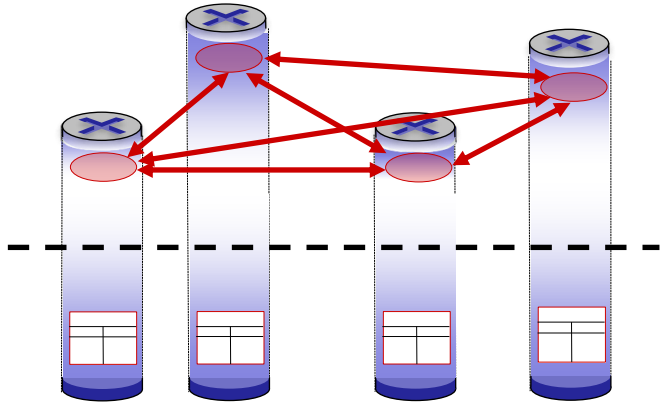

Computer Networks II

Routing Algorithms

Link State Routing

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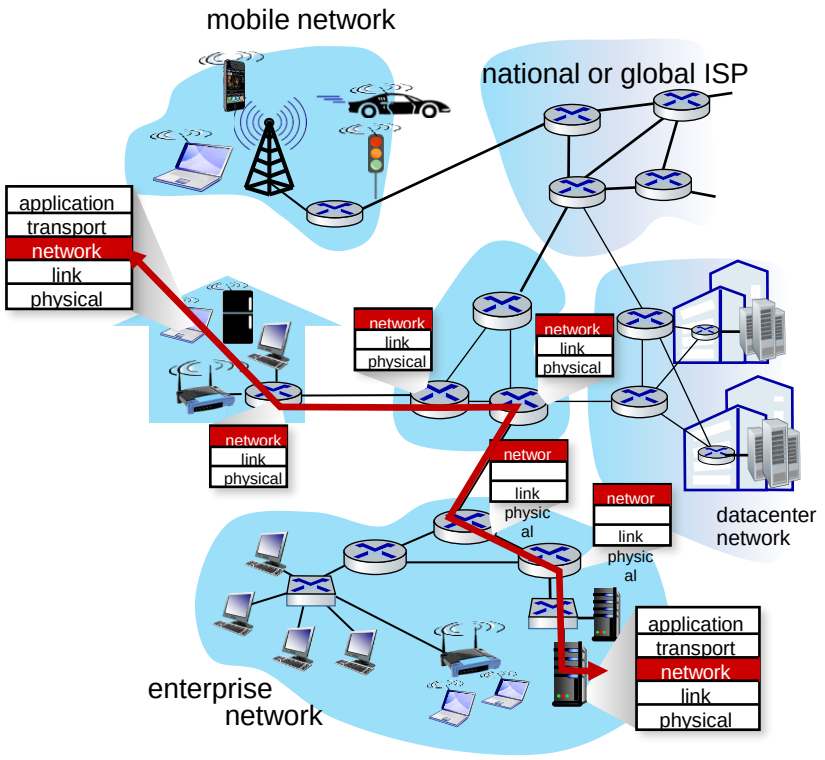
Routing Protocols

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

- Path: Sequence of routers packets traverse from given initial source host to final destination host
- "Good": least "cost", "fastest", "least congested", "shortest"



Routing Algorithm Classification

Global (centralized): All routers have complete topology, link cost info

- "Link state" algorithms

How fast do routes change?

Static: routes change slowly over time

Dynamic: routes change more quickly

- periodic updates or in response to link cost changes

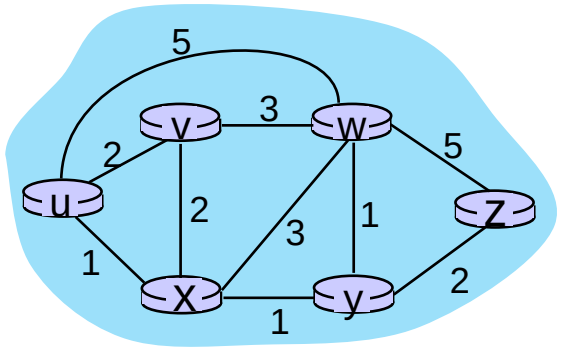
Decentralized: iterative process of computation, exchange of info with neighbors

- Routers initially only know link costs to attached neighbors
- "Distance vector" algorithms

Global or decentralized information?

Link State Routing Protocol

Graph Abstraction: Link Costs



$c_{a,b}$: cost of direct link connecting a and b

e.g., $c_{w,z} = 5$, $c_{u,z} = \infty$

cost defined by network operator: could always be 1, or inversely related to bandwidth, or related to congestion

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) }

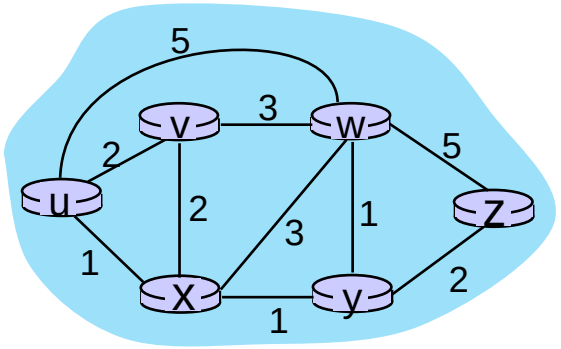
Link-state Routing Algorithm

- Runs in two steps

- Step1: Learning the network topology
  - Nodes flood the information about their neighbors and their link costs in Link State Packets
  - All nodes learn the entire network topology

- Step2: Finding the shortest path
  - Each node runs Dijkstra's algorithm to find out the shortest path (or least cost path) corresponding to each destination

Learning the Network Topology



LS packet for u

Neighbor	Cost
v	2
x	1
w	5

LS packet for v

Neighbor	Cost
u	2
x	2
w	3

LS packet for w

Neighbor	Cost
u	5
v	3
x	3
y	1
z	5

LS packet for x

Neighbor	Cost
u	1
v	2
w	3
y	1

LS packet for y

Neighbor	Cost
w	1
x	1
z	2

LS packet for z

Neighbor	Cost
w	5
y	2

Dijkstra's Link-state Routing Algorithm

- Centralized: network topology, link costs known to all nodes

- 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

- $c_{x,y}$: direct link cost from node x to y; = ∞ if not direct neighbors
- D(v): current estimate of cost of least-cost-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

Dijkstra's Link-state Routing Algorithm

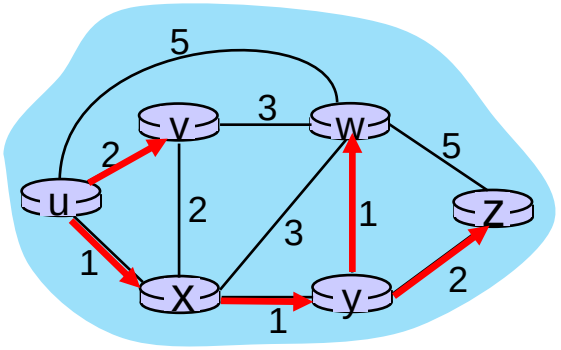
```
1  Initialization:
2    N' = {u}                    /* compute least cost path from u to all other nodes */
3    for all nodes a
4      if a adjacent to u        /* u initially knows direct-path-cost only to  direct neighbors */
5          then D(a) = c_u,a     /* but may not be minimum cost */
6      else D(a) = ∞

7    Loop
8      find a not in N' such that D(a) is minimum
9      add a to N'
10     update D(b) for all b adjacent to a and not in N' :
11         D(b) = min ( D(b),  D(a) + c_a,b )
12     /* new least-path-cost to b is either old least-cost-path to b or known least-cost-path to a plus
          direct-cost from a to b */

13   until all nodes in N'
```

Notation

- $c_{x,y}$: direct link cost from node x to y; = ∞ if not direct neighbors
- D(v): current estimate of cost of least-cost-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

Dijkstra's Algorithm: An 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					



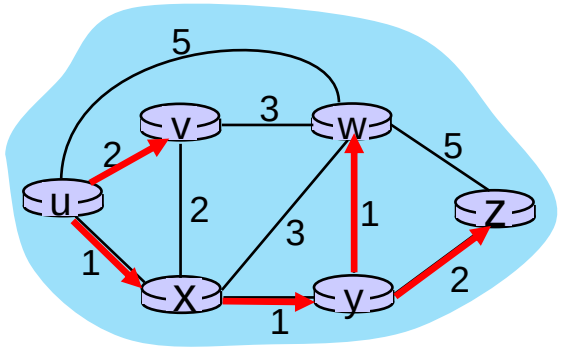
Initialization (step 0): For all **a**: if **a** adjacent to **u**, then D(**a**) = $c_{u,a}$

find **a** not in N' such that D(**a**) is a minimum
add **a** to N'
update D(**b**) for all **b** adjacent to **a** and not in N' :
D(b) = min (D(b), D(a) + $c_{a,b}$)

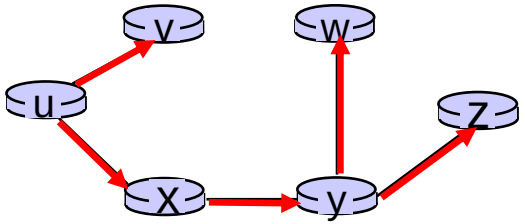
Notation

- $c_{x,y}$: direct link cost from node x to y; = ∞ if not direct neighbors
- D(v): current estimate of cost of least-cost-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

Dijkstra's Algorithm: An Example



Resulting least-cost-path tree from u:



Resulting forwarding table in u:

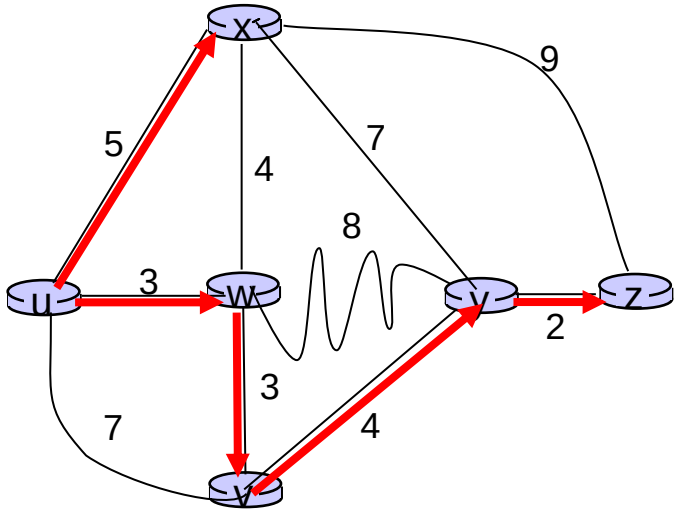
Destination	Outgoing link
v	(u,v)
x	(u,x)
y	(u,x)
w	(u,x)
x	(u,x)

route from u to v directly

route from u to all other destinations via x

Dijkstra's Algorithm: Another Example

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



Dijkstra's Algorithm: Discussion

Algorithm complexity: n nodes

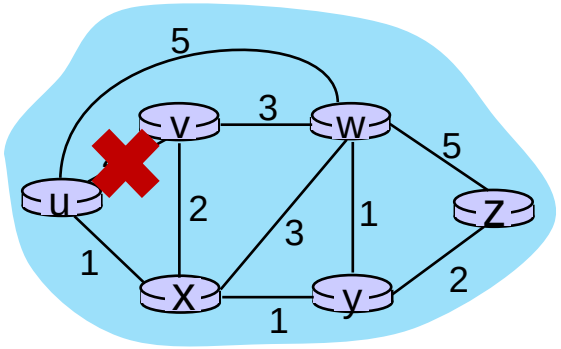
- Each of n iteration: need to check all nodes, a, not in N'
- $n(n+1)/2$ comparisons: $O(n^2)$ complexity
- More efficient implementations possible: O(nlogn)
- Memory requirement: If each nodes has k neighbors → memory required to store the link states is O(nk)

Message complexity:

- Each router must broadcast its link state information to other n routers
- Efficient broadcast algorithms: O(n) link crossings to disseminate a broadcast message from one source
- Each router's message crosses O(n) links: overall message complexity: $O(n^2)$

This means that the message travels through each link in the network only once in the best-case scenario, which is O(n).

Handling Failures



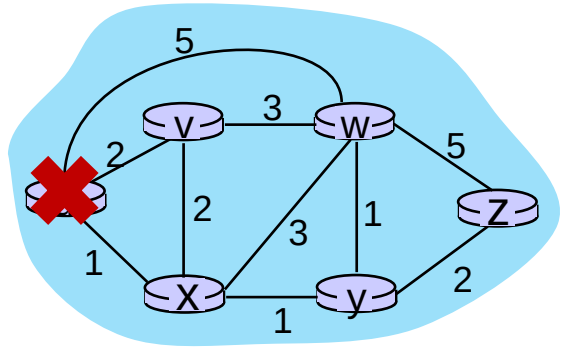
Link failure

LS packet for u

Neighbor	Cost
v	∞
x	1
w	5

LS packet for v

Neighbor	Cost
u	∞
x	2
w	3



Node failure

LS packet for x

Neighbor	Cost
u	∞
v	2
w	3
y	1

LS packet for v

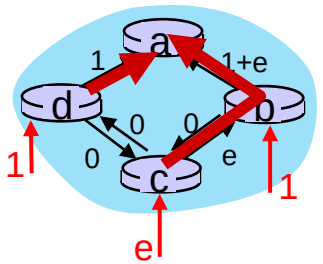
Neighbor	Cost
u	∞
x	2
w	3

LS packet for w

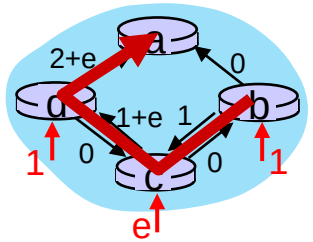
Neighbor	Cost
u	∞
v	3
x	3
y	1
z	5

Dijkstra's Algorithm: Oscillations

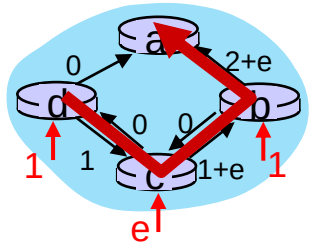
- When link costs depend on traffic volume, route oscillations possible
- Sample scenario:
  - Routing to destination a, traffic entering at b, c, d with rates 1, e (<1), 1
  - Link costs are directional, and volume-dependent



Initially



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



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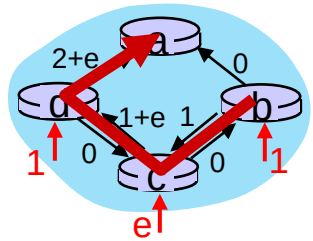

Given these costs, find new routing…. resulting in new costs

Summary

- Routing algorithms:
  - Centralized vs decentralized
  - Static vs dynamic

- Link state routing algorithm:
  - Limitations: may lead to oscillations