# Basic Electronics
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## Lecture – 24
## Bipolar Junction Transistor (continued)

Welcome back to Basic Electronics. In the last lecture we looked at the Ebers moll model which describes the BJT in all modes of operation we will now use the Ebers moll model to plot the collector current I C of a BJT as a function of the collector to emitter voltage V CE with the help of the I V characteristics. We will take another look at the earlier BJT circuit. And figure out the correct solution finally, we will look at a circuit with a PNP transistor. So, let us begin.

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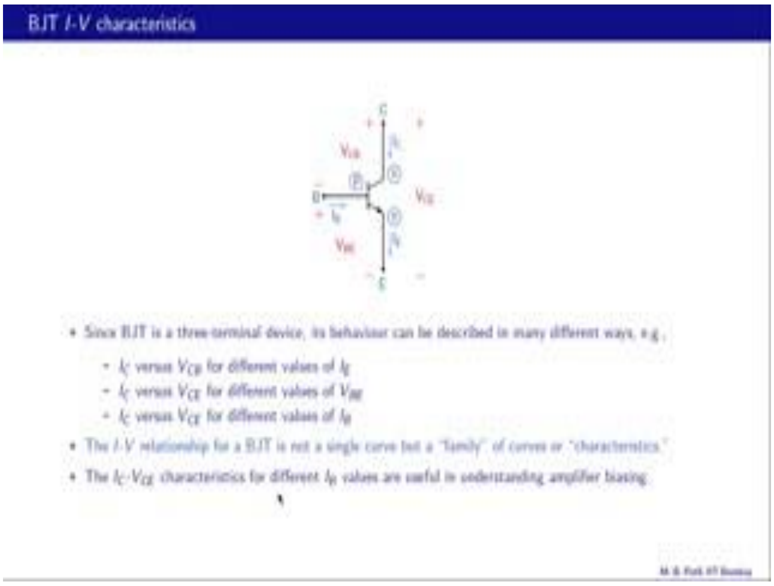

BJT $I$-$V$ characteristics

- Since BJT is a three-terminal device, its behaviour can be described in many different ways, e.g.,
    - $I_C$ versus $V_{CB}$ for different values of $I_E$
    - $I_C$ versus $V_{CE}$ for different values of $V_{BE}$
    - $I_C$ versus $V_{CE}$ for different values of $I_B$
- The $I$-$V$ relationship for a BJT is not a single curve but a "family" of curves or "characteristics."
- The $I_C$-$V_{CE}$ characteristics for different $I_B$ values are useful in understanding amplifier biasing.

We now want to discuss the I V characteristics of a BJT in a graphical from. Now we first note that BJT is quite different from a diode in that it has 3 terminals. For a diode we had only 2 terminals. So, there was exactly one current and one voltage to talk about and therefore, the entire diode behavior could be captured with just one plot the current versus voltage. That is not the case for a BJT. We can look at several different things and here is some of this I C versus VCB; so this current I C versus this voltage VCB for different values of I E. I E1 I E2 and so on or we can plot I C versus V CE I C as a function of V CE for different values of V BE, V BE1 V BE2 and so on or we can plot I

C versus V CE, I C versus V CE for different values of the base current. And of course, there are some other ways of plotting the current as well.

So, the I V relationship for a BJT is not a single curve, but family of curves or characteristics. And we will look at the I C versus V CE curves or characteristics for different I B values because they will find this is very useful in understanding amplifier biasing.

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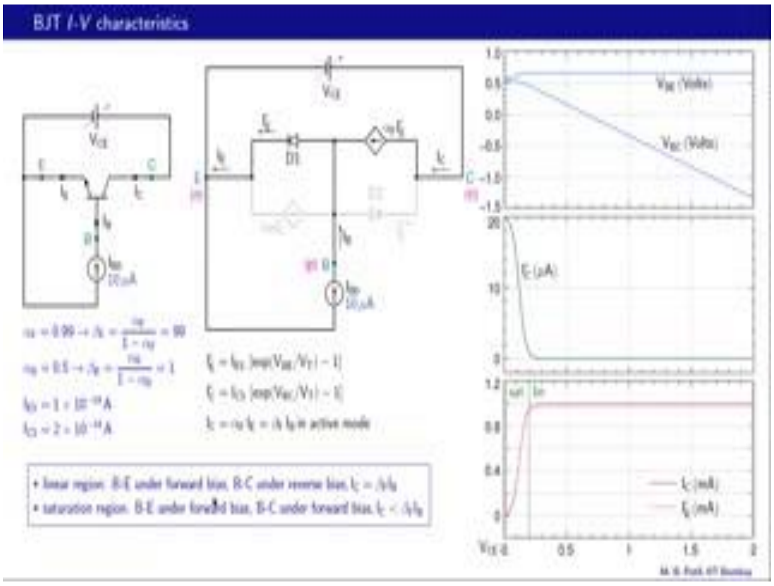

BJT *I-V* characteristics

- linear region: B-E under forward bias, B-C under reverse bias, $I_C = \beta_F I_B$
- saturation region: B-E under forward bias, B-C under forward bias, $I_C < \beta_F I_B$

What we are going to do take an NPN transistor and plot I C as a function of V CE this voltage drop for various values of I B. And we will do that by solving the Ebers moll equations. So, the experimental set up would be something like this. Voltage source is connected between collector and emitter this value is V CE. So, this is going to be our x axis variable, the collector current I C is going to be our y axis variable. So, we are going to plot I C as a function of V CE. And we will find that I C versus V CE depends very much on what this base current is. So, therefore, for a given base current let us say 10 micro amps we are going to get one of these curves I C versus V CE. If I change these 10 micro amps to 20 micro amps or 50 micro amps we are going to get another I C versus V CE curve and so on.

So therefore, the I V characteristics of a BJT like we said in the last slide are not one single curve, but a family of curves and that is the complete picture that we want to see. These are the parameters we will consider alpha F the forward alpha as 0.99 that makes beta equal to alpha by 1.3 minus alpha that is 99. Alpha R the reverse alpha equal to 0.5 that makes the reverse beta equal to alpha R by 1.3 minus alpha R or one and clearly this transistor is very poor in the reverse direction because this beta is so small in the reverse direction. And these are the saturation currents I ES 10 raise to minus 14 ampere and ICS 2 times 10 raise to minus 14 amperes.

First let us replace the transistor with the Ebers moll model like that and recall that in the active mode we need to only consider I E prime and alpha I E prime, but in general we need to consider all 4 branches. What we want to do is to get I C as a function of V CE for a fixed value of I B that is 10 microamperes. What we will do now is to take one specific value of V CE say 1.3 volt and figure out how we can calculate I C for that V CE with I V equal to 10 microamperes. So, for convenience let us take the emitter node as the reference node so; that means, p e is 0 volts and VC the collector voltage would then be 1.3 volt because we have taken V CE equal to 1.3 volt. And we do not know what VB is going to be.

So, what we need to do is to solve the Ebers moll equations for VB and once we know VB we know this difference V BE we also know this difference V BC and once we know these 2 voltages we can find I E prime given by that equation, we can find I C prime and once we know that we can find all other quantities. For example, I E is going to be I E prime minus alpha R I C prime and so, on. So, we need to get an equation in terms of VB and what is that equation that equation is given by I B equal to 10 microamperes.

What is I B? I B is equal to I E prime plus I C prime minus alpha F I E prime minus alpha R I C prime. And I E prime and I C prime essentially are functions of VB because V BE here is VB minus VE. VE is known 0 volts. V BC is equal to VB minus VC, VC is known one volt and therefore, I E prime and I C prime can be written in terms of VB. So, that is the equation we need to solve for VB, and you can see that it is going to be a non-linear equation because we have exponential terms over here. So, we need to use some iterative method to obtain VB.

So, by solving this equation that is I B equal to 10 microamperes, for V CE equal to 1.3 volt we are going to find one value of the collector current. And then we repeat this exercise for other values of V CE. And that is how we are going to plot I C as a function of V CE. And here are the results that we obtained. This axis is V CE, this is V CE equal to 0 this is V CE equal to 2 volts. This curve here is V BE; that means, the voltage across the base emitter diode, this curve is V BC the voltage across the base collector diode, this current is I C prime, this current here and the solid line here is I C the terminal current and the dashed line is I E prime this current here.

Let us look at the various quantities of interest at specific value of V CE, say V CE equal to 1.3 volt and let us start with the junction voltages. Here is V BC and for V CE equal to 1.3 volt V BC is about minus 0.3 volts; that means, the base collector diode is under reverse bias and; that means, I C prime is very small nearly 0 and therefore, this branch is like an open circuit and so is this branch. And if we look at the I C prime plot, we see that I C prime is 0 at VC equal to 1.3 volt.

Next let us look at V BE the base emitter voltage this plot here and V BE is about 0.6 volt may be between 0.6 and 0.7 and; that means, the base emitter diode is under forward bias and therefore, our transistor is operating in the active mode with the bas emitter junction under forward bias and the base collector junction under reverse biased.

Now, since I C prime is 0. ICS equal to alpha F times I E prime. What is alpha F, very close to 1.3 is 0.99 for this transistor. So, I C is nearly equal to I E prime and that is what we see over here. I C an d I E prime are nearly equal. Now since we know that the transistor is operating in the active mode, we also know that I C can be written as beta times I B and what is beta is 99. So, I C is expected to be 990 times I B or 990 times 10 microamperes, that is 990 microamperes that is nearly 1.3 milliamp and that is what we observe over here I C is about 1.3 milliamp.

Let us summarize the situation for V CE equal to 1.3 volt. We have about 0.7 volts appearing across D1. And the rest of the voltage that is 1.3 volt minus 0.7 volts about 0.3 volts appears across the base collector junction. And since this end is positive compared to this one the base collector diode is not conducting all right. What we will do now is consider another value of V CE namely V CE equal to 2 volts. For this voltage we notice that our base emitter voltage has not really changed, we cannot really tell the difference and the entire difference that is 2 volts minus 1.3 volt equal to 1.3 volt has appeared in V BC.

This was minus 0.3 volts and this is about minus 1.3.3 volts. So, the base collector junction continues to be under reverse biased the transistor continues to be in active mode I C prime continues to be 0. And our collector current also remains equal to 1.3 milliamp. So, all that has happened as we go from V CE equal to 1.3 volt to V CE equal to 2 volts is that an additional reverse biased of 1.3 volt has now appeared across this base collector diode. Earlier with VCE equal to 1.3 volt the reverse bias was minus 0.3 volts and with V CE equal to 2 volts it is now minus 1.3.3 volts apart from that there is no real change.

Let us now look at what happens, when we change V CE in the other direction let us say from 1.3 volt to 0.5 volts and let us start looking at the diode voltage is first. Now V BE has not really changed it has remained at about 0.7 volts. V BC has changed from minus 0.3 volts to about 0.2 volts. So, the entire change in V CE has actually got reflected in V BC. And I C prime continues to be small. Note that V BC has now becomes slightly positive, but it is not large enough to make I C prime substantially or significantly large and that is why on this scale I C prime is still looking like 0.

So, the transistor continues to be in the active mode and I C continues to be about 1.3 milliamp that is beta times I B. At about 0.2 volts somewhere here the current I C prime starts raising because in the forward bias across the base collector junction has now increased to make I C prime significantly large. Apart from that there is also slight reduction in V BE as we see over there and because I C is alpha F I E prime minus I C prime this current is now decreasing because V BE prime is going down a little bit and this current is increasing there what happens is I C now starts going down like that.

So, we have 2 distinct regions in BJT I V characteristics. The right of this slide is the so called linear region which we have been calling as a active region as well and we are already familiar with that. The left side is the saturation region now this region is new to us in this region both the base emitter and base collector junctions are under forward bias and the collector current is less than what it would be in the active region. So, let us summarize these observations. We have a linear region the right side of that line in which the base emitter junction is under forward bias base collector junction is under reverse biased.

And I C is beta times I B and in this example it is about 1.3 milliamp. We have the saturation region on the left of this line and in saturation region the base emitter junction is under forward bias and the base collector junction is also under forward bias. And in this region I C is less than beta times I B as we can see over here. So, here is the I C V CE curve for 10 micro amps again and in the linear region or the active mode the collector current is beta times I B which is about one milliamp.

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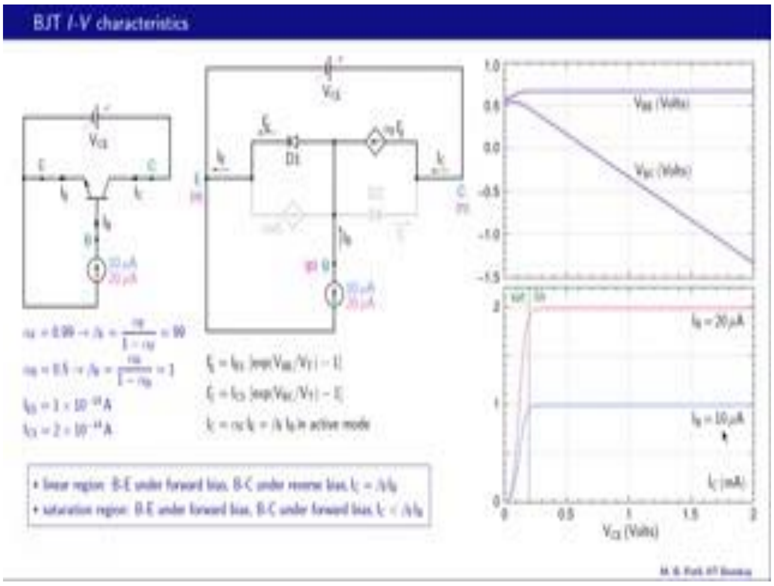

BJT I-V characteristics

- linear region: B-E under forward bias, B-C under reverse bias, $I_C = \beta_F I_B$
- saturation region: B-E under forward bias, B-C under forward bias, $I_C < \beta_F I_B$

Now, we want to look at the I C V CE curve when the base current changes from 10 micro amps to 20 micro amps. So, let us look at the results. That is the I C V CE curve now for 20 micro amps. And we see that it has not really changed much in many aspects except in the linear region I C has become 2 milliamps. Approximately 2 milliamps approximately 2 milliamps and for 10 micro amps. It was about one milliamp and this of course, is expected because in the linear region we have I C equal to beta times I B beta is about hundred. So, 100 times 20 micro amps that is 2 milliamps. So, this part is really expected simply from this equation, and the boundary between the linear and saturation regions has also not really changed the transition is happening at about the same V CE value about 0.2 volts.

So, as we go from I B equal to 10 micro amps to I B equal to 20 micro amps there is a large change in I C from 1.3 milliamp to 2 milliamps that is a factor of 2 and we now want to see how that change gets reflected in the V BE and V BC plots. What is I C in the linear region I C is alpha times I E prime. So, if I C has changed by a factor of 2 I E prime would also have changed by a factor of 2. So, let us look at the equation for I E prime, now I E prime is I ES e raised to be V BE by VT. This one is too small compared to the first term we will not worry about that and if I E prime changes by a factor of 2, it calls for a change in this factor e raised to be Ve by VT by 2.

Now, because this is an exponential relationship. That requires V BE to change only slightly. And that is what we are seeing here essentially. So, the blue curve is for I B equal to 10 micro amps and the pink one is for I B equal to 20 micro amps. And we see that for 20 micro amps the base emitter voltage is only slightly larger than the case for 10 micro amps. And because these 2 voltages must add up to V CE that changes is also reflected in V BC. So, overall there is a large change in the collector current plot, but there is hardly any change in the base emitter and base collector voltages. As we change I V from 10 micro amps to 20 micro amps. And based on this experience we can now predict what is going to happen for some other value of I B for example, if I B is made 5 micro amps, instead of 10 I C is going to be 0.5 milliamp, because we are changing I B by a factor of 2 I C will also changed by a factor of 2 because of this proportionality here and then we will get a curve I C V CE curve which looks like this. And we do not really need to do that calculation. Similarly, if I B is 15 micro amps that are between these 2 values I C would then look like that. And all of these curves will cross over from linear to saturation regions at about V CE equal to 0.2 volts.

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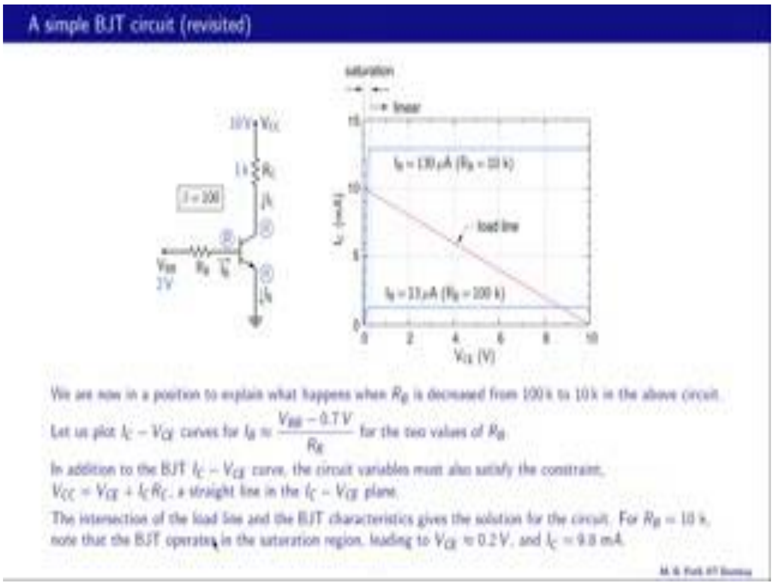

A simple BJT circuit (revisited)

We are now in a position to explain what happens when $R_B$ is decreased from 100 k to 10 k in the above circuit.

Let us plot $I_C - V_{CE}$ curves for $I_B \approx \dfrac{V_{BB} - 0.7\,V}{R_B}$ for the two values of $R_B$.

In addition to the BJT $I_C - V_{CE}$ curve, the circuit variables must also satisfy the constraint, $V_{CC} = V_{CE} + I_C R_C$, a straight line in the $I_C - V_{CE}$ plane.

The intersection of the load line and the BJT characteristics gives the solution for the circuit. For $R_B = 10$ k, note that the BJT operates in the saturation region, leading to $V_{CE} \approx 0.2\,V$, and $I_C = 9.8$ mA.

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Let us now revisit this circuit that we have looked at before, and if you remember when R B was changed from 100 k to 10 k we found that active mode was not possible anymore, and now having studied the I C V CE characteristics, we would be able to explain what happens. So, we are now in a position to explain what happens when R B is decreased from 100 k to 10 k. So, what we will do is we will plot I C e versus V CE for 2 values of I B. 100 k and 10 k and as we have seen if we take this voltage as approximately 0.7 volts then R B times I B is 2 volts minus 0.7. So, that is 1.3. So, I B is one 0.3 by 100 k or one 0.3 by 10 k, depending on the value of R B. And let us now look at the I C V CE characteristics for these 2 base currents.

So, here is I B equal to 13 micro amps, which corresponds to R B equal to 100 k and what would be collector current here in the linear region that would be 13 micro amps multiplied by beta, that is one 0.3 milliamps and that is exactly what this is. When we change R B from 100 k to 10 k our base current goes up by a factor of 10, and it now becomes 130 micro amps. And now the collector current in the linear region is 130 micro amps' times 100 or 13 milliamps. So, this collector current is now 13 milliamps.

Now, whatever solution we find for this circuit that is the value of I C and the value of VC, must satisfy either this constraint imposed by the transistor if R B is 100 k or this constraint if R B is 10 k and note that VC here this voltage is the same as V CE because the emitter is at 0 volts. Now apart from that there is one more constraint that we need to worry about that and that is imposed by this resistance R C. So, let us see what is that is. So, in addition to the BJT I C V CE curve the circuit variables must also satisfy the following constraint, and let us see where this is coming from V CC equal to V CE plus I C, R C, V CC must be equal to this voltage plus this voltage.

Now this is just V CE that is this variable here and that voltage drop is I C R C. Now these equations essentially look like a straight line in the I C V CE plane, and let us plot that straight line now. And there is what it looks like. It is x intercept is 10 volts and that is obtained by putting I C equal to 0, if I see 0 then V CE is the same as the V CC, which is 10 volts and it is y intercept is 10 milliamps and if we put V CE equal to 0, now we get I C equal to V CC by R C V CC is 10 volts R C is 1.3 k. So, that is 1.3 milliamps. So, that is the graph of this constraint which is imposed by R C. The intersection of the load line and the BJT characteristics gives us the solution for the circuit and that is because the solution has to satisfy the load line constraint as well as the constraint imposed by the transistor IP and that constraint is given this curve for R B equal to 100 k and by that curve for R B equal to 10 k.

Now, for the first case R B equal to 100 k that intersection is somewhere here and as we have seen earlier the solution is V CE equal to 8.7 volts and I C equal to 1.3 milliamps. In the second case that is R B equal to 10 k we note that the intersection of the load line and the I C V CE curve happens to be in the saturation, region not in the linear region. And that is why we found that linear region does not possible when we try to solve this same problem analytically. So, what is the solution now. So, the V CE is between 0 and 0.2 volts we often take this approximately as just 0.2 volts and so therefore, we have a voltage drop of 0.2 volts here this is 10 volts. So, 9.8 volts will drop there. So, 9.8 divided by 1.3 k that is 9.8 milliamps that would be I C. So, that is the solution V CE of about 0.2 volts and I C equal to 9.8 milliamps.

So, sometimes these graphical methods are very useful and they help us to visualize things much better than an analytical approach.

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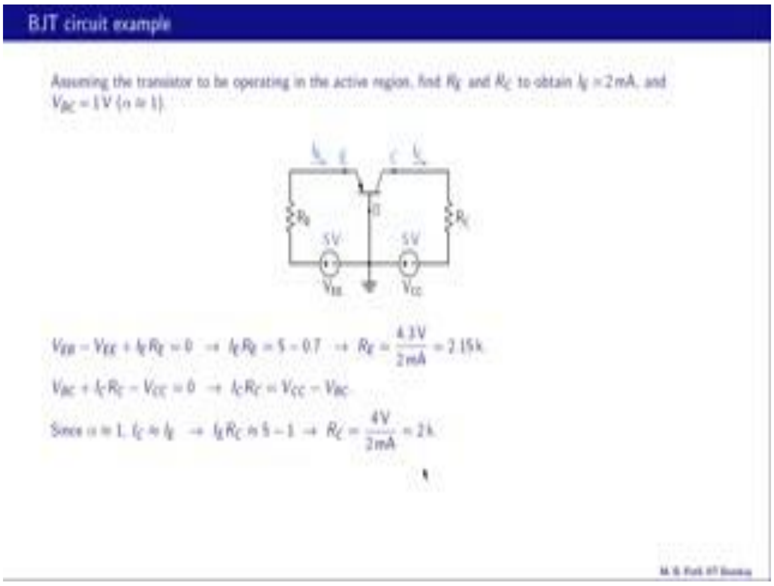

BJT circuit example

Assuming the transistor to be operating in the active region, find $R_E$ and $R_C$ to obtain $I_E = 2\,\text{mA}$, and $V_{BC} = 1\,\text{V}$ ($\alpha \approx 1$).

$V_{EB} - V_{EE} + I_E R_E = 0 \rightarrow I_E R_E = 5 - 0.7 \rightarrow R_E = \dfrac{4.3\,\text{V}}{2\,\text{mA}} = 2.15\,\text{k}$

$V_{BC} + I_C R_C - V_{CC} = 0 \rightarrow I_C R_C = V_{CC} - V_{BC}$

Since $\alpha \approx 1$, $I_C \approx I_E \rightarrow I_E R_C \approx 5 - 1 \rightarrow R_C = \dfrac{4\,\text{V}}{2\,\text{mA}} = 2\,\text{k}$

Let us take this example with a PNP transistor. Assuming that the transistor is operating in the active region we want to find RE and R C such that I E this current here diameter current is 2 milliamps and V BC this voltage is 1.3 volt. And we are given that alpha is nearly equal to 1.3. Now to begin with let us first check that this condition V BC equal to 1.3 volt does indeed corresponds to the linear region or the active region. So, we have PNP here. So, this is an n region that is a p region V BC is 1.3 volt. So, VB is higher than VC by 1.3 volt so; that means, the n type region is higher than the p type region by 1.3

volt and; that means, reverse biased. So, this junction is indeed under reverse biased and now let us calculate RE and R C.

So, in this loop we can write VEB this voltage drop which is going to be 0.7 minus this voltage raise 5 volts plus I E times RE equal to 0, and that give us I E RE equal to 5 minus 0.7 or 4.3 volts. And since we are given the value of I E 2 milliamps we can find RE turns out to be 2.15 k. For the collector resistance the R C value here we cannot write a loop equation for this loop V BC plus I C R C minus V CC equal to 0. And that gives us I C R C equal to V CC minus V BC and since alpha is nearly equal to 1.3 I C and I E are approximately equal to each other and therefore, instead of I C here we can use I E and that gives us R C. So, I E times R C is about 5 minus 1.3 and that gives us R C is equal to 4 volts by I E which is 2 milliamps that is 2 k.

In conclusion we have seen how to represent the behavior of a BJT with the help of I V curves. We have used the I V characteristics to obtain a graphical solution of the BJT circuit considered earlier we have also taken up a circuit with a PNP transistor and seen that it can be analyzed in much the same manner as an NPN transistor. Having looked at BJT basics we will now start looking at an important topic namely amplification. That is all for now see you later.