Lecture 18: Common Emitter Amplifier. Maximum Efficiency of Class A Amplifiers. Transformer Coupled Loads.

We discussed using transistors as switches in the last lecture. Amplifiers are another extremely important use for transistors.

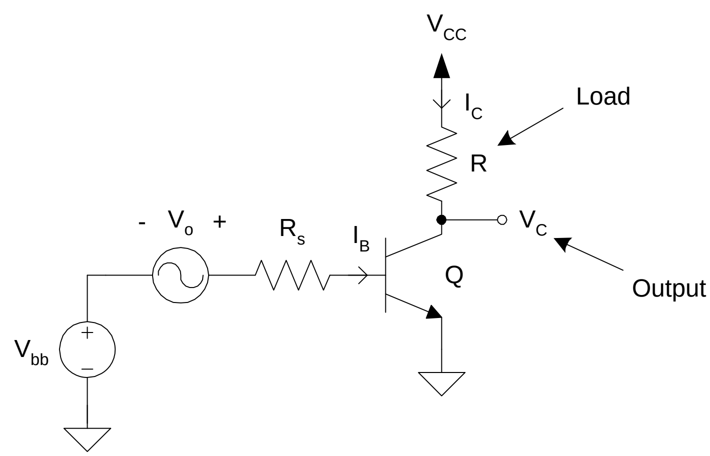
Two types of transistor amplifiers are used in the NorCal 40A:

1. Linear amplifier – Called a "class A" amplifier. The output signal is a very close replica of the input signal shape. In other words, the output is simply a scaled version of the input. The Driver Amplifier (Q6) is an example.
2. Saturating amplifier – The shape of the output signal may be very different from the input. Between these two waveforms, perhaps only the frequency is the same. Additional "signal conditioning" is usually incorporated. The Power Amplifier (Q7) is an example.

Saturating amplifiers are often much more efficient than linear amplifiers in converting power from the dc source to the signal ac (i.e., RF). The tradeoff is distortion in the amplified signal.

Common Emitter (CE) Amplifier

An example of what *can be* a linear amplifier is the common emitter amplifier shown in Fig. 9.2(a):

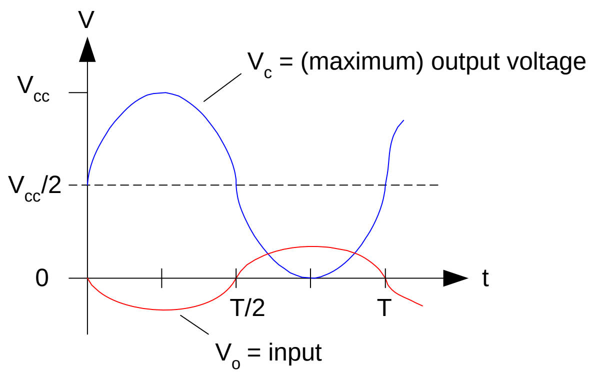


We will restrict ourselves for the time being to circuits of this type when Q remains entirely in the active region. Note that V_{bb} is the input bias (i.e, dc) voltage used to set this operational condition.

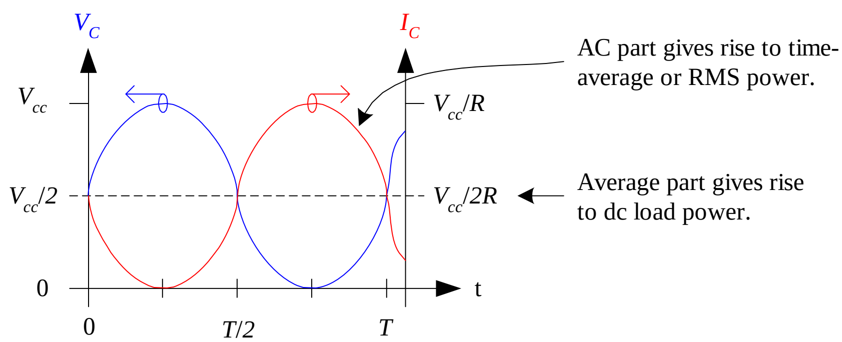
Let's now develop a qualitative understanding of this amplifier. Assume that the input voltage V_o is proportional to $\cos(\omega t)$:

1. As $V_o \downarrow$, $I_b \downarrow$ which implies $I_c(=\beta I_b) \downarrow$. Hence, $V_c \uparrow$. The maximum V_c will be below V_{cc}.
2. Conversely, as $V_o \uparrow$, $I_b \uparrow$ which implies $I_c(=\beta I_b) \uparrow$. Hence, $V_c \downarrow$. The minimum V_c will be above 0 and before Q saturates. (Actually, this minimum V_c will be quite a bit above saturation since we will see distortion in V_c as Q approaches saturation, even though it's not "technically" saturated.)

From this discussion we can sketch these voltages and the collector current. Since V_o and V_c are 180° out of phase:



and with I_c and V_c also 180º out of phase (Fig. 9.2b):



A good question to ask yourself at this point is “Just how does a transistor circuit actually amplify the input signal?”

Maximum Efficiency of Class A Amplifiers

As mentioned at the beginning of this lecture, the class A (or linear) amplifier produces as an output signal that is simply a scaled version of the input.

We stated that this amplifier is not as efficient as others. We will now compute this efficiency to (1) understand what “efficiency” means, and (2) compare this efficiency with other amplifier types.

The efficiency η of the amplifier is defined as

$$\boxed{\eta \equiv \frac{P}{P_o}} \tag{9.1}$$

where P is the RMS (ac) output power and P_o is the dc supply power. We'll separately compute expressions for each of these terms:

1. P_o – this is the power supplied by the dc source. We'll ignore the power consumed in the base circuit of Fig. 9.2(a) because it will often be small compared to the power consumed in the collector circuit. Consequently,

$$P_o = V_{cc} I_o \tag{9.2}$$

Here, V_{cc} is the dc supply voltage, but what is I_o? This is a bit tricky.

From the last figure, note that I_c is comprised of two parts:

(a) dc component, and

(b) ac component.

The ac component is useful as an amplified version of the input signal V_o. However, it is the time average value of I_c which is the needed dc current I_o in the calculation of (9.2):

$$I_o = \frac{V_{cc}}{2R} \tag{9.3}$$

Therefore,

$$P_o = \frac{V_{cc}^2}{2R} \tag{9.4}$$

This is the *maximum* dc power supplied by the bias.

2. P – this is the RMS power supplied by the ac part of V_c (and I_c). For sinusoidal voltages and currents with peak-to-peak amplitudes V_{pp} and I_{pp}, respectively,

$$P = \frac{1}{8} V_{pp} I_{pp} \tag{2.10}$$

is the RMS (effective) ac output power. In the case here for *maximum* output voltage and current (from Fig. 9.2b),

$$V_{pp} = V_{cc} \quad \text{and} \quad I_{pp} = \frac{V_{cc}}{R}$$

so that,

$$P = \frac{1}{8} V_{cc} \frac{V_{cc}}{R} = \frac{V_{cc}^2}{8R} \tag{9.5}$$

Now, substituting (9.5) and (9.4) into (9.1) we have

$$\eta = \frac{P}{P_o} = \frac{V_{cc}^2/(8R)}{V_{cc}^2/(2R)} = \frac{2}{8} = 25\%$$

This $\boxed{\eta = 25\%}$ is the **maximum** efficiency of a class A (linear) amplifier connected to a purely resistive load. (Why is this the *maximum* value?)

Practically speaking, it is unusual to operate an amplifier at its maximum output voltage. Consequently, the usual efficiencies observed for class A amplifiers range from 10% to 20%. This also helps to keep the signal distortion low.

Class A amplifiers are notoriously inefficient, but they can be very, very linear.

Power Flow in Class A Amplifiers with Resistive Loads

It is extremely insightful to calculate the "flow of power" in this amplifier, beginning from the dc source to the ac power (signal power) delivered to the resistive load.

Specifically, power flows from the dc source to both the load and transistor in the form of dc power and ac power (again, ignoring the base circuit). Let's calculate the maximum of all four of these quantities separately:

(a) DC load power. This is due to the time average values of V and I in R and has nothing to due with the time varying component. From Fig. 9.2b:

$$P_{r,dc} = V_{r,dc} I_{r,dc} = \frac{V_{cc}}{2} \frac{V_{cc}/2}{R} = \frac{V_{cc}^2}{4R} \tag{9.6}$$

(b) AC load power. We computed this earlier:

$$P_{r,ac} = P = \frac{V_{cc}^2}{8R} \tag{9.5}$$

(c) DC transistor power. $P_{t,dc}$ can easily be computed by noting that in this CE configuration (Fig. 9.2a), the **average** V and I across and through Q are the same as for the resistor R. In other words, the dc powers are the same for these two components:

$$P_{t,dc} = P_{r,dc} = \frac{V_{cc}^2}{4R} \tag{9.7}$$

(d) AC transistor power. This power is given by the usual expression

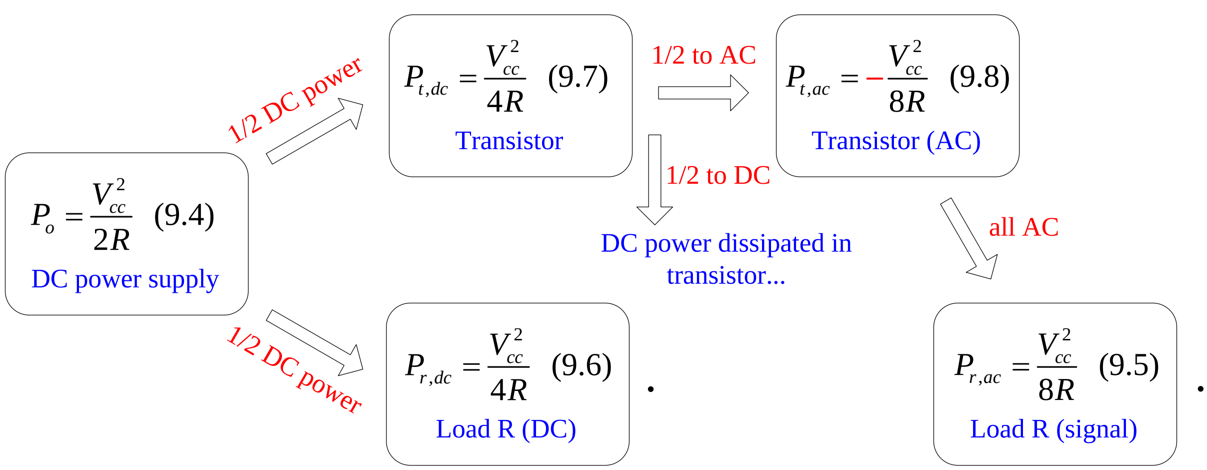
$$P_{t,ac} = \frac{1}{2} V_t I_t = \frac{1}{2} V_c I_c$$

Interestingly, since V_c and I_c 180° out of phase (as shown in Fig 9.2b), this ac power will be **negative**:

$$P_{t,ac} = -\frac{1}{2}\frac{V_{cc}}{2}\frac{V_{cc}/2}{R} = -\frac{V_{cc}^2}{8R} \tag{9.8}$$

What does this minus sign mean? Q ***produces*** the ac power for the load! Cool.

These results from (a) through (d) can be arranged pictorially as shown in Fig. 9.3:

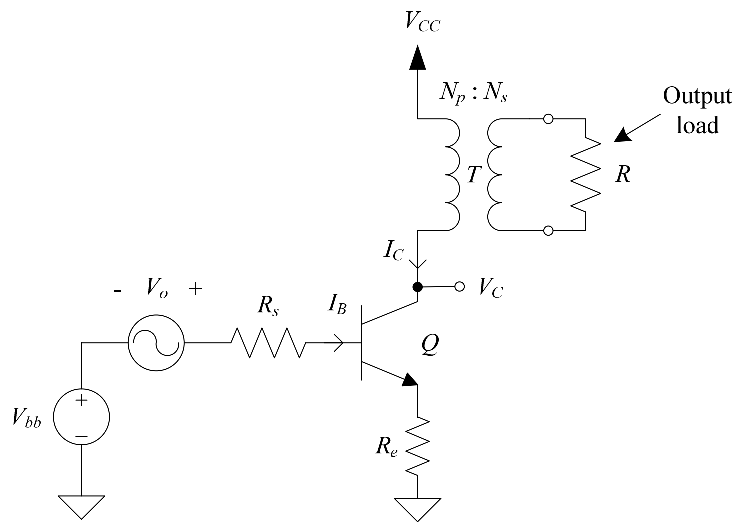


Class A Amplifier with Transformer Coupled Load

As mentioned in the text, there are two major disadvantages of class A amplifiers with resistive loads:

1. Half of the power from the supply is consumed as dc power in the load resistor.
2. Some types of loads cannot be connected to this amplifier. For example, a second amplifying stage would have the base of the transistor connected where *R* is located. The ac voltage would be excessively large for direct connection (typically want ac voltages from 10 – 100 mV or so).

An interesting variation of the class A amplifier and one that removes both of these problems is to use a transformer coupled load as shown in Fig. 9.4a:

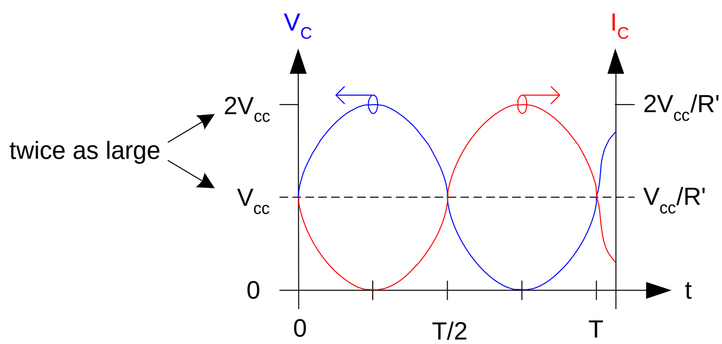


The Driver Amplifier (Q6) in the NorCal 40A is an example of such a class A amplifier with transformer load.

From this circuit, we can see immediately that there will no longer be **any** dc power consumed in *R* since DC does not couple through transformers.

Next, notice that the DC resistance between V_{cc} and Q is (nearly) zero so that the (time) average collector voltage V_c will then be V_{cc}, not $V_{cc}/2$ as before. This is very important to understand! (We will see this again later in connection with "RF chokes.")

With the transformer-coupled load, the maximum V_c and I_c can now be as much as twice as large as with a resistive load:



Why twice as large? Firstly, as just mentioned, the average value of the signal must equal V_{cc}. Then, on the negative swing the lowest voltage will be approximately 0 when Q is saturated. Hence, the signal amplitude at V_c is V_{cc}. Therefore, the maximum value is then $V_{cc} + V_{cc} = 2V_{cc}$.

To help us understand this further, note in Fig. 9.4a that V_{cc} and V_c are not the same physical node in the circuit since there is the primary winding of T separating them. But if T were removed so that V_{cc} was connected directly to V_c, then V_c would no longer even vary with time, of course, much less be anything larger than V_{cc}.

Next, let's evaluate the efficiency of this new design. First, the maximum dc supplied power P_o is

$$P_o = V_{cc} I_o = \frac{V_{cc}^2}{R'} \tag{9.9}$$

where R' is the effective load resistance due to T given as

$$R' = n^2 R \tag{9.10}$$

and n is the turns ratio N_p/N_s (see Lecture 14).

Next, the maximum ac (RMS) output power is

$$P = \frac{1}{2}\frac{V_{pp}}{2}\frac{I_{pp}}{2} = \frac{V_{pp} I_{pp}}{8}$$

but, $\quad I_{pp} = \dfrac{V_{pp}}{R'} \quad$ and $\quad V_{pp} = 2V_{cc}$.

Notice that V_{pp} is now twice V_{cc}. The ac output power is then

$$P = \frac{(2V_{cc})(2V_{cc})}{8R'} = \frac{V_{cc}^2}{2R'} \tag{9.11}$$

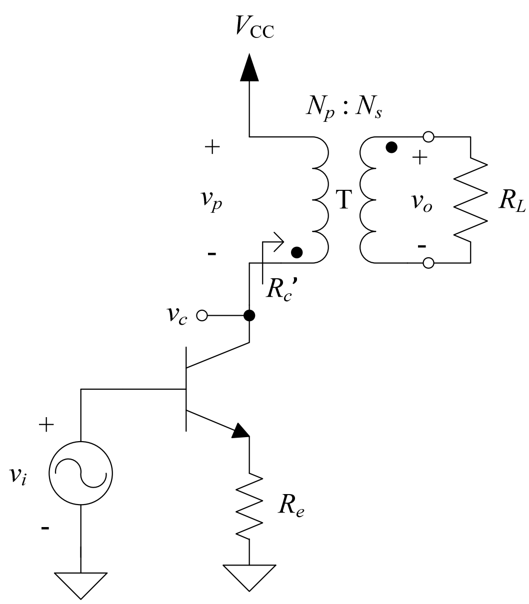
Using (9.9) and (9.11) we find that the maximum efficiency is

$$\eta = \frac{P}{P_o} = \frac{V_{cc}^2/(2R')}{V_{cc}^2/R'} = \frac{1}{2} = 50\%$$

In other words, the maximum efficiency of the class A amplifier with transformer coupled resistive load is $\boxed{\eta = 50\%}$.

This is twice the efficiency of a class A amplifier with a resistive load. This doubling of efficiency makes sense since we've eliminated the DC power to the resistive load. (See the power flow diagram above.)

Example N18.1: Determine an expression for the small-signal voltage gain for a common emitter amplifier with emitter degeneration having a transformer coupled load, as shown in the figure below.



The expected voltage gain can be calculated in two steps. We'll assume that T is an ideal transformer, meaning we'll ignore the effects of the magnetization current in the transformer T. (Would that be a good assumption for the Driver Transformer T1?)

Using the effective collector resistance, R_c', that appears as the input resistance seen at the primary terminals of T, we can then simply use (9.31) for a common emitter amplifier to calculate

$$G_v' \equiv \frac{V_p}{V_i} = -\frac{R_c'}{R_e} \tag{1}$$

where V_p is the primary voltage of T. But the input resistance seen at the primary terminals of T is

$$R_c' \underbrace{=}_{(6.19)} n^2 R_L \tag{2}$$

where

$$n \equiv \frac{N_p}{N_s} \tag{3}$$

For the second step, we recognize that the gain we wish to calculate is not G_v' but rather is

$$G_v \equiv \frac{V_o}{V_i} \tag{4}$$

However, V_o and V_p are simply the secondary and primary voltages for the transformer, which, noting the dot convention indicated in the circuit, are related from (6.15) as $V_o = V_p / n$ so that

$$\frac{V_o}{V_i} = \frac{V_p/n}{V_i} \tag{5}$$

Substituting (5) into (4) and using (1) gives

$$G_v \equiv \frac{V_o}{V_i} = \frac{V_p/n}{V_i} \underbrace{=}_{(1)} \frac{1}{n} G_v' = -\frac{R_c'}{nR_e} \underbrace{=}_{(2)} -\frac{n^2 R_L}{nR_e}$$

or finally,

$$G_v \equiv \frac{V_o}{V_i} = -\frac{nR_L}{R_e} \tag{6}$$