Chapter 4: outline

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

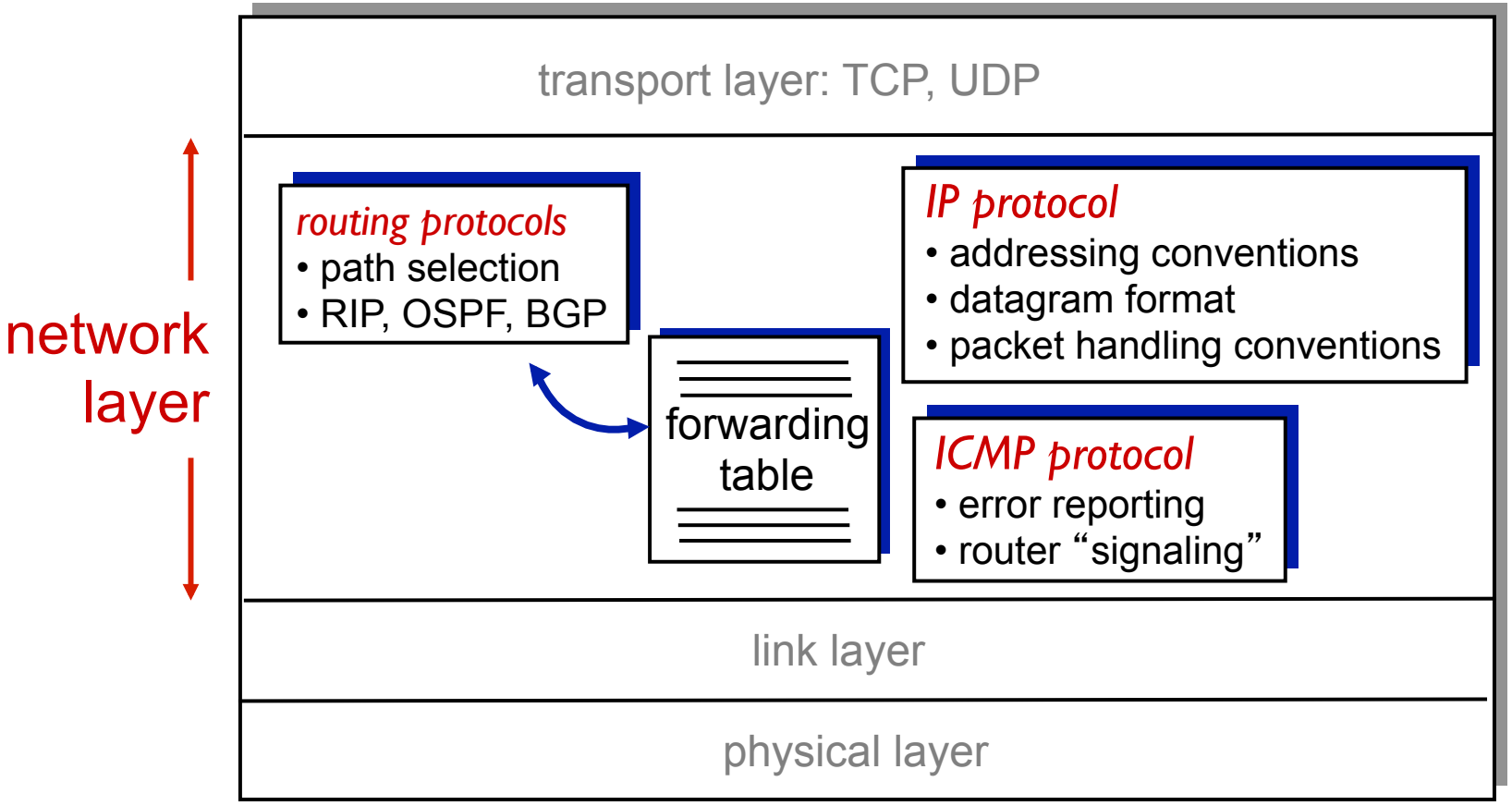
4.6 routing in the Internet

- RIP
- OSPF
- BGP

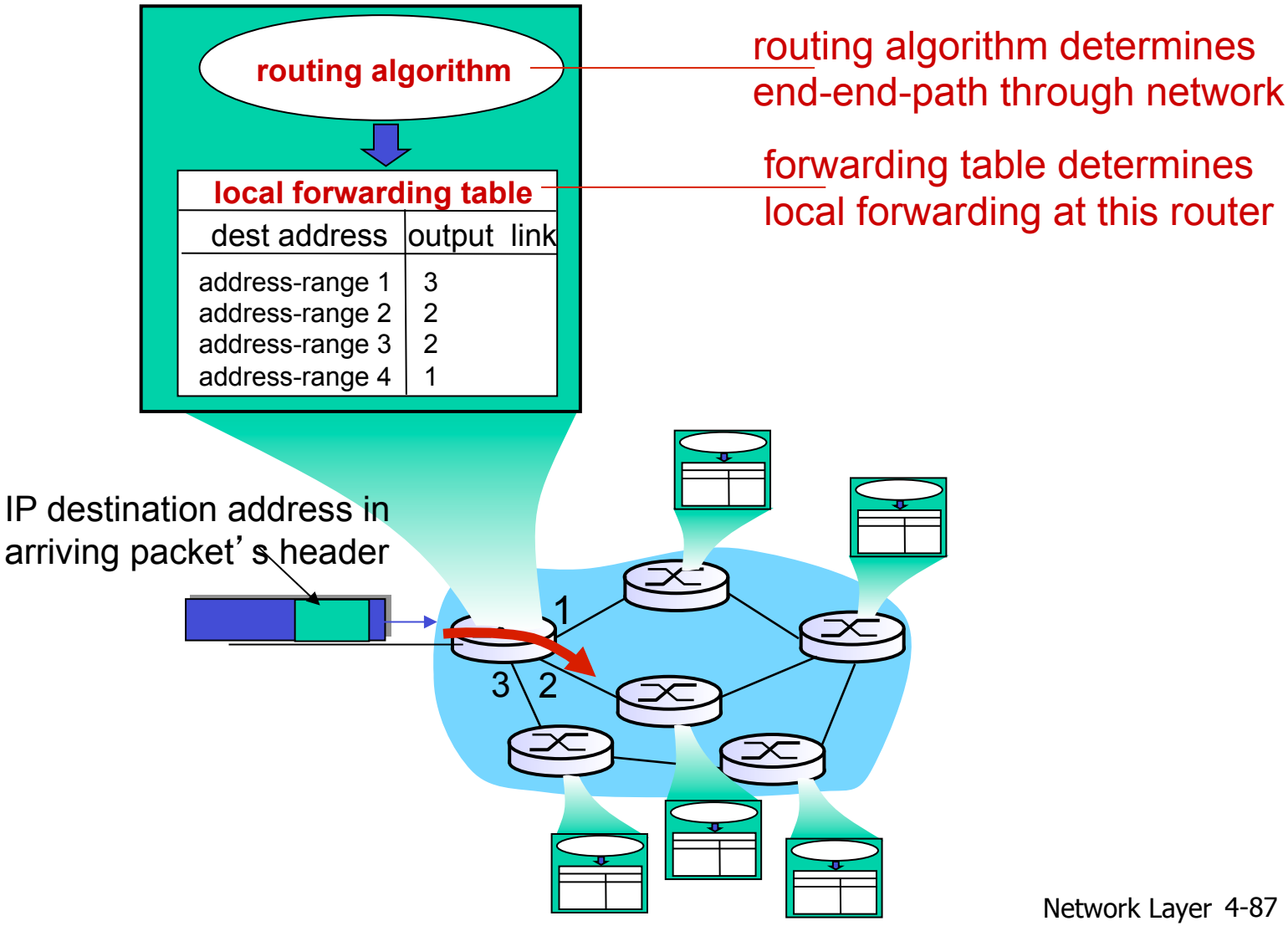
4.7 broadcast and multicast routing

The Internet network layer

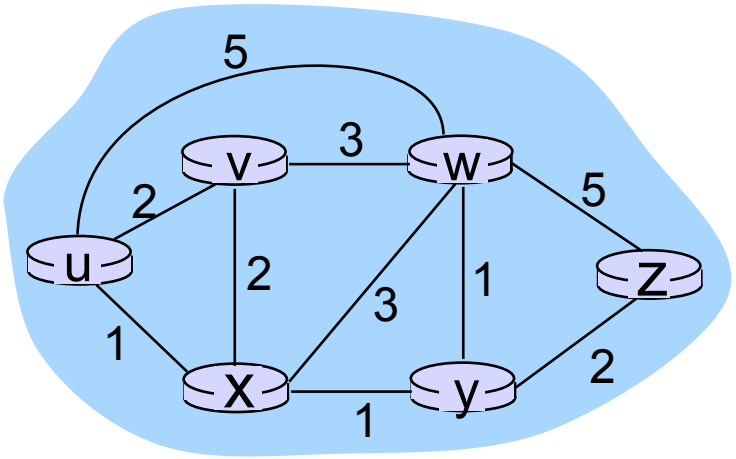
host, router network layer functions:



Interplay between routing, forwarding



Graph abstraction



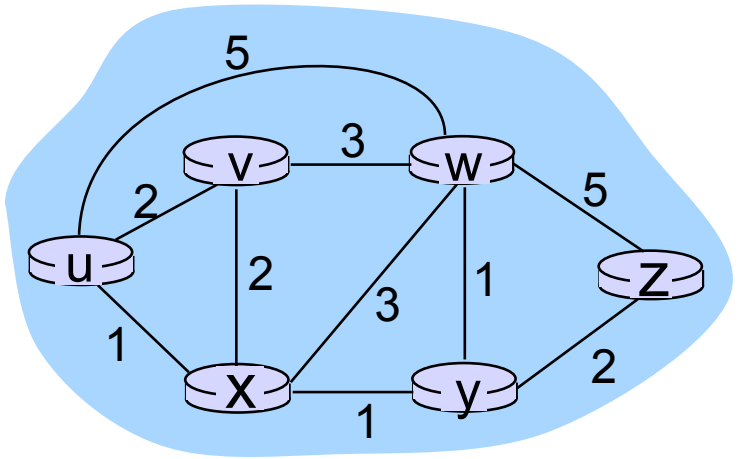
graph: G = (N,E)

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) }

aside: graph abstraction is useful in other network contexts, e.g., 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 $(x_1, x_2, x_3, \ldots, x_p) = c(x_1,x_2) + c(x_2,x_3) + \ldots + c(x_{p-1},x_p)$

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

Routing algorithm classifications

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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Detour:

See Supplemental Materials
on Dijkstra Algorithm

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 destinations

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
- S: set of nodes whose least cost path definitively known

Dijsktra's Algorithm

```
1  Initialization:
2    S = {u}
3    for all nodes v
4      if v adjacent to u
5          Then d(v) = c(u,v)
6      Else d(v) = ∞
7
8  Loop
9     find w not in S such that d(w) is a minimum
10     add w to S
11     Update d(v) for all v adjacent to w and not in S :
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 S
```

Dijkstra's algorithm: example

Step	S	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					

```
8  Loop
9   find w not in S such that d(w) is a minimum
10   add w to S
11   Update d(v) for all v adjacent to w and not in S :
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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 S
```
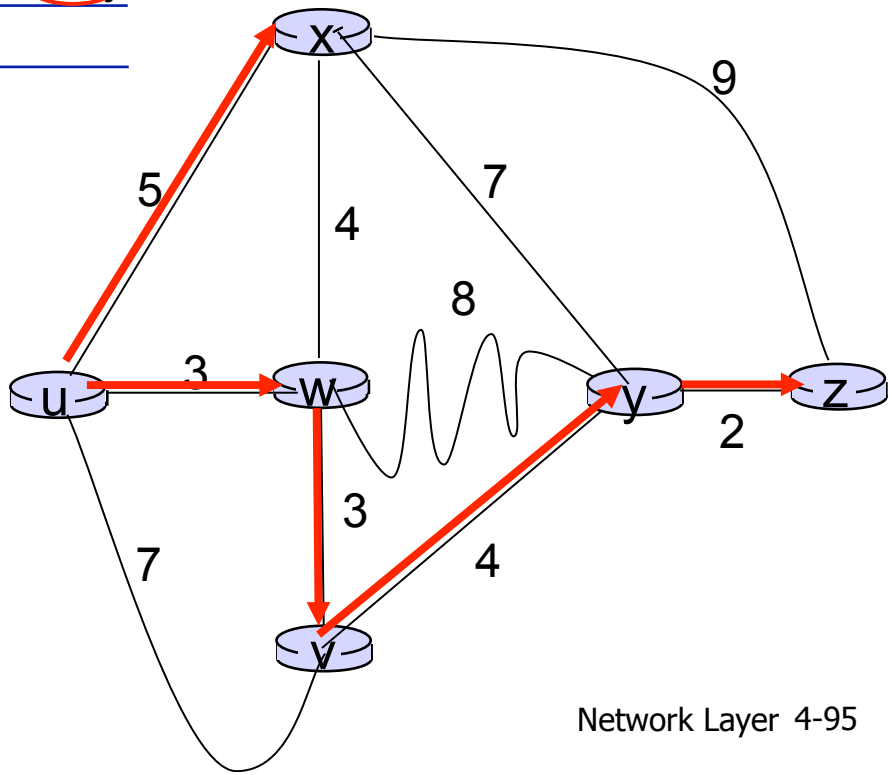
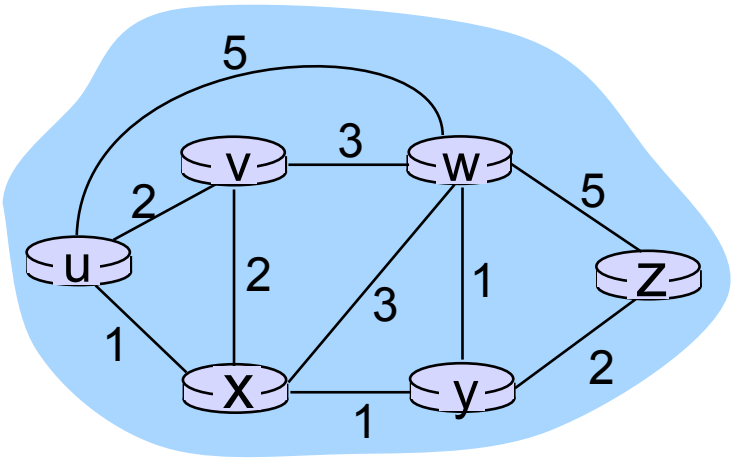

notes:

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



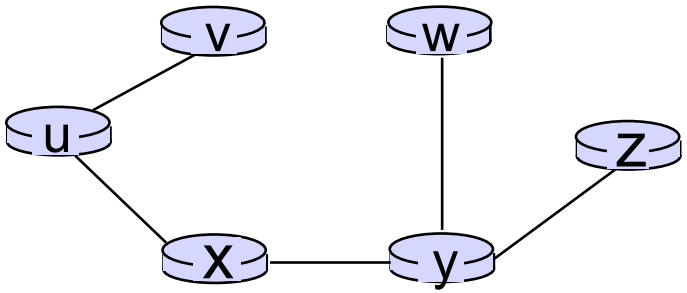
Dijkstra's algorithm: another example

Step	S	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:



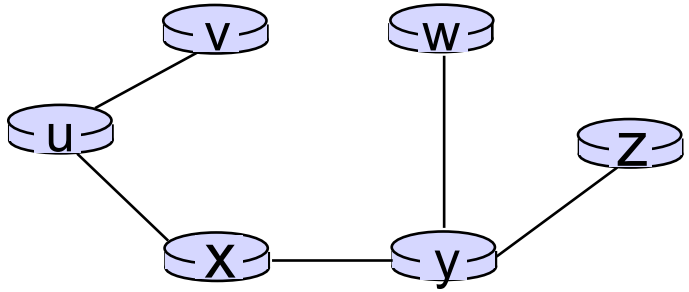
resulting forwarding table in u:

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

Dijkstra's algorithm "reversed":

compute distances from all nodes to a destination

Resulting shortest-path tree to u:



More natural for forwarding Tables (to destination u):

from node	next hop	distance
v	u	2
x	u	1
y	x	2
w	y	3
z	y	4

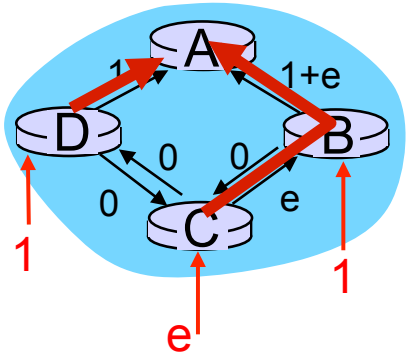
Dijkstra's algorithm, discussion

algorithm complexity: n nodes

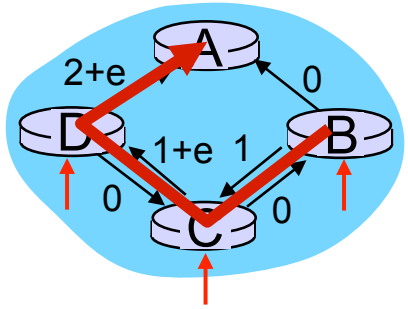
- each iteration: need to check all nodes, w, not in S
- n(n+1)/2 comparisons: $O(n^2)$
- more efficient implementations possible: O(mlogn)

oscillations possible:

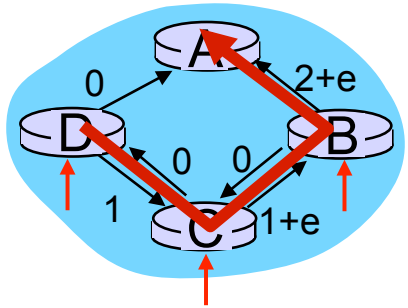
- e.g., suppose link cost = amount of carried traffic:



initially



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



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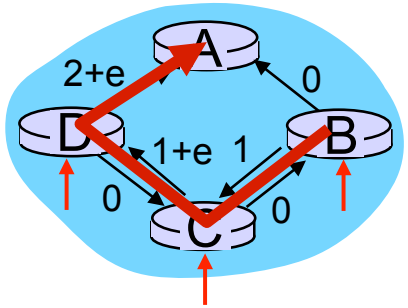

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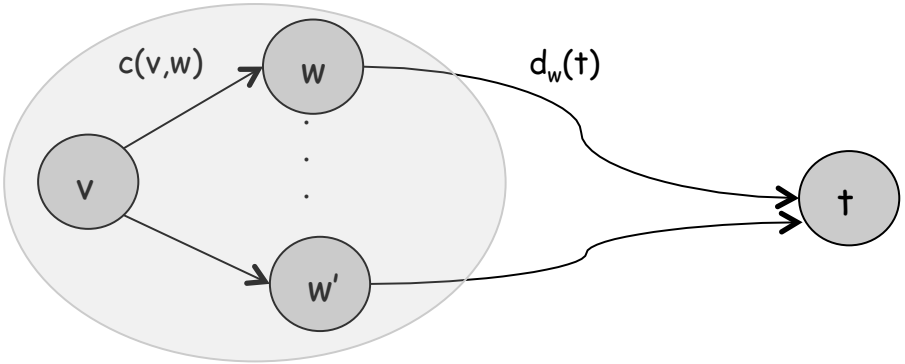
Bellman-Ford Algorithm (Dynamic Programming)



Let $d_v(t)$:= cost of shortest path from v to t

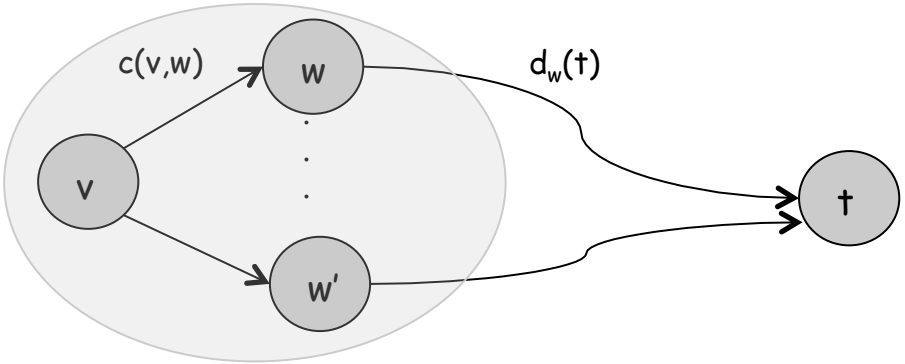
Then $d_v(t) = \min_w \{c(v,w) + d_w(t)\}$

cost from neighbor w to destination t

cost from v to neighbor w

min taken over all neighbors w of v

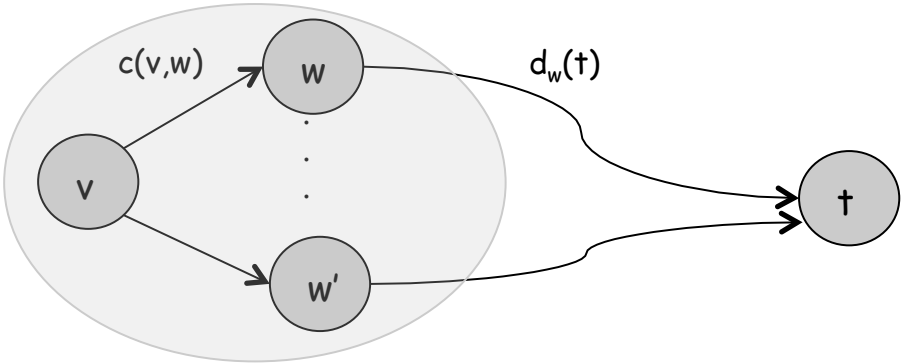
Node v's operation



- v's local view
  - v knows the costs c(v,w) to all his neighbors w
  - v exchanges updates with this neighbors about their $d_w(t)$ (and his $d_v(t)$)
- v locally computes:
  - $d_v(t) = \min_w \{c(v,w) + d_w(t)\}$
- Asynchronous and distributed operation

- v's forwarding table entry
  - $(t, d_v(t), w^*)$
  - $d_v(t)$: length of shortest path from v to t.
  - w^*: the next hop after v, on the shortest path to t

Single destination "t" can be implicit



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Then $d_v(t) = \min_w \{c(v,w) + d_w(t)\}$

cost from neighbor w to destination t

cost from v to neighbor w

min taken over all neighbors w of v

Shortest path from v ~~to t~~

- Each node v maintains local information
- 1- d(v): length of shortest path from v to t.
- 2- w: the next hop after v, on the shortest path to t.

- Each node makes local decisions

$$d(v) = \min_{w:(v,w)\in E} \{ d(w) + c_{vw} \}$$

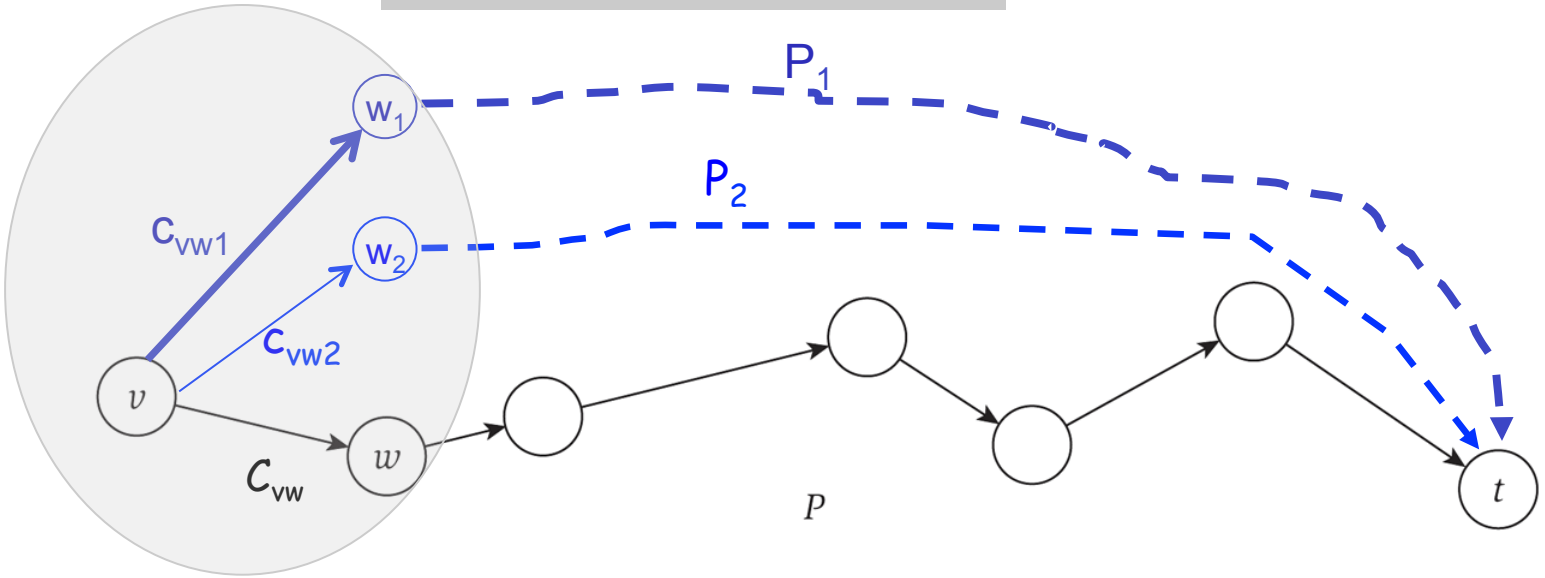
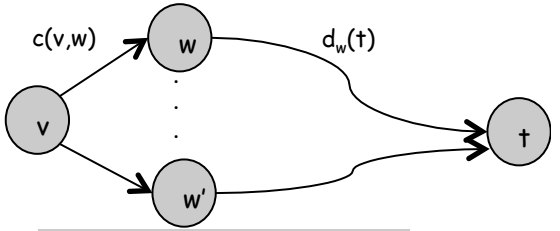


Figure 6.22 The minimum-cost path P from v to t using at most i edges.

Implementation 1 : Synchronous, Pull-based



$$d(v) = \min_{w:(v,w)\in E} \{ d(w) + c_{vw} \}$$

Def: d(i, v) = length of shortest v-t path P using at most i edges.

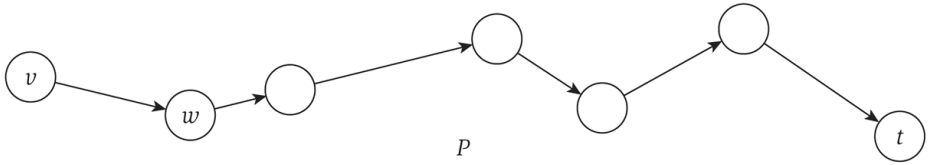


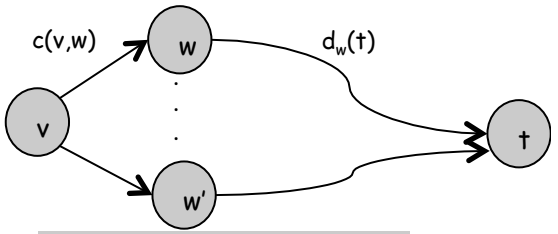
Figure 6.22 The minimum-cost path P from v to t using at most i edges.

```
Shortest-Path(G, t) {
   foreach node v ∈ V
      d[0, v] ← ∞
   d[0, t] ← 0

   for i = 1 to n-1
      foreach node v ∈ V (in any order)
         d[i, v] ← d[i-1, v]
      foreach edge (v, w) ∈ E
         d[i, v] ← min {d[i, v], d[i-1, w] + c_vw }
}
```

Implementation 2: Synchronous, Push-based

Rule: time is slotted, nodes exchange d with neighbors




```
Push-Based-Shortest-Path(G, s, t) {
   foreach node v ∈ V {
      d[v] ← ∞
      successor[v] ← ϕ
   }

   d[t] = 0
   for i= 1 to n-1 {
      foreach node w ∈ V {
      if (d[w] has been updated in previous iteration) {
         foreach node v such that (v, w) ∈ E {
            if (d[v] > d[w] + c_vw) {
               d[v] ← d[w] + c_vw
               successor[v] ← w
            }
         }
      }
      If no d[w] value changed in iteration i, stop.
   }
}
```

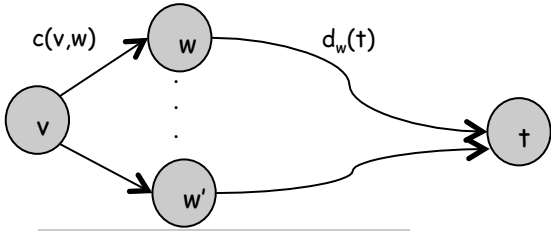
Rounds: synchronous implementation

w pushes updates (instead of v pulling)

Local +distributed update

can stop in <n-1 rounds

Implementation 3: Distributed, Asynchronous, Push-based



$$d(v) = \min_{w:(v,w)\in E} \{ d(w) + c_{vw} \}$$

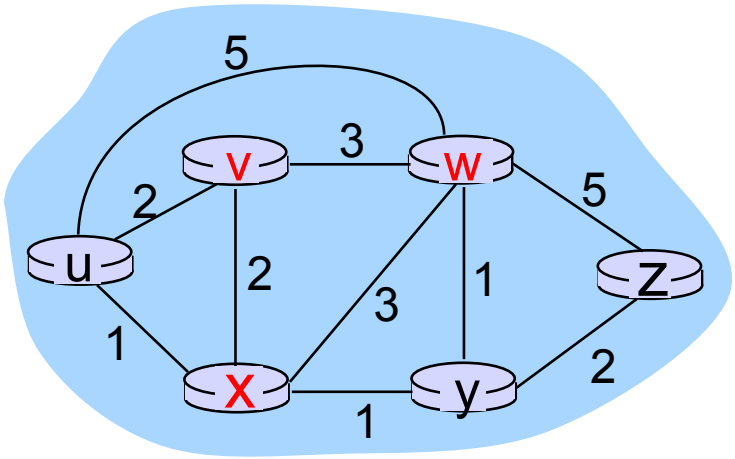
Rule: Every time a node w updates its d[w], it becomes "active" and notifies all its upstream neighbors:

```
Asynchronous-Shortest-Path(G, s, t) {
    foreach node v ∈ V {
        d[v] ← ∞; successor[v] ← ϕ; Active[v]=FALSE;
    }
    d[t]=0; successor[v]=t; Active[t]=TRUE;

    while for there exists an active node{
        choose active node w \* in any order *\
        foreach node v such that (v, w) ∈ E \*in any order*\{
              if (d[v] > d[w] + c_vw) {
                 d[v] ← d[w] + c_vw;
                 successor[v] ← w;
                   active[v]=TRUE;
              }
        }
        w becomes inactive
     }
}
```

Proof: One can prove [omitted] that the algorithm converges to the correct values of shortest paths, under mild assumptions.

Bellman-Ford example

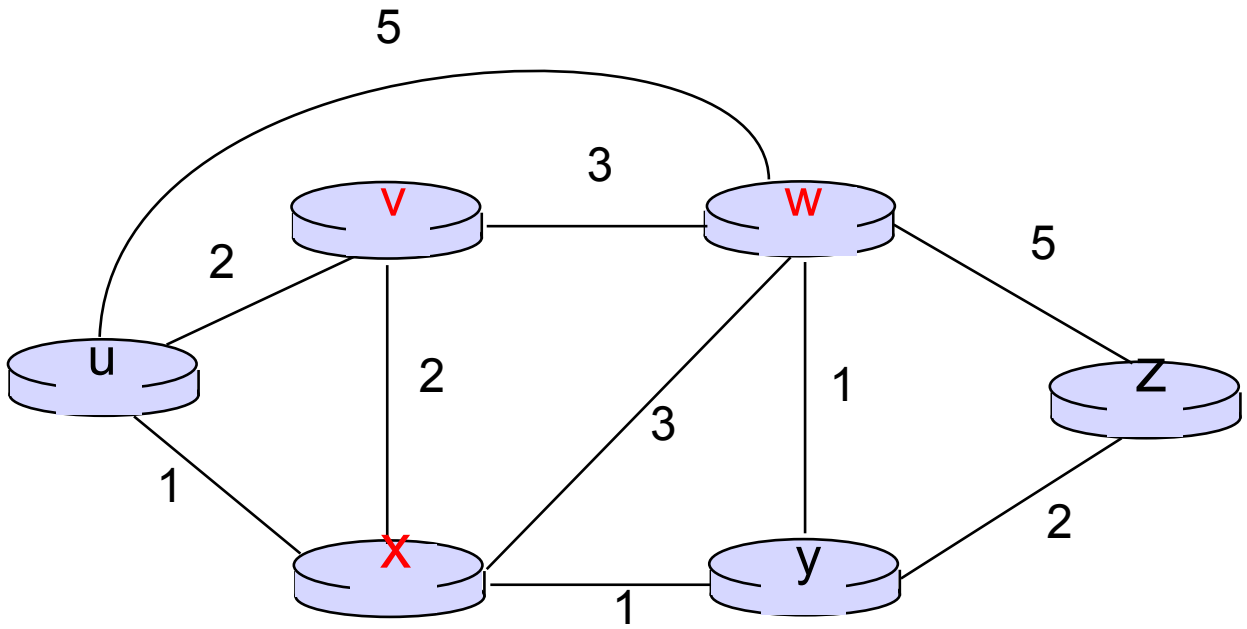


clearly, $d_v(z) = 5$, $d_x(z) = 3$, $d_w(z) = 3$

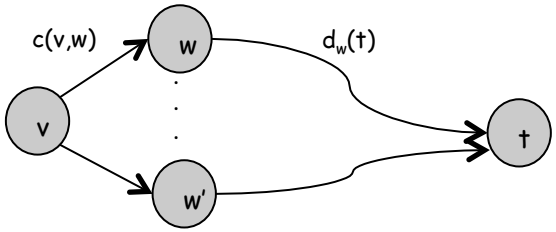
B-F equation says:

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

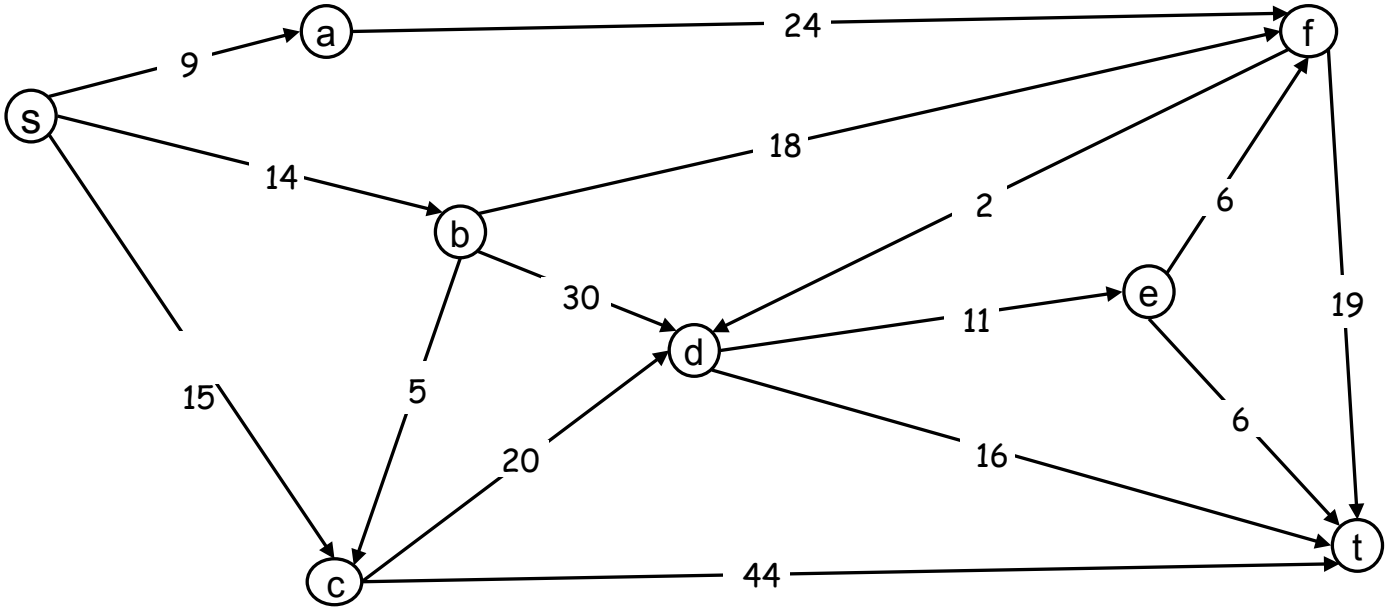
node achieving minimum is next hop in shortest path, used in forwarding table


5
3
v
w
2
5
u
2
1
z
3
1
2
x
y
1

Example
on the board



$$d(v) = \min_{w:(v,w)\in E} \{ d(w) + c_{vw} \}$$



Distance vector

- $D_v(t)$ = estimate of least cost from v to t
  - v maintains distance **vector** $\mathbf{d}_v = [d_v(t): t \in N]$ to all possible destinations $t \in N$.

- Node v:
  - knows cost to each neighbor w: c(v,w)
  - routing table maintains entries $(t, d_v(t), w^*)$, where:
    - t is any possible destination $t \in N$
    - the distance from v to t is $d_v(t)$
    - the next hop on the shortest path from v towards t is w^*
  - performs n separate computations, one for each potential destination

Distance vector algorithm

key idea:

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

$$D_v(t) \leftarrow min_w\{c(v,t) + d_w(t)\} \quad \text{for each node } t \in N$$

- under minor, natural conditions, the estimate $d_v(t)$ *converge to the actual least cost* $d_v(t)$

Distance vector algorithm

iterative, synchronous:

each node:

In each iteration

Exchange DV with all neighbors

Recompute estimates to all destinations

Until the estimate does not change

Example of Synchronous Execution: **distance to x**

node x table

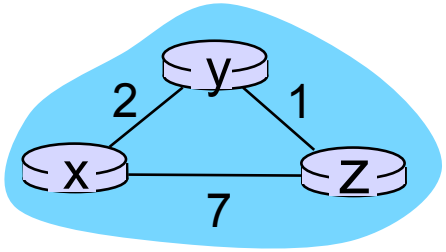
from \ cost to	x
x	0

node y table

from \ cost to	x
y	2

node z table

from \ cost to	x
z	7



time

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from \ cost to	x
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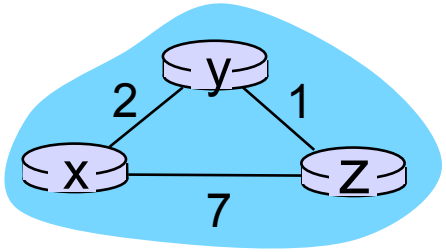
node z table

from \ cost to	x
z	7



time

Example of Synchronous Execution: **distance to x**

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

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

node x table

from	cost to x
x	0

from	cost to x
x	0

node y table

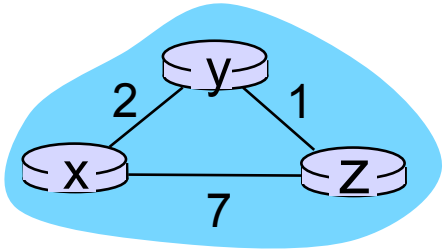
from	cost to x
y	2

from	cost to x
y	2

node z table

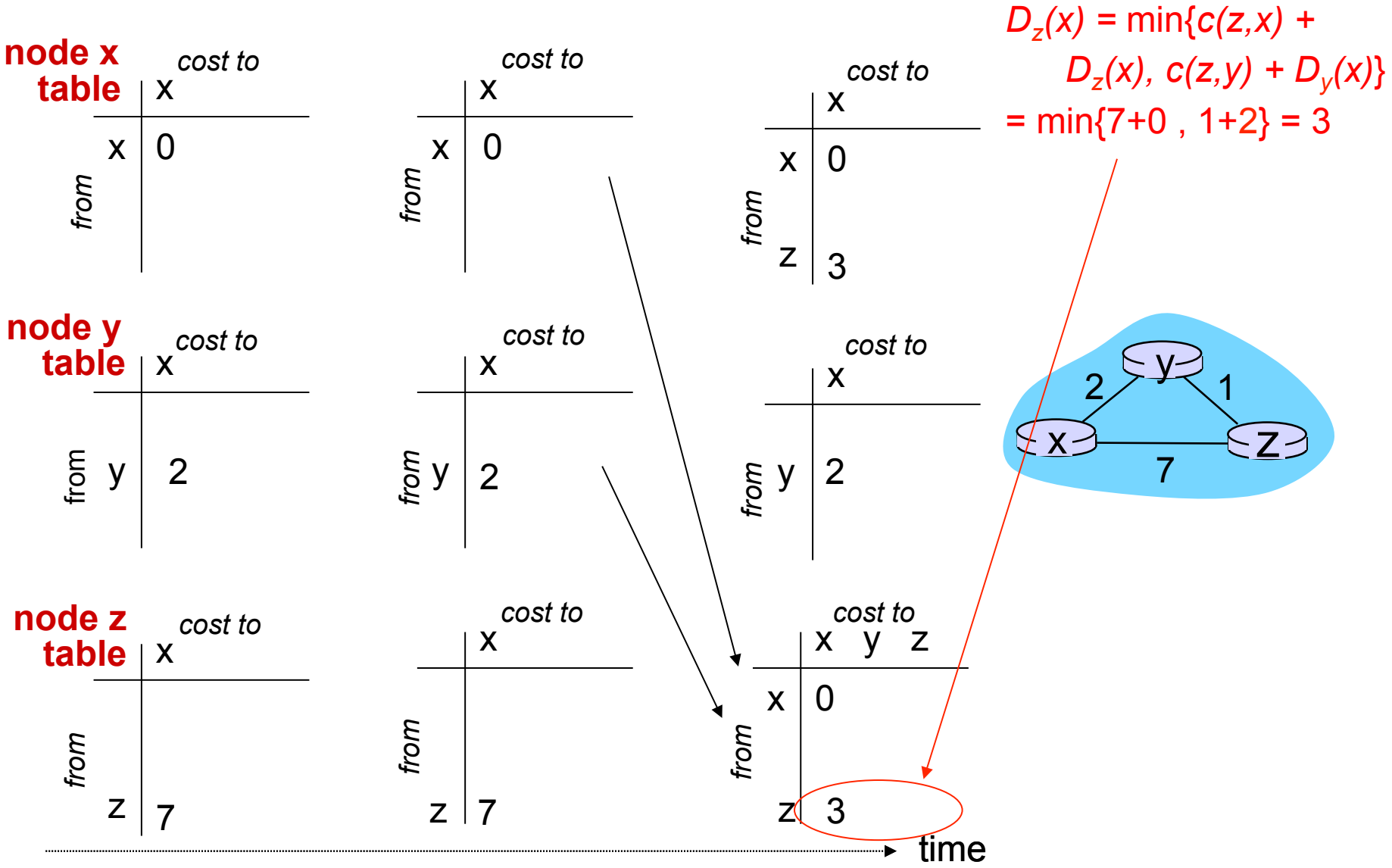
from	cost to x
z	7

from	cost to x
z	7



time

Example of Synchronous Execution: **distance to x**



Example of Synchronous Execution: **all dest**

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

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

node x table

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

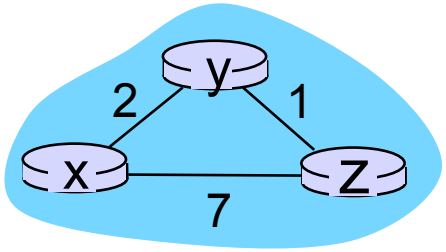
from	cost to x	cost to y	cost to z
x	0	2	3
y	2	0	1
z	7	1	0

node y table

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

node z table

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



time

Example of Synchronous Execution: **all dest**

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

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

node x table

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

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

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

node y table

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

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

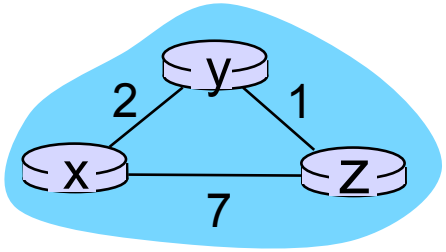
from	cost to x	cost to y	cost to z
x	0	2	3
y	2	0	1
z	3	1	0

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

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



time

Distance vector algorithm

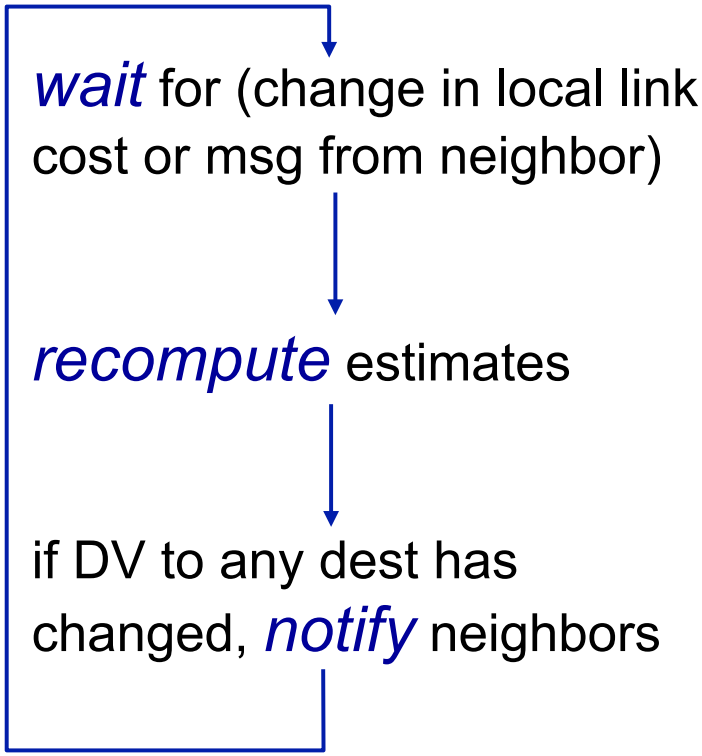
iterative, asynchronous:
each local iteration caused by:

- local link cost change
- DV update message from neighbor

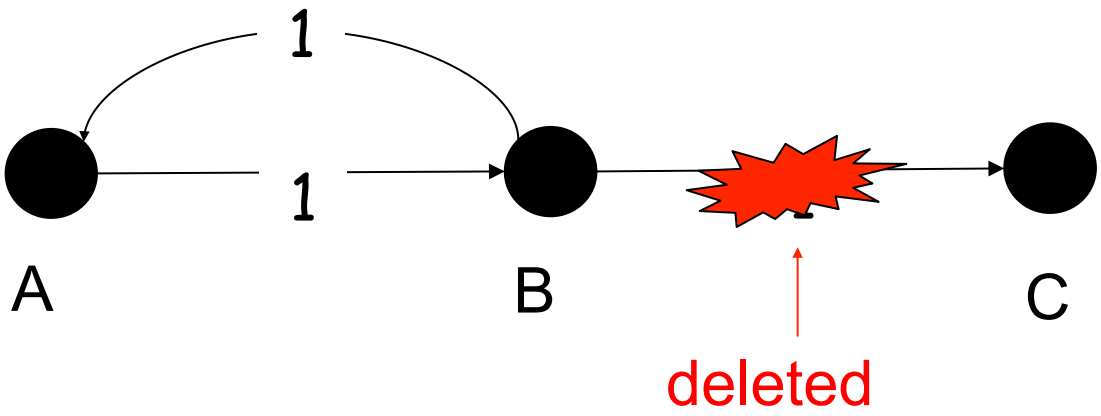
distributed:

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

each node:



"Counting to Infinity" Example



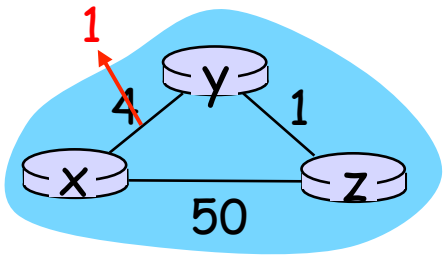
- Originally:
  - B to C: via C, cost 1,
  - A to C: via B, cost 2
- After link failure:
  - B to C: via A, cost 3
  - A to C: via B, cost 4
  - B to C: via A, cost 5
  - A to C: via B, cost 6,
  - ++

- Fixes: (1) max hop count (2) poisonous reverse (3) keep path state.

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.

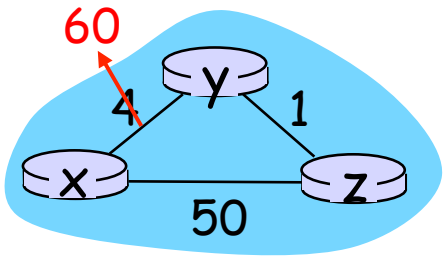
t_1 : *z* receives update from *y*, updates its table, computes new least cost to *x* , sends its neighbors its DV.

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:

- node detects local link cost change
- *bad news travels slow* - "count to infinity" problem!
- 44 iterations before convergence
  - y to x: 4 via x
  - z to x: 5 via y
  - change of c(x,y): 4→60
  - y to x: 6 via z
  - z to x: 7 via y
  - …
  - Counting to 50



Solutions:

- *Poisoned Reverse:* if Z routes through Y to get to X, then Z advertises to Y that 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?
  - No, if loops involve more than 2 nodes.
- Other fixes: (1) max hop count (2) keep path state.

Comparison of LS and DV algorithms

- ***In LS:*** each node broadcasts to all other nodes information about its neighborhood (neighbors+link costs)
- ***In DV:*** each node talks only to its neighbors and tells them its estimates of path costs to all other destinations

message complexity

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

speed of convergence

- ***LS:***
  - Naïve: $O(n^2)$
  - Efficient implementation: O(nlogE)
  - may have oscillations
- ***DV:*** convergence time varies
  - Efficient implementation: O(mn) time, O(m+n) memory
  - may be routing loops
  - count-to-infinity problem

robustness: what happens if router malfunctions?

LS:

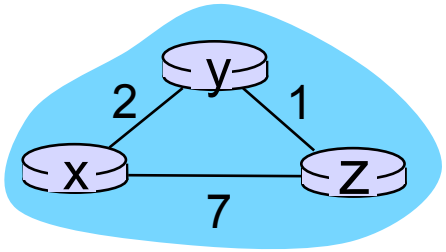
- node can advertise incorrect *link* cost
- each node computes only its *own* table

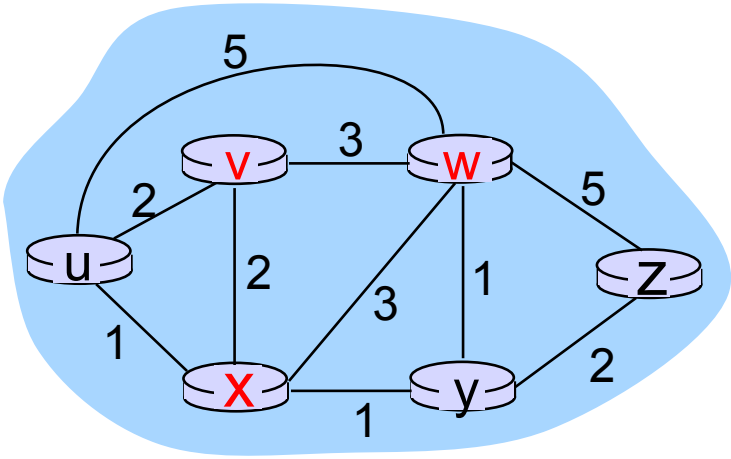
DV:

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

Examples of asynchronous execution

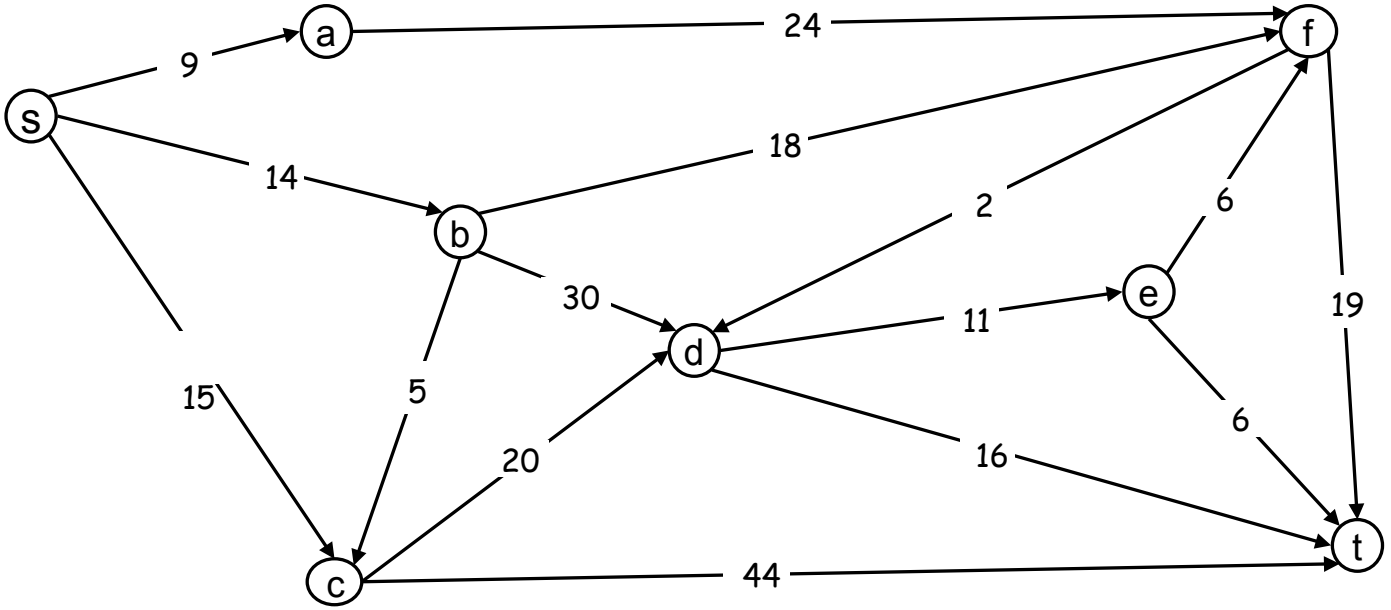
(on the board)





Example for your own practice/discussion

- Find shortest paths from s to all other nodes, using Dijkstra
- Find shortest paths from all nodes to T, using Bellman-Ford
  - asynchronous execution
  - consider that a link fails or changes cost. What happens?
- Also interactive exercises



Chapter 4: outline

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

Hierarchical routing

our routing study thus far - idealization

- all routers identical
- network "flat"

… *not* true in practice

scale: with 600 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

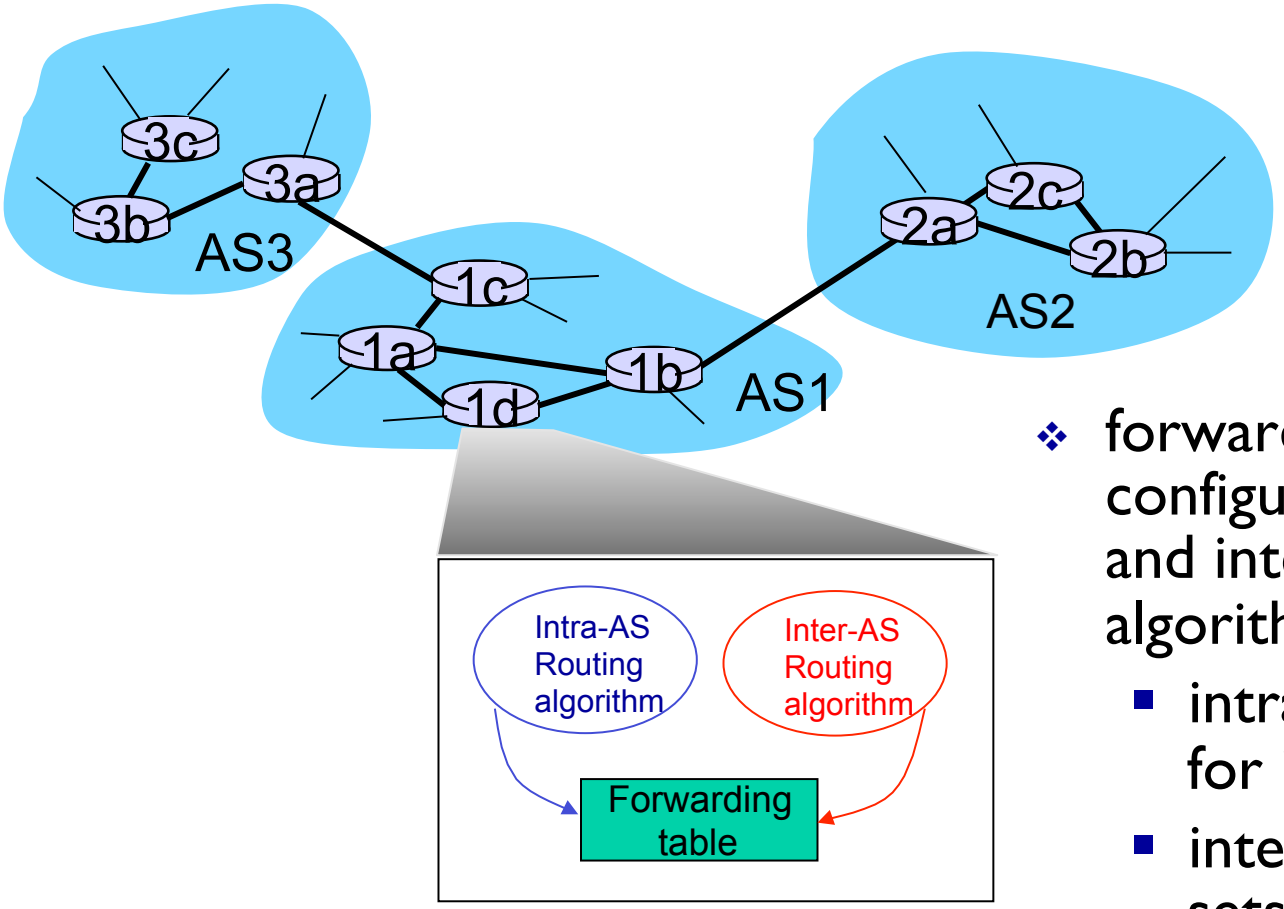
Hierarchical routing

- 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:

- at "edge" of its own AS
- has link to router in another AS

Interconnected ASes



- forwarding table 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

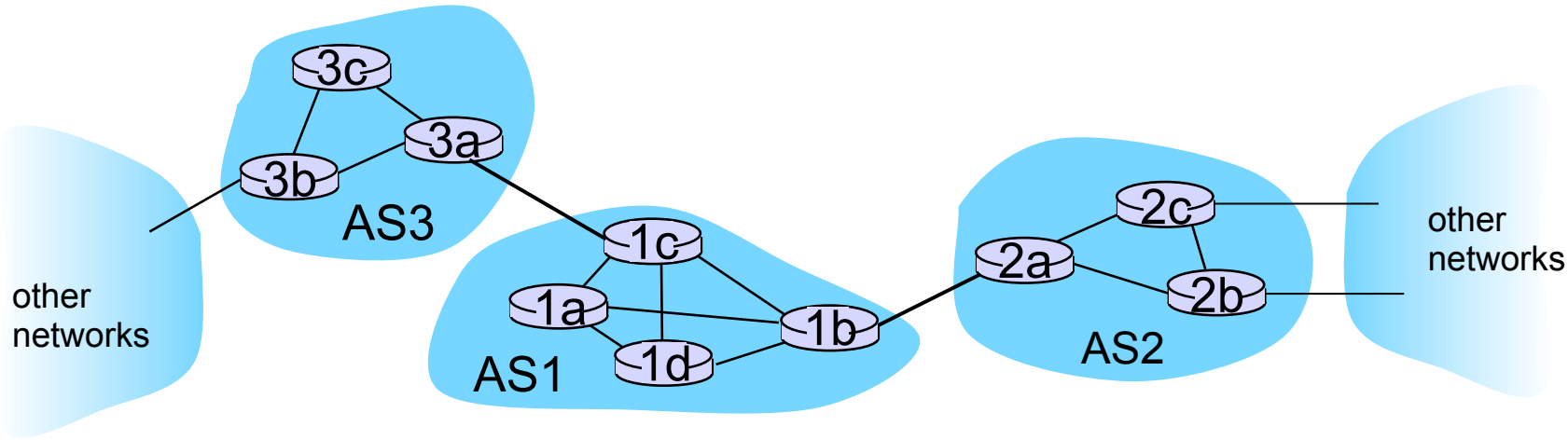
Inter-AS tasks

- suppose router in AS1 receives datagram destined outside of AS1:
  - router should forward packet to gateway router, but which one?

AS1 must:

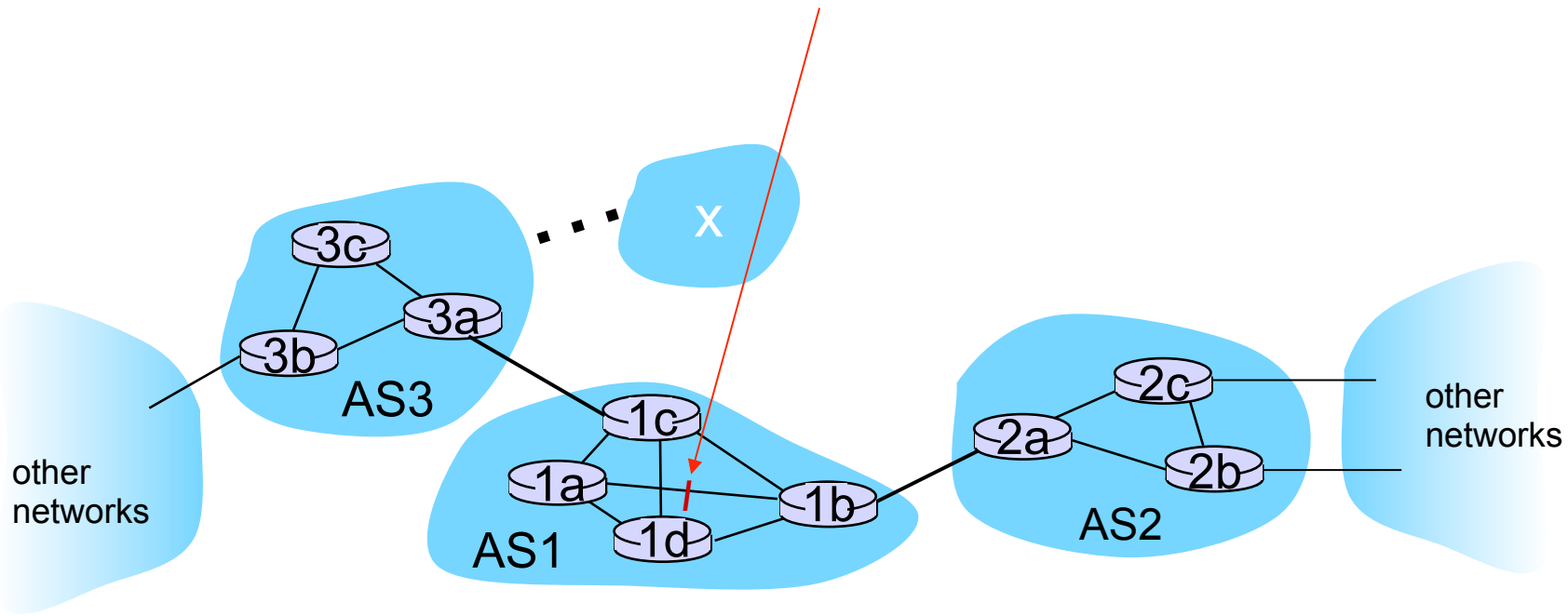
1. learn which dests are reachable through AS2, which through AS3
2. propagate this reachability info to all routers in AS1

job of inter-AS routing!



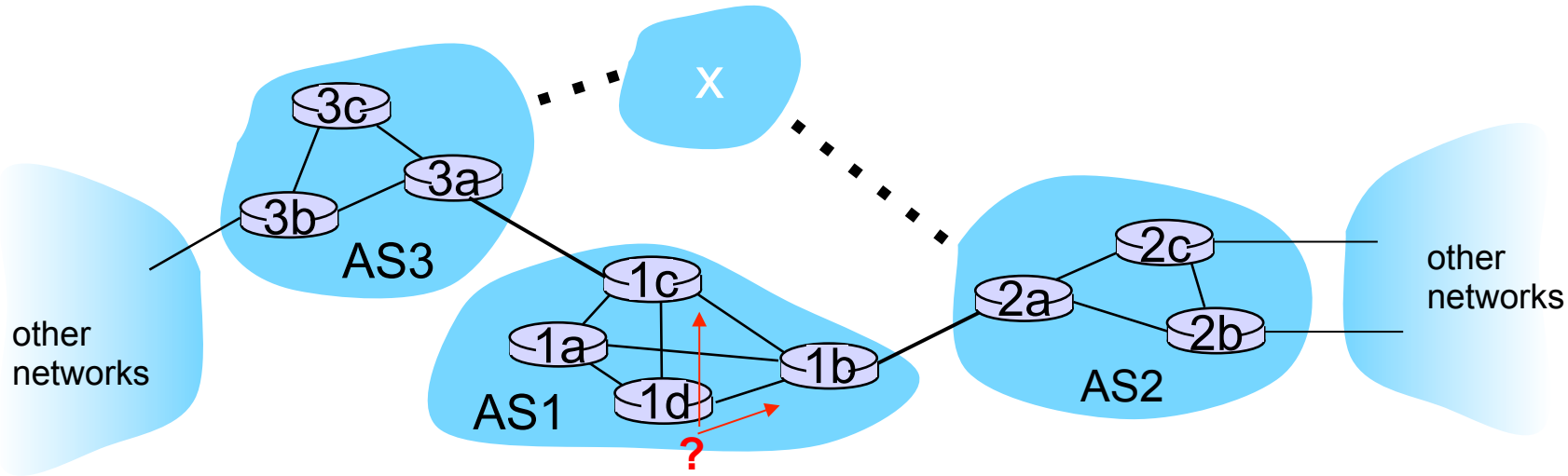
Example: setting forwarding table in router 1d

- suppose AS1 learns (via inter-AS protocol) that subnet *x* reachable via AS3 (gateway 1c), but not via AS2
  - inter-AS protocol propagates reachability info to all internal routers
- router 1d determines from intra-AS routing info that its interface *I* is on the least cost path to 1c
  - installs forwarding table entry *(x,I)*



Example: choosing among multiple ASes

- now suppose AS1 learns from inter-AS protocol that subnet *x* is reachable from AS3 *and* from AS2.
- to configure forwarding table, router 1d must determine which gateway it should forward packets towards for dest x
  - this is also job of inter-AS routing protocol!
- *hot potato routing: send* packet towards closest of two routers.



Summary: routing outside the AS