Chapter 4: Routing Algorithms
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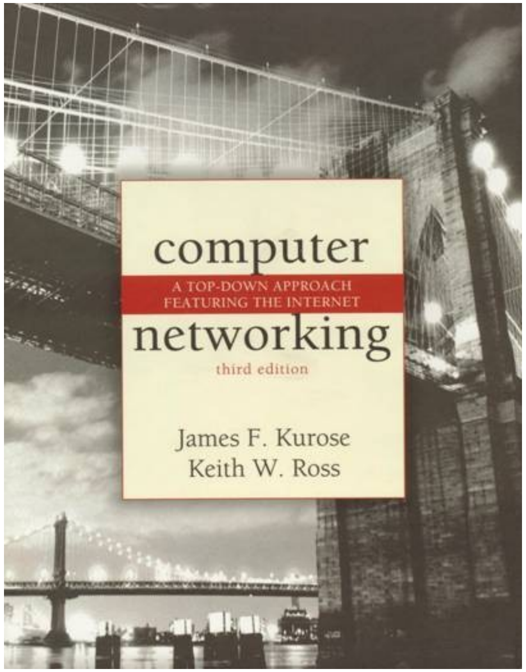

Computer Networking: A Top Down Approach Featuring the Internet, 3rd edition.
Jim Kurose, Keith Ross
Addison-Wesley, July 2004.

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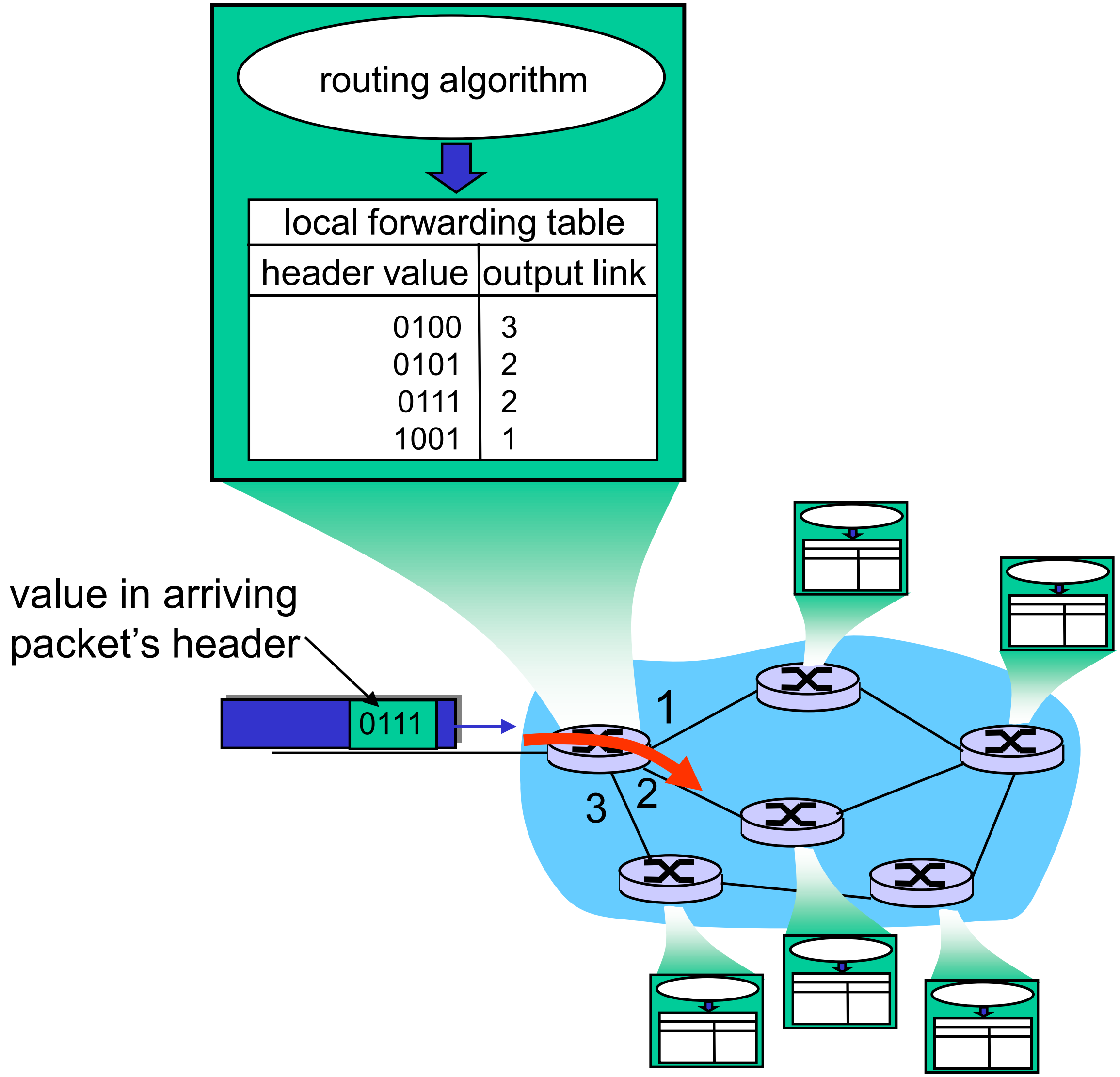
Routing Algorithms

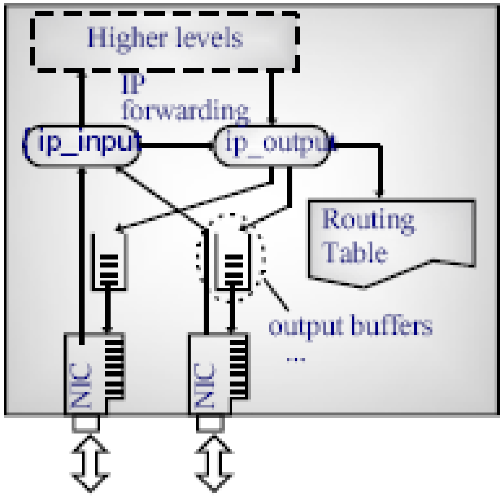
- Link-State Routing
- Distance-Vector Routing
- Hierarchical Routing

Interplay between routing and forwarding



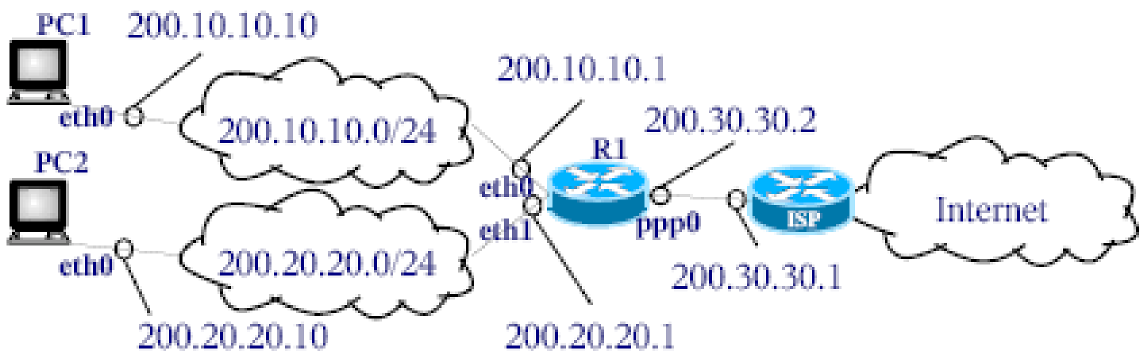
Routing Table

- ip_output() kernel function consults the routing table for each datagram.
- Routing can be:
    - Direct: The destination is directly connected to an interface.
    - Indirect: Otherwise. In this case, the datagram is sent to a router.
- Default route: Is an entry where to send all datagrams with a destination address to a network not present in the routing table. The default route address is 0.0.0.0/0.
- Hosts usually have two entries: The network where they are connected and a default route.



Basic router architecture

Routing Table – Unix Example



known destinations

how to reach the destinations

PC1 routing table:

Destination	Genmask	Gateway	Iface
200.10.10.0	255.255.255.0	0.0.0.0	eth0
0.0.0.0	0.0.0.0	200.10.10.1	eth0

PC2 routing table:

Destination	Genmask	Gateway	Iface
200.20.20.0	255.255.255.0	0.0.0.0	eth0
0.0.0.0	0.0.0.0	200.20.20.1	eth0

R1 routing table:

Destination	Genmask	Gateway	Iface
200.10.10.0	255.255.255.0	0.0.0.0	eth0
200.20.20.0	255.255.255.0	0.0.0.0	eth1
0.0.0.0	0.0.0.0	200.30.30.1	ppp0

Routing Table – Datagram Delivery Algorithm

- Check if it is the destination:

```
if(Datagram Destination == address of any of the interfaces) {
    send the datagram to the loopback (send to upper layers)
}
```

- Consult the routing table:

```
for each routing table entry ordered from longest to shortest mask
   (Longest Prefix Match) {
  if(Datagram Destination IP address & mask == Destination table
     entry) {
      return (gateway, interface) ;
  }
```

- Forward the datagram

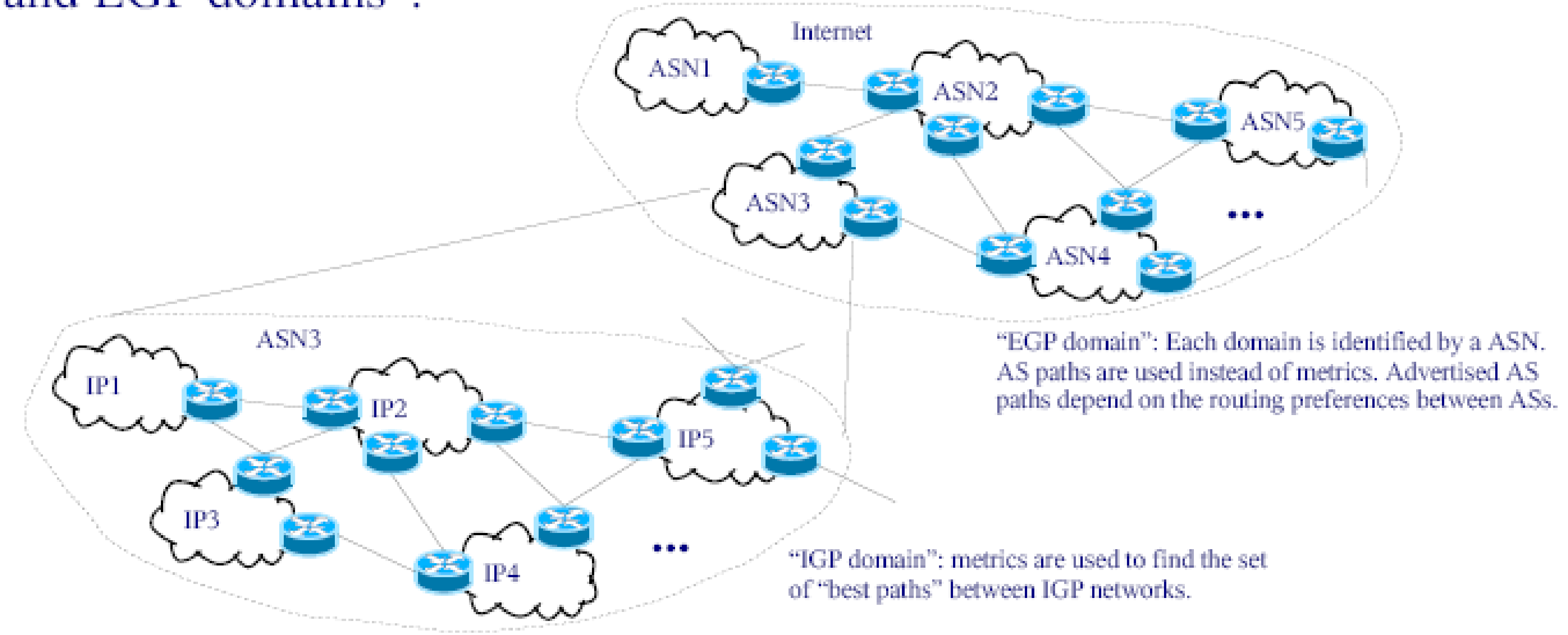
```
if(it is a direct routing) {
    send the datagram to the Datagram Destination IP address by
       the entry interface
} else { /* it is an indirect routing */
    send the datagram to the gateway IP address by the entry
       interface
}
```

Routing algorithms

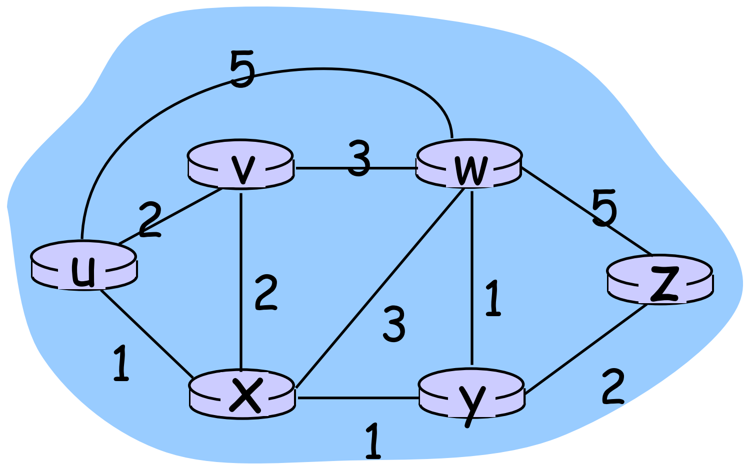
- Add entries to routing tables. Can be:
  - Static: Manual, scripts, DHCP.
  - Adaptive: Automatically update table entries, e.g. when a topology change occurs.
- Internet is organized in Autonomous Systems (AS). In terms of ASs, routing algorithms are classified as:
  - Interior Gateway Protocols (IGPs): Inside the same AS. Examples:
    - RFC standards: RIP, OSPF.
    - Proprietary: CISCO IGRP.
  - Exterior Gateway Protocols (EGPs): Between different ASs. Currently BGPv4.

Routing algorithms - Autonomous Systems (AS)

- AS definition (RFC 1930): "An AS is a connected group of one or more IP prefixes run by one or more network operators which has a SINGLE and CLEARLY DEFINED routing policy".
- Each AS is identified by a 16 bits AS Number (ASN) assigned by IANA.
- ASs facilitate Internet routing by introducing a two-level hierarchy: "IGP and EGP domains".



Graph abstraction



Graph: G = (N,E)

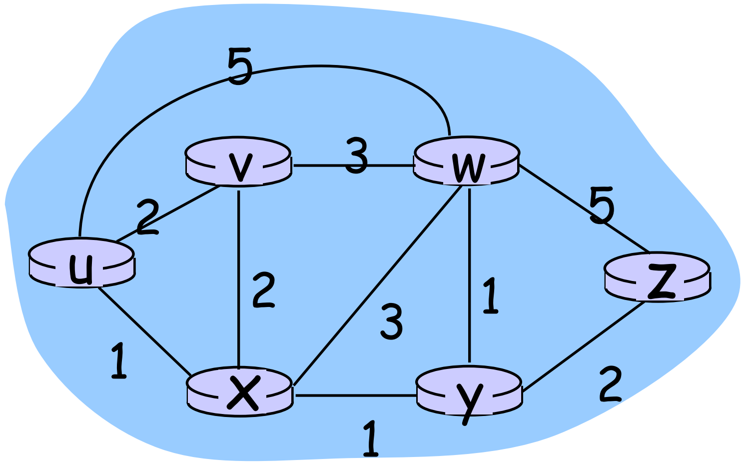
N = set of routers = { u, v, w, x, y, z }

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

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

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; = ∞ 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

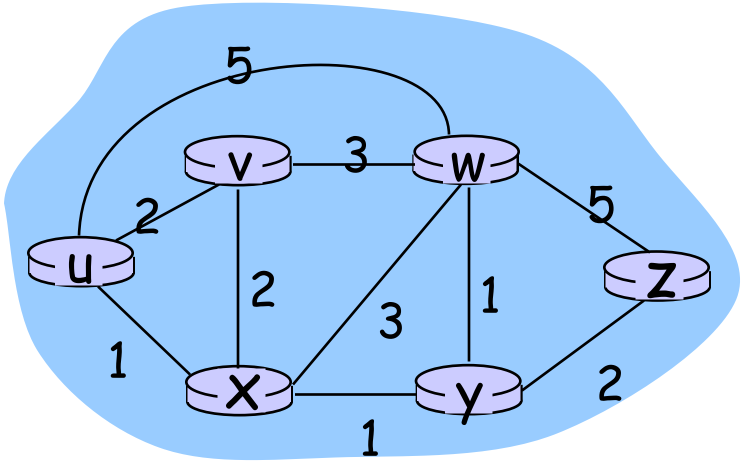
Dijsktra's Algorithm

```
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'
```

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					



Quiz_01

- Run the Dijkstra algorithm on a specific graph, step-by-step and find all the shortest path!

Distance Vector Algorithm (1)

Bellman-Ford Equation (dynamic programming)

Define

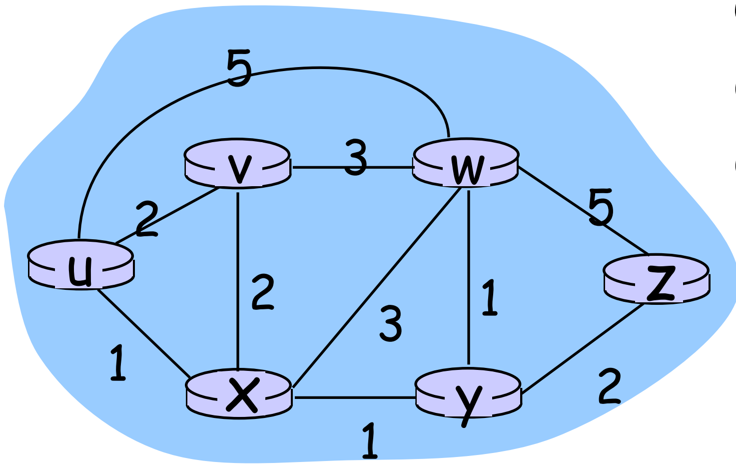
$d_x(y)$:= cost of least-cost path from x to y

Then

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

where min is taken over all neighbors of x

Bellman-Ford example (2)



Clearly, $d_v(z)/(v\text{-}x\text{-}y\text{-}z)=5$,
$d_x(z)/(x\text{-}y\text{-}z) = 3$,
$d_w(z)/(w\text{-}y\text{-}z) = 3$

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 (3)

- $D_x(y)$ = 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 neighbors, 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 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:

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

↓

recompute estimates

↓

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

Distance Vector Routing Algorithm

iterative:

- continues until no nodes exchange info.
- *self-terminating*: no "signal" to stop

asynchronous:

- nodes need *not* exchange info

distributed:

- each node communicates *only* with directly-attached neighbors

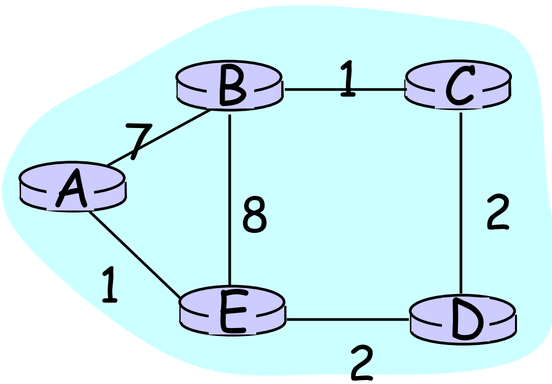
Distance Table data structure

- each node has its own row for each possible destination, and column for each directly-attached neighbor to node
- example: in node X, for dest. Y via neighbor Z:

$$D^X(Y,Z) = \text{distance } \textit{from} \text{ X } \textit{to} \text{ Y, } \textit{via} \text{ Z as next hop}$$

$$= c(X,Z) + \min_w \{D^Z(Y,w)\}$$

Distance Table example



Distance Table in E:
Finding routes from E to A,B,C,D

$D^E()$	cost to destination via A	B	D
destination A	1	14	5
B	7	8	5
C	6	9	4
D	4	11	2

$$D^E(C,D) = c(E,D) + \min_w \{D^D(C,w)\} = 2+2 = 4$$

$$D^E(A,D) = c(E,D) + \min_w \{D^D(A,w)\} = 2+3 = 5$$

loop!

$$D^E(A,B) = c(E,B) + \min_w \{D^B(A,w)\} = 8+6 = 14$$

loop!

$D^X(Y,Z)$ = distance *from* X *to* Y, *via* Z as next hop

$= c(X,Z) + \min_w \{D^Z(Y,w)\}$

Distance table gives routing table

cost to destination via

$D^E()$	A	B	D
A	1	14	5
B	7	8	5
C	6	9	4
D	4	11	2

destination

	Outgoing link to use, cost
A	A,1
B	D,5
C	D,4
D	D,4

destination

Distance table $\longrightarrow$ Routing table

Distance Vector Algorithm

At all nodes, X:

Initialization:
  for all adjacent nodes v:
    $D^X(*,v)$ = infty   /* the * operator means "for all rows" */
    $D^X(v,v) = c(X,v)$
  for all destinations, y
    send $\min_w D^X(y,w)$ to each neighbor /* w over all X's neighbors */

Distance Vector Algorithm (cont)

loop
  wait (until I see a link cost change to neighbor V
      or until I receive update from neighbor V)

  if (c(X,V) changes by d)
    /* change cost to all dest's via neighbor v by d */
    /* note: d could be positive or negative */
    for all destinations y: $D^X(y,V) = D^X(y,V) + d$

  else if (update received from V wrt destination Y)
    /* shortest path from V to some Y has changed */
    /* V has sent a new value for its $\min_w\{D^V(Y,w)\}$ */
    /* call this received new value is "newval" */
    for the single destination y: $D^X(Y,V) = c(X,V) + newval$

  if we have a new $\min_w\{D^X(Y,w)\}$ for any destination Y
    send new value of $\min_w\{D^X(Y,w)\}$ to all neighbors

forever

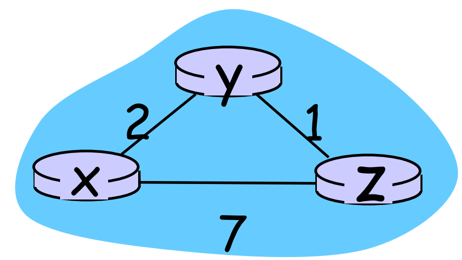
$D_x(y) = \min\{c(x,y) + D_y(y),\ c(x,z) + D_z(y)\}$
$= \min\{2+0\ ,\ 7+1\} = 2$

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

Line 23-24: only sending new value of $\min_w D^X(Y,w)$ to all neighbors

Only D^X, D^Z changed

D^Y does not changed



node x table

Initially:

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

Next:

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

NEW

Next:

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

node y table

Initially:

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

Next:

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

OLD

Next:

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

node z table

Initially:

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

Next:

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

NEW

Next:

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

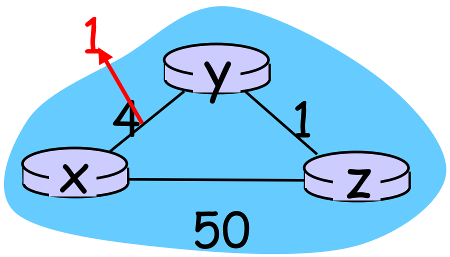
time

Initially Next Next

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"

At time t_0, y detects the link-cost change (4 to 1), updates its DV, and informs its neighbors (x, z).

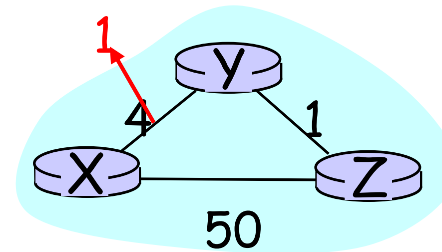
At time t_1, z receives the update from y and updates its table. It computes a new least cost to x (2 instead of 5) and sends its neighbors (x, y) its DV.

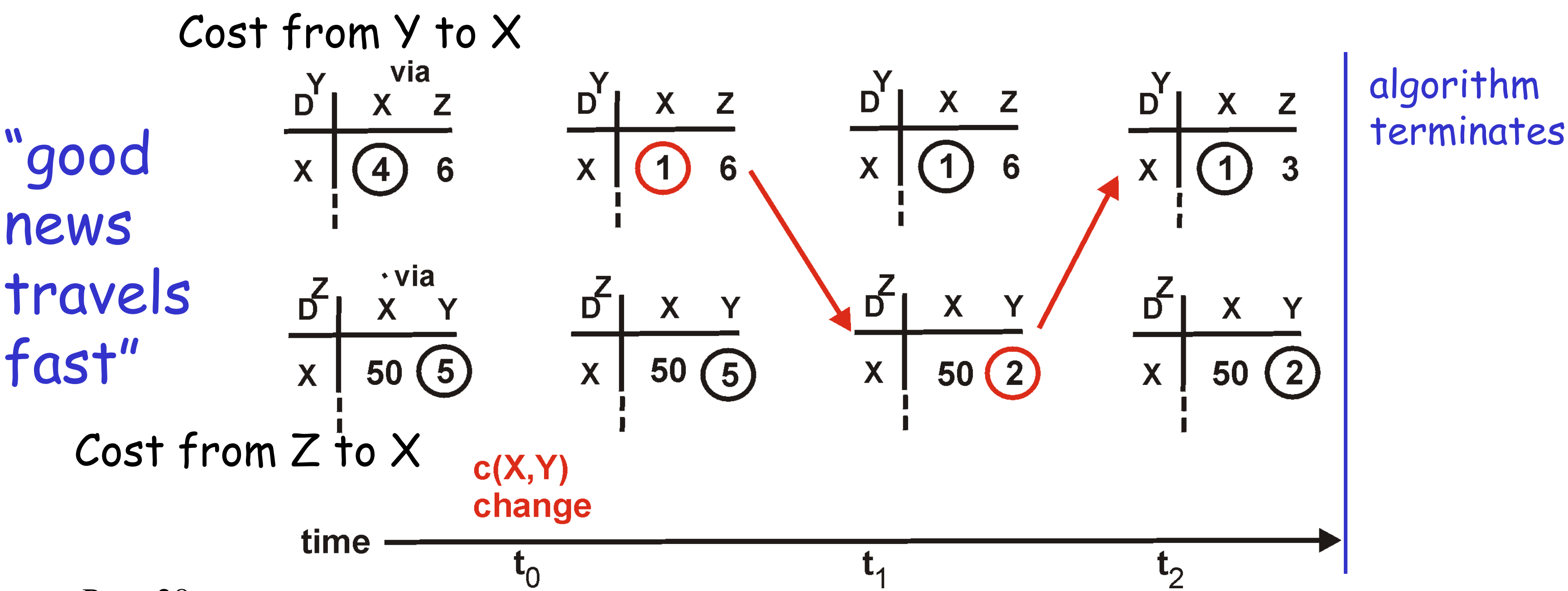
At time t_2, y receives z's update and updates its distance table. y's least costs do not change and hence y does *not* send any message to z.

Distance Vector link cost changes

Link cost changes:

- node detects local link cost change
- updates distance table (line 15)
- if cost change in least cost path, notify neighbors (lines 23,24)

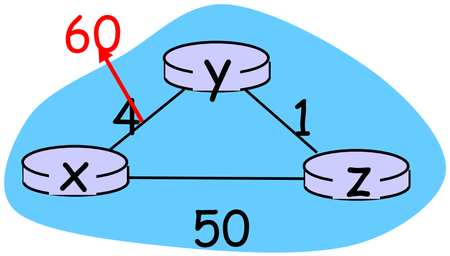




Distance Vector: link cost changes

Link cost changes:

- good news travels fast
- bad news travels slow - "count to infinity" problem!
- 44 iterations before algorithm stabilizes: see next



Distance Vector link cost changes

Link cost changes:

- good news travels fast
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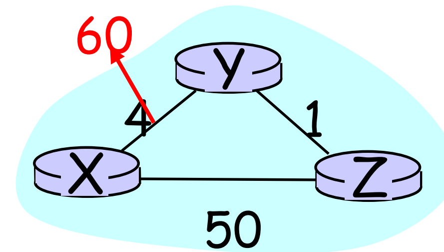
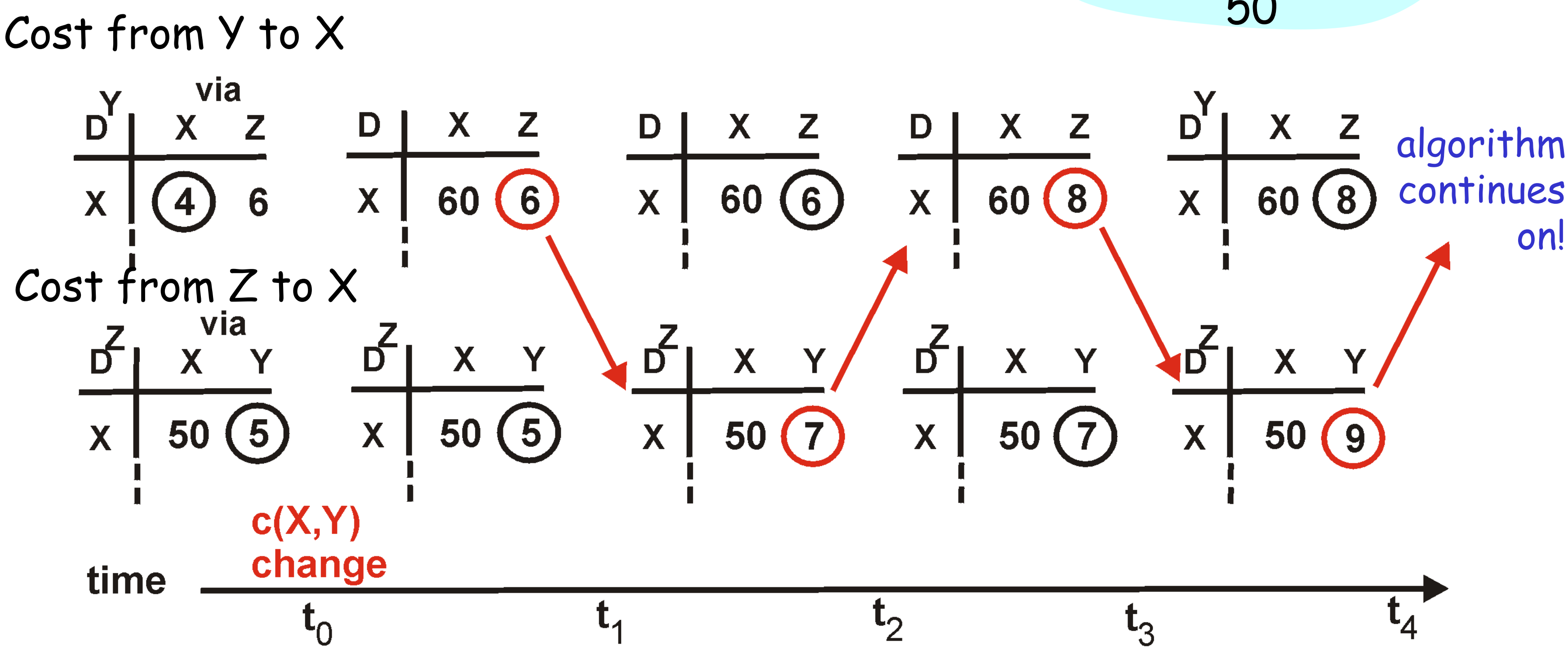
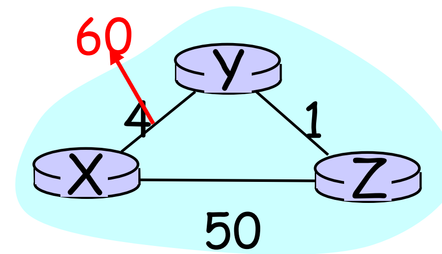


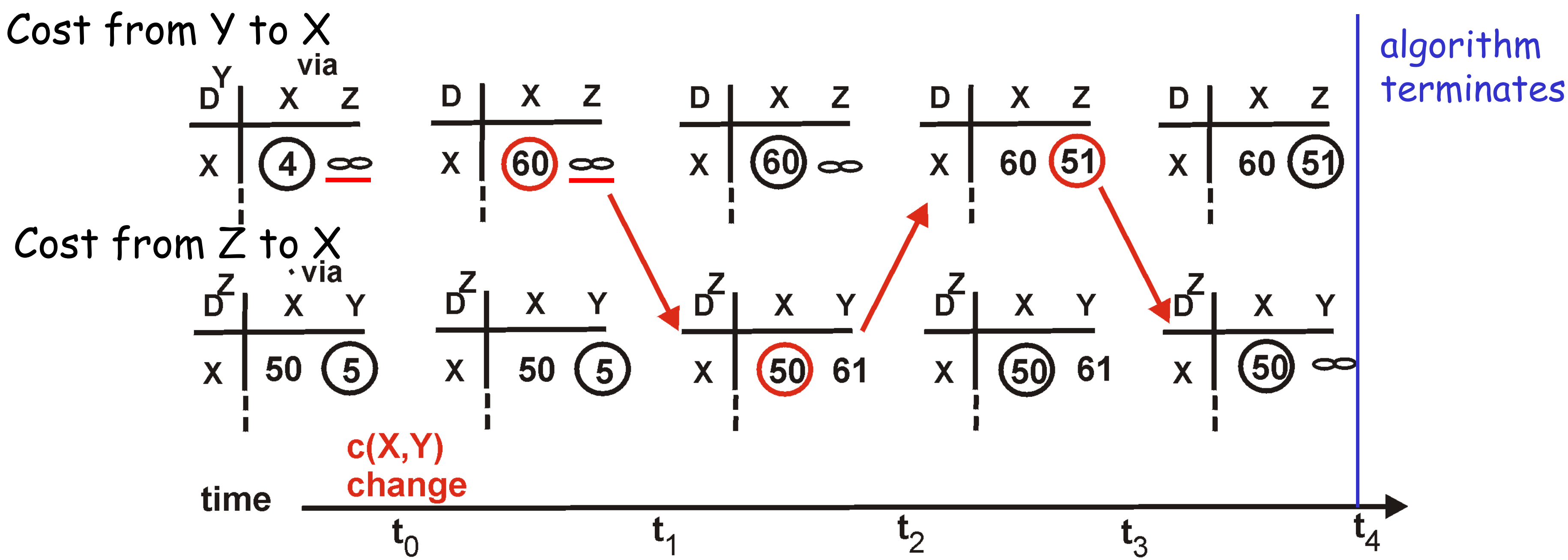


Distance Vector poisoned reverse

If Z routes through Y to get to X (Z->Y->X):

- Z tells Y its (Z's) distance to X is infinite (so Y won't route to X via Z) -> reserved route is prevented, i.e., Y->Z->Y->X (loop)!





D^Y	X (via X)	Z (via Z)
t_0: X	4	∞
t_1: X	60	∞
t_2: X	60	∞
t_3: X	60	51
t_4: X	60	51

D^Z	X (via X)	Y (via Y)
t_0: X	50	5
t_1: X	50	5
t_2: X	50	61
t_3: X	50	61
t_4: X	50	∞

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

Hierarchical Routing

Our routing study thus far - idealization

- all routers identical
- network "flat"

… *not* true in practice

scale: with 200 million destinations:

- can't store all dest's in routing tables!
- routing table exchange would swamp links!

administrative autonomy

- internet = network of networks
- each network admin may want to control routing in its own network

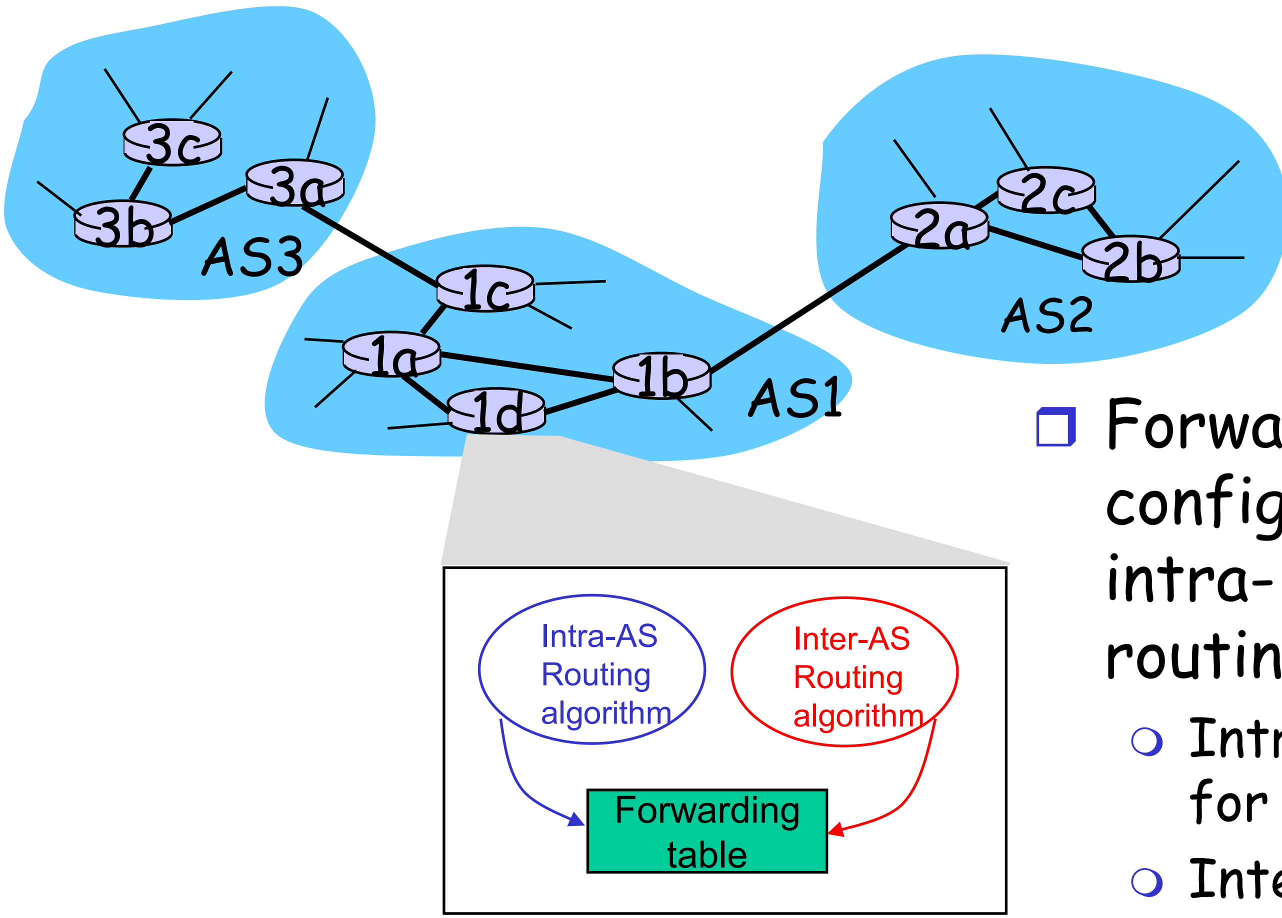
Hierarchical Routing

- aggregate routers into regions, "autonomous systems" (AS)
- routers in same AS run same routing protocol
  - "intra-AS" routing protocol
  - routers in different AS can run different intra-AS routing protocol

Gateway router

- Direct link to router in another AS

Interconnected ASes



- Forwarding table is configured by both intra- and inter-AS routing algorithm
  - Intra-AS sets entries for internal dests
  - Inter-AS & Intra-As sets entries for external dests

Inter-AS tasks

- Suppose router in AS1 receives datagram for which dest is outside of AS1
  - Router should forward packet towards on of the gateway routers, but which one?

AS1 needs:

1. to learn which dests are reachable through AS2 and which through AS3
2. to propagate this reachability info to all routers in AS1

Job of inter-AS routing!