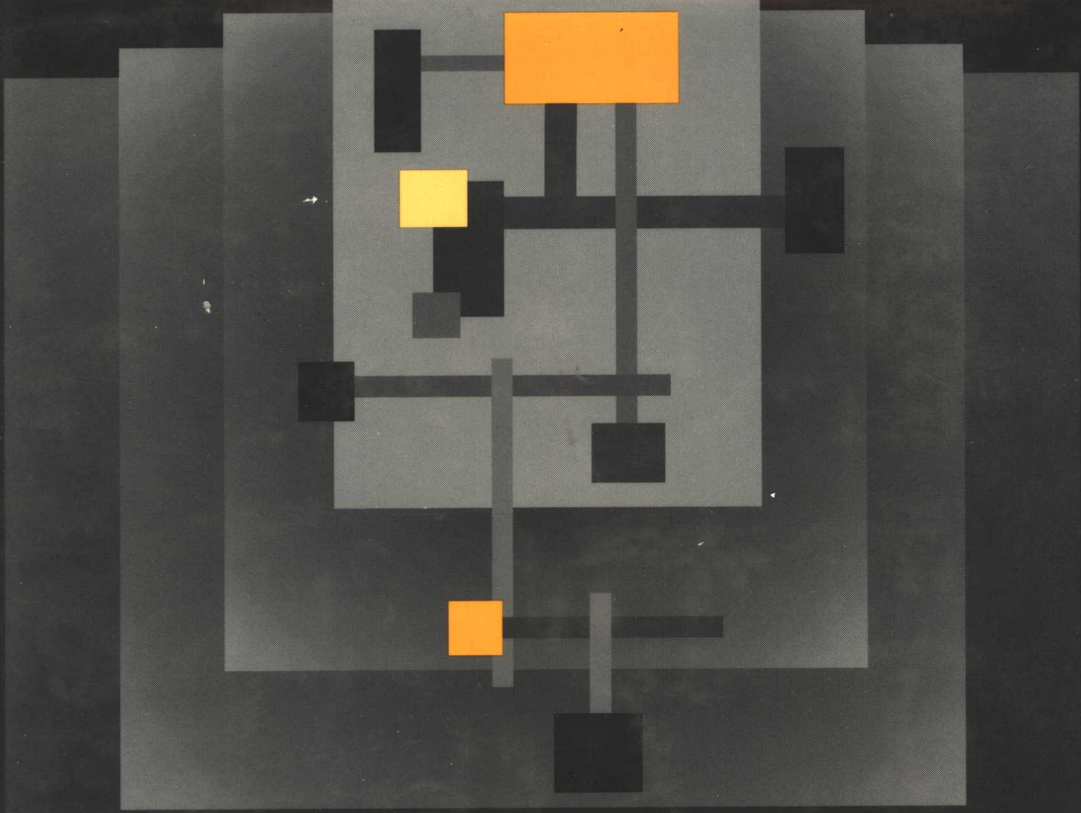

OPERATIONAL AMPLIFIERS

Integrated and Hybrid Circuits

George B. Rutkowski

OPERATIONAL AMPLIFIERS: INTEGRATED AND HYBRID CIRCUITS

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Computek

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PREFACE

For scientific and engineering applications, analog computers preceded digital computers. Analog computers were able to perform complex calculations with relatively few parts, an important advantage in the days when the parts were much larger and far less reliable than they are today. The basic building blocks of these analog computers were operational amplifiers (Op Amps). The early Op Amps were large, bulky vacuum tube circuits. As transistors replaced vacuum tubes, Op Amps became smaller, more reliable, and less expensive. These features, combined with the flexibility and ease of use of Op Amps, catapulted them into many industrial and military applications. The demands of the space age stimulated development and growth of integrated circuits (ICs) that offer more size reductions and much improved reliability. A large variety of IC Op Amps are now available. They are inexpensive and offer circuit designers virtually unlimited applications.

While digital ICs change convulsively with time, IC Op Amps are relatively stable. As a near-perfect electronic device for the niche it fills, the IC Op Amp has reached an evolutionary plateau. Metaphorically, we can say that there is an island of stability in the turbulent sea of electronics, the isle of the IC Op amp. Since old and new applications abound with Op Amps, you can rely on the knowledge that you gain here to be useful for many years to come.

For more than two decades, IC Op Amps have been mainly small-signal devices. This means that the signal power levels out of IC Op Amps are quite small; typically hundreds of milliwatts at best. In applications where signal power levels need to be larger, Op Amps are followed by power amplification. This typically includes one or more power amplifier stages that consist of discrete parts. Or, as is now the trend, the power stages and the preceding Op Amp are all placed into one package. This mix of ICs and discrete parts is called a hybrid circuit. A number of manufacturers are producing quality hybrid power Op Amps which are also discussed in this text.

In summary, this text was developed to:

1. provide an understandable and sufficiently detailed explanation of the IC and hybrid Op Amps for practicing or student engineers, technologists, and technicians;
2. serve as a text with abundant examples and end-of-chapter problems; and
3. be a reference by including a collection of Op Amp circuit applications with guidelines to selecting their component values and by providing manufacturers' data sheets with tables of Op Amp types and their comparative characteristics.

- Chapter 1 of this book contains a review of bipolar junction transistors (BJTs) and of unipolar transistors (FETs), their use in differential amplifiers, and the fundamentals of the circuitry inside an IC Op Amp. This chapter can be omitted if a functional block approach to Op Amps is preferred.
- Op Amps have a distinctive language of their own. Chapter 2 provides definitions and explanations of important Op Amp characteristics and compares their real practical values to hypothetical ideal ones.
- Chapters 3–7 contain detailed discussions of the significance of IC Op Amp parameters in common practical circuits. Manufacturers' data (spec) sheets are provided and frequently referenced in the way engineers and technologists are required to do in practice.
- Chapters 8–11 show and explain a variety of practical circuit applications with methods of selecting circuit component values emphasized.
- Chapter 12 discusses power amplification and the principles of power Op Amps. Power Op Amps are expensive and work at relatively high energy levels. Therefore, their proper use, including precautions and protections, is emphasized.
- When the source of an equation is relatively simple, it is explained in the text. Where the derivations are more complex or lengthy, they are given in the Appendices. These Appendices also include the manufacturers' Op Amp specifications (specs). Many application circuits are included also. BASIC programs that can plot gain versus frequency characteristics of active filters are listed. They can be used in conjunction with appropriate examples and end-of-chapter problems.
- A very thorough glossary of terms related to Op Amps and their applications is provided. This is useful, not only when learning the principles of Op Amps while progressing through this text, but also as a handy reference for years after.

George B. Rutkowski

Cleveland, Ohio
January 1993

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1

DIFFERENTIAL AND OPERATIONAL AMPLIFIERS

The differential amplifier, as its name implies, amplifies the difference between two input voltages. These input voltages are applied to two separate input terminals with respect to ground or a common. Their difference is called the *differential input voltage* V_{id}. The differential amplifier has two output terminals, and output signals can be taken from either output with respect to ground or across the two terminals themselves. The signals across the output terminals are usually amplified versions of the differential input voltages. Differential amplifiers, and variations of them, are found in many applications: measuring instruments, transducer amplifiers, industrial controls, signal generators, digital-to-analog (D/A) converters, and analog-to-digital (A/D) converters, to name just a few.

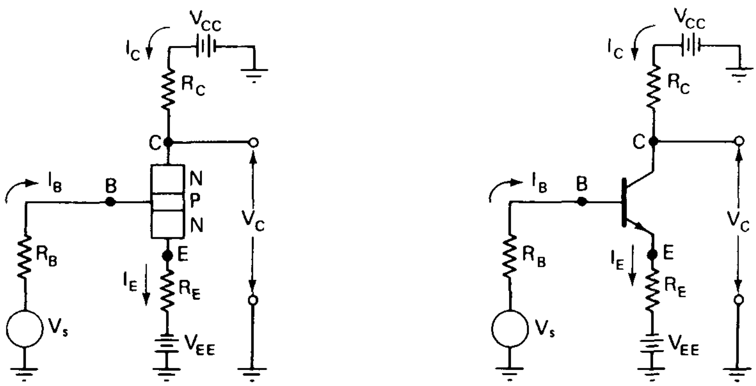
In this chapter we will first consider the construction and operating fundamentals of junction transistor and field-effect transistor differential amplifiers. Then we will see how differential amplifiers can be cascaded, as they are in typical *integrated circuits* (ICs), to obtain very high gain. Finally, we will see how level-shifting circuitry is added to modify the two output terminals of a differential-type circuit to a single output from which a signal can be taken with respect to ground or a common. Level shifting changes a differential amplifier into an *operational amplifier* (Op Amp).

1.1 TRANSISTOR REVIEW

Since bipolar junction transistors (BJTs) and field-effect transistors (FETs) are frequently used in discrete and IC differential and operational amplifiers, a review of these devices is helpful in developing an understanding of the inner workings of linear ICs.

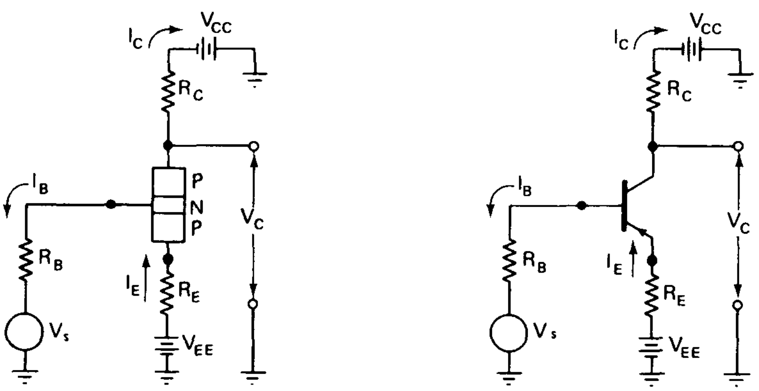
The *junction transistor* is a current-operated device with three terminals: an emitter E, a collector C, and a base B. In most applications, the relatively small base current I_B is controlled or varied by a signal source. The varying base current I_B in turn controls or varies a much larger collector current I_C and emitter current I_E.

Properly biased transistors are shown in Fig. 1-1. The term *bias* refers to the use of proper dc voltages on the transistor that are necessary to make it work as an amplifier. As shown in Fig. 1-1, the collector C is biased positively



(a) The NPN transistor contains a P-type semiconductor between two N-type materials.

(b) Arrow on emitter points out on NPN transistor symbol.



(c) The PNP transistor contains N-type semiconductor between two P-type materials.

(d) Arrow on the emitter points in on PNP transistor symbol.

Figure 1-1 Properly biased transistor circuits.

with respect to the emitter E on NPN transistors, whereas the collector C is normally negative with respect to the emitter E on PNP transistors. In either case, a NPN or PNP circuit, the base-emitter junction of N- and P-type semiconductors is forward biased. This means that V_{EE} is applied with a polarity that will cause current I_B across the base-emitter junction. The values of V_{EE}, V_S, R_E, and R_B determine the value of I_B.

As base current flows, it causes a collector current flow I_C that is about β* or h_{FE} times larger. That is,

$$\boxed{I_C \cong \beta I_B} \tag{1-1}$$

or

$$\boxed{I_C \cong h_{FE} I_B,} \tag{1-2}$$

where β or h_{FE} is specified by the transistor manufacturer. In modern transistors, h_{FE} typically ranges from about 60 to 200. Thus, the base current I_B is typically smaller than the collector current I_C by a factor between 60 and 200.

Note in Fig. 1-1 that the sum of the currents I_B and I_C is equal to I_E. That is,

$$\boxed{I_E = I_C + I_B.} \tag{1-3}$$

Since I_C is typically much larger than I_B, the base current I_B is often assumed negligible compared to either I_C or I_E. Therefore, Eq. (1-3) can be simplified to

$$\boxed{I_E \cong I_C.} \tag{1-4}$$

Variations of the input voltage V_s on any of the circuits of Fig. 1-1 will cause variations of I_B, which in turn varies I_C flowing through R_C. Thus the voltage across R_C and the output voltage V_C will vary too. Usually, the output variations of V_C are much larger than the input variations of V_s, which means that these circuits are capable of voltage gain—also called voltage amplification A_v.

The *field-effect transistor*, FET, unlike the junction transistor, draws negligible current from the signal source V_s and therefore is referred to as a voltage-operated device. It has three terminals: a source S, a drain D, and a

*A transistor's beta (β) is about equal to its h_{FE}. In the symbol h_{FE}, the h means *hybrid* parameter, F means *forward* current transfer ratio, and E means that the *emitter* is common. The capital letters in subscript in h_{FE} specify that this is a dc parameter or dc beta.

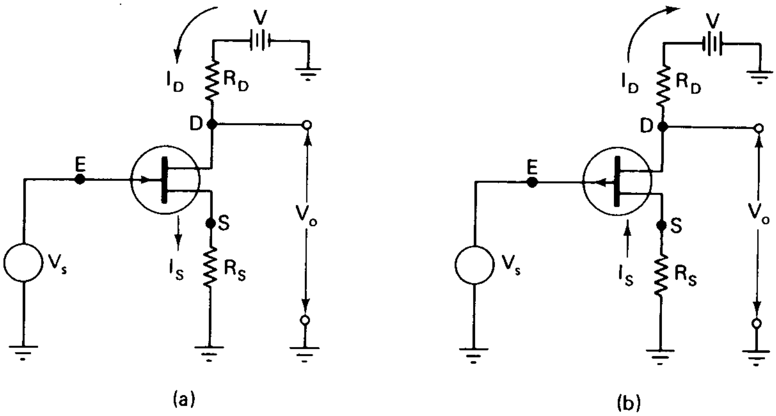


Figure 1-2 Properly biased FETs: (a) N channel, (b) P channel.

gate G. Properly biased FETs are shown in Fig. 1-2. Basically, variations of a voltage across the gate G and the source S cause drain current I_D and source current I_S variations. Thus, a varying input signal V_s causes a varying gate-to-source voltage V_{GS} which in turn varies I_D, the drop across R_D, and the output voltage V_o. The ratio of the change in drain current I_D to the change in gate-to-source voltage V_{GS} is the FET's transadmittance* g_m; that is,

$$\boxed{g_m \cong \frac{\Delta I_D}{\Delta V_{GS}}.} \tag{1-5}$$

Because of the very high gate input resistance of the FET, negligible gate current flows, and therefore the drain and source currents are essentially equal; that is, $I_D = I_S$. FET amplifiers are capable of voltage gain, but not as high as junction transistors. FETs are used where extremely high input resistance is important, as in some applications of differential and operational amplifiers. As we will see, some types of Op Amps on ICs have FETs in their first stage.

FETs are made in two general types: (1) junction field effect transistors, JFETs, whose input resistances are on the order of 10^6 to 10^9 ohms, and whose symbols appear in Fig. 1-2, and (2) metal-oxide silicon field effect transistors, MOSFETs, which are also known as insulated gate field-effect transistors, IGFETs. MOSFETs or IGFETs have higher gate input resistance values than do JFETs, typically 10^{10} to 10^{14} ohms. Some common symbols in use for MOSFETs are shown in Fig. 1-3.

*The forward transadmittance, sometimes called *transconductance*, is referred to by several symbols: y_{fs}, g_{fs}, g_m, and g_{21}.

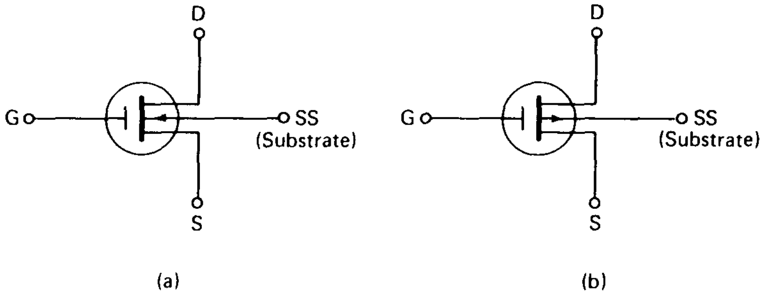


Figure 1-3 Symbols used to represent MOSFETs or IGFETs: (a) N channel, (b) P channel.

1.2 THE DIFFERENTIAL CIRCUIT

Figure 1-4a shows a simple BJT differential amplifier, and Fig. 1-4b, its typical symbol. If signal voltages are applied to input terminals 1 and 2, their difference V_{id} is amplified and appears as V_{od} across output terminals 3 and 4. Ideally, if both inputs are at the same potential with respect to ground or a common point, causing an input differential voltage $V_{id} = 0$ V, the differential output voltage $V_{od} = 0$ V too, regardless of the circuit's gain.

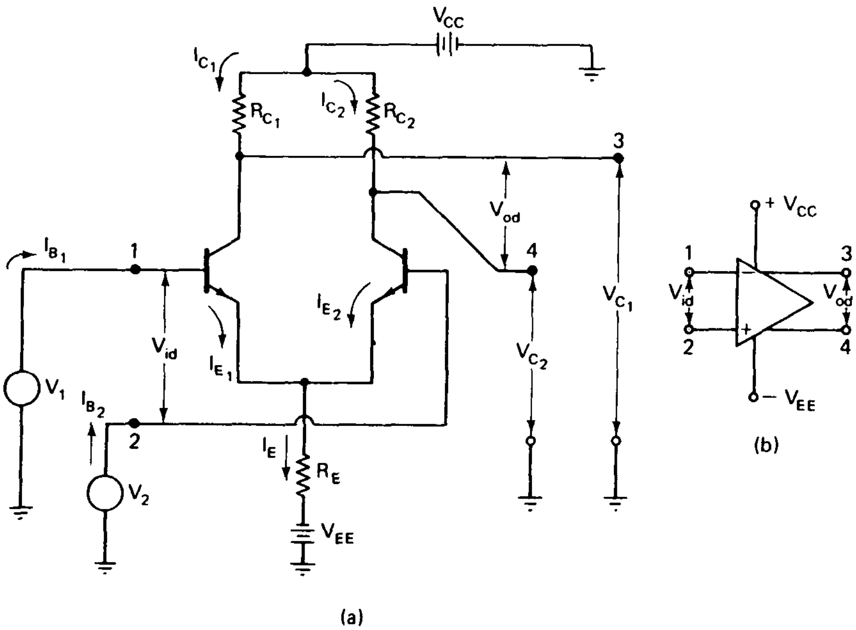


Figure 1-4 (a) Simple differential amplifier, (b) symbol for the differential amplifier.

With input signal sources V_1 and V_2 applied as shown in Fig. 1-4, each base has a dc path to ground, and base currents I_{B_1}, and I_{B_2} flow. If the average voltages and internal resistances of the signal sources V_1 and V_2 are equal, then equal base currents flow. This causes equal collector currents $I_{C_1} = I_{C_2}$ and equal emitter currents I_{E_1} and I_{E_2}, assuming that the transistors have identical characteristics. Since β or h_{FE} of a typical transistor is much larger than 1, the base current is very small compared to the collector or the emitter current, and therefore the collector and emitter currents are about equal to each other [see Eqs. (1-3) and (1-4)]. In this circuit, the current I_E in resistor R_E is equal to the sum of currents I_{E_1} and I_{E_2}. This current can be approximated with the equation

$$\boxed{I_E = \frac{V_{EE} - V_{BE}}{R_E + R_B/2h_{FE}},} \qquad (1\text{-}6)^*$$

where V_{BE} is the dc drop across each forward-biased base-emitter junction, which is in the range of about 0.5 to 0.7 V in silicon transistors and about 0.1–0.3 V in germanium transistors, and

R_B is the dc resistance seen looking to the left of either input terminal 1 or 2. In the circuit of Fig. 1-4, R_B is the internal resistance of each signal source.

Since the dc source voltage V_{EE} is usually much larger than the base-emitter drop V_{BE}, and since R_E is frequently much larger than $R_B/2h_{FE}$, Eq. (1-6) can often be simplified to

$$\boxed{I_E \cong \frac{V_{EE}}{R_E}.} \qquad (1\text{-}7)$$

The significance of Eq. (1-7) is that the value of I_E is determined mainly by the values of V_{EE} and R_E and that if V_{EE} and R_E are fixed values, the current I_E is practically constant. Ideally, I_E should be very constant for reasons we will see later. The source V_{EE} and resistor R_E, or their equivalent, are often represented with the symbol for a constant-current source shown in Fig. 1-5b.

The dc voltage to ground at each output terminal is simply the V_{CC} voltage minus the drop across the appropriate collector resistor. Thus the voltage at

*See Appendix A for derivation.

output 3 to ground, in Fig. 1-4, is

$$\boxed{V_{C_1} = V_{CC} - R_{C_1} I_{C_1}.} \tag{1-8a}$$

Similarly, the voltage at output 4 to ground is

$$\boxed{V_{C_2} = V_{CC} - R_{C_2} I_{C_2}.} \tag{1-8b}$$

Their difference is the output differential voltage

$$\boxed{V_{od} = V_{C_1} - V_{C_2},} \tag{1-9}$$

just as the input differential voltage is

$$\boxed{V_{id} = V_1 - V_2}. \tag{1-10}$$

With I_E constant, as in the circuit of Fig. 1-4, the sum of the collector currents $I_{C_1} + I_{C_2}$ is also constant. Thus, if I_{C_1} is increased, I_{C_2} is forced to decrease, and vice versa. In other words, if the input voltage V_1 is made more positive, base current I_{B_1} increases, increasing I_{C_1} and the voltage drop across R_{C_1}. This in turn causes the voltage V_{C_1} at output 3 to ground to decrease. And the increase in I_{C_1} forces I_{C_2} to decrease, which decreases the drop across R_{C_2} and increases the voltage V_{C_2} at output 4. On the other hand, if V_1 is made more negative than V_2, causing a larger differential input voltage V_{id} of opposite polarity, then output 3 becomes more positive while output 4 becomes more negative.

The ratio of the output voltage V_{od} to the input V_{id} is the differential voltage gain A_d of the differential amplifier. Therefore, combining Eqs. (1-9) and (1-10), we can show that

$$\boxed{A_d = \frac{V_{od}}{V_{id}} = \frac{V_{C_1} - V_{C_2}}{V_1 - V_2}.} \tag{1-11}$$

The differential gain can be estimated with the following equation:

$$\boxed{A_d \cong \frac{R_C}{r'_e + R_B/h_{fe}},} \tag{1-12a}^*$$

*See Appendix B for derivation. The parameter r'_e is the dynamic (ac) resistance of the forward-biased emitter-base junction and is also referred to as h_{ib}. It is a hybrid parameter for the input resistance of a common emitter amplifier.