**Basic electronics**
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**Lecture- 20**

**Integrated Chip (IC's)**
**Operation Amplifier-Introduction**

Hello everybody! In a series of lecture on basic electronics learning by doing let us move on to the next one. Before we do that let us recapitulate what we discussed in the previous lecture.

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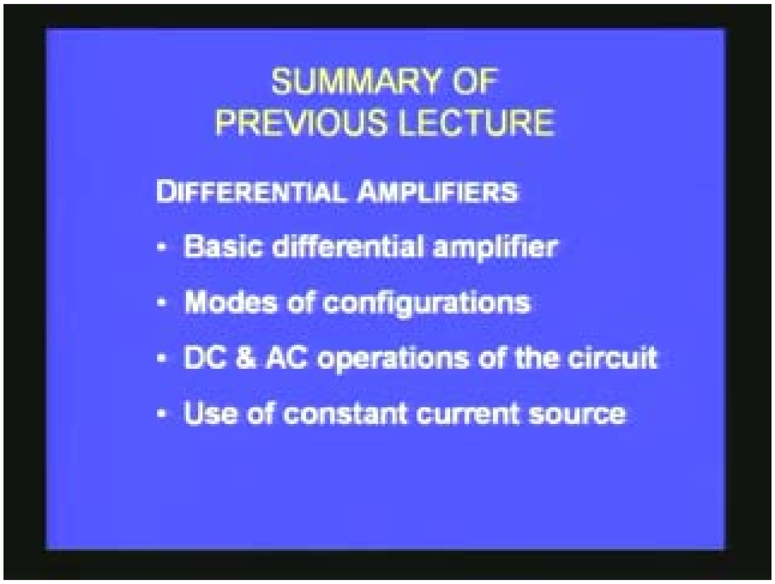


You might recall in the previous lecture we discussed about transistorized differential amplifier. We discussed the basic differential amplifier formed by two transistors what is known generally as the long tail pair and then we discussed about the different configurations like single ended, double ended input and output. We also discussed the ac and the dc configuration of the circuits and how a constant current source when used for biasing the emitter of the two transistors can improve on the common mode with ….. ratio. I hope you remember these things. Now we will move on to the next topic which is integrated circuit operational amplifiers. All the discussions which we had so far is basically to prepare us to understand this idea and the circuit and the applications of operational amplifiers. Before we go further it is important to understand what is an integrated circuit? What are operational amplifiers? What are its characteristics and what are its application which is most important for us for learning and applying electronics in different situations. What is an integration circuit? A preliminary background for understanding what is an integrated circuit was already given in the last portion of the previous lecture immediately after differential amplifier I was mentioning to you that when you have the resistors, capacitors all can be prepared along with the transistors on the same silicon chip. Then they can be positioned very close to each other on the same silicon chip and that means you can now have a whole circuit which involves basically resistors, capacitors and transistors together all integrated all the functionalities are integrated on to the same area of the silicon and then it becomes an integrated circuit. It is no more a device like a transistor or a resistor or a field effect transistor. Now it is a whole circuit which has been now formed on the silicon chip. That is why it is called integrated circuit. It is all integrated on a very small region of the silicon chip by using what is known as a planar technology. In a planar technology on the same side of the plane you are able to generate the various resistors, capacitors and transistors. We will see how it is in a moment. Before we do that you can actually classify the integrated circuits into a number of ways. For example there are monolithic circuits. Monolithic means one single silicon chip on which the entire circuit is built. Then it becomes monolithic.

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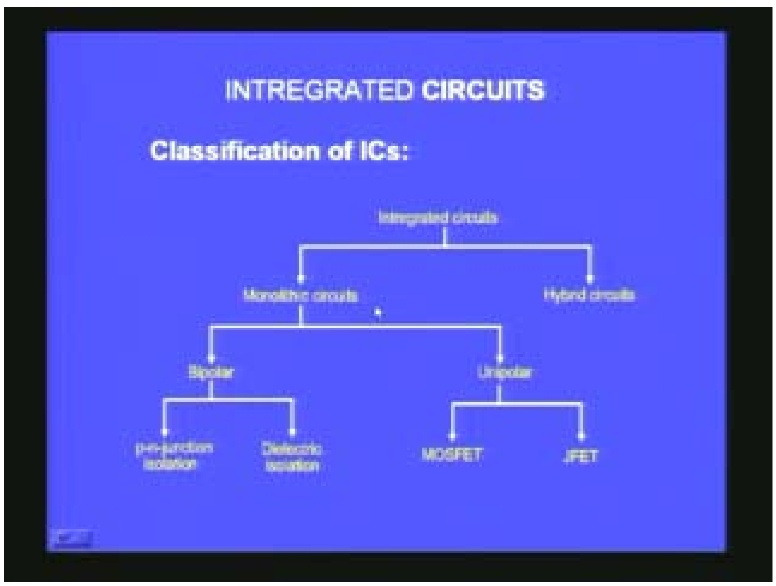


You also have hybrid circuits. There you will have some integrated components apart from some discrete components together forming a circuit. For example making inductances is very difficult in integration circuit that I mentioned also earlier. If I want to make a LC oscillator I can actually integrate all the rest of the components on to the same silicon chip and then also have the inductance alone put as a separate unit, discrete unit along with this silicon ship. Then together they form our oscillator that we wanted to design. Then it becomes a hybrid. In the sense there are two different types. You have an integrated version of the circuit you also have a discrete version of the circuit. Therefore we call it as a hybrid circuit. Together this entire thing can come inside a small package and therefore it will still appear very small as an integrated circuit. But we know that it has got two different components one is an integrated component and the other is the discrete component both together incorporated into the same encapsulation. So that becomes a hybrid circuit.

Then if you take the monolithic circuit which is the most popular among the integrated circuits you can have a monolithic circuit based on bipolar transistors like normal BJT's, or what they are known as bipolar junction transistors which are the usual transistors that we have been discussing about all along. You can also have another type of circuit built with unipolar devices. Basically unipolar devices are field effect transistors. Among the bipolar in the actual design of the integrated circuit there could be a difference. For example there could be a pn junction isolation or dielectric isolation. Let me not go deeper into that. Similarly on the unipolar you can have two different things. MOSFET, metal oxide semi conductor field effect transistor or you can have junction field effect transistors integrated into the circuit. MOSFET is the most popular among these two for several reasons. So you have different classification of the integrated circuits and then you also have another type of classification in terms of the number of components that are integrated into the same silicon chip.

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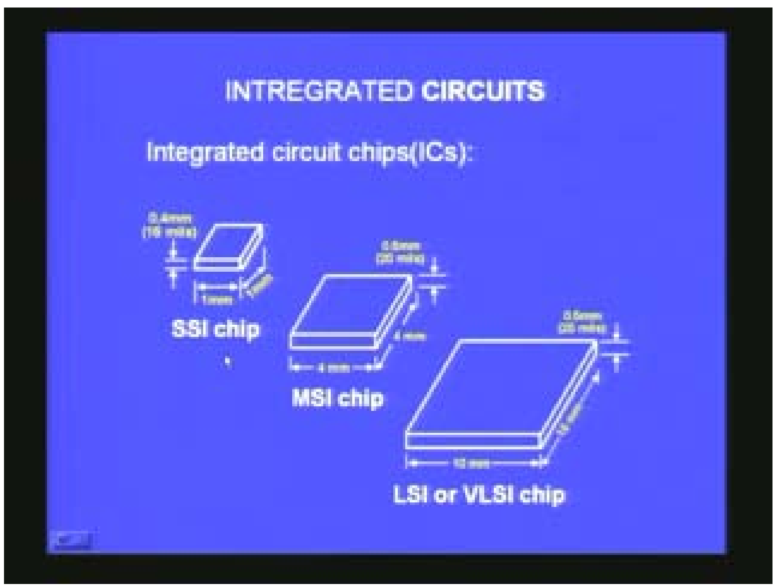


Here in the first picture what is shown is called SSi chip which is the small scale integrated circuit. This chip has got different components in a smaller number. Usually less than around 10 if you have in single silicon chip then it is called SSi chip, small scale integration. But the typical dimension of such a chip will be for example 1 mm by 1 mm square with a very small width or thickness about 0.4 mm silicon. You can also have much larger number of components integrated into the circuit. When you go to more complicated levels then you get what you call MSI chip. MSI mean medium scale integration where the number of components can be anywhere between 10 to 100 and the area of the silicon chip also increases. You have now not 1 millimeter but 4 millimeter by 4 millimeter square and you can get about 0.5 millimeter thickness. On this one can integrate several tonnes of components together. Then it becomes an integrated circuit which is medium scale integration. Then what is more popular these days is the LSI or the VLSI where you have components which are any where from 100 to several millions.

All these million components or thousands of components or hundreds of components can all be formed on the same side of the silicon chip where the dimensions will be typically 10 millimeter by 10 millimeter square with the thickness of about 0.5 millimeter.

All these technologies were possible because of the developments in the actual semi conductor field. The whole difficulty is in terms of forming very fine connections between the various components. You can provide isolation between one device and the other device and these are the very big issues which have to be overcome before we can increase the level of integration. Now it is very common place to have millions of components. In several memory devices that we will talk about they are all made with the VLSI design. Several new designs have come which are coming under the group of very large scale integration. VLSI mean very large scale integration and LSI means large scale. Anything above 100 is called LSI. Anything very large like thousands and millions we call it as very large scale integration and the whole technology by itself is a subject of study. One can take a very systematic study of the design of VLSI chip at a future stage. But before we go into the actual thing briefly let us look at how it is all done. To demystify how the various components can be done on the same side of a silicon wafer I have given a typical example here.

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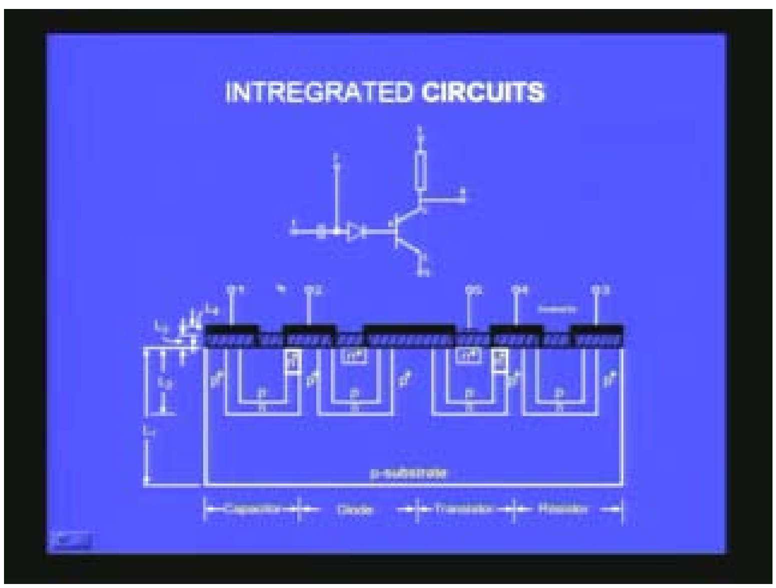


You see a circuit on top which has got a capacitor at the input, coupling capacitor. You have a diode; you have a transistor; you have a resistor. These are the different components. But you want to get all these components on the same side of the silicon wafer. The silicon strip is called silicon wafer; the thin wafer. It is done by different stages of manufacturing. I have given here a very simple typical example where you can see this portion corresponds to a capacitor and the second portion is the diode and third portion is actually the transistor and the last one is a resistor. All of them are positioned side by side and on top you put the metal interconnections in the way you want to have the connections in the circuit. For example the diode cathode will be connected to the base by properly connecting them together. This is actually the collector being connected to the resistor and this is on the base that is being connected to the diode. You can see the interconnections are also made by using gold or any other metal and you form small tracks of metal to interconnect the various devices and the whole thing becomes now a circuit. Starting with a p subscript you try to generate the different layers like the p or the n whenever you want the diode or a transistor and you can form the whole device on that. This is a very ingenious way of building circuit on the same thing and you know there are two great men who are associated with this idea. They are Jack Kilby and Robert Noyce. Jack Kilby as you might perhaps know got his Nobel Prize in physics in the year 2000 for his invention of this integrated circuit technology. Robert Noyce is also associated with this. But unfortunately he died before the Nobel committee found fit for awarding Nobel Prize to this invention and he could not be given. Jack Kilby and Robert Noyce both of them are associated with this integrated circuit technology.

To go little deeper into that how do we get the different n type, p type, etc I just want to briefly indicate to you that you have a basic silicon wafer on which you form a photo resist which is actually a chemical polymer which is sensitive to light, ultra violet light for example.

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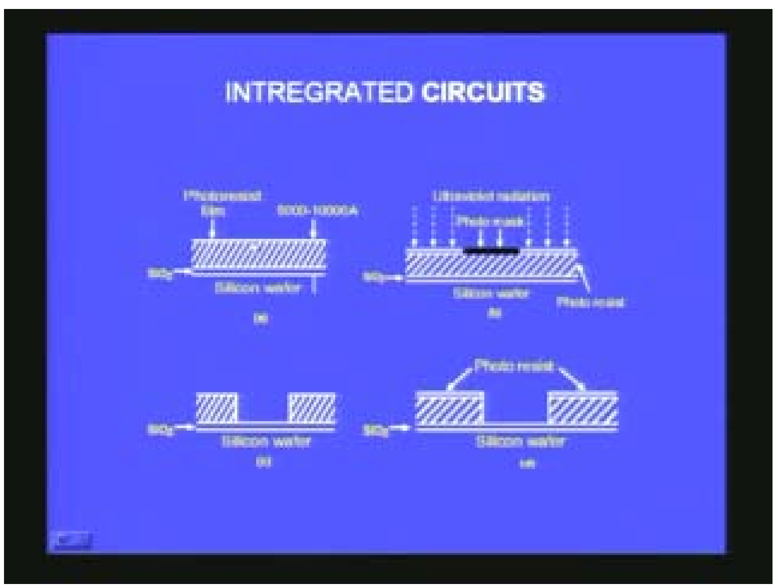


You form a very thin layer by what is known as a skin coating over about 5000 to 10,000 Armstrong, very thin area. One Armstrong is 10 to the power of -8 cm or 10 to the power of -10 meter. You have on the silicon wafer a small layer of silicon dioxide, oxide layer which is called an insulating layer and over which you put a photo resist film and then you put a mask on top where you want no device and where you want the device you don't put any mask and you expose it to ultra violet radiation. Then wherever the light comes for example in this region, in this region there is no mask and you get the ultra violet rays reaching here and they react with the photo resist film and when you develop it like a photographic film these things will go away and they will expose the rest of the region below it. Whereas in this place you have put a photo mask and it will cover the region. Then you can actually etch. When you put an etch, the etching will happen only in the place where there is the mask and in all other places there won't be any etching. Thereby you can form different patterns, very sharp, fine details on the silicon chip and therefore you can have different types of devices developed over this. Let me do not go too much deep into that but I just want to show you another picture here where we have shown actually a transistor.

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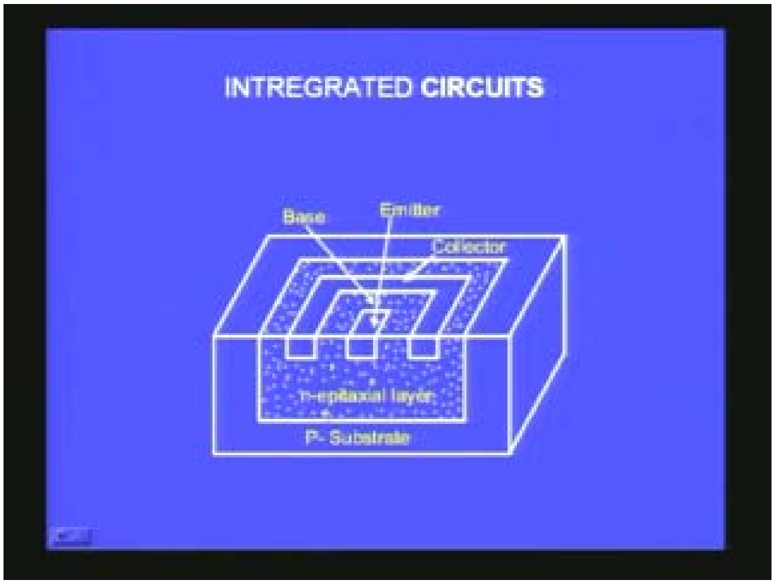


You have a basic p type substrate into which you would generate n type epitaxial layer and then you have a collector and you have an emitter and whatever is in between the n type epitaxial layer forms the base and you have pnp transistor on the same surface. On the same surface you have the pnp transistor. One is the emitter, the other is the base and the other is the collector. So you can form them and you can take metal leads from this and then they can be connected to other parts of the circuit. So this forms an integrated transistor.

There is another advantage in the integrated circuit design and that is from the same transistor you can have multiple emitters. This is an example of Schottky transistor where this is one emitter region where that is shown as p and you have taken three n type regions and you can take three emitters.

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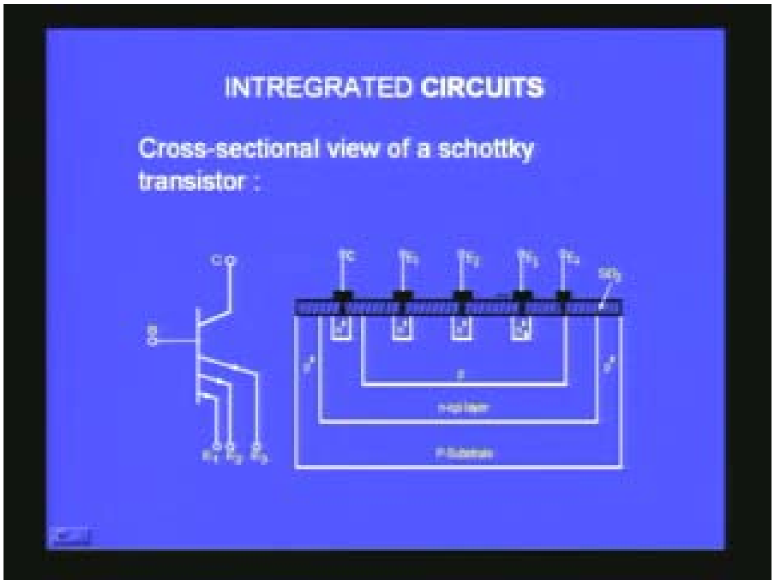


These three are emitters. This is the base and this is the collector; so collector, base and emitter. For the emitter you can choose a very small region and form n type region here and in the same again one more and one more; you can have multiple emitters form on the same p region and thereby you will get multiple emitters. That is what is shown here. This is one great advantage especially when you go to logic circuits you require multiple inputs. ICs they will look very similar to transistors.

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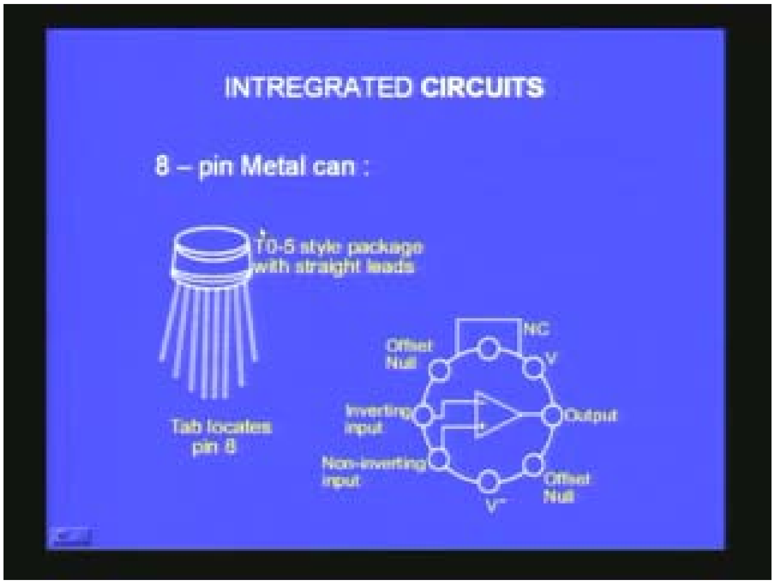

For example I have shown here different types of encapsulation. How the IC is mounted for application you have to take the small silicon chip, mount it on to a package and then take the leads to the pins of the package so that externally you can put them in a given circuit and form a different application circuit that you want. Otherwise it is very difficult for us to use in the lab. Here you have got two different packages. I have explained to you here. One is the metal can package which is basically like your SL 100 with which I showed some demonstrations earlier. The TO 5, transistor outline 5 style of package with 8 leads for the case of an operational amplifier for example. It is an 8 pin metal can with a tab. There will be a small projection in the metal can which gives us the idea of from where it starts; some reference point. I have shown the bottom view of the same metal can here. You can see this is the tab and you have got various pins here. All the pins are designated. For example this is the voltage, this is an output point, this is an offset null, $V^-$, non-inverting, inverting, etc and this is the symbol for op amp. We have already seen when we discussed about difference amplifier. This is one metal can. The other one is a mini dip, DIP. DIP means dual in line package. You have one line of outputs here and one more line of outputs on the opposite side parallel to each other. This we call dual in line plastic package.

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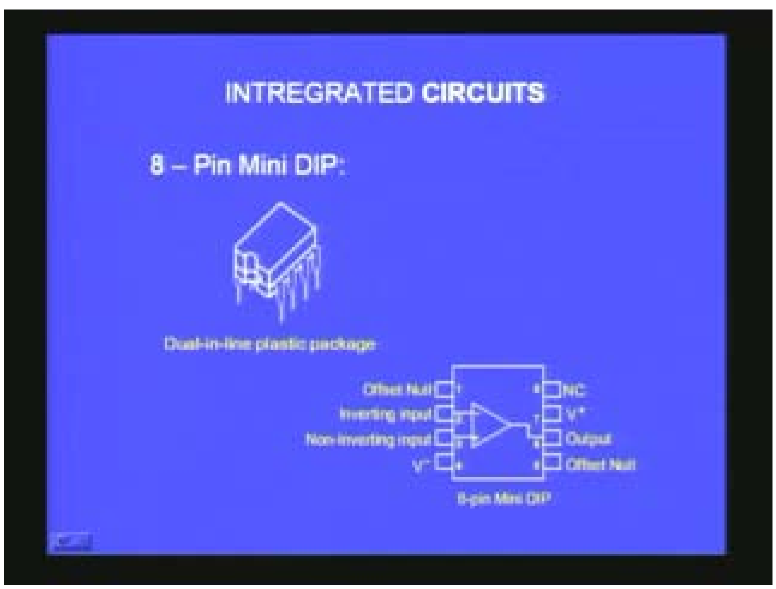


There is a plastic cover put on the silicon chip and the various contact points are taken from the silicon chip to the small pins over here; 4 + 4, 8 pins as the case may be and you can form different circuits encapsulated in plastic mini DIP. You can see here the corresponding pin diagram. These are usually from the top view. So you have 1, 2 , 3, 4; from the top you have to look at this and to identify that usually you will have a inundation here. That is what is shown here, small cavity. That cavity will come at the top here and that shows that to the left of that is 1, 2 and 3 when you look from the top side. This is mini DIP. To just give you an idea I have brought here two devices. I have brought two such operational amplifiers. One on a metal can another on a plastic dual in line package.

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You can see here on the screen this is the metal can TO 5 package. It has got 8 pins and the other one is actually a mini dip; 4 + 4, 8 pins are there. This is also an operational amplifier. So this is an operational amplifier this is also an operational amplifier. Both are integrated circuits 741 operational amplifiers which is one of the very popular operational amplifiers. If you look at the sides you will be able to see the pins here. There are several pins over here. Similarly the 4 pins on one side you are able to see. Other packaging schemes are also available. For example here is a 14 lead dual in line package.

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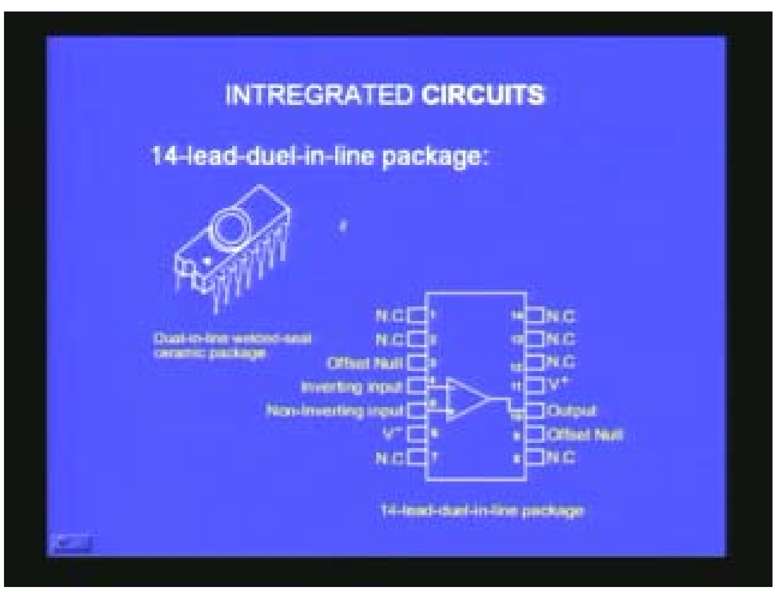

When you come to digital electronics you will come across several such devices. All of them have 7 on one side and another 7 on the other side 14 pin …….. 16 pin. You have several other; 40 pin for different types of circuits. You also have a 10 lead flat pack where you have a flat pack with 4 + 4, 8 pins on either side and that also is another package.

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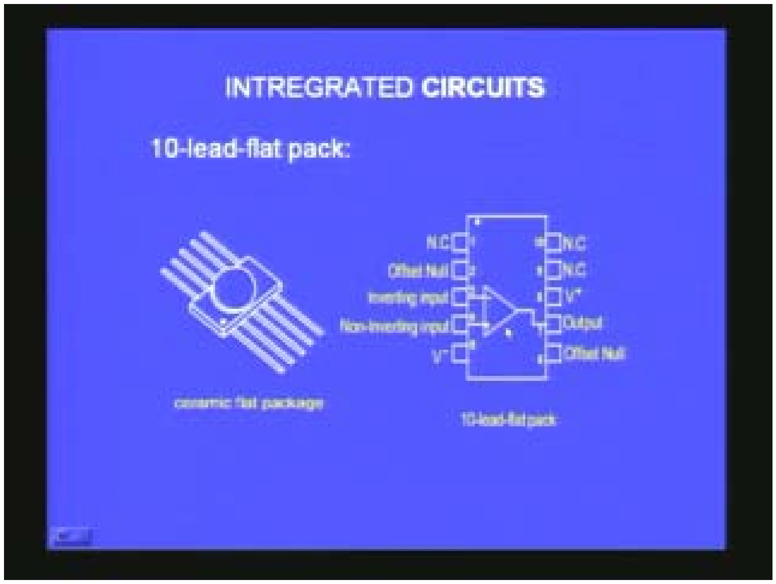


Generally for the general purpose use we use either the metal can or the plastic. One other thing that we should realize when we go to the operational amplifier is that most of the time we require a dual supply. What do you mean by a dual supply?

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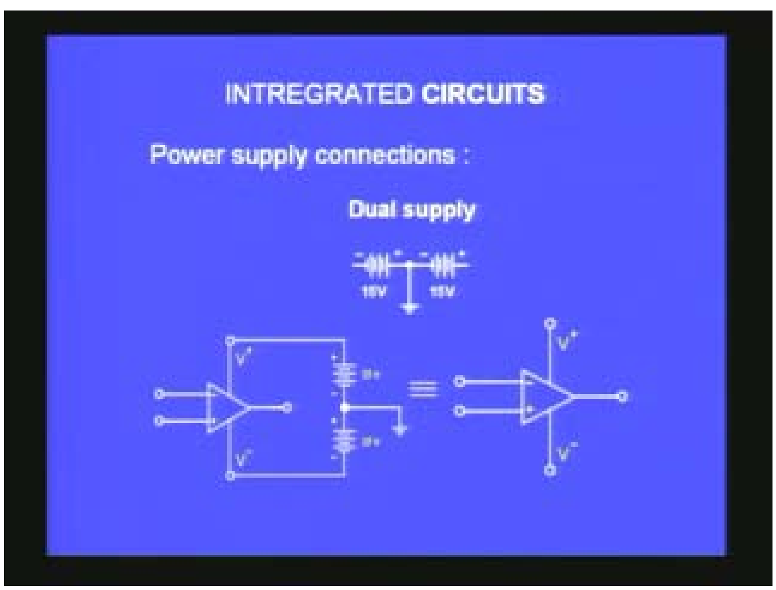

I have shown here what is a dual supply? A dual supply as the name suggests is actually two supplies. You have to have two supplies. For example I have used 2 15 volts batteries. Then you interconnect them in series. How do you interconnect them in series? You take the positive of one of the battery connect to the negative of the other battery and keep that junction point which is connecting the two batteries as your common point or the ground point. If you now look at this end of the battery, one of the batteries, this is grounded. That means the negative is grounded and therefore it becomes a plus supply, plus with reference to ground. If you look at the other side the plus end of this battery is connected to the ground and what you get is a minus supply with reference to the ground. So you have now 3 terminals from 2 batteries. One is the plus terminal the other is the minus terminal the third one is the common terminal which is the zero terminal. With reference to zero this end is + 15 volts this end is -15 volts. So we require this. I have shown here a very simple picture where the op amp, the symbol is shown here, is connected to $V^+$ and $V^-$ are now connected to two batteries the way I showed you here and the center point is maintained as the common ground and you have plus going here and minus going here. This is what we call a dual supply. We require a dual supply so that you can have large amplitudes of signals amplified by the operational amplifier when you have ac signals.

But normally when we draw different circuit in operational amplifier we will not show this power supply connection in detail because this is understood. That is why I spent lot of time explaining to you how to do this in an actual situation by using two different batteries so that in future you need not worry about this. Every body knows and so we will just show that there is one $V^+$ and one $V^-$. That means there is also a common ground. So this will be the symbol that we will be using when we describe different circuits using op amp. But in the lab you don't have a dual supply; you don't have two different supplies which are having floating terminals, terminals not connected to any common or ground. If you don't have such then it becomes difficult. How do you generate a dual supply?

I have given couple of suggestions here. You can see if I have one single power supply I can put two resistors R and R reasonably large value resistors and keep the center to a ground. Then with reference to this ground this end will be half the voltage of $V_S$, $V_S/2$ and this end will be half the voltage on the other side $–V_S/2$. I can have additionally some capacitors here so that that takes care of any transients and when I have such an RC combination parallel connected together and the center connected to ground I can have plus $+V_S/2$ and $-+V_S/2$ corresponding to $V_S$ that I use and this can be used in our operational amplifier circuits. The other ways to do that is use the same $V_S$ supply and introduce two zener diodes. You have a $R_S$ here. You have already seen that no zener diode which should be connected without the series resistor. So there is a $R_S$ which takes care of the current to limit the current and you have the two zener diodes and depending upon the break down voltage of the two zener's you will have two voltages corresponding to the break down voltage in zener and because this end is connected to the ground this end will become minus this end becomes plus. So you will have +V and minus on the other side with reference to the ground. This can be used as a dual supply for an operational amplifier.

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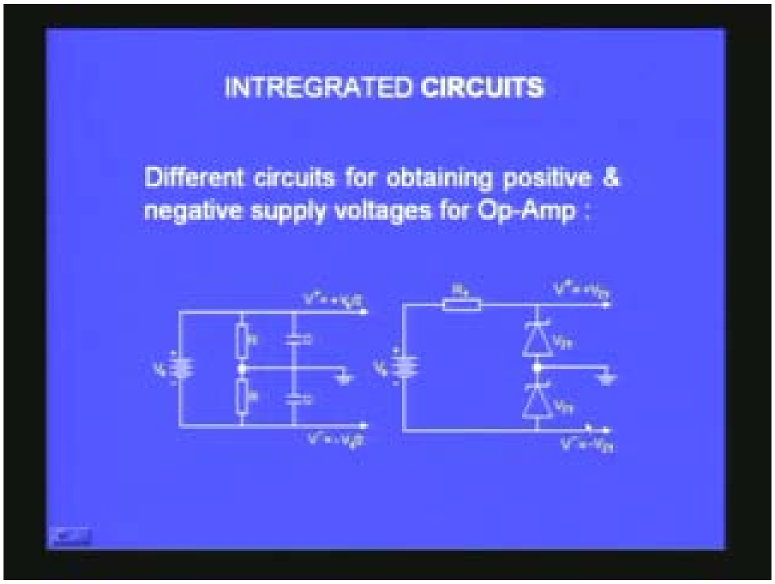


I have shown you that we require a dual supply and you can get it from two different batteries by series connection and keeping the common to the ground or we can use a single supply and generate a dual output from that by using a couple of resistors or Zener diodes.

This is another example of obtaining the dual supply.

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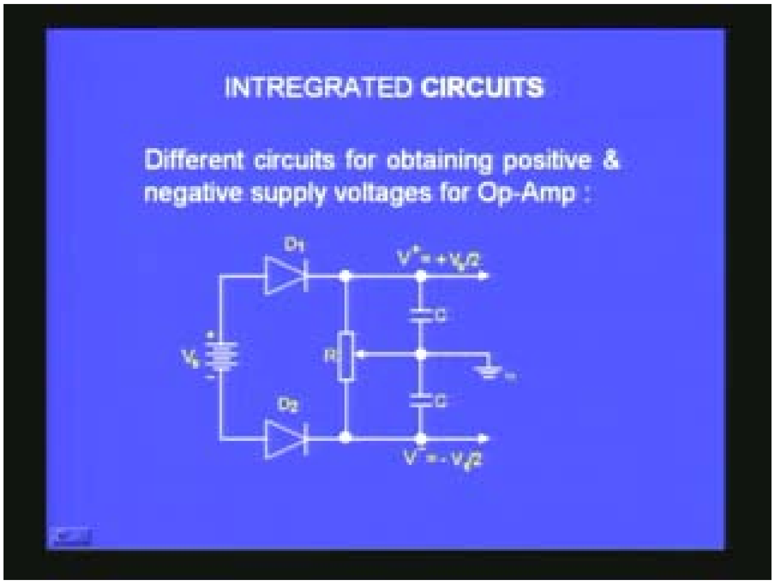

I will not spend too much time on that. I have to explain two different types. Let me move on to show you, not to frighten you but to indicate to you the importance of the actual circuit inside the operational amplifier.

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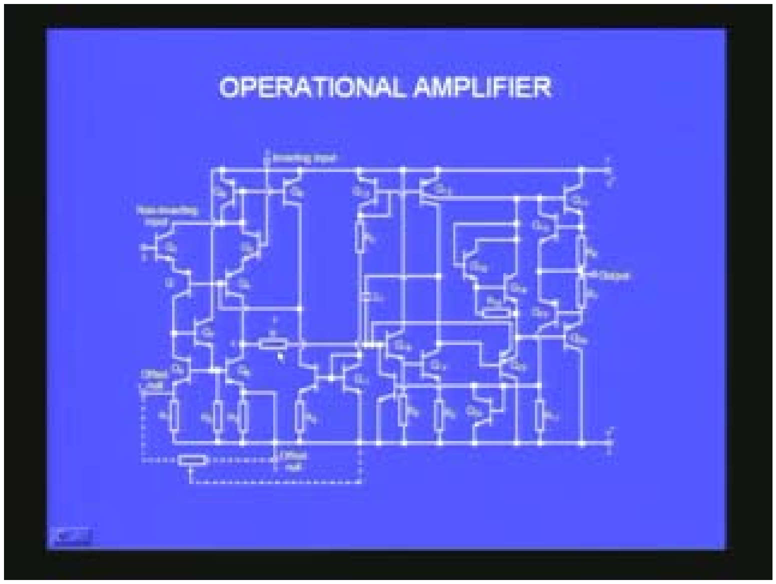


I talked to you about the operational amplifier 741. This is a typical schematic diagram circuit diagram of a 741 operational amplifier. There are some striking things that I wish you recognize immediately on seeing the picture and that is you have more transistors. The transistors are numbered here $Q_1$, $Q_2$, $Q_3$, $Q_4$, etc. The last transistor is $Q_{20}$. That means you have 20 transistors in the circuit and if you look at the resistors they are only up to $R_{11}$. You have only about 11 resistors, 20 transistors. You have more transistors than resistors and do you have any capacitors? Yes, you have 1 capacitor at the center which is actually a compensating capacitor, frequency compensation. So you have 20 transistors, about 11 resistors and 1 capacitor. This is a striking contrast to what you normally come across in discrete electronics. In discrete electronics you will have very few active devices. You will have more number of passive devices like resistors and capacitors. On the contrary when you come to the integrated circuit you have more number of active devices and less number of passive devices. This is a very important characteristic. This is due to the basic technology itself and that is one of the reasons you would perhaps realize that learning integrated circuit operational amplifier can be very exiting because you can start afresh. The whole technology, whole design of circuit everything has to be completely different from the philosophy that we normally follow when we make discrete circuits with different transistors etc. So this is what I wanted to show you and later on we would try to understand some of the basic ideas in this.

To make things simpler to you I have shown this in the form of a block diagram.

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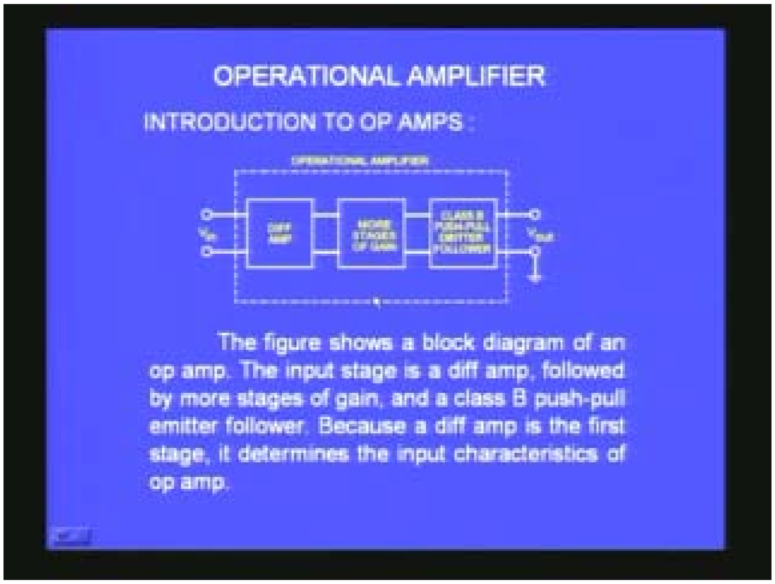


Basically the operational amplifier will have a difference amplifier at the input because you cannot have capacitors, large value capacitors in integrated circuit formalism. Then you go for a differential amplifier which again looks only for the difference in signals and it will eliminate the common dc signals coming from one stage to the other. You have a difference amplifier as the first stage and you can have additional stages of gain and finally you have a class B push pull emitter follower drive circuit for driving the loads across the amplifier. So this is a general block diagram. This simple diagram is the simplification of what you saw previously in the earlier style which has got 20 transistors, 11 resistors, capacitors, etc.

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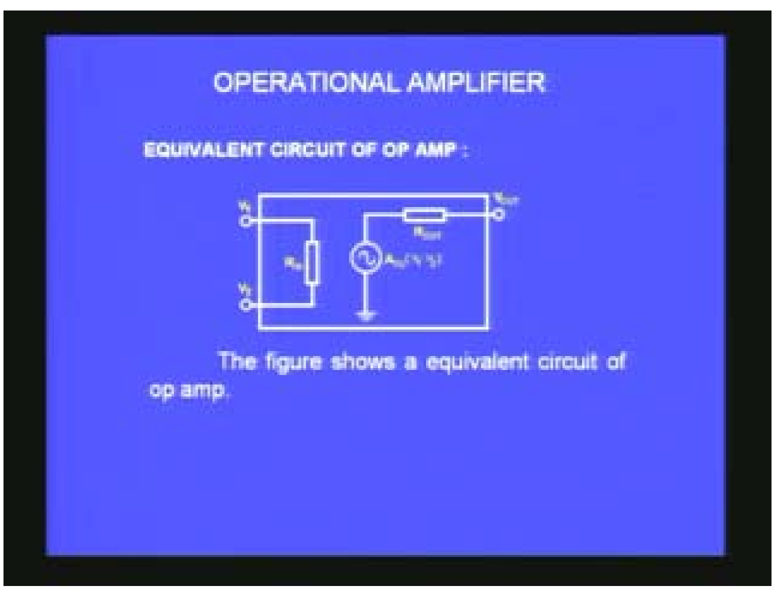

But as far as a given circuit is concerned when you want to analyze the circuit it is much simpler to look at an amplifier be it a normal amplifier or an operational amplifier. Every amplifier at the input side will have one simple $R_{in}$ resistance, input resistance and at the output side I can isolate and replace it with a voltage source where the voltage source is given by $A_{OL}$ into $V_1$-$V_2$. There are two voltages $V_1$ and $V_2$. Because it is a difference amplifier at the input stage it is the $V_1$-$V_2$ which matters and that is multiplied by a gain factor $A_{OL}$ gain open loop and that becomes the voltage source for the output side and you have a small resistor in series which is called the output resistance. This is a very simple diagram or the equivalent circuit of an operational amplifier when you want to analyze the various configuration of the op amp with the external resistors, capacitors, etc.

What are operational amplifiers? Let us start looking at it in some detail.

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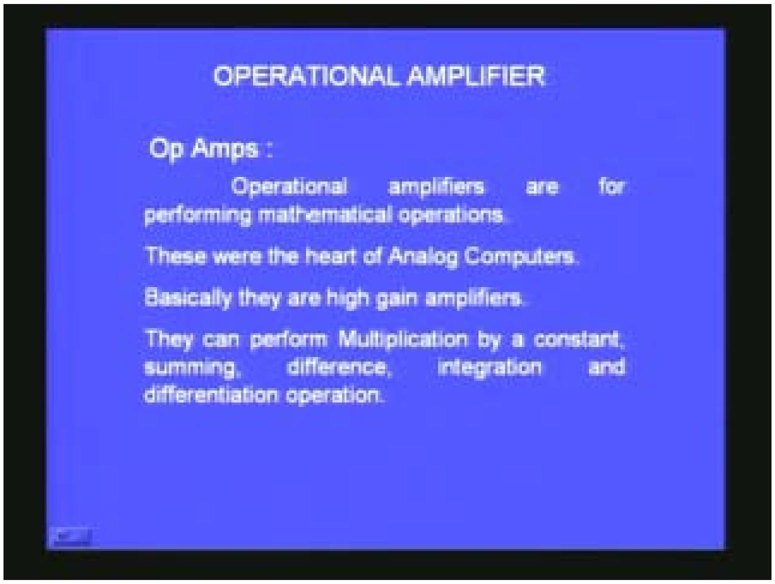


Operational, that name itself suggests that they are capable of performing mathematical operations. That is why they are called operational amplifiers. These were the heart of analog computers in those days. We had plenty of analog computers in those days. Now most of the computers are digital computers. These analog computers, some of you may not have heard of them, they used to have large number of these operational amplifiers. They would perform different types of mathematical operations like the multiplication, by a constant summing amplifier, difference amplifier, integrating circuit and differentiating circuit. Several of the mathematical operations can be performed electrically on electrical voltage, electrical signals and that becomes very useful. How? We would see now.

Basically they are very high gain dc amplifier. How an analog circuit works? I will briefly give you a simple introduction. Any physical phenomena can be represented by a mathematical model; we all know that usually in the form of a differential equation.

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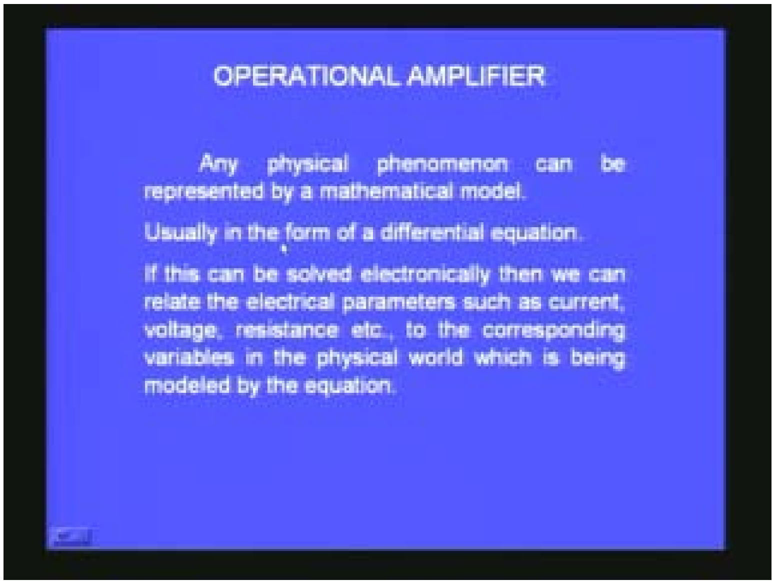


If I want a heat conduction in a metal it can be very easily written in the form of a differential equation where you can introduce some boundary conditions with reference to the source and the boundary of the metal and you can solve and get complete information about the distribution of 'T' the temperature. For every physical phenomena in principle one can obtain a mathematical model and that mathematical model if it is in a differential form many physicists will be very happy because differential equation can be very easily solved and you can impose some of the boundary conditions and try to realize the actual situation with reference to the model that you have looked at. If the differential equation can be solved electronically it provides you an additional feature. Then for every electrical parameter you can associate an actual physical parameter in the real world and thereby instead of building different designs in the real world you can build a simple circuit which involves only inexpensive components like resistors, capacitors and real type sources and you can form your differential equation out of that and try to solve the differential equation electrically and measure the different voltages and you would be able to understand, relate those values, magnitudes to the actual magnitudes of the parameters which we are representing in the electrical analog with reference to the real physical world.

For example I have discussed here in a simple way the study of the radiation leak from a nuclear power point, may be Kalpakkam through a concrete wall. We are worried about radiation leakage from the reactor. So what is that we have to do? We can always write an equation corresponding to the ……. We want to know what thickness will be able to optimize the radiation leak from inside.

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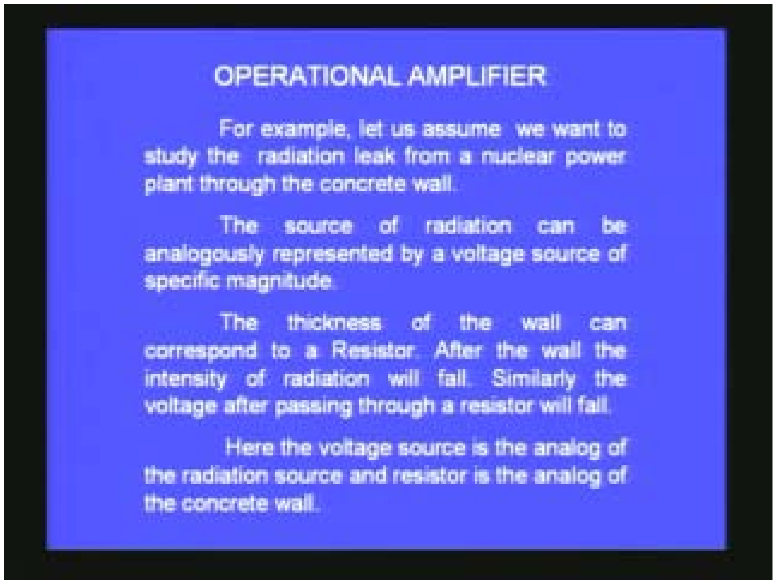


The radiation source is inside. You have a concrete block which is a wall and you have an outside world in which you want to detect what is the radiation leak state persisting after passing through the concrete wall? This can be very easily equated to a voltage source connected to a series resistor and then you are trying to find out the potential drop through the resistor at the end of the resistor in a circuit. It is a very similar situation. If I increase the magnitude of the resistor more will be dropped across the resistor and less will be available at the output terminals. Similarly if I have a bigger concrete wall thicker concrete wall the radiation coming out at the end will be much smaller in magnitude, perhaps. You can see now the radiation source can be equated to a voltage source. The thickness of the wall can be related to a resistance and what you get at the output will correspond to a leak that happens. In this case the measured voltage at the output can be related to the radiation leak at the output. So this is a very simple scheme to show you that an electrical analog can be built to a real world situation and if the real world situation requires a differential equation then we must be able to formulate the differential equation and solve it electrically. Then we would have perhaps modeled the actual real situation with an electrical analog and what is the advantage? If you want to change the thickness all we have to do is increase the value of the resistor which is much simpler than building a concrete wall and changing the thickness and the cost of trying out modeling or prototyping becomes very, very simple. You have to have only very inexpensive components like resistors, capacitors and you would be able to model the actual real world situation. This was the impetus for designing things like operational amplifiers in those days and it will be interesting to know that in those days the operational amplifiers were designed with vacuum tubes and transistors even. But with the development of the integrated circuit technology now-a-days all the op amps are in the IC form. They are very, very small in size. They have several advantages. They operate at very low voltages, very low power level whereas if I have vacuum tubes and transistors for example I have to operate them at very high voltages like 100, 200 volts and in the case of transistors I should apply 20, 30 volts. In the case of op amps you can have even 1 volt, 2 volt operational amplifiers which can operate on very low voltages and very low power levels. Apart from these advantages of linearization and power supply you also have several additional features when we go to operational amplifiers.

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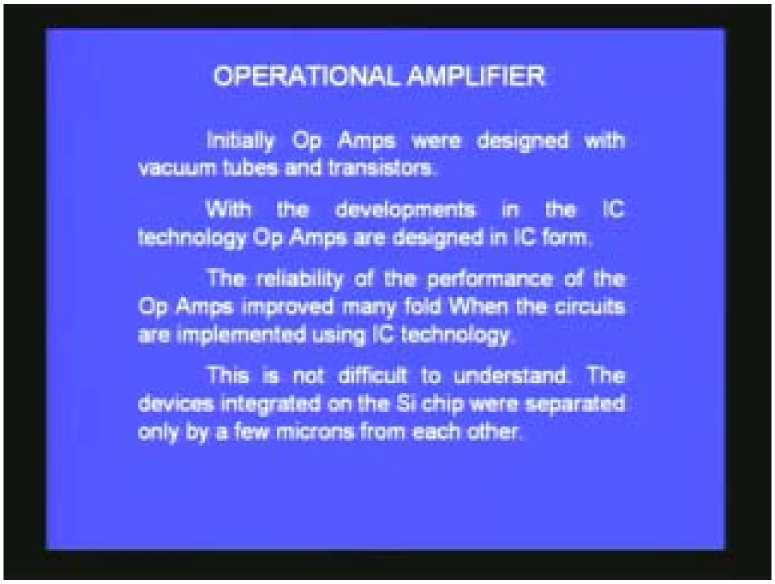


One of the important features I would perhaps briefly mention is that the reliability of the performance of the op amps improves because you have made them in integrated circuit form. Why is it so? This is not difficult to understand. The devices are integrated on silicon. I have shown to you 20 transistors, 11 resistors and 1 capacitor all integrated in a very small region of less than 1 millimeter by 1 millimeter square. What is the advantage of that? If I have two transistors formed on a silicon substrate for a differential amplifier configuration they perhaps may not have identical characteristics if I have designed those using discrete transistors. But the same circuit if I design with integrated circuit then the two transistors will be very, very close to each other only separated by few microns, micrometers away and they will perform almost identically much better than two discrete transistors. This is because even if the discrete transistors are obtained from the same batch while manufacturing, they would have been formed at two different points in a furnace. When you try to dope them with p type or n type in the semiconductor they will be separated by few millimeters or centimeters and the pressure, the temperature, the doping level and the concentration of the gases all will be different at the two different points which are separated by several millimeters or centimeters in the furnace.

But if you look at the same design in an integrated circuit form, in the same furnace these two will be few microns away and the differences in temperature, the doping level, the pressure, etc will be very, very, very small and both the transistors will almost be forming in an identical manner. They will have identical characteristics. If they have identical characteristics as a difference amplifier their performance will be enormously improved; improvement in the performance of these transistors when you do them in integrated circuit technology. An operational amplifier which started with an application for the case of analog computers when they came in a very tiny form with excellent performance characteristics people found that it will be very useful beyond the levels of analog computers. Every designer who wants to design quickly some good amplifier for his instrumentation application or medical application or aerospace application then for those people the first choice will be to buy an integrated circuit operational amplifier and use it for their own applications and there is an explosion of applications when it comes to making use of op amps by different people.

Having talked so much about operational amplifiers then we should try to look at some of the characteristics of the typical operational amplifier.

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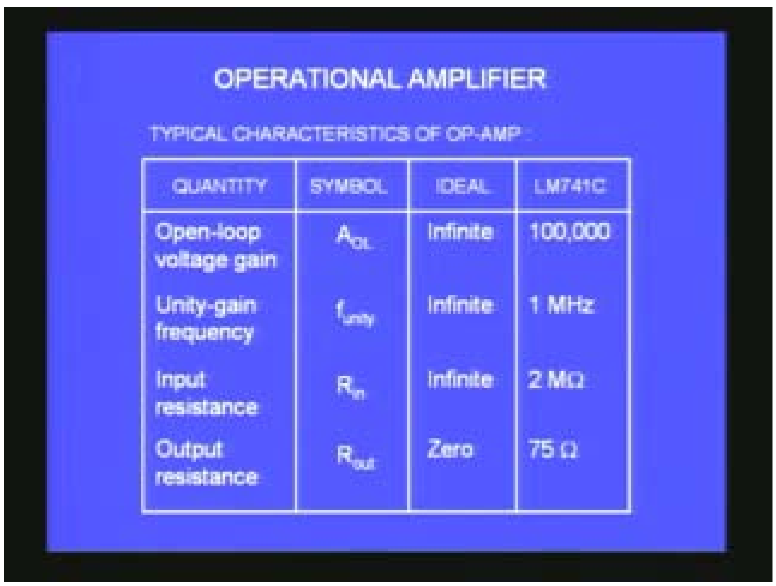


I have given here in the table the characteristics of an ideal operational amplifier and also a typical operational amplifier. In this case I have taken LM 741 as a typical operational amplifier which is very popular; 741 is a popular operational amplifier. First characteristic is what is called open-loop voltage gain. We show it by a symbol $A_{OL}$ and ideally the open loop gain should be infinity. But in reality for a typical case of 741 it is 10 to the power of 5 or 100,000. It is an enormous gain. This is actually the gain factor, the relationship between the output voltage and input voltage is 100,000. Even to get 20 or 100 with transistors we have to put lot of effort and then analyze it using 'h' parameter. So it takes enormous effort to design even a gain of 100 or 200 in the case of transistors. But here in the integrated circuit form you can very easily get a gain of 100,000 by special circuit design.

When you look at the bandwidth, the unity gain frequency bandwidth the ideal operational amplifier will have infinite bandwidth. That means all frequencies from zero that is DC to very high frequencies will have the same gain without any drop. Whereas in the case of the typical example of a 741it is about 1 mega hertz. So up to 1 mega hertz the gain will be almost the same; it will not fall. From 1 it will perhaps come up to about 0.7

times or 70% of 1. But then it is the bandwidth it is 1 mega hertz which is a very large number 10 to the power of 6. Similarly if you take the input resistance $R_{in}$ for an ideal case it is infinity and for actual typical case it is about 2 meg ohm. That means 2 million ohms; 2 followed by 6 zeroes very large number. If the input resistance of the input amplifier is very high it is good. We have already seen the characteristic of a basic voltage amplifier is that it should have very high input resistance. Similarly output resistance of an operational amplifier in an ideal case should be zero. In an actual case it is about 75 ohms which is reasonably very, very low; few ohms and this is device, 741 device, is very close to the ideal situation. 100,000 is almost very large; 1 mega hertz is about 1 million times and 2 meg ohm is again 2 million very large and 75 ohm is very small in terms of magnitude and operational amplifiers are much closer to an ideal situation than transistors which are non-ideal devices and that is the reason why you have to model them by different ways. We can do it in different ways. You can do 'h' parameter, 'r' parameter or 'y' parameter and even then you have to incorporate number of approximations to analyze otherwise the circuit analysis becomes very complicated whereas here it is very, very simple because it is very close to the ideal situation.

There are other parameters like input bias current, input offset current, input offset voltage, etc. We will discuss at a later stage in detail about some of these things. If you look at the ideal situation they will be either 0 or infinity depending upon the characteristic whereas in a typical case these are some magnitude 80 nano amperes for example is the input bias current. Input offset current is about 20 nano amperes.

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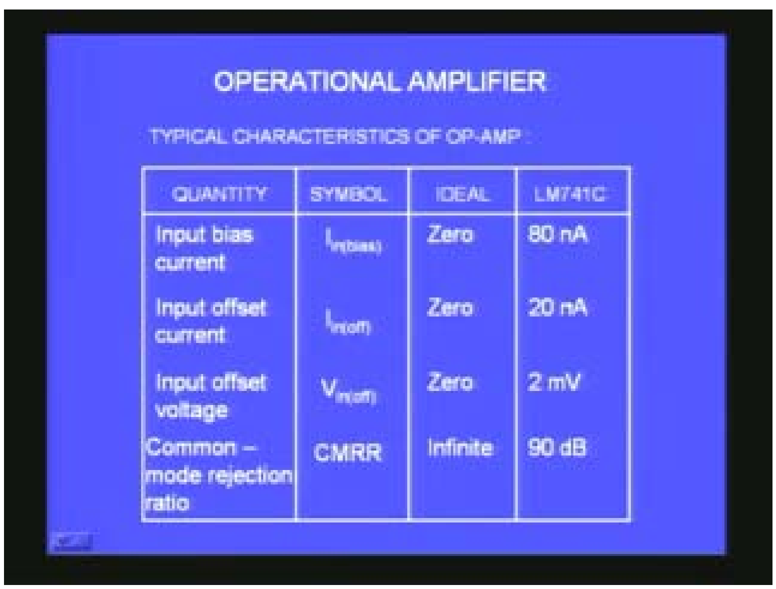


Input offset voltage is around 2 milli volt. Common mode rejection ratio is expressed in db, decibel which we have already seen is around 90 db. 80 db is 10 to the power of 4. So 90 db is about 10,000 times or more. We will try to look at in some detail now. Ideal op amp has infinite input impedance. This is understandable because when I apply a signal from a signal source the entire signal source should be applied across the amplifier. I don't want anything to be lost.

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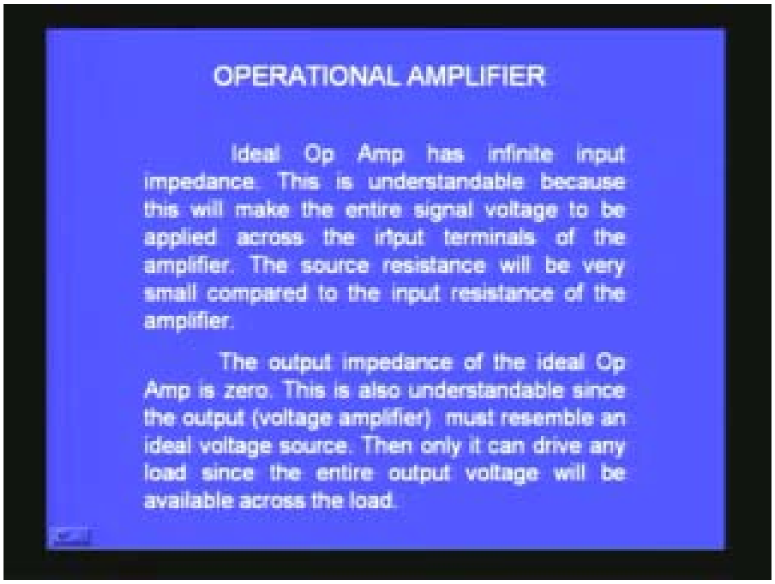


But you know all sources will have a source resistance or source impedance. So this voltage will be now applied across not one resistance or one impedance but two impedances. One is the source impedance the other is the input impedance of your amplifier. Only when the input impedance of the amplifier is very large compared to the source impedance the entire signal voltage will be applied across the amplifier terminals. In principle we don't know anything about the input source and it is better to design an amplifier which has got very large input resistance so that it will take care of any kind of source even if it has very large input impedance. Because your input impedance of the amplifier is very large you would be able to manage and get all the signal applied, most of the signal applied across the input terminals of the amplifier and you will be able to get the entire voltage. So it is understandable why the input impedance of an ideal amplifier should be infinity or in the typical case it is about 2 meg ohms or something like that. That is clear.

The output impedance of the ideal amplifier is zero. This also is understandable because the output of an amplifier is used to drive a load.

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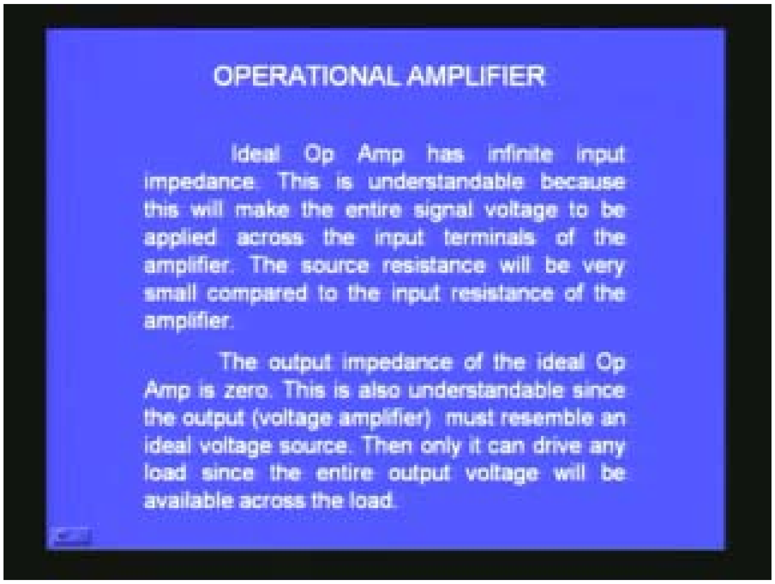


When you want to drive a load then your amplifier output now becomes a source and the source impedance should be very, very minimum. Then only the entire voltage will be applied across the load and that way the output of an operational amplifier should be an ideal voltage source with zero internal resistance and that is why the output impedance of an amplifier should be minimum. Ideally it is zero. In actual case it is about 75 ohms. So this also we are able to understand why we should have. But even the unity gain bandwidth should be infinity; we can understand.

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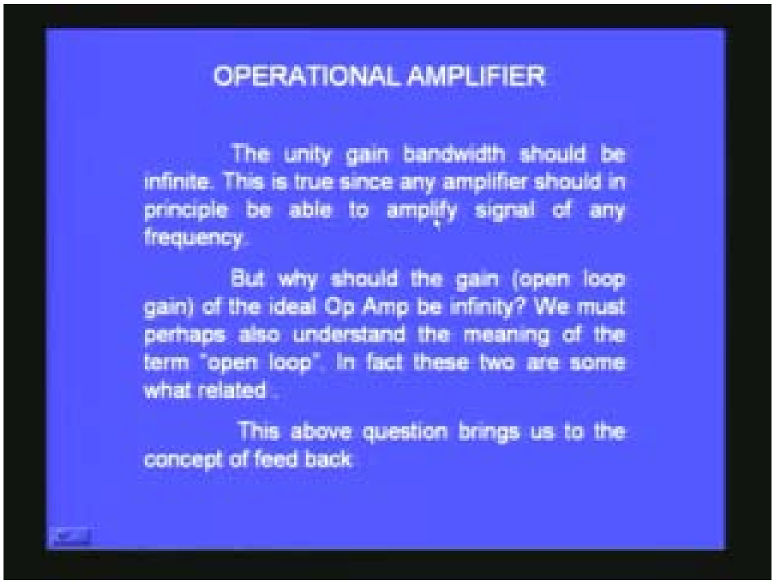

We want amplifiers which will amplify all signals irrespective of the frequency; whether it is low frequency or high frequency it should amplify by the same extent, by the same magnitude of the gain. It is always very difficult to realize such amplifiers. Every amplifier will have a finite bandwidth. In principle ideally we should have infinite bandwidth; understood. Why should the gain of an ideal operational amplifier be infinity? Why should it be infinity or why should a typical operational amplifier be very large 100,000? Why not less? There is also a term I used for the gain. I didn't call it as a gain. I mentioned it as an open loop gain. What is the meaning of the open loop? Why we should have a very large gain magnitude and these two statements, these two questions have got some link in between them. When I explain them perhaps you will be able to appreciate this. We can understand this by looking at the concept of feedback in amplifiers.

Feedback as a matter of fact is a very important concept in all electronics and in control.

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If you want to close a pen for example you take the example of a pen and try to close the lid of the pen by closing your eyes. I can assure you if you keep trying you would find it is very difficult to close the pen exactly to the nib. That is you just take the pen; you open up the lid, close your eyes and try to match them. You would find you will always miss. You will not able to do that unless you see them with your eyes and then you will move automatically. Your hands will get the message because your eyes are seeing the movement of your hands. They will inform the brain how your hand is moving whether it is moving in alignment or not and then the hand will be automatically given the command by the brain to move and close it correctly. Here is a case of bio feedback. The pen and the hands are coordinated through the signal obtained through the eye to the brain and so the brain is able to control using the feedback that it obtains from the eyes; through the eye, through the bio feedback and feedback is a very important innovative concept in all electronics and that is one of the very important things that we should perhaps look at.

Feedback is employed in an amplifier also.

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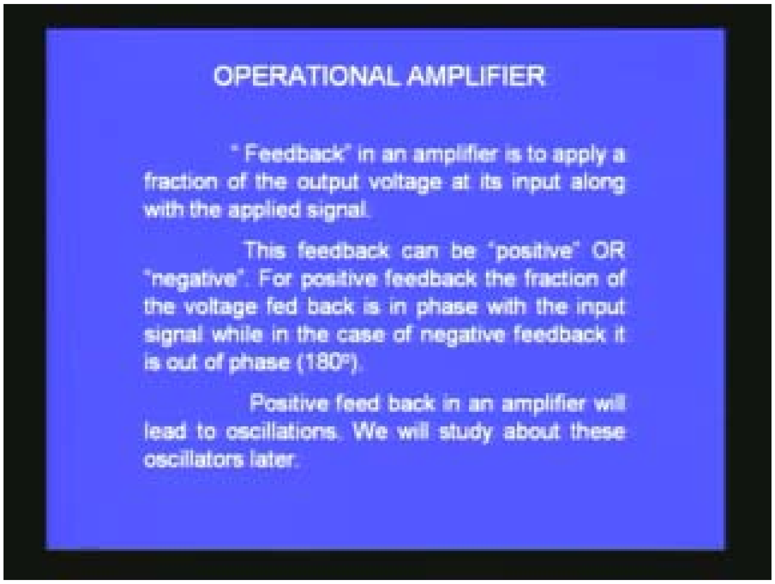


What do you mean by the feedback? You have to take a small fraction of the output voltage and apply it at the input along with the signal. When you take an amplifier given input you get an output. Take a fraction of the output and then give it along with the input. Then you have given a feedback. You are feeding it back into the input. This feedback can be of two different types. One corresponds to negative feedback when the output is not in phase; actually it is out of phase with the input and you have another feedback which is called positive feedback where the output voltage is in phase with the input voltage. So you have two different types of feedback; negative feedback and positive feedback.

Positive feedback in an amplifier will in general lead to oscillations. So when we discuss about oscillators we will perhaps go much deeper into positive feedback and show you the consequences of positive feedback. How positive feedback can be exploited to design different types of oscillators, etc. But right now we would concentrate more on negative feedback. What do you mean by negative feedback? I take a fraction of the output and connect it at the input out of phase with the input signal; 180 degrees out of phase. So if the input is increasing the output will be decreasing. The feedback voltage will be also decreasing. Then it becomes a negative feedback. When I do that some of the input voltage will be cancelled by the feedback and the actual input voltage which is applied to the amplifier will be decreasing and the gain will also decrease. You can intuitively guess that when you give negative feedback the gain will decrease and it is indeed true that when you give negative feedback in an amplifier the gain will decrease.

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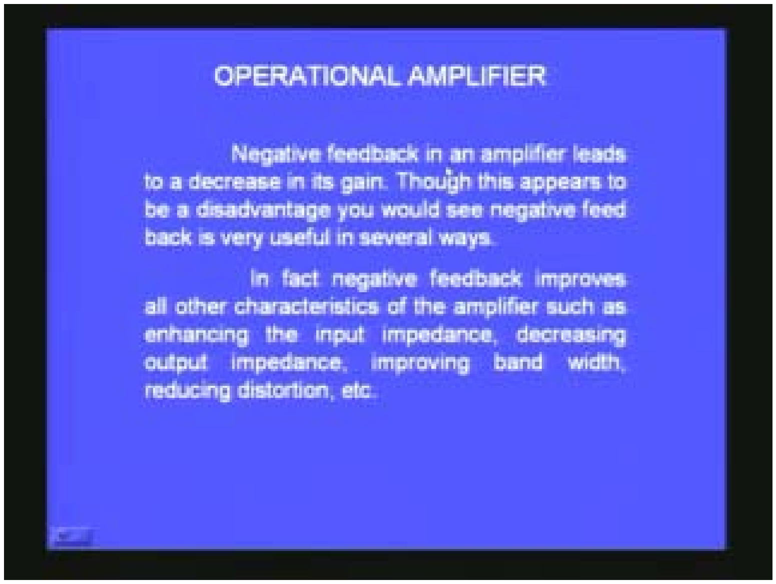


Though you feel that this will be a disadvantage to the amplifier because you don't want the gain to decrease; you want the gain to be more. But this is a great advantage in several other parameters of an amplifier like input impedance, output impedance, bandwidth, distortion all these characteristics will enormously improve depending upon the degree of feedback that we give amount of feedback that you give. The more the feedback that you give more will be an improvement in input impedance, output impedance, bandwidth, distortion all those things. So people are very much interested in introducing feedback that too negative feedback in amplifiers to improve the characteristics of the amplifier. That is one of the reasons why we want to have very large gain for power amplifier. I will explain to you in a minute now

I have here on the screen an amplifier with a gain A without any feedback. You have the input terminal, you have the output terminal. Then what we do is take the output terminal in parallel and connect to a network here. B is another box with the network there which is a fraction. Beta is a fraction. A fraction of the output voltage will be taken which is called $V_f$ the feedback voltage and that is given in opposition to the input voltage. This is plus minus and this is minus plus. When it is given in opposition what will be the balance that is applied across the terminal? I call it V epsilon and that is what is applied now. What is $V_f$? $V_f$ is actually beta times V output. Beta is less than 1. It is a fraction and a fraction of the output is given as the feedback voltage $V_f$ and the V epsilon which is the voltage actually connected across the amplifier is what I connect outside $V_{in}$ minus whatever I have given as the feedback $V_f$ because they are in opposition,180 degrees out of phase. But $V_f$ is beta $V_o$. Therefore I substitute here $V_{in}$ - beta $V_o$ and we also know from this amplifier characteristic V output is A times V epsilon which is the actual input connected at the terminal. So V output is A times V epsilon and V epsilon is $V_{in}$ - beta $V_o$. When you rearrange them $V_o$ by $V_{in}$ which is the gain of the total amplifier including feedback I call it $A_f$, A with the suffix f. This is the amplifier gain with feedback and that is equal to A by one plus A beta.

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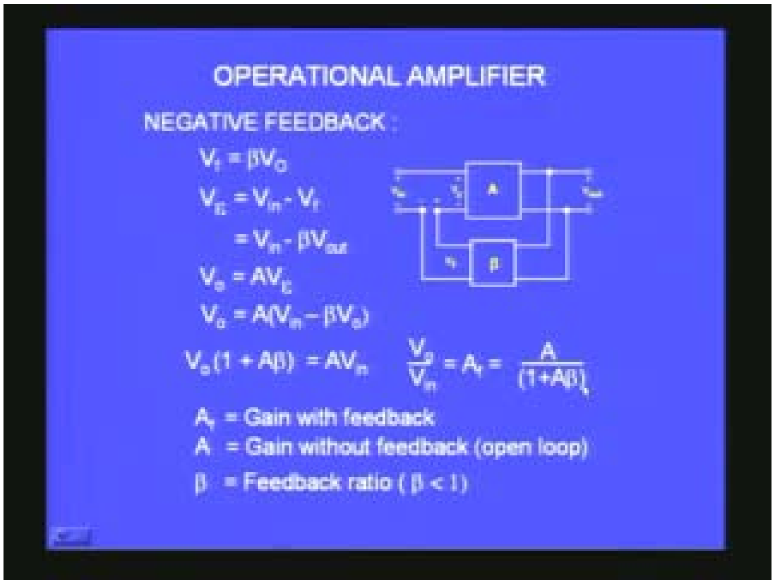


This is what I get; an expression for the gain of the amplifier with negative feedback. If it is a positive feedback this plus sign will be minus where $A_f$ is the gain with the feedback. A is the gain without feedback which we call open loop because there is no feedback loop. This is the feedback loop. This loop when it is missing then we call it as an open loop and beta is the feedback ratio. I already told you beta is always less than 1. What will happen in the limit A tending to infinity?

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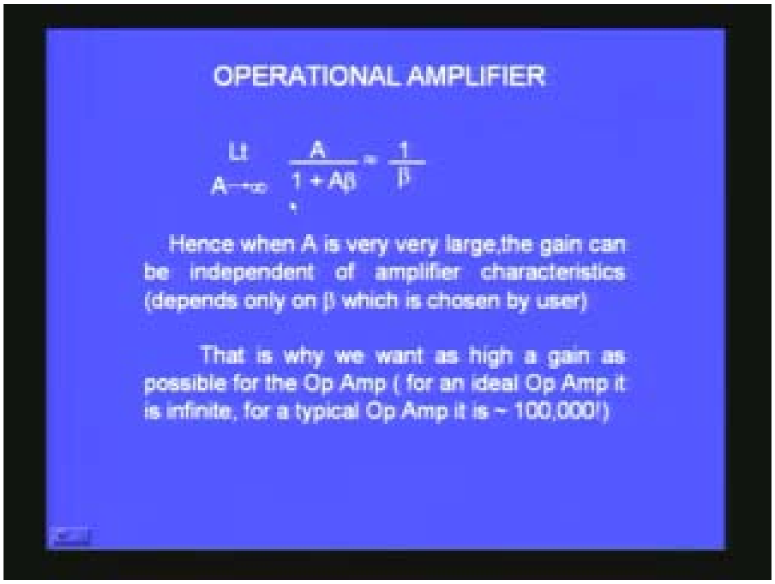


When A tends to infinity A by one plus A beta will almost be equal to 1 by beta. You divide numerator by A. This is very easy to see that the gain with feedback when A tending to infinity will be 1 by beta and that means it is independent of A. The gain of the amplifier depends only on beta which is the feedback ratio which is actually in our hands. The beta is done by us outside the amplifier by using some small resistor network and the amplifier becomes independent of its own characteristic and it can be very easily controlled by having a couple of resistors outside by controlling the feedback and the operational amplifier becomes an excellent device for different applications. That is the reason we must have very high gain A tending to infinity only. This will be true that larger the value of A the better will be with reference to 1 by beta and in general ideal operational amplifier should have infinite gain. An actual amplifier for example 741 has an open loop gain of 100,000. Having said that now I must also perhaps discuss in the next lecture what are the different types of feedback that we can give. I have only talked about the general principles of feedback.

We can have different types of feedback. I can sense voltage or current from the outside output side and then given as a voltage or current at the input side. This variation in the way the type of feedback that I incorporate in a given amplifier, the amplifier characteristics can be completely modified. It will no more be a voltage amplifier it may become a current amplifier or it may become a current to voltage converter or it may become a voltage to current converter. So by just manipulating the external resistors for a given operational amplifier I will be able to design different types of circuits which are very close to ideal, which are performing wonderfully well. All these are possible by the simple device that I have which is called operational amplifier which in principle from the market you will get it for about 5 to 10 rupees or so; not very expensive and with that you can try to build different types of exotic circuits for different types of applications. We will discuss in the next class about the different types of feedback that we can give and you try to incorporate the different feedbacks and try to see what results from that type of a feedback. What type of a circuit, what type of characteristic we achieve by giving such feedback we will discuss next time. Thank you!