Chapter 4
Network Layer

A note on the use of these ppt slides:
We’re making these slides freely available to all (faculty, students, readers). They’re in PowerPoint form so you can add, modify, and delete slides (including this one) and slide content to suit your needs. They obviously represent a lot of work on our part. In return for use, we only ask the following:

❖ If you use these slides (e.g., in a class) in substantially unaltered form, that you mention their source (after all, we’d like people to use our book!)
❖ If you post any slides in substantially unaltered form on a www site, that you note that they are adapted from (or perhaps identical to) our slides, and note our copyright of this material.

Thanks and enjoy! JFK/KWR

All material copyright 1996-2010
J.F Kurose and K.W. Ross, All Rights Reserved

Computer Networking: A Top Down Approach
5th edition.
Jim Kurose, Keith Ross
Addison-Wesley, April 2009.
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 increases

<table>
<thead>
<tr>
<th>Node X Table</th>
<th>Node Y Table</th>
<th>Node Z Table</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost to</strong></td>
<td><strong>Cost to</strong></td>
<td><strong>Cost to</strong></td>
</tr>
<tr>
<td>x y z</td>
<td>x y z</td>
<td>x y z</td>
</tr>
<tr>
<td>x 0 4 5</td>
<td>x 0 51 50</td>
<td>x 0 51 50</td>
</tr>
<tr>
<td>y 4 0 1</td>
<td>y 4 0 1</td>
<td>y 4 0 1</td>
</tr>
<tr>
<td>z 5 1 0</td>
<td>z 5 1 0</td>
<td>z 5 1 0</td>
</tr>
<tr>
<td><strong>Time</strong></td>
<td><strong>Time</strong></td>
<td><strong>Time</strong></td>
</tr>
<tr>
<td>60 4 50</td>
<td>60 4 0 1</td>
<td>7 1 0</td>
</tr>
<tr>
<td>4 0 1</td>
<td>4 0 1</td>
<td>8 0 1</td>
</tr>
<tr>
<td>50 1 0</td>
<td>51 50</td>
<td></td>
</tr>
</tbody>
</table>

Network Layer 4-3
Same with poison reverse!

node x table

<table>
<thead>
<tr>
<th></th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>0</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>y</td>
<td>∞</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>z</td>
<td>5</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

cost to

node y table

<table>
<thead>
<tr>
<th></th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>0</td>
<td>∞</td>
<td>∞</td>
</tr>
<tr>
<td>y</td>
<td>0</td>
<td>∞</td>
<td>∞</td>
</tr>
<tr>
<td>z</td>
<td>60</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

cost to

node z table

<table>
<thead>
<tr>
<th></th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>50</td>
<td>1</td>
<td>∞</td>
</tr>
<tr>
<td>y</td>
<td>4</td>
<td>0</td>
<td>∞</td>
</tr>
<tr>
<td>z</td>
<td>5</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

cost to

Network Layer  4-4
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
Chapter 4: Network Layer

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 200 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!
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 towards which gateway it should forward packets for dest \( x \).
  - this is also job of inter-AS routing protocol!
- hot potato routing: send packet towards closest of two routers.

```
Learn from inter-AS protocol that subnet x is reachable via multiple gateways
→ Use routing info from intra-AS protocol to determine costs of least-cost paths to each of the gateways
→ Hot potato routing: Choose the gateway that has the smallest least cost
→ Determine from forwarding table the interface I that leads to least-cost gateway. Enter (x,I) in forwarding table
```
Chapter 4: Network Layer

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
Intra-AS Routing

- also known as Interior Gateway Protocols (IGP)
- most common Intra-AS routing protocols:
  - RIP: Routing Information Protocol
  - OSPF: Open Shortest Path First
  - IGRP: Interior Gateway Routing Protocol (Cisco proprietary)
RIP (Routing Information Protocol)

- included in BSD-UNIX distribution in 1982
- distance vector algorithm
  - distance metric: # hops (max = 15 hops), each link has cost 1
  - DVs exchanged with neighbors every 30 sec in response message (aka advertisement)
  - each advertisement: list of up to 25 destination subnets (in IP addressing sense)

from router A to destination subnets:

<table>
<thead>
<tr>
<th>subnet</th>
<th>hops</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>1</td>
</tr>
<tr>
<td>v</td>
<td>2</td>
</tr>
<tr>
<td>w</td>
<td>2</td>
</tr>
<tr>
<td>x</td>
<td>3</td>
</tr>
<tr>
<td>y</td>
<td>3</td>
</tr>
<tr>
<td>z</td>
<td>2</td>
</tr>
</tbody>
</table>
RIP: Example

routing table in router D

<table>
<thead>
<tr>
<th>destination subnet</th>
<th>next router</th>
<th># hops to dest</th>
</tr>
</thead>
<tbody>
<tr>
<td>w</td>
<td>A</td>
<td>2</td>
</tr>
<tr>
<td>y</td>
<td>B</td>
<td>2</td>
</tr>
<tr>
<td>z</td>
<td>B</td>
<td>7</td>
</tr>
<tr>
<td>x</td>
<td>--</td>
<td>1</td>
</tr>
<tr>
<td>.....</td>
<td>.....</td>
<td>.....</td>
</tr>
</tbody>
</table>
RIP: Example

**A-to-D advertisement**

<table>
<thead>
<tr>
<th>dest</th>
<th>next hops</th>
</tr>
</thead>
<tbody>
<tr>
<td>w</td>
<td>-</td>
</tr>
<tr>
<td>x</td>
<td>-</td>
</tr>
<tr>
<td>z</td>
<td>C</td>
</tr>
<tr>
<td>…</td>
<td>…</td>
</tr>
</tbody>
</table>

Routing table in router D

<table>
<thead>
<tr>
<th>destination subnet</th>
<th>next router</th>
<th># hops to dest</th>
</tr>
</thead>
<tbody>
<tr>
<td>w</td>
<td>A</td>
<td>2</td>
</tr>
<tr>
<td>y</td>
<td>B</td>
<td>2</td>
</tr>
<tr>
<td>z</td>
<td>B</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>5</td>
</tr>
<tr>
<td>x</td>
<td>--</td>
<td>1</td>
</tr>
<tr>
<td>…</td>
<td>…</td>
<td>…</td>
</tr>
</tbody>
</table>

Network Layer 4-18
RIP: Link Failure and Recovery

If no advertisement heard after 180 sec --> neighbor/link declared dead

- routes via neighbor invalidated
- new advertisements sent to neighbors
- neighbors in turn send out new advertisements (if tables changed)
- link failure info quickly (?) propagates to entire net
- *poison reverse* used to prevent ping-pong loops (infinite distance = 16 hops)
RIP Table processing

- RIP routing tables managed by application-level process called route-d (daemon)
- advertisements sent in UDP packets, periodically repeated
OSPF (Open Shortest Path First)

- “open”: publicly available
- uses Link State algorithm
  - LS packet dissemination
  - topology map at each node
  - route computation using Dijkstra’s algorithm

- OSPF advertisement carries one entry per neighbor router
- advertisements disseminated to entire AS (via flooding)
  - carried in OSPF messages directly over IP (rather than TCP or UDP)
**OSPF “advanced” features (not in RIP)**

- **security:** all OSPF messages authenticated (to prevent malicious intrusion)
- **multiple same-cost paths** allowed (only one path in RIP)
- for each link, multiple cost metrics for different **TOS** (e.g., satellite link cost set “low” for best effort ToS; high for real time ToS)
- integrated uni- and **multicast** support:
  - Multicast OSPF (MOSPF) uses same topology data base as OSPF
- **hierarchical** OSPF in large domains.
Hierarchical OSPF

- Backbone router
- Boundary router
- Area 1: Area border routers
- Area 2: Internal routers
- Area 3

Network Layer 4-23
Hierarchical OSPF

- **two-level hierarchy**: local area, backbone.
  - link-state advertisements only in area
  - each node has detailed area topology; only know direction (shortest path) to nets in other areas.

- **area border routers**: “summarize” distances to nets in own area, advertise to other Area Border routers.

- **backbone routers**: run OSPF routing limited to backbone.

- **boundary routers**: connect to other AS’s.