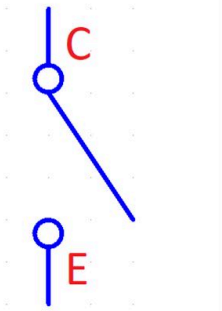
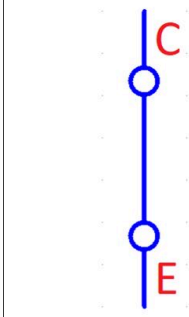
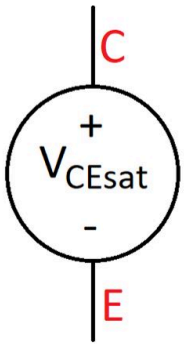
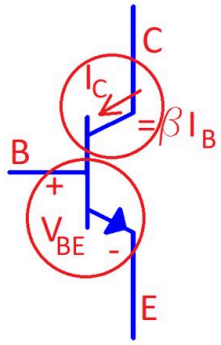
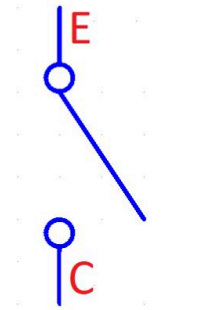
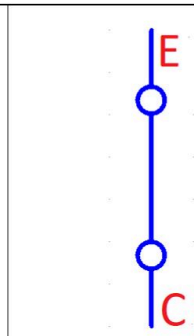
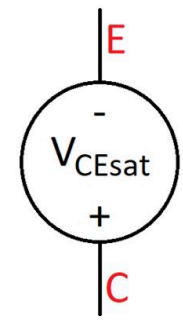
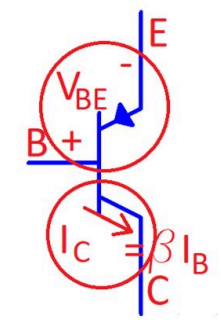
BJT Models

Since transistors are fairly complex devices with lots of characteristics we haven't discussed (temperature dependency, internal capacitance, saturation storage time, differences in DC and AC characteristics, etc.), there are quite a few models around. This author has developed his own models to help with a basic understanding of transistors to help predict reasonably accurately how they will behave in the circuits you are likely to encounter. You won't see these models in any other textbooks.

			
NPN Cutoff	NPN Saturated, Ideal	NPN Saturated, Practical	NPN Active

			
PNP Cutoff	PNP Saturated, Ideal	PNP Saturated, Practical	PNP Active

These models help with the analysis of DC biasing circuits for transistors.

Since there are three distinct modes of operation, there are three distinct models -- Cut-off, Saturation, and Active. There are times when the small voltage drop for a saturated transistor is significant, so we have two saturation models -- Ideal and Practical.

Cut-off should be the easiest one to spot and to use. If there is no way of generating Base current, there will be no Collector current, and the transistor will behave as an open in the circuit -- hence the open switch model.

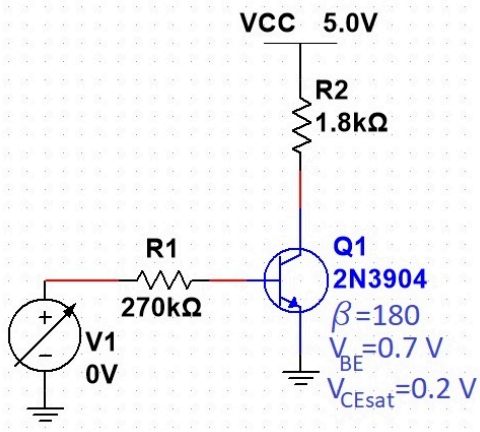
Saturation isn't as easy to spot, but it's fairly easy to use. It's analysis is essentially like that of a forward-biased diode, except that V_{CEsat} is typically much smaller than the diode's barrier potential.

Active -- in the Active region, the transistor is treated as an Ideal Current source, in which $I_C = \beta I_B$. If we can determine I_B we can analyze the output. To help us determine I_B, the model reminds us that there is a forward-biased P-N junction between the Base and the Emitter when the transistor is conducting. The only other thing to remember is the the Collector current and the Base current combine to become the Emitter current.

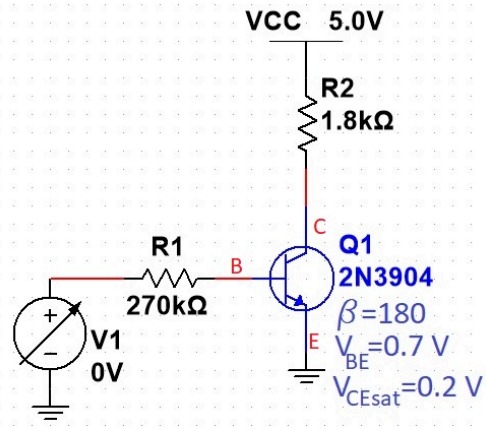
The problem comes in trying to determine if a transistor that's conducting is in the Active mode or in Saturation. The best we can do to distinguish these is to analyze the circuit as if it were in the Active mode, and if the answers don't make sense (i.e. if they go off the Saturation end of the DC Load Line), then the transistor must be saturated; throw away the Active model results and use the Saturation model instead.

Here are a few worked examples and questions to get you used to applying these models.

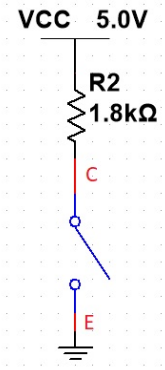
We'll start with an easy one.



Always start by labelling the pins on the transistor -- this will prevent you from confusing the Collector and Emitter if you're in too much of a hurry.



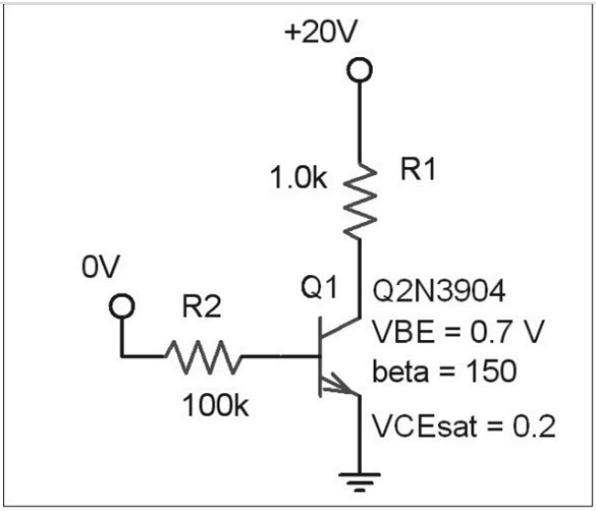
The first thing to notice about this circuit is that V_{BB} = 0 V and the Emitter is grounded. With no potential difference between these two voltages, there is no chance of current flowing through R1. This means that the transistor is in Cutoff. We immediately replace the transistor with the Cutoff Model, and proceed.



From this, we can answer all the necessary questions about this circuit:

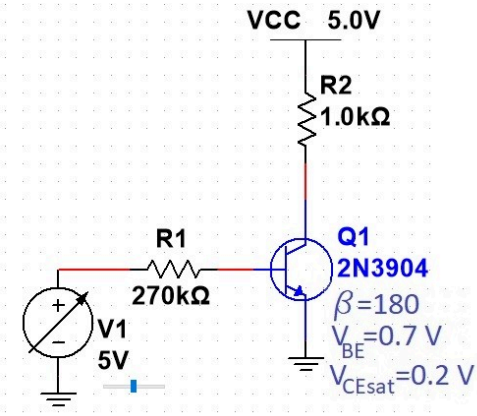
- I_B = 0 mA (that was the basis for choosing this model)
- I_C = 0 mA (open switch)
- I_E = 0 mA (I_C + I_B)
- V_B = 0 V (no drop across R_B because there's no I_B)
- V_E = 0 V (connected directly to ground)
- V_C = 5 V (no drop across R_C because there's no I_C)
- V_{CE} = 5 V (V_C - V_E)

Give it a try!

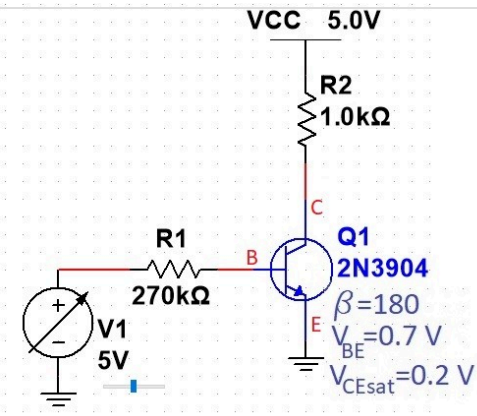


1. Is it possible for current to flow from V_{BB} to V_{EE}? No
2. What condition is this transistor in? Cutoff Draw the appropriate model before answering the following questions, and label the transistor pins.
3. If no current is flowing through R_C, what is V_C? 20 V
4. What is V_E, by inspection? 0 V
5. Therefore, what is V_{CE}? 20 V

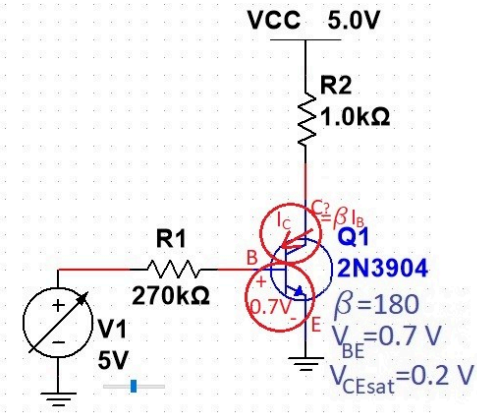
Here's another example.



Again, start by labelling the pins.



This time, V_{BE} is higher than V_{EE}, so current will flow through the forward-biased B-E junction. Since the transistor isn't in cutoff, we start with the Active Model, but keep an eye open for indications that it may not be the correct model. Notice the question mark over the '=' sign -- put it there to remind yourself that this may not be the right model.



The Current Source in the Collector is a good thing -- ideal current sources have infinite internal impedances, so, for all intents and purposes, the circuit involving the Base and Emitter is isolated (effectively disconnected) from anything on the Collector side of the circuit. That means we can just use KVL to determine what the Base current will be:

$$I_B = \frac{\Delta V_{R_B}}{R_B}$$ = (5 - 0.7)/270 kΩ = 15.9 μA

Now, we can use the transfer function to determine what Collector current is predicted using the Active Model:

$$I_C = \beta I_B$$ = 180*15.9 μA = 2.87 mA

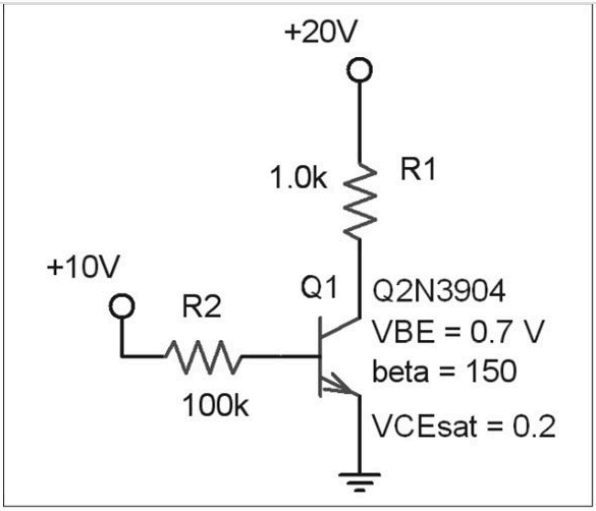
We're still not sure if this is the correct model, but we can check now. The maximum current that could flow in this circuit would exist if the transistor was completely shorted. In this case, the entire V_{CC} would appear across R_C:

$$I_{Cmax} = \frac{V_{CC}}{R_C}$$ = 5.0/1.0 kΩ = 5.0 mA

Since the predicted I_C is less than the maximum I_C, the model has predicted a reasonable value. Therefore, the Active Model was the right choice. We'll continue on with the analysis. We now have enough information to determine all of the characteristics of this circuit:

- V_E = 0 V (connected to ground)
- V_B = 0.7 V (V_E + V_{BE})
- V_C = V_{CC} - $I_C R_C$ = 2.13 V (**watch this one! Make sure you're clear that V_C is referenced to ground!)
- V_{CE} = 2.13 V (V_C - V_E)
- I_E = 2.89 mA (I_C + I_B)

Your turn.



6. Is it possible for current to flow from V_{BB} to V_{EE}? Yes

7. Following the discussion above, draw the model needed to continue the analysis of this circuit. What would the voltage at the Base, V_B, be? 0.7 V

8. What current would flow through the Base resistor? 93 μA

9. What does the model you've chosen predict as the Collector current? 13.95 mA

10. If the transistor was shorted (0 V drop), what is the maximum current that could flow through R1? 20 mA

11. Has the model you chose predicted a possible result for the Collector current? Yes

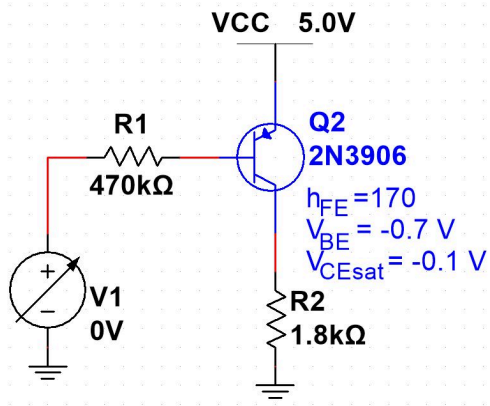
12. Assuming your answer was "Yes", what voltage drop would appear across R_C? 13.95 V

13. What, then, would the Collector voltage be? 6.05 V

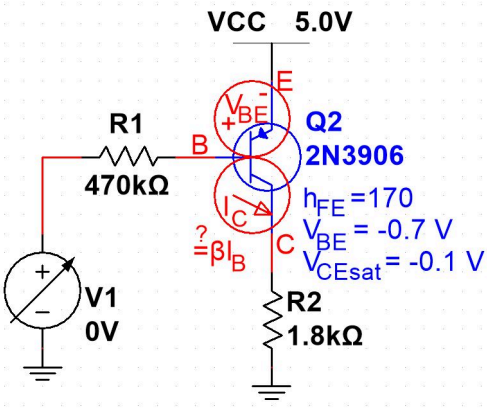
14. What would V_{CE} be? 6.05 V

15. Looking back, what condition is this transistor in? Active

Let's try a couple with PNP transistors.



Notice that V_{BB} is considerably less than V_{EE}, (make sure you know which pin is the Emitter -- label them right away, as in the diagram below) so current can flow through the forward-biased Emitter to Base junction. Therefore, the transistor is not in Cutoff, so we'll start with the Active Model, again checking to see if anything we discover indicates otherwise. In the following diagram, the labels have been added and the Active Model has been drawn over the transistor. Notice that the Emitter is at the top -- that establishes all the relationships we will be investigating. Also notice the use of h_{FE} -- that's just β.



Notice that the power supply is labelled "V_{CC}". It should, strictly speaking, be "V_{EE}", because it's powering the Emitter. However, in a schematic package, it's not possible to use different labels for the same power supply, so, if other components in the circuit are using "V_{CC}", we have to live with it even for PNP devices.

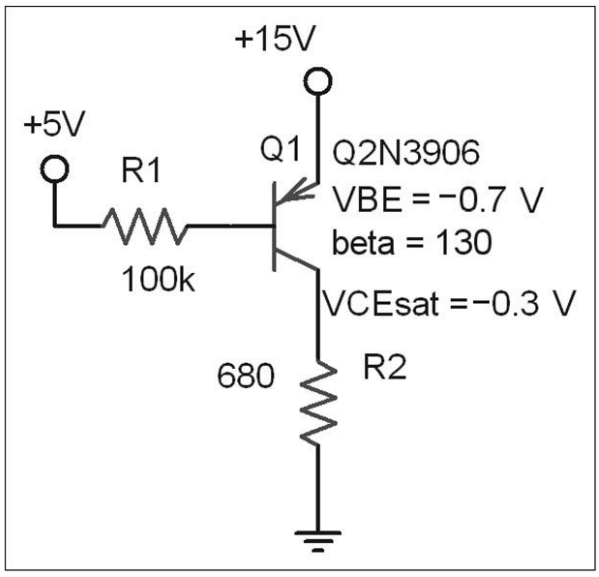
The negative sign on V_{BE} indicates that the Base voltage is below the Emitter voltage. That also shows up in the orientation of the signs in the V_{BE} symbol in the model. All it means is the Base voltage is less than "V_{CC}",or maybe better put, less than "V_E".

- V_E = 5.0 V (directly connected to "V_{CC}")
- V_B = 4.3 V
- $I_B = V_B/R_B$ = 9.15 μA (R_B is connected to ground, so V_B appears across it)
- I_C is predicted to be 1.56 mA by the Active Model. It's time to check to see if this is the right model.

If the transistor was completely shorted, we'd be left with 5.0 V across R_C, so I_{Cmax} = 5/1.8 kΩ = 2.78 mA. So, since the Active Model predicted a current that's less than the maximum current, that's a reasonable result, confirming that the Active Model is the right choice. So we can continue with the results we've gotten so far.

- $V_C = I_C * R_C$ = 2.80 V (R_C is connected to ground this time, so V_C appears across it in this example)
- $I_E = I_C + I_B$ = 1.56 mA (rounds to the same value as I_C because β is so big)
- $V_{CE} = V_C - V_E$ = -2.2 V (because the Collector voltage is less than the Emitter voltage)

Your turn again.



16. Is it possible for current to flow between V_{BB} and V_{EE}? Yes

17. If so, in which direction? Out of the Base

18. Replace the transistor with the appropriate model, and determine the magnitude of I_B. 93 μA

19. What does your chosen model predict for the magnitude of the Collector current? 12.09 mA

20. Which direction does the Collector current flow? Out of the Coll…

21. If the transistor were shorted out, what is the maximum current that could flow in the circuit? 22.1 mA

22. Is the Active Model the correct choice? Yes

23. What is V_E? 15 V

24. What is V_B? 14.3 V

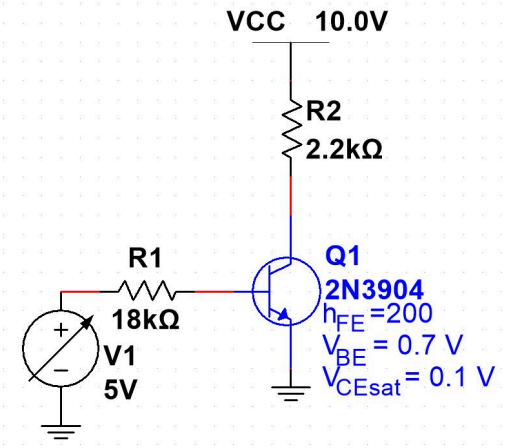
25. What is V_C? 8.22 V

26. What is V_{CE}? - 6.78 V

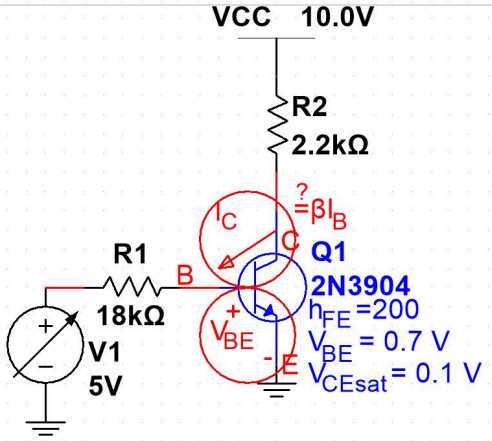
27. What is the magnitude of I_E? 12.18 mA

28. Looking back, what condition is this transistor in? Active

So far, the examples have been either in Cutoff or in the Active Linear Region of operation. Let's check out the following circuit.



To begin, V_{BB} is higher than the Emitter voltage, so current can flow. That means it's not in Cutoff, so we start with the Active Model, again keeping in mind that it might be the wrong model.



We can get some of the basics down right away:

- V_E = 0 V (connected to ground)
- V_B = 0.7 V (V_E + V_{BE})

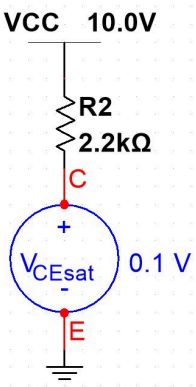
Using KVL, we determine I_B:

- $I_B = \Delta V_{RB}/R_B$ = (5 - 0.7)/18 kΩ = 239 μA

Now we move over to the collector side, and check to see if the prediction made by the Active Model makes sense:

- The model says $I_C = \beta I_B$ = 47.8 mA
- I_{Cmax} = 10 V/2.2 kΩ = 4.55 mA

The Active Model is clearly wrong, because it predicted a current that's much higher than the maximum current that could flow in this circuit. So, we toss out the Active Model and use the Saturated Model instead. For this course, we'll usually use the Practical Model, but in the future, you'll probably discover that the Ideal Model is usually good enough.

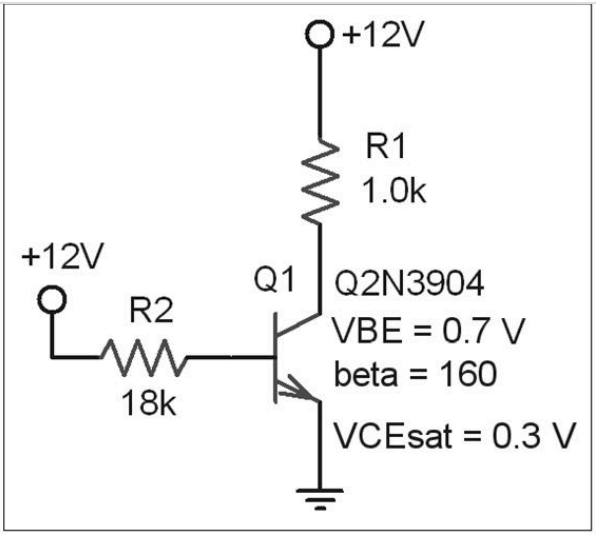


From this, we can determine the rest of the circuit's characteristics:

- $V_{CE} = V_{CEsat}$ = 0.1 V
- V_C = 0.1 V (V_E + V_{CE})
- I_C (which can also be called I_{Csat}) = $\Delta V_{RC}/R_C$ = (V_{CC} - V_C)/R_C = 4.50 mA
- I_E = 4.74 mA (I_C + I_B)

The Saturation Model predicts a reasonable current, since I_C is slightly less than I_{Cmax}.

Your turn.



29. Is Base current possible? Yes

30. What is V_B? 0.7 V

31. Choose a suitable model, then follow the steps required to predict the Collector current using that model.

100.4 mA

32. What is the maximum possible Collector current, based on only the Collector resistor? 12 mA

33. Has the model you've chosen predicted a plausible Collector current? No

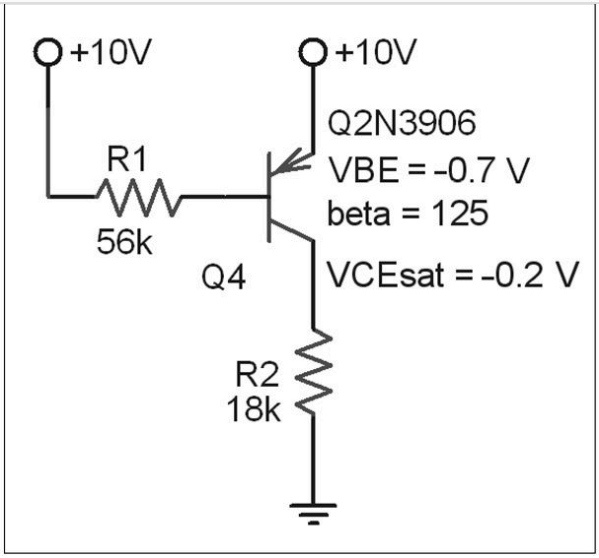
34. Proceed with the appropriate model. What is V_{CE}? 0.3 V

35. What is V_C? 0.3 V

36. What is I_C? 11.7 mA

37. Looking back, what condition is this transistor in? Saturation

By now, you should be getting familiar with using the models, so try this one on your own.



39. Is the flow of Base current possible? No

40. What is V_B? 10 V

41. What is I_C? 0 mA

42. What is V_C? 0 V

43. What is V_{CE}? - 10 V

44. Looking back, what condition is this transistor in? Cutoff

You have now learned how to apply a simple set of transistor models to help you predict the DC characteristics of various transistor circuits. What you have learned here will continue to be useful to you as you learn how to make simple transistor logic switches, transistor current switches, and transistor amplifier biasing circuits.