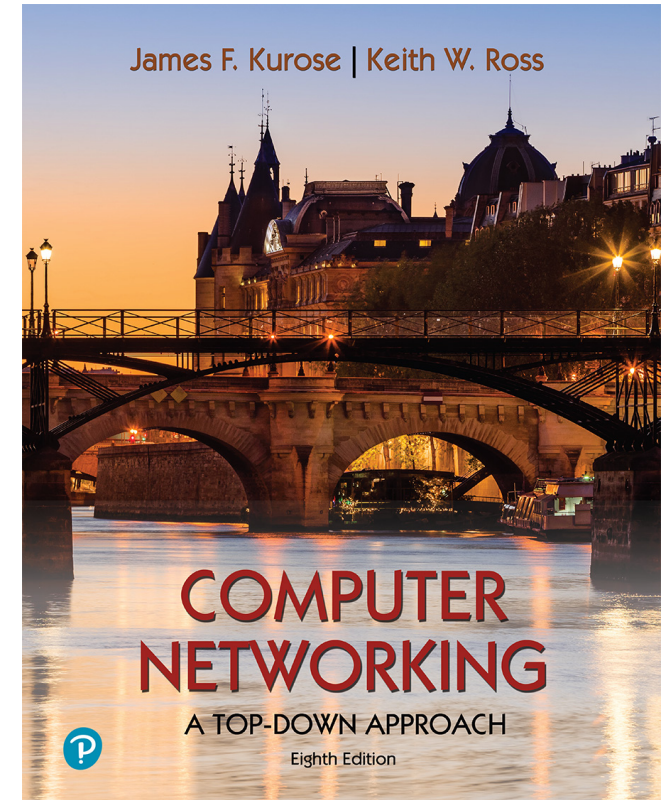


Chapter 5

Network Layer: Control Plane



Computer Networking: A Top-Down Approach

8th edition

Jim Kurose, Keith Ross
Pearson, 2020

Acknowledgement: Based on the textbook's website:
https://gaia.cs.umass.edu/kurose_ross/index.php

Network layer control plane: our goals

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

Network layer: “control plane” roadmap

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



- network management, configuration
 - SNMP
 - NETCONF/YANG

Network-layer functions

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

data plane

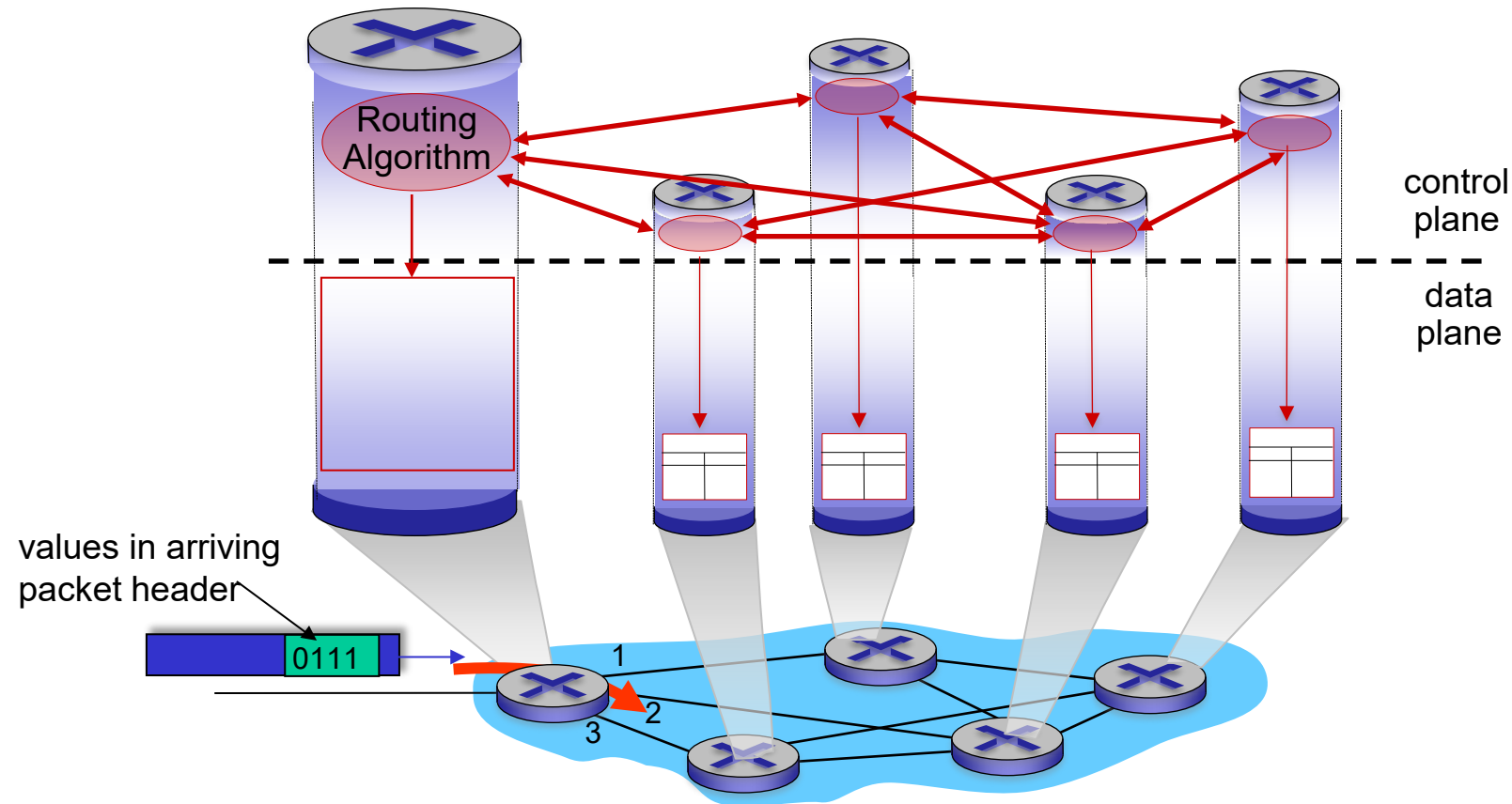
control plane

Two approaches to structuring network control plane:

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

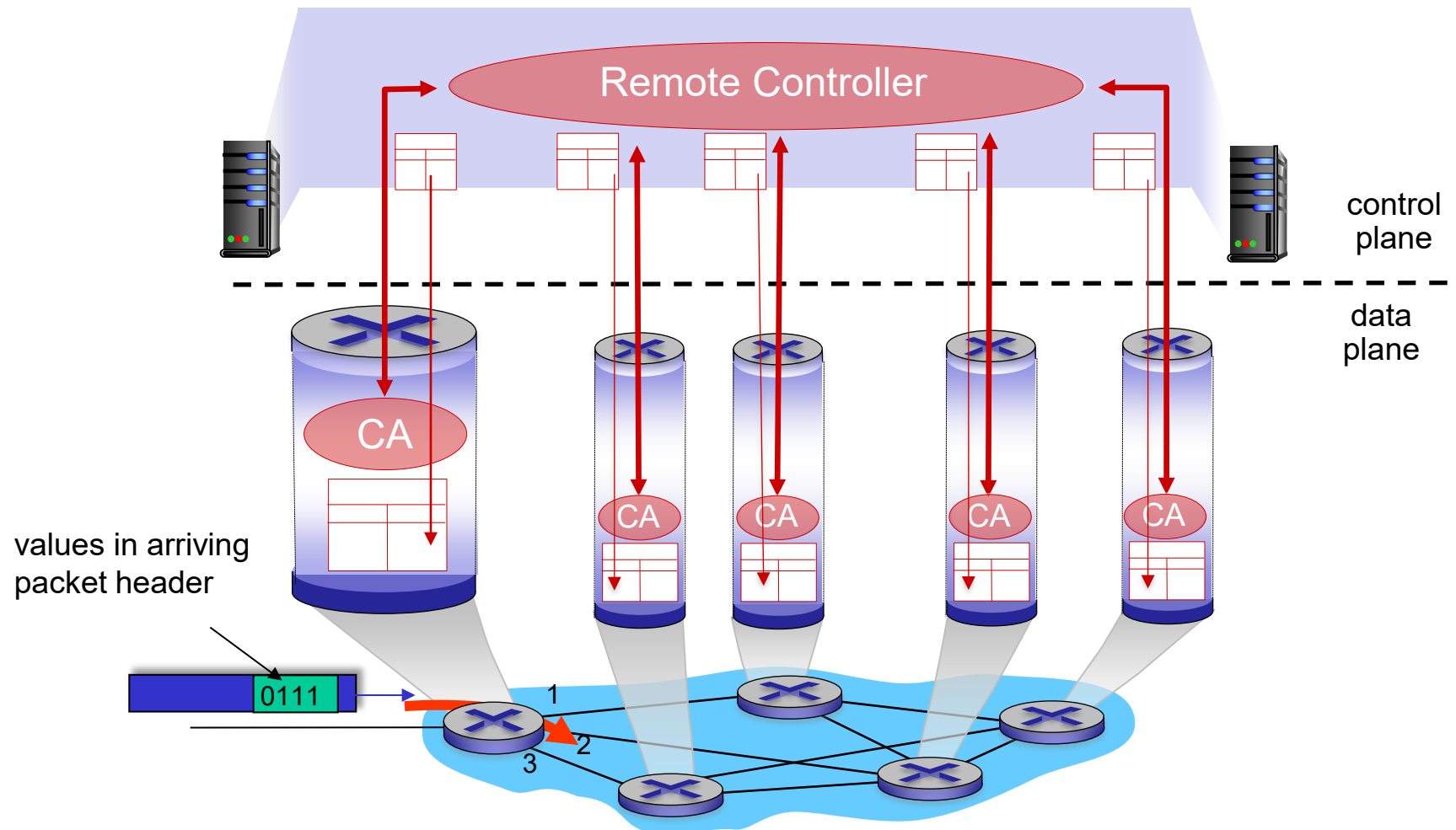
Per-router control plane

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

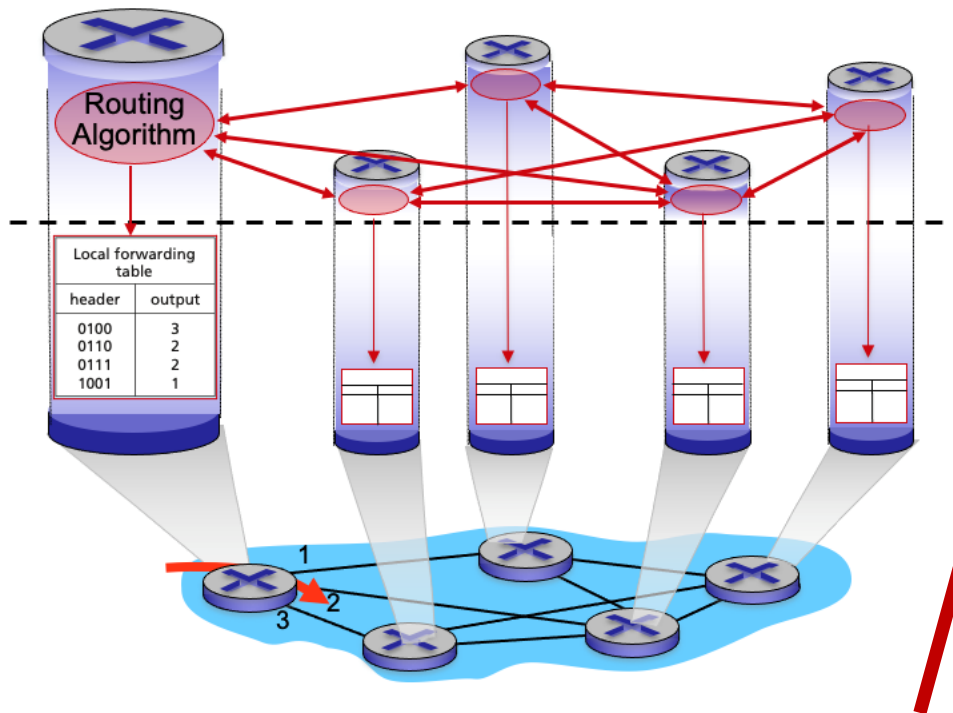


Software-Defined Networking (SDN) control plane

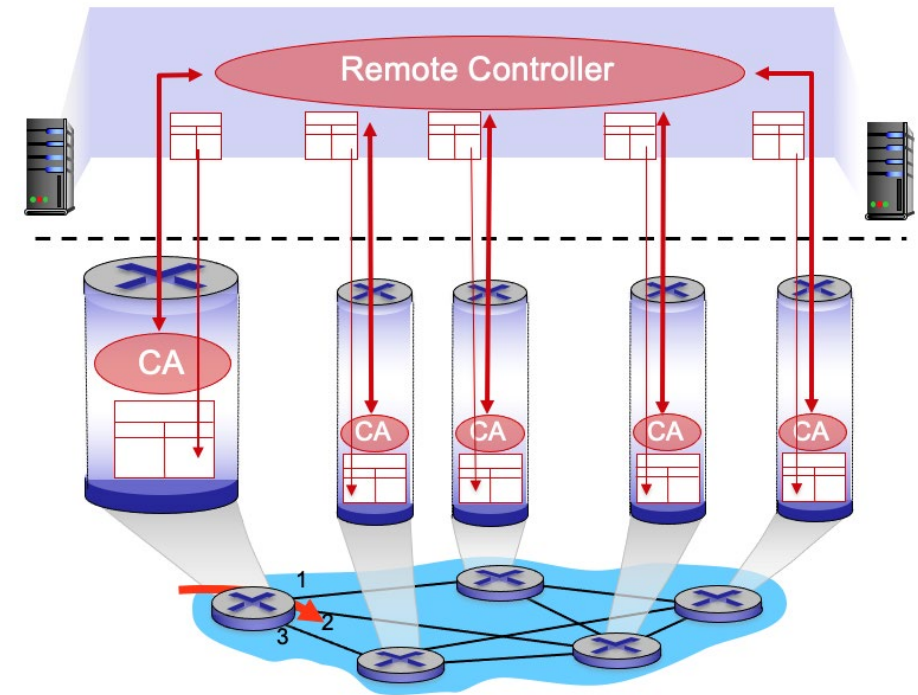
Remote controller computes, installs forwarding tables in routers



Per-router control plane



SDN control plane



Network layer: “control plane” roadmap

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

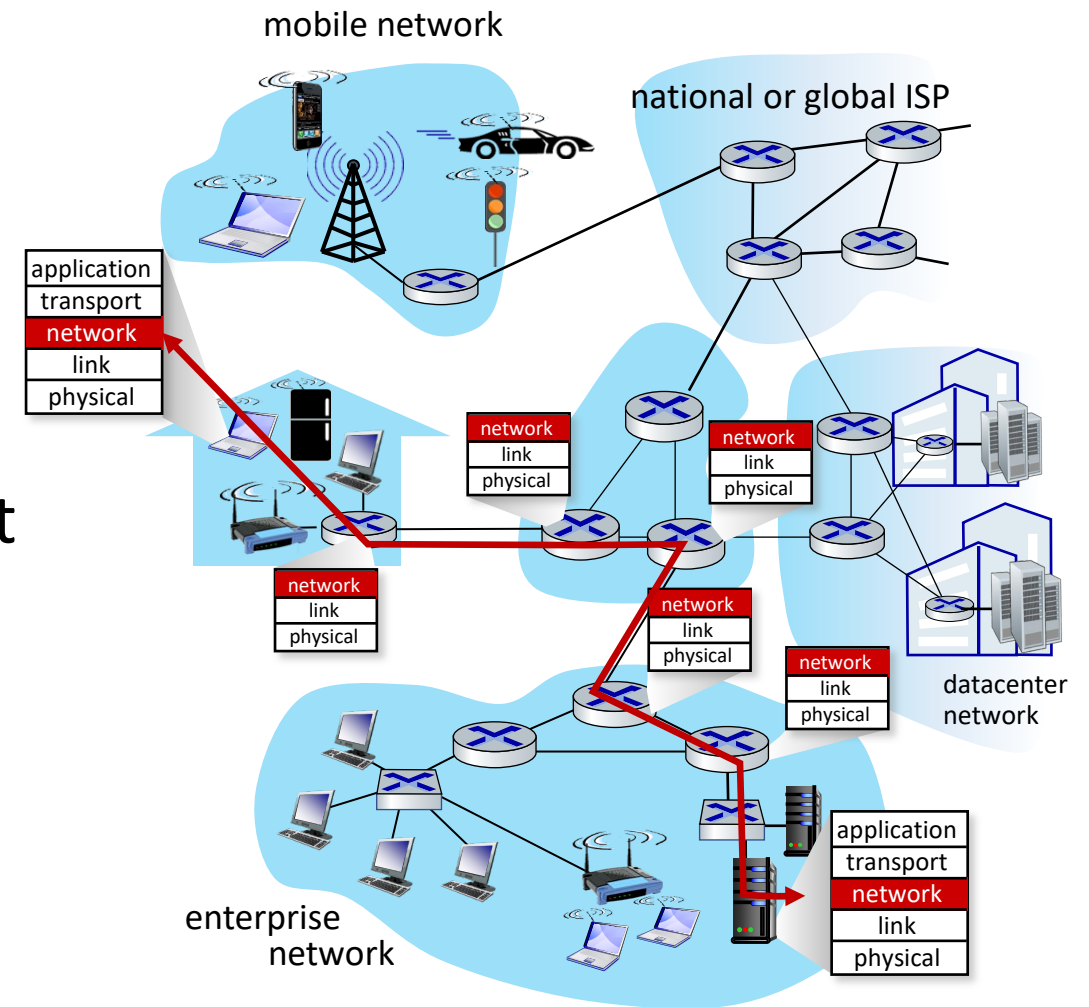


- network management, configuration
 - SNMP
 - NETCONF/YANG

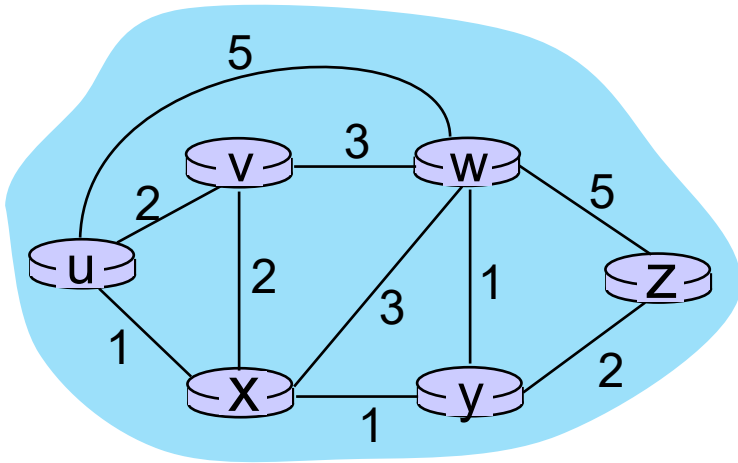
Routing protocols

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

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



Graph abstraction: link costs



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

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

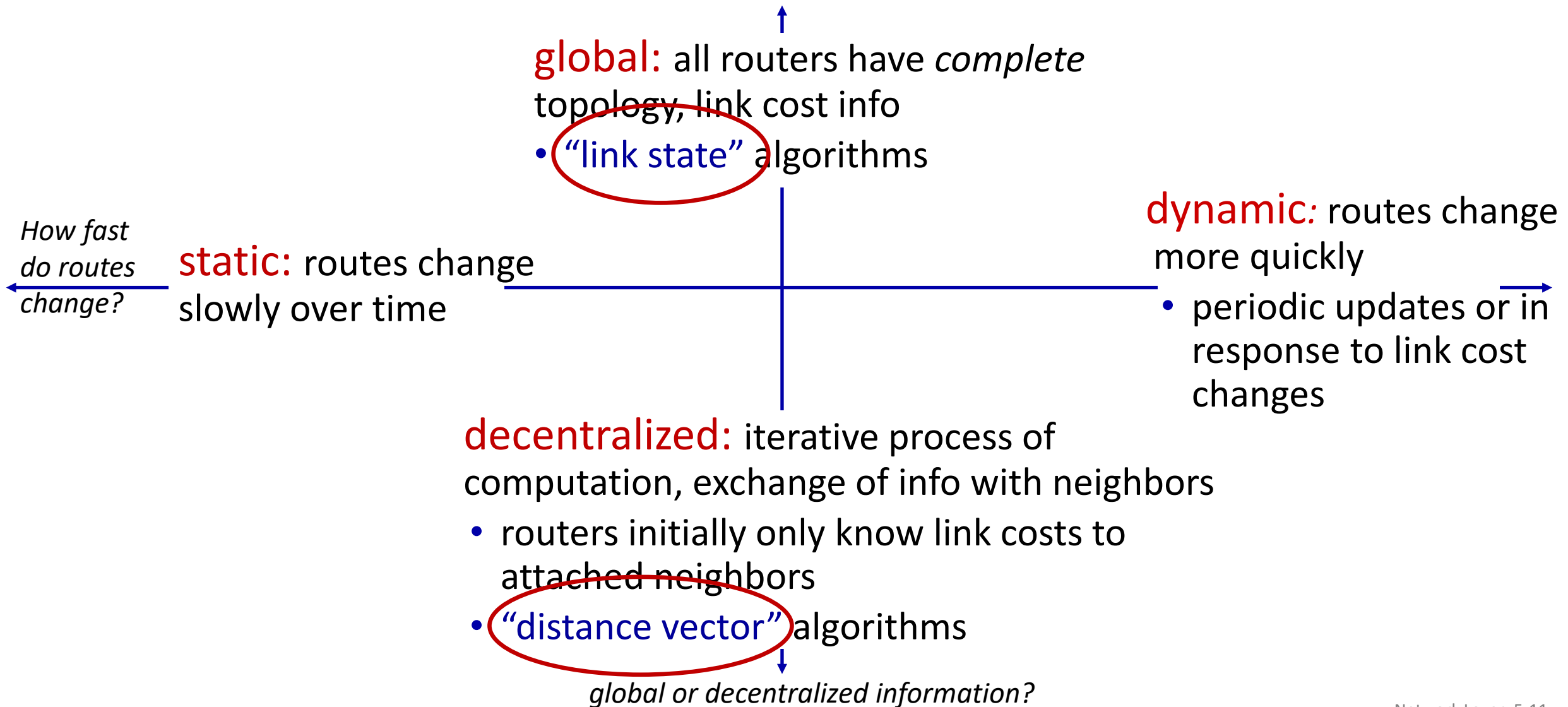
cost defined by network operator:
could always be 1, or inversely related
to bandwidth, or inversely related to
congestion

graph: $G = (N, E)$

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

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

Routing algorithm classification



Network layer: “control plane” roadmap

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- network management, configuration
 - SNMP
 - NETCONF/YANG

Dijkstra's link-state routing algorithm

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

notation

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

Dijkstra's link-state routing algorithm

1 *Initialization:*

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

3 for all nodes v

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

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

6 else $D(v) = \infty$

7



8 *Loop*

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

10 add w to N'

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

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

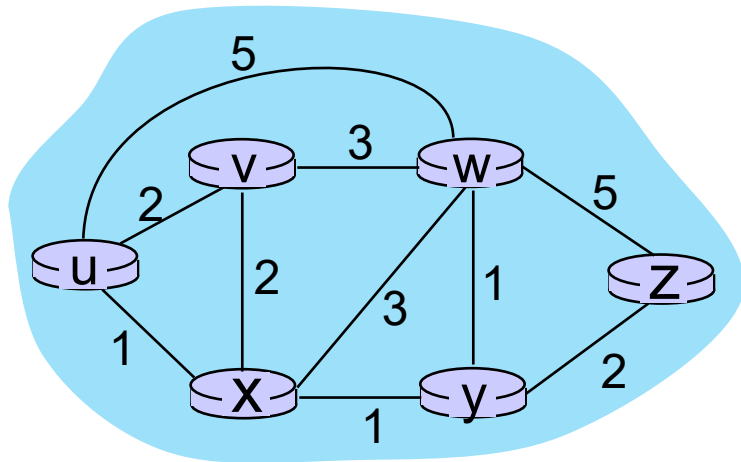
13 /* new least-path-cost to v is either old least-cost-path to v or known

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

15 *until all nodes in N'*

Dijkstra's algorithm: an example

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	2,u	5,u	1,u	∞	∞
1						
2						
3						
4						
5						

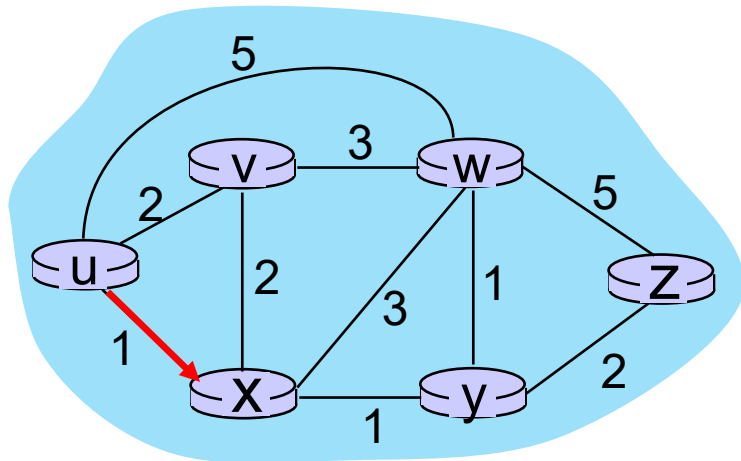


Initialization (step 0):

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

Dijkstra's algorithm: an example

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



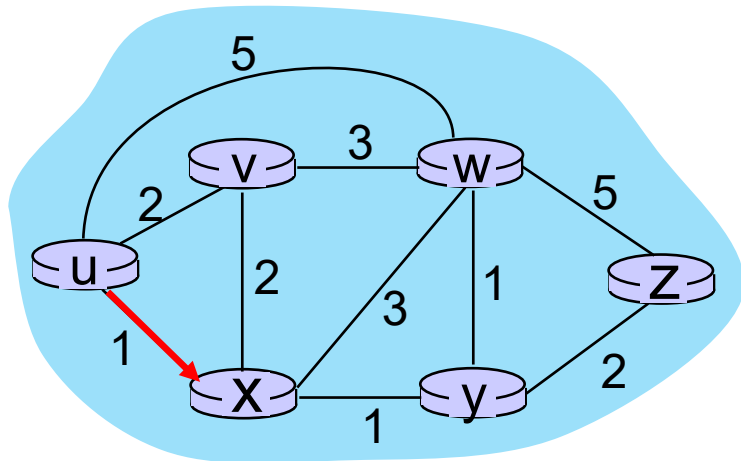
8 Loop

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

10 add a to N'

Dijkstra's algorithm: an example

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



8 Loop

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

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

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

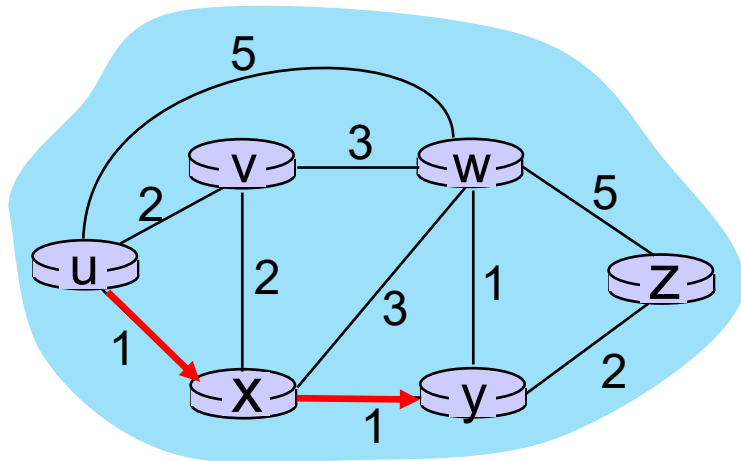
$$D(w) = \min (D(w), D(x) + c_{x,w}) = \min(5, 1+3) = 4$$

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



Dijkstra's algorithm: an example

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



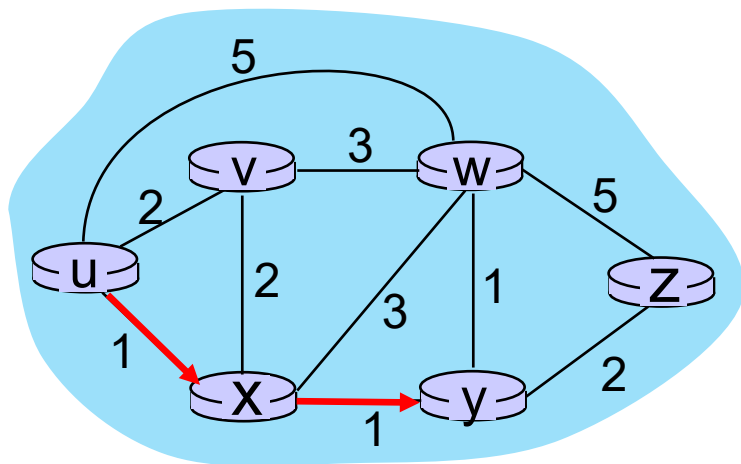
8 Loop

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

10 add a to N'

Dijkstra's algorithm: an example

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



8 Loop

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

10 add a to N'

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

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

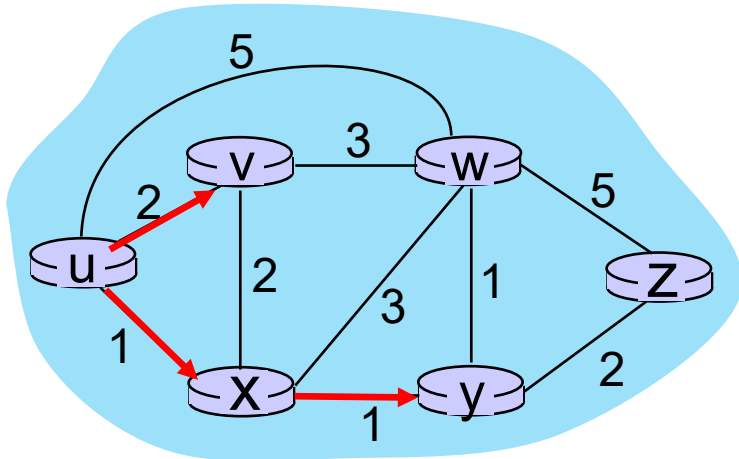
$$D(w) = \min (D(w), D(y) + c_{y,w}) = \min (4, 2+1) = 3$$

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



Dijkstra's algorithm: an example

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



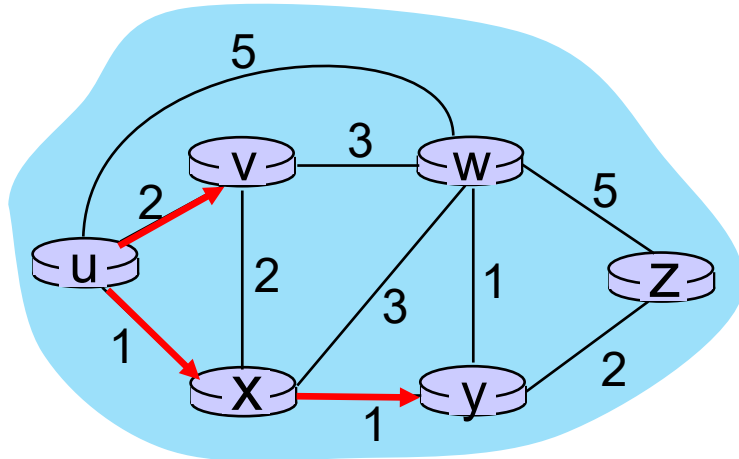
8 Loop

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

10 add a to N'

Dijkstra's algorithm: an example

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



8 Loop

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

10 add a to N'

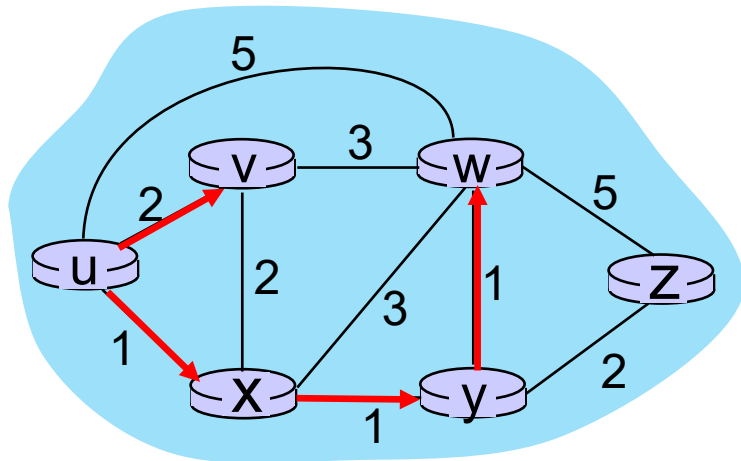
11 update $D(b)$ for all b adjacent to a and not in N' :

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

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

Dijkstra's algorithm: an example

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



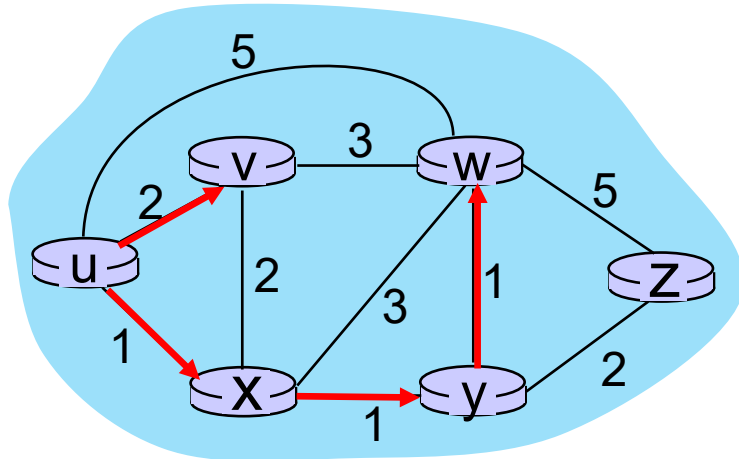
8 Loop

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

10 add a to N'

Dijkstra's algorithm: an example

		v	w	x	y	z
Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					4,y
5						



8 Loop

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

10 add a to N'

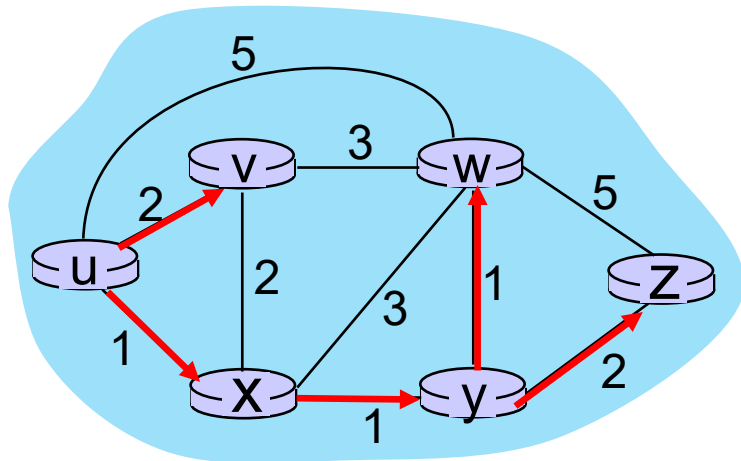
11 update $D(b)$ for all b adjacent to a and not in N' :

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

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

Dijkstra's algorithm: an example

		v	w	x	y	z
Step	N'	$D(v), p(v)$	$D(w), p(w)$	$D(x), p(x)$	$D(y), p(y)$	$D(z), p(z)$
0	u	2, u	5, u	1, u	∞	∞
1	ux	2, u	4, x		2, x	∞
2	uxy	2, u	3, y			4, y
3	uxyv		3, y			4, y
4	uxyvw					4, y
5	uxyvwz					



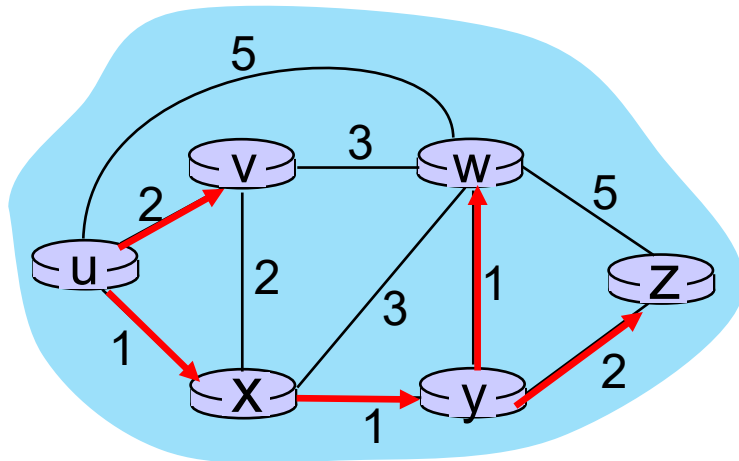
8 Loop

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

10 add a to N'

Dijkstra's algorithm: an example

		v	w	x	y	z
Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					4,y
5	uxyvwz					

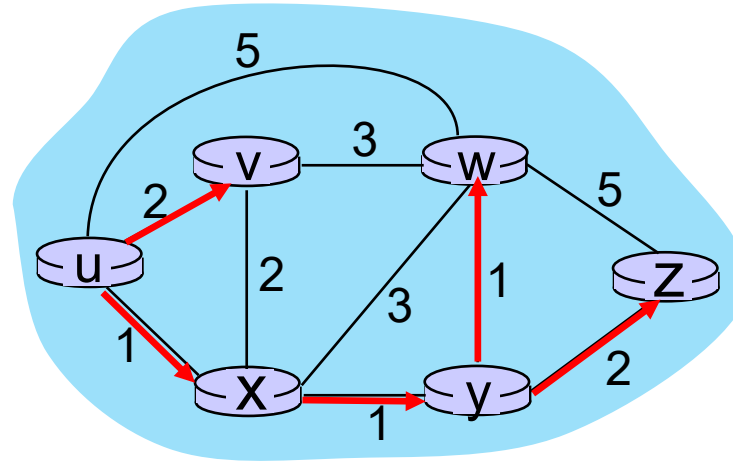


8 Loop

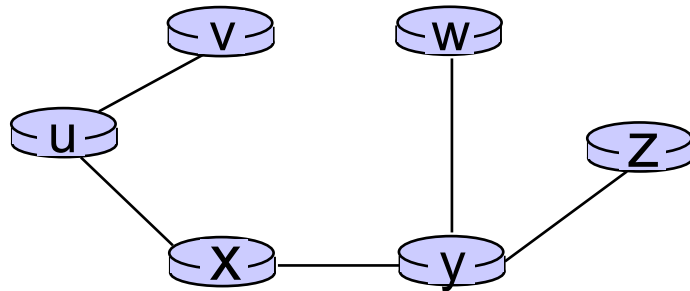
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- 10 add a to N'
- 11 update $D(b)$ for all b adjacent to a and not in N' :

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

Dijkstra's algorithm: an example



resulting least-cost-path tree from u:



resulting forwarding table in u:

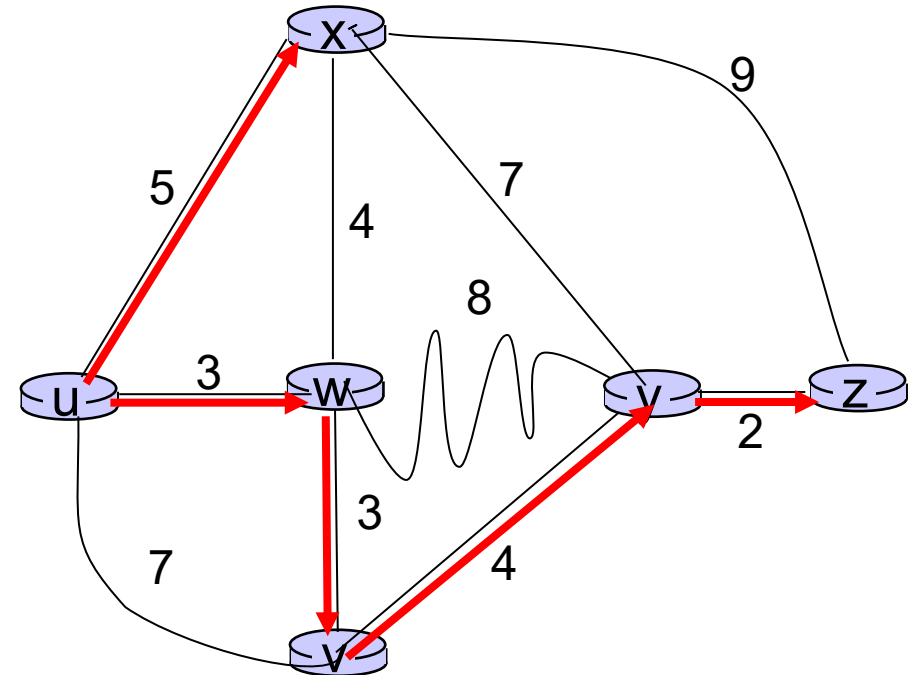
destination	outgoing link
v	(u,v)
x	(u,x)
y	(u,x)
w	(u,x)
z	(u,x)

route from *u* to *v* directly

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

Dijkstra's algorithm: another example

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



notes:

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

Dijkstra's algorithm: discussion

algorithm complexity: n nodes

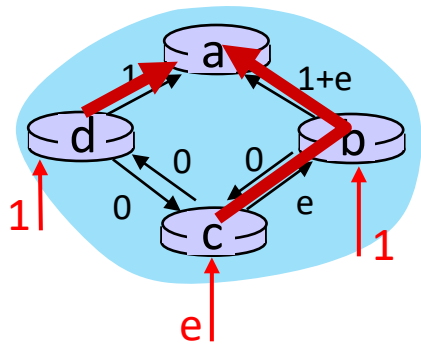
- each of n iteration: need to check all nodes, w , not in N
- $n(n+1)/2$ comparisons: $O(n^2)$ complexity
- more efficient implementations possible: $O(n \log n)$

message complexity:

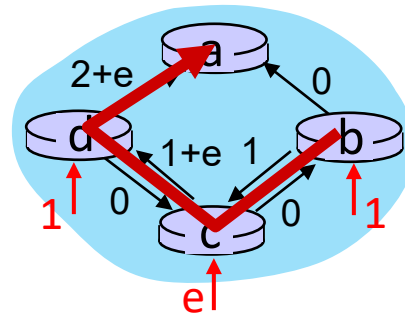
- each router must *broadcast* its link state information to other n routers
- efficient (and interesting!) broadcast algorithms: $O(n)$ link crossings to disseminate a broadcast message from one source
- each router's message crosses $O(n)$ links: overall message complexity: $O(n^2)$

Dijkstra's algorithm: oscillations possible

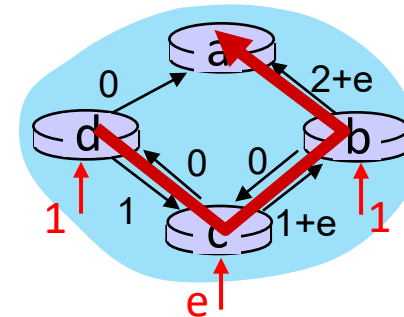
- when link costs depend on traffic volume, **route oscillations** possible
- sample scenario:
 - routing to destination a, traffic entering at d, c, e with rates 1, e (<1), 1
 - link costs are directional, and volume-dependent



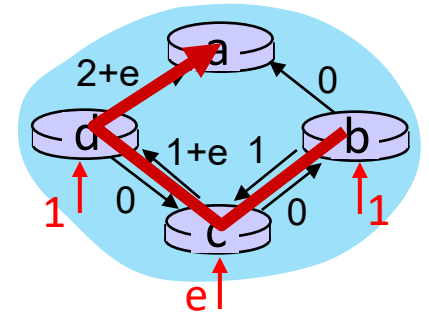
initially



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



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



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

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

direct cost of link from x to v

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

Bellman-Ford (BF) equation

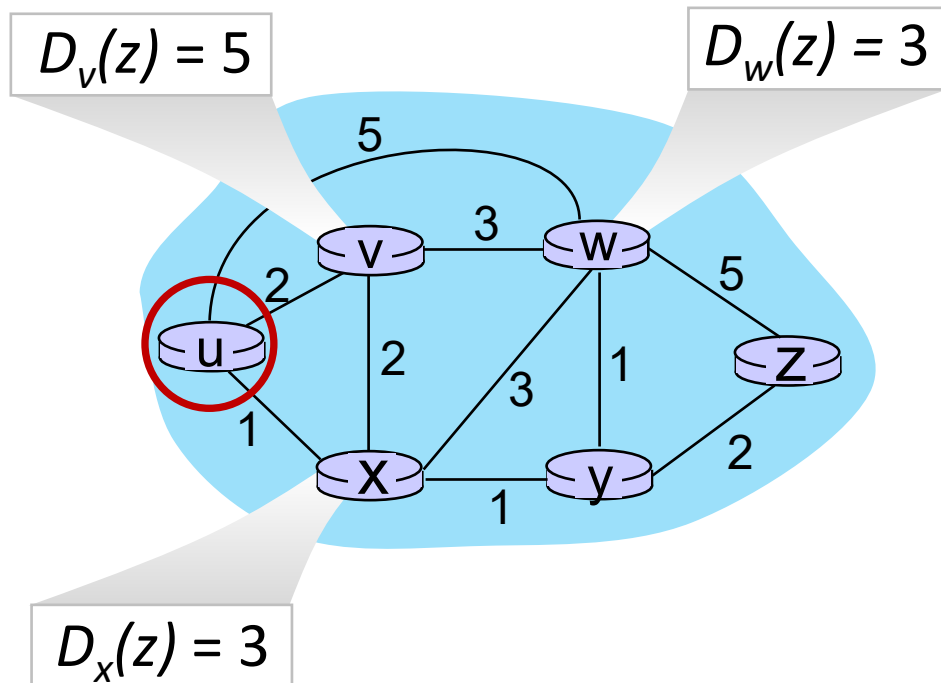
- Recall edge relaxation for the one edge connecting v and y :
 - $D_x(y) = \min \{ D_x(y), c_{x,v} + D_v(y) \}$
- Perform edge relaxation for all vertices v connected to x , we have the B-F equation
 - $D_x(y) = \min_v \{ c_{x,v} + D_v(y) \}$
- In L. 5.0 we centralized global synchronous version of BF algorithm, where all edges are relaxed in each iteration. Here we consider decentralized asynchronous version of BF algorithm.

Bellman-Ford Algorithm

- Each router maintains a Distance Vector table containing the distance between itself and All possible destination nodes. Distances, based on a chosen metric, are computed using information from the neighbors' distance vectors.
- Information kept by DV router:
 - Each router has an ID
 - Associated with each link connected to a router, there is a link cost (static or dynamic).
 - Intermediate hops
- Distance Vector Table Initialization:
 - Distance to itself = 0
 - Distance to ALL other routers = ∞

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:

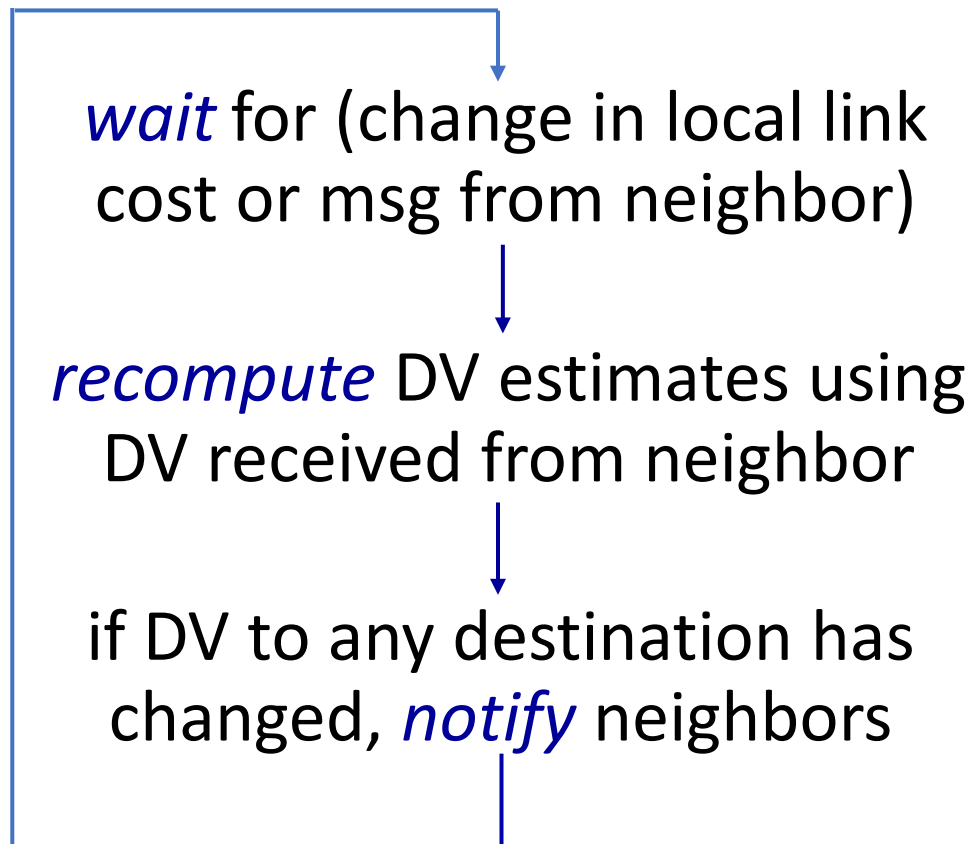
- Decentralized gossip algorithm based on local information: “I tell my neighbors, you tell yours.”
- from time-to-time, each node sends its own distance vector estimate to neighbors
- when x receives new DV estimate from any neighbor v , it updates its own DV using B-F equation:

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

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

Distance vector algorithm:

each node:



iterative, asynchronous: each local iteration caused by:

- local link cost change
- DV update message from neighbor

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

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

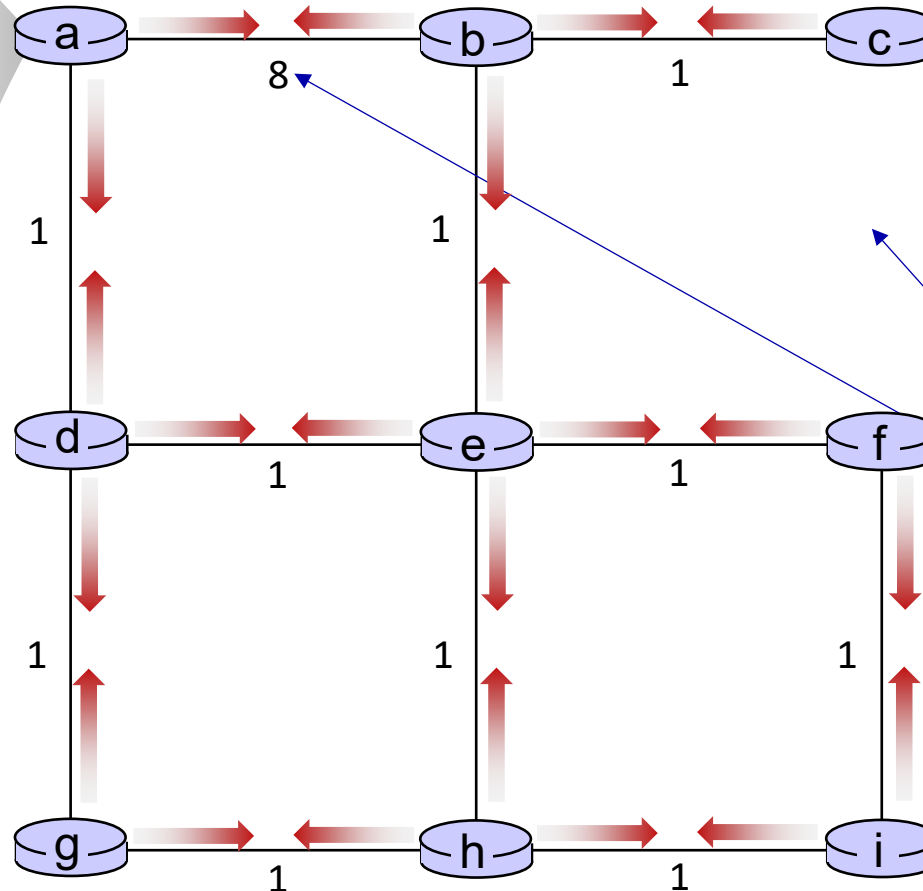
Distance vector: example



t=0

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

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



A few asymmetries:

- missing link
- larger cost

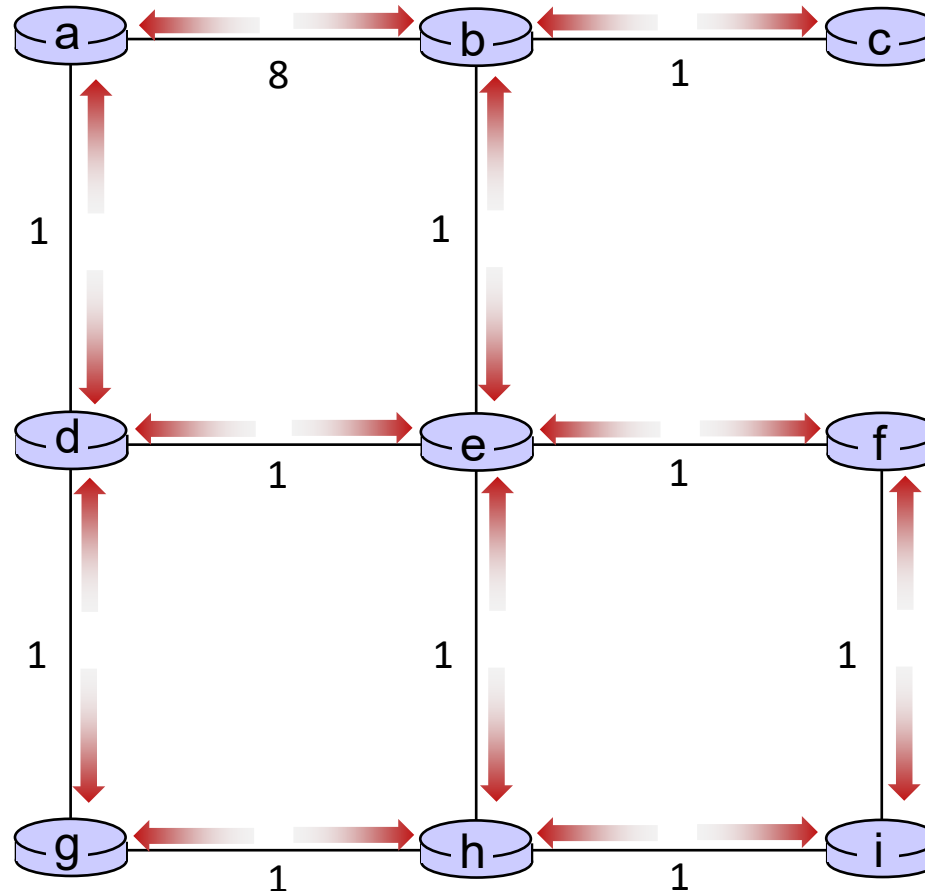
Distance vector example: iteration



t=1

All nodes:

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



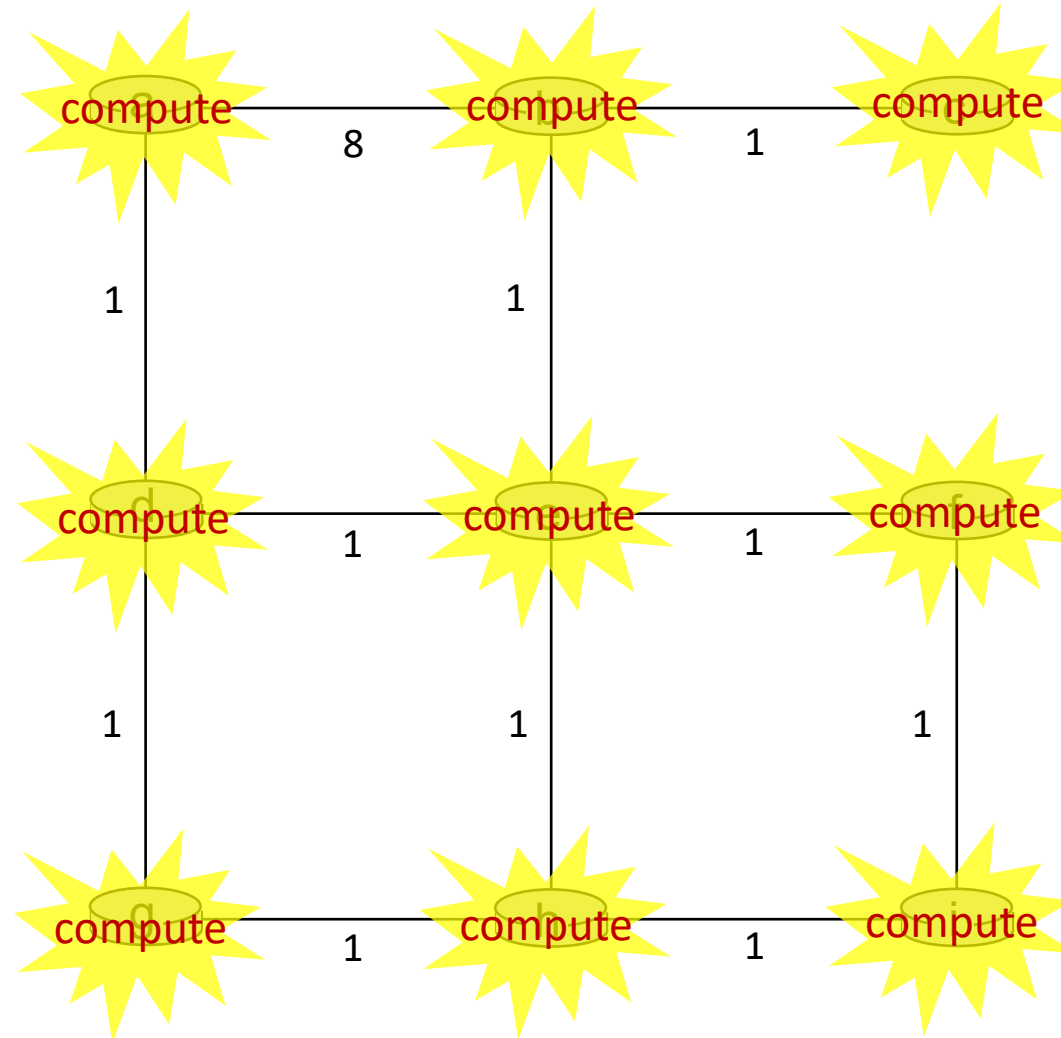
Distance vector example: iteration



t=1

All nodes:

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



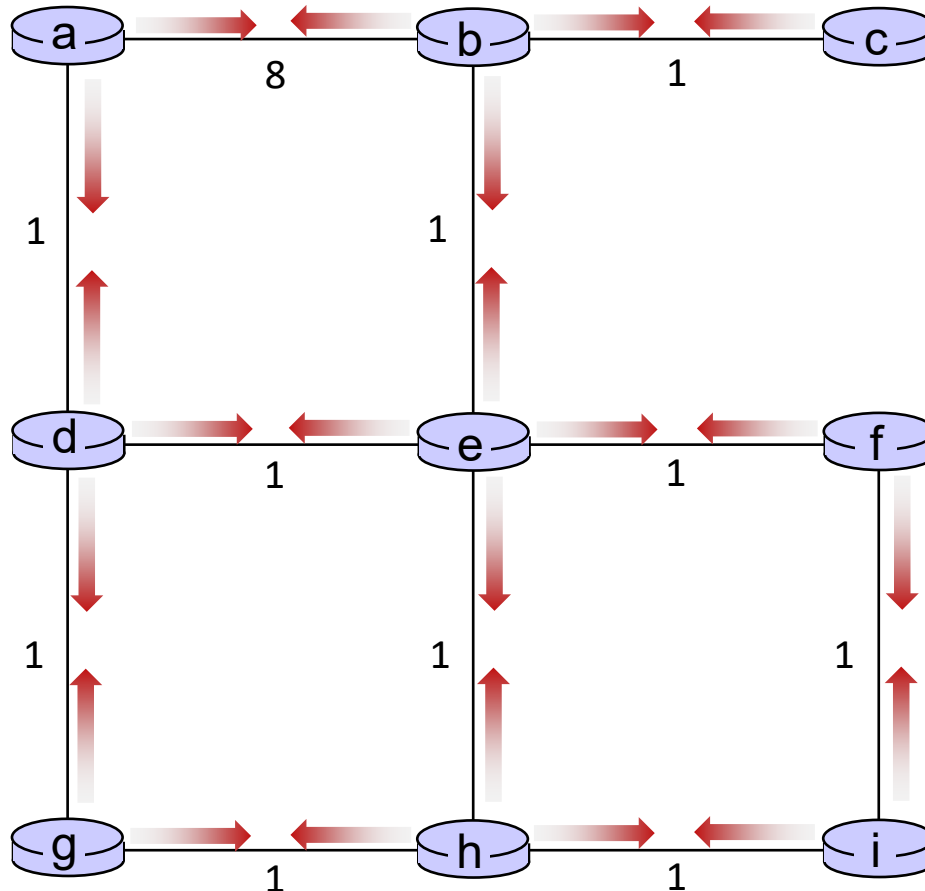
Distance vector example: iteration



t=1

All nodes:

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



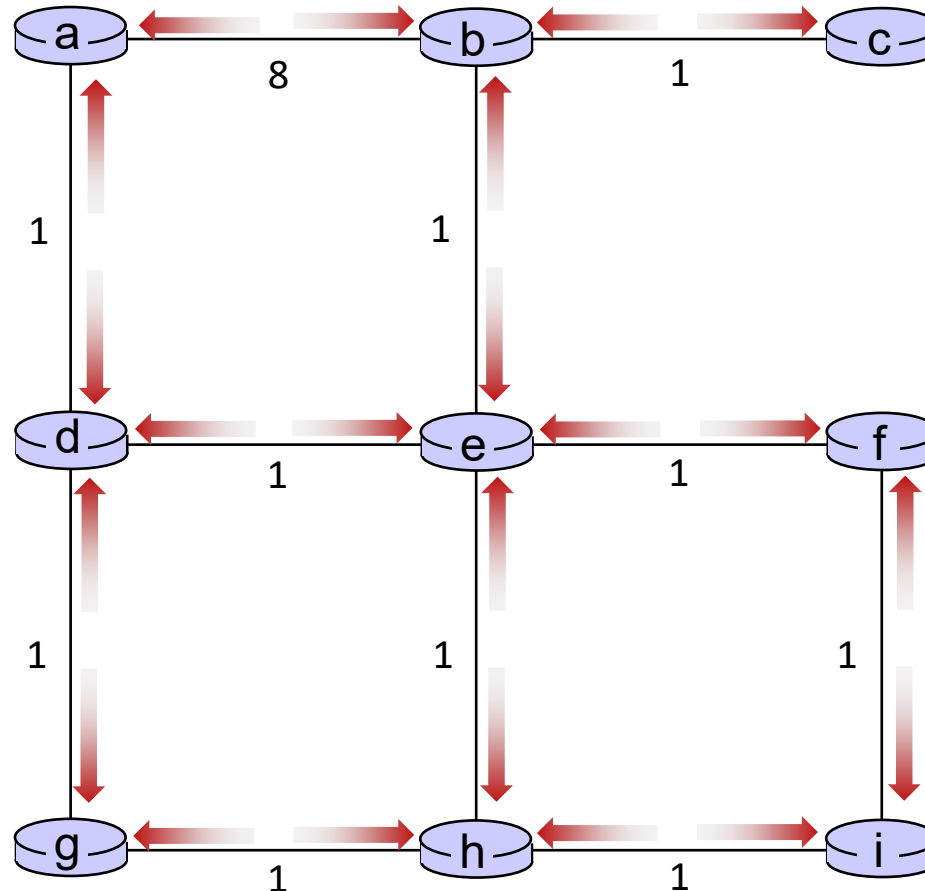
Distance vector example: iteration



t=2

All nodes:

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



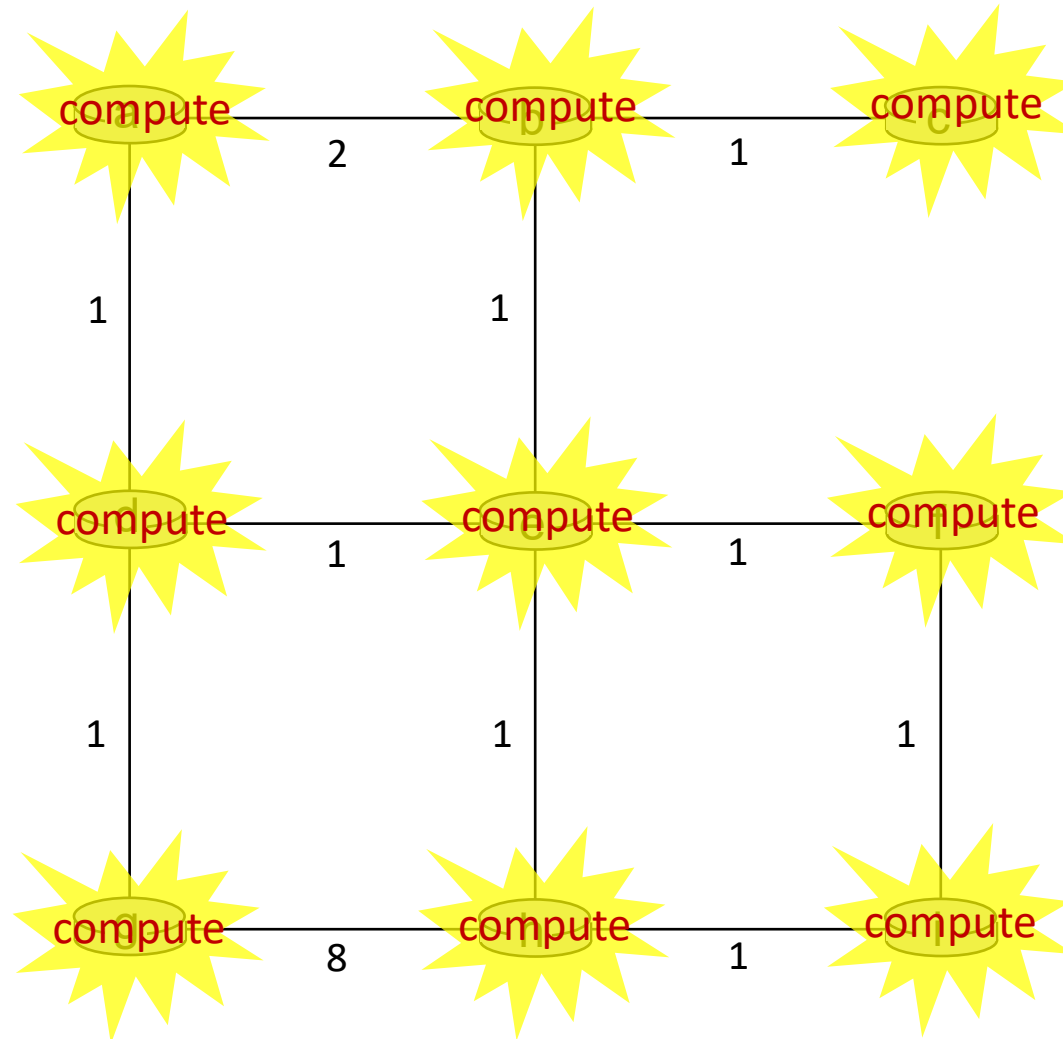
Distance vector example: iteration



t=2

All nodes:

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



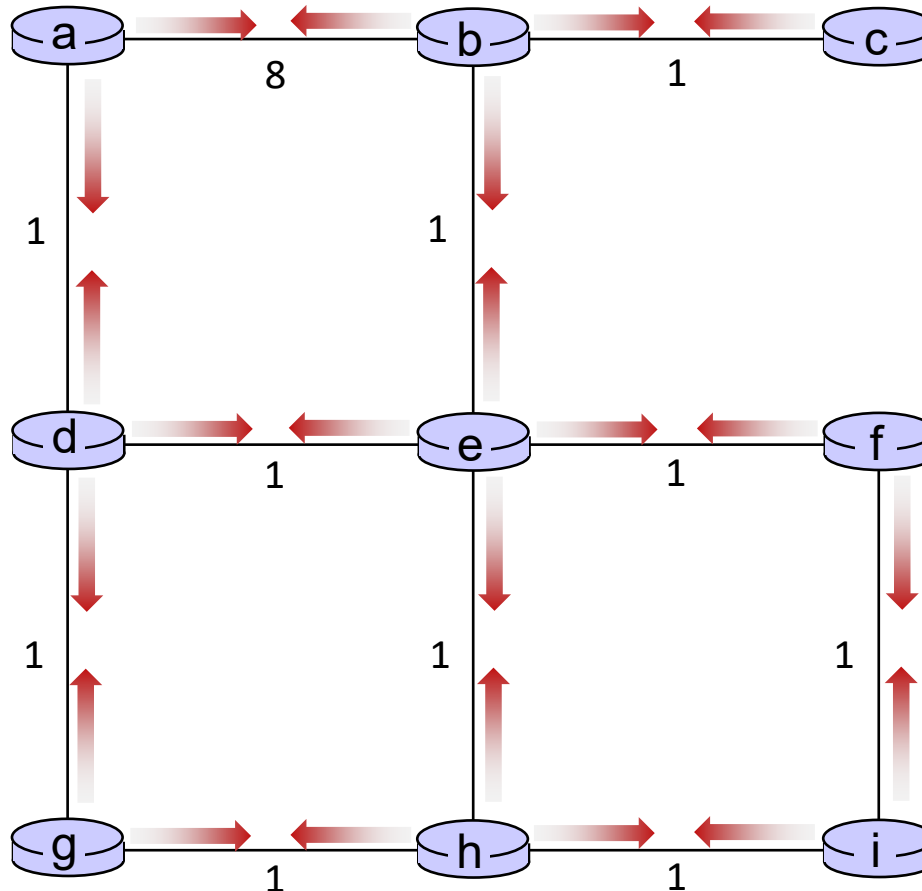
Distance vector example: iteration



t=2

All nodes:

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



Distance vector example: iteration

.... and so on

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

Distance vector example:



t=1

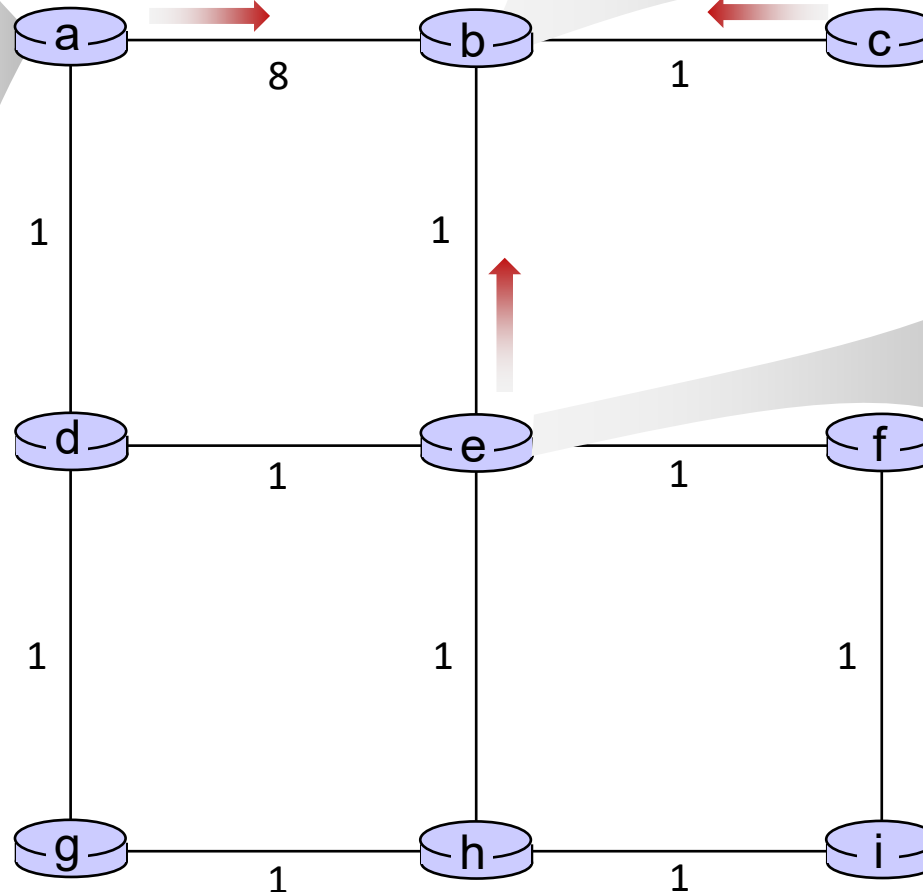
- b receives DVs from a, c, e

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

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

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

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



Distance vector example:

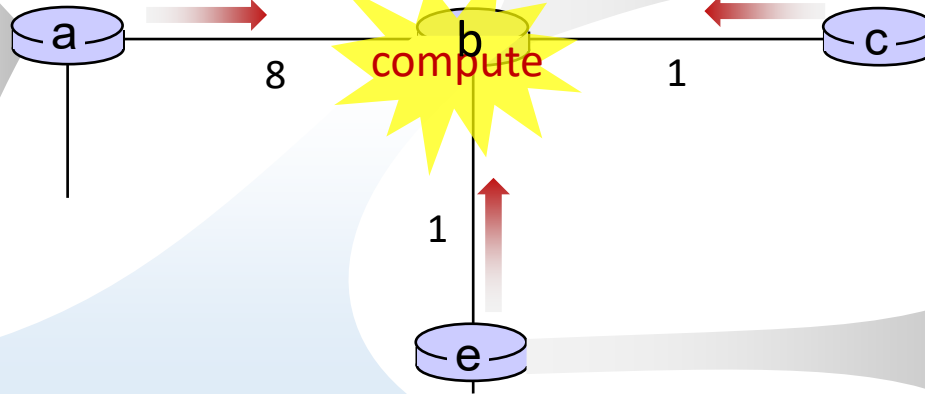


t=1

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

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

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



DV in b:

$$D_b(a) = 8$$

$$D_b(c) = 1$$

$$D_b(d) = \infty$$

$$D_b(e) = 1$$

$$D_b(f) = \infty$$

$$D_b(g) = \infty$$

$$D_b(h) = \infty$$

$$D_b(i) = \infty$$

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

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

DV in b:

$$D_b(a) = 8$$

$$D_b(f) = 2$$

$$D_b(c) = 1$$

$$D_b(g) = \infty$$

$$D_b(d) = 2$$

$$D_b(h) = 2$$

$$D_b(e) = 1$$

$$D_b(i) = \infty$$

Distance vector example:



t=1

- c receives DVs from b

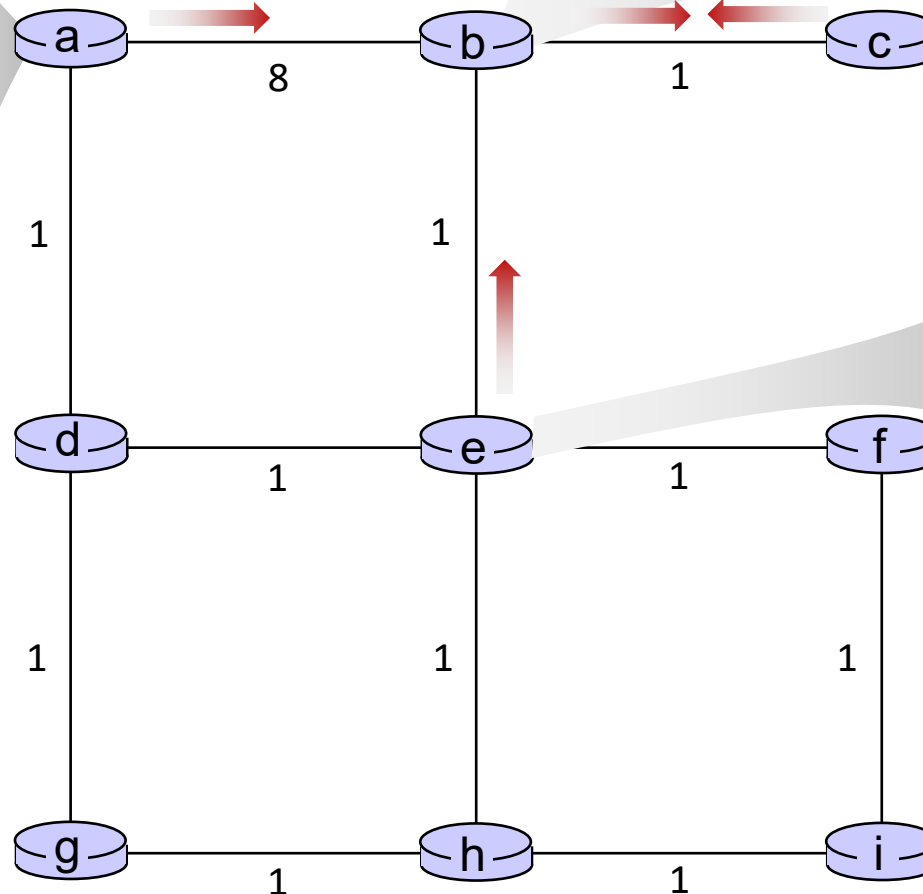
DV in a:
$D_a(a) = 0$
$D_a(b) = 8$
$D_a(c) = \infty$
$D_a(d) = 1$
$D_a(e) = \infty$
$D_a(f) = \infty$
$D_a(g) = \infty$
$D_a(h) = \infty$
$D_a(i) = \infty$

DV in b:

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

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



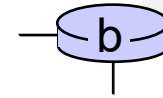
Distance vector example:



t=1

- c receives DVs from b computes:

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



1

compute

DV in b:

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

DV in c:

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

DV in c:

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

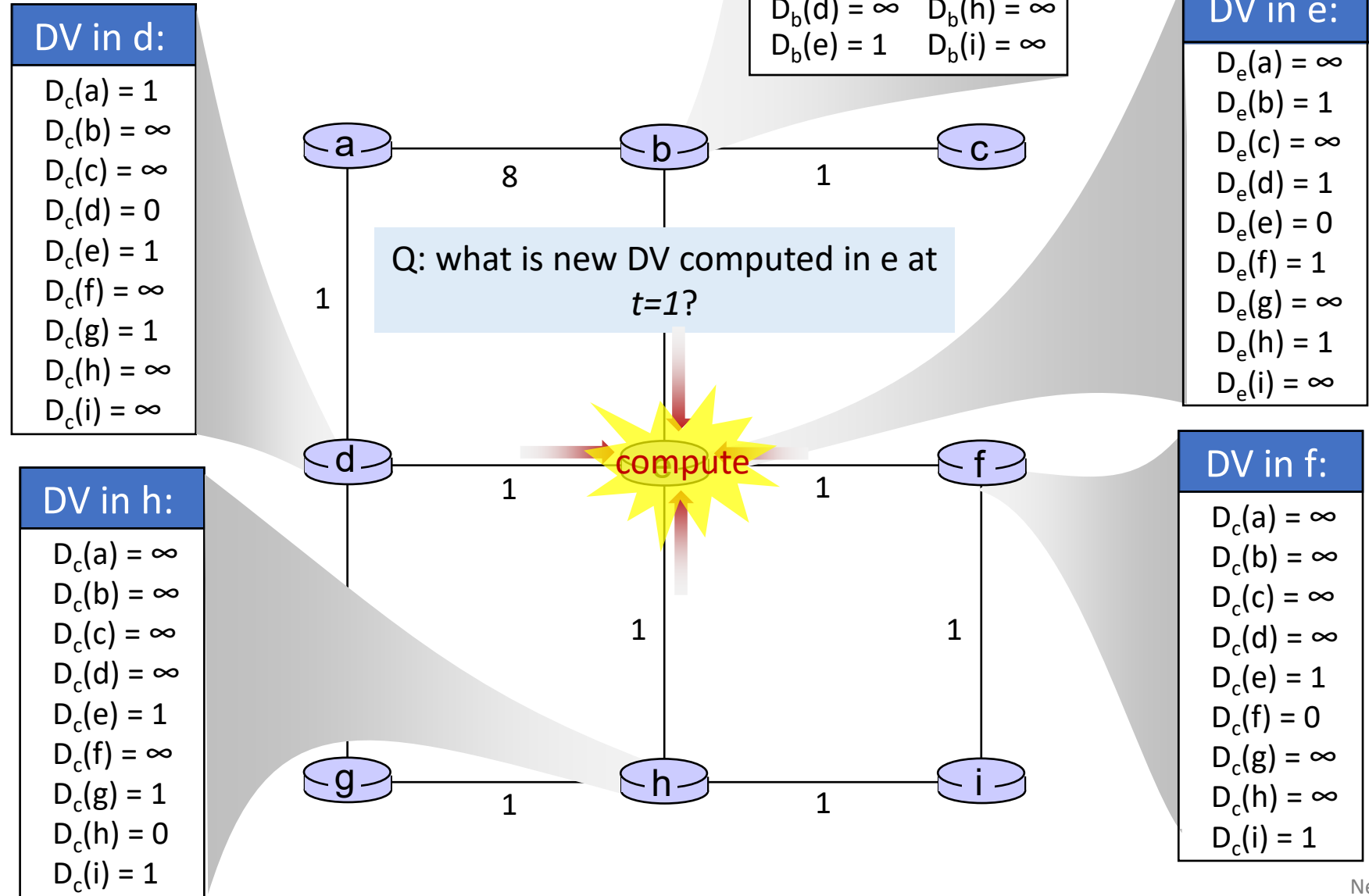
* Check out the online interactive exercises for more examples:
http://gaia.cs.umass.edu/kurose_ross/interactive/

Distance vector example:








t=1

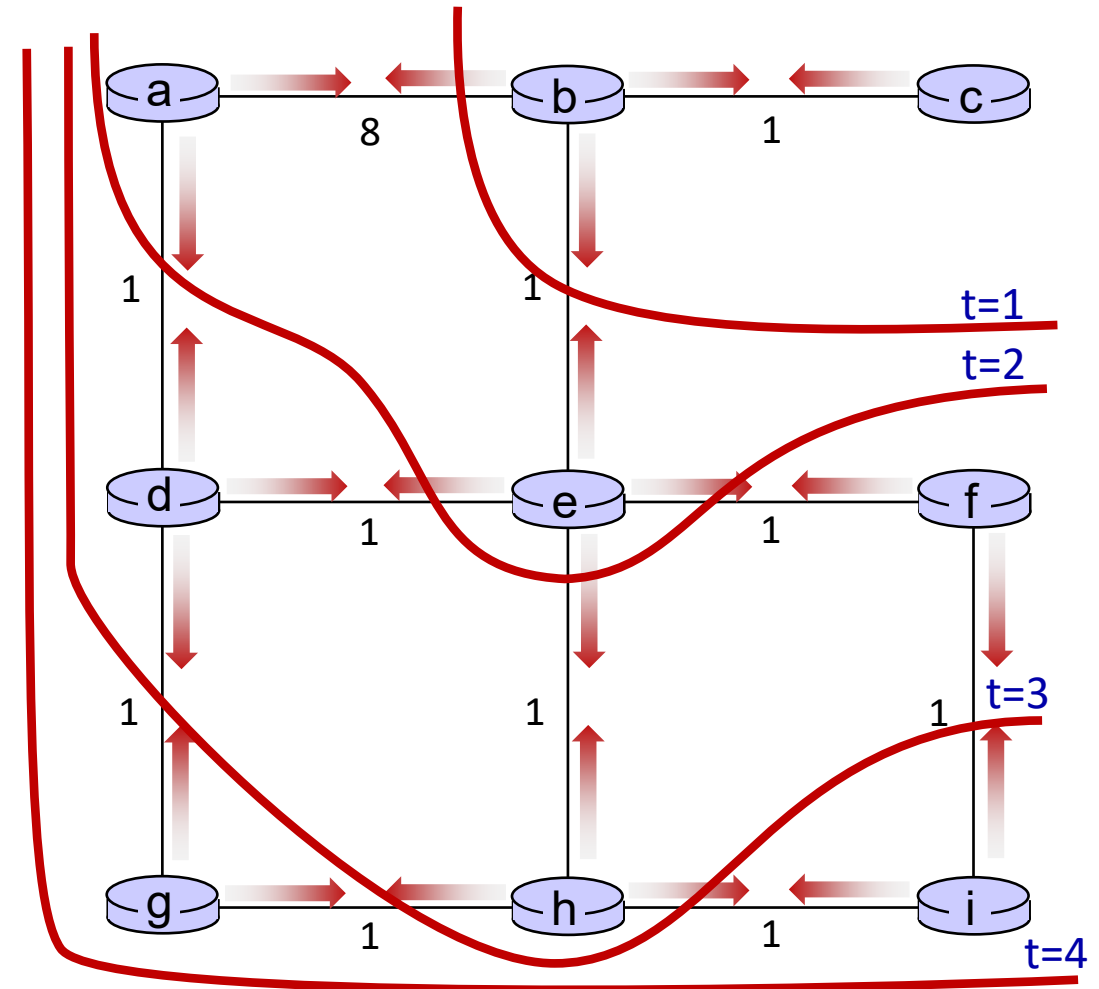
- e receives DVs from b, d, f, h



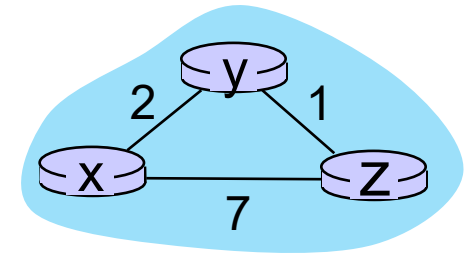
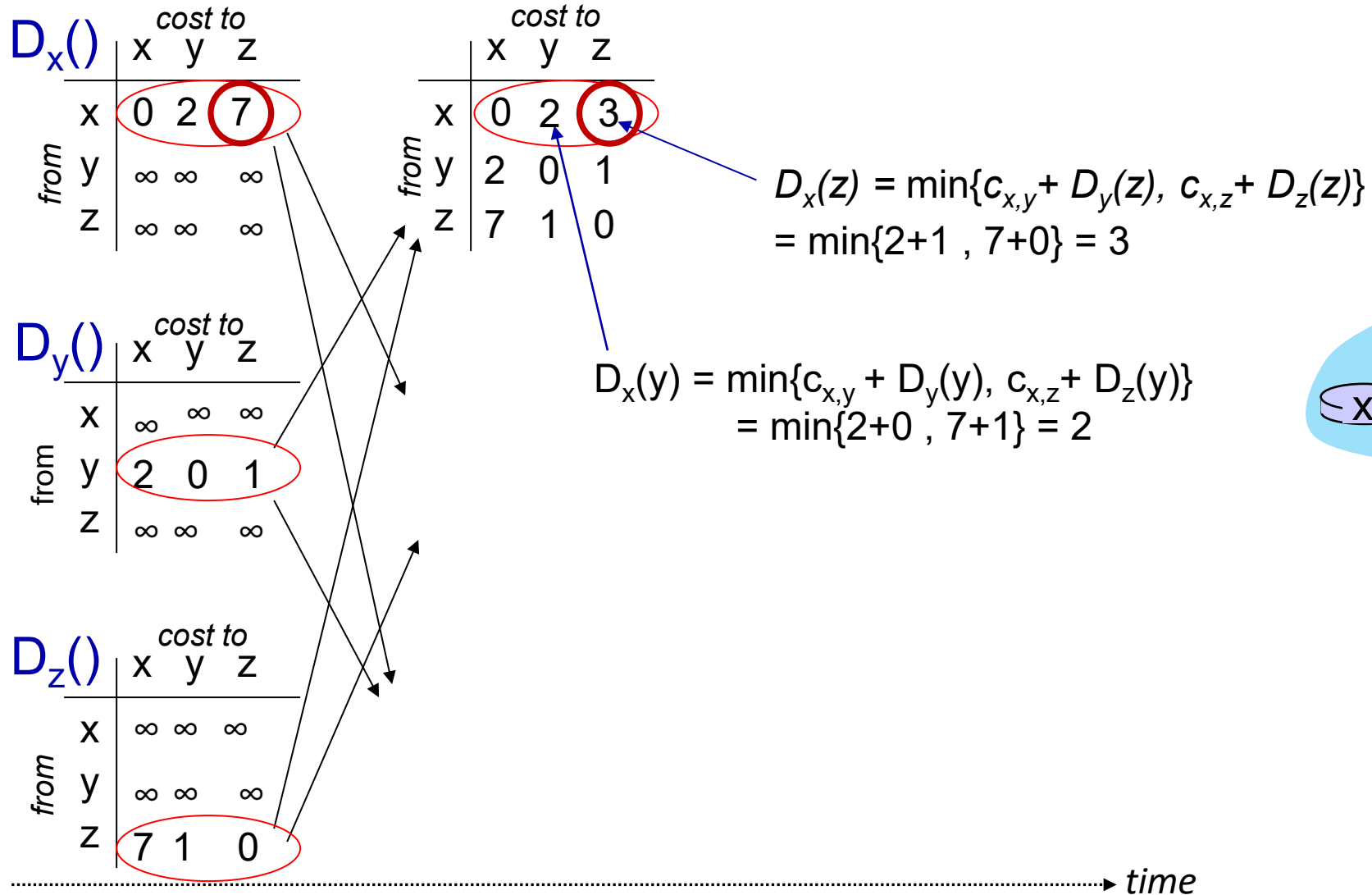
Distance vector: state information diffusion

Iterative communication, computation steps diffuses information through network:

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

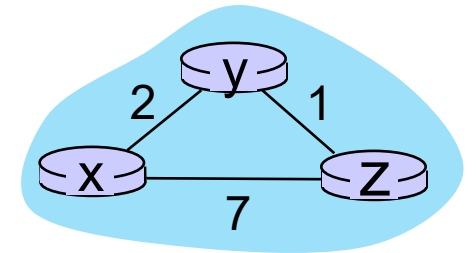
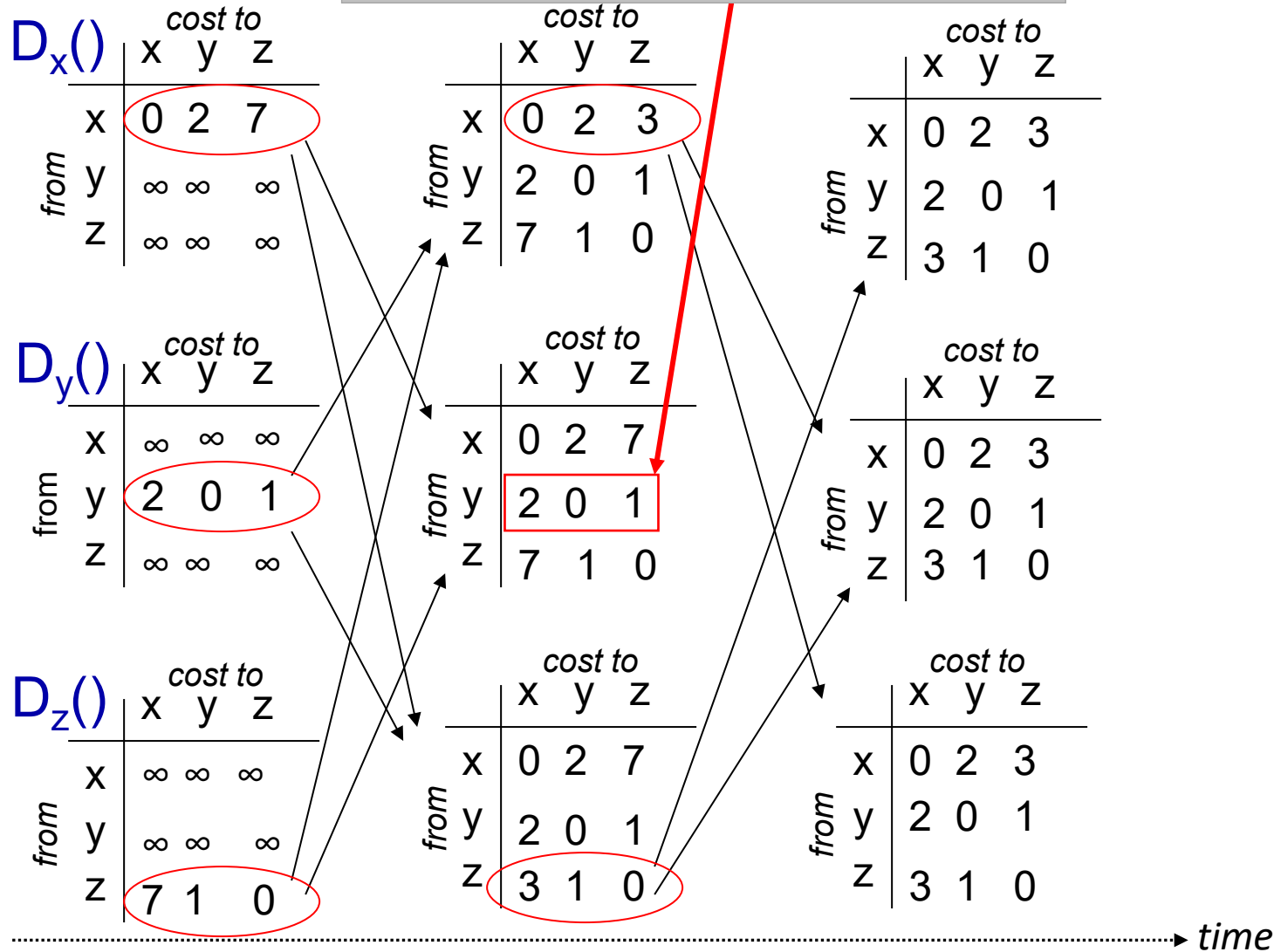


Distance vector: another example



Distance vector: another example

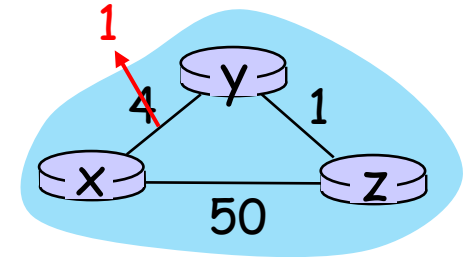
y's DV did not change after 1st iteration, so do not propagate its DV to neighbors



Distance vector: link cost changes

link cost changes:

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



“good news
travels fast”

t_0 : y detects link-cost change, updates its DV $D_y(x)=1$, informs its neighbors.

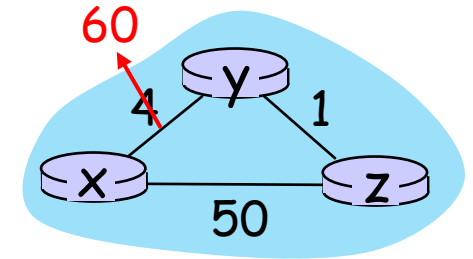
t_1 : z receives update from y , updates its DV, computes new least cost to x to be $\min(50, 1+1)=2$, sends its neighbors its DV.

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

Distance vector: link cost changes

link cost changes:

- node detects local link cost change
- “bad news travels slowly” :
 - 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 $D_y(x) = \min\{c_{y,x} + D_x(x), c_{y,z} + D_z(x)\} = \min\{60+0, 1+5\} = 6$ “my new cost to x will be 6 via z); notifies z of new cost of $D_y(x)=6$ to x.
 - z learns that path to x via y has new cost 6, so z computes $D_z(x) = \min\{c_{z,x} + D_x(x), c_{z,y} + D_y(x)\} = \min\{50+0, 1+6\} = 7$ “my new cost to x will be $D_z(x)=7$ 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 $D_y(x) = \min\{c_{y,x} + D_x(x), c_{y,z} + D_z(x)\} = \min\{60+0, 1+7\} = 8$ “my new cost to x will be 8 via z), notifies z of new cost of $D_y(x)=8$ to x.
 - z learns that path to x via y has new cost 8, so z computes $D_z(x) = \min\{c_{z,x} + D_x(x), c_{z,y} + D_y(x)\} = \min\{50+0, 1+8\} = 9$ “my new cost to x will be $D_z(x)=9$ via y), notifies y of new cost of 9 to x.
 - The iterations will stop when $D_z(x)$ reaches 50 and $D_y(x)$ reaches 51



Comparison of LS and DV algorithms

message complexity

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

DV: exchange between neighbors; convergence time varies

speed of convergence

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

- may have oscillations

DV: convergence time varies

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

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

LS:

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

DV:

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