CSCE 463/612
Networks and Distributed Processing
Spring 2024

Network Layer V

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April 17, 2024

Chapter 4: Roadmap

4.1 Introduction

4.2 Virtual circuit and datagram networks

4.3 What's inside a router

4.4 IP: Internet Protocol

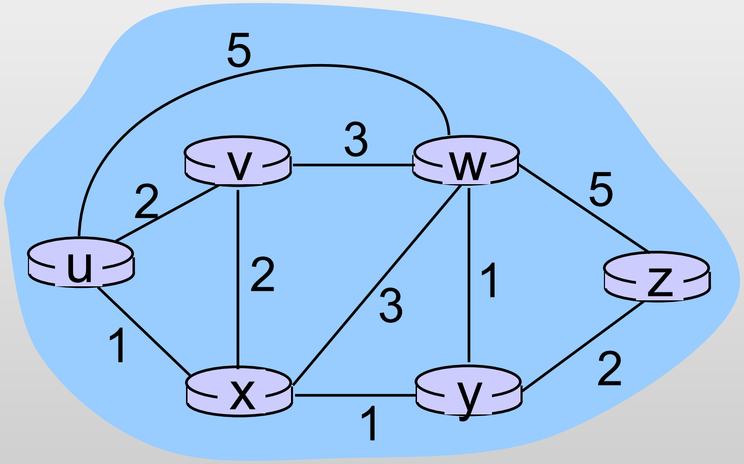
4.5 Routing algorithms

- Link state
- Distance Vector
- Hierarchical routing

4.6 Routing in the Internet

4.7 Broadcast and multicast routing

Graph Abstraction

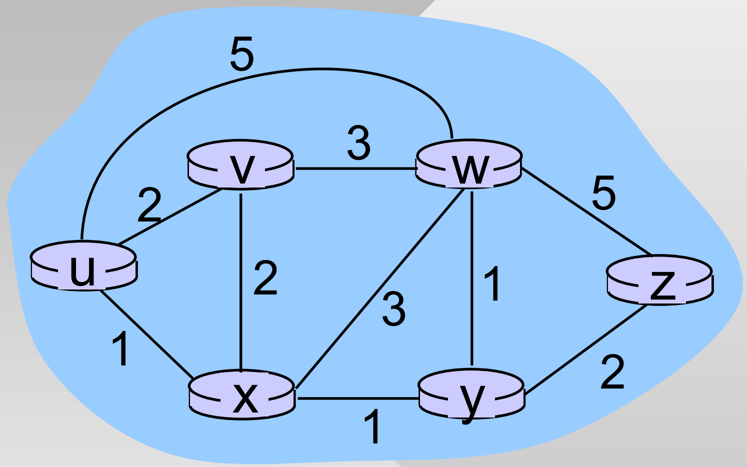


Graph: $G = (V, E)$

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

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

Graph Abstraction: Costs



- $c(x,y)$ = cost of link (x,y)
  - E.g., $c(w,z) = 5$
- Cost options:
  - Could always be 1
  - Could be inversely related to bandwidth or be proportional to congestion
  - Physical distance/delay

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

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

Routing algorithms find least-cost paths

Routing Algorithm Classification

Global or local information?

- Global:
  - Routers have complete topology, link cost info
  - "Link state" algorithms
- Local (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:
  - Useful when routes change slowly over time
  - Manual or DHCP-based route creation
- Dynamic:
  - Routes change more quickly
  - Periodic update in response to link cost changes

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Simple Link-State Routing Algorithm

Dijkstra's algorithm

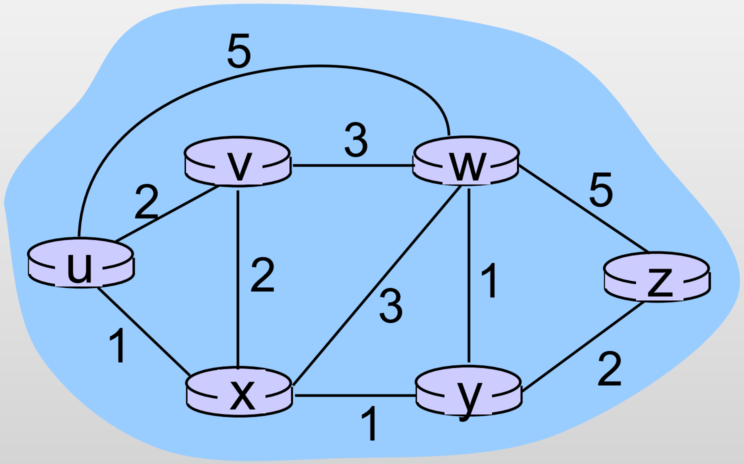
- Entire network topology and link costs known
  - Accomplished via "link state broadcast"
  - Eventually, all nodes have same info
- Computes least cost paths from one node ("source") to all other nodes
  - Gives forwarding table for that node

- *Iterative*: after k iterations, know least-cost path to k closest destinations

Notation:

- $c(x,y)$: link cost from x to y
  - Cost is ∞ if not direct neighbors
- $D(v)$: current estimate of the cost from source to destination v
- $p(v)$: predecessor of v along the least-cost path back to source
- F : set of closest nodes whose least-cost path has been finalized (i.e., known for a fact)

Dijsktra's Algorithm



Initialization:

$F = \{u\}$, $D(u) = 0$

for all nodes $v \neq u$

  if v is adjacent to u

    $D(v) = c(u,v)$

  else

    $D(v) = \infty$

do {

  find node i not in F such that $D(i)$ is minimum

  add i to F

  for all j adjacent to i and not in F:

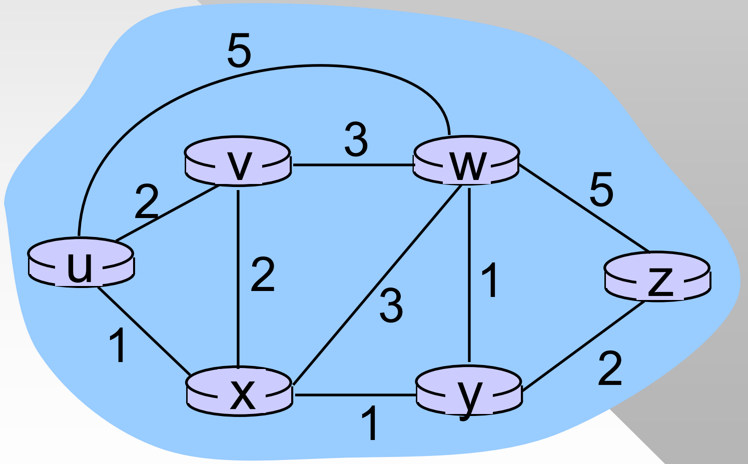
    $D(j) = \min(D(j), D(i) + c(i,j))$

    /* new cost to j is either old cost to j or known shortest path cost to i plus cost from i to j */

} while (not all nodes in F)

Dijkstra's Algorithm: Example

Step	F	$D(v),p(v)$	$D(w),p(w)$	$D(x),p(x)$	$D(y),p(y)$	$D(z),p(z)$
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	$uxyvwz$					



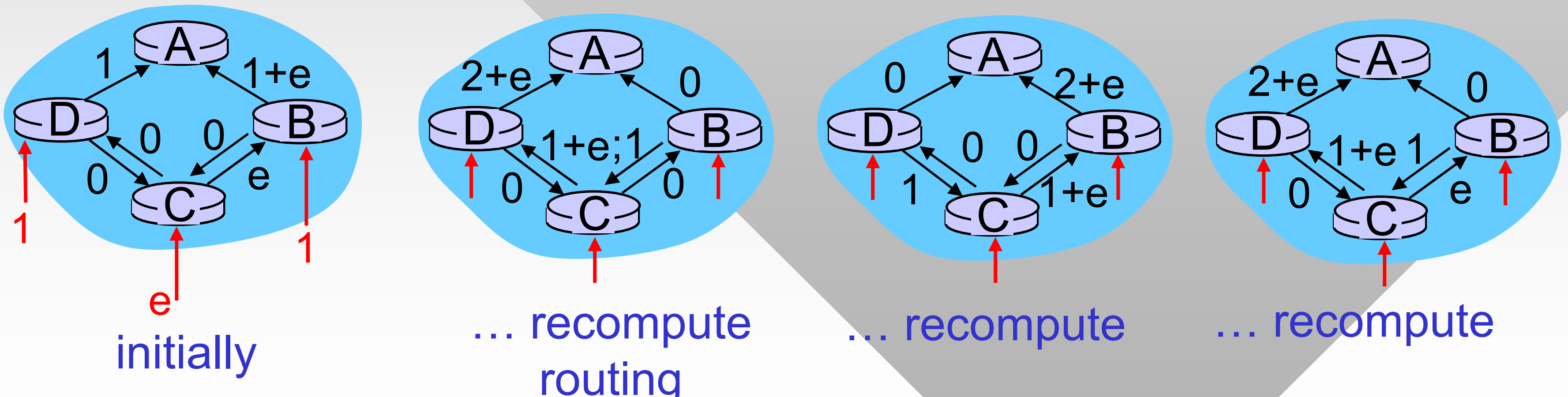
Dijkstra's Algorithm Discussion

Algorithm complexity: n nodes

- Iteration k: need to find min of $(n-k)$ costs, visit d_i neighbors
- Naïve implementation: O(|E|+|V|^2) complexity
- Heap-based implementation: O(|E|+|V|·log|V|)

Oscillations possible, but only for traffic-dependent cost:

- e.g., Link cost $=$ amount of carried traffic



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Distance Vector (DV) Algorithm

- Two metrics known to each node x
  - Estimate $D_x(y)$ of least cost from x to y
  - Link cost $c(x,v)$ to reach x's immediate neighbors
- Each node maintains a distance vector:

$$\vec{D}_x = \{D_x(y) : y \in V\}$$

- Node x periodically receives from neighbors their distance vectors
  - Thus, x has access to the following for each neighbor v

$$\vec{D}_v = \{D_v(y) : y \in V\}$$

Distance Vector (DV) Algorithm (cont'd)

Basic idea (Bellman-Ford):

- When a node x receives new DV estimate from neighbor v, it updates its own DV using the Bellman-Ford equation:

$$D_x(y) \leftarrow \min\{D_x(y),\, c(x,v) + D_v(y)\},\ \forall\ y \in V$$

- Centralized Bellman Ford requires O(|V|·|E|) time
  - Dijkstra's algorithm was O(|V|·log|V|)
  - Convergence of decentralized version depends on topology, link weights, update delays, and timing of events
- Bellman Ford advantage – no need for entire graph

Distance Vector (DV) Algorithm (cont'd)

Iterative, asynchronous

Each 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 or msg from neighbor)

recompute estimates

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

node x table

cost to

from	x	y	z
x	0	2	7
y	∞	∞	∞
z	∞	∞	∞

cost to

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

cost to

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

node y table

cost to

from	x	y	z
x	∞	∞	∞
y	2	0	1
z	∞	∞	∞

cost to

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

cost to

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

node z table

cost to

from	x	y	z
x	∞	∞	∞
y	∞	∞	∞
z	7	1	0

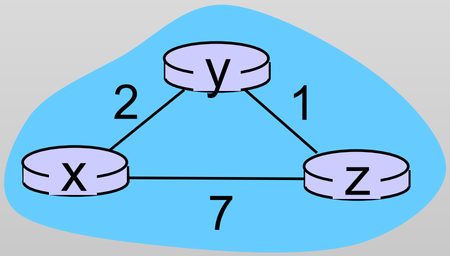
cost to

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

cost to

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

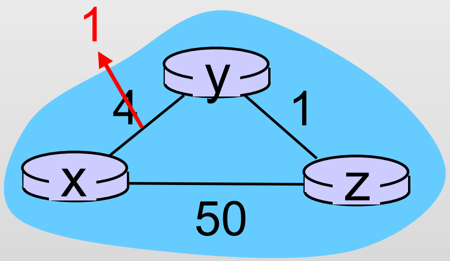
time



Distance Vector: Link Cost Changes

Link cost changes:

- Node detects local link cost change
- Recalculates distance vector, updates routing info if needed
- If DV changes, notifies neighbors



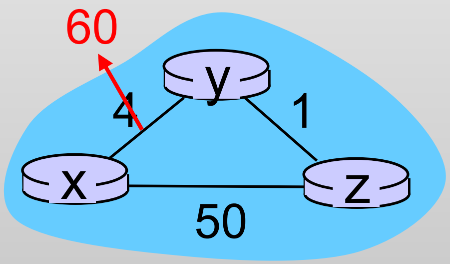
"good news travels fast"

- Node y detects link-cost change, updates its distance to x, and informs its neighbors
- Node z receives y's message and updates its table; computes a new least-cost to x and sends its DV to x and y
- Finally, node y receives z's vector and updates its distance table; y's least costs do not change and hence y does *not* send any messages after that

Distance Vector: Link Cost Changes

Link cost changes:

- Good news travels fast
- Bad news travels slow – “count to infinity” problem!
- 46 iterations before algorithm stabilizes



Poisoned reverse (“split horizon”):

- If z routes through y to get to x:
  - z tells 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?

Comparison of LS and DV Algorithms

Message complexity

- LS: with n nodes & E links, nE msgs sent
- DV: exchange between neighbors only
  - Depends on convergence time

Time to Convergence

- LS: |V|·log|V| CPU time + delay to send nE msgs
  - Oscillations (cost = congestion)
- DV: convergence time varies
  - May have routing loops
  - Count-to-infinity problem

Robustness: what happens if router malfunctions?

LS:

- Node can advertise incorrect *link* cost
- Affects only a small portion of the graph

DV:

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