Finally, there is a management cost for the administrative entity that is responsible for setting up the tunnels and making sure they are correctly handled by the routing protocols.

3.3 ROUTING

So far in this chapter we have assumed that the switches and routers have enough knowledge of the network topology so they can choose the right port onto which each packet should be output. In the case of virtual circuits, routing is an issue only for the connection request packet; all subsequent packets follow the same path as the request. In datagram networks, including IP networks, routing is an issue for every packet. In either case, a switch or router needs to be able to look at a destination address and then to determine which of the output ports is the best choice to get a packet to that address. As we saw in Section 3.1.1, the switch makes this decision by consulting a forwarding table. The fundamental problem of routing is how switches and routers acquire the information in their forwarding tables.

We restate an important distinction, which is often neglected, between *forwarding* and *routing*. Forwarding consists of taking a packet, looking at its destination address, consulting a table, and sending the packet in a direction determined by that table. We saw several examples of forwarding in the preceding section. Routing is the process by which forwarding tables are built. We also note that forwarding is a relatively simple and well-defined process performed locally at a node, whereas routing depends on complex distributed algorithms that have continued to evolve throughout the history of networking.

While the terms *forwarding table* and *routing table* are sometimes used interchangeably, we will make a distinction between them here. The forwarding table is used when a packet is being forwarded and so must contain enough information to accomplish the forwarding function. This means that a row in the forwarding table contains the mapping from a network prefix to an outgoing interface and some MAC information, such as the Ethernet address of the next hop. The routing table, on the other hand, is the table that is built up by the routing algorithms as a precursor to building the forwarding table. It generally contains mappings from network prefixes to next hops. It may also contain information about how this

Table 3.9 Example Rows from (a) Routing and (b) Forwarding Tables

(a)

Prefix/Length	Next Hop
18/8	171.69.245.10

(b)

Prefix/Length	Interface	MAC Address
18/8	if0	8:0:2b:e4:b:1:2

information was learned, so that the router will be able to decide when it should discard some information.

Whether the routing table and forwarding table are actually separate data structures is something of an implementation choice, but there are numerous reasons to keep them separate. For example, the forwarding table needs to be structured to optimize the process of looking up an address when forwarding a packet, while the routing table needs to be optimized for the purpose of calculating changes in topology. In many cases, the forwarding table may even be implemented in specialized hardware, whereas this is rarely if ever done for the routing table. Table 3.9 provides an example of a row from each sort of table. In this case, the routing table tells us that network prefix 18/8 is to be reached by a next hop router with the IP address 171.69.245.10, while the forwarding table contains the information about exactly how to forward a packet to that next hop: Send it out interface number 0 with a MAC address of 8:0:2b:e4:b:1:2. Note that the last piece of information is provided by the Address Resolution Protocol.

Before getting into the details of routing, we need to remind ourselves of the key question we should be asking anytime we try to build a mechanism for the Internet: "Does this solution scale?" The answer for the algorithms and protocols described in this section is "not so much." They are designed for networks of fairly modest size—up to a few hundred nodes, in practice. However, the solutions we describe do serve as a building block for a hierarchical routing infrastructure that is used in the Internet today. Specifically, the protocols described in this section are

collectively known as *intradomain* routing protocols, or *interior gateway protocols* (IGPs). To understand these terms, we need to define a routing *domain*. A good working definition is an internetwork in which all the routers are under the same administrative control (e.g., a single university campus, or the network of a single Internet Service Provider). The relevance of this definition will become apparent in the next chapter when we look at *interdomain* routing protocols. For now, the important thing to keep in mind is that we are considering the problem of routing in the context of small to midsized networks, not for a network the size of the Internet.

3.3.1 Network as a Graph

Routing is, in essence, a problem of graph theory. Figure 3.28 shows a graph representing a network. The nodes of the graph, labeled A through F, may be hosts, switches, routers, or networks. For our initial discussion, we will focus on the case where the nodes are routers. The edges of the graph correspond to the network links. Each edge has an associated *cost*, which gives some indication of the desirability of sending traffic over that link. A discussion of how edge costs are assigned is given in Section 3.3.4.[11]

The basic problem of routing is to find the lowest-cost path between any two nodes, where the cost of a path equals the sum of the costs of all the edges that make up the path. For a simple network like the one in Figure 3.28, you could imagine just calculating all the shortest paths and

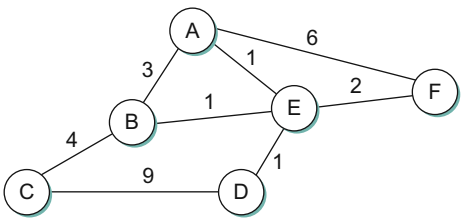


FIGURE 3.28 Network represented as a graph.

[11] In the example networks (graphs) used throughout this chapter, we use undirected edges and assign each edge a single cost. This is actually a slight simplification. It is more accurate to make the edges directed, which typically means that there would be a pair of edges between each node—one flowing in each direction, and each with its own edge cost.

loading them into some nonvolatile storage on each node. Such a static approach has several shortcomings:

- It does not deal with node or link failures.
- It does not consider the addition of new nodes or links.
- It implies that edge costs cannot change, even though we might reasonably wish to have link costs change over time (e.g., assigning high cost to a link that is heavily loaded).

For these reasons, routing is achieved in most practical networks by running routing protocols among the nodes. These protocols provide a distributed, dynamic way to solve the problem of finding the lowest-cost path in the presence of link and node failures and changing edge costs. Note the word *distributed* in the previous sentence; it is difficult to make centralized solutions scalable, so all the widely used routing protocols use distributed algorithms.[12]

The distributed nature of routing algorithms is one of the main reasons why this has been such a rich field of research and development—there are a lot of challenges in making distributed algorithms work well. For example, distributed algorithms raise the possibility that two routers will at one instant have different ideas about the shortest path to some destination. In fact, each one may think that the other one is closer to the destination and decide to send packets to the other one. Clearly, such packets will be stuck in a loop until the discrepancy between the two routers is resolved, and it would be good to resolve it as soon as possible. This is just one example of the type of problem routing protocols must address.

To begin our analysis, we assume that the edge costs in the network are known. We will examine the two main classes of routing protocols: *distance vector* and *link state*. In Section 3.3.4, we return to the problem of calculating edge costs in a meaningful way.

3.3.2 Distance-Vector (RIP)

The idea behind the distance-vector algorithm is suggested by its name.[13] Each node constructs a one-dimensional array (a vector) containing the "distances" (costs) to all other nodes and distributes that vector to its

[12]This widely held assumption, however, has been re-examined in recent years—see the Further Reading section.
[13]The other common name for this class of algorithm is Bellman-Ford, after its inventors.

immediate neighbors. The starting assumption for distance-vector routing is that each node knows the cost of the link to each of its directly connected neighbors. These costs may be provided when the router is configured by a network manager. A link that is down is assigned an infinite cost.

To see how a distance-vector routing algorithm works, it is easiest to consider an example like the one depicted in Figure 3.29. In this example, the cost of each link is set to 1, so that a least-cost path is simply the one with the fewest hops. (Since all edges have the same cost, we do not show the costs in the graph.) We can represent each node's knowledge about the distances to all other nodes as a table like Table 3.10. Note that each

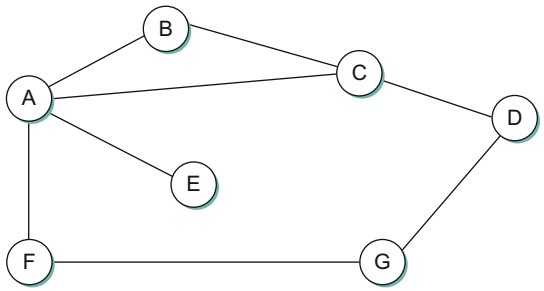


FIGURE 3.29 Distance-vector routing: an example network.

Table 3.10 Initial Distances Stored at Each Node (Global View)

Information Stored at Node	Distance to Reach Node						
	A	B	C	D	E	F	G
A	0	1	1	∞	1	1	∞
B	1	0	1	∞	∞	∞	∞
C	1	1	0	1	∞	∞	∞
D	∞	∞	1	0	∞	∞	1
E	1	∞	∞	∞	0	∞	∞
F	1	∞	∞	∞	∞	0	1
G	∞	∞	∞	1	∞	1	0

node knows only the information in one row of the table (the one that bears its name in the left column). The global view that is presented here is not available at any single point in the network.

We may consider each row in Table 3.10 as a list of distances from one node to all other nodes, representing the current beliefs of that node. Initially, each node sets a cost of 1 to its directly connected neighbors and ∞ to all other nodes. Thus, A initially believes that it can reach B in one hop and that D is unreachable. The routing table stored at A reflects this set of beliefs and includes the name of the next hop that A would use to reach any reachable node. Initially, then, A's routing table would look like Table 3.11.

The next step in distance-vector routing is that every node sends a message to its directly connected neighbors containing its personal list of distances. For example, node F tells node A that it can reach node G at a cost of 1; A also knows it can reach F at a cost of 1, so it adds these costs to get the cost of reaching G by means of F. This total cost of 2 is less than the current cost of infinity, so A records that it can reach G at a cost of 2 by going through F. Similarly, A learns from C that D can be reached from C at a cost of 1; it adds this to the cost of reaching C (1) and decides that D can be reached via C at a cost of 2, which is better than the old cost of infinity. At the same time, A learns from C that B can be reached from C at a cost of 1, so it concludes that the cost of reaching B via C is 2. Since this is worse than the current cost of reaching B (1), this new information is ignored.

Table 3.11 Initial Routing Table at Node A

Destination	Cost	NextHop
B	1	B
C	1	C
D	∞	—
E	1	E
F	1	F
G	∞	—

At this point, A can update its routing table with costs and next hops for all nodes in the network. The result is shown in Table 3.12.

In the absence of any topology changes, it takes only a few exchanges of information between neighbors before each node has a complete routing table. The process of getting consistent routing information to all the nodes is called *convergence*. Table 3.13 shows the final set of costs from each node to all other nodes when routing has converged. We must stress that there is no one node in the network that has all the information in this table—each node only knows about the contents of its own routing table. The beauty of a distributed algorithm like this is that it enables all

Table 3.12 Final Routing Table at Node A

Destination	Cost	NextHop
B	1	B
C	1	C
D	2	C
E	1	E
F	1	F
G	2	F

Table 3.13 Final Distances Stored at Each Node (Global View)

Information Stored at Node	Distance to Reach Node						
	A	B	C	D	E	F	G
A	0	1	1	2	1	1	2
B	1	0	1	2	2	2	3
C	1	1	0	1	2	2	2
D	2	2	1	0	3	2	1
E	1	2	2	3	0	2	3
F	1	2	2	2	2	0	1
G	2	3	2	1	3	1	0

nodes to achieve a consistent view of the network in the absence of any centralized authority.

There are a few details to fill in before our discussion of distance-vector routing is complete. First we note that there are two different circumstances under which a given node decides to send a routing update to its neighbors. One of these circumstances is the *periodic* update. In this case, each node automatically sends an update message every so often, even if nothing has changed. This serves to let the other nodes know that this node is still running. It also makes sure that they keep getting information that they may need if their current routes become unviable. The frequency of these periodic updates varies from protocol to protocol, but it is typically on the order of several seconds to several minutes. The second mechanism, sometimes called a *triggered* update, happens whenever a node notices a link failure or receives an update from one of its neighbors that causes it to change one of the routes in its routing table. Whenever a node's routing table changes, it sends an update to its neighbors, which may lead to a change in their tables, causing them to send an update to their neighbors.

Now consider what happens when a link or node fails. The nodes that notice first send new lists of distances to their neighbors, and normally the system settles down fairly quickly to a new state. As to the question of how a node detects a failure, there are a couple of different answers. In one approach, a node continually tests the link to another node by sending a control packet and seeing if it receives an acknowledgment. In another approach, a node determines that the link (or the node at the other end of the link) is down if it does not receive the expected periodic routing update for the last few update cycles.

To understand what happens when a node detects a link failure, consider what happens when F detects that its link to G has failed. First, F sets its new distance to G to infinity and passes that information along to A. Since A knows that its 2-hop path to G is through F, A would also set its distance to G to infinity. However, with the next update from C, A would learn that C has a 2-hop path to G. Thus, A would know that it could reach G in 3 hops through C, which is less than infinity, and so A would update its table accordingly. When it advertises this to F, node F would learn that it can reach G at a cost of 4 through A, which is less than infinity, and the system would again become stable.

Unfortunately, slightly different circumstances can prevent the network from stabilizing. Suppose, for example, that the link from A to E goes down. In the next round of updates, A advertises a distance of infinity to E, but B and C advertise a distance of 2 to E. Depending on the exact timing of events, the following might happen: Node B, upon hearing that E can be reached in 2 hops from C, concludes that it can reach E in 3 hops and advertises this to A; node A concludes that it can reach E in 4 hops and advertises this to C; node C concludes that it can reach E in 5 hops; and so on. This cycle stops only when the distances reach some number that is large enough to be considered infinite. In the meantime, none of the nodes actually knows that E is unreachable, and the routing tables for the network do not stabilize. This situation is known as the *count to infinity* problem.

There are several partial solutions to this problem. The first one is to use some relatively small number as an approximation of infinity. For example, we might decide that the maximum number of hops to get across a certain network is never going to be more than 16, and so we could pick 16 as the value that represents infinity. This at least bounds the amount of time that it takes to count to infinity. Of course, it could also present a problem if our network grew to a point where some nodes were separated by more than 16 hops.

One technique to improve the time to stabilize routing is called *split horizon*. The idea is that when a node sends a routing update to its neighbors, it does not send those routes it learned from each neighbor back to that neighbor. For example, if B has the route (E, 2, A) in its table, then it knows it must have learned this route from A, and so whenever B sends a routing update to A, it does not include the route (E, 2) in that update. In a stronger variation of split horizon, called *split horizon with poison reverse*, B actually sends that route back to A, but it puts negative information in the route to ensure that A will not eventually use B to get to E. For example, B sends the route (E, ∞) to A. The problem with both of these techniques is that they only work for routing loops that involve two nodes. For larger routing loops, more drastic measures are called for. Continuing the above example, if B and C had waited for a while after hearing of the link failure from A before advertising routes to E, they would have found that neither of them really had a route to E. Unfortunately, this approach delays the convergence of the protocol; speed of convergence is one of the key advantages of its competitor, link-state routing, the subject of Section 3.3.3.

Implementation

The code that implements this algorithm is very straightforward; we give only some of the basics here. Structure Route defines each entry in the routing table, and constant MAX_TTL specifies how long an entry is kept in the table before it is discarded.

```
#define MAX_ROUTES      128     /* maximum size of routing table */
#define MAX_TTL         120     /* time (in seconds) until route expires */

typedef struct {
    NodeAddr    Destination;    /* address of destination */
    NodeAddr    NextHop;        /* address of next hop */
    int         Cost;           /* distance metric */
    u_short     TTL;            /* time to live */
} Route;

int      numRoutes = 0;
Route    routingTable[MAX_ROUTES];
```

The routine that updates the local node's routing table based on a new route is given by mergeRoute. Although not shown, a timer function periodically scans the list of routes in the node's routing table, decrements the TTL (time to live) field of each route, and discards any routes that have a time to live of 0. Notice, however, that the TTL field is reset to MAX_TTL any time the route is reconfirmed by an update message from a neighboring node.

```
void
mergeRoute (Route *new)
{
    int i;

    for (i = 0; i < numRoutes; ++i)
    {
        if (new->Destination == routingTable[i].Destination)
        {
            if (new->Cost + 1 < routingTable[i].Cost)
            {
                /* found a better route: */
                break;
            } else if (new->NextHop == routingTable[i].NextHop) {
```

```
                /* metric for current next-hop may have
                   changed: */
                break;
            } else {
                /* route is uninteresting---just ignore
                  it */
                return;
            }
        }
    }
    if (i == numRoutes)
    {
        /* this is a completely new route; is there room
           for it? */
        if (numRoutes < MAXROUTES)
        {
            ++numRoutes;
        } else {
            /* can't fit this route in table so give up */
            return;
        }
    }
    routingTable[i] = *new;
    /* reset TTL */
    routingTable[i].TTL = MAX_TTL;
    /* account for hop to get to next node */
    ++routingTable[i].Cost;

}
```

Finally, the procedure updateRoutingTable is the main routine that calls mergeRoute to incorporate all the routes contained in a routing update that is received from a neighboring node.

```
void
updateRoutingTable (Route *newRoute, int numNewRoutes)
{
    int i;

    for (i=0; i < numNewRoutes; ++i)
    {
```

```
            mergeRoute(&newRoute[i]);
        }
    }
```

Routing Information Protocol (RIP)

One of the more widely used routing protocols in IP networks is the Routing Information Protocol (RIP). Its widespread use in the early days of IP was due in no small part to the fact that it was distributed along with the popular Berkeley Software Distribution (BSD) version of Unix, from which many commercial versions of Unix were derived. It is also extremely simple. RIP is the canonical example of a routing protocol built on the distance-vector algorithm just described.

Routing protocols in internetworks differ very slightly from the idealized graph model described above. In an internetwork, the goal of the routers is to learn how to forward packets to various *networks*. Thus, rather than advertising the cost of reaching other routers, the routers advertise the cost of reaching networks. For example, in Figure 3.30, router C would advertise to router A the fact that it can reach networks 2 and 3 (to which it is directly connected) at a cost of 0, networks 5 and 6 at cost 1, and network 4 at cost 2.

We can see evidence of this in the RIP (version 2) packet format in Figure 3.31. The majority of the packet is taken up with ⟨address, mask, distance⟩ triples. However, the principles of the routing algorithm are just the same. For example, if router A learns from router B that network X can be reached at a lower cost via B than via the existing next hop in the routing table, A updates the cost and next hop information for the network number accordingly.

RIP is in fact a fairly straightforward implementation of distance-vector routing. Routers running RIP send their advertisements every 30 seconds;

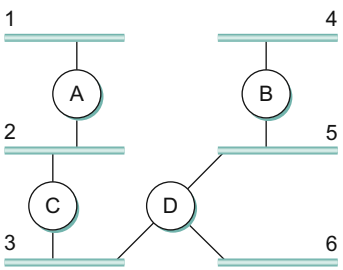


FIGURE 3.30 Example network running RIP.

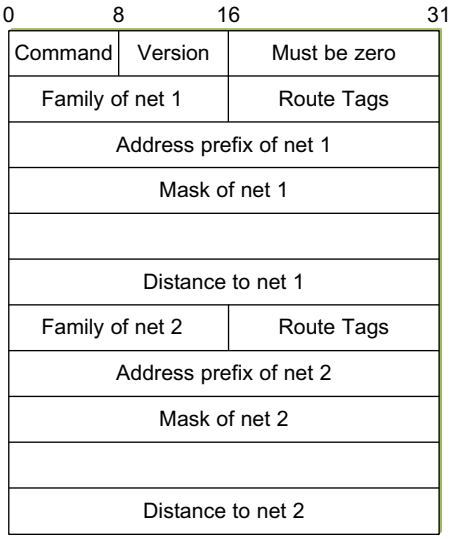


FIGURE 3.31 RIPv2 packet format.

a router also sends an update message whenever an update from another router causes it to change its routing table. One point of interest is that it supports multiple address families, not just IP—that is the reason for the Family part of the advertisements. RIP version 2 (RIPv2) also introduced the subnet masks described in Section 3.2.5, whereas RIP version 1 worked with the old classful addresses of IP.

As we will see below, it is possible to use a range of different metrics or costs for the links in a routing protocol. RIP takes the simplest approach, with all link costs being equal to 1, just as in our example above. Thus, it always tries to find the minimum hop route. Valid distances are 1 through 15, with 16 representing infinity. This also limits RIP to running on fairly small networks—those with no paths longer than 15 hops.

LAB 07: OSPF

3.3.3 Link State (OSPF)

Link-state routing is the second major class of intradomain routing protocol. The starting assumptions for link-state routing are rather similar to those for distance-vector routing. Each node is assumed to be capable of finding out the state of the link to its neighbors (up or down) and the cost of each link. Again, we want to provide each node with enough information to enable it to find the least-cost path to any destination. The basic

idea behind link-state protocols is very simple: Every node knows how to reach its directly connected neighbors, and if we make sure that the totality of this knowledge is disseminated to every node, then every node will have enough knowledge of the network to build a complete map of the network. This is clearly a sufficient condition (although not a necessary one) for finding the shortest path to any point in the network. Thus, link-state routing protocols rely on two mechanisms: reliable dissemination of link-state information, and the calculation of routes from the sum of all the accumulated link-state knowledge.

Reliable Flooding

Reliable flooding is the process of making sure that all the nodes participating in the routing protocol get a copy of the link-state information from all the other nodes. As the term *flooding* suggests, the basic idea is for a node to send its link-state information out on all of its directly connected links; each node that receives this information then forwards it out on all of *its* links. This process continues until the information has reached all the nodes in the network.

More precisely, each node creates an update packet, also called a *link-state packet* (LSP), which contains the following information:

- The ID of the node that created the LSP
- A list of directly connected neighbors of that node, with the cost of the link to each one
- A sequence number
- A time to live for this packet

The first two items are needed to enable route calculation; the last two are used to make the process of flooding the packet to all nodes reliable. Reliability includes making sure that you have the most recent copy of the information, since there may be multiple, contradictory LSPs from one node traversing the network. Making the flooding reliable has proven to be quite difficult. (For example, an early version of link-state routing used in the ARPANET caused that network to fail in 1981.)

Flooding works in the following way. First, the transmission of LSPs between adjacent routers is made reliable using acknowledgments and retransmissions just as in the reliable link-layer protocol described in Section 2.5. However, several more steps are necessary to reliably flood an LSP to all nodes in a network.

Consider a node X that receives a copy of an LSP that originated at some other node Y. Note that Y may be any other router in the same routing domain as X. X checks to see if it has already stored a copy of an LSP from Y. If not, it stores the LSP. If it already has a copy, it compares the sequence numbers; if the new LSP has a larger sequence number, it is assumed to be the more recent, and that LSP is stored, replacing the old one. A smaller (or equal) sequence number would imply an LSP older (or not newer) than the one stored, so it would be discarded and no further action would be needed. If the received LSP was the newer one, X then sends a copy of that LSP to all of its neighbors except the neighbor from which the LSP was just received. The fact that the LSP is not sent back to the node from which it was received helps to bring an end to the flooding of an LSP. Since X passes the LSP on to all its neighbors, who then turn around and do the same thing, the most recent copy of the LSP eventually reaches all nodes.

Figure 3.32 shows an LSP being flooded in a small network. Each node becomes shaded as it stores the new LSP. In Figure 3.32(a) the LSP arrives at node X, which sends it to neighbors A and C in Figure 3.32(b). A and C do not send it back to X, but send it on to B. Since B receives two identical copies of the LSP, it will accept whichever arrived first and ignore the second as a duplicate. It then passes the LSP onto D, which has no neighbors to flood it to, and the process is complete.

Just as in RIP, each node generates LSPs under two circumstances. Either the expiry of a periodic timer or a change in topology can cause a node to generate a new LSP. However, the only topology-based reason for a node to generate an LSP is if one of its directly connected links or

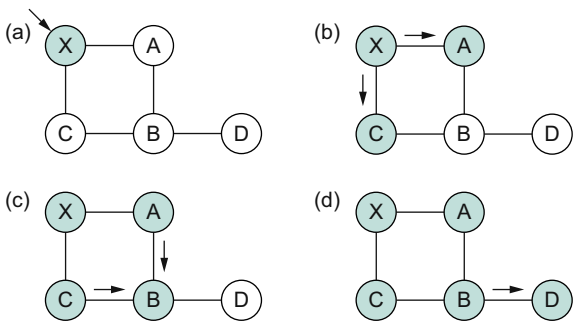


FIGURE 3.32 Flooding of link-state packets: (a) LSP arrives at node X; (b) X floods LSP to A and C; (c) A and C flood LSP to B (but not X); (d) flooding is complete.

immediate neighbors has gone down. The failure of a link can be detected in some cases by the link-layer protocol. The demise of a neighbor or loss of connectivity to that neighbor can be detected using periodic "hello" packets. Each node sends these to its immediate neighbors at defined intervals. If a sufficiently long time passes without receipt of a "hello" from a neighbor, the link to that neighbor will be declared down, and a new LSP will be generated to reflect this fact.

One of the important design goals of a link-state protocol's flooding mechanism is that the newest information must be flooded to all nodes as quickly as possible, while old information must be removed from the network and not allowed to circulate. In addition, it is clearly desirable to minimize the total amount of routing traffic that is sent around the network; after all, this is just overhead from the perspective of those who actually use the network for their applications. The next few paragraphs describe some of the ways that these goals are accomplished.

One easy way to reduce overhead is to avoid generating LSPs unless absolutely necessary. This can be done by using very long timers—often on the order of hours—for the periodic generation of LSPs. Given that the flooding protocol is truly reliable when topology changes, it is safe to assume that messages saying "nothing has changed" do not need to be sent very often.

To make sure that old information is replaced by newer information, LSPs carry sequence numbers. Each time a node generates a new LSP, it increments the sequence number by 1. Unlike most sequence numbers used in protocols, these sequence numbers are not expected to wrap, so the field needs to be quite large (say, 64 bits). If a node goes down and then comes back up, it starts with a sequence number of 0. If the node was down for a long time, all the old LSPs for that node will have timed out (as described below); otherwise, this node will eventually receive a copy of its own LSP with a higher sequence number, which it can then increment and use as its own sequence number. This will ensure that its new LSP replaces any of its old LSPs left over from before the node went down.

LSPs also carry a time to live. This is used to ensure that old link-state information is eventually removed from the network. A node always decrements the TTL of a newly received LSP before flooding it to its neighbors. It also "ages" the LSP while it is stored in the node. When the TTL reaches 0, the node refloods the LSP with a TTL of 0, which is interpreted by all the nodes in the network as a signal to delete that LSP.

Route Calculation

Once a given node has a copy of the LSP from every other node, it is able to compute a complete map for the topology of the network, and from this map it is able to decide the best route to each destination. The question, then, is exactly how it calculates routes from this information. The solution is based on a well-known algorithm from graph theory—Dijkstra's shortest-path algorithm.

We first define Dijkstra's algorithm in graph-theoretic terms. Imagine that a node takes all the LSPs it has received and constructs a graphical representation of the network, in which N denotes the set of nodes in the graph, $l(i,j)$ denotes the nonnegative cost (weight) associated with the edge between nodes $i,j \in N$ and $l(i,j) = \infty$ if no edge connects i and j. In the following description, we let $s \in N$ denote this node, that is, the node executing the algorithm to find the shortest path to all the other nodes in N. Also, the algorithm maintains the following two variables: M denotes the set of nodes incorporated so far by the algorithm, and $C(n)$ denotes the cost of the path from s to each node n. Given these definitions, the algorithm is defined as follows:

$M = \{s\}$
for each n in $N - \{s\}$
  $C(n) = l(s,n)$
while $(N \neq M)$
  $M = M \cup \{w\}$ such that $C(w)$ is the minimum for all w in $(N - M)$
  for each n in $(N - M)$
    $C(n) = \text{MIN}(C(n), C(w) + l(w,n))$

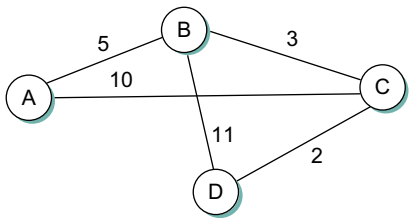
Basically, the algorithm works as follows. We start with M containing this node s and then initialize the table of costs (the $C(n)$s) to other nodes using the known costs to directly connected nodes. We then look for the node that is reachable at the lowest cost (w) and add it to M. Finally, we update the table of costs by considering the cost of reaching nodes through w. In the last line of the algorithm, we choose a new route to node n that goes through node w if the total cost of going from the source to w and then following the link from w to n is less than the old route we had to n. This procedure is repeated until all nodes are incorporated in M.

In practice, each switch computes its routing table directly from the LSPs it has collected using a realization of Dijkstra's algorithm called the *forward search* algorithm. Specifically, each switch maintains two lists,

known as Tentative and Confirmed. Each of these lists contains a set of entries of the form (Destination, Cost, NextHop). The algorithm works as follows:

1. Initialize the Confirmed list with an entry for myself; this entry has a cost of 0.
2. For the node just added to the Confirmed list in the previous step, call it node Next and select its LSP.
3. For each neighbor (Neighbor) of Next, calculate the cost (Cost) to reach this Neighbor as the sum of the cost from myself to Next and from Next to Neighbor.
   (a) If Neighbor is currently on neither the Confirmed nor the Tentative list, then add (Neighbor, Cost, NextHop) to the Tentative list, where NextHop is the direction I go to reach Next.
   (b) If Neighbor is currently on the Tentative list, and the Cost is less than the currently listed cost for Neighbor, then replace the current entry with (Neighbor, Cost, NextHop), where NextHop is the direction I go to reach Next.
4. If the Tentative list is empty, stop. Otherwise, pick the entry from the Tentative list with the lowest cost, move it to the Confirmed list, and return to step 2.

This will become a lot easier to understand when we look at an example. Consider the network depicted in Figure 3.33. Note that, unlike our previous example, this network has a range of different edge costs. Table 3.14 traces the steps for building the routing table for node D. We denote the two outputs of D by using the names of the nodes to which they connect, B and C. Note the way the algorithm seems to head off on



■ FIGURE 3.33 Link-state routing: an example network.

Table 3.14 Steps for Building Routing Table for Node D (Figure 3.33)

Step	Confirmed	Tentative	Comments
1	(D,0,–)		Since D is the only new member of the confirmed list, look at its LSP.
2	(D,0,–)	(B,11,B) (C,2,C)	D's LSP says we can reach B through B at cost 11, which is better than anything else on either list, so put it on Tentative list; same for C.
3	(D,0,–) (C,2,C)	(B,11,B)	Put lowest-cost member of Tentative (C) onto Confirmed list. Next, examine LSP of newly confirmed member (C).
4	(D,0,–) (C,2,C)	(B,5,C) (A,12,C)	Cost to reach B through C is 5, so replace (B,11,B). C's LSP tells us that we can reach A at cost 12.
5	(D,0,–) (C,2,C) (B,5,C)	(A,12,C)	Move lowest-cost member of Tentative (B) to Confirmed, then look at its LSP.
6	(D,0,–) (C,2,C) (B,5,C)	(A,10,C)	Since we can reach A at cost 5 through B, replace the Tentative entry.
7	(D,0,–) (C,2,C) (B,5,C) (A,10,C)		Move lowest-cost member of Tentative (A) to Confirmed, and we are all done.

false leads (like the 11-unit cost path to B that was the first addition to the Tentative list) but ends up with the least-cost paths to all nodes.

The link-state routing algorithm has many nice properties: It has been proven to stabilize quickly, it does not generate much traffic, and it responds rapidly to topology changes or node failures. On the downside, the amount of information stored at each node (one LSP for every other node in the network) can be quite large. This is one of the fundamental problems of routing and is an instance of the more general problem of scalability. Some solutions to both the specific problem (the amount of storage potentially required at each node) and the general problem (scalability) will be discussed in the next section.

The difference between the distance-vector and link-state algorithms can be summarized as follows. In distance-vector, each node talks only to its directly connected neighbors, but it tells them everything it has learned (i.e., distance to all nodes). In link-state, each node talks to all other nodes, but it tells them only what it knows for sure (i.e., only the state of its directly connected links).