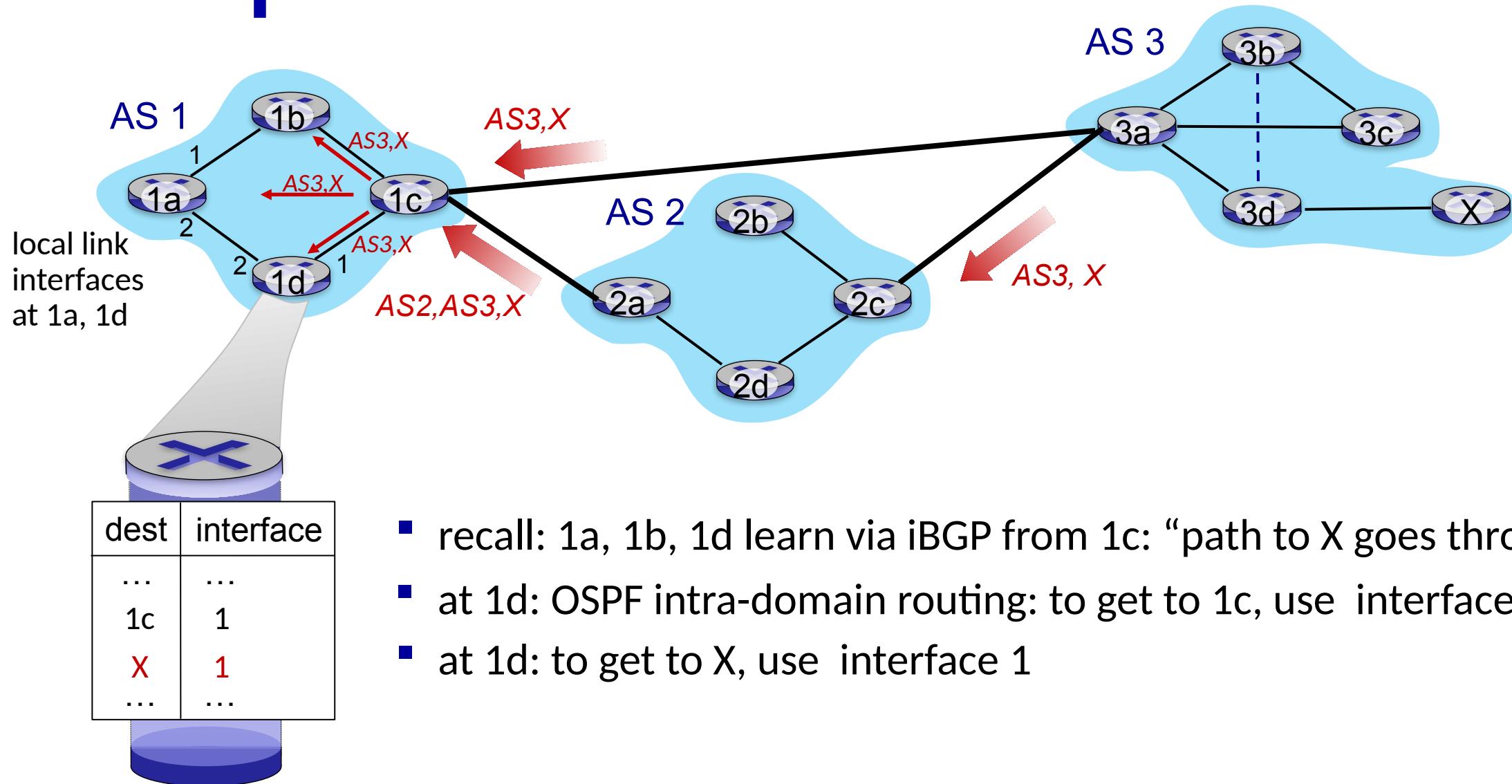
# BGP path advertisement (more)



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

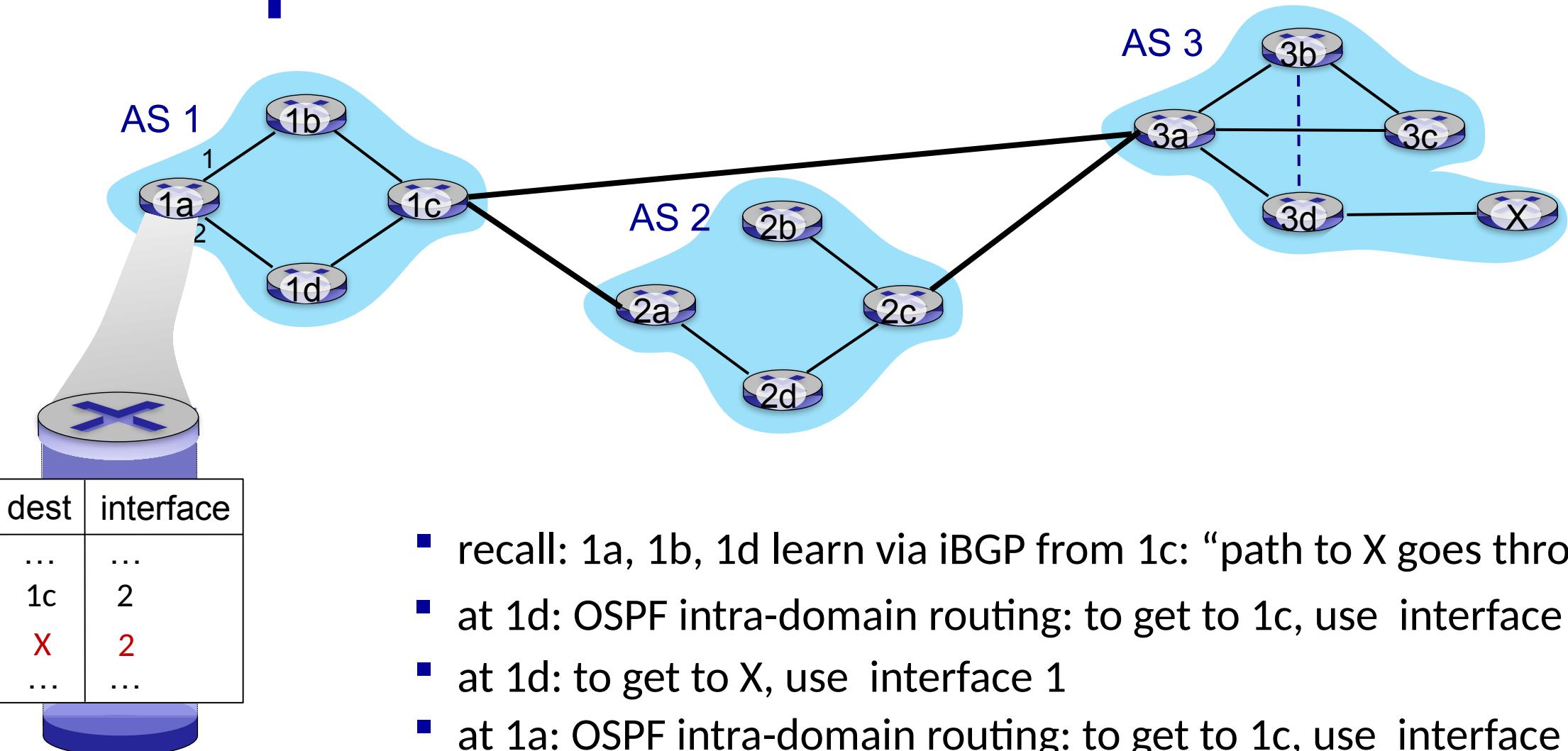
- AS1 gateway router 1c learns path **AS2,AS3,X** from 2a
- AS1 gateway router 1c learns path **AS3,X** from 3a
- based on *policy*, AS1 gateway router 1c chooses path **AS3,X** and advertises path within AS1 via iBGP

# BGP 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

# 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

# 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

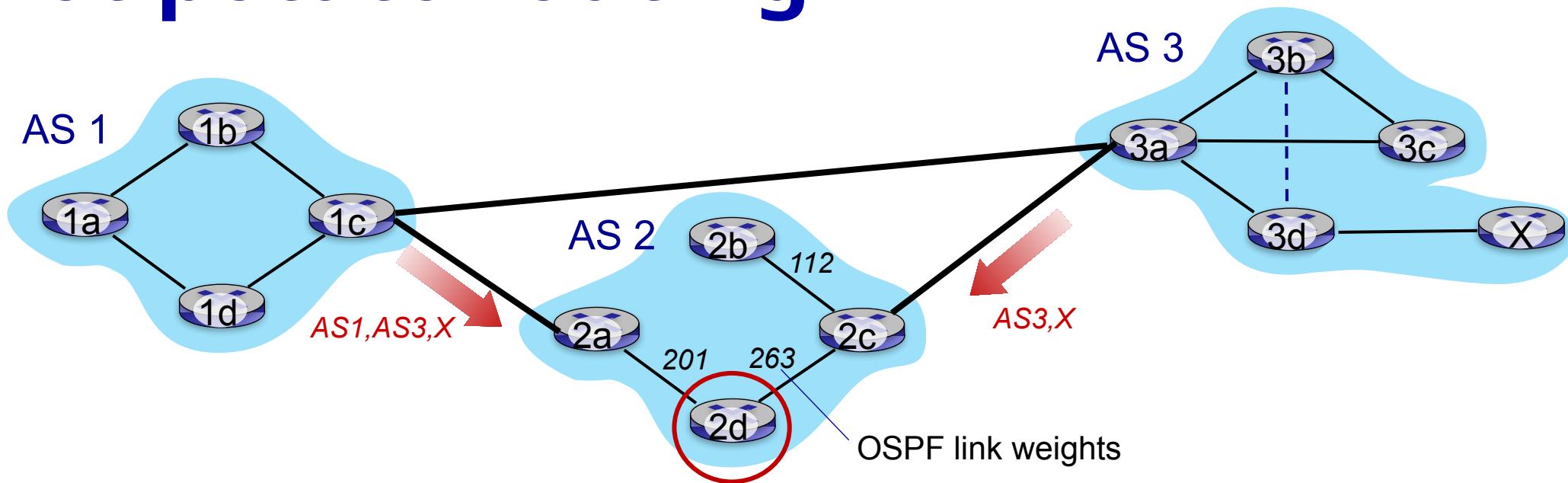
scale:

- hierarchical routing saves table size, reduced update traffic

performance:

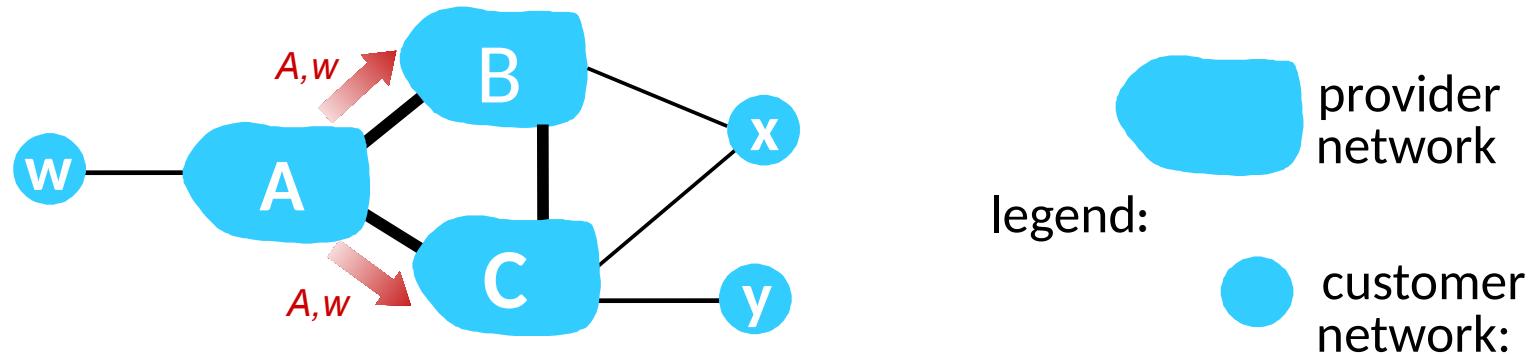
- intra-AS: can focus on performance
- inter-AS: policy dominates over performance

# 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!

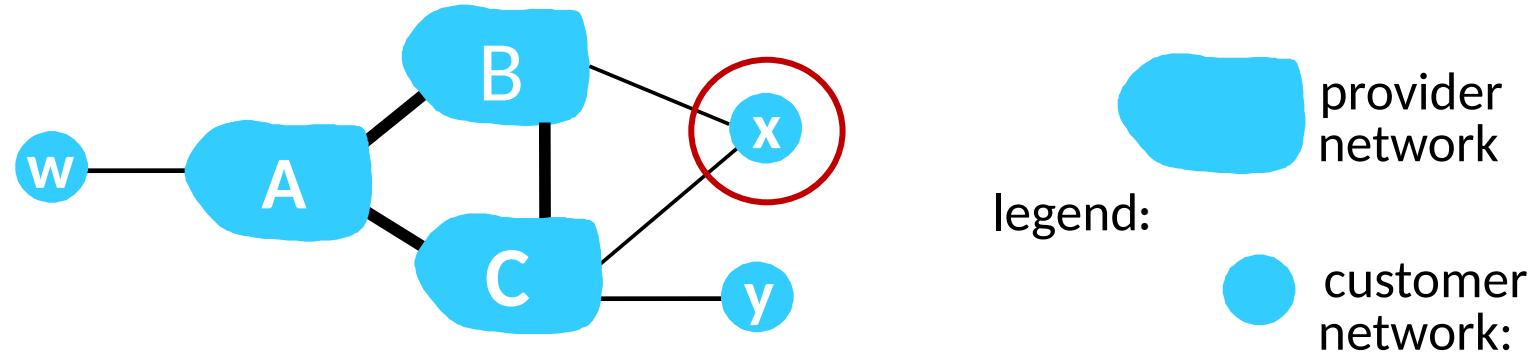
# BGP: achieving policy via advertisements



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
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- intra-ISP routing: OSPF
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- Internet Control Message Protocol

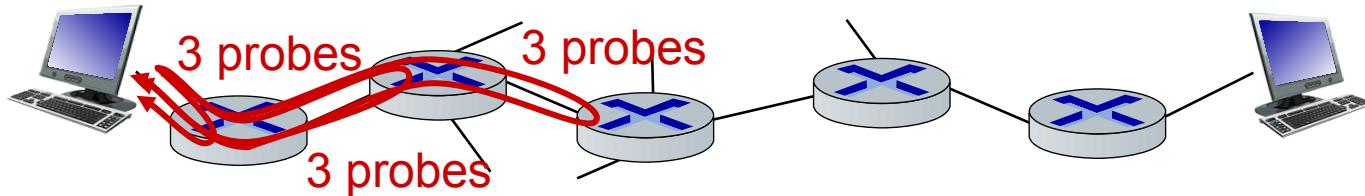


# ICMP: internet control message protocol

- 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
  - 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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# **Additional Chapter 5 slides**

# Distance vector: another example

$D_x()$

	x	y	z
x	0	2	7
y	$\infty$	$\infty$	$\infty$
z	$\infty$	$\infty$	$\infty$

$cost \text{ to}$

	x	y	z
x	0	2	3
y	2	0	1
z	7	1	0

from

to

$D_y()$

	x	y	z
x	$\infty$	$\infty$	$\infty$
y	2	0	1
z	$\infty$	$\infty$	$\infty$

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

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

$D_z()$

	x	y	z
x	$\infty$	$\infty$	$\infty$
y	$\infty$	$\infty$	$\infty$
z	7	1	0

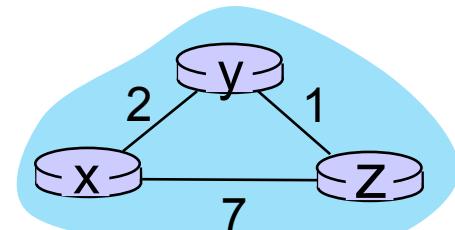
from

to

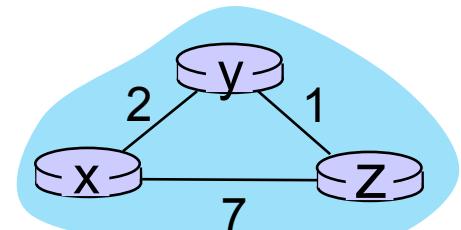
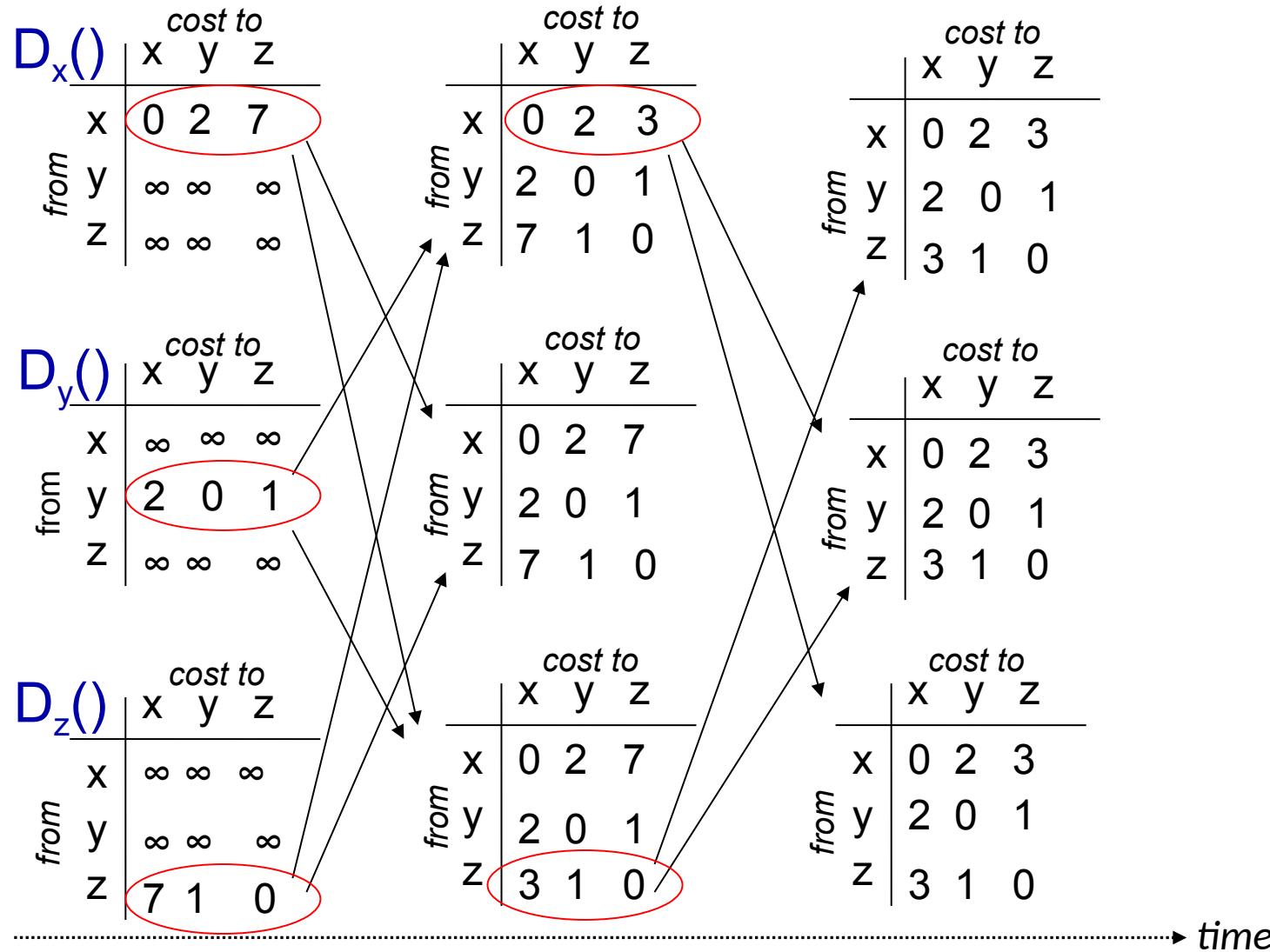
$$D_x(z) = \min\{c_{x,y} + D_y(z), c_{x,z} + D_z(z)\}$$

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

time



# Distance vector: another example



time