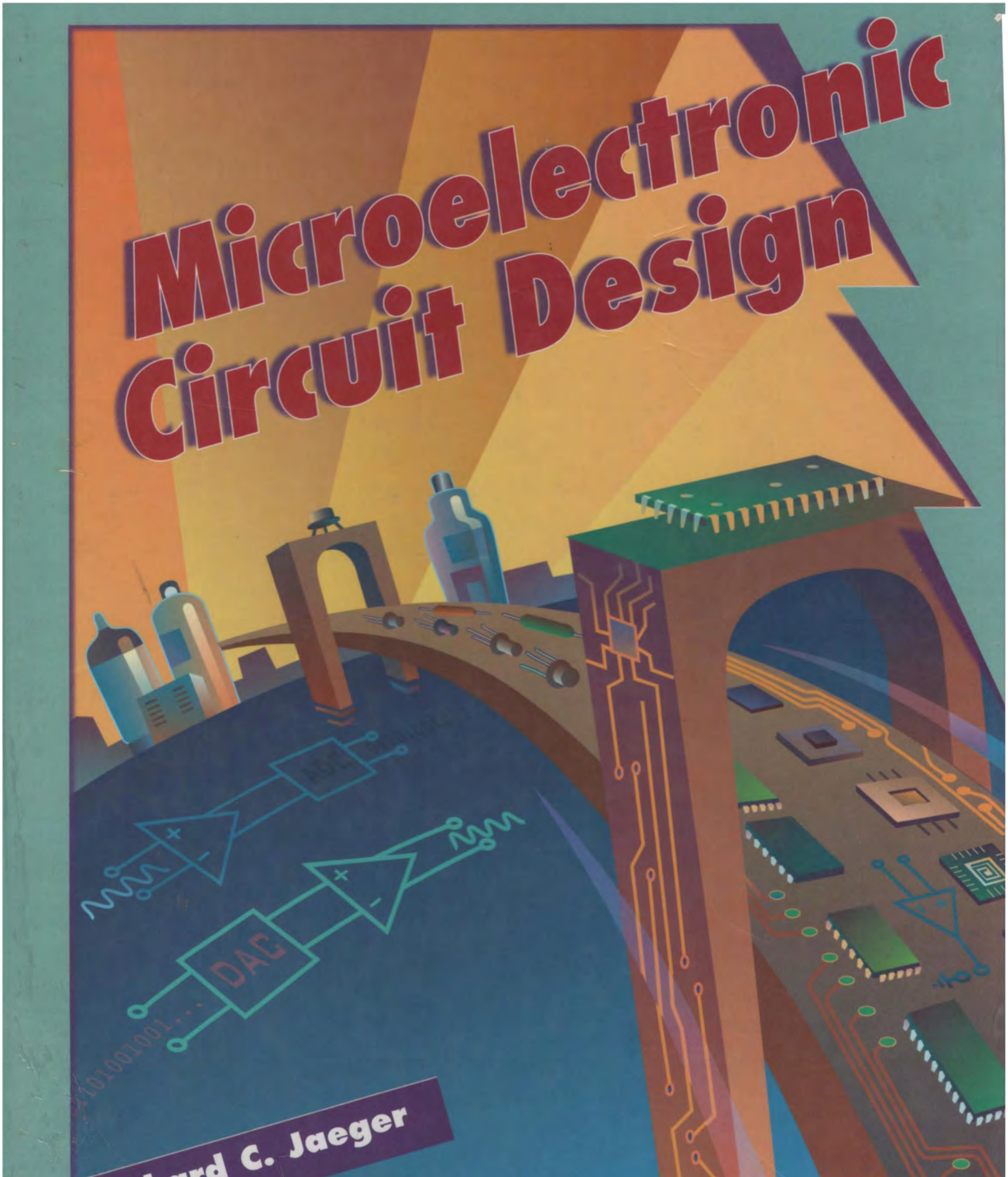
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12.1 THE DIFFERENTIAL AMPLIFIER

The basic **differential amplifier** is shown in schematic form in Fig. 12.1. The amplifier has two inputs, to which the input signals v_+ and v_- are connected, and a single output v_O, all referenced to the common (ground) terminal between the two power supplies V_{CC} and V_{EE}. In most applications, $V_{CC} \geq 0$ and $-V_{EE} \leq 0$, and the voltages are often symmetric—that is, ±5 V, ±12 V, ±15 V, ±18 V, ±22 V, and so on. These power supply voltages limit the output voltage range: $-V_{EE} \leq v_O \leq V_{CC}$.

For simplicity, the amplifier is most often drawn without explicitly showing the power supplies, as in Fig. 12.2(a), or the ground connection, as in Fig. 12.2(b)—but we must remember that the power and ground terminals are always present in the implementation of a real circuit.

For purposes of signal analysis, the differential amplifier can be represented by its input resistance R_{ID}, output resistance R_O, and controlled voltage source Av_{id}, as in Fig. 12.3. This is the simplified g-parameter two-port representation from Chap. 11 with $g_{12} = 0$.

$$\begin{aligned} A &= \text{voltage gain (open-circuit voltage gain)} \\ v_{id} &= (v_+ - v_-) = \text{differential input signal voltage} \\ R_{ID} &= \text{amplifier input resistance} \\ R_O &= \text{amplifier output resistance} \end{aligned} \tag{12.1}$$

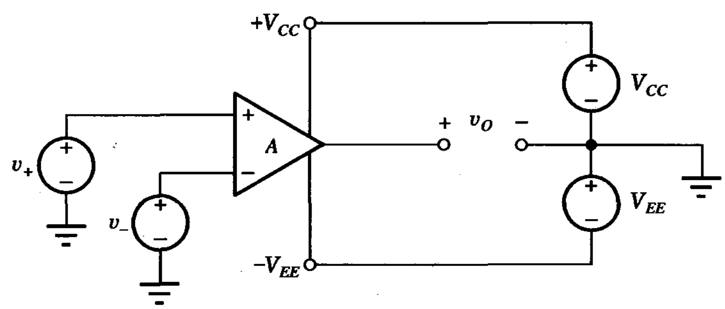

Figure 12.1 The differential amplifier, including power supplies.

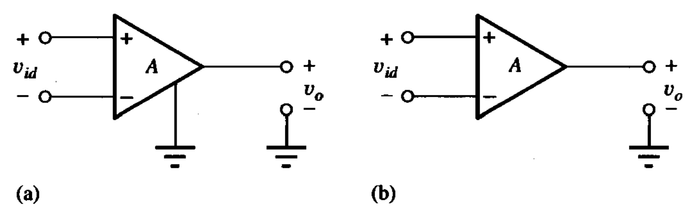

Figure 12.2 (a) Amplifier without power supplies explicitly included. (b) Differential amplifier with implied ground connection.

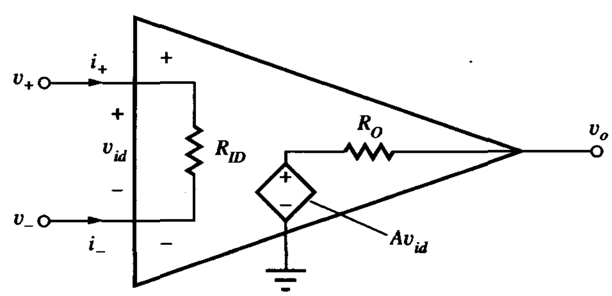

Figure 12.3 Differential amplifier.

The signal voltage developed at the output of the amplifier is in phase with the voltage applied to the + input terminal and 180° out of phase with the signal applied to the − input terminal. The v_+ and v_- terminals are therefore referred to as the **noninverting input** and **inverting input,** respectively.

In a typical application, the amplifier is driven by a signal source having a Thévenin equivalent voltage v_S and resistance R_S and is connected to a load represented by the resistor R_L, as in Fig. 12.4. For this simple circuit, the output voltage can be written in terms of the dependent source as

$$\mathbf{v_o}^* = A\mathbf{v_{id}}\frac{R_L}{R_O + R_L} \tag{12.2}$$

and the voltage $\mathbf{v_{id}}$ is

$$\mathbf{v_{id}} = \mathbf{v_s}\frac{R_{ID}}{R_{ID} + R_S} \tag{12.3}$$

Combining Eqs. (12.2) and (12.3) yields an expression for the overall voltage gain of the amplifier circuit in Fig. 12.4 for arbitrary values of R_S and R_L:

$$A_V = \frac{\mathbf{v_o}}{\mathbf{v_s}} = A\frac{R_{ID}}{R_S + R_{ID}}\frac{R_L}{R_O + R_L} \tag{12.4}$$

Operational-amplifier circuits are most often **dc-coupled amplifiers,** and the signals v_o and v_s may in fact have a dc component that represents a dc shift of the input away from the Q-point. The op amp amplifies not only the ac components of the signal but also this dc component. We must remember that the ratio needed to find A_V, as indicated in Eq. (12.4), is determined by the amplitude and phase of the individual signal components and is not a time-varying quantity, but $\omega = 0$ is a valid signal frequency!

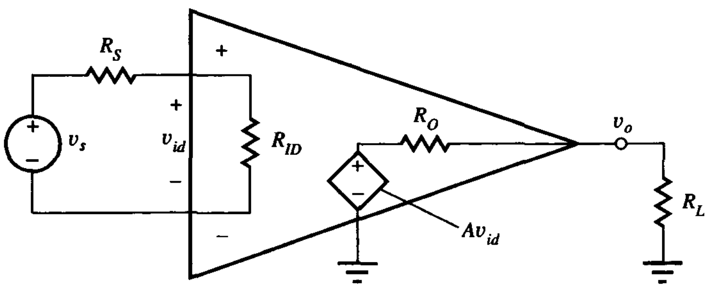

Figure 12.4 Amplifier with source and load attached.

EXAMPLE 12.1: Calculate the voltage gain for an amplifier with the following parameters: $A = 100$, $R_{ID} = 100\ \text{k}\Omega$, and $R_O = 100\ \Omega$, with $R_S = 10\ \text{k}\Omega$ and $R_L = 1000\ \Omega$. Express the result in dB.

SOLUTION: Using Eq. (12.4)

$$A_V = 100\left(\frac{100\ \text{k}\Omega}{10\ \text{k}\Omega + 100\ \text{k}\Omega}\right)\left(\frac{1000\ \Omega}{100\ \Omega + 1000\ \Omega}\right) = 82.6$$

$$A_{V\text{dB}} = 20\log|A_V| = 20\log|82.6| = 38.3\ \text{dB}$$

Author's note:* Recall from Chapters 1 and 11 that v_s, v_o, i_2 and so on represent our signal voltages and currents and are generally functions of time: $v_s(t)$, $v_o(t)$, $i_2(t)$. But whenever we do algebraic calculations of voltage gain, current gain, input resistance, output resistance, and so on, we must use **phasor representations of the individual signal components in our calculations: $\mathbf{v_s}$, $\mathbf{v_o}$, $\mathbf{i_2}$. Note that the signals $v_s(t)$, $v_o(t)$, $i_2(t)$ may be composed of many individual signal components, one of which may be a dc shift away from the Q-point value.

DISCUSSION: The amplifier's internal voltage gain capability is $A = 100$, but an overall gain of only 82.6 is being realized because a portion of the signal source voltage ($\approx$ 9 percent) is being dropped across R_S and part of the internal amplifier voltage (Av_{id}) (also $\approx$ 9 percent) is being lost across R_O. ◆

The Ideal Differential Amplifier

An ideal differential amplifier would produce an output that depends only on the voltage difference v_{id} between its two input terminals, and this voltage would be independent of source and load resistances. Referring to Eq. (12.4), we see that this behavior can be achieved if the input resistance of the amplifier is infinite and the output resistance is zero (as pointed out previously in Sec. 11.5). For this case, Eq. (12.4) reduces to

$$\mathbf{v_o} = A\mathbf{v_{id}} \quad \text{or} \quad A_V = \frac{\mathbf{v_o}}{\mathbf{v_{id}}} = A \tag{12.5}$$

and the full amplifier gain is realized. A is referred to as either the **open-circuit voltage gain** or **open-loop gain** of the amplifier and represents the maximum voltage gain available from the device.

As also mentioned in Chapter 11, we often want to achieve the fully mismatched resistance condition in voltage amplifier applications ($R_{ID} \gg R_S$ and $R_O \ll R_L$), so that maximum voltage gain in Eq. (12.5) can be achieved. For the mismatched case, the overall amplifier gain is independent of the source and load resistances, and multiple amplifier stages can be cascaded without concern for interaction between stages.

12.2 THE IDEAL OPERATIONAL AMPLIFIER

As noted earlier, the term "operational amplifier" grew from use of these high-performance amplifiers to perform specific electronic circuit functions or operations, such as scaling, summation, and integration, in analog computers. The operational amplifier used in these applications is an ideal differential amplifier with an additional property: infinite voltage gain. Although it is impossible to realize the **ideal operational amplifier,** its conceptual use allows us to understand the basic performance to be expected from a given analog circuit and serves as a model to help in circuit design. Once the properties of the ideal amplifier and its use in basic circuits are understood, then various ideal assumptions can be removed in order to understand their effect on circuit performance.

The ideal operational amplifier is a special case of the ideal difference amplifier in Fig. 12.3, in which $R_{ID} = \infty$, $R_O = 0$, and, most importantly, voltage gain $A = \infty$. Infinite gain leads to the first of two assumptions used to analyze circuits containing ideal op amps. Solving for $\mathbf{v_{id}}$ in Eq. (12.5),

$$\mathbf{v_{id}} = \frac{\mathbf{v_o}}{A} \quad \text{and} \quad \lim_{A\to\infty} \mathbf{v_{id}} = 0 \tag{12.6}$$

If A is infinite, then the input voltage v_{id} will be zero for any finite output voltage. We will refer to this condition as Assumption 1 for ideal op-amp circuit analysis.

An infinite value for the input resistance R_{ID} forces the two input currents i_+ and i_- to be zero, which will be Assumption 2 for analysis of ideal op-amp circuits. These two results, combined with Kirchhoff's voltage and current laws, form the basis for analysis of all ideal op-amp circuits.