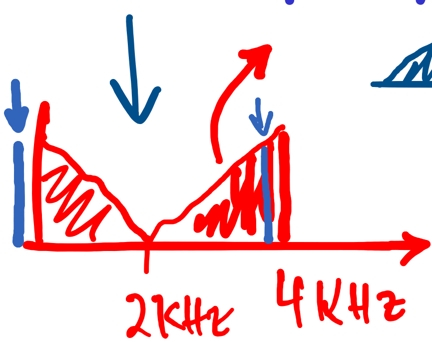
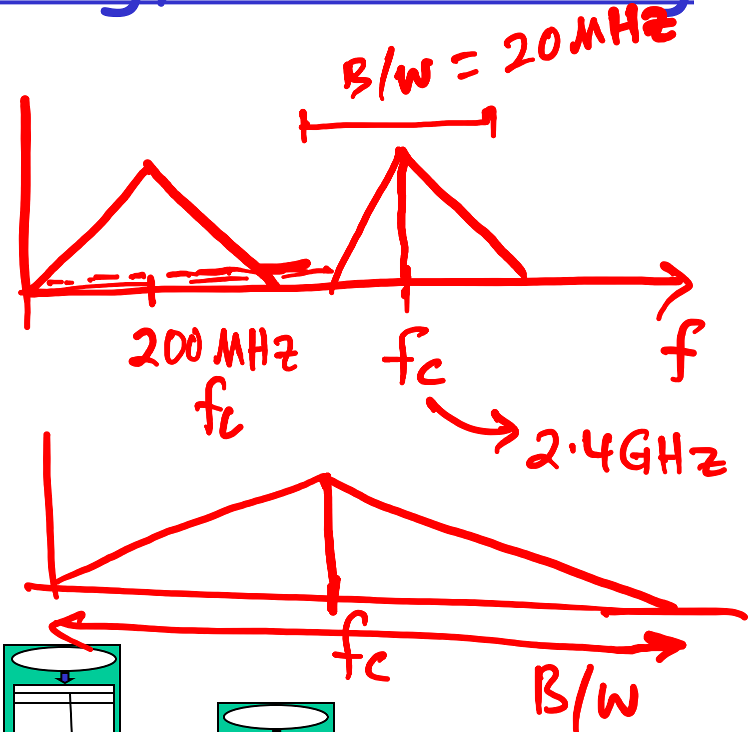
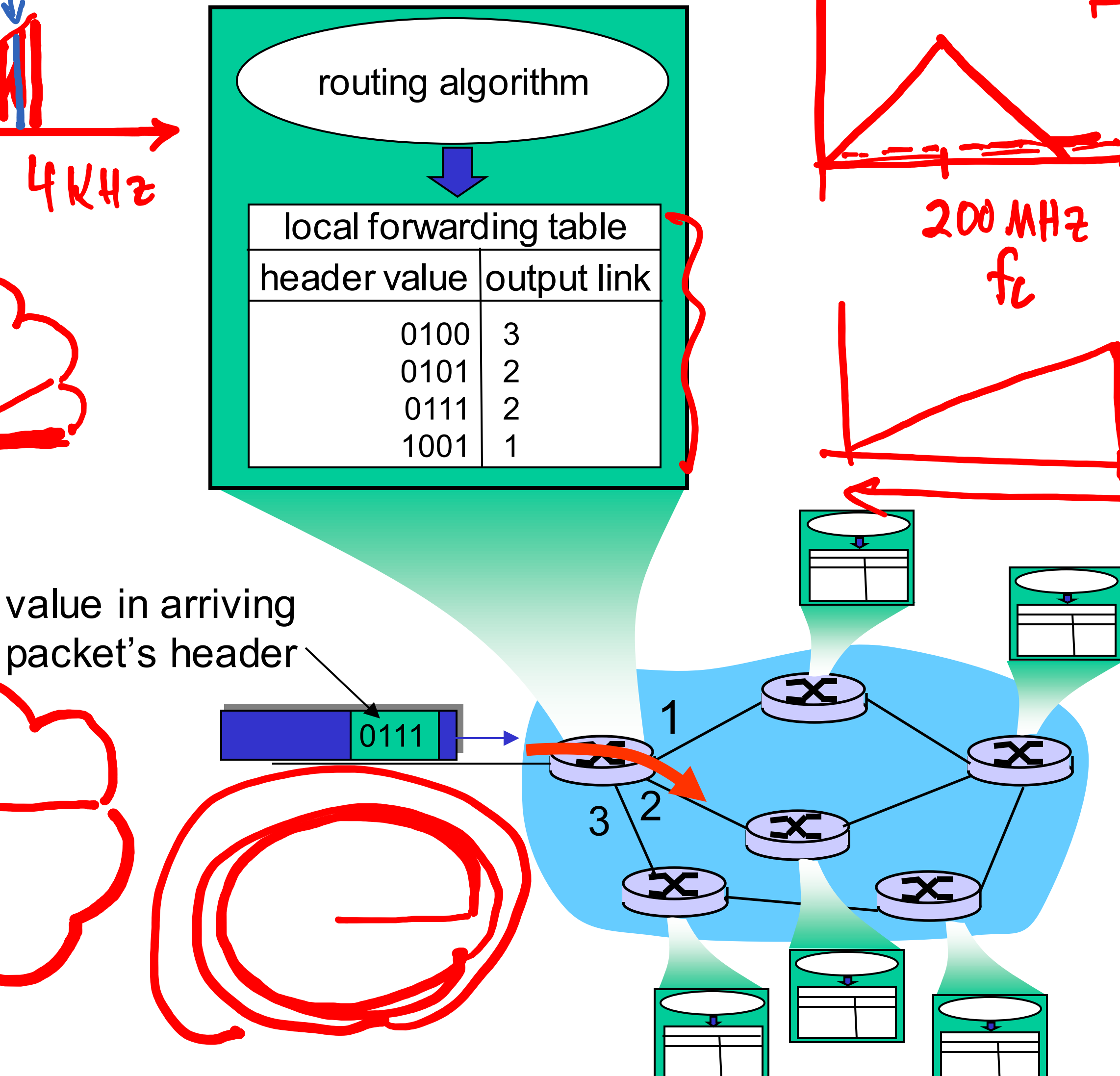
Chapter 4: Network Layer

- 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



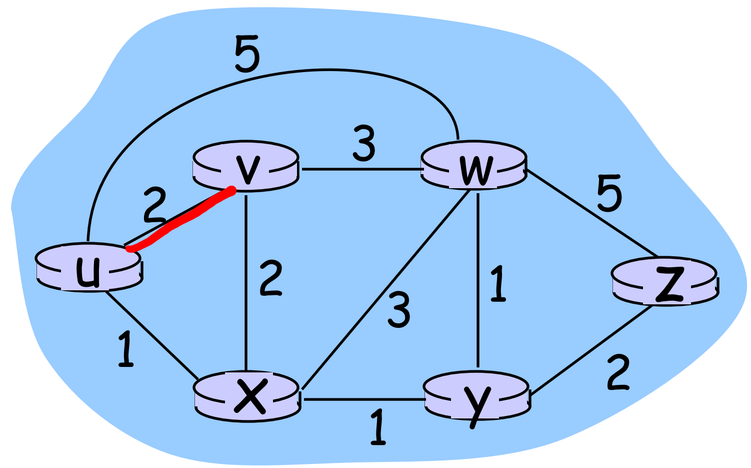




local forwarding table

header value	output link
0100	3
0101	2
0111	2
1001	1

Graph abstraction



Graph: G = (N,E)

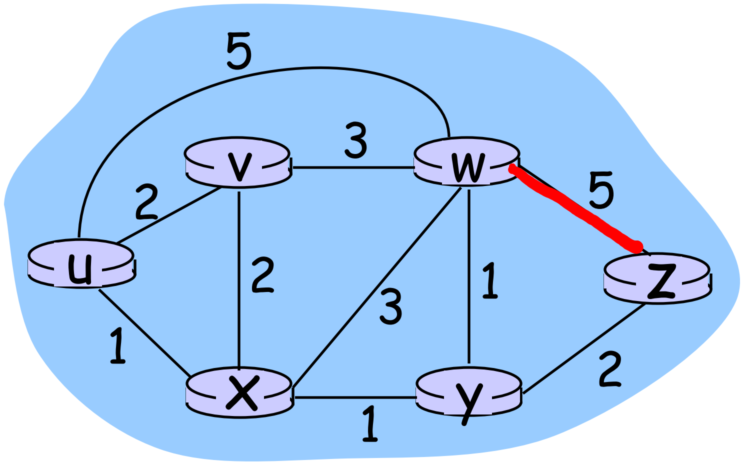
N = set of routers = { u, v, w, x, y, z }

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



- $c(x,x')$ = 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 $(x_1, x_2, x_3,\ldots, x_p) = c(x_1,x_2) + c(x_2,x_3) + \ldots + c(x_{p-1},x_p)$

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

Routing algorithm: algorithm that finds least-cost path

Global / Local

Routing Algorithm classification

Centralized / Distributed

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

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

A Link-State Routing Algorithm

u, G → D.A → all opt. routes from u to all other nodes in G.

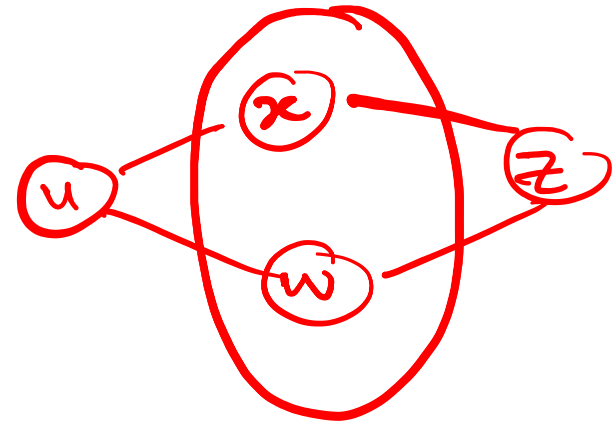
Dijkstra's algorithm

- 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; = ∞ 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




```
Initialization:
  N' = {u}
  for all nodes v
    if v adjacent to u
       then D(v) = c(u,v)
    else D(v) = ∞

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 cost to v is either old cost to v or known
   shortest path cost to w plus cost from w to v */
until all nodes in N'
```

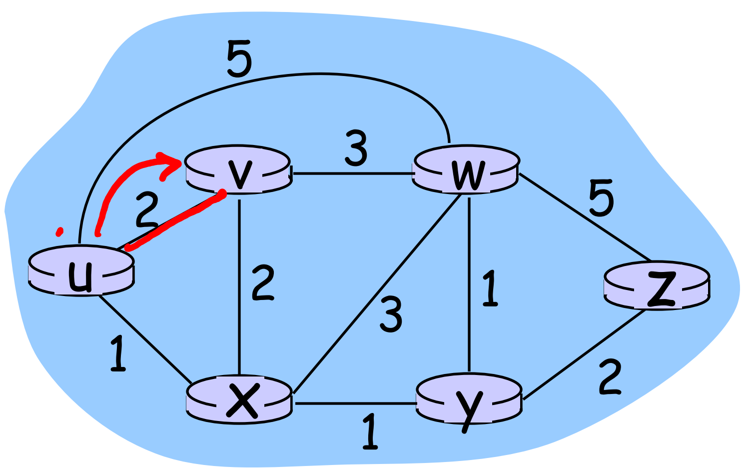
cost from u to v

$c(u,z) = \infty$

Dijkstra's algorithm: example

D(·)

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	∞	∞

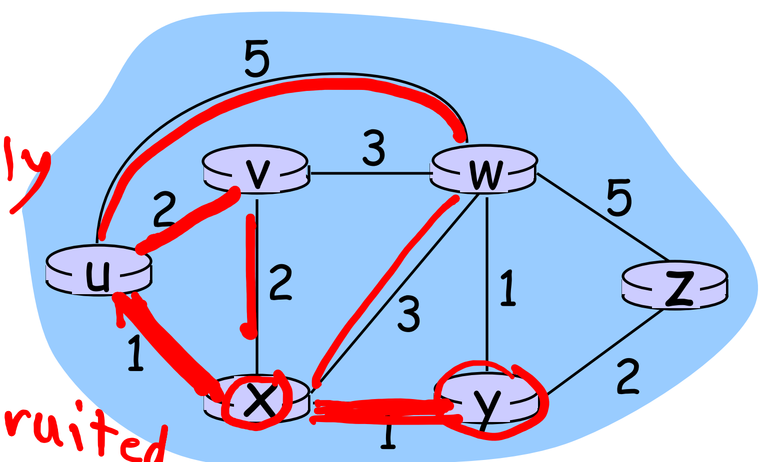


Dijkstra's algorithm: example

D(·)

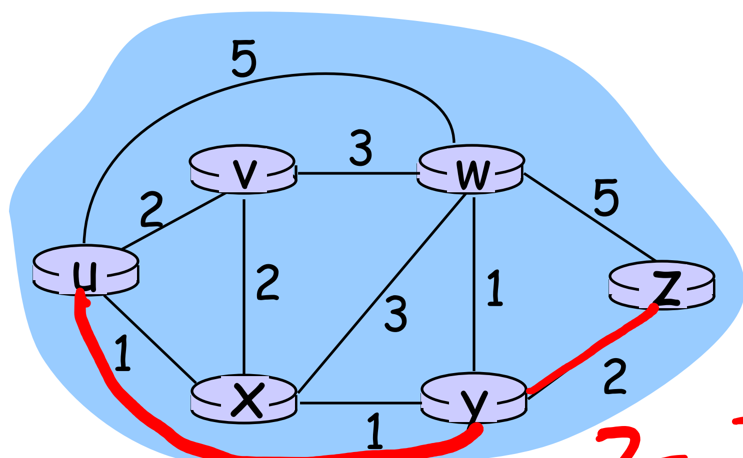
Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	~~5~~,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞

Compare going directly to V vs. going to V via my recruited node x.



Dijkstra's algorithm: example

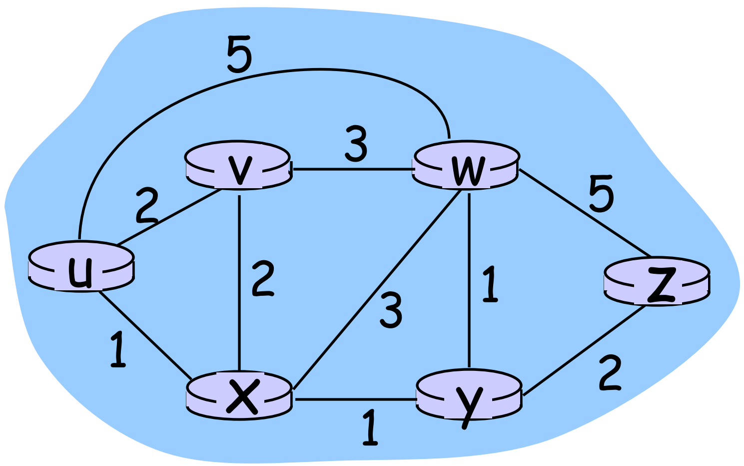
Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y



2 + 2 = 4

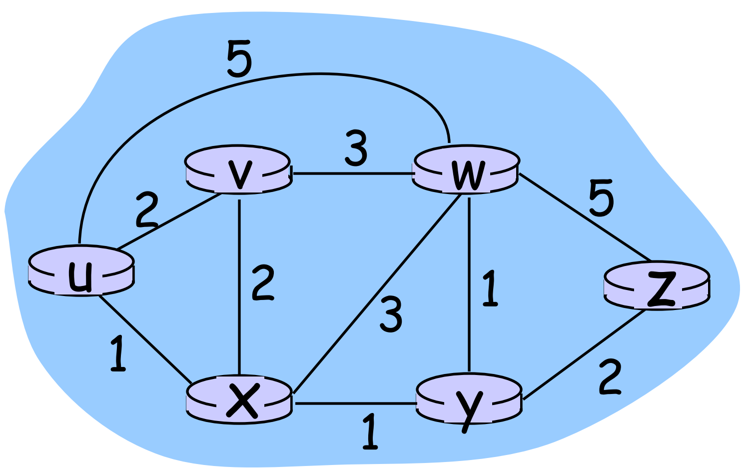
Dijkstra's algorithm: example

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



Dijkstra's algorithm: example

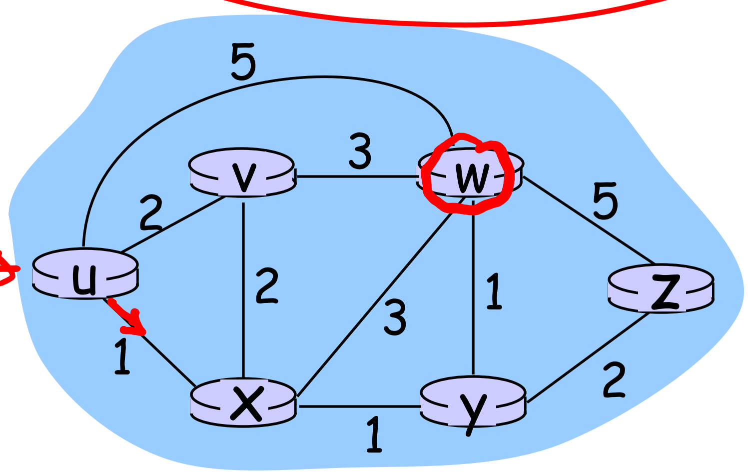
Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					4,y



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	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					

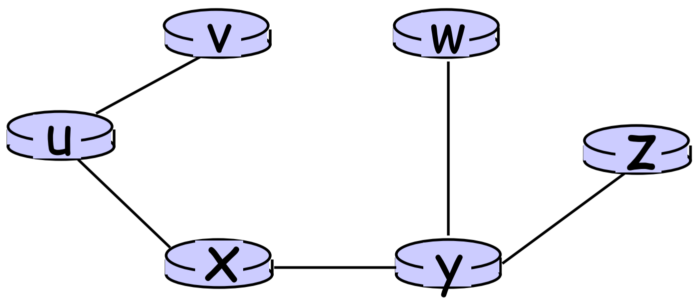
Dest IP add = W



F.T. u	Forward to
x	x
y	x
v	v
w	x
z	x

Dijkstra's algorithm: example (2)

Resulting shortest-path tree from u:



Resulting forwarding table in u:

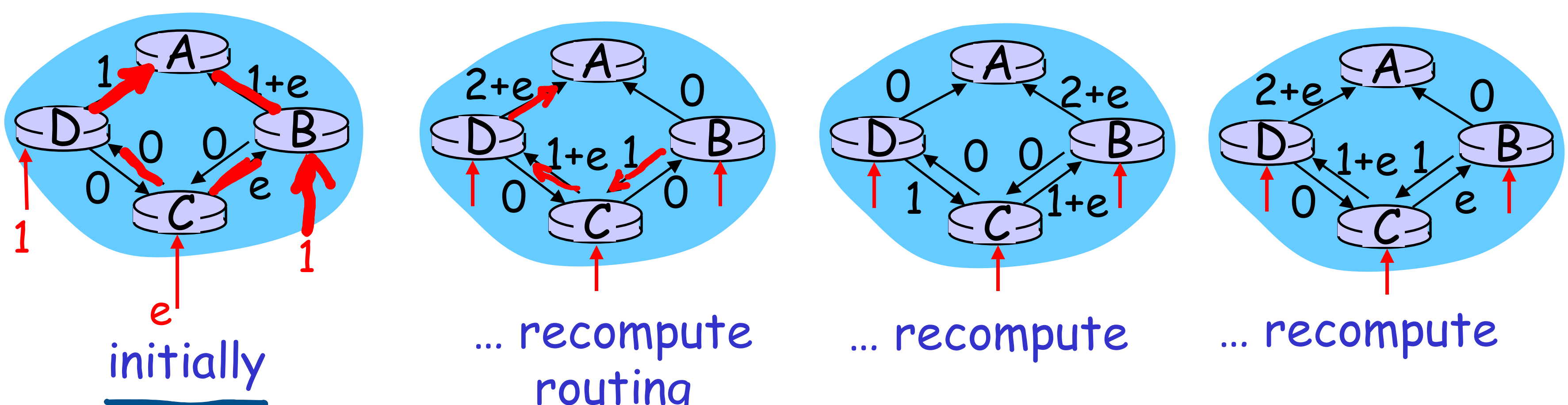
destination	link
v	(u,v)
x	(u,x)
y	(u,x)
w	(u,x)
z	(u,x)

In reality, link cost =f(traffic on link)

Does that lead to a problem?

Oscillations possible:

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



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

Distance Vector Algorithm

Bellman-Ford Equation (dynamic programming)

Define

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

Then

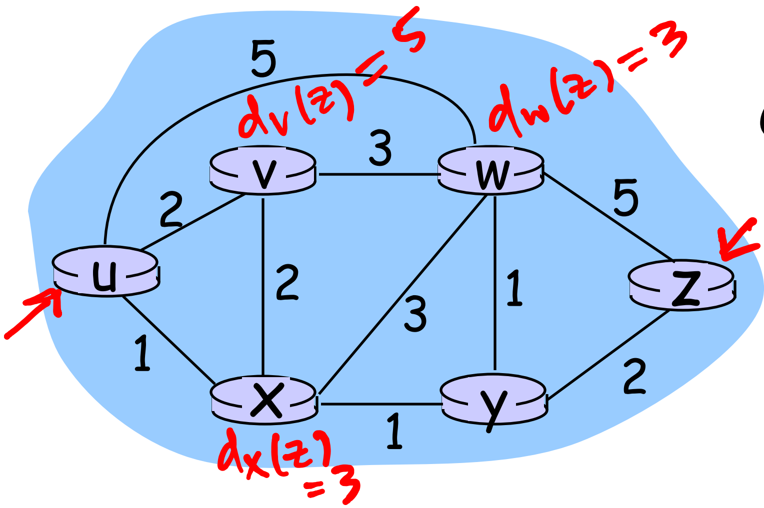
Dynamic Program.

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

$$\min\{c(x,v_1) + d_{v_1}(y),\ c(x,v_2) + d_{v_2}(y),\ c(x,v_3) + d_{v_3}(y)\}$$

where min is taken over all neighbors v of x

Bellman-Ford example



u's neighbors are v, x, w

$d_v(z)$, $d_x(z)$, $d_w(z)$

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

B-F equation says:

$$
\begin{aligned}
d_u(z) &= \min \{\, c(u,v) + d_v(z),\\
&\qquad c(u,x) + d_x(z),\\
&\qquad c(u,w) + d_w(z) \,\}\\
&= \min \{2 + 5,\\
&\qquad 1 + 3,\\
&\qquad 5 + 3\} = 4
\end{aligned}
$$

Node that achieves minimum is next hop in shortest path ➔ forwarding table

Distance Vector Algorithm

scalar

- $D_x(y)$ = estimate of least cost from x to y
- Distance vector: $\mathbf{D}_x = [D_x(y): y \in N]$
- Node x knows cost to each neighbor v: $c(x,v)$
- Node x maintains $\mathbf{D}_x = [D_x(y): y \in N]$
- Node x also maintains its neighbors' distance vectors
  - For each neighbor v, x maintains
    $\mathbf{D}_v = [D_v(y): y \in N]$

Distance vector algorithm (4)

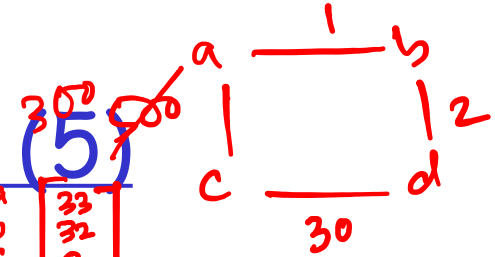
Basic idea:

- Each node periodically sends its own distance vector estimate to neighbors
- When a node 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)



$$\begin{array}{c} a \\ b \\ c \\ d \end{array} \begin{bmatrix} 33 \\ 32 \\ 0 \\ 30 \end{bmatrix}$$

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:

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

recompute estimates

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

Does this mean a network flood every time a link cost changes?

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

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

$$\underset{\underset{2}{\shortparallel}}{c(x,y)} + \underset{1}{D_y(z)}$$

$D_z(y)$

node x table

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

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

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

node y table

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

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

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

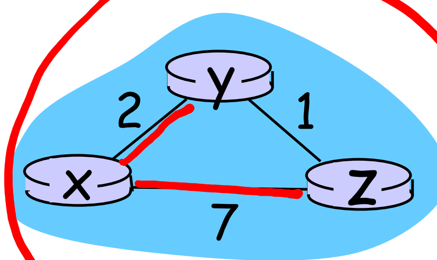
node z table

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

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

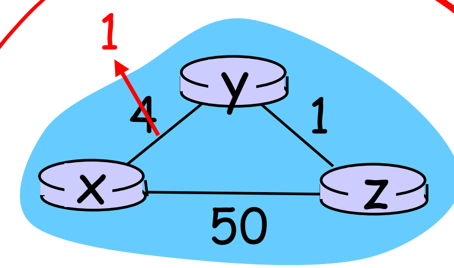
from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

time



Distance Vector: link cost changes

x $\begin{bmatrix} 1\ \cancel{4} \\ 2\ \cancel{5} \end{bmatrix}$



y $\begin{bmatrix} \cancel{4}\ 1 \\ 1 \end{bmatrix}$

Link cost changes:

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

"good news travels fast"

At time t_0, y detects the link-cost change, updates its DV, and informs its neighbors.

$\begin{bmatrix} 1\ \cancel{4} \\ 0 \\ 1 \end{bmatrix}$

At time t_1, z receives the update from y and updates its table. It computes a new least cost to x and sends its neighbors its DV.

At time t_2, y receives z's update and updates its distance table. y's least costs do not change and hence y does *not* send any message to z.

$d_x(y) = \min\{60+0,\ 50+1\} = 51$

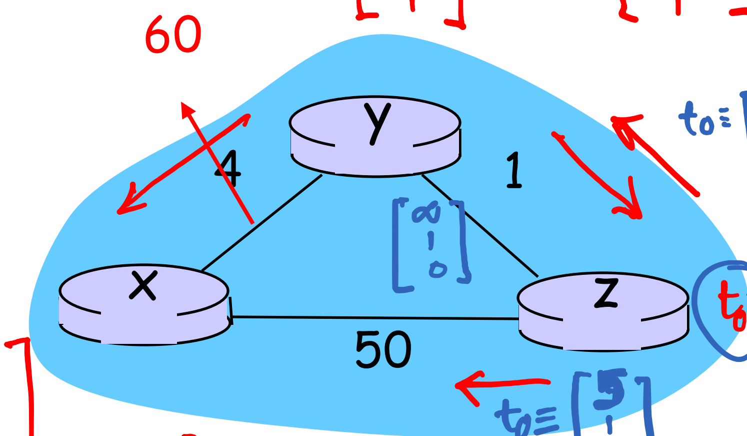
Distance Vector: link cost changes

N = # of iterations until convergence

$y \begin{bmatrix} 4 \\ 0 \\ 1 \end{bmatrix} \rightarrow \begin{bmatrix} 60 \\ 0 \\ 1 \end{bmatrix}$

$t_0 \equiv \begin{bmatrix} 4 \\ 0 \\ 1 \end{bmatrix} \quad t_1 \equiv \begin{bmatrix} 6 \\ 0 \\ 1 \end{bmatrix} \quad t_2 \equiv \begin{bmatrix} 8 \\ 0 \\ 1 \end{bmatrix} \rightarrow \rightarrow \rightarrow \begin{bmatrix} 48 \\ 0 \\ 1 \end{bmatrix}$

$z \begin{bmatrix} 5 \\ 1 \\ 0 \end{bmatrix}$



$t_0 \equiv \begin{bmatrix} 0 \\ 4 \\ 5 \end{bmatrix} \quad t_1 \equiv \begin{bmatrix} 0 \\ 51 \\ 50 \end{bmatrix}$

$t_0 \equiv \begin{bmatrix} 5 \\ 1 \\ 0 \end{bmatrix} \quad t_1 \equiv \begin{bmatrix} 7 \\ 1 \\ 0 \end{bmatrix}$

$\begin{bmatrix} 51 \\ 0 \\ 1 \end{bmatrix} \quad \begin{bmatrix} 50 \\ 0 \\ 1 \end{bmatrix} \quad \begin{bmatrix} 49 \\ 1 \\ 0 \end{bmatrix} \quad \begin{bmatrix} 50 \\ 1 \\ 0 \end{bmatrix}$

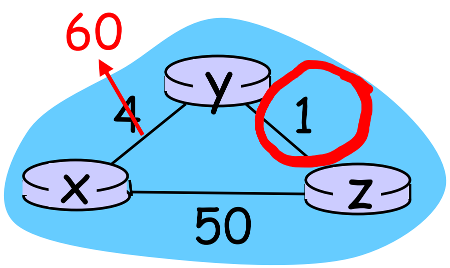
What happens now ?

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

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



Poissoned 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?

Tradeoffs

What will you recommend ?

Link State?
Distance Vector?

There is no right answer

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

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