ROUTING AND FORWARDING

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Routing

Determine a path through the network for packets
Forwarding

→ Advance packets through the network

→ Includes a routing decision
Forwarding and Routing

1. Routing (proactive)

2. Forwarding (on-the-fly routing)
Proactive Routing

- Independent of actual traffic
- Determine reachable destinations
- Compute best route
- Commonly referred to as “routing”
On-the-fly Routing

- Realized when handling each packet
- Based on local information
  - Routing/forwarding table
    - Output of proactive routing or signaling
- A.k.a. route
On-the-fly Routing Algorithms

- Routing by Network Address
- Label Swapping
- Source Routing

Each protocol architecture adopts one or more
Forwarding Phases

→ Routing (on-the-fly)
  → Output port selection
  → Possibly next-hop selection
→ Switching: transfer to output port
→ Transmission
A Proactive Routing Algorithm Classification

→ Non-adaptive algorithms (static)

→ Adaptive algorithms (dynamic)
NON-ADAPTIVE ROUTING
Non-adaptive Algorithms

- Fixed Directory routing
- AKA static routing
- Manual configuration
- (Selective) flooding and derivates
Fixed Directory Routing

Routing Table of B
A,E \leftrightarrow C,D →

Routing Table of D
A,B,C,E \leftrightarrow

Routing Table of C
A,B \leftrightarrow D → E ↓

Routing Table of E
A,B \leftrightarrow C,D →

Routing Table of A
B,D → E,C ↓
Pros and Cons

→ Administrator has full control
→ Error prone
→ It does not adapt to topology changes
Static vs. Dynamic

The only way to the rest of network

Edge Static routing

Multiple alternative routes

Core Dynamic routing

Small routing tables
DYNAMIC ROUTING
Adaptive Algorithms

→ Centralized Routing
→ Isolated Routing
→ Distributed Routing
  → Distance Vector
  → Link State
Centralized Routing

→ Routing Control Center (RCC)

→ Calculates and distributes routing tables

→ Needs information from all nodes
Centralized Routing

→ Optimizes performance
→ Simplifies troubleshooting
→ Significant network load in proximity of RCC
Centralized Routing

→ RCC is single point of failure

→ RCC is bottleneck

→ Not suitable for highly dynamic networks
Isolated Routing

- Each node decides independently
- No exchange of information
- E.g., Backward Learning
- IEEE 802.1D bridges
Distributed Routing

Combines advantages of isolated and centralized routing

- Routers co-operate in exchanging connectivity information
- Each router decides independently, but coherently
Basic Principle

1. E at dist 0

2. A at dist 0 and E at 1 (from A1)

3. A at 0 and E at 1

4. C at 0, A at 1 (from C1), F at 1 (from C2), and E at 2 (from C1 and C2, same dist)

2. F at 0 and E at 1 (from F1)

3. F at 0 and E at 1

© see page 2
Distance Vector

→ List of reachable destinations (all!)
→ Distance from announcing router
→ Generated by each router
→ Received from neighbors
Sample Scenario

Routing information stored by A

<table>
<thead>
<tr>
<th>Loc (A)</th>
<th>DV (B)</th>
<th>DV (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, 0</td>
<td>A, 1</td>
<td>A, 1</td>
</tr>
<tr>
<td>B, 0</td>
<td>B, 1</td>
<td></td>
</tr>
<tr>
<td>C, 1</td>
<td>C, 2</td>
<td></td>
</tr>
<tr>
<td>D, 1</td>
<td>D, 0</td>
<td></td>
</tr>
<tr>
<td>E, 1</td>
<td></td>
<td>E, 1</td>
</tr>
</tbody>
</table>
### Distance Vector Merging and Generation

A diagram of a network with nodes A, B, C, D, E and links A1, A2 is shown. The diagram illustrates the process of distance vector (DV) merging and generation.

#### Received from line A1

- **Loc (A)**: A, 0
- **DV (B)**: A, 1
- **DV (D)**: A, 1

#### Received from line A2

- **Loc (A)**: A, 1
- **DV (B)**: B, 0
- **DV (D)**: B, 1

#### ROUT. TABLE (A)

- A, local, 0
- B, A1, 1
- C, A1, 2
- D, A2, 1
- E, A2, 2

#### DV (A)

- A, 0
- B, 1
- C, 2
- D, 1
- E, 2
Topology Change

Loc (A) | DV (B) | DV (D) | ROUT. TABLE (A) | DV (A)
---|---|---|---|---
A, 0 | A, 1 | A, 1 | A, local, 0 | A, 0
B, 0 | B, 1 | B, 1 | B, A2, 2 | B, 2
C, 1 | C, 2 | C, 2 | C, A2, 3 | C, 3
D, 1 | D, 0 | D, 0 | D, A2, 1 | D, 1
E, 1 | E, 1 | E, 1 | E, A2, 2 | E, 2

A1
A2
## Example: Cold Start

<table>
<thead>
<tr>
<th>RT (A)</th>
<th>RT (B)</th>
<th>RT (C)</th>
<th>RT (D)</th>
<th>RT (E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, loc, 0</td>
<td>B, loc, 0</td>
<td>C, loc, 0</td>
<td>D, loc, 0</td>
<td>E, loc, 0</td>
</tr>
</tbody>
</table>

A sends its DV

<table>
<thead>
<tr>
<th>RT (A)</th>
<th>RT (B)</th>
<th>RT (C)</th>
<th>RT (D)</th>
<th>RT (E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, loc, 0</td>
<td>A, B1, 1</td>
<td>C, loc, 0</td>
<td>A, D1, 1</td>
<td>E, loc, 0</td>
</tr>
<tr>
<td>B, loc, 0</td>
<td>C, loc, 0</td>
<td>A, D1, 1</td>
<td>D, loc, 0</td>
<td></td>
</tr>
</tbody>
</table>

B and D send their DVs

<table>
<thead>
<tr>
<th>RT (A)</th>
<th>RT (B)</th>
<th>RT (C)</th>
<th>RT (D)</th>
<th>RT (E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, loc, 0</td>
<td>A, B1, 1</td>
<td>A, C1, 2</td>
<td>A, D1, 1</td>
<td>A, E2, 2</td>
</tr>
<tr>
<td>B, A1, 1</td>
<td>B, loc, 0</td>
<td>B, C1, 1</td>
<td>B, D2, 1</td>
<td>B, E2, 1</td>
</tr>
<tr>
<td>D, A2, 1</td>
<td>D, B2, 1</td>
<td>C, loc, 0</td>
<td>D, loc, 0</td>
<td>D, E1, 1</td>
</tr>
</tbody>
</table>

All send their DVs

<table>
<thead>
<tr>
<th>RT (A)</th>
<th>RT (B)</th>
<th>RT (C)</th>
<th>RT (D)</th>
<th>RT (E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, loc, 0</td>
<td>A, B1, 1</td>
<td>A, C1, 2</td>
<td>A, D1, 1</td>
<td>A, E2, 2</td>
</tr>
<tr>
<td>B, A1, 1</td>
<td>B, loc, 0</td>
<td>B, C1, 1</td>
<td>B, D2, 1</td>
<td>B, E2, 1</td>
</tr>
<tr>
<td>C, A1, 2</td>
<td>C, B4, 1</td>
<td>C, loc, 0</td>
<td>C, D2, 2</td>
<td>C, E3, 1</td>
</tr>
<tr>
<td>D, A2, 1</td>
<td>D, B2, 1</td>
<td>D, C2, 2</td>
<td>D, loc, 0</td>
<td>D, E1, 1</td>
</tr>
<tr>
<td>E, A2, 2</td>
<td>E, B3, 1</td>
<td>E, C2, 1</td>
<td>E, D3, 1</td>
<td>E, loc, 0</td>
</tr>
</tbody>
</table>
Issues

→ Several problems
→ Black Hole
→ Count to infinity
→ Bouncing Effect (loop)

Instability
Count to Infinity

IS B:

<table>
<thead>
<tr>
<th>Loc (B)</th>
<th>DV (A)</th>
<th>DV (C)</th>
<th>RT (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B, 0</td>
<td>A, 0</td>
<td>A, 2</td>
<td>A, B2</td>
</tr>
<tr>
<td>B, 1</td>
<td>B, 1</td>
<td>B, loc</td>
<td>B, loc</td>
</tr>
<tr>
<td>C, 2</td>
<td>C, 0</td>
<td>C, 0</td>
<td>C, B2</td>
</tr>
</tbody>
</table>

B sends DV

IS C:

<table>
<thead>
<tr>
<th>Loc (C)</th>
<th>DV (B)</th>
<th>RT (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C, 0</td>
<td>A, 1</td>
<td>A, C1</td>
</tr>
<tr>
<td>B, 0</td>
<td>B, 0</td>
<td>B, C1</td>
</tr>
<tr>
<td>C, 1</td>
<td>C, 1</td>
<td>C, loc</td>
</tr>
</tbody>
</table>

C sends DV

Count to Infinity!
Bouncing Effect

IS B:

<table>
<thead>
<tr>
<th>Loc (B)</th>
<th>DV (A)</th>
<th>DV (C)</th>
<th>RT (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B, 0</td>
<td>A, 0</td>
<td>A, 2</td>
<td>A, B2, 3</td>
</tr>
<tr>
<td>B, 1</td>
<td>B, 1</td>
<td>B, 1</td>
<td>B, loc, 0</td>
</tr>
<tr>
<td>C, 2</td>
<td>C, 0</td>
<td>C, 0</td>
<td>C, B2, 1</td>
</tr>
</tbody>
</table>

B sends its DV

IS C:

<table>
<thead>
<tr>
<th>Loc (C)</th>
<th>DV (B)</th>
<th>RT (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C, 0</td>
<td>A, 1</td>
<td>A, C1, 2</td>
</tr>
<tr>
<td>B, 0</td>
<td>B, 0</td>
<td>B, C1, 1</td>
</tr>
<tr>
<td>C, 1</td>
<td>C, 1</td>
<td>C, loc, 0</td>
</tr>
</tbody>
</table>
Issues

→ Partial solutions
→ Split Horizon
→ Path Hold Down
→ Route Poisoning
Split Horizon

“If C reaches destination A through B, it is useless for B trying to reach A through C”
Split Horizon

→ Prevents loops between two nodes
→ Speeds up convergence
→ “Personalized” DVs to neighbors
  → DV of C to B does not contain destinations reached through B
→ In actual implementations, route has to expire
Split Horizon on Mesh

IS A:

IS B:

IS C:

IS D:

B sends its DV
Split Horizon on Mesh

IS C: (from the previous slide)

<table>
<thead>
<tr>
<th>Loc (C)</th>
<th>DV (B)</th>
<th>DV (D)</th>
<th>RT (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C, 0</td>
<td>B, 0</td>
<td>A, 2</td>
<td>A,C2, 3</td>
</tr>
<tr>
<td>D, 1</td>
<td>B, 1</td>
<td></td>
<td>B,C1, 1</td>
</tr>
<tr>
<td>D, 0</td>
<td>C, loc, 0</td>
<td></td>
<td>C,D2, 1</td>
</tr>
</tbody>
</table>

C and D send their DVs

IS B:

<table>
<thead>
<tr>
<th>Loc (B)</th>
<th>DV (C)</th>
<th>DV (D)</th>
<th>RT (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B, 0</td>
<td>A, 3</td>
<td>A, 3</td>
<td>A,B3, 4</td>
</tr>
<tr>
<td>C, 0</td>
<td>C, 1</td>
<td></td>
<td>B,loc, 0</td>
</tr>
<tr>
<td>D, 1</td>
<td>D, 0</td>
<td></td>
<td>C,B2, 1</td>
</tr>
<tr>
<td>D, B3</td>
<td></td>
<td></td>
<td>D,B3, 1</td>
</tr>
</tbody>
</table>

IS C:

<table>
<thead>
<tr>
<th>Loc (C)</th>
<th>DV (B)</th>
<th>DV (D)</th>
<th>RT (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C, 0</td>
<td>B, 0</td>
<td>B, 1</td>
<td>B,C1, 1</td>
</tr>
<tr>
<td>D, 1</td>
<td>D, 0</td>
<td></td>
<td>C,loc, 0</td>
</tr>
<tr>
<td>D, C2</td>
<td></td>
<td></td>
<td>D,C2, 1</td>
</tr>
</tbody>
</table>

IS D:

<table>
<thead>
<tr>
<th>Loc (D)</th>
<th>DV (B)</th>
<th>DV (C)</th>
<th>RT (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D, 0</td>
<td>B, 0</td>
<td>A, 2</td>
<td>A,D2, 3</td>
</tr>
<tr>
<td>C, 1</td>
<td>B, 1</td>
<td></td>
<td>B,D1, 1</td>
</tr>
<tr>
<td>C, D2</td>
<td></td>
<td></td>
<td>D,loc, 0</td>
</tr>
</tbody>
</table>

(from the previous slide)

C and D send their DVs
Path Hold Down

If link L fails, all destinations reachable through link L are considered unreachable for a certain period of time. I.e., no routes to them are computed.
Path Hold Down

- High convergence time for the examined node (even with an alternative path)
- The router that noted the fault may not participate to any loop at least until the timeout of Hold Down timer
React on Cost Increase

Routing loops happen when routes have increasing costs

→ Cost-increasing routes in DVs are not used
→ Two subsequent advertisements show a cost increase
→ Possibly with Path Hold Down
→ Might block routes with legitimate cost increase
Route Poisoning

An invalid route is advertised at infinite distance

→ Instead of just omitting it
→ It would have to expire
→ Faster convergence time
→ E.g., when link fails or cost increases

→ It can substitute or complement Path Hold Down
Split Horizon with Poisonous Reverse

→ More aggressive
→ No theoretical advantages
→ Practically, no need to wait for route expiration
The Bottom Line

Routers do not know the network topology

Based on distance vectors B cannot distinguish
Advantages

→ Simple to implement
→ Protocols simple to deploy
→ Very little configuration
Shortcomings

- Exponential worst case complexity and convergence time
  \[ O(n^2) \text{ to } O(n^3) \]
Shortcomings

- Convergence limited by slower links and routers set pace
- Complex tuning
Shortcomings

→ Complex troubleshooting
→ Large routing traffic (and storage)

Not suitable for large complex networks
Path Vector

Eliminates routing loops

IS A:

<table>
<thead>
<tr>
<th>Path</th>
<th>Location (Loc)</th>
<th>Path Vector (PV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>A, 0</td>
<td>A, 1, [B]</td>
</tr>
<tr>
<td>B</td>
<td>B, 0, [-]</td>
<td>B, 1, [B]</td>
</tr>
<tr>
<td>C</td>
<td>C, 1, [B]</td>
<td>C, 0, [-]</td>
</tr>
<tr>
<td>D</td>
<td>D, 2, [B,C]</td>
<td>D, 1, [D]</td>
</tr>
</tbody>
</table>

PV (A) = A, 0, [-]
PV (B) = B, 1, [A]
PV (C) = C, 1, [A]
PV (D) = D, 2, [A,C]
LINK STATE ROUTING ALGORITHM
Basic Principles

1. I, node E, connect to A and F

2. I, node A, connect to E and C

3. I, node F, connect to E and C
Basic Principles

- Information on the state of each link
  - Link state
- A local map
- Sent by each node to all other nodes
- Selective flooding
Basic Principles

- Nodes build a network map
- The same on all nodes
- Each node computes routes on the map
- Dijkstra (shortest path first) algorithm
Link State Database

Stored by each router

<table>
<thead>
<tr>
<th>LS (A)</th>
<th>LS (B)</th>
<th>LS (C)</th>
<th>LS (D)</th>
<th>LS (E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B, 1</td>
<td>A, 1</td>
<td>B, 1</td>
<td>A, 1</td>
<td>B, 1</td>
</tr>
<tr>
<td>D, 1</td>
<td>C, 1</td>
<td>E, 1</td>
<td>B, 1</td>
<td>C, 1</td>
</tr>
<tr>
<td></td>
<td>D, 1</td>
<td></td>
<td>B, 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>E, 1</td>
<td></td>
<td>E, 1</td>
<td>D, 1</td>
</tr>
</tbody>
</table>
Dijkstra Algorithm

⇒ Low complexity
⇒ $L \cdot \log(N)$
⇒ $L$: number of links
⇒ $N$: number of nodes
⇒ Shortest Path First
Shortest Path First

⇒ The next node “nearest” to the root is identified

⇒ Its path is inserted into the routing table
Example

1) B A C D E F
   1 2 3 2 3
   1 3 2 2 3

2) B A C D E F
   1 2 3 2 3
   1 3 2 2 3

3) B A C D E F
   1 2 3 2 3
   1 3 2 2 3

4) B A C D E F
   1 2 3 2 3
   1 3 2 2 3

5) B A C D E F
   1 2 3 2 3
   1 3 2 2 3

6) B A C D E F
   1 2 3 2 3
   1 3 2 2 3

7) B A C D E F
   1 2 3 2 3
   1 3 2 2 3

8) B A C D E F
   1 2 3 2 3
   1 3 2 2 3

9) B A C D E F
   1 2 3 2 3
   1 3 2 2 3

10) B A C D E F
    1 2 3 2 3
    1 3 2 2 3
Rapid Convergence

- LSs spread quickly
- No intermediate processing
Limited Routing Traffic and Storage

- Link states are small
- Fast and efficient neighbor greeting
Other Advantages

→ It rarely generates loops
→ Simple to understand and troubleshoot
→ All nodes have identical databases
Shortcoming

- High implementation complexity
- Selective flooding
- First implementation took several years
- Protocols with complex configuration
Link State Generation

⇒ In principle: when there is a topology change

⇒ Actual protocols: LS are generated periodically

⇒ Increased reliability