A New Look at Subnetting

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Introduction

The process of subnetting is both a mathematical process and a network design process. The network design and requirements of the organization drive how many subnets are needed and how many hosts an individual subnet needs to support. Mathematics drives how subnets are calculated, identified, and assigned.

This document predominantly focuses on the mathematics of subnetting, while providing a glimpse of design considerations to help expand and reinforce the mathematical calculations. It discusses the following topics:

1) Construct and representation of an IPv4 address.
2) Binary numbering system.
3) Process to convert a decimal number to a binary number.
4) Process to convert a binary number to a decimal number.
5) Fundamental aspects of an IPv4 address.
6) Need for subnets.
7) Process of subnetting.
8) Formulas for subnet calculation.
9) Examples putting everything together.
10) Variable Length Subnet Mask (VLSM).
11) Determine the subnet, usable range of host addresses, and broadcast address for a given host.
12) Helpful tables.

NOTE: Throughout this document, the term IP address refers to an IPv4 address. This document does not discuss IPv6.

IP Address Construct and Representation

An IP address is a 32-bit binary number. The 32 bits are separated into four groups of eight bits called octets. However, an IP address is represented as a dotted decimal number. (Example: 205.57.32.9) Since an IP address is a binary number represented in dotted decimal format, an examination of the binary numbering system is needed.

The Binary Numbering System

When discussing numbering systems, they are described as having a base. A base means how many unique, or base, numbers are in the numbering system. For example, humans use the decimal numbering system, which is a base 10 numbering system. In the decimal numbering system there are only 10 base numbers; 0 through 9. All other numbers are created from these 10 numbers. The position of a number determines its value. For example, the number 2,534 means the following: there are two-thousands; five-hundreds; three-tens; and four-ones. The table below shows each number, its position, and the value of the position.

$\text{Power}^{\text{Exponent}}$	10^3	10^2	10^1	10^0
Place Value	**1000**	**100**	**10**	**1**
Name (Place)	**Thousands**	**Hundreds**	**Tens**	**Ones**
Example Number	**2**	**5**	**3**	**4**

Computers, routers, and switches use the binary numbering system. The binary numbering system is a base 2 numbering system, meaning there are only 2 base numbers; 0 and 1. All other numbers are created from these two numbers. Just like in the decimal numbering system, the location of the number determines its value. The table below shows the value of the first eight binary positions.

$\text{Base}^{\text{Exponent}}$	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
Place Value	**128**	**64**	**32**	**16**	**8**	**4**	**2**	**1**

For exponents above 7, double the previous place value. For example, $2^8 = 256$, $2^9 = 512$, $2^{10} = 1{,}024$, so on and so on.

Decimal to Binary Conversion

Since IP addresses are a binary number represented in dotted decimal format, it is often necessary to convert a decimal number to a binary number.

$\text{Base}^{\text{Exponent}}$	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
Place Value	128	64	32	16	8	4	2	1
Example: Convert decimal 35 to binary	0	0	1	0	0	0	1	1

35 = $(2^7*0)+(2^6*0)+(2^5*1)+(2^4*0)+(2^3*0)+(2^2*0)+(2^1*1)+(2^0*1)$

35 = (32*1) + (2*1) + (1*1)

35 = 0 + 0 + 1 + 0 + 0 + 0 + 1 + 1

35 = 00100011

In the figure above, the decimal number 35 is converted to the binary number 00100011. The steps to perform this conversion are below.

1) Determine your decimal number. In this scenario, it is 35.

2) Write out the base number and its exponent. Since an IP address uses groups of eight binary bits, eight base 2 exponents are listed.

3) Below the base number and its exponent, write the place value. For example, 2^0 has a value of 1; 2^2 has a value of 4; 2^3 has a value of 8; etc.

4) Compare the value of the decimal number to the value of the highest bit position. If the value of the highest bit position is greater than the decimal number, place a 0 below the bit position. A 0 below the bit position means that position is not used.

   However, if the value of the highest bit position is less than or equal to the decimal number, place a 1 below the bit position. A 1 below the bit position means that position is used.

   In the figure, the value of the highest bit position is 128. It is greater than the decimal number 35, so a 0 is placed below the bit position of 2^7.

5) Go to the next bit position to the right. Make the same comparison and apply the same rules. In the figure, the value of the next bit position to the right is 64. It is greater than the decimal number 35, so a 0 is placed below the bit position of 2^6.

6) In the next bit position to the right, the value is 32. 32 is less than 35, so a 1 is placed below the bit position of 2^5.

7) Since the bit position of 2^5 (32) is used, that means 32 of 35 has been accounted for. To determine how much is not accounted for, subtract 32 from 35. The result is 3. (35 - 32 = 3)

8) Compare the remaining value against the value of the remaining bit positions, moving to the right one position at a time. Since the bit positions of 2^4 (16), 2^3 (8), and 2^2 (4) are all larger than 3, a 0 is placed below each of those bit positions.

9) The bit position of 2^1 (2) is less than 3, so a 1 is placed below that bit position. This means 2 of 3 has been accounted for, so subtract 2 from 3 to determine what value is not accounted for. The result is 1. (3 - 2 = 1)

10) The bit position of 2^0 (1) is the same as 1, so a 1 is place below the bit position of 2^0. This means 1 of 1 has been accounted for, so subtract 1 from 1 to determine what value is not accounted for. The result is 0. (1 - 1 =0)

11) This means the number 00100011 is binary equivalent of the decimal number 35.

12) Whenever the amount remaining equals 0, then all remaining binary positions, if any, have a 0 placed below them. For example, the decimal number 160 is represented in binary by the number 1010000. The table below demonstrates the process.

Power $^{\text{Exponent}}$	**2^7**	**2^6**	**2^5**	**2^4**	**2^3**	**2^2**	**2^1**	**2^0**
Place Value	**128**	**64**	**32**	**16**	**8**	**4**	**2**	**1**
Convert	**1**	**0**	**1**	**0**	**0**	**0**	**0**	**0**

Decimal 160 to Binary								
Calculations	**160** **<u>-128</u>** **32**	**64>32**	**32** **<u>-32</u>** **0**					

Binary to Decimal Conversion
Since IP addresses are a binary number represented in dotted decimal format, it is often necessary to convert a binary number to a decimal number.

Base^{Exponent}	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
Place Value	128	64	32	16	8	4	2	1
Example: Binary Number	1	0	1	1	1	0	0	1
Decimal Number Total: 185	128	0	32	16	8	0	0	1

10111001 = (128*1)+(64*0)+(32*1)+(16*1)+(8*1)+(4*0)+(2*0)+(1*1)
10111001 = 128 + 0 + 32 + 16 + 8 + 0 + 0 + 1
10111001 = <u>185</u>

In the figure above, the binary number 10111001 is converted to the decimal number 185. The steps to perform this conversion are below.

1) Determine your decimal number. In this scenario, it is 35.

2) Write out the base number and its exponent. Since an IP address uses groups of eight binary bits, eight base 2 exponents are listed.

3) Below the base number and its exponent, write the place value. For example, 2^0 has a value of 1; 2^2 has a value of 4; 2^3 has a value of 8; etc.

4) Below the place value, write the binary number. To avoid placing the wrong number in the wrong position, start at the right and move to the left.

5) Add the value of all positions that contain 1 in the binary number. In the example, the positions with values of 128, 32, 16, 8, and 1 all have binary 1s, so these values are to be added. The total is 185.
(128 + 32 = 160 + 16 = 176 + 8 = 184 + 1 = 185)

6) This means 185 is the decimal equivalent of 10111001.

7) Here's another example. The binary number 11100010 is the represented in decimal by the number 226. The table below demonstrates the process.

Base $^{\text{Exponent}}$	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
Place Value	**128**	**64**	**32**	**16**	**8**	**4**	**2**	**1**
Binary Number	**1**	**1**	**1**	**0**	**0**	**0**	**1**	**0**
Calculations	**128**	**128 +64 192**	**192 +32 224**	**224 +0 224**	**224 +0 224**	**224 +0 224**	**224 +2 226**	**226 +0 226**

The Fundamentals

Just like every physical location requires a unique address for the delivery of mail and packages, every device on a computer network requires a unique IP address for the delivery of data. Given the importance of IP addresses to the communications process, a good understanding of the fundamentals of IP addresses is crucial.

IP Address Construct and Representation

1) An IP address is a 32 bit binary number.

2) The 32 bits are separated into four groups of eight bits. Each group is called an octet. Each bit has a value. The value of the bits in each octet are as follows:

2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
128	64	32	16	8	4	2	1

3) The maximum value an octet can have is 255.
(128 + 64 = **192** + 32 = **224** + 16 = **240** + 8 = **248** + 4 = **252** + 2 = **254** + 1 = **255**)

4) An IP address is represented in dotted decimal format. This means each octet is converted to a decimal number, and a dot (period) is placed between each octet. (Example: 192.168.5.3)

5) An IP address has a network portion and a host portion. The network portion is ALWAYS to the left. The network portion describes the IP network or IP subnetwork (subnet) to which a host belongs. The host portion is ALWAYS to the right. The host portion describes the individual device within the IP network or IP subnet.

   Think of the network portion as a city, and think of the host portion as a specific location within the city. The network portion describes a group of devices in general terms; it is similar to referencing Atlanta or New York or Seattle. These cities are large and describe a general area. The host portion describes a specific device on the network; it is similar to referencing a specific location, such as Turner Field or the Empire State Building or the Space Needle. These are specific locations within a city.

The Classes

1) As per Request For Comment (RFC) 1700, there are five classes of IP address used for computer networks. This document focuses on the first three classes, as only the first three classes are assigned to computer networks. The other two classes are reserved for special purposes.

   The class of an IP address is determined solely by the value in the first octet. The classes are listed below.

   a) **Class A** = 1 - 126 in the first octet. (Addresses with 127 in the first octet are reserved and cannot be assigned to hosts.)
   b) **Class B** = 128 - 191 in the first octet.
   c) **Class C** = 192 - 223 in the first octet.

2) The class of an IP address determines the default dividing point between the network portion and the host portion.

   a) **Class A** = The first octet (the first 8 bits) is the network portion; the last three octets (the last 24 bits) are the host portion. This can be represented as N.H.H.H, where each letter represents 8 bits.
   b) **Class B** = The first two octets (the first 16 bits) are the network portion; the last two octets (the last 16 bits) are the host portion. This can be represented as N.N.H.H, where each letter represents 8 bits.
   c) **Class C** = The first three octets (the first 24 bits) are the network portion; the last octet (the last 8 bits) is the host portion. This can be represented as N.N.N.H, where each letter represents 8 bits.

3) Each class of IP network has a default number of hosts it can support.

   a) **Class A** = 16,777,214 hosts (2^{24} - 2; The power of 24 of is used because a class A network has 24 host bits by default.)
   b) **Class B** = 65,534 (2^{16} - 2; The power of 16 is used because a class B network has 16 host bits by default.)
   c) **Class C** = 254 hosts (2^{8} - 2; The power of 8 is used because a Class C network has 8 host bits by default.)

4) An IP network is assigned to an organization (general area), and the host portion is assigned to a device (specific location) by the network administrator. For example, the Class B network 175.15.0.0 (N.N.H.H) is assigned to the Acme Co. Any IP address that has 175.15 in the first two octets are considered to be under

the administrative control of the Acme Co. On the other hand, the Class B network 175.17.0.0 is assigned to WileE.Coyote Inc. Any IP address that has 175.17 in the first two octets are considered to be under the administrative control of WileE.Coyote Inc.

Subnet Mask

The subnet mask identifies the network bits and host bits of an IP address.

1) The subnet mask is a 32 bit binary number. Like an IP address, the 32 bits are separated into four octets. The individual bit values and the maximum value of an octet are the same as an IP address. However, there are two methods to represent the subnet mask.

    a) **Dotted Decimal Format**--This is the same format as that used for IP addresses. (Examples: 255.255.240.0 and 255.224.0.0)
    b) **Prefix Notation**--When using prefix notation, the total number of network bits are represented by a slash and number following the IP address. For example, if given 156.14.253.198 /16, the /16 is the prefix length, meaning the first 16 bits are the network portion of the IP address.

2) In the subnet mask, a binary one represents a network bit; a binary zero represents a host bit. The tables below show examples:

Subnet Mask in Dotted Decimal Format	255.0.0.0
Subnet Mask in Binary	11111111.00000000.00000000.0000000
Prefix Notation	/8
Interpretation	The first eight bits are network bits (binary 1s); The last 24 bits are host bits (binary 0s).

Subnet Mask in Dotted Decimal Format	255.240.0.0
Subnet Mask in Binary	11111111.11110000.00000000.00000000
Prefix Notation	/12
Interpretation	The first 12 bits are network bits (binary 1s); The last 20 bits are host bits (binary 0s).

3) A subnet mask MUST start with a string of consecutive 1s and end with a string of consecutive 0s. This requirement means there is a limited set of valid values for an octet of an subnet mask. The figure below shows these valid values.

128	64	32	16	8	4	2	1		
0	0	0	0	0	0	0	0	=	0
1	0	0	0	0	0	0	0	=	128
1	1	0	0	0	0	0	0	=	192
1	1	1	0	0	0	0	0	=	224
1	1	1	1	0	0	0	0	=	240
1	1	1	1	1	0	0	0	=	248
1	1	1	1	1	1	0	0	=	252
1	1	1	1	1	1	1	0	=	254
1	1	1	1	1	1	1	1	=	255

a) **Valid--**255.255.252.0 (11111111.11111111.11111100.00000000)
b) **Invalid--**255.255.192.240 (11111111.11111111.11000000.11110000) Mixing of 1s and 0s is not allowed in a subnet mask.

4) Every class of IP network has a default subnet mask. They are shown below.

a) **Class A** = 255.0.0.0 (N.H.H.H)
b) **Class B** = 255.255.0.0 N.N.H.H)
c) **Class C** = 255.255.255.0 (N.N.N.H)

5) The tables below summarize the default subnet mask information for each class of IP address.

Class of Address	A
Default Subnet Mask in Dotted Decimal Format	255.0.0.0
Subnet Mask in Binary	11111111.00000000.00000000.0000000
Prefix Notation	/8

Class of Address	B
Default Subnet Mask in Dotted Decimal Format	255.255.0.0
Subnet Mask in Binary	11111111.11111111.00000000.0000000
Prefix Notation	/16

Class of Address	C
Default Subnet Mask in Dotted Decimal Format	255.255.255.0
Subnet Mask in Binary	11111111.11111111.11111111.0000000
Prefix Notation	/24

Reserved IP Addresses

There are several reserved IP addresses that cannot be assigned to host devices.

1) **Network Address**--The network address (often referred to as the network) represents an entire IP network or subnet. In a network address, all host bits are a binary 0. The table below shows example network addresses.

Class A	115.0.0.0
Class B	138.44.0.0
Class C	207.56.224.0

2) **Directed Broadcast Address**--The directed broadcast address (often referred to as the broadcast) is used to communicate with all hosts in a particular IP network or subnet. In a directed broadcast address, all host bits are a binary 1. The table below shows example directed broadcast addresses.

Class A	115.255.255.255
Class B	138.44.255.255
Class C	207.56.224.255

3) **Local Broadcast Address**--The local broadcast is used to communicate with all devices on the local network. A PC configured to use Dynamic Host Configuration Protocol (DHCP) sends a packet with the local broadcast address as the destination IP address in order to find a DHCP server. The local broadcast address is 255.255.255.255

4) **Local Loopback Address**--The local loopback address is used for by host for testing connectivity to its Network Interface Card (NIC). The IP address 127.0.0.1 is very commonly used as the local loopback address, but the entire Class A range of addresses that start with 127 in the first octet are reserved.

5) **All Zeros Address**--The all zeros address is used by an end host when it does have an IP address. It is used as a source IP address only. A PC configured to use DHCP uses the all zeros address as the source address when it sends a message to locate a DHCP server. The all zeros address is 0.0.0.0.

The Need for Subnets

What exactly is subnetting? Subnetting is taking an IP network and subdividing it into smaller IP networks called subnetworks, or subnets. Every IP network or subnet is a broadcast domain. A broadcast domain is a collection of devices that can receive broadcast traffic from each other. Broadcast traffic is traffic that is delivered to every device on the network.

Having a single broadcast domain, or a "flat network", presents two main problems.

1) In a single large broadcast domain, there is a large amount of broadcast traffic. Broadcast traffic is very inefficient and consumes large amounts of resources, such as bandwidth, processor cycles, and memory. In fact, enough broadcast traffic on a network can cause other applications, such as e-mail, word processors, and spreadsheets, to be negatively impacted.

2) When all devices are part of the same broadcast domain, there are no boundaries between devices, so implementing security policies is difficult. In other words, there is no easy way to protect one device from another device without using host-based mechanisms, such as host-based firewalls, permissions, rights, and anti-virus. These methods serve a valuable purpose, but they are not very efficient, and they can degrade performance of the host.

The solution to these problems is to break the single large broadcast domain into several smaller broadcast domains. By doing this, the number of devices connected to each broadcast domain is smaller. This reduces the amount of broadcast traffic, improving the performance of all devices on the network. Additionally, a boundary between devices is created, which greatly improves and simplifies the implementation of security policies.

Here is a physical analogy. Imagine a single room, and in this room are five different groups of people; one group in each corner and one group in the center. Each group of people has a microphone and is discussing a different topic. Imagine being a member of one of the groups. Imagine how difficult it would be to hear people in your group; how difficult it would be to concentrate on your topic; how difficult it would be to share confidential information.

Now imagine the single room being separated into five smaller rooms. Each group of people now has its own room with a door. Now, each group can communicate without competing with the other groups. A person can hear better; concentrate better; more easily keep confidential information within the group.

The concept of dividing a large room into smaller rooms is the same as the concept of dividing a large broadcast domain (IP network) into smaller broadcast domains (subnets).

The Subnetting Process

In order to create IP subnets, host bits are changed to network bits. This is often called borrowing bits. It is also often referred to as taking host bits and giving them to the network. By borrowing host bits, more IP subnets are created, but each subnet can support fewer hosts.

To change a host bit to a network bit, the subnet mask must be changed. Remember, a binary 0 in the subnet mask means that bit is part of the host portion of an IP address. A binary 1 in the subnet mask mean that bit is part of the network portion of an IP address. So, to change a bit from a host bit to a network bit, the binary value of the bit must be changed from 0 to 1 in the subnet mask.

When calculating subnets, the following process should be used. Each step of the process will described in further detail later in this document.

1) Determine the assigned IP address space.

2) Determine the number of subnets required. This is based on the design of the existing network, along with the structure of the organization. It is common to assign a subnet to each department within the organization.

3) Based on the class of the IP address space and the number of required subnets, determine how many host bits need to be borrowed. Also determine how many hosts each subnet can support.

4) Calculate the decimal value and prefix value of the new subnet mask.

5) Apply the subnet mask to the assigned IP address space to calculate the network address of the new possible subnets, the broadcast address for each possible subnet, and the range of usable IP addresses in each possible subnet.

6) Assign IP addresses to all devices, including router interfaces, that are connected to that subnet.

Formulas for Subnet Calculation

There are several formulas and rules used to calculate subnets. The formulas and rules are discussed below.

Possible Number of Subnets

To calculate the number of possible subnets, use the formula 2^n, where n equals the number of host bits borrowed. For example, if three host bits are borrowed, then n=3. $2^3 = 8$, so eight subnets are possible if three host bits are borrowed. The table below lists the powers of 2.

Bits Borrowed	Formula	Possible Subnets		Bits Borrowed	Formula	Possible Subnets

1	2^1	2		12	2^{12}	4,096
2	2^2	4		13	2^{13}	8,192
3	2^3	8		14	2^{14}	16,384
4	2^4	16		15	2^{15}	32,268
5	2^5	32		16	2^{16}	65,536
6	2^6	64		17	2^{17}	131,072
7	2^7	128		18	2^{18}	262,144
8	2^8	256		19	2^{19}	524,288
9	2^9	512		20	2^{20}	1,048,576
10	2^{10}	1,024		21	2^{21}	2,097,152
11	2^{11}	2,048		22	2^{22}	4,194,304

To complete the third step of the subnetting process--determine how many host bits need to be borrowed, rewrite the formula as 2^n > (number of required subnets). For example, if the number of required subnets is 18, then write the formula as $2^n > 18$. Solve for n by getting as close to the number of required subnets as possible without going under. In this example, n = 5 ($2^5 = 32$). This means that to create at least 18 subnets, 5 host bits must be borrowed.

Possible Number of Hosts Per Subnet

To calculate the number of possible hosts per subnet, use the formula $2^h - 2$, where h equals the number of host bits. The reason two addresses must be subtracted is because of the network address and the broadcast address.

There are two ways to determine the number of host bits.

1) Determine the number of remaining host bits based on the class of address and the number of host bits borrowed.

    a) Determine the assigned IP address space.

    b) Determine number of host bits available.

    c) Determine number of host bits borrowed.

    d) Determine the number of remaining host bits by subtracting the number of host bit borrowed from the default number of host bits. The difference is h in the formula.

    e) Determine the number of possible hosts by using the formula $2^h - 2$. Use the table above to

    f) Calculate the new subnet mask and prefix

Examples for each class of IP address space are shown in the table below.

Given IP Address Space	A	B	C
Number of Host Bits Available	24	16	8
Number of Host Bits Borrowed	14	7	4
Number of Host Bits Remaining (h)	24 - 14 = **10**	16 - 7 = **9**	8 - 4 = **4**
Number of Possible Hosts	2^{10} = 1,024 1024 - 2 = **1,022**	2^{7} = 128 128 - 2 = **126**	2^{4} = 16 16 - 2 = **14**
New Subnet Mask	255.255.252.0	255.255.254.0	255.255.255.240
New Prefix	/22	/23	/28

2) Determine how many host bits need to be saved based on the number of hosts the subnet needs to support. This scenario is coming from a design perspective and is very common.

   a) Determine the assigned IP space.

   b) Determine the number of host bits available.

   c) Determine how many hosts the subnet needs to support.

   d) Rewrite the formula as $2^h - 2 >$ (number of required hosts), where h equals the number of host bits that must be saved.

   e) Solve for h, by finding the exponent of 2 whose value is as close to the number of required hosts as possible without going under. That exponent is the value of h.

   f) All other bits not saved for host bits become network bits. Use the following formula to determine how many host bits are given to the network portion: (Number of Host Bits Available) - h

   g) Calculate the new subnet mask and prefix.

Understanding the concept of saving host bits is critical. Remember, host bits are always the bits to the far right of the IP address. So, when saving host bits, start with the far right bit (the last bit of the last octet) and count to the left. Remaining host bits are given to the network portion.

For example, suppose that six host bits need to be saved. This means the last six bits of the last octet are saved as host bits, while the first two bits of the last octet, along with any host bits from the second and third octet, are given to the network portion. The table below shows this concept.

Last Octet of Subnet Mask								
Base $^{\text{Exponent}}$	2^7	2^6	2^5	2^4	2^3	2^2	2^1	2^0
Place Value	128	64	32	16	8	4	2	1
Binary Value	1	1	**0**	**0**	**0**	**0**	**0**	**0**
Meaning	Network Bit	Network Bit	**Host Bit**	**Host Bit**	**Host Bit**	**Host Bit**	**Host Bit**	**Host Bit**

Examples for each class of IP address space are shown in the table below.

Given IP Address Space	A	B	C
Number of Host Bits Available	24	16	8
Number of Required Hosts Per Subnet	500	200	25
Number of Host Bits to Save (h)	$2^h - 2 > 500$ $2^9 = 512$ $512 - 2 = 510$ **h = 9**	$2^h - 2 > 200$ $2^8 = 256$ $256 - 2 = 254$ **h = 8**	$2^h - 2 > 25$ $2^5 = 32$ $32 - 2 = 30$ **h = 5**
Number of Host Bits Given to the Network Portion	24 - h 24 - 9 = **15**	16 - h 16 - 8 = **8**	8 - h 8 - 5 = **3**
New Subnet Mask	255.255.254.0	255.255.255.0	255.255.255.224
New Prefix	/23	/24	/27

Calculate New Subnet Mask

To complete the fourth step of the subnetting process--calculate the decimal and prefix values of the new subnet mask--perform the following steps.

1) Determine the class of IP network.

2) Determine the default subnet mask or prefix for the class of address.

3) Determine how many host bits were borrowed or given to the network.

4) Calculate the new subnet mask and prefix. To calculate the new subnet mask, start with the first binary 0 in the default subnet mask and change it to a binary 1. Continue doing this, moving left to right, for the number of bits borrowed.

   For example, if the default subnet mask is 255.255.0.0, and if the number of bits borrowed is four, then the first four bits of the third octet must be changed from binary 0s to binary 1s. In this example, the new subnet mask is 255.255.240.0.

   The table below provides an example of these steps.

Assigned IP Address Space	159.43.0.0
Class of Assigned IP Address Space	B
Default Subnet Mask (Dotted Decimal Format)	255.255.0.0
Default Subnet Mask in Binary	11111111.11111111.00000000.00000000
Default Subnet Mask (Prefix Format)	/16
Number of Host Bits Borrowed	4
New Subnet Mask (Dotted Decimal Format)	255.255.240.0
New Subnet Mask in Binary	11111111.11111111.11110000.00000000
New Subnet Mask (Prefix Format)	/20

Calculate The New Subnets

Calculating the new subnets is part of the fifth step of the subnetting process. In the subnet mask, the last bit borrowed is called the Least Significant Bit (LSB). The figure below shows an example.

Subnet Mask (Dotted Decimal Format)	**Subnet Mask (Binary Format)**	**3rd Octet Expanded**							
255.255.240.0	11111111.11111111.11110000.00000000	2^7	2^6	2^5	$\mathbf{2^4}$	2^3	2^2	2^1	2^0
		128	64	32	**16**	8	4	2	1
		1	1	1	**1 LSB**	0	0	0	0

In the subnet mask 255.255.240.0, the LSB is the 4th bit of the 3rd octet. This bit has a value of 16. This is important to note, because the value of the LSB determines the multiples of the new IP subnets. In other words, the network numbers of the new possible subnets go in increments of 16 in the 3rd octet. The table below shows the new possible subnets.

159.43.**0**.0		159.43.**128**.0
159.43.**16**.0		159.43.**144**.0

159.43.**32**.0	159.43.**160**.0
159.43.**48**.0	159.43.**176**.0
159.43.**64**.0	159.43.**192**.0
159.43.**80**.0	159.43.**208**.0
159.43.**96**.0	159.43.**224**.0
159.43.**112**.0	159.43.**240**.0

Using the value of the LSB to determine the new possible subnets works for every class of IP network with any subnet mask.

Calculate the Broadcast Address and Usable Range of the New Subnets

Once the network address of the new possible subnets is known, the broadcast address and the usable range for the new subnets can be quickly calculated.

To calculate the broadcast address for a given subnet, identify the next subnet, then go back one address. The table below shows the new subnets and their broadcast addresses.

Subnet Address	Broadcast Address
159.43.0.0	159.43.15.255
159.43.16.0	159.43.31.255
159.43.32.0	159.43.47.255
159.43.48.0	159.43.63.255
159.43.64.0	159.43.79.255
159.43.80.0	159.43.95.255
159.43.96.0	159.43.111.255
159.43.112.0	159.43.127.255
159.43.128.0	159.43.143.255
159.43.144.0	159.43.159.255
159.43.160.0	159.43.175.255
159.43.176.0	159.43.191.255
159.43.192.0	159.43.207.255
159.43.208.0	159.43.223.255
159.43.224.0	159.43.239.255
159.43.240.0	159.43.255.255

To calculate the usable range of IP addresses--meaning, the range of IP addresses that can be assigned to devices connected to the subnet--do the following:

1) Add one address to the subnet address to find the first usable IP address.

2) Subtract one address from the broadcast address to find the last usable IP address.

The following table shows all of the new possible subnets; the usable range of IP addresses for each subnet; and the broadcast address for each subnet.

Subnet Address	Usable Range of Host IP Addresses	Broadcast Address
159.43.0.0	159.43.0.1 through 159.43.15.254	159.43.15.255
159.43.16.0	159.43.16.1 through 159.43.32.254	159.43.31.255
159.43.32.0	159.43.32.1 through 159.43.47.254	159.43.47.255
159.43.48.0	159.43.48.1 through 159.43.63.254	159.43.63.255
159.43.64.0	159.43.64.1 through 159.43.79.254	159.43.79.255
159.43.80.0	159.43.80.1 through 159.43.95.254	159.43.95.255
159.43.96.0	159.43.96.1 through 159.43.111.254	159.43.111.255
159.43.112.0	159.43.112.1 through 159.43.127.254	159.43.127.255
159.43.128.0	159.43.128.1 through 159.43.143.254	159.43.143.255
159.43.144.0	159.43.144.1 through 159.43.159.254	159.43.159.255
159.43.160.0	159.43.160.1 through 159.43.175.254	159.43.175.255
159.43.176.0	159.43.176.1 through 159.43.190.254	159.43.191.255
159.43.192.0	159.43.192.1 through 159.43.207 254	159.43.207.255
159.43.208.0	159.43.208.1 through 159.43.223.254	159.43.223.255
159.43.224.0	159.43.224.1 through 159.43.239.254	159.43.239.255
159.43.240.0	159.43.240.1 through 159.43.255.254	159.43.255.255

Putting It All Together

Here's a class C example demonstrating everything. The given IP address space is 209.44.33.0 /24. The required number of subnets is 6. The table below shows the six step subnetting process.

Step 1--Given IP Address Space	209.44.33.0 (Class C) Default Subnet Mask = 255.255.255.0 Default Number of Host Bits = 8
Step 2--Number of Required Subnets	6
Step 3A--Determine Number of Bits to Borrow	**3** (2^n > 6, where n = the number of host bits to borrow. n=3 (2^3 = 8))
Step 3B--Determine Number of Hosts per Subnet	**30** (Number of host bits available) - n = h 8 - 3 = 5

	h = 5 $2^h - 2$ = (Number of hosts per subnet) $2^5 = 32 - 2 = 30$
Step 4--Calculate new subnet mask and prefix	Default Class C Subnet Mask = 255.255.255.0 Default Class C Prefix = /24 New Subnet Mask = 255.255.255.224 New Prefix = /27

Step 5--Apply the Subnet Mask to the IP Space

Subnet	Usable Range	Broadcast
209.44.33.0	209.44.33.1 - 30	209.44.33.31
209.44.33.32	209.44.33.33 - 62	209.44.33.63
209.44.33.64	209.44.33.65 - 94	209.44.33.95
209.44.33.96	209.44.33.97 - 126	209.44.33.127
209.44.33.128	209.44.33.129 - 158	209.44.33.159
209.44.33.160	209.44.33.161 - 190	209.44.33.191
209.44.33.192	209.44.33.193 - 222	209.44.33.223
209.44.33.224	209.44.33.225 - 254	209.44.33.255

Step 6--Assign IP Addresses to Devices as Appropriate	The router interface usually receives the first IP address of the subnet, but this is not required.

There's a class B example demonstrating everything. The given IP address space is 147.38.0.0 /16. The required number of subnets is 400. The table below shows the six step subnetting process.

Step 1--Given IP Address Space	147.38.0.0 (Class B)
Step 2--Number of Required Subnets	400
Step 3--Determine Number of Bits to Borrow	9 ($2^n > 400$, where n = the number of host bits to borrow. n=9 ($2^9 = 512$))
Step 4--Calculate new subnet mask and prefix	Default Class B Subnet Mask = 255.255.0.0 Default Class C Prefix = /16 New Subnet Mask = 255.255.255.128 New Prefix = /25

Step 5--Apply the Subnet Mask to the IP Space (Only the first 10 are shown.)

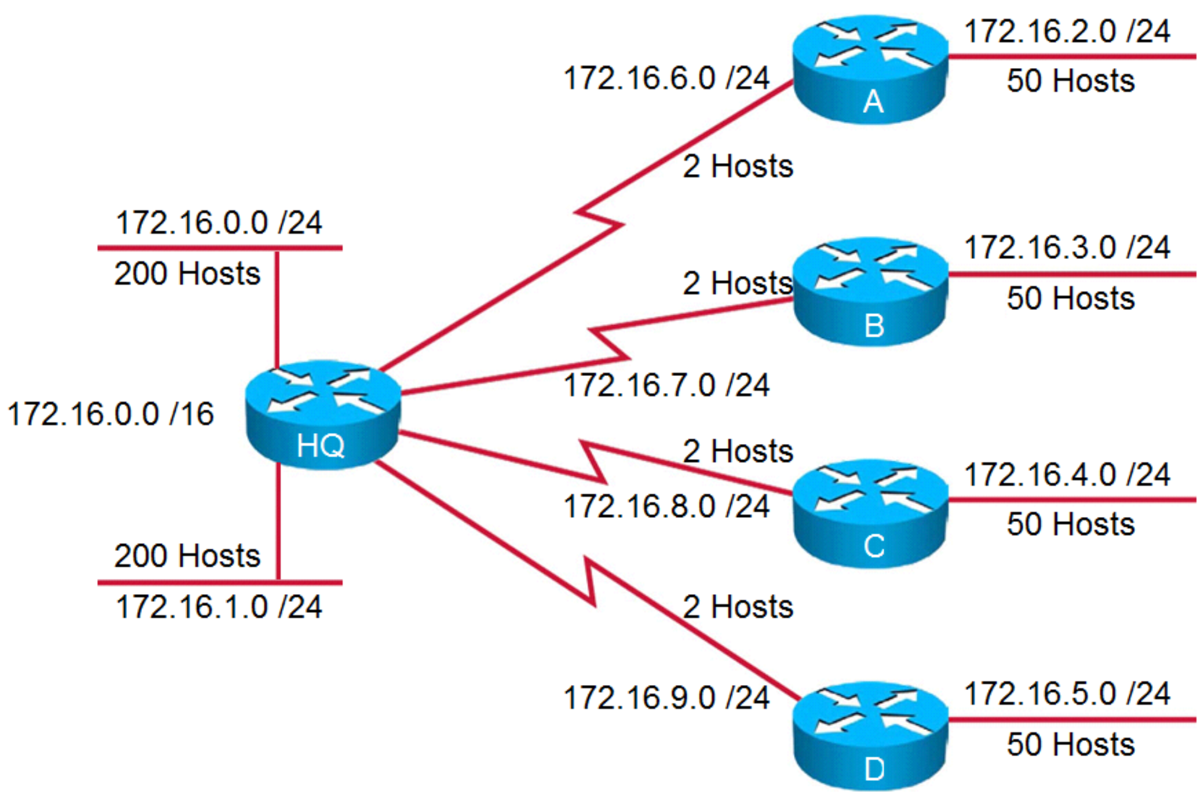
Subnet	Usable Range	Broadcast
147.38.0.0	147.38.0.1 - 147.38.0.126	147.38.0.127
147.38.0.128	147.38.0.129 - 147.38.0.254	147.38.0.255
147.38.1.0	147.38.1.1 - 147.38.1.126	147.38.1.127
147.38.1.12	147.38.1.129 - 147.38.1.254	147.38.1.255

	8		
	147.38.2.0	147.38.2.1 - 147.38.2.126	147.38.2.127
	147.38.2.12 8	147.38.2.129 - 147.38.2.254	147.38.2.255
	147.38.3.0	147.38.3.1 - 147.38.3.126	147.38.3.127
	147.38.3.12 8	147.38.3.129 - 147.38.3.254	147.38.3.255
	147.38.4.0	147.38.4.1 - 147.38.4.126	147.38.4.127
	147.38.4.12 8	147.38.4.129 - 147.38.4.254	147.38.4.255
Step 6--Assign IP Addresses to Devices as Appropriate	The router interface usually receives the first IP address of the subnet, but this is not required.		

Variable Length Subnet Masking

When the subnet mask is fixed throughout the IP network, meaning the subnet mask is the same for every subnet, it is called Static Length Subnet Masking (SLSM). SLSM often leads to wasted IP addresses.

Network Using Static Length Subnet Mask



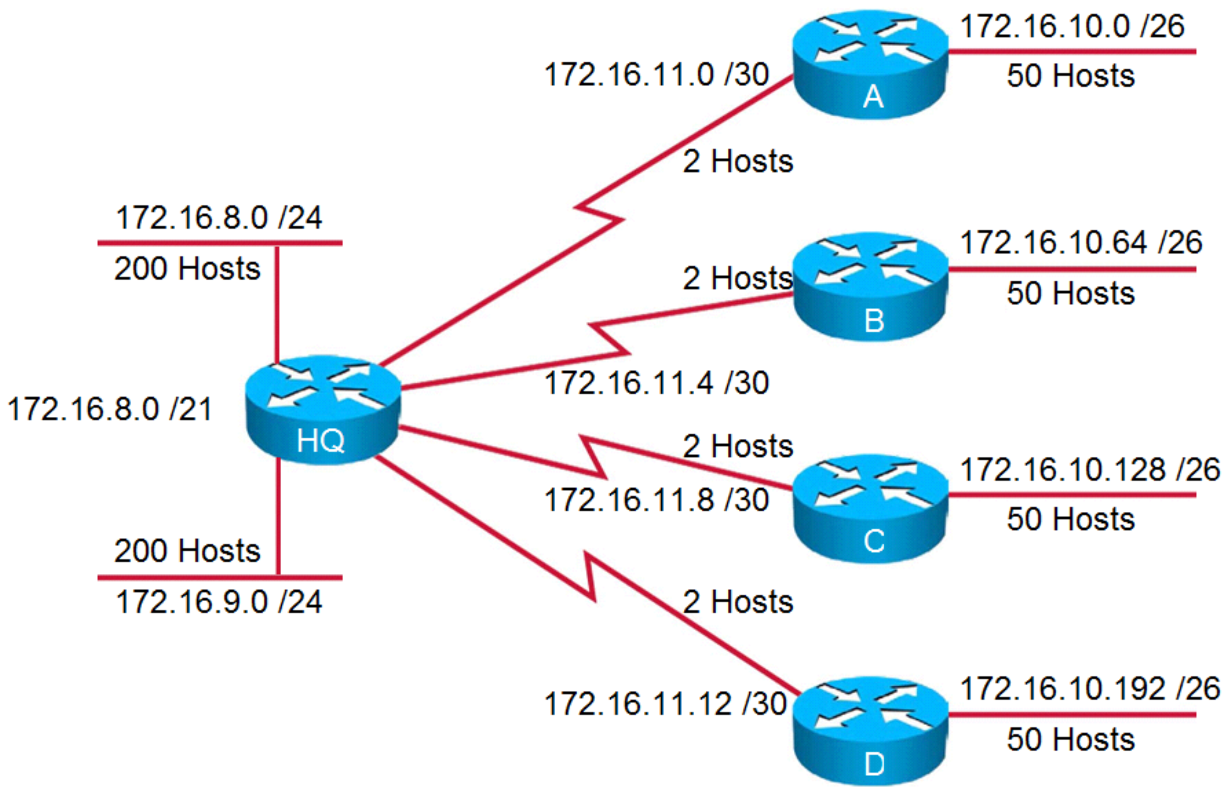
The IP network 172.16.0.0 /16 has been assigned to an organization. The organization has subnetted this IP network into multiple /24 (255.255.255.0) subnets. A /24 subnet means there are eight host bits, which means each subnet can support up to 254 hosts.

The figure above shows a region of the organization. For the LANs connected to the HQ router, 254 hosts per subnet is appropriate. However, for the LANs connected to the branch routers, where only 50 hosts reside, 254 possible hosts is too many. In fact, there are 204 wasted IP addresses per branch. For the WAN links between the routers, where only two hosts reside, 254 possible hosts is extreme overkill. In fact, there are 252 IP addresses wasted on each WAN link. That means there is a total of 1,824 wasted IP addresses in this design.

In order to make more efficient use of the assigned IP address space, a Variable Length Subnet Mask (VLSM) can be used. In VLSM, the number of network and host bits assigned to a subnet can vary from one subnet to the next based on the number of hosts the subnet is required to support.

Additionally, implementing VLSM provides more levels of hierarchy within the IP address space. This because a subnet can be further subnetted. More levels of hierarchy provides opportunities for route aggregation, also called route summarization. When routes are summarized, a single entry in the routing table of a router represents multiple smaller networks. Route summarization improves the efficiency of routing protocols and the overall routing process.

Network Using Variable Length Subnet Mask



The figure above shows the IP addressing scheme for the same region utilizing VLSM. The organization is still assigned the 172.16.0.0 /16 network, but now the region is assigned the 172.16.8.0 /21 subnet. This subnet has a total of 11 host bits available.

Within the region, the 172.16.8.0 /21 subnet is further subnetted as follows:

1) The networks connected to the HQ router are assigned the 172.16.8.0 /24 and 172.16.9.0 /24 subnets. The reason a 24 bit prefix is chosen is based on the number of hosts the subnet needs to support. Each of these subnets needs to support 200 hosts. In order to support 200 hosts, eight host bits must be saved. If eight host bits are saved, 24 bits can be given to the network portion. (11 total host bits - 8 saved host bits = 3 additional bits given to the network. 21 existing network bits + 3 additional network bits = 24 total network bits.) While this creates 254 possible host IP addresses, this overage is acceptable for two reasons:

    a) 254 possible host IP addresses is as close to 200 without going under as possible. If only seven host bits were saved, there would only be 126 possible host IP addresses.

b) 54 additional host IP addresses leaves room for growth within the subnet. As a general rule, add 20% to the actual number of hosts to allow for growth. For example, the networks attached to the HQ router need to support 200 hosts, so planning for 240 hosts allows a buffer for growth within the subnet.

2) The next available subnet after the 172.16.9.0 /24 subnet is the 172.16.10.0 /24. This subnet is further subnetted into subnets using 26 network bits (a 26 bit prefix) for the LANs at the branch offices. Again, the prefix is chosen for these subnets based on the need for each of the branch subnets to support 50 hosts. In order to support 50 hosts, six host bits must be saved. If six host bits are saved, 26 bits can be given to the network portion. While this creates 62 possible hosts per subnet, this overage is acceptable.

3) The next available subnet after the 172.16.10.192 /26 subnet is the 172.16.11.0 /26. This subnet is further subnetted into subnets using 30 networks bits (a 30 bit prefix) for the WAN links between the routers. Again, the prefix is chosen based on the need for each of the WAN links to support two hosts. In order to support two hosts, two host bits must be saved. If two host bits are saved, 30 bits can be given to the network portion. In this instance, having exactly two host IP addresses is acceptable because these are serial WAN links. Serial WAN links are point-to-point, meaning they have only two devices. Since no more than two devices can connect to a point-to-point link, there is no need to account for possible growth on those networks.

The figure also demonstrates route aggregation or summarization. In other words, all 10 of the subnets within the region can be represented by the subnet 172.16.8.0 /21. This means that routers for other regions within the organization have only one entry in their routing tables instead of 10. Having a smaller routing table enables a router to forward packets faster. Additionally, by having a summarized route, if there is a topology change within the region, the routers at other regions do not need to rerun the routing protocol. This, again, makes forwarding of packets much faster.

Determine the Subnet, Usable Range of Addresses, and Broadcast Address for Given Host

Often times it is necessary to determine the subnet, the usable range of host IP addresses, and the broadcast address for a given host. This process is described below.

1) Identify the IP address and subnet mask of the host.

2) Identify the LSB to determine the interval of the subnets.

3) Identify the subnet to which the host belongs. To do this, find the subnet ID that is closest to the host IP address without going over. (Think the TV game show, *The Price Is Right*--Get as close to the price without going over.)

4) Identify the broadcast address for the subnet. To do this, find the next subnet ID and subtract one address.

5) Identify the usable range of host IP addresses. To do this, add one address to the subnet ID, and subtract one address from the broadcast address.

The tables below show an example for each class of address.

<table>
<tr><td>Given Host IP Address & Prefix</td><td colspan="8">207.59.22.34 /28</td></tr>
<tr><td rowspan="4">Identify the LSB</td><td colspan="8">16</td></tr>
<tr><td colspan="8">The 28th bit is the 4th bit of the 4th octet.</td></tr>
<tr><td>128</td><td>64</td><td>32</td><td>16</td><td>8</td><td>4</td><td>2</td><td>1</td></tr>
<tr><td>1</td><td>1</td><td>1</td><td>1
(LSB)</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td rowspan="2">Identify the Subnet to Which the Host Belongs</td><td colspan="8">207.59.22.32</td></tr>
<tr><td colspan="8">Because the LSB is 16, the interval of the new subnets is 16. 32 is the multiple of 16 closest to 34 without going over.</td></tr>
<tr><td rowspan="2">Identify the Broadcast Address for the Subnet</td><td colspan="8">207.59.22.47</td></tr>
<tr><td colspan="8">The broadcast address is one less than the next subnet ID. The next subnet ID after 207.59.22.32 is 207.59.22.48.</td></tr>
<tr><td rowspan="2">Identify the Usable Range of Host IP Addresses</td><td colspan="8">207.59.22.33 - 207.59.22.46</td></tr>
<tr><td colspan="8">The first usable IP address is one more than the subnet ID. The last usable IP address is one less than the broadcast address.</td></tr>
</table>

<table>
<tr><td>Given Host IP Address & Prefix</td><td colspan="8">175.38.54.188 /23</td></tr>
<tr><td rowspan="4">Identify the LSB</td><td colspan="8">2</td></tr>
<tr><td colspan="8">The 23rd bit is the 7th bit of the 3rd octet.</td></tr>
<tr><td>128</td><td>64</td><td>32</td><td>16</td><td>8</td><td>4</td><td>2</td><td>1</td></tr>
<tr><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1
LSB</td><td>0</td></tr>
<tr><td rowspan="2">Identify the Subnet to Which the Host Belongs</td><td colspan="8">175.38.54.0</td></tr>
<tr><td colspan="8">Because the LSB is 2, the interval of the new subnets is 2. 54 is the multiple of 2 closest to 54 without going over.</td></tr>
<tr><td rowspan="2">Identify the Broadcast Address for the Subnet</td><td colspan="8">172.38.55.255</td></tr>
<tr><td colspan="8">The broadcast address is one less than the next subnet ID. The next subnet ID after 172.38.54.0 is 172.38.56.0.</td></tr>
<tr><td>Identify the Usable</td><td colspan="8">172.38.54.1 - 172.38.55.254</td></tr>
</table>

Range of Host IP Addresses	The first usable IP address is one more than the subnet ID. The last usable IP address is one less than the broadcast address.

Given Host IP Address & Prefix	**98.165.33.250 /11**							
Identify the LSB	**32**							
	The 23rd bit is the 7th bit of the 3rd octet.							
	128	64	32	16	8	4	2	1
	1	1	1 LSB	0	0	0	0	0
Identify the Subnet to Which the Host Belongs	**98.160.0.0**							
	Because the LSB is 32, the interval of the new subnets is 32. 160 is the multiple of 32 closest to 165 without going over.							
Identify the Broadcast Address for the Subnet	**98.191.255.255**							
	The broadcast address is one less than the next subnet ID. The next subnet ID after 98.160.0.0 is 98.192.0.0.							
Identify the Usable Range of Host IP Addresses	**98.160.0.1 - 98.191.255.254**							
	The first usable IP address is one more than the subnet ID. The last usable IP address is one less than the broadcast address.							

Helpful Tables

Below are some helpful tables. Memorization of these tables is encouraged.

Prefix Notation to Dotted Decimal Notation Conversion

The table below shows the prefix notation and its equivalent dotted decimal notation.

Prefix	Dotted Decimal		Prefix	Dotted Decimal		Prefix	Dotted Decimal
/8	255.0.0.0		/16	255.255.0.0		/24	255.255.255.0
/9	255.128.0.0		/17	255.255.128.0		/25	255.255.255.128
/10	255.192.0.0		/18	255.255.192.0		/26	255.255.255.192
/11	255.224.0.0		/19	255.255.224.0		/27	255.255.255.224
/12	255.240.0.0		/20	255.255.240.0		/28	255.255.255.240
/13	255.248.0.0		/21	255.255.248.0		/29	255.255.255.248
/14	255.252.0.0		/22	255.255.252.0		/30	255.255.255.252

/15	255.254.0.0	/23	255.255.254.0	/31	255.255.255.254

List of Multiples

The table below lists the multiples, or intervals, for the bit values. These are used to calculate the list of new subnets created based on the LSB.

128	**32**	**16**	**8**		**4**			
0	0	0	0	128	0	64	128	192
128	32	16	8	136	4	68	132	196
	64	32	16	144	8	72	136	200
64	96	48	24	152	12	76	140	204
0	128	64	32	160	16	80	144	208
64	160	80	40	168	20	84	148	212
128	192	96	48	176	24	88	152	216
192	224	112	56	184	28	92	156	220
		128	64	192	32	96	160	224
		144	72	200	36	100	164	228
		160	80	208	40	104	168	232
		176	88	216	44	108	172	236
		192	96	224	48	112	176	240
		208	104	232	52	116	180	244
		224	112	240	56	120	184	248
		240	120	248	60	124	188	252

Conclusion

The ability to interpret and understand IP addresses and subnet masks is a critical skill for an IT professional to possess. This skill is the foundation for troubleshooting numerous problems, from the assignment of an IP address to a host to routing problems to access-control list problems. It is also a necessary skill for designing and configuring efficient IP networks.

Learn More

Learn more about subnetting and other crucial skills for an IT professional through these courses:

ICND1 - Interconnecting Cisco Network Devices, Part 1

ICND2 - Interconnecting Cisco Network Devices, Part 2

ROUTE - Implementing Cisco IP Routing v 1.