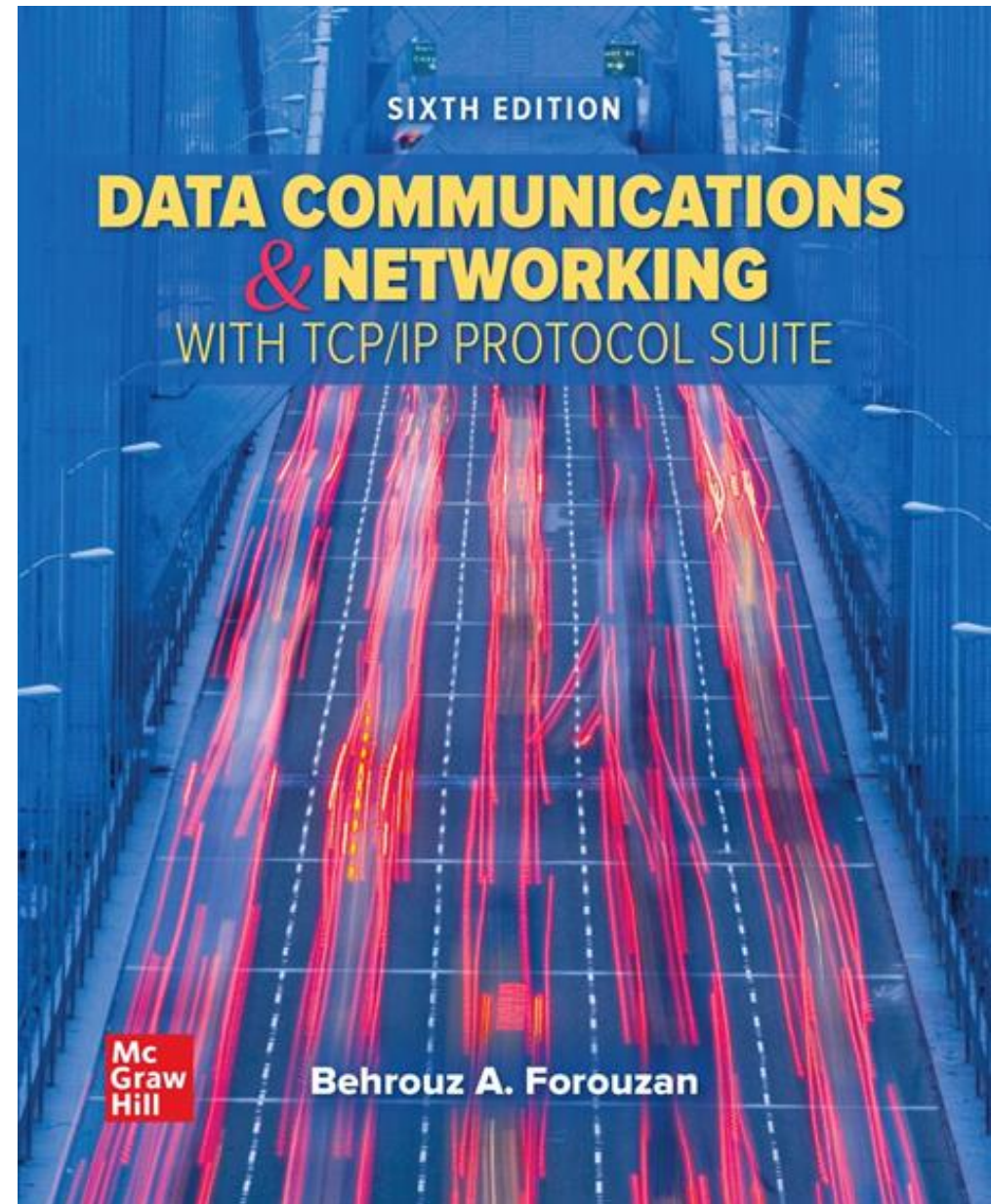


Chapter 08

Network Layer: Routing of Packets

- Data Communications and Networking, With TCP/IP protocol suite Sixth Edition
- Behrouz A. Forouzan



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Chapter 8: Outline

- **8.1 Introduction**
- **8.2 Routing Algorithms**

Routing (IP routing)

- Routing Protocol: determines the **best path** (route) that the packets should follow to arrive to the desired destination
- Routing Protocols: A **software** in the network layer that implements **routing algorithms** and responsible for:
 - **Filling and updating** routing tables (by finding the shortest paths (**best path**) from each source to each destination) This part is called **Routing**
 - **Deciding which output interface** an incoming packet should be transmitted on (by referring to the routing table). This part is called **Forwarding**

8-1 INTRODUCTION

- Unicast routing in the Internet, with a large number of routers and a huge number of hosts, can be done only by using hierarchical routing: routing in several steps using different routing algorithms.

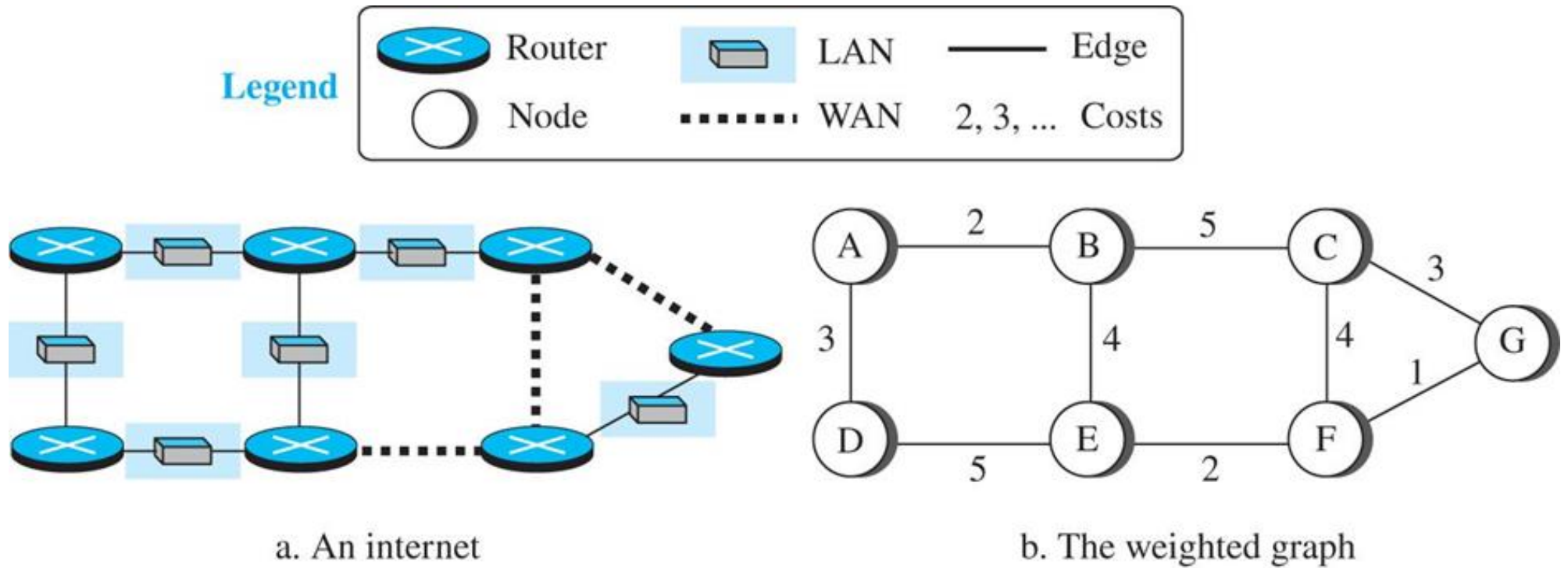
8.1.1 General Idea

- In unicast routing, a packet is routed, hop by hop, from its source to its destination by the help of forwarding tables.
- The source host needs no forwarding table because it delivers its packet to the default router in its local network.
- The destination host needs no forwarding table either because it receives the packet from its default router in its local network.
- This means that only the routers that glue together the networks in the internet need forwarding tables.

An Internet as a Graph

- To find the best route, an internet can be modeled as a graph.
- A graph in computer science is a set of nodes and edges (lines) that connect the nodes.
- To model an internet as a graph, we can think of each router as a node and each network between a pair of routers as an edge.
- An internet is, in fact, modeled as a weighted graph, in which each edge is associated with a cost.

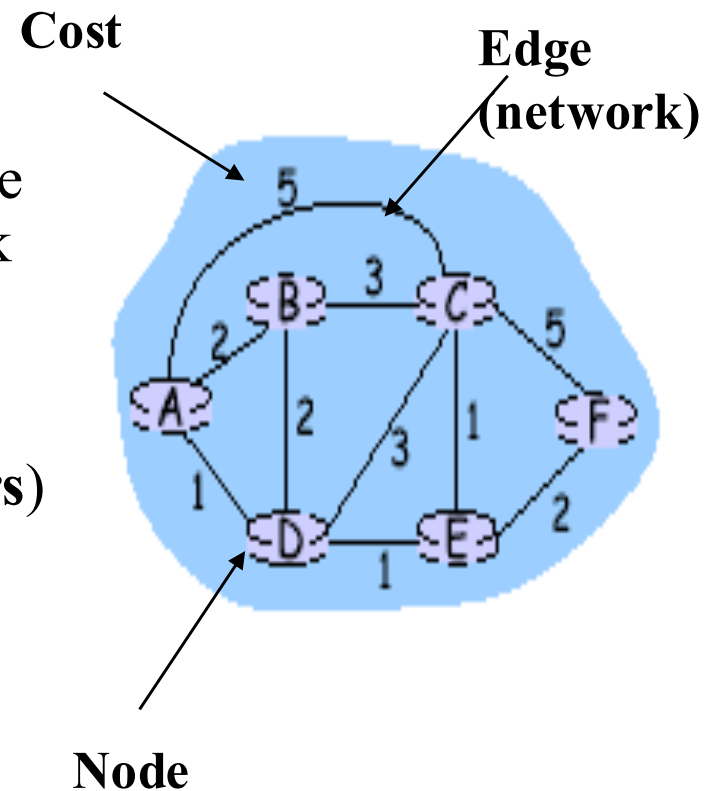
Figure 8.1 An internet and its graphical representation



Graph representation of a network

- Graph **nodes** are **routers**
- Graph **edges** are **physical links**
 - Each link has a value which represents the “cost” of sending a packet across the link
 - The **cost** is assigned based on a **metric**
 - Cost metric can be:
 - Number of networks (**hops or routers**)
 - Geographic distance
 - Link delay
 - Capacity (speed)
 - Reliability
 - Combination of the above
- How to select a “good” path???

- Good path is the one with **minimum cost** = \sum **Total cost from src to dest**

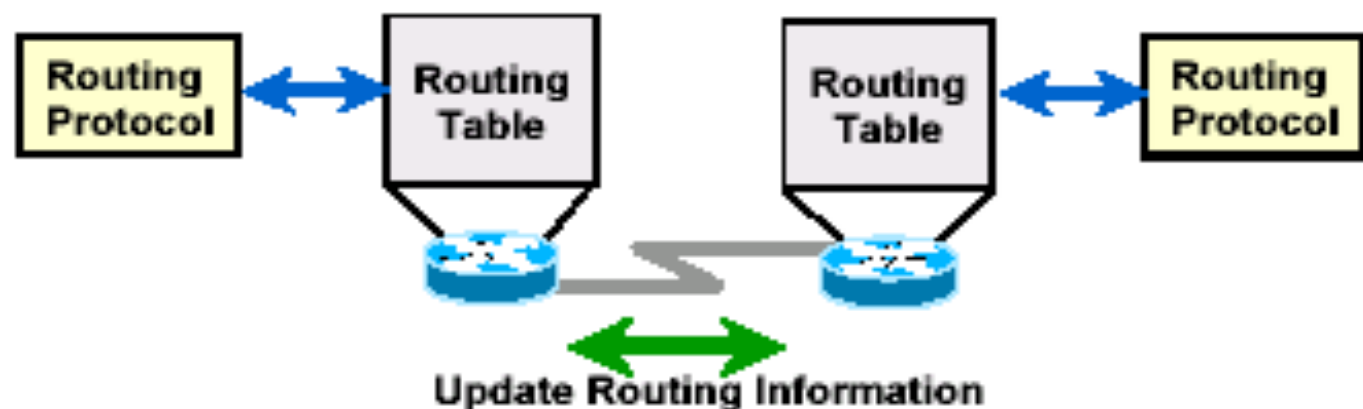


Routing Algorithms Classifications

- Static
 - Routes change **slowly** over time
 - Shortest paths are precomputed offline by a special computer running the routing algorithm
 - Resulted information is entered manually by the administrator into the routing tables
 - **Can not** update automatically if there is a change in the network or failure
 - Used in **small** networks
- Dynamic (adaptive)
 - Each router or host learns the state of the network by **communicating** with its **neighbours (routers that are directly connected to each other).**
 - Based on the collected information, each node (router) can fill its routing table
 - More complexity is added to the router

Routing algorithm: Dynamic Route operation

- Routing protocol maintains and distributes routing information



How to **reduce** number of entries in the **routing table**?

- Network-Specific routing (Destination Network IP Address is listed in the table)
- Host Specific Routing (Destination Host IP Address is listed in the table)
- Default Routing

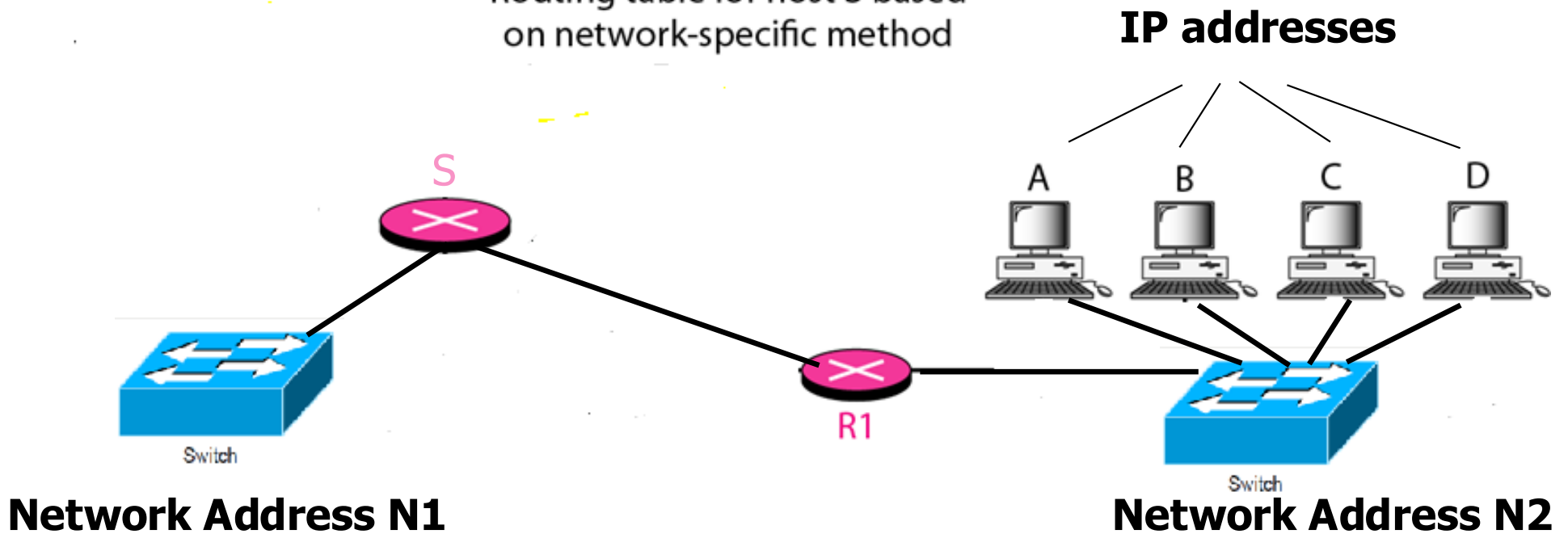
Host-specific versus network-specific method

| Destination | Next Hop |
|-------------|--------------------|
| N1 | Directly Connected |
| A | R1 |
| B | R1 |
| C | R1 |
| D | R1 |

Routing table for host S based on host-specific method

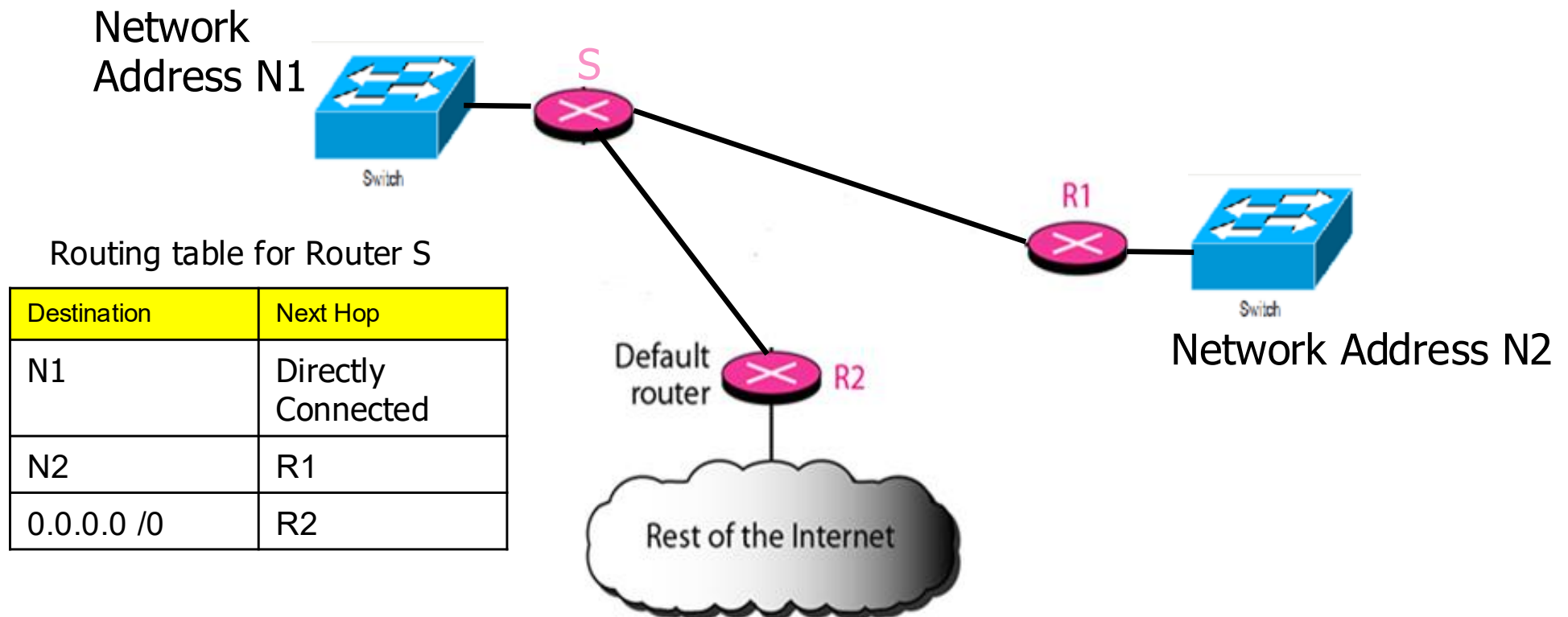
| Destination | Next Hop |
|-------------|--------------------|
| N1 | Directly Connected |
| N2 | R1 |

Routing table for host S based on network-specific method



Default Route

- Default route is used if the destination network address is not found in the routing table
- 0.0.0.0 /0 is the address used for default route
- 0.0.0.0 /0 corresponds to any other in the routing table



18-5 FORWARDING OF IP PACKETS

We discussed the concept of forwarding at the network layer earlier in this chapter. In this section, we extend the concept to include the role of IP addresses in forwarding. As we discussed before, forwarding means to place the packet in its route to its destination.

Destination Address Forwarding

We first discuss forwarding based on the **destination address**. This is a traditional approach, which is prevalent today. In this case, forwarding requires a host or a router to have **a forwarding table**. When a host has a packet to send or when a router has received a packet to be forwarded, it looks at this table to find the next hop to deliver the packet to.

Classful addressing routing table

| | Mask | Destination address | Next-hop address | Interface |
|-----------------|------|---------------------|------------------|-----------|
| | /8 | 14.0.0.0 | 118.45.23.8 | m1 |
| Host-specific → | /32 | 192.16.7.1 | 202.45.9.3 | m0 |
| | /24 | 193.14.5.0 | 84.78.4.12 | m2 |
| Default → | /0 | 0.0.0.0 | 145.11.10.6 | m0 |

- **When a packet arrives:**
 - **Apply all the available masks to the IP destination address**
 - **If a match is found in the destination address column, the packet has to be forwarded to the next hop IP address through the corresponding interface**
 - **If no match is found, send the packet through the default interface**
 - **Otherwise, a message “host unreachable error” is sent back to the sender.**

Example

| | Mask | Destination address | Next-hop address | Interface |
|-----------------|------|---------------------|------------------|-----------|
| | /8 | 14.0.0.0 | 118.45.23.8 | m1 |
| Host-specific → | /32 | 192.16.7.1 | 202.45.9.3 | m0 |
| | /24 | 193.14.5.0 | 84.78.4.12 | m2 |
| Default → | /0 | 0.0.0.0 | 145.11.10.6 | m0 |

Using the table above, the router receives a packet for destination 193.14.5.22. For each row, the mask is applied to the destination address until a match with the next-hop address is found. In this example, the router sends the packet through interface m2 (**network specific**).

Example

| | Mask | Destination address | Next-hop address | Interface |
|-----------------|------|---------------------|------------------|-----------|
| | /8 | 14.0.0.0 | 118.45.23.8 | m1 |
| Host-specific → | /32 | 192.16.7.1 | 202.45.9.3 | m0 |
| | /24 | 193.14.5.0 | 84.78.4.12 | m2 |
| Default → | /0 | 0.0.0.0 | 145.11.10.6 | m0 |

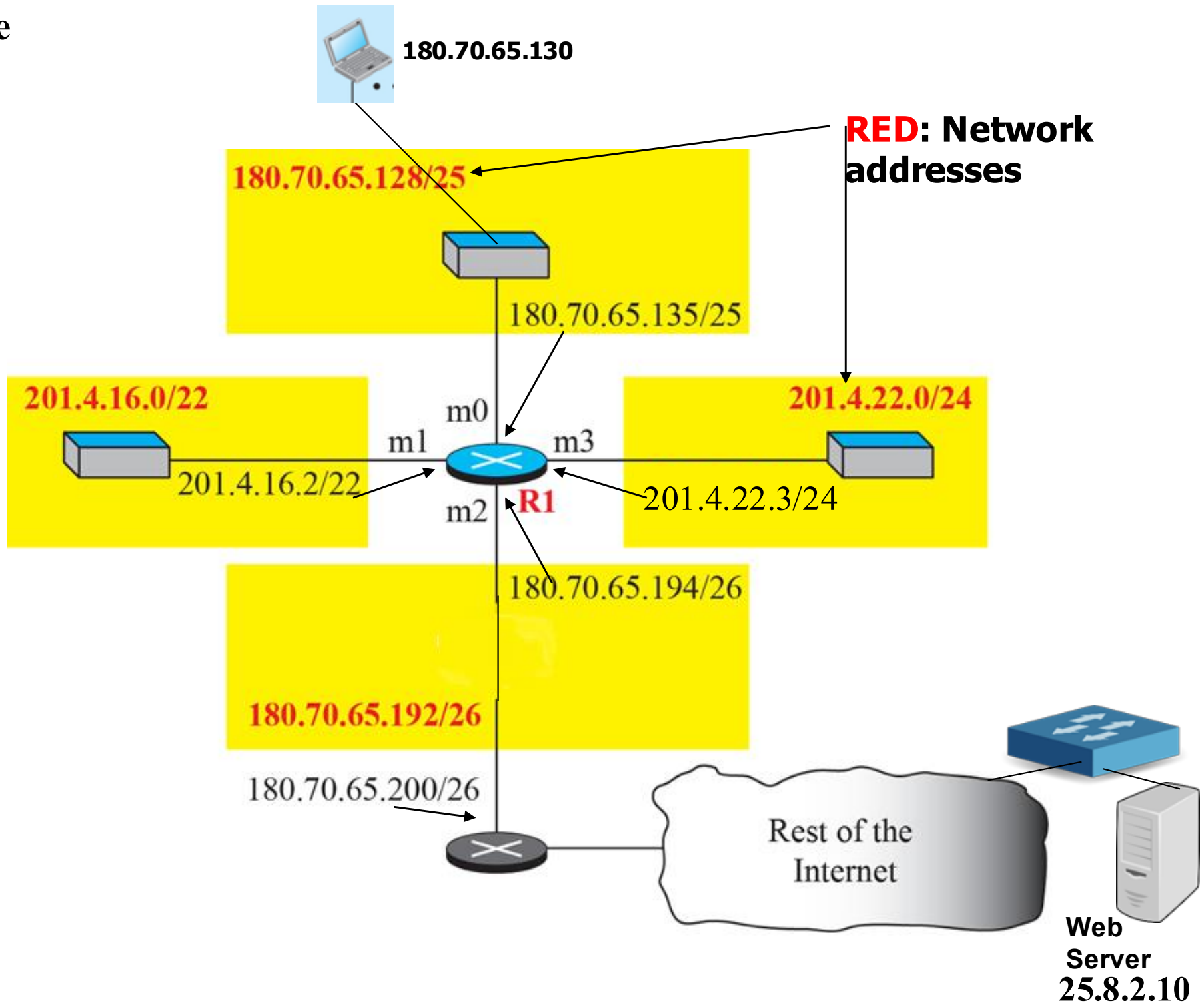
Using the table above, the router receives a packet for destination 200.34.12.34. For each row, the mask is applied to the destination address, but no match is found. In this example, the router sends the packet through the **default interface** m0.

Example

| | Mask | Destination address | Next-hop address | Interface |
|-----------------|------|---------------------|------------------|-----------|
| | /8 | 14.0.0.0 | 118.45.23.8 | m1 |
| Host-specific → | /32 | 192.16.7.1 | 202.45.9.3 | m0 |
| | /24 | 193.14.5.0 | 84.78.4.12 | m2 |
| Default → | /0 | 0.0.0.0 | 145.11.10.6 | m0 |

Using the table above, the router receives a packet for destination **192.16.7.1**. For each row, the mask is applied to the destination address until a match with the destination address is found. In this example, the router sends the packet through interface m0 (**host specific**).

Example



Make a forwarding table for router R1 using the configuration in previous slide

Solution

"-" means Directly connected network

Forwarding table for router R1

| <i>Network address/mask</i> | <i>Next hop</i> | <i>Interface</i> |
|-----------------------------|-----------------|------------------|
| 180.70.65.192/ 26 | — | m2 |
| 180.70.65.128/ 25 | — | m0 |
| 201.4.22.0/ 24 | — | m3 |
| 201.4.16.0/ 22 | — | m1 |
| 0.0.0.0 /0 | 180.70.65.200 | m2 |

Show the forwarding process if a packet arrives at R1 with the **destination address 180.70.65.130**.

Solution

The router performs the following steps:

1. The first mask (**/26**) is applied to the destination address. The result is **180.70.65.128**, which does not match the corresponding network address.
2. The second mask (**/25**) is applied to the destination address. The result is **180.70.65.128**, which matches the corresponding network address. The next-hop address and the interface number m0 are extracted for forwarding the packet

Show the forwarding process if a packet arrives at R1 with the **destination address 25.8.2.10**.

Solution

The router performs the following steps:

- 1.** The first mask (**/26**) is applied to the destination address. The result is **25.8.2.0**, which does not match the corresponding network address.
- 2.** The second mask (**/25**) is applied to the destination address. The result is **25.8.2.0**, which does not match the corresponding network address.
- 3.** The second mask (**/24**) is applied to the destination address. The result is **25.8.2.0**, which does not match the corresponding network address.
- 4.** The second mask (**/22**) is applied to the destination address. The result is **25.8.0.0**, which does not match the corresponding network address.

In this example, the router sends the packet to the **default route**. The **next-hop address will be 180.70.65.200** through **interface m2**.

Shortest Path Routing

- Algorithms used to determine the shortest path between two nodes according to some cost condition.
- The shortest path is the path with the *least cost* (the sum of the cost of the links on the path is minimum over all possible paths between the source and destination)
- Two main algorithms to find the shortest path between any two nodes
 - Distance Vector (**Bellman-Ford** Algorithm)
 - Link State – (**Dijkstra's** Algorithm)

Distance Vector (DV) Routing

- Basic idea: each network node maintains a **Distance Vector (DV) table** containing the *distances from* itself to **ALL** possible destination nodes in the domain.
- Distances are based on a chosen metric (Metric: *usually number of hops, bandwidth, delay*)
- Router transmits its *distance vector table* to each of its **neighbors** (**directly connected to it**) **periodically** or when there is a change.
- A router **recalculates** its distance vector when:
 - It receives a *distance vector table* from a neighbor containing different information than before.
 - It discovers that a link to a neighbor has gone down or up (i.e., a **topology changes**).
- Distances to all destinations are computed using information from thereceived **neighbors'** distance vectors.
- The DV calculation is based on minimizing the cost to each destination.
- From its DV, a router can directly derive its **routing table**.
- **Enhanced Interior Gateway Routing Protocol (EIGRP) and Routing Information Protocol (RIP) are examples of distance vector protocols**

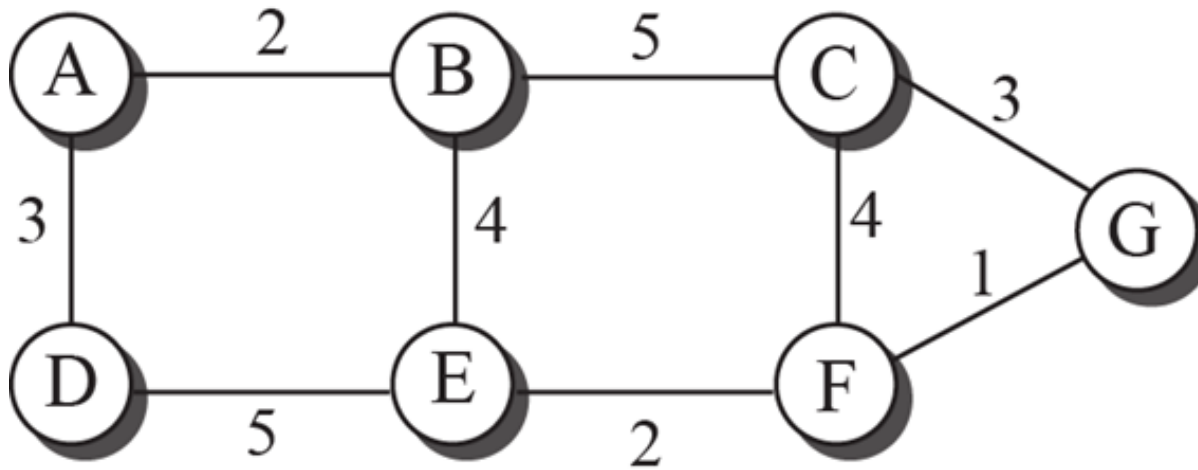
The **first round** distance vector for an internet
 It has only the cost to the directly
 connected neighbors

| | |
|---|----------|
| A | 0 |
| B | 2 |
| C | ∞ |
| D | 3 |
| E | ∞ |
| F | ∞ |
| G | ∞ |

| | |
|---|----------|
| A | 2 |
| B | 0 |
| C | 5 |
| D | ∞ |
| E | 4 |
| F | ∞ |
| G | ∞ |

| | |
|---|----------|
| A | ∞ |
| B | 5 |
| C | 0 |
| D | ∞ |
| E | ∞ |
| F | 4 |
| G | 3 |

∞ : means not
 reachable



| | |
|---|----------|
| A | ∞ |
| B | ∞ |
| C | 3 |
| D | ∞ |
| E | ∞ |
| F | 1 |
| G | 0 |

| | |
|---|----------|
| A | 3 |
| B | ∞ |
| C | ∞ |
| D | 0 |
| E | 5 |
| F | ∞ |
| G | ∞ |

| | |
|---|----------|
| A | ∞ |
| B | 4 |
| C | ∞ |
| D | 5 |
| E | 0 |
| F | 2 |
| G | ∞ |

| | |
|---|----------|
| A | ∞ |
| B | ∞ |
| C | 4 |
| D | ∞ |
| E | 2 |
| F | 0 |
| G | 1 |

Updating distance vectors (case for node B)

| New B | | Old B | | A | |
|-------|---|-------|---|---|---|
| A | 2 | A | 2 | A | 0 |
| B | 0 | B | 0 | B | 2 |
| C | 5 | C | 5 | C | ∞ |
| D | 5 | D | ∞ | D | 3 |
| E | 4 | E | 4 | E | ∞ |
| F | ∞ | F | ∞ | F | ∞ |
| G | ∞ | G | ∞ | G | ∞ |

$B[] = \min (B[], 2 + A[])$

a. First event: B receives a copy of A's vector.

Minimum Cost from B to A is 2

A sends its distance vector table to B

Note:
X[]: the whole vector

E sends its distance vector table to B

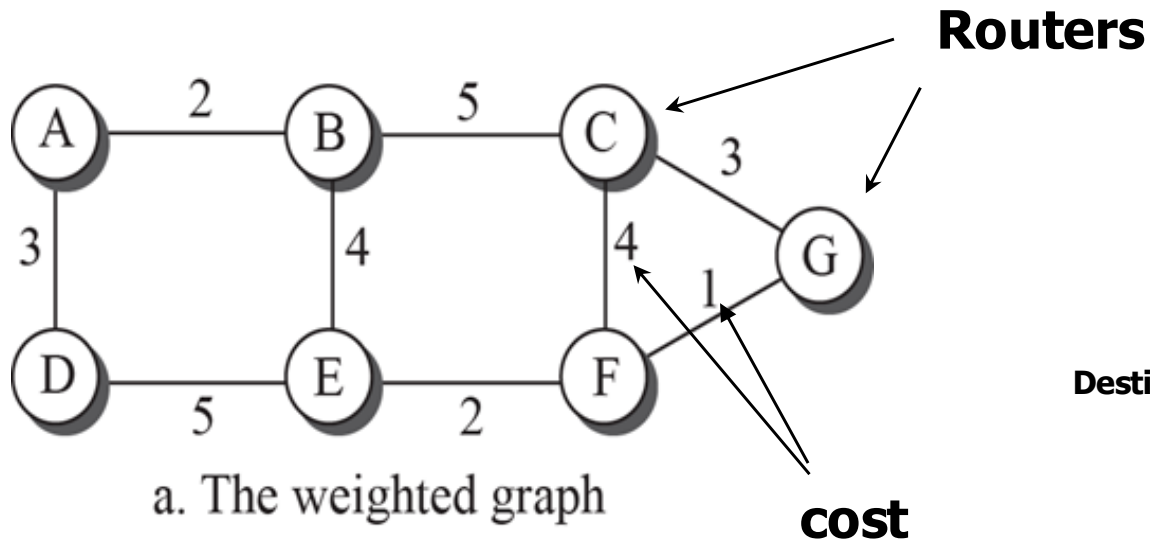
| New B | | Old B | | E | |
|-------|---|-------|---|---|---|
| A | 2 | A | 2 | A | ∞ |
| B | 0 | B | 0 | B | 4 |
| C | 5 | C | 5 | C | ∞ |
| D | 5 | D | 5 | D | 5 |
| E | 4 | E | 4 | E | 0 |
| F | 6 | F | ∞ | F | 2 |
| G | ∞ | G | ∞ | G | ∞ |

$B[] = \min (B[], 4 + E[])$

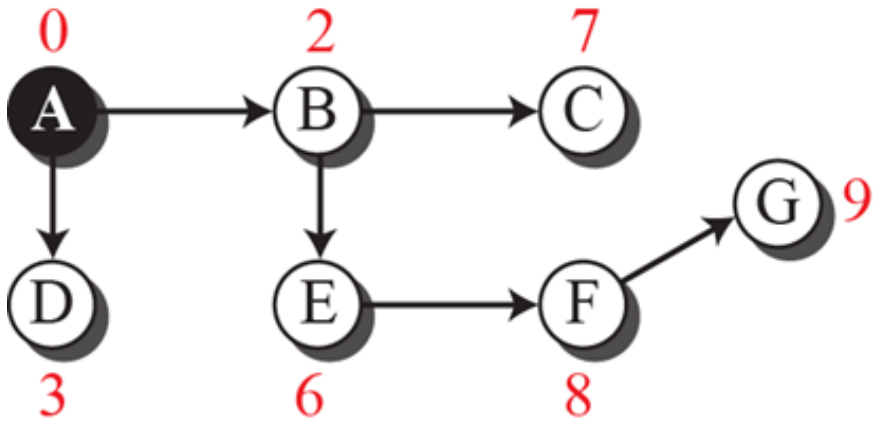
b. Second event: B receives a copy of E's vector.

Minimum Cost from B to E is 4

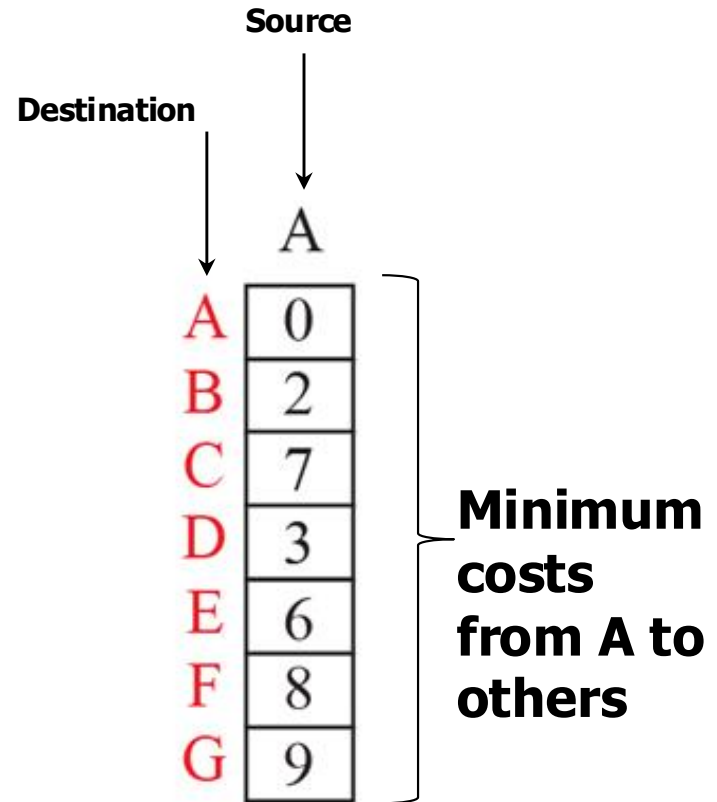
The distance vector corresponding to a tree



a. The weighted graph

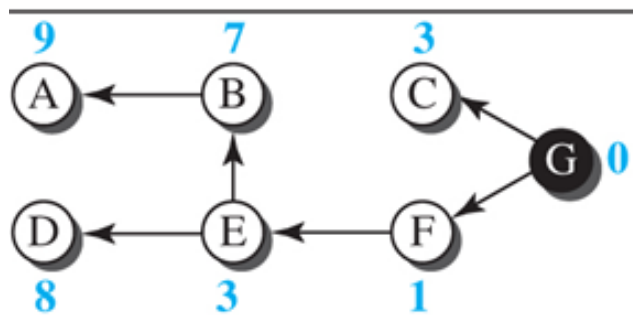
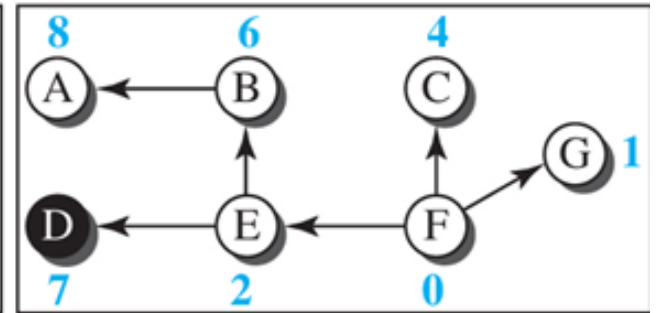
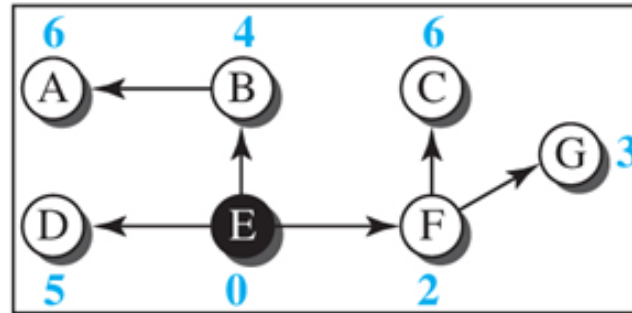
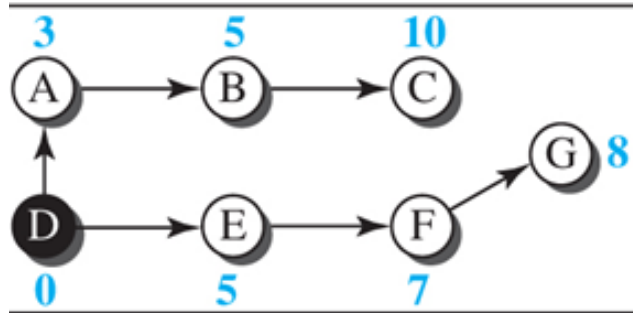
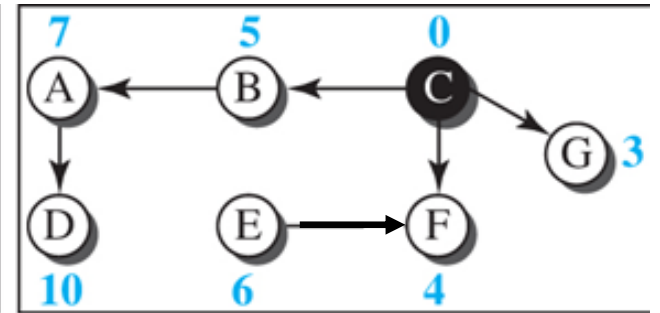
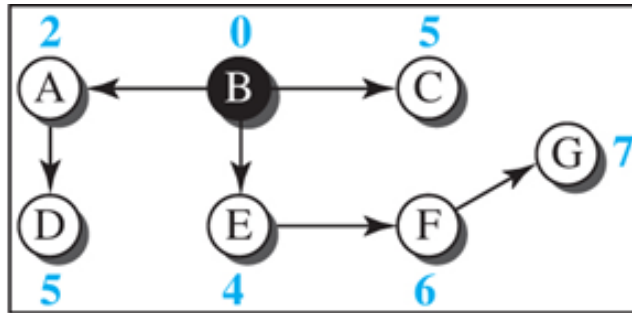
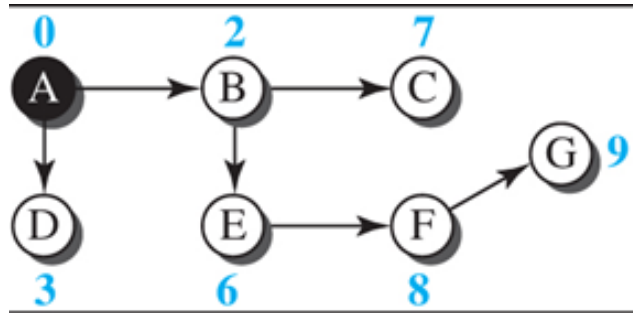


a. Tree for node A





b. Distance vector for node A

Least-cost trees for nodes for the previous network



Legend

-  Root of the tree
-  Intermediate or end node
- 1, 2, ... Total cost from the root

Link State Routing

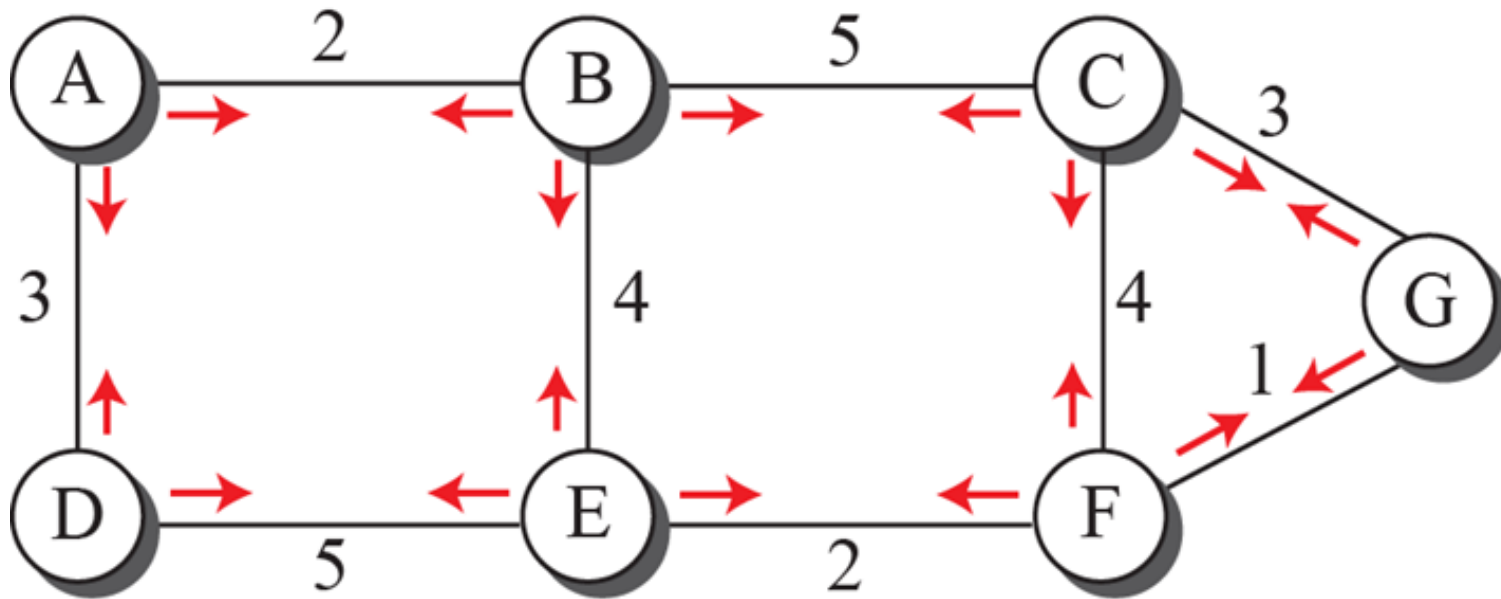
- Each router measures the cost (in either delay, Bandwidth) between itself and its neighbour routers (directly connected)
- The router builds a packet containing all these costs.
- Each router distributes these packets using **flooding** to **ALL** other routers in **the routing area**
- Information is then sent when **there a change** in the link between the router and its neighbours (to reduce traffic)
- Each router builds map (database) of the **entire network**, uses a **shortest-path algorithm** (usually Dijkstra algorithm) to compute a shortest path between itself and any other node in the area (creates the routing table)
- **OSPF** (Open Shortest Path first is an Example)

Link State Packets (LSPs) created and sent out by each node to build LSDB

| Node | Cost |
|------|------|
| B | 2 |
| D | 3 |

| Node | Cost |
|------|------|
| A | 2 |
| C | 5 |
| E | 4 |

| Node | Cost |
|------|------|
| B | 5 |
| F | 4 |
| G | 3 |



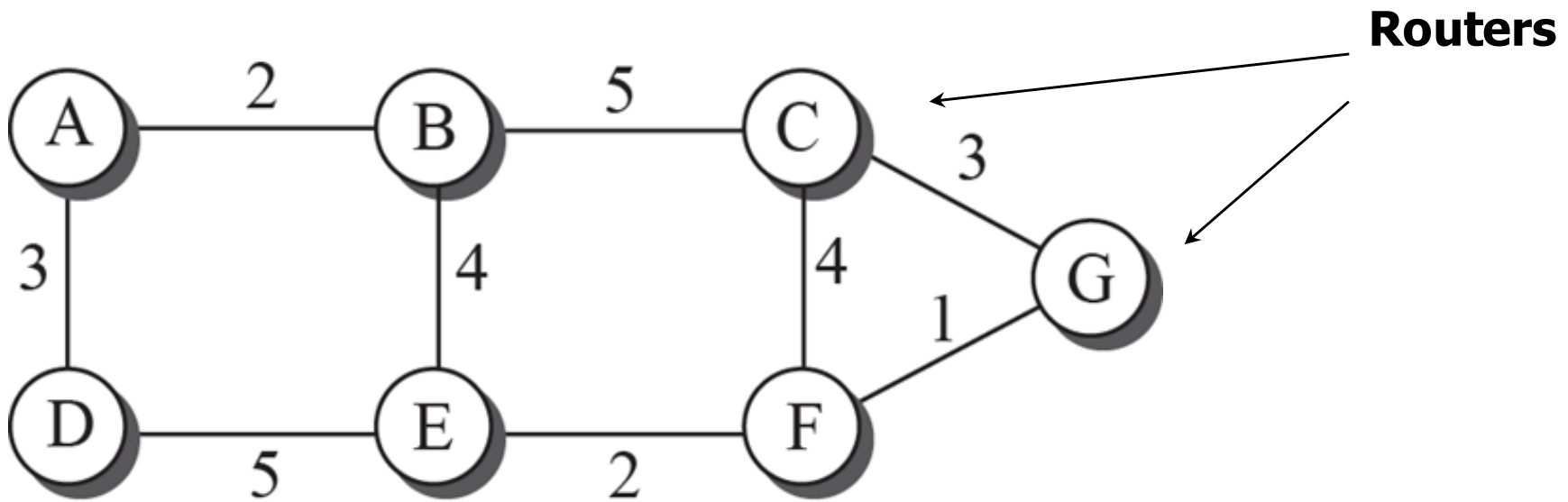
| Node | Cost |
|------|------|
| C | 3 |
| F | 1 |

| Node | Cost |
|------|------|
| A | 3 |
| E | 5 |

| Node | Cost |
|------|------|
| B | 4 |
| D | 5 |
| E | 2 |

| Node | Cost |
|------|------|
| C | 4 |
| E | 2 |
| G | 1 |

Example of a link-state database (LSDB)



a. The weighted graph

Each router will have the same link state database

| | A | B | C | D | E | F | G |
|---|----------|----------|----------|----------|----------|----------|----------|
| A | 0 | 2 | ∞ | 3 | ∞ | ∞ | ∞ |
| B | 2 | 0 | 5 | ∞ | 4 | ∞ | ∞ |
| C | ∞ | 5 | 0 | ∞ | ∞ | 4 | 3 |
| D | 3 | ∞ | ∞ | 0 | 5 | ∞ | ∞ |
| E | ∞ | 4 | ∞ | 5 | 0 | 2 | ∞ |
| F | ∞ | ∞ | 4 | ∞ | 2 | 0 | 1 |
| G | ∞ | ∞ | 3 | ∞ | ∞ | 1 | 0 |

b. Link state database

Comparison between distance vector & Link state

■ Distance vector routing

- Each router Sends routing information to its neighbours
- The information sent is an estimate of the path cost to all known destinations in the area
- Information is sent periodically (every 30 s) by the router's own timer
- React to link failure very slowly

■ Link state routing

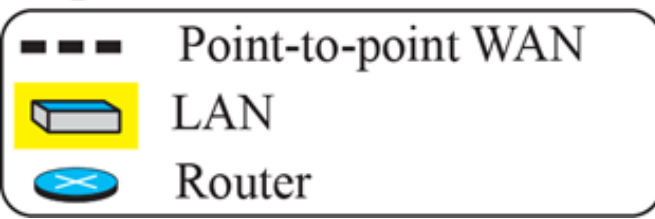
- Each router sends routing information to ALL routers in the area
- The information sent is the exact value of the links cost that connect the router to its neighbours
- Information is sent when there is a change
- React to network failure quickly

Autonomous systems (AS)

- On the Internet, Autonomous system (AS) is either a **single network** or a **group of networks** that is controlled by a **common network administrator**
- An autonomous system is assigned **a globally unique number**, sometimes called an Autonomous System Number (ASN).
- AS systems are connected by special routers called **boarder routers or gateways routers**.
- Routers in **same** AS run **same** routing protocol this is called “**intra-AS**” (**interior**) routing protocol
- Routing between autonomous systems is called **inter-AS** or **exterior routing**
- Gateways routers (boarder routers) are special routers in AS that run **intra-AS** routing protocol and also responsible for routing to destinations outside AS by running **inter-AS (exterior) routing** protocol with other gateway (boarder) routers

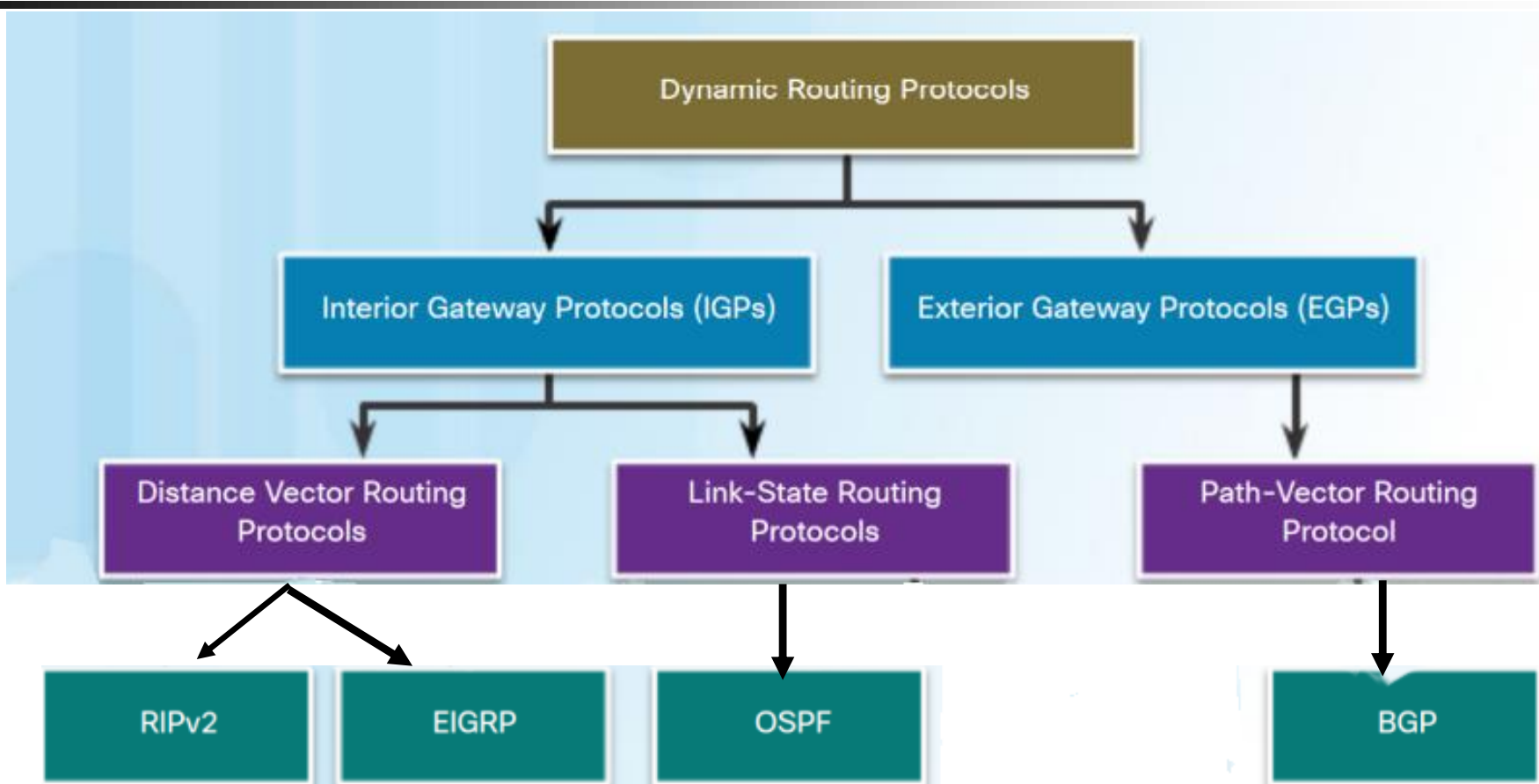
A sample internet with four ASs

Legend



- **Routers R1, R4, R5, R6 are designated as border gateway routers**
- **These routers run both interior and exterior routing protocols**

Popular routing protocols



- **Interior routing (RIP, OSPF, EIGRP):** between routers inside a single AS
- **Exterior routing (BGP):** between routers connecting several AS
 - **BGP stands for Border Gateway Protocol Routing**