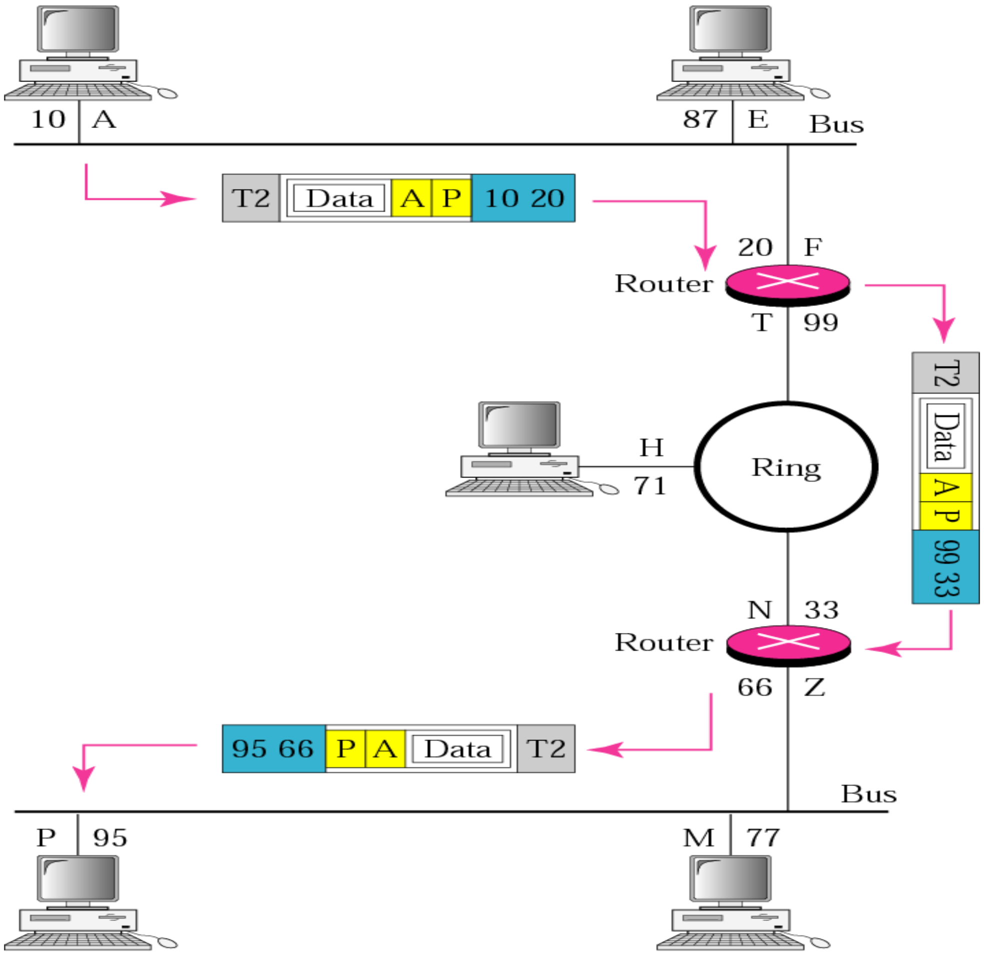
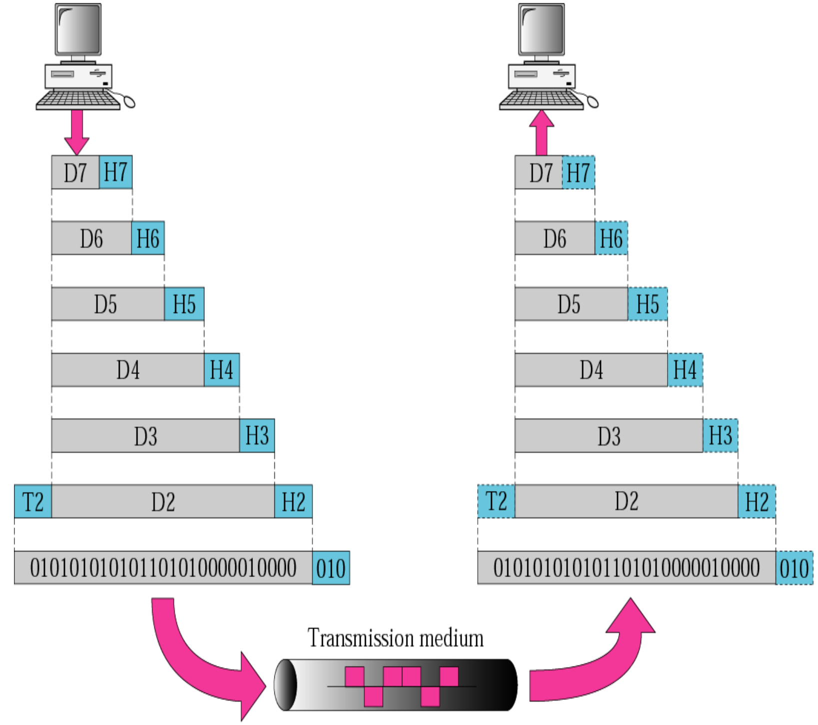
Computer Network Protocols (CNP)

Delivery and Forwarding of IP Packets


10
A
87
E
Bus
T2
Data
A
P
10 20
20
F
Router
T
99
H
71
Ring
T2
Data
A
P
99 33
N
33
Router
66
Z
95 66
P
A
Data
T2
Bus
P
95
M
77


D7 H7
D6 H6
D5 H5
D4 H4
D3 H3
T2 D2 H2
01010101010110101000001000 010
Transmission medium
D7 H7
D6 H6
D5 H5
D4 H4
D3 H3
T2 D2 H2
01010101010110101000001000 010

6-1 DELIVERY

- The network layer supervises the handling of the packets by the underlying physical networks.

- We define this handling as the delivery of a packet.

- Delivery of a packet to its final destination is accomplished using two different methods of delivery:

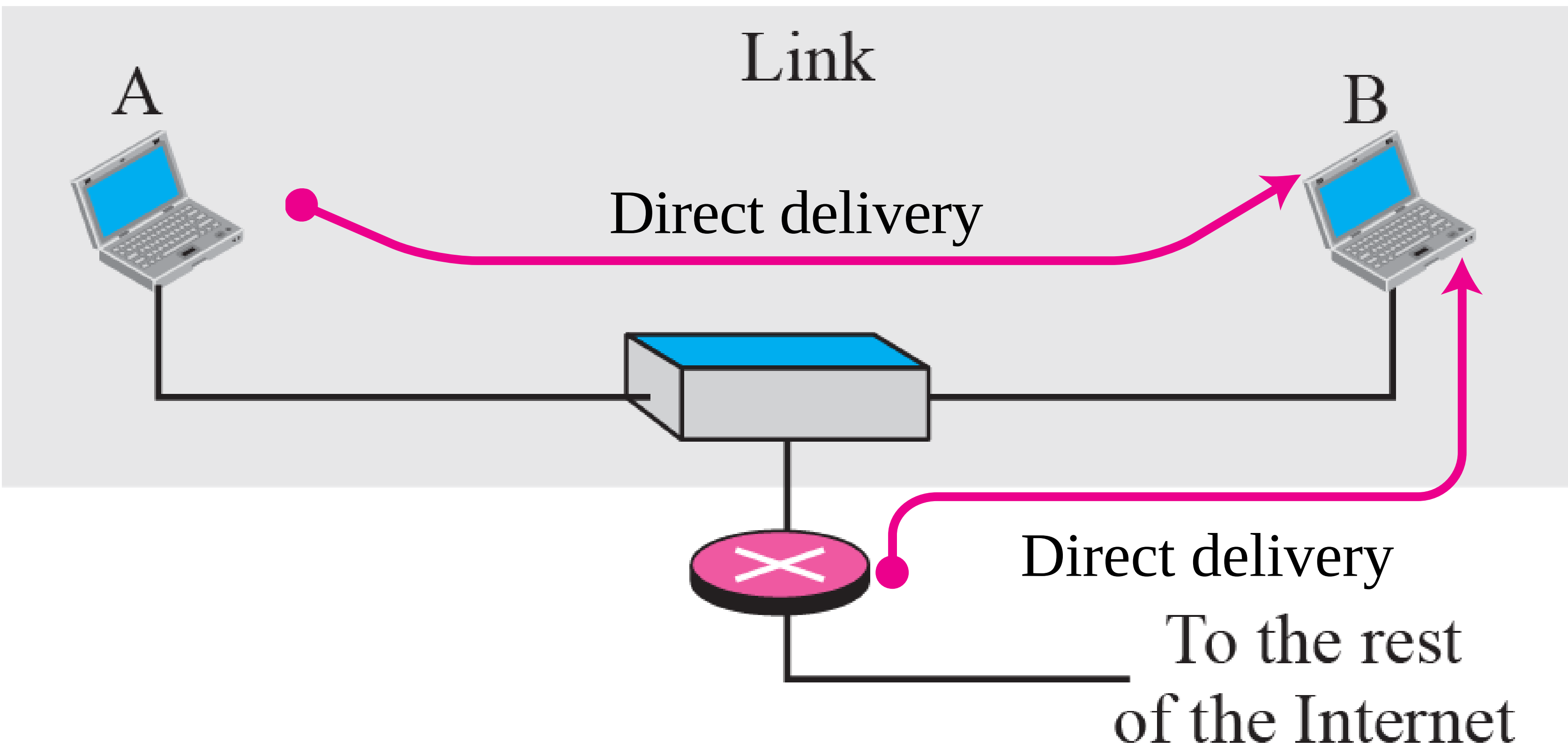
    - Direct
    - Indirect

Direct delivery

- ✓ In a direct delivery, the final destination of the packet is a host connected to the same physical network as the deliverer.

- ✓ Direct delivery occurs when the source and destination of the packet are located on the same physical network or if the delivery is between the last router and the destination host.

Figure 6.1 *Direct delivery*



Direct delivery

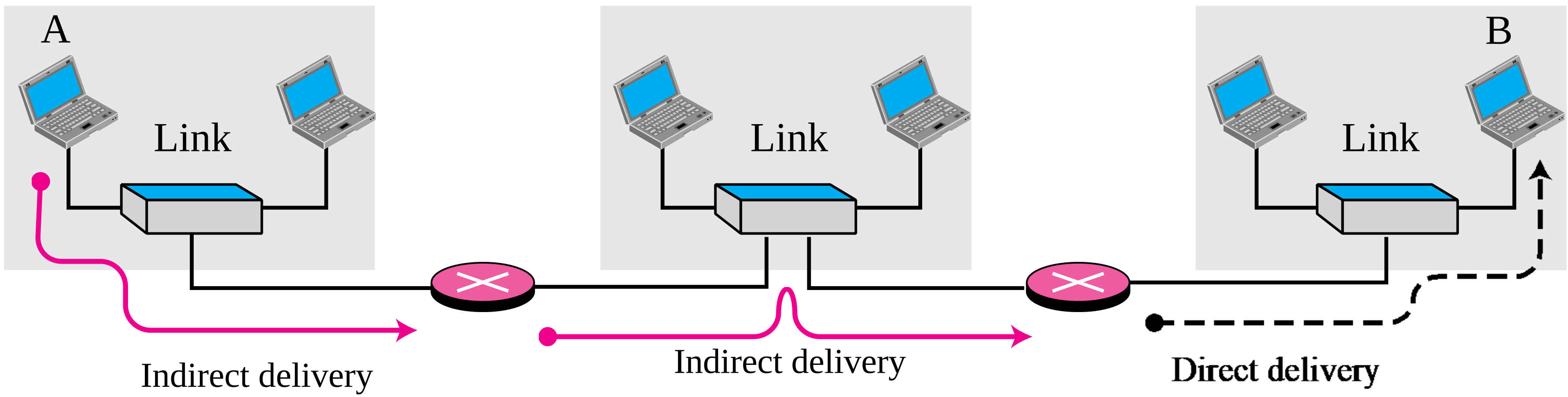
- ✓ The sender can easily determine if the delivery is direct.
- ✓ It can extract the network address of the destination (using the mask) and compare this address with the addresses of the networks to which it is connected.
- ✓ If a match is found, the delivery is direct.
- ✓ In direct delivery, the sender uses the destination IP address to find the destination physical address.
- ✓ The IP software then gives the destination IP address with the destination physical address to the data link layer for actual delivery.

Indirect delivery

- ✓ If the destination host is not on the same network as the deliverer, the packet is delivered indirectly.

- ✓ In an indirect delivery, the packet goes from router to route reaches the one connected to the same physical network as its final destination.

Figure 6.2 *Indirect delivery*



Indirect delivery

- ✓ In an indirect delivery, the sender uses the destination IP address and a routing table to find the IP address of the next router to which the packet should be delivered.

- ✓ The sender then uses ARP (Address Resolution Protocol) to find the physical address of the next router.

- ✓ In direct delivery, the address mapping is between the IP address of the final destination and the physical address of the final destination.

- ✓ In an indirect delivery, the address mapping is between the IP address of the next router and the physical address of the next router.

- ✓ Delivery always involves one direct delivery but zero or more indirect deliveries.

6-2 FORWARDING

- ✓ Forwarding means to place the packet in its route to its destination.

- ✓ Forwarding means to deliver the packet to the next hop (which can be the final destination or the intermediate connecting device).

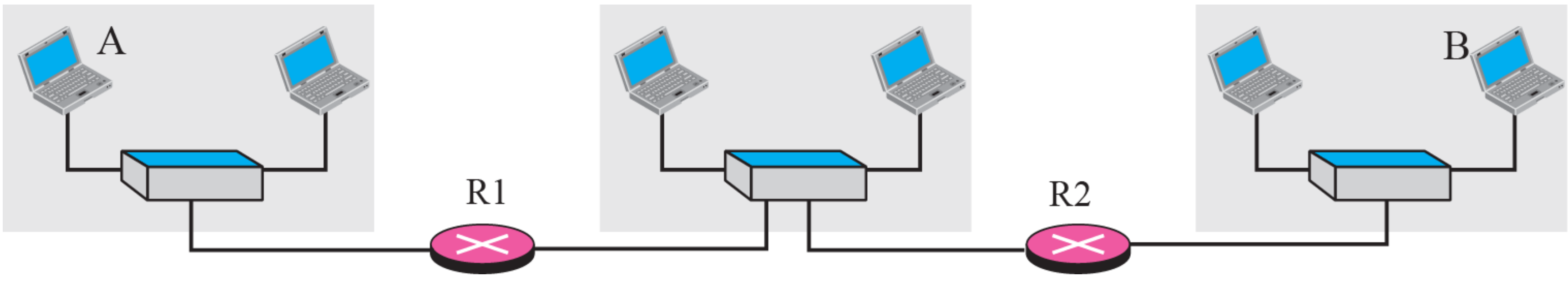
- ✓ IP protocol was originally designed as a connectionless protocol, today the tendency is to use IP as a connection-oriented protocol.

- ✓ When IP is used as a connectionless protocol, forwarding is based on the destination address of the IP datagram;

- ✓ When the IP is used as a connection-oriented protocol, forwarding is based on the label attached to an IP datagram

Forwarding Based on Destination Address

- ✓ In this case, forwarding requires a host or a router to have a routing 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 route to the final destination.
- ✓ This simple solution is inefficient today in an internetwork such as the Internet because the number of entries needed in the routing table would make table lookups inefficient.



A

Destination	Route
Host B	R1, R2, Host B

R1

Destination	Route
Host B	R2, Host B

R2

Destination	Route
Host B	Host B

a. Routing tables based on route

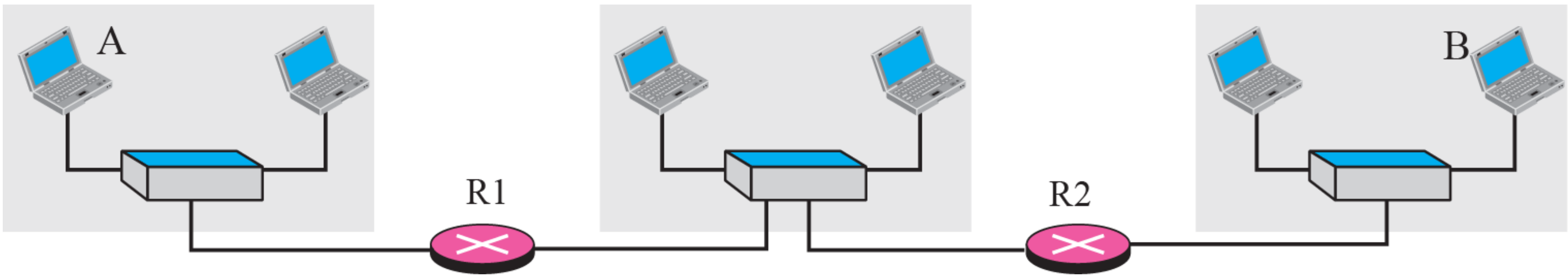
Forwarding Techniques

Several techniques can make the size of the routing table manageable and also handle issues such as security.

Next-Hop Method

- ✓ One technique to reduce the contents of a routing table.
- ✓ Here, the routing table holds only the address of the next hop instead of information about the complete route.

Figure 6.3 *Next-hop method*



A

Destination	Next Hop
Host B	R1

R1

Destination	Next Hop
Host B	R2

R2

Destination	Next Hop
Host B	---

b. Routing tables based on next hop

Network-specific method

- ✓ Another techniques to reduce the routing table and simplify the searching process.

- ✓ Here, instead of having an entry for every destination host connected to the same physical network, we have only one entry that defines the address of the destination network itself.

- ✓ Treat all hosts connected to the same network as one single entity.

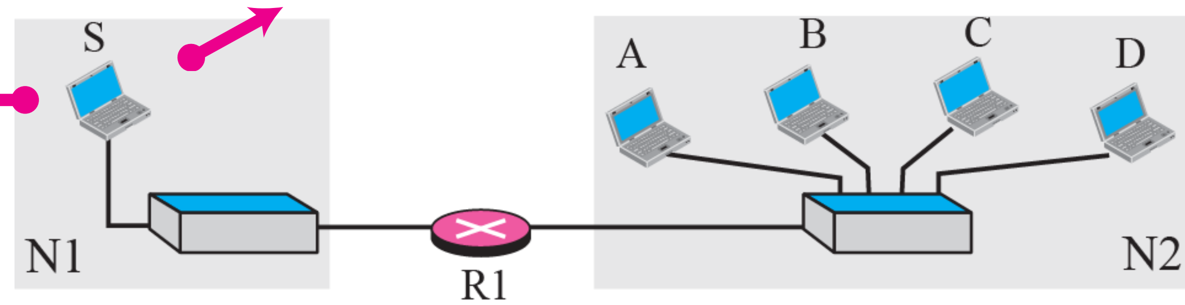
Figure 6.4 ***Network-specific method***

Network-specific
routing table for host S

Destination	Next Hop
N2	R1

Host-specific
routing table for host S

Destination	Next Hop
A	R1
B	R1
C	R1
D	R1



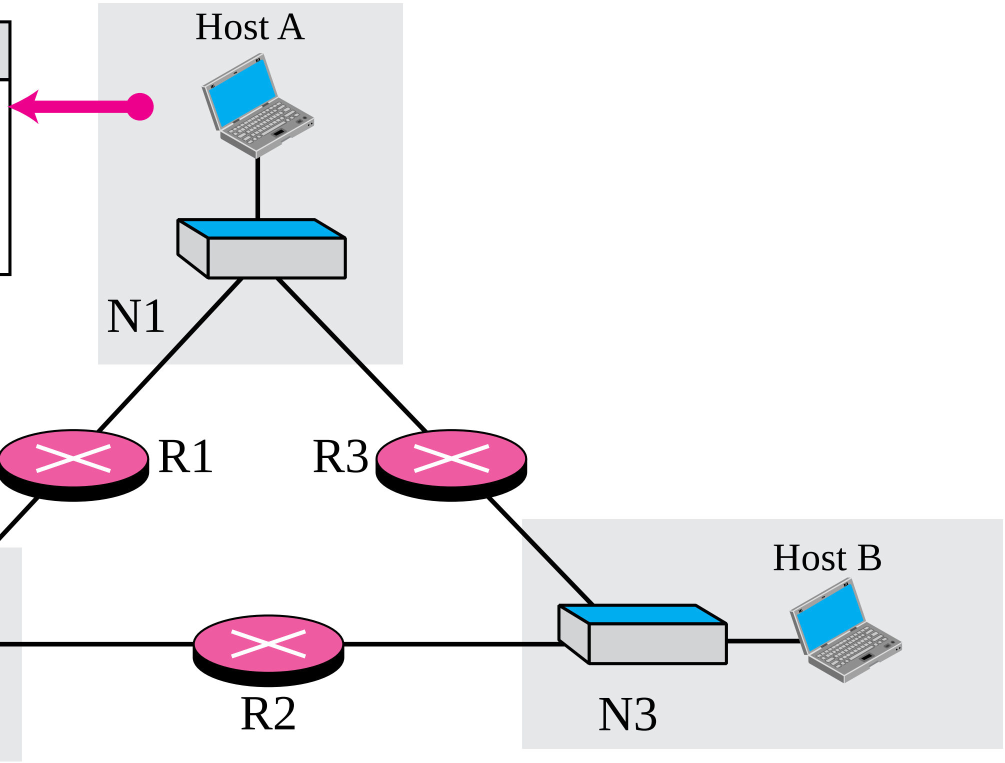
Host-specific Method

- ✓ In the host-specific method, the destination host address is given in the routing table.
- ✓ Here efficiency is sacrificed for other advantages: There are occasions in which the administrator wants to have more control over routing.
- ✓ For example, if the administrator wants all packets arriving for host B delivered to router R3 instead of R1, one single entry in the routing table of host A can explicitly define the route.
- ✓ Host-specific routing is used for purposes such as checking the route or providing security measu**res.**

Figure 6.5 *Host-specific routing*

Routing table for host A

Destination	Next Hop
Host B	R3
N2	R1
N3	R3
……	……



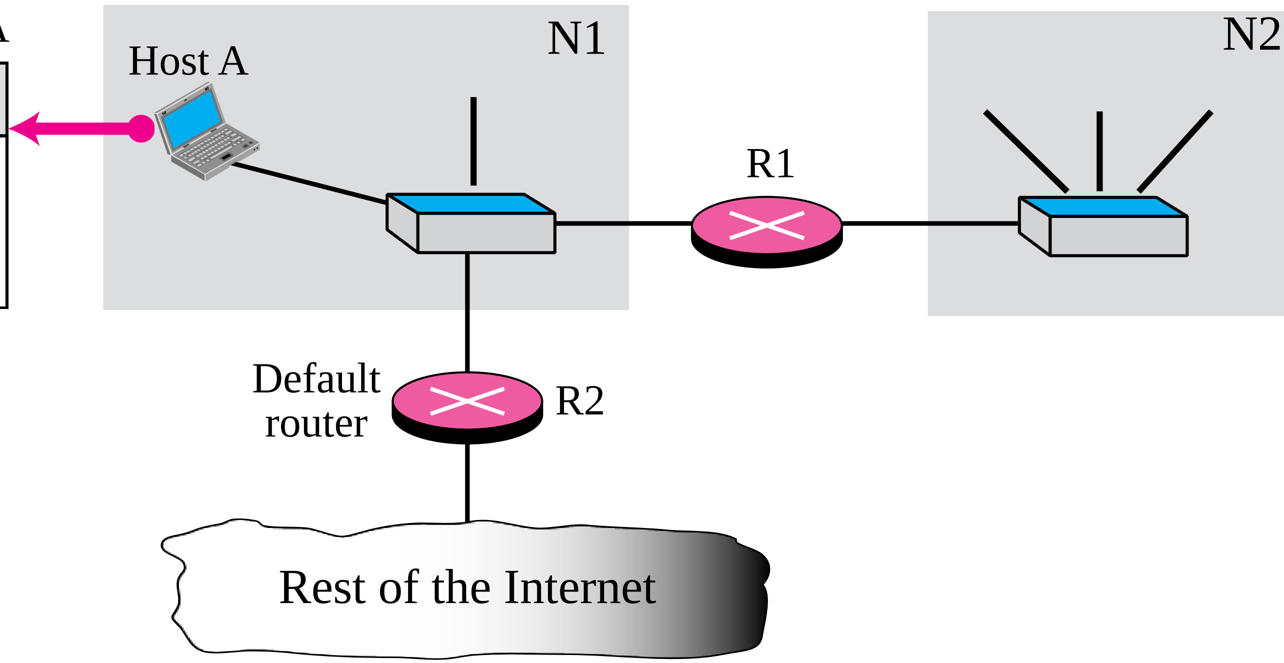
Default Method

- ✓ Another technique to simplify routing is called the default method.
- ✓ In Figure 6.6 host A is connected to a network with two routers. Router R1 routes the packets to hosts connected to network N2. However, for the rest of the Internet, router R2 is used.
- ✓ So instead of listing all networks in the entire Internet, host A can just have one entry called the default (normally defined as network address 0.0.0.0).

Figure 6.6 *Default routing*

Routing table for host A

Destination	Next Hop
N2	R1
......	......
Default	R2



Forwarding with classful addressing

- ✓ Classful addressing has several disadvantages.
- ✓ However, the existence of a default mask in a classful address makes the forwarding process simple.

Discuss

- ✓ Forwarding without subnetting : contents of a routing table and forwarding module for the situation in which there is no subnetting.
- ✓ Forwarding with subnetting

Forwarding without Subnetting

- ✓ In classful addressing, most of the routers in the global Internet are not involved in subnetting.
- ✓ Subnetting happens inside the organization.
- ✓ A typical forwarding module in this case can be designed using three tables, one for each unicast class (A, B, C).
- ✓ If the router supports multicasting, another table can be added to handle class D addresses.
- ✓ Having three different tables makes searching more efficient.

Forwarding without Subnetting

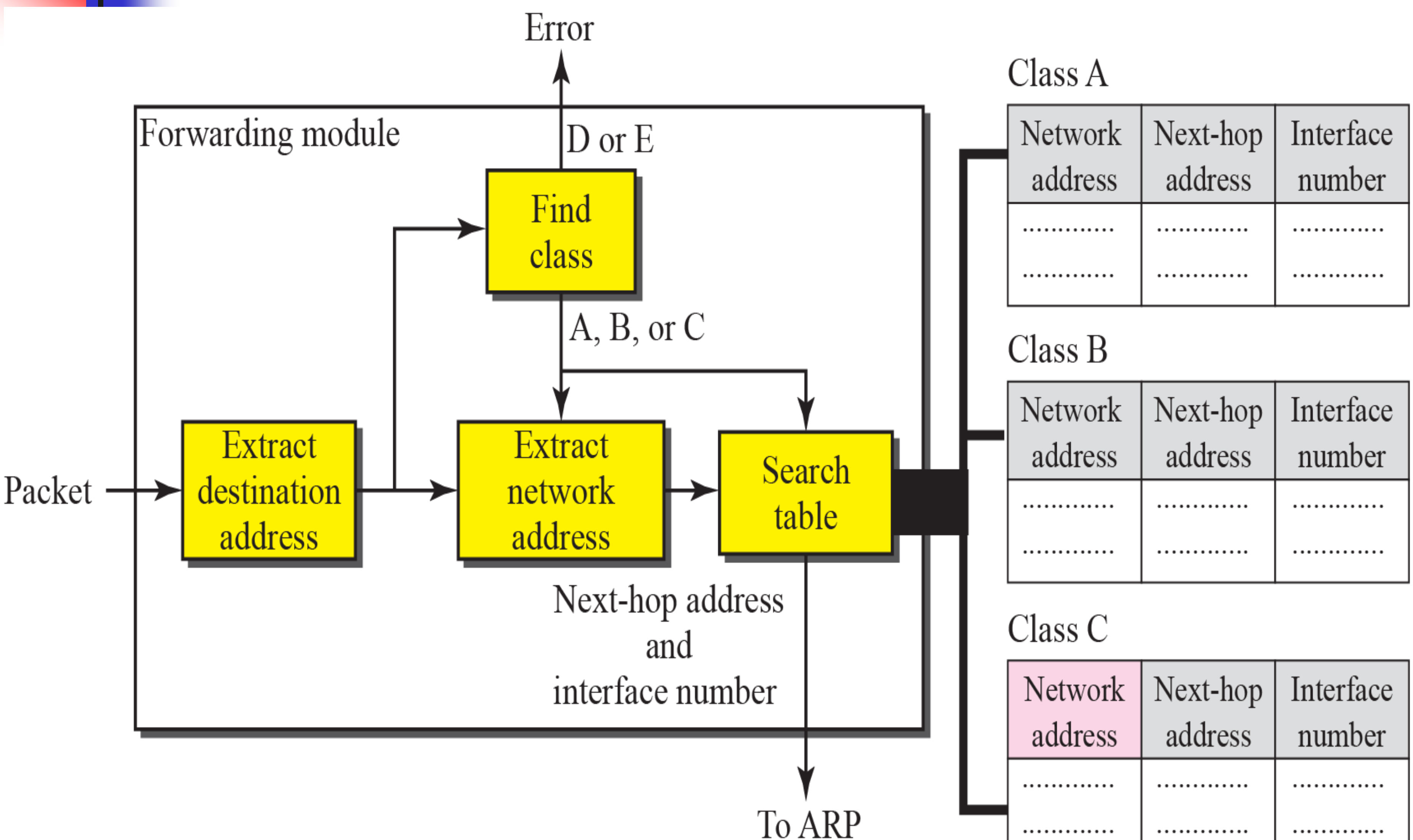
Each routing table has a minimum of three columns:

1. The network address of the destination network.

2. The next-hop address tells us to which router the packet must be delivered for an indirect delivery. This column is empty for a direct delivery.

3. The interface number defines the outgoing port from which the packet is sent out.

Figure 6.7 *Simplified forwarding module in classful address without subnetting*



The ARP module uses the next-hop address and the interface number to find the physical address of the next router.

Forwarding without Subnetting

The forwarding module follows these steps:

1. The destination address of the packet is extracted.

2. A copy of the destination address is used to find the class of the address. This is done by shifting the copy of the address 28 bits to the right. The result is a 4-bit number between 0 and 15. If the result is

   - ✓ 0 to 7, the class is A.
   - ✓ 8 to 11, the class is B.
   - ✓ 12 or 13, the class is C .
   - ✓ 14, the class is D.
   - ✓ 15, the class is E.

3. The result of Step 2 for class A, B, or C and the destination address are used to extract the network address. This is done by masking off (changing to 0s) the rightmost 8, 16, or 24 bits based on the class.

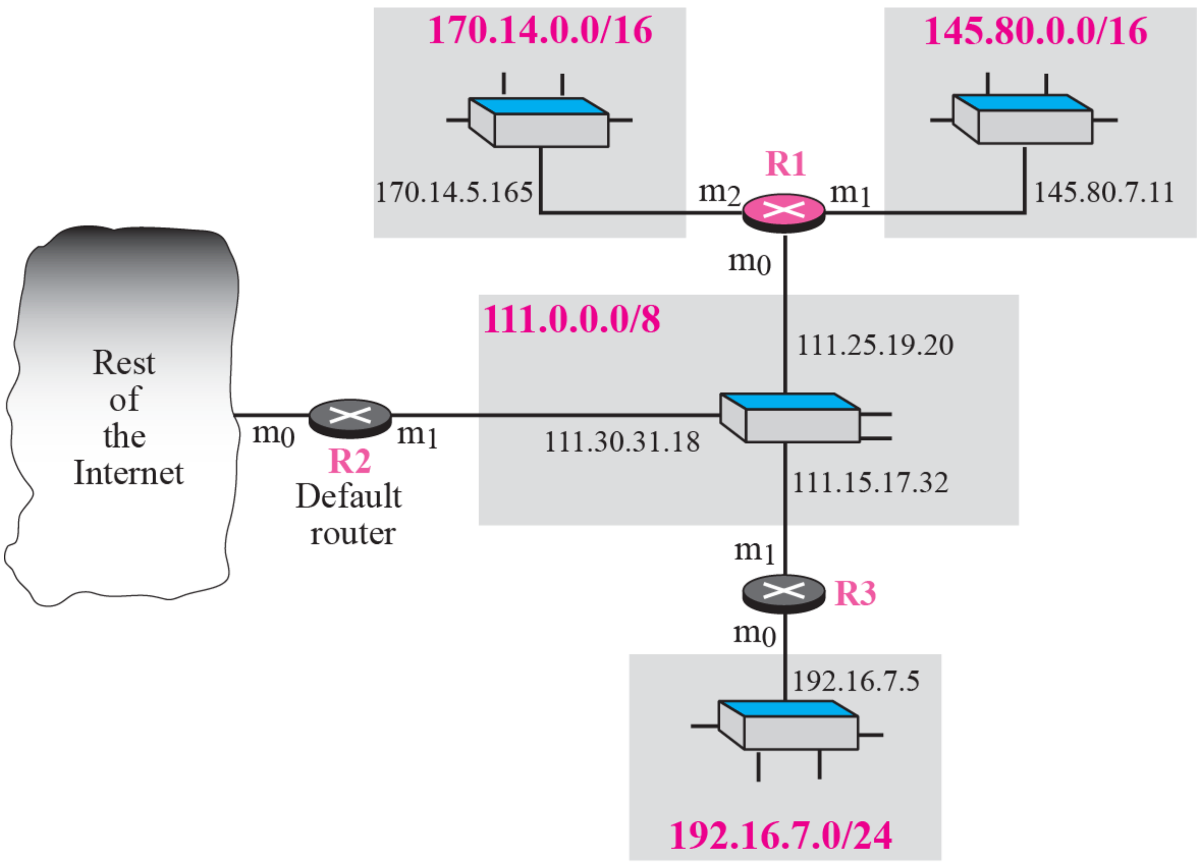
Forwarding without Subnetting

4. The class of the address and the network address are used to find next-hop information. The class determines which table is to be searched. The module searches this table for the network address. If a match is found, the next-hop address and the interface number of the output port are extracted from the table. If no match is found, the default is used.

5. The ARP (Address Resolution Protocol) module uses the next-hop address and the interface number to find the physical address of the next router. It then asks the data link layer to deliver the packet to the next hop.

Figure 6.8 *Configuration for routing, Example 6.1*

Figure 6.8 shows an imaginary part of the Internet. Show the routing tables for router R1.



Example 6.1

Solution

The three tables used by router R1.

some entries in the next-hop address column are empty because in these cases, the destination is in the same network to which the router is connected (direct delivery).

Class A

Network address	Next-hop address	Interface
111.0.0.0	------------	m0

Class B

Network address	Next-hop address	Interface
145.80.0.0	------------	m1
170.14.0.0	------------	m2

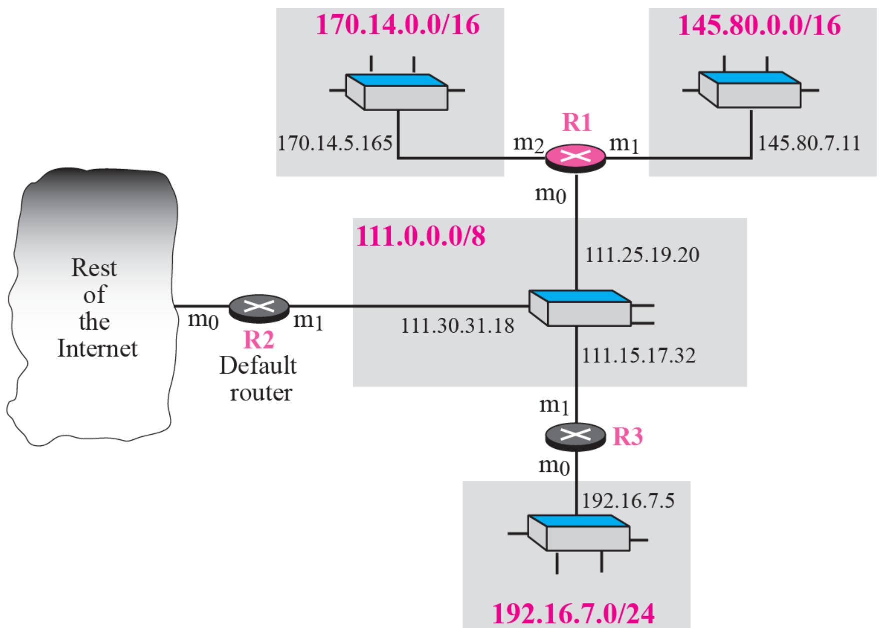
Class C

Network address	Next-hop address	Interface
192.16.7.0	111.15.17.32	m0

Default: 111.30.31.18, m0

Example 6.2

Router R1 in Figure receives a packet with destination address 192.16.7.14. Show how the packet is forwarded.



Class A

Network address	Next-hop address	Interface
111.0.0.0	------------	m0

Class B

Network address	Next-hop address	Interface
145.80.0.0	------------	m1
170.14.0.0	------------	m2

Class C

Network address	Next-hop address	Interface
192.16.7.0	111.15.17.32	m0

Default: 111.30.31.18, m0

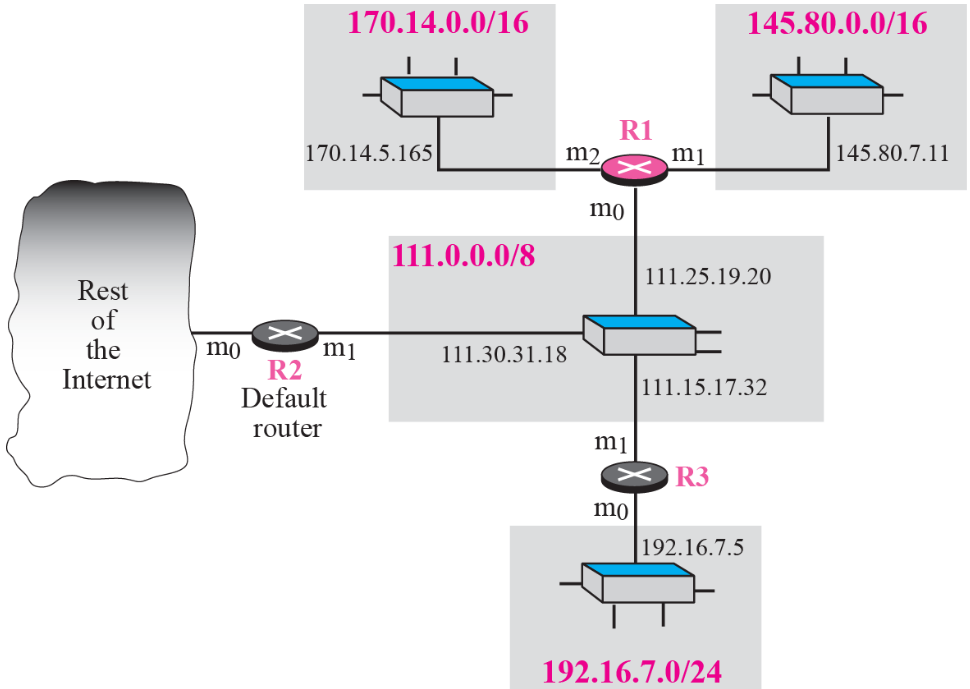
Example 6.2

Solution

- The destination address is
  11000000 00010000 000001110 0001110.
- A copy of the address is shifted 28 bits to the right. The result is
  00000000 00000000 00000000 00001100 or 12.
- The destination network is class C.
- The network address is extracted by masking off the leftmost 24 bits of the destination address; the result is 192.16.7.0.
- The table for Class C is searched.
- The network address is found in the first row. The next-hop address 111.15.17.32. and the interface m0 are passed to ARP.

Example 6.3

Router R1 in Figure receives a packet with destination address 167.24.160.5. Show how the packet is forwarded.



Class A

Network address	Next-hop address	Interface
111.0.0.0	------------	m0

Class B

Network address	Next-hop address	Interface
145.80.0.0	------------	m1
170.14.0.0	------------	m2

Class C

Network address	Next-hop address	Interface
192.16.7.0	111.15.17.32	m0

Default: 111.30.31.18, m0

Example 6.3

Solution

The destination address in binary is

10100111 00011000 10100000 00000101.

A copy of the address is shifted 28 bits to the right. The result is

00000000 00000000 00000000 00001010 or 10.

The class is B.

The network address can be found by masking off 16 bits of the destination address, the result is 167.24.0.0.

The table for Class B is searched. No matching network address is found.

The packet needs to be forwarded to the default router (the network is somewhere else in the Internet).

The next-hop address 111.30.31.18 and the interface number m0 are passed to ARP.

Forwarding with Subnetting

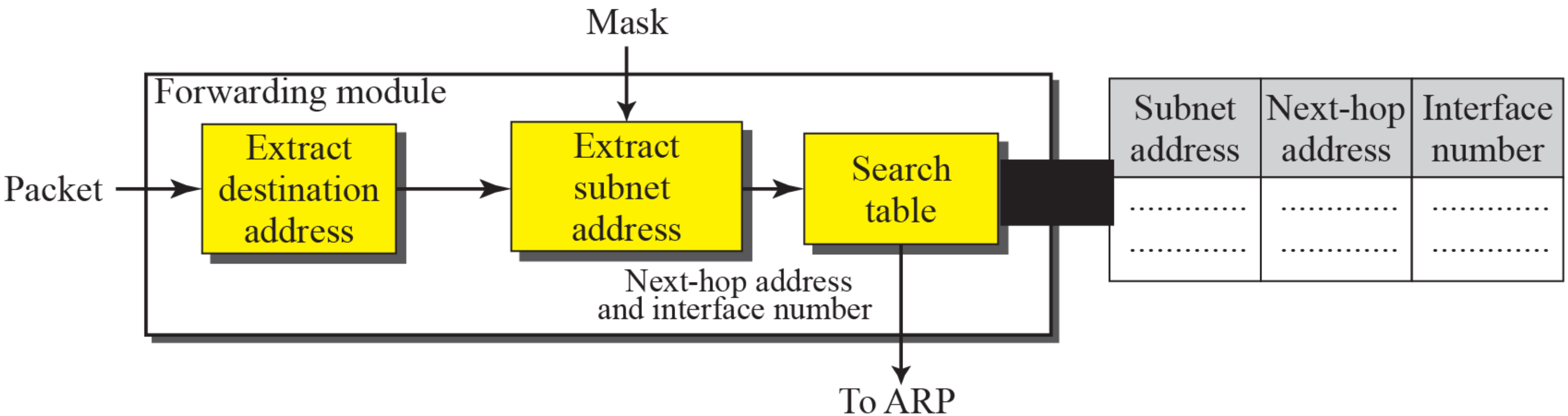
- In classful addressing, subnetting happens inside the organization.

- The routers that handle subnetting are either at the border of the organization site or inside the site boundary.

- If the organization is using variable-length subnetting, we need several tables; otherwise, we need only one table.

Figure 6.10 *Simplified forwarding module in classful address with subnetting*

Figure 6.10 shows a simplified module for fixed-length subnetting



Forwarding with Subnetting

1. The module extracts the destination address of the packet.

2. If the destination address matches any of the host-specific addresses in the table, the next-hop and the interface number is extracted from the table.

3. The destination address and the mask are used to extract the subnet address.

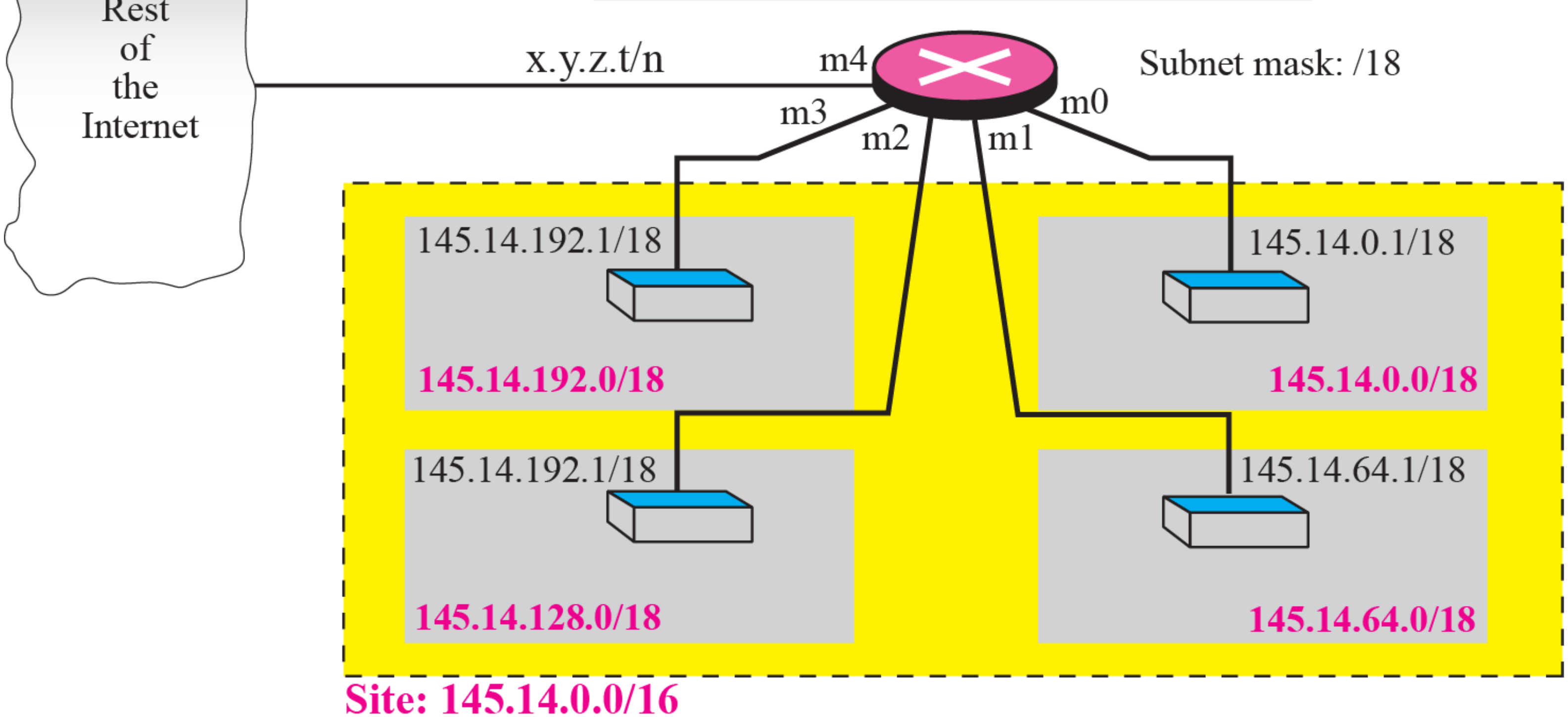
4. The table is searched using the subnet address to find the next-hop address and the interface number. If no match is found, the default is used.

5. The next-hop address and the interface number are given to ARP .

Figure 6.11 ***Configuration for Example 6.4***

Figure shows a router connected to four subnets.

Subnet address	Next-hop address	Interface number
145.14.0.0	----------	m0
145.14.64.0	----------	m1
145.14.128.0	----------	m2
145.14.192.0	----------	m3
0.0.0.0	default router	m4



Example 6.4

First, the site address is 145.14.0.0/16 (a class B address).

- ✓ Every packet with destination address in the range 145.14.0.0 to 145.14.255.255 is delivered to the interface m4 and distributed to the final destination subnet by the router.

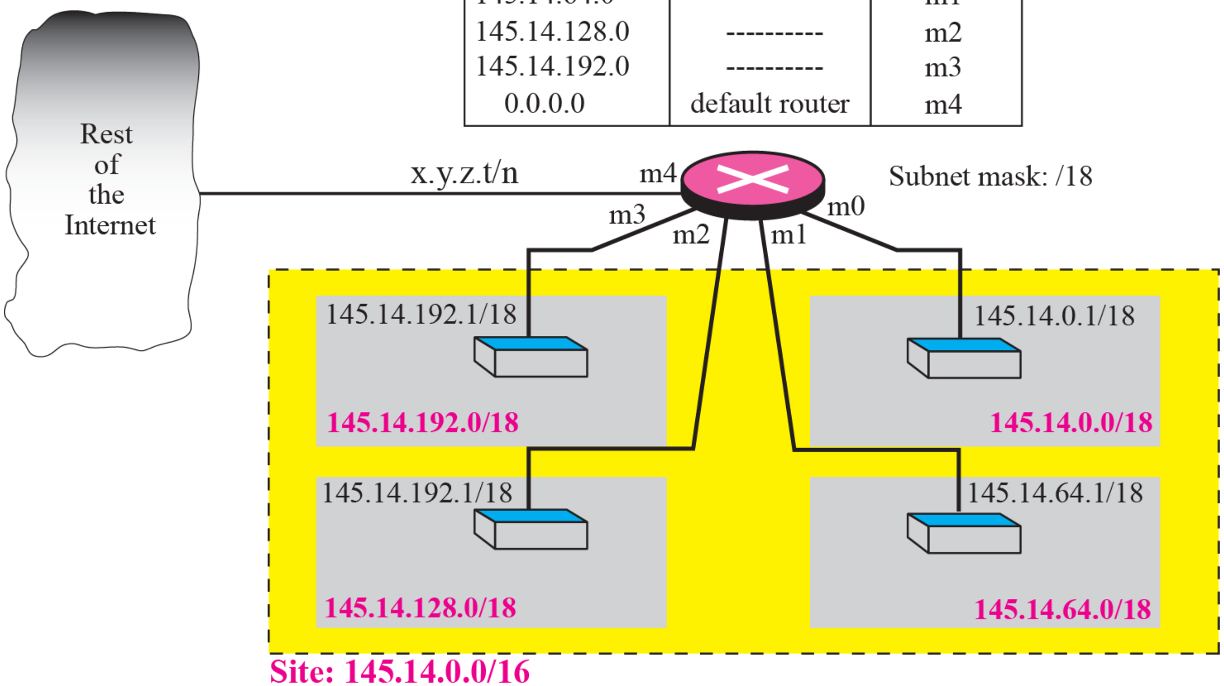
- ✓ Second, the address x.y.z.t/n for the interface m4 because we do not know to which network this router is connected.

- ✓ Third, the table has a default entry for packets that are to be sent out of the site. The router is configured to apply the subnet mask /18 to any destination address.

Example 6.5

The router in Figure receives a packet with destination address 145.14.32.78. Show how the packet is forwarded.

Subnet address	Next-hop address	Interface number
145.14.0.0	----------	m0
145.14.64.0	----------	m1
145.14.128.0	----------	m2
145.14.192.0	----------	m3
0.0.0.0	default router	m4



Example 6.5

Solution

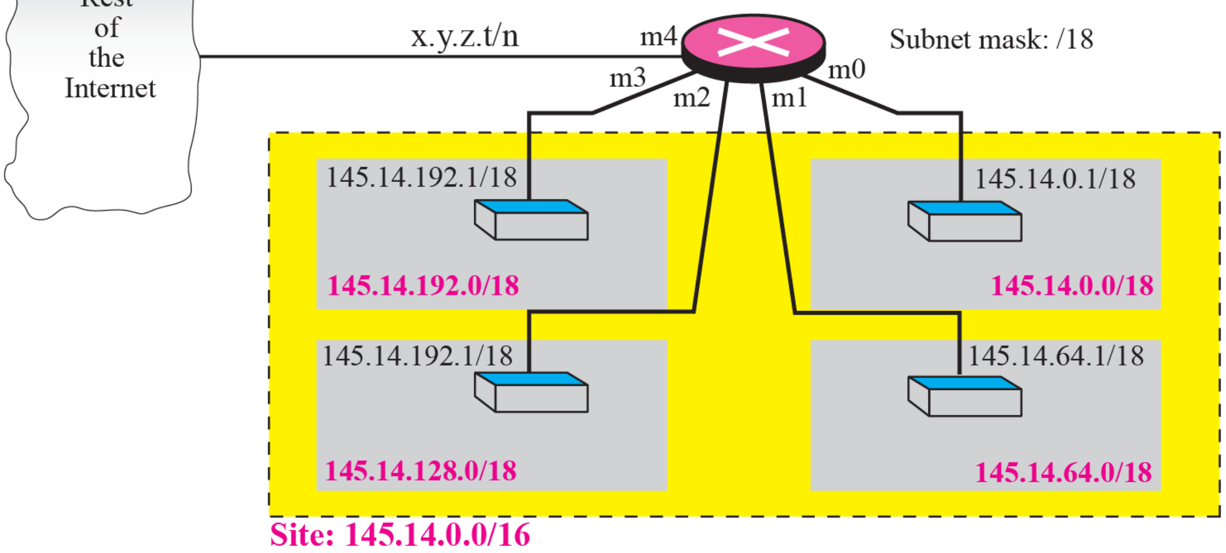
The mask is /18. After applying the mask, the subnet address is 145.14.0.0.

The packet is delivered to ARP with the next-hop address 145.14.32.78 and the outgoing interface m0.

Example 6.6

A host in network 145.14.0.0 in Figure has a packet to send to the host with address 7.22.67.91. Show how the packet is routed.

Subnet address	Next-hop address	Interface number
145.14.0.0	----------	m0
145.14.64.0	----------	m1
145.14.128.0	----------	m2
145.14.192.0	----------	m3
0.0.0.0	default router	m4



Example 6.6

Solution

The router receives the packet and applies the mask (/18). The network address is 7.22.64.0.

The table is searched and the address is not found.

The router uses the address of the default router (not shown in figure) and sends the packet to that router.

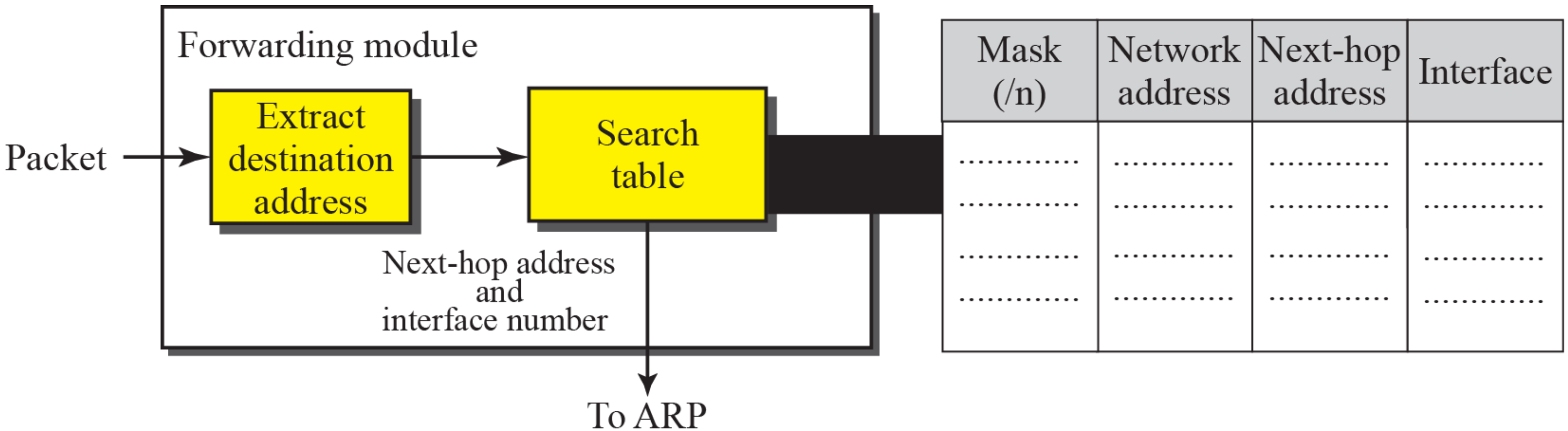
Forwarding with Classless Addressing

- ✓ Destination address in the packet gives no clue about the network address.
- ✓ Need to include the mask (/n) in the table;
- ✓ Need to have an extra column that includes the mask for the corresponding block.
- ✓ classless routing table needs at least four columns.

Note

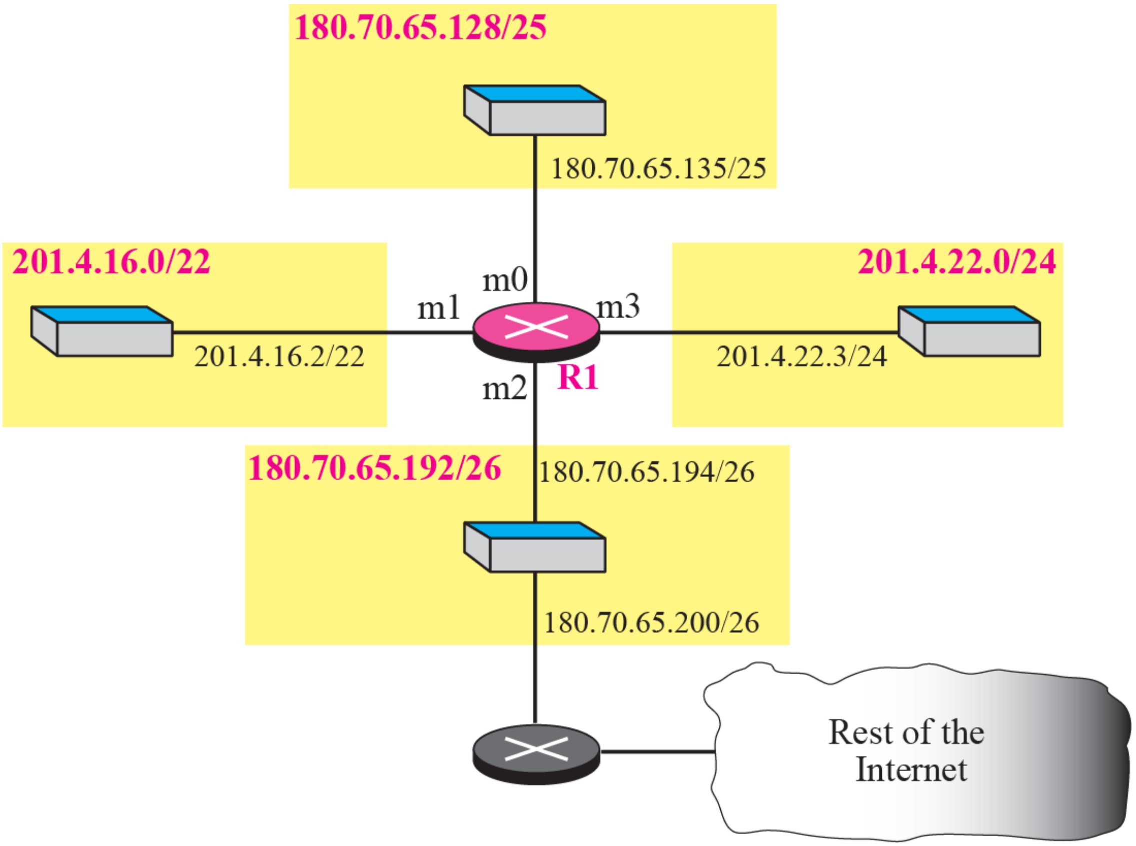
In classful addressing we can have a routing table with three columns; in classless addressing, we need at least four columns.

Figure 6.12 *Simplified forwarding module in classless address*



Example 6.7

Make a routing table for router R1 using the configuration in Figure.



Example 6.7

Make a routing table for router R1 using the configuration in Figure 6.13.

Solution

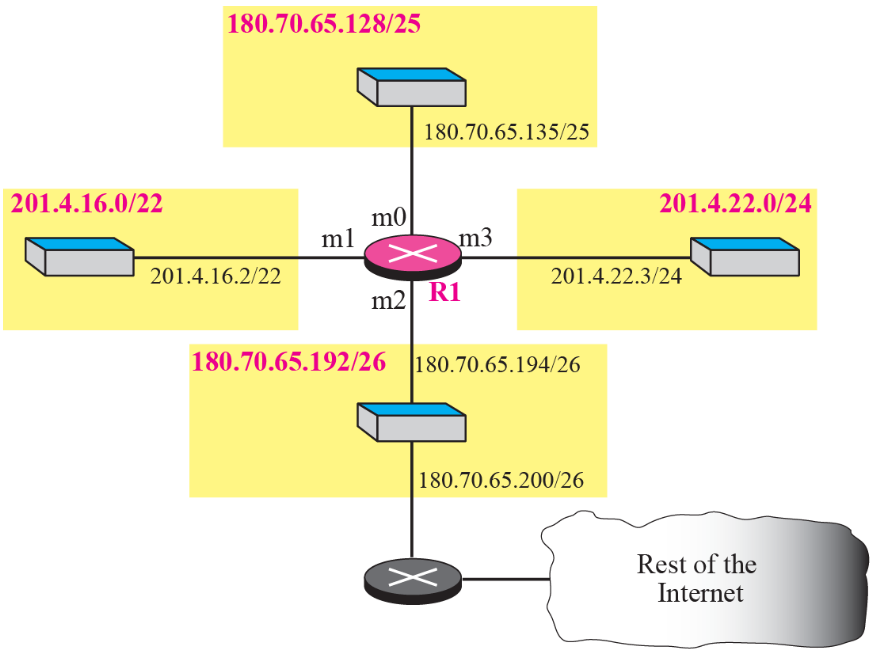


Table 6.1 *Routing table for router R1 in Figure 6.13*

Mask	*Network Address*	*Next Hop*	*Interface*
/26	180.70.65.192	-	m2
/25	180.70.65.128	-	m0
/24	201.4.22.0	-	m3
/22	201.4.16.0	....	m1
Default	Default	180.70.65.200	m2

Example 6.8

Show the forwarding process if a packet arrives at R1 in Figure with the destination address 180.70.65.140.

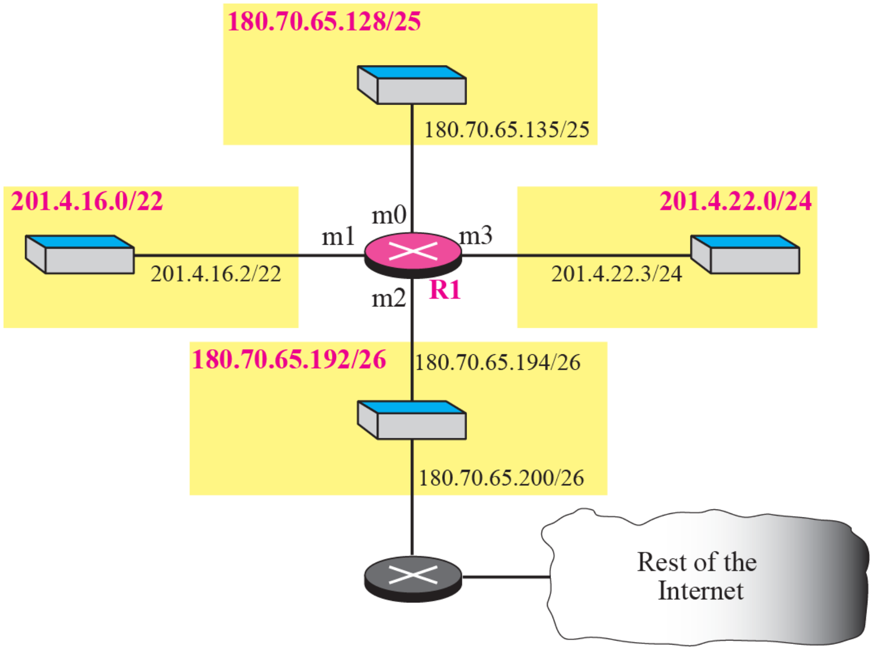


Table 6.1 *Routing table for router R1 in Figure 6.13*

Mask	*Network Address*	*Next Hop*	*Interface*
/26	180.70.65.192	-	m2
/25	180.70.65.128	-	m0
/24	201.4.22.0	-	m3
/22	201.4.16.0	....	m1
Default	Default	180.70.65.200	m2

Example 6.8

Show the forwarding process if a packet arrives at R1 in Figure 6.13 with the destination address 180.70.65.140.

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 (the destination address of the packet in this case) and the interface number m0 are passed to ARP for further processing.

Example 6.9

Show the forwarding process if a packet arrives at R1 in Figure with the destination address 201.4.22.35.

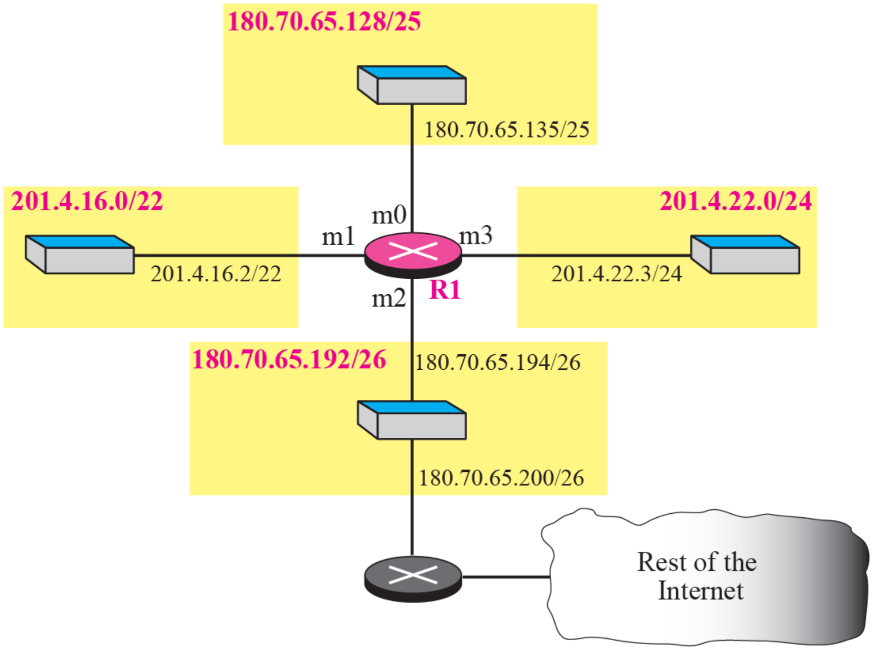


Table 6.1 *Routing table for router R1 in Figure 6.13*

Mask	*Network Address*	*Next Hop*	*Interface*
/26	180.70.65.192	-	m2
/25	180.70.65.128	-	m0
/24	201.4.22.0	-	m3
/22	201.4.16.0	....	m1
Default	Default	180.70.65.200	m2

Example 6.9

Show the forwarding process if a packet arrives at R1 in Figure 6.13 with the destination address 201.4.22.35.

Solution

The router performs the following steps:

1. The first mask (/26) is applied to the destination address. The result is 201.4.22.0, which does not match the corresponding network address .

2. The second mask (/25) is applied to the destination address. The result is 201.4.22.0, which does not match the corresponding network address.

3. The third mask (/24) is applied to the destination address. The result is 201.4.22.0, which matches the corresponding network address.

The destination address of the packet and the interface number m3 are passed to ARP

Example 6.10

Show the forwarding process if a packet arrives at R1 in Figure with the destination address 18.24.32.78.

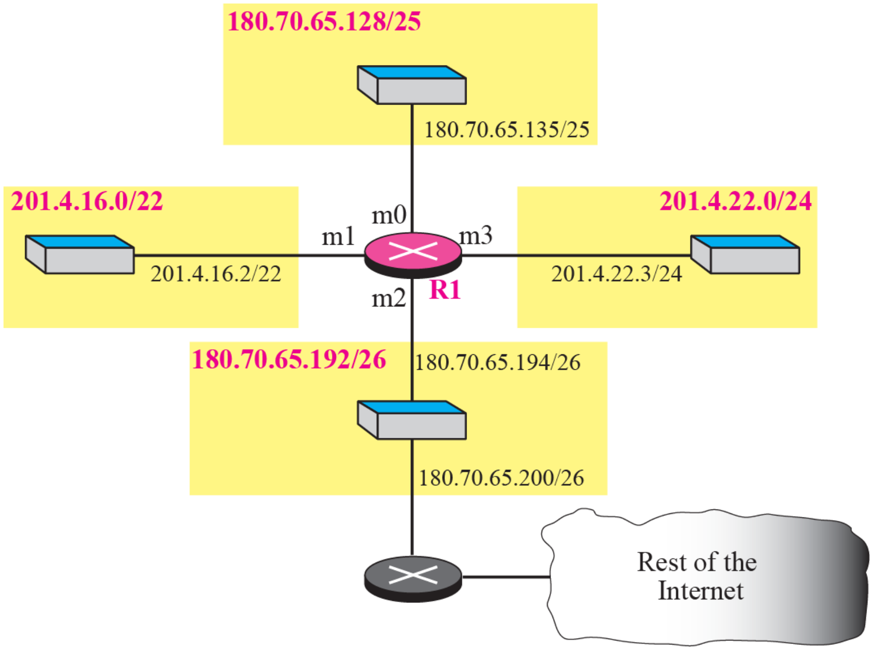


Table 6.1 *Routing table for router R1 in Figure 6.13*

Mask	*Network Address*	*Next Hop*	*Interface*
/26	180.70.65.192	-	m2
/25	180.70.65.128	-	m0
/24	201.4.22.0	-	m3
/22	201.4.16.0	....	m1
Default	Default	180.70.65.200	m2

Example 6.10

Show the forwarding process if a packet arrives at R1 in Figure 6.13 with the destination address 18.24.32.78.

Solution

This time all masks are applied to the destination address, but no matching network address is found.

When it reaches the end of the table, the module gives the next-hop address 180.70.65.200 and interface number m2 to ARP.

This is probably an outgoing package that needs to be sent, via the default router, to someplace else in the Internet.

Example 6.11

The routing table for router R1 is given in Table 6.2. Draw its topology?

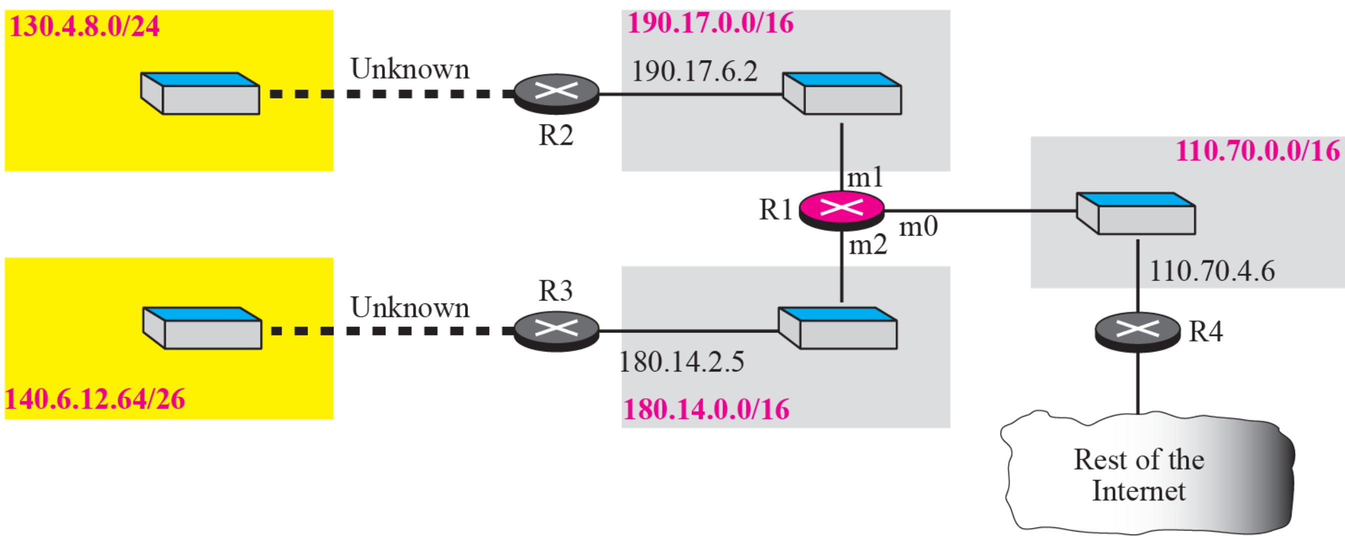
Table 6.2 *Routing table for Example 6.11*

Mask	*Network Address*	*Next-Hop Address*	*Interface Number*
/26	140.6.12.64	180.14.2.5	m2
/24	130.4.8.0	190.17.6.2	m1
/16	110.70.0.0	----------------	m0
/16	180.14.0.0	----------------	m2
/16	190.17.0.0	----------------	m1
Default	Default	110.70.4.6	m0

Figure 6.14 *Guessed topology for Example 6.11*

Table 6.2 *Routing table for Example 6.11*

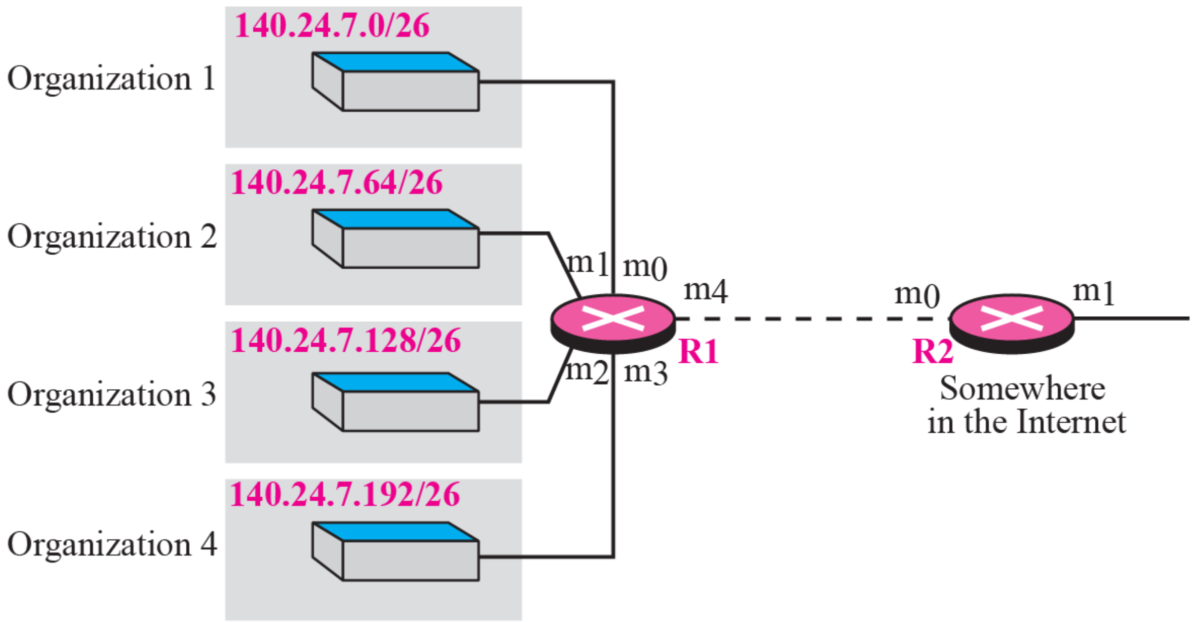
Mask	*Network Address*	*Next-Hop Address*	*Interface Number*
/26	140.6.12.64	180.14.2.5	m2
/24	130.4.8.0	190.17.6.2	m1
/16	110.70.0.0	----------------	m0
/16	180.14.0.0	----------------	m2
/16	190.17.0.0	----------------	m1
Default	Default	110.70.4.6	m0



Address aggregation

- ✓ In classful addressing, there is only one entry in the routing table for each site outside the organization.
- ✓ The entry defines the site even if that site is subnetted. When a packet arrives at the router, the router checks the corresponding entry and forwards the packet accordingly.
- ✓ In case of classless addressing, it is likely that the number of routing table entries will increase.
- ✓ This is because the intent of classless addressing is to divide up the whole address space into manageable blocks.
- ✓ The increased size of the table results in an increase in the amount of time needed to search the table.
- ✓ To alleviate the problem, the idea of address aggregation was designed.

Address aggregation



Mask	Network address	Next-hop address	Interface
/26	140.24.7.0	----------	m0
/26	140.24.7.64	----------	m1
/26	140.24.7.128	----------	m2
/26	140.24.7.192	----------	m3
/0	0.0.0.0	default router	m4

Routing table for R1

Mask	Network address	Next-hop address	Interface
/24	140.24.7.0	----------	m0
/0	0.0.0.0	default router	m1

Routing table for R2

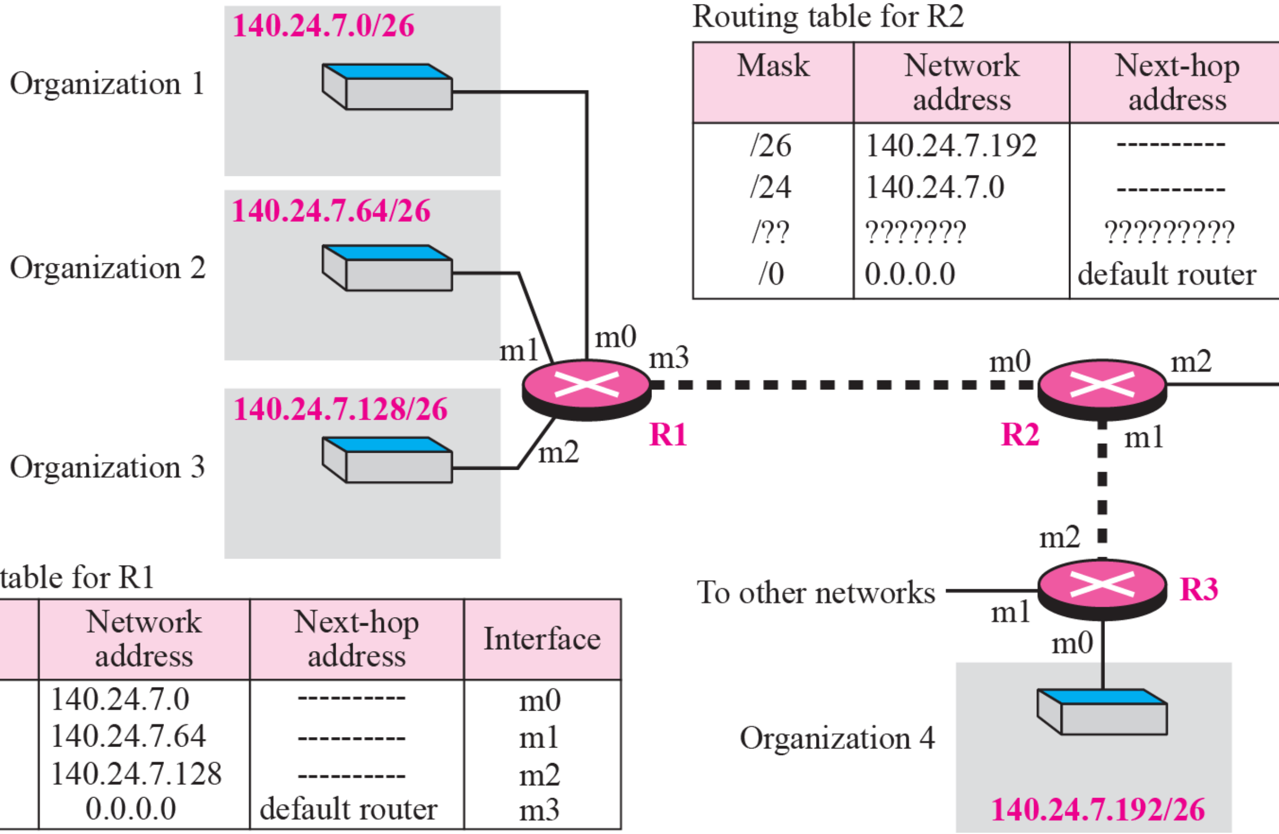
Address aggregation

- ✓ R1 is connected to networks of four organizations that each use 64 addresses. R2 is somewhere far from R1.
- ✓ R1 has a longer routing table because each packet must be correctly routed to the appropriate organization.
- ✓ R2, on the other hand, can have a very small routing table. For R2, any packet with destination 140.24.7.0 to 140.24.7.255 is sent out from interface m0 regardless of the organization number.
- ✓ This is called address aggregation because the blocks of addresses for four organizations are aggregated into one larger block.
- ✓ R2 would have a longer routing table if each organization had addresses that could not be aggregated into one block.

Longest mask matching

- ✓ What happens if one of the organizations in the previous figure is not geographically close to the other three?
- ✓ For example, if organization 4 cannot be connected to router R1 for some reason, can we still use the idea of address aggregation and still assign block 140.24.7.192/26 to organization 4?
- ✓ The answer is yes because routing in classless addressing uses another principle, longest mask matching.
- ✓ This principle states that the routing table is sorted from the longest mask to the shortest mask.
- ✓ In other words, if there are three masks, /27, /26, and /24, the mask /27 must be the first entry and /24 must be last.
- ✓ Let us see if this principle solves the situation in which organization 4 is separated from the other three organizations

Longest mask matching



Routing table for R2

Mask	Network address	Next-hop address	Interface
/26	140.24.7.192	----------	m1
/24	140.24.7.0	----------	m0
/??	???????	?????????	m1
/0	0.0.0.0	default router	m2

Routing table for R1

Mask	Network address	Next-hop address	Interface
/26	140.24.7.0	----------	m0
/26	140.24.7.64	----------	m1
/26	140.24.7.128	----------	m2
/0	0.0.0.0	default router	m3

Routing table for R3

Mask	Network address	Next-hop address	Interface
/26	140.24.7.192	----------	m0
/??	???????	?????????	m1
/0	0.0.0.0	default router	m2

Example: Packet arrived at R2: 140.24.7.200.

Longest mask matching

- ✓ Suppose a packet arrives for organization 4 with destination address 140.24.7.200.
- ✓ The first mask at router R2 is applied, which gives the network address 140.24.7.192. The packet is routed correctly from interface m1 and reaches organization 4.
- ✓ If, however, the routing table was not stored with the longest prefix first, applying the /24 mask would result in the incorrect routing of the packet to router R1.

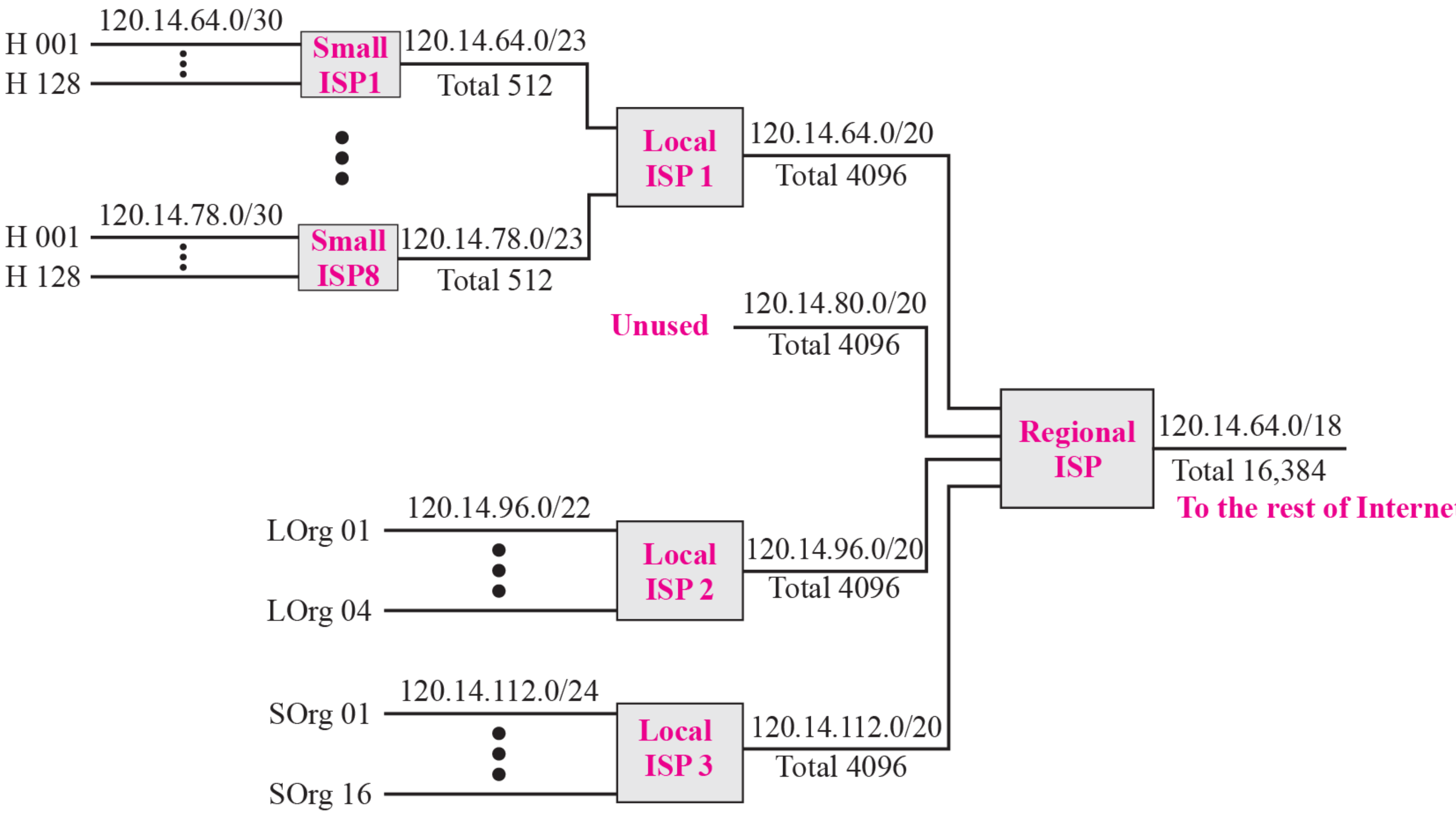
Hierarchical routing with ISPs

- ✓ To solve the problem of gigantic routing tables, we can create a hierarchy in the routing tables.
- ✓ The Internet today has a sense of hierarchy. Internet is divided into backbone, regional and local ISPs.
- ✓ If the routing table has a sense of hierarchy like the Internet architecture, the routing table can decrease in size.
- ✓ Let us take the case of a local ISP. A local ISP can be assigned a single, but large, block of addresses with a certain prefix length.
- ✓ The local ISP can divide this block into smaller blocks of different sizes, and assign these to individual users and organizations.
- ✓ If the block assigned to the local ISP starts with a.b.c.d/n, the ISP can create blocks starting with e.f.g.h/m, where m may vary for each customer and is greater than n.

Hierarchical routing with ISPs

- ✓ How to reduce the size of the routing table ?
- ✓ All customers of the local ISP are defined as a.b.c.d/n to the rest of the Internet.
- ✓ Every packet destined for one of the addresses in this large block is routed to the local ISP. There is only one entry in every router in the world for all of these customers.
- ✓ Inside the local ISP, the router must recognize the subblocks and route the packet to the destined customer.

Figure 6.17 *Hierarchical routing with ISPs*



Geographical Routing

- ✓ To decrease the size of the routing table even further, we need to extend hierarchical routing to include geographical routing.
- ✓ We must divide the entire address space into a few large blocks.
- ✓ We assign a block to America, a block to Europe, a block to Asia, a block to Africa, and so on.
- ✓ The routers of ISPs outside of Europe will have only one entry for packets to Europe in their routing tables.

Searching in Classful Addressing

- In classful addressing, the routing table is organized as a list.
- To make searching more efficient, the routing table can be divided into three tables (called buckets), one for each class.
- When the packet arrives, the router applies the default mask to find the corresponding bucket (A, B, or C).
- The router then searches the corresponding bucket instead of the whole table.

Searching in Classless Addressing

- ✓ In classless addressing, there is no network information in the destination address.
- ✓ The simplest, but not the most efficient, search method is called the longest prefix match.
- ✓ The routing table can be divided into buckets, one for each prefix. The router first tries the longest prefix.
- ✓ If the address is not found, the next prefix is searched. And so on.
- ✓ It is obvious that this type of search takes a long time. One solution is to change the data structure used for searching.
- ✓ Instead of a list, other data structures (such as a tree or a binary tree) can be used.

Forwarding Based on Label

- ✓ In a connectionless network (datagram approach), a router forwards a packet based on the destination address.
- ✓ In a connection-oriented network (virtual-circuit approach), a switch forwards a packet based on the label attached to a packet.
- ✓ Routing is normally based on searching the contents of a table while switching can be done by accessing a table using an index.
- ✓ In other words, routing involves searching; switching involves accessing.

Figure 6.18 *Example 6.13: Forwarding based on destination address*

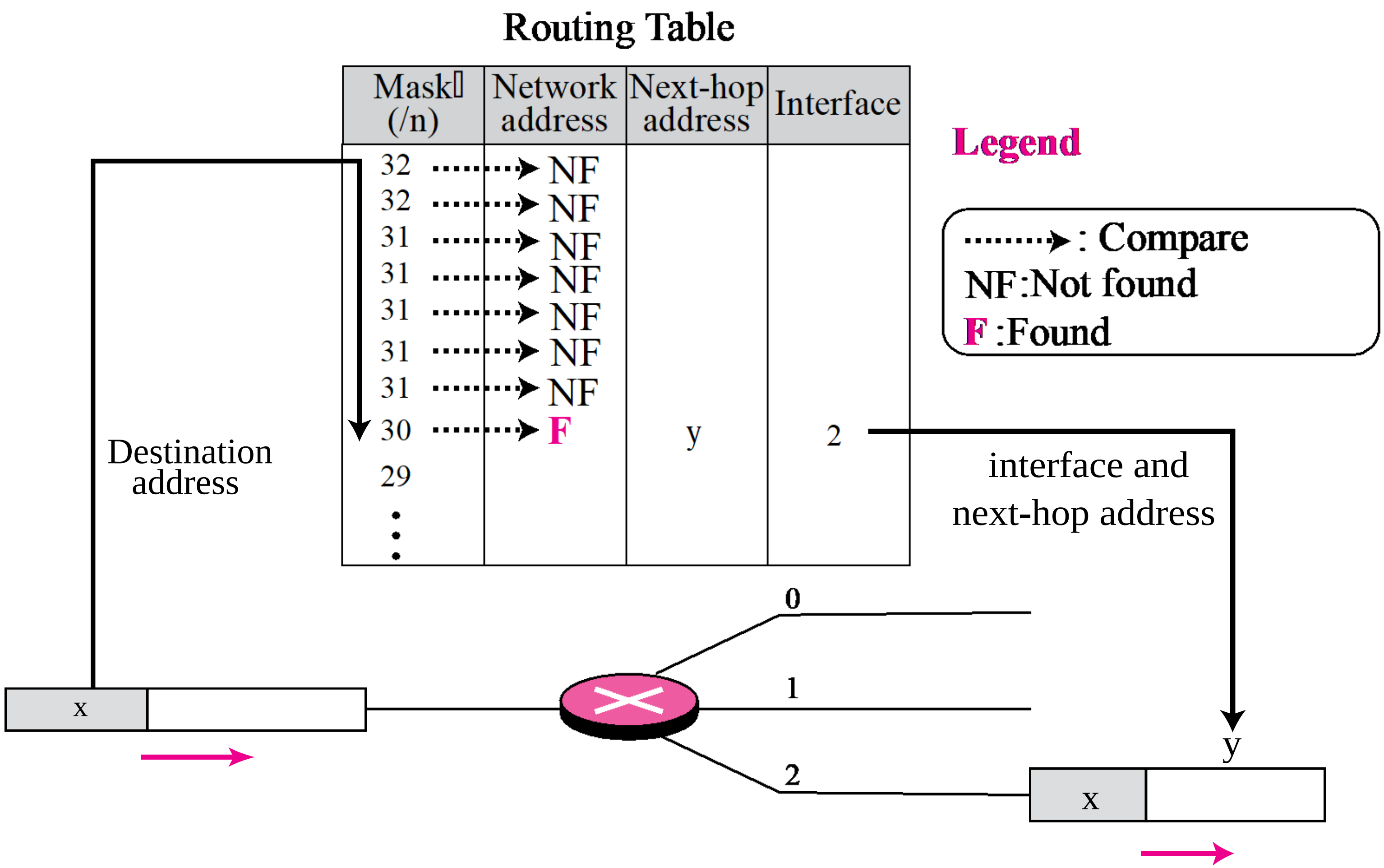
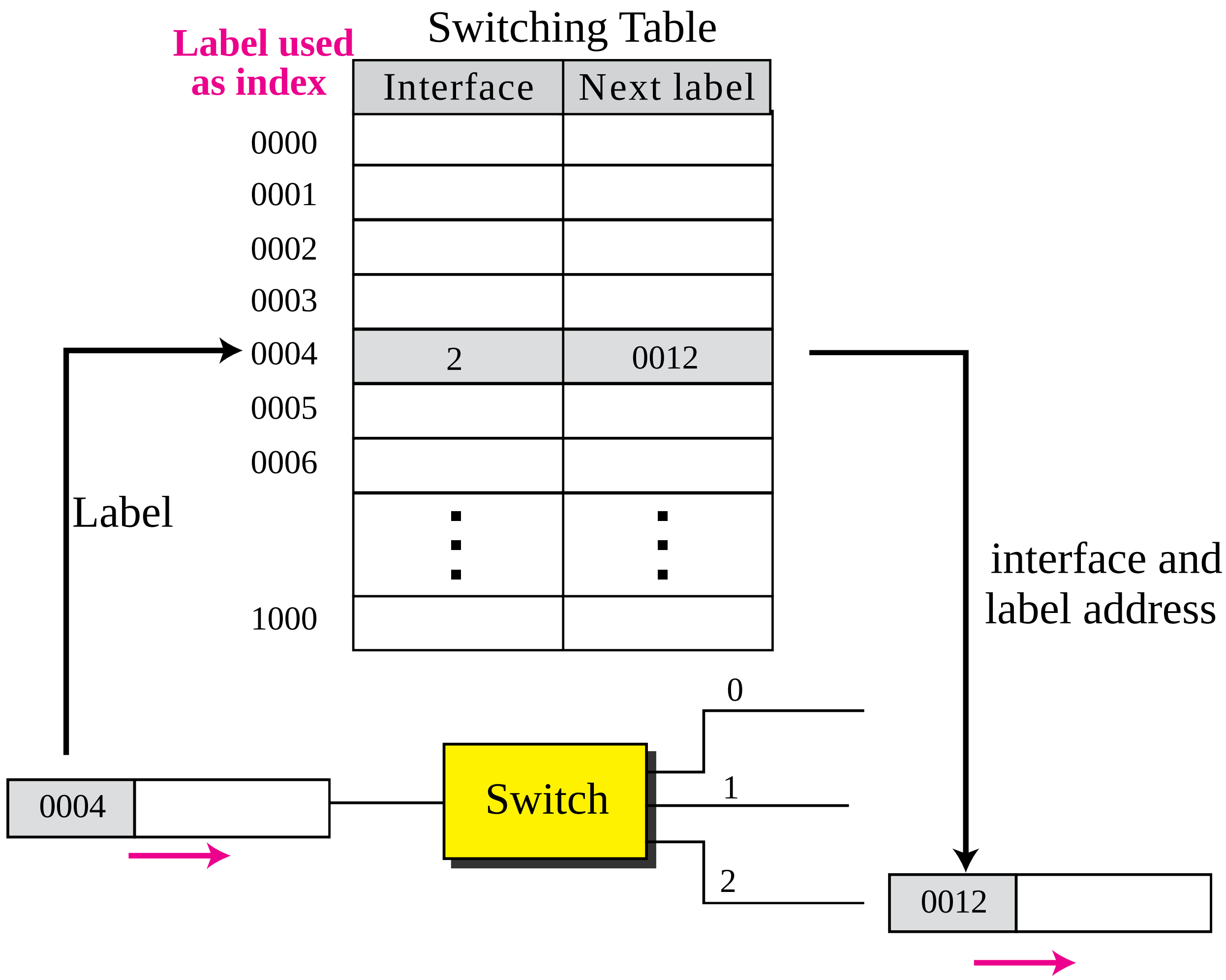


Figure 6.19 *Example 6.14: Forwarding based on label*



MPLS (Multi Protocol Label Switching)

- ✓ Here some conventional routers in the Internet can be replaced by MPLS routers that can behave like a router and a switch.
- ✓ When behaving like a router, MPLS can forward the packet based on the destination address; when behaving like a switch, it can forward a packet based on the label.
- ✓ To simulate connection-oriented switching using a protocol like IP, the first thing needed is to add a field to the packet that carry the label.
- ✓ The whole IP packet is encapsulated as the payload in an MPLS packet and MPLS header is added.

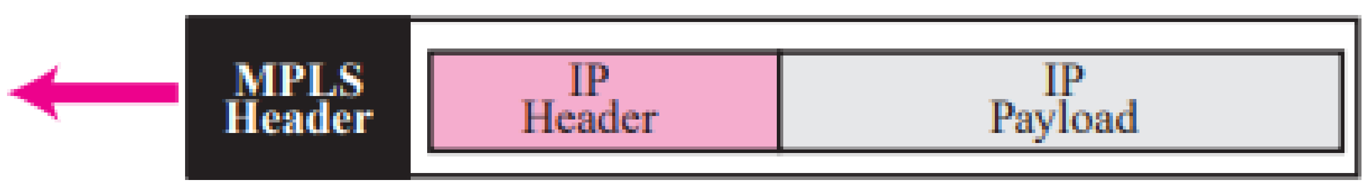


Figure 6.20 MPLS header added to an IP packet

END.