IP Addressing

8.0. Introduction

Currently, there are still plenty of networks using IPv4 addressing, even as the organizations which use them are making the transition to IPv6. So it is still very important for network administrators to know everything they can about IPv4 addressing. This module covers the fundamental aspects of IPv4 addressing in detail. It includes how to segment a network into subnets and how to create a variable-length subnet mask (VLSM) as part of an overall IPv4 addressing scheme. Subnetting is like cutting a pie into smaller and smaller pieces. Subnetting may seem overwhelming at first, but we show you some tricks to help you along the way. This module includes several videos, activities to help you practice subnetting, Packet Tracers and a lab. Once you get the hang of it, you'll be on your way to network administration!

Topic Title	**Topic Objective**
IPv4 Address Structure	Describe the structure of an IPv4 address including the network portion, the host portion, and the subnet mask.
IPv4 Unicast, Broadcast, and Multicast	Compare the characteristics and uses of the unicast, broadcast and multicast IPv4 addresses.
Types of IPv4 Addresses	Explain public, private, and reserved IPv4 addresses.
Network Segmentation	Explain how subnetting segments a network to enable better communication.
Subnet an IPv4 Network	Calculate IPv4 subnets for a /24 prefix.
Subnet a /16 and a /8 Prefix	Calculate IPv4 subnets for a /16 and /8 prefix.
Subnet To Meet Requirements	Given a set of requirements for subnetting, implement an IPv4 addressing scheme.
Variable Length Subnet Masking	Explain how to create a flexible addressing scheme using variable length subnet masking (VLSM).
Structured Design	Implement a VLSM addressing scheme.
IPv4 Issues	Explain the need for IPv6 addressing.
IPv6 Address Representation	Explain how IPv6 addresses are represented.
IPv6 Address Types	Compare types of IPv6 network addresses.
GUA and LLA Static Configuration	Explain how to Configure static global unicast and link-local IPv6 network addresses.
Dynamic Addressing for IPv6 GUAs	Explain how to configure global unicast addresses dynamically.
Dynamic Addressing for IPv6 LLAs	Configure link-local addresses dynamically.
IPv6 Multicast Addresses	Identify IPv6 addresses.
Subnet an IPv6 Network	Implement a subnetted IPv6 addressing scheme.

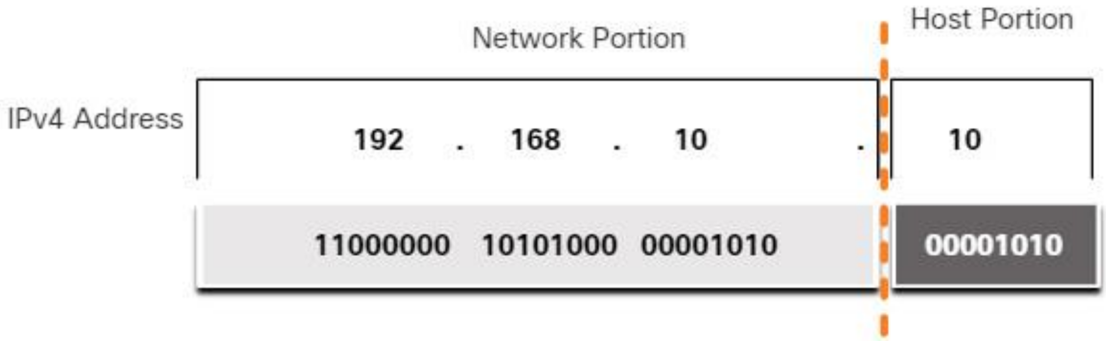
8.1. IPv4 Address Structure

8.1.1. Network and Host Portions

An IPv4 address is a 32-bit hierarchical address that is made up of a network portion and a host portion. When determining the network portion versus the host portion, you must look at the 32-bit stream, as shown in the figure.

The diagram shows the breakdown of an IPv4 address into the network and host portions. The IPv4 address is 192.168.10.10. Underneath, the address is converted into 11000000 10101000 00001010 00001010. A dashed line shows the separation between the network and host portions. This occurs after the third octet and the 24th bit.

IPv4 Address



The bits within the network portion of the address must be identical for all devices that reside in the same network. The bits within the host portion of the address must be unique to identify a specific host within a network. If two hosts have the same bit-pattern in the specified network portion of the 32-bit stream, those two hosts will reside in the same network.

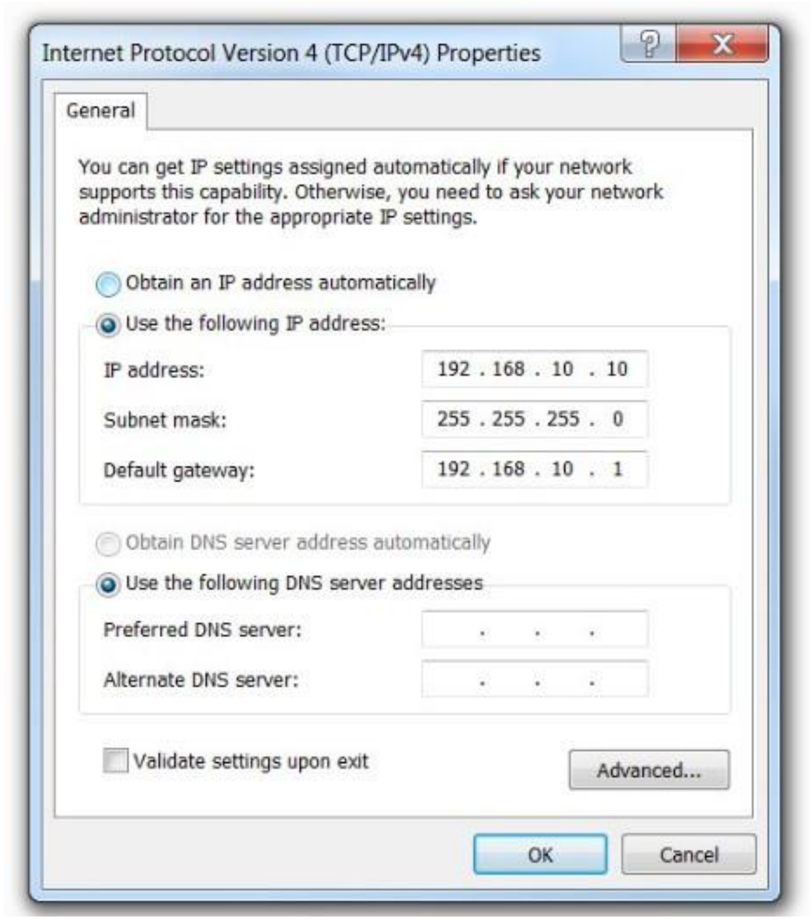
But how do hosts know which portion of the 32-bits identifies the network and which identifies the host? That is the role of the subnet mask.

8.1.2. The Subnet Mask

As shown in the figure, assigning an IPv4 address to a host requires the following:

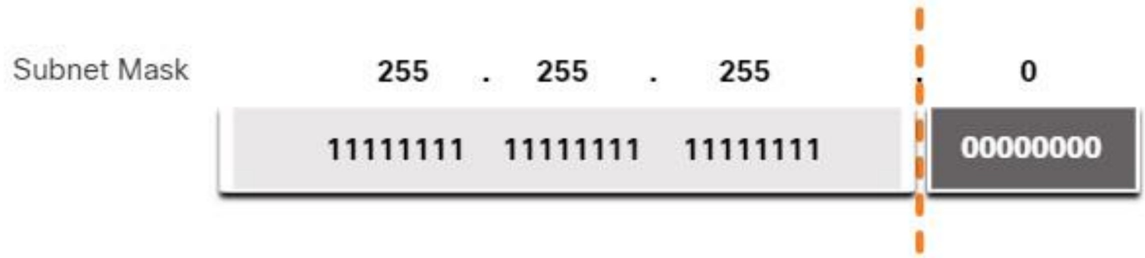
- **IPv4 address** – This is the unique IPv4 address of the host.
- **Subnet mask**– This is used to identify the network/host portion of the IPv4 address.

IPv4 Configuration on a Windows Computer



Note: A default gateway IPv4 address is required to reach remote networks and DNS server IPv4 addresses are required to translate domain names to IPv4 addresses.
The IPv4 subnet mask is used to differentiate the network portion from the host portion of an IPv4 address. When an IPv4 address is assigned to a device, the subnet mask is used to determine the network address of the device. The network address represents all the devices on the same network.
The next figure displays the 32-bit subnet mask in dotted decimal and binary formats.

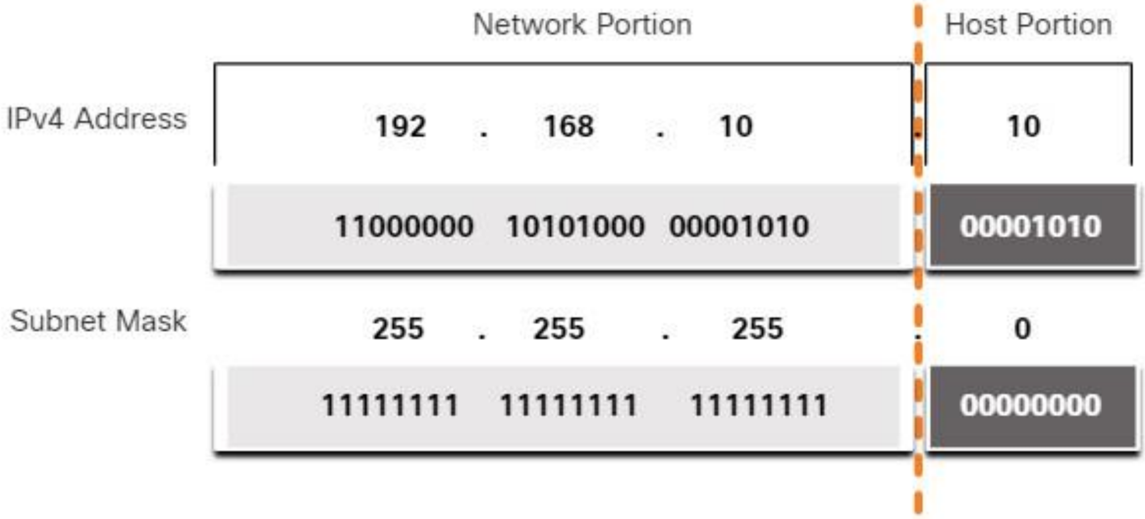
Subnet Mask
subnet mask of 255.255.255.0 on top with the binary representation of 11111111 111111111 11111111 0000000 underneath; a dashed line is drawn after the third octet and the 24th bit



Notice how the subnet mask is a consecutive sequence of 1 bits followed by a consecutive sequence of 0 bits.
To identify the network and host portions of an IPv4 address, the subnet mask is compared to the IPv4 address bit for bit, from left to right as shown in the figure.

Associating an IPv4 Address with its Subnet Mask

The figure shows an IPv4 address, written in both dotted-decimal and binary, with the subnet mask below, also written in dotted-decimal and binary, used to show the division between the network portion and host portion of the address. The IPv4 address is 192.168.10.10 which is converted to 11000000 10101000 00001010 00001010. The subnet mask is 255.255.255.0 which is converted to 11111111 11111111 11111111 00000000. A dashed line shows the separation between the network and host portions. This occurs after the third octet and 24th bit.



Note that the subnet mask does not actually contain the network or host portion of an IPv4 address, it just tells the computer where to look for the part of the IPv4 address that is the network portion and which part is the host portion.
The actual process used to identify the network portion and host portion is called ANDing.

8.1.3. The Prefix Length

Expressing network addresses and host addresses with the dotted decimal subnet mask address can become cumbersome. Fortunately, there is an alternative method of identifying a subnet mask, a method called the prefix length.
The prefix length is the number of bits set to 1 in the subnet mask. It is written in “slash notation”, which is noted by a forward slash (/) followed by the number of bits set to 1. Therefore, count the number of bits in the subnet mask and prepend it with a slash.
Refer to the table for examples. The first column lists various subnet masks that can be used with a host address. The second column displays the converted 32-bit binary address. The last column displays the resulting prefix length.

Comparing the Subnet Mask and Prefix Length

Subnet Mask	32-bit Address	Prefix Length
255.0.0.0	11111111.00000000.00000000.00000000	/8
255.255.0.0	11111111.11111111.00000000.00000000	/16
255.255.255.0	11111111.11111111.11111111.00000000	/24
255.255.255.128	11111111.11111111.11111111.10000000	/25
255.255.255.192	11111111.11111111.11111111.11000000	/26
255.255.255.224	11111111.11111111.11111111.11100000	/27
255.255.255.240	11111111.11111111.11111111.11110000	/28
255.255.255.248	11111111.11111111.11111111.11111000	/29

Subnet Mask	32-bit Address	Prefix Length
255.255.255.252	11111111.11111111.11111111.11111100	/30

Note: A network address is also referred to as a prefix or network prefix. Therefore, the prefix length is the number of 1 bits in the subnet mask.

When representing an IPv4 address using a prefix length, the IPv4 address is written followed by the prefix length with no spaces. For example, 192.168.10.10 255.255.255.0 would be written as 192.168.10.10/24. Using various types of prefix lengths will be discussed later. For now, the focus will be on the /24 (i.e. 255.255.255.0) prefix

8.1.4. Determining the Network: Logical AND

A logical AND is one of three Boolean operations used in Boolean or digital logic. The other two are OR and NOT. The AND operation is used in determining the network address.

Logical AND is the comparison of two bits that produce the results shown below. Note how only a 1 AND 1 produces a 1. Any other combination results in a 0.

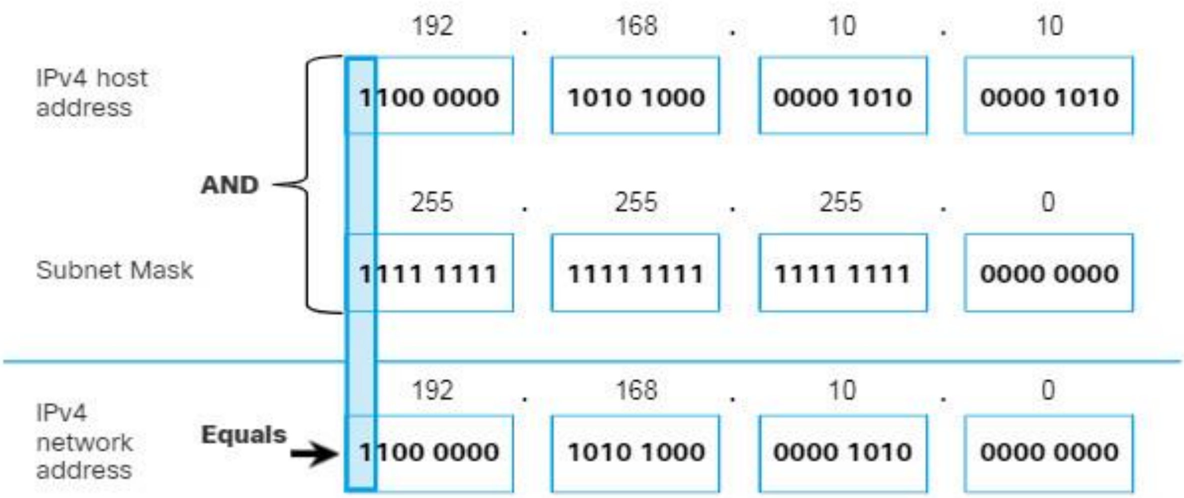
- 1 AND 1 = 1
- 0 AND 1 = 0
- 1 AND 0 = 0
- 0 AND 0 = 0

Note: In digital logic, 1 represents True and 0 represents False. When using an AND operation, both input values must be True (1) for the result to be True (1).

To identify the network address of an IPv4 host, the IPv4 address is logically ANDed, bit by bit, with the subnet mask. ANDing between the address and the subnet mask yields the network address.

To illustrate how AND is used to discover a network address, consider a host with IPv4 address 192.168.10.10 and subnet mask of 255.255.255.0, as shown in the figure:

- **IPv4 host address (192.168.10.10)** – The IPv4 address of the host in dotted decimal and binary formats.
- **Subnet mask (255.255.255.0)** – The subnet mask of the host in dotted decimal and binary formats.
- **Network address (192.168.10.0)** – The logical AND operation between the IPv4 address and subnet mask results in an IPv4 network address shown in dotted decimal and binary formats.



Using the first sequence of bits as an example, notice the AND operation is performed on the 1-bit of the host address with the 1-bit of the subnet mask. This results in a 1 bit for the network address. 1 AND 1 = 1.

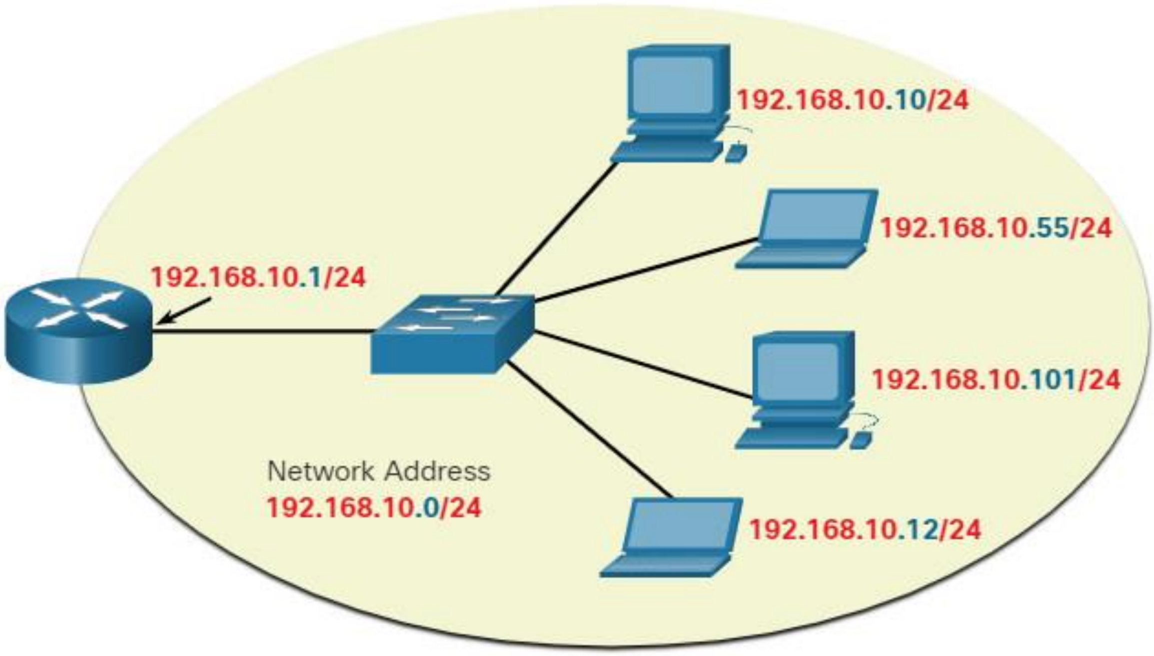
The AND operation between an IPv4 host address and subnet mask results in the IPv4 network address for this host. In this example, the AND operation between the host address of 192.168.10.10 and the subnet mask 255.255.255.0 (/24), results in the IPv4 network address of 192.168.10.0/24. This is an important IPv4 operation, as it tells the host what network it belongs to.

8.1.5. Network, Host, and Broadcast Addresses

Within each network are three types of IP addresses:

- Network address
- Host addresses
- Broadcast address

Using the topology in the figure, these three types of addresses will be examined.



Network address

A network address is an address that represents a specific network. A device belongs to this network if it meets three criteria:

- It has the same subnet mask as the network address.
- It has the same network bits as the network address, as indicated by the subnet mask.
- It is located on the same broadcast domain as other hosts with the same network address.

A host determines its network address by performing an AND operation between its IPv4 address and its subnet mask.

As shown in the table, the network address has all 0 bits in the host portion, as determined by the subnet mask. In this example, the network address is 192.168.10.0/24. A network address cannot be assigned to a device.

Network, Host, and Broadcast Addresses

	Network Portion	Host Portion	Host Bits
Subnet mask **255.255.255.**0 or **/24**	255 255 255 11111111 11111111 11111111	0 00000000	
Network address **192.168.10.**0 or **/24**	192 168 10 11000000 10100000 00001010	0 00000000	All 0s
First address **192.168.10**.1 or **/24**	192 168 10 11000000 10100000 00001010	1 00000001	All 0s and a 1
Last address **192.168.10**.254 or **/24**	192 168 10 11000000 10100000 00001010	254 11111110	All 1s and a 0
Broadcast address **192.168.10**.255 or **/24**	192 168 10 11000000 10100000 00001010	255 11111111	All 1s

Host addresses

Host addresses are addresses that can be assigned to a device such as a host computer, laptop, smart phone, web camera, printer, router, etc. The host portion of the address is the bits indicated by 0 bits in the subnet mask. Host addresses can have any combination of bits in the host portion except for all 0 bits (this would be a network address) or all 1 bits (this would be a broadcast address).

All devices within the same network, must have the same subnet mask and the same network bits. Only the host bits will differ and must be unique.

Notice that in the table, there is a first and last host address:

- **First host address** – This first host within a network has all 0 bits with the last (right-most) bit as a 1 bit. In this example it is 192.168.10.1/24.
- **Last host address** – This last host within a network has all 1 bits with the last (right-most) bit as a 0 bit. In this example it is 192.168.10.254/24.

Any addresses between and including, 192.168.10.1/24 through 192.168.10.254/24 can be assigned to a device on the network.

Broadcast address

A broadcast address is an address that is used when it is required to reach all devices on the IPv4 network. As shown in the table, the network broadcast address has all 1 bits in the host portion, as determined by the subnet mask. In this example, the network address is 192.168.10.255/24. A broadcast address cannot be assigned to a device.

8.1.6. ANDing to Determine the Network Address

Instructions:

Use the ANDing process to determine the network address (in binary and decimal formats).

Host Address	172	23	163	220
Subnet Mask	255	255	255	192
Host Address in binary	10101100	00010111	10100011	11011100
Subnet Mask in binary	11111111	11111111	11111111	11000000
Network Address in binary	10101100	00010111	10100011	11000000
Network Address in decimal	172	23	163	192

8.2. IPv4 Unicast, Broadcast, and Multicast

8.2.1. Unicast

In the previous topic you learned about the structure of an IPv4 address; each has a network portion and a host portion. There are different ways to send a packet from a source device, and these different transmissions affect the destination IPv4 addresses.
Unicast transmission refers to one device sending a message to one other device in one-to-one communications.
A unicast packet has a destination IP address that is a unicast address which goes to a single recipient. A source IP address can only be a unicast address, because the packet can only originate from a single source. This is regardless of whether the destination IP address is a unicast, broadcast or multicast.

8.2.2. Broadcast

Broadcast transmission refers to a device sending a message to all the devices on a network in one-to-all communications.
A broadcast packet has a destination IP address with all ones (1s) in the host portion, or 32 one (1) bits.

Limited Broadcast Transmission

Broadcast packets use resources on the network and make every receiving host on the network process the packet. Therefore, broadcast traffic should be limited so that it does not adversely affect the performance of the network or devices. Because routers separate broadcast domains, subdividing networks can improve network performance by eliminating excessive broadcast traffic.

IP Directed Broadcasts

In addition to the 255.255.255.255 broadcast address, there is a broadcast IPv4 address for each network. Called a directed broadcast, this address uses the highest address in the network, which is the address where all the host bits are 1s. For example, the directed broadcast address for 192.168.1.0/24 is 192.168.1.255. This address allows communication to all the hosts in that network. To send data to all the hosts in a network, a host can send a single packet that is addressed to the broadcast address of the network.

A device that is not directly connected to the destination network forwards an IP directed broadcast in the same way it would forward unicast IP packets destined to a host on that network. When a directed broadcast packet reaches a router that is directly connected to the destination network, that packet is broadcast on the destination network.
Note: Because of security concerns and prior abuse from malicious users, directed broadcasts are turned off by default starting with Cisco IOS Release 12.0 with the global configuration command no ip directed-broadcasts.

8.2.3. Multicast

Multicast transmission reduces traffic by allowing a host to send a single packet to a selected set of hosts that subscribe to a multicast group.

A multicast packet is a packet with a destination IP address that is a multicast address. IPv4 has reserved the 224.0.0.0 to 239.255.255.255 addresses as a multicast range.
Hosts that receive particular multicast packets are called multicast clients. The multicast clients use services requested by a client program to subscribe to the multicast group.
Each multicast group is represented by a single IPv4 multicast destination address. When an IPv4 host subscribes to a multicast group, the host processes packets addressed to this multicast address, and packets addressed to its uniquely allocated unicast address.
Routing protocols such as OSPF use multicast transmissions. For example, routers enabled with OSPF communicate with each other using the reserved OSPF multicast address 224.0.0.5. Only devices enabled with OSPF will process these packets with 224.0.0.5 as the destination IPv4 address. All other devices will ignore these packets.
The animation demonstrates clients accepting multicast packets.

8.3. Types of IPv4 Addresses

8.3.1. Public and Private IPv4 Addresses

Just as there are different ways to transmit an IPv4 packet, there are also different types of IPv4 addresses. Some IPv4 addresses cannot be used to go out to the internet, and others are specifically allocated for routing to the internet. Some are used to verify a connection and others are self-assigned. As a network administrator, you will eventually become very familiar with the types of IPv4 addresses, but for now, you should at least know what they are and when to use them.
Public IPv4 addresses are addresses which are globally routed between internet service provider (ISP) routers. However, not all available IPv4 addresses can be used on the internet. There are blocks of addresses called private addresses that are used by most organizations to assign IPv4 addresses to internal hosts.
In the mid-1990s, with the introduction of the World Wide Web (WWW), private IPv4 addresses were introduced because of the depletion of IPv4 address space. Private IPv4 addresses are not unique and can be used internally within any network.
Note: The long-term solution to IPv4 address depletion was IPv6.

The Private Address Blocks

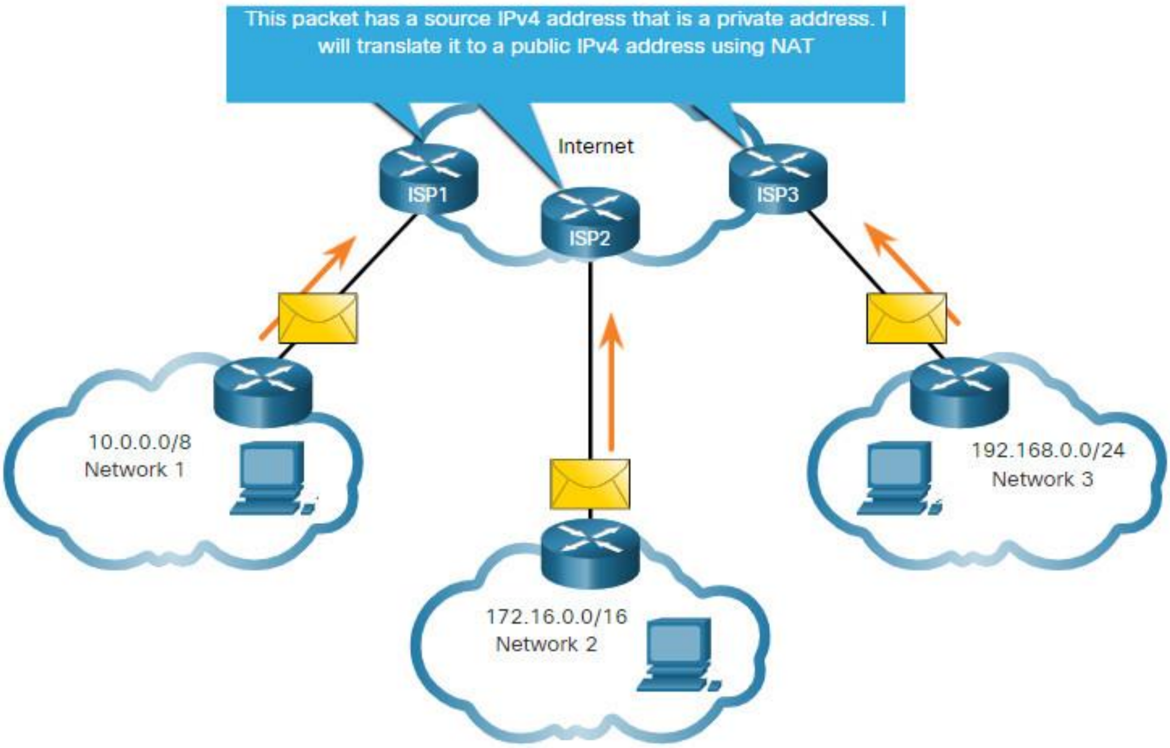
Network Address and Prefix	RFC 1918 Private Address Range
10.0.0.0/8	10.0.0.0 – 10.255.255.255
172.16.0.0/12	172.16.0.0 – 172.31.255.255
192.168.0.0/16	192.168.0.0 – 192.168.255.255

Note: Private addresses are defined in RFC 1918 and sometimes referred to as RFC 1918 address space.

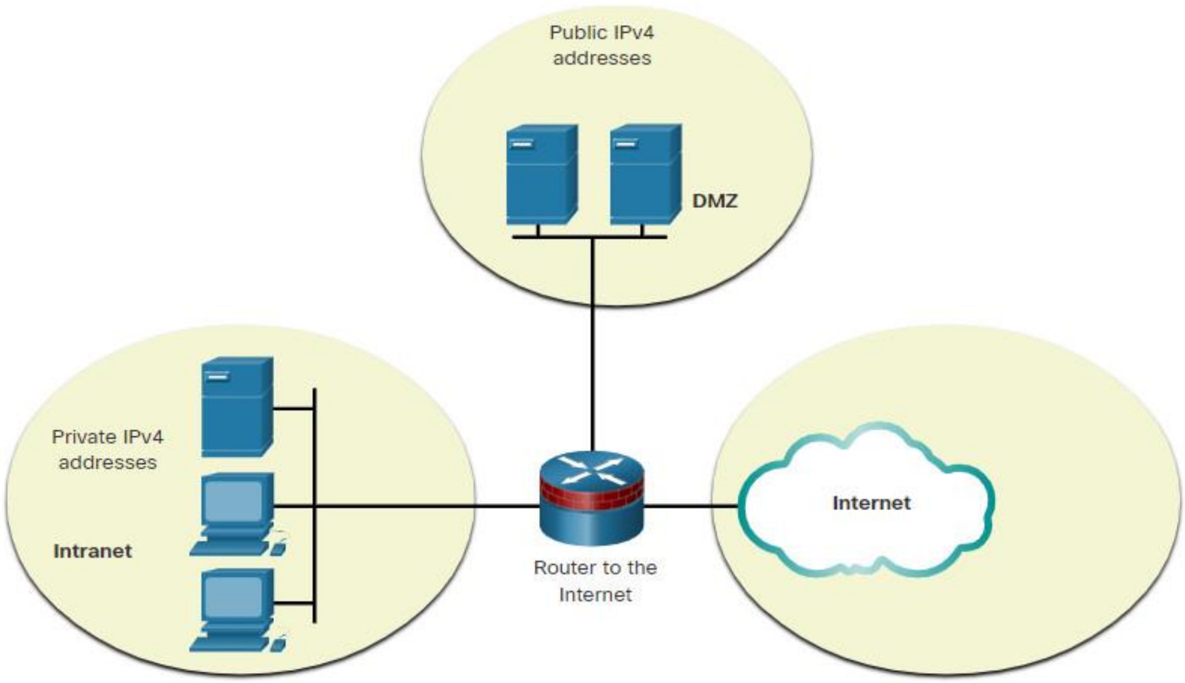
8.3.2. Routing to the Internet

Most internal networks, from large enterprises to home networks, use private IPv4 addresses for addressing all internal devices (intranet) including hosts and routers. However, private addresses are not globally routable.
In the figure, customer networks 1, 2, and 3 are sending packets outside their internal networks. These packets have a source IPv4 address that is a private address and a destination IPv4 address that is public (globally routable). Packets with a private address must be filtered (discarded) or translated to a public address before forwarding the packet to an ISP.
The diagram is a network topology with three networks, each connected to a different ISP router. The ISP routers are performing NAT between each network and the Internet.

Private IPv4 Addresses and Network Address Translation (NAT)
Before the ISP can forward this packet, it must translate the source IPv4 address, which is a private address, to a public IPv4 address using Network Address Translation (NAT). NAT is used to translate between private IPv4 and public IPv4 addresses. This is usually done on the router that connects the internal network to the ISP network. Private IPv4 addresses in the organization's intranet will be translated to public IPv4 addresses before routing to the internet.
Note: Although, a device with a private IPv4 address is not directly accessible from another device across the internet, the IETF does not consider private IPv4 addresses or NAT as effective security measures.



Organizations that have resources available to the internet, such as a web server, will also have devices that have public IPv4 addresses. As shown in the figure, this part of the network is known as the DMZ (demilitarized zone). The router in the figure not only performs routing, it also performs NAT and acts as a firewall for security.



8.3.3. Special Use IPv4 Addresses

There are certain addresses, such as the network address and broadcast address, that cannot be assigned to hosts. There are also special addresses that can be assigned to hosts, but with restrictions on how those hosts can interact within the network.

Loopback addresses

Loopback addresses (127.0.0.0 /8 or 127.0.0.1 to 127.255.255.254) are more commonly identified as only 127.0.0.1, these are special addresses used by a host to direct traffic to itself. For example, it can be used on a host to test if the TCP/IP configuration is operational, as shown in the figure. Notice how the 127.0.0.1 loopback address replies to the ping command. Also note how any address within this block will loop back to the local host, which is shown with the second ping in the figure.

Pinging the Loopback Interface

```
C:\Users\NetAcad> ping 127.0.0.1
Pinging 127.0.0.1 with 32 bytes of data:
Reply from 127.0.0.1: bytes=32 time<1ms TTL=128
Reply from 127.0.0.1: bytes=32 time<1ms TTL=128
Reply from 127.0.0.1: bytes=32 time<1ms TTL=128
Reply from 127.0.0.1: bytes=32 time<1ms TTL=128
Ping statistics for 127.0.0.1:
    Packets: Sent = 4, Received = 4, Lost = 0 (0% loss),
Approximate round trip times in milli-seconds:
    Minimum = 0ms, Maximum = 0ms, Average = 0ms
C:\Users\NetAcad> ping 127.1.1.1
Pinging 127.1.1.1 with 32 bytes of data:
Reply from 127.1.1.1: bytes=32 time<1ms TTL=128
Reply from 127.1.1.1: bytes=32 time<1ms TTL=128
Reply from 127.1.1.1: bytes=32 time<1ms TTL=128
Reply from 127.1.1.1: bytes=32 time<1ms TTL=128
Ping statistics for 127.1.1.1:
    Packets: Sent = 4, Received = 4, Lost = 0 (0% loss),
Approximate round trip times in milli-seconds:
    Minimum = 0ms, Maximum = 0ms, Average = 0ms
```

```
C:\Users\NetAcad>
```

Link-Local addresses

Link-local addresses (169.254.0.0 /16 or 169.254.0.1 to 169.254.255.254) are more commonly known as the Automatic Private IP Addressing (APIPA) addresses or self-assigned addresses. They are used by a Windows DHCP client to self-configure in the event that there are no DHCP servers available. Link-local addresses can be used in a peer-to-peer connection but are not commonly used for this purpose.

8.3.4. Legacy Classful Addressing

In 1981, IPv4 addresses were assigned using classful addressing as defined in RFC 790 (https://tools.ietf.org/html/rfc790), Assigned Numbers. Customers were allocated a network address based on one of three classes, A, B, or C. The RFC divided the unicast ranges into specific classes as follows:

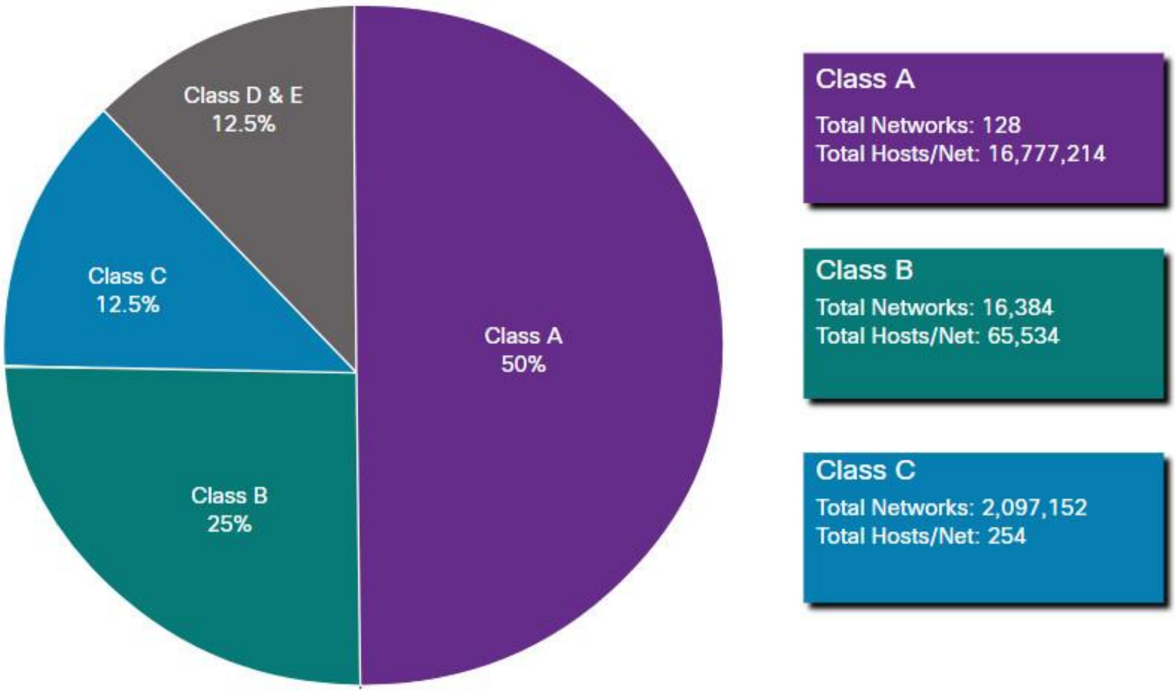
- **Class A (0.0.0.0/8 to 127.0.0.0/8)** – Designed to support extremely large networks with more than 16 million host addresses. Class A used a fixed /8 prefix with the first octet to indicate the network address and the remaining three octets for host addresses (more than 16 million host addresses per network).
- **Class B (128.0.0.0 /16 – 191.255.0.0 /16)** – Designed to support the needs of moderate to large size networks with up to approximately 65,000 host addresses. Class B used a fixed /16 prefix with the two high-order octets to indicate the network address and the remaining two octets for host addresses (more than 65,000 host addresses per network).
- **Class C (192.0.0.0 /24 – 223.255.255.0 /24)** – Designed to support small networks with a maximum of 254 hosts. Class C used a fixed /24 prefix with the first three octets to indicate the network and the remaining octet for the host addresses (only 254 host addresses per network).

Note: There is also a Class D multicast block consisting of 224.0.0.0 to 239.0.0.0 and a Class E experimental address block consisting of 240.0.0.0 – 255.0.0.0.

At the time, with a limited number of computers using the internet, classful addressing was an effective means to allocate addresses. As shown in the figure, Class A and B networks have a very large number of host addresses and Class C has very few. Class A networks accounted for 50% of the IPv4 networks. This caused most of the available IPv4 addresses to go unused.

Summary of Classful Addressing

The diagram is a pie chart showing the percentage of Class A, B, C, D, & E IPv4 addressing with the total number of networks and hosts per class A, B, and C networks. Percentages are: class A = 50%, class B = 25%, class C = 12.5%, and class D and E = 12.5%. For the total number of networks and total number of hosts per network: class A = 128 networks with 16,777,214 total hosts per network; class B = 16,384 networks with 65,534 total hosts per network; and class C = 2,097,152 networks with 254 total hosts per network.



In the mid-1990s, with the introduction of the World Wide Web (WWW), classful addressing was deprecated to more efficiently allocate the limited IPv4 address space. Classful address allocation was replaced with classless addressing, which is used today. Classless addressing ignores the rules of classes (A, B, C). Public IPv4 network addresses (network addresses and subnet masks) are allocated based on the number of addresses that can be justified.

8.3.5. Assignment of IP Addresses

Public IPv4 addresses are addresses which are globally routed over the internet. Public IPv4 addresses must be unique.

Both IPv4 and IPv6 addresses are managed by the Internet Assigned Numbers Authority (IANA). The IANA manages and allocates blocks of IP addresses to the Regional Internet Registries (RIRs). The five RIRs are shown in the figure.

RIRs are responsible for allocating IP addresses to ISPs who provide IPv4 address blocks to organizations and smaller ISPs. Organizations can also get their addresses directly from an RIR (subject to the policies of that RIR).

Regional Internet Registries

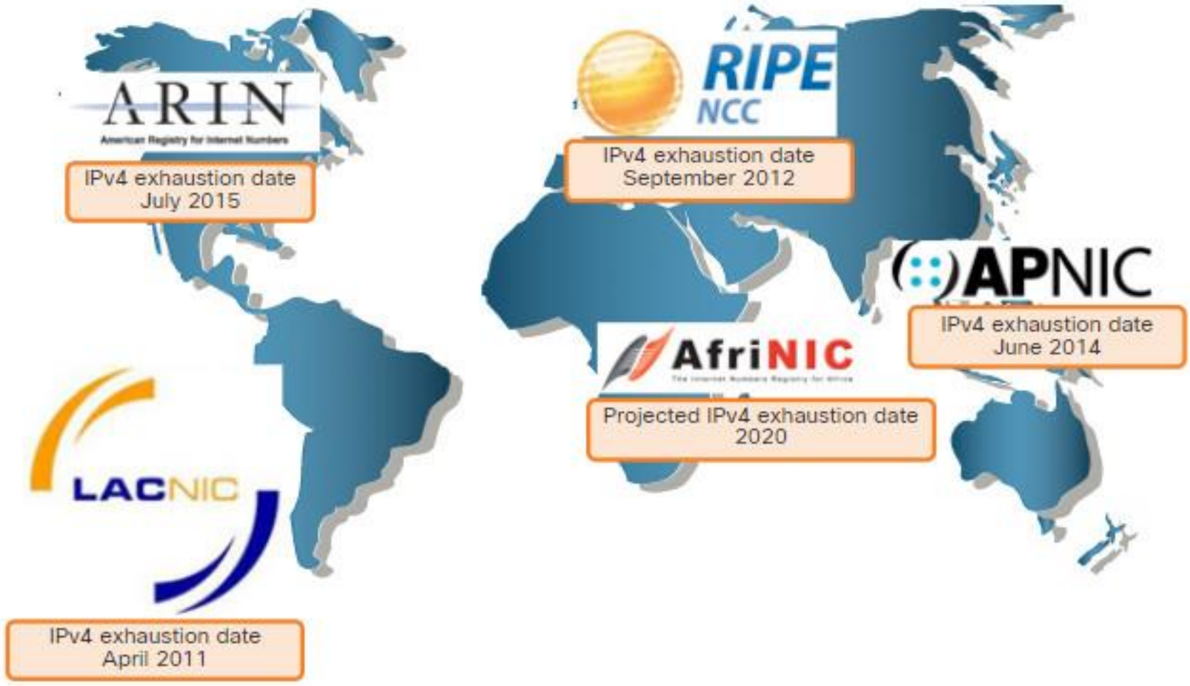
- **AfriNIC** (African Network Information Centre) – Africa Region
- **APNIC** (Asia Pacific Network Information Centre) – Asia/Pacific Region
- **ARIN** (American Registry for Internet Numbers) – North America Region
- **LACNIC** (Regional Latin-American and Caribbean IP Address Registry) – Latin America and some Caribbean Islands
- **RIPE NCC** (Réseaux IP Européens Network Coordination Centre) – Europe, the Middle East, and Central Asia

9.1. IPv4 Issues

9.1.1. Need for IPv6

IPv6 is designed to be the successor to IPv4. IPv6 has a larger 128-bit address space, providing 340 undecillion (i.e., 340 followed by 36 zeroes) possible addresses. However, IPv6 is more than just larger addresses.
When the IETF began its development of a successor to IPv4, it used this opportunity to fix the limitations of IPv4 and include enhancements. One example is Internet Control Message Protocol version 6 (ICMPv6), which includes address resolution and address autoconfiguration not found in ICMP for IPv4 (ICMPv4).
The depletion of IPv4 address space has been the motivating factor for moving to IPv6. As Africa, Asia and other areas of the world become more connected to the internet, there are not enough IPv4 addresses to accommodate this growth. As shown in the figure, four out of the five RIRs have run out of IPv4 addresses.

RIR IPv4 Exhaustion Dates
The graphic shows a global map of the five regional internet registries and there IPv4 exhaustion dates. ARINs IPv4 exhaustion date is July 2015, RIPE NCCs exhaustion data is September 2012, APNICs exhaustion date is June 2014, LACNICs exhaustion date is April 2011, and AfriNICs projected exhaustion date is 2020.



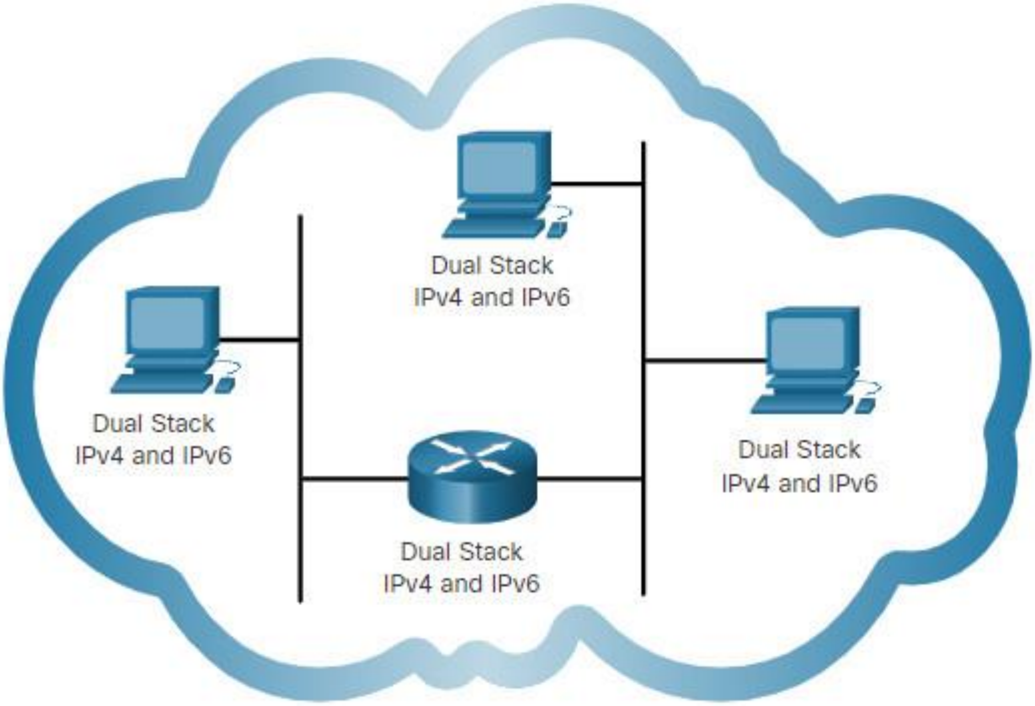
IPv4 has a theoretical maximum of 4.3 billion addresses. Private addresses in combination with Network Address Translation (NAT) have been instrumental in slowing the depletion of IPv4 address space. However, NAT is problematic for many applications, creates latency, and has limitations that severely impede peer-to-peer communications.
With the ever-increasing number of mobile devices, mobile providers have been leading the way with the transition to IPv6. The top two mobile providers in the United States report that over 90% of their traffic is over IPv6.
Most top ISPs and content providers such as YouTube, Facebook, and NetFlix, have also made the transition. Many companies like Microsoft, Facebook, and LinkedIn are transitioning to IPv6-only internally. In 2018, broadband ISP Comcast reported a deployment of over 65% and British Sky Broadcasting over 86%.

Internet of Things
The internet of today is significantly different than the internet of past decades. The internet of today is more than email, web pages, and file transfers between computers. The evolving internet is becoming an Internet of Things (IoT). No longer will the only devices accessing the internet be computers, tablets, and smartphones. The sensor-equipped, internet-ready devices of tomorrow will include everything from automobiles and biomedical devices, to household appliances and natural ecosystems.
With an increasing internet population, a limited IPv4 address space, issues with NAT and the IoT, the time has come to begin the transition to IPv6.

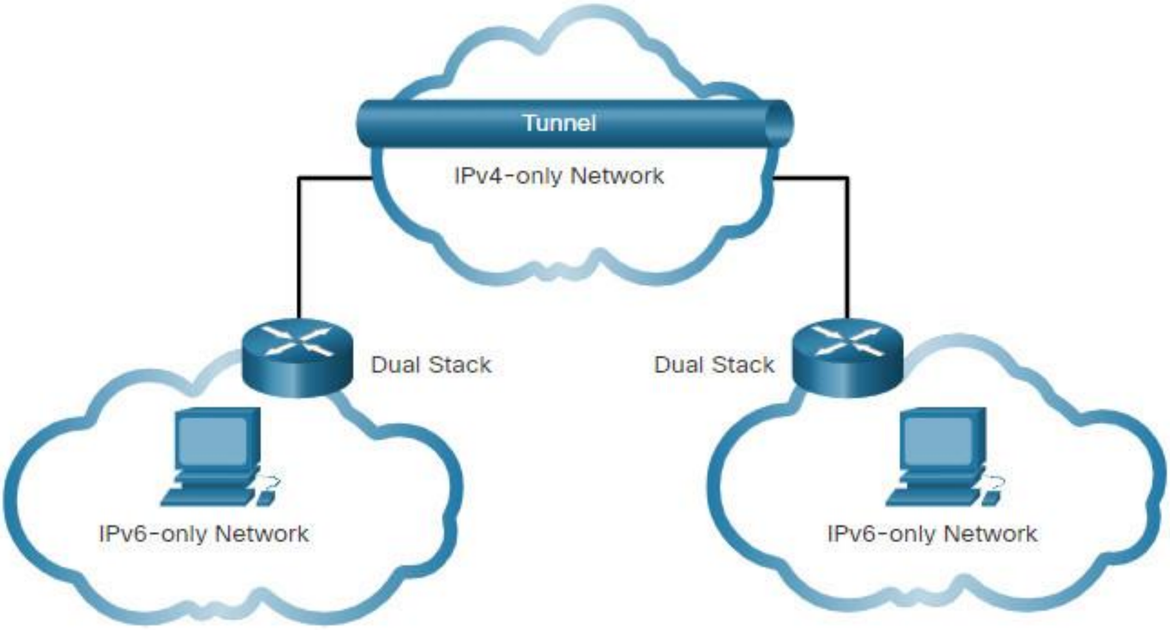
9.1.2. IPv4 and IPv6 Coexistence

There is no specific date to move to IPv6. Both IPv4 and IPv6 will coexist in the near future and the transition will take several years. The IETF has created various protocols and tools to help network administrators migrate their networks to IPv6. The migration techniques can be divided into three categories:

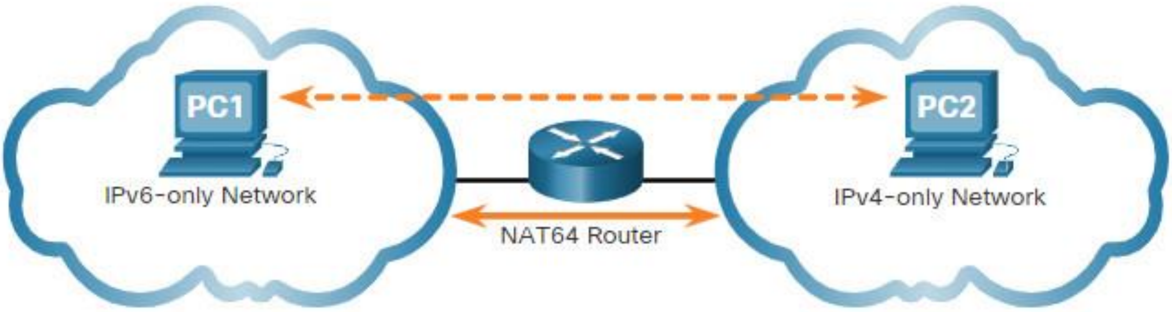
Dual stack allows IPv4 and IPv6 to coexist on the same network segment. Dual stack devices run both IPv4 and IPv6 protocol stacks simultaneously. Known as native IPv6, this means the customer network has an IPv6 connection to their ISP and is able to access content found on the internet over IPv6.



Tunneling is a method of transporting an IPv6 packet over an IPv4 network. The IPv6 packet is encapsulated inside an IPv4 packet, similar to other types of data.



Network Address Translation 64 (NAT64) allows IPv6-enabled devices to communicate with IPv4-enabled devices using a translation technique similar to NAT for IPv4. An IPv6 packet is translated to an IPv4 packet and an IPv4 packet is translated to an IPv6 packet.



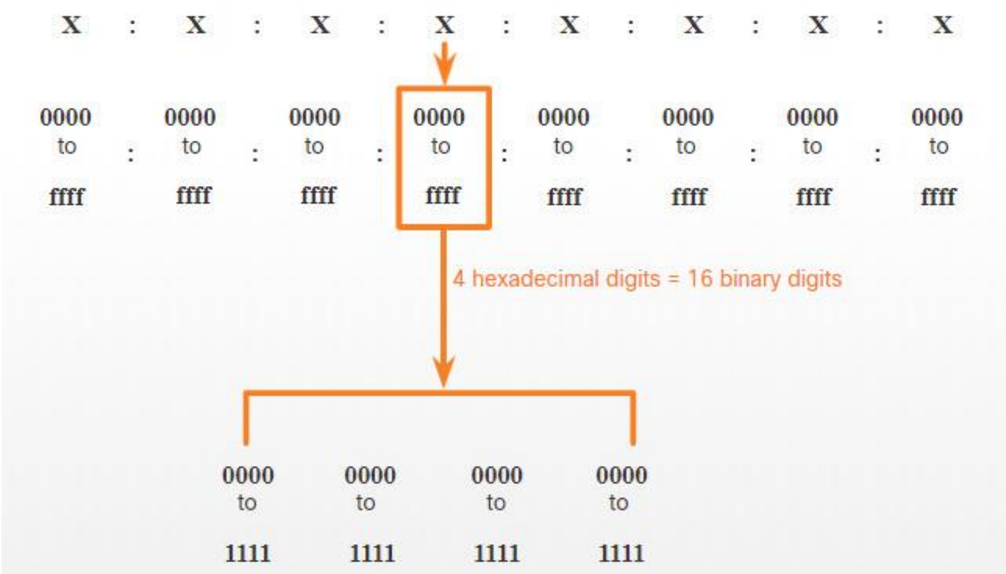
Note: Tunneling and translation are for transitioning to native IPv6 and should only be used where needed. The goal should be native IPv6 communications from source to destination.

9.2. IPv6 Address Representation

9.2.1. IPv6 Addressing Formats

The first step to learning about IPv6 in networks is to understand the way an IPv6 address is written and formatted. IPv6 addresses are much larger than IPv4 addresses, which is why we are unlikely to run out of them.
IPv6 addresses are 128 bits in length and written as a string of hexadecimal values. Every four bits is represented by a single hexadecimal digit; for a total of 32 hexadecimal values, as shown in the figure. IPv6 addresses are not case-sensitive and can be written in either lowercase or uppercase.

16-bit Segments or Hextets



Preferred Format

The previous figure also shows that the preferred format for writing an IPv6 address is x:x:x:x:x:x:x:x, with each "x" consisting of four hexadecimal values. The term octet refers to the eight bits of an IPv4 address. In IPv6, a hextet is the unofficial term used to refer to a segment of 16 bits, or four hexadecimal values. Each "x" is a single hextet which is 16 bits or four hexadecimal digits.

Preferred format means that you write IPv6 address using all 32 hexadecimal digits. It does not necessarily mean that it is the ideal method for representing the IPv6 address. In this module, you will see two rules that help to reduce the number of digits needed to represent an IPv6 address.
These are examples of IPv6 addresses in the preferred format.

```
2001 : 0db8 : 0000 : 1111 : 0000 : 0000 : 0000: 0200
2001 : 0db8 : 0000 : 00a3 : abcd : 0000 : 0000: 1234
2001 : 0db8 : 000a : 0001 : c012 : 9aff : fe9a: 19ac
2001 : 0db8 : aaaa : 0001 : 0000 : 0000 : 0000: 0000
fe80 : 0000 : 0000 : 0000 : 0123 : 4567 : 89ab: cdef
fe80 : 0000 : 0000 : 0000 : 0000 : 0000 : 0000: 0001
fe80 : 0000 : 0000 : 0000 : c012 : 9aff : fe9a: 19ac
fe80 : 0000 : 0000 : 0000 : 0123 : 4567 : 89ab: cdef
0000 : 0000 : 0000 : 0000 : 0000 : 0000 : 0000: 0001
0000 : 0000 : 0000 : 0000 : 0000 : 0000 : 0000: 0000
```

9.2.2. Rule 1 – Omit Leading Zeros

The first rule to help reduce the notation of IPv6 addresses is to omit any leading 0s (zeros) in any hextet. Here are four examples of ways to omit leading zeros:

- 01ab can be represented as 1ab
- 09f0 can be represented as 9f0
- 0a00 can be represented as a00
- 00ab can be represented as ab

This rule only applies to leading 0s, NOT to trailing 0s, otherwise the address would be ambiguous. For example, the hextet “abc” could be either “0abc” or “abc0”, but these do not represent the same value.

Omitting Leading 0s

Type	Format
Preferred	2001 : **0**db8 : **000**0 : 1111 : **000**0 : **000**0 : **000**0 : **0**200
No leading 0s	2001 : db8 : 0 : 1111 : 0 : 0 : 0 : 200
Preferred	2001 : **0**db8 : **000**0 : **00**a3 : ab00 : **0**ab0 : **00**ab : 1234
No leading 0s	2001 : db8 : 0 : a3 : ab00 : ab0 : ab : 1234
Preferred	2001 : **0**db8 : **000**a : **000**1 : c012 : 90ff : fe90 : **000**1
No leading 0s	2001 : db8 : a : 1 : c012 : 90ff : fe90 : 1
Preferred	2001 : **0**db8 : aaaa : **000**1 : **000**0 : **000**0 : **000**0 : **000**0
No leading 0s	2001 : db8 : aaaa : 1 : 0 : 0 : 0 : 0
Preferred	fe80 : **000**0 : **000**0 : **000**0 : **0**123 : 4567 : 89ab : cdef
No leading 0s	fe80 : 0 : 0 : 0 : 123 : 4567 : 89ab : cdef
Preferred	fe80 : **000**0 : **000**0 : **000**0 : **000**0 : **000**0 : **000**0 : **000**1
No leading 0s	fe80 : 0 : 0 : 0 : 0 : 0 : 0 : 1
Preferred	**000**0 : **000**0 : **000**0 : **000**0 : **000**0 : **000**0 : **000**0 : **000**1
No leading 0s	0 : 0 : 0 : 0 : 0 : 0 : 0 : 1
Preferred	**000**0 : **000**0 : **000**0 : **000**0 : **000**0 : **000**0 : **000**0 : **000**0
No leading 0s	0 : 0 : 0 : 0 : 0 : 0 : 0 : 0

9.2.3. Rule 2 – Double Colon

The second rule to help reduce the notation of IPv6 addresses is that a double colon (::) can replace any single, contiguous string of one or more 16-bit hextets consisting of all zeros. For example, 2001:db8:cafe:1:0:0:0:1 (leading 0s omitted) could be represented as 2001:db8:cafe:1::1. The double colon (::) is used in place of the three all-0 hextets (0:0:0).

The double colon (::) can only be used once within an address, otherwise there would be more than one possible resulting address. When used with the omitting leading 0s technique, the notation of IPv6 address can often be greatly reduced. This is commonly known as the compressed format.

Here is an example of the incorrect use of the double colon: 2001:db8::abcd::1234.

The double colon is used twice in the example above. Here are the possible expansions of this incorrect compressed format address:

- 2001:db8::abcd:0000:0000:1234
- 2001:db8::abcd:0000:0000:0000:1234
- 2001:db8:0000:abcd::1234
- 2001:db8:0000:0000:abcd::1234

If an address has more than one contiguous string of all-0 hextets, best practice is to use the double colon (::) on the longest string. If the strings are equal, the first string should use the double colon (::).

Omitting Leading 0s and All 0 Segments

Type	**Format**
Preferred	2001 : **0**db8 : **000**0 : 1111 : **0000** : **0000** : **0000** : **0**200
Compressed/spaces	2001 : db8 : 0 : 1111 : : 200
Compressed	2001:db8:0:1111::200
Preferred	2001 : **0**db8 : **000**0 : **000**0 : ab00 : **0000** : **0000** : **0000**
Compressed/spaces	2001 : db8 : 0 : 0 : ab00 ::
Compressed	2001:db8:0:0:ab00::
Preferred	2001 : **0**db8 : aaaa : **000**1 : **0000** : **0000** : **0000** : **0000**
Compressed/spaces	2001 : db8 : aaaa : 1 ::
Compressed	2001:db8:aaaa:1::
Preferred	fe80 : **0000** : **0000** : **0000** : **0**123 : 4567 : 89ab : cdef
Compressed/spaces	fe80 : : 123 : 4567 : 89ab : cdef
Compressed	fe80::123:4567:89ab:cdef
Preferred	fe80 : **0000** : **0000** : **0000** : **0000** : **0000** : **0000** : **000**1
Compressed/spaces	fe80 : : 1
Compressed	fe80::0
Preferred	**0000** : **0000** : **0000** : **0000** : **0000** : **0000** : **0000** : **000**1
Compressed/spaces	:: 1
Compressed	::1
Preferred	**0000** : **0000** : **0000** : **0000** : **0000** : **0000** : **0000** : **0000**
Compressed/spaces	::
Compressed	::

9.3. IPv6 Address Types

9.3.1. Unicast, Multicast, Anycast

As with IPv4, there are different types of IPv6 addresses. In fact, there are three broad categories of IPv6 addresses:

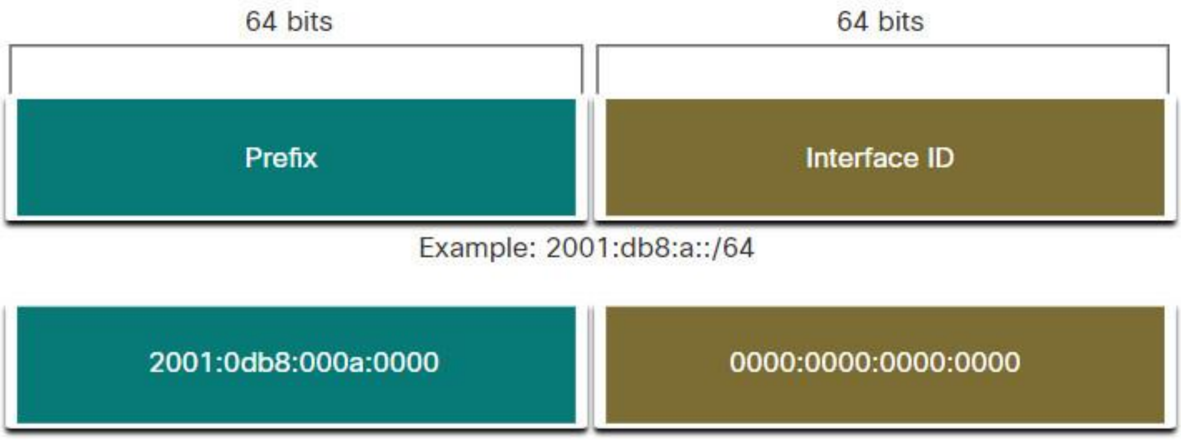
- **Unicast** – An IPv6 unicast address uniquely identifies an interface on an IPv6-enabled device.
- **Multicast** – An IPv6 multicast address is used to send a single IPv6 packet to multiple destinations.
- **Anycast** – An IPv6 anycast address is any IPv6 unicast address that can be assigned to multiple devices. A packet sent to an anycast address is routed to the nearest device having that address. Anycastaddresses are beyond the scope of this course.

Unlike IPv4, IPv6 does not have a broadcast address. However, there is an IPv6 all-nodes multicast address that essentially gives the same result.

9.3.2. IPv6 Prefix Length

The prefix, or network portion, of an IPv4 address can be identified by a dotted-decimal subnet mask or prefix length (slash notation). For example, an IPv4 address of 192.168.1.10 with dotted-decimal subnet mask 255.255.255.0 is equivalent to 192.168.1.10/24.
In IPv4 the /24 is called the prefix. In IPv6 it is called the prefix length. IPv6 does not use the dotted-decimal subnet mask notation. Like IPv4, the prefix length is represented in slash notation and is used to indicate the network portion of an IPv6 address.
The prefix length can range from 0 to 128. The recommended IPv6 prefix length for LANs and most other types of networks is /64, as shown in the figure.

IPv6 Prefix Length



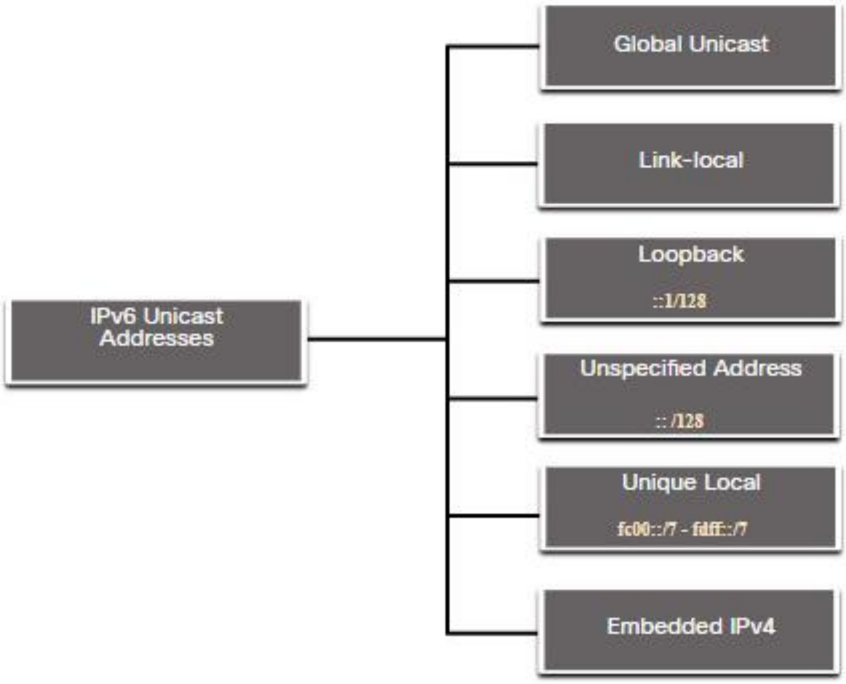
The prefix or network portion of the address is 64 bits in length, leaving another 64 bits for the interface ID (host portion) of the address.
It is strongly recommended to use a 64-bit Interface ID for most networks. This is because stateless address autoconfiguration (SLAAC) uses 64 bits for the Interface ID. It also makes subnetting easier to create and manage.

9.3.3. Types of IPv6 Unicast Addresses

An IPv6 unicast address uniquely identifies an interface on an IPv6-enabled device. A packet sent to a unicast address is received by the interface which is assigned that address. Similar to IPv4, a source IPv6 address must be a unicast address. The destination IPv6 address can be either a unicast or a multicast address. The figure shows the different types of IPv6 unicast addresses.

IPv6 Unicast Addresses

The graphic shows a chart of six types of IPv6 unicast addresses. From top to bottom, the types of Ipv6 addresses in the chart are: Global Unicast, Link-local, Loopback ::1/128, Unspecified ::/128, Unique local fc00::/7 – fdff::/7, and Embedded IPv4.



Unlike IPv4 devices that have only a single address, IPv6 addresses typically have two unicast addresses:

- **Global Unicast Address (GUA)** – This is similar to a public IPv4 address. These are globally unique, internet-routable addresses. GUAs can be configured statically or assigned dynamically.
- **Link-local Address (LLA)** – This is required for every IPv6-enabled device. LLAs are used to communicate with other devices on the same local link. With IPv6, the term link refers to a subnet. LLAs are confined to a single link. Their uniqueness must only be confirmed on that link because they are not routable beyond the link. In other words, routers will not forward packets with a link-local source or destination address.

9.3.4. A Note About the Unique Local Address

Unique local addresses (range fc00::/7 to fdff::/7) are not yet commonly implemented. Therefore, this module only covers GUA and LLA configuration. However, unique local addresses may eventually be used to address devices that should not be accessible from the outside, such as internal servers and printers.

The IPv6 unique local addresses have some similarity to RFC 1918 private addresses for IPv4, but there are significant differences:

- Unique local addresses are used for local addressing within a site or between a limited number of sites.
- Unique local addresses can be used for devices that will never need to access another network.
- Unique local addresses are not globally routed or translated to a global IPv6 address.

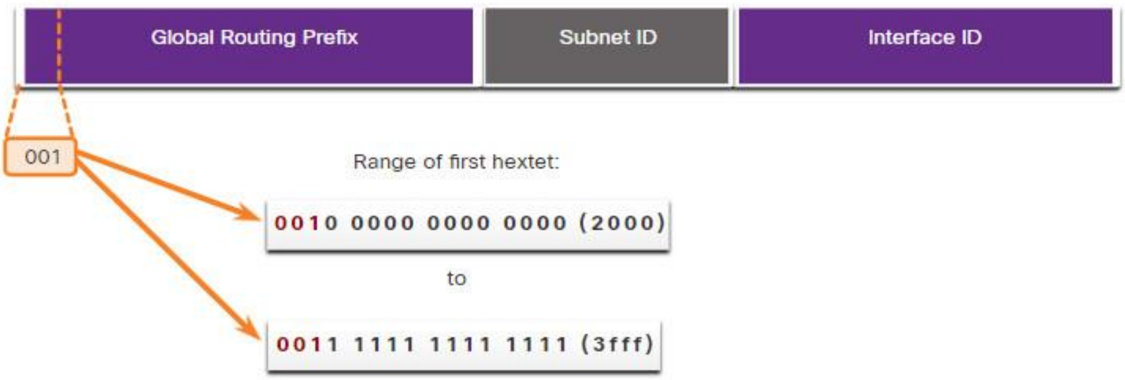
Note: Many sites also use the private nature of RFC 1918 addresses to attempt to secure or hide their network from potential security risks. However, this was never the intended use of these technologies, and the IETF has always recommended that sites take the proper security precautions on their internet-facing router.

9.3.5. IPv6 GUA

IPv6 global unicast addresses (GUAs) are globally unique and routable on the IPv6 internet. These addresses are equivalent to public IPv4 addresses. The Internet Committee for Assigned Names and Numbers (ICANN), the operator for IANA, allocates IPv6 address blocks to the five RIRs. Currently, only GUAs with the first three bits of 001 or 2000::/3 are being assigned, as shown in the figure.

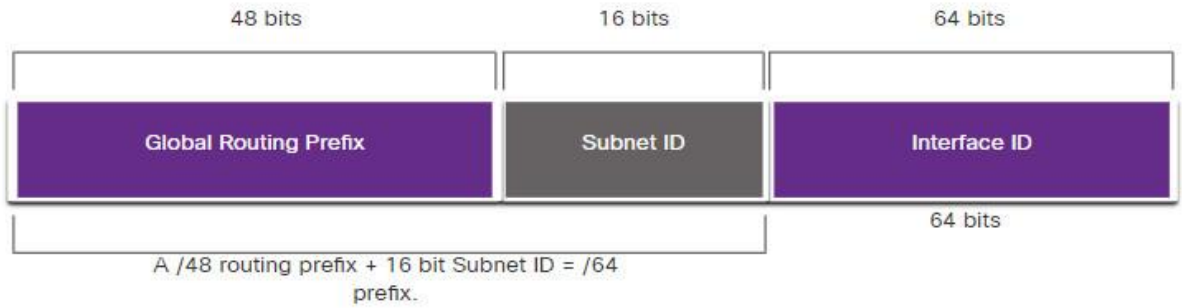
The figure shows the range of values for the first hextet where the first hexadecimal digit for currently available GUAs begins with a 2 or a 3. This is only 1/8th of the total available IPv6 address space, excluding only a very small portion for other types of unicast and multicast addresses.

Note: The 2001:db8::/32 address has been reserved for documentation purposes, including use in examples.



IPv6 Address with a /48 Global Routing Prefix and /64 Prefix

The graphic shows the three parts of a GUA: First is the global routing prefix which is 48 bits in length, then the Subnet ID which is 16 bits in length, then finally the Interface ID which is 64 bits in length. Text under the graphic states A /48 routing prefix + 16 bit Subnet ID = /64 prefix.



A GUA has three parts:

- Global Routing Prefix
- Subnet ID
- Interface ID

9.3.6. IPv6 GUA Structure

Global Routing Prefix

The global routing prefix is the prefix, or network, portion of the address that is assigned by the provider, such as an ISP, to a customer or site. For example, it is common for ISPs to assign a /48 global routing prefix to its customers. The global routing prefix will usually vary depending on the policies of the ISP.

The previous figure shows a GUA using a /48 global routing prefix. /48 prefixes are a common global routing prefix that is assigned and will be used in most of the examples throughout this course.

For example, the IPv6 address 2001:db8:acad::/48 has a global routing prefix that indicates that the first 48 bits (3 hextets) (2001:db8:acad) is how the ISP knows of this prefix (network). The double colon (::) following the /48 prefix length means the rest of the address contains all 0s. The size of the global routing prefix determines the size of the subnet ID.

Subnet ID

The Subnet ID field is the area between the Global Routing Prefix and the Interface ID. Unlike IPv4 where you must borrow bits from the host portion to create subnets, IPv6 was designed with subnetting in mind. The Subnet ID is used by an organization to identify subnets within its site. The larger the subnet ID, the more subnets available.

Note: Many organizations are receiving a /32 global routing prefix. Using the recommended /64 prefix in order to create a 64-bit Interface ID, leaves a 32 bit Subnet ID. This means an organization with a /32 global routing prefix and a 32-bit Subnet ID will have 4.3 billion subnets, each with 18 quintillion devices per subnet. That is as many subnets as there are public IPv4 addresses!

The IPv6 address in the previous figure has a /48 Global Routing Prefix, which is common among many enterprise networks. This makes it especially easy to examine the different parts of the address. Using a typical /64 prefix length, the first four hextets are for the network portion of the address, with the fourth hextet indicating the Subnet ID. The remaining four hextets are for the Interface ID.

Interface ID

The IPv6 interface ID is equivalent to the host portion of an IPv4 address. The term Interface ID is used because a single host may have multiple interfaces, each having one or more IPv6 addresses. The figure shows an example of the structure of an IPv6 GUA. It is strongly recommended that in most cases /64 subnets should be used, which creates a 64-bit interface ID. A 64-bit interface ID allows for 18 quintillion devices or hosts per subnet.

A /64 subnet or prefix (Global Routing Prefix + Subnet ID) leaves 64 bits for the interface ID. This is recommended to allow SLAAC-enabled devices to create their own 64-bit interface ID. It also makes developing an IPv6 addressing plan simple and effective.

Note: Unlike IPv4, in IPv6, the all-0s and all-1s host addresses can be assigned to a device. The all-1s address can be used because broadcast addresses are not used within IPv6. The all-0s address can also be used, but is reserved as a Subnet-Router anycast address, and should be assigned only to routers.

9.3.7. IPv6 LLA

An IPv6 link-local address (LLA) enables a device to communicate with other IPv6-enabled devices on the same link and only on that link (subnet). Packets with a source or destination LLA cannot be routed beyond the link from which the packet originated.

The GUA is not a requirement. However, every IPv6-enabled network interface must have an LLA.

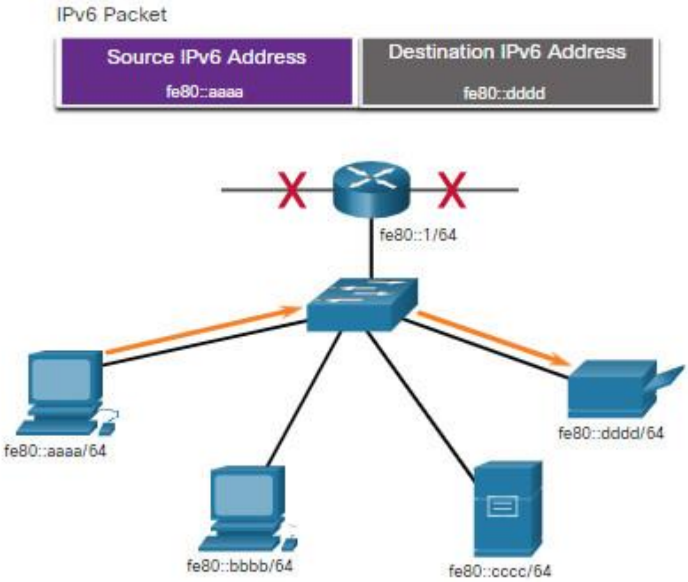
If an LLA is not configured manually on an interface, the device will automatically create its own without communicating with a DHCP server. IPv6-enabled hosts create an IPv6 LLA even if the device has not been assigned a global unicast IPv6 address. This allows IPv6-enabled devices to communicate with other IPv6-enabled devices on the same subnet. This includes communication with the default gateway (router).

IPv6 LLAs are in the fe80::/10 range. The /10 indicates that the first 10 bits are 1111 1110 10xx xxxx. The first hextet has a range of 1111 1110 10**00 0000** (fe80) to 1111 1110 10**11 1111** (febf).

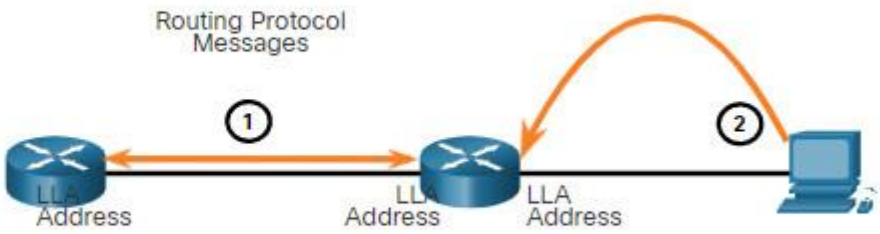
The figure shows an example of communication using IPv6 LLAs. The PC is able to communicate directly with the printer using the LLAs.

IPv6 Link-Local Communications

Physical topology showing two PCs, a server, a printer, a switch, and a router. It depicts that link-local communications are not routed outside the network.



The next figure shows some of the uses for IPv6 LLAs.



1. Routers use the LLA of neighbor routers to send routing updates.
2. Hosts use the LLA of a local router as the default-gateway.

Note: Typically, it is the LLA of the router, and not the GUA, that is used as the default gateway for other devices on the link.

There are two ways that a device can obtain an LLA:

- **Statically** – This means the device has been manually configured.
- **Dynamically** – This means the device creates its own interface ID by using randomly generated values or using the Extended Unique Identifier (EUI) method, which uses the client MAC address along with additional bits.

9.4. GUA and LLA Static Configuration

9.4.1. Static GUA Configuration on a Router

As you learned in the previous topic, IPv6 GUAs are the same as public IPv4 addresses. They are globally unique and routable on the IPv6 internet. An IPv6 LLA lets two IPv6-enabled devices communicate with each other on the same link (subnet). It is easy to statically configure IPv6 GUAs and LLAs on routers to help you create an IPv6 network. This topic teaches you how to do just that!

Most IPv6 configuration and verification commands in the Cisco IOS are similar to their IPv4 counterparts. In many cases, the only difference is the use of **ipv6** in place of **ip** within the commands.

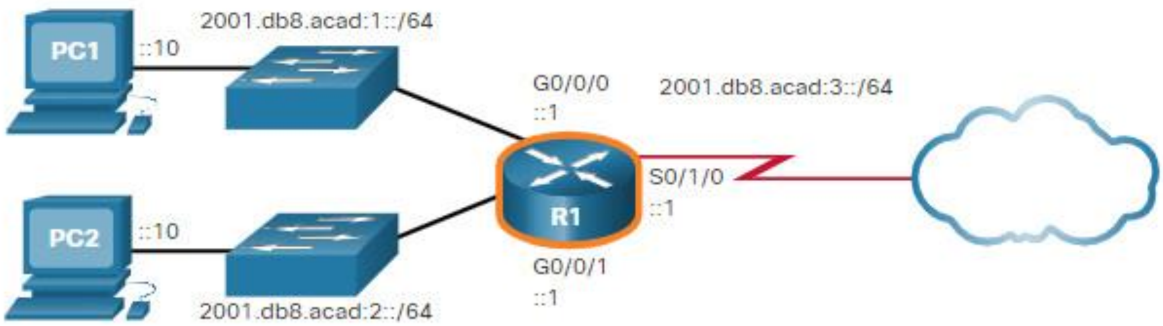
For example, the Cisco IOS command to configure an IPv4 address on an interface is **ip address** *ip-address subnet-mask*. In contrast, the command to configure an IPv6 GUA on an interface is **ipv6 address** *ipv6-address/prefix-length.*

Notice that there is no space between *ipv6-address* and *prefix-length.*

The example configuration uses the topology shown in the figure and these IPv6 subnets:

- 2001:db8:acad:1:/64
- 2001:db8:acad:2:/64
- 2001:db8:acad:3:/64

Example Topology



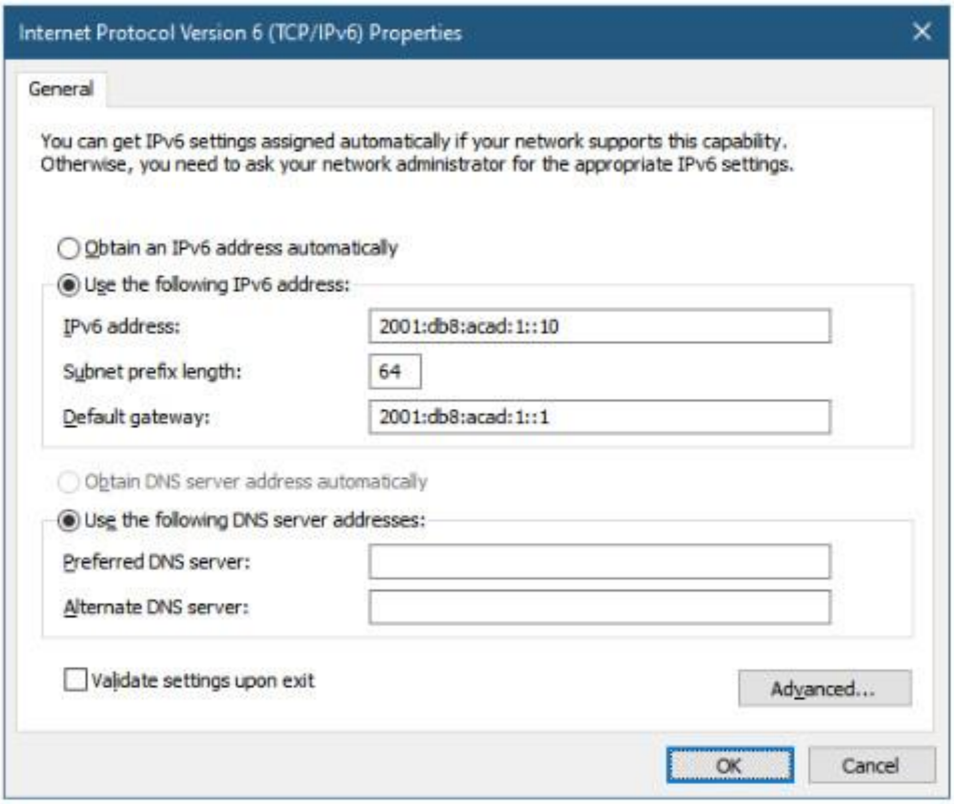
The example shows the commands required to configure the IPv6 GUA on GigabitEthernet 0/0/0, GigabitEthernet 0/0/1, and the Serial 0/1/0 interface of R1.

IPv6 GUA Configuration on Router R1

```
R1(config)# interface gigabitethernet 0/0/0
R1(config-if)# ipv6 address 2001:db8:acad:1::1/64
R1(config-if)# no shutdown
R1(config-if)# exit
R1(config)# interface gigabitethernet 0/0/1
R1(config-if)# ipv6 address 2001:db8:acad:2::1/64
R1(config-if)# no shutdown
R1(config-if)# exit
R1(config)# interface serial 0/1/0
R1(config-if)# ipv6 address 2001:db8:acad:3::1/64
R1(config-if)# no shutdown
```

9.4.2. Static GUA Configuration on a Windows Host

Manually configuring the IPv6 address on a host is similar to configuring an IPv4 address. As shown in the figure, the default gateway address configured for PC1 is 2001:db8:acad:1::1. This is the GUA of the R1 GigabitEthernet interface on the same network. Alternatively, the default gateway address can be configured to match the LLA of the GigabitEthernet interface. Using the LLA of the router as the default gateway address is considered best practice. Either configuration will work.



Just as with IPv4, configuring static addresses on clients does not scale to larger environments. For this reason, most network administrators in an IPv6 network will enable dynamic assignment of IPv6 addresses.

There are two ways in which a device can obtain an IPv6 GUA automatically:

- Stateless Address Autoconfiguration (SLAAC)
- Stateful DHCPv6

SLAAC and DHCPv6 are covered in the next topic.

Note: When DHCPv6 or SLAAC is used, the LLA of the router will automatically be specified as the default gateway address.

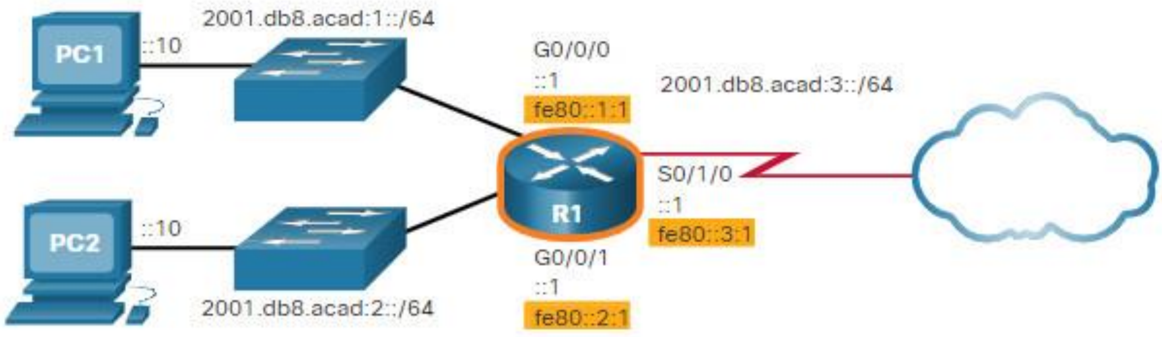
9.4.3. Static Configuration of a Link-Local Unicast Address

Configuring the LLA manually lets you create an address that is recognizable and easier to remember. Typically, it is only necessary to create recognizable LLAs on routers. This is beneficial because router LLAs are used as default gateway addresses and in routing advertisement messages.

LLAs can be configured manually using the **ipv6 address** *ipv6-link-local-address* **link-local** command. When an address begins with this hextet within the range of fe80 to febf, the **link-local** parameter must follow the address.

The figure shows an example topology with LLAs on each interface.

Example Topology with LLAs



The example shows the configuration of an LLA on router R1.

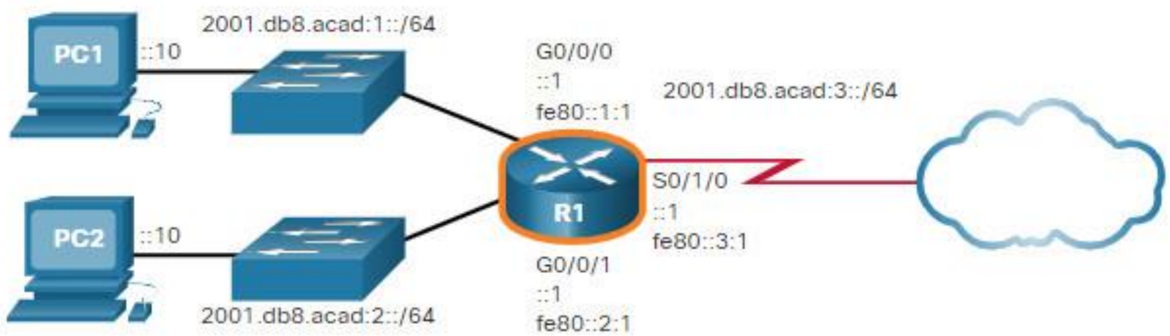
```
R1(config)# interface gigabitethernet 0/0/0
R1(config-if)# ipv6 address fe80::1:1 link-local
R1(config-if)# exit
R1(config)# interface gigabitethernet 0/0/1
R1(config-if)# ipv6 address fe80::1:2 link-local
R1(config-if)# exit
R1(config)# interface serial 0/1/0
R1(config-if)# ipv6 address fe80::1:3 link-local
R1(config-if)# exit
```

Statically configured LLAs are used to make them more easily recognizable as belonging to router R1. In this example, all the interfaces of router R1 have been configured with an LLA that begins with **fe80::1:n** and a unique right-most digit "n". The "**1**" represents router R1. Following the same syntax as router R1, if the topology included router R2, it would have its three interfaces configured with the LLAs fe80::2:1, fe80::2:2, and fe80::2:3.

Note: The exact same LLA could be configured on each link as long as it is unique on that link. This is because LLAs only have to be unique on that link. However, common practice is to create a different LLA on each interface of the router to make it easy to identify the router and the specific interface.

9.4.4. GUA and LLA Static Configuration

Assign IPv6 GUAs and LLAs to the specified interfaces on router R1.



Configure and activate IPv6 on the Gigabit Ethernet 0/0/0 interface with the following addresses:

- Use g0/0/0 as the interface name
- LLA – fe80::1:1
- GUA – 2001:db8:acad:1::1/64
- Activate the interface
- Exit interface configuration mode

```
R1(config)#interface g0/0/0
R1(config-if)#ipv6 address fe80::1:1 link-local
```

```
R1(config-if)#ipv6 address 2001:db8:acad:1::1/64
R1(config-if)#no shutdown
%LINK-3-UPDOWN: Interface GigabitEthernet0/0/0, changed state to up
R1(config-if)#exit
```

Configure and activate IPv6 on the Gigabit Ethernet 0/0/1 interface with the following addresses:

- Use g0/0/1 as the interface name
- LLA – fe80::2:1
- GUA – 2001:db8:acad:2::1/64
- Activate the interface
- Exit interface configuration mode

```
R1(config)#interface g0/0/1
R1(config-if)#ipv6 address fe80::2:1 link-local
R1(config-if)#ipv6 address 2001:db8:acad:2::1/64
R1(config-if)#no shutdown
%LINK-3-UPDOWN: Interface GigabitEthernet0/0/1, changed state to up
R1(config-if)#exit
```

Configure and activate IPv6 on the serial 0/1/0 interface with the following addresses:

- Use s0/1/0 as the interface name
- GUA – 2001:db8:acad:3::1/64
- LLA – fe80::1:3
- Activate the interface
- Exit interface configuration mode

```
R1(config)#interface s0/1/0
R1(config-if)#ipv6 address fe80::3:1 link-local
R1(config-if)#ipv6 address 2001:db8:acad:3::1/64
R1(config-if)#no shutdown
%LINK-3-UPDOWN: Interface Serial0/1/0, changed state to up
R1(config-if)#exit
R1(config)#
```

You successfully configured IPv6 GUAs on the interfaces of router R1.

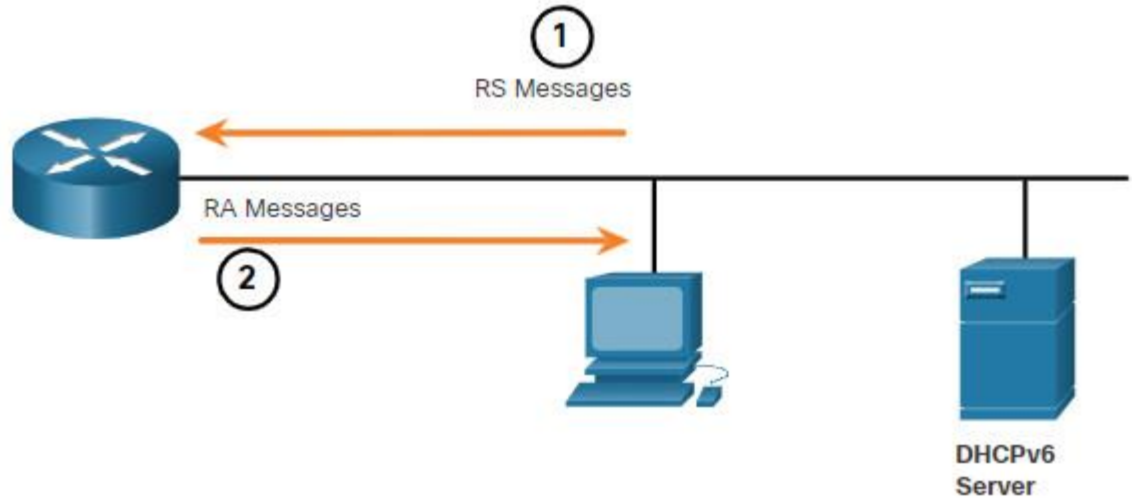
9.5. Dynamic Addressing for IPv6 GUAs

9.5.1. RS and RA Messages

If you do not want to statically configure IPv6 GUAs, no need to worry. Most devices obtain their IPv6 GUAs dynamically. This topic explains how this process works using Router Advertisement (RA) and Router Solicitation (RS) messages. This topic gets rather technical, but when you understand the difference between the three methods that a router advertisement can use, as well as how the EUI-64 process for creating an interface ID differs from a randomly generated process, you will have made a huge leap in your IPv6 expertise!

For the GUA, a device obtains the address dynamically through Internet Control Message Protocol version 6 (ICMPv6) messages. IPv6 routers periodically send out ICMPv6 RA messages, every 200 seconds, to all IPv6-enabled devices on the network. An RA message will also be sent in response to a host sending an ICMPv6 RS message, which is a request for an RA message. Both messages are shown in the figure.

ICMPv6 RS and RA Messages



1. RS messages are sent to all IPv6 routers by hosts requesting addressing information.
2. RA messages are sent to all IPv6 nodes. If Method 1 (SLAAC only) is used, the RA includes network prefix, prefix-length, and default-gateway information.

RA messages are on IPv6 router Ethernet interfaces. The router must be enabled for IPv6 routing, which is not enabled by default. To enable a router as an IPv6 router, the **ipv6 unicast-routing** global configuration command must be used.

The ICMPv6 RA message is a suggestion to a device on how to obtain an IPv6 GUA. The ultimate decision is up to the device operating system. The ICMPv6 RA message includes the following:

- **Network prefix and prefix length** – This tells the device which network it belongs to.
- **Default gateway address** – This is an IPv6 LLA, the source IPv6 address of the RA message.
- **DNS addresses and domain name** – These are the addresses of DNS servers and a domain name.

There are three methods for RA messages:

- **Method 1: SLAAC** – “I have everything you need including the prefix, prefix length, and default gateway address.”
- **Method 2: SLAAC with a stateless DHCPv6 server** – “Here is my information but you need to get other information such as DNS addresses from a stateless DHCPv6 server.”
- **Method 3: Stateful DHCPv6 (no SLAAC)** – “I can give you your default gateway address. You need to ask a stateful DHCPv6 server for all your other information.”

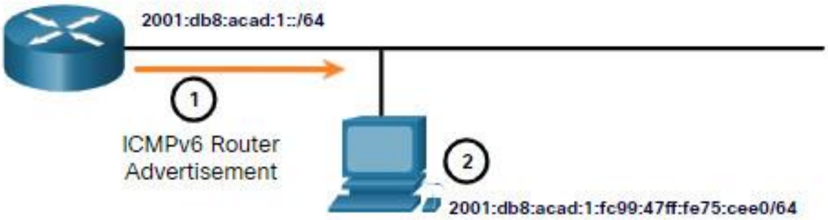
9.5.2. Method 1: SLAAC

SLAAC is a method that allows a device to create its own GUA without the services of DHCPv6. Using SLAAC, devices rely on the ICMPv6 RA messages of the local router to obtain the necessary information.

By default, the RA message suggests that the receiving device use the information in the RA message to create its own IPv6 GUA and all other necessary information. The services of a DHCPv6 server are not required.

SLAAC is stateless, which means there is no central server (for example, a stateful DHCPv6 server) allocating GUAs and keeping a list of devices and their addresses. With SLAAC, the client device uses the information in the RA message to create its own GUA. As shown in the figure, the two parts of the address are created as follows:

- **Prefix** – This is advertised in the RA message.
- **Interface ID** – This uses the EUI-64 process or by generating a random 64-bit number, depending on the device operating system.



1. The router sends an RA message with the prefix for the local link.
2. The PC uses SLAAC to obtain a prefix from the RA message and creates its own Interface ID.

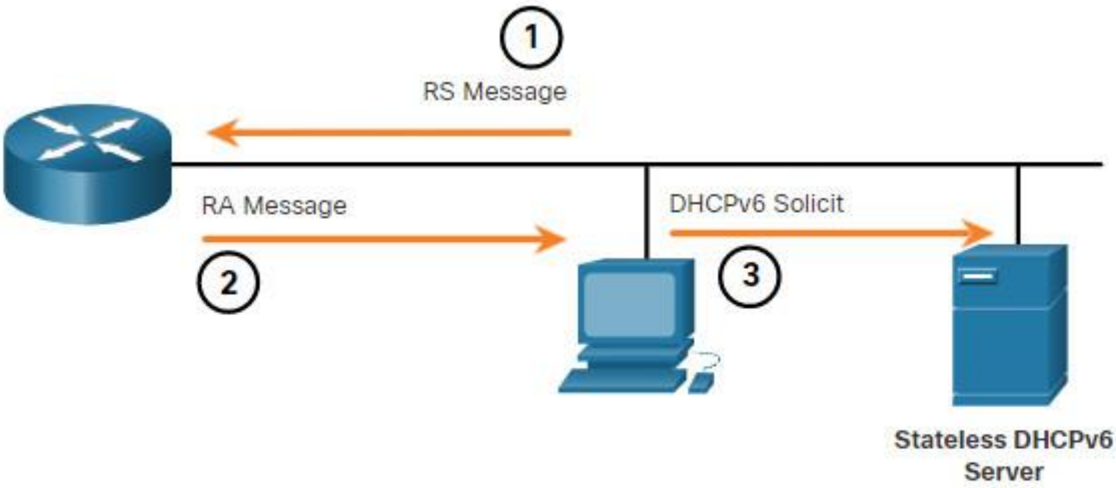
9.5.3. Method 2: SLAAC and Stateless DHCPv6

A router interface can be configured to send a router advertisement using SLAAC and stateless DHCPv6.

As shown in the figure, with this method, the RA message suggests devices use the following:

- SLAAC to create its own IPv6 GUA
- The router LLA, which is the RA source IPv6 address, as the default gateway address
- A stateless DHCPv6 server to obtain other information such as a DNS server address and a domain name

Note: A stateless DHCPv6 server distributes DNS server addresses and domain names. It does not allocate GUAs.

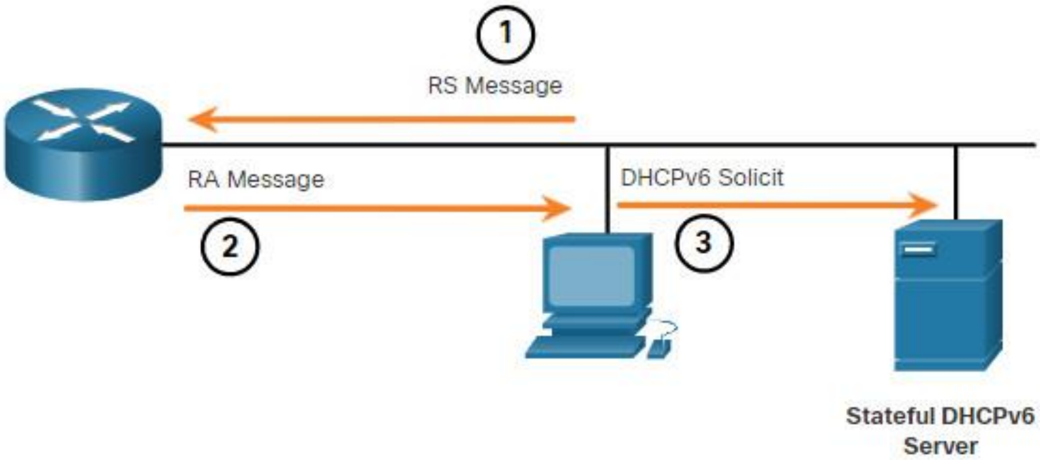


1. The PC sends an RS to all IPv6 routers, “I need addressing information.”
2. The router sends an RA message to all IPv6 nodes with Method 2 (SLAAC and DHCPv6) specified. “Here is your prefix, prefix-length, and default gateway information. But you will need to get DNS information from a DHCPv6 server.”
3. The PC sends a DHCPv6 Solicit message to all DHCPv6 servers. “I used SLAAC to create my IPv6 address and get my default gateway address, but I need other information from a stateless DHCPv6 server.”

9.5.4. Method 3: Stateful DHCPv6

A router interface can be configured to send an RA using stateful DHCPv6 only.
Stateful DHCPv6 is similar to DHCP for IPv4. A device can automatically receive its addressing information including a GUA, prefix length, and the addresses of DNS servers from a stateful DHCPv6 server.
As shown in the figure, with this method, the RA message suggests devices use the following:

- The router LLA, which is the RA source IPv6 address, for the default gateway address.
- A stateful DHCPv6 server to obtain a GUA, DNS server address, domain name and other necessary information.



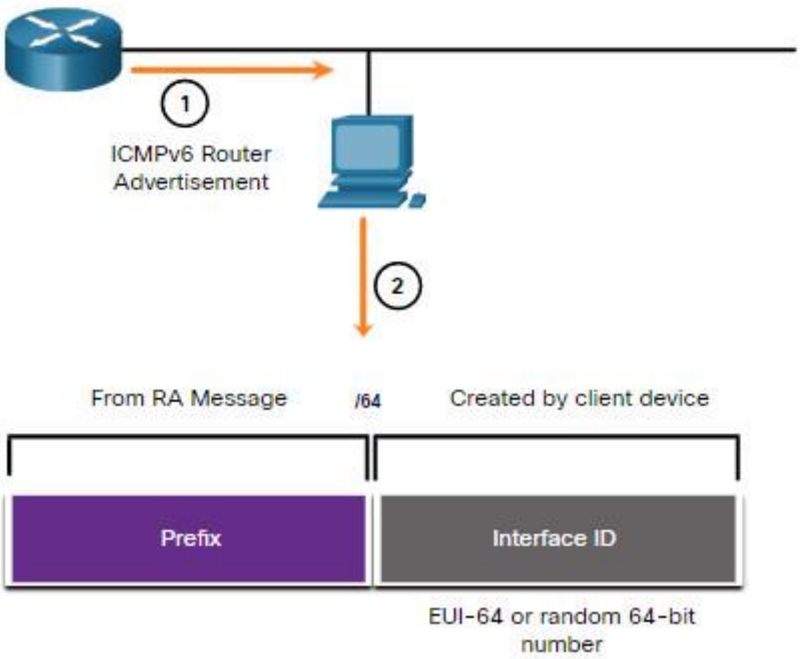
1. The PC sends an RS to all IPv6 routers, “I need addressing information.”
2. The router sends an RA message to all IPv6 nodes with Method 3 (Stateful DHCPv6) specified, “I am your default gateway, but you need to ask a stateful DHCPv6 server for your IPv6 address and other addressing information.”
3. The PC sends a DHCPv6 Solicit message to all DHCPv6 servers, ” I received my default gateway address from the RA message, but I need an IPv6 address and all other addressing information from a stateful DHCPv6 server.”

A stateful DHCPv6 server allocates and maintains a list of which device receives which IPv6 address. DHCP for IPv4 is stateful.
Note: The default gateway address can only be obtained dynamically from the RA message. The stateless or stateful DHCPv6 server does not provide the default gateway address.

9.5.5. EUI-64 Process vs. Randomly Generated

When the RA message is either SLAAC or SLAAC with stateless DHCPv6, the client must generate its own interface ID. The client knows the prefix portion of the address from the RA message, but must create its own interface ID. The interface ID can be created using the EUI-64 process or a randomly generated 64-bit number, as shown in the figure.

Dynamically Creating an Interface ID



1. The router sends an RA message.
2. The PC uses the prefix in the RA message and uses either EUI-64 or a random 64-bit number to generate an interface ID.

9.5.6. EUI-64 Process

IEEE defined the Extended Unique Identifier (EUI) or modified EUI-64 process. This process uses the 48-bit Ethernet MAC address of a client, and inserts another 16 bits in the middle of the 48-bit MAC address to create a 64-bit interface ID.

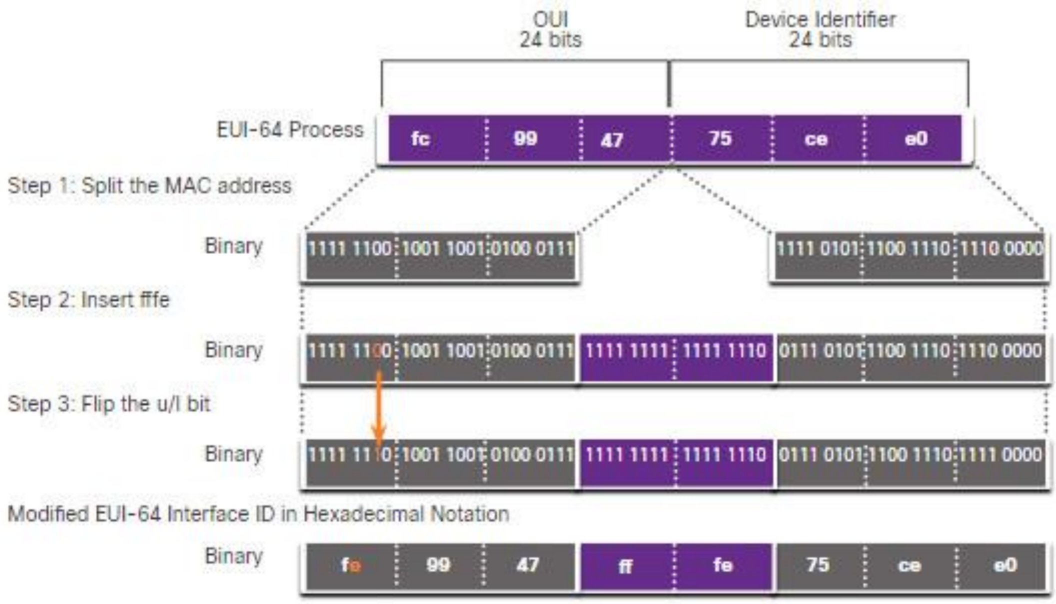
Ethernet MAC addresses are usually represented in hexadecimal and are made up of two parts:

- **Organizationally Unique Identifier (OUI)** – The OUI is a 24-bit (6 hexadecimal digits) vendor code assigned by IEEE.
- **Device Identifier** – The device identifier is a unique 24-bit (6 hexadecimal digits) value within a common OUI.

An EUI-64 Interface ID is represented in binary and is made up of three parts:

- 24-bit OUI from the client MAC address, but the 7th bit (the Universally/Locally (U/L) bit) is reversed. This means that if the 7th bit is a 0, it becomes a 1, and vice versa.
- The inserted 16-bit value fffe (in hexadecimal).
- 24-bit Device Identifier from the client MAC address.

The EUI-64 process is illustrated in the figure, using the R1 GigabitEthernet MAC address of fc99:4775:cee0.



Step 1: Divide the MAC address between the OUI and device identifier.
Step 2: Insert the hexadecimal value fffe, which in binary is: 1111 1111 1111 1110.
Step 3: Convert the first 2 hexadecimal values of the OUI to binary and flip the U/L bit (bit 7). In this example, the 0 in bit 7 is changed to a 1.
The result is an EUI-64 generated interface ID of fe99:47ff:fe75:cee0.
Note: The use of the U/L bit, and the reasons for reversing its value, are discussed in RFC 5342.
The example output for the **ipconfig** command shows the IPv6 GUA being dynamically created using SLAAC and the EUI-64 process. An easy way to identify that an address was probably created using EUI-64 is the **fffe** located in the middle of the interface ID.
The advantage of EUI-64 is that the Ethernet MAC address can be used to determine the interface ID. It also allows network administrators to easily track an IPv6 address to an end-device using the unique MAC address. However, this has caused privacy concerns among many users who worried that their packets could be traced to the actual physical computer. Due to these concerns, a randomly generated interface ID may be used instead.

EUI-64 Generated Interface ID

```
C:\> ipconfig
Windows IP Configuration
Ethernet adapter Local Area Connection:
   Connection-specific DNS Suffix  . :
   IPv6 Address. . . . . . . . . . . : 2001:db8:acad:1:fc99:47ff:fe75:cee0
   Link-local IPv6 Address . . . . . : fe80::fc99:47ff:fe75:cee0
   Default Gateway . . . . . . . . . : fe80::1
C:\>
```

9.5.7. Randomly Generated Interface IDs

Depending upon the operating system, a device may use a randomly generated interface ID instead of using the MAC address and the EUI-64 process. Beginning with Windows Vista, Windows uses a randomly generated interface ID instead of one created with EUI-64. Windows XP and previous Windows operating systems used EUI-64.
After the interface ID is established, either through the EUI-64 process or through random generation, it can be combined with an IPv6 prefix in the RA message to create a GUA, as shown in the figure.

Random 64-bit Generated Interface ID

```
C:\> ipconfig
Windows IP Configuration
Ethernet adapter Local Area Connection:
   Connection-specific DNS Suffix . :
   IPv6 Address. . . . . . . . . . . . : 2001:db8:acad:1:50a5:8a35:a5bb:66e1
   Link-local IPv6 Address . . . . . : fe80::50a5:8a35:a5bb:66e1
   Default Gateway . . . . . . . . . : fe80::1
C:\>
```

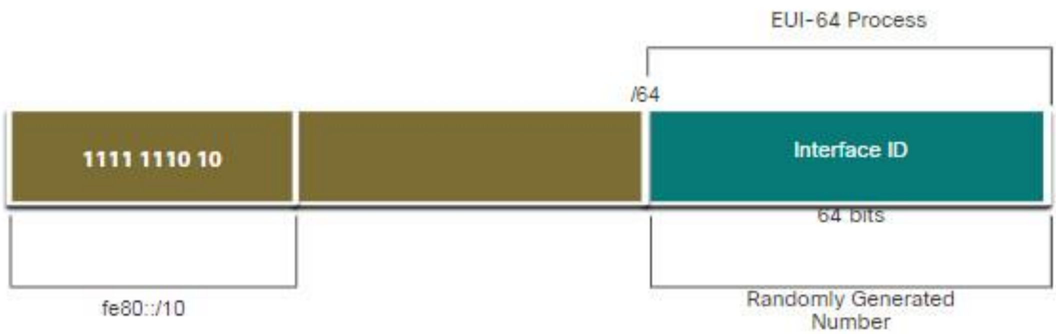
Note: To ensure the uniqueness of any IPv6 unicast address, the client may use a process known as Duplicate Address Detection (DAD). This is similar to an ARP request for its own address. If there is no reply, then the address is unique.

9.6. Dynamic Addressing for IPv6 LLAs

9.6.1. Dynamic LLAs

All IPv6 devices must have an IPv6 LLA. Like IPv6 GUAs, you can also create LLAs dynamically. Regardless of how you create your LLAs (and your GUAs), it is important that you verify all IPv6 address configuration. This topic explains dynamically generated LLAs and IPv6 configuration verification.

The figure shows the LLA is dynamically created using the fe80::/10 prefix and the interface ID using the EUI-64 process, or a randomly generated 64-bit number.



9.6.2. Dynamic LLAs on Windows

Operating systems, such as Windows, will typically use the same method for both a SLAAC-created GUA and a dynamically assigned LLA. See the highlighted areas in the following examples that were shown previously.

EUI-64 Generated Interface ID

```
C:\> ipconfig
Windows IP Configuration
Ethernet adapter Local Area Connection:
Connection-specific DNS Suffix . :
IPv6 Address. . . . . . . . . . . . : 2001:db8:acad:1:fc99:47ff:fe75:cee0
Link-local IPv6 Address . . . . . : fe80::fc99:47ff:fe75:cee0
Default Gateway . . . . . . . . . : fe80::1
C:\>
```

Random 64-bit Generated Interface ID

```
C:\> ipconfig
Windows IP Configuration
Ethernet adapter Local Area Connection:
Connection-specific DNS Suffix . :
```

```
IPv6 Address. . . . . . . . . . . : 2001:db8:acad:1:50a5:8a35:a5bb:66e1
Link-local IPv6 Address . . . . . : fe80::50a5:8a35:a5bb:66e1
Default Gateway . . . . . . . . . : fe80::1
C:\>
```

9.6.3. Dynamic LLAs on Cisco Routers

Cisco routers automatically create an IPv6 LLA whenever a GUA is assigned to the interface. By default, Cisco IOS routers use EUI-64 to generate the interface ID for all LLAs on IPv6 interfaces. For serial interfaces, the router will use the MAC address of an Ethernet interface. Recall that an LLA must be unique only on that link or network. However, a drawback to using the dynamically assigned LLA is its long interface ID, which makes it challenging to identify and remember assigned addresses. The example displays the MAC address on the GigabitEthernet 0/0/0 interface of router R1. This address is used to dynamically create the LLA on the same interface, and also for the Serial 0/1/0 interface.

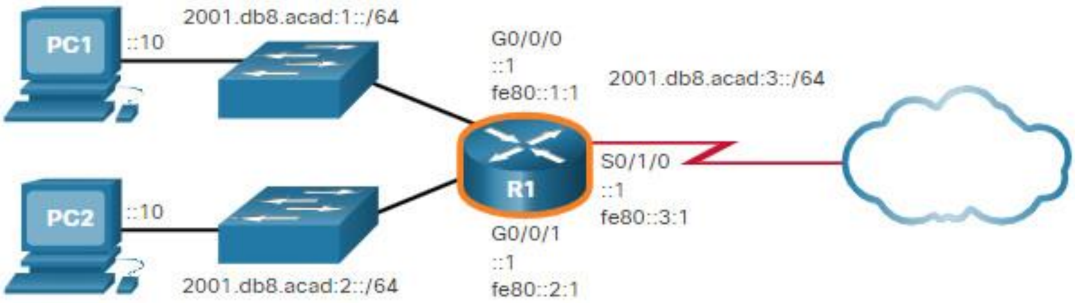
To make it easier to recognize and remember these addresses on routers, it is common to statically configure IPv6 LLAs on routers.

IPv6 LLA Using EUI-64 on Router R1

```
R1# show interface gigabitEthernet 0/0/0
GigabitEthernet0/0/0 is up, line protocol is up
  Hardware is ISR4221-2x1GE, address is 7079.b392.3640 (bia 7079.b392.3640)
(Output omitted)
R1# show ipv6 interface brief
GigabitEthernet0/0/0   [up/up]
    FE80::7279:B3FF:FE92:3640
    2001:DB8:ACAD:1::1
GigabitEthernet0/0/1   [up/up]
    FE80::7279:B3FF:FE92:3641
    2001:DB8:ACAD:2::1
Serial0/1/0            [up/up]
    FE80::7279:B3FF:FE92:3640
    2001:DB8:ACAD:3::1
Serial0/1/1            [down/down]
    unassigned
R1#
```

9.6.4. Verify IPv6 Address Configuration

The figure shows the example topology.



show ipv6 interface brief command

The **show ipv6 interface brief** command displays the MAC address of the Ethernet interfaces. EUI-64 uses this MAC address to generate the interface ID for the LLA. Additionally, the **show ipv6 interface brief** command displays abbreviated output for each of the interfaces. The [up/up] output on the same line as the interface indicates the Layer 1/Layer 2 interface state. This is the same as the Status and Protocol columns in the equivalent IPv4 command.

Notice that each interface has two IPv6 addresses. The second address for each interface is the GUA that was configured. The first address, the one that begins with fe80, is the link-local unicast address for the interface. Recall that the LLA is automatically added to the interface when a GUA is assigned.

Also, notice that the R1 Serial 0/1/0 LLA is the same as its GigabitEthernet 0/0/0 interface. Serial interfaces do not have Ethernet MAC addresses, so Cisco IOS uses the MAC address of the first available Ethernet interface. This is possible because link-local interfaces only have to be unique on that link.

The show ipv6 interface brief Command on R1

```
R1# show ipv6 interface brief
GigabitEthernet0/0/0    [up/up]
     FE80::1:1
     2001:DB8:ACAD:1::1
GigabitEthernet0/0/1    [up/up]
     FE80::1:2
     2001:DB8:ACAD:2::1
Serial0/1/0             [up/up]
     FE80::1:3
     2001:DB8:ACAD:3::1
Serial0/1/1             [down/down]
     unassigned
R1#
```

show ipv6 route command

As shown in the example, the **show ipv6 route** command can be used to verify that IPv6 networks and specific IPv6 interface addresses have been installed in the IPv6 routing table. The **show ipv6 route** command will only display IPv6 networks, not IPv4 networks.

Within the route table, a **C** next to a route indicates that this is a directly connected network. When the router interface is configured with a GUA and is in the “up/up” state, the IPv6 prefix and prefix length is added to the IPv6 routing table as a connected route.

Note: The **L** indicates a Local route, the specific IPv6 address assigned to the interface. This is not an LLA. LLAs are not included in the routing table of the router because they are not routable addresses.

The IPv6 GUA configured on the interface is also installed in the routing table as a local route. The local route has a /128 prefix. Local routes are used by the routing table to efficiently process packets with a destination address of the router interface address.

The show ipv6 route Command on R1

```
R1# show ipv6 route
IPv6 Routing Table - default - 7 entries
Codes: C - Connected, L - Local, S - Static, U - Per-user Static route
C   2001:DB8:ACAD:1::/64 [0/0]
     via GigabitEthernet0/0/0, directly connected
L   2001:DB8:ACAD:1::1/128 [0/0]
     via GigabitEthernet0/0/0, receive
C   2001:DB8:ACAD:2::/64 [0/0]
     via GigabitEthernet0/0/1, directly connected
L   2001:DB8:ACAD:2::1/128 [0/0]
     via GigabitEthernet0/0/1, receive
C   2001:DB8:ACAD:3::/64 [0/0]
     via Serial0/1/0, directly connected
L   2001:DB8:ACAD:3::1/128 [0/0]
     via Serial0/1/0, receive
L   FF00::/8 [0/0]
     via Null0, receive
R1#
```

ping command

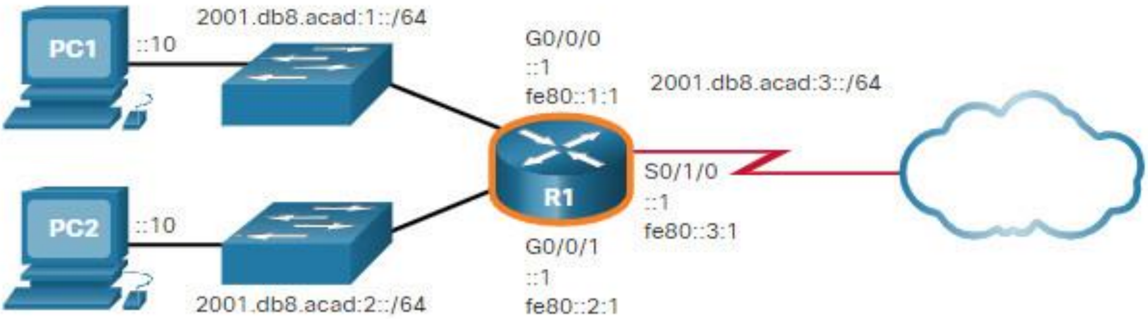
The **ping** command for IPv6 is identical to the command used with IPv4, except that an IPv6 address is used. As shown in the example, the command is used to verify Layer 3 connectivity between R1 and PC1. When pinging an LLA from a router, Cisco IOS will prompt the user for the exit interface. Because the destination LLA can be on one or more of its links or networks, the router needs to know which interface to send the ping to.

The ping Command on R1

```
R1# ping 2001:db8:acad:1::10
Type escape sequence to abort.
Sending 5, 100-byte ICMP Echos to 2001:DB8:ACAD:1::10, timeout is 2
seconds:
!!!!!
Success rate is 100 percent (5/5), round-trip min/avg/max = 1/1/1 ms
R1#
```

9.6.5. Verify IPv6 Address Configuration

Use show commands to verify IPv6 address configuration on router R1 interfaces.




```
R1#show ipv6 interface brief
GigabitEthernet0/0/0  \[up/up\]
    FE80::1:1
    2001:DB8:ACAD:1::1
GigabitEthernet0/0/1  \[up/up\]
    FE80::2:1
    2001:DB8:ACAD:2::1
Serial0/1/0          \[up/up\]
    FE80::3:1
    2001:DB8:ACAD:3::1
Serial0/1/1          \[down/down\]
    unassigned
GigabitEthernet0     \[administratively down/down\]
    unassigned
```

Verify connectivity from R1 to PC2 at 2001:db8:acad:1::10.

```
R1#show ipv6 route
IPv6 Routing Table - default - 7 entries
Codes: C - Connected, L - Local, S - Static, U - Per-user Static route
       B - BGP, HA - Home Agent, MR - Mobile Router, R - RIP
       H - NHRP, I1 - ISIS L1, I2 - ISIS L2, IA - ISIS interarea
       IS - ISIS summary, D - EIGRP, EX - EIGRP external, NM - NEMO
       ND - ND Default, NDp - ND Prefix, DCE - Destination, NDr - Redirect
       O - OSPF Intra, OI - OSPF Inter, OE1 - OSPF ext 1, OE2 - OSPF ext 2
       ON1 - OSPF NSSA ext 1, ON2 - OSPF NSSA ext 2, la - LISP alt
       lr - LISP site-registrations, ld - LISP dyn-eid, a - Application
C   2001:DB8:ACAD:1::/64 \[0/0\]
     via GigabitEthernet0/0, directly connected
L   2001:DB8:ACAD:1::1/128 \[0/0\]
     via GigabitEthernet0/0, receive
C   2001:DB8:ACAD:2::/64 \[0/0\]
     via GigabitEthernet0/1, directly connected
L   2001:DB8:ACAD:2::1/128 \[0/0\]
     via GigabitEthernet0/1, receive
C   2001:DB8:ACAD:3::/64 \[0/0\]
     via Serial0/0/1, directly connected
L   2001:DB8:ACAD:3::1/128 \[0/0\]
     via Serial0/0/1, receive
L   FF00::/8 \[0/0\]
     via Null0, receive
R1#ping 2001:db8:acad:1::10
Type escape sequence to abort.
Sending 5, 100-byte ICMP Echos to 2001:DB8:ACAD:1::10, timeout is 2 seconds:
!!!!!
Success rate is 100 percent (5/5), round-trip min/avg/max = 1/1/1 ms
```

You successfully verified IPv6 address configuration.

9.7. IPv6 Multicast Addresses

9.7.1. Assigned IPv6 Multicast Addresses

Earlier in this module, you learned that there are three broad categories of IPv6 addresses: unicast, anycast, and multicast. This topic goes into more detail about multicast addresses.

IPv6 multicast addresses are similar to IPv4 multicast addresses. Recall that a multicast address is used to send a single packet to one or more destinations (multicast group). IPv6 multicast addresses have the prefix ff00::/8.

Note: Multicast addresses can only be destination addresses and not source addresses.

There are two types of IPv6 multicast addresses:

- Well-known multicast addresses
- Solicited node multicast addresses

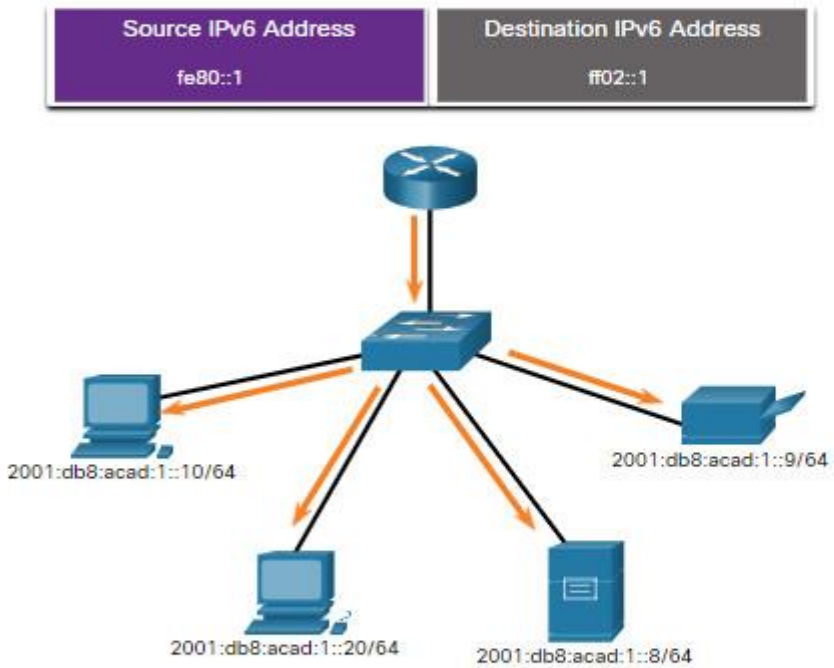
9.7.2. Well-Known IPv6 Multicast Addresses

Well-known IPv6 multicast addresses are assigned. Assigned multicast addresses are reserved multicast addresses for predefined groups of devices. An assigned multicast address is a single address used to reach a group of devices running a common protocol or service. Assigned multicast addresses are used in context with specific protocols such as DHCPv6.

These are two common IPv6 assigned multicast groups:

- **ff02::1 All-nodes multicast group** – This is a multicast group that all IPv6-enabled devices join. A packet sent to this group is received and processed by all IPv6 interfaces on the link or network. This has the same effect as a broadcast address in IPv4. The figure shows an example of communication using the all-nodes multicast address. An IPv6 router sends ICMPv6 RA messages to the all-node multicast group.
- **ff02::2 All-routers multicast group** – This is a multicast group that all IPv6 routers join. A router becomes a member of this group when it is enabled as an IPv6 router with the **ipv6 unicast-routing** global configuration command. A packet sent to this group is received and processed by all IPv6 routers on the link or network.

IPv6 All-Nodes Multicast: RA Message



IPv6-enabled devices send ICMPv6 RS messages to the all-routers multicast address. The RS message requests an RA message from the IPv6 router to assist the device in its address configuration. The IPv6 router responds with an RA message, as shown.

9.7.3. Solicited-Node IPv6 Multicast Addresses

A solicited-node multicast address is similar to the all-nodes multicast address. The advantage of a solicited-node multicast address is that it is mapped to a special Ethernet multicast address. This allows the Ethernet NIC to filter the frame by examining the destination MAC address without sending it to the IPv6 process to see if the device is the intended target of the IPv6 packet.