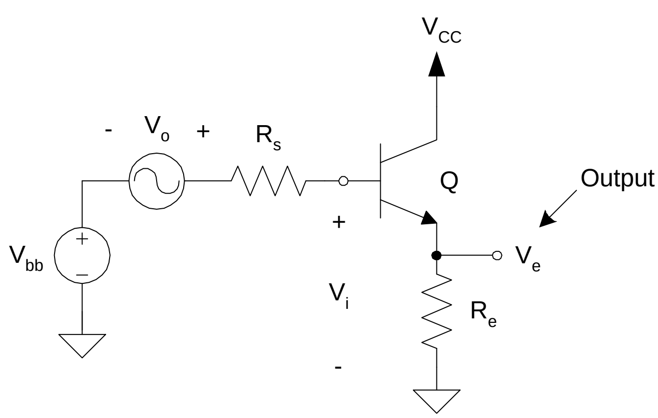
Lecture 20: Emitter Follower and Differential Amplifiers

The next two amplifier circuits we will discuss are very important to electrical engineering in general, and to the NorCal 40A specifically.

However, neither of these amplifiers appears in discrete form in the NorCal 40A. Instead, you will find these amplifiers performing their important functions inside ICs.

Emitter Follower (aka Common Collector) Amplifier

A typical emitter follower amplifier is shown in Fig. 9.12:



There are two big differences between this amplifier and the common emitter amplifier:

1. there is no collector resistor,
2. the output voltage is taken at the emitter.

There are four important characteristics of the emitter follower amplifier (presented here without derivation):

1. voltage gain $\lessapprox 1$,
2. current gain > 1,
3. high input impedance,
4. low output impedance ($\approx 1\ \Omega$).

Consequently, the emitter follower is useful as

1. a buffer amplifier,
2. an almost ideal voltage source.

In the NorCal 40A, emitter followers can be found internally in the:

1. Audio Amplifier U3 (LM 386). See the equivalent schematic on p. 399.
2. Oscillator circuits of the Product Detector U2 and the Transmit Mixer U4. Both are SA602 ICs. See the equivalent circuit shown in Fig. 4 on p. 419 of the text.

Differential Amplifier

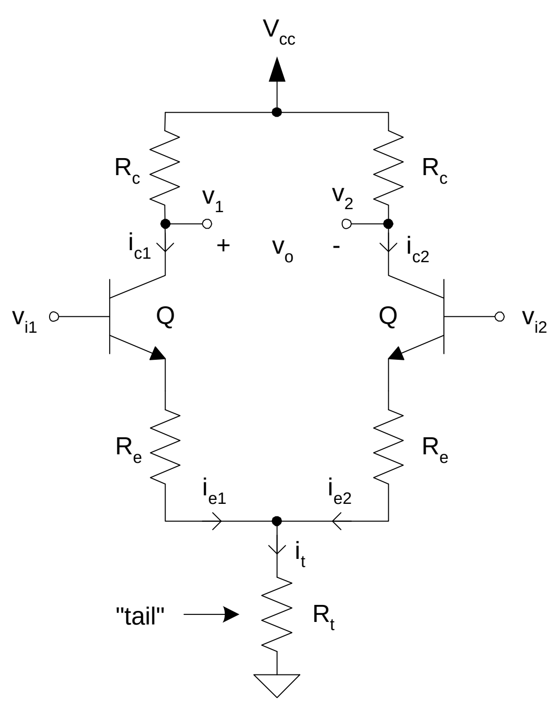
This is probably a new circuit for you. The differential amplifier is an interesting circuit in that it amplifies only a difference in the two input voltages.

Actually, you've used differential amplifiers for years now, though you probably didn't know it. A differential amplifier appears as the input circuit for an operational amplifier. It is this circuit that gives rise to the familiar $v_o = A(v_+ - v_-)$ relationship for the op amp (where A is the open-loop gain).

The differential amplifier also appears in the Audio Amplifier and the SA602 mixer ICs in the NorCal 40A. In the latter case, the "diff amps" appear in the form of Gilbert Cells (see p. 227).

We will spend some time here on the operation of the differential amplifier, considering its importance to the mixing process.

A typical differential amplifier is shown in Fig. 9.13:



It's important that the circuit have matched transistors and resistors for satisfactory performance (more specifically, to ensure symmetry in the circuit).

This diff amp is a moderately complicated circuit to analyze. A relatively simple method of analysis, however, is to consider two special cases of input signals:

1. $v_{i1} = -v_{i2}$, called the differential (or "odd") input,
2. $v_{i1} = v_{i2}$, called the common-mode (or "even") input.

After determining the response of the diff amp to each of these two excitations, **arbitrary combinations of inputs can be analyzed as weighted combinations of these two**. (This so-called even-odd mode analysis method is commonly used in electrical engineering, physics, and other disciplines. It is covered in more detail in EE 481/581 *Microwave Engineering*.)

I. Differential Input, $v_{i1} = -v_{i2}$: For these input voltages,

$$i_{e1} = -i_{e2} \quad \Rightarrow \quad i_t = i_{e1} + i_{e2} = 0 \qquad (9.53),(9.54)$$

With each amplifier effectively grounded at R_t, then we can use the common-emitter small-signal amplifier gain

$$G_v = -\frac{R_c}{R_e} \qquad (9.31)$$

to give

$$v_1 = -\frac{R_c}{R_e} v_{i1} \quad \text{and} \quad v_2 = -\frac{R_c}{R_e} v_{i2} \qquad (9.55),(9.56)$$

The output voltage for this specific input combination is defined as the differential output voltage v_d as

$$v_d = v_o = v_1 - v_2 = -\frac{R_c}{R_e} v_{i1} + \frac{R_c}{R_e} v_{i2} \qquad (1)$$

which is written

$$v_d = -\frac{R_c}{R_e} v_{id} \qquad (9.57)$$

where $v_{id} \equiv v_{i1} - v_{i2}$ is the differential input voltage. Therefore, the differential gain G_d is

$$\boxed{G_d = \frac{v_d}{v_{id}} = -\frac{R_c}{R_e}} \qquad (9.59)$$

Note that this is the same gain for just one half of the differential amplifier.

II. Common-Mode Input, $v_{i1} = v_{i2}$: For these input voltages,

$$i_{e1} = i_{e2} \quad \Rightarrow \quad i_t = i_{e1} + i_{e2} \qquad (9.62),(9.63)$$

Applying KVL through the transistor bases to R_t and then to ground, the input voltages can be expressed as

$$v_{i1} = R_e i_{e1} + R_t i_t = \left(R_e + 2R_t\right) i_{e1} \qquad (9.64)$$

$$v_{i2} = R_e i_{e2} + R_t i_t = \left(R_e + 2R_t\right) i_{e2} \qquad (9.65)$$

The last equalities use the relationships $i_t = 2i_{e1}$ and $i_t = 2i_{e2}$, respectively.

Next, using KVL from V_{cc} to v_1 (ac small signals only) gives

$$v_1 = -R_c i_{c1} \underbrace{\approx}_{\substack{\text{Q} \\ \text{active}}} -R_c i_{e1} \underbrace{=}_{(9.64)} -\frac{R_c}{R_e + 2R_t} v_{i1} \qquad (9.66)$$

Similarly, it can be shown that

$$v_2 = -\frac{R_c}{R_e + 2R_t} v_{i2} \tag{9.67}$$

Notice that with this common-mode input, both v_1 and v_2 are equal. Consequently, the output voltage is

$$\boxed{v_o = v_1 - v_2 = 0}$$

This last result clearly shows that the differential amplifier does not amplify signals that are common to both inputs. Cool!

Since these voltages v_1 and v_2 are the same, we define either of them as the common-mode voltage v_c

$$v_c = v_1 = v_2$$

so that

$$\frac{v_1 + v_2}{2} = v_c. \tag{2}$$

Using (9.66) or (9.67),

$$v_c = -\frac{R_c}{R_e + 2R_t} v_{ic} \tag{9.68}$$

where $v_{ic} = v_{i1} = v_{i2}$. Hence, the common-mode gain G_c is

$$\boxed{G_c \equiv \frac{v_c}{v_{ic}} = -\frac{R_c}{R_e + 2R_t}} \tag{9.69}$$

Differential Amplifiers in the SA602 Mixers

As mentioned previously, the differential amplifier plays a critical role in the SA602 mixer. Specifically, the diff amp appears as the two input terminals 1 and 2 (see p. 419).

However, in the NorCal 40A, only one diff amp input is connected to the signal (SA602 pin 1). The other input (pin 2) is connected to ground (through a dc block capacitor). This input configuration is *not* one of the two considered earlier.

We can account for this type of input, however, simply as a weighted sum of differential and common-mode inputs. That is, in order to account for the inputs $v_{i1} = v_i$ and $v_{i2} = 0$, use (1) and (2) to give:

1. $v_{id} = v_{i1} - v_{i2} = v_i - 0 = v_i$ (9.70)
2. $v_{ic} = \dfrac{v_{i1} + v_{i2}}{2} = \dfrac{v_i + 0}{2} = \dfrac{v_i}{2}$ (9.71)

Let's check that **weighted** sums of these two inputs (9.70) and (9.71) are indeed equivalent to the desired inputs $v_{i1} = v_i$ and $v_{i2} = 0$.

First, calculate (9.70)+2·(9.71) (i.e., the sum $v_{id} + 2v_{ic}$) giving

$$v_{i1} - v_{i2} + 2\left(\frac{v_{i1} + v_{i2}}{2}\right) = v_i + 2\frac{v_i}{2}$$

or, $v_{i1} = v_i$ ✓ (input to Q_1 is indeed v_i).

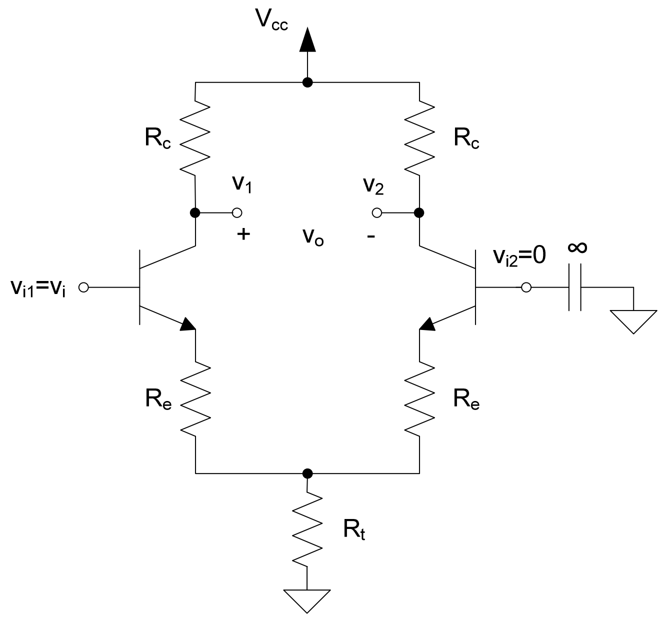
Next, calculate 2·(9.71)-(9.70) (i.e., the sum $2v_{ic} - v_{id}$) giving

$$2\left(\frac{v_{i1} + v_{i2}}{2}\right) - \left(v_{i1} - v_{i2}\right) = 2\frac{v_i}{2} - v_i$$

or, $v_{i2} = 0$ ✓ (input to Q_2 is indeed 0).

Determine Differential Mode Output for SA602

The check we just performed illustrates the usefulness of the common and differential input analysis. We began with



Then we asked: What v_{id} and v_{ic} (differential and common-mode inputs) yield the same v_1 and v_2 as for the non-symmetric inputs shown above? The answers, as we just saw, are

$$v_{id} = v_i \quad \text{and} \quad v_{ic} = \frac{v_i}{2}.$$

Finally, we can use these differential and common mode input voltages to determine the differential and common mode output voltages. That is, from (9.59)

$$\begin{aligned} v_d &= v_1 - v_2 \\ &= G_d v_{id} = G_d v_i \end{aligned} \tag{9.72}$$

while from (9.69)

$$\begin{aligned} v_c &= v_1 = v_2 \\ &= G_c v_{ic} = G_c \frac{v_i}{2} \end{aligned} \tag{9.73}$$

As mentioned earlier in this lecture, you won't be creating and measuring discrete component differential amplifiers in the NorCal 40A. Rather, this important circuit exists in the LM 386 audio amplifier and the SA602 mixer ICs. However, a knowledge of the operation of the diff amp is very important for understanding the operation of these ICs.