Broadband Networks
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Lecture No.21
IP Addressing Scheme

So today, we will learn about IP address lookup and packet classification in routers. In short we will see how packet processing is performed in internet routers.

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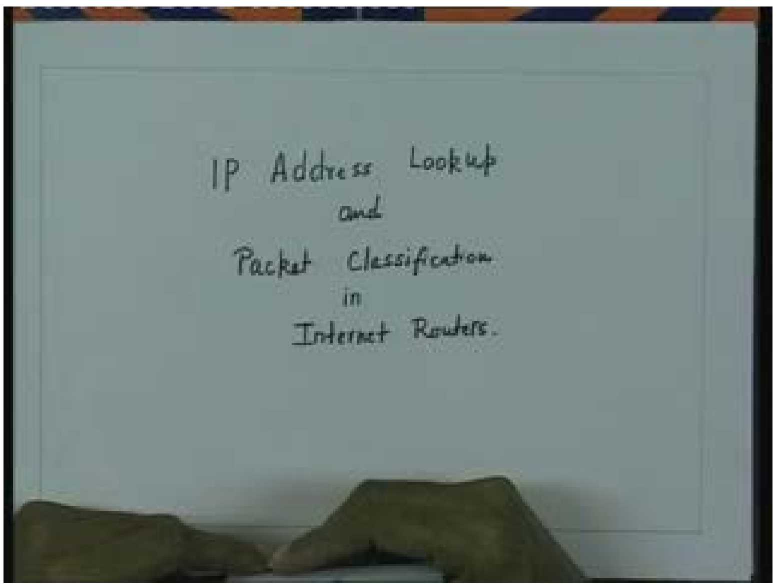

So today, our topic will be IP address lookup and packet classification in Internet Routers. Before actually we formulate the problem of IP address lookup in internet routers, we will first try to understand how addressing is done in the internet world. Now as opposed to the telephone networks where the addressing is what is called as flag addressing. In internet, we use a hierarchical addressing scheme. The reason being that in internet routers, a decision to forward a packet is taken by looking at the destination address. By looking at the destination address, the router determines on which port the packet needs be forwarded.

Since the router may receive packets from any host and it may have to forward it to any other host in the world, it is therefore necessary but the routers must have the forwarding table for all the possible hosts which are connected to the internet. Now this would make the forwarding table to be very large and therefore the IP addressing scheme has been designed to be hierarchical. So the IP addresses therefore are divided into two parts a network number and a host number. So we will see what are the properties of the IP addressing schemes?

So, first of all the IP addresses are globally unique. So we have the property of these being globally unique and second which i was just discussing that IP addresses are hierarchical in the sense that, an IP address is divided into two parts. One is the network number and another is the host number. So if you have an IP address then it may be divided into two parts. One denoting the network number or network address and another denoting it to be the host number.

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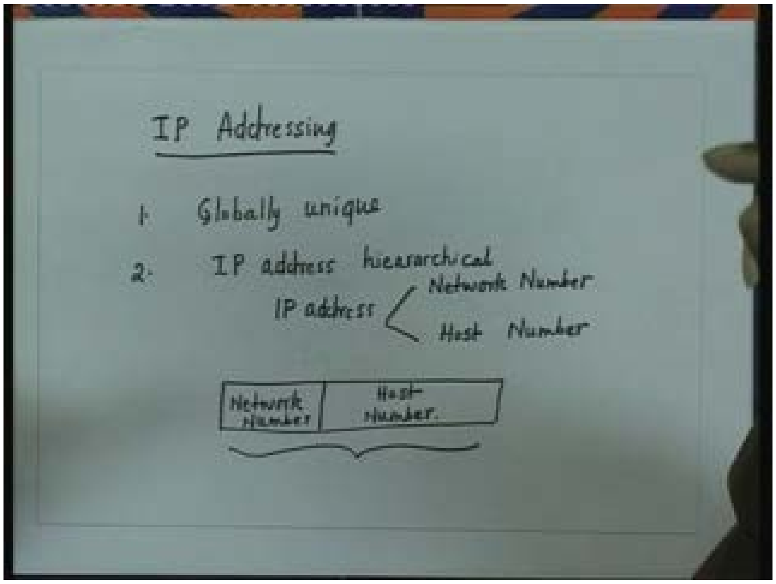

Now with this hierarchical addressing schemes, the core routers, the intermediate routers or the intermediate nodes may have to store the entries corresponding to the network numbers only and the nodes or the routers which is directly attached to a particular host it may have to store the entries corresponding to all the hosts which are attached to it. So that it can correctly forward to the packets.

This addressing scheme is something very similar to the addressing scheme that is used in post offices for you know posting the letters. For example: you know if somebody posts in New Delhi a letter which is addressed to me, let us say Abhay Karandikar, Department of Electrical Engineering, Indian Institute of Technology Bombay-Mumbai, then the post office in Delhi just needs to see that the letter needs to be forwarded to Mumbai city and when it comes to the Mumbai city then it looks that the nearest post office is a Powaii post office. The letter will come to the Powaii post office. Now, it is the Powaii post office then really needs to figure out the exact addressee of the letter in order to deliver it correctly.

Now, this kind of hierarchical addressing scheme leads to the scalability in the internet that means a node can come up anywhere in the network without having it to register with all the possible routers in the internet. It needs to only register with its, you know immediate router okay and the immediate router will contain the entries corresponding to all the hosts which are directly attached to it and the packet will actually come to this immediate router, since it belongs to the same network to which a particular host has been connected. So, this kind of hierarchical addressing scheme has led to what is now called as an explosive growth in internet.

One of the factors responsible for the explosive growth of internet is the hierarchical addressing scheme employed in the current internet. Now, when it was decided that IP addressing scheme will be hierarchical, it will be divided into the network number and the host number. Now we know that the IP address is a thirty-two bit IP address. So therefore possible nodes which can be there on the internet can be as large as 2 raised to the power 32. Now when we are dividing this 32 bit into two parts one denoting the network number and the other denoting the host number. Clearly the question is that, how many bits we should denote it to the network number and how many bits we should denote it to the host number. Accordingly you know several classes of IP addresses have been defined. So let us study what are those classes of IP addresses.

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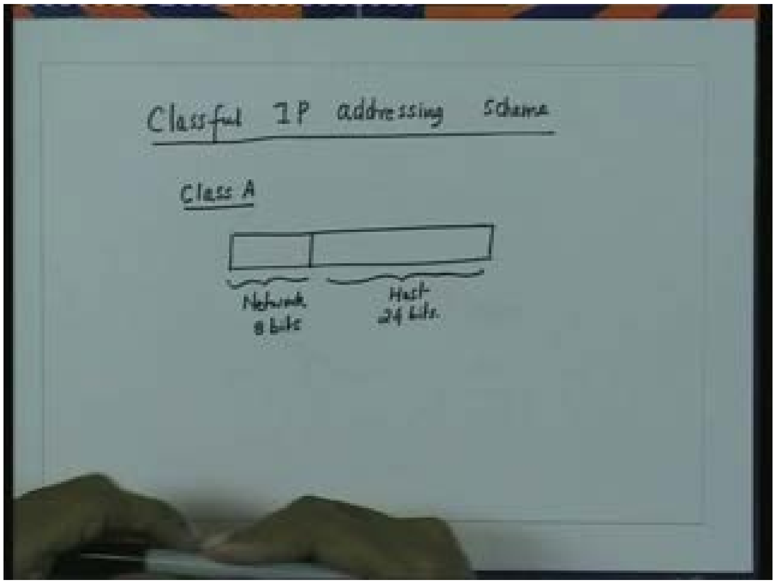

Classful IP addressing scheme: Earlier you know, it was decided that we can have a class A IP addressing scheme where essentially eight bits denotes the network number. Eight bits denote the network numbers in class A IP addressing scheme and twenty-four bits denote the host number.
Now if eight bits are used to denote the network number then the possible number of networks which can be there in the internet world can only be limited to two fifty-six and so when this class A IP addressing scheme was introduced, it was realized that this is a too few number as the internet was evolving. So, therefore you know a class B IP addressing scheme was introduced in class B IP addressing scheme. Sixteen bits are reserved for the network number and sixteen bits are reserved for the host number.

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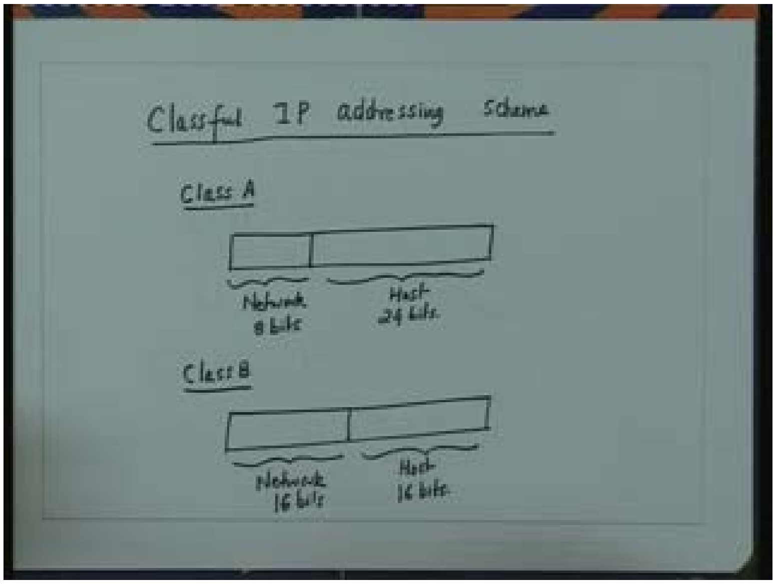

Now the number of networks can be as large as 2 raised to power 16 which is some number like 65000 and on each network you can have as many host as 2 raised to power 16. So, therefore you know the class B IP addressing scheme was thought appropriate from the point of view or the fact that the number of networks were adequate. However you know this led a problem of IP address inefficiency, the usage of IP address inefficiency.

For example: if you allot a network a particular 16 bit number as its network number, then this particular network consumes a block of 2 raised to power 16 IP addresses, that means the network can actually have 65000 hosts on its network because 16 bits are used to represent host on this particular network. Now suppose if this network just has some five thousand machines, just to give you an idea that if i use a class B IP address, some particular class B IP address. If i fix it, these 16 bits then i can address 2 raised to power 16 hosts which is approximately you know 64 k hosts i can address.

Now if i just have five thousands hosts on the network then my address inefficiency, so if there are only 5000 hosts on the network, then my address inefficiency will be approximately five thousand upon 64 k sixty-fifty thousand you know some number which leads to less than one percent efficiency.

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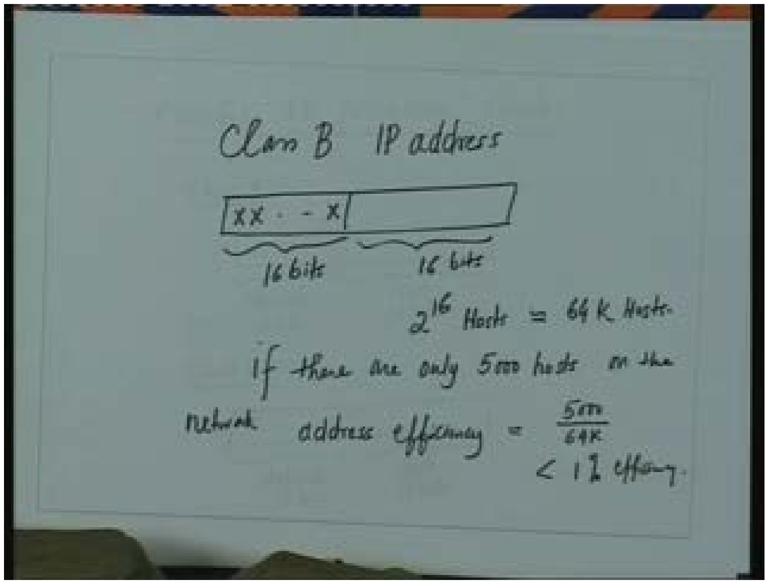

This leads to around not less than one percent around you know five to six percent six percent efficiency, six to seven percent of efficiency. So that means the IP addressing scheme is being used very very inefficiently. The IP addressing scheme is being used very very inefficiently, if we are using class B IP addresses. Now to resolve this, also however it was also found that sixteen bit therefore which are used to represent the host number appears to be too large number and therefore new addressing scheme was designed which was called as class C IP addresses.

Now in class C IP addresses, you assign twenty-four bits for network numbers and eight bits for the host.

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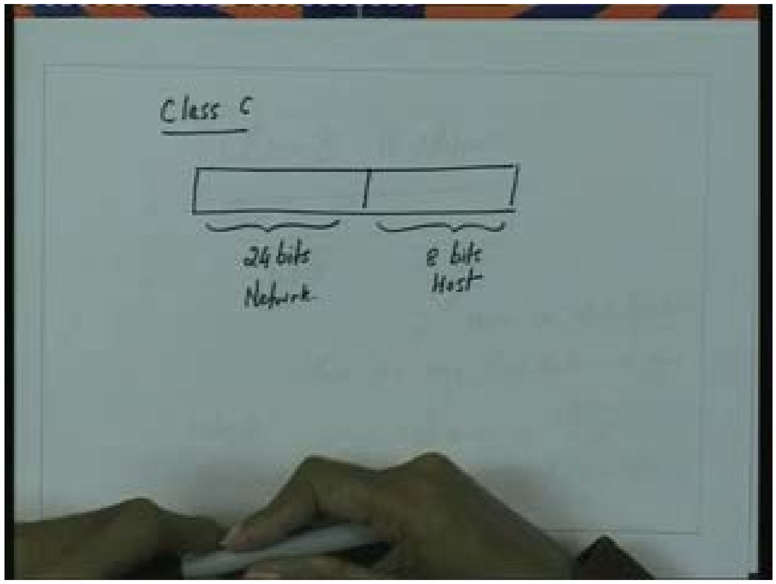

Now this means, then you can have large number of networks two raise to the power twenty-four you know networks, but each networks is now required to have only 256 machine. So now by using class C IP addresses we can actually addresses the problem of IP address inefficiency quite well. Just take the example that was just taken that suppose, there are in a network which was earlier assigned at class B IP address there were five thousand machines. Now if i use class B IP address then has we have seen that my IP address inefficiency is five by 64 that is the efficiency that which i would be operated. The other way would be to look at that i instead of having one class B network i can have as many as around 20 class C networks.

If there are and each class C network having 256 machines. As a result, i would be able to address the problem of IP address efficiency quite well but what will be the disadvantage? The disadvantage will be that since the number of networks which are earlier only one class B network and now there will be as many as 20 class C networks. Since the number of networks has increased the number of entries in the intermediate routers or in the core routers will also increase and this will lead to an increase in the size of forwarding table. So, there is a trade off that exists by using this class full IP addressing scheme. On the one hand, you have the danger of IP addresses being used inefficiently. On the other hand, you have an increase in the size of the forwarding table.

So one has to you know really find an efficient solution which addresses the problem of not only reducing the size of the forwarding table. The size of the forwarding tables needs to be made more compact because, the memory is ultimately will be used to store the forwarding table and typically the cost of such memory in the core routers will tend to be very high and which will make the cost of the router to be very high if the size of such forwarding table is made high. It is large.

So we have to reduce the size of the forwarding table and by reducing the size of the forwarding table also it helps us in reducing the search time when an IP address when a packet comes with an IP address. On the other hand, we would also like to use the IP addresses efficiently because we have just two raised to power 32 IP addresses and considering the fact that there is an explosion of hosts on the internet. We have to use judiciously the IP addresses. So, with this you know to balance this out several schemes were proposed to address the problem of both the scalability in the internet should be maintained, the efficiency of the IP address space should be maintained, as well as the size of the forwarding tables should be reduced.

So we have to you know address a somewhat a conflicting requirements from an IP addressing scheme. By the way here, i would just like to tell you that since three classes of IP addresses were defined class A, class B, class C. When an IP address when a destination when a packet comes to the destination IP address and we need to look, then the look up is very simple. You first need to determine whether it is a class A IP address or whether it is a class B IP address or whether it is a class C IP address and once you determine that, it is a class A or class B, you can make you know pointer to the three different routing tables.

So we may have a three forwarding tables each for class A, class B and class C IP address and then try to do it. So once you determine that it is a class A IP address, then you know you can do an exact match for the network number in your entry. So, therefore the search operation is very simple. You have to first determine whether it is a class A, class B or class C IP address and then perform an exact match. Now, to distinguish whether it is a class A, class B or class C IP address, what it is done is, in a class A the first bit here is 0.

so actually speaking only seven bits are used to determine the network number. So this first bit so if we are employing a classful IP address scheme and the first bit happens to be 0, then it is a class A IP address. Similarly in the class B IP address the first two bits are you know 1 and 0

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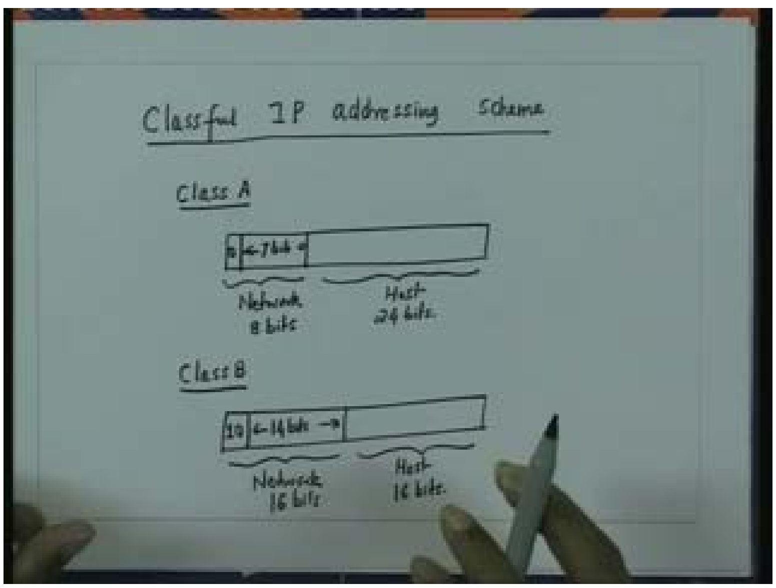

So which means only 14 bits are available to address the network. So, in the class A actually the number of networks which can be there is very limited to 2 raised to power of 7 which is 128 networks and in class B the number of networks are really limited to 2 raised to power 14. Now since first two bits are 1 0, they are used to represent the class B IP address.

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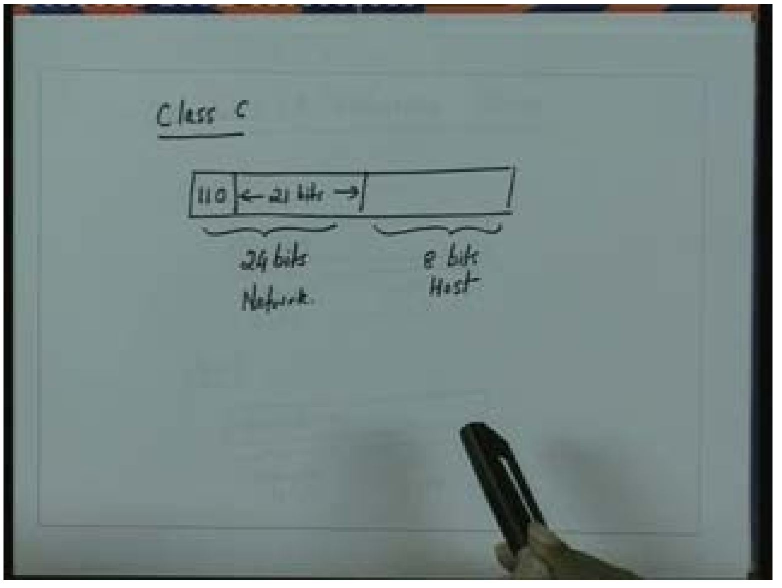

The class C IP address is indicated by first three bits being 110. So, as a result in class C actually only 21 bits are available to represent a network. So the remaining three bits are actually used to determine whether it is a class C IP address. So the algorithm would be that you will determine whether the first bit is zero. So if the first bit is zero, then you know it is a class A IP address. However the first bit is 1, then you search for the second bit okay and the second bit happens to be zero then you know that it is a class B IP address and if the second bit happens to be 1, then you examine for the third bit if it is 0 then it is a class C IP address and if it is 1 then it is a class D IP address which is used for the multitask purposes but we are not going to discuss the class D IP addresses here.

So, initially you know the first three bits s is in search in first three bits you can determine whether it is a class A IP address, class B IP address and class C IP address and accordingly you can go into the respective forwarding tables, perform an exact match and determine where the packet needs to be forwarded. So, the search operation is very simple if we are using classful IP addressing scheme but just as we discussed that we yet to address the problem of scalability of the internet efficiency of the IP addressing schemes and keeping the size of the forwarding table simple.

Now let us see how this problem was introduced? How this problem was addressed? Particularly you know to resolve the problems of class B IP addressing schemes. So, to resolve the problem of class B IP addressing schemes which is that 16 bits of the host numbers is too large number, the concept of sub netting was introduced.

So, in sub netting you are having another level of another level of addressing hierarchy apart from the network number and the host number and this is called as the subnet number. So what you do is that typically you know in IP address, you have the network number and you have the host number.

Now, if the entire network does not have let us say 65,000 machines, then what you do is that geographically networks which are geographically together treat them as one class B networks. So there maybe four five geographically co-located networks, you can treat them as one network as far as the outside internet world is concerned they are one network. Now between them, what you can do is that this host number in 16 bits, you can divide them into subnet number and the actual host number. So what you can do is, subnet number, subnet id and host id.

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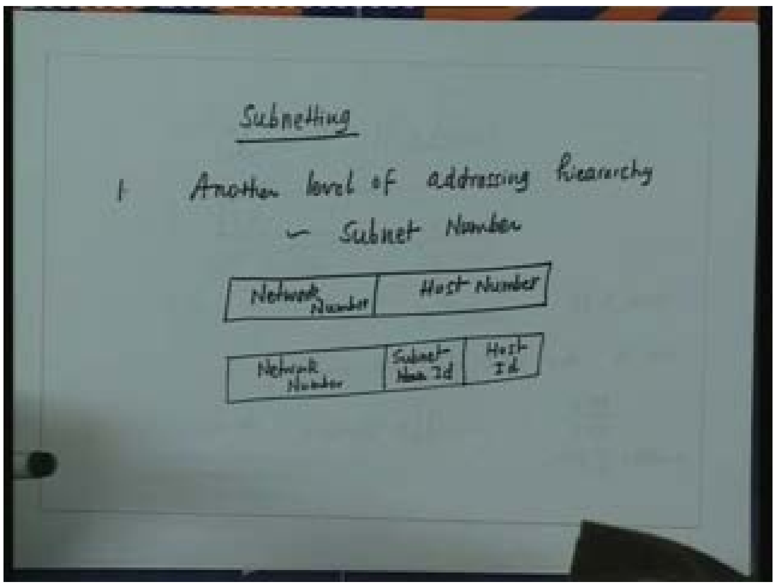

So for example: this 16 bit of the host number, you can divide it into eight bits for the subnet id and eight bits for the host ids. For example: this could be eight bits and this could be eight bits. So as a result what can happen is that, suppose there are something like 200 geographically co-located networks are there and each of these networks is having let us say about 200 to 250 machines, then what we can do is that, all these networks can be treated as one single network as far as the outside internet world is concerned.

Now between them, we can distinguish each of these networks by their subnet id by this, first you know eight bits. We can distinguish each of them like that and so basically what we can do is when a packet comes the router which is connected to you know all these networks. All the packets which are meant for any of the machines on any of these geographically co-located networks will get forwarded to the immediate router which is connected. Now last hop for getting it connected to these geographically co-located networks. Now once the packet comes to this router, this router will then determine from the subnet id to which one of the subnets, now the packet needs to be forwarded.

Now this router will then forward the packets to that router, you know the respective router which is connected to you know the particular subnet and then the subnet router finally will forward the packet to an appropriate host. Now the division of the host number into subnet id and the host id can be done by a network administrator. If there are just four subnets, then your subnet id can be just 2 bits and your host id can be 14 bits. Now this boundary is therefore variable and this can be identified by what we called as the subnet mask. So the network administrator can actually define what is called as a subnet mask and that can be used to create the division of the host number between the subnet id and the host id. For example: in this particular case,

You can have the subnet mask. It consists of the network number and the subnet ids you know all 1s all 1s and here all 0s. So your subnet mask in this case could be 255 dot in the decimal notation if we write 255 dot 255 dot 255 dot 0, this could be your subnet mask.

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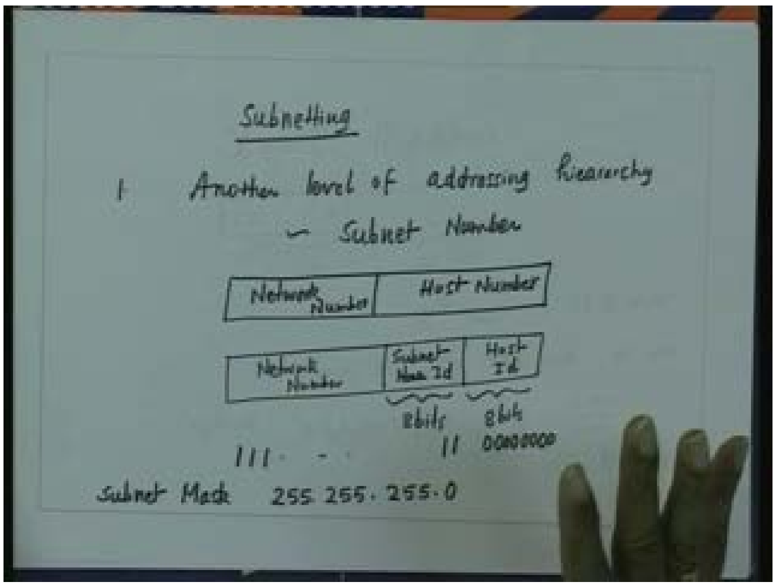

Now this can to a large extent address the problem of IP address scheme inefficiency that has come because of the class B IP addresses you know if you assign a full 16 bit to a particular network. So sub netting can actually address that problem to a large extent. The other extreme of addressing this problem fully is what is called as classless inter-domain routing. So, let me just explain what is a classless inter domain routing?

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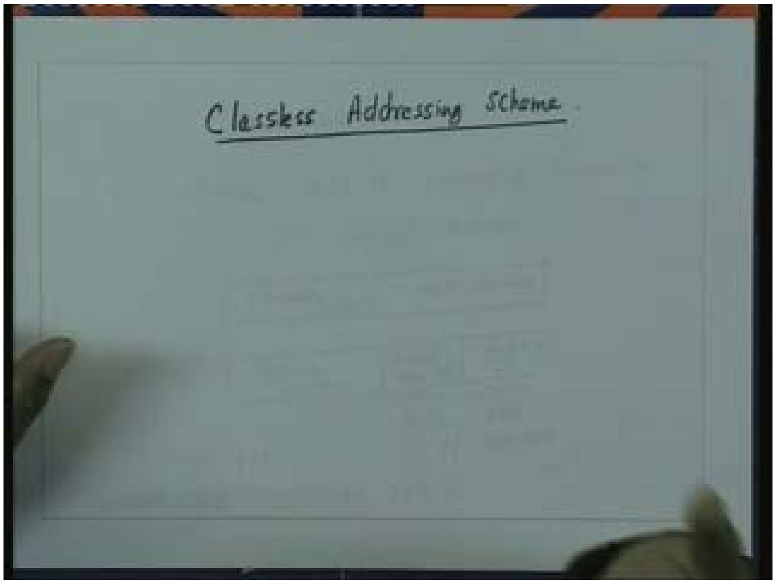

Although the sub netting does address the problem of IP address inefficiency of the class B IP addresses, it still does does not resolve the problem completely because what you can have, it really depends on the fact that how many those geographically co-located networks are there which can be classified as subnet. Suppose there are four such networks only, then in that case you will require only two bits for the subnet id and then remaining 14 bits have to be there for the host id. Now if 14 bits are there for the host id, then you can address as many as 2 raised to power 14 machines and if each of these subnets have only 300 to 400 or you know 500 machines, then again you land up in the problem of the same IP address inefficiency. We are not using the bits which are being allocated to the host number in an efficient manner.

So, you know the ideal situation for the class B IP addresses scheme to be get resolved completely by using sub netting is that you have as many number of subnets and on each subnet these hosts are very nicely divided in such a manner that you can make a nice division of the host number and the subnet id and host id and then make use of the IP addresses addressing scheme in an efficient manner. Now, therefore you know it is required to have a new scheme and classless addressing scheme was then introduced which is now very prevalent today in the internet world. So let us understand what is classless addressing scheme, which is also called CIDR which is called classless inter domain routing.

The basic idea of the classless inter domain routing is very simple. It stresses that the bits remember that, in the classful addressing schemes fixed number of bits are used to represent the network number, that is 7 bits in class A, 14 bits in class B and 21 bits in class C. So that there are fixed number of bits which are used to represent a network number. The basic idea in the classless inter domain routing is, that these prefixes which are used to represent the network numbers, they can be of any length. So, the basic idea is that the prefixes should not be fixed seven bits or fourteen bits or twenty-one bits or eight bits or sixteen bits or twenty-four bits.

They should not be fixed, but they can be of any arbitrary length. So the basic idea is that the prefixes the address prefixes can be of arbitrary length and not fixed.

Now, how many bits will be used to represent that network number that will actually depend upon, what is the aggregation of various hosts into a network that is possible? Now, remember that in classful IP addressing scheme, the aggregation was fixed. It was either at 7 bits or 8 bits or 16 bits or 24 bits. Now here in the classless inter domain routing you can have aggregation at any level. So therefore, aggregation can be performed at several levels and not just as at the fixed boundaries.

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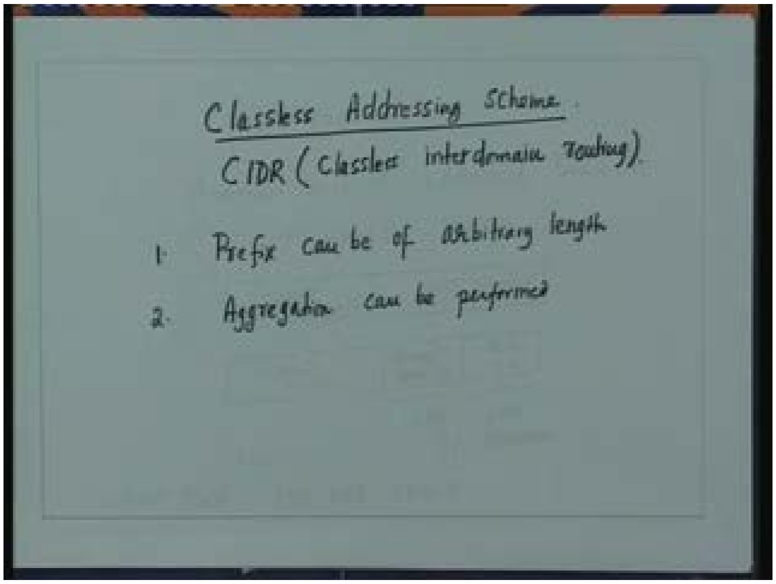

Now let us take up an example to explain these schemes. Consider for example: 16 networks and these 16 networks are let us say 144 dot 16 dot 16 dot x to 144 dot 16 dot 31 dot x. These are you know 16 networks and they are reachable through an through an isp router. Now actually these are class B IP addresses and they maybe reachable through an isp router. Now, if you look at these addresses you will find that of course the first 16 bits are common in these IP addresses, but if you look carefully actually the first 20 bits are common. So, you can see from here observation that leftmost. Let us say that these are reachable through an isp, so leftmost 20 bits are common.

Now typically in the forwarding table, since these are 16 separate networks, you would have had 16 entries in that isp router but you recognize that all the 16 networks are reachable through a particular isp router and the first 20 bits of these addresses are common. In that case, these 16 networks can be aggregated into one network where the network number is this first 20 bits which are common to all the networks. So that means, these 16 networks can be aggregated into a super network and the forwarding table of the core routers now, we have just one entry instead of having 16 entries and that one entry will be 144 dot 16 dot 16 20. This is represented by this.

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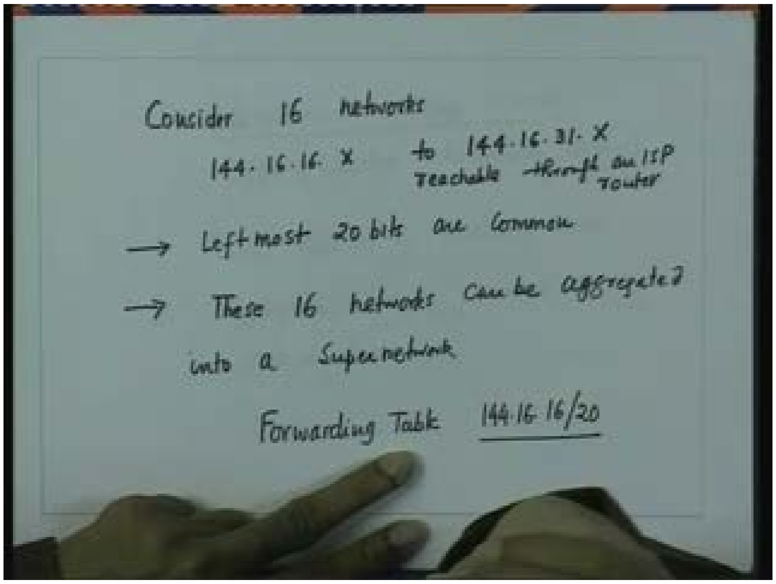

This means that if i write this in the binary notation 144 dot 16 dot 16. These are 24 bits but the first 20 bits of this represent the address of these super networks. Now, this can lead to not only the IP addressing efficiency and i will just explain how this leads to the IP addressing scheme efficiency but it can also you know this can not only leads to an IP addresses efficiency, but it can also reduce the size of the forwarding table considerably. Look at this way: Instead of these class B IP addresses this could have been class C IP address which was 192.16 dot 16. This could have been a class C IP addresses also.

Now as you are just saying that suppose that, there was a network which was having 5000 hosts. Now one alternative would have been to allot this network a block of class B IP address. If you do that, then we can have possible number of hosts 2 raised to power 16, but this particular host has only 5000 hosts. So, therefore as we have seen the address inefficiency of 5 by 64, instead of that what we could have done is that this network of 5000 machines we could have divided into 20 class C networks. Each networks having something like 250 machines 250 into 20. There will be around 5000 machines. We can have each of these networks to be class C networks.

Now while allotting the addresses what we could have done is that we could have allotted consecutive blocks of class C IP addresses. If i allocate consecutive blocks of class C IP addresses, i can say that some of the bits in them will be common. So instead of therefore having, 20 entries for class C networks which actually increases the size of the forwarding table. I can do the aggregation not necessarily at 24 bits or 16 bits but i can just find how many bits are common okay and then have only one entry in the forwarding table by representing it to be the address prefix which is common among all the hosts in the network. So, therefore what is done in the classless inter domain routing that really speaking, the first bits which are common among all the hosts are used to represent the address of the network number rather than you know the fixed 8 bit 16 bit or at 24 bit boundary.

This can not only lead to the efficient use of the IP addresses, but can also reduce the size of the forwarding table. So, that is the advantage of classless Inter domain routing. However it does lead to some serious problem in the look up search. Remember that when we were having classful IP addressing scheme, the search was very simple there were three tables corresponding to class A IP addresses, class B IP addresses, and class C IP addresses.

All you need to determine whether the destination IP address is a class A IP address or class B IP address or class C IP address and once you determine that, it is a particular class address you just do an exact match in that forwarding table and once the match is found, you will determine that on which output port the packet needs to be forwarded. So the search operation was extremely simple when we were employing classful IP addressing scheme but with the classless IP addressing scheme the search problem becomes little more complicated. Let me just illustrate with an example.

Now suppose you were earlier having the entry which we were just saying 144, you know dot or let us say you know let us say take the example of class C IP addresses. Let us say we had this 192 dot 14 dot 16 to 192 dot 4 dot 30 sorry 31 right. So, these were your 16 networks and you can see that they were aggregated to 192 dot 14 dot 16/20. First leftmost 20 bits are common. Now all these networks can be you know reached are reachable if you represent them by the first 20 bit. Now suppose out of these the network 192 dot 4 dot 21 dot x, it changes its isp and therefore it is no longer reachable through the same router through which these networks were reachable.

So if that is so, then what we will have to do is that now the forwarding table will have two entries. Now has two entries one is 192 dot 4 dot 16 twenty and another one is 192 dot 4 dot 21 24 because this now represents the complete IP address. Now what happens when a particular destination IP address comes when a packet comes with a particular destination IP address that needs to be looked up unfortunately it matches both the entries. Let us take a concrete case you know, let us say that an IP address something like 192 dot 4 dot 17 dot 192 it comes. Now this IP address as we can see that oh sorry it matches the entry like 21 sorry an IP address like 192 dot 4 dot 21 dot 192 comes.

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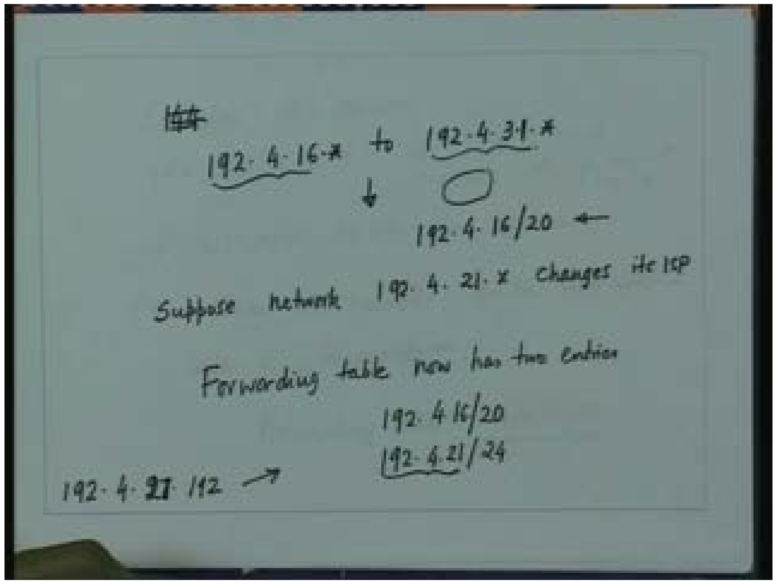

Now remember that, this host lies on this network, but it matches both the entries because in this case also the first 20 bits are common. However, we know that this particular host lies on this network and therefore a forwarding decision must be taken based upon this second entry. So what is the rule that we need to use? If a particular IP address matches more than one entry, then we need to select the longest match. We need to select actually the longest match. So this is what is called as the so basically what we are saying is that some addresses will match both the entries or several entries and we need to select the longest prefix match.

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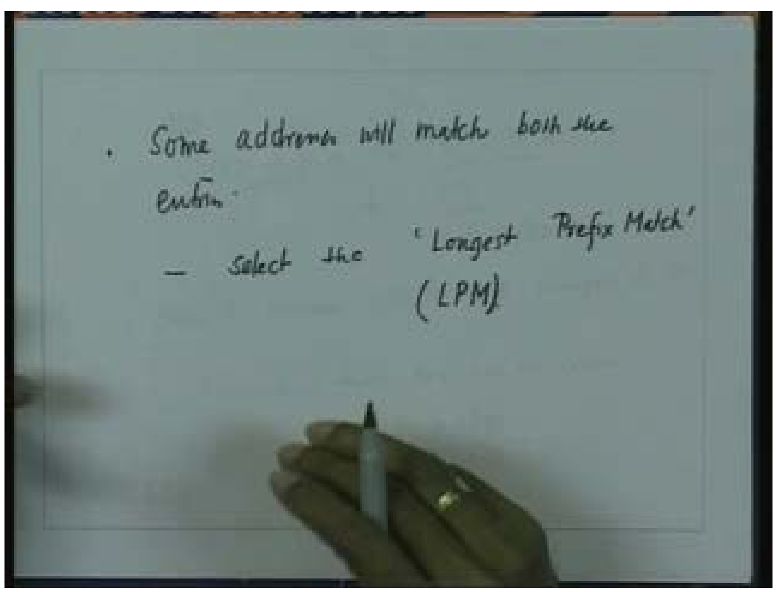

So while classless inter domain routing has addressed the problem of IP address efficiency quite nicely and also has reduced the size of the forwarding table by allowing aggregation at arbitrary levels, it has led to a serious problem that the IP address lookup or the search is no longer exact match, but it is a longest prefix match. Now, the longest prefix match therefore becomes one of the bottleneck in the forwarding performance of an internet router and therefore there has been a host of research on developing algorithms, for finding the longest prefix match in the shortest possible time because the forwarding performance of a router depends upon determining the next hop by taking a decision based on the longest prefix match.

So, what we will be doing now is? We will be studying some of the algorithms which have been used for the longest prefix match in an internet router. The solutions which have been proposed for the longest prefix match are both you know the software based solutions and a second one is the hardware solutions. Typically, you know the software based solutions will work like something like this that there is a network processor to which a memory is attached, something like you know a network processor to an sd ram.

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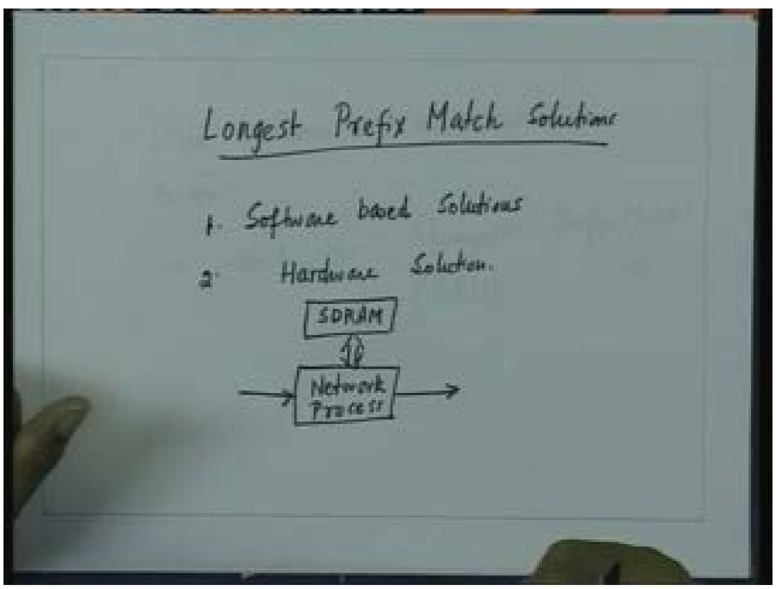

The forwarding table is stored in this sd ram and the network processor runs an algorithm whenever a destination IP packet comes the network processor runs an algorithm and does a search in the memory and determines to which hop, the packet needs to be forwarded. Now various in innovative algorithms have been proposed and specific the crux of all these algorithms is to arrange the forwarding database in the memory in such a manner that the search becomes faster.

So that is you know the IP address scheme which are basically implemented in a network processor in a internet router. The other schemes are hardware based which are using either content addressable memory key cam or specific or chips which have been designed to address the problem of lookup efficiently. So we will be discussing both the software based solutions as well as the hardware based solutions. Now one important thing one must look up from the performances of an IP addressing scheme is there are two issues of the performance matrix of a lookup algorithm.

One thing of course is that, the algorithms should be having a very small search time. So, it should be having a good search time. Typically, we need wire speed performances of an IP lookup algorithm. So we are looking for wire speed performance. Secondly, the important thing is that when a route change occurs in an internet this also gets reflected in the routing database. Now this routing database is really a database of these prefixes which are in store. Whenever a routing change occurs, whenever this aggregation hierarchy changes it reflects a change in the routing database. Now if a routing database change occurs then your forwarding database therefore needs to be updated and the performance of a lookup algorithm will also be determined by how much is the update time?

On an average, it has been found that the route changes approximately 100 times a second. Therefore the update performance of an algorithm must be of the order of few milliseconds and the search time will of course depend upon what is the packet processing power that you are seeking from the IP lookup algorithms?

If the interfaces happen to be the gigabit speed, then the lookup times must be in microseconds or in nanoseconds range the search time or the lookup time and update times can be of few milliseconds. So, now that is the performance levels that we are seeking from an IP lookup algorithm. The lookup algorithm should also be scalable with respect to the number of prefixes.

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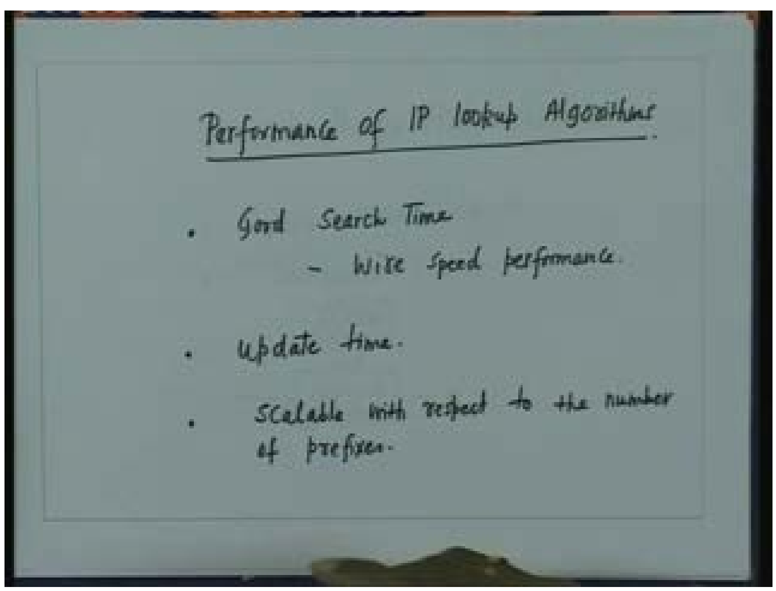

Earlier, you know there was a heavy when the classless inter domain routing was introduced. There was a considerable level of aggregation, in the internet routers and therefore the classless inter domain routing really reduced the size of the forwarding table, but today you know we are seeing actually if there are shorter prefixes are there, then they actually represent more aggregations.

Today, we have seen that the size of the routing table also exploding. There are many exceptions in the routing table. Exception means where aggregations cannot take place and therefore we need to store an entry separately. So therefore the size of the routing table is also increasing and therefore the performance of any IP lookup algorithm needs to be scalable with respect to the size of the forwarding table entries also. So we will look at the issues of the lookup time, the update time and the scalability of an IP lookup algorithm with regard to the number of prefixes you know which are there.

Typically, as i was pointing out in the internet routers, when a packet comes, the packet needs to undergo the IP address lookup and then the packet needs to be classified into one of the classes. We will actually later on see that IP address lookup actually is a special case of packet classification. So, a generic router will have a generic classification engine which can do the job of both the lookup as well as the packet classification and special purpose processors are used to do these jobs which have been actually optimized for doing this lookup and packet classification operations and that is why they have been termed as network processors. So what we will do in the next lecture is that lookup at some of the IP address lookup algorithms, both which can be implemented on the network processors and some of the hardware architectures that have been proposed recently for performing the IP address lookup at wire speed.