Analog Electronic Circuits
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Lecture 22
Discussion on Minor I Problems and Differential Amplifiers (Continued)

We are going to have a brief discussion on minor 1 problems and then we continue with differential amplifiers. Before we take the minor 1 problems the business of a common mode operation of the differential amplifier output impedance. This posed a problem. Apparently you have not tried. I should have left it to you but for the benefit of recording let me tell you what the trick is. This is the equivalent circuit R sub C, okay.

And in order to find out the output impedance what we are going to do is to connect a voltage source here V and find out the (resist) current I, okay. With the input voltage source short circuit, that means this comes to ground, okay.

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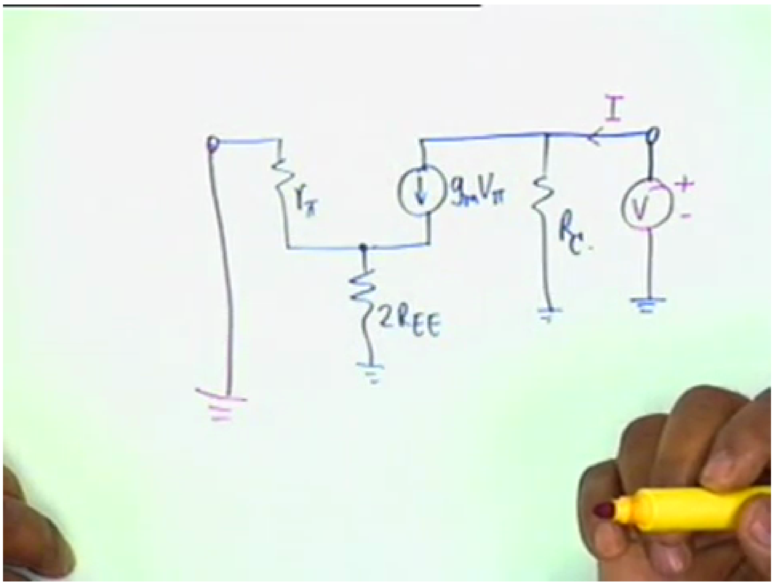

Let us say if I find V by I then I will know what this is V pie. I will know or there is something else. R s, that is right. I forgot about that. R s has to be brought in. Now if I draw this circuit in a little, is the point clear? What we are trying to find out is this and the question is I had claimed that it is equal to R C. There is objection from the class because there is another current g m V pie. That we will see the trick what happens and V and I, I did draw the circuit in a slightly different manner.

There is an R sub C, this is grounded. Then you have g m V pie, you have two resistances, one is twice R E E and the other is r pie. I will not combine them because then I will lose V pie. V pie with this polarity, plus minus and then an R s, alright.

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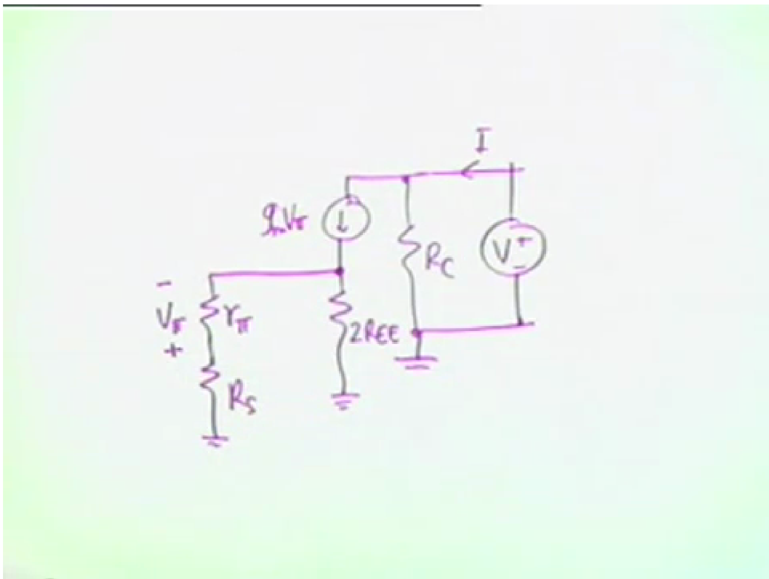

Now what is the current through r pie? Obviously this current goes up, equals to V pie by r pie, agreed? So what is the voltage across this? This will be V pie then 1 plus R s by r pie with this polarity plus and minus, agreed? This is the voltage. So now you can write a node equation at this node. What is the node equation? All the currents coming in should add to zero.

So g m V pie, this is one current plus V pie by r pie, okay, plus this voltage by 2 R E E. So V pie 1 plus R s divided by r pie divided by twice R E E, this should be equal to zero. Is that point clear?

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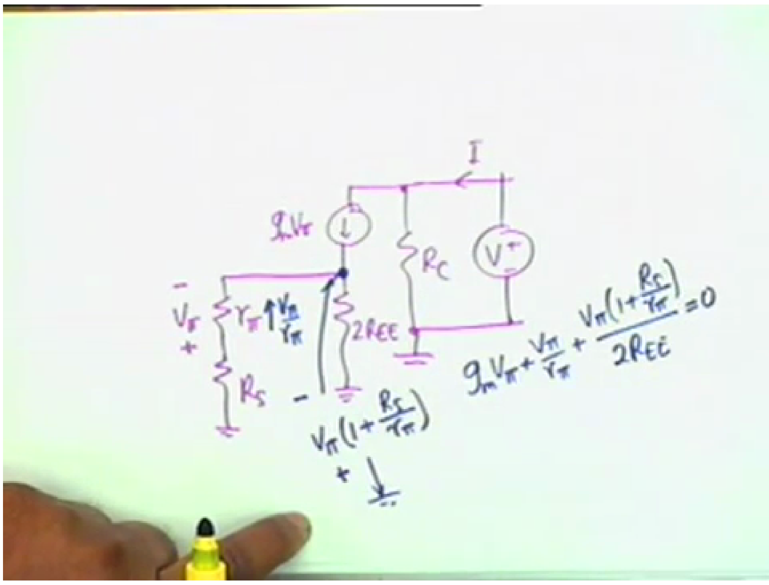

We had not assumed the voltage across g m V pie. We do not have to. We write a case here. Now in this equation what is the variable? Variable is V pie and this equation should be true for all values of r pie, R s and R E E. So what is the solution? V pie equal to zero which means, I beg your pardon. Please repeat, okay.

In this equation we are trying to find this voltage V pie, okay. V pie is the unknown and these are constants R s, r pie, R E E and therefore the only possibility is that V pie shall be equal to zero which means that there is no current here and therefore the input impedance is indeed R sub C. Do you see the trick?

Student: Yes sir.

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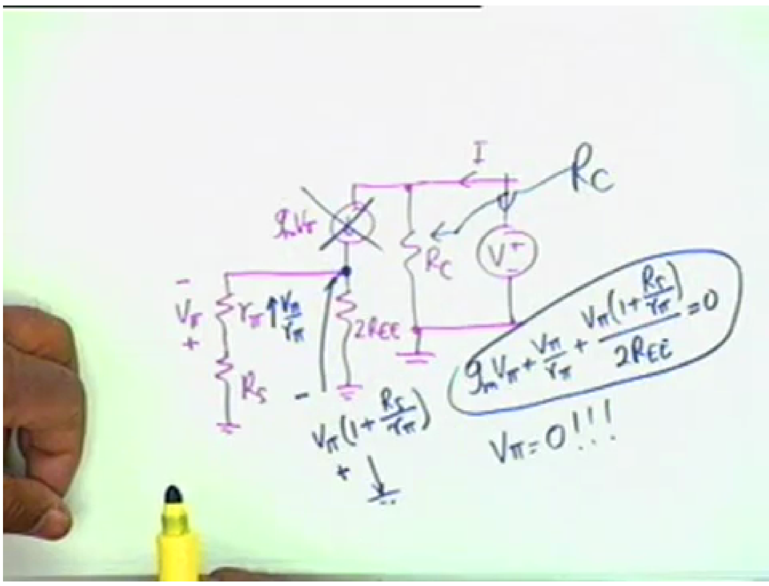

It is a hidden value. Even though the circuit looks complicated, the output impedance is very simple. We shall give another example of this maybe in the next class. Another example of such complicated thing but ultimately the voltage is zero. Yes?

Student: What is the trick in that sir? It is directly coming from the equation.

Trick is I saw this. You know you have to observe, not just see. I observed that all currents coming here depend on V pie only, nothing else and therefore the sum of all these currents will be equal to zero which means V pie equal to zero. I do not have to write all these equations. Yes?

Student: What happens if you consider small r 0?

What happens if we consider small r 0, then the situation is quite different. Then the situation is quite different. Then you have to have V minus this voltage divided by r 0. Therefore V will come. If r 0 is there then all this simplification vanishes. And life becomes a little bit uncomfortable, okay. Any other question? Yes?

Student: Why cannot we take the impedance at infinite directly?

Which impedance?

Student: The current source we get directly.

No, you may not because if this current depends on V, for example if we have an r 0 in parallel then there is a problem. You see if V pie depends on V then there is a problem. This is not an independent source. It is a dependent source. So we cannot take this as zero because then there will be a current drawn from here, okay. Now about minor 1 problems. Since the people who will be watching the film did not take minor 1 I have to repeat the question.

Question 1 was 11 point 2 volt, 21 K, then we have a current here Q 2, the base and collector are connected, then you have Q 1 which is connected here, there is in addition a resistance R sub B. This is the only difference between the ordinary current and the question that I have said. And this is R sub C and then connected here and this voltage is V C E 1 plus minus. The question that we have asked for is to determine I sub R.

This current is I sub R, then I sub C 2 and I sub C 1 determine this as functions of R B because R B has come into the picture. Find out these three currents I R, I C 2 and I C 1 as functions of R B and show how they vary with R B by means of a sketch then determine R B in order that I sub C 1 is equal to I R by 2. Obviously this question itself shows that this current which normally should be equal to I R is now being controlled by I sub B.

This current can be as low as half of this value by appropriate choosing R sub B and that is very obvious that R sub B draws a current. In addition to I B 1 and I B 2 there is an I B through R sub B and therefore R sub B controls the current. And for this under this condition we have to find out, V C E 1 is 6 volt so we have to find out what is R sub C? If V C E 1 equal to 6 volt, we have to find out R sub C.

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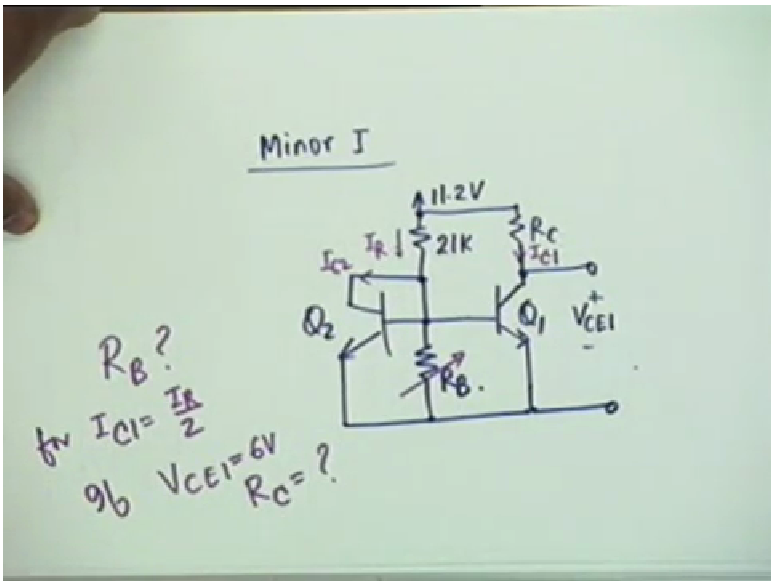

The solution should be obvious that first is that I sub R is obviously the power supply 11 point 2 minus V B E 1 or V B E 2 because the two are equal, point 7 divided by 21 K which is equal to point 5 milliampere. And this is independent of R B. On the other hand point 5 milliampere that is this I R, if I write KCL at this node , okay, this would be equal to first I sub C 2 plus I sub B 1 plus I sub B 2 plus I B which is equal to point 7 divided by R B, okay, point 7 divided by R B.

Now these two are equal because the bases are tied together and therefore I can write this as I sub, what we wrote I C 2 and I C 1. This should also be equal. So I can write this as I sub C 1, 1 plus 2 by beta, agreed? Plus point 7 divided by R B from which I get I sub C 1 as equal to point 5 milliampere minus point 7 divided by R sub B divided by, beta has been given as 200, so 2 by 200 is point 01. So it is 1 point 01 and this is also equal to I sub C 2.

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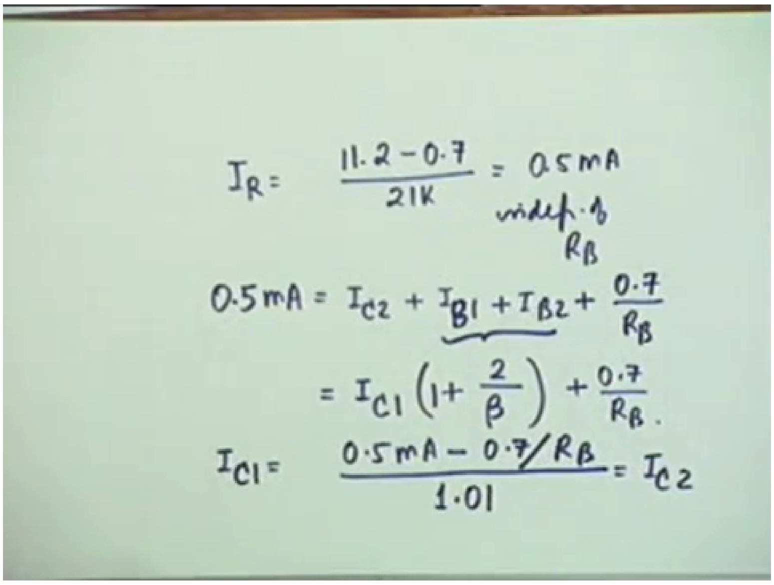

Obviously this sketch would be, where did it start from? If I plot I C 1 and I C 2 the maximum value obviously is point 5 divided by 1 point 01 milliampere. This occurs when R B is infinity. Can you start from R B equal to zero? No, we must start from a non zero small value such that the voltage can be maintained at point 7 which we had not asked you to determine but it is possible to determine. So do not start at R B equal to zero. At R B equal to infinity the curve goes towards point 5 divided by 1 point 01 milliampere, okay. Yes?

Student: Sir if we take R B equal to zero, it is a short circuit.

So point 7.

Student: The current is zero sir.

Pardon me.

Student: So the current would be zero sir, I C would be zero.

No but the transistor would be.

Student: But it is not been said that the transistor should be in active region sir. It is not specified.

Then all this calculation will vanish. That point 7.

Student: But sir I C would be zero if there is a short circuit.

If it is short circuit there cannot be a current. Correct, V B E 1. That is it, exponential this minus 1 would be zero, yes. Okay. I C 1 would be equal to zero when R B equal to zero.

Student: Yes sir.

Okay, wonderful. So we can start from here. Agreed all of you? Okay. I will however leave this a little dotted line here. Little dots because the region is a bit uncertain when actually it goes into the active region.

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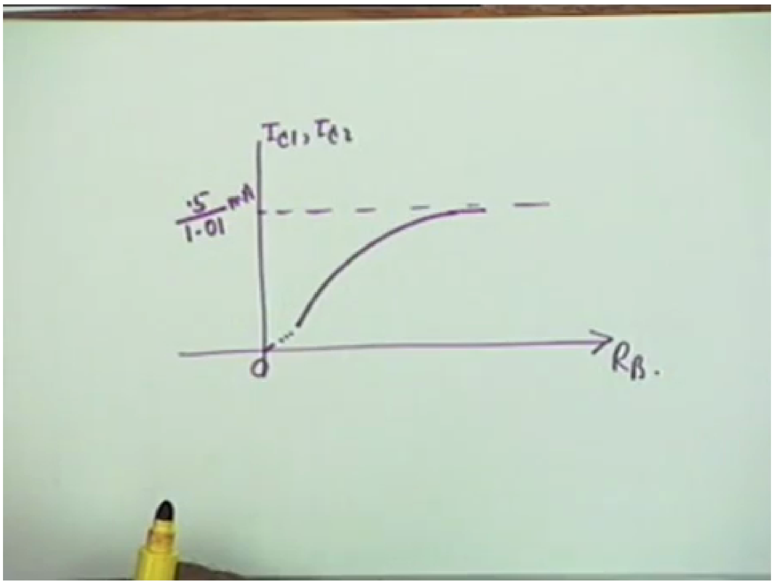

You have thought correct that this is the perfect short circuit then the current has to be zero because V B E equal to zero, exponential V B E by V T is 1 that minus 1 is equal to zero. That is perfectly alright, okay.

Student: Nature of the curve would be different in this region.

Nature of the curve would be different in this region. Yes.

Student: (())(14:30)

We assume that it is silicon and you can assume a general thing, we will give you full credit.

Student: Sir, I have used a diode equation instead of V B E and then I have done the whole calculation.

That we will see.

Student: Sir, in that case I R will also matter because it has to be equal to (())(14:52).

That is correct. The whole calculation will fall to the ground, okay. The other question was what value of R B is required for I C 1 equal to I R by 2? So what we do is point 5 divided by

1 point 01 milliampere minus point 7 divided by 1 point 01 point R B is equal to point 25 milliampere. Then find out R B.

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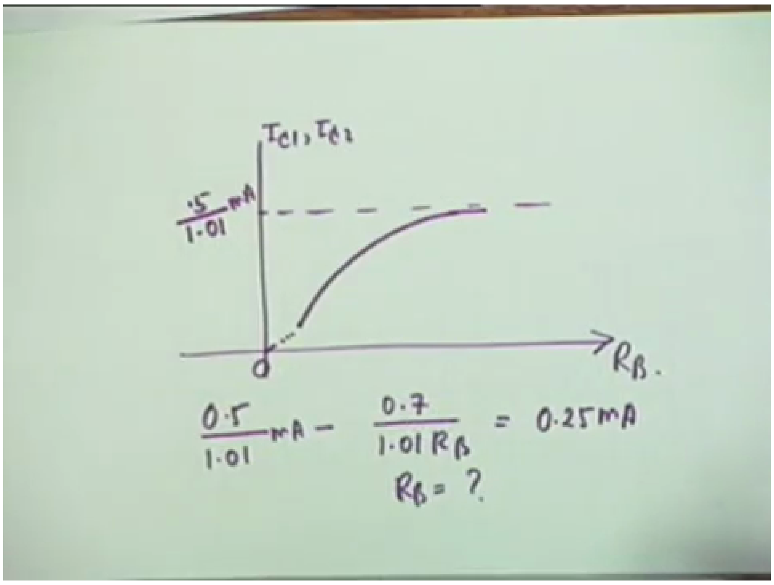

That is very simple and the other condition is that V C E 1 has to be equal to 6 volt. If V C E 1 is 6 volt this means that 11 point 2 minus R sub C into point 25 milliampere, this is V C E 1, this has to be 6 volt and therefore find out R sub C. These are not problems. Any question in question 1? Question 2, question 2 requires keeping your eyes and ears open, alright. Let me draw this circuit. There is a C 1, V s, then 100 K, 100 K, then you have two transistors in what is called a Darlington connection.

Q 1, Q 2, a Darlington connection, this is 1 K and you have 10 K. Then this goes to plus 6 volt. The output is taken from here C 2. This is V 0. Oh no! I have made a mistake. This is I am sorry. There is a capacitor. There is a 10 K here. This is not there. I have made a mess. Anyway this connection is not there. This is connected, Q 1 and Q 2 collectors are connected. There is a capacitor and this is 10 K, okay. The question was draw the midband equivalent circuit of the amplifier shown below.

Its numerical value components that is r pie, g m and everything has to be calculated numerically. Only the equivalence where no calculations were needed. R X 1 and R x 2 were to be ignored. The data given was beta 1 equal to beta 2 equal to 100. V A 1, the two early voltages are also equal 150 volt and V B E 1 is equal to V B E 2 for calculation. Assume that the points are involved.

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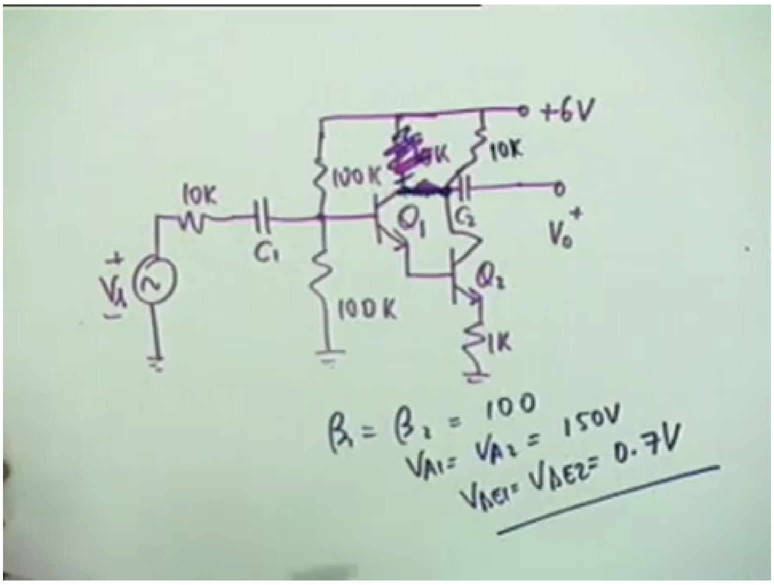

The point of this example, suppose we draw the equivalent circuit blindly. Let us say what the equivalent circuit will look like? Then we will come to the actual intricacies of the problem. The midband equivalent circuit will obviously be V s, 10 K, C 1 is a short, 100 K and 100 K in parallel gives 50 K. Then from the base to emitter 1 is r pie 1. This is V pie 1, this is E 1 and B 2, emitter 1 and base 2, okay. Now from the collector, collectors are also common. C 1 and C 2 are connected together.

So from the collector you have a g m 1, V pie 1, the current source and r 0 1 , okay. From B 2 to E 2 you have an r pie 2. This is E 2 and this voltage is V pie 2 plus minus. Then from E 2 goes to ground 1 K, alright. Then go to collector 2 C 2. From C 2 two emitter to E 2 you shall have g m 2 V pie 2, agreed. This will come and in parallel with this will come r 02. What else do we have? We have an R C which is 10 K and this is my V 0. This is the equivalent circuit, very simple.

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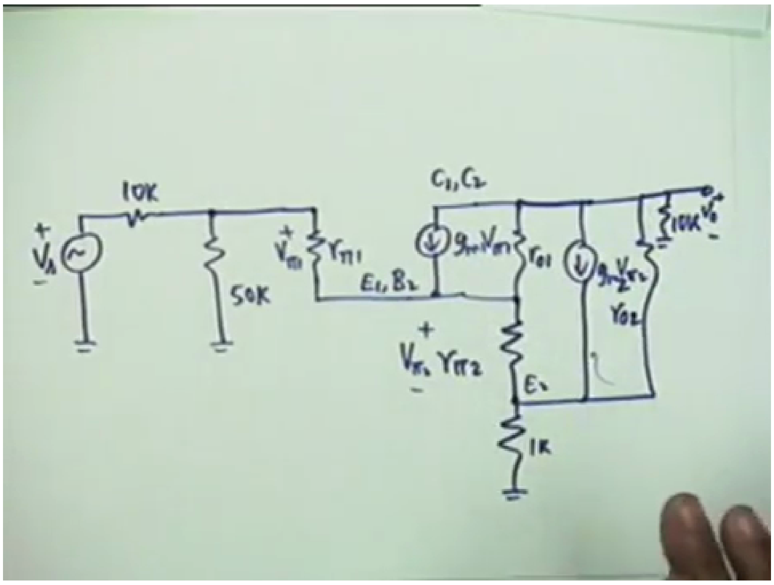

Equivalent circuit drawing is not complicated and you can find out all the parameters if you know the currents I C 1 and I C 2 and that is where the problem lies. The current can be let us start from the Q 1 end. You see that 6 volt divides into 200 K. So, 3 volt is the equivalent voltage that should be equal to 50 K multiplied by I B 1, okay, plus V B E 1 which is point 7 plus V B E 2 which is point 7 plus the drop in 1 K, okay. We are going from here to here, here to here and then drop in 1 K.

Now the current would be 1 plus beta 2 times I B 2 which is 1 plus beta 1, I B 1 multiplied by 1 K. And beta 1 and beta 2 are given to be 100 then therefore this equation can be solved. And my solution had come out to be how much, point 16 microampere. If this is point 16 microampere then obviously I C 1 which is hundred times this is 16 microamperes, okay.

Multiplied by 100, point 016 milliamperes, okay. And I sub C 2 I have not multiplied by 101. It will get slightly different multiplied by 100. If I multiply this by 100 then this comes as 1 point 6 milliampere and that is where the complete problem fills.

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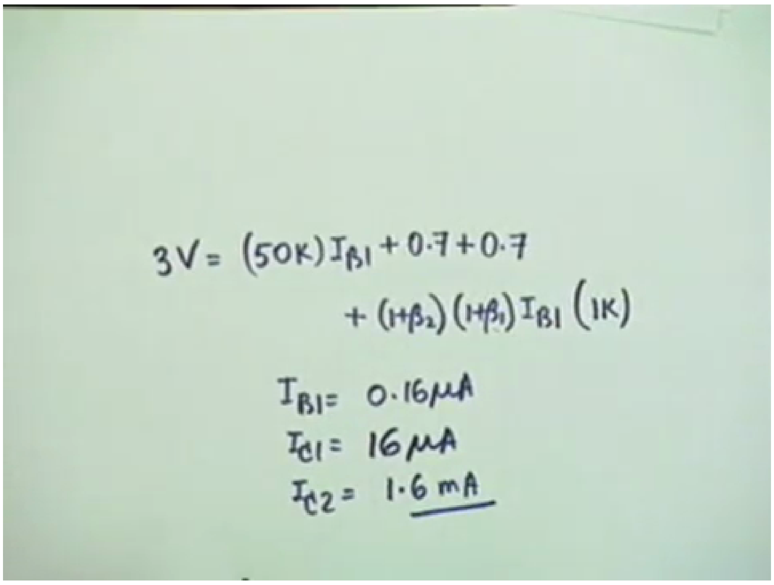

You see if I C 2 is 1 point 6 milliampere then the drop in 10 K should be 16 volts and the drop in 1 K has to be 1 point 6 volt. So 17 point 6 volts is the minimum V C C that we need but the V C C given was plus 6 volt only and therefore the conclusion is that Q 2 goes into saturation and the equivalent circuit in terms of g m, r pie and r 0 is no longer valid and therefore the equivalent circuit is valid only up to the output of the first transistor. The rest of it is not valid.

There is an equivalent circuit in terms of the diode which contains a voltage of point 2 across the collector to emitter. You can still calculate the currents by assuming this voltage to be point 2, the rest of it is dropped in 1 K and therefore you can find the current. The base obviously is over driven. The current that will flow now in I C 2, if you divide that by beta it would be much less than what actually comes here, that is 1 plus beta 1, I B 1. And if you have recognised this point I will give you full credit.

But if you have not, if you have drawn it blindly, I have also been generous and ask mister Joshi to give you full credit. You do not expect it in the final. You must be able to recognize this. A few people recognize this. I do not remember the minor paper or outside the minor paper. Outside, but anyway I appreciate that. That is what I said that you have to keep your ears and eyes open. Now go to third problem.

The third problem was a common base amplifier and the question is this, V s plus minus, then you have a common base. So a bypass capacitor, a resistance R sub 2, a resistance R sub 1, R sub C, this is plus V C C and the output is taken here as R L. This is V 0. The question was to draw the high frequency equivalent circuit of this and show that A V S is of the form A V S 0 over 1 plus j omega by omega 1 times 1 plus j omega by omega 2. That was the question, show.

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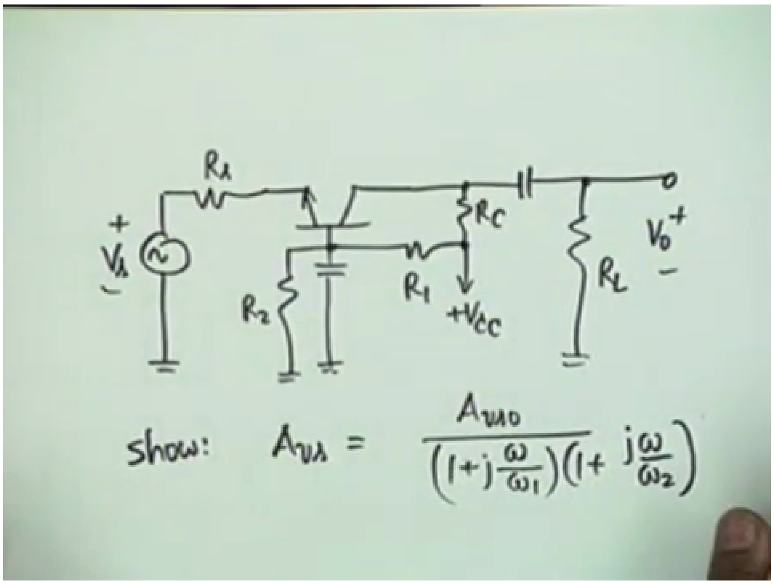

Now here one has to be careful drawing the equivalent circuit, okay. The equivalent circuit if I proceed step by step I have an R s. Then from emitter to base, base is connected to ground so this is r pie and V pie would now be of this polarity plus minus, okay. This fact has to be recognized. Many people did not recognize it. I read question number 3. So I remember many people did not recognize it. So they wrote this current is V s minus V pie by R s. Obviously that is a mistake, okay. Then what do we have? From emitter 1 we have a g m V pie.

Now here comes the question of simplification. Should you recognize r 0 or not? Okay. Well suppose we do, many people have also recognized the C 0 despite my saying that C 0 mainly is contributed by stray and stray should occur at the output, not across g m V pie. Nevertheless let us grant it that they include a C 0 which is the very small device capacitance, okay, let us grant it that this is the collector and the collector goes to R sub C. What else? R s and this is V 0. Is this the equivalent circuit?

Student: Sir C mu.

Where is C mu?

Student: Sir, in the output.

From the collector to base and there is no reason why you cannot include r mu also because fortunately they come in parallel.

Student: Sir, C pie also.

Where is C pie? Okay, good there is a C pie also, alright.

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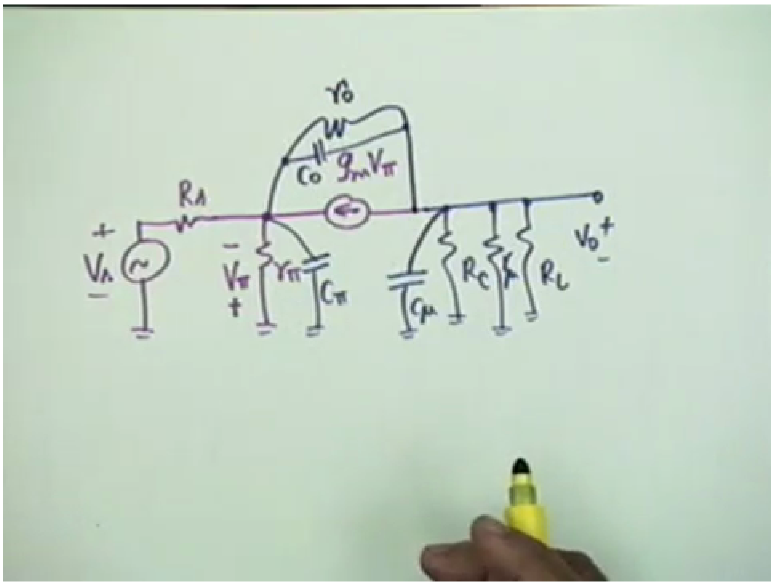

Now the problem is obviously this combination, r 0, C 0. There is no other problem. But suppose this can be combined into single resistance R L prime, okay. Now will there be three critical frequencies or two critical frequencies?

Student: Three.

Is the house divided between three and two?

Student: Three.

You got three? You got it wrongly then, okay. If I write it should be two. I will tell you. Can you tell me the reason why it should be two?

Student: (())(28:59)

One loop which means that the voltages are not independent of each other. You see if I write a KVL around this loop, voltage across C 0 plus voltage across C pie plus voltage across C mu should be equal to zero which means this is a fundamental thing of circuit theory. This means that these three capacitors are not independent of each other and therefore we shall get only two critical frequencies. If you have got three then you have got it wrongly or you have not been able to simplify, that is it, okay.

Three capacitors forming a loop is equivalent to two capacitors. That is two dynamic state not three. Similarly if you have a number of inductors connected at a common node then the degrees of freedom is reduced by one. If you have three (capci) inductors connected to a common node, the state of the system or the dynamics of the system will be governed by second order differential equation, not a third order. Similarly here it would be a second order differential equation.

So you have only two critical frequencies. Now if you ignore r 0 and C 0 then these critical frequencies can be obtained explicitly. On the other hand if you do not ignore r 0 and C 0 then you get a quadratic which you have to solve for omega 1 and omega 2. But if you have left it as a quadratic and say that omega 1 and omega 2 are the two roots of this equation I have given you full credit.

There are two or three people whom I have given 12 out of 12. Was it 12 or 13? 12. I have given 12 out of 12 even though they have not completed because they saw the point. Only thing they did not do was to ignore r 0 and C 0. If you ignore r 0 and C 0 life becomes very simple, absolutely simple.

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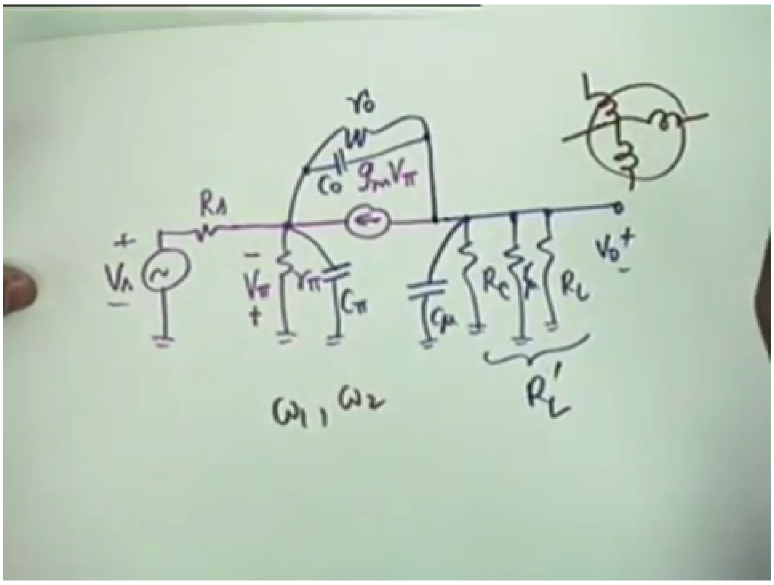

Now I do not blame you if you did not ignore. I have given you full credit but in practice if this was required to be designed then you better do that because otherwise you shall require a spies program or you have to write a program and writing a program cost engineer the time. And after all the exact calculations we will have to change resistances anyway. So, rough approximation would be alright for omega 1, omega 2 and then the question of design.

So I will simply give you the approximate results that is if I assume g m much greater than g pie plus G s, if this is true and if g 0 is assumed to tend to 0, C 0 assumed to tend to 0 then A V s 0 is approximately equal to R L prime by R s. This result we have derived earlier A V s 0 and omega 1 is approximately equal to g m by C pie and omega 2 is approximately equal to 1 over C mu R L prime.

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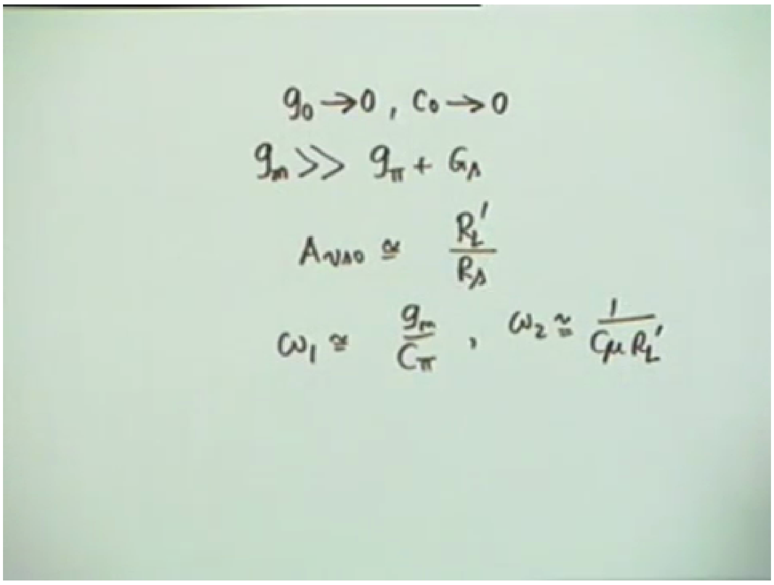

These are the final results under these simplifications. The last part of the question number 3 was if omega 1 and omega 2 are comparable, some people asked me during the minor, comparable means they are equal? Comparable and equal are two different terms. If they are identical why should we use two terms? We call each of you by one name. Of course your father calls you by some other name but that is a different story. As far as public is concerned you are named by one name.

Why should we give two names unless they are synonymous? Okay, so comparable means that they are not much different. They are not different by the ratio of 1 is to 10. For an electronics engineer comparable means 1 is to 3, 1 is to 4, they are comparable. If they are comparable then the (())(33:23) point is neither omega 1 nor omega 2. We have to calculate it exactly and the equation that gives it is 1 plus omega H square divided by omega 1 square multiplied by 1 plus omega H square divided by omega 2 square.

That should be equal to 2. That is correct and this gives you a quadratic from which you have to choose one solution. The solution which gives omega H square as a positive quantity, okay.

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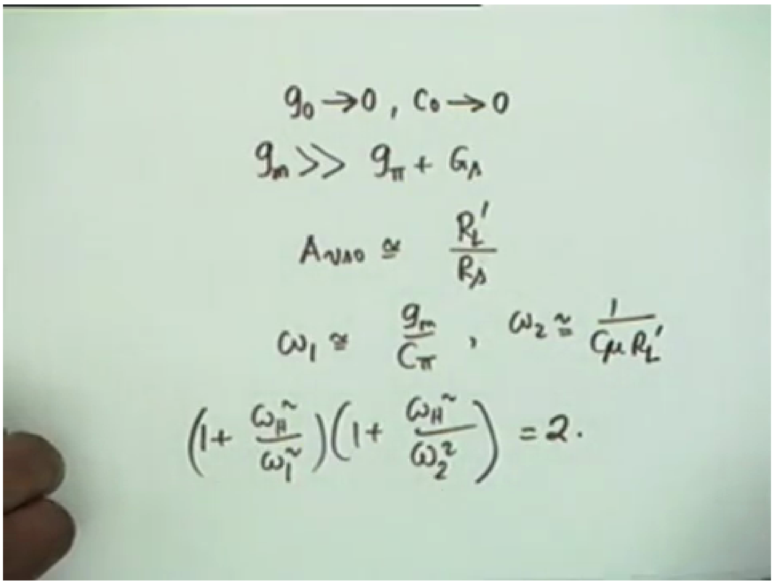

Next the only discrimination or only judgement that you have to apply. Any other question on minor 1? Okay. Last time we had considered the question of the equivalent impedance offered by (())(34:25) current source. So we were in the process of drawing its equivalent circuit. The current source was a resistance R which is the reference resistance then the (()) (34:42) current source. This goes here and this base is tied to another and there is a resistance of R sub E.

This is Q 1 and this is Q 2 and this is the current I sub C 1. You see we replaced R E E of a differential amplifier by this circuit and therefore it is of interest to know what output impedance is offered by Q 1? That would be our equivalent R E E, okay. Then what is the purpose? Why did you use the current period? Because we wanted to increase. Why should we increase R E E? To increase the C M R R. And why do we tend to increase the lumped resistor? Why did we take help of two transistors?

Because of integrated circuits we cannot go beyond the certain resistor. The absolute limit is 50 K. 20 K is honoured by IC designers as the limit that they can go. But absolute maximum is 50 K. Then if you increase R E E lumped value we also have to increase what? The power supply V C C and V E E which means that there will be much more dissipation in the circuit and integrated circuits are not designed to withstand heat, okay, because the volume is very small. Now we want to draw the equivalent circuit and find out R E E.

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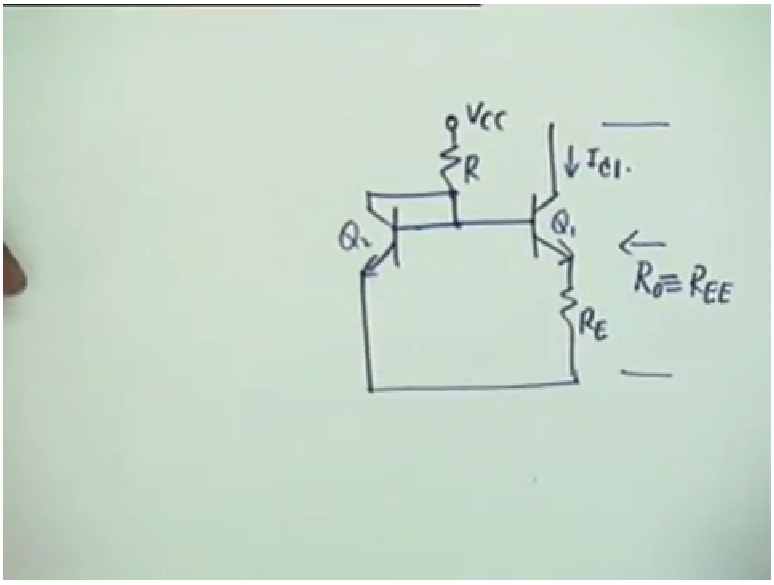

This is an interesting exercise. What we do is we start from C 1 and you see from collector 1, we shall have an r 0 1 to, what is this point? Emitter 1 and we shall have from collector to emitter a current source g m 1 V pie 1, alright? Then from the emitter of Q 1 we have a resistance R sub C to ground and from the emitter to the base of transistor B 1 we have the resistance r pie 1 and the voltage is V pie 1 with this polarity plus minus, agreed? Now B 1 is also the same as C 2, collector 2.

Base 1, base 2 and collector 2 are connected together. So B 1 is the same as B 2 and C 2. So as far as C 2 is concerned we shall have a resistance r 02, okay, to ground because the emitter of Q 2 is grounded, alright, r 02 and we shall have a g m 2 V pie 2 from C 2 to emitter 2. What else do we have? We have an r pie 2. What we must have? R pie 2 and the voltage is V pie 2. Which polarity? Plus up or plus down? Plus up, okay, this polarity. This is B 2. In addition we have ignored something else.

R X we have ignored completely but there is something. Capital R which will come from C 2 to ground and therefore capital R comes here. And here is some observation we did. The observation is that if you look from here all of them are equivalent to a single resistance because V pie 2 is the voltage across g m to V pie 2. So what is its (impe) equivalent impedance is 1 by g m 2. And therefore if you call this resistance as r 1, it is simply r pie 2 parallel, R parallel, 1 by g m 2 parallel, r 02, agreed?

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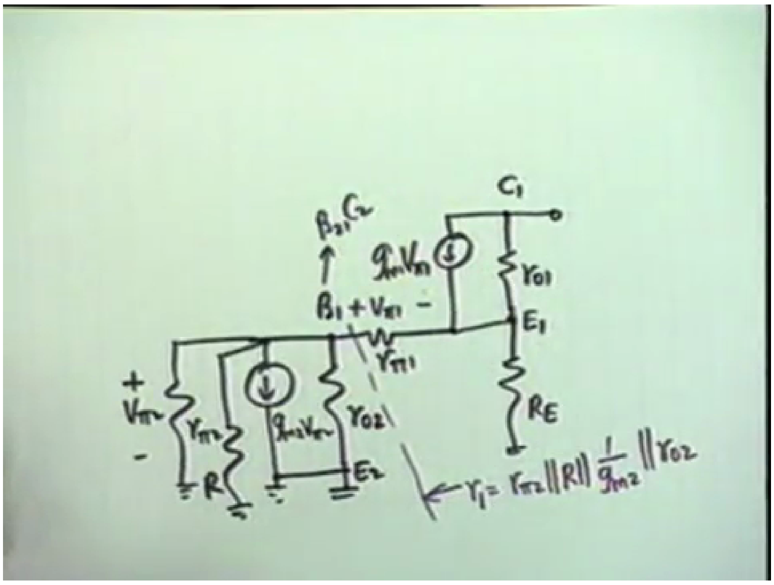

So this whole thing can be replaced by a single resistance and obviously 1 by g m 2 is a small resistance, right? This is being combined with r pie 2. Now since beta is much greater than 1 what is this combination r pie 2 parallel g m 2 approximately? Approximately, 1 by g m 2. This is a small resistance which is being parallel to r 02 so we can ignore that and capital R we can ignore that also and therefore r 1 shall be a very small resistance and it tends to zero.

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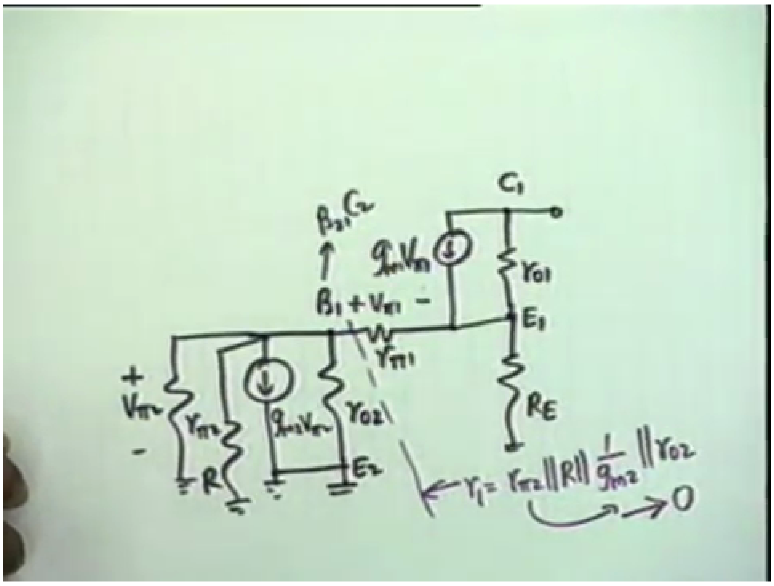

The other reason is suppose now what does r 1 connect to? R 1 comes in series with r pie 1, is not it right? Now if r 1 is comparable with r pie 1 obviously we cannot ignore it. But can you show that r 1 is much less than r pie 1? Let us look at this circuit. I C 1 and I C 2 what is their relationship? Which one is greater? I C 2. I C 1 is much less because its V B E 1 is less than this by this drop and therefore I C 1 is usually much less than I C 2. In the example that we took 50 microampere and this is 1 point 43 milliampere, okay.

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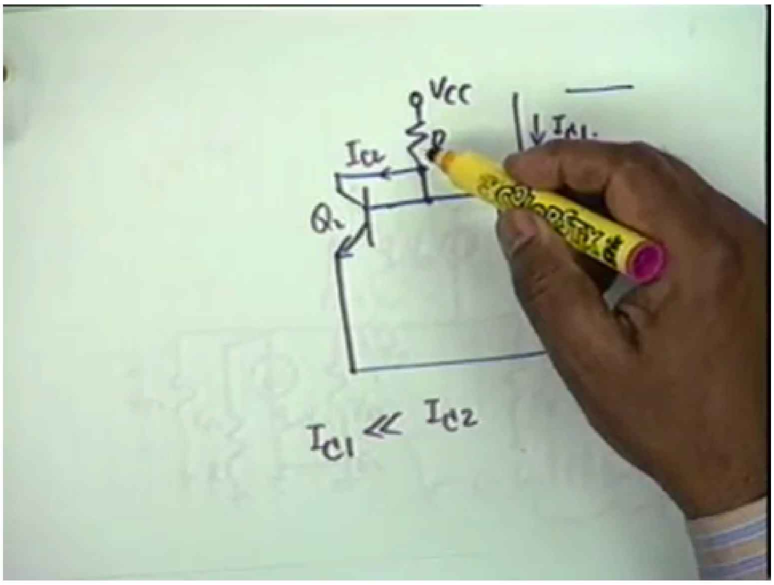

Now if the currents are different what about their g m? No, what about their r pie? R pie is beta by g m which means that r pie would be proportional to 1 by I C. R pie would be proportional to 1 by I C and since I C 1 is much less, r pie 1 will be much greater than r pie 2 which means that we are quite justified in assuming that r 1 is far much less than r pie 1, so we ignore it. And then the equivalent circuit becomes very simple. R pie 1 V pie 1 plus minus.

No, short circuit this, okay and we have a g m 1 V pie 1 here, r 0 1 then an R E. We want to find out this resistance. Have we ignored something? We have ignored of course R 1. That we have made equal to zero. So what we want to do is to calculate this. You connect a voltage source here and find the current I.

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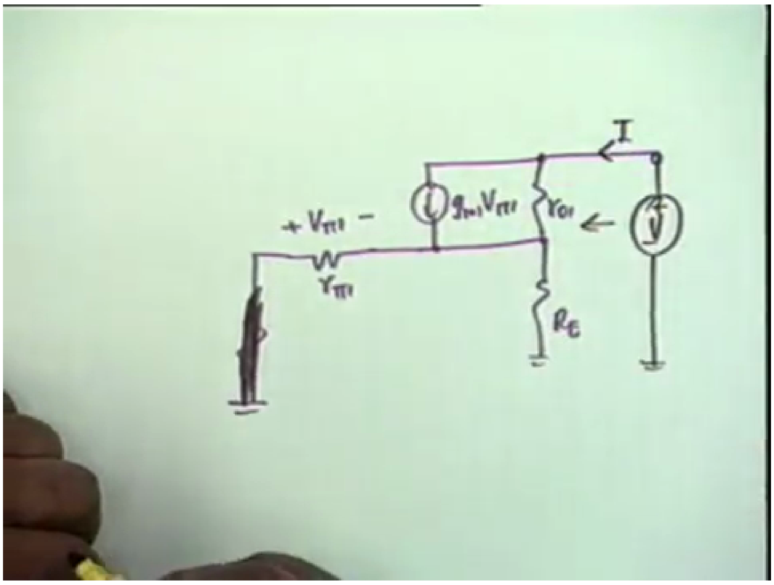

Now you cannot ignore g m 1 V pie 1 as having an infinite internal impedance because there is an impedance r 0 1. And I asked you to solve this circuit and show that r 0 is equal to, I will give you the final result only, approximately equal to r 0 1, 1 plus g m 1 R E provided two conditions are valid that is if g m 1 far much greater than 1 by r 0 1 and r pie 1 is much greater compared to R E. If these are true then the output impedance is this.

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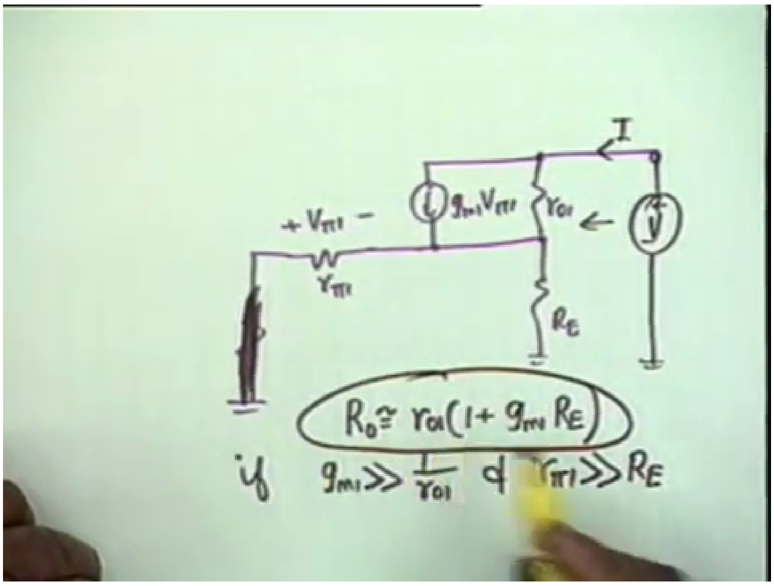

You see r 0 1 what is the order? Meg. Okay and therefore the effective output impedance effective R E E is not of the order of the meg. Not just a meg it is also enhanced by a factor of g m R E which can be let us say if it is three then you have four times r 0 1. And what about r 0 1, the current was only 50 microampere and therefore V a by r 0 1 will be of the order of a meg and therefore capital R 0 would be a very large resistance and there is no (())(44:12) in the world which does not use a current source for its R EE. We will stop here.