The dc Load Line

The DC load line is a ***graph that represents all the possible combinations of I_C and V_{CE} for a given amplifier***.

To illustrate, look at Figure 1. This is the circuit we used earlier in the notes to explain the three regions of operation namely, cutoff, active, and saturation.

The Cutoff Region

In figure 1, the base current (I_B) is 0. This means that the collector current (I_C) should also be 0. V_{CE} would be approximately 12 V. If we were to graph V_{CE} vs. I_C, we would have ***point 1*** on a graph.(See Fig. 4). This point is called $V_{CE\ (off)}$.

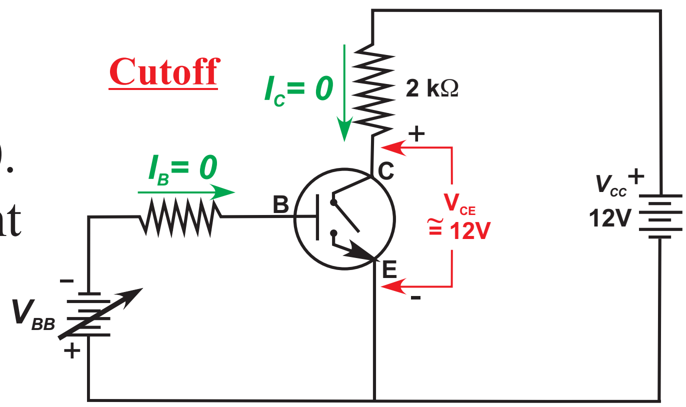


Figure 1 Collector to Emitter is like an open switch

The Saturation Region

Figure 2 represents the opposite extreme. Here, the transistor is in saturation and the collector and emitter appear like a closed switch. The value of V_{CE} is close to 0 and the value of I_C is that its maximum. The value of I_C is limited by the resistance in the circuit and can be determined by.

$$I_{C(sat)} = \frac{V_{CC}}{R_C} = 6\ mA$$

This current is called the saturation current $I_{C(sat)}$. This gives us ***point 2*** on the graph shown in Figure 4.

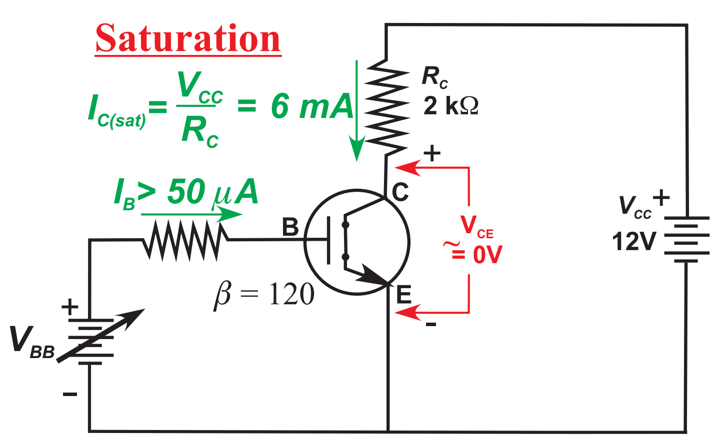


Figure 2 Collector to Emitter is like a closed switch

The dc Load Line
The Active Region

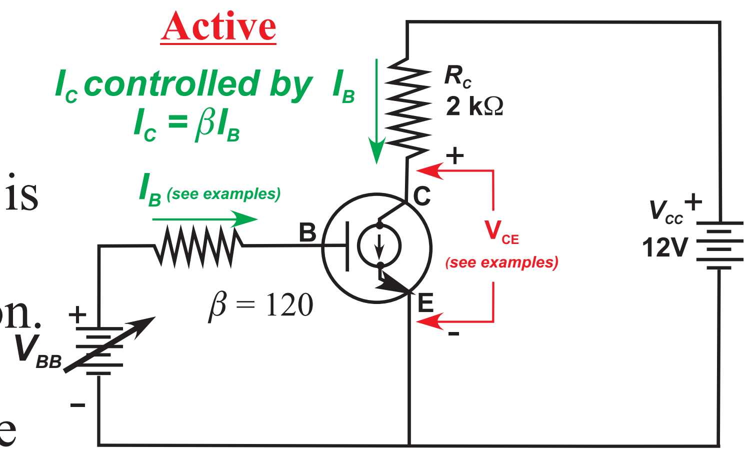


Figure 3 Collector current is controlled by base current

$I_B = 10\ \mu A$ ------ $I_C = 1.2\ mA$ ------ $V_{CE} = 9.6\ V$
$I_B = 25\ \mu A$ ------ $I_C = 3.0\ mA$ ------ $V_{CE} = 6.0\ V$
$I_B = 40\ \mu A$ ------ $I_C = 4.8\ mA$ ------ $V_{CE} = 2.4\ V$

We know that the active region is anywhere between the two extremes of cutoff and saturation.

In this region, we know that the value of I_C is determined by βI_B.

Figure 3 shows three values of I_B in the active region. It also shows the value of I_C and V_{CE} for these three values. When these values of I_C and V_{CE} are plotted in Figure 4, we can see that a line can be drawn through all the points. This line is called the load line and it represents all the combinations of I_C and V_{CE} for this particular transistor circuit.

The Q Point

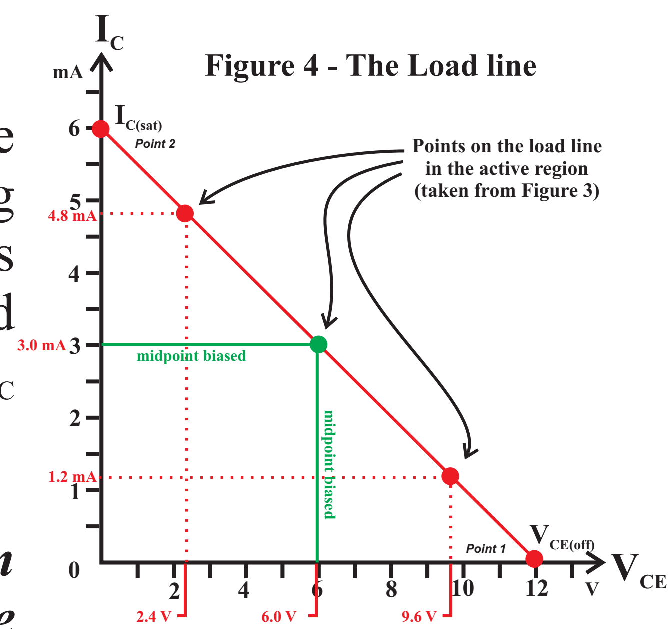


Figure 4 - The Load line

The main purpose of a voltage amplifier is to amplify an incoming AC signal. A quiescent amplifier is one that has no ac signal applied and therefore has constant dc values of I_C and V_{CE}. The amplifier is at rest.

The Q point is defined as a point on the dc loadline that indicates the values of I_C and V_{CE} for an amplifier at rest. Ideally, we want the Q point to reside at the center of the load line. For figure 3, the amplifier is midpoint biased when I_C is 3 mA.

When you have a centred Q point, V_{CE} is half the value of V_{CC}, and I_C is half the value of $I_{C(sat)}$. This is illustrated in Figure 4. As you can see, the centred Q point provides values of the I_C and V_{CE} that are one-half their maximum possible values. When the circuit is designed to have a centred Q point, the amplifier is said to be midpoint biased.

Midpoint biasing allows optimum ac operation of the amplifier. This point is illustrated in Figure 5.

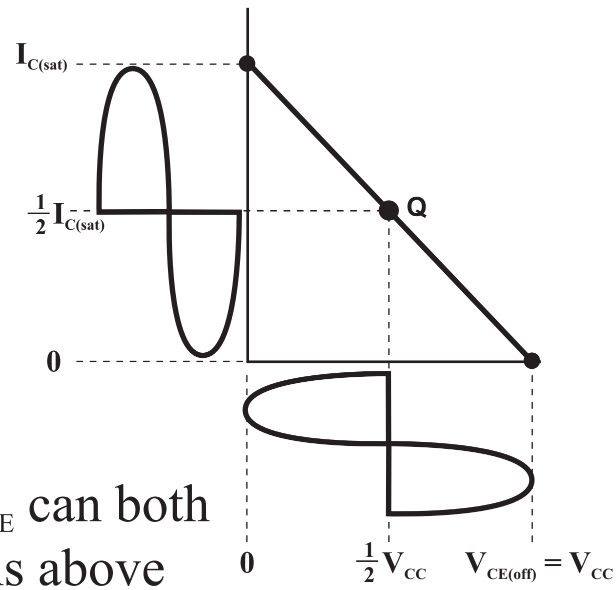


Figure 5 Optimum Amplifier Operation

When an ac signal is applied to the base of the transistor, I_C and V_{CE} both vary around their Q point values. When the Q point is centred, I_C and V_{CE} can both make the maximum possible transitions above and below their initial dc values.

See Example 7.1 and 7.2 in the text.

Creating a Stable Q Point - Bias Circuit Types

For our amplifier to work properly, it is essential to have a Q Point that is in the center of the load line. There are several different circuits that we can use to achieve this.

Base Bias

Base bias or ***fixed bias*** is an adaptation of the circuit we used in Figure 3. Instead of using two supplies, we use only one. The base voltage (and current) is supplied through R_B. The value of I_C is simply βI_B when the transistor is operating in the active region.

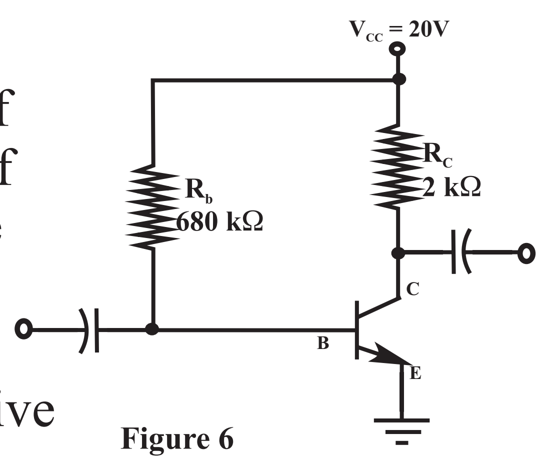


Figure 6
A typical base bias circuit

If we use the 2N3904 transistor, we know β can vary anywhere from 100 to 300. Unfortunately this also means that I_C will vary widely depending on which transistor we use. This means the ***base bias*** will provide us with an ***unstable Q point*** because we cannot predict where on the load line it will be. It is limited to switching operations and is not widely used for amplifiers.

Circuit Analysis

Our purpose is find the Q point for this amplifier. We can find I_B easily since it is the current through R_B. The voltages on each side of R_B are shown in Fig. 7.

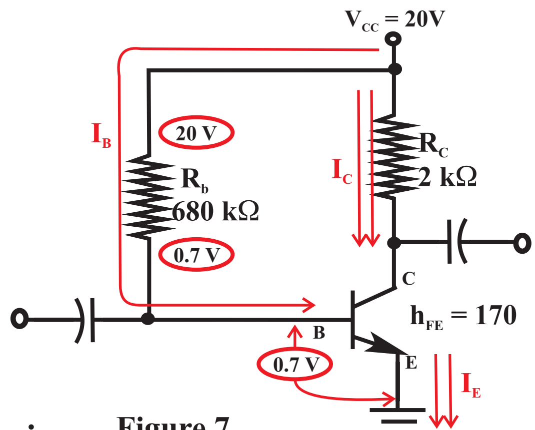


Figure 7
A typical base bias circuit

Note that the voltage from base to emitter is 0.7 V. We know that the voltage across a forward biased Silicon diode is approx. 0.7V. Figure 8 shows the base-emitter diode. Since it is forward biased in the circuit shown, then the voltage across it is 0.7V. We know that the emitter end of the diode is at ground or 0 volts. Then the base end of the diode must be at +0.7V. Since the base is connected directly to the bottom of R_B, this makes the bottom of R_B at +0.7V.

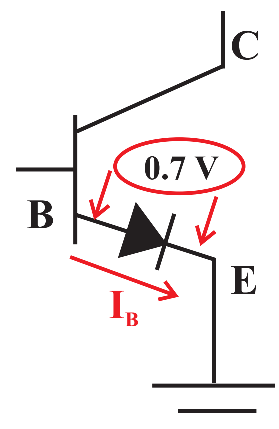


Figure 8
The forward biased base-emitter junction

Calculating I_B is then:

$$I_B = \frac{V_{CC} - V_{BE}}{R_B}$$

$$= \frac{20V - 0.7V}{680\ k\Omega} = \frac{19.3\ V}{680\ k\Omega} = 28.38\mu A$$

Now find I_C $\quad I_{CQ} = h_{FE} I_B$

$$= 170(28.38\mu A)$$
$$= 4.82\ mA$$

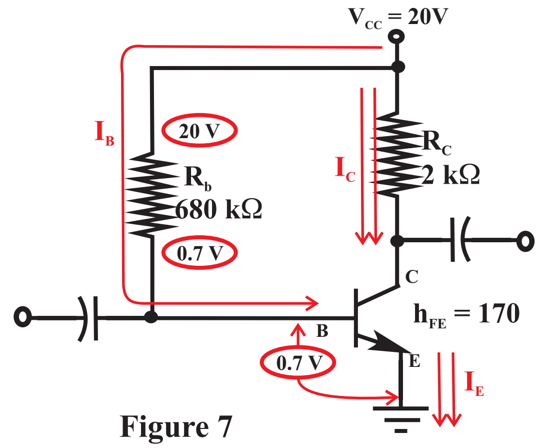


Figure 7
A typical base bias circuit

Note I_C and I_{CQ} are the same thing here. I_{CQ} means that this is the quiescent value of I_C

Now find V_{CE} $\quad V_{CEQ} = V_{CC} - I_{CQ}R_C$

$$= 20V - (4.82\ mA(2\ k\Omega))$$
$$= 20V - 9.64V$$
$$= 10.36V$$

Note V_{CE} and V_{CEQ} are the same thing here. V_{CEQ} means that this is the quiescent value of V_{CE}

Now we know the quiescent value of I_C and $V_{CE.}$ These are now the values of V_{CEQ} and I_{CQ} above. These values represent the Q point of the circuit.

Now we need to determine if the circuit is midpoint biased.

Find the ends of the load line:

$$I_{C(sat)} = \frac{V_{CC}}{R_C}$$

$$= \frac{20V}{2\ k\Omega} = 10mA$$

$$V_{CE(off)} = V_{CC}$$

$$= 20V$$

Using the values for the ends of the load line, plot them as shown below. Connect these ends with a straight line.

The midpoint is at V_{CE} = 10 V and I_{CQ} = 5 mA

When we plot the actual values of V_{CE} = 10.36V and I_{CQ} = 4.82 mA, we can see that this circuit is midpoint biased.

Q-Point Shift

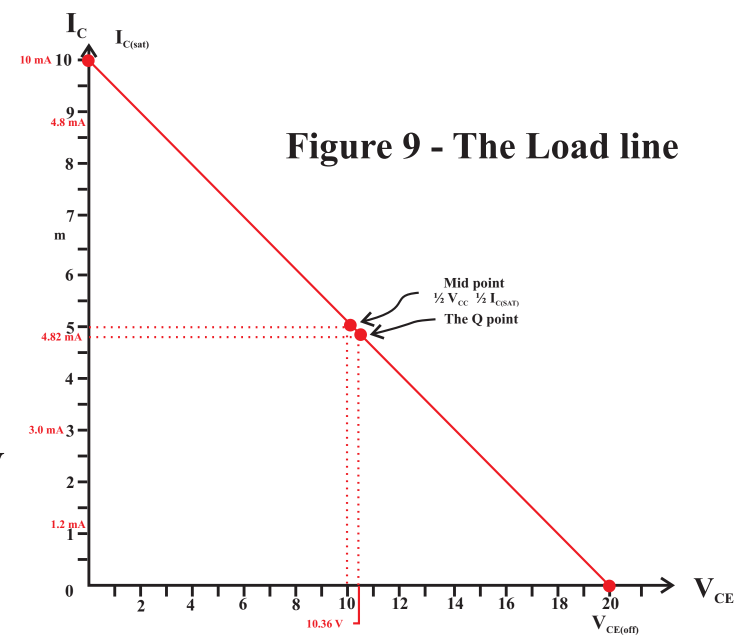


Figure 9 - The Load line

Our amplifier circuit above is midpoint biased because the value of h_{FE} is 170.

We know that h_{FE} can vary with temperature. This means that any change in temperature will cause the Q point to shift.

If the temperature increases, then h_{FE} will increase. This in turn will cause the value of I_C to increase. This will further cause the value of V_{CE} to decrease. This will cause the Q point to move on the load line. The circuit will no longer be mid point biased. Another problem exists with base biased circuits. We know that the 2N3904 can have an h_{FE} of between 100 & 300 at I_C = 10 mA.

This circuit requires an h_{FE} of 170 to be midpoint biased. In a production situation, we cannot guarantee a constant value of h_{FE}. This means the Q point will vary widely. This is another reason that this circuit is not used widely for amplifiers that require a constant Q point.

Emitter Bias

Emitter bias will provide us with a stable Q point.

This is because the value of I_C does not depend on β of the transistor.

Emitter bias was commonly used in stereo systems as a voltage amplifier.

As you can see in Figure 10, it requires a bipolar power supply.

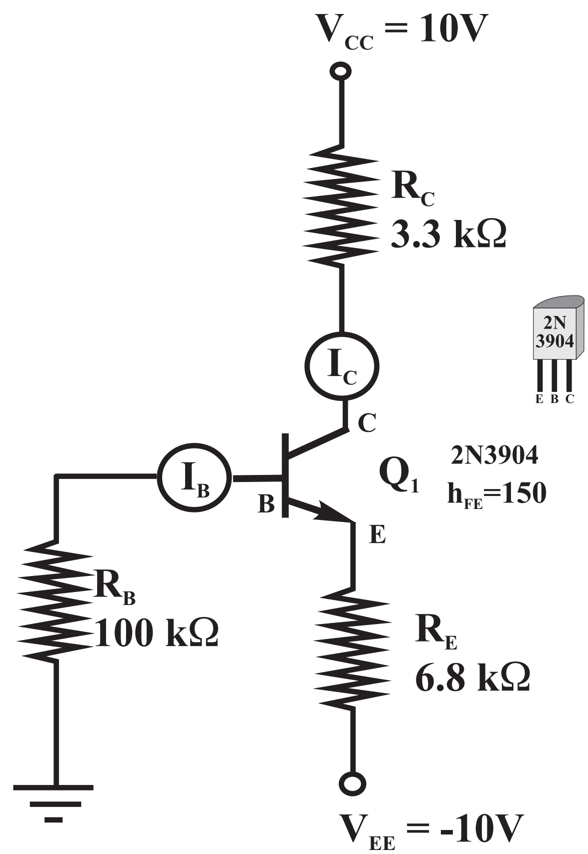


Figure 10 Emitter Bias
Note it needs a negative supply voltage

Voltage Divider Bias

Voltage divider bias or Universal bias is the most common dc biasing method mainly because of its stable Q point

It uses a simple voltage divider in the base circuit to provide a set value of V_B.

The collector current I_C, is controlled solely by the emitter resistor R_E. This means that I_C is relatively independent of the transistors current gain .

Voltage Divider Bias

Voltage divider bias or Universal bias is the most common dc biasing method mainly because of its stable Q point. It uses a simple voltage divider is the base circuit to provide a set value of V_B.If we ignore the effects of R_{base} for the moment, the value of V_B is found as:

$$V_B = V_{CC}\frac{R_2}{R_1+R_2}$$

$$=15\text{ V}\frac{1.8\text{ k}\Omega}{11.8\text{ k}\Omega} = \boxed{2.29\text{ V}}$$

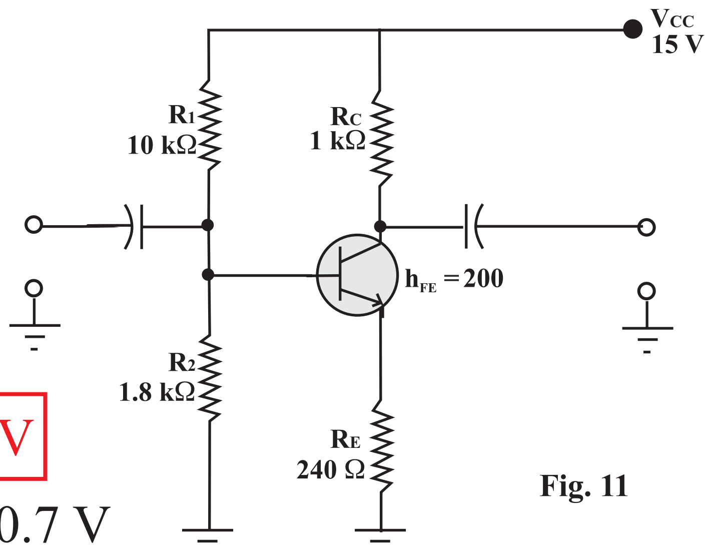


Fig. 11

V_E can be found as $V_E = V_B - 0.7\text{ V}$

$$=2.29\text{ V} - 0.7\text{ V}$$

$$=\boxed{1.59\text{ V}}$$

Now find I_E $\quad I_E = \frac{V_E}{R_E}$

$$= \frac{1.59\text{ V}}{240\ \Omega}$$

$$=\boxed{6.62\text{ mA}}$$

Now we assume that $I_{CQ} = I_E$

$$I_E \cong I_{CQ} = 6.62\text{ mA}$$

Find V_{CEQ}

$$V_{CEQ} = V_{CC} - I_{CQ}(R_C + R_E)$$

$$=15\text{V} - 6.62\text{ mA}(1.24\text{ k}\Omega)$$

$$=\boxed{6.79\text{ V}}$$

Find I_B using the value of I_E

$$I_B = \frac{I_E}{h_{FE}+1}$$

$$=\frac{6.69\text{ mA}}{201} = \boxed{33.28\ \mu\text{A}}$$

Midpoint bias is at $1/2V_{CC}$ (7.5V) This circuit is close at 6.79 V

Similar examples are 7.7 and 7.8 in the text

The Effects Of Transistor Loading

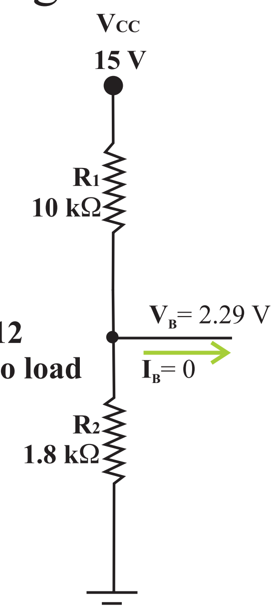
The calculation in example on page 1-8 will not give us exact results, however they usually will be reasonably close. The problem here is that each analysis begins with an assumption, that is not completely correct. The problem is with the voltage value for V_B.

Figure 12 shows just the part of the circuit required to produce the voltage V_B. We calculated this voltage to be:

$$V_B = V_{CC}\frac{R_2}{R_1+R_2}$$

$$= 15\text{ V}\frac{1.8\text{ k}\Omega}{11.8\text{ k}\Omega} = \boxed{2.29\text{ V}}$$

Fig. 12
V_B with no load



<u>This value of voltage will exist only if I_B is zero.</u>

We know that in order for a transistor to operate in the active region, there ***must be*** a small base current (see Figure 13) In our previous example, the value of I_B was 33.28 μA. As soon as we draw any current from the point at V_B, we "load down" the circuit and the voltage V_B will drop to a value of less than 2.29 V.

As I_B increases, the loading effect increases, and the value of V_B will drop further. As you can see, as I_B increases, more and more error is introduced in our original calculation, for V_B.

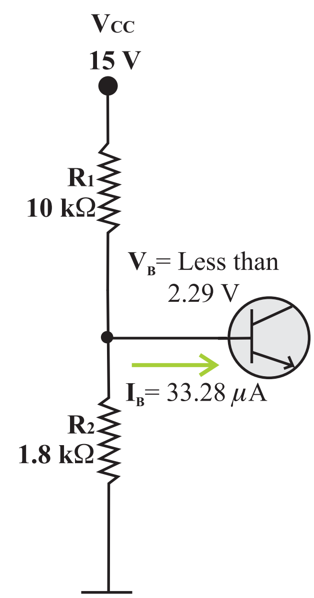


Fig. 13 - with the transistor connected, the base current will cause the calculated voltage to drop.

The value of I_B. is dependent on the value of h_{FE} for our transistor. As the value of h_{FE} increases, the value of I_B will decrease.

We need a Rule

We now know that, as the base current increases, more and more error is introduced into our calculation for the value of V_B.

When will there be too much error? We need a rule to follow that will help us to compensate for the error.

Before defining the rule we need to add another piece to the puzzle.

Determining the value of R_{base}

What is R_{base} ? This is the resistance that the current I_B sees as it looks into the base of out transistor. (See Fig. 14 a) It sees the emitter resistance R_E magnified by the value of value of h_{FE}. (See Fig. 14 b).

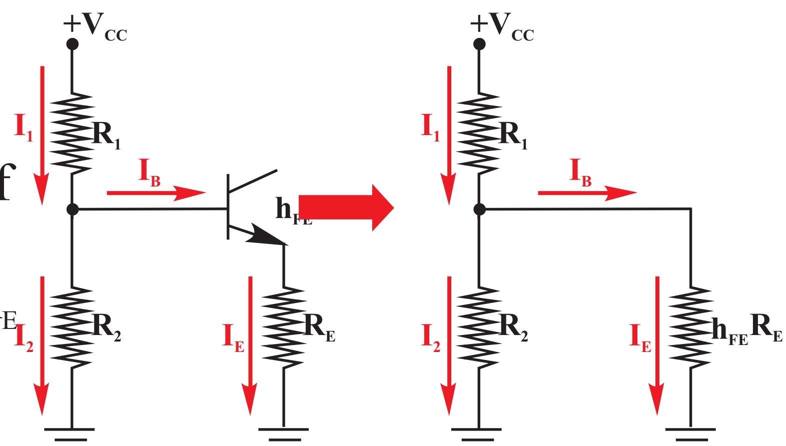


Fig 14 (a) Fig 14 (b)

The h_{FE} of the transistor has a large effect on the value of $h_{FE}R_{E.}$ If h_{FE} is a low value, then $h_{FE}R_E$ will have a relatively low value. Since the base current increases as $h_{FE}R_E$ decreases, then we can use the value of $h_{FE}R_E$ to determine our rule.

How much error is acceptable? Our rule of thumb is simple. If $h_{FE}R_E$ is greater or equal to $10R_2$ then it is large enough to be ignored. If it is smaller than $10R_2$, then we will use an alternative approach to analyzing the circuit. This will be described shortly.

The Rule for Finding V_B

❸ Find R_{base} $$R_{base} = h_{FE}R_E$$

❷ Find $10R_2$ by simply multiplying the ohmic value of R_2 by 10

❸ Compare the two values (R_{base} and $10R_2$)

If R_{base} is greater or equal to $10R_2$ *-- ignore it.*
It will not introduce a significant error in our calculations.

If R_{base} is smaller than $10R_2$ then: *-- use the Thevenin alternative*

See the appendix at the end of this notepak for a description of Thevenin's Theorem as it relates to this alternative solution

The Thevenin Alternative Approach

The Thevenin alternative approach, will provide more exact values for I_{CQ} and V_{CEQ}. This is because it will takes into account the loading effect caused by the transistor base current I_B.

❸ Find the Thevenin voltage $$V_{TH} = V_{CC}\frac{R_2}{R_1 + R_2}$$

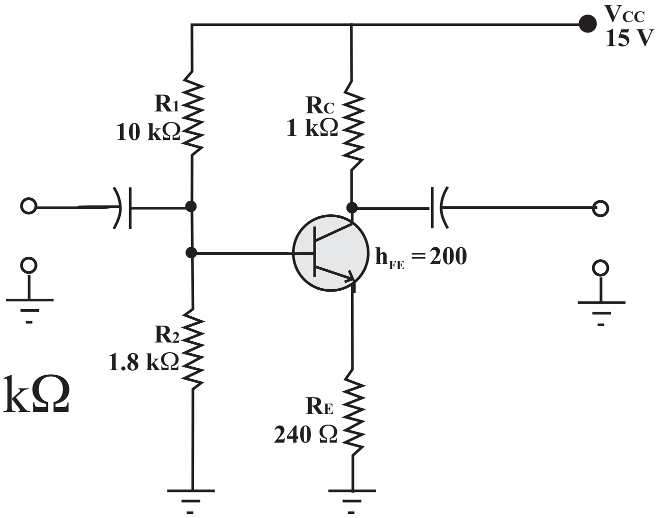
❷ Find the Thevenin resistance $$R_{TH} = R_1 \| R_2$$

❸ Find I_{CQ} using this formula $$I_{CQ} = \frac{V_{TH} - V_{BE}}{\frac{R_{TH}}{h_{FE}} + R_E}$$

❹ Find V_{CEQ} in the normal way $$V_{CEQ} = V_{CC} - I_{CQ}(R_C + R_E)$$

Example where R_{base} can be ignored

Find the values of I_{CQ} and V_{CEQ} for the following circuit.
Is the circuit mid-point biased ?



Find R_{base}

$$R_{base} = h_{FE}R_E = 200(240\Omega) = 48\ k\Omega$$

Find $10R_2$

$$10R_2 = 10(1.8\ k\Omega) = 18\ k\Omega$$

Since 48 kΩ is much larger than 18 kΩ we can ignore the effects of R_{base}

Find V_B

$$V_B = V_{CC}\frac{R_2}{R_1+R_2} = 15\ V\frac{1.8\ k\Omega}{11.8\ k\Omega} = \boxed{2.29\ V}$$

Find V_E

$$V_E = V_B - 0.7\ V = 2.29\ V - 0.7\ V = \boxed{1.59\ V}$$

Find I_E

$$I_E = \frac{V_E}{R_E} = \frac{1.59\ V}{240\ \Omega} = \boxed{6.62\ mA}$$

$$I_E \cong I_{CQ} = 6.62\ mA$$

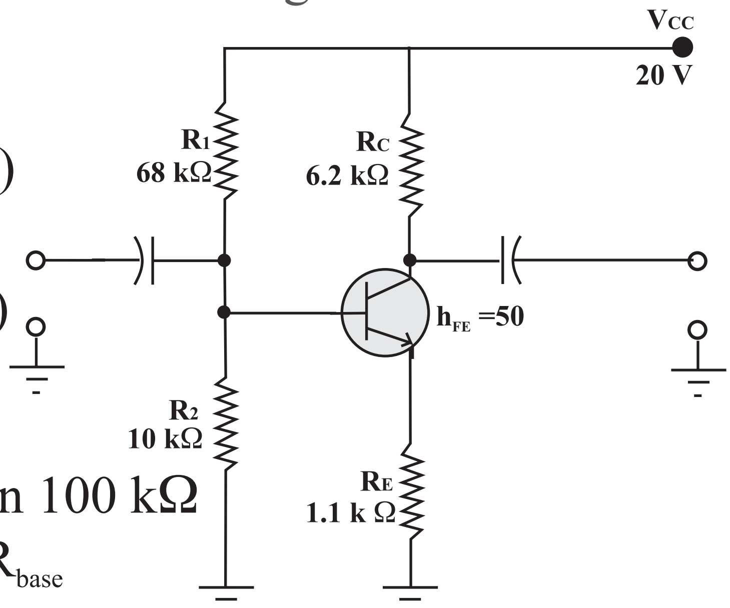
Find V_{CEQ}

$$V_{CEQ} = V_{CC} - I_{CQ}(R_C+R_E) = 15V - 6.62\ mA(1.24\ k\Omega) = \boxed{6.79\ V}$$

Midpoint bias is at $1/2V_{CC}$ (7.5V) This circuit is close at 6.79 V

Example where R_{base} cannot be ignored

Find the values of I_{CQ} and V_{CEQ} for the following circuit.
Is the circuit mid-point biased ?



Find R_{base}

$$R_{base} = h_{FE}R_E = 50(1.1\ k\Omega) = 55\ k\Omega$$

Find $10R_2$

$$10R_2 = 10(10\ k\Omega) = 100\ k\Omega$$

Since 55 kΩ is much smaller than 100 kΩ we ***cannot*** ignore the effects of R_{base}

Use the Thevenin Alternative

Find V_{TH}

$$V_{TH} = V_{CC}\frac{R_2}{R_1+R_2} = 20\ V\frac{10\ k\Omega}{78\ k\Omega} = \boxed{2.56\ V}$$

Find R_{TH}

$$R_{TH} = R_1 \parallel R_2 = 68\ k\Omega \parallel 10\ k\Omega = \boxed{8.72\ k\Omega}$$

Find I_{CQ}

$$I_{CQ} = \frac{V_{TH} - V_{BE}}{\frac{R_{TH}}{h_{FE}} + R_E} = \frac{2.56\ V - 0.7V}{\frac{8.72\ k\Omega}{50} + 1.1\ k\Omega} = \frac{1.86\ V}{1.2744\ k\Omega} = \boxed{1.46\ mA}$$

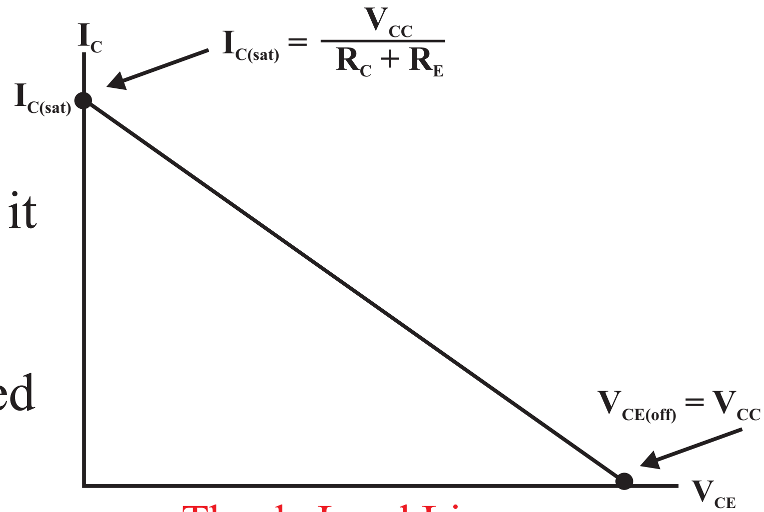
Find V_{CEQ}

$$V_{CEQ} = V_{CC} - I_{CQ}(R_C+R_E) = 20V - 1.46\ mA(7.3\ k\Omega) = \boxed{9.34\ V}$$

Midpoint bias is at $1/2V_{CC}$ (10 V)
This circuit is close at 9.34 V

Saturation and Cutoff

The dc load line is plotted using the end points of $I_{C(sat)}$ and $V_{CE(off)}$.



The dc Load Line

When the transistor is saturated, it acts like a closed switch. The voltage across it (V_{CE}) is approx. zero and the current is determined by:

$$I_{C(sat)} = \frac{V_{CC}}{R_C + R_E}$$

When the transistor is in cutoff, it acts like an open switch The current is zero and the voltage across it (V_{CE}) is the supply voltage V_{CC}.

$$V_{CE(off)} = V_{CC}$$

The load line itself represents all of the possible operating points for the transistor.

The Geometric Average

Often, a value for h_{FE} is not given for a circuit. In this case we must use a spec. sheet to determine the value to use.

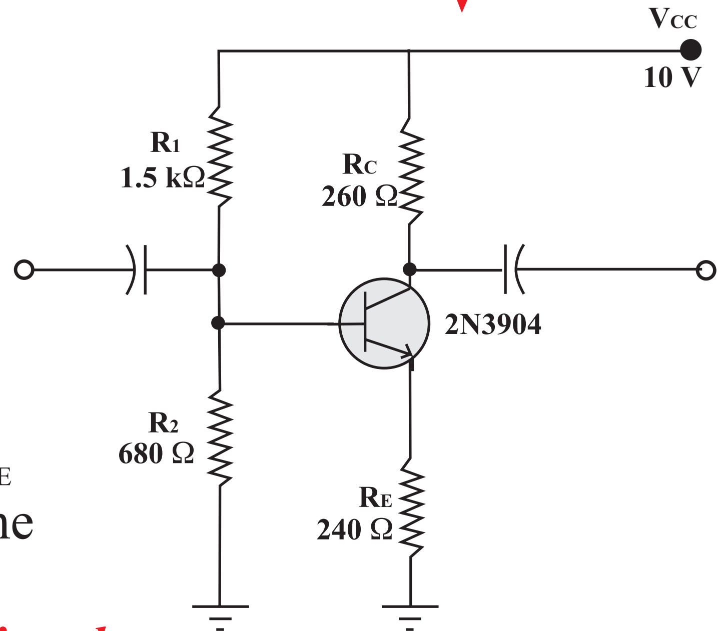
If a typical value is given , use that value.

If a maximum and minimum value are given, then find the geometric average of the two values and use it in your calculations.

See the example on the next page.

Example

Find the values of I_{CQ} and V_{CEQ} for the following circuit.
Is the circuit mid-point biased ?

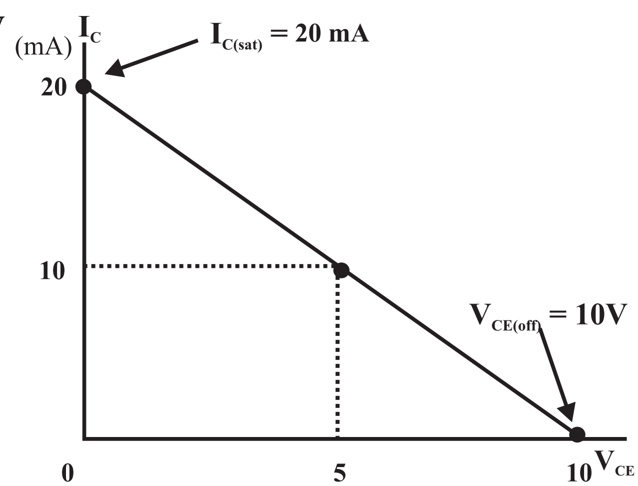


We do not know the value of h_{FE}

We can determine the range of h_{FE} from the spec sheet if we know the value of I_C.

Assume the circuit is midpoint biased.

Since this is an amplifier, it would normally be designed for midpoint bias. We will find $I_{C(sat)}$, then take half of this value to find the midpoint.



Find $I_{C(sat)}$

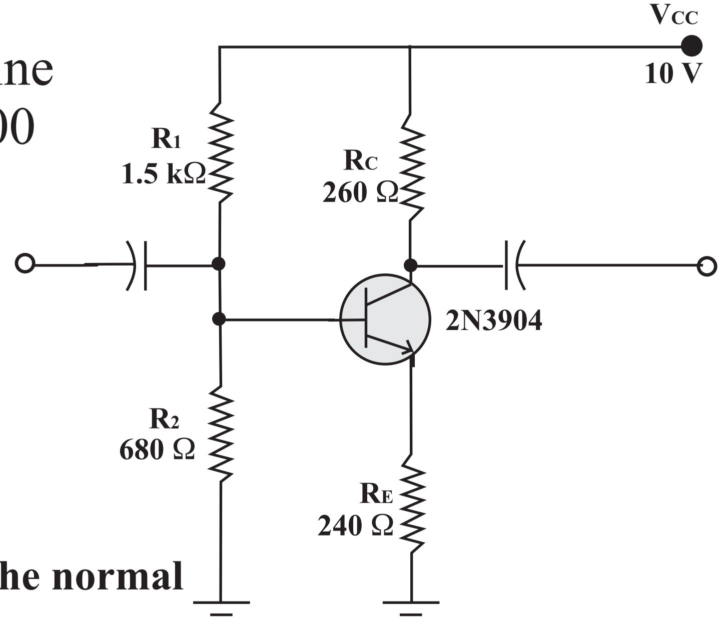
$$I_{C(sat)} = \frac{V_{CC}}{R_C + R_E} = \frac{10\ \text{V}}{500\ \Omega} = 20\ \text{mA}$$

Midpoint bias is at 10 mA

From the spec sheet find the range of h_{FE} for $I_C = 10$ mA

ON CHARACTERISTICS

DC Current Gain(1)		h_{FE}			—
(I_C = 0.1 mAdc, V_{CE} = 1.0 Vdc)	2N3903		20	—	
	2N3904		40	—	
(I_C = 1.0 mAdc, V_{CE} = 1.0 Vdc)	2N3903		35	—	
	2N3904		70	—	
(I_C = 10 mAdc, V_{CE} = 1.0 Vdc)	2N3903		50	150	
	2N3904		100	300	
(I_C = 50 mAdc, V_{CE} = 1.0 Vdc)	2N3903		30	—	
	2N3904		60	—	
(I_C = 100 mAdc, V_{CE} = 1.0 Vdc)	2N3903		15	—	
	2N3904		30	—	
Collector-Emitter Saturation Voltage(1)		$V_{CE(sat)}$			Vdc
(I_C = 10 mAdc, I_B = 1.0 mAdc)			—	0.2	
(I_C = 50 mAdc, I_B = 5.0 mAdc)			—	0.3	
Base-Emitter Saturation Voltage(1)		$V_{BE(sat)}$			Vdc
(I_C = 10 mAdc, I_B = 1.0 mAdc)			0.65	0.85	
(I_C = 50 mAdc, I_B = 5.0 mAdc)			—	0.95	



From the spec sheet we determine that $h_{FE(max)} = 300$ and $h_{FE(min)} = 100$

Find the geometric average

$$h_{FE(ave)} = \sqrt{h_{FE(min)} \times h_{FE(max)}}$$
$$= \sqrt{100 \times 300}$$
$$= 173$$

Use this value and solve the circuit in the normal way.

Find R_{base}

$$R_{base} = h_{FE}R_E$$
$$= 173(240\ \Omega)$$
$$= 41.52\ k\Omega$$

Find $10R_2$

$$10R_2 = 10(680\ \Omega)$$
$$= 6.8\ k\Omega$$

Since 41.52 kΩ is much larger than 6.8 kΩ we can ignore the effects of R_{base}

Find V_B

$$V_B = \frac{R_2}{R_1+R_2}V_{CC}$$
$$= \frac{680\ \Omega}{2.18\ k\Omega}\ 10\ V$$
$$= \boxed{3.12\ V}$$

Find V_E

$$V_E = V_B - 0.7\ V$$
$$= 3.12\ V - 0.7\ V$$
$$= \boxed{2.42\ V}$$

Find I_E

$$I_E = \frac{V_E}{R_E} = \frac{2.42\ V}{240\ \Omega}$$
$$= \boxed{10.08\ mA}$$
$$I_E \cong I_{CQ} = 10.08\ mA$$

Find V_{CEQ}

$$V_{CEQ} = V_{CC} - I_{CQ}(R_C+R_E)$$
$$= 10V - 10.08\ mA(500\ \Omega)$$
$$= \boxed{4.96\ V}$$

Midpoint bias is at $1/2V_{CC}$ (5 V)
This circuit is very close at 4.96 V

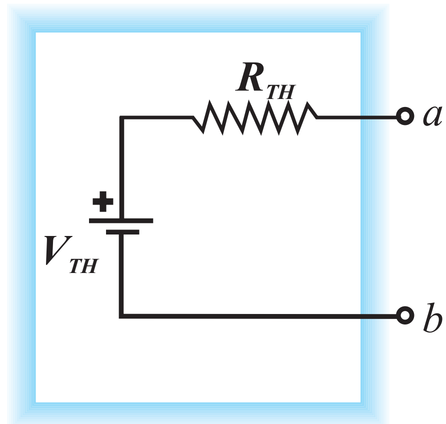
Thevenin's Theorem is one of the most important of the basic theorems we have for circuit analysis. It allows us to simplify complicated circuits that contain many resistances and one or more energy sources down to one voltage source and one single resistance.

Brief Definition

Any linear bilateral network may be simplified to a simple two terminal circuit consisting of a single voltage source in series with a single resistor as shown to the right.

V_{TH} is the ***open circuit voltage*** appearing at the output terminals *a* and *b*.

R_{TH} is the ***Thevenin equivalent resistance*** that represents the total resistance ***"seen"*** between the output terminals *a* and *b*.



Thevenin Equivalent Circuit

How to use it

1) Remove the load from the circuit.
2) Label the resulting two terminals *a* and *b* (any notation will do)
3) Set all the sources in the circuit to zero.

    Voltage sources are replaced with short circuits
    Current sources are replaced with open circuits

4) Calculate the Thevenin equivalent resistance $R_{TH.}$ as seen from the output terminals *a* and *b*.
5) Replace the sources back to their original positions. Calculate the open circuit voltage at the output terminals.
6) Draw the new equivalent Thevenin circuit above using your calculated values of $\mathbf{V_{TH}}$ and $\mathbf{R_{TH}}$.
7) Replace the load on the new circuit.

How The Thevenin's Alternative Works

This is the example on page 1-13 where we said that R_{base} cannot be ignored. The problem here was that enough base current flows in this circuit to cause a significant drop in the calculated base voltage (see ***The Effects of Transistor Loading*** p 1-9) We need an alternative method for calculating the base voltage and I_{CQ} that will compensate for this voltage drop.

Using the Thevenin's alternative method will provide this. Here is how it works:

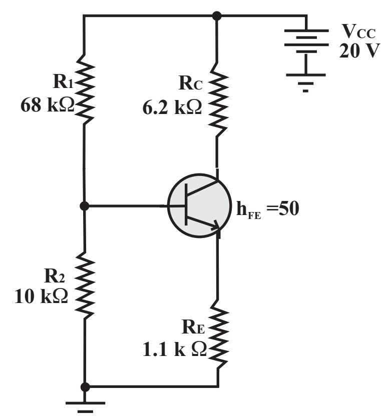


Fig. A1 - Circuit redrawn for simplicity

Fig. A1 is the same circuit we used in the example. The capacitors have no effect here and have been removed. The power supply has been added to help explain the steps.

1) Remove the load from the base circuit.
Here the load is the transistor.
See Fig. A2

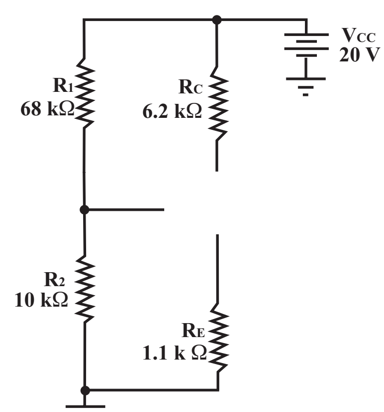


Fig. A2 - the transistor is removed

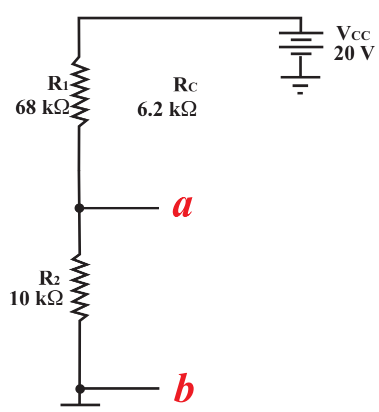


Fig. A3 - Terminals ***a*** & ***b*** are labeled R_C and R_E are removed.

2) label the resulting two terminals a & b
Since R_C and R_E are no longer connected, they can be removed. The two points remaining are labeled ***a & b***
See Fig. A3

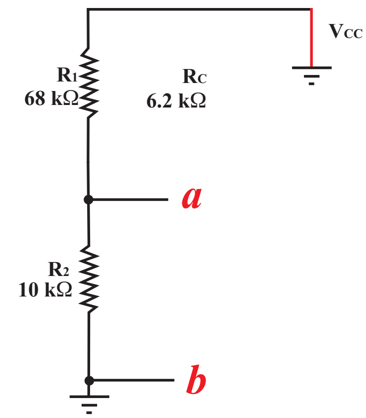


Fig. A4 - V_{CC} is now shorted to ground

3) Set all the sources in the circuit to zero.

Voltage sources are replaced with short circuits

See Fig. A4

4) ***Calculate the Thevenin equivalent resistance R_{TH}. as seen from the output terminals a and b.***

The circuit shown in A5 is redrawn to show that R_1 is in parallel with R_2. The resultant is R_{TH}

$$R_{TH} = R_1 \parallel R_2$$

$$= 68\text{ k}\Omega \parallel 10\text{ k}\Omega \quad = \boxed{8.72\text{ k}\Omega}$$

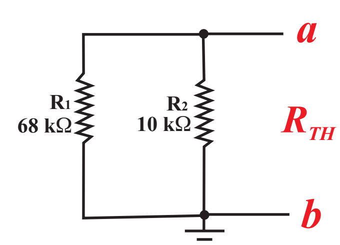


Fig. A5 - R_1 and R_2 are in parallel

5) ***Replace the sources back to their original positions. Calculate the open circuit voltage at the output terminals.***

Fig. A6 shows the V_{CC} supply back in place. We now calculate the value of V_{TH} as we have in the past. Remember that V_{TH} is the voltage from point (a) to point (b) provided that ***no current is flowing*** from point (a).

V_{TH} is often called the "open circuit voltage"

$$V_{TH} = V_{CC}\frac{R_2}{R_1+R_2}$$

$$= 20\text{ V}\frac{10\text{ k}\Omega}{78\text{ k}\Omega} \quad = \boxed{2.56\text{ V}}$$

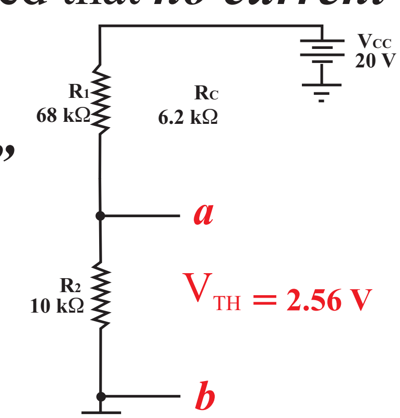


Fig. A6 - V_{CC} has been replaced and V_{TH} has been calculated

6) ***Draw the new equivalent Thevenin circuit using your calculated values of V_{TH} and R_{TH}.***

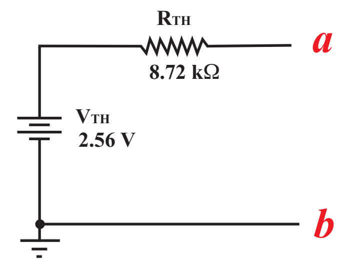


Fig. A7 - The Thevenin Equivalent Circuit

Figure A7 is the exact equivalent to A3 as shown below

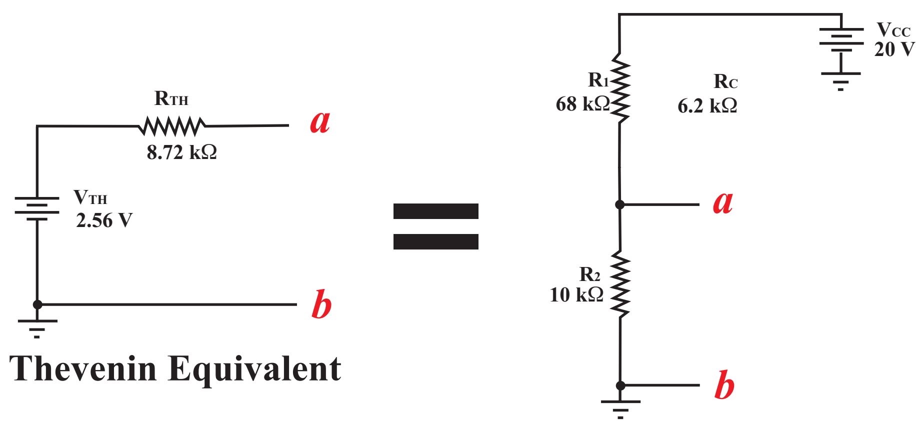


Fig. A7 is the Thevenin equivalent of Figure A3

7) ***Replace the load on the new circuit.***

Figure A8 now has the transistor, R_C and R_E replaced in the circuit.

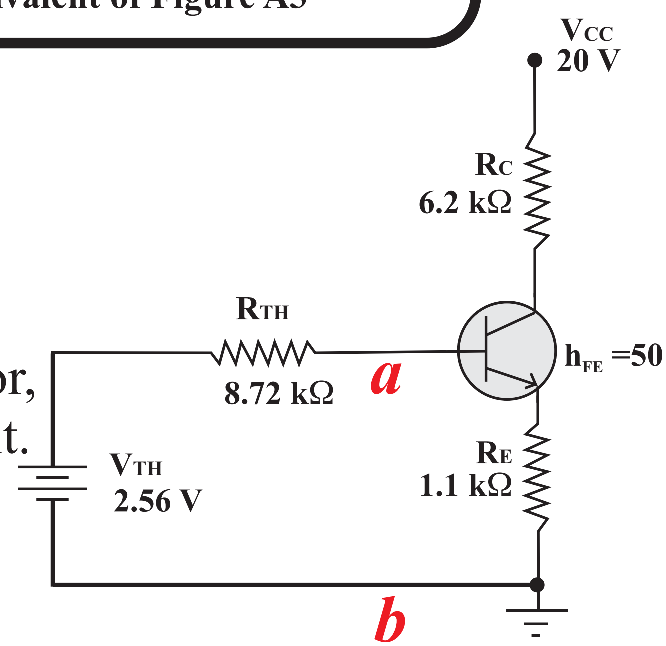


Fig. A8 - The complete Thevenin circuit

We have now completed the new Thevenin equivalent circuit. Now we will analyze this simple circuit to see how it works.

Analysis of the Thevenin Circuit

We begin by simply analyzing the part of the circuit within the oval.

The base voltage "sees" the base-emitter junction as a diode with approximately 0.7 V across it as shown in Fig. A9.

The voltages around the circuit are shown in the squares.

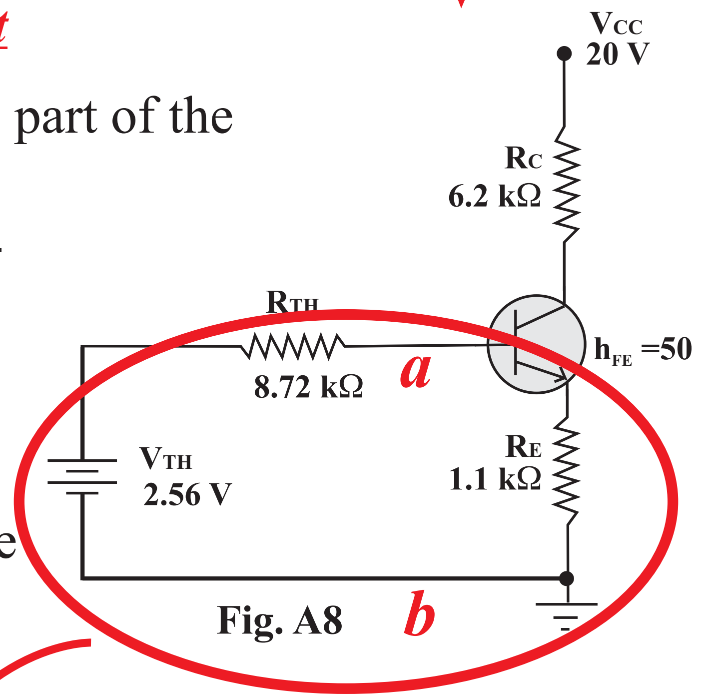


Fig. A8

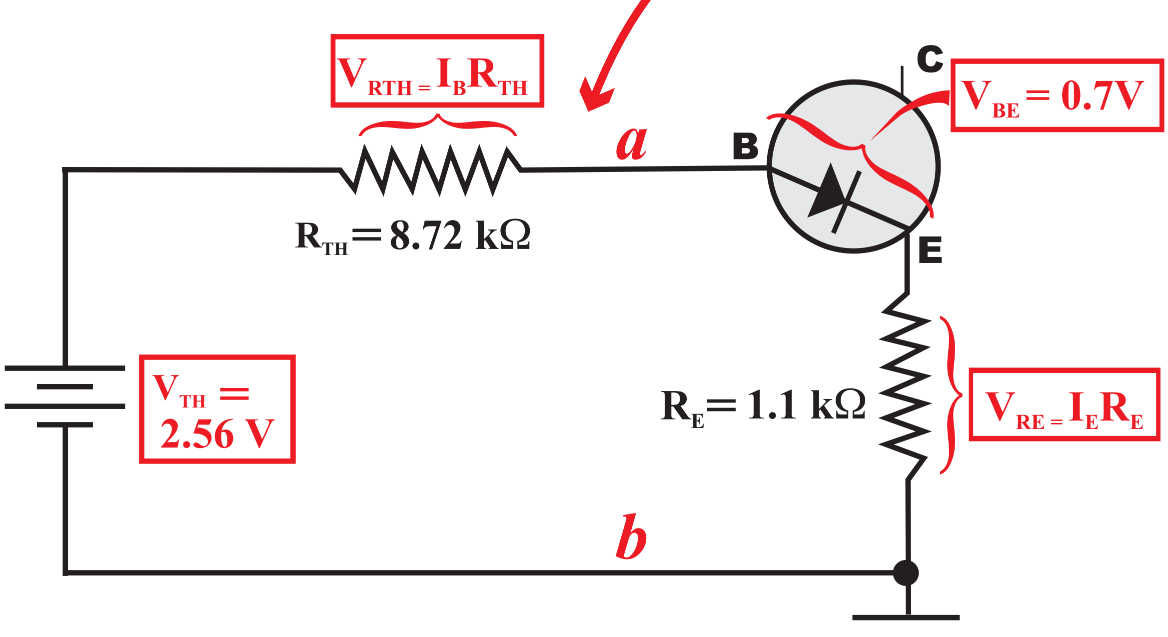


Fig. A9 - Base Circuit showing the Base-Emitter diode and the voltages around the circuit

Figure A9 is a series circuit. Kirchoff's Voltage Law says that the sum of the voltage drops in this circuit must equal the voltage rises.

This means that:

$$V_{TH} = V_{RTH} + V_{BE} + V_{RE}$$

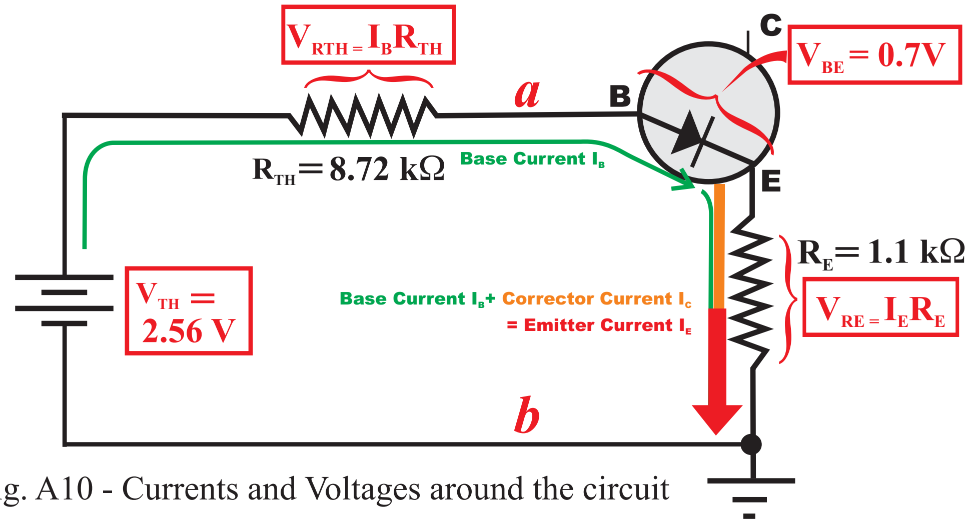


Fig. A10 - Currents and Voltages around the circuit

Kirchoff's Law says : $V_{TH} = V_{RTH} + V_{BE} + V_{RE}$

Using Ohm's Law substitute in the equation $V_{TH} = I_B R_{TH} + V_{BE} + I_E R_E$

We need to find I_B. From last term we know that:

$h_{FE} = \frac{I_C}{I_B}$ Changing this around: $I_B = \frac{I_C}{h_{FE}}$

Substitute $I_B = \frac{I_C}{h_{FE}}$ into the equation and we have

$$V_{TH} = \frac{I_C}{h_{FE}} R_{TH} + V_{BE} + I_E R_E$$

Re-arrange to find I_C

$$V_{TH} = \frac{I_C}{h_{FE}} R_{TH} + V_{BE} + I_E R_E$$

$$V_{TH} - V_{BE} = I_C \left(\frac{R_{TH}}{h_{FE}} + R_E \right)$$ since $I_C = I_E$

$$I_C = I_{CQ} = \frac{V_{TH} - V_{BE}}{\frac{R_{TH}}{h_{FE}} + R_E}$$

This formula finds the value of I_{CQ} and takes into account, the loading effect of the transistor

The Thevenin Alternative Works

The original problem with this circuit is the fact that the transistor "loads down" the biasing resistors, and the value of V_B will be considerably less than what we calculated. This is a direct result of the base current. Since this transistor has an h_{FE} of 50, the base current is high enough to inject an unacceptable error in our calculations.

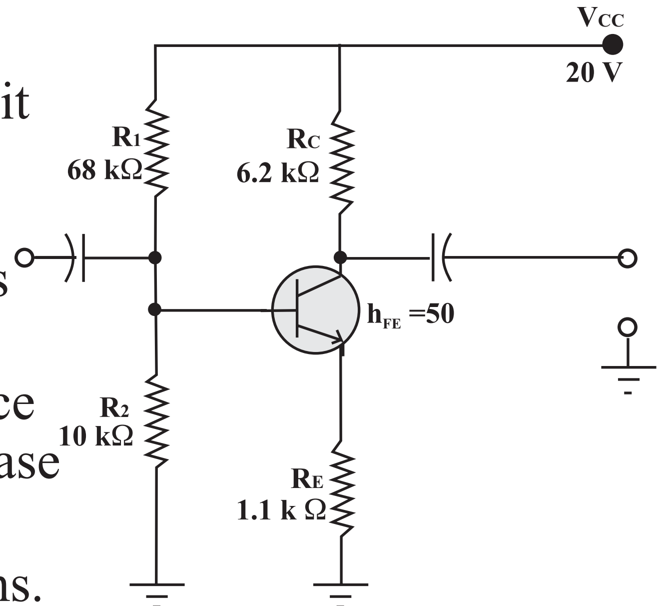


Fig A12 - The Original Circuit

Our answer to this problem was to analyze the circuit using the Thevenin alternative method. This method takes into account the loading of the transistor on the biasing resistors. Here, we will show that this method works.

Fig. A12 is the original circuit and Fig. A13 is the Thevenin equivalent. Our original calculations using the Thevenin alternative are below.

Find V_{TH} $\quad V_{TH} = V_{CC}\dfrac{R_2}{R_1+R_2} = 20\text{ V}\dfrac{10\text{ k}\Omega}{78\text{ k}\Omega} = \boxed{2.56\text{ V}}$

Find R_{TH} $\quad R_{TH} = R_1 \parallel R_2 = 68\text{ k}\Omega \parallel 10\text{ k}\Omega = \boxed{8.72\text{ k}\Omega}$

Find I_{CQ}

$$I_{CQ} = \frac{V_{TH} - V_{BE}}{\dfrac{R_{TH}}{h_{FE}} + R_E}$$

$$= \frac{2.56\text{ V} - 0.7\text{V}}{\dfrac{8.72\text{ k}\Omega}{50} + 1.1\text{ k}\Omega}$$

$$= \frac{1.86\text{ V}}{1.2744\text{ k}\Omega} = \boxed{1.46\text{ mA}}$$

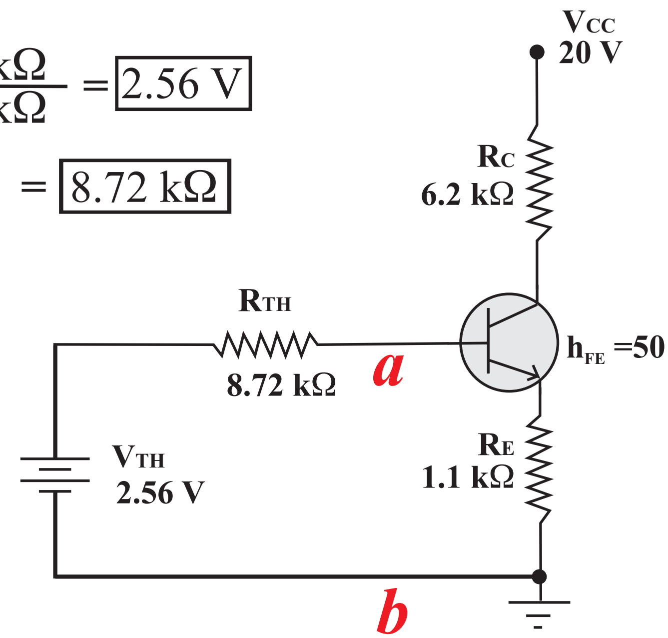


Fig. A13 - The complete Thevenin circuit

The Thevenin Alternative Works

I_{CQ} = 1.46 mA. We said that this method accounts for the loading effect. Now we can find "loaded down" value of V_B. First, find the actual I_B.

$$I_{CQ} = 1.46 \text{ mA}$$

$$h_{FE} = \frac{I_C}{I_B} \quad \text{and} \quad I_B = \frac{I_C}{h_{FE}}$$

$$I_B = \frac{I_{CQ}}{h_{FE}} = \frac{1.46 \text{ mA}}{50} = \boxed{29.2\,\mu\text{A}}$$

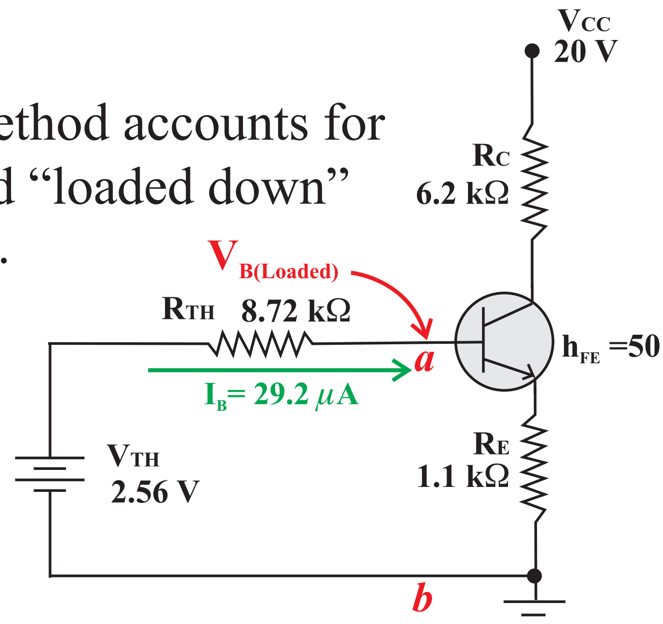


Fig. A14 - The complete Thevenin circuit

As shown in Fig A14 the base current I_B is the current through R_{TH}

Find the voltage drop across R_{TH}

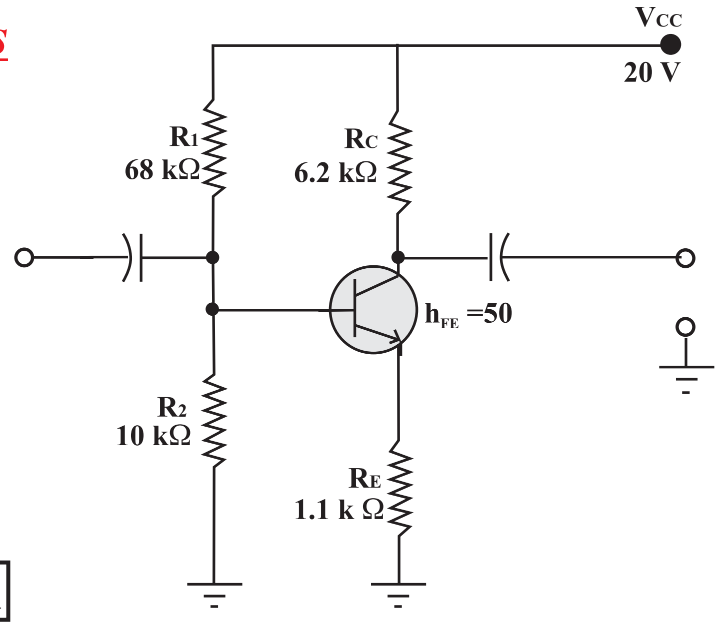
$$\begin{aligned} V_{RTH} &= I_B R_{TH} \\ &= (29.2\,\mu\text{A})(8.72\text{ k}\Omega) \\ &= 254.6 \text{ mV} \end{aligned}$$

The real "loaded" value of V_B is:

$$\begin{aligned} V_{B\,(Loaded)} &= V_{TH} - V_{RTH} \\ &= 2.56\text{V} - 254.6 \text{ mV} \\ &= \boxed{2.31\text{V}} \end{aligned}$$

$V_{B\,(Loaded)}$ is 2.31 V. This is the value of the base voltage that would exist if we were to build the circuit, and actually measured it. Now that we have the actual value of V_B, we should now be able to use the original formulas to find I_{CQ}.

The Thevenin Alternative Works



Find V_B

$$V_{B\,(Loaded)} = \boxed{2.31V}$$

Find V_E

$$V_E = V_B - 0.7\text{ V}$$
$$= 2.31\text{ V} - 0.7\text{ V}$$
$$= \boxed{1.61\text{ V}}$$

Find I_E

$$I_E = \frac{V_E}{R_E} = \frac{1.61\text{ V}}{1.1\text{ k}\Omega}$$
$$= \boxed{1.46\text{ mA}}$$

$$\boxed{I_E \cong I_{CQ} = 1.46\text{ mA}}$$

I_{CQ} =1.46 mA. This is the same value for I_{CQ} that we calculated using the Thevenin alternative method for this question on page 1-13 of these notes.