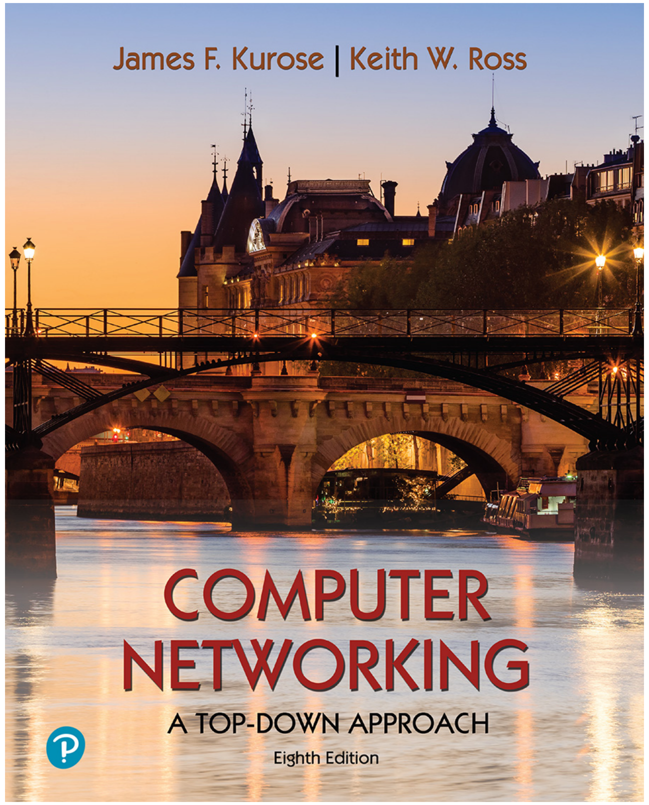
Chapter 5
Network Layer: Control Plane



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

IMPORTANT

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

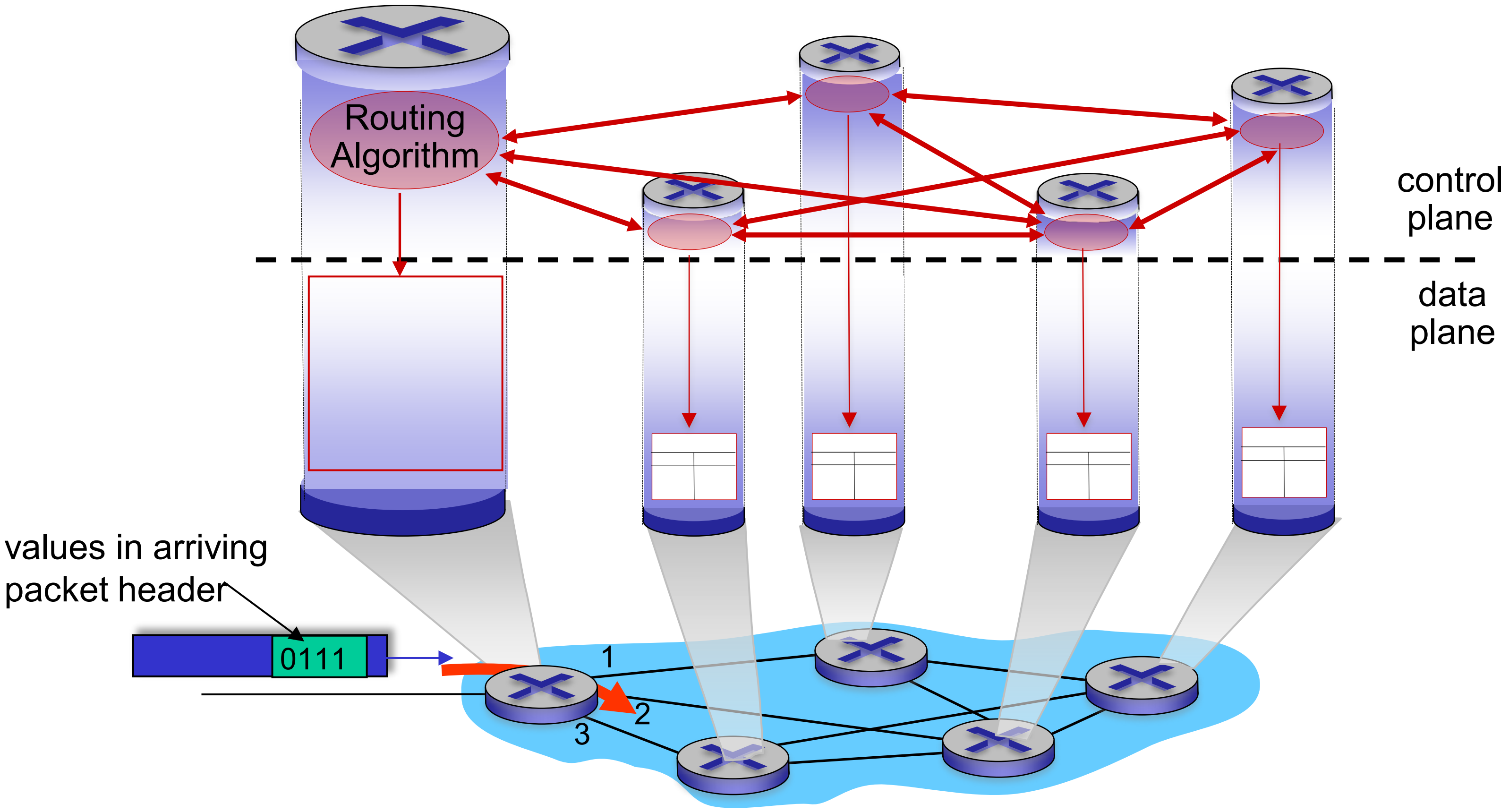
Two approaches to structuring network control plane:

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

IMPORTANT

Per-router control plane

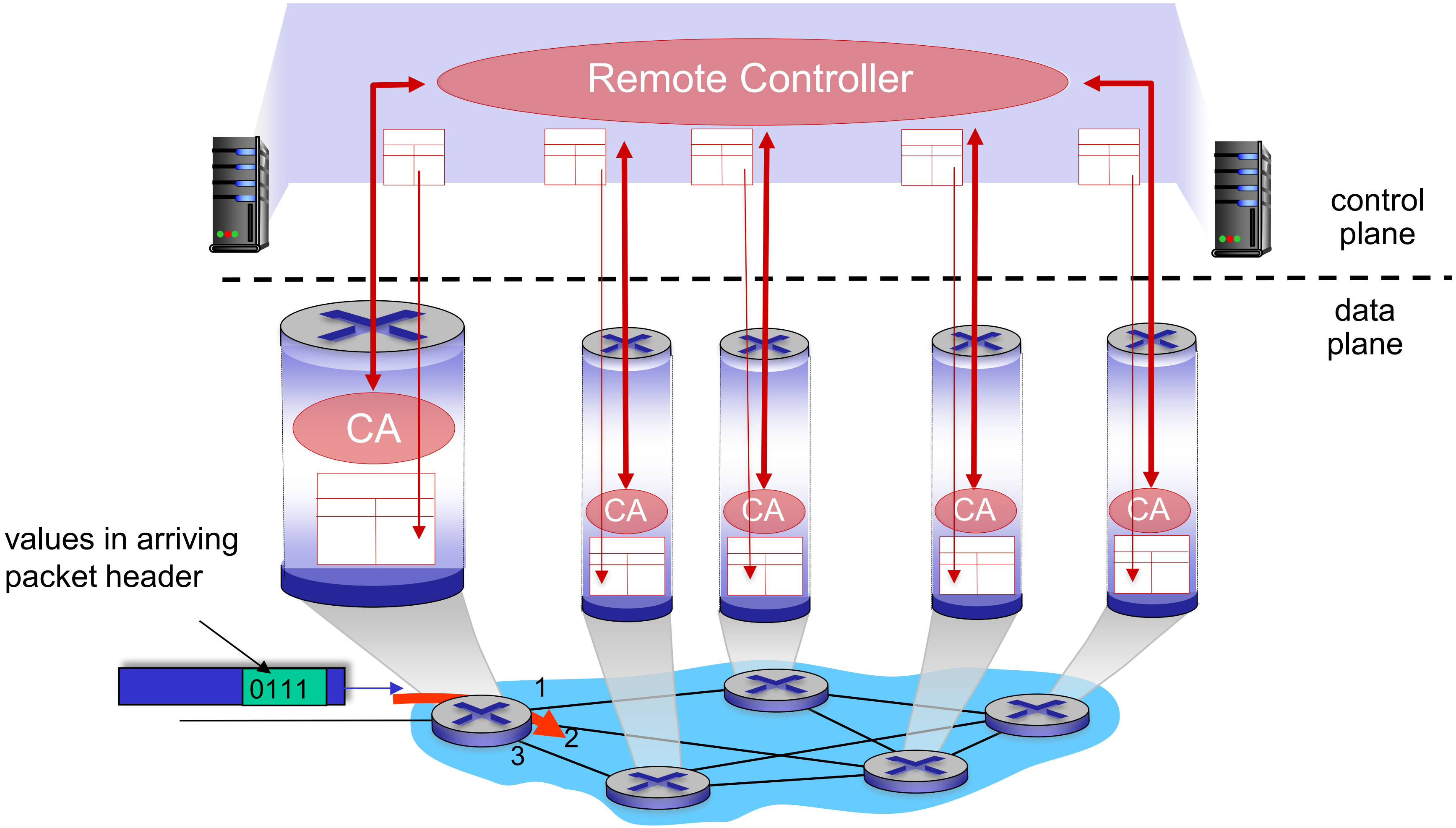
Individual routing algorithm components *in each and every router* interact in the control plane



IMPORTANT

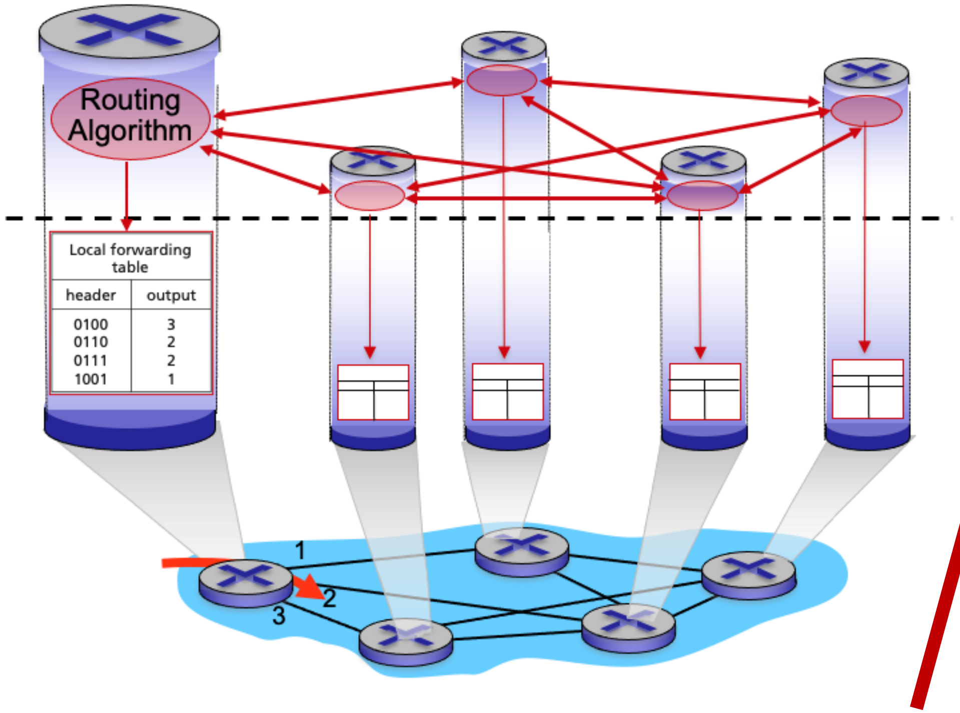
Software-Defined Networking (SDN) control plane

Remote controller computes, installs forwarding tables in routers



IMPORTANT

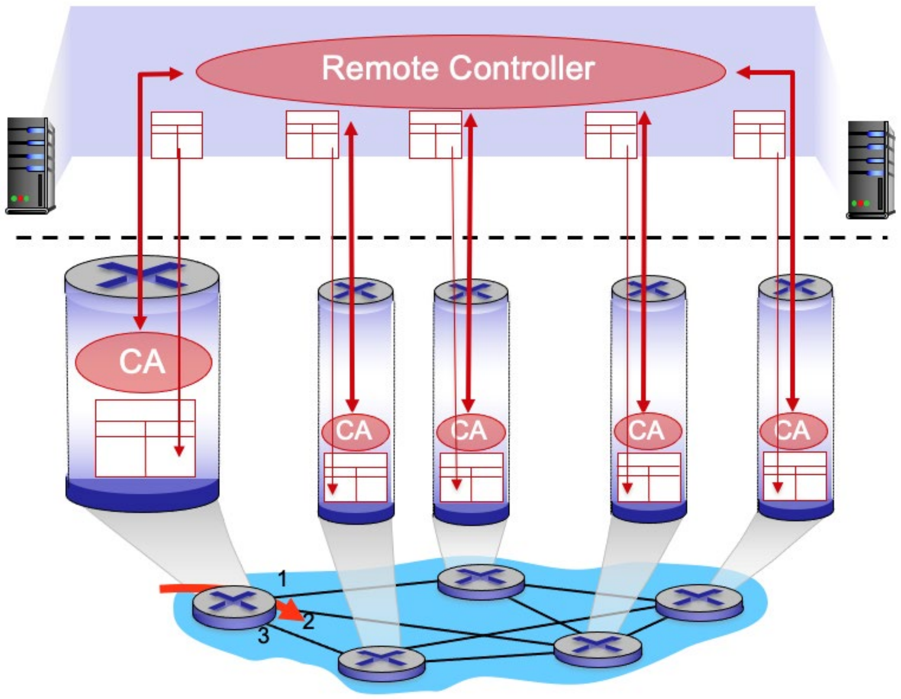
Per-router control plane



Local forwarding table

header	output
0100	3
0110	2
0111	2
1001	1

SDN control plane



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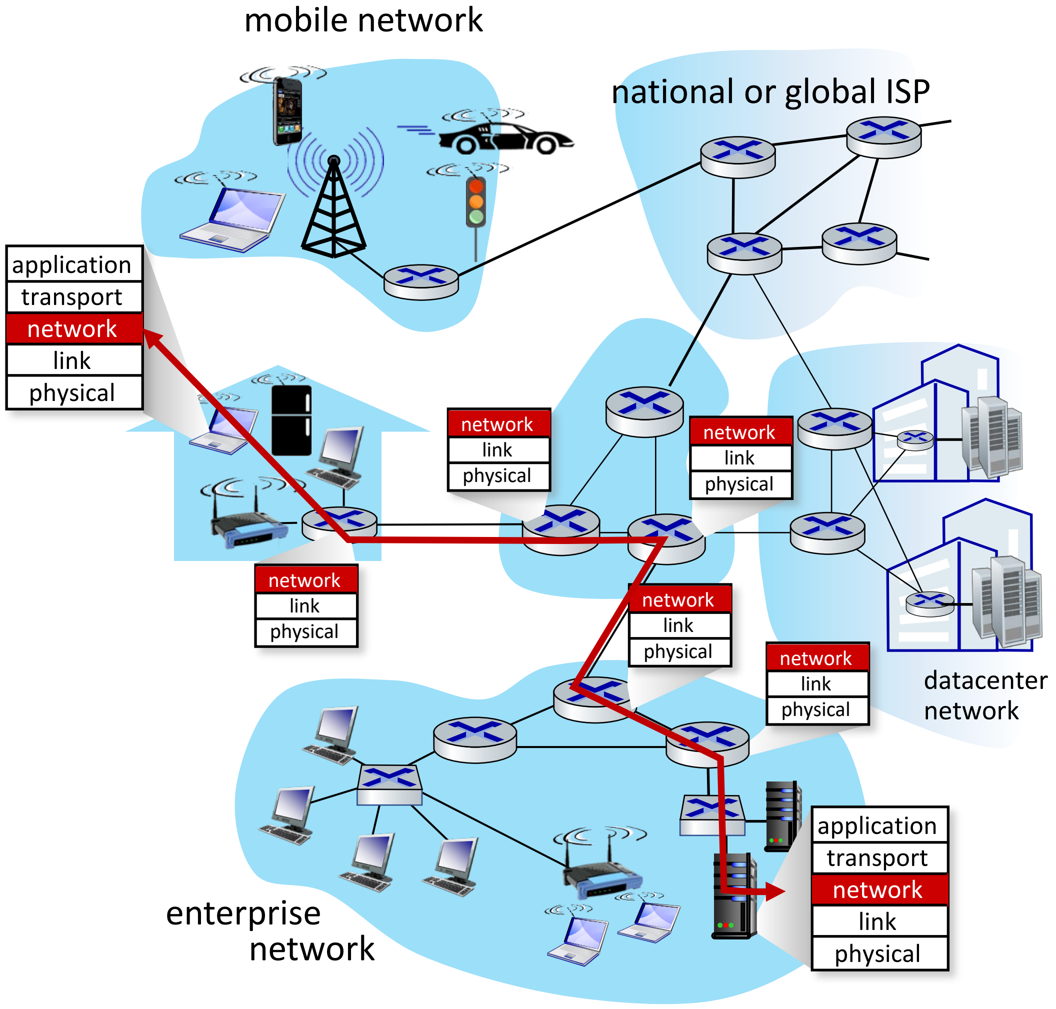
IMPORTANT

Routing protocols

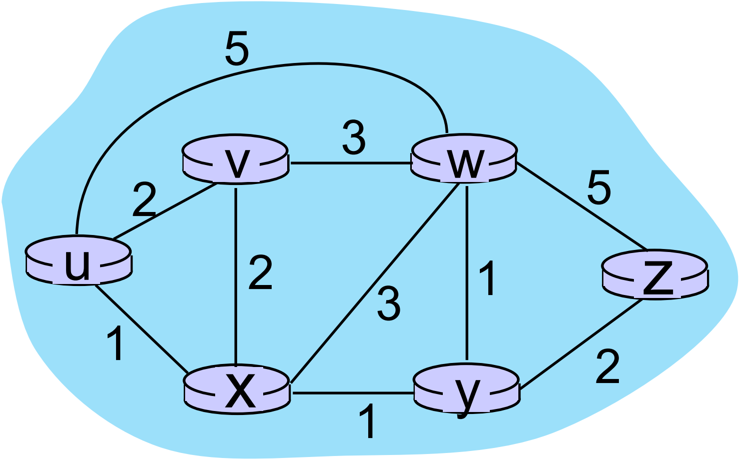
Routing protocol goal: determine "good" paths (equivalently, routes), from sending hosts to receiving host, through network of routers

- 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!



IMPORTANT

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)* }

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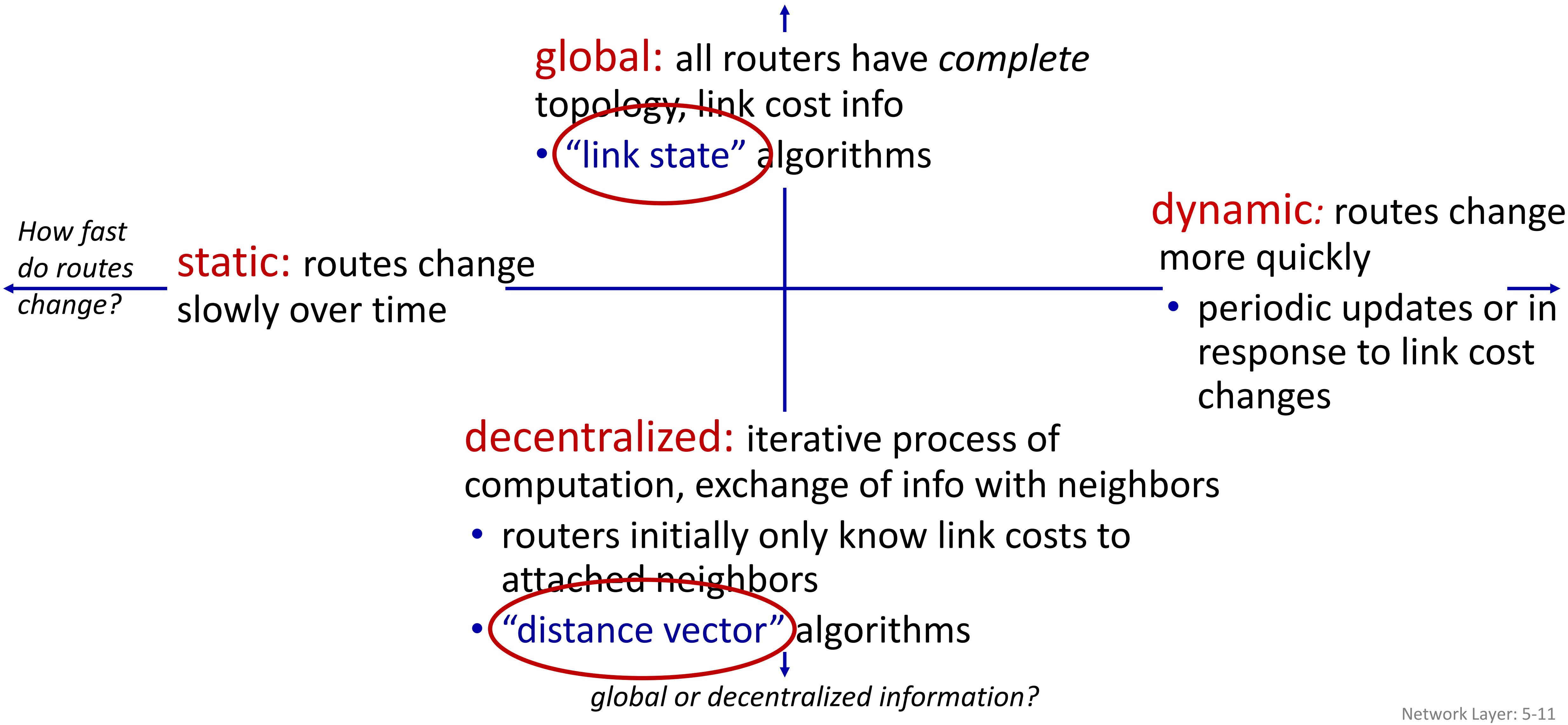
Routing algorithm classification



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

- "link state" algorithms

How fast do routes change?

static: routes change slowly over time

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?

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IMPORTANT

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*; = ∞ 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

IMPORTANT

Dijkstra’s link-state routing algorithm

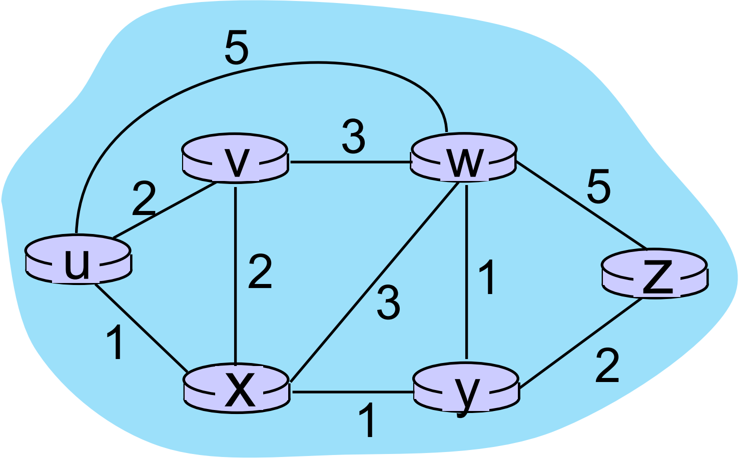
```
Initialization:
  $N' = \{u\}$                          /* compute least cost path from u to all other nodes */
  for all nodes $v$
    if $v$ adjacent to $u$              /* $u$ initially knows direct-path-cost only to  direct neighbors    */
        then $D(v) = c_{u,v}$           /* but may not be minimum cost!                                       */
    else $D(v) = \infty$

Loop
    find $w$ not in $N'$ such that $D(w)$ is a minimum
    add $w$ to $N'$
    update $D(v)$ for all $v$ adjacent to $w$ and not in $N'$ :
        $D(v) = \min ( D(v),  D(w) + c_{w,v} )$
    /* new least-path-cost to $v$ is either old least-cost-path to $v$ or known
    least-cost-path to $w$ plus direct-cost from $w$ to $v$ */
until all nodes in $N'$
```

IMPORTANT

Dijkstra’s algorithm: an example

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



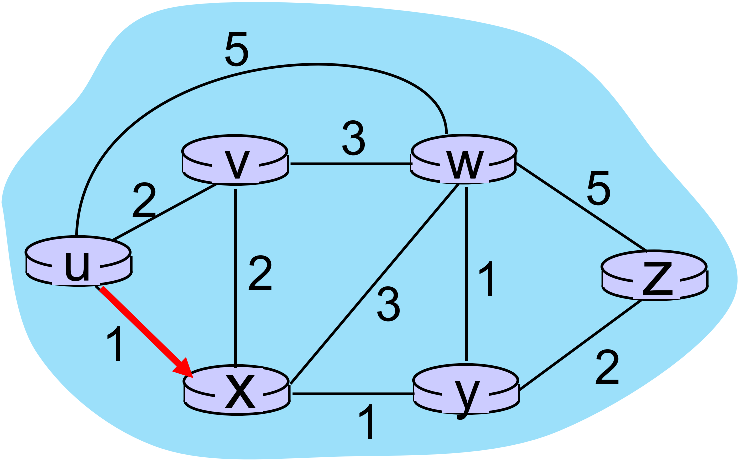
Initialization (step 0):

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

IMPORTANT

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						
3						
4						
5						

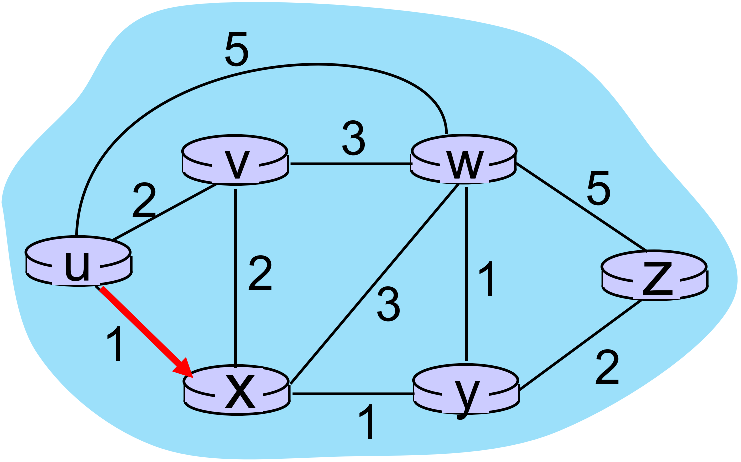


```
Loop
    find a not in N′ such that D(a) is a minimum
    add a to N′
```

IMPORTANT

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						



```
Loop
    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 $N'$ :
        $D(b) = \min ( D(b), D(a) + c_{a,b} )$
```

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

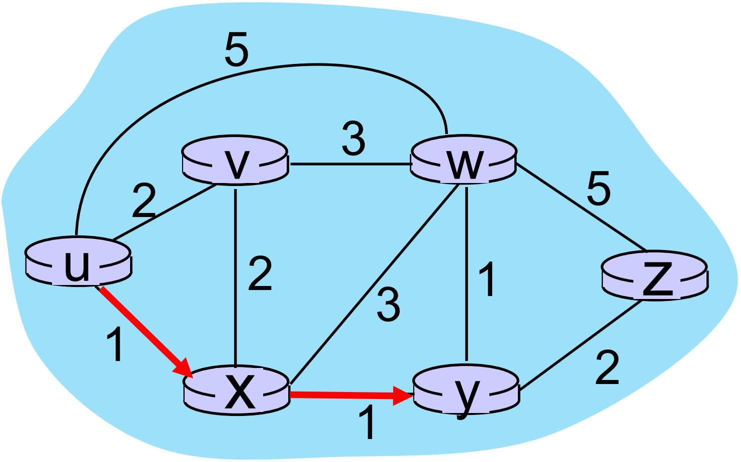
$D(w) = \min (D(w), D(x) + c_{x,w}) = \min (5, 1+3) = 4$

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

IMPORTANT

Dijkstra’s algorithm: an example

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



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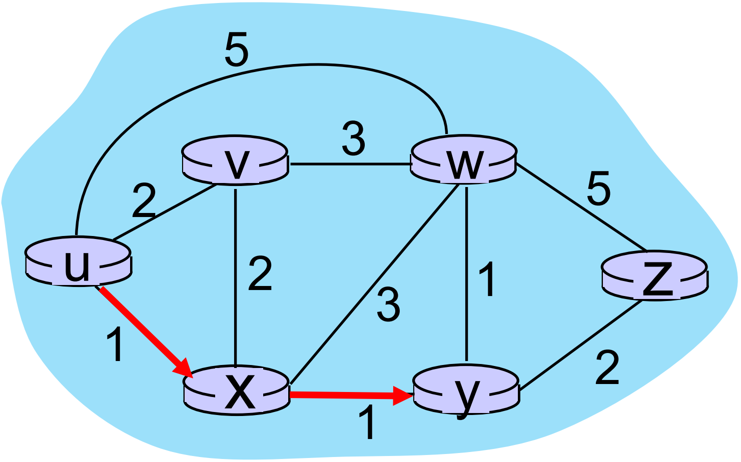
Loop
    find $a$ not in $N'$ such that $D(a)$ is a minimum
    add $a$ to $N'$
```

IMPORTANT

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						



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```

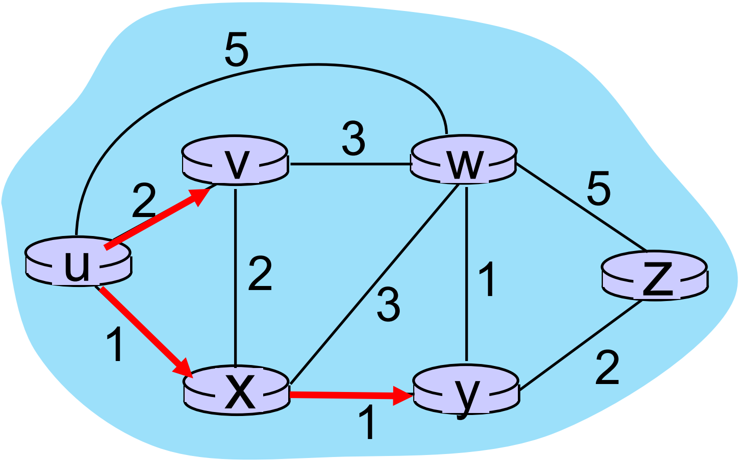
$D(w) = \min (D(w), D(y) + c_{y,w}) = \min (4, 2+1) = 3$

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

IMPORTANT

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

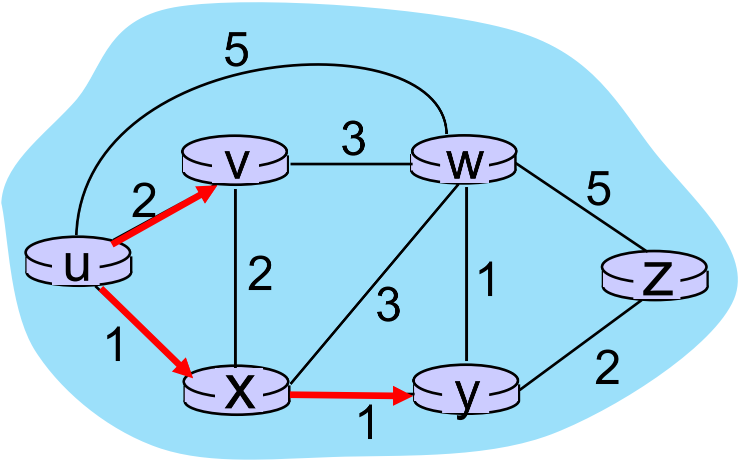


```
8   Loop
9       find $a$ not in $N'$ such that $D(a)$ is a minimum
10      add $a$ to $N'$
```

IMPORTANT

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						



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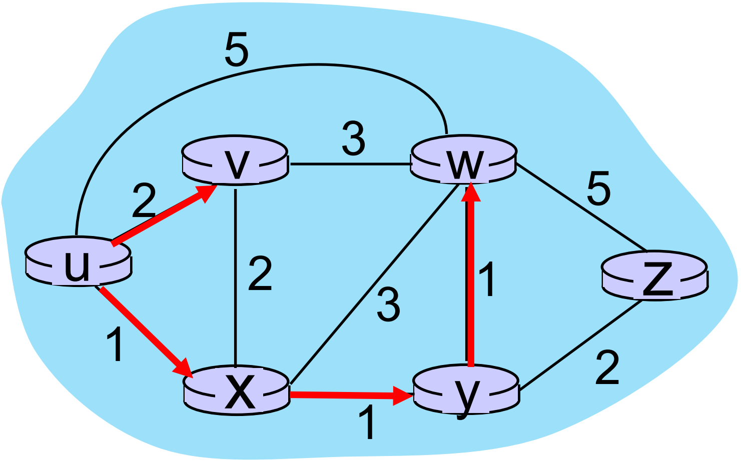
3	uxyv		3,y			4,y
4	uxyvw					
5						



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    find $a$ not in $N'$ such that $D(a)$ is a minimum
    add $a$ to $N'$
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IMPORTANT

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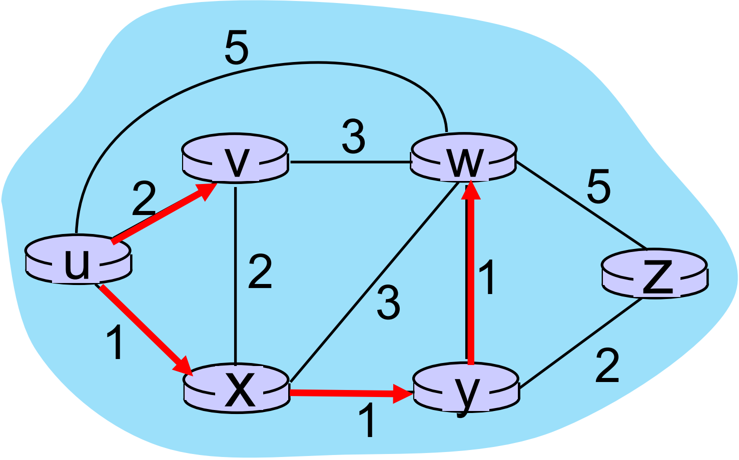
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					4,y
5						



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

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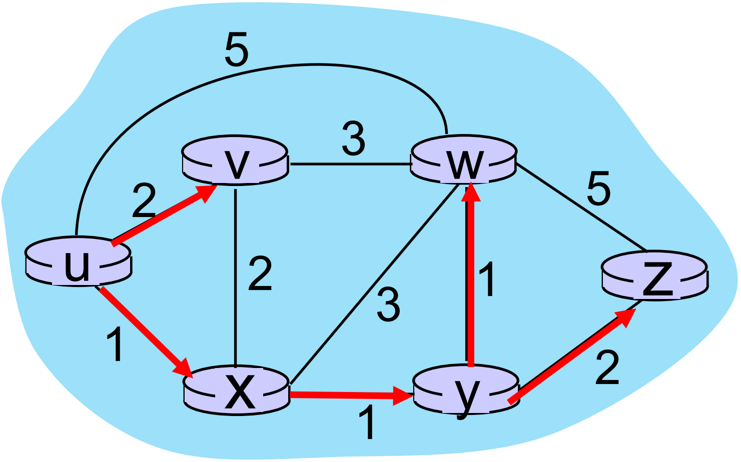
4	uxyvw					4,y
5	uxyvwz					



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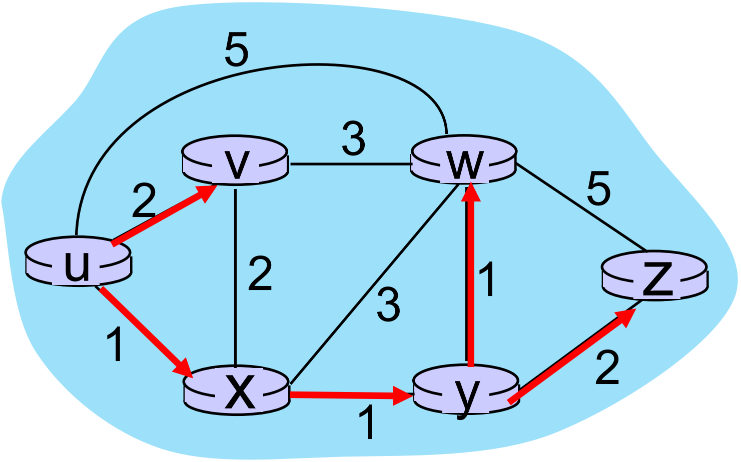
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					4,y
5	uxyvwz					



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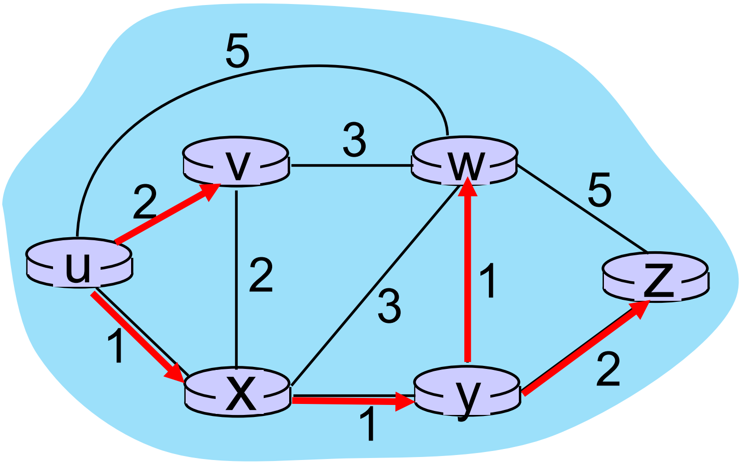
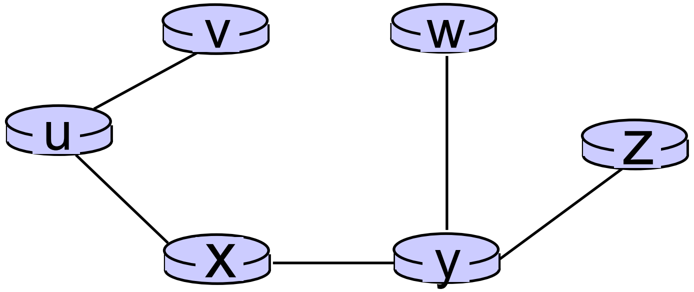


resulting least-cost-path tree from u:



resulting forwarding table in u:

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

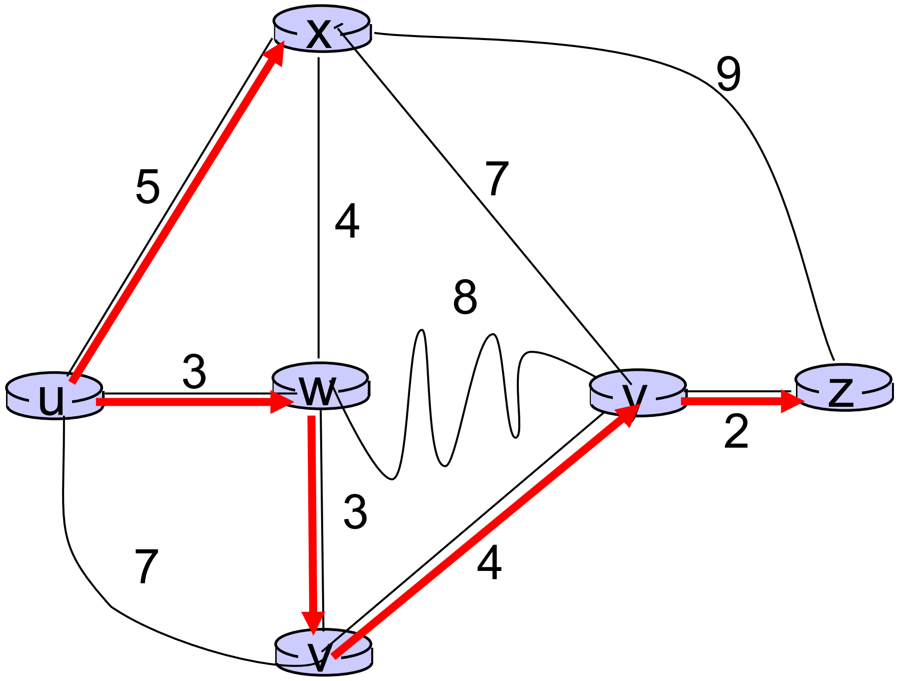
route from *u* to *v* directly

route from u to all other destinations via *x*

IMPORTANT

Dijkstra’s algorithm: another 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	7,u	3,u	5,u	∞	∞
1	uw	6,w		5,u	11,w	∞
2	uwx	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)

IMPORTANT

Dijkstra’s algorithm: discussion

algorithm complexity: *n* nodes

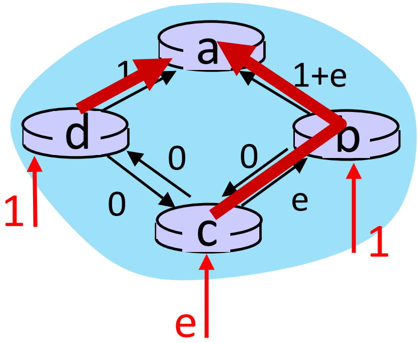
- each of *n* iteration: need to check all nodes, *w*, not in *N*
- $n(n+1)/2$ comparisons: $O(n^2)$ complexity
- more efficient implementations possible: $O(n\log n)$

message complexity:

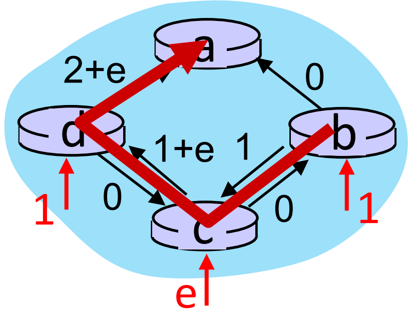
- each router must *broadcast* its link state information to other *n* routers
- efficient (and interesting!) broadcast algorithms: $O(n)$ link crossings to disseminate a broadcast message from one source
- each router’s message crosses $O(n)$ links: overall message complexity: $O(n^2)$

Dijkstra’s algorithm: oscillations possible

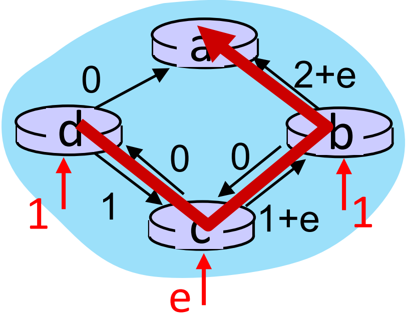
- when link costs depend on traffic volume, route oscillations possible
- sample scenario:
  - routing to destination a, traffic entering at d, c, e with rates 1, e (<1), 1
  - link costs are directional, and volume-dependent



initially



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



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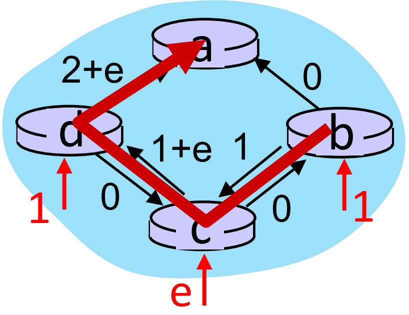

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Network layer: “control plane” roadmap

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IMPORTANT

Distance vector algorithm

Based on *Bellman-Ford* (BF) equation (dynamic programming):

Bellman-Ford equation

Let $D_x(y)$: cost of least-cost path from x to y.

Then:

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

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

min taken over all neighbors v of x

direct cost of link from x to v

IMPORTANT

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.

IMPORTANT

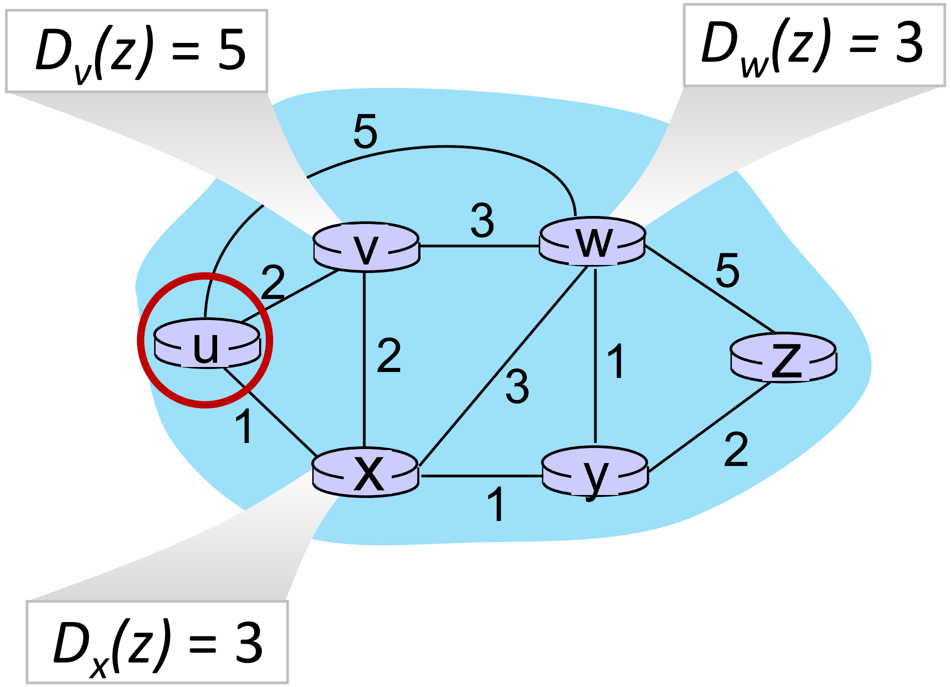
Bellman-Ford Algorithm

- 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 = ∞

IMPORTANT

Bellman-Ford Example

Suppose that *u*'s neighboring nodes, *x,v,w,* know that for destination *z*:



Bellman-Ford equation says:

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

node achieving minimum (x) is next hop on estimated least-cost path to destination (z)

IMPORTANT

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:

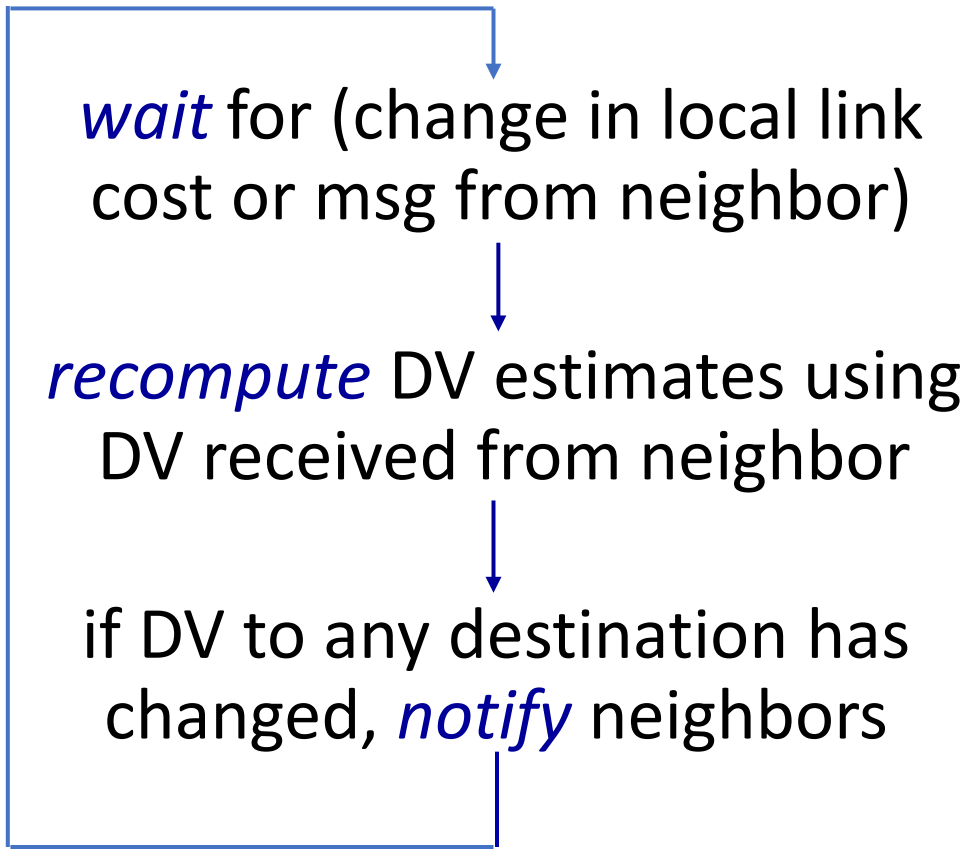
$$D_x(y) \leftarrow min_v\{c_{x,v} + D_v(y)\} \text{ for each node } y \in N$$

- under minor conditions, the estimate $D_x(y)$ *converge to the actual least cost* $\mathrm{d}_\mathrm{x}(\mathrm{y})$

IMPORTANT

Distance vector algorithm:

each node:



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

recompute DV estimates using DV received from neighbor

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

iterative, asynchronous: each local iteration caused by:

- local link cost change
- DV update message from neighbor

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

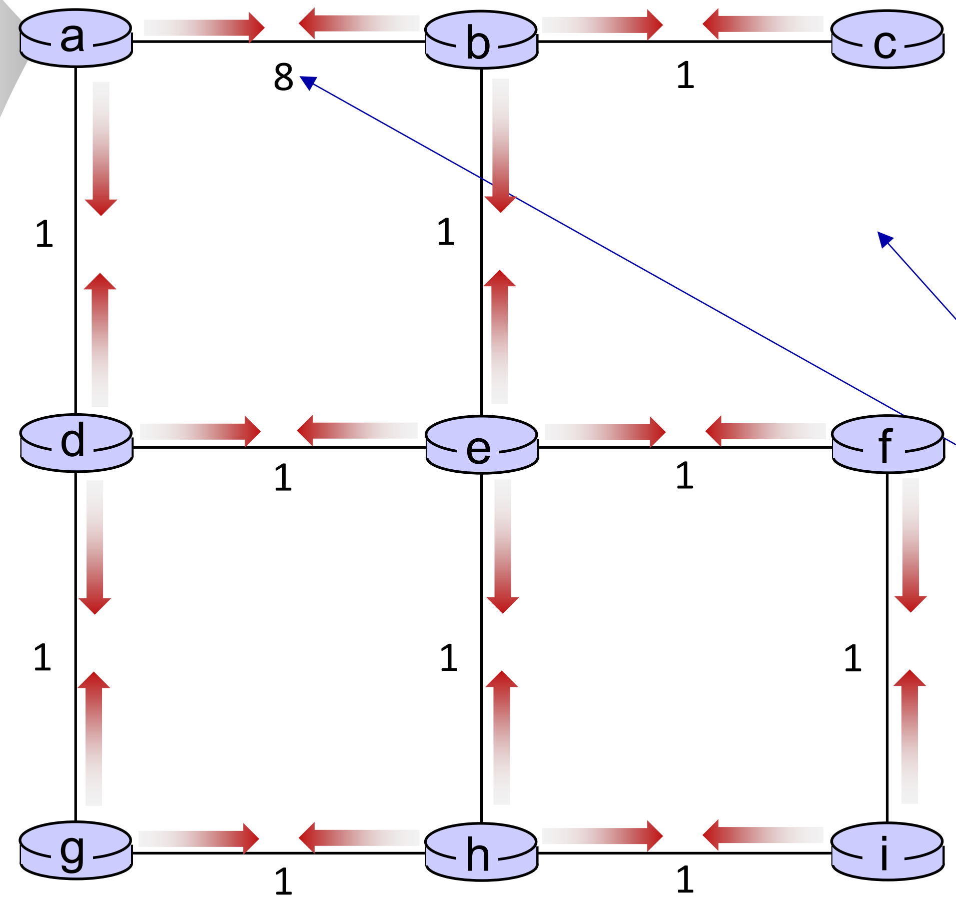
- neighbors then notify their neighbors – *only if necessary*
- no notification received, no actions taken!

Distance vector: example

t=0

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

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



A few asymmetries:

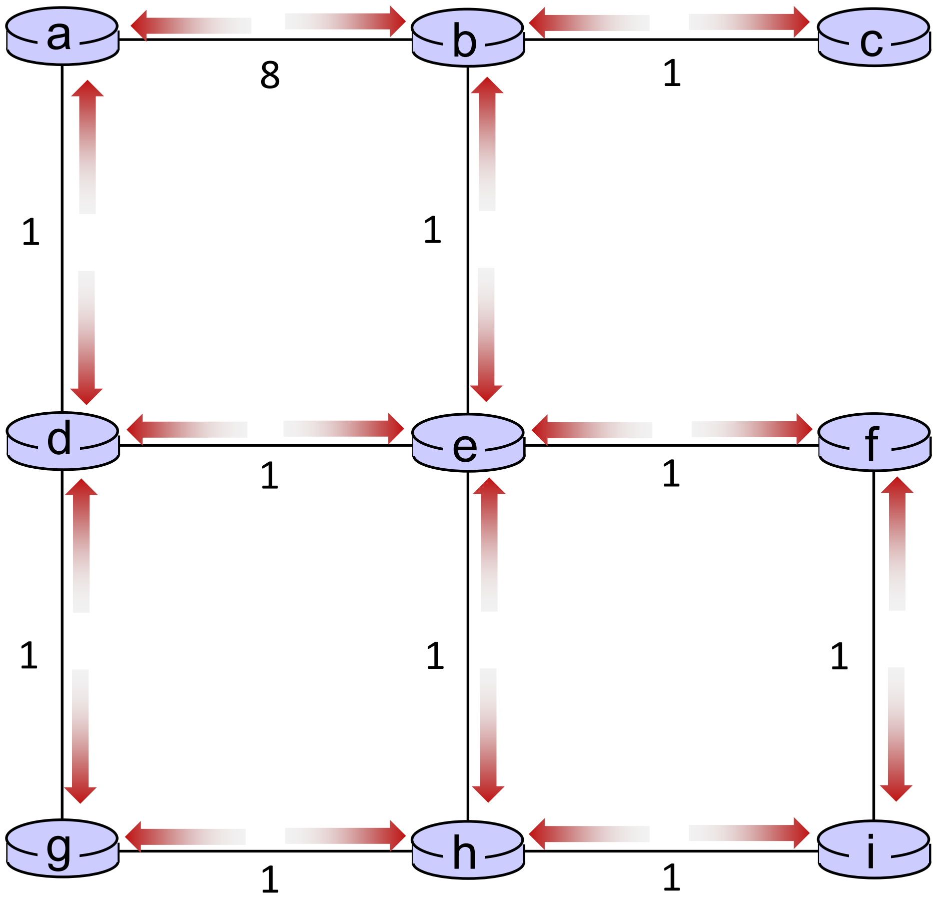
- missing link
- larger cost

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

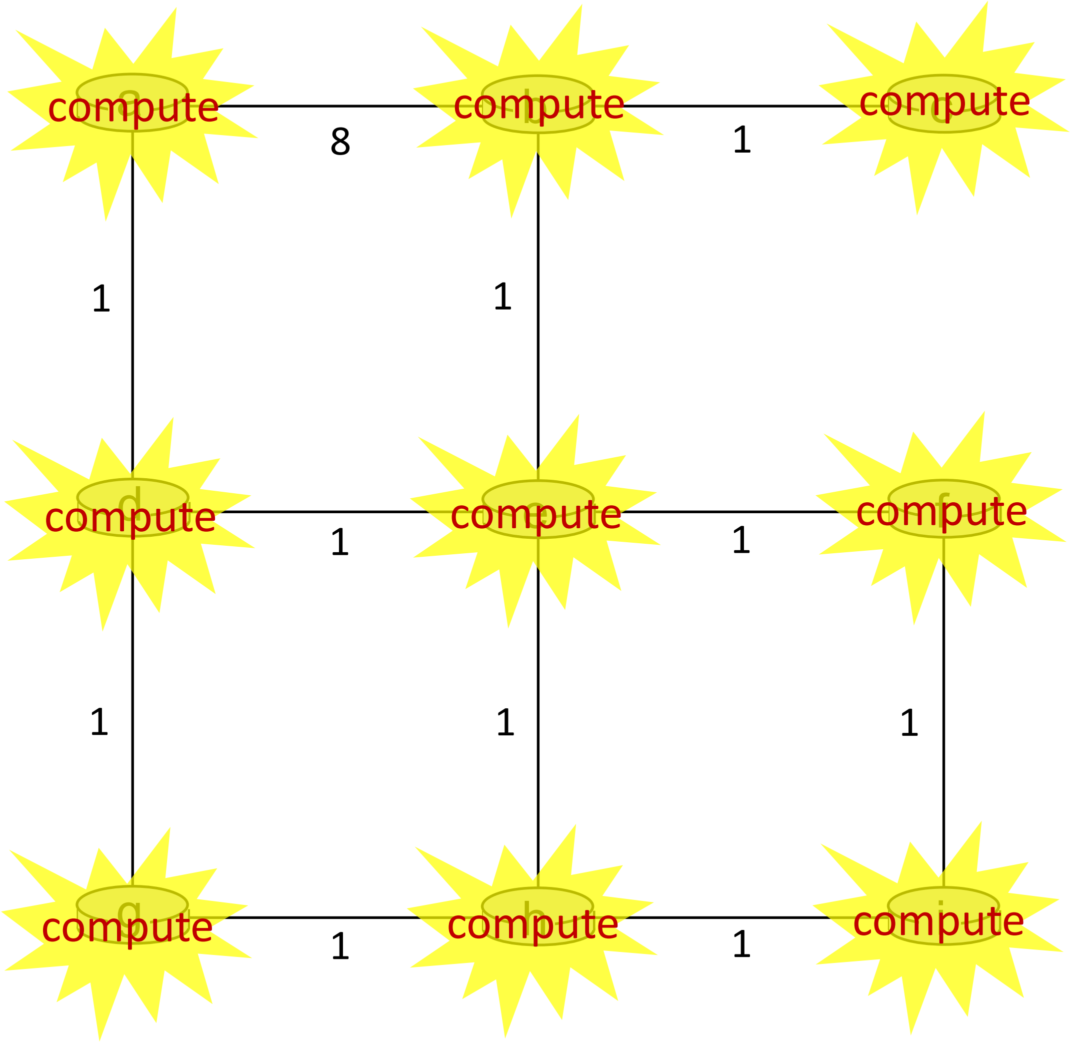


Distance vector example: iteration

t=1

All nodes:

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

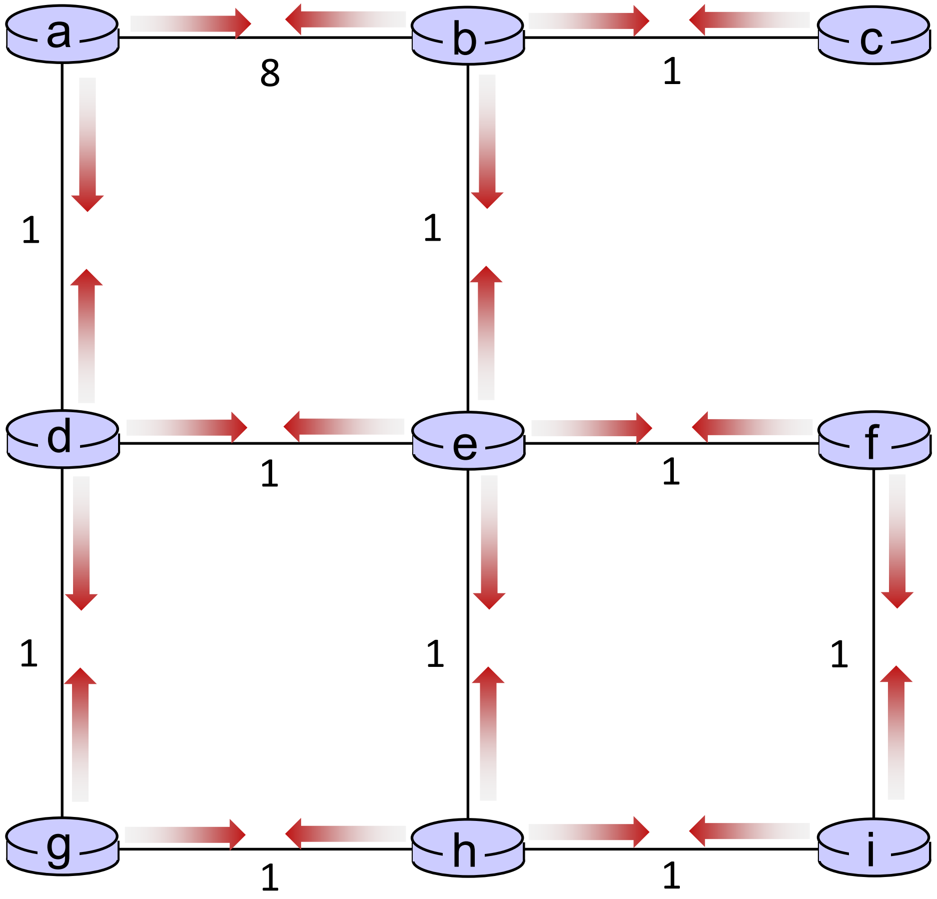


Distance vector example: iteration

t=1

All nodes:

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

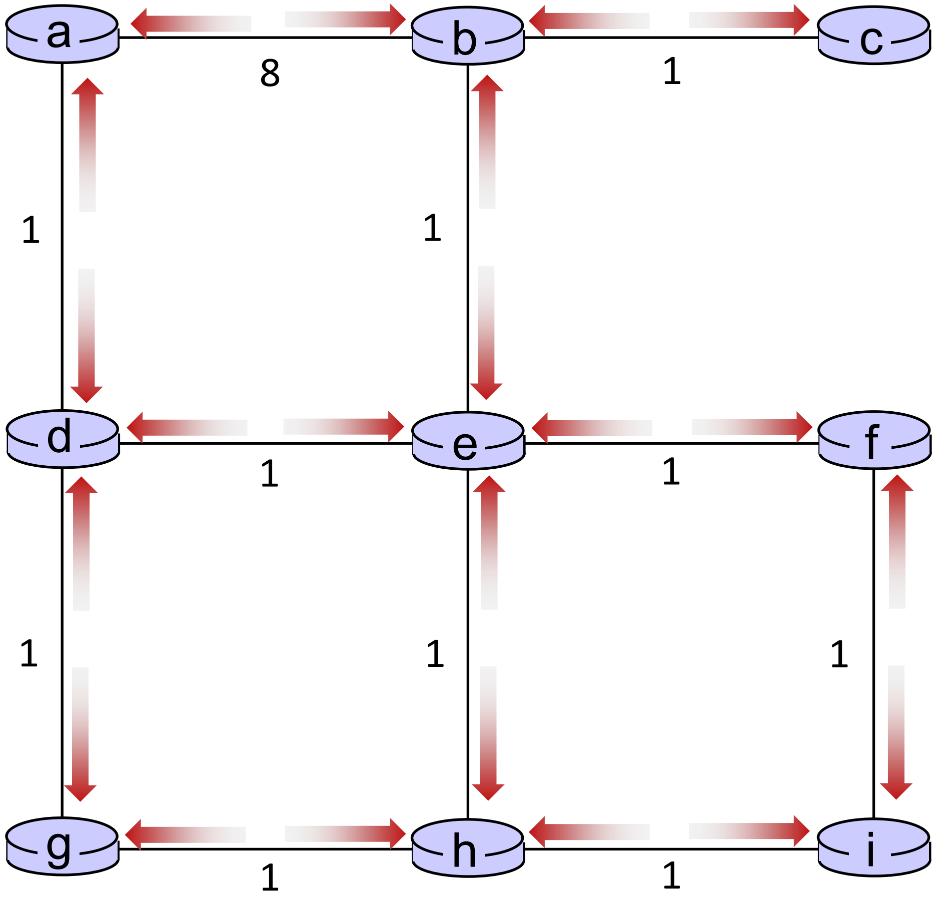


Distance vector example: iteration

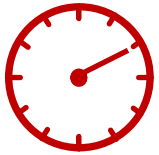
t=2

All nodes:

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



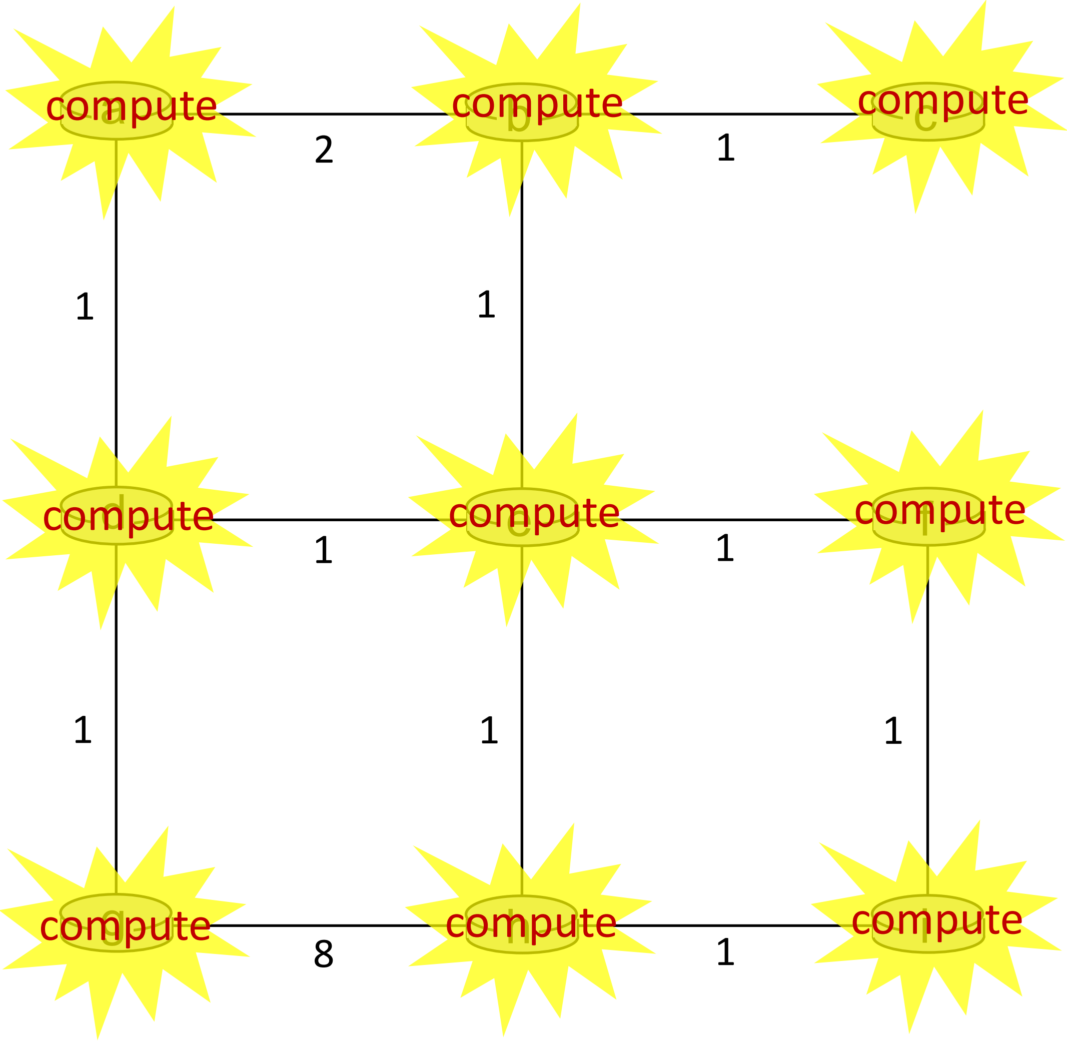
Distance vector example: iteration



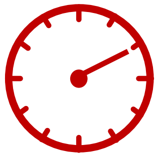
t=2

All nodes:

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



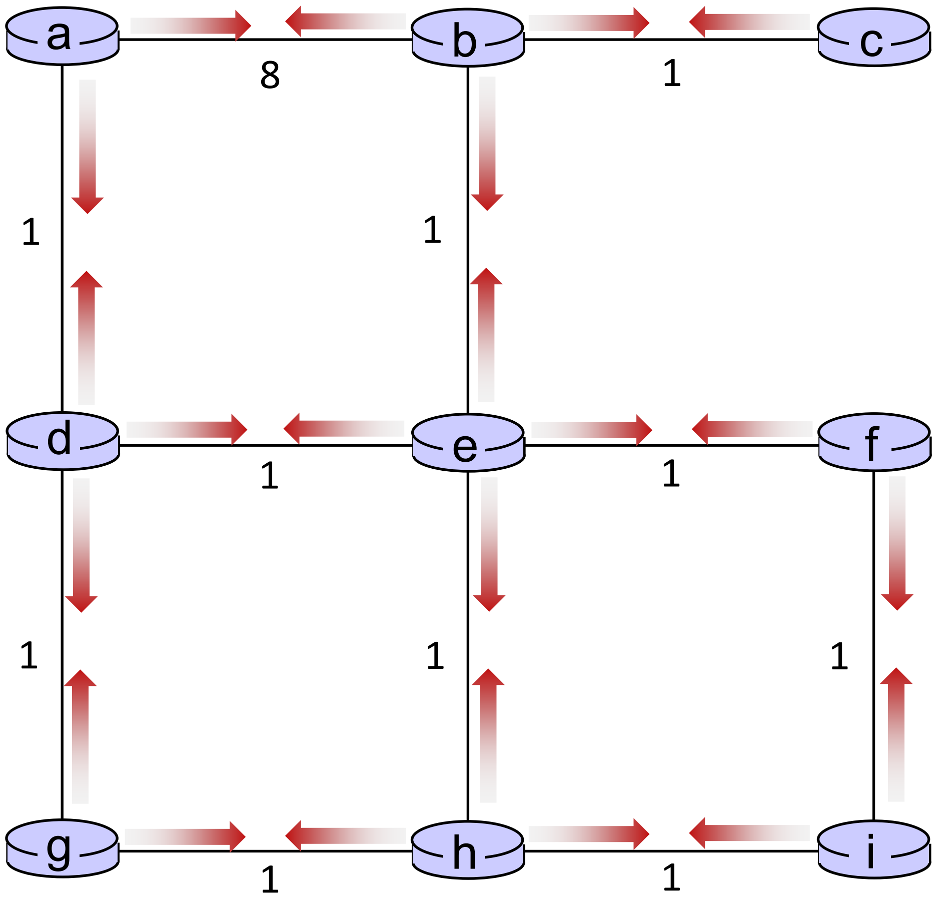
Distance vector example: iteration



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

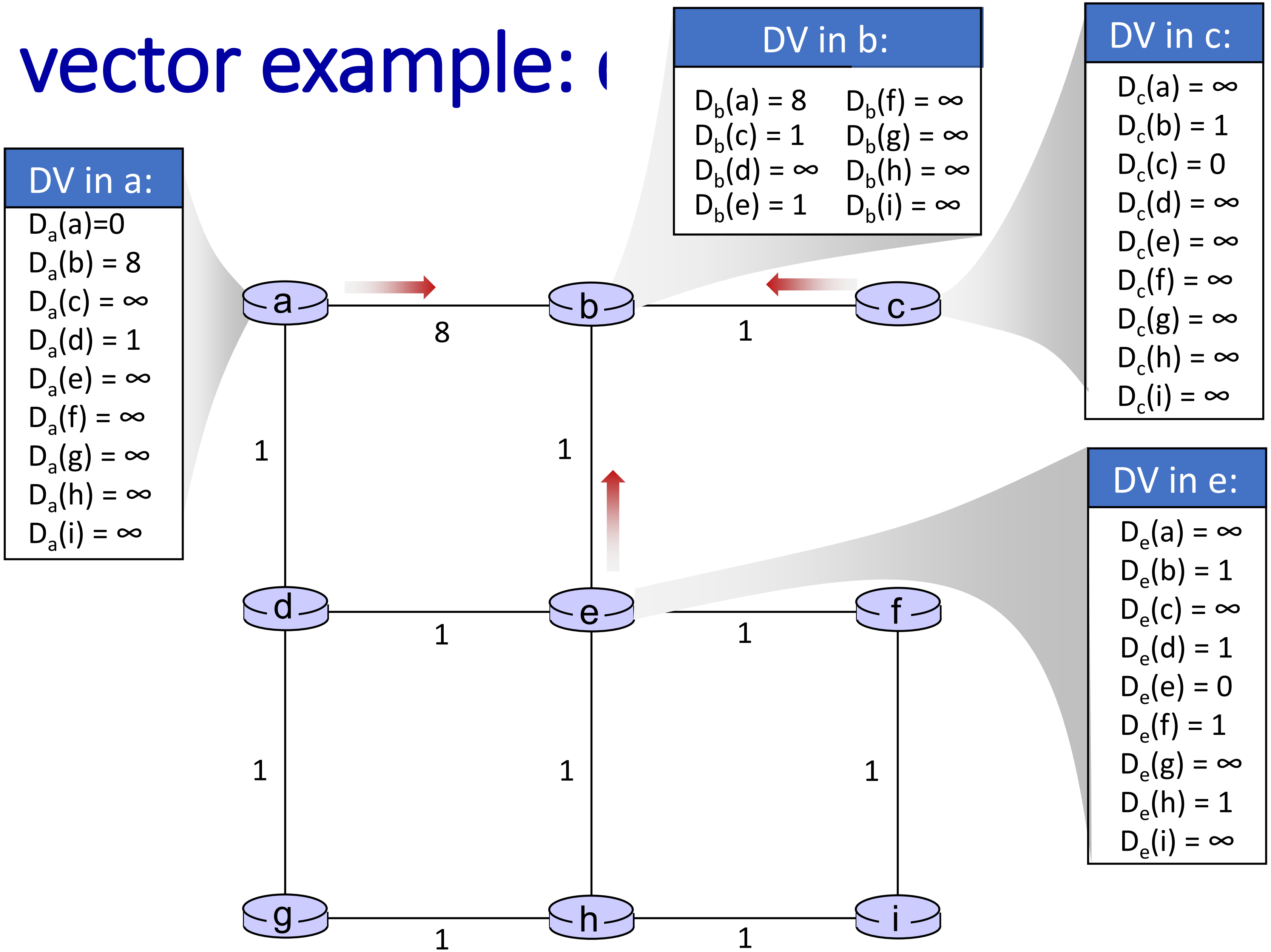
…. and so on

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:

DV in a:

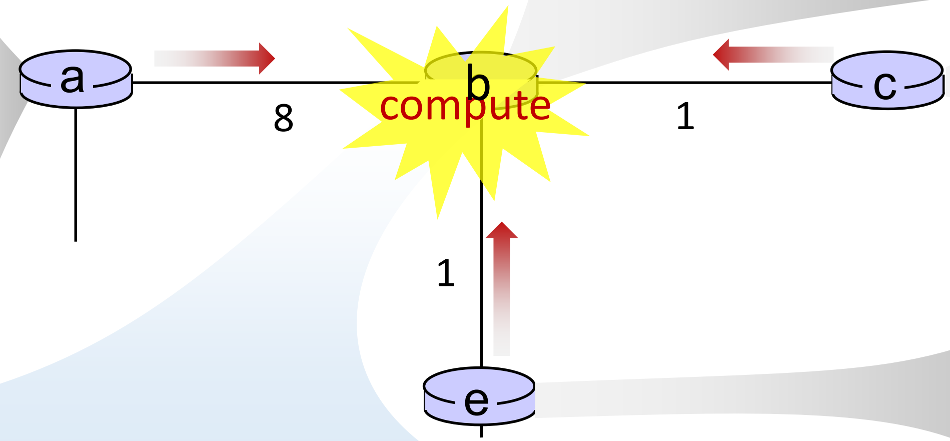
$D_a(a)=0$
$D_a(b) = 8$
$D_a(c) = \infty$
$D_a(d) = 1$
$D_a(e) = \infty$
$D_a(f) = \infty$
$D_a(g) = \infty$
$D_a(h) = \infty$
$D_a(i) = \infty$

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:

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

$D_b(a) = \min\{c_{b,a}+D_a(a),\ c_{b,c}+D_c(a),\ c_{b,e}+D_e(a)\} = \min\{8,\infty,\infty\} = 8$

$D_b(c) = \min\{c_{b,a}+D_a(c),\ c_{b,c}+D_c(c),\ c_{b,e}+D_e(c)\} = \min\{\infty,1,\infty\} = 1$

$D_b(d) = \min\{c_{b,a}+D_a(d),\ c_{b,c}+D_c(d),\ c_{b,e}+D_e(d)\} = \min\{9,\infty,2\} = 2$

$D_b(e) = \min\{c_{b,a}+D_a(e),\ c_{b,c}+D_c(e),\ c_{b,e}+D_e(e)\} = \min\{\infty,\infty,1\} = 1$

$D_b(f) = \min\{c_{b,a}+D_a(f),\ c_{b,c}+D_c(f),\ c_{b,e}+D_e(f)\} = \min\{\infty,\infty,2\} = 2$

$D_b(g) = \min\{c_{b,a}+D_a(g),\ c_{b,c}+D_c(g),\ c_{b,e}+D_e(g)\} = \min\{\infty, \infty, \infty\} = \infty$

$D_b(h) = \min\{c_{b,a}+D_a(h),\ c_{b,c}+D_c(h),\ c_{b,e}+D_e(h)\} = \min\{\infty, \infty, 2\} = 2$

$D_b(i) = \min\{c_{b,a}+D_a(i),\ c_{b,c}+D_c(i),\ c_{b,e}+D_e(i)\} = \min\{\infty, \infty, \infty\} = \infty$

DV in b:

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

Distance vector example:

t=1

- c receives DVs from b

DV in a:

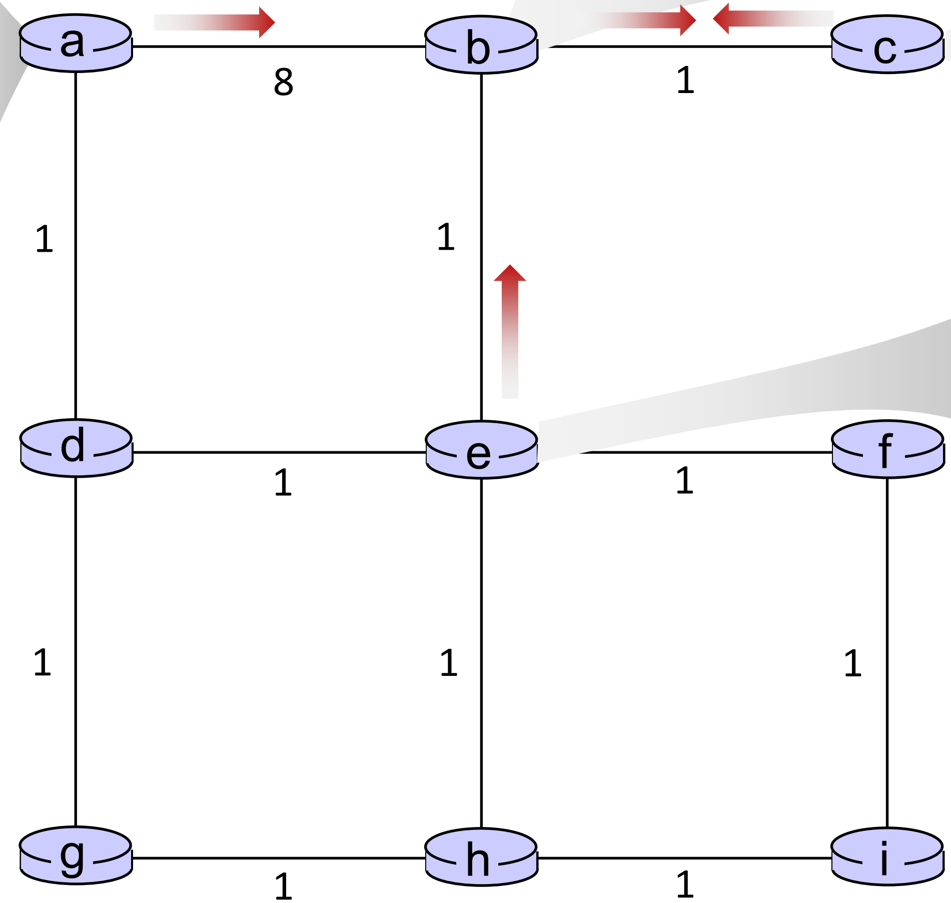
$D_a(a)=0$
$D_a(b) = 8$
$D_a(c) = \infty$
$D_a(d) = 1$
$D_a(e) = \infty$
$D_a(f) = \infty$
$D_a(g) = \infty$
$D_a(h) = \infty$
$D_a(i) = \infty$

DV in b:

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

DV in c:

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



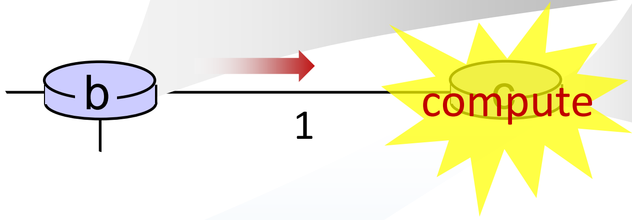
DV in e:

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

Distance vector example:

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



t=1

- c receives DVs from b computes:

$D_c(a) = \min\{c_{c,b}+D_b(a)\} = 1 + 8 = 9$

$D_c(b) = \min\{c_{c,b}+D_b(b)\} = 1 + 0 = 1$

$D_c(d) = \min\{c_{c,b}+D_b(d)\} = 1+ \infty = \infty$

$D_c(e) = \min\{c_{c,b}+D_b(e)\} = 1 + 1 = 2$

$D_c(f) = \min\{c_{c,b}+D_b(f)\} = 1+ \infty = \infty$

$D_c(g) = \min\{c_{c,b}+D_b(g)\} = 1+ \infty = \infty$

$D_c(h) = \min\{c_{bc,b}+D_b(h)\} = 1+ \infty = \infty$

$D_c(i) = \min\{c_{c,b}+D_b(i)\} = 1+ \infty = \infty$

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

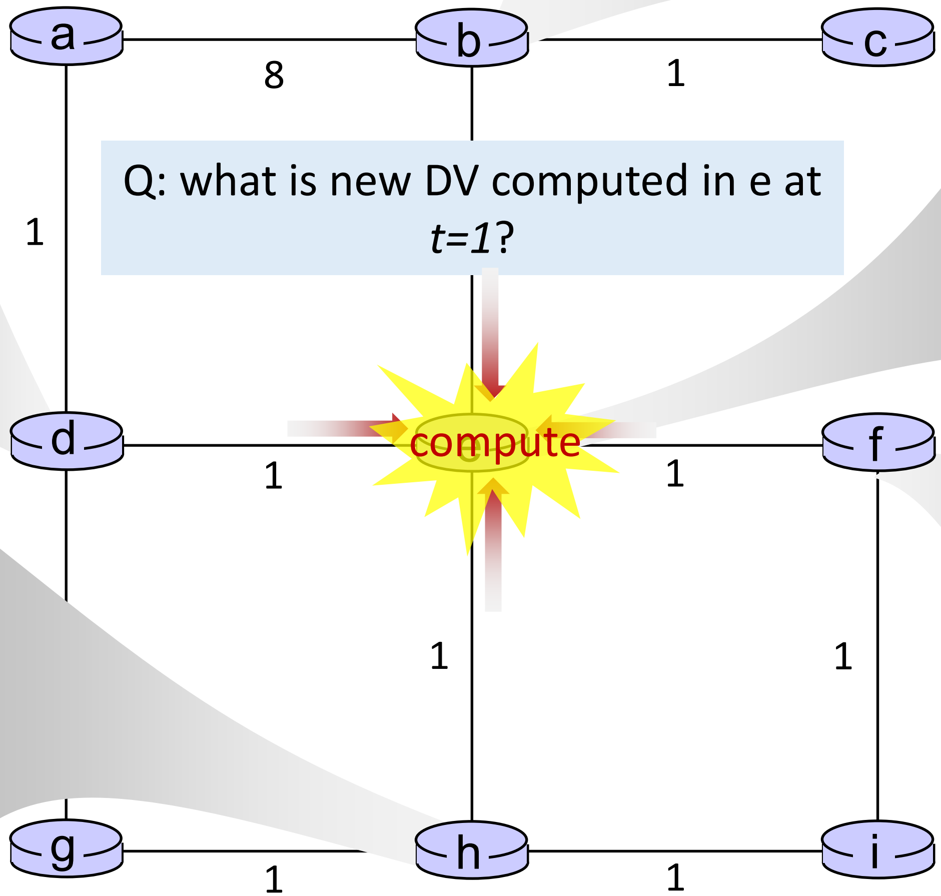
- e receives DVs from b, d, f, h

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:

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



Q: what is new DV computed in e at *t=1*?

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 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:

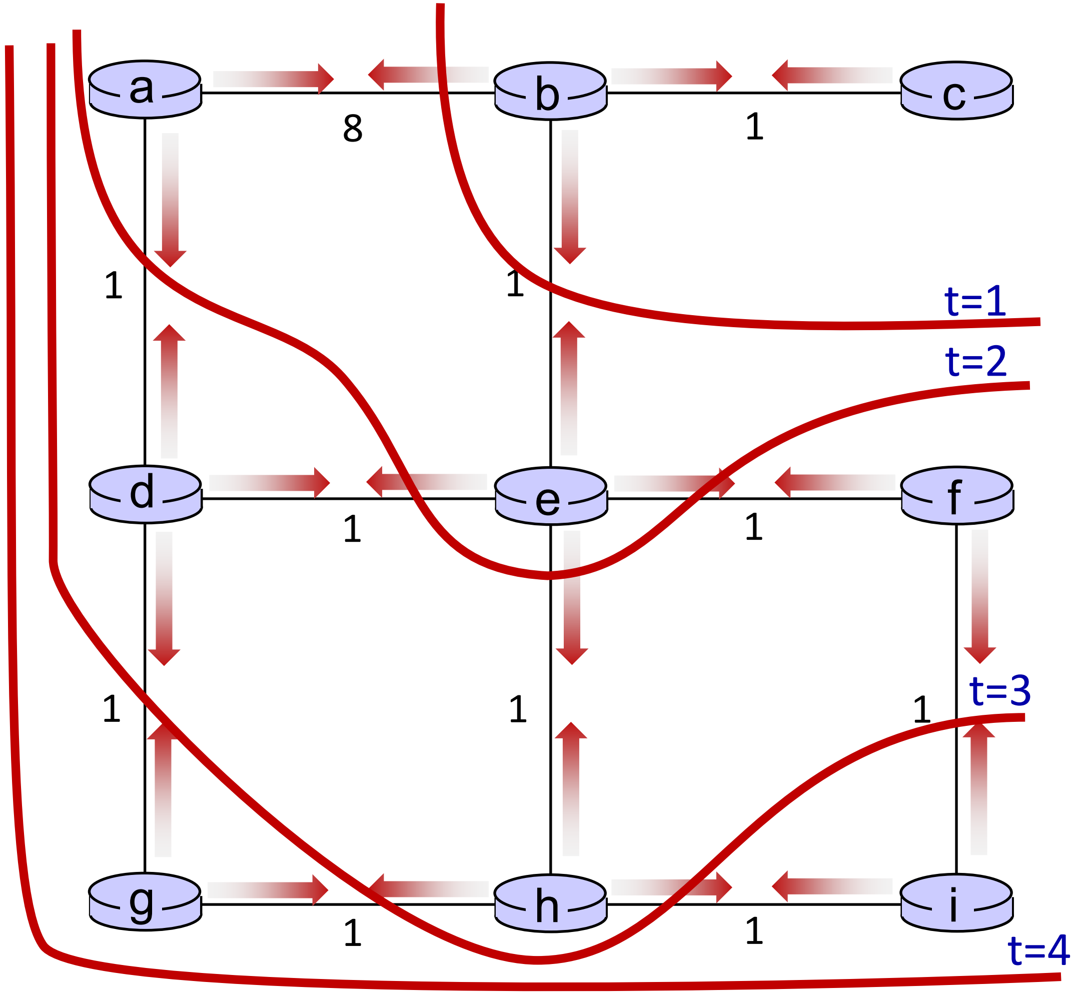
t=0 c's state at t=0 is at c only

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 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

$D_x()$

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

$D_y()$

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

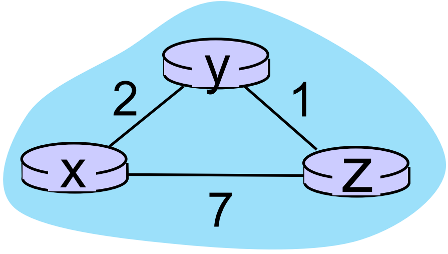
$D_z()$

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

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

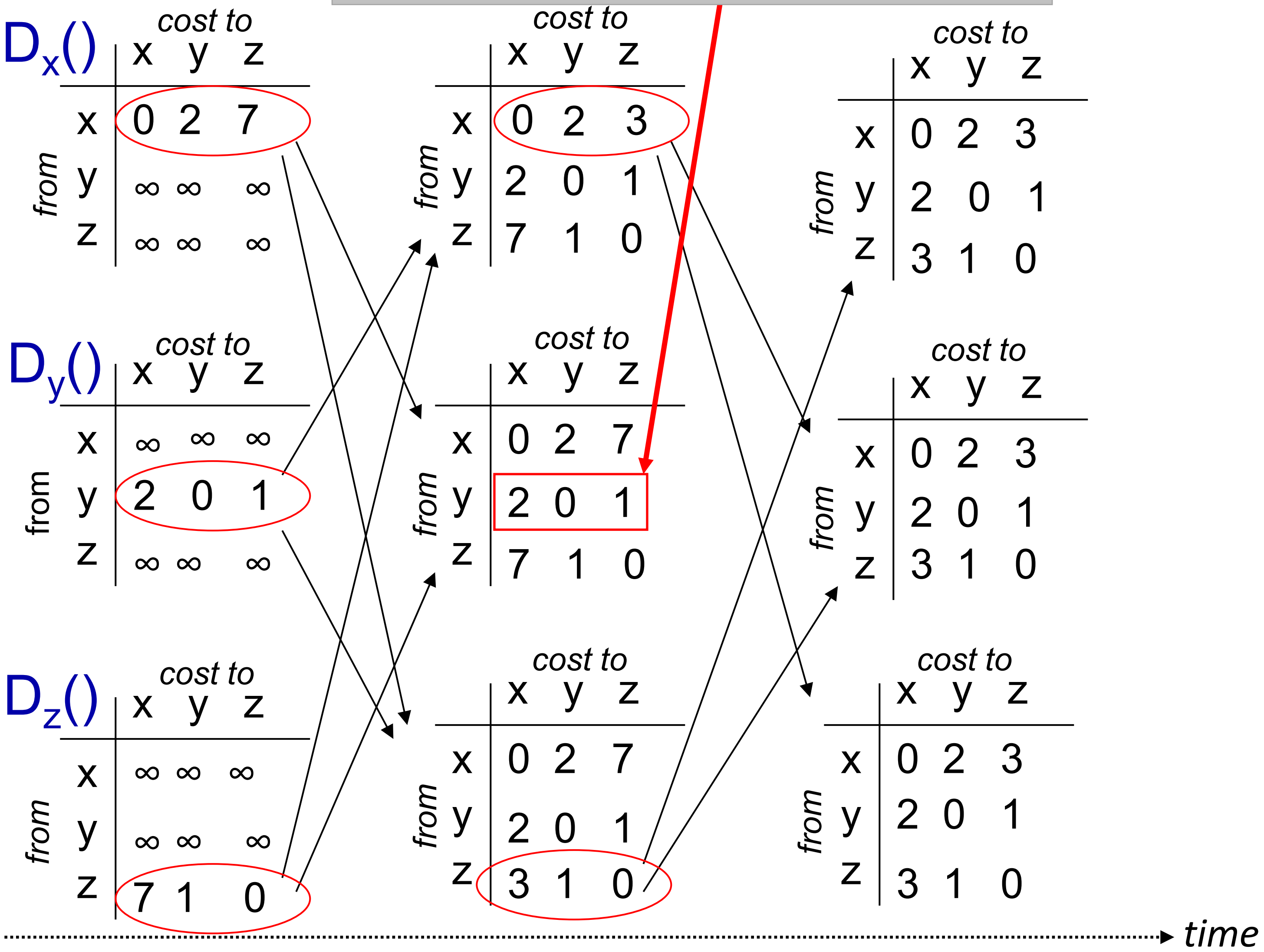
$$D_x(z) = \min\{c_{x,y} + D_y(z),\ c_{x,z} + D_z(z)\}$$
$$= \min\{2+1\ ,\ 7+0\} = 3$$

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



time

Distance vector: another example



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

$D_x()$

cost to

from	x	y	z
x	0	2	7
y	∞	∞	∞
z	∞	∞	∞

$D_y()$

cost to

from	x	y	z
x	∞	∞	∞
y	2	0	1
z	∞	∞	∞

$D_z()$

cost to

from	x	y	z
x	∞	∞	∞
y	∞	∞	∞
z	7	1	0

cost to

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

cost to

from	x	y	z
x	0	2	7
y	2	0	1
z	7	1	0

cost to

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

cost to

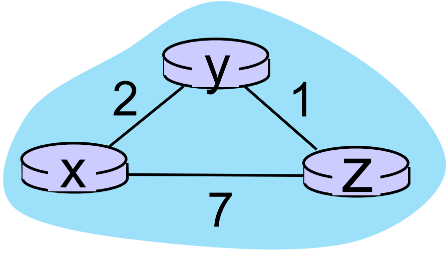
from	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

cost to

from	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

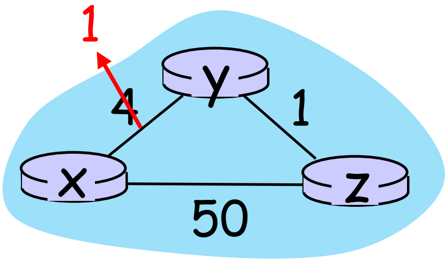
cost to

from	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0



IMPORTANT

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"

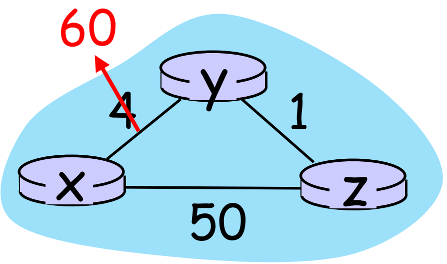
t_0 : *y* detects link-cost change, updates its DV $D_y(x)$=1, informs its neighbors.

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

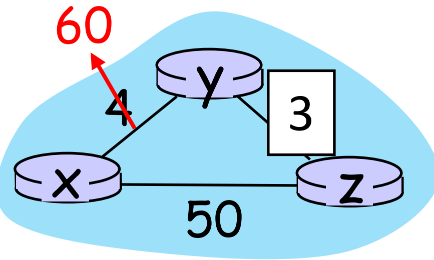
IMPORTANT

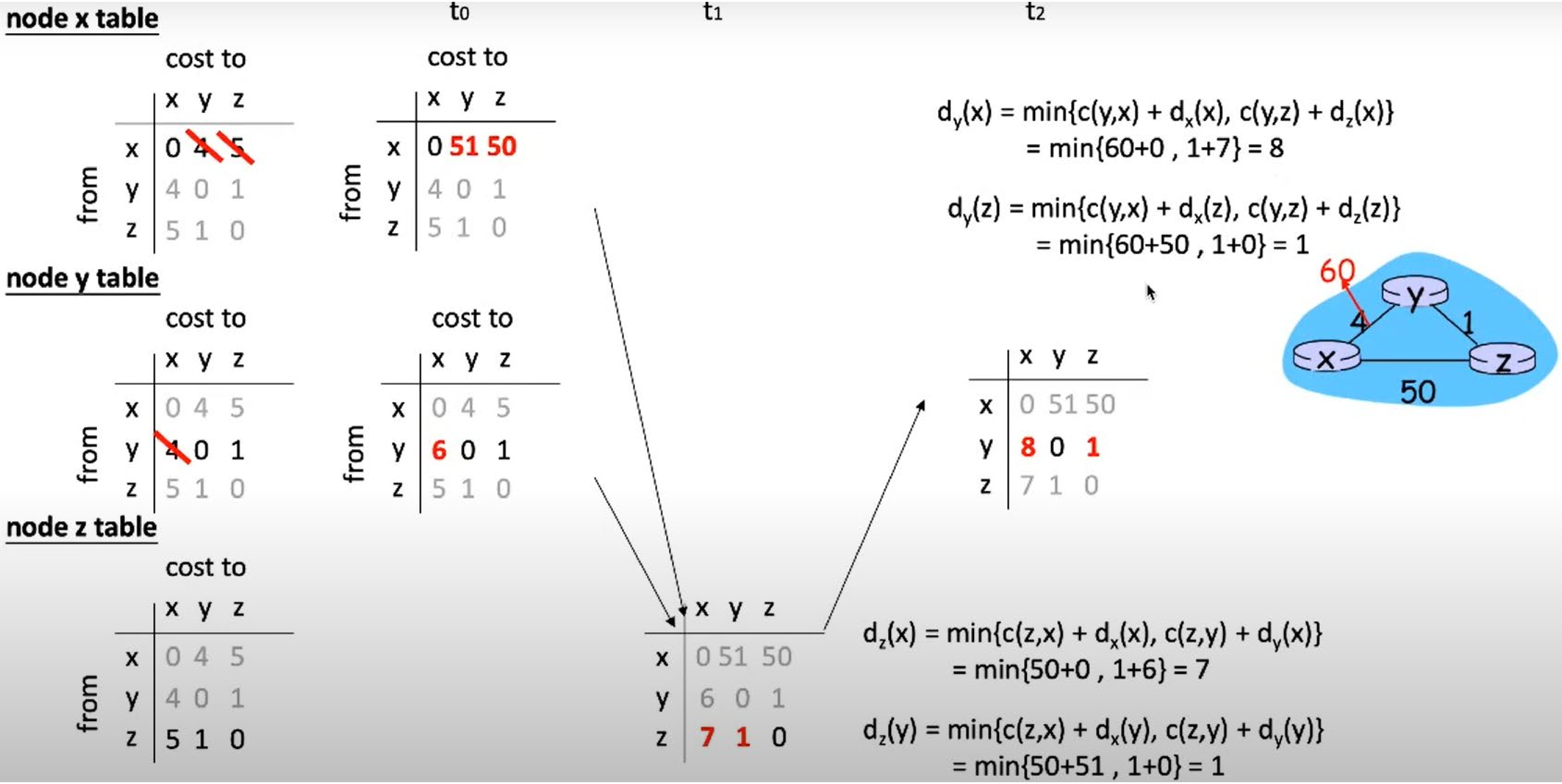


link cost changes:

- 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 ($D_z(x)$, $D_y(x)$ going from 5 to 50 in step of 1). And then $D_y(x)$ will reach 51.
- Q: what if link cost between y and z is 3 instead of 1?
- Q: ($D_z(x), D_y(x)$ going from 5 to 8 to 11 to 14… until reaching or exceeding 50 in step of 3





node x table

cost to

from	x	y	z
x	0	~~4~~	~~5~~
y	4	0	1
z	5	1	0

cost to

from	x	y	z
x	0	51	50
y	4	0	1
z	5	1	0

node y table

cost to

from	x	y	z
x	0	4	5
y	~~4~~	0	1
z	5	1	0

cost to

from	x	y	z
x	0	4	5
y	6	0	1
z	5	1	0

node z table

cost to

from	x	y	z
x	0	4	5
y	4	0	1
z	5	1	0

	x	y	z
x	0	51	50
y	6	0	1
z	7	1	0

$$d_z(x) = \min\{c(z,x) + d_x(x),\ c(z,y) + d_y(x)\}$$
$$= \min\{50+0\ ,\ 1+6\} = 7$$

$$d_z(y) = \min\{c(z,x) + d_x(y),\ c(z,y) + d_y(y)\}$$
$$= \min\{50+51\ ,\ 1+0\} = 1$$

$$d_y(x) = \min\{c(y,x) + d_x(x),\ c(y,z) + d_z(x)\}$$
$$= \min\{60+0\ ,\ 1+7\} = 8$$

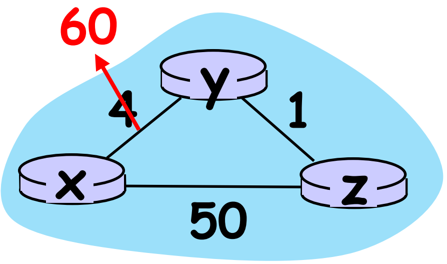
$$d_y(z) = \min\{c(y,x) + d_x(z),\ c(y,z) + d_z(z)\}$$
$$= \min\{60+50\ ,\ 1+0\} = 1$$

	x	y	z
x	0	51	50
y	8	0	1
z	7	1	0

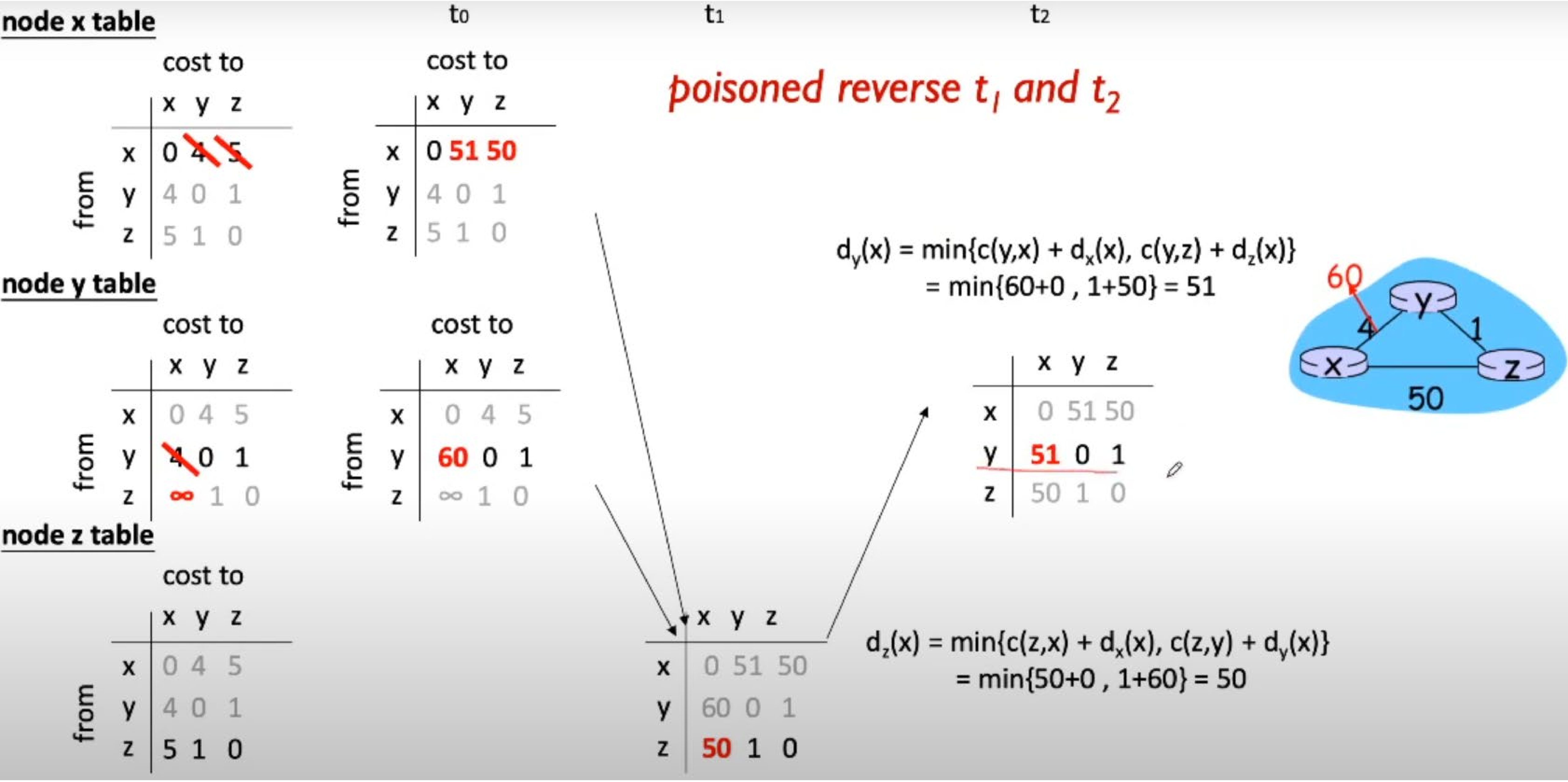
ch52 ep#12 DV Bad News Travel Slow Part II
https://www.youtube.com/watch?v=kLmhxtL2FRI

IMPORTANT

Solution: Poisoned Reverse



- If z routes through y to get to x:
  - In y’s routing table, set z's distance to x $D_z(x)=\infty$ (so y won't route to x via z, removing the circular dependency)
- *y* sees direct link to *x* has new cost 60, so *y* computes $D_y(x)$ = min{$c_{y,x}$+ $D_x(x)$, $c_{y,z}$+ $D_z(x)$}=min{$60+0$, $1+\infty$}=60 “my new cost to x will be 60 via direct link; notifies *z* of new cost of $D_y(x)$=60 to *x.*
- *z* learns that path to *x* via *y* has new cost 60, so *z* computes $D_z(x)$ = min{$c_{z,x}$+ $D_x(x)$, $c_{z,y}$+ $D_y(x)$}=min{$50+0$, $1+60$}=50 “my new cost to *x* will be $D_z(x)$=50 via direct link, notifies *y* of new cost of 50 to *x.*
- *y* learns that path to *x* via *z* has new cost 50, so *y* computes $D_y(x)$ = min{$c_{y,x}$+ $D_x(x)$, $c_{y,z}$+ $D_z(x)$}=min{$60+0$, $1+50$}=51 “my new cost to *x* will be 51 via z, notifies *z* of new cost of $D_y(x)=51$ to *x.*
- Algorithm has converged.



poisoned reverse t_1 and t_2

node x table

t_0

cost to

from	x	y	z
x	0	~~4~~	~~5~~
y	4	0	1
z	5	1	0

t_1

cost to

from	x	y	z
x	0	51	50
y	4	0	1
z	5	1	0

node y table

t_0

cost to

from	x	y	z
x	0	4	5
y	~~4~~	0	1
z	∞	1	0

t_1

cost to

from	x	y	z
x	0	4	5
y	60	0	1
z	∞	1	0

t_2

$$d_y(x) = \min\{c(y,x) + d_x(x),\ c(y,z) + d_z(x)\}$$
$$= \min\{60+0\ ,\ 1+50\} = 51$$

	x	y	z
x	0	51	50
y	51	0	1
z	50	1	0

node z table

t_0

cost to

from	x	y	z
x	0	4	5
y	4	0	1
z	5	1	0

t_1

	x	y	z
x	0	51	50
y	60	0	1
z	50	1	0

$$d_z(x) = \min\{c(z,x) + d_x(x),\ c(z,y) + d_y(x)\}$$
$$= \min\{50+0\ ,\ 1+60\} = 50$$

ch52 ep#13 DV Poisoned Reverse
https://www.youtube.com/watch?v=UcTgNZwGmRU

Summary

- Link State: Cost of link to neighbors sent to the entire network. Large # of small messages.
  - *n* routers, O(n^2) messages sent among all routers
  - Dijkstra's algorithm is used to compute the shortest path using the link state
- Distance Vectors: Distance to all nodes in the network sent to neighbors. Small # of large messages
  - Message exchange between neighbors; convergence time varies
  - Bellman Ford's algorithm is used to compute shortest paths using distance vectors