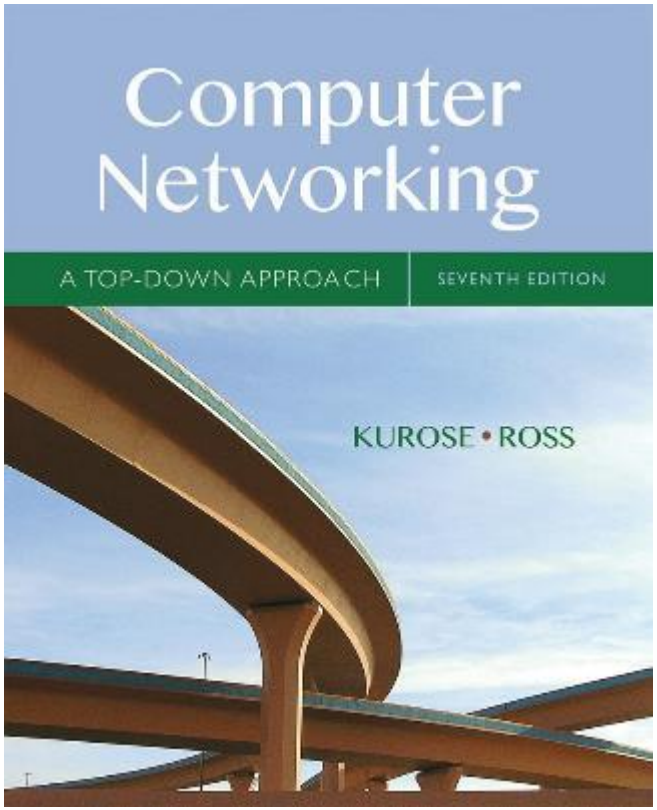
Chapter 5
Network Layer: The Control Plane (Part 1/3)



Computer Networking: A Top Down Approach

7th edition
Jim Kurose, Keith Ross
Pearson/Addison Wesley
April 2016

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Thanks and enjoy! JFK/KWR

Chapter 5: outline

5.1 introduction

5.2 routing protocols

- link state
- distance vector

5.3 ICMP: The Internet Control Message Protocol

Network-layer functions

Recall: two 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

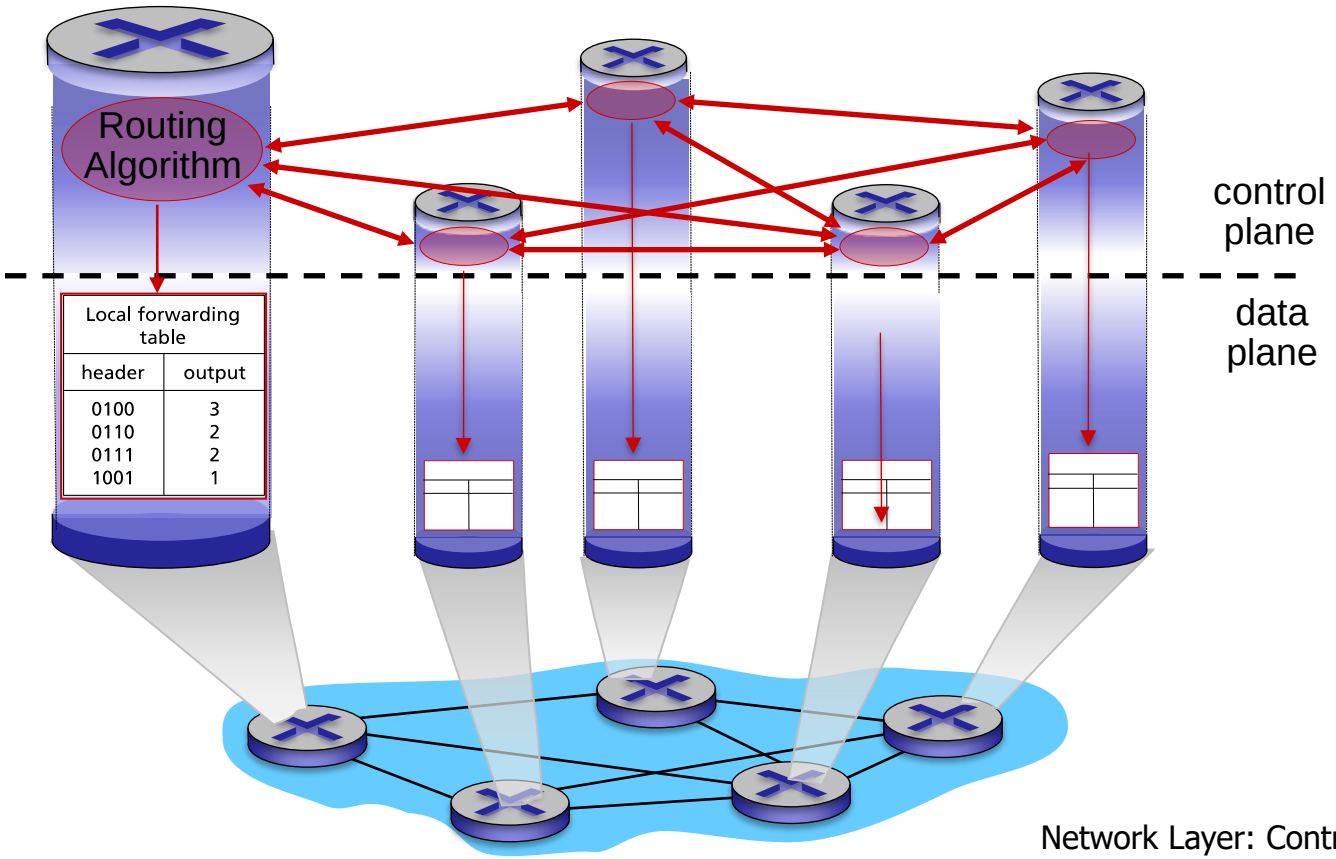
control plane

Two approaches to structuring network control plane:

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

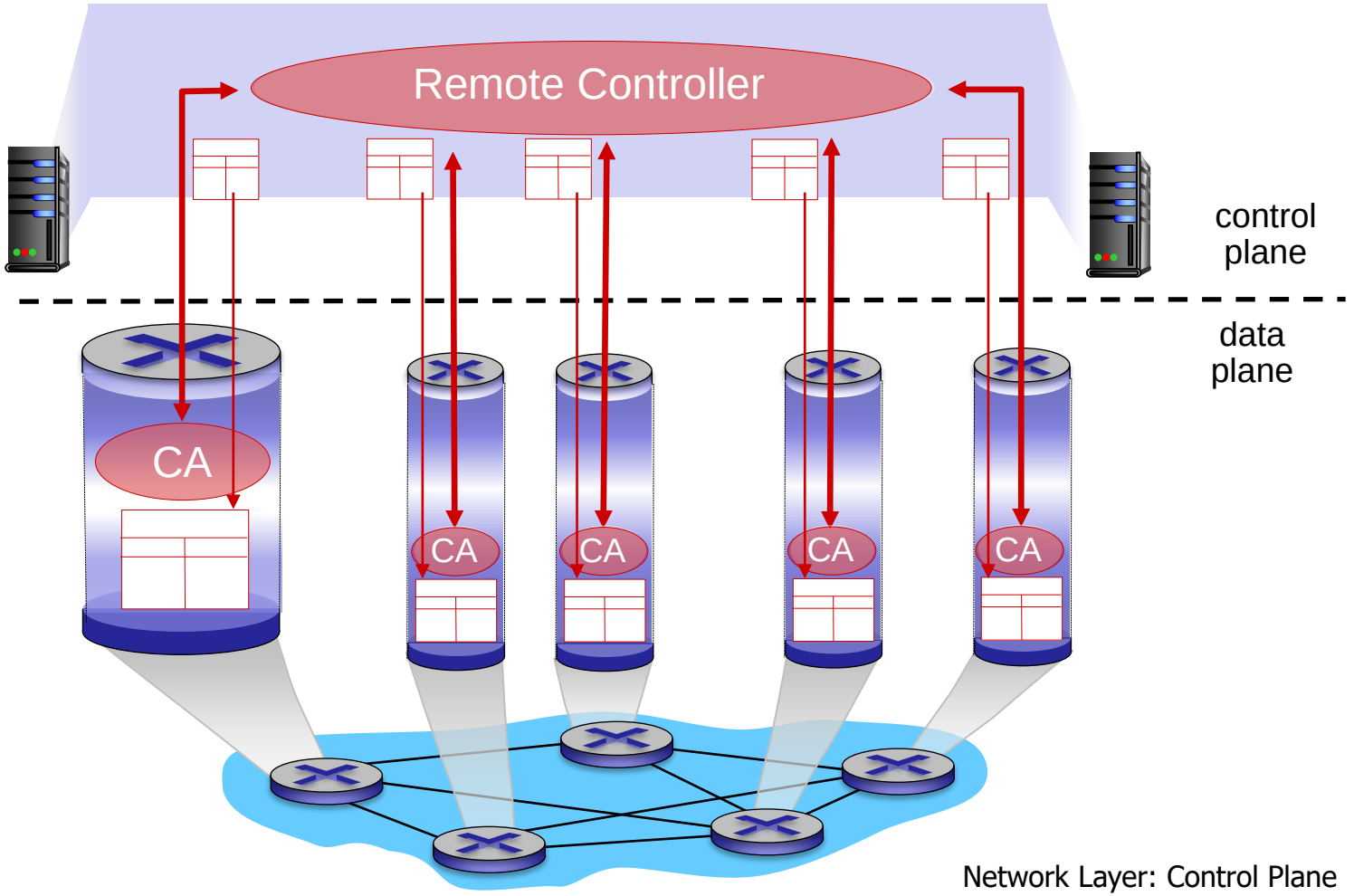
Per-router control plane

Individual routing algorithm components *in each and every router* interact with each other in control plane to compute forwarding tables



Logically centralized control plane

A distinct (typically remote) controller interacts with local control agents (CAs) in routers to compute forwarding tables



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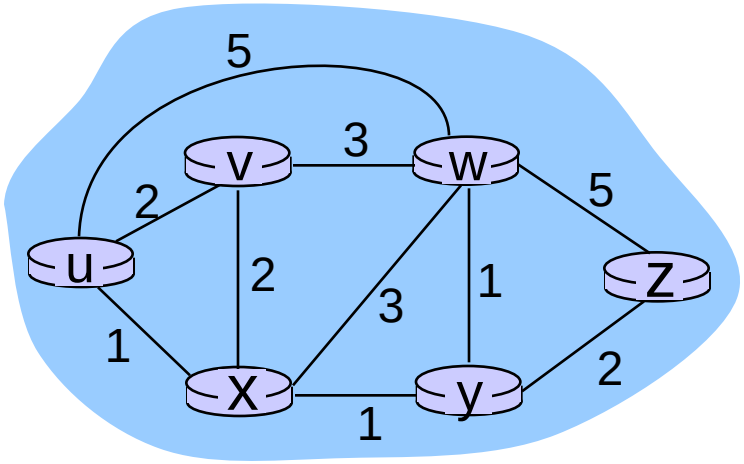
Routing protocols

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

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

Graph abstraction of the network

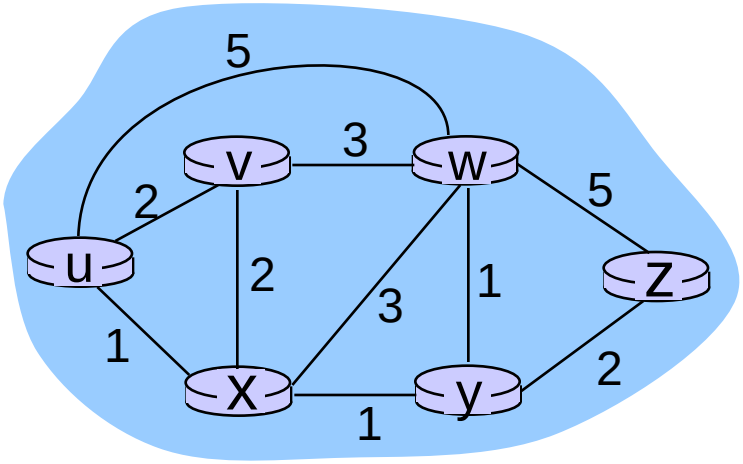


graph: G = (N,E)

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) }

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

key question: what is the least-cost path between u and z ?
routing algorithm: algorithm that finds that least cost path

Routing algorithm classification

Q: 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

Q: 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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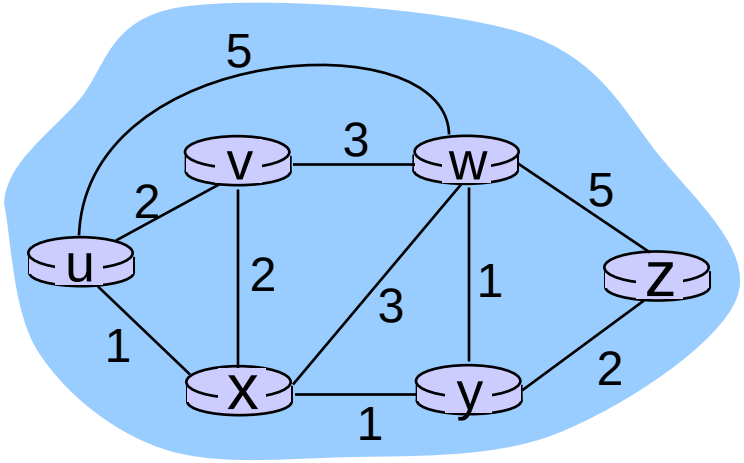
A link-state routing Protocol

Dijkstra's algorithm

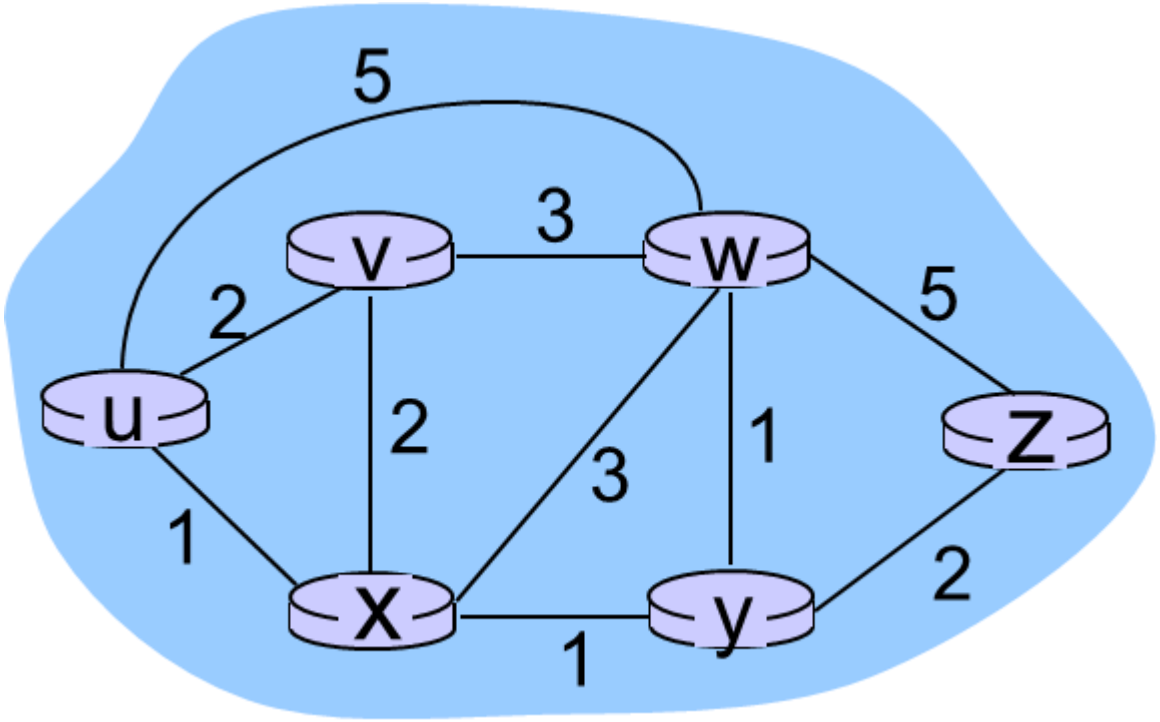
- network topology, link costs known to all nodes
  - accomplished via "link state broadcast"
  - all nodes have same info
- computes least cost paths from one node ("source") to all other nodes
  - gives *forwarding table* for that node
- iterative: after k iterations, know least cost path to k destinations

notation:

- c(x,y): link cost from node x to y if x , y are neighbors else = ∞ if not direct neighbors
- D(v): current value of cost of 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



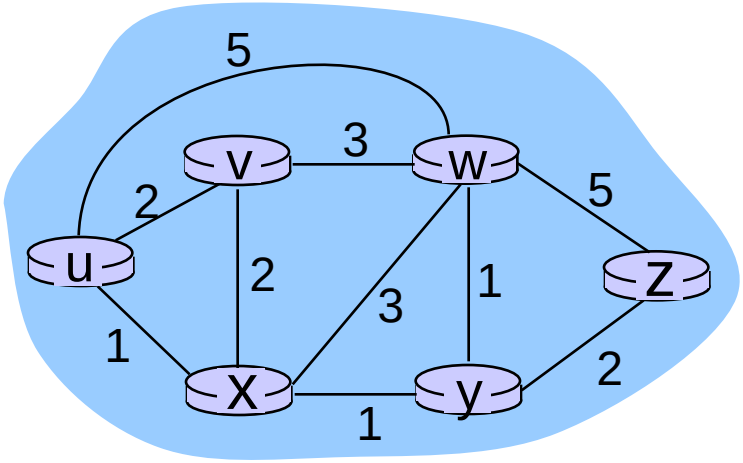
Find the shortest Path using Dijkstra algorithm



Dijkstra's algorithm: another example

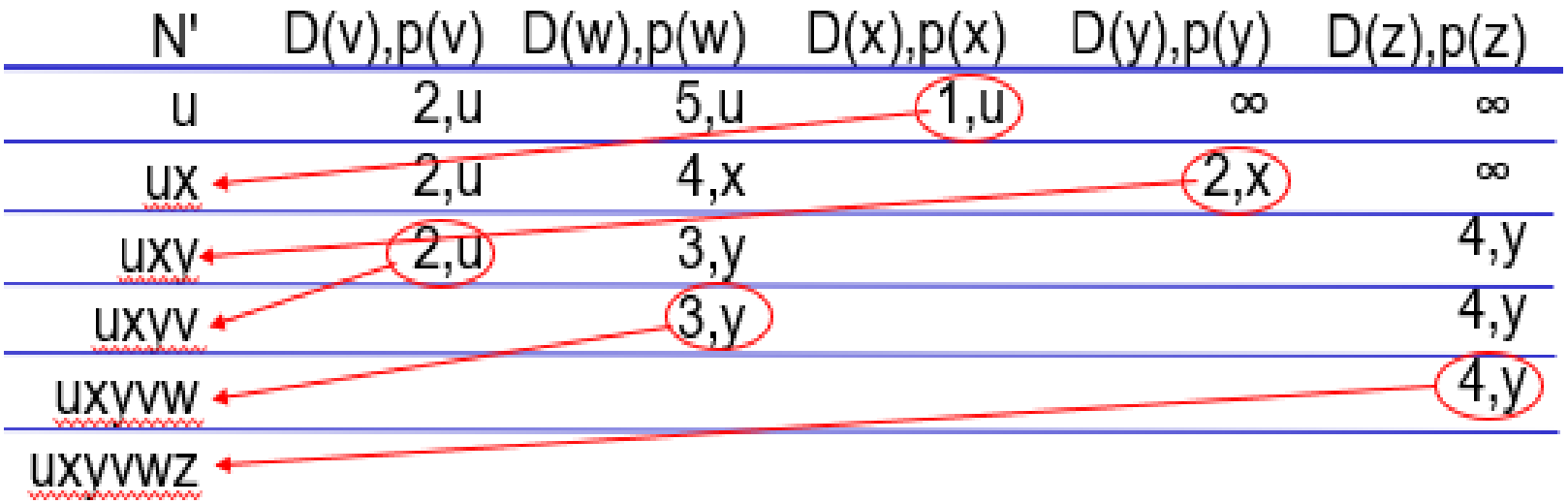
From Source node 'u'

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					



D(v) = min(D(v), D(w) + c(w,v))

Dijkstra's algorithm: example



N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
u	2,u	5,u	1,u	∞	∞
ux	2,u	4,x		2,x	∞
uxv	2,u	3,y			4,y
uxvv		3,y			4,y
uxvvw					4,y
uxvvwz					

resulting shortest-path tree from u?

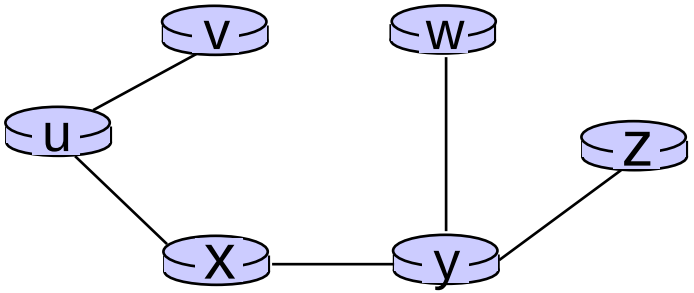
resulting forwarding table in u ?

notes:

- construct shortest path tree by tracing predecessor nodes

Dijkstra's algorithm: example

resulting shortest-path tree from u:



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

resulting forwarding table in u ?

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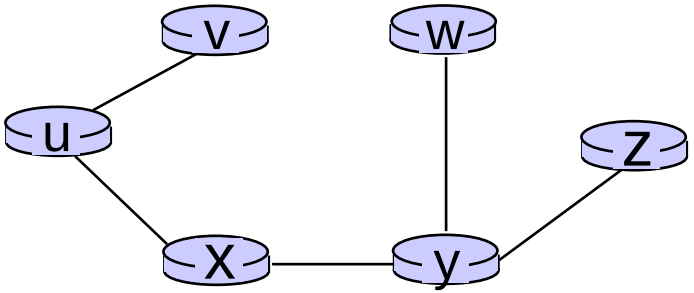
Dijkstra's algorithm: example

resulting shortest-path tree from u:



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

resulting forwarding table in u:

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

notes:

- construct shortest path tree by tracing predecessor nodes

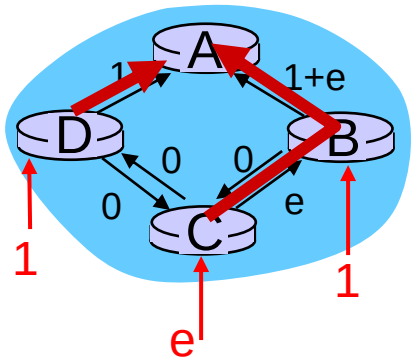
Dijkstra's algorithm, discussion

oscillations possible:

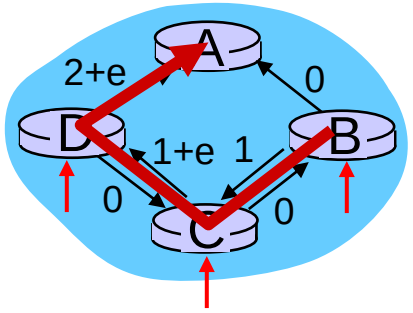
- e.g., 'link cost' = amount of carried traffic:

Possible solution:

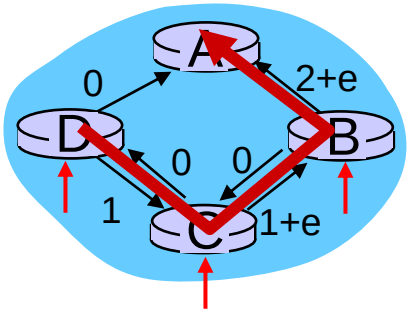
- Make link cost independent of traffic load
- Randomize time of link state advertisement
  - prevent the routers from running the routing algorithm simultaneously. If this is not done carefully, the routers will tend to self-synchronize.



initially



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



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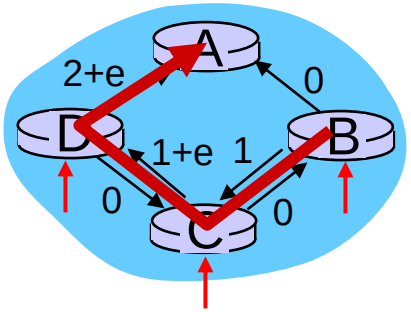
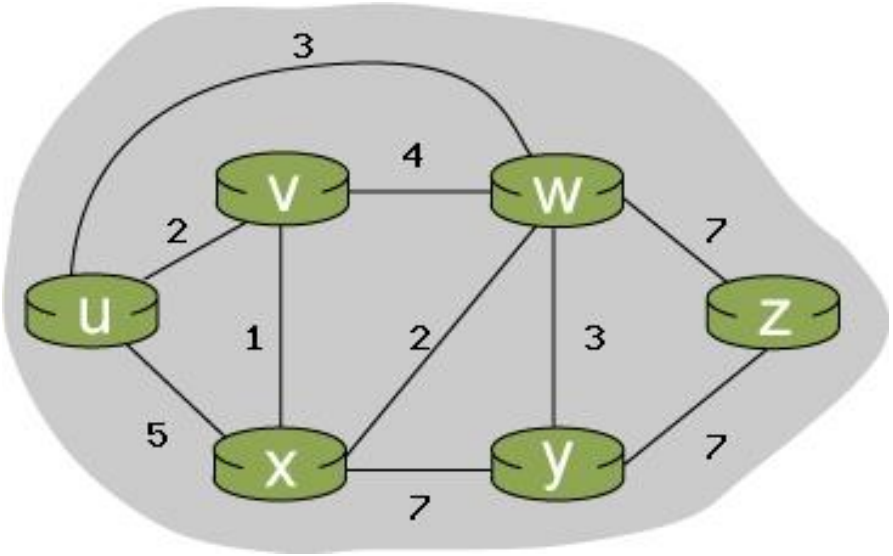


given these costs, find new routing…. resulting in new costs

Class exercise

Using Dijkstra's algorithm, find the least cost path from source node **u** to all other destinations. Show your work in tabular format

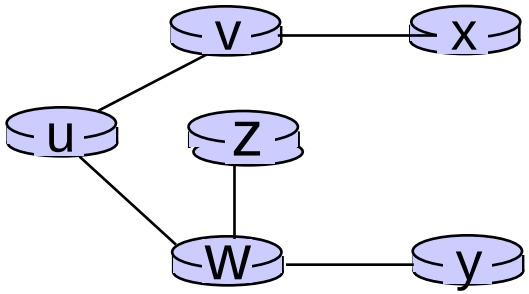


Class exercise (solution)

Using Dijkstra's algorithm, find the least cost path from source node **u** to all other destinations. Show your work in tabular format

D(u),p(u)	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
-	2,u	3,u	5,u	infty	infty
-	-	3,u	3,v	infty	infty
-	-	-	3,v	6,w	10,w
-	-	-	-	6,w	10,w
-	-	-	-	-	10,w
-	-	-	-	-	-

resulting shortest-path tree from u and resulting forwarding table from u:



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

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- link state
- distance vector

5.3 ICMP: The Internet Control Message Protocol

Distance vector algorithm

Bellman-Ford equation

let

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

then

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

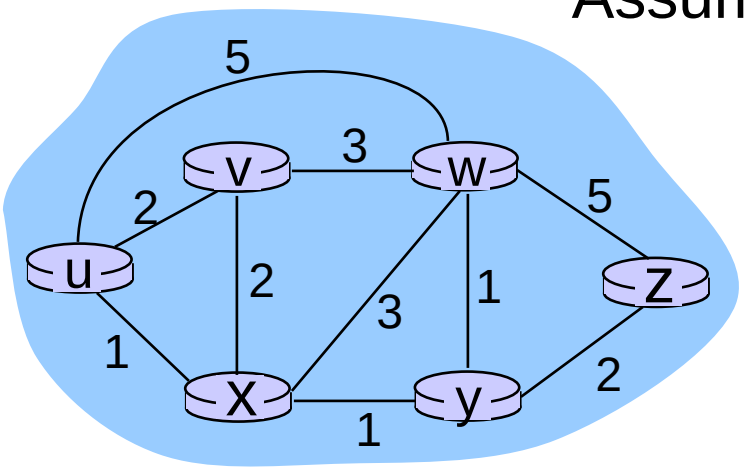
cost from neighbor v to destination y

cost to neighbor v

min taken over all neighbors v of x

Bellman-Ford example

Assume we know $d_v(z) = 5$, $d_x(z) = 3$, $d_w(z) = 3$



B-F equation says:

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

To find cost from source u to destination z using B-F equation:

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

node achieving minimum is next hop in shortest path, used in forwarding table

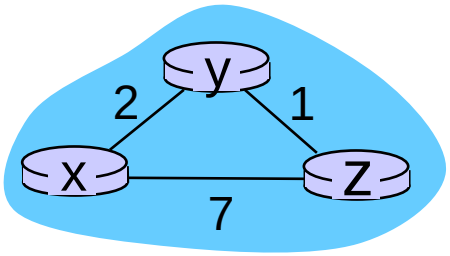
Distance vector algorithm

key 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* $d_x(y)$



node x table

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

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

node y table

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

node z table

from \ cost to	x	y	z
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

from \ cost to	x	y	z
x	0	2	7
y	∞	∞	∞
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from \ cost to	x	y	z
x	0	2	3
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node y table

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node z table

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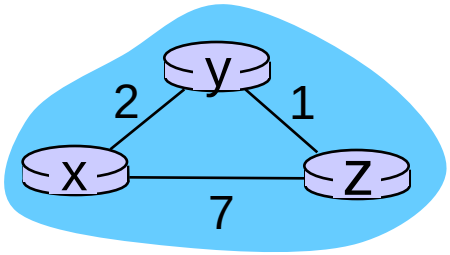

time

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$= \min\{2+0 , 7+1\} = 2$

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

node x table

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z	∞	∞	∞

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node y table

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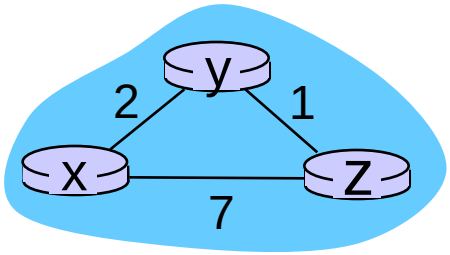
x	0	2	7
y	2	0	1
z	7	1	0

node z table

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

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



time

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

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

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

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

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from \ cost to	x	y	z
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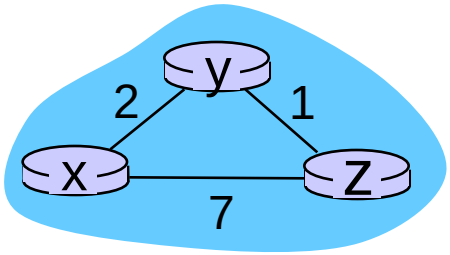


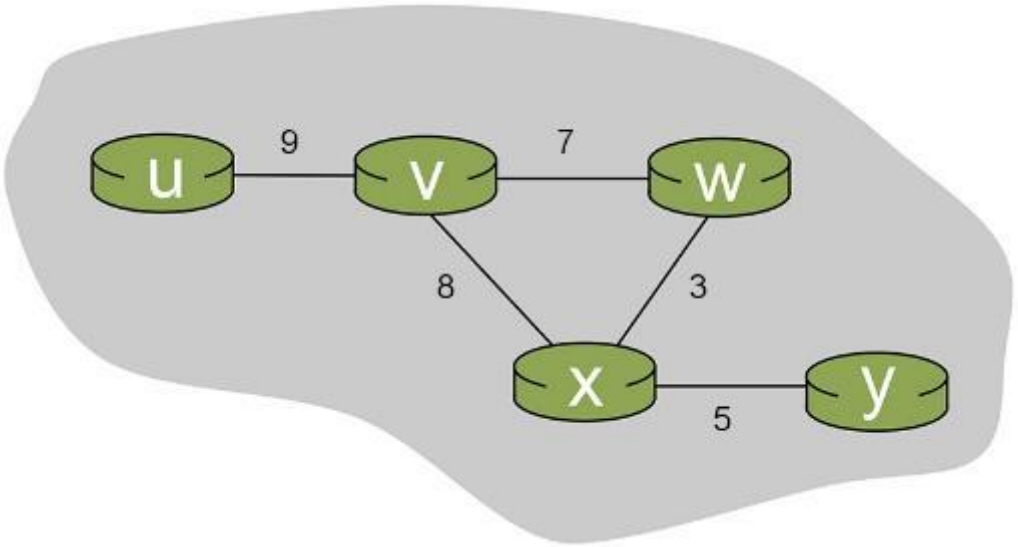
time

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

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

Class Exercise: Bellman Ford Equation

- When the algorithm converges, what are the distance vectors in each of the routers.



Class Exercise: Bellman Ford Equation

- When the algorithm converges, what are the distance vectors in each of the routers.

- The initial distance vectors at each router will be:

  Du = [0,9,∞,∞,∞]
  Dv = [9,0,8,7,∞]
  Dx = [∞,8,0,3,5]
  Dw = [∞,7,3,0,∞]
  Dy = [∞,∞,5,∞,0]

- The distance vector of the nodes after first iteration:

  Du = [0,9,17,∞,∞]
  Dv = [9,0,8,7,13]
  Dx = [17,8,0,3,5]
  Dw = [∞,7,3,0,8]
  Dy = [∞,13,5,8,0]

  The distance vector of the nodes after second iteration:
  Du = [0,9,17,16,∞]
  Dv = [9,0,8,7,13]
  Dx = [17,8,0,3,5]
  Dw = [16,7,3,0,8]
  Dy = [∞,13,5,8,0]

Class Exercise: Bellman Ford Equation

- When the algorithm converges, what are the distance vectors in each of the routers.

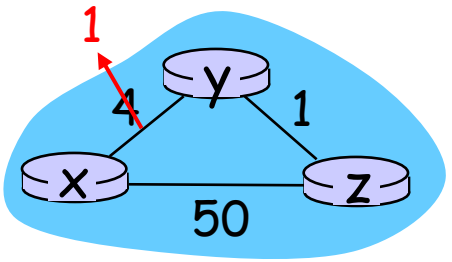
```
The distance vector of the nodes after third iteration:
Du = [0,9,17,16,22]
Dv = [9,0,8,7,13]
Dx = [17,8,0,3,5]
Dw = [16,7,3,0,8]
Dy = [22,13,5,8,0]

The distance vector of the nodes after fourth iteration:
Du = [0,9,17,16,22]
Dv = [9,0,8,7,13]
Dx = [17,8,0,3,5]
Dw = [16,7,3,0,8]
Dy = [22,13,5,8,0]
```

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"

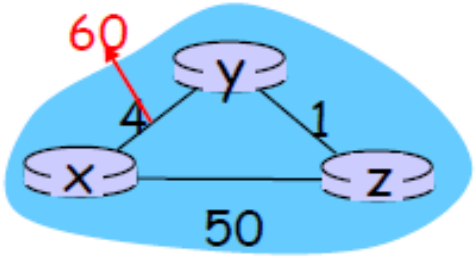
t_0 : *y* detects link-cost change, updates its DV, informs its neighbors.

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

Count-to-infinity Problem



Link cost changes:

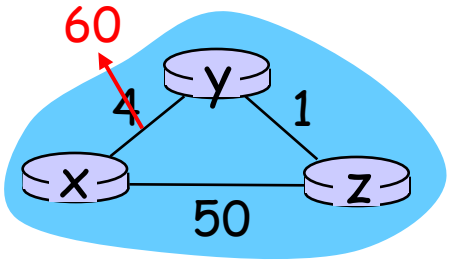
- Before change, $D_y(x)=4$, $D_y(z)=1$, $D_z(y)=1$, $D_z(x)=5$
- New min. cost from y to x, $D_y(x) = \min(60, 1+5) = 6$
  ➔ WRONG!!! and routing loop (ping-pong between y and z) until z receives y's advertisement
- After y's advertisement ($D_y(x)=6$), z updates path to x, $D_z(x) = \min(c(z,x), c(z,y)+D_y(x)) = 7$
- After z's advertisement ($D_z(x)=7$), y updates path to x, $D_y(x) = \min(c(y,x), c(y,z)+D_z(x)) = 8$
- .....
- After 44 iterations, routing stabilizes $D_y(x)=51$

Good news travels fast, but bad news travels slow!!!

Distance vector: link cost changes

link cost changes:

- node detects local link cost change
- *bad news travels slow* - "count to infinity" problem!
- 44 iterations before algorithm stabilizes: see text



t_0 : *y* detects link-cost change, (changed from 4 to 60). y computes the new minimum-cost path to x to have a cost of ***6*** via z. updates its DV, informs its neighbors.

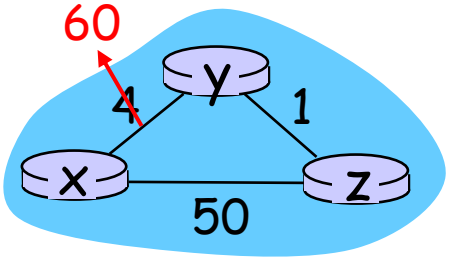
t_1 : there is a routing loop – to get to x router y routes through *z and z routes through y.*

t_2 : *y* computed new minimum cost to x and informs z.
z receives y's new DV indicating y's minimum cost to x is 6.
z knows it can get to y with a cost of 1 and computes least cost to x as 7.

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)

Distance vector: Poisoned Reverse



How to prevent routing loop and slow convergence
→ Poisoned reverse

- If Z receives packets from Y to X, but it routes through Y to get to X :
  - Z tells Y as $D_Z(x) = \infty$ (little white lie)
  - Y will not route to X via Z
- Y updates $D_y(x)=60$
- Z updates $D_Z(x)=\min(c(z,x), c(z,y)+D_y(x))=\min(50, 61) = 50$
- Y updates $D_y(x)=\min(c(y,x), c(y,z)+D_z(x))=\min(60, 51) = 51$

no route change → stabilized

Comparison of LS and DV algorithms

- ***LS:***
  - suffers from 'oscillation problem'
  - A lot of advertisements have to be flooded to the network
- ***DV:***
  - suffers from count-to-infinity problem
  - Takes time in convergence

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 5: outline

5.1 introduction

5.2 routing protocols

- link state
- distance vector

5.3 ICMP: The Internet Control Message Protocol

ICMP: internet control message protocol

- ICMP used by hosts & routers to communicate network-level information
  - error reporting: unreachable host, network, port
  - echo request/reply (used by ping)
- network-layer "above" IP:
  - ICMP msgs carried in IP datagrams
- ICMP message: type, code, IP header and first 8 bytes of IP datagram causing error

Type	Code	description
0	**0**	**echo reply (ping)**
3	0	dest. network unreachable
3	1	dest host unreachable
3	2	dest protocol unreachable
3	**3**	**dest port unreachable**
3	6	dest network unknown
3	7	dest host unknown
4	0	source quench (congestion control - not used)
8	**0**	**echo request (ping)**
9	0	route advertisement
10	0	router discovery
11	**0**	**TTL expired**
12	0	bad IP header

Traceroute and ICMP

- Sender sends series of UDP segments to destination. TTL field is incremented for each set of datagrams. For example,
  - first set has TTL =1
  - second set has TTL=2, etc.
- In addition, unlikely port number is set in the udp segment.
- when datagram in n^{th} set arrives to n^{th} router:
  - router discards datagram and sends source ICMP message with type 11 and code 0, which means "TTL expired"
  - ICMP message include name of router & IP address
- when ICMP message arrives, sender records RTTs

stopping criteria:

- UDP segment eventually arrives at destination host
- destination returns ICMP "port unreachable (invalid)" message **(type 3, code 3)**
- source stops