Lecture 22

- Sections 5.1, 5.2, 5.2.1 and 5.2.2
- Overview of network layer
  - Forwarding and control planes
  - Network service models
- What is inside a router
  - Input port processing & destination-based forwarding
  - Switching

Chapter 5: Network Layer Control Plane

Chapter objectives:

- understand principles behind network control plane:
  - traditional routing algorithms
  - network management, configuration
- instantiation, implementation in the Internet:
  - OSPF, DV (RIP), BGP
  - Internet Control Message Protocol: ICMP

Chapter 5: Network Layer

5. 1 Introduction

Network-layer functions

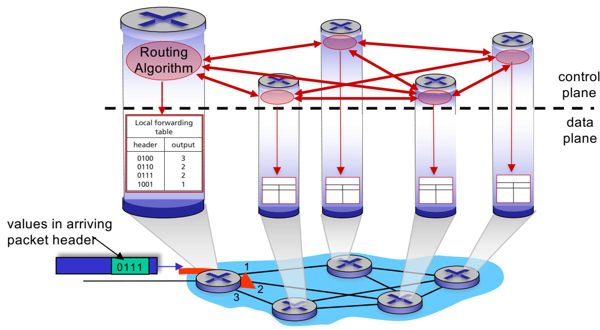
- forwarding: move packets from router's input to appropriate router output — *data plane*
- routing: determine route taken by packets from source to destination — *control plane*

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 in the control plane



5

Chapter 5: Network Layer

5. 1 Introduction

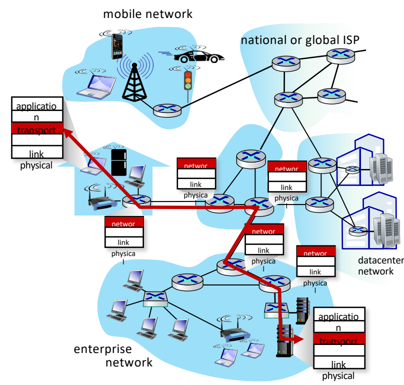
5.2 Routing algorithms

6

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"
- routing: a "top-10" networking challenge!



7

Routing protocols

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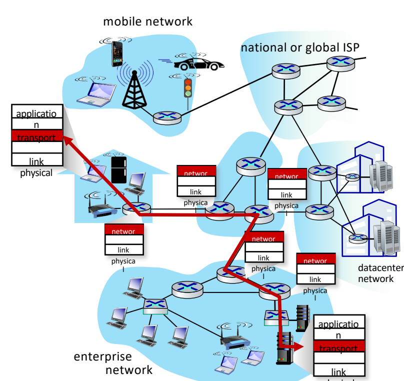


8

Routing Algorithm classification

Global or decentralized information?

Global:
- all routers have complete topology, link cost info
- recursive computation
- "link state" algorithms

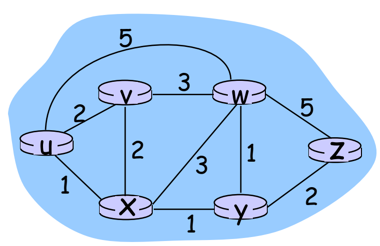
Decentralized:
- router knows physically-connected neighbors, link costs to neighbors
- iterative process of computation, exchange of info with neighbors
- "distance vector" algorithms

Static or dynamic?

Static:
- routes change slowly over time

Dynamic:
- routes change more quickly
  - periodic update
  - in response to link cost changes
- used in Internet

Graph abstraction

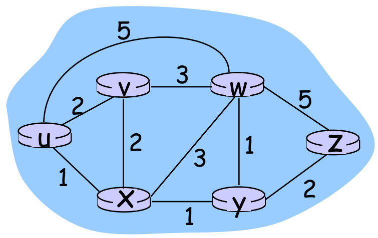


Graph: G = (N,E)

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) }

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

Chapter 5: Network Layer

5. 1 Introduction

5.2 Routing algorithms

  5.2.1 link-state routing 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 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

13

Overview of Dijkstra's Algorithm:

- The algorithm starts by calculating the known direct distances from the source, *u*, to all nodes, *v*, D(v), which is equal to *c(u,v)*.
- The algorithm selects the closest node to *u*, *v* (with minimum D(v)) and adds it to *N'*
- The algorithm recalculates the minimum distance to the nodes not in *N'* as the minimum of the already known distance and the distance through the newly added node, & updates the routes accordingly

14

Dijsktra's Algorithm

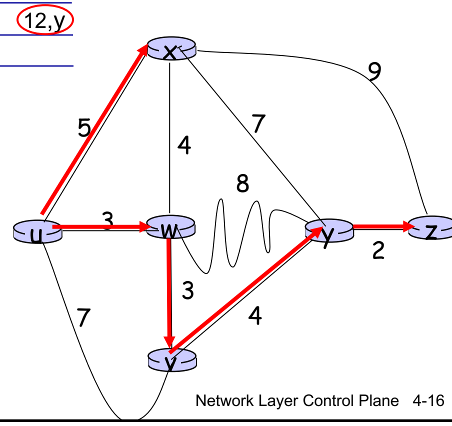
```
Initialization:
  N' = {u}
  for all nodes v
    if v adjacent to u
        then D(v) = c(u,v)
    else D(v) = ∞

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 are 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	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					

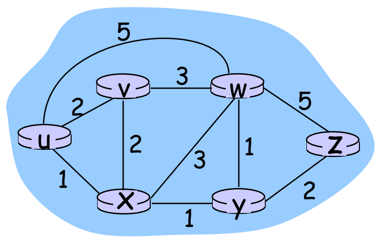
Notes:

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



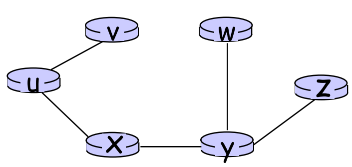
Dijkstra's algorithm: another example

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					



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, discussion

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

Chapter 5: Network Layer

5. 1 Introduction

5.2 Routing algorithms

  5.2.1 link-state routing algorithm

  5.2.2 distance vector routing

Distance Vector Algorithm

Bellman-Ford Equation (dynamic programming)

Define

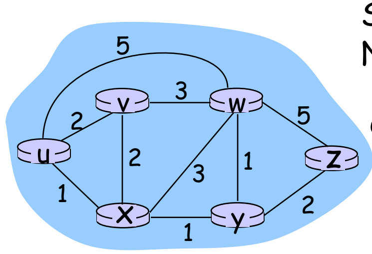
$d_x(y)$:= cost of least-cost path from x to y

Then

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

where min is taken over all neighbors v of x

Bellman-Ford example



Source is u, and wants to reach z

Neighbors of u are v, w and x

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

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 (node x) ➜ forwarding table

Distance Vector Algorithm

- $D_x(y)$ = estimate of least cost from x to y
  - x maintains distance vector $\mathbf{D}_x = [D_x(y): y \in N]$
- node x:
  - knows cost to each neighbor v: $c(x,v)$
  - 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:

- 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* $d_x(y)$

Distance Vector Algorithm (5)

Distributed:

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

Iterative, asynchronous:
each local iteration caused by:

- local link cost change
- DV update message from neighbor

Each node:

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

↓

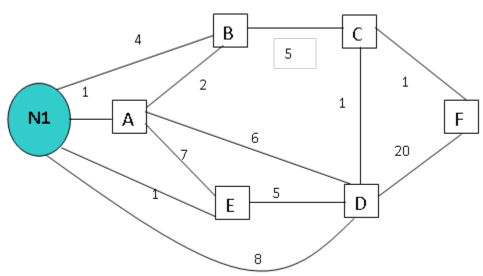
recompute estimates

↓

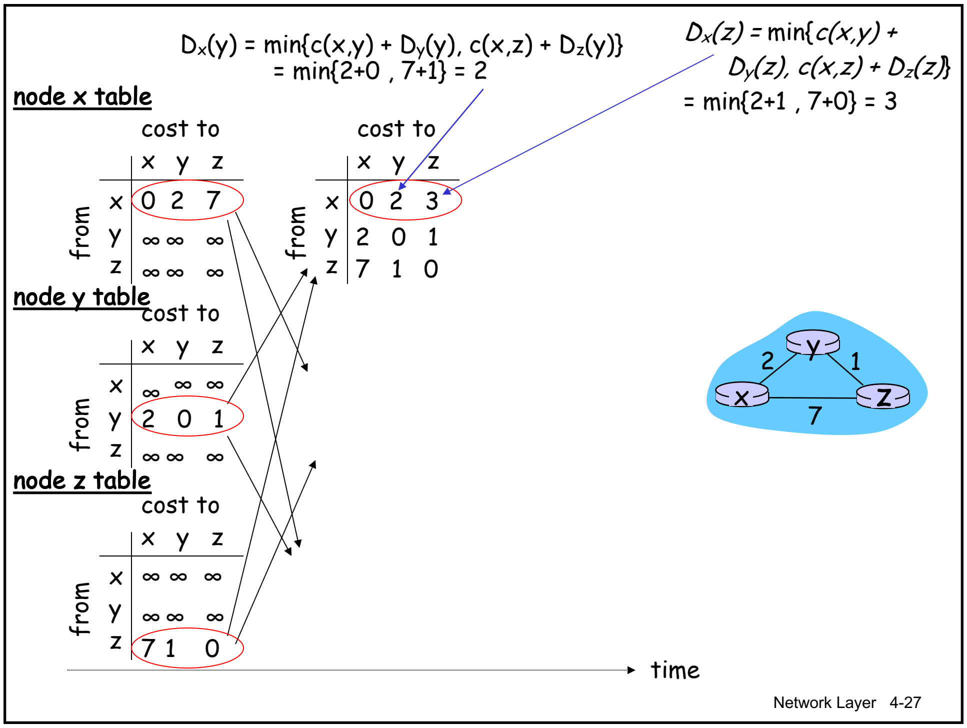
if DV to any dest has changed, *notify* neighbors

Distance Vector Routing: Example

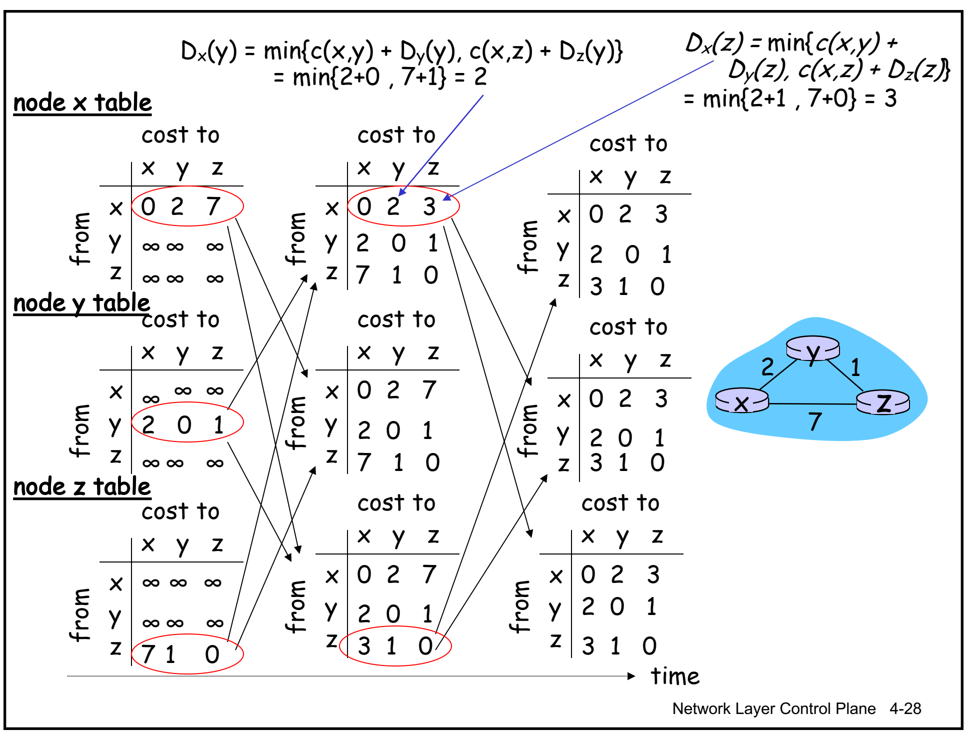
(X,i):
X: next hop to N1
i: distance to N1



Iter.	A	B	C	D	E	F
0	(-,1)	(-,4)	(•,∞)	(-,8)	(-,1)	(•,∞)
1	(-,1)	(A,3)	(B,9)	(E,6)	(-,1)	(D,28)
2	(-,1)	(A,3)	(D,7)	(E,6)	(-,1)	(C,10)
3	(-,1)	(A,3)	(D,7)	(E,6)	(-,1)	(C,8)


$D_x(y) = \min\{c(x,y) + D_y(y), c(x,z) + D_z(y)\}$
$= \min\{2+0 , 7+1\} = 2$
$D_x(z) = \min\{c(x,y) + D_y(z), c(x,z) + D_z(z)\}$
$= \min\{2+1 , 7+0\} = 3$
node x table
node y table
node z table
cost to
from
time
2
1
7
Network Layer 4-27

27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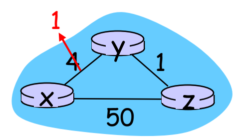
$= \min\{2+1 , 7+0\} = 3$
node x table
node y table
node z table
cost to
from
time
2
1
7
Network Layer Control Plane 4-28

28

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.

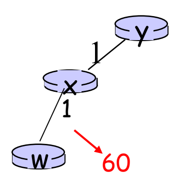
t_1 : *z* receives update from *y*, updates its table, computes new least cost to *x* , sends its neighbors its DV.

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

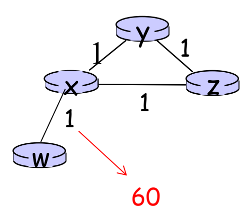
Link cost changes:

- **bad news travels slow** - "count to infinity" problem!
- Many iterations before algorithm stabilizes: how many?



Poisoned reverse:

- If Y routes through X to get to W :
  - Y tells X its (Y's) distance to W is infinite (so X won't route to W via Y)
- will this completely solve count to infinity problem?



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