Physics 219 – Fall, 2007

LabNotes5 – Transistor Amplifiers

Friday, October 26..................................................................................... 2
Amplification and Gain ................................................................. 2
Emitter Follower........................................................................ 4
  Student Manual Section 4-2 ......................................................... 6
  Input Impedance of the Emitter Follower .................................... 6
  Output Impedance of the Emitter Follower ................................ 9
  Student Manual Section 4-3 ....................................................... 10
Single Supply Follower.................................................................. 10
  Student Manual Section 4-4 ....................................................... 11
Transistor Current Source................................................................. 11
  Student Manual Section 4-6 ....................................................... 14
Common Emitter Amplifier.............................................................. 14
  Input Impedance of The Common Emitter ............................... 15
  Output Impedance of The Common Emitter ............................. 16
  Summary of results for emitter follower and common emitter amplifiers ......................................................... 17
  Student Manual Section 4-7 ....................................................... 17
Crossover Distortion in a Push-Pull Amplifier.................................... 18
  Student Manual Section 5-6 ....................................................... 21
**Friday, October 26**

**Amplification and Gain**

So far we have seen the value of a transistor in acting as an electronic switch. Another important capability of a transistor is to provide a means for amplifying electronic signals.

Consider the following example, which is representative of a very broad and important class of problem. Suppose we want to build a “public address system” where the goal is to use a microphone to "detect" a sound and then ultimately have a louder version of the sound emanate from a loudspeaker.

"Source" = Microphone 

"Load" = Speaker

Your first impulse might be to simply to connect the microphone directly to the speaker. This approach won't work at all for two reasons: 1) The amplitude of the voltage signal produced by the microphone is usually quite small to begin with. and 2) Worse still, the output impedance of the microphone is typically quite high (~ 1 kΩ). If one were to connect the microphone directly to the speaker, which typically has an input impedance of only 8 Ω, then the already small voltage produced by the microphone would undergo further severe attenuation.

As I said this problem can be viewed as emblematic of a near universal problem: there’s a small electronic signal, and you want to make it bigger!
We will solve these difficulties in two stages. First we'll show how a
transistor configured as an “emitter follower” can help solve the "impedance mismatch" problem:

"Source" = Microphone

"Load" = Speaker

An emitter follower configuration

Later we'll show how a different transistor circuit, the common emitter, can
amplify the signal and allow you to really rattle the windows. (Well, not really, but at least we’ll be able to generate an audible sound in a speaker.)

Before we formally analyze the input and output impedances of the emitter follower, let us first develop a more intuitive understanding of what is going on. When we say "the microphone has a large output impedance”, what does that really mean?

The key point is that sources with large output impedances cannot supply a large current to a load. (Remember, the maximum current that can be supplied is the "short circuit" current given by

\[ I_{sc} = \frac{V_{source}}{Z_{out}} \]

where \(Z_{out}\) and \(V_{source}\) are the output impedances and the Thevenin voltages
of the device.) Because of the transistor's current gain, the emitter follower boosts the amount of current that can be delivered from the source (e.g. microphone) to the load (e.g. speaker).

**The output impedance of a device can be thought of as a measure of its ability to provide current to a load.**

![Diagram](image)

The fundamental criterion that we must keep in mind can be stated as

*When connecting a “load” to a “source” the output impedance of the source must be small compared to the input impedance of the load.*

That is, we require

\[ Z_{out} \ll Z_{in} \]

In practice a useful, somewhat arbitrary, rule of thumb is to require

\[ Z_{out} \leq \frac{1}{10} Z_{in} \]

**Emitter Follower**

The circuit arrangement shown below, known as an emitter follower, is used as a “buffer”, allowing a “high impedance source to drive a low impedance load”.
To analyze how this circuit works, let us recall:

**The Four Golden Rules of Bipolar Transistors**

Here are the rules for npn transistors:

**Rule 1.** \( V_C > V_E \) by at least a few tenths of a volt. The collector voltage must be more positive than the emitter.

**Rule 2.** In "normal operation" the base emitter junction behaves like a forward-biased diode, so that there is approximately a 0.6 V drop from base to emitter. Thus \( V_B = V_E + 0.6 \) V or \( V_{BE} \approx 0.6 \) V.

**Rule 3.** There are limits on \( I_C, I_B, I_E, V_{CE} \), etc. which, if exceeded, will destroy the transistor.

**Rule 4.** When rules 1 through 3 are obeyed, then \( I_C \approx \beta I_B \) where \( \beta \) is a constant with a typical value of about 100.

Also, since from Kirchoff’s Node Theorem” we know that \( I_E = I_B + I_C \), it follows from Rule #4 that \( I_E = (\beta + 1)I_C \).

With these rules in mind, let us analyze the above circuit:

1) Golden Rule #2 implies

\[ V_E = V_B - 0.6 \text{ V} \]

Since very little base current flows across the small base resistor, we can assume
\[ V_B \approx V_{in} \]

so that

\[ V_{out} \approx V_{in} - 0.6 \text{ V} \]

**Thus, in the emitter follower circuit, the output voltage \( V_{out} \), "follows" the input voltage \( V_{in} \).**

This analysis will hold true provided \( V_{in} > 0.6 \text{ V} \). If \( V_{in} < 0.6 \text{ V} \) then \( V_{out} \) won't follow \( V_{in} \) since current can only flow in the direction of the arrow through the 3.3 k\( \Omega \) resistor to ground. Thus \( V_{out} \) must always be \( \geq 0 \text{ V} \).

Thus if we want the output to follow an ac signal we need to modify this circuit. One strategy is to connect the load resistor to a negative power supply, as shown below.

**Student Manual Section 4-2**

- Complete Lab 4-2 in the *Student Manual* on the Emitter Follower. For the ±15V power supplies you can use either the big black breadboards (*Global Specialties* PB-503), which have built-in power supplies, or the *BK Precision* bench-top power supplies.

**Input Impedance of the Emitter Follower**

At first glance the emitter follower seems pointless. Why just “replicate” an
existing voltage signal. The value of the circuit only becomes apparent when you start thinking in terms of input and output impedances.

Let's start by calculating the input impedance of the circuit. Recall that for ac signals we define the input impedance by

\[ Z_{in} = \frac{\Delta V_{in}}{\Delta I_{in}} \]

where the "\( \Delta \)" denotes that the quantities are undergoing small changes associated with a small amplitude ac signal.

For the emitter follower

\[ \Delta V_{out} = \Delta V_{in} = \Delta V_E \]

Ohm's Law implies:

\[ \Delta I_E = \frac{\Delta V_E}{R_E} = \frac{\Delta V_{in}}{R_E} \]

or

\[ \Delta V_{in} = \Delta I_E R_E \]

Now, Golden Rule #4 implies
\[ \Delta I_E = (\beta + 1) \Delta I_B = (\beta + 1) \Delta I_{in} \]

These last two results, taken together imply:

\[ \Delta V_{in} = (\beta + 1) \Delta I_{in} R_E \]

so, finally,

\[ Z_{in} = \frac{\Delta V_{in}}{\Delta I_{in}} = \frac{(\beta + 1) \Delta I_{in} R_E}{\Delta I_{in}} \]

\[ Z_{in} = (\beta + 1) R_E \]

**Therefore, the emitter follower increases the input impedance of the load by a factor \((\beta + 1)\).**

This shows that the emitter follower acts as a **buffer** between the source and the load, making it easier for the source to drive the load without being attenuated.

To measure the input impedance of the emitter follower **experimentally**, you will be asked to build the following circuit:

Now,

\[ Z_{in} = \frac{\Delta V_{in}}{\Delta I_{in}} = \frac{\Delta V_{base}}{\Delta I_{base}} \]
You can measure amplitude of the input voltage, $\Delta V_{in}$, directly with the oscilloscope. You can then deduce $\Delta I_{in}$ by looking at the voltage drop across the resistor:

$$\Delta I_{in} = \Delta I_{base} = \frac{\text{change in amplitude across resistor}}{10k}$$

**Output Impedance of the Emitter Follower**

Alternatively we can view the emitter follower as a circuit as something that lowers the impedance of a source by a factor of $(\beta + 1)$:

We can verify this claim with the following argument:

First, recall that we defined the output impedance of a source by

$$Z_{out} = \frac{\delta V_{out}}{\delta I_{out}}$$

Because of the transistor’s current gain, when an amount of current $\delta I_{out}$ is drawn from the output the amount of current that flows through the source impedance is only $\frac{\delta I_{out}}{\beta + 1}$. Thus $\delta V_{out}$ is factor of $\beta + 1$ less than it would be without the transistor.

**Therefore, the emitter follower decreases the impedance of the source by a factor $(\beta + 1)$.**
Student Manual Section 4-3

• Complete Lab 4-3 in the Student Manual on the Input and Output Impedance of the Emitter Follower.

Single Supply Follower

(See p.86 of the Student Manual for additional notes on this topic.)

Sometimes one only has access to a power supply with only one polarity (in a battery operated device this is often the case.) We can use a single polarity power supply to operate the emitter follower by pulling the transistor’s quiescent voltages (the voltages that the terminals are out when there is zero input voltage) off-center, “biasing” it away from zero volts. The following circuit shows how this can be done.

The biasing divider must be “stiff enough” to hold the base of the transistor where we want it (about midway between the positive power supply voltage (often referred to as $V_{cc}$) and ground. In this case, the fundamental requirement that

When connecting a “load” to a “source” the output impedance of the source must be small compared to the input impedance of the load.
leads to two distinct requirements:

1) The voltage divider must be “stiff enough” to drive the load, so that it can create a 7.5 V offset:

\[ Z_{\text{divider}} \leq \frac{1}{10} Z_{\text{in-follower}} = \frac{1}{10}(\beta + 1)R_E \]

and

2) The source impedance (for ac signals) must be low enough to be able to drive both the voltage divider and the buffered load:

\[ Z_{\text{source}} \leq \frac{1}{10} Z_{\text{divider}} \]

where as we know, the impedance of the divider is given in this case by

\[ Z_{\text{divider}} = 130 \, k \parallel 150 \, k \]

**In words:** We require that the impedance of the divider small compared to the input impedance of the emitter follower, but large compared to the impedance of the source.

**Student Manual Section 4-4**

- Complete Lab 4-4 in the *Student Manual* on the Single Supply Follower. If you want you can use a pair of 6V battery packs, wired in series, to power the circuit.

**Transistor Current Source**

An “Ideal Voltage Source” supplies a *constant voltage* regardless of the value of the load resistor.

Similarly: An “Ideal Current Source” supplies a *constant current* regardless of the value of the load resistor.
In practice a very simple way to make a not so bad constant current source is to simply use a battery and a big resistor:

\[ I \approx \frac{V}{R} \]

independent of the value of \( R_{load} \).

There are two drawbacks to this approach:

1) Since \( R \) must be large, we need a big \( V \) in order to appreciable \( I \).

2) A lot of power is dissipated (and hence wasted) in the resistor \( R \). The power “lost” in \( R \) is given by

\[ P_{lost} = I^2 R \]

while the power actually “used” by the load is given by

\[ P_{used} = I^2 R_{load} \]

so if \( R >> R_{load} \) then \( P_{used} << P_{lost} \). This is very inefficient!

We can do much better at the cost of using just one transistor. For example, consider the following circuit:
The analysis of this circuit is as easy as 1–2-3:

1) The base of the transistor is held at 5 V so, from golden rule #2
   \[ V_E = 4.4 \text{ V} \, . \]

2) From Ohm’s Law
   \[ I_E = \frac{4.4 \text{ V}}{680 \text{ } \Omega} = 6.5 \text{ mA} \]

3) From Golden Rule #4
   \[ I_C = \frac{\beta}{\beta + 1} I_E \approx 6.5 \text{ mA} \]

\textit{independent of } R_{load}.

Thus the current through the load is \textbf{constant} regardless of the value of the load resistor.

\textbf{Some Jargon:}

\textbf{Stiffness} – This term is used to describe the ability of a voltage source to supply a constant voltage as the resistance of the load varies.

\textbf{Compliance} – This term is used to describe the ability of a current source to
supply a constant current as the resistance of the load varies.

**Limits on the compliance of the transistor current source:**

1) When $R_{\text{load}}$ becomes large enough so that $V_C \rightarrow V_E$ then the transistor saturates and the current will begin to drop.

2) We assumed above that $V_{BE} = 0.6$ V always. But actually $V_{BE}$ varies somewhat as $V_{CE}$ changes. (This is known as the **Early Effect**)

3) See p. 61 of Horowitz and Hill for more.

**Student Manual Section 4-6**

Complete Lab 4-6 in the *Student Manual* on the Transistor Current Source.

**Common Emitter Amplifier**

The **common emitter amplifier**, shown below, produces an output signal whose amplitude is greater than that of the input signal.

![Common Emitter Amplifier Diagram]

This circuit is similar to the current source except now $V_{in} = V_B$ changes. Since $V_{in} = V_B$ changes, $I_C$ changes as well. Since $I_C$ changes, Ohm’s law implies that $V_C = V_{out}$ changes. We can calculate exactly how a given change in the input voltage is manifest at the output. Here’s the analysis:

1) Golden Rule #2 implies that
\[ \Delta V_E = \Delta V_B \]

2) Ohm’s Law implies that

\[ \Delta I_E = \frac{\Delta V_E}{R_E} \]

3) Golden Rule #4 implies that

\[ \Delta I_C = \Delta I_E = \frac{\Delta V_E}{R_E} = \frac{\Delta V_B}{R_E} \]

4) Ohm’s law implies that

\[ \Delta V_C = -\Delta I_C R_C \]

Thus

\[ \Delta V_{out} = \Delta V_C = -\Delta I_C R_C = -\frac{\Delta V_B}{R_E} R_C \]

\[ \Delta V_{out} = -\frac{R_C}{R_E} \Delta V_{in} \]

(The minus sign means phase is shifted by 180 degrees.)

The Common Emitter amplifier is a **voltage amplifier** with a **gain** equal to

\[-\frac{R_C}{R_E} \]

**Input Impedance of The Common Emitter**

The input impedance of the common emitter is the same as for the emitter follower (The analysis is the same):

\[ Z_{in} = (\beta + 1)R_E \]
To calculate the output impedance of the common emitter amplifier, we start by recalling that

\[ Z_{out} = \frac{\delta V_{out}}{\delta I_{out}} \]

It is easy to see that, since in a common emitter amplifier all output current must come through the collector resistor

\[ Z_{out} = R_C. \]
Summary of results for emitter follower and common emitter amplifiers

<table>
<thead>
<tr>
<th></th>
<th>Input Impedance</th>
<th>Output Impedance</th>
<th>Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emitter Follower</td>
<td>$(\beta + 1)R_E$</td>
<td>$\frac{Z_{\text{source}}}{(\beta + 1)}$</td>
<td>1</td>
</tr>
<tr>
<td>Common Emitter</td>
<td>$(\beta + 1)R_E$</td>
<td>$R_C$</td>
<td>$\frac{R_C}{R_E}$</td>
</tr>
</tbody>
</table>

Student Manual Section 4-7

- Complete Lab 4-7 in the Student Manual on the Common Emitter Amplifier. Try using a microphone as an input voltage. With only x10 gain, the output signal is probably quite small.
- Now change to the “grounded emitter” configuration shown below

![Circuit Diagram](image)

Again try using the microphone as a source. What is the gain of the amplifier for ac signals now? What is the gain for dc signals?
- Try feeding in a small amplitude 10 kHz triangle wave from a function generator. Can you observe any “distortion” in the output signal. (See pp. 100-105 in the Student Manual for a discussion of the origins of the distortion.)
These days it is becoming increasingly rare to build or use circuits that rely on a few discrete transistors. More commonly one makes use of integrated circuits (ICs), which contain anywhere from a few to millions of transistors on a single piece of silicon. The time we have spent studying "simple" circuits with one or two transistors has been useful in large part because of the insights provided into what is going on inside the ICs that will occupy much of our attention for the remainder of the course. Much of the material in labs 5 and 6 is interesting and useful, but we will skip most of it in the interest of spending our time on even more important topics. In fact, the only lab sections that you are asked to do are 5-6, which covers the push-pull amplifier.

**Crossover Distortion in a Push-Pull Amplifier**

Recall the emitter follower:

The *npn* emitter follower can only "source" current into the load resistor.

Similarly, a *pnp* emitter follower can only "sink" current out of the load resistor.

Previously, in order to be able to follow both polarities of an ac input signal we resorted either to a dc bias scheme:
or we used a "split" power supply that provided both positive and negative bias voltages:

Both of these schemes suffer from the drawback of requiring large “quiescent currents”. That is lots of current flow even when there is no ac signal. In addition, the voltage divider employed in the first scheme often serves to lower the input impedance of the amplifier.

One simple alternative is the push-pull amplifier:
When $V_{in}$ is positive the npn transistor “turns on” and “sources” current to the load while when $V_{in}$ is negative the pnp transistor “turns on” and “sinks” current from the load.

This circuit has many advantages. Unlike the "split supply follower" (Lab section 46) this circuit can drive a load that has one side grounded. Also there is no dc offset and no quiescent current. Furthermore, no voltage divider is required at the input.

There is however one potentially serious problem: The crossover distortion that results from the fact that for input voltages between -0.6 V and +0.6 V neither transistor is “on”.

The result It is that the output voltage looks like:

See if you can hear the crossover distortion on your speakers. Shortly, we will see a beautiful way to virtually eliminate this problem with the clever
use of an op amp.

**Student Manual Section 5-6**

- Complete Lab 5-6 in the *Student Manual* on the Push–Pull Amplifier.