IP Forwarding

Relates to Lab 3.
Covers the principles of end-to-end datagram delivery in IP networks.

Delivery of an IP datagram

- View at the data link layer layer:
  - Internetwork is a collection of LANs or point-to-point links or switched networks that are connected by routers
Delivery of an IP datagram

• View at the IP layer:
  – An IP network is a logical entity with a network number
  – We represent an IP network as a “cloud”
  – The IP delivery service takes the view of clouds, and ignores the data link layer view

Tenets of end-to-end delivery of datagrams

The following conditions must hold so that an IP datagram can be successfully delivered

1. The network prefix of an IP destination address must correspond to a unique data link layer network (=LAN or point-to-point link or switched network). (The reverse need not be true!)
2. Routers and hosts that have a common network prefix must be able to exchange IP datagrams using a data link protocol (e.g., Ethernet, PPP)
3. Every data link layer network must be connected to at least one other data link layer network via a router.
Routing tables

- Each router and each host keeps a routing table which tells the router how to process an outgoing packet.
- Main columns:
  1. Destination address: where is the IP datagram going to?
  2. Next hop: how to send the IP datagram?
  3. Interface: what is the output port?
- Next hop and interface column can often be summarized as one column.
- Routing tables are set so that datagrams gets closer to its destination.

Routing table of a host or router
IP datagrams can be directly delivered (“direct”) or is sent to a router (“R4”).

<table>
<thead>
<tr>
<th>Destination</th>
<th>Next Hop</th>
<th>Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1.0.0/24</td>
<td>direct</td>
<td>eth0</td>
</tr>
<tr>
<td>10.1.2.0/24</td>
<td>direct</td>
<td>eth0</td>
</tr>
<tr>
<td>10.2.1.0/24</td>
<td>R4</td>
<td>serial0</td>
</tr>
<tr>
<td>10.3.1.0/24</td>
<td>direct</td>
<td>eth1</td>
</tr>
<tr>
<td>20.1.0.0/16</td>
<td>R4</td>
<td>eth0</td>
</tr>
<tr>
<td>20.2.1.0/28</td>
<td>R4</td>
<td>eth0</td>
</tr>
</tbody>
</table>

Delivery with routing tables
Delivery of IP datagrams

- There are two distinct processes to delivering IP datagrams:
  1. **Forwarding**: How to pass a packet from an input interface to the output interface?
  2. **Routing**: How to find and setup the routing tables?

- Forwarding must be done as fast as possible:
  - on routers, is often done with support of hardware
  - on PCs, is done in kernel of the operating system
- Routing is less time-critical
  - On a PC, routing is done as a background process

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Processing of an IP datagram in IP
Processing of an IP datagram in IP

- Processing of IP datagrams is very similar on an IP router and a host
- **Main difference:**
  
  “IP forwarding” is enabled on router and disabled on host

- **IP forwarding enabled**
  → if a datagram is received, but it is not for the local system, the datagram will be sent to a different system

- **IP forwarding disabled**
  → if a datagram is received, but it is not for the local system, the datagram will be dropped

Processing of an IP datagram at a router

Receive an IP datagram

1. IP header validation
2. Process options in IP header
3. Parsing the destination IP address
4. Routing table lookup
5. Decrement TTL
6. Perform fragmentation (if necessary)
7. Calculate checksum
8. Transmit to next hop
9. Send ICMP packet (if necessary)
Routing table lookup

- When a router or host need to transmit an IP datagram, it performs a routing table lookup.

- **Routing table lookup**: Use the IP destination address as a key to search the routing table.

- Result of the lookup is the IP address of a next hop router, and/or the name of a network interface.

<table>
<thead>
<tr>
<th>Destination address</th>
<th>Next hop/interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>network prefix or host IP address or loopback address or default route</td>
<td>IP address of next hop router or Name of a network interface</td>
</tr>
</tbody>
</table>

Type of routing table entries

- **Network route**
  - Destination addresses is a network address (e.g., 10.0.2.0/24)
  - Most entries are network routes

- **Host route**
  - Destination address is an interface address (e.g., 10.0.1.2/32)
  - Used to specify a separate route for certain hosts

- **Default route**
  - Used when no network or host route matches
  - The router that is listed as the next hop of the default route is the default gateway (for Cisco: "gateway of last resort")

- **Loopback address**
  - Routing table for the loopback address (127.0.0.1)
  - The next hop lists the loopback (lo0) interface as outgoing interface
### Routing table lookup: Longest Prefix Match

- **Longest Prefix Match**: Search for the routing table entry that has the longest match with the prefix of the destination IP address

1. Search for a match on all 32 bits
2. Search for a match for 31 bits
   ... 
32. Search for a match on 0 bits

#### Host route, loopback entry
- 32-bit prefix match

#### Default route
- 0-bit prefix match

<table>
<thead>
<tr>
<th>Destination address</th>
<th>Next hop</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0.0.0/8</td>
<td>R1</td>
</tr>
<tr>
<td>128.143.0.0/16</td>
<td>R2</td>
</tr>
<tr>
<td>128.143.64.0/20</td>
<td>R3</td>
</tr>
<tr>
<td>128.143.192.0/20</td>
<td>R3</td>
</tr>
<tr>
<td>128.143.71.0/24</td>
<td>R3</td>
</tr>
<tr>
<td>128.143.71.55/32</td>
<td>R3</td>
</tr>
<tr>
<td>default</td>
<td>R5</td>
</tr>
</tbody>
</table>

The longest prefix match for 128.143.71.21 is for 24 bits with entry 128.143.71.0/24

Datagram will be sent to R4

### Route Aggregation

- Longest prefix match algorithm permits to aggregate prefixes with identical next hop address to a single entry
- This contributes significantly to reducing the size of routing tables of Internet routers

<table>
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<th>Destination</th>
<th>Next Hop</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1.0.0/24</td>
<td>R3</td>
</tr>
<tr>
<td>10.1.2.0/24</td>
<td>direct</td>
</tr>
<tr>
<td>10.2.1.0/24</td>
<td>direct</td>
</tr>
<tr>
<td>10.3.1.0/24</td>
<td>R3</td>
</tr>
<tr>
<td>20.2.0.0/16</td>
<td>R2</td>
</tr>
<tr>
<td>30.1.1.0/28</td>
<td>R2</td>
</tr>
</tbody>
</table>

<table>
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<tr>
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<td>direct</td>
</tr>
<tr>
<td>10.2.1.0/24</td>
<td>direct</td>
</tr>
<tr>
<td>10.3.1.0/24</td>
<td>R3</td>
</tr>
<tr>
<td>20.0.0.0/8</td>
<td>R2</td>
</tr>
</tbody>
</table>
**How do routing tables get updated?**

- Adding an interface:
  - Configuring an interface eth2 with 10.0.2.3/24 adds a routing table entry:

<table>
<thead>
<tr>
<th>Destination</th>
<th>Next Hop/ interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.0.2.0/24</td>
<td>eth2</td>
</tr>
</tbody>
</table>

- Adding a default gateway:
  - Configuring 10.0.2.1 as the default gateway adds the entry:

<table>
<thead>
<tr>
<th>Destination</th>
<th>Next Hop/ interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0.0.0/0</td>
<td>10.0.2.1</td>
</tr>
</tbody>
</table>

- Static configuration of network routes or host routes
- Update of routing tables through routing protocols
- ICMP messages

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**Routing table manipulations with ICMP**

- When a router detects that an IP datagram should have gone to a different router, the router (here R2)
  - forwards the IP datagram to the correct router
  - sends an ICMP redirect message to the host
- Host uses ICMP message to update its routing table
ICMP Router Solicitation
ICMP Router Advertisement

- After bootstrapping a host broadcasts an **ICMP router solicitation**.
- In response, routers send an **ICMP router advertisement** message.
- Also, routers periodically broadcast **ICMP router advertisement**.

This is sometimes called the Router Discovery Protocol.