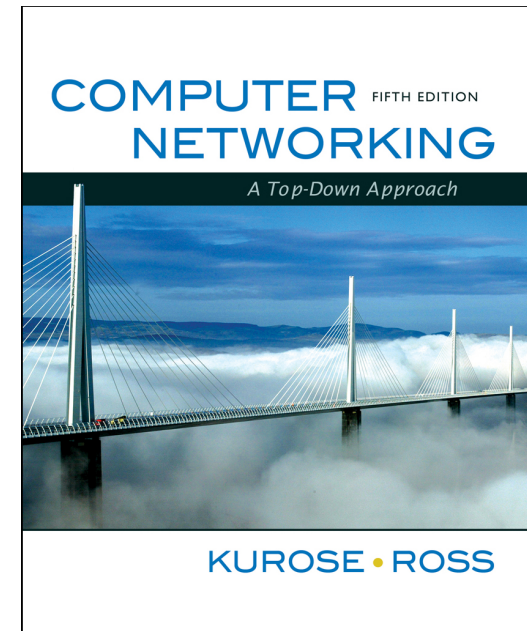


Chapter 4

Network Layer



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*Computer Networking:
A Top Down Approach
5th edition.
Jim Kurose, Keith Ross
Addison-Wesley, April
2009.*

Chapter 4: Network Layer

4.1 Introduction

4.2 Virtual circuit and datagram networks

4.3 What's inside a router

4.4 IP: Internet Protocol

- Datagram format
- IPv4 addressing
- ICMP
- IPv6

4.5 Routing algorithms

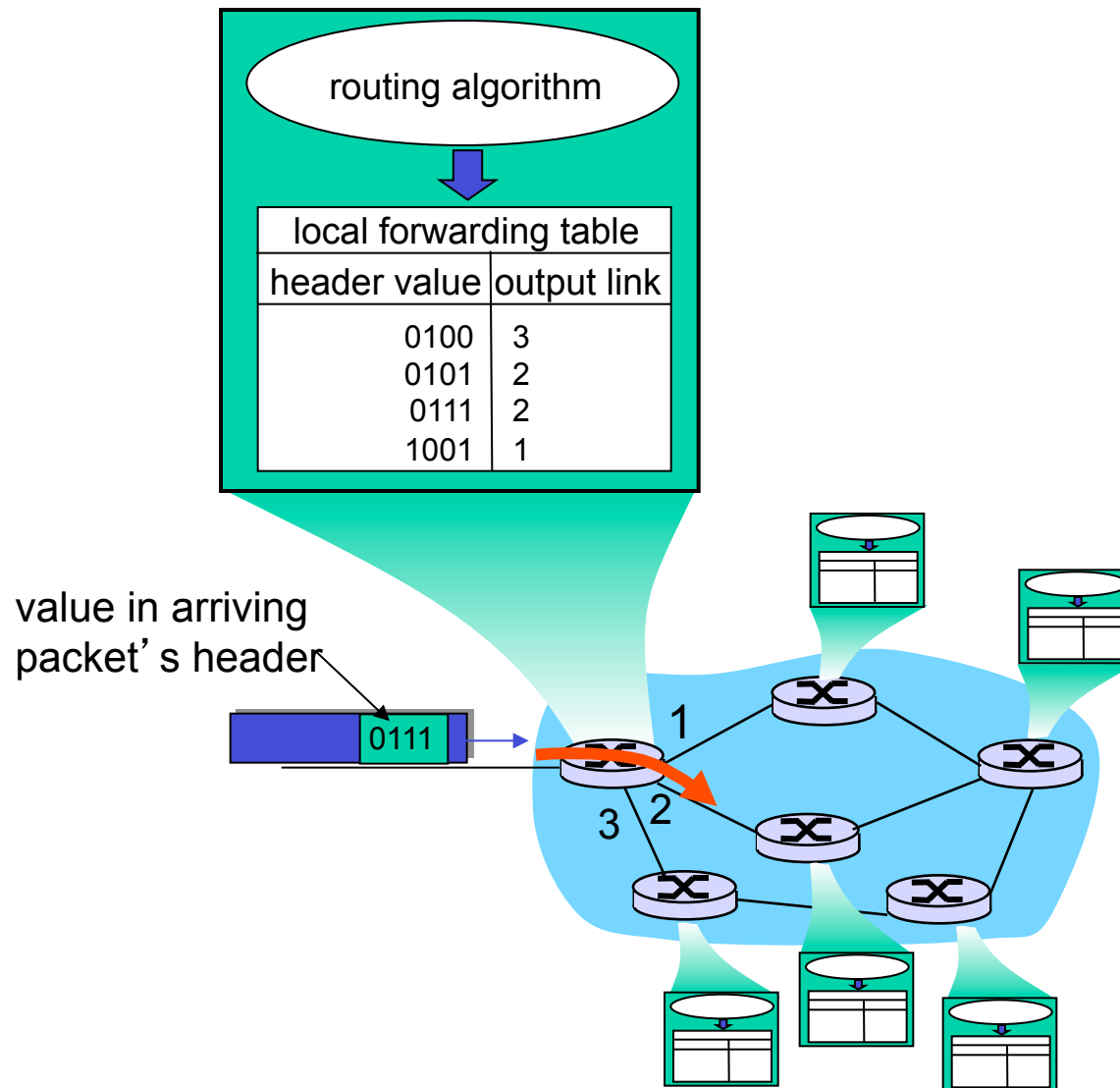
- Link state
- Distance Vector
- Hierarchical routing

4.6 Routing in the Internet

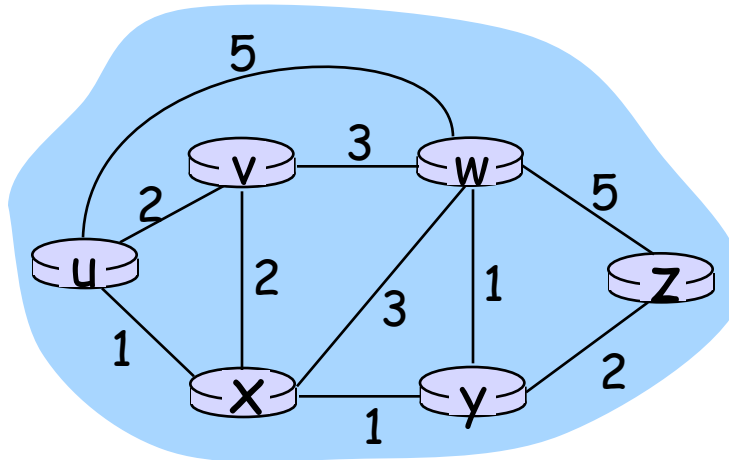
- RIP
- OSPF
- BGP

4.7 Broadcast and multicast routing

Interplay between routing, forwarding



Graph abstraction



Graph: $G = (N, E)$

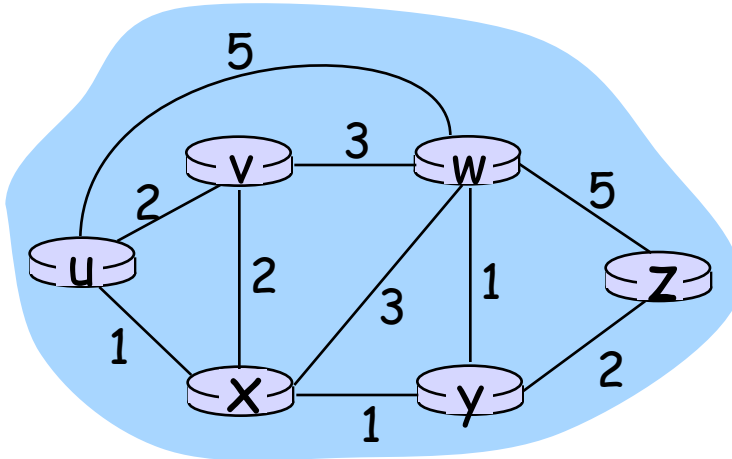
$N = \text{set of routers} = \{ u, v, w, x, y, z \}$

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

Remark: Graph abstraction is useful in other network contexts

Example: P2P, where N is set of peers and E is set of TCP connections

Graph abstraction: costs



- $c(x,x')$ = cost of link (x,x')

- e.g., $c(w,z) = 5$

- cost could always be 1, or inversely related to bandwidth, or inversely related to congestion

Cost of path $(x_1, x_2, x_3, \dots, x_p) = c(x_1, x_2) + c(x_2, x_3) + \dots + c(x_{p-1}, x_p)$

Question: What's the least-cost path between u and z ?

Routing algorithm: algorithm that finds least-cost path

Routing Algorithm classification

Global or decentralized information?

Global:

- ❖ all routers have complete topology, link cost info
- ❖ “link state” algorithms

Decentralized:

- ❖ router knows physically-connected neighbors, link costs to neighbors
- ❖ iterative process of computation, exchange of info with neighbors
- ❖ “distance vector” algorithms

Static or dynamic?

Static:

- ❖ routes change slowly over time

Dynamic:

- ❖ routes change more quickly
 - periodic update
 - in response to link cost changes

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A Link-State Routing Algorithm

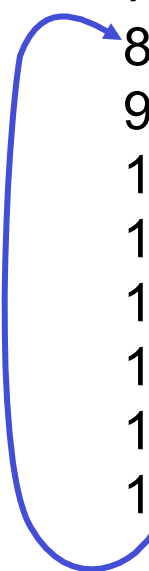
Dijkstra's algorithm

- ❖ net 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 dest.'s

Notation:

- ❖ $c(x,y)$: link cost from node x to y ; $= \infty$ if not direct neighbors
- ❖ $D(v)$: current value of cost of path from source to dest. v
- ❖ $p(v)$: predecessor node along path from source to v
- ❖ N' : set of nodes whose least cost path definitively known

Dijsktra' s Algorithm

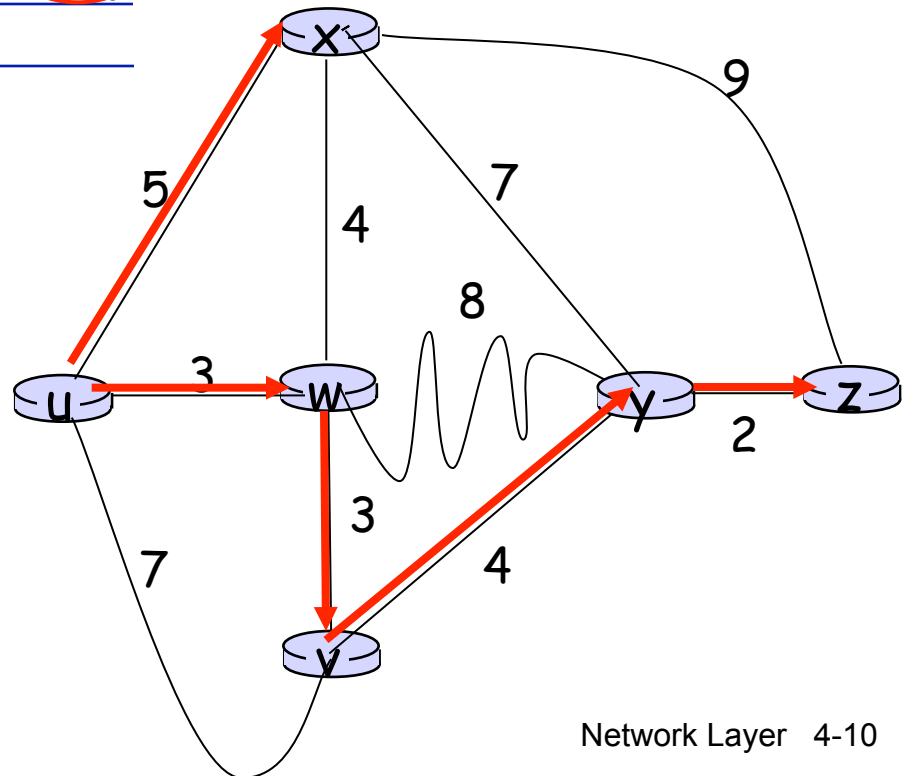
- 1 **Initialization:**
 - 2 $N' = \{u\}$
 - 3 for all nodes v
 - 4 if v adjacent to u
 - 5 then $D(v) = c(u,v)$
 - 6 else $D(v) = \infty$
 - 7
 - 8 **Loop**
 - 9 find w not in N' such that $D(w)$ is a minimum
 - 10 add w to N'
 - 11 update $D(v)$ for all v adjacent to w and not in N' :
 - 12 $D(v) = \min(D(v), D(w) + c(w,v))$
 - 13 /* new cost to v is either old cost to v or known
 - 14 shortest path cost to w plus cost from w to v */
 - 15 **until all nodes in N'**
- 

Dijkstra's algorithm: 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	uwx	6,w			11,w	14,x
3	uwxv				10,v	14,x
4	uwxvy				12,y	
5	uwxvyz					

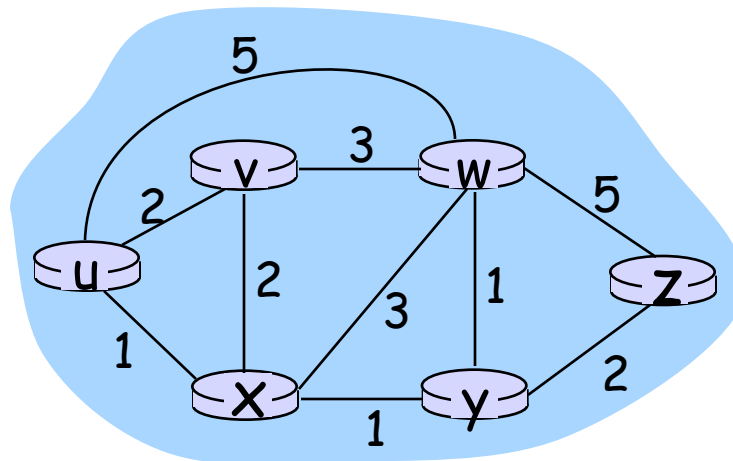
Notes:

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



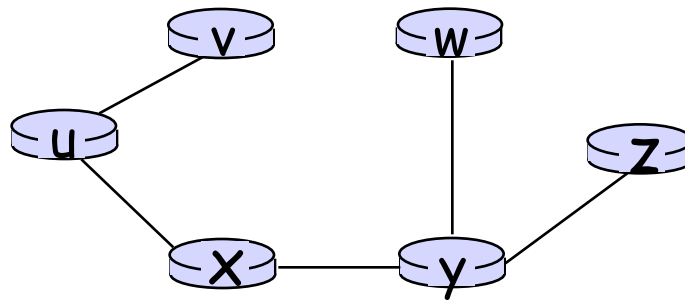
Dijkstra's algorithm: another example

Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	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					



Dijkstra's algorithm: example (2)

Resulting shortest-path tree from u:



Resulting forwarding table in u:

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

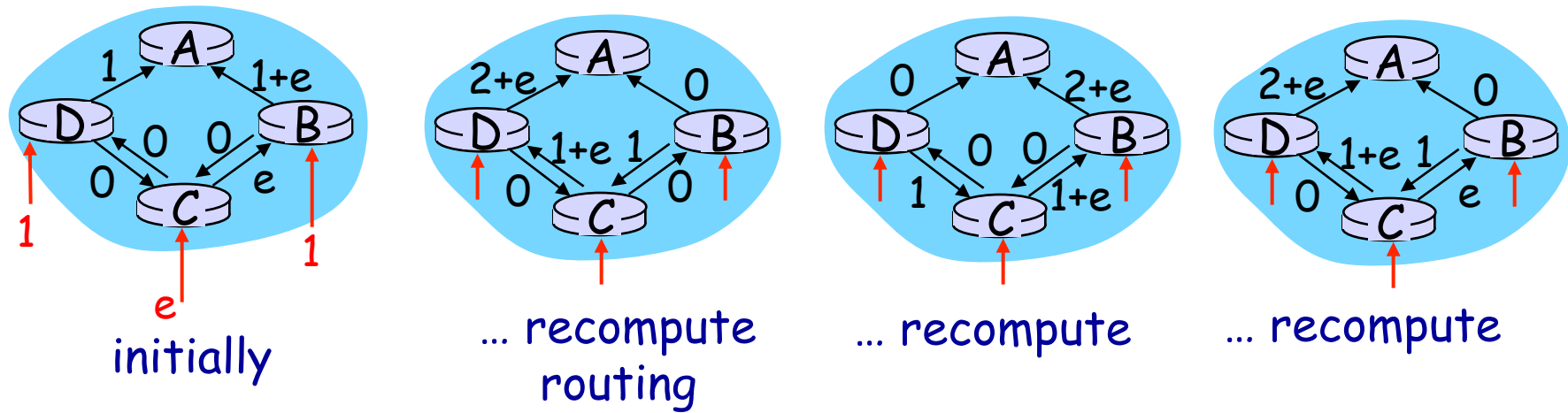
Dijkstra's algorithm, discussion

Algorithm complexity: n nodes

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

Oscillations possible:

- ❖ e.g., link cost = amount of carried traffic



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- **Distance Vector**
- Hierarchical routing

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Distance Vector Algorithm

Bellman-Ford Equation (dynamic programming)

Define

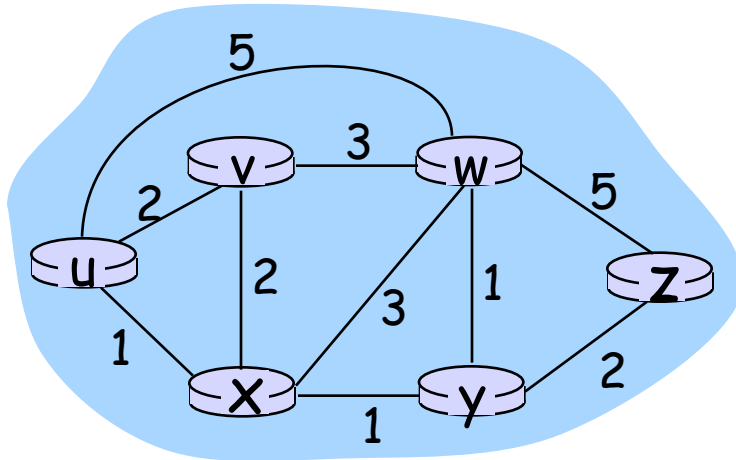
$d_x(y) :=$ cost of least-cost path from x to y

Then

$$d_x(y) = \min_v \{c(x,v) + d_v(y)\}$$

where min is taken over all neighbors v of x

Bellman-Ford example



Clearly, $d_v(z) = 5$, $d_x(z) = 3$, $d_w(z) = 3$

B-F 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 that achieves minimum is next hop in shortest path → forwarding table

Distance Vector Algorithm

- ❖ $D_x(y)$ = estimate of least cost from x to y
 - x maintains distance vector $D_x = [D_x(y): y \in N]$
- ❖ node x :
 - knows cost to each neighbor v : $c(x,v)$
 - maintains its neighbors' distance vectors.
For each neighbor v , x maintains $D_v = [D_v(y): y \in N]$

Distance vector algorithm (4)

Basic idea:

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

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

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

Distance Vector Algorithm (5)

Iterative, asynchronous:

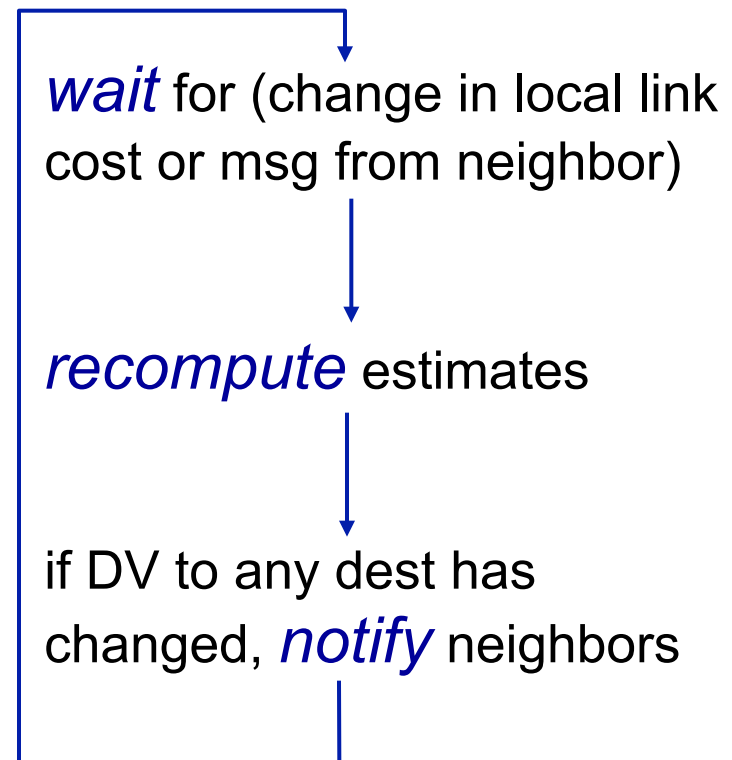
each local iteration caused by:

- ❖ local link cost change
- ❖ DV update message from neighbor

Distributed:

- ❖ each node notifies neighbors *only* when its DV changes
 - neighbors then notify their neighbors if necessary

Each node:



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

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

node x table

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

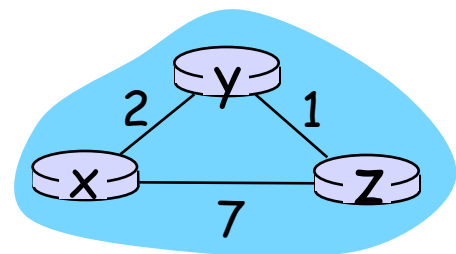
		cost to		
		x	y	z
from	x	0	2	3
	y	2	0	1
	z	7	1	0

node y table

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

node z table

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



.....> time

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

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

node x table

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

node y table

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

node z table

		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

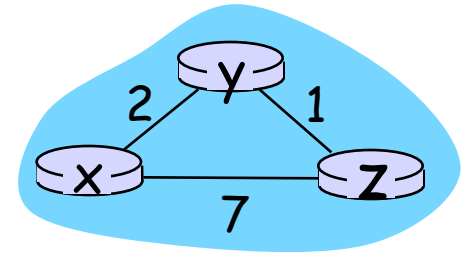
		cost to		
		x	y	z
from	x	0	2	7
	y	2	0	1
	z	7	1	0

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

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

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

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

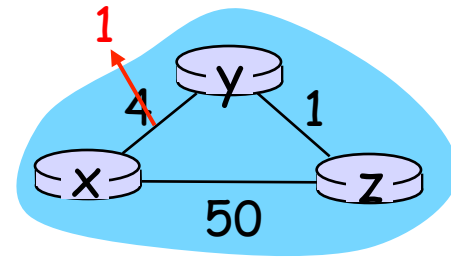


time →

Distance Vector: link cost changes

Link cost changes:

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



“good
news
travels
fast”

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

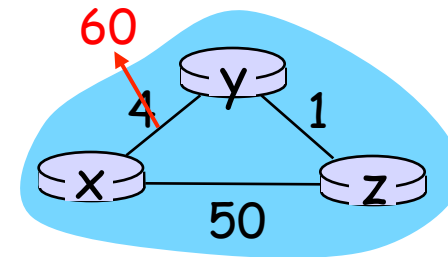
t_1 : z receives update from y, updates its table, computes new least cost to x, sends its neighbors its DV.

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:

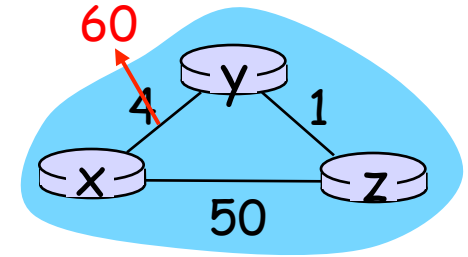
- ❖ good news travels fast
- ❖ bad news travels slow - “count to infinity” problem!
- ❖ 44 iterations before algorithm stabilizes: see text



Poisoned reverse:

- ❖ If Z routes through Y to get to X :
 - Z tells Y its (Z's) distance to X is infinite (so Y won't route to X via Z)
- ❖ will this completely solve count to infinity problem?

Distance Vector: link cost increases



node x table

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

node y table

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

node z table

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

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

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

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

		cost to		
		x	y	z
from	x	idem		
	y	idem		
	z	idem		

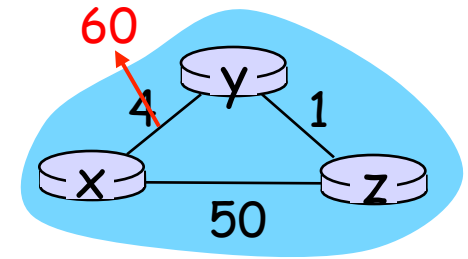
		cost to		
		x	y	z
from	x	0	51	50
	y	6	0	1
	z	5	1	0

		cost to		
		x	y	z
from	x	0	51	50
	y	6	0	1
	z	7	1	0

		cost to		
		x	y	z
from	x	0	4	5
	y	8	0	1
	z	7	1	0

time

Same with poison reverse!



node x table

		cost to		
		x	y	z
from	x	0	4	5
	y	∞	0	1
	z	5	1	0

node y table

		cost to		
		x	y	z
from	x	0	∞	∞
	y	4	0	1
	z	∞	∞	0

node z table

		cost to		
		x	y	z
from	x	0	4	5
	y	4	0	∞
	z	5	1	0

		cost to		
		x	y	z
from	x	0	51	50
	y	∞	0	1
	z	5	1	0

		cost to		
		x	y	z
from	x	0	∞	∞
	y	60	0	1
	z	∞	∞	0

		cost to		
		x	y	z
from	x	0	4	5
	y	4	0	∞
	z	5	1	0

		cost to		
		x	y	z
from	x			
	y	idem		
	z			

		cost to		
		x	y	z
from	x			
	y	idem		
	z			

		cost to		
		x	y	z
from	x	0	∞	∞
	y	60	0	∞
	z	50	1	0

		cost to		
		x	y	z
from	x	0	51	50
	y	51	0	1
	z	50	∞	0

time

Comparison of LS and DV algorithms

Message complexity

- ❖ LS: with n nodes, E links, $O(nE)$ msgs sent
- ❖ DV: exchange between neighbors only
 - convergence time varies

Speed of Convergence

- ❖ LS: $O(n^2)$ algorithm requires $O(nE)$ msgs
 - may have oscillations
- ❖ DV: convergence time varies
 - may be routing loops
 - count-to-infinity problem

Robustness: what happens if router malfunctions?

LS:

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

DV:

- DV node can advertise incorrect *path* cost
- each node's table used by others
 - error propagate thru network