CS 352
Network: Routing

Lecture 23
http://www.cs.rutgers.edu/~sn624/352-F22
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Routing is a fundamental problem in networking.

How would one design a “Google Maps” to navigate the Internet?
Routing Algorithm

In this example, a routing algorithm runs in each and every router and both forwarding and routing functions are contained within a router. As we'll see in Sections 5.3 and 5.4, the routing algorithm function in one router communicates with the routing algorithm function in other routers to compute the values for its forwarding table. How is this communication performed? By exchanging routing messages containing routing information according to a routing protocol! We'll cover routing algorithms and protocols in Sections 5.2 through 5.4.

The distinct and different purposes of the forwarding and routing functions can be further illustrated by considering the hypothetical (and unrealistic, but technically feasible) case of a network in which all forwarding tables are configured directly by human network operators physically present at the routers. In this case, no routing protocols would be required! Of course, the human operators would need to interact with each other to ensure that the forwarding tables were configured in such a way that packets reached their intended destinations. It's also likely that human configuration would be more error-prone and much slower to respond to changes in the network topology than a routing protocol. We're thus fortunate that all networks have both a forwarding and a routing function!

Routing protocol

Q1. What information is exchanged?
Q2. What computation is performed?
The graph abstraction

- Routing algorithms work over an abstract representation of a network: the graph abstraction

Ex: Rutgers campus

- Each router is a node in a graph
- Each link is an edge in the graph
- Edges have weights (also called link metrics). Set by netadmin
The graph abstraction

- Routing algorithms work over an abstract representation of a network: the graph abstraction

Ex: Rutgers campus

- u: Computer Science
- v: School of Engineering

\[ G = (N, E) \]
\[ N = \{ u, v, w, x, y, z \} \]
\[ E = \{ (u,v), (u,x), (v,x), (v,w), (x,w), (x,y), (w,y), (w,z), (y,z) \} \]
The graph abstraction

- Cost of an edge: $c(x, y)$
  - Examples: $c(u, v) = 2$, $c(u, w) = 5$
- Cost of a path = sum of edge costs
  - $c(\text{path } x \rightarrow w \rightarrow y \rightarrow z) = 3 + 1 + 2 = 6$

- **Outcome** of routing: each node should determine the **least cost path** to every other node
- Q1: What information should nodes exchange with each other to enable this computation?
- Q2: What **algorithm** should each node run to compute the least cost path to every node?
Coming up next

Routing protocols

Link state protocols
Each router has **complete information** of the graph
Messages exchanged by **flooding** all over the network
Communication expensive, but complete

Distance vector protocols
Each router only maintains **distances & next hop** to others
Messages are exchanged over each link and **stay within the link**
Communication cheap, but incomplete
Link State Protocols
Link state protocol

• Each router knows the **state** of all the links and routers in the network

• Every router performs an **independent** computation on **globally shared** knowledge of network’s **complete** graph representation
Q1: Information exchange

- **Link state flooding**: the process by which neighborhood information of each network router is transmitted to all other routers.
  - Each router sends a link state advertisement (LSA) to each of its neighbors.
  - LSA contains the router ID, the IP prefix owned by the router, the router’s neighbors, and link cost to those neighbors.
  - Upon receiving an LSA, a router forwards it to each of its neighbors: *flooding*
Q1: Information exchange

• Eventually, the entire network receives LSAs originated by each router
• LSAs put into a link state database
• LSAs occur periodically and whenever the graph changes
  • Example: if a link fails
  • Example: if a new link or router is added
• The routing algorithm running at each router can use the entire network’s graph to compute least cost paths
Q2: The algorithm

Dijkstra’s algorithm

• Given a network graph, the algorithm computes the least cost paths from one node (source) to all other nodes

• This can then be used to compute the forwarding table at that node

• Iterative algorithm: maintain estimates of least costs to reach every other node. After k iterations, each node definitively knows the least cost path to k destinations

Notation:

• $c(x,y)$: link cost from node $x$ to $y$; $= \infty$ if not direct neighbors

• $D(v)$: current estimate of cost of path from source to destination $v$

• $p(v)$: (predecessor node) the last node before $v$ on the path from source to $v$

• $N'$: set of nodes whose least cost path is definitively known
Dijkstra’s Algorithm

1 *Initialization:*
2 \( N' = \{ u \} \)
3 for all nodes \( v \)
4 if \( v \) adjacent to \( u \)
5 then \( D(v) = c(u,v) \)
6 else \( D(v) = \infty \)

8 *Loop*
9 find \( w \) not in \( N' \) such that \( D(w) \) is a minimum
10 add \( w \) to \( N' \)
11 update \( D(v) \) for all \( v \) adjacent to \( w \) and not in \( N' \):
12 \[ D(v) = \min( D(v), D(w) + c(w,v) ) \]
13 /* new cost to \( v \) is either old cost to \( v \) or known shortest path cost to \( w \) plus cost from \( w \) to \( v \) */
15 until all nodes in \( N' \)
Visualization

$N'$ nodes whose least cost paths from $u$ are definitively known

$W$ should move to $N'$. 

$N \setminus N'$ Nodes with estimated least path costs, not definitively known to be smallest possible

Relaxation: for each $v$ in $N \setminus N'$, is the cost of the path via $w$ smaller than known least cost path to $v$? If so, update $D(v)$

Predecessor of $v$ is $w$.

Cost of path via $w$: $D(w) + c(w,v)$

Cost of known best path: $D(v)$
## Dijkstra’s algorithm: example

<table>
<thead>
<tr>
<th>Step</th>
<th>N'</th>
<th>$D(v),p(v)$</th>
<th>$D(w),p(w)$</th>
<th>$D(x),p(x)$</th>
<th>$D(y),p(y)$</th>
<th>$D(z),p(z)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>u</td>
<td>2,u</td>
<td>5,u</td>
<td>1,u</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>1</td>
<td>ux</td>
<td>2,u</td>
<td>4,x</td>
<td>2,x</td>
<td>$\infty$</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>uxy</td>
<td>2,u</td>
<td>3,y</td>
<td></td>
<td>4,y</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>uxyv</td>
<td>3,y</td>
<td></td>
<td></td>
<td>4,y</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>uxyvw</td>
<td></td>
<td></td>
<td></td>
<td>4,y</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>uxyvwz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The graph is shown below, illustrating the algorithm's progression.
Constructing the forwarding table

- To find the router port to use for a given destination (router), find the **predecessor of the node iteratively** until reaching an **immediate neighbor of the source u**

- The port connecting u to this neighbor is the output port for this destination
Constructing the forwarding table

• Suppose we want forwarding entry for z.

<table>
<thead>
<tr>
<th>D(v),p(v)</th>
<th>D(w),p(w)</th>
<th>D(x),p(x)</th>
<th>D(y),p(y)</th>
<th>D(z),p(z)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,u</td>
<td>3,y</td>
<td>1,u</td>
<td>2,x</td>
<td>4,y</td>
</tr>
</tbody>
</table>

Forwarding table at u:

<table>
<thead>
<tr>
<th>destination</th>
<th>link</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td>(u,x)</td>
</tr>
</tbody>
</table>

z: p(z) = y
y: p(y) = x
x: p(x) = u
x is an immediate neighbor of u
Summary of link state protocols

- Each router announces link state to the entire network using flooding

- Each node independently computes least cost paths to every other node using the full network graph

- Dijkstra’s algorithm can efficiently compute these best paths
  - Easy to populate the forwarding table from predecessor information computed during the algorithm
Distance Vector Protocols
Distance Vector Protocol

• Each router only exchanges a distance vector with its neighbors
  • Distance: how far the destination is
  • Vector: a value for each destination

• DVs are only exchanged between neighbors; not flooded

• Use incomplete view of graph derived from neighbors’ distance vectors to compute the shortest paths
Q1: Distance Vectors

- $D_x(y) = $ estimate of least cost from $x$ to $y$
- Distance vector: $D_x = [D_x(y) : y \in N ]$
- Node $x$ knows cost of edge to each neighbor $v$: $c(x,v)$
- Node $x$ maintains $D_x$
- Node $x$ also maintains its neighbors’ distance vectors
  - For each neighbor $v$, $x$ maintains $D_v = [D_v(y) : y \in N ]$
- Nodes exchange distance vector periodically and whenever the local distance vector changes (e.g., link failure, cost changes)
Q2: Algorithm

Bellman-Ford algorithm

• Each node initializes its own distance vector (DV) to edge costs
• Each node sends its DVs to its neighbors
• When a node $x$ receives new DV from a neighbor $v$, it updates its own DV using the Bellman-Ford equation:
• Given $d_x(y) := \text{estimated cost of the least-cost path from } x \text{ to } y$
• Update $d_x(y) = \min_v \{ c(x,v) + d_v(y) \}$

minimum taken over all neighbors $v$ of $x$

minimum taken over all neighbors $v$ of $x$

cost to reach neighbor $v$ directly from $x$

cost of path from neighbor $v$ to destination $y$
Visualization

- Which neighbor $v$ offers the current best path from $x$ to $y$?
- Path through neighbor $v$ has cost $c(x,v) + d_v(y)$
- Choose min-cost neighbor
- Remember min-cost neighbor as the one used to reach node $y$
- This neighbor determines the output port!

Neighbor $v$ sends its distance vector to $x$.

Use $v''$ and link $(x,v'')$ to reach $y$. 
$$D_x(y) = \min\{c(x,y) + D_y(y), c(x,z) + D_z(y)\}$$
$$= \min\{2+0, 7+1\} = 2$$

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

• Suppose the link cost reduces or a new better path becomes available in a network.
• The immediate neighbors of the change detect the better path immediately.
• Since their DV changed, these nodes notify their neighbors immediately.
  • And those neighbors notify still more neighbors
  • … until the entire network knows to use the better path
• Good news travels fast through the network
• This is despite messages only being exchanged among neighbors
Bad news travels slowly

- If router goes down, could be a while before network realizes it.

Initially

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
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</table>

After 1 exchange

<table>
<thead>
<tr>
<th>3</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
</table>

After 2 exchanges

<table>
<thead>
<tr>
<th>3</th>
<th>4</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
</table>

After 3 exchanges

<table>
<thead>
<tr>
<th>5</th>
<th>4</th>
<th>5</th>
<th>4</th>
</tr>
</thead>
</table>

After 4 exchanges

<table>
<thead>
<tr>
<th>5</th>
<th>6</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
</table>

After 5 exchanges

<table>
<thead>
<tr>
<th>7</th>
<th>6</th>
<th>7</th>
<th>6</th>
</tr>
</thead>
</table>

B still thinks it can reach A through C… bad!

C thinks it can reach A through B… worse!

B, D think they can reach A through C… ugly!

Count to infinity problem etc… to infinity
Bad news travels slowly

• Reacting appropriately to bad news requires information that only other routers have. **DV does not exchange sufficient info.**

• B needs to know that C has no other path to A other than via B.

• **DV does not exchange paths; just distances!**

• **Poisoned reverse:** if X gets its route to Y via Z, then X will announce \( d_X(Y) = \infty \) in its message to Z
  
  • Effect: Z won’t use X to route to Y
  
  • However, this won’t solve the problem in general (think why.)
## Summary: Comparison of LS and DV

### Link State Algorithms
- Nodes have full visibility into the network’s graph
- Copious message exchange: each LSA is flooded over the whole network
- Robust to network changes and failures

**OSPF**
Open Shortest Path First (v2 RFC 2328)

### Distance Vector Algorithms
- Only distances and neighbors are visible
- Sparse message exchange: DVs are exchanged among neighbors only
- Brittle to router failures. Incorrect info may propagate all over net

**EIGRP**
Enhanced Interior Gateway Routing Protocol (RFC 7868)