15. Transistor Amplifier Design and Measurement

Introduction

The previous module was devoted to measuring the characteristics of a transistor. In particular, you measured the amplification parameter $\beta = I_c / I_b$ (β is also known as h_{fe} on your digital multimeter.) I_c is the current out of the collector of the transistor and I_b is the current out of the transistor base for PNP transistors. The value of β will vary from transistor to transistor. The base current is said to control the collector current and this equation $I_c = \beta I_b$ is called the "transistor action" equation. You also measured the voltage between the collector and emitter V_{ce} and graphed I_c as a function V_{ce}. This graph is called the "load line". The graphs of the above voltages and currents characterize a particular transistor (e.g. 2N2222) and are called the "transistor characteristics".

This module is devoted to the design of a transistor amplifier and this involves choosing the values of five resistors and three capacitors. Also, you will measure and calculate the amplifier voltage gain g=V_{out} / V_{in} where V_{in} is the input AC voltage and V_{out} is the output AC voltage.

Three Basic Rules of Amplifier Design

There are three basic rules that we will use to design the transistor amplifier. You already know these rules from your work in the previous module.

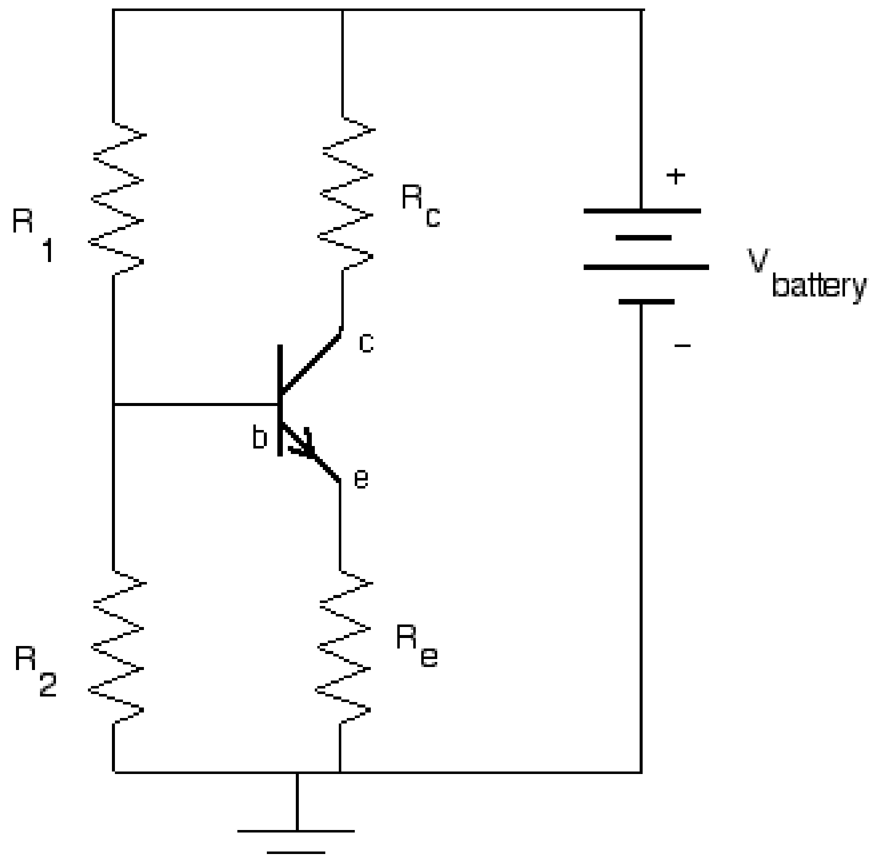
1. The base-emitter voltage is always about 0.6-0.7 volts for silicon transistors. REASON: This is because the base-emitter junction behaves like a diode and a diode has a constant voltage drop when biased in the forward direction.
2. The current amplification of the transistor β is large (typically 100-300). REASON: Small changes in the base current I_b produce large changes in the collector current I_c and this is the basic idea behind transistor operation.
3. The collector current and the emitter current almost the same size $I_c = I_e$. REASON: $I_e = I_b + I_c$ due to conservation of charge and since the collector current I_c>> I_b as a consequence of Rule 2 it follows that $I_c = I_e$.

There is no one amplifier design and a lot of designs will work OK. What will be given below is

a sort of "transistor amplifier cookbook" design. This cookbook design will work well under most situations just like a recipe usually works when you cook.

The Basic Common Emitter Transistor Amplifier

The basic transistor amplifier circuit is indicated below:



It is called a "common emitter" amplifier since the emitter is common to both the input circuti and the output circuit. There are additionally three capacitors but they do not play a role in the basic transistor amplifier design which mainly involves setting DC voltages. R_c is called the collector resistor and R_e the emitter resistor. (R_e is actually two resistors in series one of which will be call R_g and is called the "gain" resistor since it controls the voltage gain or amplification;' however, we disregard the second resistor for now. By the way, R_g will be important as it sets the overall gain of the amplifier.) $R_1$and R_2 are called the bias resistors and they help set the base current I_b (by making sure that the base-emitter voltage is at least $V_{\text{be}} = 0.6$ V for silicon transistors). The emitter resistor has the purpose of controlling "thermal runaway" which can burn up a transistor but more on thsi in a moment.

The Battery Voltage

The battery voltage is chosen such that it must be less than the maximum voltage the transistor can handle between the collector and emitter (so the transistor does not burn out). We will use $V_{\text{battery}} = 12\ V$ since this is readily available in the lab and the 2N2222 is ok with this voltage. (If you look at the data sheet at the end of this module you see the absolute maximum $V_{\text{ce0}} = 40\ V$ for the 2N2222 which is the collector-emitter voltage at the operating point) As a rule of thumb, the battery voltage is chosen less than half the maximum V_{ce0} since this allows for an addition AC voltage due to amplfication.

Choosing R_c and R_e.

The first thing we need to do is choose an "operating point" for the amplifier. The "operating point" is the DC values of I_c, I_b, and V_{ce} which are the quiescent or steady state values. When an AC input voltage is applied to the amplifier, there are deviations from these values which are denoted by lower case letters i_c, i_b, and v_{ce}.

Choosing an Operating Point

COOKBOOK RULES:

(1) **Choose an I_c such that the transistor actually does amplify.** (β is say 100 and NOT unity as happens if I_c and V_{ce} is too small or alternatively if I_c and I_b are too large.). This seems sort of obvious but it is sometimes overlooked. There are a lot of choices here as you observed in the previous module.

(2) **Given the value of I_c at the operating point, it is easy enough to determine the base current I_b at the operating point using $I_b = I_c / \beta$.**

(3) **Choose the operating point collector-emitter voltage as somewhere in the range $\frac{V_{\text{battery}}}{3} < V_{\text{ce}} < \frac{V_{\text{battery}}}{2}$.** A V_{ce} somewhere in this range will allow for amplification of a maximum input voltage without distortion. For definiteness, we will choose $V_{\text{ce}} = \frac{V_{\text{battery}}}{3}$ in our example below.

EXAMPLE: The 2N2222 transistor might have $I_c = 4$ mA at the operating point since as you saw in the previous module this leads to a β of say 150 which means the transistor is actually working. If β=200 and

$I_c =$ 4 ma then I_b is just

$$I_b = 4. * 10^{-3} / 200.$$

0.00002

or I_b= 0.02 mA = 20 μA which might be just large enough for you to measure. The collector-emitter voltage at the operating point is then $V_{ce} = \frac{V_{battery}}{3} = \frac{12}{3} = 4\ V$.

Choosing the Collector and Emitter Resistors

The purpose of the collector resistor R_c is to set the collector current I_c as well as the emitter-collector voltage V_{ce}. In other words, R_c helps to set the transistor at the "operating point" of the amplifier.

The purpose of the emitter resistor R_e is to prevent "thermal runaway". If the emitter resistor is not present, the collector current might increase as the transistor heats up. As a result of $I_b = I_c / \beta$ there is then an increased base current which further heats up the transistor etc until the transistor burns up. At the very least, this effect is a cause of amplifier instability.

COOKBOOK RULE #4: **We choose the voltage across R_e equal the voltage across R_c. It follows that $R_e = R_c$ if we follow this rule**. (Recall Rule #3 says that the collector current is almost the same size as the emitter current that is $I_c = I_e$.) Kirchoff's loop rule says the voltage across R_e , plus the voltage across R_c , plus V_{ce} equal the battery voltage $V_{battery}$. So we may write

$$I_c\ (R_e + R_c) + V_{ce} = V_{battery} \quad \text{or} \quad R_c = \left(V_{battery} - V_{ce}\right) / (2\ I_c) \qquad (1)$$

This is enough to determine the emitter and collector resistors since $R_e = R_c$, and I_c , V_{ce}, and $V_{battery}$ have already been determined so

Example: Using $V_{battery} = 12\ V$, $V_{ce} = 4\ V$, $I_c = 4$ mA and $R_e = R_c$ together with equation (1) yields

$$R_c = \frac{12 - 4}{2 * 0.004}$$

1000.

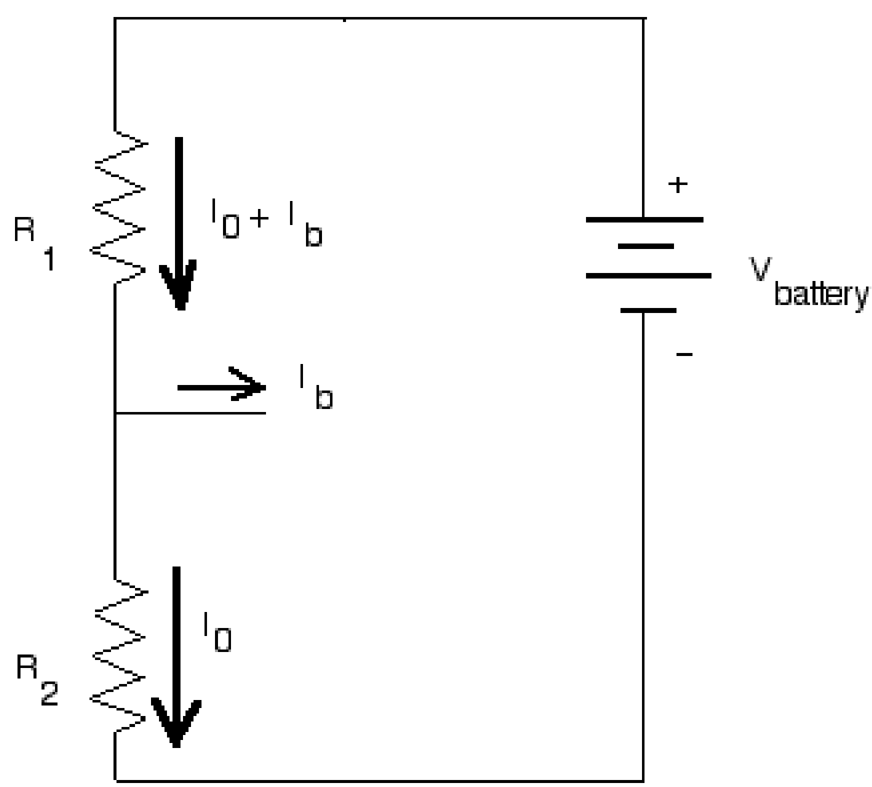
so $R_e = R_c = 1$ kΩ. You might not be able to find this value resistor in the lab and if so, you should just use a resistor that is as close as possible. The voltage across the emitter resistor plus the voltage across the collector resistor is $(V_{battery} - V_{ce})$ and since $R_e = R_c$ it follows that the voltage across each resistor is just $(V_{battery} - V_{ce})/2$. For the example, this is (12 V- 4 V)/2=4V.

However, the way the battery voltage divided up is somewhat arbitrary. It would just as well to take $V_{ce}=V_{battery}/2$ with the remainder divided equally across R_e and R_c. You might try this and see what changes it makes in the amplifier operation.

The Choice of the Bias Resistors R_1 and R_2.

The bias resistors R_1 and R_2 essentially work as a voltage divider for the battery voltage $V_{battery.}$ The values of R_1 and R_2 are chosen **so that the base-emitter junction is biased in the forward direction at least 0.6 volts since otherwise the transistor will not work.**

The cookbook design (below) makes sure that the bias resistors are large compared with R_e and R_c so that the voltage divider works the same way regardless of the size of I_c (and I_b). When the bias resistors are large we can essentially disregard the rest of the circuit in the process of determining R_1 and R_2 so a simplified circuit is shown below:



A current I_0 goes through resistors R_1 and R_2 and a current I_b just goes through R_1 and enters the base from the connection with R_1 and R_2. Conservation of current allows us to conclude the current in R_1 is the sum of these currents that is $(I_0 + I_b)$. Previously we determined the base current I_b using $I_b = I_c / \beta$. For example, if β=200 and $I_c =$ 4 ma then I_b is just 0.02 ma.

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4. * 10^-3 / 200
```

```
0.00002
```

The voltage between the transistor base and the ground is V_{be}=0.6 volts plus the voltage across the emitter resistor. From the diagram above, it should be clear this is also the voltage across the resistor R_2 so

$$V_{be} + V_e = I_0 R_2 \quad \text{or} \quad I_0 R_2 = \mathbf{4.4}\ \boldsymbol{V} \tag{2}$$

since for our example, $V_{be} = 0.6\ V$ and $V_e = 4.0\ V$ so equation (2) becomes 4.4 V=$I_0\, R_2$ but I_0 and R_2 are not known. The voltage across both resistors is just the battery voltage

$$(I_0 + I_b)\ R_1 + I_0 R_2 = V_{battery} \tag{3}$$

For our example, $\boldsymbol{I_0\, R_2}$**=4.4 V**, $I_b =$ 0.02 mA, and $V_{battery} =$ 12 V so plugging into equation (3) we get

$$(I_0 + I_b)\ R_1 + 4.4\ V = 12\ V \tag{4}$$

and thus

$$(I_0 + I_b)\ R_1 = 7.6\ V \tag{5}$$

Remember we know $I_b =$ 0.02 mA so if we know I_0 we could calculated R_1 so we still have too many unknowns.

COOKBOOK RULE: It is a good idea to choose I_0 >> I_b since in this case changes in I_b (due to for example, an input AC voltage) will not change the bias voltage. **Our cookbook rule is**

$$\mathbf{I_0 = 25\ I_b} \tag{6}$$

although many other choices will also work. (Later you should try say $I_0 = 50\, I_b$ and see if your amplifier still works. Also try $I_0 = I_b$ and see what happens.) Since I_b = 0.02 mA in our example, equation (4) means that I_0 is

```
I0 = 25 * 0.02
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```
0.5
```

or I_0= 0.5 mA Equation (5) now yields R_1 (neglecting $I_b << I_0$)

$$\mathbf{R_1} = \frac{7.6}{0.5 * 10^{-3}}$$

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15200.
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so $R_1 =$ 15 kΩ . Equation (3) now yields R_2

```
R2 = 4.4 / 0.5
```

8.8

so $R_2 = 8.8\,\text{k}\Omega$.

R_1 is roughly 9 times R_c and this is important since R_1+R_2 must be large enough to keep the bias current small.

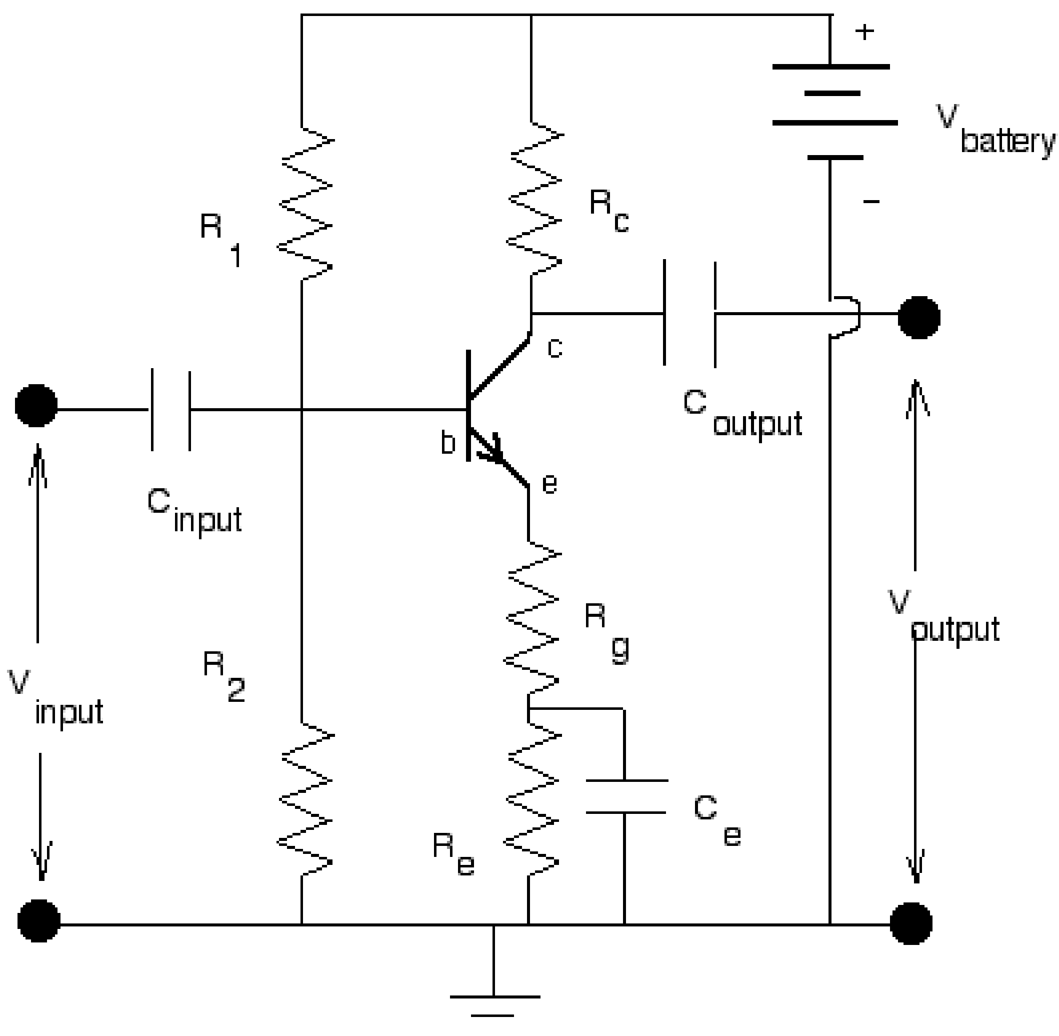
Lab Exercises: Amplifier at Operating Point

Build the common emitter amplifier circuit using a 2N2222 transistor and $R_C = 1,000\,\Omega$, $R_e = 1,000\,\Omega$, $R_1 = 15,000\,\Omega$, and $R_2 = 9,000\,\Omega$. You will not be able to find those exact resistor values but get one as close as possible. Uses 12 Volts for the battery voltage. You should get something like $I_C = 4$ mA and $I_b = 0.02$ mA. Check to make sure your amplfier is actually working by measuring the base current and collector current. The base current is small but it should be barely measureable with you meter. Recall that the transistor equation say I_C=β I_b where β=150 in the case of the 2N2222. If I_b=0 then I_C=0 and your amplifier is not working. So indirectly if I_C is NOT zero you could infer I_b is not zero but the object of this lab is to verify this relation not assume it is true.

Try making an amplifer were the voltage across the collector resistor is 3 volts, the voltage across the emitter resistor is 3 volts and the collector-emitter voltage of the transistor is 6 volts with the battery 12 volts. Choose all four resistors so the amplifier is at the operating point. Measure I_b and I_C and make sure they are not zero.

The Complete Common Emitter Transistor Amplifier

The complete common emitter transistor amplifier circuit is indicated below:



There is now an additional resistor R_g between the emitter resistor and the transistor. Also there are three capacitors.

The Choice of R_g

The input voltage is entirely AC since the input capacitor C_{input} blocks any DC voltage from getting to the transistor. (Later we will explain how to choose C_{input}.) Also, the emitter capacitor C_e will be chosen so that it effectively short circuits AC voltages around R_e. (Later we will explain how to pick C_e.) The voltage between the emitter and base is fixed at 0.6 volts DC and there is no AC voltage between the emitter and base. The entire AC input voltage appears across R_g so that in terms of the AC emitter current i_e we have from Ohm's law

$$i_e = \frac{v_{input}}{R_g} \tag{7}$$

The output capacitor serves to block the DC from the output voltage so the output voltage is entirely AC. The output AC voltage v_{output} is given by

$$v_{output} = i_c R_c = i_e R_c \tag{8}$$

since to a good approximation $i_e = i_c$. The battery acts as a short or just a wire for AC so the top of the collector resistor is at the ground potential as far as AC is concerned. Utilization of equation (7) in equation (8) yields

$$v_{output} = \frac{R_c}{R_g} v_{input} \tag{9}$$

from which the AC gain g is

$$g = \frac{v_{output}}{v_{input}} = \frac{R_c}{R_g} \tag{10}$$

Now R_c has already been determined ($R_C = 1\ \text{k}\Omega$ in the example.) The amplifier gain g must be less than β the current gain of the transistor. Suppose we want the amplifier gain g=25 then equation (10) determines R_g=R_c/g. (In this example, $R_g = 1\ \text{k}\Omega/25\ =\ 40\ \Omega$.) Again you will probably NOT find a resistor with this exact value in the lab so use one as close as possible. Notice the value of R_g is small and this is typical.

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1000. / 25
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40.
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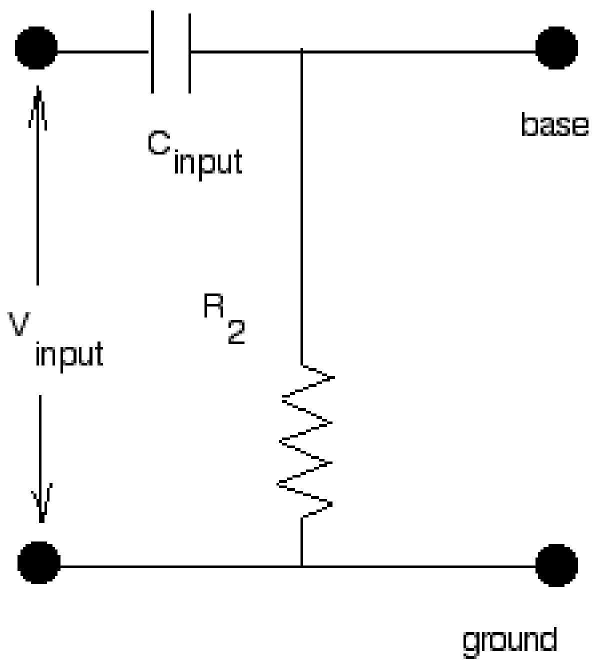
The Values of the Capacitors

Choosing the input capacitor

The relevant part of the amplifier as far a choosing C_{input} is concerned is



The value of R_2 has already been determined. (For example, $R_2 = 15\ \text{k}\Omega$.) The above circuit passes the larger frequencies of the input voltage on to the base and ground (that is the voltage across R_2). The resistor and capacitor act as a voltage divider of the input voltage. The voltage across the resistor V_R is

$$V_R = \frac{R}{\sqrt{R^2 + \frac{1}{\omega^2 C^2}}} V_{input} \tag{11}$$

where $\omega = 2\pi f$ and f is the frequency of the signal generator that provides the input voltage. The resistor $R = R_2$ and the capacitor $C = C_{input}$. If the amplifier is for audio frequencies, then the lowest f=20 Hz. Choose C so that $V_R = \frac{V_{input}}{2}$ at the lowest audio frequency so that at the lowest audio frequency, half the input voltage appears across the resistor. So we can write equation (11) in the form

$$\frac{1}{2} = \frac{V_R}{V_{input}} = \frac{R}{\sqrt{R^2 + \frac{1}{\omega^2 C^2}}} \tag{12}$$

where both R and ω have known numerical values (e.g. $\omega = 2\pi \times 20$ and $R = 15{,}000\ \Omega$.) It should be clear from equation (12) that increasing ω increases the voltage across the resistor.

We can solve for C with *Mathematica* obtaining

```
R = 15000.;
ω = 2 * π * 20.;
```

$$\text{NSolve}\left[0.5 == R \Big/ \sqrt{R^2 + \frac{1}{\omega^2 * C0^2}}, \{C0\}\right]$$

$$\{\{C0 \to -3.06294 \times 10^{-7}\}, \{C0 \to 3.06294 \times 10^{-7}\}\}$$

You can solve equation (12) easily yourself. The physical (positive) solution is about C=0.3 μF for the input capacitor. The output capacitor is determined by similar reasoning since AC (but not DC) is passed along to the output which may be a speaker or another stage of amplification. Choose C_{input} in the lab as close to the above value as possible.

Choosing the output capacitor

The output capacitor can be chosen using a similar argument to finding the input capacitor value. However, in this case, the role of the output capacitor is to make sure the DC voltage is not passed along to a second amplifier stage thus disturging the bias voltage of that stage. Also, the output voltage is developed across the output capacitor and the output voltage can be taken as half the total AC voltage across C_{output} and R_C. Choosing C_{output}=0.3 μF should work

Choosing the emitter capacitor

We want the emitter capacitor to be a short circuit for AC around the emitter resistor. The time constant of the resistor and capacitor is τ=RC where τ=1/f and f=20 Hz is the lowest AC frequency. R=R_e is already known (for example, $R_e = 1,000\ \Omega$.) so we can compute the value of C=C_e. Specifically

```
f = 20.;
τ = 1 / f;
RE = 1000.;
CE = τ / RE
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```
0.00005
```

so $C_e = 5\ \mu$F.

So the emitter capacitor should be roughly 5 μF.

An Experiment: Amplfication of an AC signal

Build a common emitter amplifier according to the cookbook design. Choose R_g so the g is approximately 25. After you pick R_x calculate the gain g you expect.

Attach a signal generator with a Sine wave output at about 500 Hz to the terminals marked V_{input} in the diagram above. Also, attach the probe of channel A of your oscilloscope to the input terminal so you can measure the input voltage. Attach the probe of channel B of your oscilloscope to the output terminal and measure the output voltage. What is the measured gain g of your amplifier? Does it agree with your calculated gain?

Double the value of your R_g . Calculate the new gain? Did the gain increase or decrease? Measure the new gain of your amplifier.

APPENDIX: Some 2N2222A Characteristics from various websites:

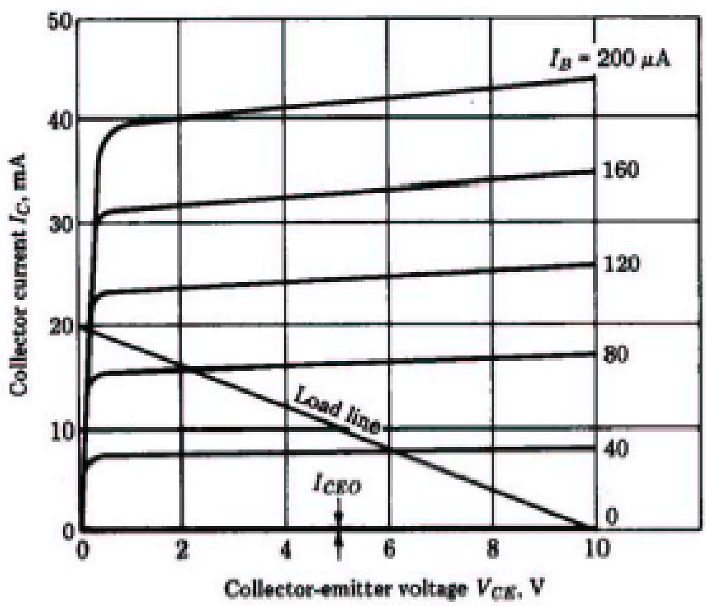
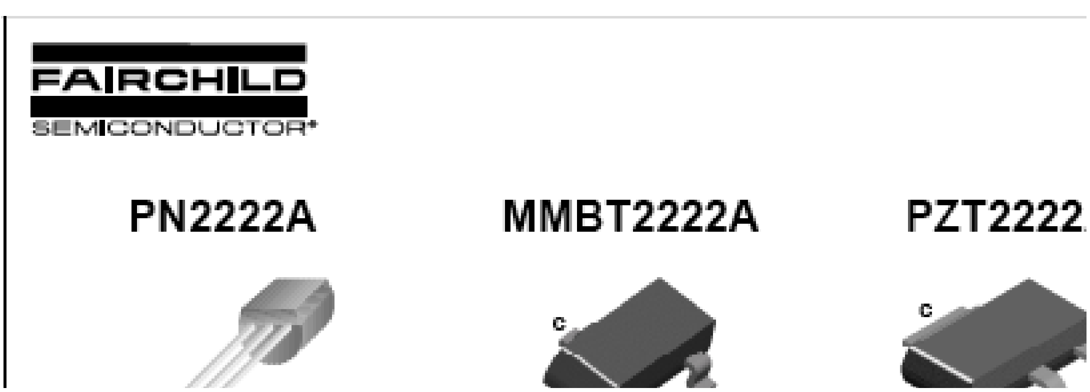


Figure 3-9 Common-emitter o
put characteristics of a 2N222
n-p-n silicon transistor. A lo
line corresponding to V_{CC} = 1(
and R_L = 500 is superimpose

Fairchild is one of many manufacturers of the 2N2222A and the characteristics are listed below.



NPN General Purpose Amplifier

- This device is for use as a medium power amplifier and switch requiring collector currents up to 500mA.
- Sourced from process 19.

Absolute Maximum Ratings * T_a=25°C unless otherwise noted

Symbol	Parameter	Value
V_{CEO}	Collector-Emitter Voltage	40
V_{CBO}	Collector-Base Voltage	75
V_{EBO}	Emitter-Base Voltage	6.0
I_C	Collector Current	1.0
T_{STG}	Operating and Storage Junction Temperature Range	- 55 ~ 150

* These ratings are limiting values above which the serviceability of any semiconductor device may be impaired

NOTES:
1) These ratings are based on a maximum junction temperature of 150 degrees C.
2) These are steady state limits. The factory should be consulted on applications involving pulsed or low duty cycle operations

Electrical Characteristics T_a=25°C unless otherwise noted

Symbol	Parameter	Test Condition	Min.	Ma
Off Characteristics				
$BV_{(BR)CEO}$	Collector-Emitter Breakdown Voltage *	I_C = 10mA, I_B = 0	40	
$BV_{(BR)CBO}$	Collector-Base Breakdown Voltage	I_C = 10µA, I_E = 0	75	
$BV_{(BR)EBO}$	Emitter-Base Breakdown Voltage	I_E = 10µA, I_C = 0	6.0	
I_{CEX}	Collector Cutoff Current	V_{CE} = 60V, $V_{EB(off)}$ = 3.0V		1
I_{CBO}	Collector Cutoff Current	V_{CB} = 60V, I_E = 0 V_{CB} = 60V, I_E = 0, T_a = 125°C		0.0 1
I_{EBO}	Emitter Cutoff Current	V_{EB} = 3.0V, I_C = 0		1
I_{BL}	Base Cutoff Current	V_{CE} = 60V, $V_{EB(off)}$ = 3.0V		2
On Characteristics				
h_{FE}	DC Current Gain	I_C = 0.1mA, V_{CE} = 10V I_C = 1.0mA, V_{CE} = 10V I_C = 10mA, V_{CE} = 10V I_C = 10mA, V_{CE} = 10V, T_a = -55°C I_C = 150mA, V_{CE} = 10V * I_C = 150mA, V_{CE} = 10V * I_C = 500mA, V_{CE} = 10V *	35 50 75 35 100 50 40	30
$V_{CE(sat)}$	Collector-Emitter Saturation Voltage *	I_C = 150mA, V_{CE} = 10V I_C = 500mA, V_{CE} = 10V		0. 1.
$V_{BE(sat)}$	Base-Emitter Saturation Voltage *	I_C = 150mA, V_{CE} = 10V I_C = 500mA, V_{CE} = 10V	0.6	1. 2.