PHENIKAA UNIVERSITY

Transistors BTJ

Van Su Luong

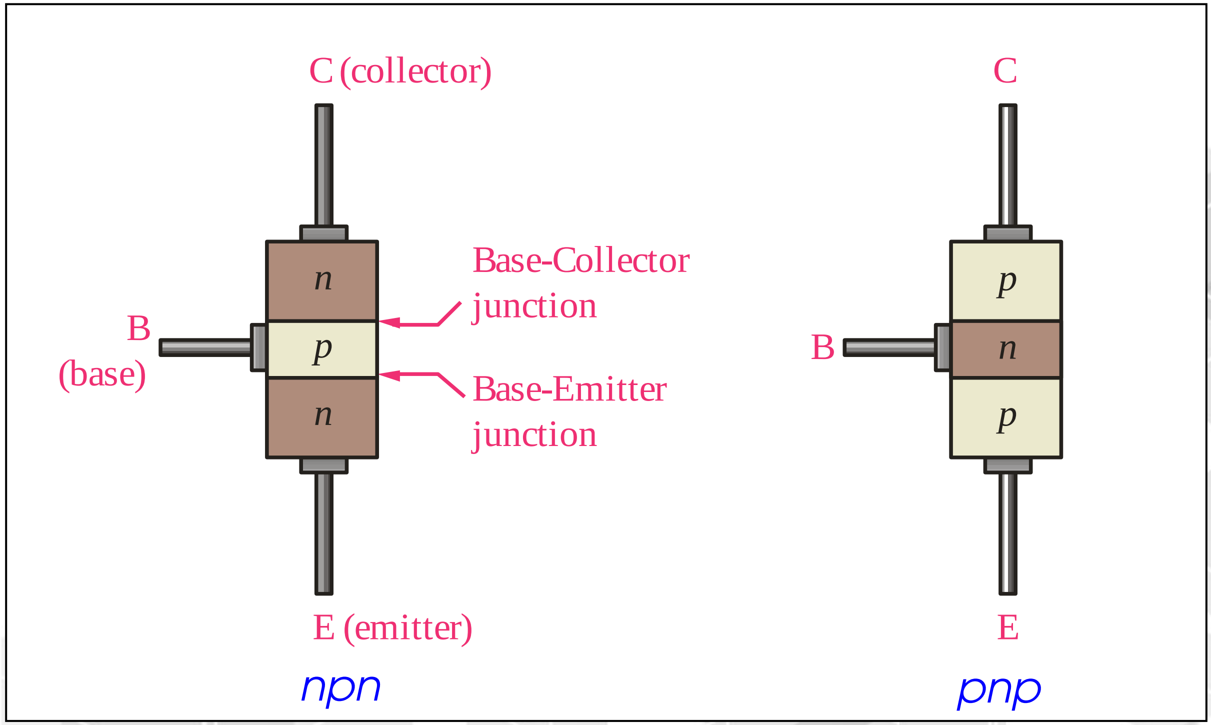
Contents

PHENIKAA UNIVERSITY

BJT Structure

The BJT has three regions called the emitter, base, and collector. Between the regions are junctions as indicated.

The base is a thin lightly doped region compared to the heavily doped emitter and moderately doped collector regions.

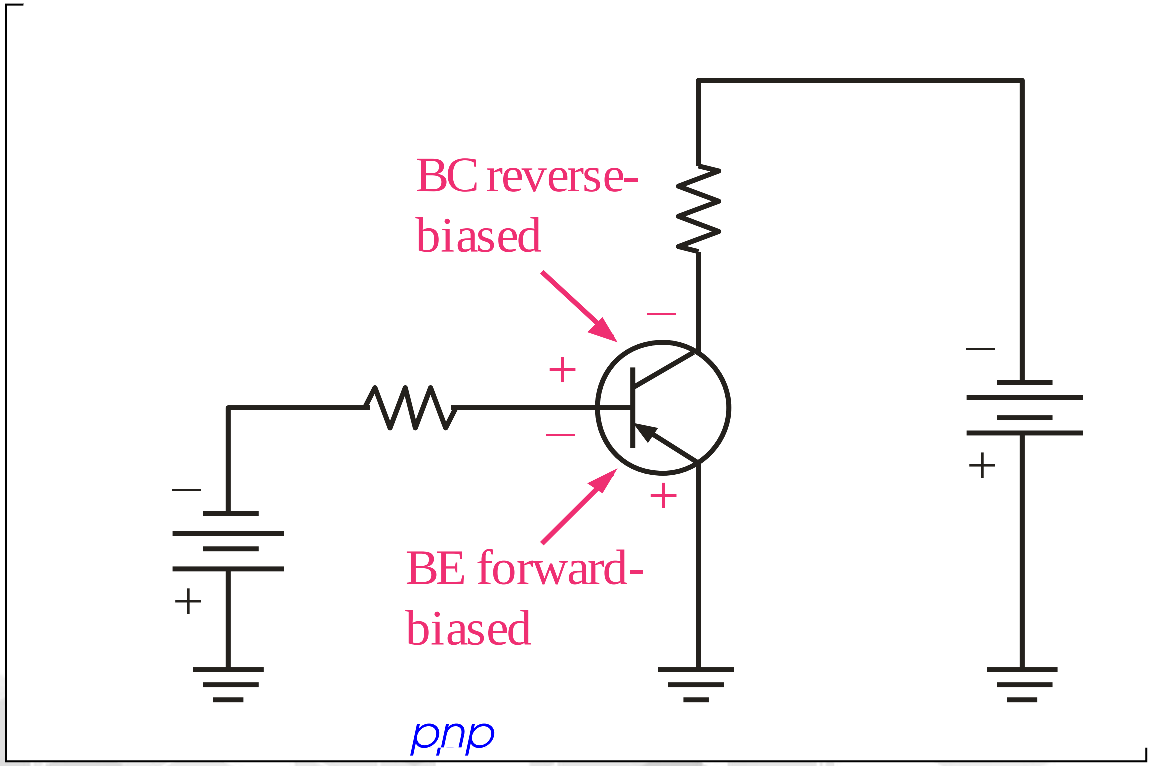


BJT Operation

In normal operation, the base-emitter is forward-biased and the base-collector is reverse-biased.

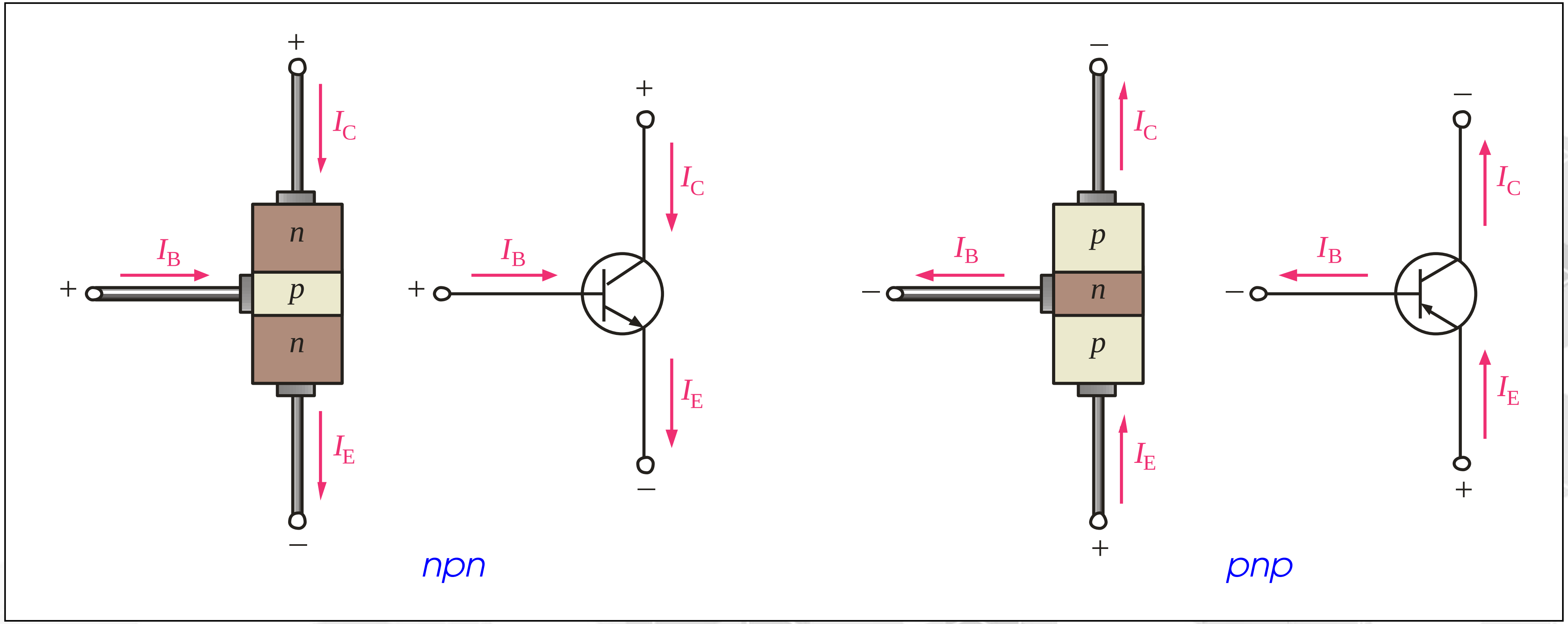
For the *npn* type shown, the collector is more positive than the base, which is more positive than the emitter.

For the *pnp type*, the voltages are reversed to maintain the forward-reverse bias.



BJT Currents

The direction of conventional current is in the direction of the arrow on the emitter terminal. The emitter current is the sum of the collector current and the small base current. That is, $I_E = I_C + I_B$.



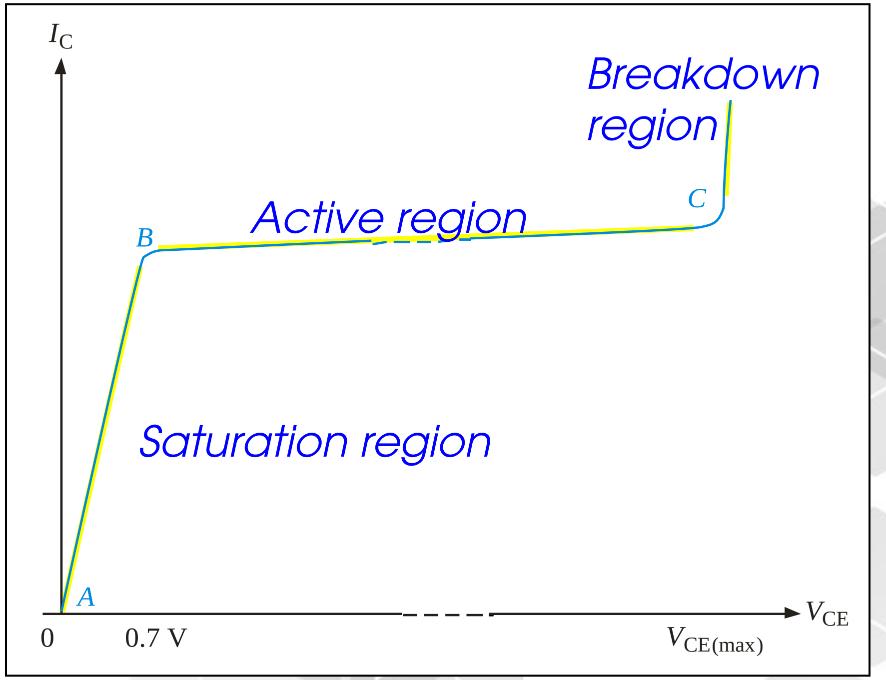
BJT Characteristics

The collector characteristic curves show the relationship of the three transistor currents.

The curve shown is for a fixed based current. The first region is the **saturation region**.

As V_{CE} is increased, I_C increases until *B*. Then it flattens in region between points *B* and *C*, which is the **active region**.

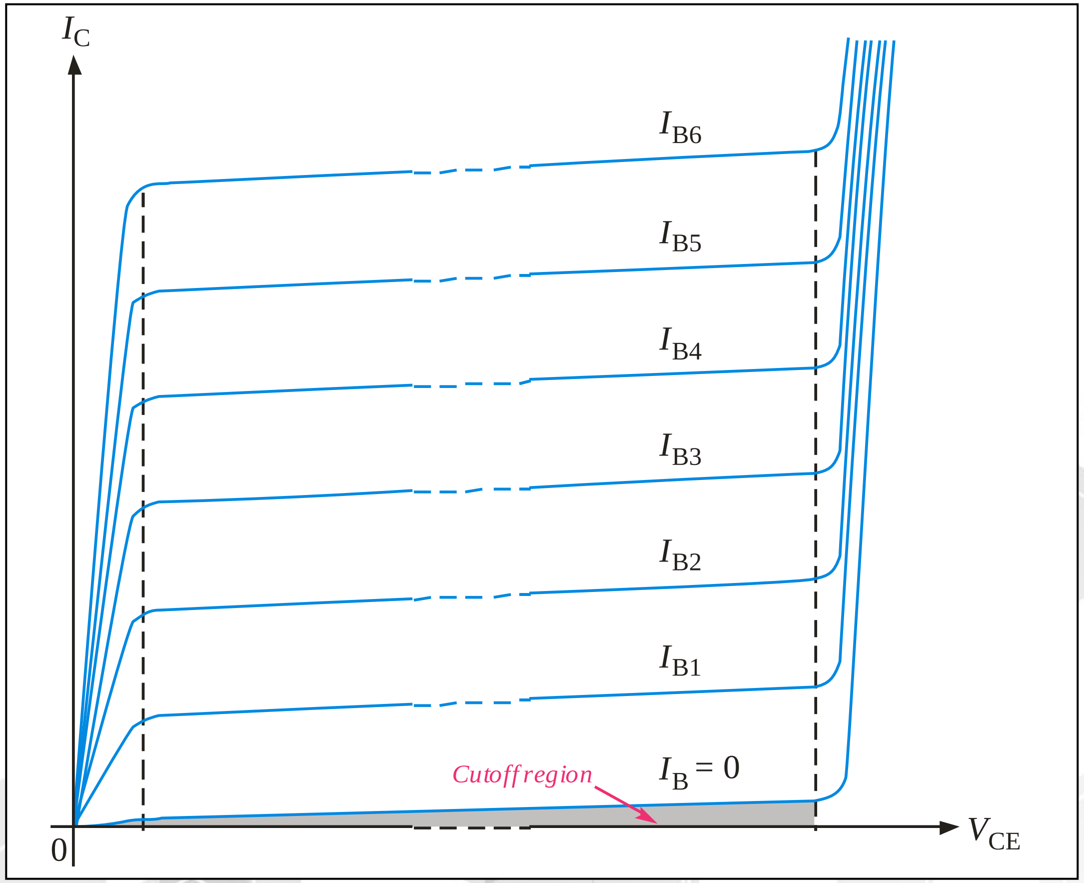
After *C*, is the **breakdown region**.



BJT Characteristics

The collector characteristic curves illustrate the relationship of the three transistor currents.

By setting up other values of base current, a family of collector curves is developed.



β_{DC} is the ratio of collector current to base current.

$$\beta_{DC} = \frac{I_C}{I_B}$$

It can be read from the curves. The value of β_{DC} is nearly the same wherever it is read.

BJT Characteristics

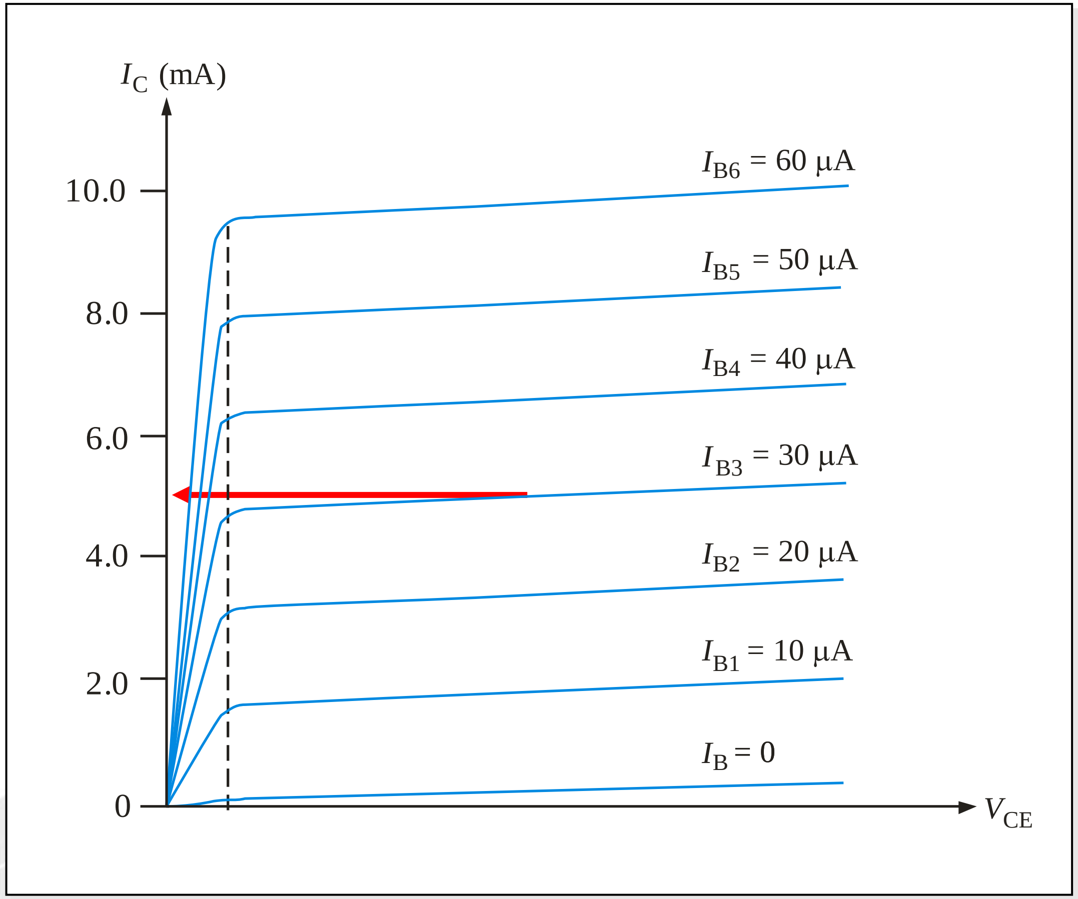
Example: What is the β_{DC} for the transistor shown?

Solution:

Choose a base current near the center of the range – in this case I_{B3} which is 30 µA.

Read the corresponding collector current – in this case, 5.0 mA. Calculate the ratio:

$$\beta_{DC} = \frac{I_C}{I_B} = \frac{5.0\ \text{mA}}{30\ \mu\text{A}} = 167$$

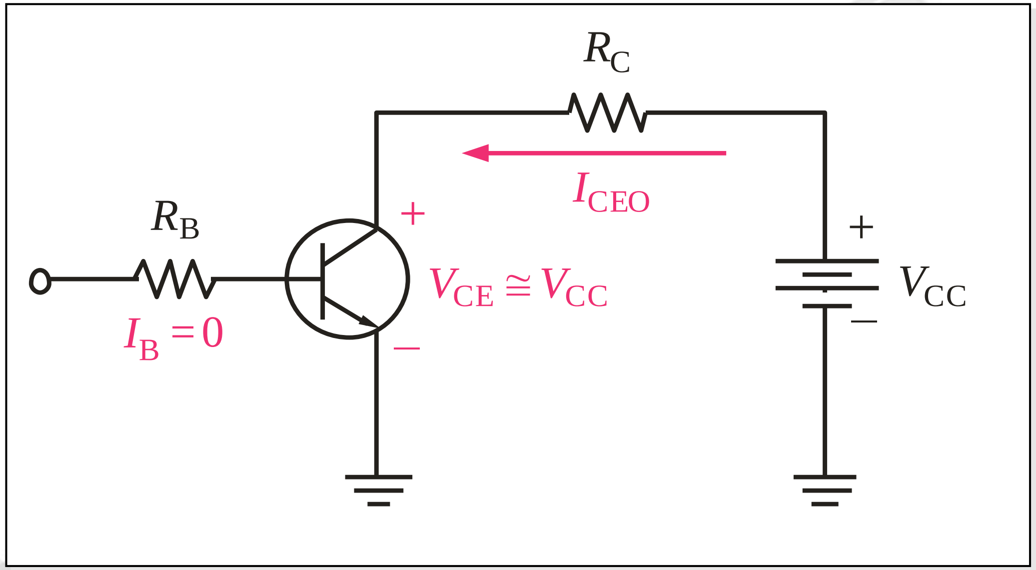


Cutoff

PHENIKAA UNIVERSITY

In a BJT, **cutoff** is the condition in which there is no base current, which results in only an extremely small leakage current (I_{CEO}) in the collector circuit. For practical work, this current is assumed to be zero.

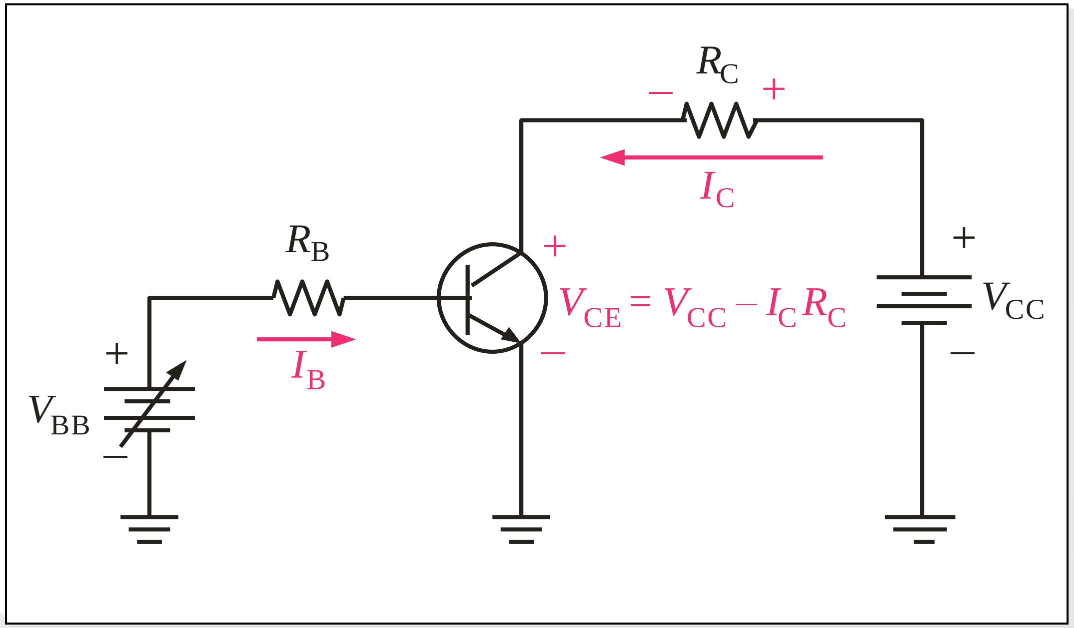
In cutoff, neither the base-emitter junction, nor the base-collector junction are forward-biased.



Saturation

In a BJT, **saturation** is the condition in which there is maximum collector current. The saturation current is determined by the external circuit (V_{CC} and R_C in this case) because the collector-emitter voltage is minimum (≈ 0.2 V)

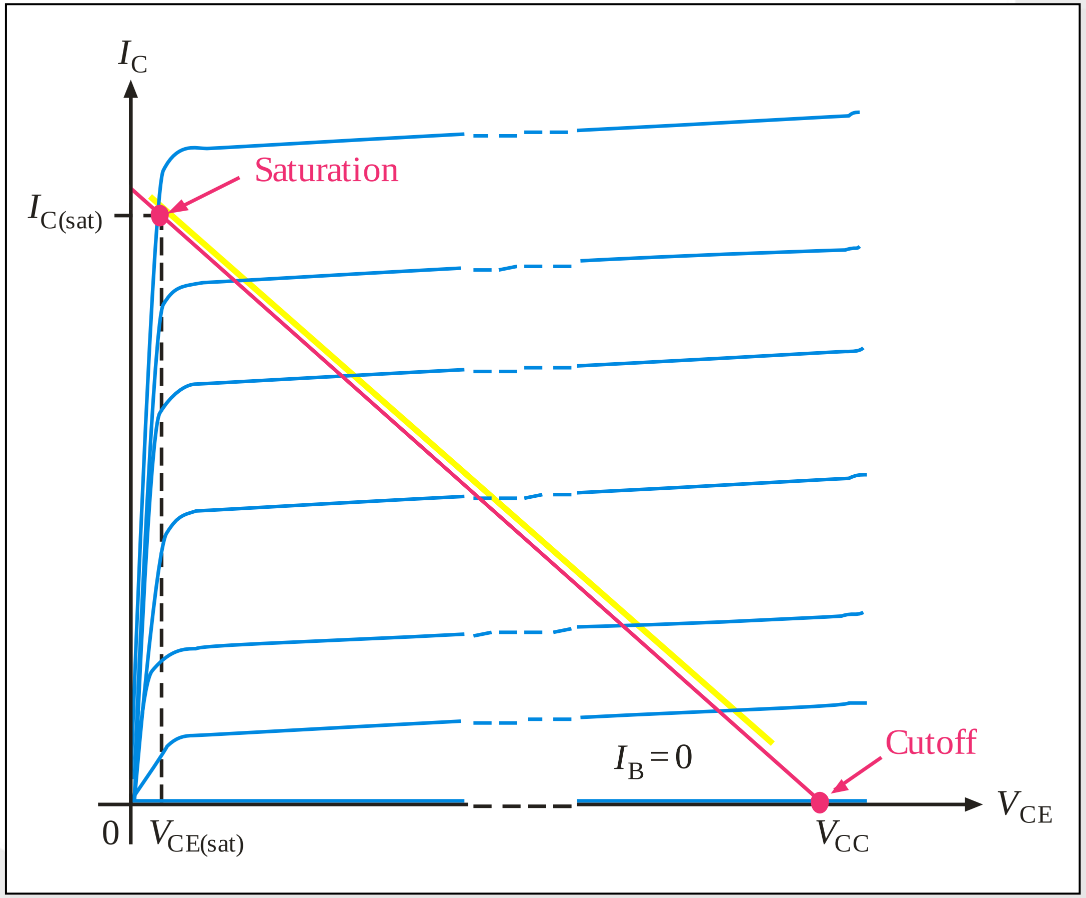
In saturation, an increase of base current has no effect on the collector circuit and the relation $I_C = \beta_{DC} I_B$ is no longer valid.



DC Load Line

The **DC load line** represents the circuit that is external to the transistor. It is drawn by connecting the saturation and cutoff points.

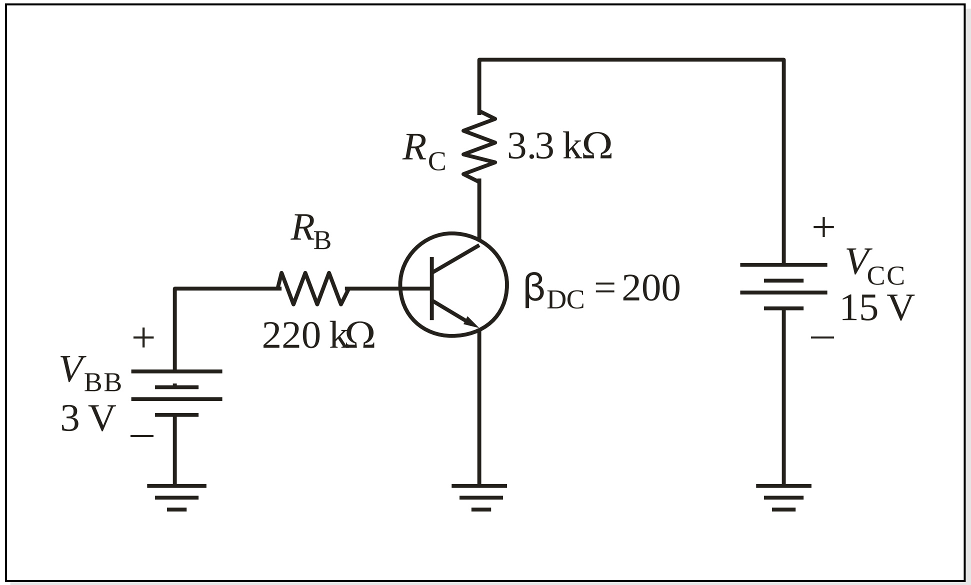
The transistor characteristic curves are shown superimposed on the load line. The region between the saturation and cutoff points is called the **active region.**



DC Load Line

Example:

What is the saturation current and the cutoff voltage for the circuit? Assume V_{CE} = 0.2 V in saturation.



Solution:

$$I_{SAT} = \frac{V_{CC} - 0.2\text{ V}}{R_C} = \frac{15\text{ V} - 0.2\text{ V}}{3.3\text{ k}\Omega} = 4.48\text{ mA} \quad V_{CE} = V_{CC} = 15\text{ V}$$

Follow-up:

Is the transistor saturated? $I_B = \dfrac{3.0\text{ V} - 0.7\text{ V}}{220\text{ k}\Omega} = 10.45\ \mu\text{A}$

$I_C = \beta I_B = 200\ (10.45\ \mu\text{A}) =$ 2.09 mA Since $I_C < I_{SAT}$, it is not saturated.

Data Sheets

PHENIKAA UNIVERSITY

Data sheets give manufacturer's specifications for maximum operating conditions, thermal, and electrical characteristics. For example, an electrical characteristic is β_{DC}, which is given as h_{FE}. The 2N3904 shows a range of β's on the data sheet from 100 to 300 for I_C = 10 mA.

Characteristic		Symbol	Min	Max	Unit
ON Characteristics					
DC current gain		h_{FE}			–
(I_C = 0.1 mA dc, V_{CE} = 1.0 V dc)	2N3903		20	–	
	2N3904		40	–	
(I_C = 1.0 mA dc, V_{CE} = 1.0 V dc)	2N3903		35	–	
	2N3904		70	–	
(I_C = 10 mA dc, V_{CE} = 1.0 V dc)	2N3903		50	150	
	2N3904		100	300	
(I_C = 50 mA dc, V_{CE} = 1.0 V dc)	2N3903		30	–	
	2N3904		60	–	
(I_C = 100 mA dc, V_{CE} = 1.0 V dc)	2N3903		15	–	
	2N3904		30	–	

DC and AC Quantities

The text uses capital letters for both AC and DC currents and voltages with rms values assumed unless stated otherwise.

DC Quantities use upper case roman subscripts. Example: V_{CE}. (The second letter in the subscript indicates the reference point.)

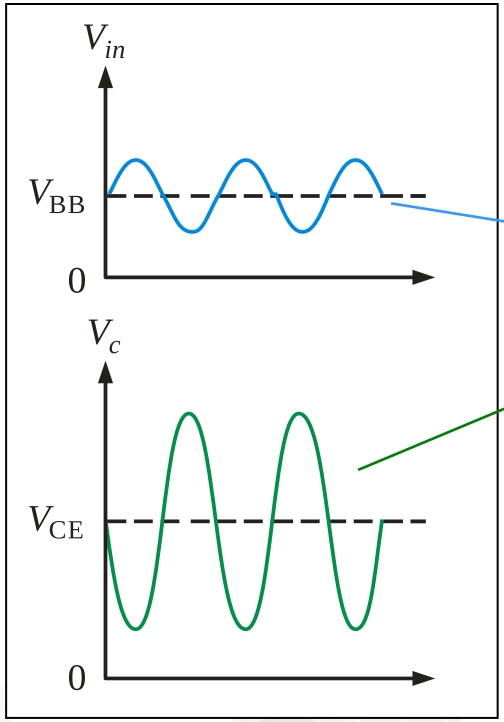
AC Quantities and time varying signals use lower case italic subscripts. Example: V_{ce}.

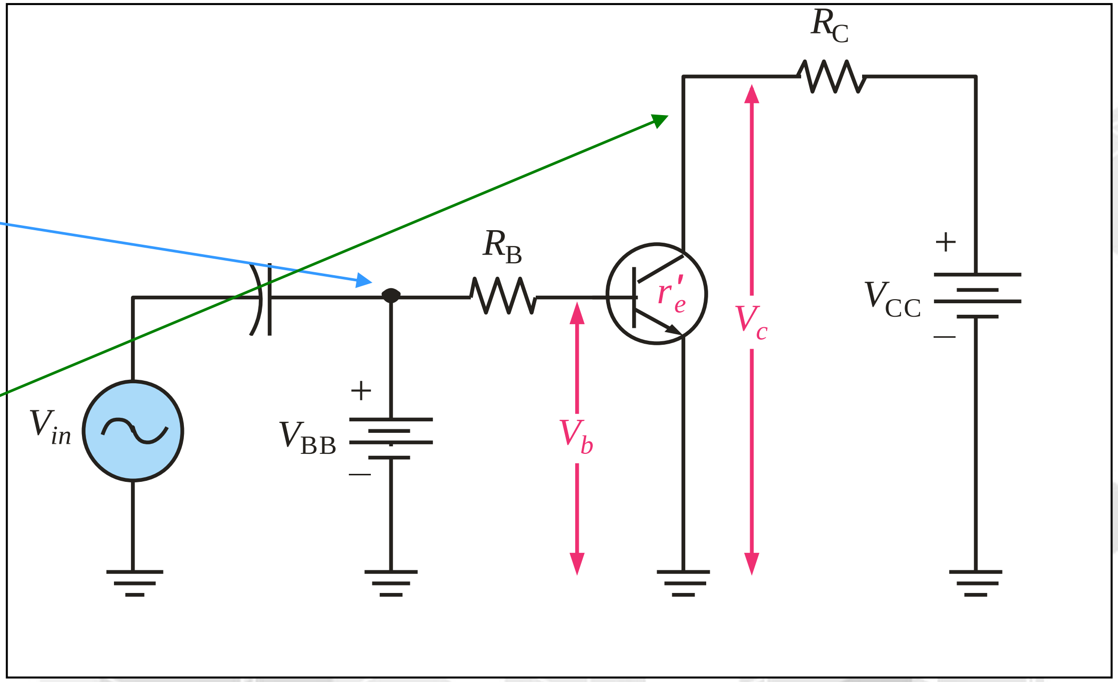
Internal transistor resistances are indicated as lower case quantities with a prime and an appropriate subscript. Example: r_e'.

External resistances are indicated as capital *R* with either a capital or lower case subscript depending on if it is a DC or ac resistance. Examples: R_{C} and R_{c}.

BJT Amplifiers

A BJT amplifies AC signals by converting some of the DC power from the power supplies to AC signal power. An ac signal at the input is superimposed in the dc bias by the capacitive coupling. The output ac signal is inverted and rides on a dc level of V_{CE}.

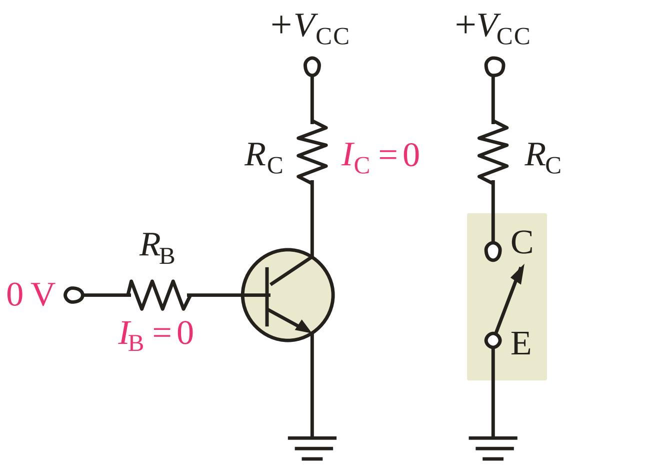




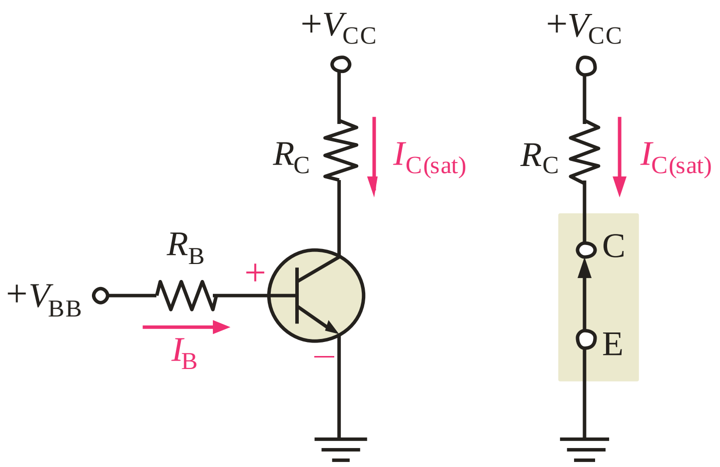
BJT Switches

PHENIKAA UNIVERSITY

A BJT can be used as a switching device in logic circuits to turn on or off current to a load. As a switch, the transistor is normally in either cutoff (load is OFF) or saturation (load is ON).



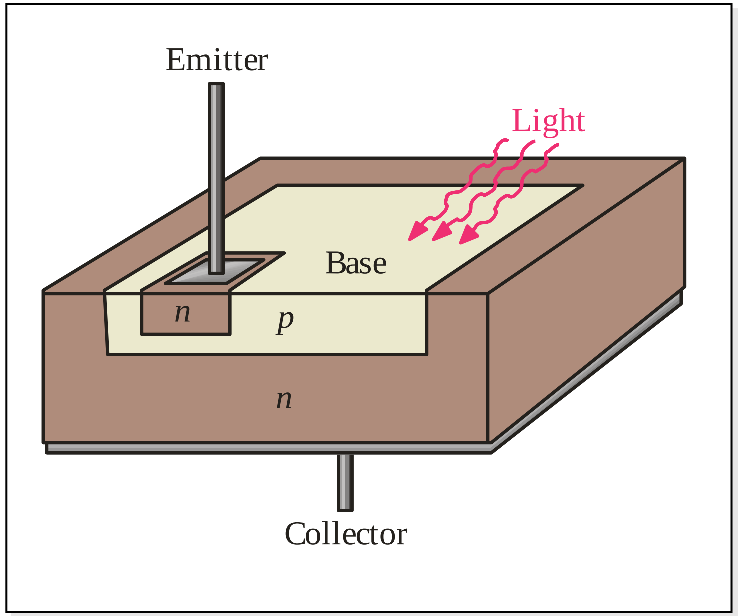
In cutoff, the transistor looks like an open switch.



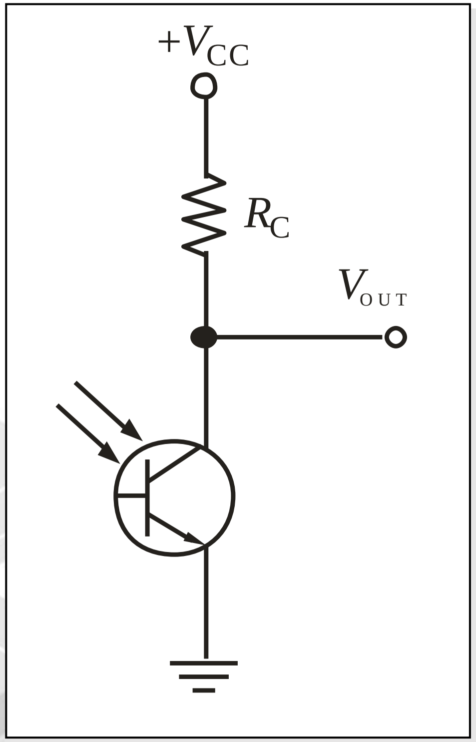
In saturation, the transistor looks like a closed switch.

Phototransistors

A phototransistor produces base current when light strikes the exposed photosensitive base region, which is the active area. Phototransistors have high gain and are more sensitive to light than photodiodes.



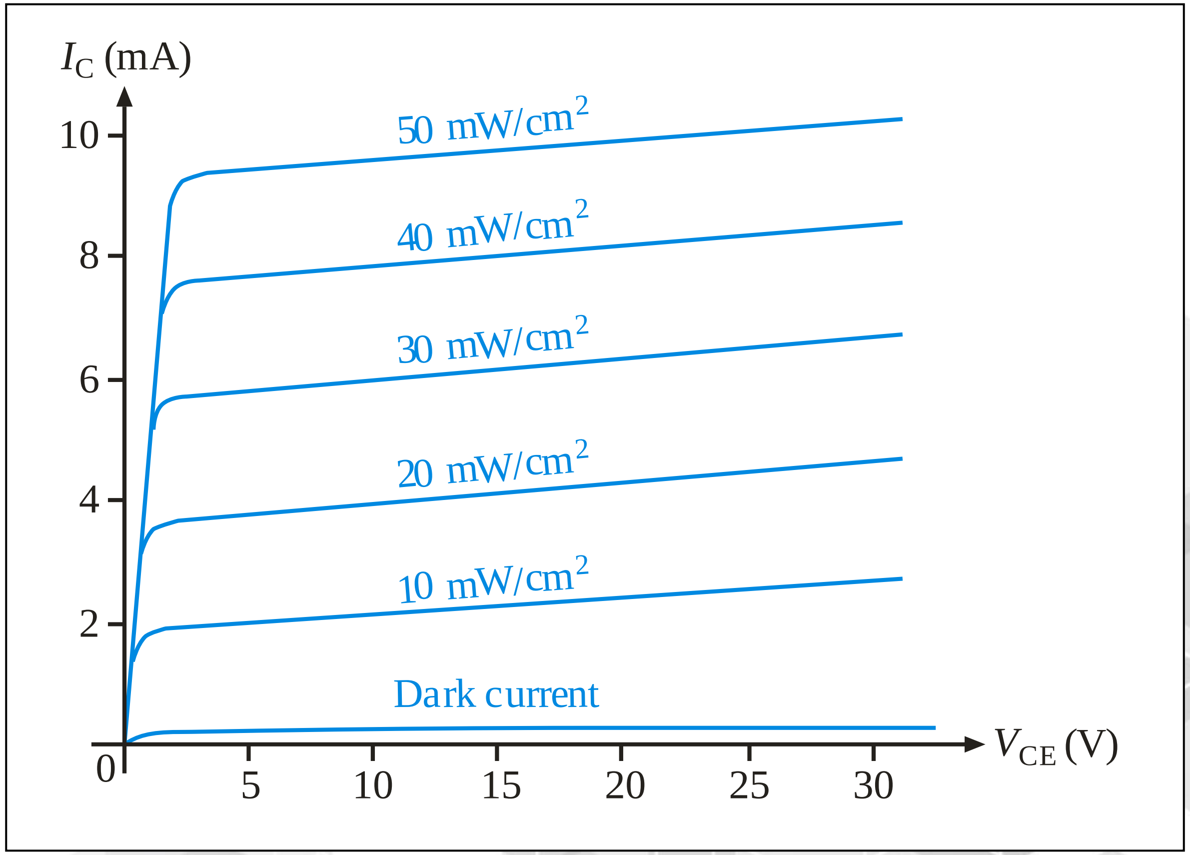
In a typical circuit the base lead is left open. In the circuit shown, the output voltage is maximum with no light and drops with increasing light.



Phototransistors

PHENIKAA UNIVERSITY

The characteristic curves for a phototransistor are based on light flux (mW/cm^2) to the base rather than base current in an ordinary transistor.



Phototransistors

PHENIKAA UNIVERSITY

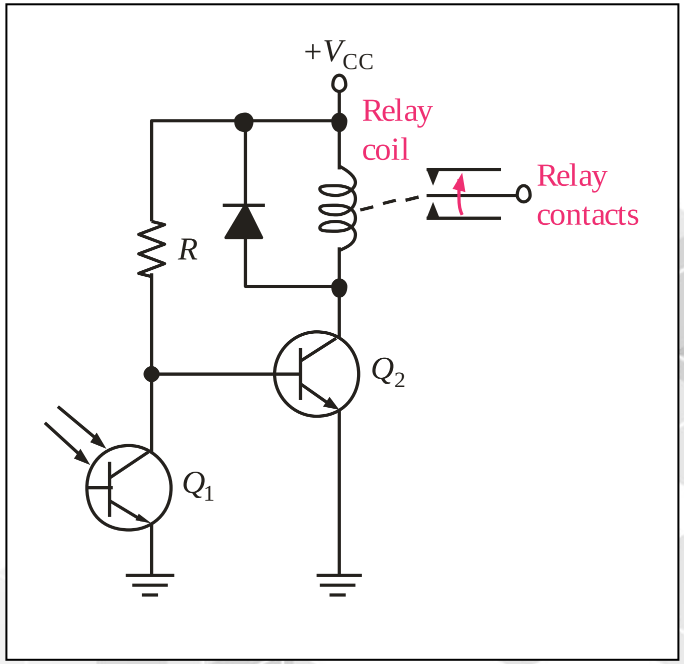
The output from the phototransistor can be used to activate or deactivate a relay. In this case, the phototransistor is part of a switching circuit.

Question:

Is either transistor ON for the circuit when there is no incident light?

Answer:

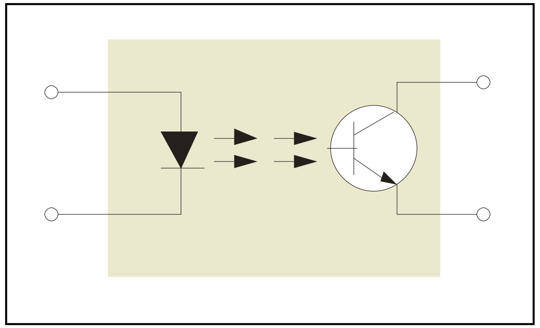
With no incident light, Q_1 will be biased OFF. Q_2 will be forward-biased through R and is ON. Collector current in Q_2 causes the relay to be energized.



Optocouplers

PHENIKAA UNIVERSITY

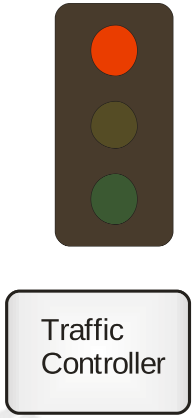
An optocoupler is a single package containing an LED and a phototransistor. Optical couplers transfer a signal from one circuit to another while providing a high degree of isolation.



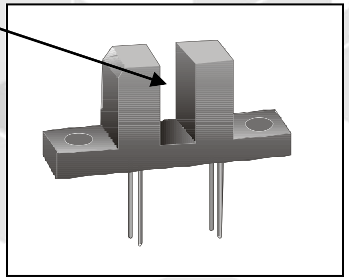
A key specification for optocouplers is the current transfer ratio or CTR, which is a measure of efficiency. The CTR is the ratio of output current to input current. Typically values are from 50% to 110% for standard optocouplers.

Applications for Optocouplers

Optocouplers are used when data or signals need to be transferred from a control circuit to a power circuit without making electrical connections between the circuits. For example, the logic circuits in a traffic light controller need to be isolated from the lights themselves.



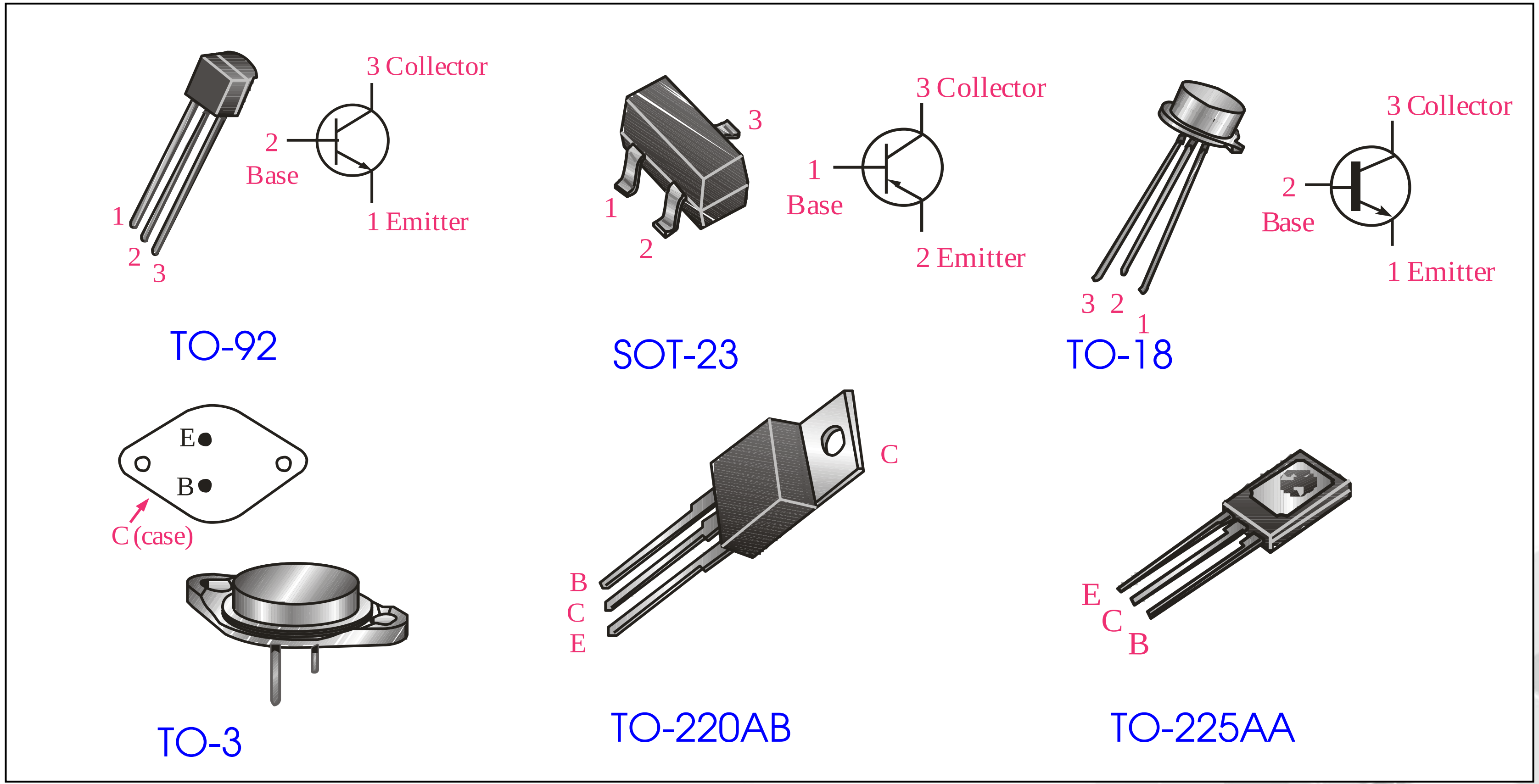
Another application for optocouplers is as a transducer to detect a light path such as a hole in a rotating disk. In this case, the LED and phototransistor are separated by a gap.



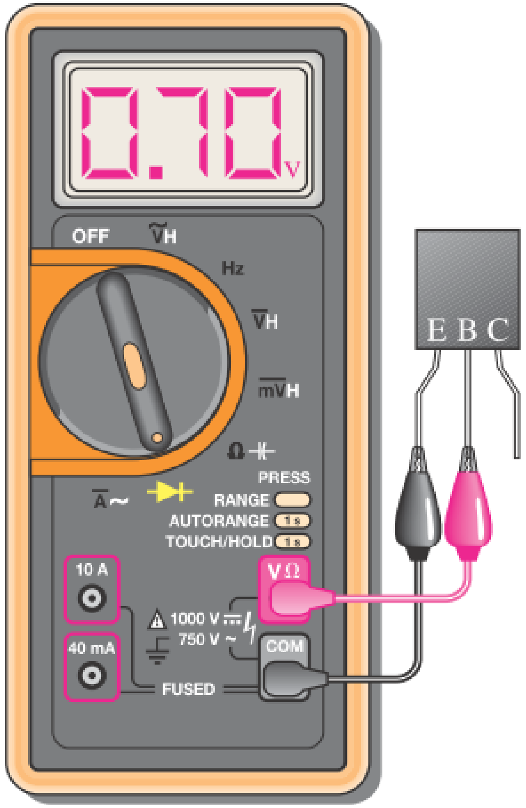
Optocouplers are also useful for isolating patients from the monitoring instruments.

A Sample of Common Transistor Packages

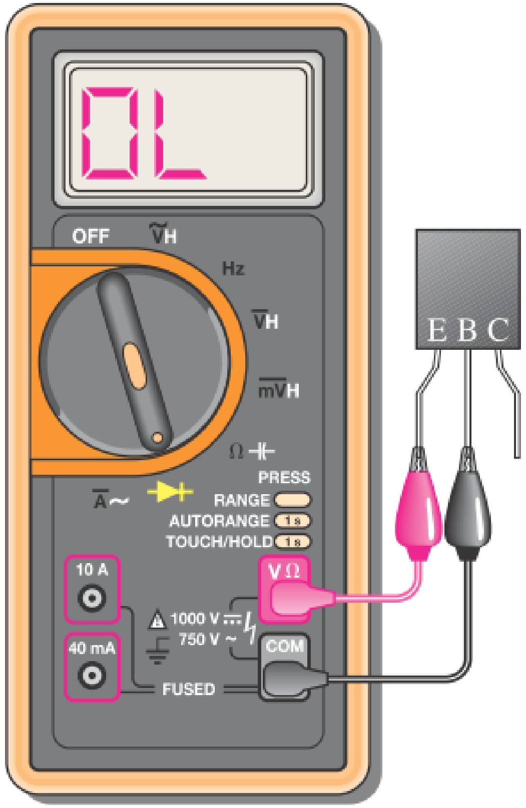
PHENIKAA UNIVERSITY



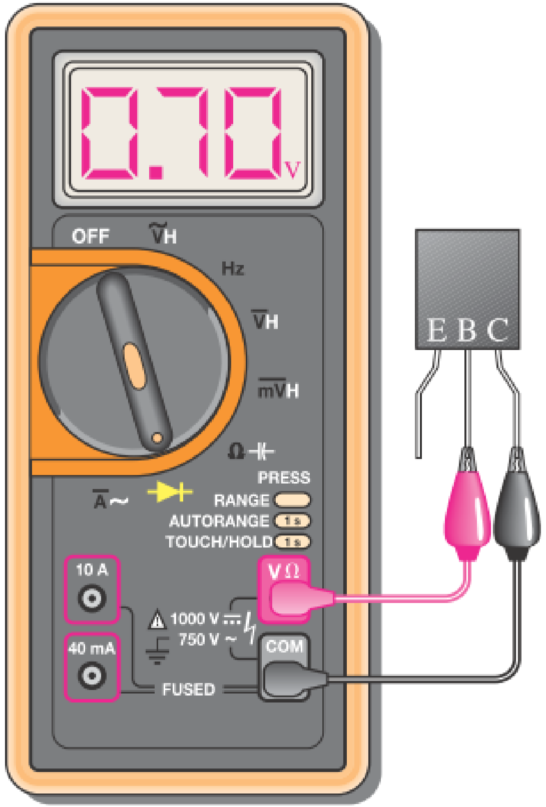
BJT Basic Test



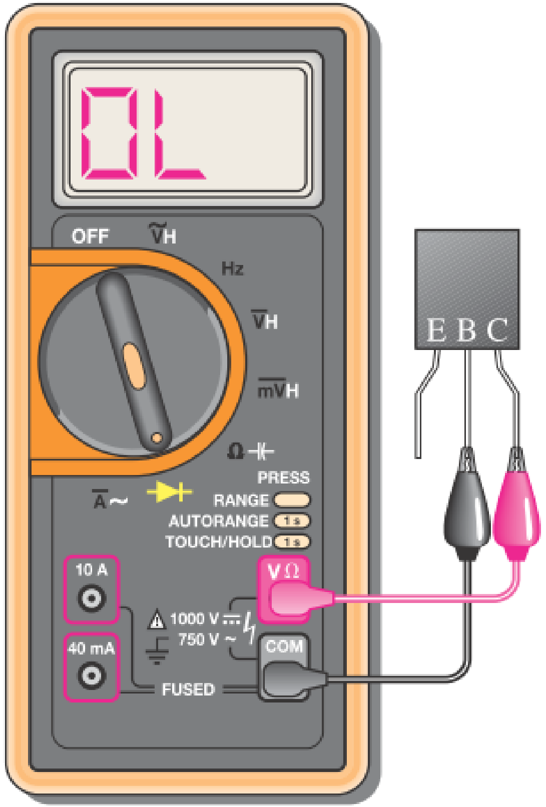
(a) Forward-bias test of the BE junction



(b) Reverse-bias test of the BE junction



(c) Forward-bias test of the BC junction



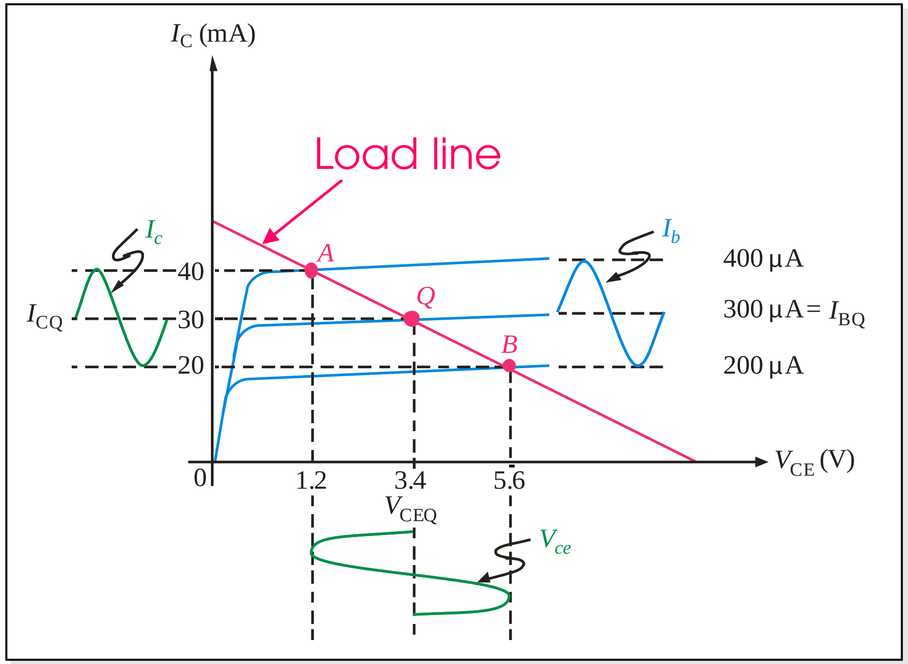
(d) Reverse-bias test of the BC junction

Transistor Bias Circuits

The DC Operating Point

Bias establishes the operating point (Q-point) of a transistor amplifier; the ac signal moves above and below this point.

For this example, the dc base current is 300 mA. When the input causes the base current to vary between 200 mA and 400 mA, the collector current varies between 20 mA and 40 mA.

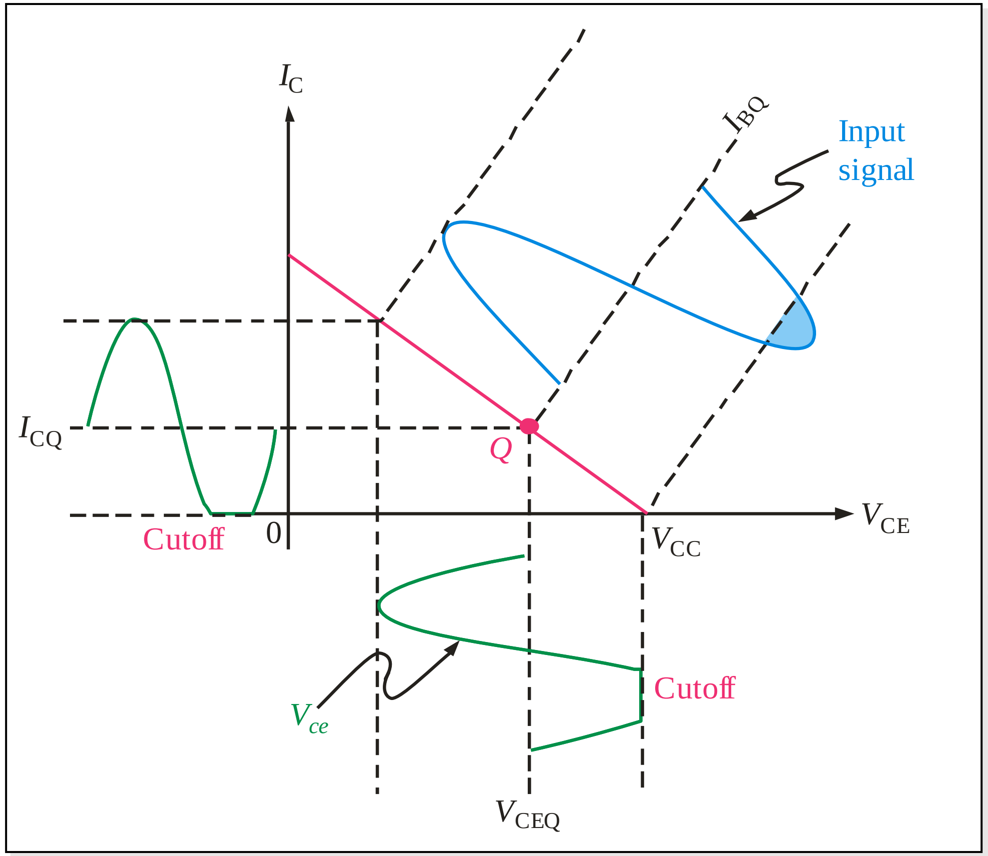


The DC Operating Point

PHENIKAA UNIVERSITY

A signal that swings outside the active region will be clipped.

For example, the bias has established a low *Q*- point. As a result, the signal is will be clipped because it is too close to cutoff.



Voltage-Divider Bias

PHENIKAA UNIVERSITY

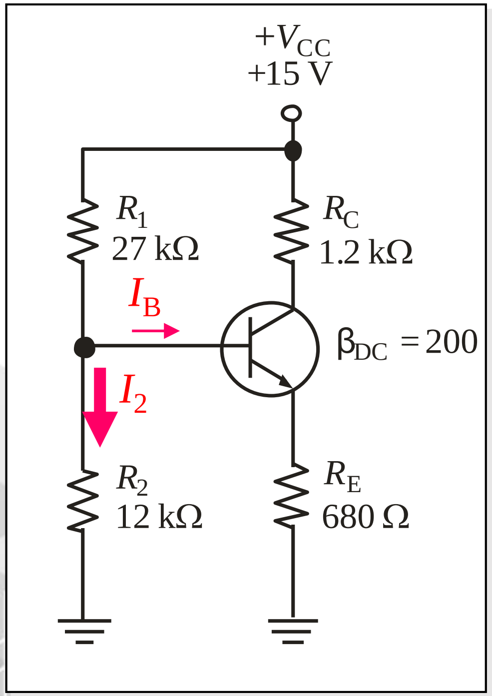
A practical way to establish a *Q*-point is to form a voltage-divider from V_{CC}.

R_1 and R_2 are selected to establish V_B. If the divider is stiff, I_B is small compared to I_2. Then,

$$V_B \approx \left(\frac{R_2}{R_1 + R_2}\right) V_{CC}$$

Example:

Determine the base voltage for the circuit.



Solution:

$$V_B = \left(\frac{R_2}{R_1 + R_2}\right) V_{CC}$$

$$= \left(\frac{12\ \text{k}\Omega}{27\ \text{k}\Omega + 12\ \text{k}\Omega}\right)(+15\ \text{V}) = 4.62\ \text{V}$$

Voltage-Divider Bias

Follow-up:

What is the emitter voltage, V_E, and current, I_E?

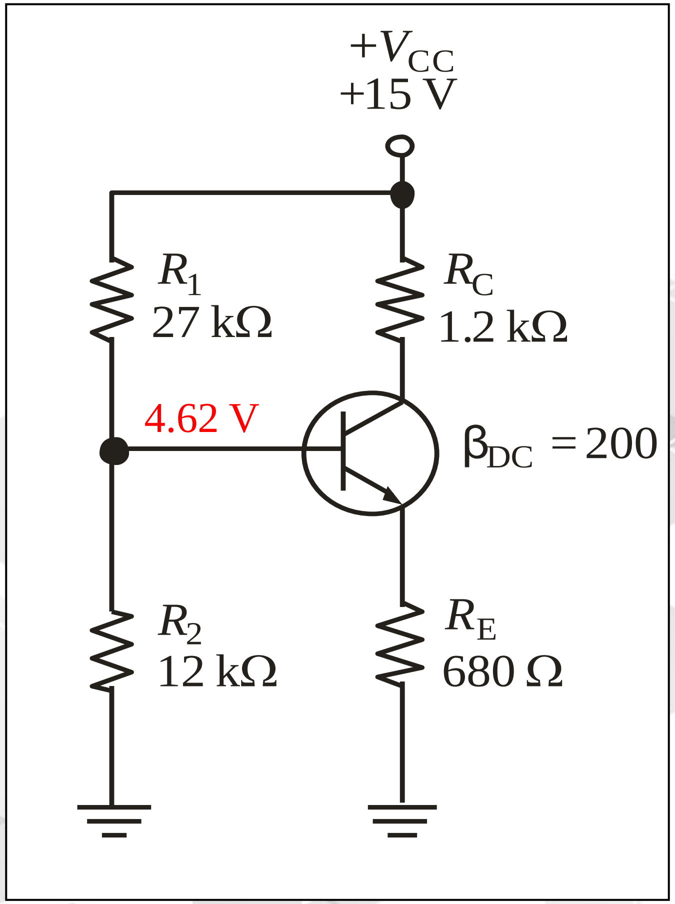
Solution:

V_E is one diode drop less than V_B:

V_E = 4.62 V – 0.7 V = 3.92 V

Applying Ohm's law:

$$I_E = \frac{V_E}{R_E} = \frac{3.92\text{ V}}{680\ \Omega} = 5.76\text{ mA}$$



Voltage-Divider Bias

The unloaded voltage divider approximation for V_B gives reasonable results. A more exact solution is to Thevenize the input circuit.

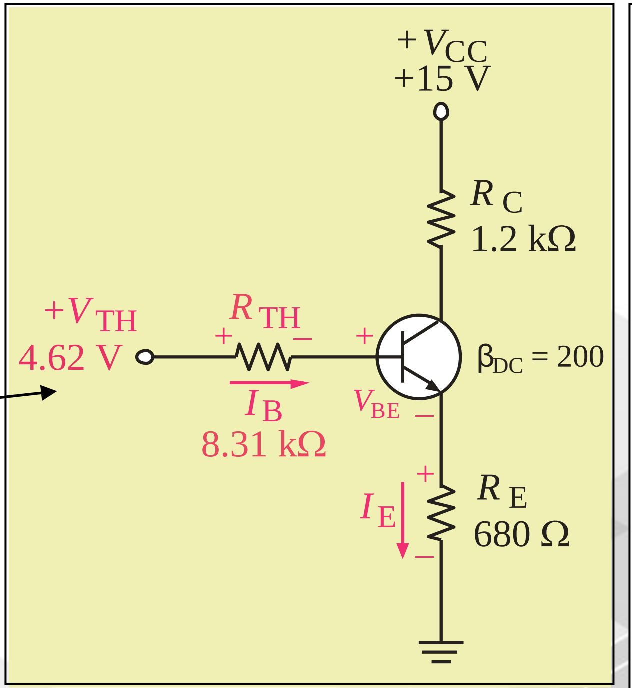
$V_{TH} = V_{B(\text{no load})}$

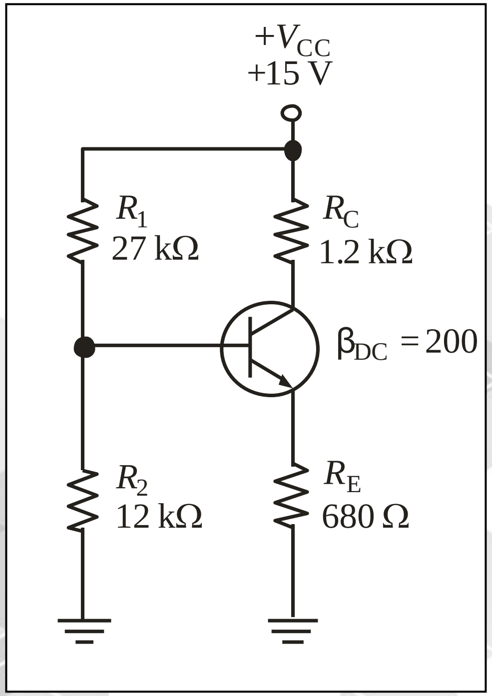
$= 4.62\ \text{V}$

$R_{TH} = R_1 \,||\, R_2 =$

$= 8.31\ \text{k}\Omega$

The Thevenin input circuit can be drawn



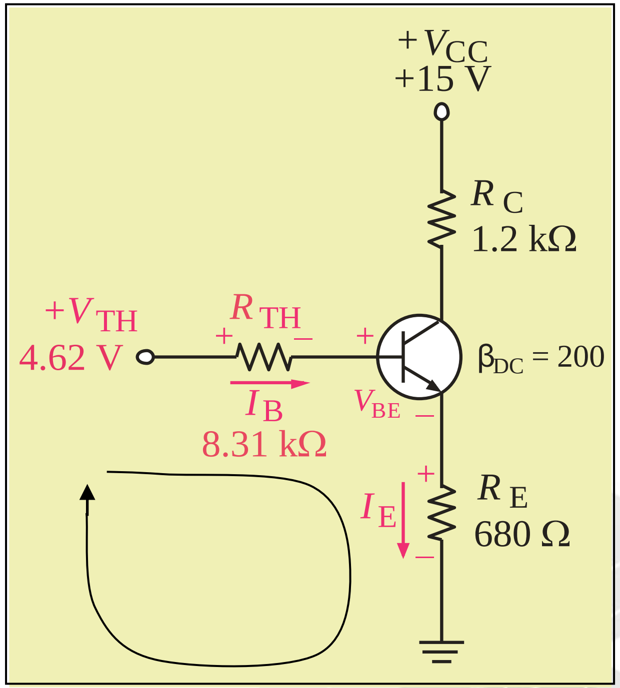


Voltage-Divider Bias

Now write KVL around the base emitter circuit and solve for I_E.

$$V_{TH} = I_B R_{TH} + V_{BE} + I_E R_E$$

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + R_{TH}/\beta_{DC}}$$



Substituting and solving,

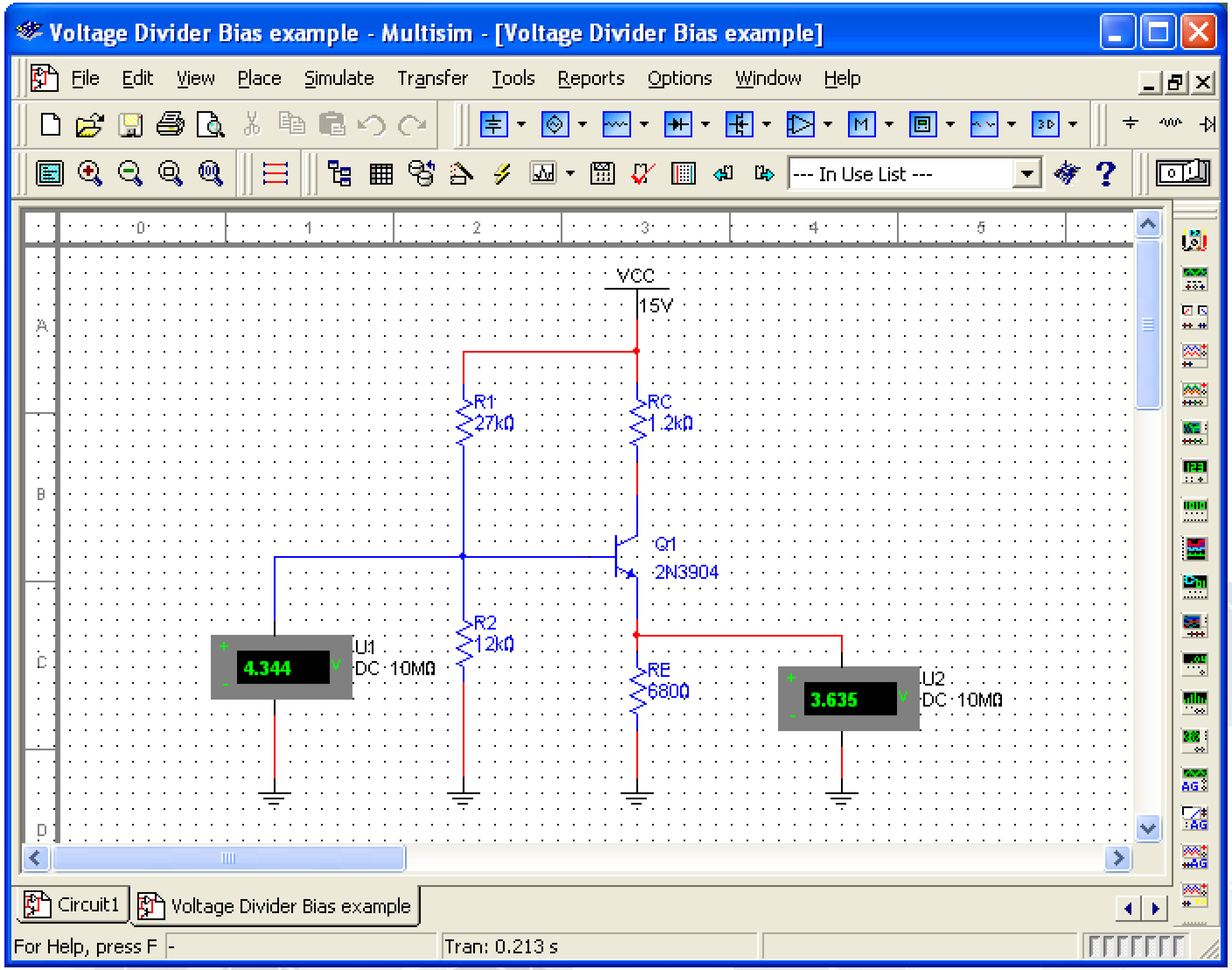
$$I_E = \frac{4.62\text{ V} - 0.7\text{ V}}{680\ \Omega + 8.31\text{ k}\Omega/200} = 5.43\text{ mA}$$

and $V_E = I_E R_E = (5.43\text{ mA})(0.68\text{ kW})$

$= 3.69\text{ V}$

Voltage-Divider Bias

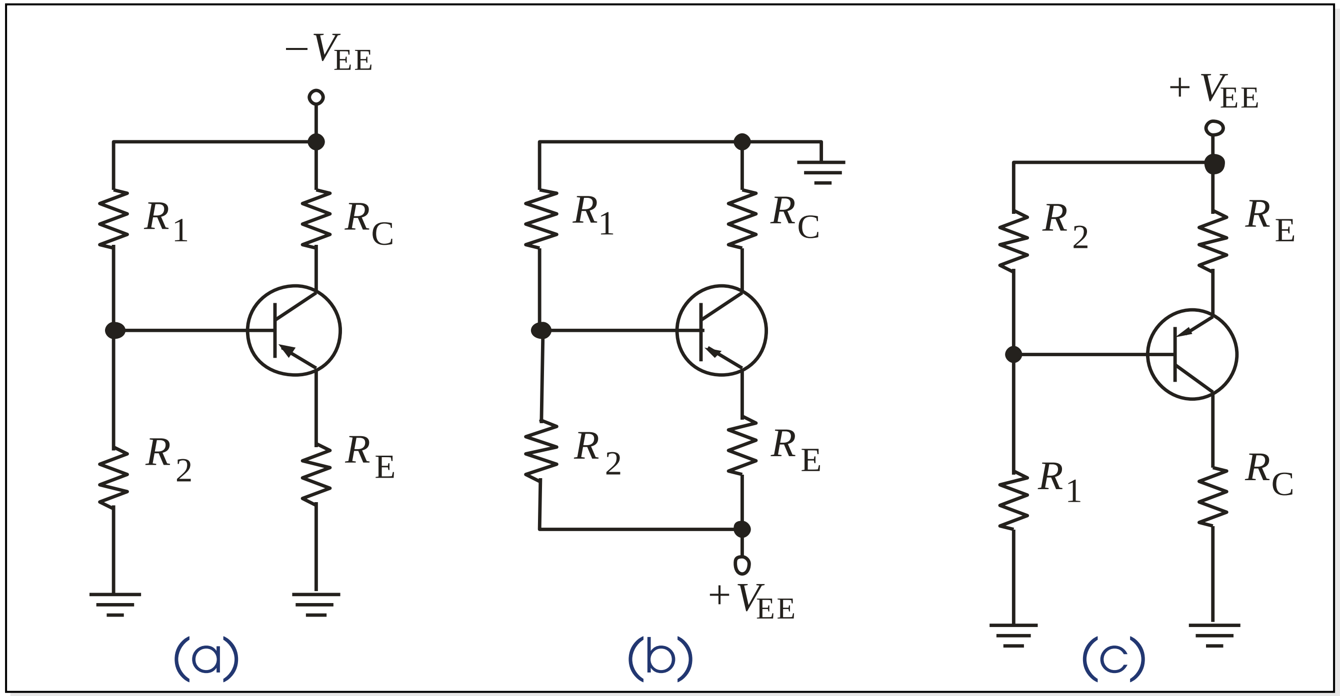
Multisim allows you to do a quick check of your result.



Voltage-Divider Bias

PHENIKAA UNIVERSITY

A *pnp* transistor can be biased from either a positive or negative supply. Notice that (b) and (c) are the same circuit; both with a positive supply.



Voltage-Divider Bias

PHENIKAA UNIVERSITY

Example: Determine I_E for the *pnp* circuit. Assume a stiff voltage divider (no loading effect).

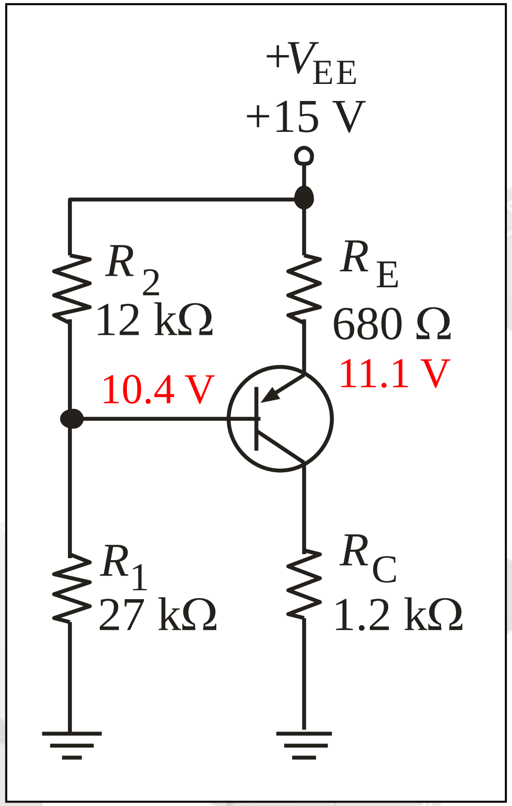
Solution:

$$V_B = \left(\frac{R_1}{R_1 + R_2}\right) V_{EE}$$

$$= \left(\frac{27\ \text{k}\Omega}{27\ \text{k}\Omega + 12\ \text{k}\Omega}\right)(+15.0\ \text{V}) = 10.4\ \text{V}$$

$$V_E = V_B + V_{BE} = 10.4\ \text{V} + 0.7\ \text{V} = 11.1\ \text{V}$$

$$I_E = \frac{V_{EE} - V_E}{R_E} = \frac{15.0\ \text{V} - 11.1\ \text{V}}{680\ \Omega} = 5.74\ \text{mA}$$



Emitter Bias

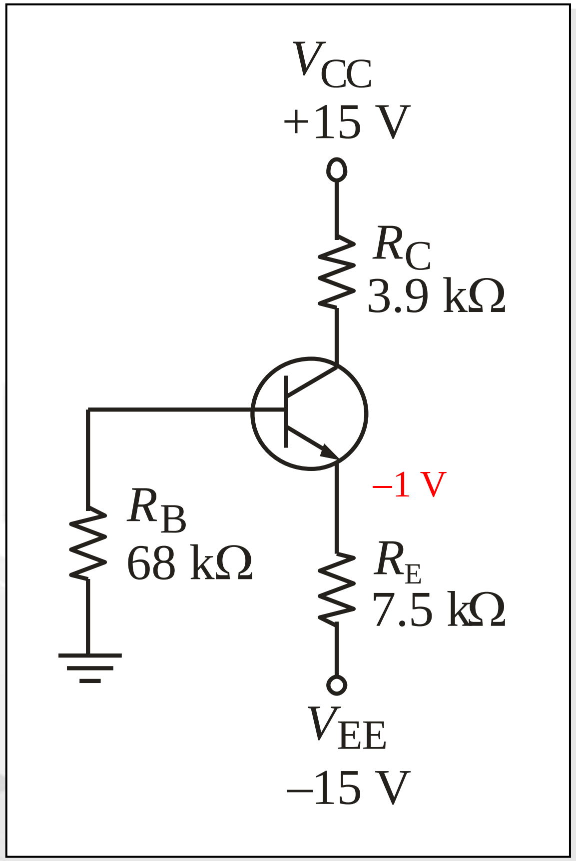
PHENIKAA UNIVERSITY

Emitter bias has excellent stability but requires both a positive and a negative source.

For troubleshooting analysis, assume that V_E for an *npn* transistor is about -1 V.

Example:

Assuming that V_E is -1 V, what is I_E?



Solution:

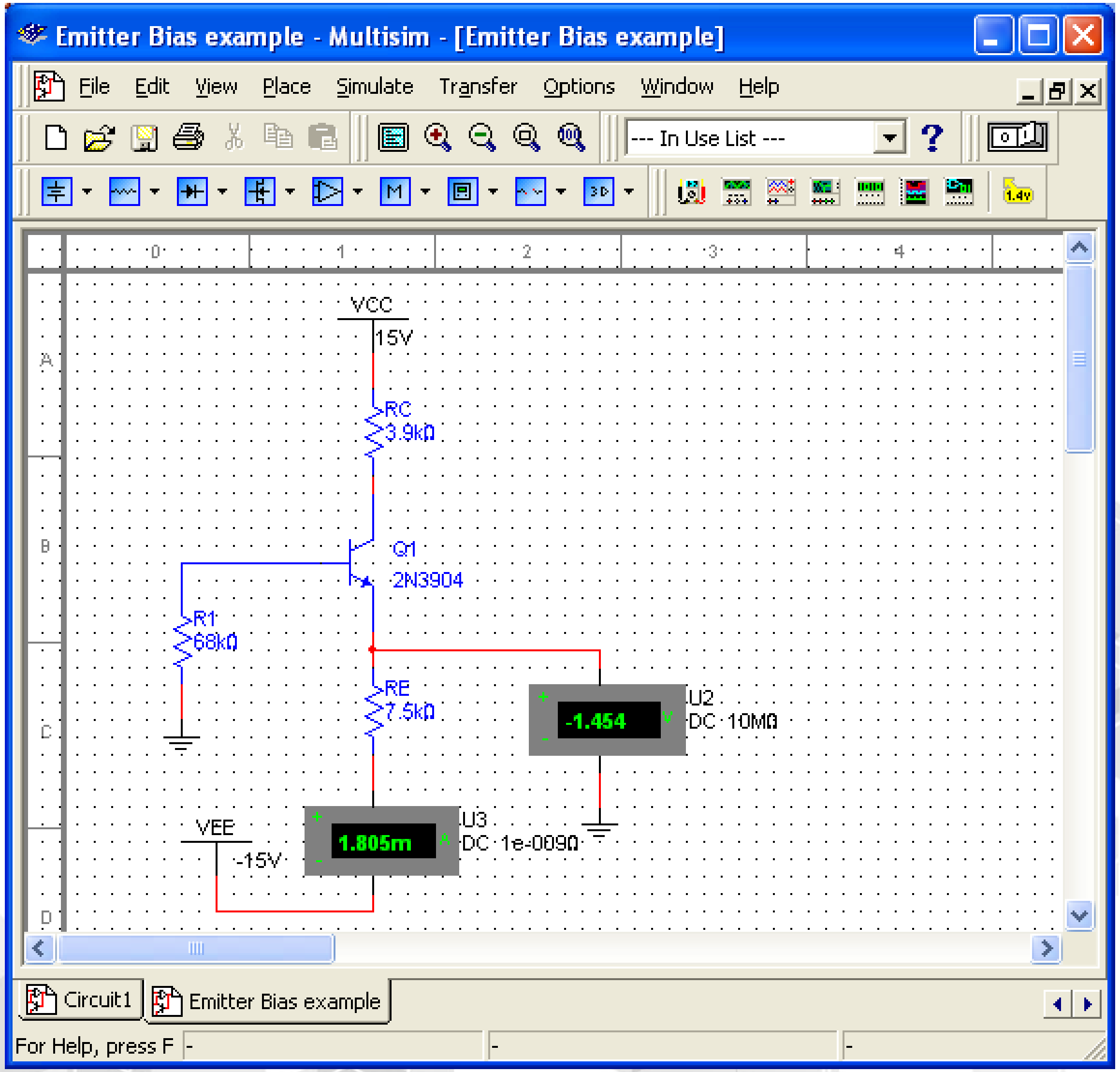
$$I_E = \frac{-V_{EE} - 1\text{ V}}{R_E} = \frac{-15\text{ V} - (-1\text{ V})}{7.5\text{ k}\Omega} = -1.87\text{ mA}$$

Emitter Bias

A check with Multisim shows that the assumption for troubleshooting purposes is reasonable.

For detailed analysis work, you can include the effect of β_{DC}. In this case,

$$I_E = \frac{-V_{EE} - 1\text{ V}}{R_E + R_B/\beta_{DC}}$$



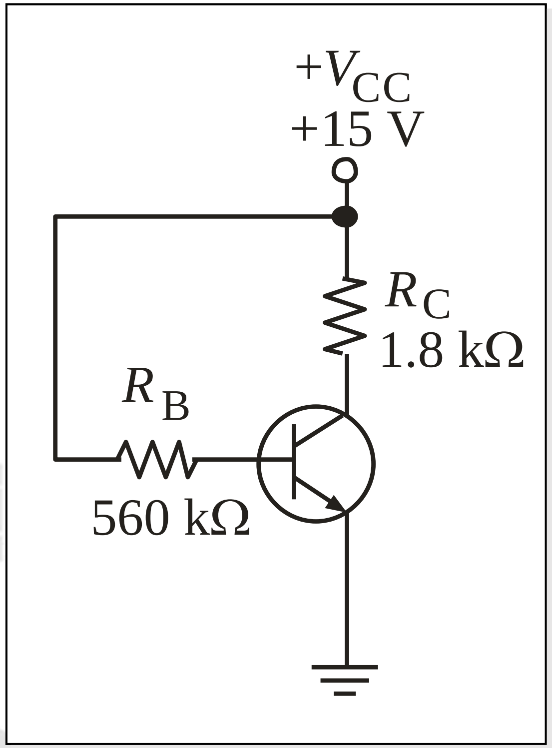
Base Bias

Base bias is used in switching circuits because of its simplicity, but not widely used in linear applications because the *Q*-point is β dependent.

Base current is derived from the collector supply through a large base resistor.

Example:

What is I_B?



Solution:

$$I_B = \frac{V_{CC} - 0.7\ \text{V}}{R_B} = \frac{15\ \text{V} - 0.7\ \text{V}}{560\ \text{k}\Omega} = 25.5\ \mu\text{A}$$

PHENIKAA UNIVERSITY

Follow up:

Compare V_{CE} for the case where β = 100 and β = 200.

Solution:

For β = 100: $I_C = \beta I_B = (100)(25.5\ \mu\text{A}) = 2.55\ \text{mA}$

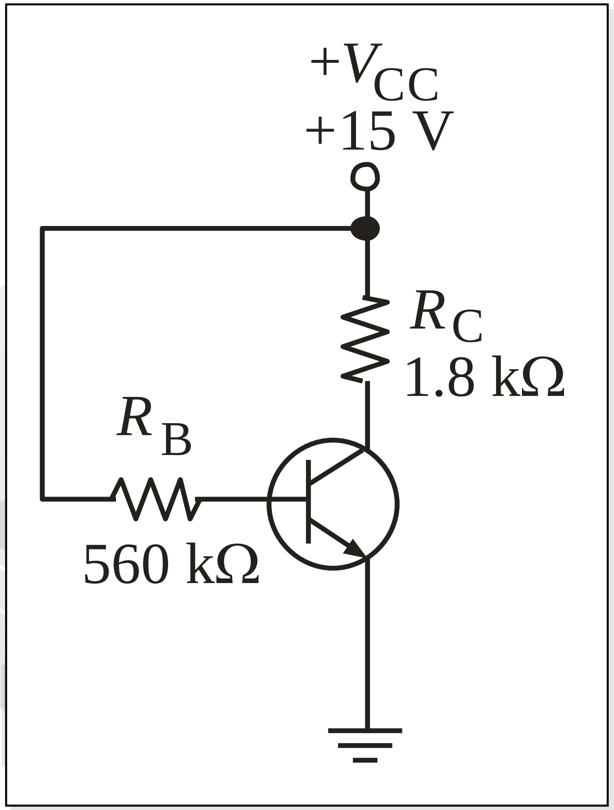
$$V_{CE} = V_{CC} - I_C R_C$$

$$= 15\ \text{V} - (2.55\ \text{mA})(1.8\ \text{k}\Omega) = 10.4\ \text{V}$$

For β = 300: $I_C = \beta I_B = (300)(25.5\ \mu\text{A}) = 7.65\ \text{mA}$

$$V_{CE} = V_{CC} - I_C R_C$$

$$= 15\ \text{V} - (7.65\ \text{mA})(1.8\ \text{k}\Omega) = 1.23\ \text{V}$$



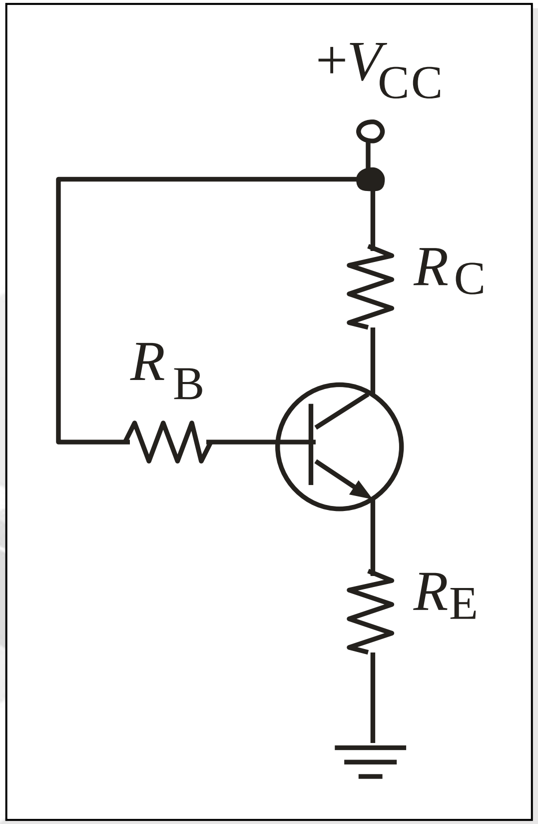
Emitter-Feedback Bias

PHENIKAA UNIVERSITY

An emitter resistor changes base bias into emitter-feedback bias, which is more predictable. The emitter resistor is a form of **negative feedback**.

The equation for emitter current is found by writing KVL around the base circuit. The result is:

$$I_E = \frac{V_{CC} - V_{BE}}{R_E + R_E/\beta_{DC}}$$

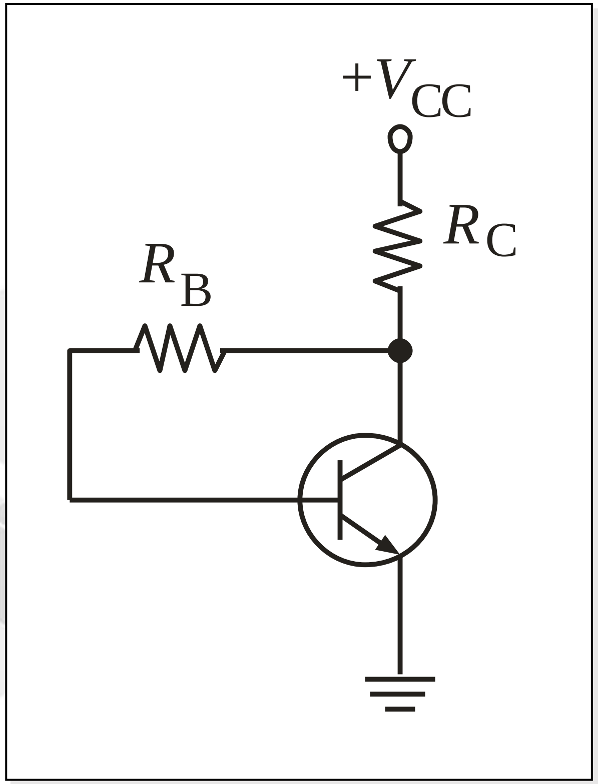


Collector-Feedback Bias

Collector feedback bias uses another form of **negative feedback** to increase stability. Instead of returning the base resistor to V_{CC}, it is returned to the collector.

The equation for collector current is found by writing KVL around the base circuit. The result is

$$I_C = \frac{V_{CC} - V_{BE}}{R_C + R_B/\beta_{DC}}$$



Collector-Feedback Bias

Example:

Compare I_C for the case when β = 100 with the case when β = 300.

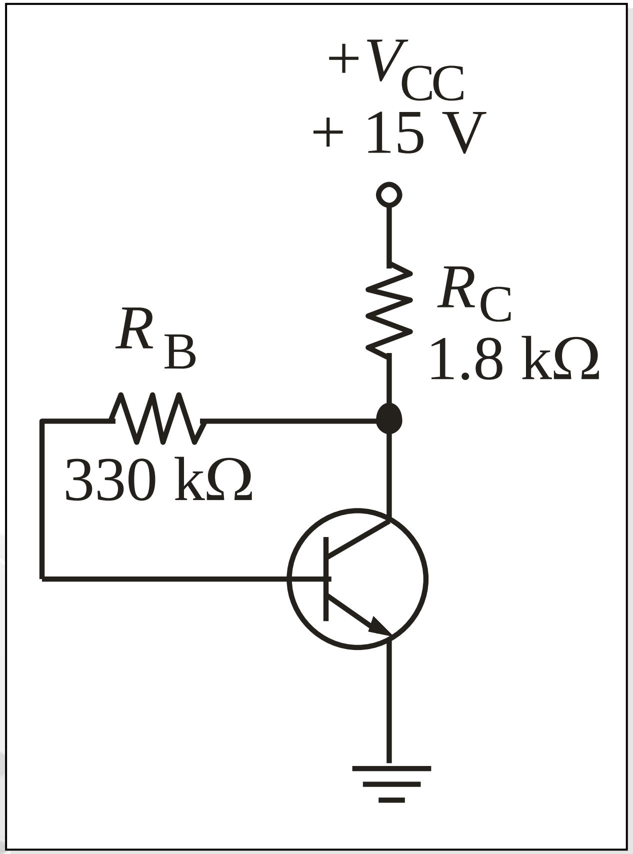
Solution:

When β = 100,

$$I_C = \frac{V_{CC} - V_{BE}}{R_C + R_B/\beta_{DC}} = \frac{15\text{ V} - 0.7\text{ V}}{1.8\text{ k}\Omega + 330\text{ k}\Omega/100} = 2.80\text{ mA}$$

When β = 300,

$$I_C = \frac{V_{CC} - V_{BE}}{R_C + R_B/\beta_{DC}} = \frac{15\text{ V} - 0.7\text{ V}}{1.8\text{ k}\Omega + 330\text{ k}\Omega/300} = 4.93\text{ mA}$$

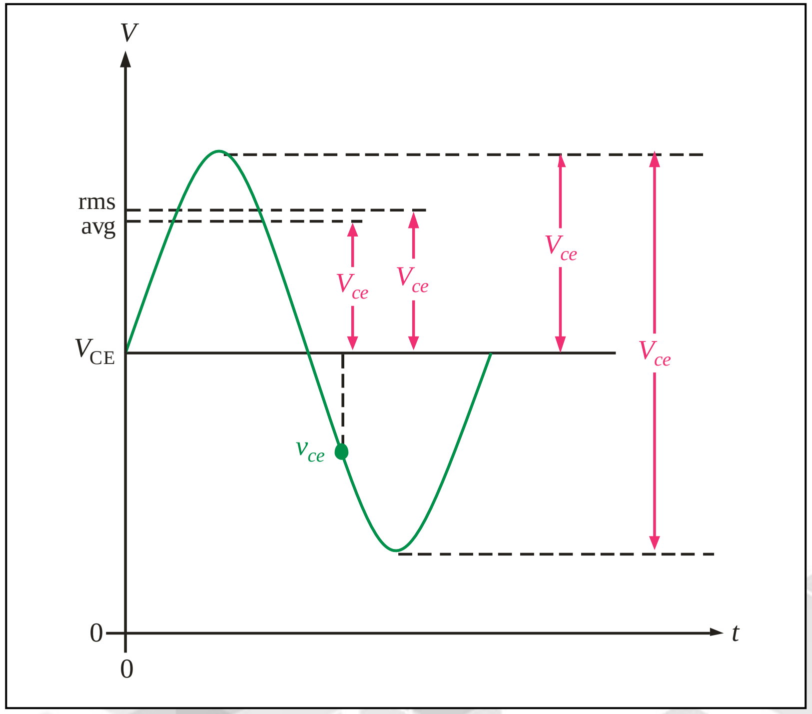


BJT Amplifiers

AC Quantities

AC quantities are indicated with a italic subscript; rms values are assumed unless otherwise stated.

The figure shows an example of a specific waveform for the collector-emitter voltage. Notice the DC component is V_{CE} and the ac component is V_{ce}.

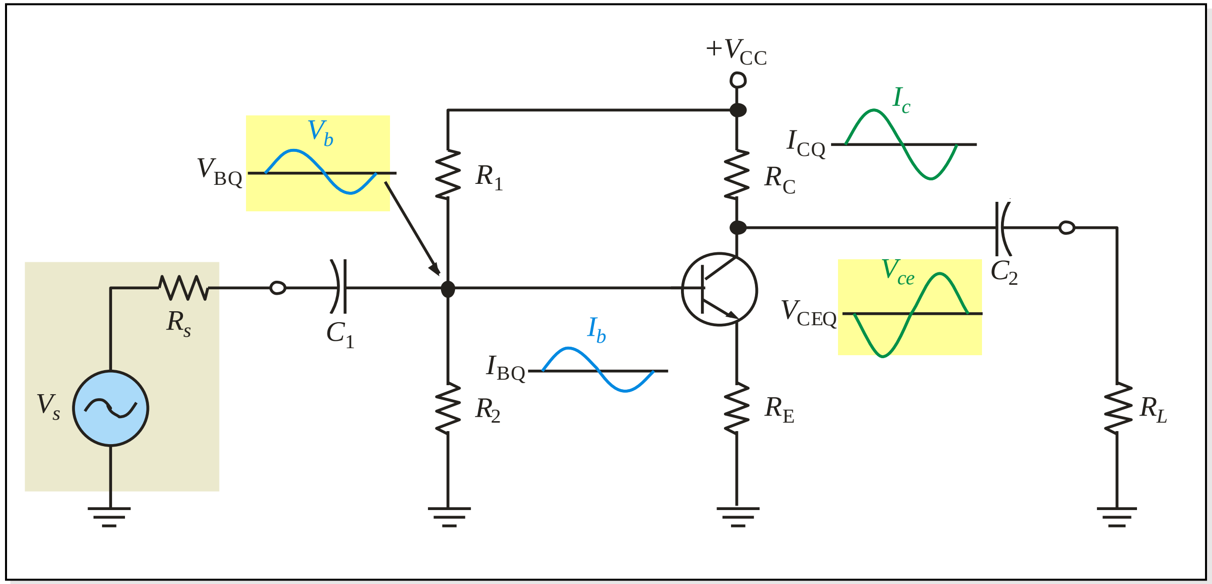


Resistance is also identified with a lower case subscript when analyzed from an ac standpoint.

Linear Amplifier

PHENIKAA UNIVERSITY

A linear amplifier produces an replica of the input signal at the output.

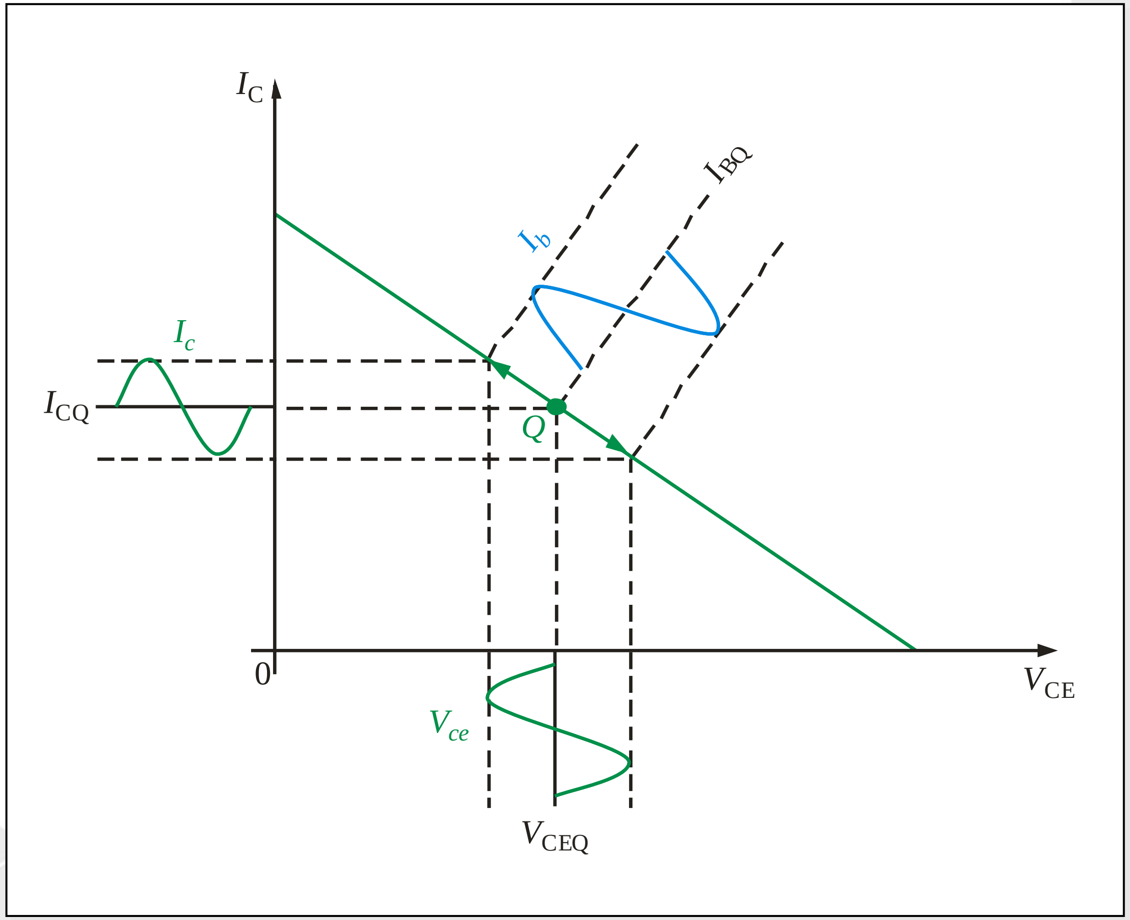


For the amplifier shown, notice that the voltage waveform is inverted between the input and output but has the same shape.

AC Load Line

Operation of the linear amplifier can be illustrated using an ac load line.

The ac load line is different than the dc load line because a capacitor looks open to dc but effectively acts as a short to ac. Thus the collector resistor appears to be in parallel with the load resistor.



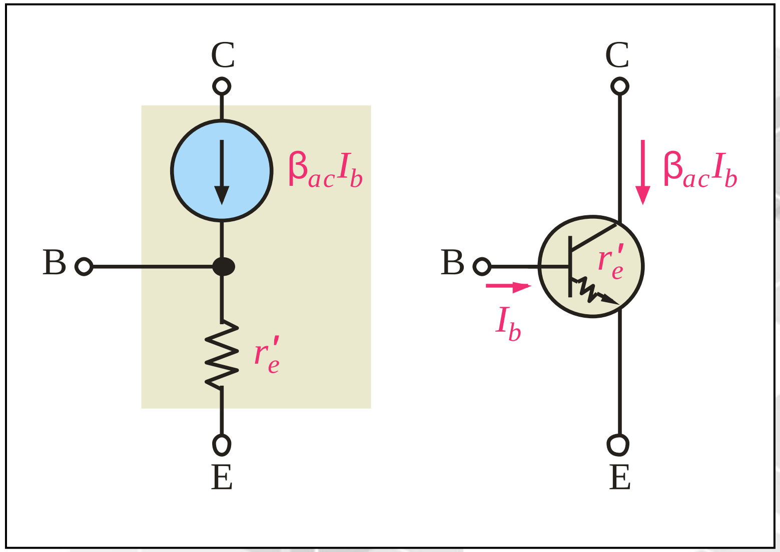
Transistor AC Model

The five resistance parameters (*r*-parameters) can be used for detailed analysis of a BJT circuit. For most analysis work, the simplified *r*-parameters give good results.

The simplified *r*-parameters are shown in relation to the transistor model.

An important *r*-parameter is r_e'. It appears as a small ac resistance between the base and emitter.

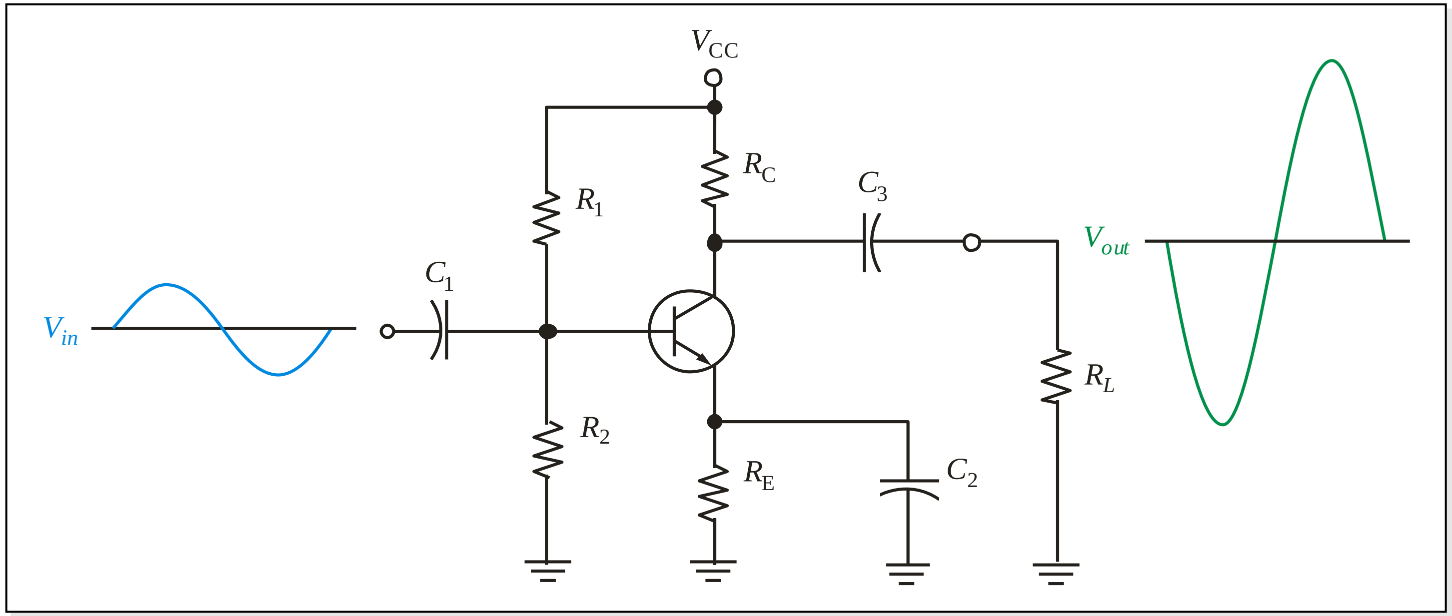
$$r_e' = \frac{25\text{ mV}}{I_E}$$



The Common-Emitter Amplifier

PHENIKAA UNIVERSITY

In the common-emitter (CE) amplifier, the input signal is applied to the base and the inverted output is taken from the collector. The emitter is *common* to ac signals.



The Common-Emitter Amplifier

Example:

What is r_e' for the CE amplifier? Assume stiff voltage-divider bias.

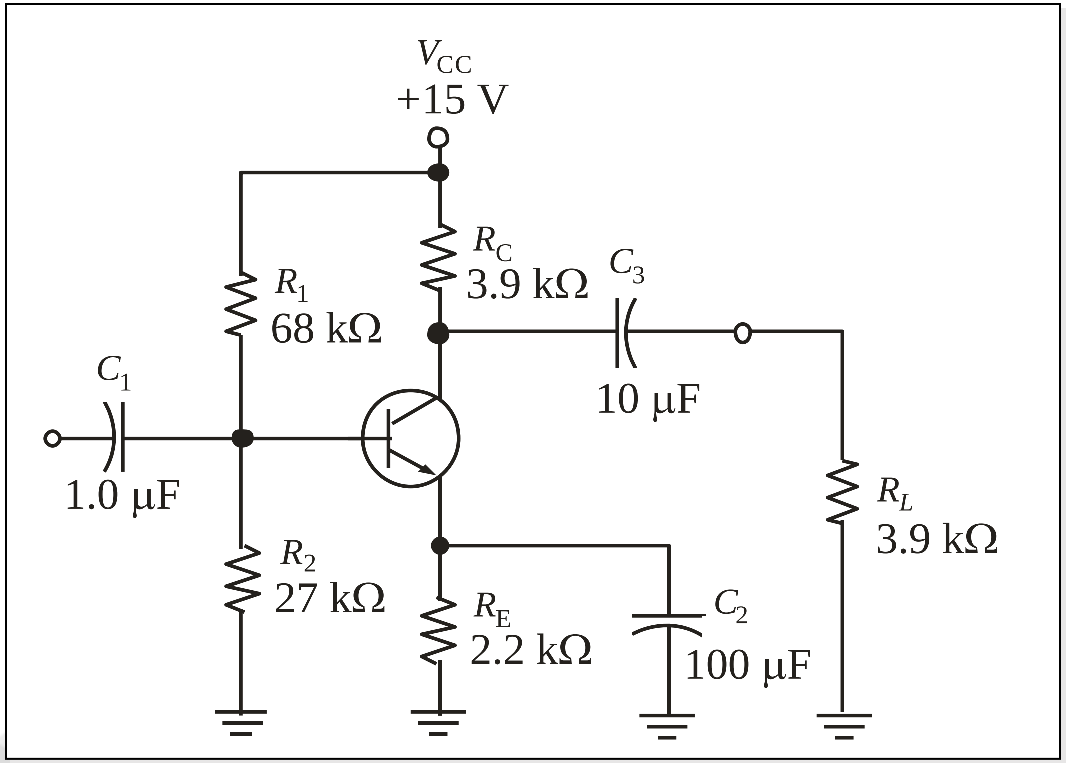
Solution:

$$V_B = \left(\frac{27\ \text{k}\Omega}{68\ \text{k}\Omega + 27\ \text{k}\Omega}\right)15\ \text{V} = 4.26\ \text{V}$$

$$V_E = 4.26\ \text{V} - 0.7\ \text{V} = 3.56\ \text{V}$$

$$I_E = \frac{V_E}{R_E} = \frac{3.56\ \text{V}}{2.2\ \text{k}\Omega} = 1.62\ \text{mA}$$

$$r_e' = \frac{25\ \text{mV}}{I_E} = \frac{25\ \text{mV}}{1.62\ \text{mA}} = 15.4\ \Omega$$



The Common-Emitter Amplifier

PHENIKAA UNIVERSITY

Follow-up:

Notice that the ac resistance of the collector circuit is $R_C \,||\, R_L$.

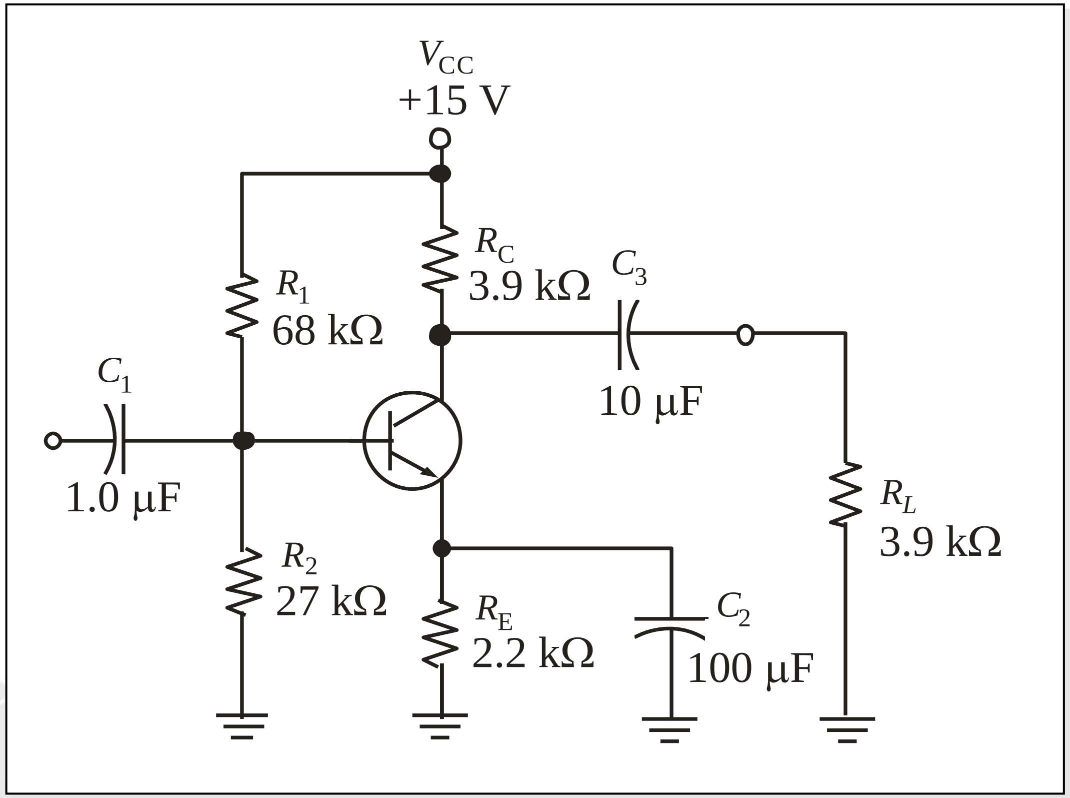
What is the gain of the amplifier?

Solution:

$$A_v = \frac{V_{out}}{V_{in}} = \frac{R_c}{r_e'} = \frac{R_C // R_L}{r_e'}$$

$$A_v = \frac{3.9\text{ k}\Omega // 3.9\text{ k}\Omega}{15.4\ \Omega} = 127$$

The gain will be a little lower if the input loading effect is accounted for.



The Common-Emitter Amplifier

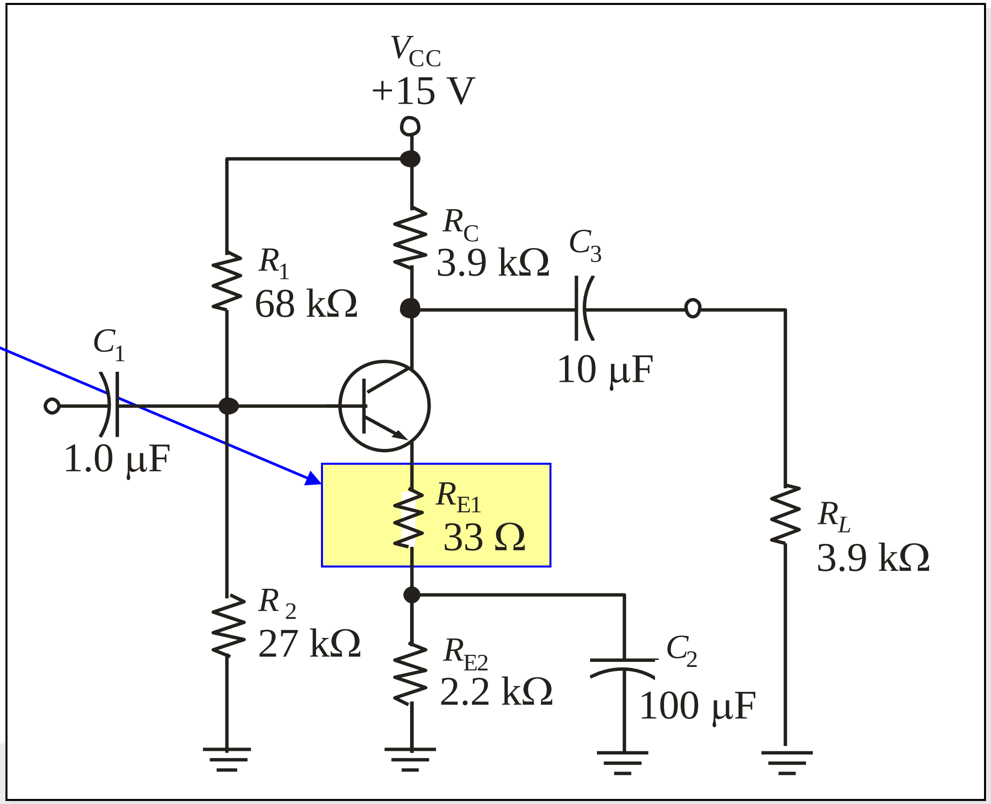
Greater gain stability can be achieved by adding a swamping resistor to the emitter circuit of the CE amplifier. The gain will be lower as a result.

Question:

What is the gain with the addition of the swamping resistor? (Ignore the small effect on $r_e{'}$.)

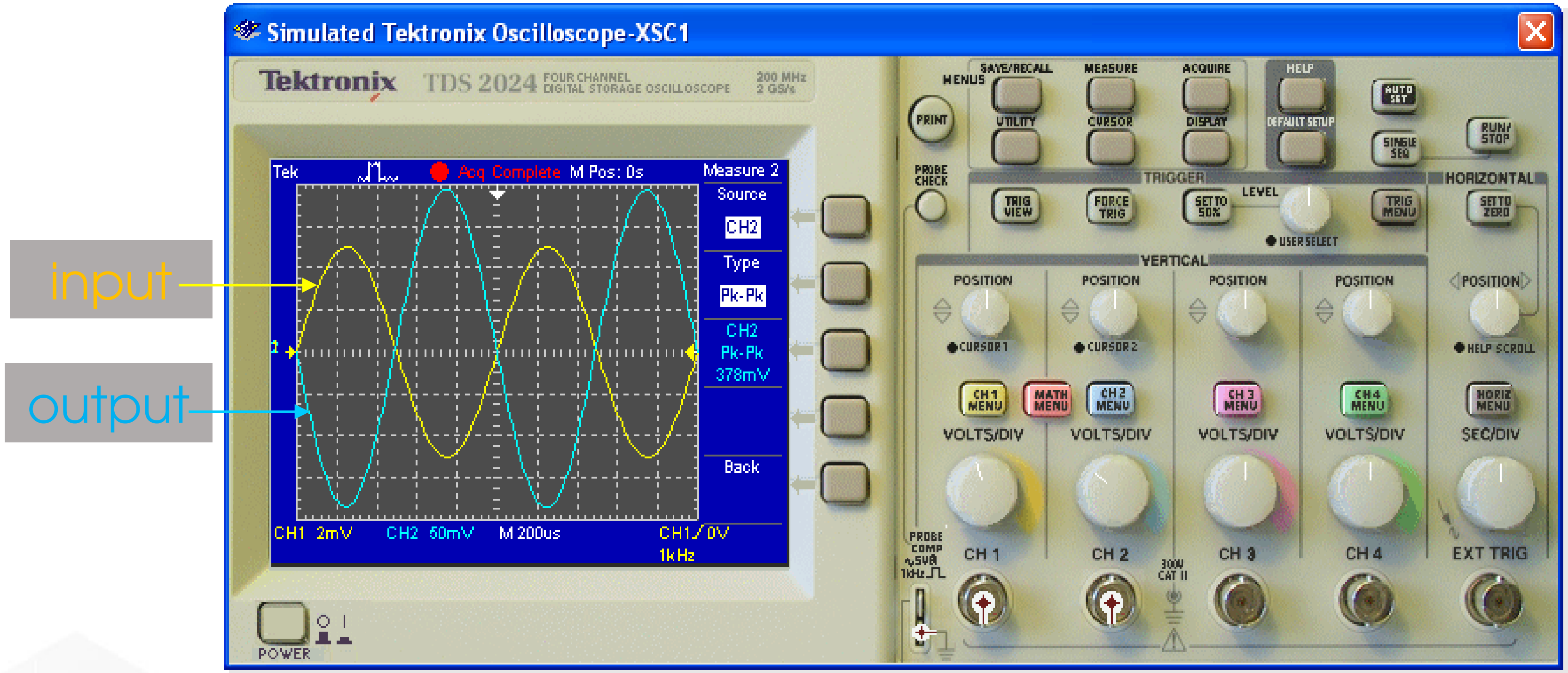
$$A_v = \frac{V_{out}}{V_{in}} = \frac{R_c}{r_e^{'} + R_{E1}} = \frac{R_C\,//\,R_L}{r_e^{'} + R_{E1}}$$

$$A_v = \frac{3.9\ \text{k}\Omega\,//\,3.9\ \text{k}\Omega}{15.4\ \Omega + 33\ \Omega} = 38.2$$



The Common-Emitter Amplifier

Multisim is a good way to check your calculation. For an input of 10 mV$_{pp}$, the output is 378 mV$_{pp}$ as shown on the oscilloscope display for the swamped CE amplifier.



The Common-Emitter Amplifier

PHENIKAA UNIVERSITY

In addition to gain stability, swamping has the advantage of increasing the ac input resistance of the amplifier. For this amplifier, $R_{in(tot)}$ is given by

$R_{in(tot)} = R_1 \,||\, R_2 \,||\, \beta_{ac}(r_e' + R_{E1})$

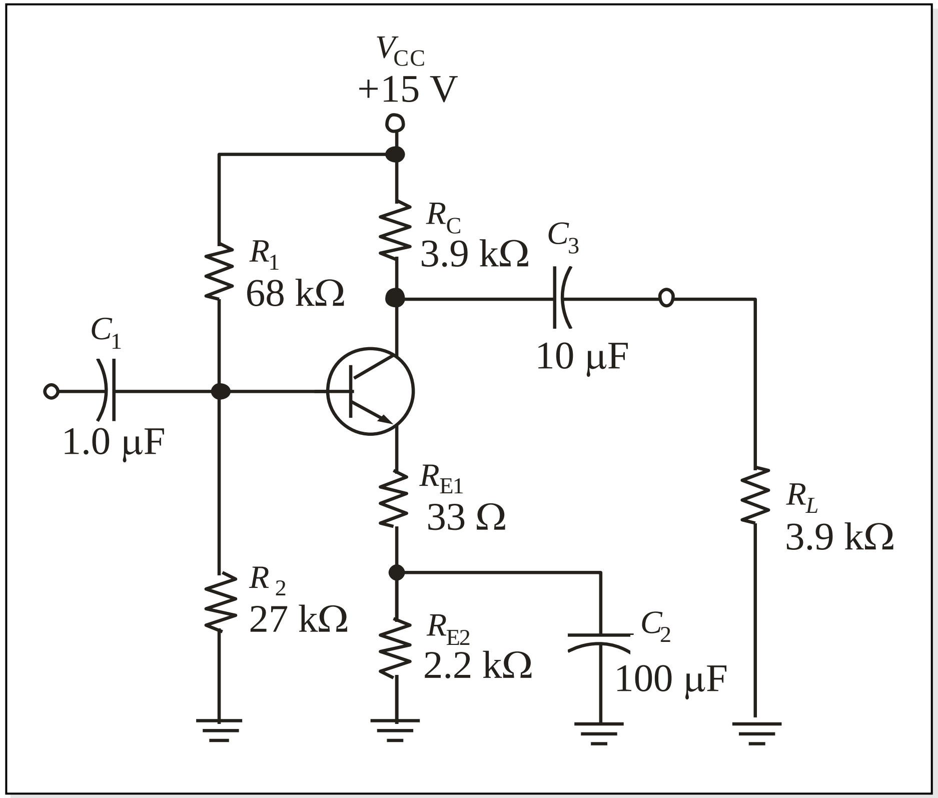
Question:

What is $R_{in(tot)}$ for the amplifier if $\beta_{ac} = 200$?

$R_{in(tot)} = R_1 \,||\, R_2 \,||\, \beta_{ac}(r_e' + R_{E1})$

$= 68\ \text{k}\Omega \,||\, 27\ \text{k}\Omega \,||\, 200(15.4\ \Omega + 33\ \Omega)$

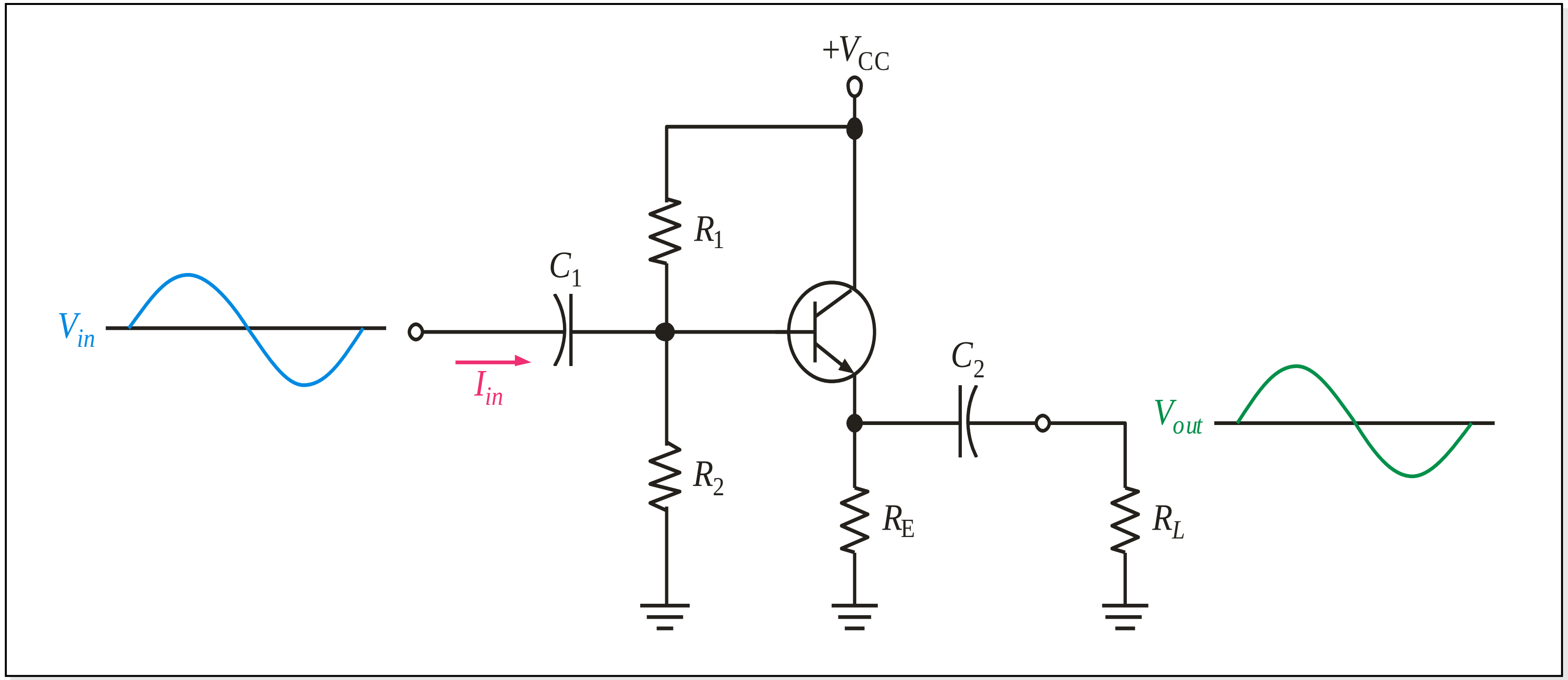
$= 6.45\ \text{k}\Omega$



The Common-Collector Amplifier

PHENIKAA UNIVERSITY

The common-collector amplifier (emitter-follower) has a voltage gain of approximately 1 but can have high input resistance and current gain. The input is applied to the base and taken from the emitter.



The Common-Collector Amplifier

PHENIKAA UNIVERSITY

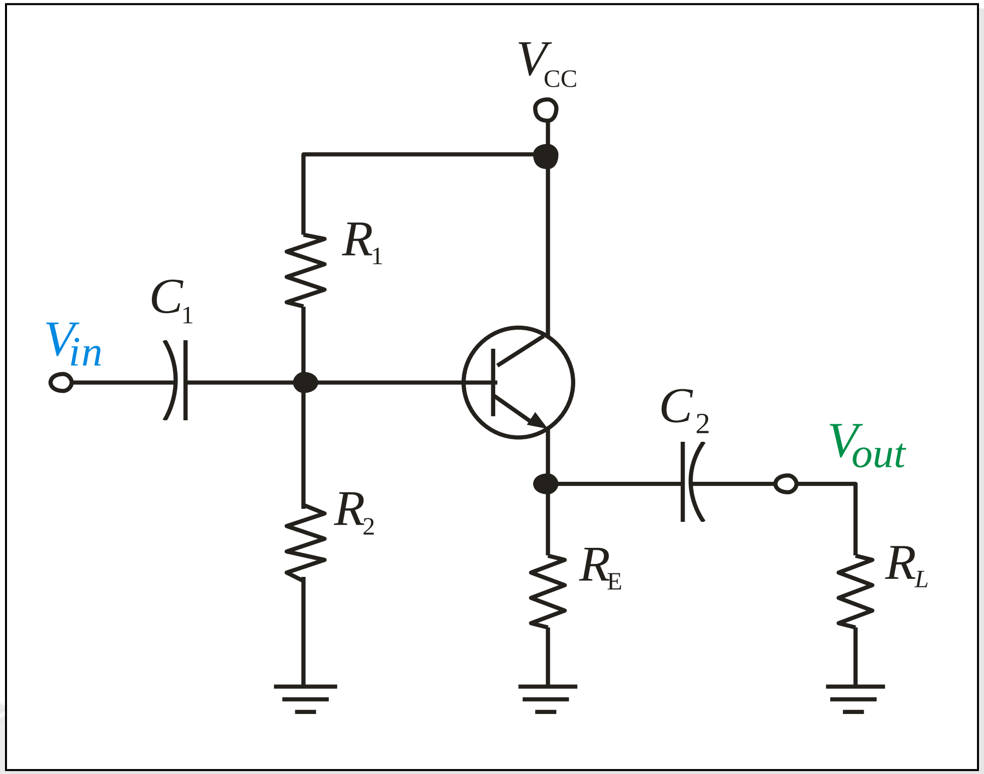
The **power gain** is the ratio of the power delivered to the input resistance divided by the power dissipated in the load. This is approximately equal to the current gain. That is, $A_p \approx A_i$.

You can also write power gain as a ratio of resistances:

$$A_p = \frac{P_L}{P_{in}} = \frac{V_L^2 / R_L}{V_{in}^2 / R_{in(tot)}} = A_v^2 \frac{R_{in(tot)}}{R_L}$$

$$\cong 1\left(\frac{R_{in(tot)}}{R_L}\right) = \frac{R_{in(tot)}}{R_L}$$

The next slide is an example…



The Common-Collector Amplifier

PHENIKAA UNIVERSITY

Example:

Calculate the power gain to the load for the CC amplifier using a ratio of resistances. Assume $A_v = 1$ and $\beta_{ac} = 200$. Use $r_e' = 2\ \Omega$.

Solution:

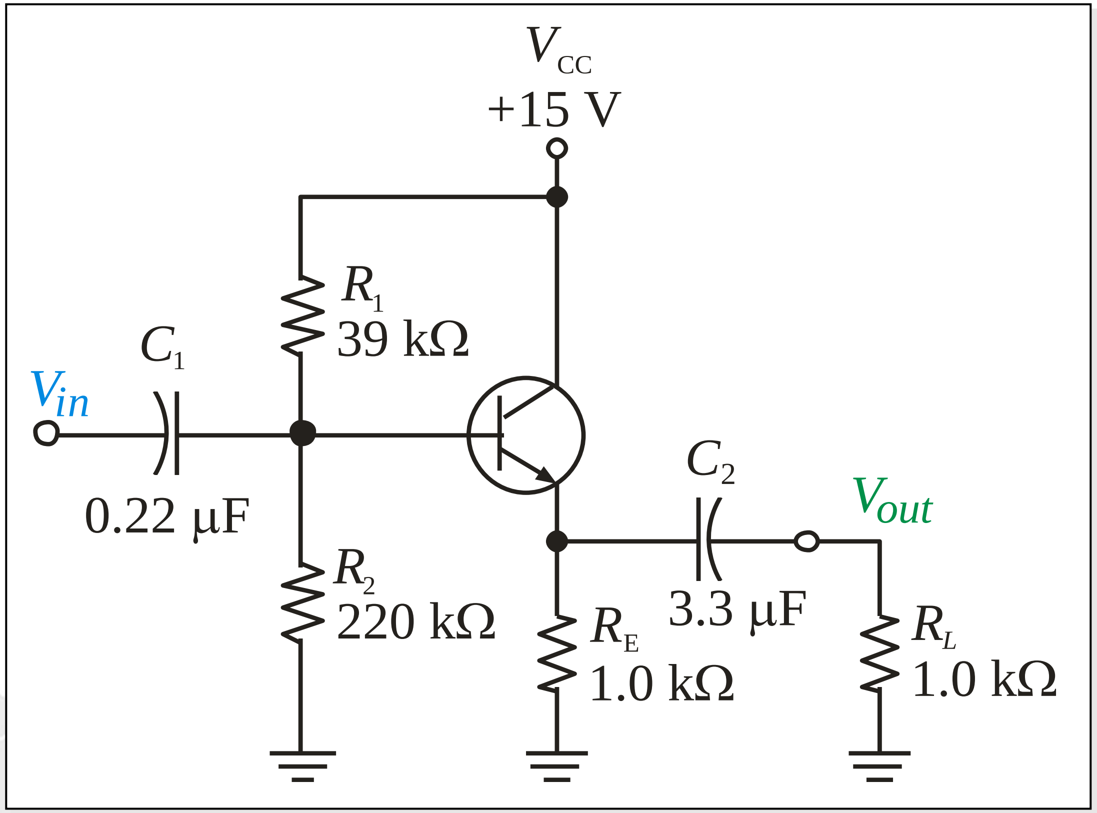
$R_{in(tot)} = R_1 || R_2 || \beta_{ac}(r_e' + R_E || R_L)$

$= 39\ \text{k}\Omega || 220\ \text{k}\Omega || 200(2\ \Omega + 500\ \Omega)$

$= 24.9\ \text{k}\Omega$

$R_L = 1.0\ \text{k}\Omega$

$$A_p = \frac{R_{in(tot)}}{R_L} = \frac{24.9\ \text{k}\Omega}{1.0\ \text{k}\Omega} = 24.9$$



The Common-Collector Amplifier

PHENIKAA UNIVERSITY

The input voltage-divider in the previous example is not "rock-solid" but the overall power gain is good. A "rock solid" stiff voltage-divider is not always the best design. Can you spot the problem illustrated here?

$$R_{in(tot)} = R_1 \| R_2 \| \beta_{ac}(r_e' + R_E \| R_L)$$

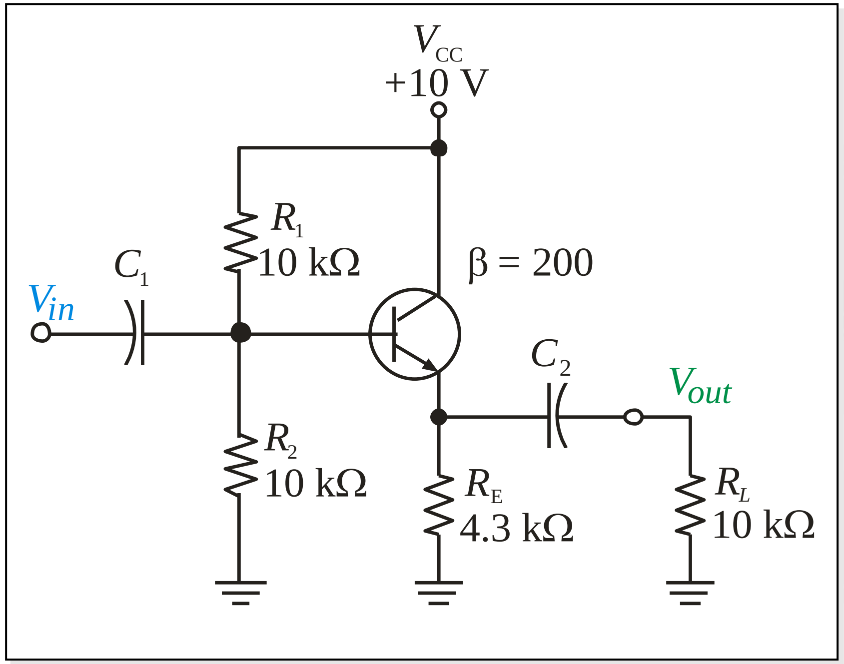
$$= 10\ \text{k}\Omega \| 10\ \text{k}\Omega \| 200(25\ \Omega + 3.0\ \text{k}\Omega)$$

$$= 4.96\ \text{k}\Omega$$

$$R_L = 10\ \text{k}\Omega$$

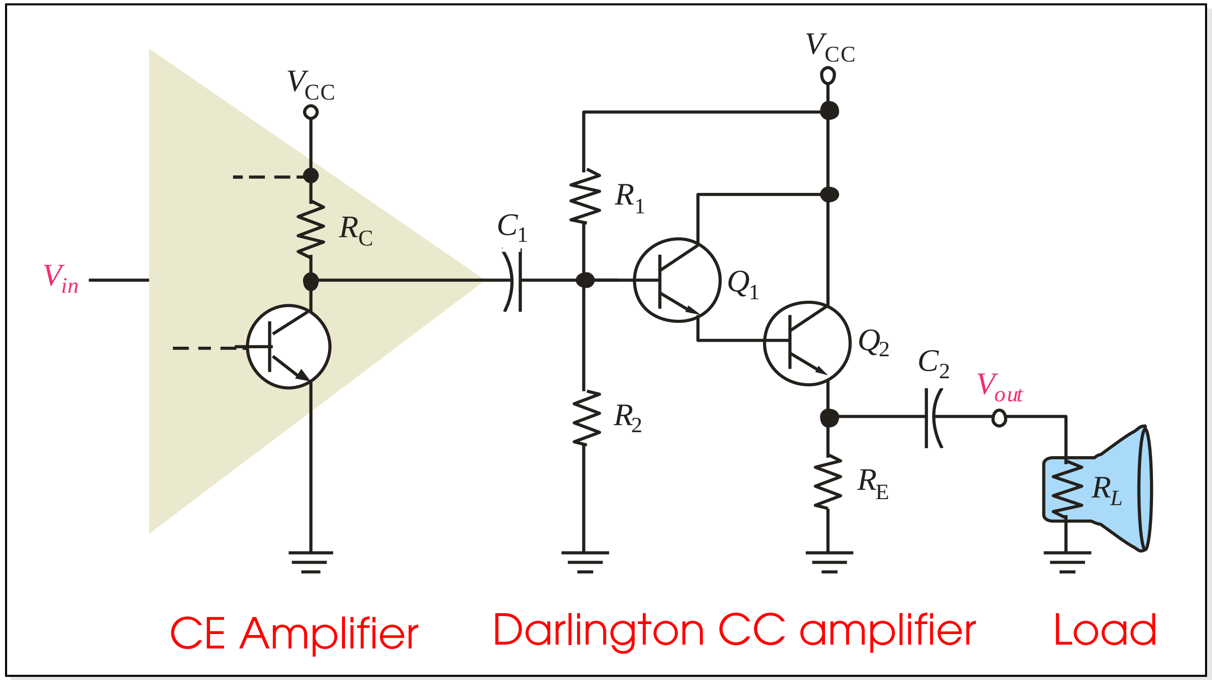
$$A_p = \frac{R_{in(tot)}}{R_L} = \frac{4.96\ \text{k}\Omega}{10\ \text{k}\Omega} = 0.496!$$

The problem is the power gain is less than 1!



The Darlington Pair

A Darlington pair is two transistors connected as shown. The two transistors act as one "super β" transistor. Darlington transistors are available in a single package. Notice there are two diode drops from base to emitter.



The Sziklai Pair

Another high β pair is the Sziklai pair (sometimes called a complementary Darlington), in which a *pnp* and *npn* transistor are connected as shown. This configuration has the advantage of only one diode drop between base and emitter.

Question:

What is the relation between I_{E2} and I_{B1}?

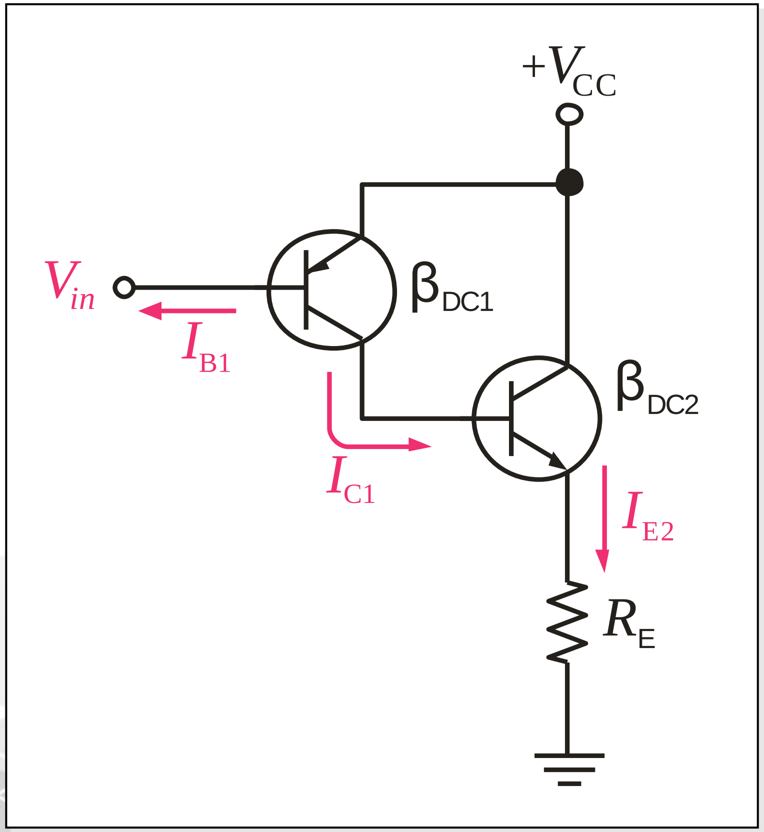
Answer:

The DC currents are:

I_{C1} is $\beta_{DC1} \times I_{B1}$ and is equal to I_{B2}

I_{E2} is approximately equal to $\beta_{DC2} \times I_{C1}$

Therefore, $I_{E2} \approx \beta_{DC1}\beta_{DC2}I_{B1}$



The CB Amplifier

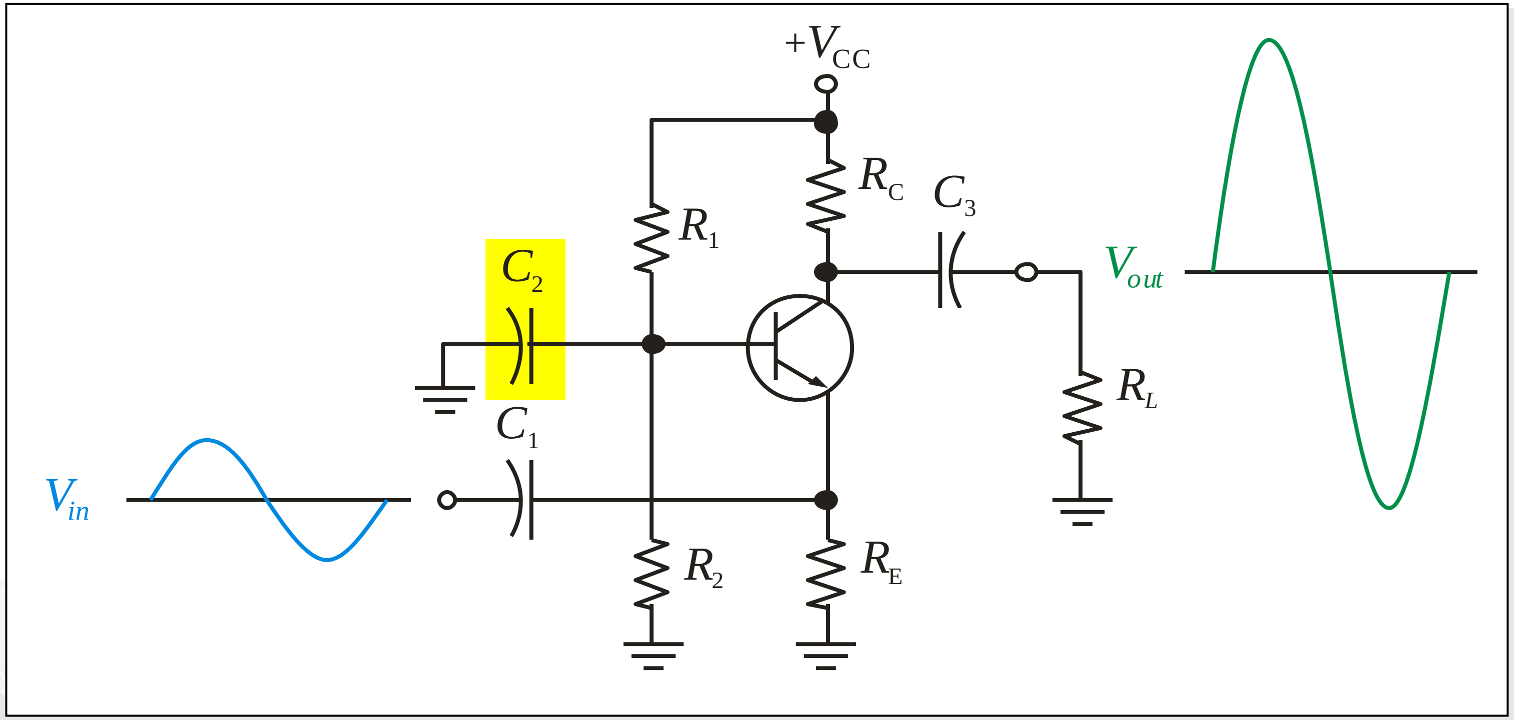
PHENIKAA UNIVERSITY

The common-base (CB) amplifier is used in applications where a low input impedance is acceptable. It does not invert the signal, an advantage for higher frequencies as you will see later when you study the Miller effect.

Question: What is the purpose of C_2?

Answer:

C_2 forces the base to be at ac ground.

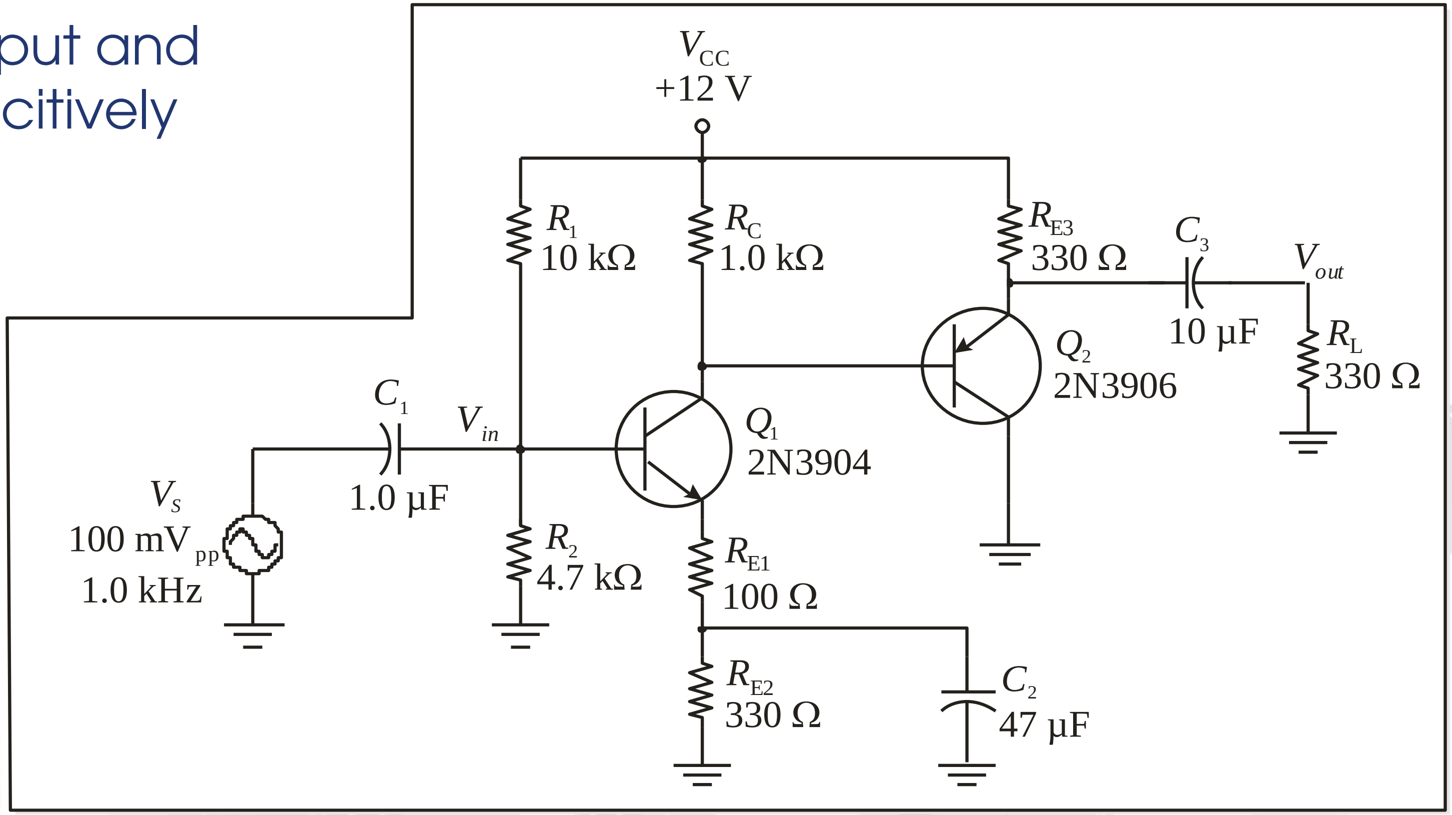


Multistage Amplifiers

PHENIKAA UNIVERSITY

To improve amplifier performance, stages are often cascaded where the output of one drives another. This an example of a two-stage direct-coupled

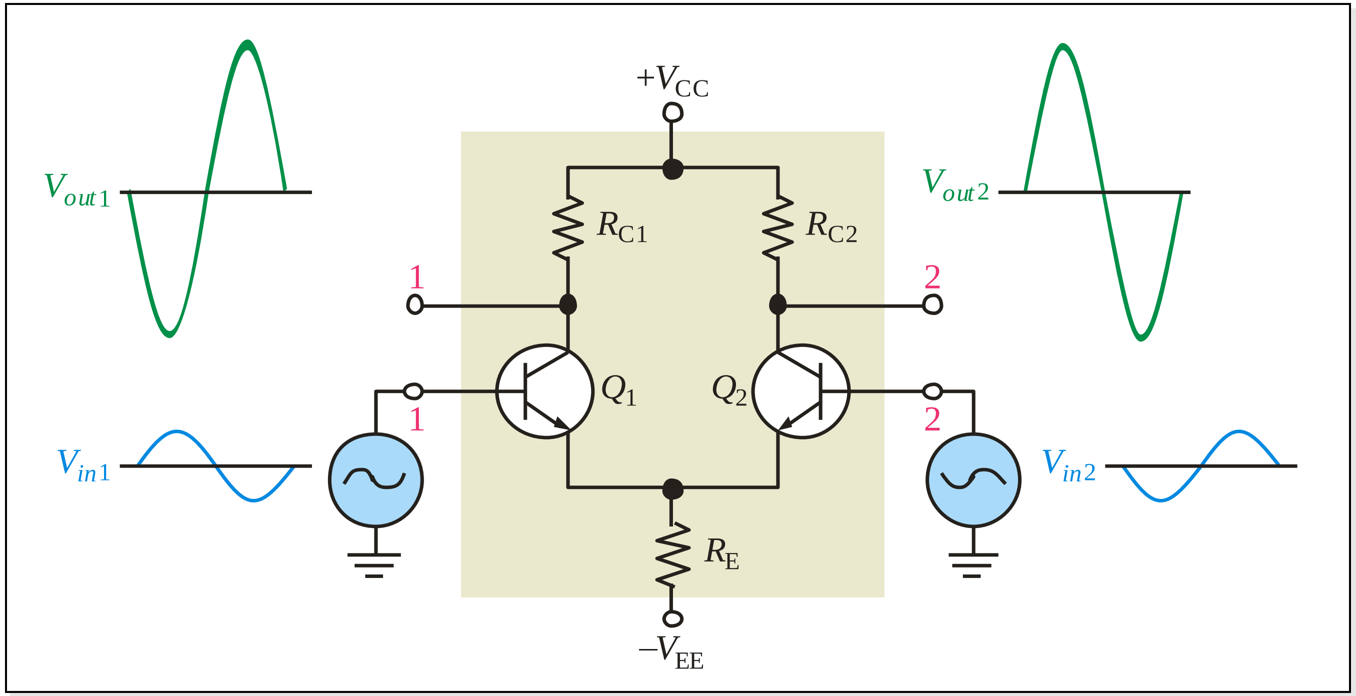
amplifier in which the input and output signals are capacitively coupled.



Differential Amplifiers

PHENIKAA UNIVERSITY

A differential amplifier (diff-amp) has two inputs. It amplifies the difference in the two input voltages. This circuit is widely used as the input stage to operational amplifiers. **Differential-mode inputs** are illustrated.



Differential Amplifiers

The same amplifier as in the last slide now is shown with **common-mode inputs**. Diff-amps tend to reject common-mode signals, which are usually due to noise. Ideally, the outputs are zero with common-mode inputs.