Analog Electronic Circuits
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Lecture – 14
Analysis of simple non - linear circuit containing a BJT

Welcome back to this course on Analog Electronic Circuits, myself Pradip Mandal associated with E and ECE Department of IIT, Kharagpur. So, after our previous modules in week 1, now we are in week 2 and we are going to discuss about the BJT and MOS related circuits. So, we will start with Analysis of simple non-linear circuit containing one BJT and later we will be discussing about one MOS and so and so. So, let us look back what is the topic we do have and what are the overall flow we do have in our program. So, this is what we do have in overall flow. So, we have completed the component things.

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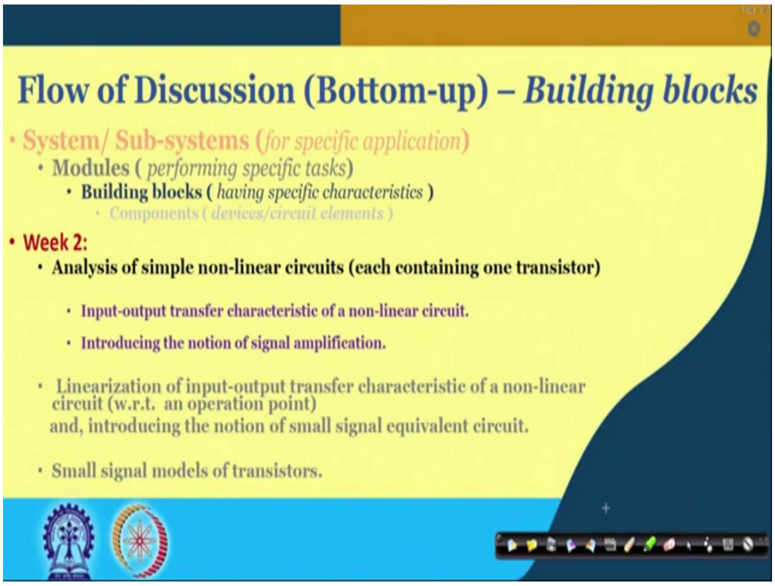

So, this is already done and now we are at this stage in building block and as I said that we are in week 2. And, we are going to start with analysis of simple non-linear circuit containing transistor and today's focus is BJT. So, what we will be doing is that we will be focusing on input to output transfer characteristic of non-linear circuit. And, then also we will be discussing about the signal amplification, how this non-linear circuit containing one transistor may be helping us to change the signal rather amplify the signal. So, what are the concepts we are going to cover today it is the following.

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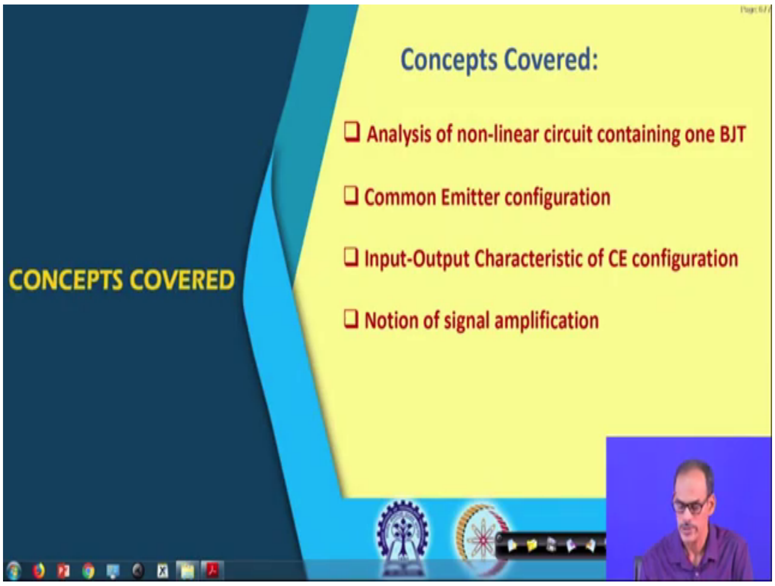

So, as I said that we will be analyzing non-linear circuit containing one BJT and the configuration will be discussing primarily it is common emitter configuration. Then we will be going to the how to get input or output transfer characteristic of this common emitter configuration. And, then we will be discussing about the signal amplification, the notion of signal amplification through this non-linear circuit containing one BJT. So, we are going to start with the in the first topic with an example. So, we do have this basic configuration namely the CE kind of configuration.

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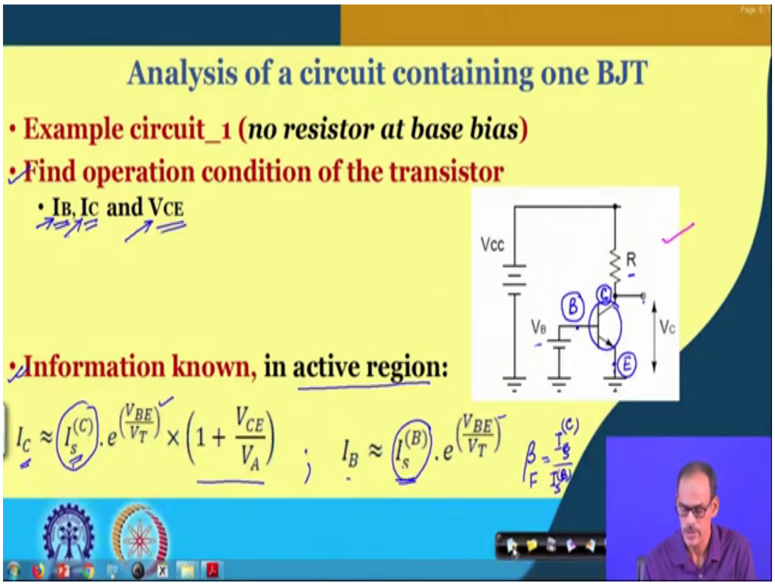

So, as you can see the circuit example is given here and the and also if you see the circuit that at the base node we do have a bias V B without having any feminine equivalent resistance. Emitter it is connected to ground and the collector it is connected to positive supply, but then through a registered R. So, we do have the collector at which we are giving a bias through this load register or sometimes it is called directly you can say R C, but whatever it is. So, this circuit we are going to discuss more detail about how we analyze this circuit and what are the things we do have it is information wise, if the transistor it is in active region of operation.

Then its collector current, it is having exponential dependency on base to emitter voltage incidentally that is base voltage V B. And, also it is having this I S C the parameter of the device, you may say that this is a reverse saturation current equivalent to a diode reverse saturation current. In addition to that we do have a factor representing the effect of collector to emitter voltage on the collector current; namely 1 plus V CE divided by the early voltage V A. And, also if the device it is in active region the base current it is again it is having exponential dependency. So, of course, here also we do have reverse saturation current, but of course, this parameter and this parameter they are different.

Ratio of these two parameters are basically the current gain for in forward direction; so, that we have discussed already. So, this is I S of collector divided by I S of the base. So, this is what the information it is available to us and we are expecting that the device it will be retained in this active region of operation, then only this equation it is valid. In this problem what you have to do, we need to find the operating point of the transistor or operating condition of the transistor; namely the base voltage intuitive is given. So, then the remaining things are the base terminal current and then the collector terminal current and the collector to emitter voltage or you can say directly the collector voltage as emitter voltage it is connected to ground.

So, that is what we need to find and we will see that what may be the procedure to find these three namely the base, base terminal current, collector terminal current and collector to emitter voltage. So, how do you proceed? So, probably we can say that first we can find the value of this or the expression of the I B, then we can get the I C and then we can go to the V CE. So, let me take the next slide where we do have the detailed steps.

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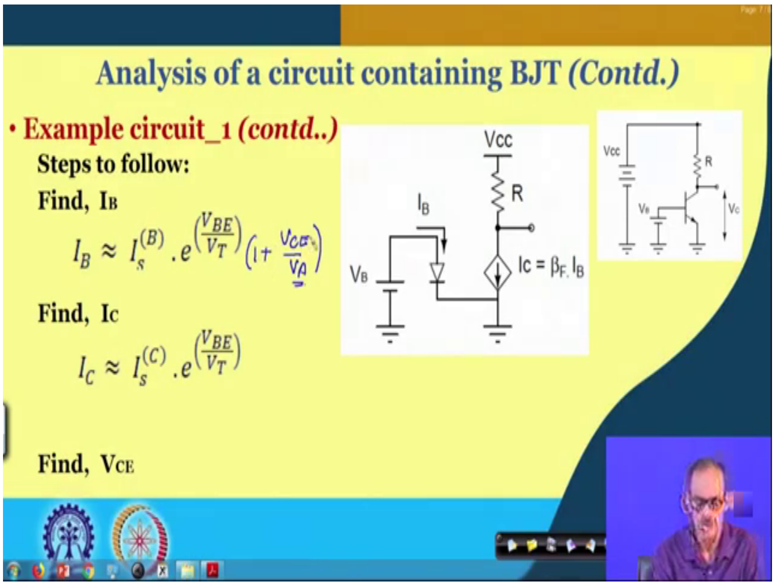

So, yeah; so, here you may you might have observed that we have dropped this term 1 plus V CE by this early voltage; intentionally we have dropped this term. For simplicity that is what normally it is done, we assume that this early voltage it is very high compared to the V C and hence we drop this part. So, let me drop this part and then we do have these steps.

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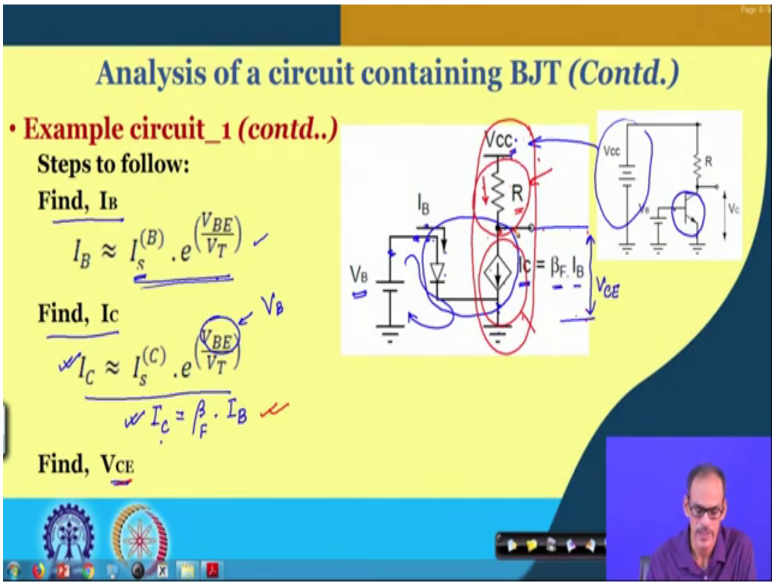

Namely first one it is, the step to find the base terminal current and the base terminal current we can directly you can use this exponential equation. And, you might have seen here that this is the actual circuit and the transistor it is getting replaced by the equivalent, equivalent circuit here. As we have discussed in the when the device related discussion where whenever it is required the transistor may be replaced by equivalent circuit. This equivalent circuit consists of the base to emitter diode and whatever the current it is flowing; if you multiply this by beta F that gives us the collector current.

In other words the collector to emitter current I C, it is actually current dependent current source and the influencing current is the base current and the corresponding factor it is beta F. So, this is the equivalent model of the BJT. And so now, if I consider the base part particularly base bias part namely this loop; since we do not have any register we can probably directly find the expression of the base current in terms of V BE because, the V BE it is directly available.

So, V B which is coming to the base ground is emitter is connected to the ground; so, V B it is actually V B. So, we can directly use this equation. So, we are assuming that the reverse saturation current namely I S B, it is given to us and then using this equation we can find the I B.

In case if we consider a generalized one later we will discuss in case if you consider a register thermal equivalent register, then the procedure it will be different. Now, once we find the base current next step it is we need to find the collector current. So, either for collector current either we can directly use this equation because the base emitter voltage it is given to us. So, this part it is actually as I said that it is nothing, but the V B.

So, either we can directly use this one or we can use this equation and then we multiply with beta F to get the I C current. So, we may get I C equals to beta F into the I B part, ok. And once we so, either we can use this one or we can use this one and once we find this collector current then our next step is to find the collector to emitter voltage.

So, this is the collector to emitter voltage V CE. Now, how do you find the collector to emitter voltage? We do have this circuit where we do have the V CC connected here. You might have observed that whenever we are writing this node as V CC indicating that with respect to ground one DC source is connected here as you can see here. So, that has been that has been equivalently you know drawn like this. So, if we consider this circuit, particularly this circuit where this node it is connected to V CC and then we do have a register here. And, then we do have a current dependent, current source and its expression it is given here.

Now, our task is to find the V CE and as you can see here at this node KCL suggests that this current is the current flow through the register, it is supposed to be same as on the current here and also the voltage here it should be consistent. So, that the voltage across the register after deducting this V C from V CC divided by whatever R should be consistent with this I R. So, we need to satisfy both KCL and KVL for this demarked network and for that we may say it may be having a generalized procedure. Namely, we can say that this part is pull apart and this is pull down part and then we can compare their characteristic.

And, then we can find what may be the solution point which is giving us consistency of both the circuit; the pull up and pull down. So, we call this part is the pull up and this part it is pull down part. So, let us see the generalized procedure to find this V CE and since this kind of circuit will be frequently experiencing; so, it is better let me discuss little detail considering this is as an example. So, what we have there it is yeah. So, this is the as I say that let us look into the generalized procedure to find the V C voltage.

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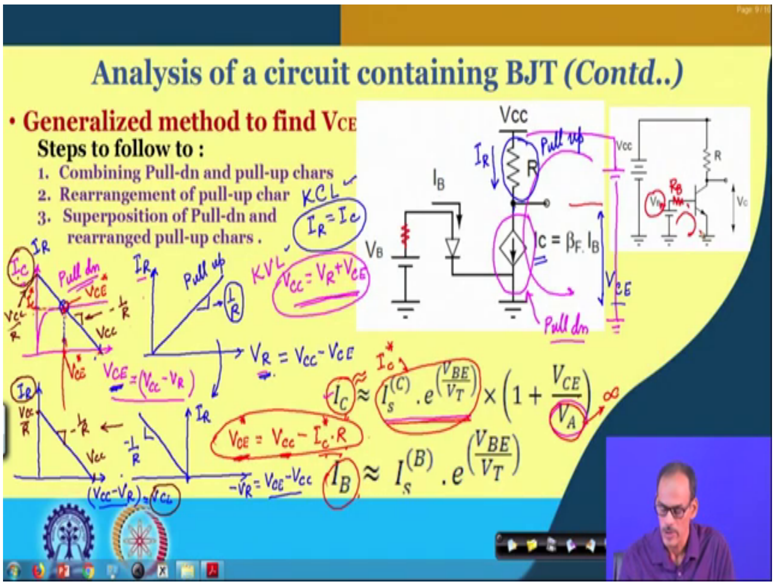

So, what we are trying to get basically let me use a different color here, we like to find what will be the V C voltage here. So, that this collector current after obtaining this collector current this current need to be consistent with the current flow here namely I R. And, when you say that consistent is basically these two currents are equal because no other branch it is connected to the collector terminal. So, the I R should be equal to I C; so, that is the first thing I R should be equal to I C for KCL at the collector node.

And, then on the other hand if we consider KVL; so, we do have V CC here. In fact, V CC it is basically saying that we do have V CC connected to ground, ok. So, if I consider say this loop on the other hand what we can say that KVL suggests that V CC equals to the drop across this resistance R and then plus V CE, in other words that the V CE and this one should need to be consistent. So, this is this is the equation we are getting by following the KVL. Now, individually if I say that this part and this part they do have their own characteristic. So, say for example, if I consider registered it is having its own characteristic.

So, what we have for the characteristic for the register? In fact, if we if we say sketch the current I R as function of the voltage drop across this resistance, it is basically a characteristic going through the origin. And, the value of the resistance it defines the slope namely the slope here it is 1 by R; so, slope here it is 1 by R. So, we do have as I said we do have KCL, we do have KVL and then we do have the characteristic of the register or the pull up element. So, we call this part it is pull up element. Why do you call it is pull up? Because, in case if nothing is connected the output node it will be pull to V CC through this element; so, we call this way it is pull up element.

On the other hand and the lower one which is we are calling with the same logic we are calling this is pull down element. So, this pull down element is also having its own characteristic and what is that characteristic is basically the device characteristic. So, either we consider this model or either you consider this model or from the device equation we may write say I C as function of V CE.

So, as you can see here for a given value of V BE, if the early voltage is very small. So, we can say if the device it is in active region of operation the I C it is having a hardly any dependency on the V CE voltage. So, you may say that it is practically this is flat.

Now if I so, this is the so, these are the things we do have in our hand and we have to make all of them are consistent; namely the pull down characteristic, pull up characteristic and KCL and KVL. So, if you see here if we if you say that KCL; that means, these two axis need to be same; whereas, V R and V CE of course, they are not same, but they are related like this. So, we may rearrange this equation and we may say that V CE equals to V CC minus V R. So, we may say that this is nothing, but V CC minus V R.

Now, KCL suggests that these two I C and I R at the solution point should be equal, but then of course, V CE and V R they are not same, but of course, they are related through the KVL. So, what you can do? The we can retain this pull down characteristic; so, we call this is pull down character or pull down element characteristic and then on the other hand this is pull up characteristic. So, one of them probably we can rearrange. In this case normally what it is done is that since we need to find the V C voltage; so, we can probably retain this one and then we can rearrange.

So, while we are rearranging we have to end of the rearrangement we like to get the x axis need to be consistent with this. So now, let us try to rearrange this one. So, we will retain this one; so, then let me try to write the V R in terms of V CE namely V R equals to V CC minus V CE. Now, to get this V CE for this axis; since it is having minus sign first thing is that we can probably plot this I R versus minus V R so, that we can get rid of this minus sign. So, once we plot this I R versus minus V R which is now V CE minus V CC. So, then of course, this characteristic it is instead of in the first quadrant it will be getting shifted to the second quadrant, ok.

So, the slopes of this characteristic namely pull up characteristic in this graph it will be 1 by R, but of course, having a minus sign. Now, still this x axis of this graph, it is not consistent with V CE it is having minus V CC part. So, what you can do? Probably we can add V CC here and we can get rid of this V CC. So now, let us do the further rearrangement. So, we have rearranged this graph here and then still it is not consistent. So, let me further rearrange this pull up characteristic. So, I R versus instead of minus V R let we observe V CC minus V R.

Now, this is of course, it becomes equals to V CE and once you consider this x axis as V CC minus V R, this characteristic it is getting shifted by V CC amount. So, this characteristic curve it is getting shifted by this amount which means that this point is getting shifted by V CC amount. So, the point here it is actually this this point it is V CC and the slope here since it is minus 1 by R; it can be shown that at this point where the x axis namely V CC minus V R axis it is 0, it is the corresponding current it is V CC minus R.

Now, if you see this characteristic the graph here the y axis and x axis if you observe and if you see the corresponding KCL then of course, these two quantities need to be equal at the final solution point and also this two-axis we already have translated to be equal. So now, if we overlay this two characteristic namely the original pull down characteristic and the rearranged the characteristic. So, what we are getting here it is the corresponding solution point.

So, if we overlay here what we are getting the load line what normally it is referred as load line characteristic. In fact, load line characteristic is nothing, but the characteristic of the pull up element after this rearrangement, where the characteristic it is cutting the x axis at V CC and as I say the slope it is minus 1 by V R. So, the slope here it is minus 1 by R and hence the point here it is V CC by R and for this characteristic of course, the y axis it is I R.

Now, wherever these two characteristic they are intersecting indicating that this is the value of the current and the corresponding voltage namely the value of the V C which is making both the pull up and pull down consistent; that means, they are satisfying KCL KVL, their characteristics are also respected and hence that is the solution point.

So, the, this point as we see it that and the procedure wise what we do? We rearrange the pull up character characteristic in this form. So, that they are x and y axis they are consistent and then once we overlay the intersection point represents the solution. Equation wise of course, you may say that this is this is pictorial generalized method, but of course, the equation wise what we can say that let me use different color here.

So, the V CE whatever the V CE we are getting here. So, let you call this is V CE star yeah. So, this is V CE star and then corresponding I C star. So, V CE star it is let me use this space. So, V CE star is V CC minus; so, this I C star into R. How do you get that? So, at this point the corresponding current of course; so, we probably we can write here this is V CC star V C star and here it is I C star or I R star. And so, the V CC it is here, slope here it is minus 1 by R and if you see that the point at which the current is I C star; so, then this voltage, this slope and this current and this voltage that makes consistent.

So in fact, if you see since this is straight line you may say that V CC minus V C start right and since this is 0 current and this is I C current. So, the slope here it is I C star divided by this difference and this difference is V CC minus V C star and that is equal to 1 by R. So, from that we can get this solution. So, this is as I said pictorial one and this is the actual one and of course, here to simplify the analysis we have assumed that this early voltage is very high that makes this I C current it is independent of V C. In fact, if you know this value of this I C from this equation you may directly say that this is I C star.

So, you may say that this is approximately equal to I C star and this approximation involves that early voltage it is very high. So, we considered this early voltage is very high and hence this whatever the current you are obtaining here we can directly say that this part is the I C star approximately and this I C star directly you can plug in to get the V C.

So, practically what you do it is basically once we get the I B current we multiply with beta F and that gives us I C star. Then we multiply with I R and then from V CC we subtract this part which is nothing, but the drop across this resistance that gives us the V CE, ok. So, that is the procedure of finding the solution point or you may say that is the analysis procedure. Let us see what may be the variance in case if we have a registered in the bias circuit at the base.

So, let us consider the corresponding example where we can put a register here and instead of calling this is V B; we may call it is something some other we can use different notation; let us call it is V BB. And, this may be whatever R B and of course, that voltage it is not directly giving the voltage at this one. So, we require additional procedure to find the corresponding I B current, because the V BB it is not giving us the V B voltage. So, let us look into that example. So, let me go to the next slide yeah.

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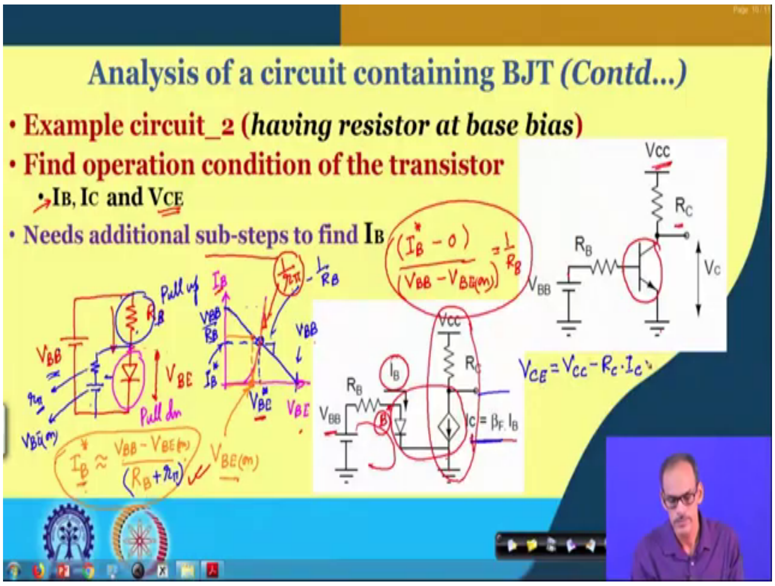

So, yeah this is the circuit where we do have the same circuit the BJT, its emitter it is connected to ground, collector it is connected to the supply, V CC through a register called R C. Earlier we are calling this is R, now we are calling R C and at the base basic difference here it is at the base we are connecting a positive voltage here to make this junction forward biased. We do have a register here and in this case what may be the procedure to find the operating point.

So, here we need to again here we need to find the corresponding operating point namely I B finding I B, I C and then V CE voltage and the, but then first procedure it is; the first step it is we need to find I B. So now, since as I say that since this external voltage it is not directly coming to the base ok; so, this is the equivalent model of the BJT.

So, at the base we are getting a different voltage of course, this voltage it is function of V BB, but it is not same as this one emitter node; however, it is connected here. And, once we get say I B probably either you can use V BE or the better approach is that simply multiplied with beta F to get the collector current.

And then of course, once you get the collector current to find the V CE we can analyze this part and the procedure it is same as what we have just now discussed. So, compared to the previous example here the additional thing we have to do it is we have to follow some sub steps to find the corresponding base terminal current. So, what is their sub steps? In fact, you may consider this and this loop this loop as equivalent non-linear circuit, diode non-linear circuit which we already have discussed when we have discussed about the simple diode circuit analysis, where instead of diode we do have base to emitter junction diode of course.

So, here we do have V BB, we do have R B and then we do have diode here and drop across this one instead of V D, we may call this is V BE. And, since it is non-linear again our task is to find this current and maybe this voltage. So, since it is non-linear circuit, the procedure to find the solution it may be we can deploy the similar technique. Namely, we consider this part is the pull up element and the diode we can think of it is pull down element. So, this part it is the pull down element and then our main objective here is to find this current. So, of course, at this node KCL we have to give it respect and then also the KVL.

So, what we can do? Again the general procedure wise the pull down characteristic we can sketch. So, this is the pull down characteristic, it is exponential relationship. So, let me say that this is the current through the base and this is the voltage across this base to emitter junction.

And, then if I consider the so, this is the pull down characteristic and then the pull up characteristic if you see and then if you rearrange the pull up characteristic as we have discuss will be getting load line like this, where this point it is equal to V BB, this V BB and slope of this line it is it is minus 1 by R B sorry this is R B.

And so, then the point here the load line it is intersecting the current axis it will be V BB divided by R B and wherever they are intersecting that gives us the solution; namely that gives us the base current I B star we may call I B star that is the solution and then corresponding voltage here it is V BE star, ok.

So, that is the graphical procedure, but what may be the actual method we should follow to get the numerical value; namely what may be the equation and all. Well, either you can go through iteration; so, if you know this characteristic and then if you know the load line then you can start from this point and then whatever the for diode circuit we have discussed about iterative procedure to find the solution.

Or, more practical method it is instead of considering this diode characteristic and the detail diode characteristic what we can say, we can approximate it by considering this is piecewise linear. And, in this piecewise linear what you can say that for diode we say this is cut in voltage whereas, for this case we call it is V BE on. Namely, it is once the base to emitter junction it is forward biased and if the device is on then whatever the voltage drop it will be appearing there you may say that is the V B 1. But of course, it is only showing this point and since this characteristic it is having a finite slope the voltage here it will not be exactly this one.

So, what you can do is that you may say I do not have this value unless otherwise I know this slope. So, it is more like a chicken and egg problem which one to where we can start from. So, instead of iterating this actual load line and actual diode characteristic probably you can you can iterate over this line and this line. And, if you know that the drop across the diode here it is almost this V BE 1 it is almost close to this point. So, what you can do, you can probably you can consider this V BE star it is approximately this point and then you can find the corresponding approximate I B star.

In other words we may see that practical procedure it is I B star equals to or approximately equal to; so, whatever the current will be having here. In fact, that current it is nothing, but from the V BB minus V BE on assuming that this V B you know on is given to us divided by R B. How did you get this one? In fact, if you see here it is very simple the slope of this line it is 1 by R B with a minus sign. And, if I know this point and if I know this point where the current is 0 and the voltage it is V BB; so, the slope of this line you can get directly from that. So, you may yeah; so, from that we can find what will be the and the corresponding current.

So, in other words we can see now 1 by R B equals to I B star minus 0 divided by V BB minus V B 1, ok. So, that gives us the I B star. So, once you get this I B star approximate I B star ok; let me just write this equation where did I get it from. As I said that if I consider slope of this line and if I know this point on this point, then the slope of the line it is basically I do have I B star or whatever you say approximate I B star minus current here it is 0 divided by the voltage here that is V BB and the voltage here it is approximately V B on. So, this is nothing, but 1 by R B and from that we obtain on this one ok.

So, anyway in case this if you really want to find what will be the more appropriate value of this V B star sometimes we consider this is approximately equal to V B 1. Or, in case if you are really interested of getting this value you need to find this slope. And, slope of this line it is basically variation of the current divided by variation of the base to emitter voltage. So, you may say the slope of this line it is 1 divided by r, for diode it is r on; in this case it is r pi, later we will discuss why it is called r pi.

So, if I know this r pi; so, from that you can get more accurate value of this one and in that case to find this one what you have to simply do; you have to you have to basically adjust this equation instead of considering only R B here you have to consider that resistance. And, how do you get that? It is very simple, if I replace this diode by an equivalent circuit like this where the drop here it is V B 1 and the resistance here it is r pi So, if that is connected here; so, instead of this one if I use say this circuit, now it is very simple that to find this current I B star I have to consider V BB minus V B 1 that is the drop across R B inside a series with r pi. So, that gives us the current.

So, it is as simple as that and as I say that once we know the I B then we can find the corresponding I C by multiplying with beta F. And then then of course, we consider this part to find the corresponding output voltage namely V CE it will be equals to V CC minus drop across this resistance R C multiplied by I C. I think that is all we have to consider. Now, we can probably we can discuss some more circuits, particularly where if the voltage here it is changing what may be the corresponding effect coming at the and the collector current as well as the output voltage. So, let me take a short break and then we will come back.

Thank you.