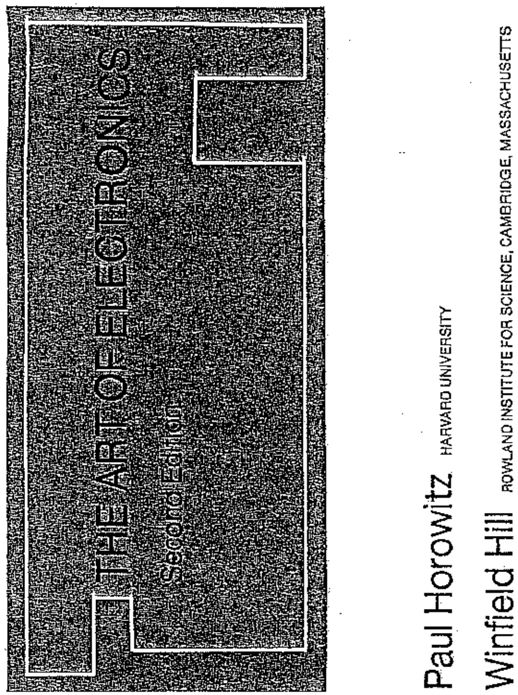

THE ART OF ELECTRONICS

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2.18 Differential amplifiers

The differential amplifier is a very common configuration used to amplify the difference voltage between two input signals. In the ideal case the output is entirely independent of the individual signal levels – only the difference matters. When both inputs change levels together, that's a *common-mode* input change. A differential change is called *normal mode.* A good differential amplifier has a high *common-mode rejection ratio* (CMRR), the ratio of response for a normal-mode signal to the response for a common-mode signal of the same amplitude. CMRR is usually specified in decibels. The common-mode input range is the voltage level over which the inputs may vary.

Differential amplifiers are important in applications where weak signals are contaminated by "pickup" and other miscellaneous noise. Examples include digital signals transferred over long cables (usually twisted pairs of wires), audio signals (the term "balanced" means differential, usually 600Ω impedance, in the audio business), radiofrequency signals (twin-lead cable is differential), electrocardiogram voltages, magnetic-core memory readout signals, and numerous other applications. A differential amplifier at the receiving end restores the original signal if the common-mode signals are not too large. Differential amplifiers are universally used in operational amplifiers, which we will come to soon. They're very important in dc amplifier design (amplifiers that amplify clear down to dc, i.e., have no coupling capacitors) because their symmetrical design is inherently compensated against thermal drifts.

Figure 2.67 shows the basic circuit. The output is taken off one collector with respect to ground; that is called a *single-ended output* and is the most common configuration. You can think of this amplifier as a device that amplifies a difference signal and converts it to a single-ended signal so that ordinary subcircuits (followers, current sources, etc.) can make use of the output. (If, instead, a differential output is desired, it is taken between the collectors.)

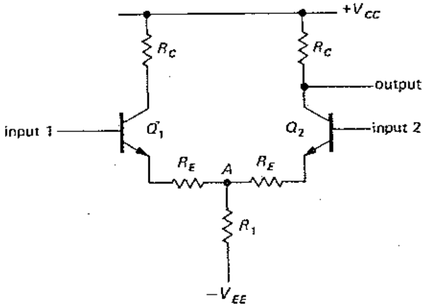


Figure 2.67. Classic transistor differential amplifier.

What is the gain? That's easy enough to calculate: Imagine a symmetrical input signal wiggle, in which input 1 rises by v_{in} (a small-signal variation) and input 2 drops by the same amount. As long as both transistors stay in the active region, point A remains fixed. The gain is then determined as with the single transistor amplifier, remembering that the input change is actually twice the wiggle on either base: $G_{\text{diff}} = R_C/2(r_e + R_E)$. Typically R_E is small, 100 ohms or less, or it may be omitted entirely. Differential voltage gains of a few hundred are typical.

The common-mode gain can be determined by putting identical signals v_{in} on both inputs. If you think about it correctly (remembering that R_1 carries both emitter currents), you'll find $G_{CM} = -R_C/(2R_1 + R_E)$. Here we've ignored the small r_e, because R_1 is typically large, at least a few thousand ohms. We really could have ignored R_E as well. The CMRR is roughly $R_1/(r_e + R_E)$. Let's look at a typical example (Fig. 2.68) to get some familiarity with differential amplifiers.

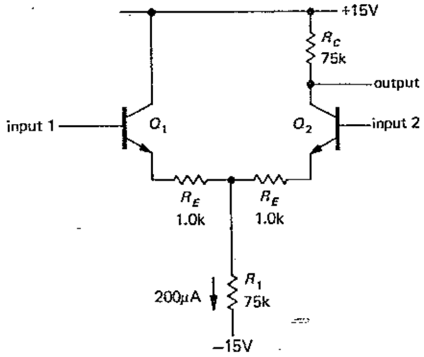
R_C is chosen for a quiescent current of 100μA. As usual, we put the collector at $0.5V_{CC}$ for large dynamic range. Q_1's collector resistor can be omitted, since no output is taken there. R_1 is chosen to give total emitter current of 200μA, split equally between the two sides when the (differential) input is zero. From the formulas just derived, this amplifier has a differential gain of 30 and a common-mode gain of 0.5. Omitting the 1.0k resistors raises the differential gain to 150, but drops the (differential) input impedance from about 250k to about 50k (you can substitute Darlington transistors in the input stage to raise the impedance into the megohm range, if necessary).

Remember that the maximum gain of a single-ended grounded emitter amplifier biased to $0.5V_{CC}$ is $20V_{CC}$. In the case of a differential amplifier the maximum differential gain ($R_E = 0$) is half that figure, or (for arbitrary quiescent point) 20 times the voltage across the collector resistor. The corresponding maximum CMRR (again with $R_E = 0$) is equal to 20 times the voltage across R_1.

EXERCISE 2.13

Verify that these expressions are correct. Then design a differential amplifier to your own specifications.

The differential amplifier is sometimes called a "long-tailed pair," because if the length of a resistor symbol indicated its magnitude, the circuit would look like Figure 2.69. The long tail determines the



$$G_{\text{diff}} = \frac{v_{\text{out}}}{v_1 - v_2} = \frac{R_C}{2(R_E + r_e)}$$

$$G_{CM} = -\frac{R_C}{2R_1 + R_E + r_e}$$

$$\text{CMRR} \approx \frac{R_1}{R_E + r_e}$$

Figure 2.68. Calculating differential amplifier performance.

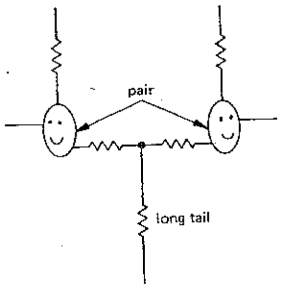


Figure 2.69

common-mode gain, and the small inter-emitter resistance (including intrinsic emitter resistance r_e) determines the differential gain.

Current-source biasing

The common-mode gain of the differential amplifier can be reduced enormously by substituting a current source for R_1. Then R_1 effectively becomes very large, and the common-mode gain is nearly zero. If you prefer, just imagine a common-mode input swing; the emitter current source maintains a constant total emitter current, shared equally by the two collector circuits, by symmetry. The output is therefore unchanged. Figure 2.70 shows an example. The CMRR of this circuit, using an LM394 monolithic transistor pair for Q_1 and Q_2 and a 2N5963 current source is 100,000:1 (100dB). The common-mode input range for this circuit goes from -12 volts to $+7$ volts; it is limited at the low end by the compliance of the emitter current source and at the high end by the collector's quiescent voltage.

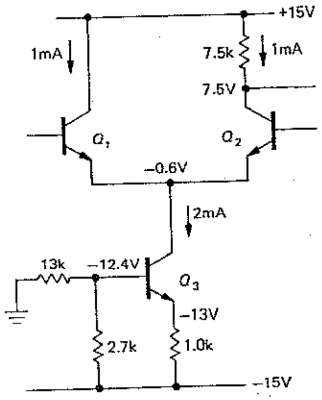


Figure 2.70. Improving CMRR of the differential amplifier with a current source.

Be sure to remember that this amplifier, like all transistor amplifiers, must have a dc bias path to the bases. If the input is capacitively coupled, for instance, you must have base resistors to ground. An additional caution for differential amplifiers, particularly those without inter-emitter resistors: Bipolar transistors can tolerate only 6 volts of base-emitter reverse bias before breakdown; thus, applying a differential input voltage larger than this will destroy the input stage (if there is no inter-emitter resistor). An inter-emitter resistor limits the breakdown current and prevents destruction, but the transistors may be degraded (in h_{fe}, noise, etc.). In either case the input impedance drops drastically during reverse conduction.

Use in single-ended dc amplifiers

A differential amplifier makes an excellent dc amplifier, even for single-ended inputs. You just ground one of the inputs and connect the signal to the other (Fig. 2.71). You might think that the "unused" transistor could be eliminated. Not so! The differential configuration is inherently compensated for temperature drifts, and even when one input is at ground that transistor is still doing something: A temperature change causes both V_{BE}s to change the same amount, with no change in balance or output. That is, changes in V_{BE} are not amplified by G_{diff} (only by G_{CM}, which can be made essentially zero). Furthermore, the cancellation of V_{BE}s means that there are no 0.6 volt drops at the input to worry about. The quality of a dc amplifier constructed this way is limited only by mismatching of input V_{BE}s or their temperature coefficients. Commercial monolithic transistor pairs and commercial differential amplifier ICs are available with extremely good matching (e.g., the MAT-01 *npn* monolithic matched pair has a typical drift of V_{BE} between the two transistors of 0.15μV/°C and 0.2μV per month).

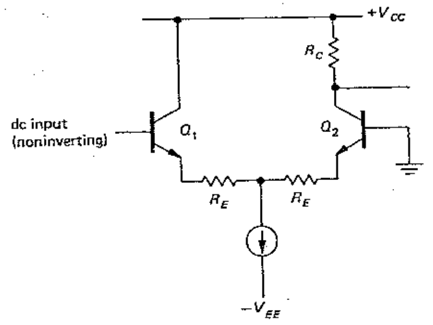


Figure 2.71. A differential amplifier can be used as a precision single-ended dc amplifier.

Either input could have been grounded in the preceding circuit example. The choice depends on whether or not the amplifier is supposed to invert the signal. (The configuration shown is preferable at high frequencies, however, because of *Miller effect*; see Section 2.19.) The connection shown is noninverting, and so the inverting input has been grounded. This terminology carries over to op-amps, which are simply high-gain differential amplifiers.

Current mirror active load

As with the simple grounded emitter amplifier, it is sometimes desirable to have a single-stage differential amplifier with very high gain. An elegant solution is a current mirror active load (Fig. 2.72). Q_1Q_2 is the differential pair with emitter current source. Q_3 and Q_4, a current mirror, form the collector load. The high effective collector load impedance provided by the mirror yields voltage gains of 5000 or more, assuming no load at the amplifier's output. Such an amplifier is usually used only within a feedback loop, or as a comparator (discussed in the next section). Be sure to load such an amplifier with a high impedance, or the gain will drop enormously.

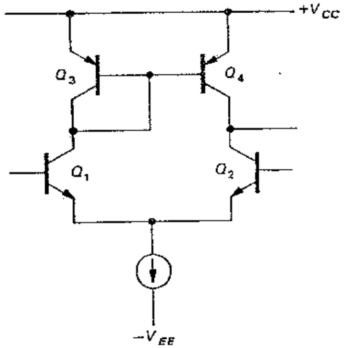


Figure 2.72. Differential amplifier with active current mirror load.

Differential amplifiers as phase splitters

The collectors of a symmetrical differential amplifier generate equal signal swings of opposite phase. By taking outputs from both collectors, you've got a phase splitter. Of course, you could also use a differential amplifier with both differential inputs and differential outputs. This differential output signal could then be used to drive an additional differential amplifier stage, with greatly improved overall common-mode rejection.

Differential amplifiers as comparators

Because of its high gain and stable characteristics, the differential amplifier is the main building block of the *comparator*, a circuit that tells which of two inputs is larger. They are used for all sorts of applications: switching on lights and heaters, generating square waves from triangles, detecting when a level in a circuit exceeds some particular threshold, class D amplifiers and pulse-code modulation, switching power supplies, etc. The basic idea is to connect a differential amplifier so that it turns a transistor switch on or off, depending on the relative levels of the input signals. The linear region of amplification is ignored, with one or the other of the two input transistors cut off at any time. A typical hookup is illustrated in the next section by a temperature-controlling circuit that uses a resistive temperature sensor (thermistor).

2.19 Capacitance and Miller effect

In our discussion so far we have used what amounts to a dc, or low-frequency, model of the transistor. Our simple current amplifier model and the more sophisticated Ebers-Moll transconductance model both deal with voltages, currents, and resistances seen at the various terminals. With these models alone we have managed to go quite far, and in fact these simple models contain nearly everything you will ever need to know to design transistor circuits. However, one important aspect that has serious impact on high-speed and high-frequency circuits has been neglected: the existence of capacitance in the external circuit and in the transistor junctions themselves. Indeed, at high frequencies the effects of capacitance often dominate circuit behavior; at 100 MHz a typical junction capacitance of 5pF has an impedance of 320 ohms!

We will deal with this important subject in detail in Chapter 13. At this point we would merely like to state the problem, illustrate some of its circuit incarnations, and suggest some methods of circumventing the problem. It would be a mistake to leave this chapter without realizing the nature of this problem. In the course of this brief discussion we will encounter the famous *Miller effect* and the use of configurations such as the cascode to overcome it.

Junction and circuit capacitance

Capacitance limits the speed at which the voltages within a circuit can swing ("slew rate"), owing to finite driving impedance or current. When a capacitance is driven by a finite source resistance, you see *RC* exponential charging behavior, whereas a capacitance driven by a current source leads to slew-rate-limited waveforms (ramps). As general guidance, reducing the source impedances and load capacitances and increasing the drive currents within a circuit will speed things up. However, there are some subtleties connected with feedback capacitance and input capacitance. Let's take a brief look.

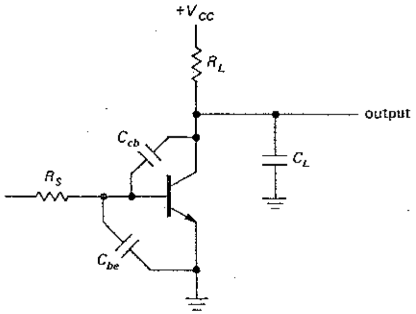


Figure 2.73. Junction and load capacitances in a transistor amplifier.

The circuit in Figure 2.73 illustrates most of the problems of junction capacitance. The output capacitance forms a time constant with the output resistance R_L (R_L includes both the collector and load resistances, and C_L includes both junction and load capacitances), giving a rolloff starting at some frequency $f = 1/2\pi R_L C_L$. The same is true for the input capacitance in combination with the source impedance R_S.

Miller effect

C_{cb} is another matter. The amplifier has some overall voltage gain G_V, so a small voltage wiggle at the input results in a wiggle G_V times larger (and inverted) at the collector. This means that the signal source sees a current through C_{cb} that is G_V+1 times as large as if C_{cb} were connected from base to ground; i.e., for the purpose of input rolloff frequency calculations, the feedback capacitance behaves like a capacitor of value $C_{cb}(G_V+1)$ from input to ground. This effective increase of C_{cb} is known as the Miller effect. It often dominates the rolloff characteristics of amplifiers, since a typical feedback capacitance of 4pF can look like several hundred picofarads to ground.

There are several methods available to beat the Miller effect. It is absent altogether in a grounded base stage. You can decrease the source impedance driving a grounded emitter stage by using an emitter follower. Figure 2.74 shows two other possibilities. The differential amplifier circuit (with no collector resistor in Q_1) has no Miller effect; you can think of it as an emitter follower driving a grounded base amplifier. The second circuit is the famous cascode configuration. Q_1 is a grounded emitter amplifier with R_L as its collector resistor. Q_2 is interposed in the collector path to prevent Q_1's collector from swinging (thereby eliminating the Miller effect) while passing the collector current through to the load resistor unchanged. V_+ is a fixed bias voltage, usually set a few volts above Q_1's emitter voltage to pin Q_1's collector and keep it in the active region. This fragment is incomplete as shown; you could either include a bypassed emitter resistor and base divider for biasing (as we did earlier in the chapter) or include it within an overall loop with feedback at dc. V_+ might be provided from a divider or zener, with bypassing to keep it stiff at signal frequencies.

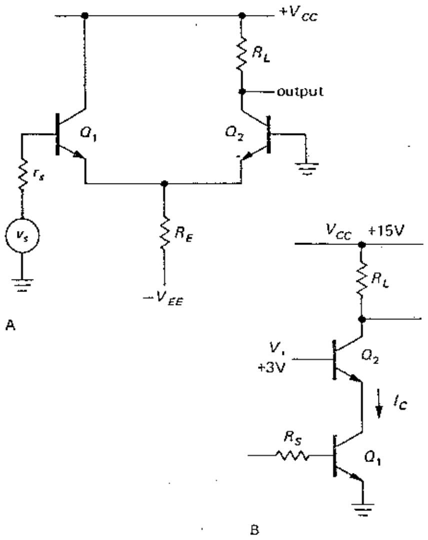


Figure 2.74. Two circuit configurations that avoid Miller effect. Circuit B is the cascode.

EXERCISE 2.14

Explain in detail why there is no Miller effect in either transistor in the preceding differential amplifier and cascode circuits.

Capacitive effects can be somewhat more complicated than this brief introduction might indicate. In particular: (a) The rolloffs due to feedback and output capacitances are not entirely independent; in the terminology of the trade there is pole splitting, an effect we will explain in the next chapter. (b) The input capacitance still