Unit 4 - Network Layer

AGENDA

- **IPv4 Addresses**: Address Space, Notations, Classful Addressing, Classless Addressing,
- Network Address Translation (NAT)
- Need for Network Layer
- Internet as a Datagram Network
- Internet as a Connectionless Network
- IPv4: Segment Header Format,
- Datagram, Fragmentation, Checksum, Options
- **IPv6:** Advantages
- Packet Format
- Extension Headers
- Forwarding Techniques
- Forwarding Process
- Routing Table.

Network Layer

- The network layer is responsible for the delivery of individual packets from the source to the destination host.
- If a packet travels through the Internet, we need a global addressing system to help distinguish the source and destination.
- This scheme is called logical addressing. We use the term IP address to mean a logical address in the network layer of the TCP/IP protocol suite.
- The network layer adds a header that includes the logical addresses of the sender and receiver to the packet corning from the upper layer.

Network Layer

- The Internet addresses are 32 bits in length; this gives us a maximum of 2^{32} addresses. These addresses are referred to as IPv4 (IP version 4) addresses or simply IP addresses if there is no confusion.
- The need for more addresses, in addition to other concerns about the IP layer, motivated a new design of the IP layer called the new generation of IP or IPv6 (lP version 6).
- In this version, the Internet uses 128-bit addresses that give much greater flexibility in address allocation. These addresses are referred to as IPv6 (IP version 6) addresses.

IPv4 ADDRESSES

- The identifier used in the IP layer of the TCP/IP protocol suite to identify the connection of each device to the Internet is called the Internet address or **IP address**.
- An IPv4 address is a 32-bit address that uniquely and universally defines the connection of a host or a router to the Internet.
- The IP address is the address of the connection, not the host or the router, because if the device is moved to another network, the IP address may be changed.
- IPv4 addresses are unique in the sense that each address defines one, and only one, connection to the Internet.
- If a device has two connections to the Internet, via two networks, it has two IPv4 addresses.

IPv4 ADDRESSES

- IPv4 is also a connection-less protocol that uses the datagram approach. Each datagram is handled independently, and each can follow a different route to the destination.
- This implies that datagrams sent by the same source to the same destination could arrive out of order.
- An IPv4 address is a 32-bit address that uniquely and universally defines the connection of a device (for example, a computer or a router) to the Internet.

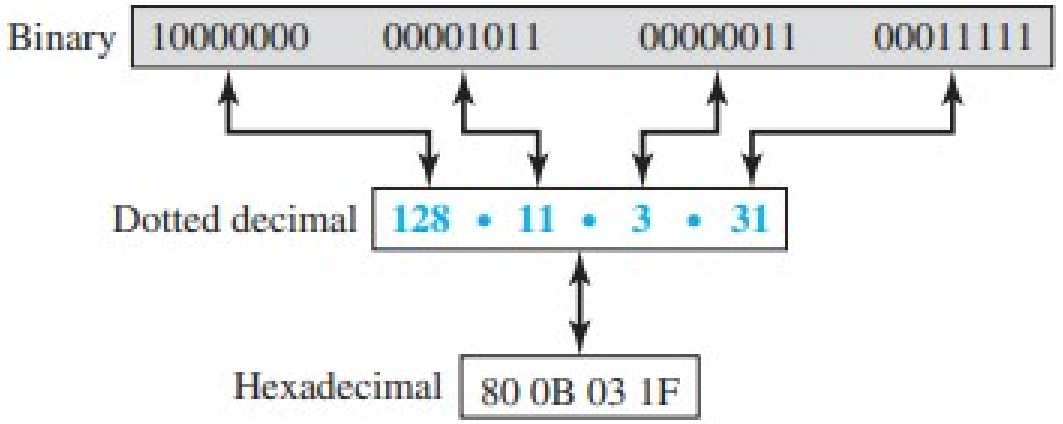
IPv4 ADDRESSES

- **Address Space**
- A protocol like IPv4 that defines addresses has an address space.
- An address space is the total number of addresses used by the protocol.
- If a protocol uses b bits to define an address, the address space is 2^b because each bit can have two different values (0 or 1).
- IPv4 uses 32-bit addresses, which means that the address space is 2^{32} or 4,294,967,296 (more than four billion).
- If there were no restrictions, more than 4 billion devices could be connected to the Internet.

Dotted-decimal notation and binary notation for an IPv4 address

- There are three common notations to show an IPv4 address: binary notation (base 2), dotted-decimal notation (base 256), and hexadecimal notation (base 16).

Figure 18.16 *Three different notations in IPv4 addressing*



Dotted-decimal notation and binary notation for an IPv4 address

- In binary notation, an IPv4 address is displayed as 32 bits. To make the address more readable, one or more spaces are usually inserted between each octet (8 bits).
- Each octet is often referred to as a byte. To make the IPv4 address more compact and easier to read, it is usually written in decimal form with a decimal point (dot) separating the bytes.
- This format is referred to as dotted-decimal notation.
- We sometimes see an IPv4 address in hexadecimal notation. Each hexadecimal digit is equivalent to four bits. This means that a 32-bit address has 8 hexadecimal digits.

IPv4 ADDRESSES

- Change the following IPv4 addresses from binary notation to dotted-decimal notation.

  a. 10000001 00001011 00001011 11101111

  b. 11000001 10000011 00011011 11111111

- We replace each group of 8 bits with its equivalent decimal number (see Appendix B) and add dots for separation.

  a. 129.11.11.239

  b. 193.131.27.255

IPv4 ADDRESSES

- Change the following IPv4 addresses from dotted-decimal notation to binary notation.

  a. 111.56.45.78

  b. 221.34.7.82

- We replace each decimal number with its binary equivalent

  a. 01101111 00111000 00101101 01001110

  b. 11011101 00100010 00000111 01010010

IPv4 ADDRESSES

- Find the error, if any, in the following IPv4 addresses.

a. 111.56.045.78

b. 221.34.7.8.20

c. 75.45.301.14

d. 11100010.23.14.67

Solution

- a. There must be no leading zero (045).
- b. There can be no more than four numbers. (One extra number)
- c. Each number needs to be less than or equal to 255. (301)
- d. A mixture of binary notation and dotted-decimal notation is not allowed.

IPv4 ADDRESSES

- **Hierarchy in Addressing**
- A 32-bit IPv4 address is also hierarchical, but divided only into two parts. The first part of the address, called the prefix, defines the network; the second part of the address, called the suffix, defines the node (connection of a device to the Internet).
- Figure 18.17 shows the prefix and suffix of a 32-bit IPv4 address. The prefix length is n bits and the suffix length is (32 − n) bits.
- A prefix can be fixed length or variable length. The network identifier in the IPv4 was first designed as a fixed-length prefix.
- This scheme, which is now obsolete, is referred to as classful addressing. The new scheme, which is referred to as classless addressing, uses a variable-length network prefix.

IPv4 ADDRESSES

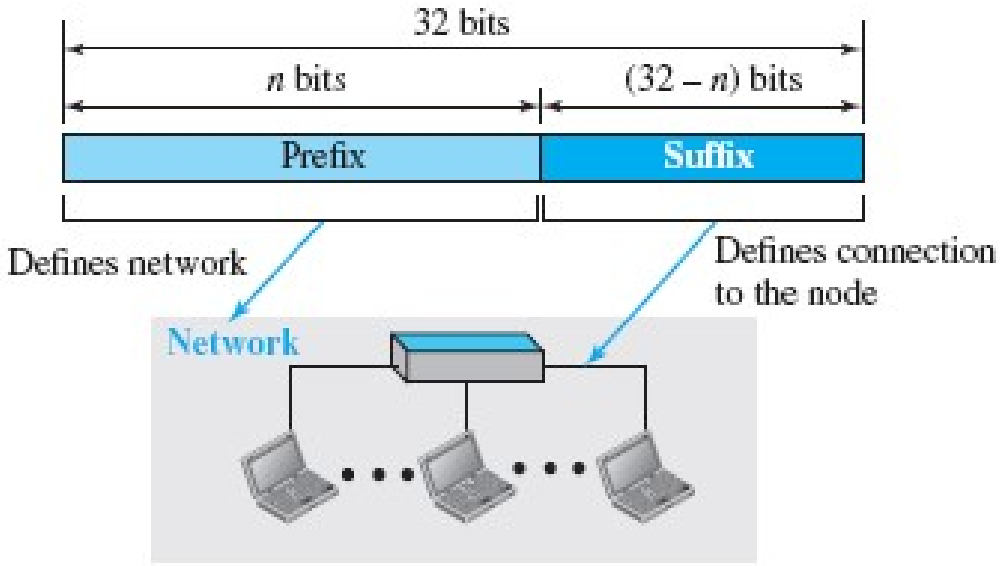


Figure 18.17 Hiearchy in Addressing

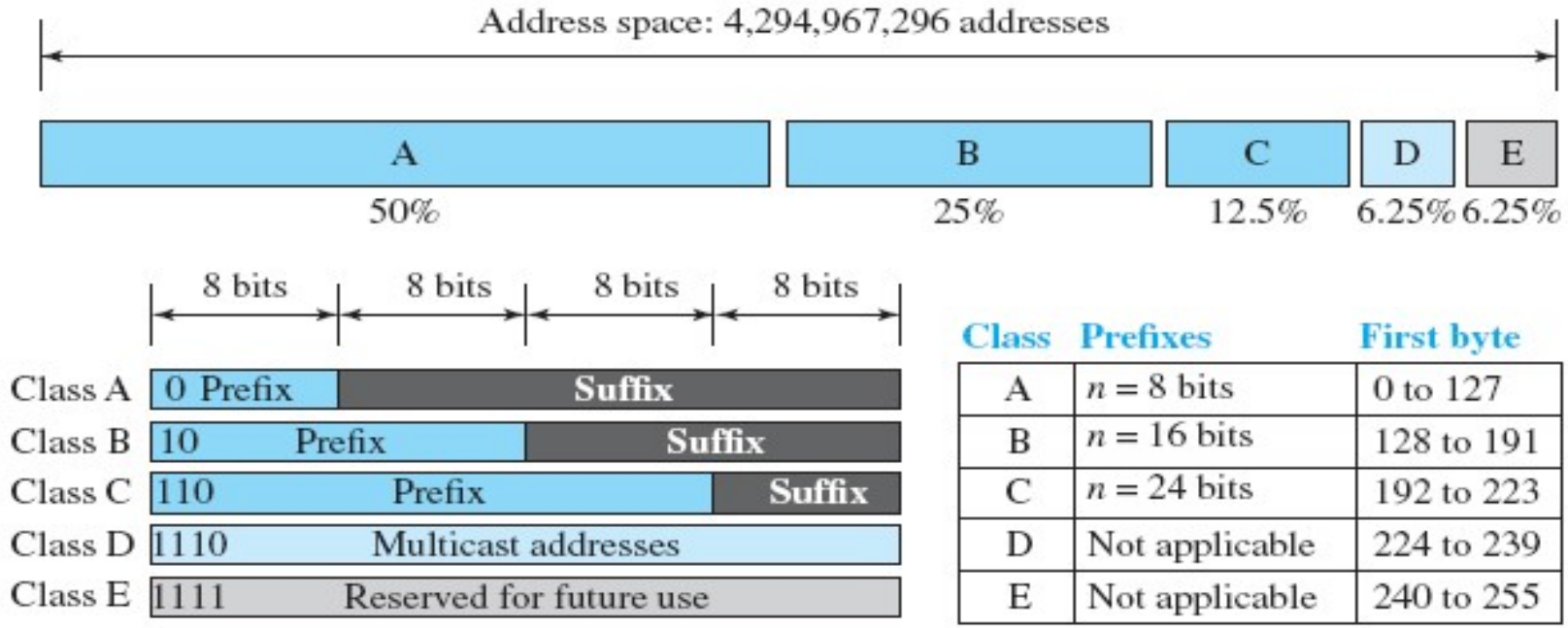
IPv4 ADDRESSES

- **Classful Addressing**
- When the Internet started, an IPv4 address was designed with a fixed-length prefix, but to accommodate both small and large networks, three fixed-length prefixes were designed instead of one (n = 8, n = 16, and n = 24).
- The whole address space was divided into five classes (class A, B, C, D, and E), as shown in Figure 18.18.
- This scheme is referred to as classful addressing.

In classful addressing, the address space is divided into five classes: A, B, C, D, and E.

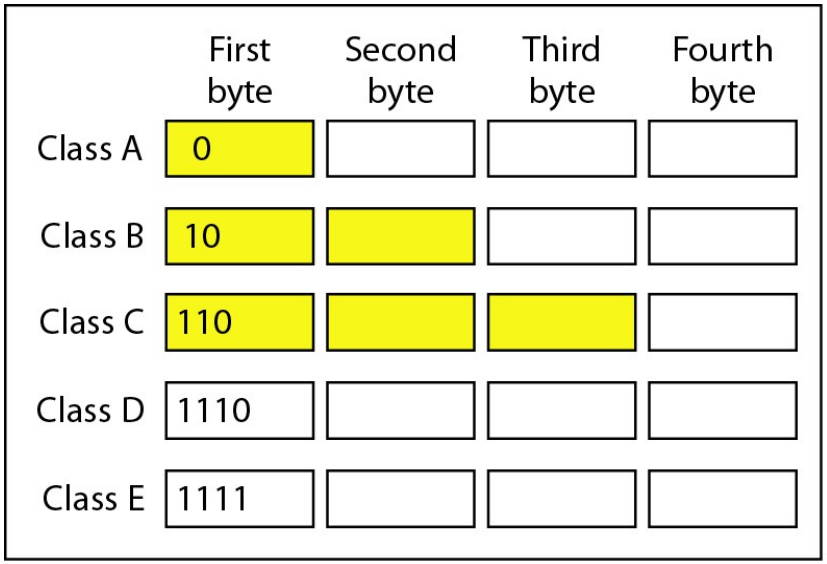
Classful Addressing

Figure 18.18 *Occupation of the address space in classful addressing*

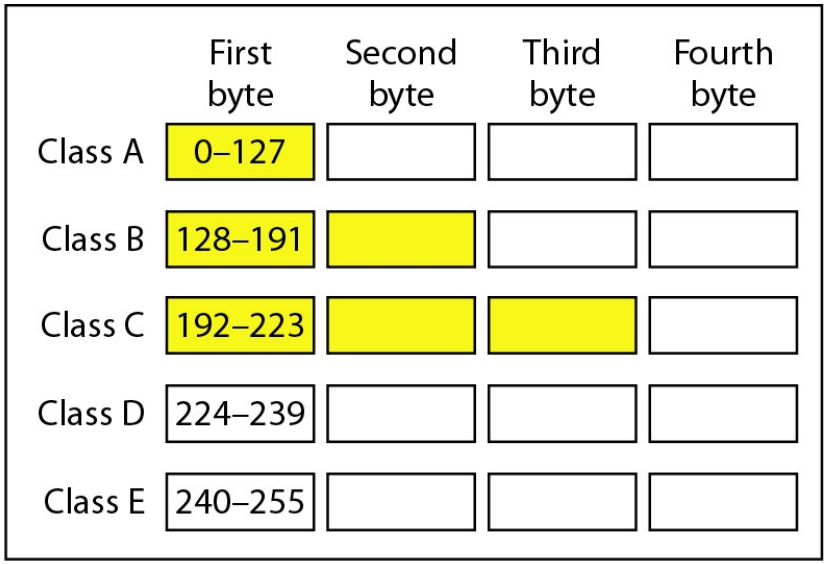


Class	Prefixes	First byte
A	$n = 8$ bits	0 to 127
B	$n = 16$ bits	128 to 191
C	$n = 24$ bits	192 to 223
D	Not applicable	224 to 239
E	Not applicable	240 to 255

Finding the classes in binary and dotted-decimal notation



a. Binary notation



b. Dotted-decimal notation

Classful Addressing

- In class A, the network length is 8 bits, but since the first bit, which is 0, defines the class, we can have only seven bits as the network identifier.
- This means there are only $2^7 = 128$ networks in the world that can have a class A address.
- In class B, the network length is 16 bits, but since the first two bits, which are (10)2, define the class, we can have only 14 bits as the network identifier.
- This means there are only $2^{14} = 16{,}384$ networks in the world that can have a class B address.
- All addresses that start with (110)2 belong to class C.

Classful Addressing

- In class C, the network length is 24 bits, but since three bits define the class, we can have only 21 bits as the network identifier.
- This means there are $2^{21} = 2{,}097{,}152$ networks in the world that can have a class C address.
- Class D is not divided into prefix and suffix. It is used for multicast addresses. All addresses that start with 1111 in binary belong to class E.
- Class D is used as reserved class.

Classful Addressing

- **Address Depletion**
- The reason that classful addressing has become obsolete is address depletion.
- Since the addresses were not distributed properly, the Internet was faced with the problem of the addresses being rapidly used up, resulting in no more addresses available for organizations and individuals that needed to be connected to the Internet.

In classful addressing, a large part of the available addresses were wasted.

Classful Addressing

- **Address Depletion**
- To understand the problem, let us think about class A. This class can be assigned to only 128 organizations in the world, but each organization needs to have a single network (seen by the rest of the world) with 16,777,216 nodes (computers in this single network).
- Since there may be only a few organizations that are this large, most of the addresses in this class were wasted (unused).
- Class B addresses were designed for midsize organizations, but many of the addresses in this class also remained unused.
- Class C addresses have a completely different flaw in design. The number of addresses that can be used in each network (256) was so small that most companies were not comfortable using a block in this address class.
- Class E addresses were almost never used, wasting the whole class.

Classes and Blocks

Table 19.1 ***Number of blocks and block size in classful IPv4 addressing***

Class	*Number of Blocks*	*Block Size*	*Application*
A	128	16,777,216	Unicast
B	16,384	65,536	Unicast
C	2,097,152	256	Unicast
D	1	268,435,456	Multicast
E	1	268,435,456	Reserved

- One problem with classful addressing is that each class is divided into a fixed number of blocks with each block having a fixed size as shown in Table

Classes and Blocks

- We can see the flaw in this design. A block in class A address is too large for almost any organization.
- This means most of the addresses in class A were wasted and were not used.
- A block in class B is also very large, probably too large for many of the organizations that received a class B block.
- A block in class C is probably too small for many organizations.
- Class D addresses were designed for multicasting

Netid and Hostid

- In classful addressing, an IP address in class A, B, or C is divided into netid and hostid. These parts are of varying lengths, depending on the class of the address.
- Figure 19.2 shows some netid and hostid bytes. The netid is in color, the hostid is in white. Note that the concept does not apply to classes D and E.
- In class A, one byte defines the netid and three bytes define the hostid. In class B, two bytes define the netid and two bytes define the hostid. In class C, three bytes define the netid and one byte defines the hostid.

Table 19.2 ***Default masks for classful addressing***

Class	*Binary*	*Dotted-Decimal*	*CIDR*
A	11111111 00000000 00000000 00000000	255.0.0.0	/8
B	11111111 11111111 00000000 00000000	255.255.0.0	/16
C	11111111 11111111 11111111 00000000	255.255.255.0	/24

Netid and Hostid

- Mask
- Although the length of the netid and hostid (in bits) is predetermined in classful addressing, we can also use a mask (also called the default mask), a 32-bit number made of contiguous 1s followed by contiguous as.
- The masks for classes A, B, and C are shown in Table 19.2. The concept does not apply to classes D and E.

Classful Addressing

- **Subnetting and Supernetting**
- To alleviate address depletion, two strategies were proposed and, to some extent, implemented: subnetting and supernetting.
- In subnetting, a class A or class B block is divided into several subnets. Each subnet has a larger prefix length than the original network.
- If all of the addresses in a network are not used, subnetting allows the addresses to be divided among several organizations.
- This idea did not work because most large organizations were not happy about dividing the block and giving some of the unused addresses to smaller organizations.
- While subnetting was devised to divide a large block into smaller ones, supernetting was devised to combine several class C blocks into a larger block to be attractive to organizations that need more than the 256 addresses available in a class C block.
- This idea did not work either because it makes the routing of packets more difficult.

Classful Addressing

- **Advantage of Classful Addressing**
- Given an address, we can easily find the class of the address and, since the prefix length for each class is fixed, we can find the prefix length immediately.
- In other words, the prefix length in classful addressing is inherent in the address; no extra information is needed to extract the prefix and the suffix.

Classful addressing, which is almost obsolete, is replaced with classless addressing.

Classless Addressing

- With the growth of the Internet, it was clear that a larger address space was needed as a long-term solution.
- The larger address space, however, requires that the length of IP addresses also be increased, which means the format of the IP packets needs to be changed.
- Although the long-range solution has already been devised and is called IPv6 (discussed later), a short-term solution was also devised to use the same address space but to change the distribution of addresses to provide a fair share to each organization.
- The short-term solution still uses IPv4 addresses, but it is called classless addressing.
- In classless addressing, variable-length blocks are used that belong to no classes. We can have a block of 1 address, 2 addresses, 4 addresses, 128 addresses, and so on.

Classless Addressing

- In classless addressing, the whole address space is divided into variablelength blocks. The prefix in an address defines the block (network); the suffix defines the node (device).
- Theoretically, we can have a block of 20, 21, 22, . . . , 232 addresses (Has to be in the power of 2).

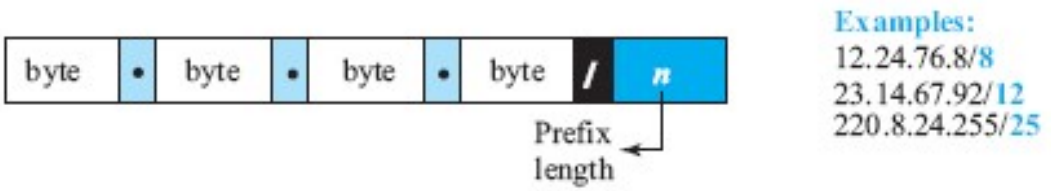
Figure 18.19 *Variable-length blocks in classless addressing*

- We can have a prefix length that ranges from 0 to 32. The size of the network is inversely proportional to the length of the prefix.
- A small prefix means a larger network; a large prefix means a smaller network.
- The idea of classless addressing can be easily applied to classful addressing. In other words, classful addressing is a special case of classless addressing.

Classless Addressing

- **Prefix Length: Slash Notation**
- How to find the prefix length if an address is given. In this case, the prefix length, n, is added to the address, separated by a slash.
- The notation is informally referred to as slash notation and formally as **c**lassless **i**nter-**d**omain **r**outing or CIDR (pronounced cider) strategy.
- An address in classless addressing can then be represented as shown in Figure 18.20.

Figure 18.20 *Slash notation (CIDR)*



Classless Addressing

- **Prefix Length: Slash Notation**
- Extracting Information from an Address Given any address in the block, we normally like to know three pieces of information about the block to which the address belongs: the number of addresses, the first address in the block, and the last address.
- Since the value of prefix length, n, is given, we can easily find these three pieces of information, as shown in Figure 18.21.
- 1. The number of addresses in the block is found as $N = 2^{(32-n)}$.
- 2. To find the first address, we keep the n leftmost bits and set the (32 − n) right most bits all to 0s.
- 3. To find the last address, we keep the n leftmost bits and set the (32 − n) rightmost bits all to 1s.

Note: IP has 32 bits, and number after the slash tells you where does the network part end, host part starts. and /24 says that first 24 bits are used for network designation, while last 8 bits are used for various hosts inside that network

Example 18.1

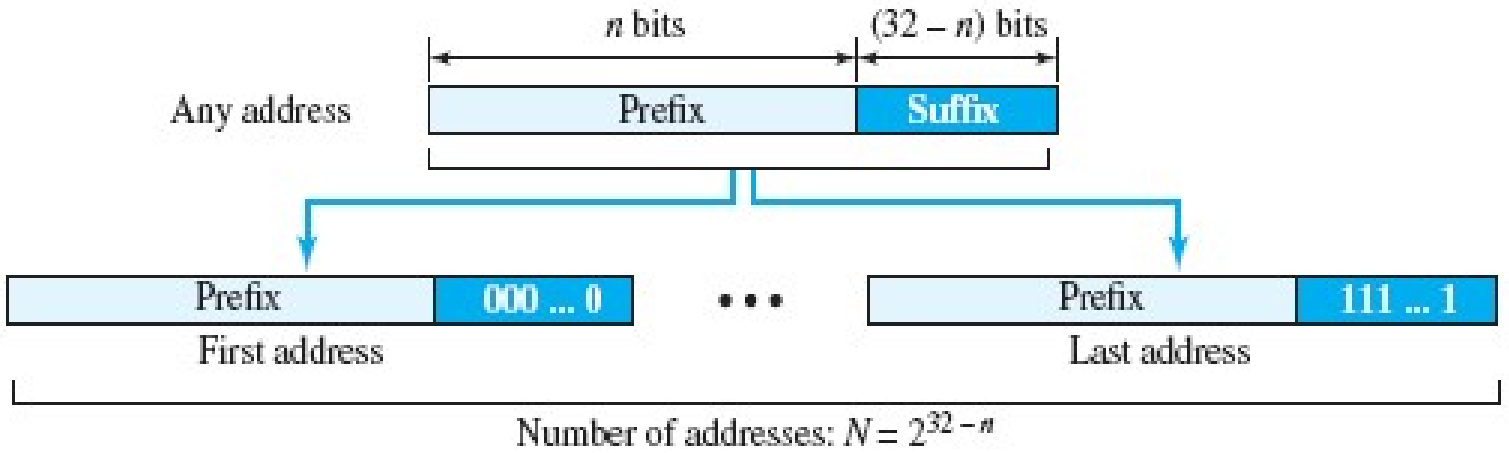
A classless address is given as 167.199.170.82/27. We can find the above three pieces of information as follows. The number of addresses in the network is $2^{32-n} = 2^5 = 32$ addresses.

The first address can be found by keeping the first 27 bits and changing the rest of the bits to 0s.

Address: 167.199.170.82/27	10100111	11000111	10101010	01010010
First address: 167.199.170.64/27	10100111	11000111	10101010	01000000

The last address can be found by keeping the first 27 bits and changing the rest of the bits to 1s.

Figure 18.21 *Information extraction in classless addressing*



Classless Addressing

- **Address Mask**
- Another way to find the first and last addresses in the block is to use the address mask.
- The address mask is a 32-bit number in which the n leftmost bits are set to 1s and the rest of the bits (32 − n) are set to 0s.
- A computer can easily find the address mask because it is the complement of (2^{32-n-1}).
- The reason for defining a mask in this way is that it can be used by a computer program to extract the information in a block, using the three bit-wise operations NOT, AND, and OR.
- 1. The number of addresses in the block N = NOT (mask) + 1.
- 2. The first address in the block = (Any address in the block) AND (mask).
- 3. The last address in the block = (Any address in the block) OR [(NOT (mask)].

Classless Addressing

- **Address Mask**

Example 18.2

We repeat Example 18.1 using the mask. The mask in dotted-decimal notation is 256.256.256.224. The AND, OR, and NOT operations can be applied to individual bytes using calculators and applets at the book website.

Number of addresses in the block:	N = NOT (mask) + 1 = 0.0.0.31 + 1 = 32 addresses
First address:	First = (address) AND (mask) = 167.199.170.82
Last address:	Last = (address) OR (NOT mask) = 167.199.170.255

Classless Addressing

- **Address Mask**

- In Example 19.5 the /28 can be represented as 11111111 11111111 11111111 11110000 (twenty-eight Is and four Os). Find
- a) The first address, b) The last address, c) The number of addresses
- **Solution**
- **a.** The first address can be found by ANDing the given addresses with the mask. ANDing here is done bit by bit. The result of ANDing 2 bits is 1 if both bits are Is; the result is 0 otherwise.
- **Address**: 11001101 00010000 00100101 00100111
- **Mask**: 11111111 11111111 11111111 11110000
- **First address**: 11001101 00010000 00100101 00100000

Classless Addressing

- **Address Mask**

- **b.** The last address can be found by ORing the given addresses with the complement of the mask. ORing here is done bit by bit.
- The result of ORing 2 bits is 0 if both bits are Os; the result is 1 otherwise. The complement of a number is found by changing each 1 to 0 and each 0 to 1
- **Address:** 11001101 00010000 00100101 00100111
- **Mask complement**: 00000000 00000000 00000000 00001111
- **Last address**: 11001101 00010000 00100101 00101111
- **c.** The number of addresses can be found by complementing the mask, interpreting it as a decimal number, and adding 1 to it.
- **Mask complement**: 000000000 00000000 00000000 00001111
- **Number of addresses**: 15 + 1 =16

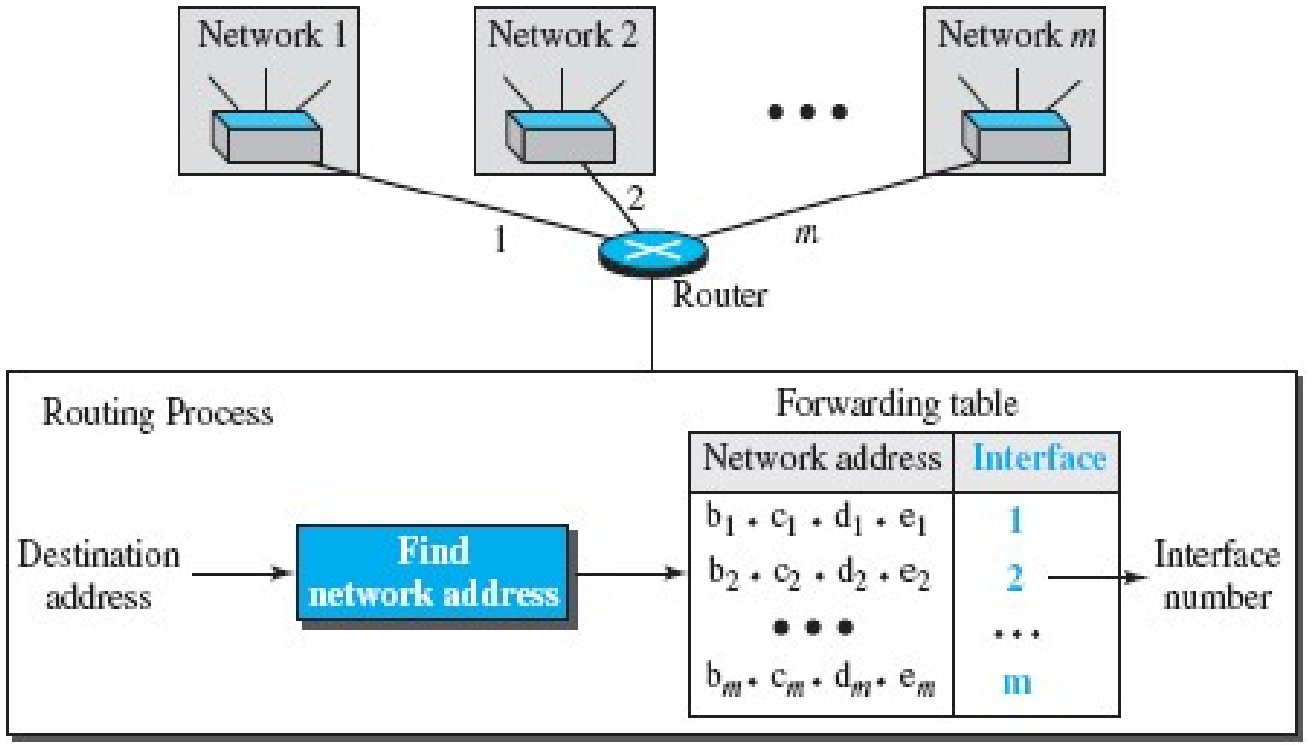
Classless Addressing

- **Network Address**
- Network address is used in routing a packet to its destination network.
- For the moment, let us assume that an internet is made of m networks and a router with m interfaces.
- When a packet arrives at the router from any source host, the router needs to know to which network the packet should be sent: from which interface the packet should be sent out.
- When the packet arrives at the network, it reaches its destination host using another strategy that we discuss later.
- Figure 18.22 shows the idea. After the network address has been found, the router consults its forwarding table to find the corresponding interface from which the packet should be sent out.
- The network address is actually the identifier of the network; each network is identified by its network address.

Classless Addressing

- **Network Address**

Figure 18.22 *Network address*



Classless Addressing

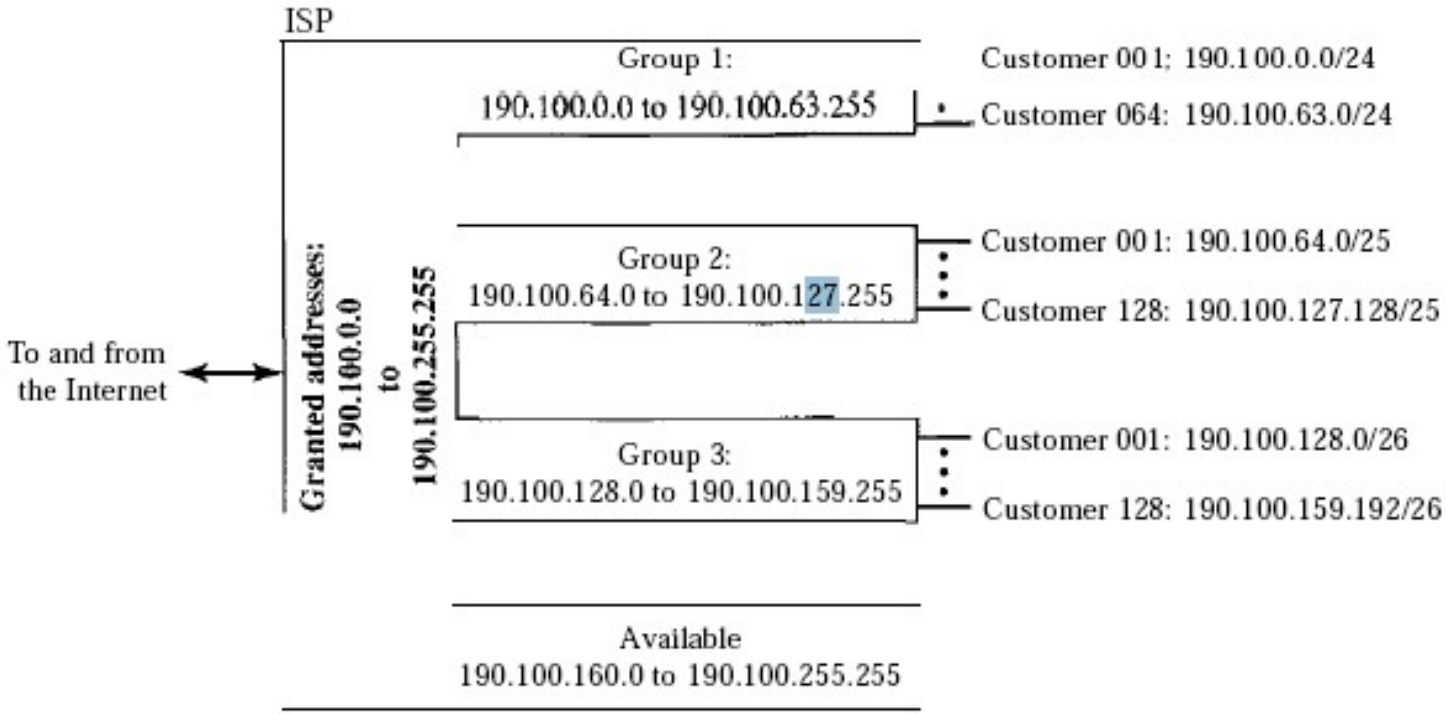
- **Network Address Block Allocation**
- The main responsibility of block allocation is given to a global authority called the Internet Corporation for Assigned Names and Numbers (ICANN).
- ICANN does not allocate addresses to individual Internet users but to an ISP (or a larger organization that is considered an ISP in this case).
- For the proper operation of the CIDR, two restrictions need to be applied to the allocated block.
- 1. The number of requested addresses, N, needs to be a power of 2. The reason is that $N = 2^{32-n}$ or $n = 32 - \log_2 N$. If N is not a power of 2, we cannot have an integer value for n.
- 2. The requested block needs to be allocated where there is an adequate number of contiguous addresses available in the address space. However, there is a restriction that the first address needs to be divisible by the number of addresses in the block.
- The reason is that the first address needs to be the prefix followed by (32 − n) number of 0s. The decimal value of the first address is then,
- first address =(prefix in decimal) × 232 − n = (prefix in decimal) □N

Example 19.10

An ISP is granted a block of addresses starting with 190.100.0.0/16 (65,536 addresses). The ISP needs to distribute these addresses to three groups of customers as follows:

a. The first group has 64 customers; each needs 256 addresses.
b. The second group has 128 customers; each needs 128 addresses.
c. The third group has 128 customers; each needs 64 addresses.

Figure 19.9 *An example of address allocation and distribution by an IS?*



Classless Addressing

- **Subnetting**
- More levels of hierarchy can be created using subnetting.
- An organization (or an ISP) that is granted a range of addresses may divide the range into several subranges and assign each subrange to a subnetwork (or subnet).
- Note that nothing stops the organization from creating more levels. A subnetwork can be divided into several sub-subnetworks.
- A sub-subnetwork can be divided into several sub-sub-subnetworks, and so on.

Classless Addressing

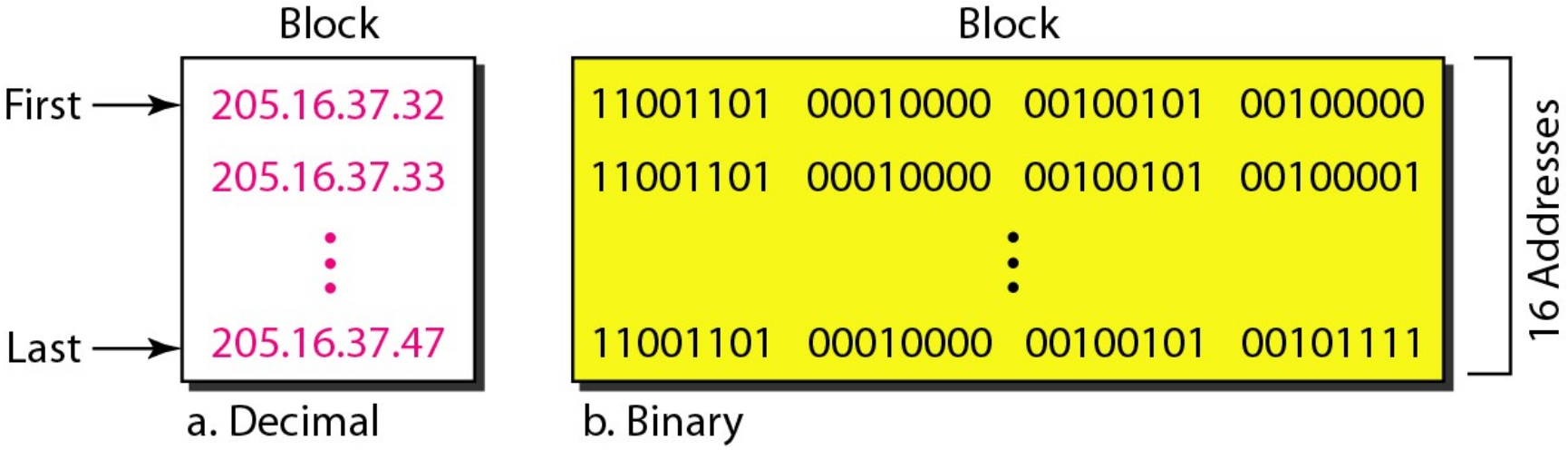
- **Designing Subnets**
- The subnetworks in a network should be carefully designed to enable the routing of packets.
- We assume the total number of addresses granted to the organization is N, the prefix length is n, the assigned number of addresses to each subnetwork is N_{sub}, and the prefix length for each subnetwork is n_{sub}. Then the following steps need to be carefully followed to guarantee the proper operation of the subnetworks.
- The number of addresses in each subnetwork should be a power of 2.
- The prefix length for each subnetwork should be found using the following formula:
- first address = (prefix in decimal) × 2^{32-n} = (prefix in decimal) × N.

$$n_{sub} = 32 - \log_2 N_{sub}$$

- The starting address in each subnetwork should be divisible by the number of addresses in that subnetwork. This can be achieved if we first assign addresses to larger subnetworks.

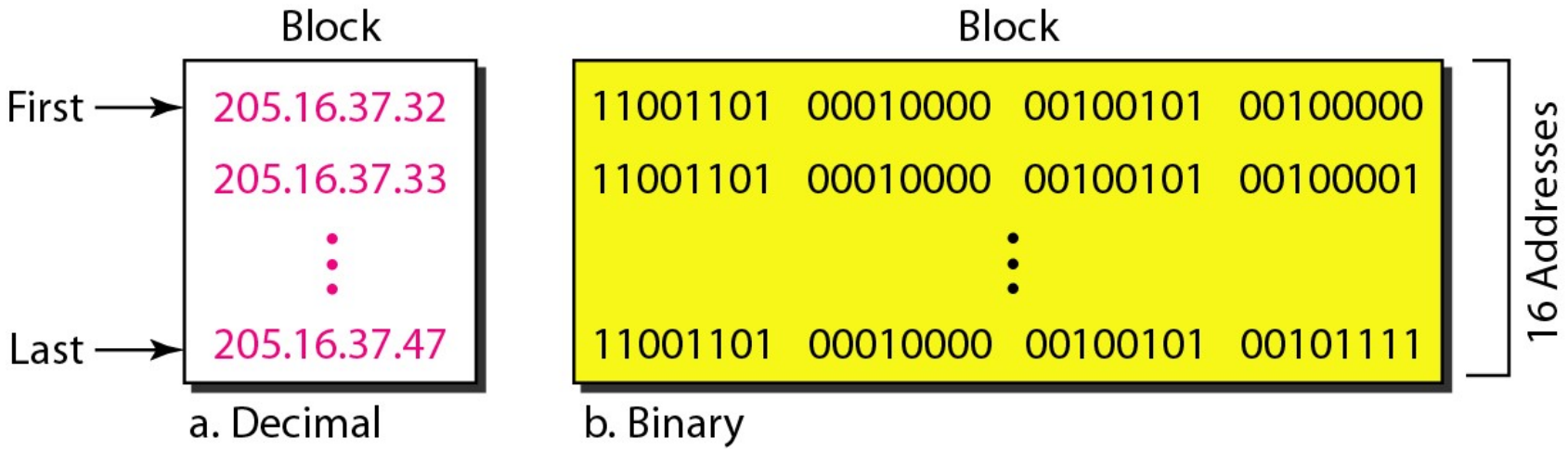
Classless Addressing

- Figure shows a block of addresses, in both binary and dotted-decimal notation, granted to a small business that needs 16 addresses.
- We can see that the restrictions are applied to this block. The addresses are contiguous.
- The number of addresses is a power of 2 ($16 = 2^4$), and the first address is divisible by 16.
- The first address, when converted to a decimal number, is 3,440,387,360, which when divided by 16 results in 215,024,210.



A block of 16 addresses granted to a small organization

Figure 19.4 *A network configuration for the block 205.16.37.32/28*



NAT- Network Address Translation

- The number of internet users that want to use the Internet is ever increasing.
- In the beginning, a user was connected to the Internet with a dial-up line. An ISP with a block of addresses could dynamically assign an address to this user.
- Home users and small businesses can be connected by an ADSL line or cable modem. In addition, many have created small networks with several hosts and need an IP address for each host.
- Having shortage of addresses, is a serious problem. A quick solution to this problem is called network address translation (NAT).
- NAT enables a user to have a large set of addresses internally and one address, or a small set of addresses, externally.
- To separate the addresses used inside the home or business and the ones used for the Internet, the Internet authorities have reserved three sets of addresses as private addresses, shown in Table 19.3.

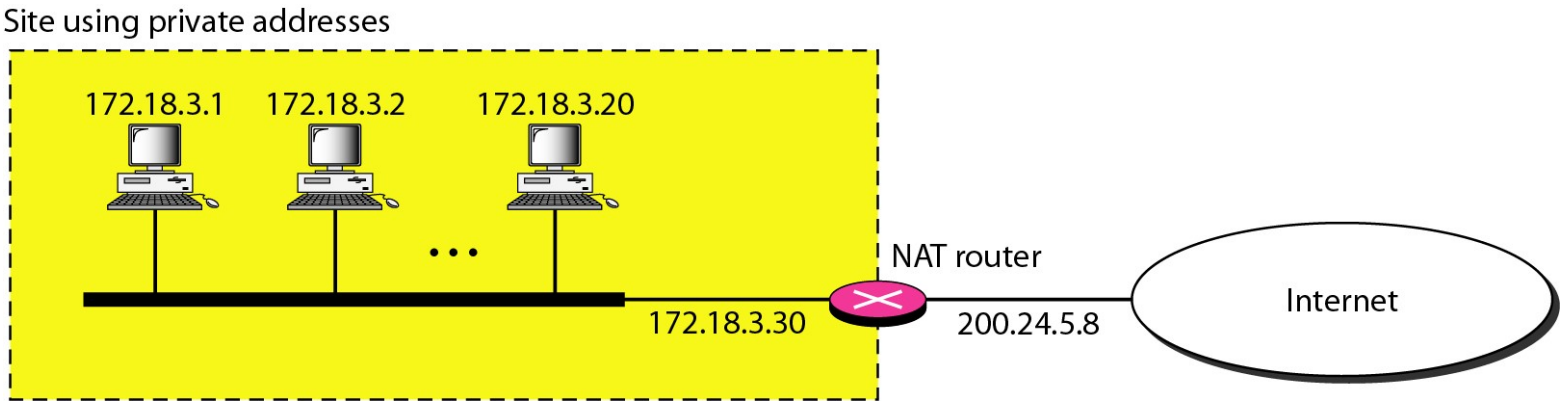
NAT- Network Address Translation

Table 19.3 *Addresses for private networks*

Range			*Total*
10.0.0.0	to	10.255.255.255	2^{24}
172.16.0.0	to	172.31.255.255	2^{20}
192.168.0.0	to	192.168.255.255	2^{16}

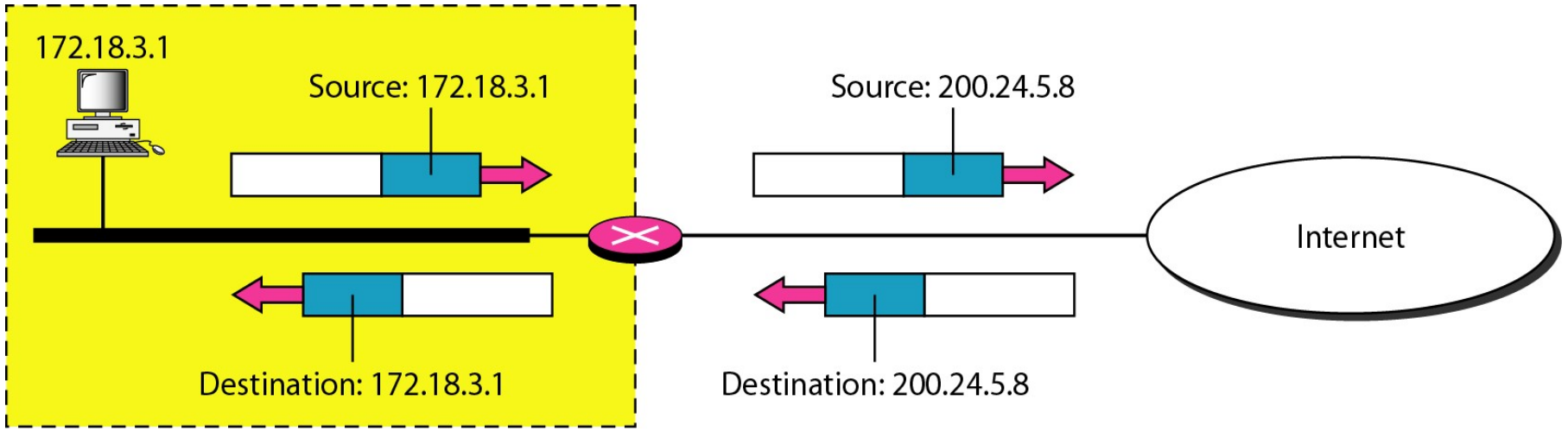
- Any organization can use an address out of this set without permission from the Internet authorities. Everyone knows that these reserved addresses are for private networks.
- They are unique inside the organization, but they are not unique globally. No router will forward a packet that has one of these addresses as the destination address.
- The site must have only one single connection to the global Internet through a router that runs the NAT software.

Figure 19.10 *A NAT implementation*



- The private network uses private addresses. The router that connects the network to the global address uses one private address and one global address.
- The private network is transparent to the rest of the Internet; the rest of the Internet sees only the NAT router with the address 200.24.5.8.

Figure 19.11 *Address translation*



- All the outgoing packets go through the NAT router, which replaces the source address in the packet with the global NAT address.
- All incoming packets also pass through the NAT router, which replaces the destination address in the packet (the NAT router global address) with the appropriate private address.

Figure 19.12 *NAT address translation*

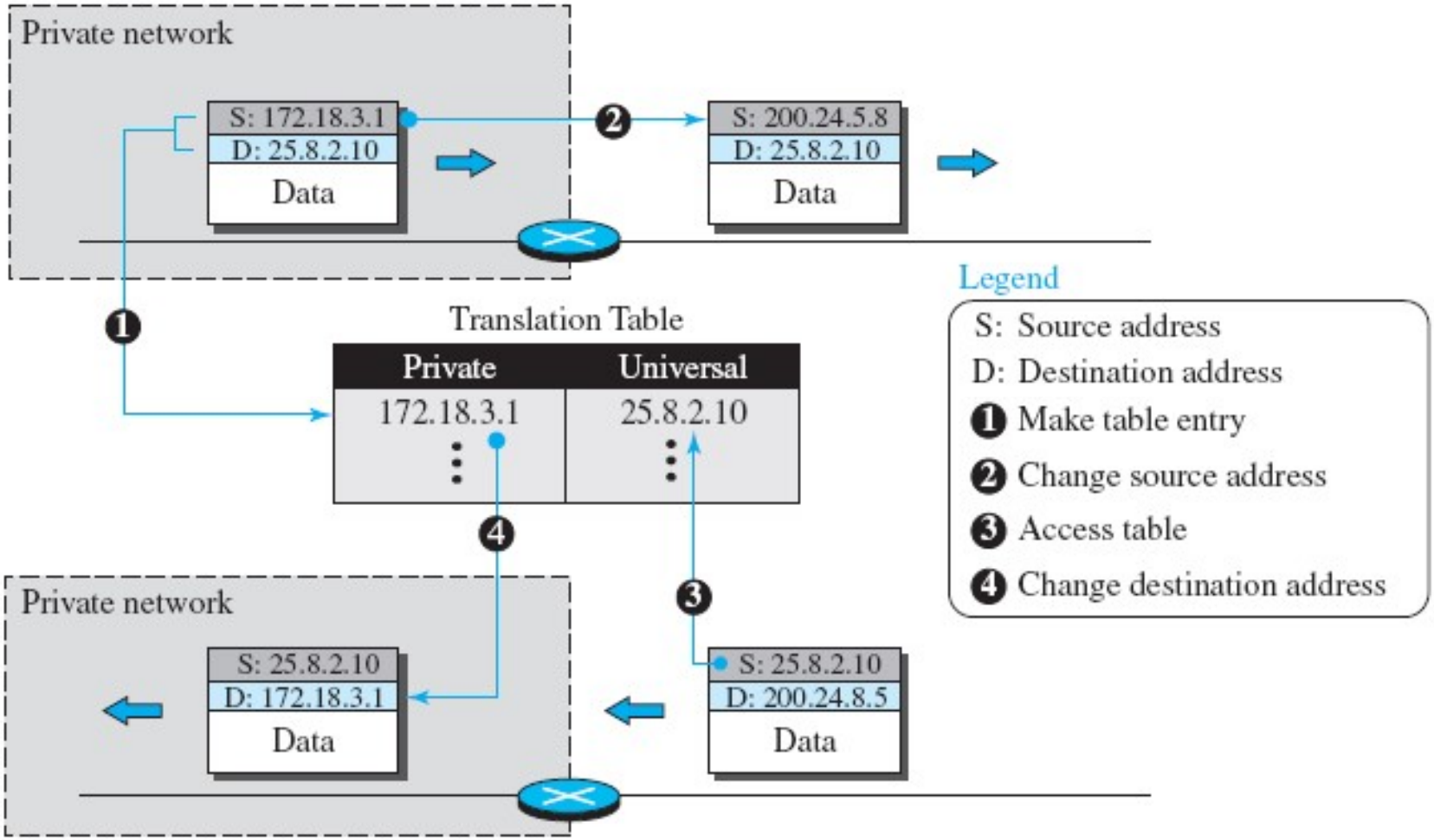


Figure 19.12 *NAT address translation*

- Translating the source addresses for outgoing packets is straightforward.
- But how does the NAT router know the destination address for a packet coming from the Internet?
- There may be tens or hundreds of private IP addresses, each belonging to one specific host. The problem is solved if the NAT router has a translation table
- A translation table has only two columns: the private' address and the external address (destination address of the packet).
- When the router translates the source address of the outgoing packet, it also makes note of the destination address-where the packet is going.
- When the response comes back from the destination, the router uses the source address of the packet (as the external address) to find the private address of the packet. Figure 19.12 shows the idea.
- Note that the addresses that are changed (translated) are shown in color.

Using a Pool of IP Addresses

- Since the NAT router has only one global address, only one private network host can access the same external host.
- To remove this restriction, the NAT router uses a pool of global addresses.
- For example, instead of using only one global address (200.24.5.8), the NAT router can use four addresses (200.24.5.8, 200.24.5.9, 200.24.5.10, and 200.24.5.11).
- In this case, four private network hosts can communicate with the same external host at the same time because each pair of addresses defines a connection. However, there are still some drawbacks.
- In this example, no more than four connections can be made to the same destination. Also, no private-network host can access two external server programs (e.g, HTTP and FTP) at the same time.

Using both IP and port

- To allow a many-to-many relationship between private-network hosts and external server programs, we need more information in the translation table.
- For example, suppose two hosts with addresses 172.18.3.1 and 172.18.3.2 inside a private network need to access the HTTP server on external host 25.8.3.2.
- If the translation table has five columns, instead of two, that include the source and destination port numbers of the transport layer protocol, the ambiguity is eliminated.
- When the response from HTTP comes back, the combination of source address (25.8.3.2) and destination port number (1400) defines the-private network host to which the response should be directed. Note also that for this translation to work, the temporary port numbers (1400 and 1401) must be unique.

Five-column translation table

Private Address	*Private Port*	*External Address*	*External Port*	*Transport Protocol*
172.18.3.1	1400	25.8.3.2	80	TCP
172.18.3.2	1401	25.8.3.2	80	TCP
. . .	. . .	. . .	. . .	. . .

19-2 IPv6 ADDRESSES

- The main reason for migration from IPv4 to IPv6 is the small size of the address space in IPv4.
- An IPv6 address is 128 bits or 16 bytes (octets) long, four times the address length in IPv4.
- Despite all short-term solutions, address depletion is still a long-term problem for the Internet. This and other problems in the IP protocol itself have been the motivation for IPv6.
- An IPv6 address is 128-bits long.

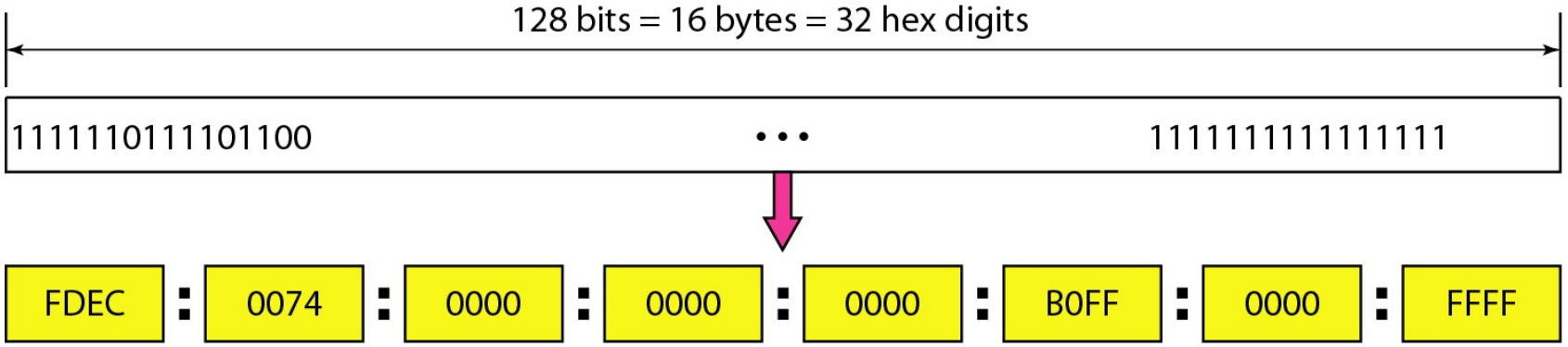
19-2 IPv6 ADDRESSES

- **Representation**
- A computer normally stores the address in binary, but it is clear that 128 bits cannot easily be handled by humans.
- Several notations have been proposed to represent IPv6 addresses when they are handled by humans. The following shows two of these notations: binary and colon hexadecimal.

Binary (128 bits)	1111111011110110	...	1111111100000000
Colon Hexadecimal	FEF6:BA98:7654:3210:ADEF:BBFF:2922:FF00		

- Binary notation is used when the addresses are stored in a computer. The colon hexadecimal notation (or colon hex for short) divides the address into eight sections, each made of four hexadecimal digits separated by colons.

IPv6 address in binary and hexadecimal colon notation



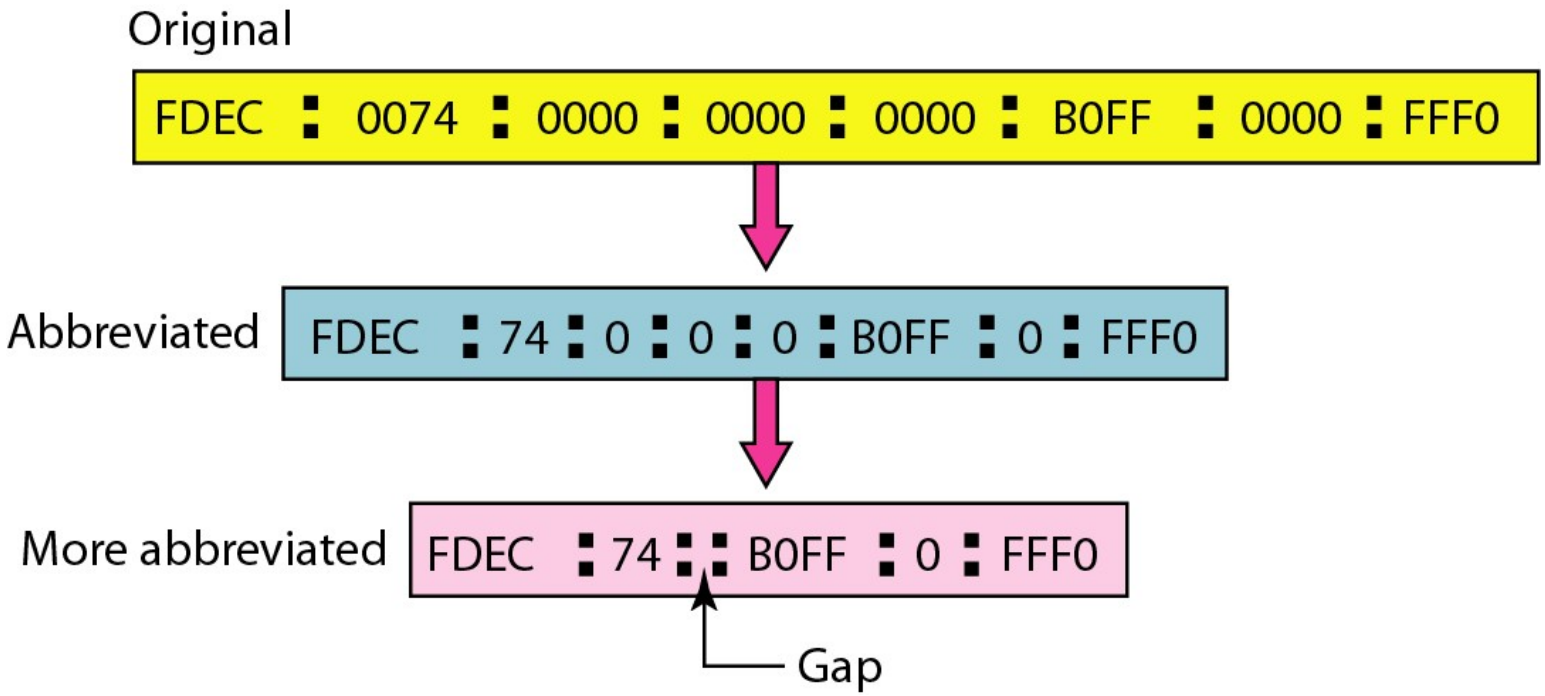
19-2 IPv6 ADDRESSES

- **Abbreviation**
- Although an IPv6 address, even in hexadecimal format, is very long, many of the digits are zeros. In this case, we can abbreviate the address.
- The leading zeros of a section can be omitted. Using this form of abbreviation, 0074 can be written as 74, 000F as F, and 0000 as 0.
- Note that 3210 cannot be abbreviated.
- Further abbreviation, often called zero compression, can be applied to colon hex notation if there are consecutive sections consisting of zeros only.
- We can remove all the zeros and replace them with a double semicolon.

FDEC:0:0:0:0:BBFF:0:FFFF ⟶ FDEC::BBFF:0:FFFF

- Note that this type of abbreviation is allowed only once per address. If there is more than one run of zero sections, only one of them can be compressed.

Abbreviated IPv6 addresses



19-2 IPv6 ADDRESSES

- **Address Space**
- IPv6 has a much larger address space; 2^{128} addresses are available. The designers of IPv6 divided the address into several categories.
- A few leftmost bits, called the type prefix, in each address define its category.
- The type prefix is variable in length, but it is designed such that no code is identical to the first part of any other code.
- In this way, there is no ambiguity; when an address is given, the type prefix can easily be determined.
- Table 19.5 shows the prefix for each type of address.
- The third column shows the fraction of each type of address relative to the whole address space. (d what fraction of the total address space each represents.)

19-2 IPv6 ADDRESSES

Table 19.5 *Type prefixes for IPv6 addresses*

Type Prefix	*Type*	*Fraction*
00000000	Reserved	1/256
00000001	Unassigned	1/256
0000001	ISO network addresses	1/128
0000010	IPX (Novell) network addresses	1/128
0000011	Unassigned	1/128
00001	Unassigned	1/32
0001	Reserved	*1/16*
001	Reserved	1/8
010	Provider-based unicast addresses	*1/8*

19-2 IPv6 ADDRESSES

Table 19.5 *Type prefixes for IPv6 addresses (continued)*

Type Prefix	*Type*	*Fraction*
011	Unassigned	1/8
100	Geographic-based unicast addresses	1/8
101	Unassigned	1/8
110	Unassigned	1/8
1110	Unassigned	1116
11110	Unassigned	1132
1111 10	Unassigned	1/64
1111 110	Unassigned	1/128
11111110 a	Unassigned	1/512
1111 111010	Link local addresses	111024
1111 1110 11	Site local addresses	1/1024
11111111	Multicast addresses	1/256

19-2 IPv6 ADDRESSES

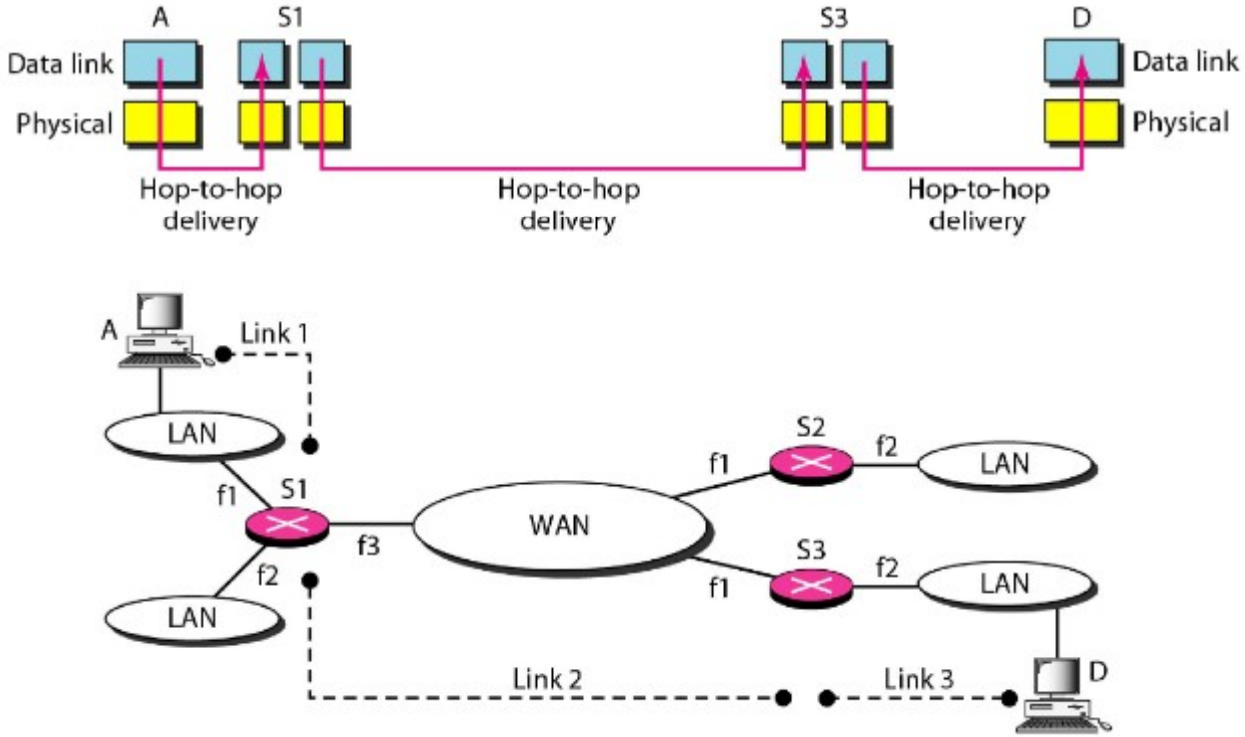
- **Unicast Addresses**
- A unicast address defines a single computer. The packet sent to a unicast address must be delivered to that specific computer. IPv6 defines two types of unicast addresses: geographically based and provider-based.
- **Multicast Addresses**
- Multicast addresses are used to define a group of hosts instead of just one. A packet sent to a multicast address must be delivered to each member of the group.
- **Anycast Addresses**
- An anycast address, like a multicast address, also defines a group of nodes. However, a packet destined for an anycast address is delivered to only one of the members of the anycast group, the nearest one.

19-2 IPv6 ADDRESSES

- **Reserved Addresses**
- Another category in the address space is the reserved address. These addresses start with eight Os (type prefix is 00000000).
- **Local Addresses**
- These addresses are used when an organization wants to use IPv6 protocol without being connected to the global Internet. In other words, they provide addressing for private networks.
- Nobody outside the organization can send a message to the nodes using these Addresses. Two types of Logical addresses are there: Link Local and Site Local.

Need for Network Layer

- The network layer is responsible for host-to-host delivery and for routing the packets through the routers or switches.
- Figure 20.1 shows Links between two hosts.



Need for Network Layer

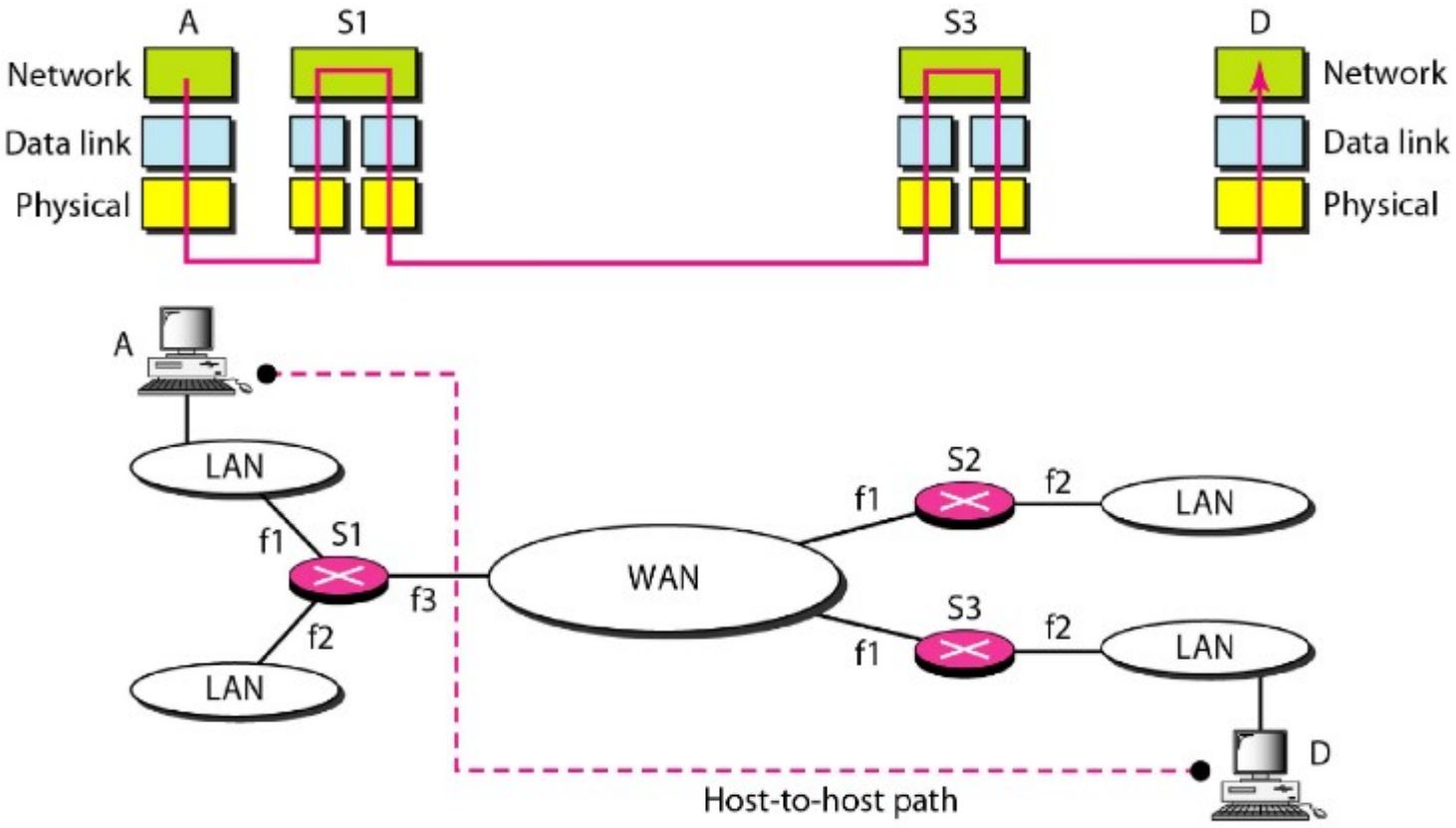


Figure 20.2 Network Layer in and Internetwork

Need for Network Layer

- The network layer at the source is responsible for creating a packet from the data coming from another protocol (such as a transport layer protocol or a routing protocol).
- The header of the packet contains, among other information, the logical addresses of the source and destination.
- The network layer is responsible for checking its routing table to find the routing information (such as the outgoing interface of the packet or the physical address of the next node). If the packet is too large, the packet is fragmented

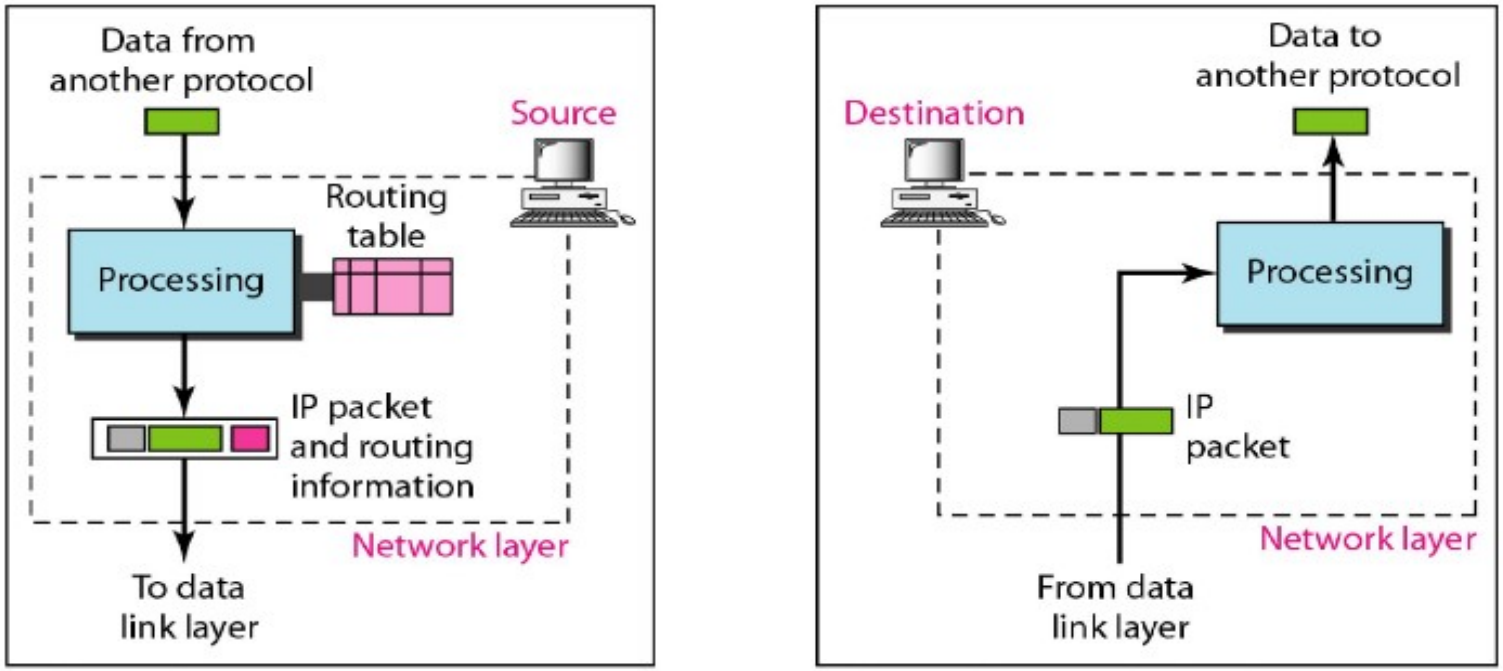


Figure 20.3 Network Layer at source, router and destination

Need for Network Layer

- The network layer at the switch or router is responsible for routing the packet. When a packet arrives, the router or switch consults its routing table and finds the interface from which the packet must be sent.
- The packet, after some changes in the header, with the routing information is passed to the data link layer again.
- The network layer at the destination is responsible for address verification; it makes sure that the destination address on the packet is the same as the address of the host.
- If the packet is a fragment, the network layer waits until all fragments have arrived, and then reassembles them and delivers the reassembled packet to the transport layer.

Internet as a Datagram Network

- Switching can be divided into three broad categories: circuit switching, packet switching, and message switching.
- Packet switching uses either the virtual circuit approach or the datagram approach.
- The Internet has chosen the datagram approach to switching in the network layer. It uses the universal addresses defined in the network layer to route packets from the source to the destination.

Internet as a Connectionless Network

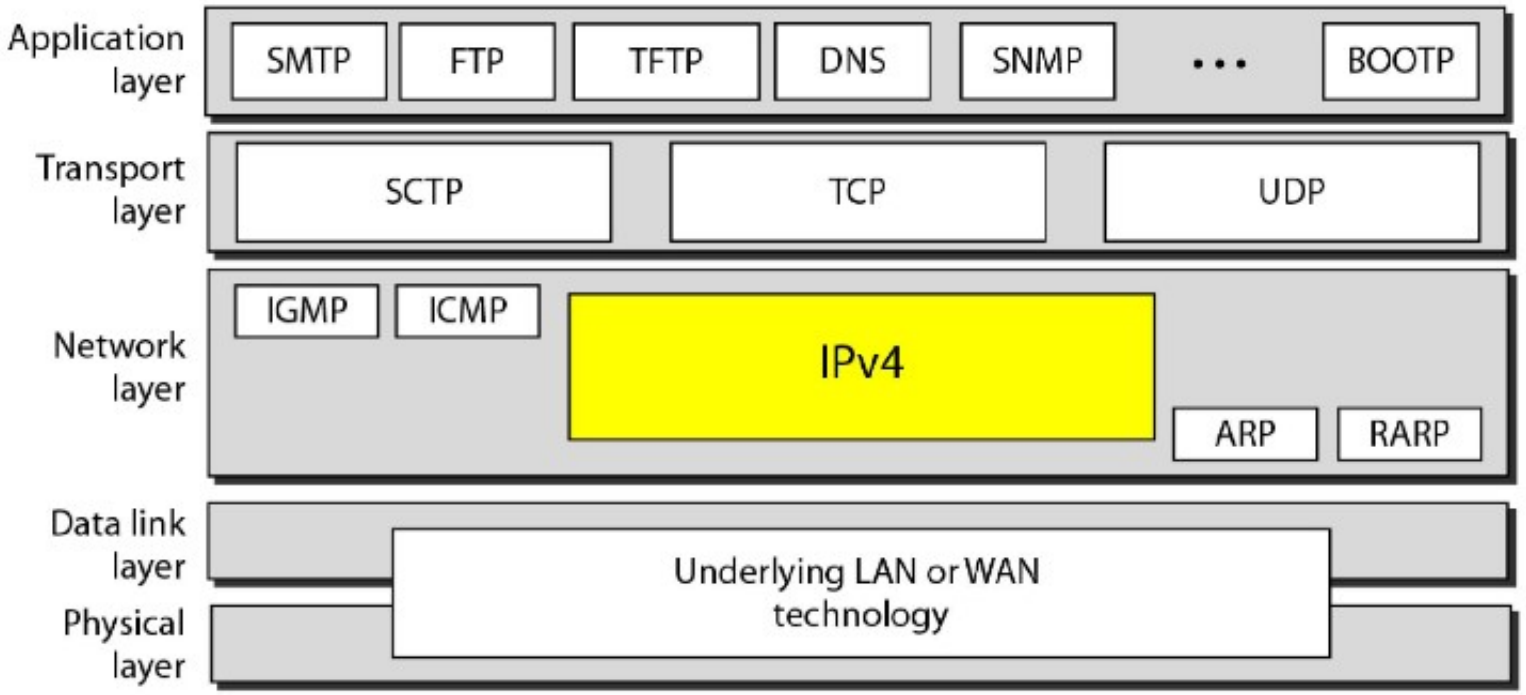
- Delivery of a packet can be accomplished by using either a connection-oriented or a connectionless network service.
- Connection-oriented service: the source first makes a connection with the destination before sending a packet. In this case, there is a relationship between packets. They are sent on the same path in sequential order.
- A packet is logically connected to the packet traveling before it and to the packet traveling after it. When all packets of a message have been delivered, the connection is terminated.
- The decision about the route of a sequence of packets with the same source and destination addresses can be made only once, when the connection is established.
- Switches do not recalculate the route for each individual packet. This type of service is used in a virtual-circuit approach. to packet switching such as in Frame Relay and ATM.

Internet as a Connectionless Network

- In conneetionless service, the network layer protocol treats each packet independently, with each packet having no relationship to any other packet. The packets in a message may or may not travel the same path to their destination.
- This type of service is used in the datagram approach to packet switching. The Internet has chosen this type of service at the network layer.
- The reason is that the Internet is made of so many heterogeneous networks that it is almost impossible to create a connection from the source to the destination without knowing the nature of the networks in advance.

IPv4

- In The Internet Protocol version 4 (IPv4) is the delivery mechanism used by the TCP/IP protocols.
- Following Figure 20.4 shows position of IPv4 in TCP/IP protocol suite.



IPv4

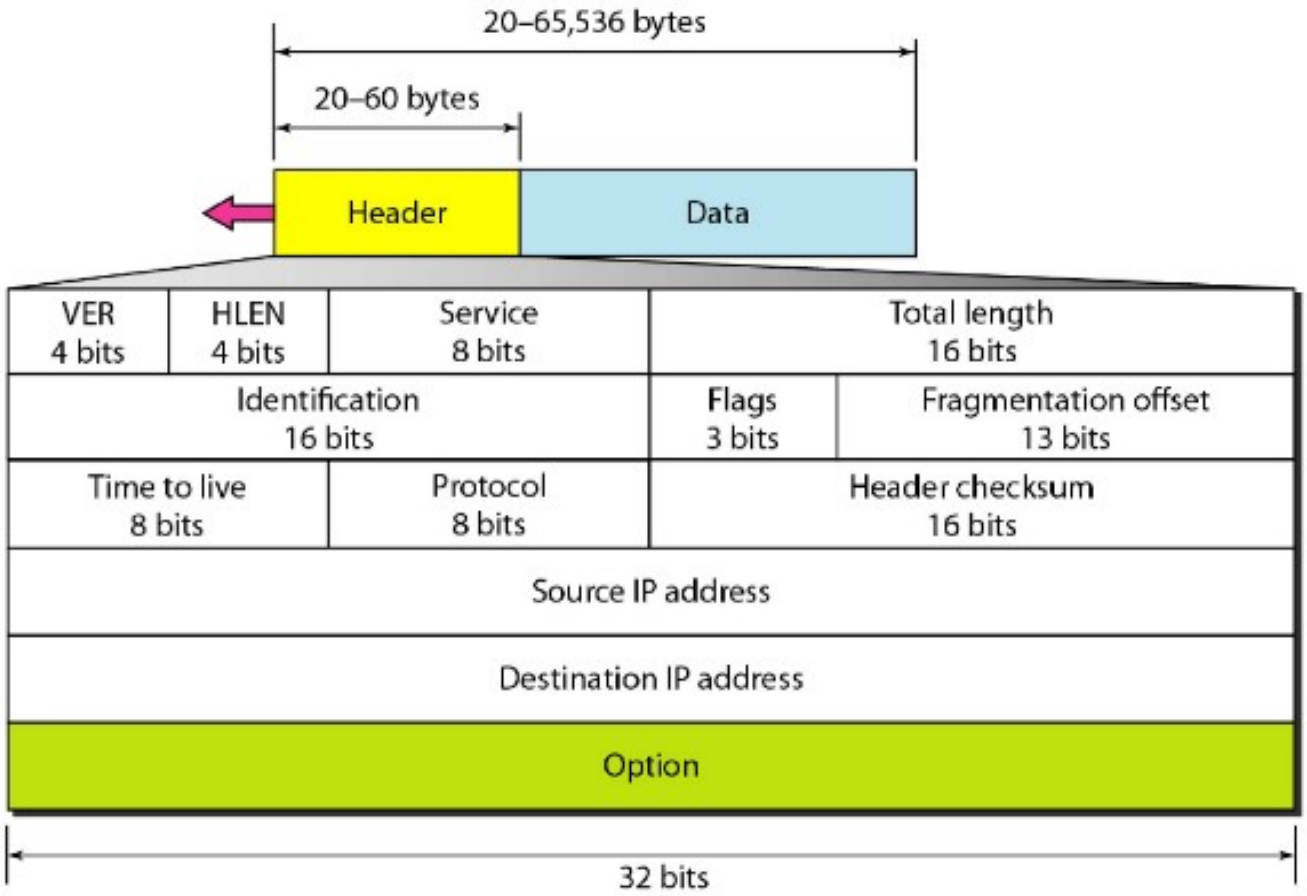
- IPv4 is an unreliable and connectionless datagram protocol-a best-effort delivery service. The term best-effort means that IPv4 provides no error control or flow control (except for error detection on the header).
- IPv4 assumes the unreliability of the underlying layers and does its best to get a transmission through to its destination, but with no guarantees.
- If reliability is important, IPv4 must be paired with a reliable protocol such as TCP.
- E.g. The post office does its best to deliver the mail but does not always succeed. If an unregistered letter is lost, it is up to the sender or would-be recipient to discover the loss and rectify the problem.
- The post office itself does not keep track of every letter and cannot notify a sender of loss or damage.

IPv4

- IPv4 is also a connectionless protocol for a packet-switching network that uses the datagram approach.
- Each datagram is handled independently, and each datagram can follow a different route to the destination, means that datagrams sent by the same source to the same destination could arrive out of order and some could be lost or corrupted during transmission.

Datagram

- Packets in the IPv4 layer are called datagrams.
- Following **Figure 20.5** shows the IPv4 datagram format.



Datagram

- A datagram is a variable-length packet consisting of two parts: header and data. The header is 20 to 60 bytes in length and contains information essential to routing and delivery. It is customary in TCP/IP to show the header in 4-byte sections as follows:
- Version (VER): This 4-bit field defines the version of the IPv4 protocol. Currently the version is 4. However, version 6 (or IPng) may totally replace version 4 in the future.
- If the machine is using some other version of IPv4, the datagram is discarded rather than interpreted incorrectly.
- Header length (HLEN): The length of the header is variable (between 20 and 60 bytes).
- When there are no options, the header length is 20 bytes, and the value of this field is 5 (5 x 4 = 20). When the option field is at its maximum size, the value of this field is 15 (15 x 4 = 60).
- Services: IETF has changed the interpretation and name of this 8-bit field. This field, previously called service type, is now called differentiated services.

Datagram

- **1. Service Type**
- In this interpretation, the first 3 bits are called precedence bits. The next 4 bits are called type of service (TOS) bits, and the last bit is not used.
- The precedence subfield was part of version 4, but never used.

TOS Bits	*Description*
0000	Normal (default)
0001	Minimize cost
0010	Maximize reliability
0100	Maximize throughput
1000	Minimize delay

Datagram

- Application programs can request a specific type of service. The defaults for some applications are shown in Table 20.2.

Table 20.2 Default types of service

Protocol	*TOS Bits*	*Description*
ICMP	0000	Normal
BOOTP	0000	Normal
NNTP	0001	Minimize cost
IGP	0010	Maximize reliability
SNMP	0010	Maximize reliability
TELNET	1000	Minimize delay
FTP (data)	0100	Maximize throughput
FTP (control)	1000	Minimize delay
TFTP	1000	Minimize delay
SMTP (command)	1000	Minimize delay
SMTP (data)	0100	Maximize throughput
DNS (UDP query)	1000	Minimize delay
DNS (TCP query)	0000	Normal
DNS (zone)	0100	Maximize throughput

Fragmentation

- A datagram can travel through different networks. Each router decapsulates the IPv4 datagram from the frame it receives, processes it, and then encapsulates it in another frame.
- The format and size of the received frame depend on the protocol used by the physical network through which the frame has just traveled.
- The format and size of the sent frame depend on the protocol used by the physical network through which the frame is going to travel.
- For example, if a router connects a LAN to a WAN, it receives a frame in the LAN format and sends a frame in the WAN format.

Fragmentation

- **Maximum Trasfer Unit (MTU)**
- Each data link layer protocol has its own frame format in most protocols. One field is the maximum size of the data field, means when a datagram is encapsulated in a frame, the total size of the datagram must be less than this maximum size.

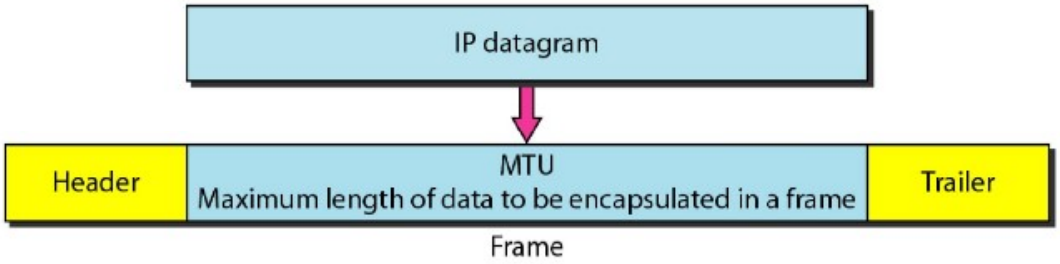


Figure 20.9 Maximum transfer unit (MTU)

Protocol	*MTU*
Hyperchannel	65,535
Token Ring (16 Mbps)	17,914
Token Ring (4 Mbps)	4,464
FDDI	4,352
Ethernet	1,500
X.25	576
PPP	296

Table 20.5 MTUs for some networks

Fragmentation

- **Maximum Trasfer Unit (MTU)**
- To make the IPv4 protocol independent of the physical network, the designers decided to make the maximum length of the IPv4 datagram equal to 65,535 bytes.
- When a datagram is fragmented, each fragment has its own header with most of the fields repeated, but with some changed.
- A fragmented datagram may itself be fragmented if it encounters a network with an even smaller MTU. In other words, a datagram can be fragmented several times before it reaches the final destination.
- When a datagram is fragmented, required parts of the header must be copied by all fragments.
- The host or router that fragments a datagram must change the values of three fields: flags, fragmentation offset, and total length.
- The rest of the fields must be copied. Of course, the value of the checksum must be recalculated regardless of fragmentation.

Checksum

- The implementation of the checksum in the IPv4 packet follows the same principles as we have seen before.
- First, the value of the checksum field is set to O. Then the entire header is divided into 16-bit sections and added together. The result (sum) is complemented and inserted into the checksum field.
- The checksum in the IPv4 packet covers only the header, not the data. There are two good reasons:
- First, all higher-level protocols that encapsulate data in the IPv4 datagram have a checksum field that covers the whole packet. Therefore, the checksum for the IPv4 datagram does not have to check the encapsulated data.
- Second, the header of the IPv4 packet changes with each visited router, but the data do not. So the checksum includes only the part that has changed.
- If the data were included, each router must recalculate the checksum for the whole packet, which means an increase in processing time.

Options

- The header of the IPv4 datagram is made of two parts: a fixed palt and a variable part.
- The fixed part is 20 bytes long and was discussed in the previous section. The variable part comprises the options that can be a maximum of 40 bytes.
- Options, as the name implies, are not required for a datagram. They can be used for network testing and debugging.
- Although options are not a required part of the IPv4 header, option processing is required of the IPv4 software.
- This means that all implementations must be able to handle options if they are present in the header.

IPv6

- Data communication has evolved since the inception of IPv4 in the 1970s. IPv4 has some deficiencies (listed below) that make it unsuitable for the fast-growing Internet.
- Despite short-term solutions, such as subnetting, classless addressing, and NAT, address depletion is still a long-term problem in the Internet.
- The Internet must accommodate real-time audio and video transmission, which requires minimum delay strategies and reservation of resources not provided in the IPv4 design.
- The Internet must accommodate encryption and authentication of data for some applications. No encryption or authentication is provided by IPv4.
- To overcome these deficiencies, IPv6 (Internetworking Protocol, version 6), also known as IPng (Internetworking Protocol, next generation), was proposed and is now a standard.

IPv6

- The format and the length of the IP address were changed along with the packet format. Related protocols, such as ICMP, were also modified.
- Other protocols in the network layer, such as ARP, RARP, and IGMP, were either deleted or included in the ICMPv6 protocol (see Chapter 21).
- Routing protocols, such as RIP and OSPF (see Chapter 22), were also slightly modified to accommodate these changes.
- Communications experts predict that IPv6 and its related protocols will soon replace the current IP version.

IPv6

Advantages

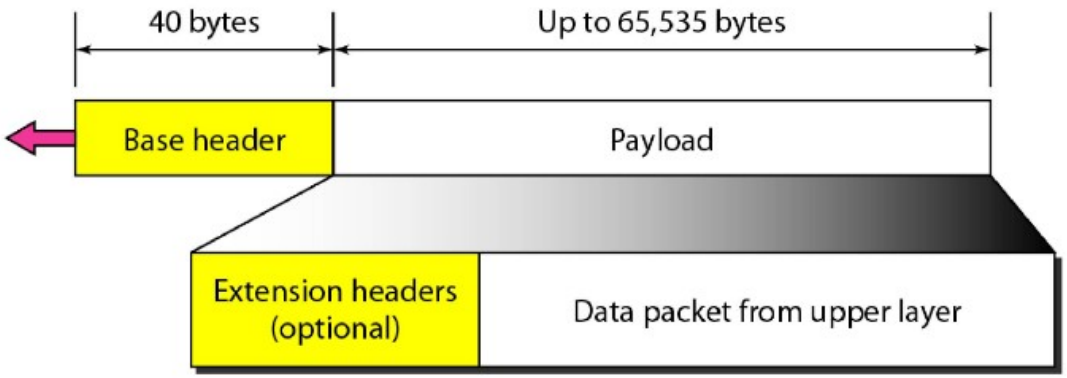
- Larger address space: An IPv6 address is 128 bits long, a huge (296) increase in the address space
- Better header format: IPv6 uses a new header format with options separated from the base header and inserted, when needed, between the base header and the upper-layer data.
- This simplifies and speeds up the routing process because most of the options do not need to be checked by routers.
- New options. IPv6 has new options to allow for additional functionalities.
- Allowance for extension. IPv6 is designed to allow the extension of the protocol if required by new technologies or applications.
- Support for resource allocation: This mechanism can be used to support traffic such as real-time audio and video.
- Support for more security: The encryption and authentication options in IPv6 provide confidentiality and integrity of the packet.

IPv6

Packet Format

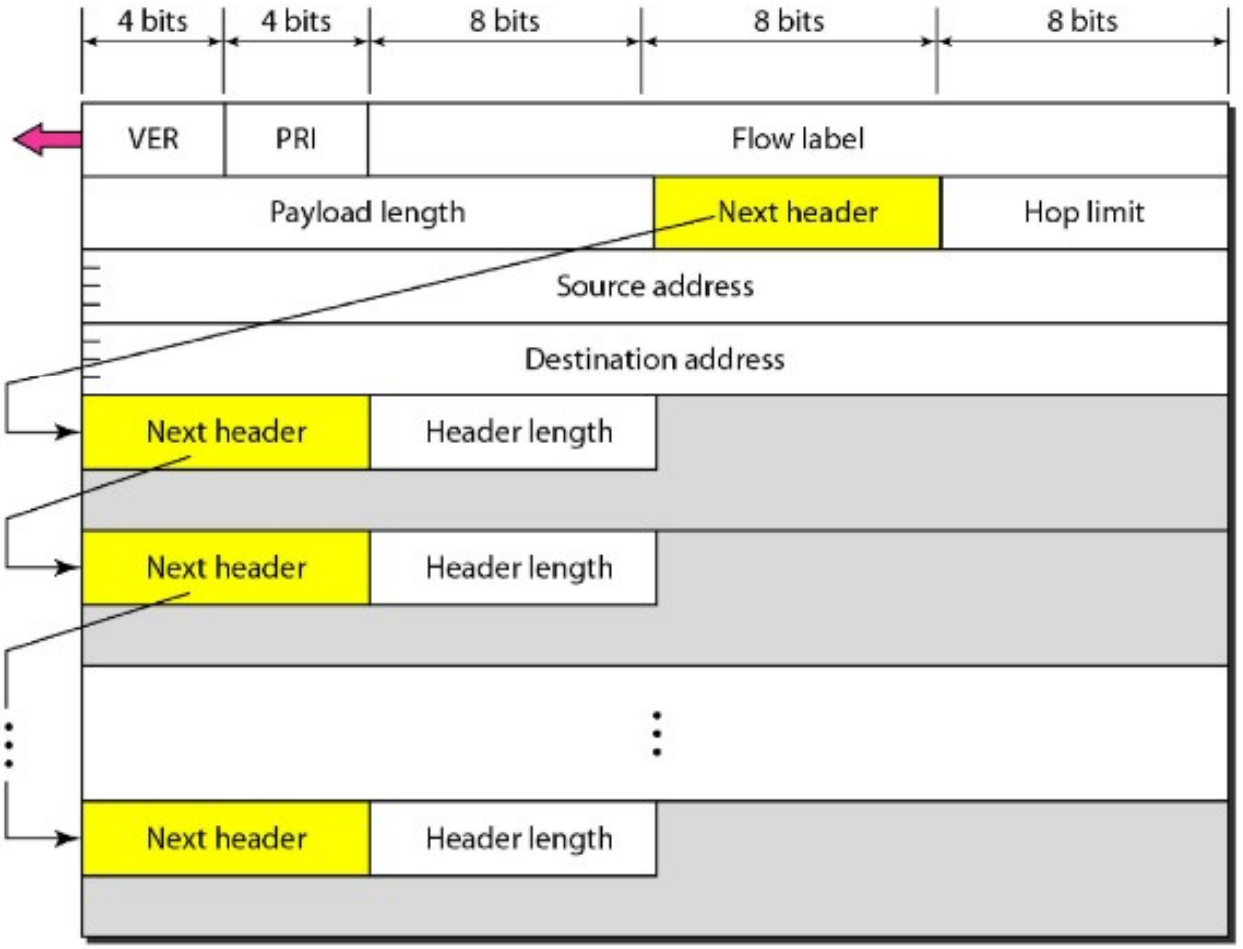
- Each packet is composed of a mandatory base header followed by the payload.
- The payload consists of two parts: optional extension headers and data from an upper layer.
- The base header occupies 40 bytes, whereas the extension headers and data from the upper layer contain up to 65,535 bytes of information.
- Base Header
- Figure 20.16 shows the base header with its eight fields. These fields are as follows:
- Version. This 4-bit field defines the version number of the IP. For IPv6, the value is 6.
- Priority. The 4-bit priority field defines the priority of the packet with respect to traffic congestion. We will discuss this field later.

IPv6


40 bytes
Up to 65,535 bytes
Base header
Payload
Extension headers
(optional)
Data packet from upper layer

IPv6

Figure 20.16 Format ofan IPv6 datagram



IPv6

Packet Format

- Flow label. The flow label is a 3-byte (24-bit) field that is designed to provide special handling for a particular flow of data.
- Payload length. The 2-byte payload length field defines the length of the IP datagram excluding the base header.
- Next header. The next header is an 8-bit field defining the header that follows the base header in the datagram. The next header is either one of the optional extension headers used by IP or the header of an encapsulated packet such as UDP or TCP.
- Hop limit. This 8-bit hop limit field serves the same purpose as the TIL field in IPv4.
- Source address. The source address field is a 16-byte (128-bit) Internet address that identifies the original source of the datagram.

IPv6

Packet Format

- Destination address: The destination address field is a 16-byte (128-bit) Internet address that usually identifies the final destination of the datagram. However, if source routing is used, this field contains the address of the next router.
- Priority
- The priority field of the IPv6 packet defines the priority of each packet with respect to other packets from the same source. For example, if one of two consecutive datagrams must be discarded due to congestion, the datagram with the lower packet priority will be discarded.
- IPv6 divides traffic into two broad categories: congestion-controlled and noncongestion-controlled.

IPv6

- **Congestion-Controlled Traffic**: If a source adapts itself to traffic slowdown when there is congestion, the traffic is referred to as congestion-controlled traffic.

Table 20.7 *Priorities for congestion-controlled traffic*

Priority	*Meaning*
0	No specific traffic
1	Background data
2	Unattended data traffic
3	Reserved
4	Attended bulk data traffic
5	Reserved
6	Interactive traffic
7	Control traffic

IPv6

- **Noncongestion-Controlled Traffic**: This refers to a type of traffic that expects minimum delay. Discarding of packets is not desirable. Retransmission in most cases is impossible.
- Priority numbers from 8 to 15 are assigned to noncongestion-controlled traffic.

Table 20.8 *Priorities for noncongestion-controlled traffic*

Priority	*Meaning*
8	Data with greatest redundancy
. . .	. . .
15	Data with least redundancy

IPv6

- **Flow Label**
- A sequence of packets, sent from a particular source to a particular destination, that needs special handling by routers is called a flow of packets.
- The combination of the source address and the value of the flow label uniquely defines a flow of packets.
- To a router, a flow is a sequence of packets that share the same characteristics, such as traveling the same path, using the same resources, having the same kind of security, and so on.
- A router that supports the handling of flow labels has a flow label table.

IPv6

- **Flow Label**
- To allow the effective use of flow labels, three rules have been defined:
- **1.** The flow label is assigned to a packet by the source host. The label is a random number between 1 and 224 - 1. A source must not reuse a flow label for a new flow while the existing flow is still active.
- **2.** If a host does not support the flow label, it sets this field to zero. If a router does not support the flow label, it simply ignores it.
- **3.** All packets belonging to the same flow have the same source, same destination, same priority, and same options..

IPv6

- Comparison Between IPv4 and IPv6 Headers

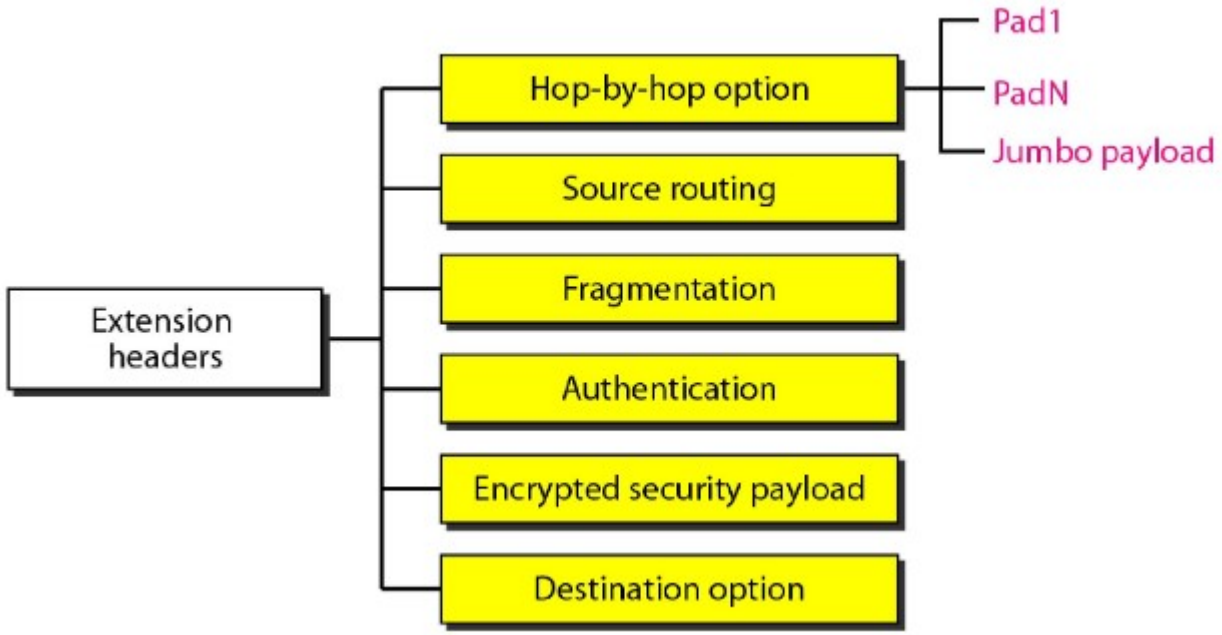
Table 20.9 *Comparison between IPv4 and IPv6 packet headers*

Comparison
1. The header length field is eliminated in IPv6 because the length of the header is fixed in this version.
2. The service type field is eliminated in IPv6. The priority and flow label fields together take over the function of the service type field.
3. The total length field is eliminated in IPv6 and replaced by the payload length field.
4. The identification, flag, and offset fields are eliminated from the base header in IPv6. They are included in the fragmentation extension header.
5. The TTL field is called hop limit in IPv6.
6. The protocol field is replaced by the next header field.
7. The header checksum is eliminated because the checksum is provided by upper-layer protocols; it is therefore not needed at this level.
8. The option fields in IPv4 are implemented as extension headers in IPv6.

IPv6

- **Extension Headers**
- The length of the base header is fixed at 40 bytes. However, to give greater functionality to the IP datagram, the base header can be followed by up to six extension headers.
- Many of these headers are options in IPv4. Six types of extension headers have been defined, as shown in Figure 20.17.

Figure 20.17 Extension header types



IPv6

- Comparison Between IPv4 Options and IPv6 Extension Headers

Comparison
1. The no-operation and end-of-option options in IPv4 are replaced by Pad1 and PadN options in IPv6.
2. The record route option is not implemented in IPv6 because it was not used.
3. The timestamp option is not implemented because it was not used.
4. The source route option is called the source route extension header in IPv6.
5. The fragmentation fields in the base header section of IPv4 have moved to the fragmentation extension header in IPv6.
6. The authentication extension header is new in IPv6.
7. The encrypted security payload extension header is new in IPv6.

Forwarding Techniques

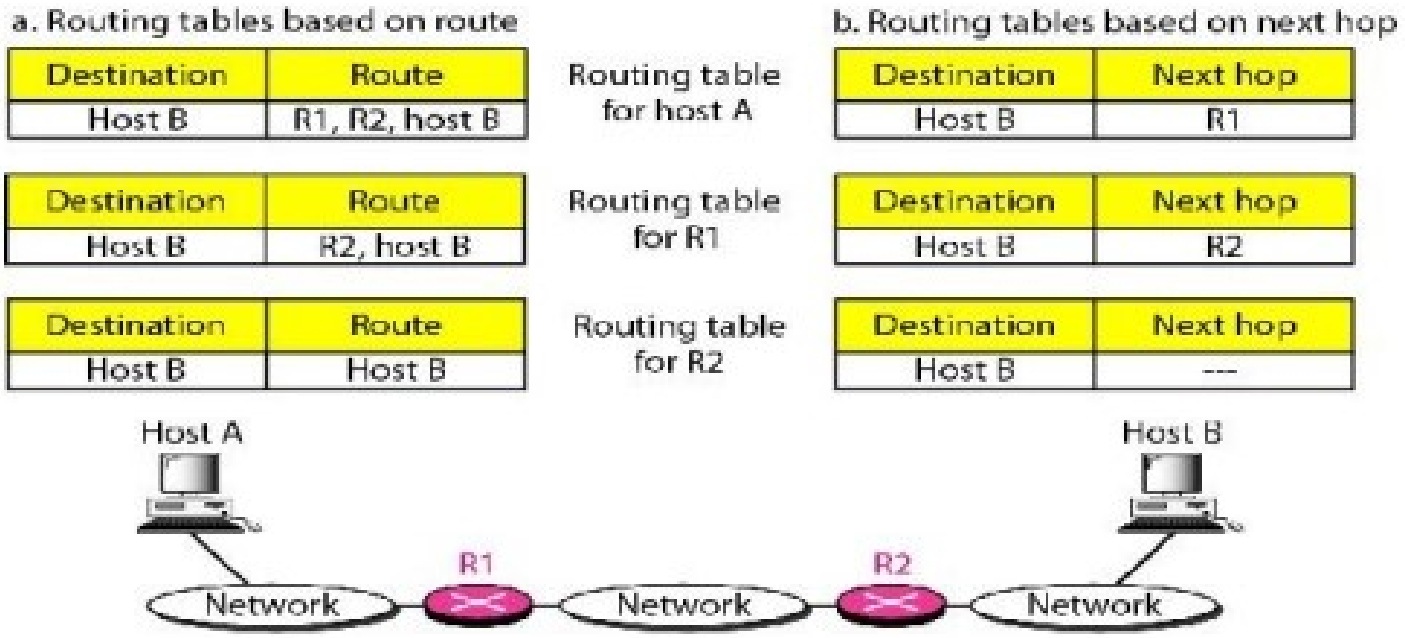
- Forwarding means to place the packet in its route to its destination. Forwarding requires a host or a router to have a routing table.
- When a host has a packet to send or when a router has received a packet to be forwarded, it looks at this table to find the route to the final destination.
- However, this simple solution is impossible today in an internetwork such as the Internet because the number of entries needed in the routing table would make table lookups inefficient.
- Several techniques can make the size of the routing table manageable and also handle issues such as security.

Forwarding Techniques

- **Next-Hop Method Versus Route Method**

- One technique to reduce the contents of a routing table is called the next-hop method.
- In this technique, the routing table holds only the address of the next hop instead of information about the complete route (route method).
- The entries of a routing table must be consistent with one another.
- Next figure shows how routing tables can be simplified by using this technique.

Forwarding Techniques



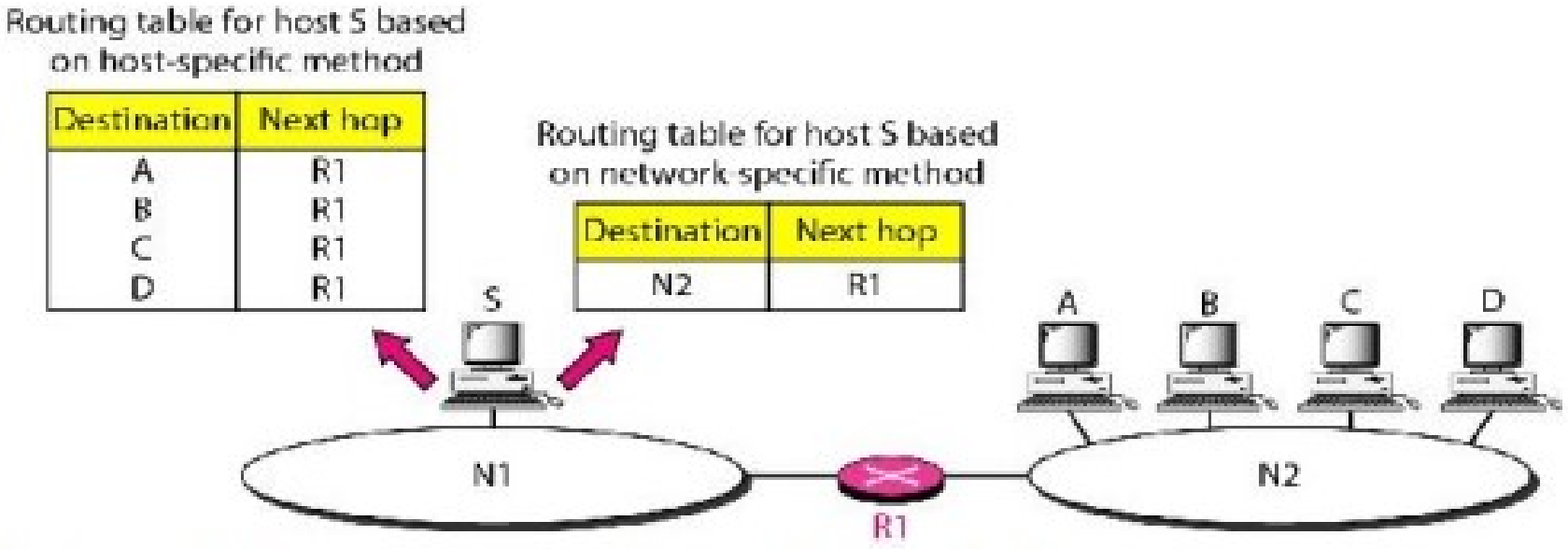
Route method Vs Next hop method

Forwarding Techniques

- Network-Specific Method Versus Host-Specific Method

- A second technique to reduce the routing table entries and simplify the searching process is called the network-specific method.
- Here, instead of having an entry for every destination host connected to the same physical network (host-specific method), we have only one entry that defines the address of the destination network itself.
- In other words, we treat all hosts connected to the same network as one single entity.

Forwarding Techniques

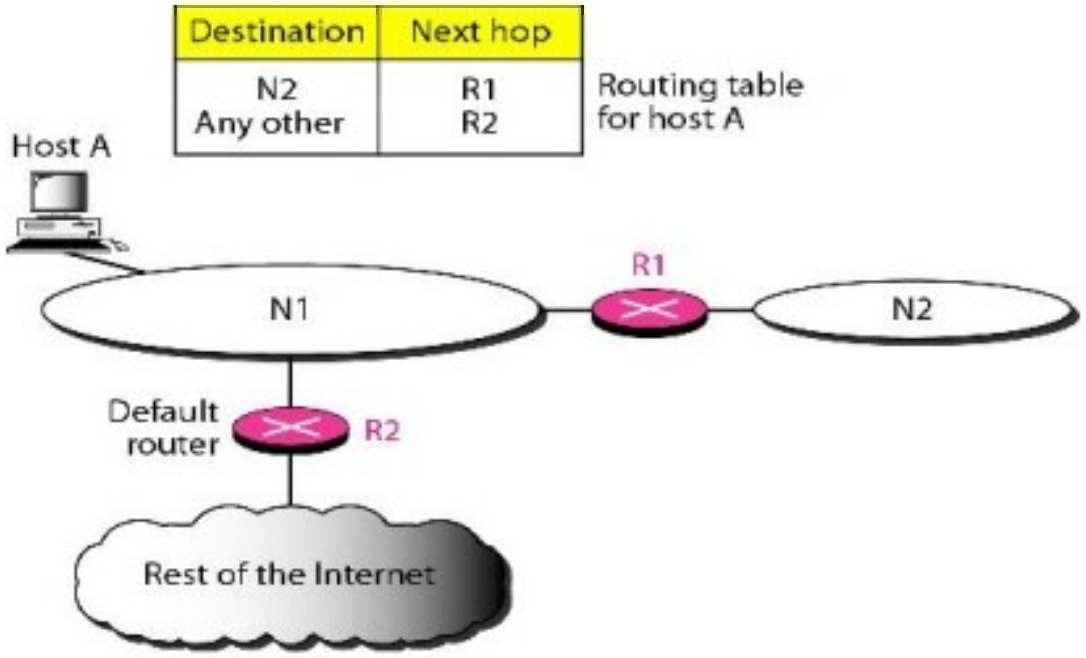


Host specific Vs Network specific method

Forwarding Techniques

- **Default Method**

- Another technique to simplify routing is called the default method. In Figure below host A is connected to a network with two routers. Router Rl 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.

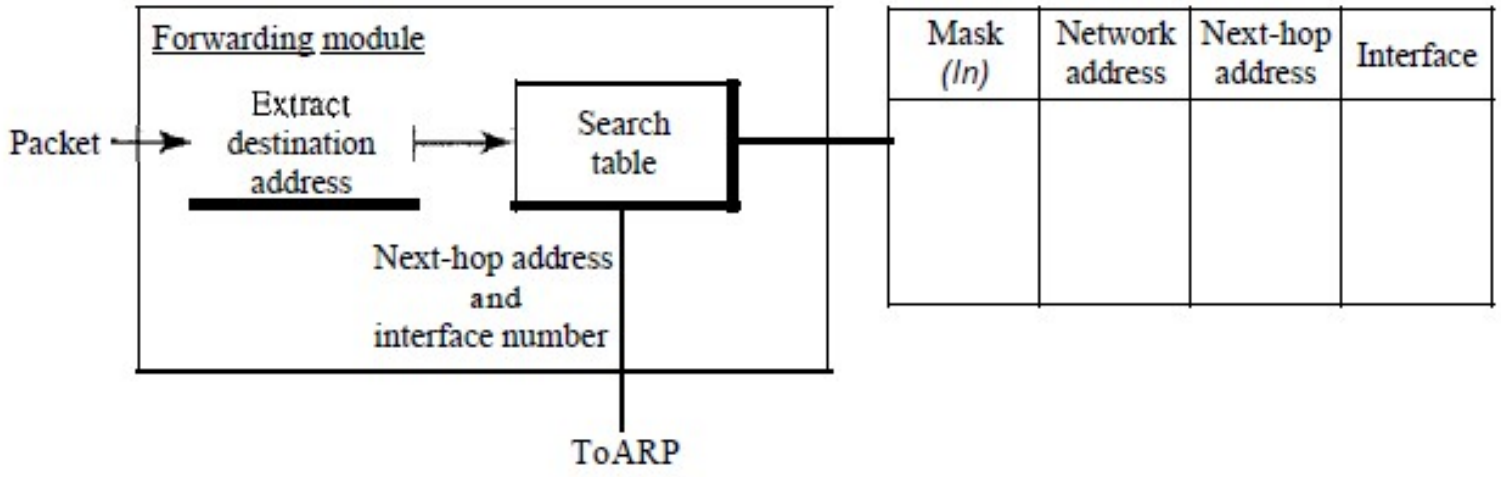


Default method

Forwarding Process

- We assume that hosts and routers use classless addressing because classful addressing can be treated as a special case of classless addressing.
- In classless addressing, the routing table needs to have one row of information for each block involved. The table needs to be searched based on the network.
- Note that we need at least four columns in our routing table; usually there are more.

Figure 22.5 *Simplified forwarding module in classless address*



Routing Table

- A host or a router has a routing table with an entry for each destination, or a combination of destinations, to route IP packets. The routing table can be either static or dynamic.

- Static Routing Table
- A static routing table contains information entered manually. The administrator enters the route for each destination into the table.
- When a table is created, it cannot be updated automatically when there is a change in the Internet. The table must be manually altered by the administrator.
- A static routing table can be used in a small internet that does not change very often, or in an experimental internet for troubleshooting.
- It is poor strategy to use a static routing table in a big internet such as the Internet.

Routing Table

- **Dynamic Routing Table**

- A dynamic routing table is updated periodically by using one of the dynamic routing protocols such as RIP (Routing Information Protocol), OSPF (Open Shortest Path First), or BGP (Border Gateway Protocol).
- Whenever there is a change in the Internet, such as a shutdown of a router or breaking of a link, the dynamic routing protocols update all the tables in the routers (and eventually in the host) automatically.
- The routers in a big network such as the Internet need to be updated dynamically for efficient delivery of the IP packets

Routing Table

- **Format**

- As mentioned previously, a routing table for classless addressing has a minimum of four columns. However, some of today's routers have even more columns.
- We should be aware that the number of columns is vendor-dependent, and not all columns can be found in all routers.
- Figure 22.10 shows some common fields in today's routers.

Figure 22.10 *Common fields in a routing table*

Mask	Network address	Next-hop address	Interlace		Reference count	Use

Routing Table

- **Format**

- Mask. This field defines the mask applied for the entry.
- Network address. This field defines the network address to which the packet is finally delivered. In the case of host-specific routing, this field defines the address of the destination host.
- Next-hop address. This field defines the address of the next-hop router to which the packet is delivered.
- Interface. This field shows the name of the interface.
- Flags. This field defines up to five flags. Flags are on/off switches that signify either presence or absence. The five flags are U (up), G (gateway), H (host-specific), D (added by redirection), and M (modified by redirection).

Routing Table

- **Format**
- Reference count. This field gives the number of users of this route at the moment.
- For example, if five people at the same time are connecting to the same host from this router, the value of this column is 5.
- Use. This field shows the number of packets transmitted through this router for the corresponding destination.

Introduction to Unicast and Multicast routing

- A message can be unicast, multicast, or broadcast. Let us clarify these terms as they relate to the Internet.
- **Unicasting**
- In unicast communication, there is one source and one destination. The relationship between the source and the destination is one-to-one.
- Hence, both the source and destination addresses, in the IP datagram, are the unicast addresses assigned to the hosts (or host interfaces, to be more exact)

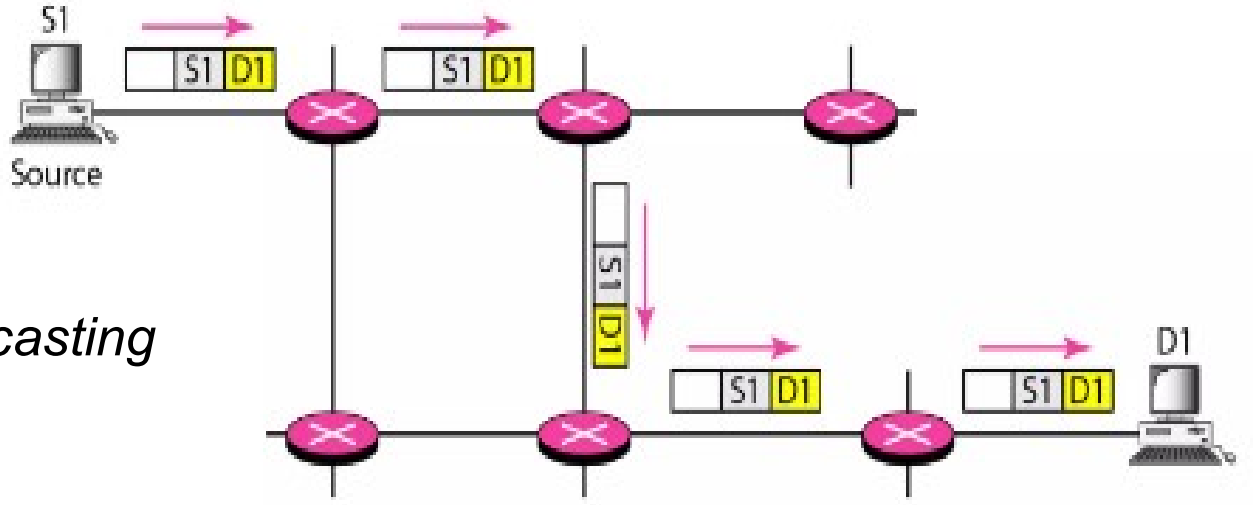


Figure 22.33 *Unicasting*

Introduction to Unicast and Multicast routing

- In figure, a unicast packet staI1s from the source S1 and passes through routers to reach the destination D1.
- In unicasting, the router forwards the received packet through only one of its interfaces, as per the routing table.
- **Multicasting**
- In multicast communication, there is one source and a group of destinations. The relationship is one-to-many.
- In multicasting, the source address is a unicast address, but the destination address is a group address, which defines one or more destinations.
- The group address identifies the members of the group.
- A multicast packet starts from the source S1 and goes to all destinations that belong to group G1.
- In multicasting, when a router receives a packet, it may forward it through several of its interfaces.

Introduction to Unicast and Multicast routing

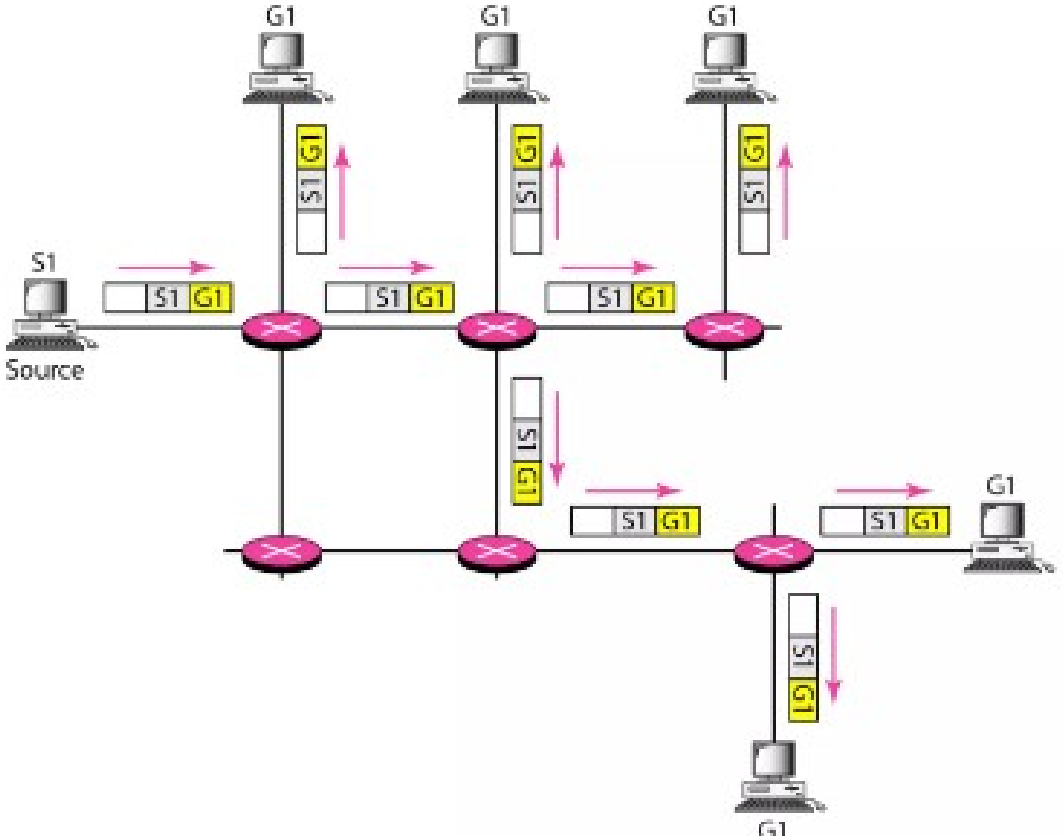


Figure 22.34 *Multicasting*