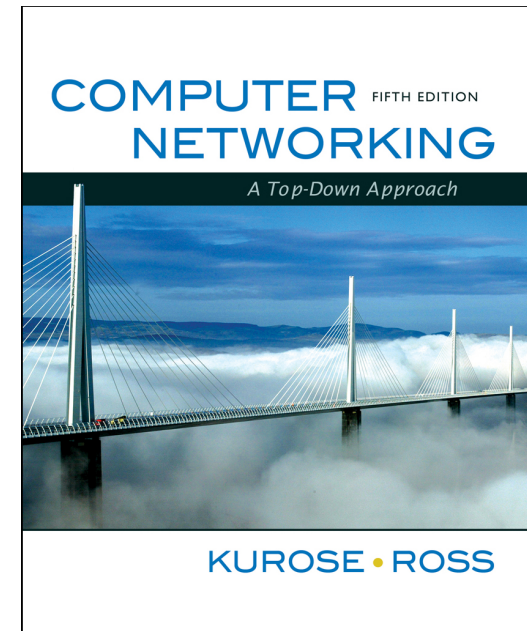


# Chapter 4

## Network Layer



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*Computer Networking:  
A Top Down Approach  
5<sup>th</sup> 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

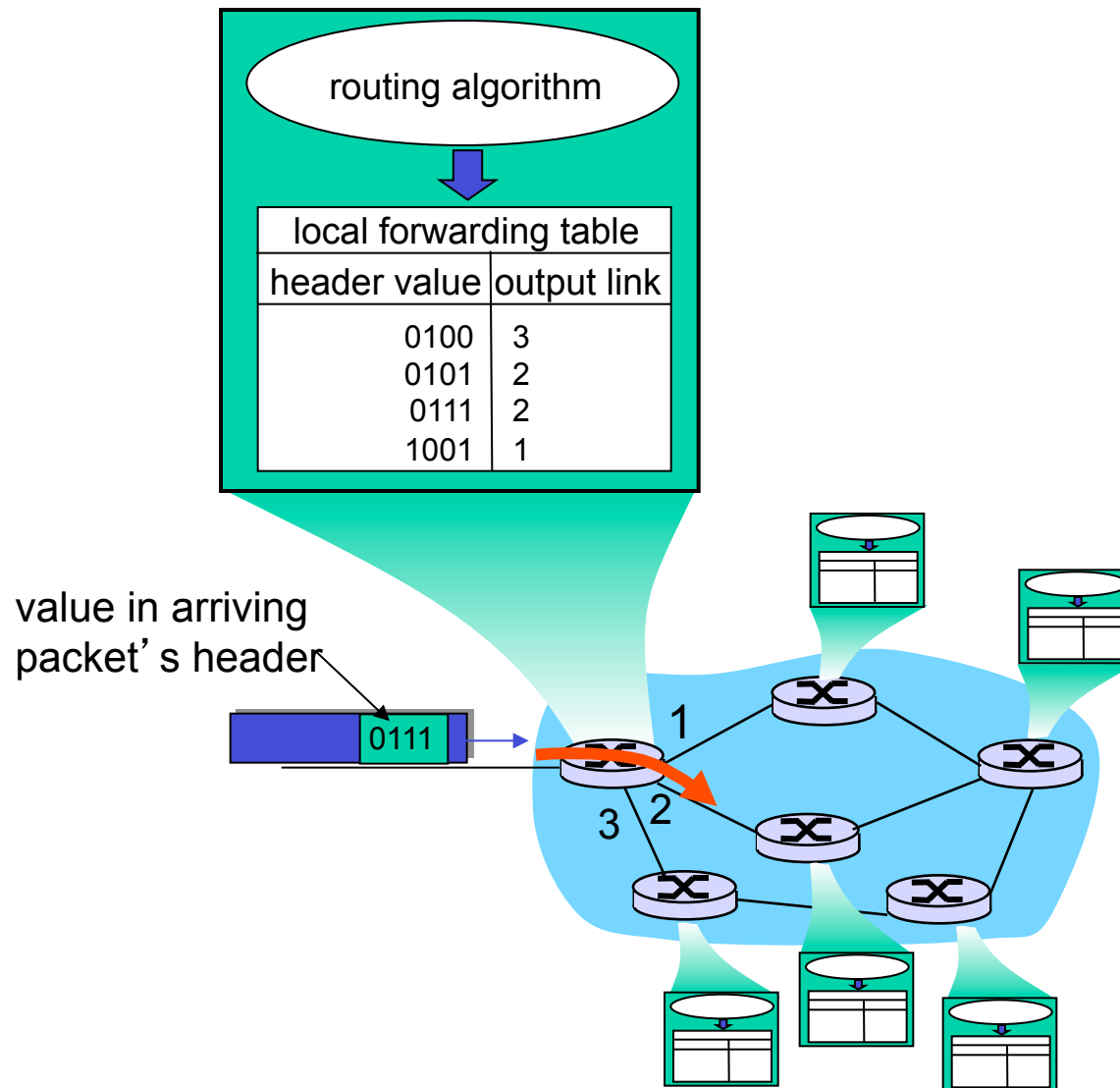
- Link state
- Distance Vector
- Hierarchical routing

## 4.6 Routing in the Internet

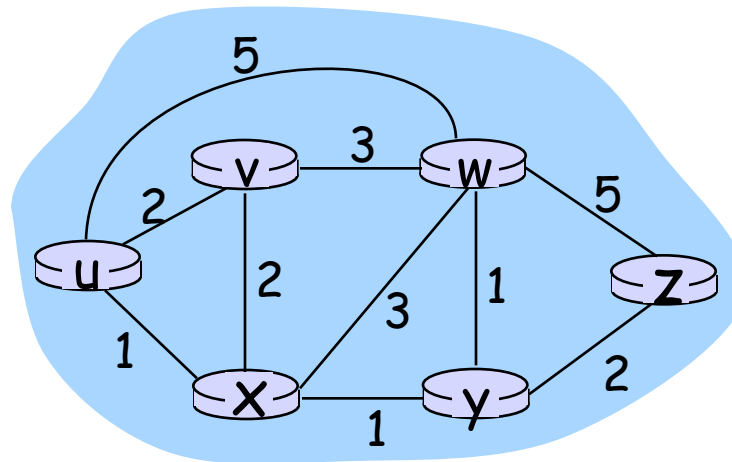
- RIP
- OSPF
- BGP

## 4.7 Broadcast and multicast routing

# Interplay between routing, forwarding



# Graph abstraction



Graph:  $G = (N,E)$

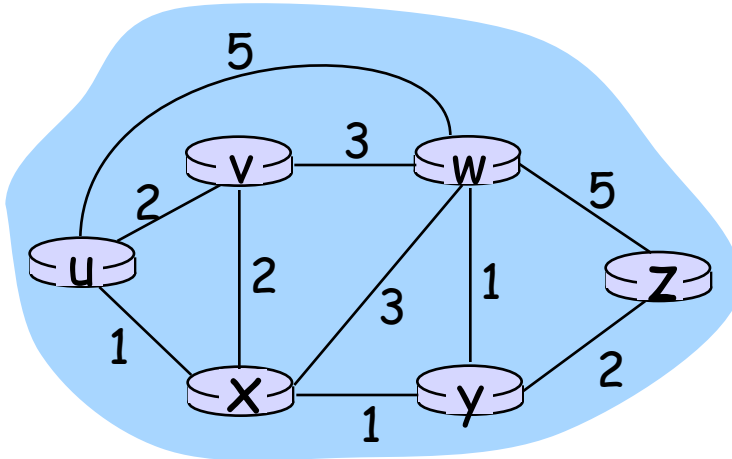
$N =$  set of routers =  $\{ u, v, w, x, y, z \}$

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

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



- $c(x, x') = \text{cost of link } (x, x')$

- 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

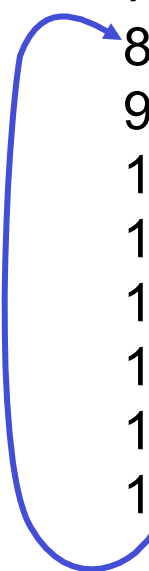
- ❖ net topology, link costs known to all nodes
  - accomplished via “link state broadcast”
  - all nodes have same info
- ❖ computes least cost paths from one node (‘source’) to all other nodes
  - gives *forwarding table* for that node
- ❖ iterative: after  $k$  iterations, know least cost path to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

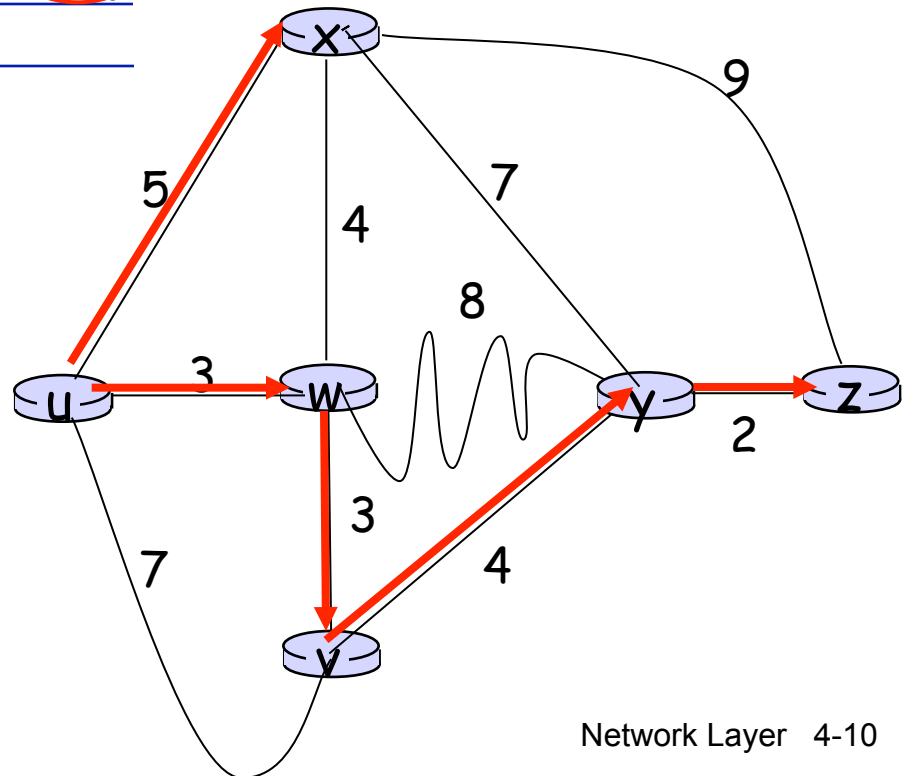
- 1 **Initialization:**
  - 2  $N' = \{u\}$
  - 3 for all nodes  $v$
  - 4 if  $v$  adjacent to  $u$
  - 5 then  $D(v) = c(u,v)$
  - 6 else  $D(v) = \infty$
  - 7
  - 8 **Loop**
  - 9 find  $w$  not in  $N'$  such that  $D(w)$  is a minimum
  - 10 add  $w$  to  $N'$
  - 11 update  $D(v)$  for all  $v$  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	$\infty$	$\infty$
1	uw	6,w		5,u	11,w	$\infty$
2	uwx	6,w			11,w	14,x
3	uwxv				10,y	14,x
4	uwxvy				12,y	
5	uwxvyz					

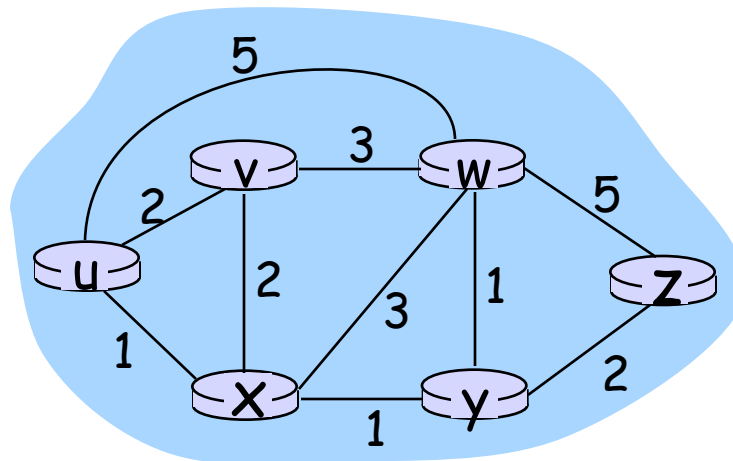
## Notes:

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



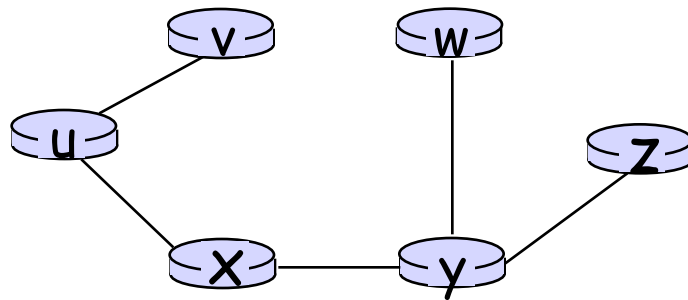
# Dijkstra's algorithm: another example

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	$\infty$	$\infty$
1	ux	2,u	4,x		2,x	$\infty$
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)

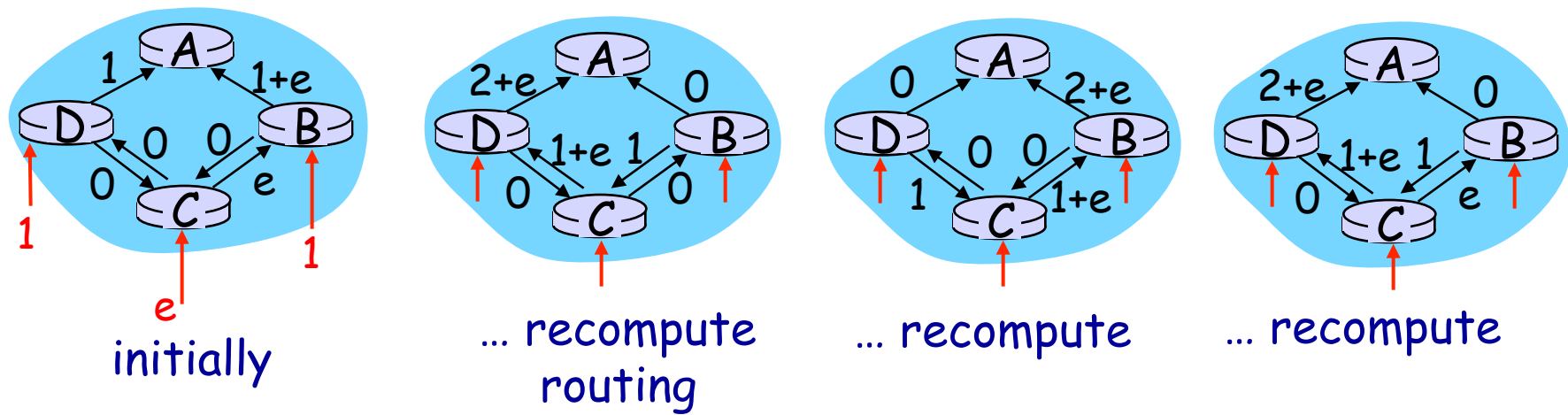
# Dijkstra's algorithm, discussion

**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

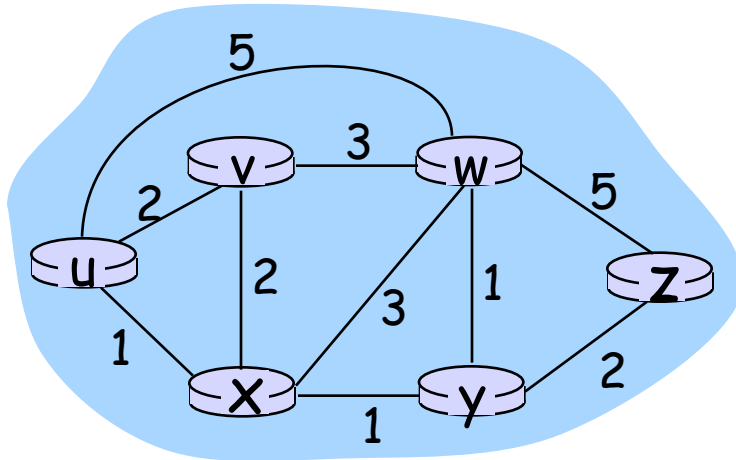
$d_x(y) :=$  cost of least-cost path from  $x$  to  $y$

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:

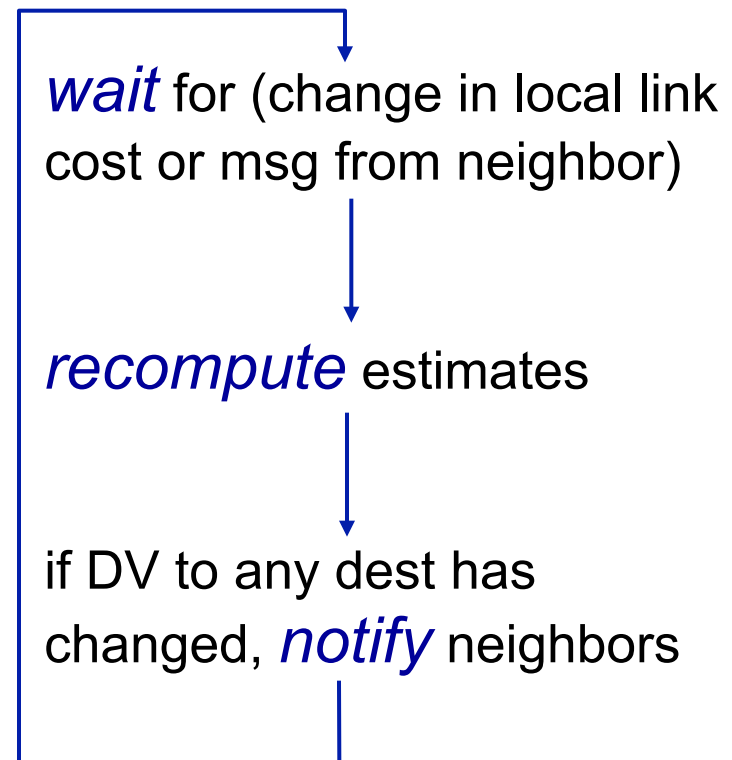
each local iteration caused by:

- ❖ 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	∞	∞	∞

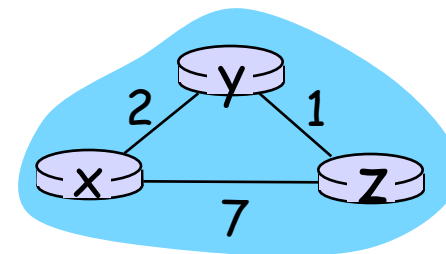
		cost to		
		x	y	z
from	x	0	2	3
	y	2	0	1
	z	7	1	0

**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

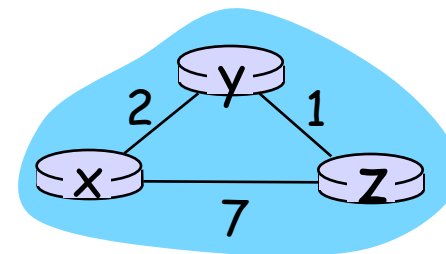
		cost to		
		x	y	z
from	x	0	2	7
	y	2	0	1
	z	7	1	0

		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

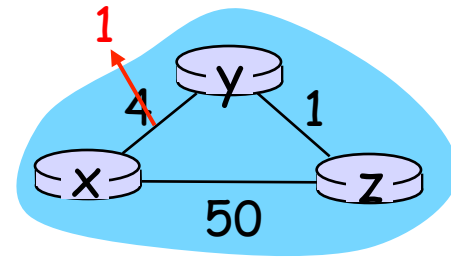


time →

# 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.

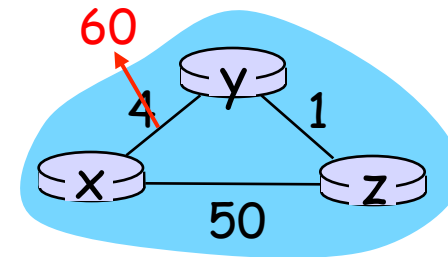
$t_1$ : z receives update from y, updates its table, computes new least cost to x, sends its neighbors its DV.

$t_2$ : 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:

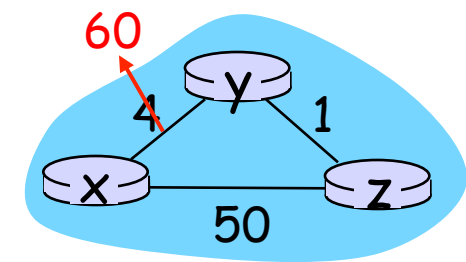
- ❖ good news travels fast
- ❖ bad news travels slow - “count to infinity” problem!
- ❖ 44 iterations before algorithm stabilizes: see text



## 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

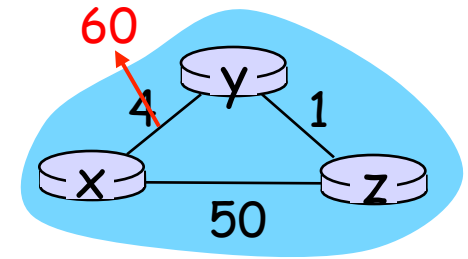
		cost to		
		x	y	z
from	x	0	51	50
	y	6	0	1
	z	7	1	0

		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	$\infty$	0	1
	z	5	1	0

node y table

		cost to		
		x	y	z
from	x	0	$\infty$	$\infty$
	y	4	0	1
	z	$\infty$	$\infty$	0

node z table

		cost to		
		x	y	z
from	x	0	4	5
	y	4	0	$\infty$
	z	5	1	0

		cost to		
		x	y	z
from	x	0	51	50
	y	$\infty$	0	1
	z	5	1	0

		cost to		
		x	y	z
from	x	0	$\infty$	$\infty$
	y	60	0	1
	z	$\infty$	$\infty$	0

		cost to		
		x	y	z
from	x	0	4	5
	y	4	0	$\infty$
	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	$\infty$	$\infty$
	y	60	0	$\infty$
	z	50	1	0

		cost to		
		x	y	z
from	x	0	51	50
	y	51	0	1
	z	50	$\infty$	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