Chapter 4
Network Layer

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Chapter 4: outline

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
Network layer

- transport segment from sending to receiving host
- on sending side, encapsulates segments into datagrams
- on receiving side, delivers segments to transport layer
- network layer protocols in every host, router
- router examines header fields in all IP datagrams passing through it
Two key network-layer functions

- **forwarding**: move packets from router’s input to appropriate router output

- **routing**: determine route taken by packets from source to dest.
  - *routing algorithms*

**analogy:**

- **routing**: process of planning trip from source to dest
- **forwarding**: process of getting through single interchange
Interplay between routing and forwarding

- Routing algorithm determines end-end-path through network.
- Forwarding table determines local forwarding at this router.

Value in arriving packet's header:

<table>
<thead>
<tr>
<th>header value</th>
<th>output link</th>
</tr>
</thead>
<tbody>
<tr>
<td>0100</td>
<td>3</td>
</tr>
<tr>
<td>0101</td>
<td>2</td>
</tr>
<tr>
<td>0111</td>
<td>2</td>
</tr>
<tr>
<td>1001</td>
<td>1</td>
</tr>
</tbody>
</table>
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  ▪ ICMP
  ▪ IPv6

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  ▪ link state
  ▪ distance vector
  ▪ hierarchical routing

4.6 routing in the Internet
  ▪ RIP
  ▪ OSPF
  ▪ BGP

4.7 broadcast and multicast routing
Datagram networks

- no call setup at network layer
- routers: no state about end-to-end connections
  - no network-level concept of “connection”
- packets forwarded using destination host address
Datagram forwarding table

Routing algorithm

Local forwarding table

<table>
<thead>
<tr>
<th>dest address</th>
<th>output link</th>
</tr>
</thead>
<tbody>
<tr>
<td>address-range 1</td>
<td>3</td>
</tr>
<tr>
<td>address-range 2</td>
<td>2</td>
</tr>
<tr>
<td>address-range 3</td>
<td>2</td>
</tr>
<tr>
<td>address-range 4</td>
<td>1</td>
</tr>
</tbody>
</table>

4 billion IP addresses, so rather than list individual destination address list range of addresses (aggregate table entries)

IP destination address in arriving packet’s header
### Datagram forwarding table

<table>
<thead>
<tr>
<th>Destination Address Range</th>
<th>Link Interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>11001000 00010111 00010000 00000000 through 11001000 00010111 00010111 11111111</td>
<td>0</td>
</tr>
<tr>
<td>11001000 00010111 00011000 00000000 through 11001000 00010111 00011000 11111111</td>
<td>1</td>
</tr>
<tr>
<td>11001000 00010111 00011001 00000000 through 11001000 00010111 00011111 11111111</td>
<td>2</td>
</tr>
<tr>
<td>otherwise</td>
<td>3</td>
</tr>
</tbody>
</table>

**Q:** but what happens if ranges don’t divide up so nicely?
Longest prefix matching

when looking for forwarding table entry for given destination address, use **longest** address prefix that matches destination address.

<table>
<thead>
<tr>
<th>Destination Address Range</th>
<th>Link interface</th>
</tr>
</thead>
<tbody>
<tr>
<td>11001000 00010111 00010*** **********</td>
<td>0</td>
</tr>
<tr>
<td>11001000 00010111 00011000 **********</td>
<td>1</td>
</tr>
<tr>
<td>11001000 00010111 00011*** **********</td>
<td>2</td>
</tr>
<tr>
<td>otherwise</td>
<td>3</td>
</tr>
</tbody>
</table>

examples:

DA: 11001000 00010111 00010110 10100001  which interface?

DA: 11001000 00010111 00011000 10101010  which interface?
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   ▪ OSPF
   ▪ BGP
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Router architecture overview

two key router functions:
- run routing algorithms/protocol (RIP, OSPF, BGP)
- forwarding datagrams from incoming to outgoing link
Input port functions

- **line termination**
- **link layer protocol (receive)**
- **lookup, forwarding queueing**

**decentralized switching:**
- given datagram dest., lookup output port using forwarding table in input port memory ("match plus action")
- goal: complete input port processing at 'line speed'
- queuing: if datagrams arrive faster than forwarding rate into switch fabric

**physical layer:**
bit-level reception

**data link layer:**
e.g., Ethernet
see chapter 5
Output ports

- **buffering** required when datagrams arrive from fabric faster than the transmission rate
- **scheduling discipline** chooses among queued datagrams for transmission
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The Internet network layer

host, router network layer functions:

- **routing protocols**
  - path selection
  - RIP, OSPF, BGP

- **IP protocol**
  - addressing conventions
  - datagram format
  - packet handling conventions

- **ICMP protocol**
  - error reporting
  - router "signaling"

- **transport layer**: TCP, UDP

- **link layer**

- **physical layer**
**IP datagram format**

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP protocol version number</td>
<td>IP protocol version number is 4.</td>
</tr>
<tr>
<td>Header length (bytes)</td>
<td>20 bytes of IP</td>
</tr>
<tr>
<td>“Type” of data</td>
<td>20 bytes of TCP</td>
</tr>
<tr>
<td>Max number remaining hops</td>
<td>32 bit source IP address</td>
</tr>
<tr>
<td>(decremented at each router)</td>
<td>32 bit destination IP address</td>
</tr>
<tr>
<td>Upper layer protocol to deliver payload to</td>
<td>[\text{options (if any)}] [\text{data}]</td>
</tr>
<tr>
<td>[\text{variable length, typically a TCP or UDP segment}]</td>
<td>[\text{e.g. timestamp, record route taken, specify list of routers to visit.}]</td>
</tr>
</tbody>
</table>

**how much overhead?**
- 20 bytes of TCP
- 20 bytes of IP
- 40 bytes + app layer overhead

**Diagram:**
- IP datagram format with fields labeled:
  - Version
  - Header length (32 bits)
  - “Type” of data
  - Data (variable length, typically a TCP or UDP segment)
  - 16-bit identifier
  - Time to live
  - Upper layer
  - Fragment
  - Offset
  - Header checksum
  - Total datagram length (bytes)
  - For fragmentation/reassembly
  - Options (if any)
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IP addressing: introduction

- **IP address**: 32-bit identifier for host, router interface
- **interface**: connection between host/router and physical link
  - router’s typically have multiple interfaces
  - host typically has one or two interfaces (e.g., wired Ethernet, wireless 802.11)
- **IP addresses associated with each interface**

```
223.1.1.1 = 11011111 00000001 00000001 00000001
  223 1 1 1 1
```
Subnets

- **IP address:**
  - subnet part - high order bits
  - host part - low order bits

- **what’s a subnet?**
  - device interfaces with same subnet part of IP address
  - can physically reach each other *without intervening router*

Network consisting of 3 subnets
**Subnets**

*recipe*

- to determine the subnets, detach each interface from its host or router, creating islands of isolated networks
- each isolated network is called a *subnet*

Network Layer  4-21
Subnets

how many?
IP addressing: CIDR

CIDR: Classless InterDomain Routing
- subnet portion of address of arbitrary length
- address format: a.b.c.d/x, where x is # bits in subnet portion of address

```
11001000  00010111  00010000  00000000
```

200.23.16.0/23
Q: how does network get subnet part of IP addr?
A: gets allocated portion of its provider ISP’s address space

<table>
<thead>
<tr>
<th>ISP's block</th>
<th>11001000 00010111 00010000 00000000   200.23.16.0/20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organization 0</td>
<td>11001000 00010111 00010000 00000000   200.23.16.0/23</td>
</tr>
<tr>
<td>Organization 1</td>
<td>11001000 00010111 00010010 00000000   200.23.18.0/23</td>
</tr>
<tr>
<td>Organization 2</td>
<td>11001000 00010111 00010100 00000000   200.23.20.0/23</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Organization 7</td>
<td>11001000 00010111 00011110 00000000   200.23.30.0/23</td>
</tr>
</tbody>
</table>
Hierarchical addressing: route aggregation

Hierarchical addressing allows efficient advertisement of routing information:

- Organization 0: 200.23.16.0/23
- Organization 1: 200.23.18.0/23
- Organization 2: 200.23.20.0/23
- Organization 7: 200.23.30.0/23

Fly-By-Night-ISP

ISPs-R-Us

Internet

"Send me anything with addresses beginning 200.23.16.0/20"

"Send me anything with addresses beginning 199.31.0.0/16"
Hierarchical addressing: more specific routes

ISPs-R-Us has a more specific route to Organization 1

Organization 0
- 200.23.16.0/23

Organization 2
- 200.23.20.0/23

Organization 7
- 200.23.30.0/23

Organization 1
- 200.23.18.0/23

Fly-By-Night-ISP

“Send me anything with addresses beginning 200.23.16.0/20”

ISPs-R-Us

“Send me anything with addresses beginning 199.31.0.0/16 or 200.23.18.0/23”

Internet
IP addressing: the last word...

Q: how does an ISP get block of addresses?
A: ICANN: Internet Corporation for Assigned Names and Numbers http://www.icann.org/
- allocates addresses
- manages DNS
- assigns domain names, resolves disputes
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ICMP: internet control message protocol

- used by hosts & routers to communicate network-level information
  - error reporting: unreachable host, network, port, protocol
  - echo request/reply (used by ping)
- network-layer “above” IP:
  - ICMP msgs carried in IP datagrams
- ICMP message: type, code plus first 8 bytes of IP datagram causing error

<table>
<thead>
<tr>
<th>Type</th>
<th>Code</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>echo reply (ping)</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>dest. network unreachable</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>dest host unreachable</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>dest protocol unreachable</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>dest port unreachable</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>dest network unknown</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>dest host unknown</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>source quench (congestion control - not used)</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>echo request (ping)</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>route advertisement</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>router discovery</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>TTL expired</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>bad IP header</td>
</tr>
</tbody>
</table>
Traceroute and ICMP

- source sends series of UDP segments to dest
  - first set has TTL = 1
  - second set has TTL = 2, etc.
  - unlikely port number
- when nth set of datagrams arrives to nth router:
  - router discards datagrams
  - and sends source ICMP messages (type 11, code 0)
  - ICMP messages includes name of router & IP address
- when ICMP messages arrives, source records RTTs

**stopping criteria:**
- UDP segment eventually arrives at destination host
- destination returns ICMP “port unreachable” message (type 3, code 3)
- source stops
IPv6: motivation

- **initial motivation**: 32-bit address space soon to be completely allocated.

- additional motivation:
  - header format helps speed processing/forwarding
  - header changes to facilitate QoS

**IPv6 datagram format:**
- fixed-length 40 byte header
- no fragmentation allowed
IPv6 datagram format

**priority**: identify priority among datagrams in flow

**flow Label**: identify datagrams in same “flow.”
   (concept of “flow” not well defined).

**next header**: identify upper layer protocol for data

<table>
<thead>
<tr>
<th>ver</th>
<th>pri</th>
<th>flow label</th>
</tr>
</thead>
<tbody>
<tr>
<td>payload len</td>
<td>next hdr</td>
<td>hop limit</td>
</tr>
<tr>
<td>source address (128 bits)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>destination address (128 bits)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>data</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

32 bits
Transition from IPv4 to IPv6

- not all routers can be upgraded simultaneously
  - no “flag days”
  - how will network operate with mixed IPv4 and IPv6 routers?
- tunneling: IPv6 datagram carried as payload in IPv4 datagram among IPv4 routers
Tunneling

logical view:

A IPv6 —— B IPv6

IPv4 tunnel connecting IPv6 routers

E IPv6 —— F IPv6

physical view:

A IPv6 —— B IPv6 —— C IPv4 —— D IPv4 —— E IPv6 —— F IPv6
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Interplay between routing, forwarding

Routing algorithm determines end-end-path through network.

Forwarding table determines local forwarding at this router.

IP destination address in arriving packet’s header.

Local forwarding table:

<table>
<thead>
<tr>
<th>dest address</th>
<th>output link</th>
</tr>
</thead>
<tbody>
<tr>
<td>address-range 1</td>
<td>3</td>
</tr>
<tr>
<td>address-range 2</td>
<td>2</td>
</tr>
<tr>
<td>address-range 3</td>
<td>2</td>
</tr>
<tr>
<td>address-range 4</td>
<td>1</td>
</tr>
</tbody>
</table>
Graph abstraction

graph: $G = (N, E)$

$N =$ set of routers $= \{ u, v, w, x, y, z \}$

$E =$ set of links $=\{(u,v), (u,x), (v,x), (v,w), (x,w), (x,y), (w,y), (w,z), (y,z) \}$

*aside:* graph abstraction is useful in other network contexts, e.g., P2P, where $N$ is set of peers and $E$ is set of TCP connections
Graph abstraction: costs

\[ c(x, x') = \text{cost of link } (x, x') \]

\[ \text{e.g., } c(w, z) = 5 \]

cost could always be 1, or inversely related to bandwidth, or inversely related to congestion

Cost of path \((x_1, x_2, x_3, \ldots, x_p) = c(x_1, x_2) + c(x_2, x_3) + \ldots + c(x_{p-1}, x_p)\)

**key question:** what is the least-cost path between \(u\) and \(z\)?

**routing algorithm:** algorithm that finds that least cost path
Routing algorithm classification

Q: global or decentralized information?

**global:**
- all routers have complete topology, link cost info
- “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

Q: static or dynamic?

**static:**
- routes change slowly over time

**dynamic:**
- routes change more quickly
  - periodic update
  - in response to link cost changes
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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; = \( \infty \) 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
Dijsktra’s Algorithm

1 **Initialization:**
2 \( N' = \{u\} \)
3 for all nodes \( v \)
4 \hspace{1em} if \( v \) adjacent to \( u \)
5 \hspace{2em} then \( D(v) = c(u,v) \)
6 \hspace{1em} else \( D(v) = \infty \)
7
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
14 shortest path cost to \( w \) plus cost from \( w \) to \( v \) */
15 **until all nodes in \( N' \)**
Dijkstra’s algorithm: example

<table>
<thead>
<tr>
<th>Step</th>
<th>N'</th>
<th>D(v)</th>
<th>D(w)</th>
<th>D(x)</th>
<th>D(y)</th>
<th>D(z)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>p(v)</td>
<td>p(w)</td>
<td>p(x)</td>
<td>p(y)</td>
<td>p(z)</td>
</tr>
<tr>
<td>0</td>
<td>u</td>
<td>7,u</td>
<td>3,u</td>
<td>5,u</td>
<td>∞</td>
<td>∞</td>
</tr>
<tr>
<td>1</td>
<td>uw</td>
<td>6,w</td>
<td>5,u</td>
<td>11,w</td>
<td>∞</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>uwx</td>
<td>6,w</td>
<td>11,w</td>
<td>14,x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>uwxv</td>
<td></td>
<td>10,y</td>
<td>14,x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>uwxvy</td>
<td></td>
<td></td>
<td></td>
<td>12,y</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>uwxvzy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- Construct shortest path tree by tracing predecessor nodes
- Ties can exist (can be broken arbitrarily)
Dijkstra’s algorithm: another 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>∞</td>
<td>∞</td>
</tr>
<tr>
<td>1</td>
<td>ux</td>
<td>2,u</td>
<td>4,x</td>
<td>2,x</td>
<td>2,x</td>
<td>∞</td>
</tr>
<tr>
<td>2</td>
<td>uxy</td>
<td>2,u</td>
<td>3,y</td>
<td>4,y</td>
<td>4,y</td>
<td>4,y</td>
</tr>
<tr>
<td>3</td>
<td>uxyv</td>
<td>3,y</td>
<td>3,y</td>
<td>4,y</td>
<td>4,y</td>
<td>4,y</td>
</tr>
<tr>
<td>4</td>
<td>uxyvw</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>uxyvwz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Diagram:

```
  5
 /   \
/     /
V-----W
|     |
2-----3
|     |
X-----Y
|     |
1-----2
     |
U-----Z
```
Dijkstra’s algorithm: example (2)

resulting shortest-path tree from u:

resulting forwarding table in u:

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

**Oscillations possible:**

- e.g., support link cost equals amount of carried traffic:

![Diagram](Image)

Initially

1. given these costs, find new routing..., resulting in new costs
2. given these costs, find new routing..., resulting in new costs
3. given these costs, find new routing..., resulting in new costs

Network Layer 4-46
Chapter 4: outline

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4.2 virtual circuit and datagram networks
4.3 what’s inside a router
4.4 IP: Internet Protocol
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   - IPv4 addressing
   - ICMP
   - IPv6

4.5 routing algorithms
   - link state
   - distance vector
   - hierarchical routing

4.6 routing in the Internet
   - RIP
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4.7 broadcast and multicast routing
Distance vector algorithm

Bellman-Ford equation (dynamic programming)

let
\[ d_x(y) := \text{cost of least-cost path from } x \text{ to } y \]
then
\[ d_x(y) = \min_v \{ c(x,v) + d_v(y) \} \]

- cost from neighbor \( v \) to destination \( y \)
- cost to neighbor \( v \)

\( \min \) taken over all neighbors \( v \) of \( x \)
Bellman-Ford example

clearly, \( d_v(z) = 5 \), \( d_x(z) = 3 \), \( d_w(z) = 3 \)

B-F equation says:

\[
d_u(z) = \min \{ c(u,v) + d_v(z), \quad c(u,x) + d_x(z), \quad c(u,w) + d_w(z) \}
\]

\[
= \min \{ 2 + 5, \quad 1 + 3, \quad 5 + 3 \} = 4
\]

node achieving minimum is next hop in shortest path, used in forwarding table
Distance vector algorithm

- $D_x(y) = \text{estimate of least cost from } x \text{ to } y$
  - $x$ maintains distance vector $D_x = [D_x(y) : y \in N]$
- node $x$:
  - knows cost to each neighbor $v$: $c(x, v)$
  - maintains its neighbors’ distance vectors. For each neighbor $v$, $x$ maintains $D_v = [D_v(y) : y \in N]$
**Distance vector algorithm**

**key 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

iterative, asynchronous:
  each local iteration caused by:
  - local link cost change
  - DV update message from neighbor

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

each node:

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

recompute estimates

if DV to any dest has changed, *notify* neighbors
\[ D_x(y) = \min\{c(x,y) + D_y(y), c(x,z) + D_z(y)\} \]
\[ = \min\{2+0 , 7+1\} = 2 \]

\[ D_x(z) = \min\{c(x,y) + D_y(z), c(x,z) + D_z(z)\} \]
\[ = \min\{2+1 , 7+0\} = 3 \]
$D_x(y) = \min\{c(x,y) + D_y(y), c(x,z) + D_z(y)\} = \min\{2+0, 7+1\} = 2$

$D_x(z) = \min\{c(x,y) + D_y(z), c(x,z) + D_z(z)\} = \min\{2+1, 7+0\} = 3$
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:**
- node detects local link cost change
- *bad news travels slow* - “count to infinity” problem!
- 44 iterations before algorithm stabilizes: see text

**poisoned reverse:**
- If Z routes through Y to get to X:
  - Z tells Y its (Z’s) distance to X is infinite (so Y won’t route to X via Z)
- 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
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   - 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 600 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!*

![Diagram of AS networks](image)
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.

### Flowchart:

1. **learn from inter-AS protocol that subnet $x$ is reachable via multiple gateways**
2. **use routing info from intra-AS protocol to determine costs of least-cost paths to each of the gateways**
3. **hot potato routing:** choose the gateway that has the smallest least cost
4. **determine from forwarding table the interface $I$ that leads to least-cost gateway. Enter $(x,I)$ in forwarding table**
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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)

![Diagram of network with routers A, B, C, D and subnets u, v, w, x, y, z with their respective hops from router A to destination subnets.]

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 diagram:
- **W** connected to **A**
- **X** connected to **D**
- **Y** connected to **B**
- **Z** connected to a router off the diagram

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</th>
<th>hops</th>
</tr>
</thead>
<tbody>
<tr>
<td>w</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>x</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>z</td>
<td>C</td>
<td>4</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>x</td>
<td>--</td>
<td>1</td>
</tr>
<tr>
<td>....</td>
<td>....</td>
<td>....</td>
</tr>
</tbody>
</table>
RIP: link failure, 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
- advertisements flooded to entire AS
  - 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 database as OSPF
- **hierarchical** OSPF in large domains.
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.
Internet inter-AS routing: BGP

- BGP (Border Gateway Protocol): the de facto inter-domain routing protocol
  - “glue that holds the Internet together”
- BGP provides each AS a means to:
  - **eBGP**: obtain subnet reachability information from neighboring ASs.
  - **iBGP**: propagate reachability information to all AS-internal routers.
  - determine “good” routes to other networks based on reachability information and policy.
- allows subnet to advertise its existence to rest of Internet: “I am here”
**BGP basics**

- **BGP session:** two BGP routers ("peers") exchange BGP messages:
  - advertising *paths* to different destination network prefixes ("path vector" protocol)
  - exchanged over semi-permanent TCP connections

- **when AS3 advertises a prefix to AS1:**
  - AS3 *promises* it will forward datagrams towards that prefix
  - AS3 can aggregate prefixes in its advertisement
BGP basics: distributing path information

- using eBGP session between 3a and 1c, AS3 sends prefix reachability info to AS1.
  - 1c can then use iBGP do distribute new prefix info to all routers in AS1
  - 1b can then re-advertise new reachability info to AS2 over 1b-to-2a eBGP session

- when router learns of new prefix, it creates entry for prefix in its forwarding table.
BGP route selection

- router may learn about more than 1 route to destination AS, selects route based on:
  1. local preference value attribute: policy decision
  2. shortest AS-PATH
  3. closest NEXT-HOP router: hot potato routing
  4. additional criteria
BGP routing policy

- A, B, C are *provider networks*
- X, W, Y are customer (of provider networks)
- X is *dual-homed:* attached to two networks
  - X does not want to route from B via X to C
  - .. so X will not advertise to B a route to C
BGP routing policy (2)

- A advertises path AW to B
- B advertises path BAW to X
- Should B advertise path BAW to C?
  - No way! B gets no “revenue” for routing CBAW since neither W nor C are B’s customers
  - B wants to force C to route to w via A
  - B wants to route only to/from its customers!
Why different Intra-, Inter-AS routing?

Policy:
- inter-AS: admin wants control over how its traffic routed, who routes through its net.
- intra-AS: single admin, so no policy decisions needed

Scale:
- hierarchical routing saves table size, reduced update traffic

Performance:
- intra-AS: can focus on performance
- inter-AS: policy may dominate over performance
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4.6 routing in the Internet
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   - OSPF
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4.7 broadcast and multicast routing
Broadcast routing

- deliver packets from source to all other nodes
- source duplication is inefficient:

- source duplication: how does source determine recipient addresses?
In-network duplication

- **flooding**: when node receives broadcast packet, sends copy to all neighbors
  - problems: cycles & broadcast storm
- **controlled flooding**: node only broadcasts pkt if it hasn’t broadcast same packet before
  - node keeps track of packet ids already broadcasted
  - or reverse path forwarding (RPF): only forward packet if it arrived on shortest path between node and source
- **spanning tree**:
  - no redundant packets received by any node
Spanning tree

- first construct a spanning tree
- nodes then forward/make copies only along spanning tree

(a) broadcast initiated at A

(b) broadcast initiated at D
Spanning tree: creation

- center node
- each node sends unicast join message to center node
  - message forwarded until it arrives at a node already belonging to spanning tree

(a) stepwise construction of spanning tree (center: E)
(b) constructed spanning tree
Multicast routing: problem statement

**goal:** find a tree (or trees) connecting routers having local mcast group members

- **tree:** not all paths between routers used
- **shared-tree:** same tree used by all group members
- **source-based:** different tree from each sender to rcvrs

**legend**
- group member
- not group member
- router with a group member
- router without group member

shared tree

source-based trees
Approaches for building mcast trees

approaches:

- **source-based tree**: one tree per source
  - shortest path trees
  - reverse path forwarding

- **group-shared tree**: group uses one tree
  - minimal spanning (Steiner)
  - center-based trees

...we first look at basic approaches, then specific protocols adopting these approaches
Shortest path tree

- mcast forwarding tree: tree of shortest path routes from source to all receivers
  - Dijkstra’s algorithm

![Diagram showing shortest path tree with routers and links]

**LEGEND**
- Router with attached group member
- Router with no attached group member
- Link used for forwarding, i indicates order link added by algorithm

s: source
Reverse path forwarding

- rely on router’s knowledge of unicast shortest path from it to sender
- each router has simple forwarding behavior:

\[
\text{if} \ (\text{mcast datagram received on incoming link on shortest path back to center}) \\
\text{then} \ \text{flood datagram onto all outgoing links} \\
\text{else} \ \text{ignore datagram}
\]
Reverse path forwarding: example

- result is a source-specific reverse SPT
  - may be a bad choice with asymmetric links
Reverse path forwarding: pruning

- forwarding tree contains subtrees with no mcast group members
  - no need to forward datagrams down subtree
  - “prune” msgs sent upstream by router with no downstream group members

LEGEND
- router with attached group member
- router with no attached group member
- prune message
- links with multicast forwarding

s: source
Shared-tree: steiner tree

- **steiner tree**: minimum cost tree connecting all routers with attached group members
- problem is NP-complete
- excellent heuristics exists
- not used in practice:
  - computational complexity
  - information about entire network needed
  - monolithic: rerun whenever a router needs to join/leave
Center-based trees

- single delivery tree shared by all
- one router identified as “center” of tree
- to join:
  - edge router sends unicast join-msg addressed to center router
  - join-msg “processed” by intermediate routers and forwarded towards center
  - join-msg either hits existing tree branch for this center, or arrives at center
  - path taken by join-msg becomes new branch of tree for this router
Center-based trees: example

suppose R6 chosen as center:

LEGEND

- router with attached group member
- router with no attached group member
- path order in which join messages generated
Internet Multicasting Routing: DVMRP

- **DVMRP**: distance vector multicast routing protocol, RFC1075
- **flood and prune**: reverse path forwarding, source-based tree
  - RPF tree based on DVMRP’s own routing tables constructed by communicating DVMRP routers
  - no assumptions about underlying unicast
  - initial datagram to mcast group flooded everywhere via RPF
  - routers not wanting group: send upstream prune msgs
DVMRP: continued…

- **soft state**: DVMRP router periodically (1 min.) “forgets” branches are pruned:
  - mcast data again flows down unpruned branch
  - downstream router: reprune or else continue to receive data

- routers can quickly regraft to tree
  - following IGMP join at leaf

- odds and ends
  - commonly implemented in commercial router
Tunneling

Q: how to connect “islands” of multicast routers in a “sea” of unicast routers?

- mcast datagram encapsulated inside “normal” (non-multicast-addressed) datagram
- normal IP datagram sent thru “tunnel” via regular IP unicast to receiving mcast router (recall IPv6 inside IPv4 tunneling)
- receiving mcast router unencapsulates to get mcast datagram
PIM: Protocol Independent Multicast

- not dependent on any specific underlying unicast routing algorithm (works with all)

- two different multicast distribution scenarios:
  - dense:
    - group members densely packed, in “close” proximity.
    - bandwidth more plentiful
  - sparse:
    - # networks with group members small wrt # interconnected networks
    - group members “widely dispersed”
    - bandwidth not plentiful
Consequences of sparse-dense dichotomy:

**dense**
- group membership by routers *assumed* until routers explicitly prune
- *data-driven* construction on mcast tree (e.g., RPF)
- bandwidth and non-group-router processing *profligate*

**sparse:**
- no membership until routers explicitly join
- *receiver-driven* construction of mcast tree (e.g., center-based)
- bandwidth and non-group-router processing *conservative*
PIM- Dense mode

flood-and-prune RPF: similar to DVMRP but…

- underlying unicast protocol provides RPF info for incoming datagram
- less complicated (less efficient) downstream flood than DVMRP reduces reliance on underlying routing algorithm
- has protocol mechanism for router to detect if it is a leaf-node router
PIM - sparse mode

- center-based approach
- router sends *join* msg to rendezvous point (RP)
  - intermediate routers update state and forward *join*
- after joining via RP, router can switch to source-specific tree
  - increased performance: less concentration, shorter paths

![Diagram with labeled nodes R1 to R7 showing join messages and data multicast paths](image-url)
sender(s):

- unicast data to RP, which distributes down RP-rooted tree
- RP can extend mcast tree upstream to source
- RP can send stop msg if no attached receivers
  - “no one is listening!”
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   - RIP, OSPF, BGP
4.7 broadcast and multicast routing

- understand principles behind network layer services:
  - network layer service models, forwarding versus routing
  - how a router works, routing (path selection), broadcast, multicast
- instantiation, implementation in the Internet