INTRODUCTION TO OPERATIONAL AMPLIFIER THEORY AND APPLICATIONS

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Introduction to Operational Amplifier Theory and Applications

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PREFACE

During the 1960s transistorized solid-state amplifier technology evolved rapidly. Today such amplifiers in microminiature form have become basic building blocks that are used in a broad range of electronic circuit applications, e.g., amplification, filtering, nonlinear waveshaping, waveform generation, and switching. This text has been developed to be used with a course in operational amplifier circuit design for senior and graduate students in electrical engineering; it is intended to cover techniques of analysis and design of electronic circuits, using operational amplifiers, resistors, capacitors, diodes, and other special components as needed.

This book does not discuss the internal design of operational amplifiers themselves. Considerable attention is paid, however, to the ways in which nonideal properties that arise from internal design limitations affect circuit performance. The text assumes the typical background of an electrical engineering senior, including some prior knowledge of Laplace transforms, frequency response operators, and Bode plots, and a basic feeling for solid-state device characteristics.

This book should also be quite useful to the practicing electrical engineer as a self-teaching aid and as a source of applications ideas.

Chapter 1 provides a thorough presentation of *basic linear operational amplifier circuit design,* using the *ideal operational amplifier model.* This chapter also reviews important active circuit analysis techniques in general by using many examples. The ideal model is carefully defined, with an eye toward a treatment of nonideal effects in Chapter 2. The following sections present detailed discussions of the major circuit configurations, including the summer-inverter, the inverting summer-integrator (including mode control), the generalized inverting amplifier with two-port networks, the noninverting amplifier, and the differential amplifier. The eighth section is a general discussion of combined inverting and noninverting summer-amplifiers, which is not readily available elsewhere. The ninth section describes important first-order filter circuits; we postpone a detailed treatment of active *RC* filter circuits until Chap. 4, however. The last section presents a few of the well-known miscellaneous applications, such as instrumentation amplifiers, reference sources, and voltage-current converters. The reader will also find that the more advanced exercises will suggest many more useful applications.

Chapter 2 discusses means for analyzing the effects of *amplifier performance limitations* (nonidealness) on circuit performance. A general nonideal small-signal linear model is presented first, and we discuss techniques based on this model that may be used to estimate closed-loop circuit gain and circuit output and input impedance. Next we present a discussion of Bode plot techniques for estimating closed-loop circuit stability, and the problem of compensation is examined. Common-mode effects are described in the fourth section. Dc offsets and temperature drift effects are described in the fifth section, and standard compensation and balancing techniques are also described. A description of random noise effects, based upon a power spectral density model, is presented in the sixth section; the reader may want to skip this part on a first reading, since some appreciation of the principles of random process theory is required in order to apply the model. Large-signal limitations are discussed in the seventh section, e.g., slewing rate, full-power bandwidth, settling time, overload recovery time, and maximum common-mode voltage. The last three sections are devoted to some practical considerations involved in operational amplifier use. The eighth section discusses output power boosting techniques; the ninth section surveys power-supply requirements, grounding, and shielding; and finally, the last section describes the typical properties of passive components used in linear circuit design.

Chapter 3 is concerned with the design of *nonlinear circuits.* This chapter presents a number of nonlinear circuit design methods that are hopefully of general value. Piecewise-linear diode and transistor models are reviewed and applied to some simple examples. The second section discusses a variety of limiter and comparator circuits, and compares their merits. The use of hysteresis for noise-immune comparator design is included. General piecewise-linear-function generation methods are presented in the third section. The fourth section is devoted to logarithmic operators to help the reader evaluate these types of nonlinear operators in a specific application. Conventional methods for multiplying, dividing, and squaring are described and compared in the fifth section, and typical applications are presented. Finally, the sixth section presents a collection of well-known waveform generation circuits. Again, the examples and exercises suggest additional applications.

The remaining chapters cover advanced applications. Chapter 4 discusses one of the more important applications of operational amplifiers, namely, *active* RC *filters.* In the first section, some general design and analysis techniques are introduced. A discussion of sensitivity is included to permit the reader to evaluate different filter realizations. The following two sections present several of the most important filter configurations. These include the Sallen and Key structures and the infinite-gain multiple feedback configurations. The fourth section covers active *RC* filter realizations for the high-*Q* case. Both state-variable and Tarmy-Ghausi realizations are presented. The effect of finite amplifier bandwidth on the realizations is discussed. In the fifth section, the use of cascade techniques to realize filters of higher than second order is covered. The sixth and seventh sections discuss alternative methods of active *RC* filter realization, including the use of gyrators or negative-impedance converters, and the recently proposed technique of using frequency-dependent negative resistors as produced by generalized impedance converters. In all cases, design tables are provided which enable the reader to easily realize specific filter configurations for several of the commonest maximally flat magnitude (Butterworth), equal ripple (Chebychev), maximally flat delay (Thomson), and elliptic (Cauer) characteristics. Approximation tables for these characteristics are provided through the sixth order. In many cases alternative realizations are provided to make fabrication easier by specifying equal-valued *R* and *C* elements or to reduce sensitivity by using integer-valued gains. A discussion of tuning procedures for high-order realizations is also included. Many of the tables included in this chapter have never before appeared in the literature. Of special importance is the compilation of quadratic factors for a wide range of high-order filter characteristics.

Chapter 5 introduces up-to-date *electronic switching circuits*, including diode, transistor, JFET, MOSFET, and CMOS switches. Many examples show how to minimize circuit error due to leakage, ON resistance, offsets, and switching spikes. Electronic multiplexer circuits, sample-holds, and integrator-control switching are discussed, together with error sources and modern design practice.

Chapter 6 deals with *digital-to-analog and analog-to-digital converters*, both now low-cost, indispensable items in the system designer's bag of tricks. Separate sections describe digital codes, representation of negative voltages, and voltage, inverted, and current ladder circuits. The text then goes on to describe the design and use of current-switching monolithic digital-to-analog converters, error sources, and settling time. Descriptions of the principal types of analog-to-digital converters include the complete logic for a simple successive-approximation converter. A final section shows how to interpret function-module specifications.

There is clearly more material provided than one can thoroughly cover in a typical three-hour one-semester course. This has been done intentionally so that the book may be used for both an in-depth course on design fundamentals and a survey course on applications. We have been using class notes, from which this book originated, in a senior technical elective at the University of Arizona for four years, with considerable success. Our approach is to spend about 40 percent of the semester on the fundamental principles in Chaps. 1 and 2; we work many problems here. Then we use the material of Chap. 3 for about 20 percent of the course, with the primary goal of sharpening up the student's ability to design and analyze nonlinear circuits using primarily piecewise-linear diode and transistor models. The remaining 40 percent of the course is devoted to surveying the applications described in Chaps. 4 to 6.

Depending upon specific course goals, other instructors might choose a different emphasis. For example, Chaps. 1 to 3 form a nice introduction to design fundamentals; indeed, Chap. 1 could serve alone for a one-hour introductory course unit. Chapter 2 could be skipped if one wanted to put more emphasis on applications and less on detailed design. Chapters 1 and 4 together would support a full course in active *RC* filter design, with more time spent on the advanced problems provided at the end of Chap. 4. Chapters 1, 5 and 6 would similarly serve for a course in A/D, D/A, and data acquisition subsystems.

We have many friends who have contributed to the development of the book, and there is no room to thank them all. We do want to expressly thank Dr. Roy H. Mattson, Head of the Department of Electrical Engineering of the University of Arizona, for the assistance of the department in the course of this book's preparation. Thanks should also go to Dr. Gerald R. Peterson, who encouraged us to start the course from which this text has evolved. We are also particularly grateful to the Burr-Brown Research Corporation and Analog Devices, Inc., for providing technical specifications and applications information. Finally, we must very gratefully thank the many students in EE 226, who over the years have assisted in the proofreading and criticizing of the manuscript, including Mssrs. Yuchee Chih and Thomas Bruhns.

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1

BASIC OPERATIONAL AMPLIFIER CIRCUITS

During the 1960s the solid-state dc operational amplifier grew rapidly in importance to the electronic circuit designer. Today, such amplifiers, in microminiature form (Fig. 1.1), have become so *reliable, compact,* and *easy to use* that they are *basic electronic circuit building blocks* used in an extremely broad range of applications, including amplification, filtering, nonlinear waveshaping, wave generation, and switching. Today, instead of assembling an amplifier from dozens of components, the wise circuit designer frequently develops his circuit around a few standard, commercially available *prepackaged operational amplifiers,* which *comprise the active elements;* the rest of the circuit will be made up of resistors, capacitors, diodes, and other special components as needed.

The use of such standard active elements eliminates the need for detailed design of individual transistor stages. When they are properly used, the overall transfer characteristics of a circuit (gain, frequency response, etc.) can be precisely controlled by stable passive elements (e.g., resistors, capacitors, diodes). *Feedback techniques* are used to suppress any nonideal properties of the operational amplifier so that individual variations

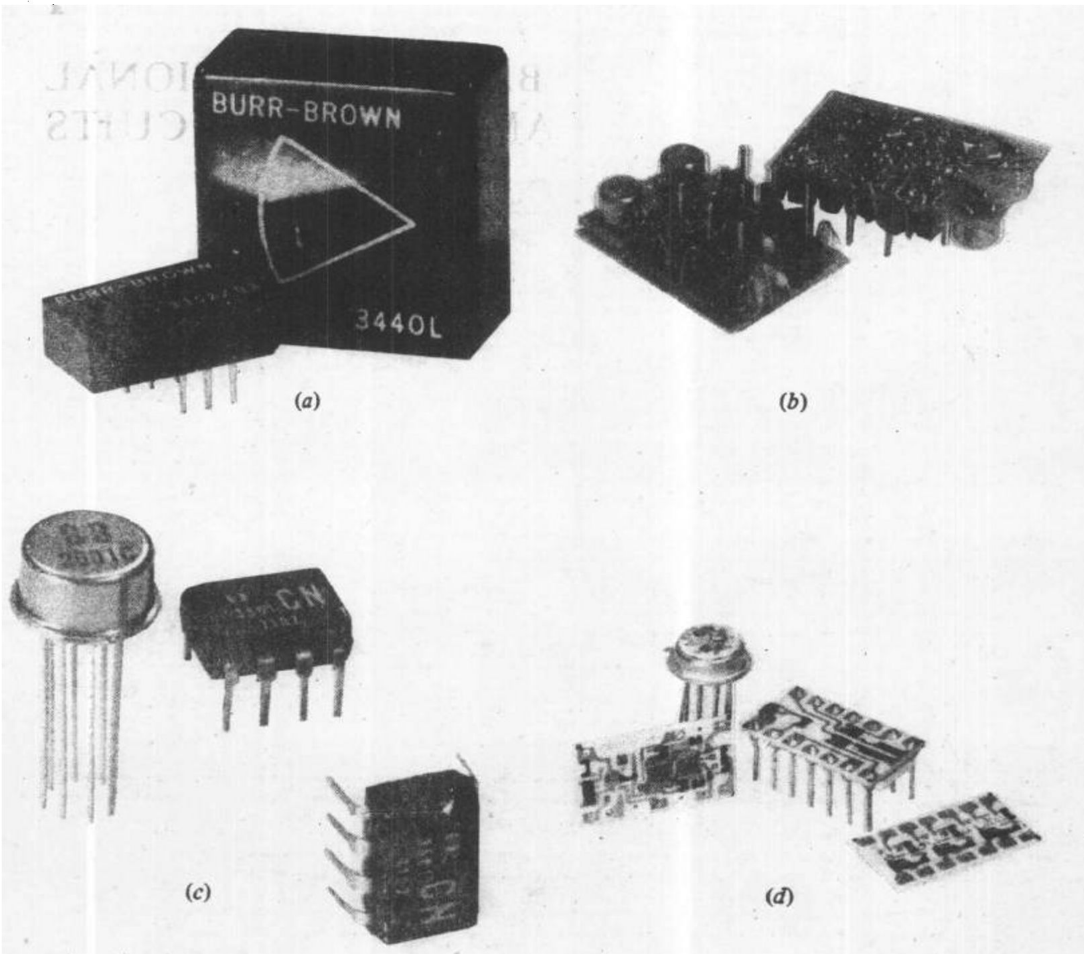


FIGURE 1.1
Operational amplifier packaging. (*a*) Epoxy-encapsulated amplifier made up of discrete components; (*b*) interior construction of discrete-component units; (*c*) typical packaging of integrated-circuit units; (*d*) hybrid construction.

in particular amplifiers have a negligible effect on final circuit performance. Hence circuit designs based on the use of operational amplifiers usually have ***highly predictable performance.***

When most of the active elements of a circuit are concentrated into the small space occupied by a modern solid-state operational amplifier, ***miniaturization*** of electronic circuits ***is facilitated.*** Moreover, today's operational amplifiers are ***highly reliable,*** and the circuit designer can expect that production copies of his final system will closely emulate the performance of the prototype, and will require a minimum of initial debugging and little long-term maintenance (if he has chosen operational amplifiers supplied by a competent manufacturer).

1.1 GENERAL CHARACTERISTICS OF OPERATIONAL AMPLIFIERS

Fig. 1.1 shows some typical operational amplifier modules. Two basic methods of fabrication are employed: discrete and integrated-circuit. In Fig. 1.1*a*, we see an epoxy-encapsulated amplifier made up of discrete elements, viz., transistors and resistors. In such a form, the elements are usually mounted on small printed-circuit boards (Fig. 1.1*b*). Connecting pins are attached to one of the boards, and the final unit is surrounded by the encapsulating material. Both bipolar and field-effect transistors (FETs) may be employed. Integrated-circuit operational amplifiers are currently made using conventional monolithic techniques, and packaged either in a round TO-99 type of transistor case or in an epoxy-clad dual-in-line package (Fig. 1.1*c*). Hybrid thin-film, thick-film, and/or monolithic IC techniques may also be used (Fig. 1.1*d*).

In this book we will not discuss the techniques for designing the operational amplifier itself; the reader is referred to Refs. 1 to 3 for information about the internal design of modern solid-state operational amplifiers. We are primarily interested here in *applications* of operational amplifiers to signal-processing tasks (see also Refs. 1, 3 to 6, and 12 as further sources of application ideas).

Figure 1.2 illustrates the typical environment in which an operational amplifier is used. Often several operational amplifiers in a given system are supplied from a single pair of matched positive and negative sources of regulated dc power (for example, ±15 V) via low-impedance dc buses. An internal ground lead is sometimes provided on the amplifier package, although typically *all signals* are merely *referenced* to the *power* supply common-ground potential (see Sec. 2.9 for details of power and grounding systems). Operational amplifiers usually have two input terminals (inverting and noninverting) and an output terminal. In addition to these main signal terminals, connector pins are sometimes provided for connection of frequency response compensation and dc offset balancing networks.

Figure 1.3 shows the conventional operational amplifier symbol that will be used throughout this text. In this symbol, only the principal signal terminals are illustrated; the other necessary connections to the amplifier (for power, etc.) are assumed to be made as specified by the amplifier manufacturer.

Table 1.1 lists the features normally required in an operational amplifier.

1.2 THE IDEAL AMPLIFIER MODEL

In this chapter we will present the so-called ideal operational amplifier model (Fig. 1.4*b* or *c*); in the next chapter, the important nonideal properties of actual amplifiers will be described, and methods for estimating their effect on circuit performance will be treated. Here, however, we will neglect almost all the nonideal properties and describe an operational amplifier in terms of how we would like it to behave. First of all, we will assume there are no internal dc offsets or nonlinearities associated with the amplifier. With this assumption, we can represent an operational amplifier fairly completely by the idealized linear model of Fig. 1.4*a*. Here we see that the operational amplifier is an active

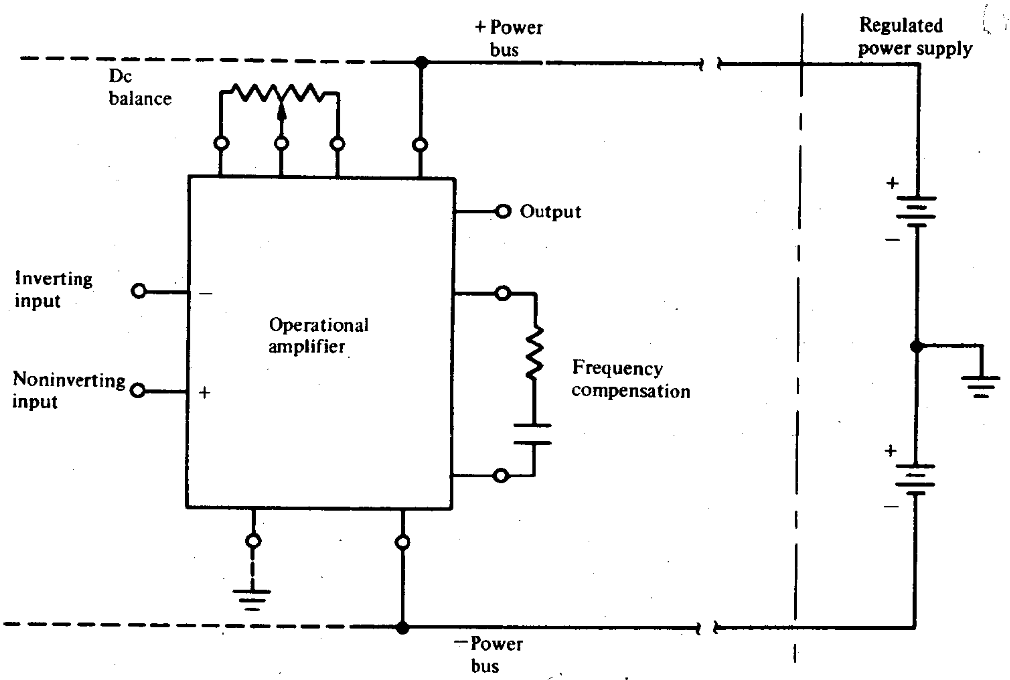
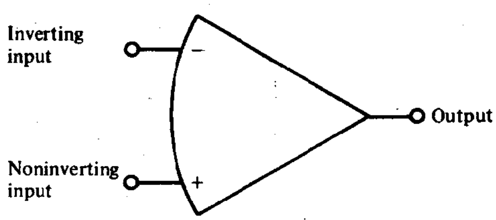


FIGURE 1.2
Typical operational amplifier environment. This diagram illustrates a typical manner in which power is supplied and external balancing and compensation networks are connected (not always required). Several amplifiers may be powered from a single pair of regulated power supplies.

device. The Thévenin equivalent circuit associated with the output terminal is modeled by an ideal controlled voltage source $-Ae_g$ in series with an equivalent output impedance Z_0. The input terminals are associated with a passive equivalent circuit representing the *common-mode impedances* Z_{cm1} and Z_{cm2} between each input and the common-signal ground, and the *differential input impedance* Z_i between the input terminals.

In this chapter, *a yet simpler model suffices,* as depicted in Fig. 1.4*b* and *c*. In Fig. 1.4*b*, we have assumed that the internal impedances associated with the input terminals are negligibly large, and that the internal output impedance is negligibly small. All that

FIGURE 1.3
Conventional operational amplifier symbol; only active signal lines are shown, and all signals are referenced to ground.



remains is the active voltage source $-Ae_g$ at the output terminal. Throughout the rest of this chapter, we will adopt the more convenient notation of Fig. 1.4c, where the amplifier terminal voltages e_1, e_2, and e_0 are assumed to be referenced to a common ground.

In summary, we can describe the ideal operational amplifier model as follows:

1. The ideal operational amplifier is a *linear voltage-controlled voltage source* (VCVS), with

$$e_0 = A(e_2 - e_1) = -Ae_g \tag{1.1a}$$

where

$$e_g = e_1 - e_2 \tag{1.1b}$$

e_g is the differential voltage between the amplifier input terminals.

2. The amplifier *open-loop voltage gain* A is assumed to be a *very large constant,* that is,

$$A \ggg 1 \quad \text{essentially infinite} \tag{1.2}$$

3. Implicit in (1) is the assumption that the amplifier input terminals are essentially open-circuit control nodes, i.e., the impedance between terminals e_1 and e_2 is infinite, and the impedance between each input terminal and the ground is infinite. Thus the input terminal currents are zero.
4. Also implicit in (1) is the assumption that the amplifier output voltage is unaffected by external loads.

NOTE: We have made the choice of polarity indicated in Fig. 1.4 so that the amplifier *open-loop voltage gain* A can be treated as a large *positive* constant at low frequencies. The polarity relationship between the respective input terminals is as specified in (1.1); therefore with the sign marking on the Thévenin voltage

Table 1.1 FEATURES OF OPERATIONAL AMPLIFIERS

1. ***High,*** **relatively linear, *voltage gain,* down to and including direct current; open-loop gain at direct current may be 10^7 or greater.**
2. **There must be a *polarity inversion* between input and output. In some cases the noninverting input is not externally available, but it is preferable for a *differential input* to be provided, with both an *inverting* and *noninverting* terminal.**
3. ***Direct current offsets should be minimized;* i.e., the input voltage (e_g, Fig. 1.4c) should be near zero when the output voltage is zero (good direct current *balance*). *Temperature compensation* techniques (in some cases chopper stabilization systems) should be employed to provide long-term stability to this balance. Drifts due to power-supply variations should also be minimized.**
4. **There should be *careful control of high-frequency response,* so that the amplifier will accommodate a large amount of negative feedback.**
5. **The *differential impedance* between the input terminals and the *common-mode impedance* between the terminals and ground should be *high.***
6. **The amplifier *output impedance* should be *low.***
7. **The amplifier *output stage should have the ability to deliver specified maximum current to or absorb it from* an output load over some nominal *bipolar* (±) *voltage range,* e.g., ±10 V.**
8. **When a differential input is provided, there should be *good common-mode rejection*; i.e., the output depends only on the *difference* between the input voltages, and is not dependent on the magnitude of either input voltage.**

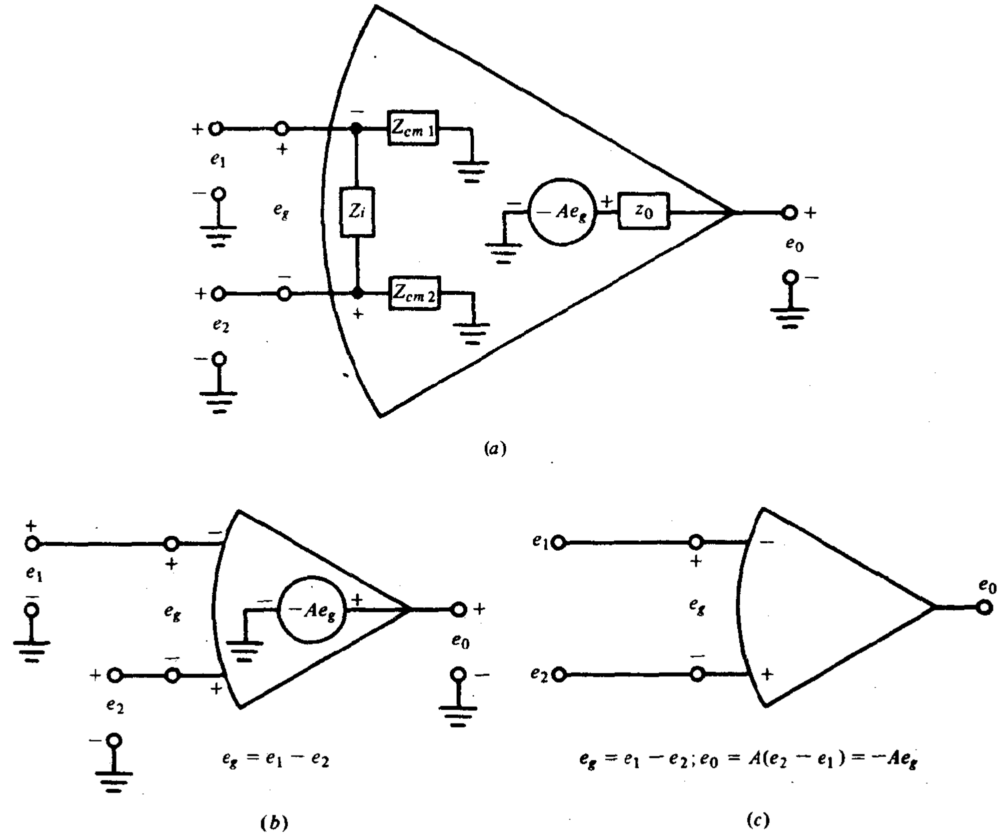
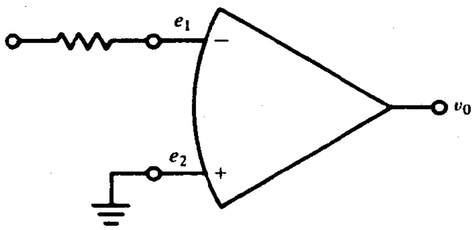


FIGURE 1.4
Operational amplifier circuit models. (*a*) Detailed linear model; (*b*) simplified model, neglecting internal impedances; (*c*) abbreviated notation for simplified model; voltages e_1, e_2, and e_0 are assumed to be referenced to ground.

generator in Fig. 1.4*a* or *b*, the value of the generator is $-Ae_g$. The reader is cautioned to study this thoroughly; it is easy to make mistakes in writing circuit equations. It must be remembered that e_1 is associated with the inverting terminal, and e_2 with the noninverting terminal.

As mentioned in Sec. 1.1, the operational amplifier is usually embedded in a circuit that provides *large amounts* of *negative feedback,* especially at low frequencies. The effect of the feedback is to make the amplifier behavior more ideal, viz., dc offsets are suppressed, the amplifier characteristics are linearized, the amplifier is made less sensitive to external output loads, and the differential input voltage e_g is forced to be close to zero, so that input currents are indeed very low.

If the circuit designer will accept the model in good faith, and use a few basic design practices to ensure that a reasonable amount of negative feedback is employed in



AVOID THIS !!

FIGURE 1.5
This circuit condition is normally to be avoided; operational amplifiers are not designed to run open-loop, without feedback.

the overall circuit design, he will normally find that the ideal model is quite valid for his initial design efforts.

NOTE: Even though the model described by (1.1), (1.2), and Fig. 1.4*b* is often adequate for analysis, it is frequently necessary to know the allowable deviations of the terminal voltages from ground, especially the maximum output voltage swing, which is typically ±10 V. In special applications, the maximum allowable input swing for voltages e_1 and e_2 is also important. Also the available amplifier output current often must be considered.

Of course, the ideal model is not truly attainable; Table 1.1 hints at the myriad considerations one may have to include if the ideal model is not sufficiently complete to fully predict circuit performance. The reader may well ask how big the amplifier voltage gain A actually is. Indeed, this is a very important question. Typically, at low frequencies the gain may be very high, perhaps as large as 10^6 or 10^8. Of course, at higher frequencies, the voltage gain will be less, and will include phase shift. In Chap. 2, we will explore the ramifications of the variation of A with frequency in some detail, but in many simple applications, the assumptions of (1.1) and (1.2) suffice, at least to make a first try at a circuit design.

1.3 THE SUMMER-INVERTER

Operational amplifiers are normally *not operated open-loop*; some form of *feedback* is used to control the overall circuit transfer characteristics. If the amplifier were energized in an open-loop configuration (Fig. 1.5), the output voltage would saturate (amplitude-overload) with even a very small input signal because of the high open-loop gain; in fact, small internal dc offsets which are always present would normally be sufficient to cause overload without feedback.

Figure 1.6*a* shows a typical inverting operational amplifier configuration; the noninverting terminal is grounded for single-ended operation, either directly or through a drift-compensating resistor (see Sec. 2.5). The simplified diagram of Fig. 1.6*b*, where the noninverting terminal is assumed to be effectively at ground potential and all voltages are assumed to be referred to this same ground potential, is often used. Here also we use v's for the voltages on the external nodes of the complete circuit.