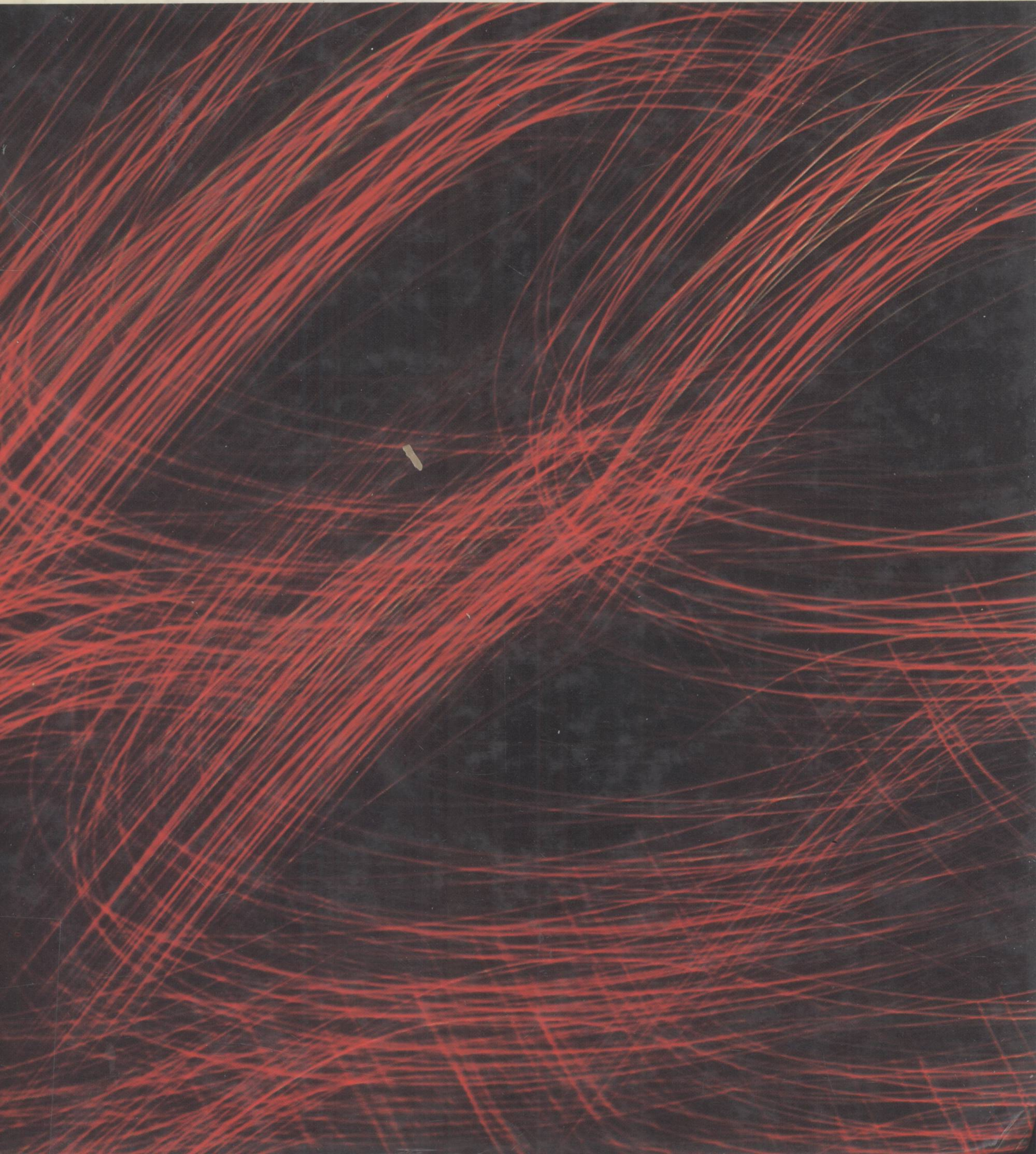
WILLIAM STANLEY

OPERATIONAL AMPLIFIERS WITH LINEAR INTEGRATED CIRCUITS



OPERATIONAL AMPLIFIERS WITH LINEAR INTEGRATED CIRCUITS

WILLIAM D. STANLEY
Old Dominion University

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Dedicated to the late
Joseph S. Reeves
who introduced me to the
exciting world of electronics
when I was a teenager

PREFACE

The primary objectives of this book are as follows:

1. To establish the general methods for analyzing, modeling, and predicting the performance of operational amplifiers and related linear integrated circuits
2. To develop the reader's facility in designing realistic circuits to perform specified operations
3. To provide familiarity with many of the common circuit configurations as well as the ability to select available devices to use with these circuits.

Care has been taken in writing the book to allow all or portions to be usable for at least the following groups:

1. Upper-division engineering technology students (junior or senior level)
2. Lower-division engineering technology students (following the basic course sequence in discrete electronic devices and circuits)
3. Applied engineering students
4. Practicing design engineers, technologists, and technicians

Engineering or engineering technology students who have had a course in circuit analysis employing frequency response analysis methods and a course in calculus should be able to cover the entire book. However, with the exception of a few derivations and analytical developments, virtually all the analysis and design results can be understood and applied with lower-division basic dc and ac circuit analysis. With the exception of one derivation in Chapter 3, the use of calculus is limited to integrator and differentiator circuits in Chapter 4. Finally, the large number of example problems and exercises enhances the value of the book for self-study by practicing technical personnel.

The primary emphasis throughout the book is on developing the reader's facility for analyzing and designing the various circuit functions, rather than on simply presenting a rote collection of existing circuits or showing numerous wiring diagrams for specialized integrated circuit modules. In this manner, a foundation is established for understanding new developments as they arise. Since new devices constantly appear on the market and existing ones become obsolete quickly, only a few devices are studied in detail. Those that have been selected for this purpose have withstood the test of time and are widely used. It has been proven that the best way to adapt to new technology is to have a firm grasp of the basic principles, and this book has been organized toward that goal.

A brief overview of the book will now be given. Chapter 1 provides some general models of linear amplifier circuits, definitions, and parameters. Students often miss these general concepts from the detailed material covered in basic electronic courses. This common deficiency is a case of the classical pattern of "not seeing the forest for the trees," and it is felt that the material provided should help to solve this problem.

Chapter 2 begins the analysis and design of operational amplifier circuits using ideal model assumptions. While the reader will not be able to see all the limitations of the circuits at this point, actual workable designs can be produced almost immediately from the information in this chapter, including amplifiers of various types, current sources, summing circuits, and various other applications.

Chapter 3 provides a detailed treatment of the practical limitations of realistic operational amplifiers and the associated effects on operating performance. Emphasis here is on understanding specifications and using them to design circuits properly.

Additional linear applications are considered in Chapter 4, including frequency-dependent circuits such as integrators, differentiators, and phase shift networks. Chapter 4 also includes precision instrumentation amplifiers.

Nonlinear applications are covered in Chapter 5. Included are comparator circuits, precision rectifiers, peak detectors, sample-and-hold circuits, clamps, limiters, regulator circuits, and logarithmic amplifiers.

Timers and oscillators are considered in Chapter 6. The general op-amp multivibrator circuit and the very popular 555 timer are considered. The Barkhausen criterion is introduced, and the Wein bridge oscillator is analyzed. Finally, the 8038 function generator chip is discussed.

Chapter 7 is devoted to active filters. Emphasis is on the widely used Butterworth function for low-pass filters and the standard resonance characteristic for band-pass filters. Finite-gain low-pass and high-pass filter design data are included, and the infinite-gain band-pass circuit design is considered. The last portion of the chapter deals with the very important state-variable filter, for which low-pass, band-pass, high-pass, and band-rejection filters can be realized. After completing this chapter, a serious reader should be able to design and implement a variety of practical active filters.

Chapter 8 considers the timely topic of data conversion, which can be considered as the bridge between the analog and digital worlds. Both digital-to-analog and analog-to-digital conversion are considered, and some of the most common circuits are studied. The concepts of voltage-to-frequency and frequency-to-voltage conversion are discussed, and phase-locked loops are introduced.

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CONTENTS

1 GENERAL AMPLIFIER CONCEPTS 1

1–1 Introduction *1*
1–2 Linear versus Digital Electronics *1*
1–3 Controlled-Source Models *4*
1–4 Complete Amplifier Signal Model *6*
1–5 Cascade of Amplifier Stages *7*
1–6 Decibel Gain Computations *11*
1–7 Frequency Response Considerations *16*
1–8 One-Pole Low-Pass Model *19*
Problems *28*

2 IDEAL OPERATIONAL AMPLIFIER ANALYSIS AND DESIGN 31

2–1 Introduction *31*
2–2 Operational Amplifier (Op-Amp) *32*

2–3 Ideal Operational Amplifier *35*
2–4 Simplified Design of Amplifier Circuits *45*
2–5 Voltage-Controlled Current Sources *50*
2–6 Current-Controlled Sources *56*
2–7 Linear Combination Circuit *60*
2–8 Closed-Loop Differential Amplifier *64*
Problems *66*

3 PRACTICAL OPERATIONAL AMPLIFIER CONSIDERATIONS 73

3–1 Introduction *73*
3–2 Noninverting Amplifier: Gain, Input Impedance, and Output Impedance *74*
3–3 Inverting Amplifier: Gain, Input Impedance, and Output Impedance *82*
3–4 Noise Gain *86*
3–5 Closed-Loop Frequency Response *89*
3–6 Slew Rate *97*
3–7 Combination of Linear Bandwidth and Slew Rate *102*
3–8 Offset Voltage and Currents *109*
3–9 Noise in Operational Amplifiers *117*
3–10 Common-Mode Rejection *120*
Problems *122*

4 LINEAR OPERATIONAL AMPLIFIER CIRCUITS 129

4–1 Introduction *129*
4–2 Instrumentation Amplifier *130*
4–3 Integrator and Differentiator Circuits *134*
4–4 General Inverting Gain Circuit *138*
4–5 ac Integrator *139*
4–6 Low-Frequency Differentiator *148*
4–7 Phase Shift Circuits *155*
4–8 Single Power Supply Operation *159*
Problems *165*

5 NONLINEAR OPERATIONAL AMPLIFIER CIRCUITS 169

5–1 Introduction *169*
5–2 General Considerations *170*
5–3 Comparators *170*

5–4 Signal-Processing Rectifier Circuits *179*
5–5 Holding Circuits *185*
5–6 Clamping Circuits *191*
5–7 Limiting Circuits *194*
5–8 Voltage Regulators *196*
5–9 Multipliers *202*
5–10 Logarithmic Amplifiers *205*
Problems *209*

6 OSCILLATORS AND WAVEFORM GENERATORS 215

6–1 Introduction *215*
6–2 Classification Scheme *215*
6–3 Operational Amplifier Astable Multivibrator *216*
6–4 The 555 Timer *222*
6–5 Barkhausen Criterion *231*
6–6 Wein Bridge Oscillator *234*
6–7 The 8038 Waveform Generator *238*
Problems *239*

7 ACTIVE FILTERS 243

7–1 Introduction *243*
7–2 Filter Classifications *244*
7–3 Frequency and Impedance Scaling *249*
7–4 Butterworth Filter Responses *254*
7–5 Low-Pass and High-Pass Unity-Gain Designs *260*
7–6 Two-Pole Band-Pass Response *267*
7–7 Multiple-Feedback Band-Pass Filter *271*
7–8 State-Variable Filter *274*
Problems *283*

8 DATA CONVERSION CIRCUITS 287

8–1 Introduction *287*
8–2 Sampling and Data Conversion *287*
8–3 Digital-to-Analog Conversion *291*
8–4 Analog-to-Digital Conversion *299*
8–5 Integrating Analog-to-Digital Converters *305*
8–6 Converter Specifications *309*

8–7 Analog Switches and Multiplexers *318*
8–8 Voltage and Frequency Conversions *320*
8–9 Phase-Locked Loops *322*
Problems *324*

General References *327*
Appendix A: Resistor and Capacitor Values *329*
Appendix B: Linear Integrated Circuit Manufacturers *331*
Appendix C: Specification Sheets *333*

ANSWERS TO SELECTED PROBLEMS 373
INDEX 377

1

GENERAL AMPLIFIER CONCEPTS

INTRODUCTION

The primary objective of this introductory chapter is to present some of the most important 1–1
models for representing basic linear amplifier operations, including the various controlled- or dependent-source models as well as an overall amplifier model delineating input impedance, output impedance, and voltage gain. These representations apply to the signal input-output characteristics irrespective of whether a given linear amplifier is implemented with integrated circuits or with discrete components.

The one-pole, low-pass, roll-off frequency response model will be developed and discussed in some detail. This form is quite important because many amplifier circuits (including operational amplifiers) are dominated by this type of response over a wide range of operation. The use of decibel computations in electronic circuit analysis will also be reviewed and extended.

LINEAR VERSUS DIGITAL ELECTRONICS

There are many ways to classify the various divisions of electronics, most of which are 1–2
ambiguous because of the complexity of the field and the overlap between the different application areas. One particular classification scheme, however, deserves some attention

here because of its relevance to the focus of this book. At a relatively broad level, electronics can be separated into the divisions of (1) ***digital electronics*** and (2) ***linear electronics***. There is a temptation to call the second category *analog electronics*, but in accordance with widespread usage, the term *linear electronics* will be used.

Digital electronics is concerned with all phases of electronics in which signals are represented in terms of a finite number of digits, the most common of which is the binary number system. Digital electronics also includes all arithmetic computations on such numbers, as well as associated logic operations. The distinguishing feature of digital electronics is the representation of all possible variables by a finite number of digits. Obvious examples in which digital electronics plays the major role are computers and calculators.

Linear electronics is concerned with all phases of electronics in which signals are represented by continuous or *analog* variables. Linear electronics also includes all signal-processing functions (for example, amplification) associated with such signals.

Actually, the term *linear* is a misnomer since many of the circuits classified as such are nonlinear in nature. On a slightly humorous vein, a better term might be *nondigital electronics* to indicate that a large percentage of electronic applications other than digital are often classified under the category of linear electronics. However, the classification term *linear electronics* has become so imbedded within the electronics industry that its usage will no doubt continue. The reader should realize, however, that many nonlinear circuits are classified in this category.

This book will be devoted to the consideration of linear integrated electronic circuits and devices. This major segment of the linear electronics field has widespread application to many specialty fields.

There are a number of electronic circuits that involve a combination of digital and linear electronics, and some of the most important of these will be considered in this book. Foremost among such circuits are analog-to-digital and digital-to-analog converters. Such devices are used in the interfacing areas between analog and digital circuits, and they utilize both linear and digital circuit principles.

One of the most important applications in the field of linear electronics is the process of ***amplification***. This operation was one of the very earliest applications of electronic devices, and it still remains an essential operation in virtually all phases of the industry. Consequently, many of the linear applications in this book either directly or indirectly involve amplification.

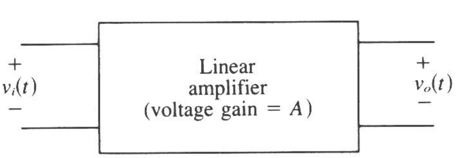

FIGURE 1–1 *Block diagram representation of a linear amplifier.*

An ideal linear amplifier is characterized by the fact that the output signal is directly proportional to the input signal, but the level will be changed in the process. Amplifiers in system form are often represented by a block diagram such as shown in Figure 1–1. The input voltage signal is denoted as $v_i(t)$, and the output voltage signal is denoted as $v_o(t)$. The quantity t represents time, and the functional forms $v_i(t)$ and $v_o(t)$

represent the fact that both voltages are functions of time; that is, they vary in some fashion as time passes. When it is not necessary to emphasize this functional notation, the parentheses and t will be omitted, in which case v_i and v_o may be used to represent the quantities involved. The functional notation was introduced at this point so that the reader can recognize it throughout the book when it occurs.

In this case, the quantity A represents the voltage gain. For an ideal linear amplifier, it can be defined as

$$A = \frac{v_o(t)}{v_i(t)} \tag{1–1}$$

If the amplifier is not perfectly linear, the basic definition of (1–1) is no longer correct. For the moment, we will avoid that situation and assume ideal linear amplification. If the gain and input voltage are known, the output signal is

$$v_o(t) = Av_i(t) \tag{1–2}$$

The input and output ideal signal relationships are illustrated by the waveforms shown in Figure 1–2. To simplify this illustration, a signal consisting of pulselike segments is assumed in (a). The corresponding form of the output of an ideal linear amplifier is shown in (b). All points on the output waveform are A times the corresponding points on the input waveform. For example, if $A = 5$ and the input voltage is 2 V, the output voltage is $5 \times 2 = 10$ V.

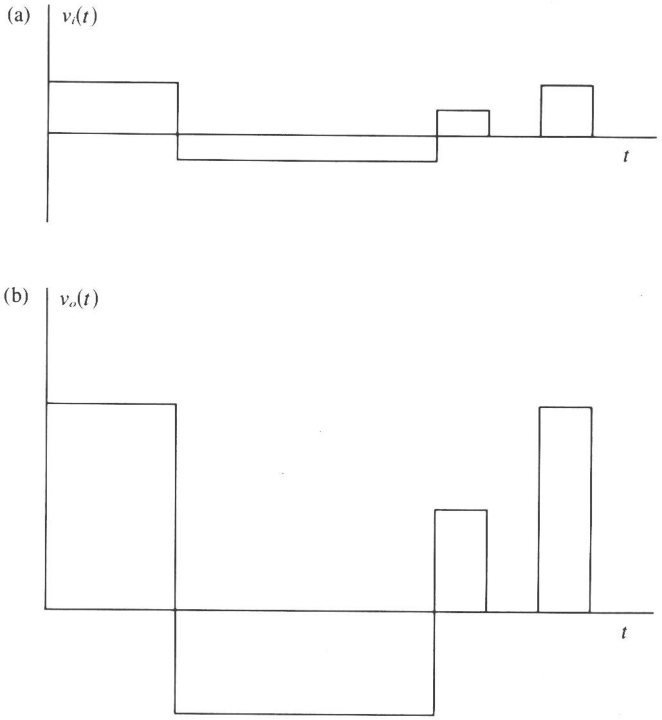

FIGURE 1–2 *Input and output waveform examples for an ideal linear amplifier.*

It should be stressed that virtually all amplifiers require a dc power input in order to provide amplification. It is customary to show only signal levels on many block diagrams for signal-processing analysis, and any dc power supplies (or *bias* supplies as they are often called) are understood to be present. Such a diagram could cause someone to assume incorrectly that the amplifier is creating energy. Most active amplifier devices permit a small signal input to control a larger signal output, but the extra power is furnished by the dc power supply.

CONTROLLED-SOURCE MODELS

1–3

Linear active devices are used to amplify and control signals in many different ways. For example, the physical movements of a stylus on a phonograph record generate a small signal at the output of the cartridge, which represents the recorded music. After sufficient amplification by linear devices, the signal controls the output of a power amplifier stage, which provides enough power to the speaker to convert the electrical energy to acoustical energy. Throughout this system all stages should ideally have linear relationships; that is, the output of each stage should be a constant times the input.

Consider a linear active device with one set of input signal terminals and one set of output signal terminals. Depending on the electronic device and the manner in which it operates, either voltage or current at the input may be the controlling variable. Further, the output controlled may be either voltage or current. Thus, there are four possible combinations of input-output control, and all of these occur in actual systems:

1. Voltage-controlled voltage source
2. Voltage-controlled current source
3. Current-controlled voltage source
4. Current-controlled current source

We will investigate each of these four conditions in this section and present certain models to represent their behavior. The models given will be considered in the most idealized forms.

No consideration will be given at this point as to how the control functions to be considered are actually implemented. There are various ways of achieving these operations using such varied devices as bipolar junction transistors, field effect transistors, operational amplifiers, vacuum tubes, and so on. We will be dealing strictly with the ideal input-to-output control operations in their simplest mathematical forms. Thus, the relatively simple looking models shown in the figures could represent the effect of complex circuits containing many individual active and passive circuit components.

Voltage-Controlled Voltage Source (VCVS)

The most common combination is a voltage-controlled voltage source (VCVS), whose idealized model is shown in Figure 1–3(a). An independent signal voltage v_i is assumed to be applied across the input terminals. The action of the control circuit is to create a signal voltage v_o at the output given by

$$v_o = Av_i \tag{1–3}$$

The voltage source on the right is an example of a ***dependent*** or ***controlled*** source because it is dependent on a variable in a different part of the circuit. The output voltage is thus a constant times the input voltage, a basic requirement for a linear amplifier. The quantity A is the ***voltage gain,*** and it is dimensionless. This model could be used to represent the ideal linear amplifier discussed in Section 1–2.

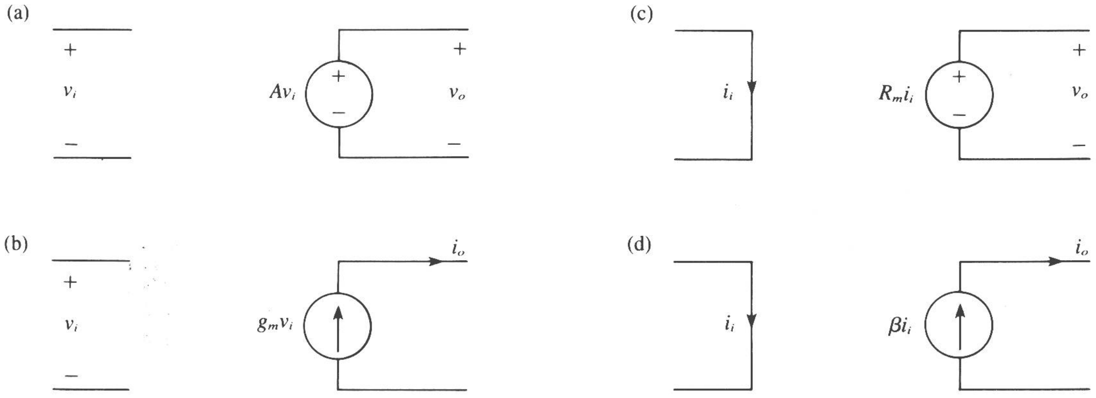

FIGURE 1–3 *Four possible models of ideal controlled (or dependent) sources in electronic circuits.*

Voltage-Controlled Current Source (VCIS)

The idealized model of a VCIS is shown in Figure 1–3(b). The input-controlling variable is the signal voltage shown on the left. However, the controlled variable in this case is the output current, whose operation is represented by the dependent current source on the right. The value of this current at the output is

$$i_o = g_m v_i \tag{1–4}$$

The constant g_m is the ***transconductance*** of the device, and it has the units of siemens (S).

Current-Controlled Voltage Source (ICVS)

The idealized model of an ICVS is shown in Figure 1–3(c). Unlike the previous two models, in this case the input signal current i_i is the controlling variable. The controlled variable is the output voltage, which is represented by the dependent voltage source on the right. The value of this voltage at the output is

$$v_o = R_m i_i \tag{1–5}$$

The constant R_m is the ***transresistance*** of the device, and it has the units of ohms (Ω).

Current-Controlled Current Source (ICIS)

The last of the four possible combinations is the ICIS, and its idealized model is shown in Figure 1–3(d). The controlling variable is the input current, shown on the left. The controlled variable is the output current, which is represented by the dependent current source shown on the right. The value of the output current is

$$i_o = \beta i_i \tag{1–6}$$

The constant β is the ***current gain,*** and it is dimensionless.

Various electronic devices approximate the behavior of the different source models just discussed. For example, bipolar junction transistors in their ideal form may be represented by the ICIS model. Conversely, field effect transistors may be represented very closely by the VCIS model.

In many applications, it is desirable to design circuitry to perform one of the operations previously discussed. For example, consider a device in which the output signal voltage is of interest. It may be desired to transfer this signal to a load that responds primarily to current. In this case, a voltage-controlled current source having a suitable value of g_m would be required. In later chapters, we will learn how to design circuits using modern linear integrated circuits that will perform all the basic processing operations just discussed.

COMPLETE AMPLIFIER SIGNAL MODEL

1–4

The four ideal controlled-source models defined in Section 1–3 are used in representing various linear signal amplification functions. Consequently, a number of possible complete circuit models arise in practice. However, at this point we will focus on one particular complete amplifier model because of its widespread usage and because some of its parameters are similar to those used in other circuits as well. As previously discussed, only signal quantities will be shown in the diagrams.

A general block diagram of a linear amplifier with one set of input terminals and one set of output terminals is shown in Figure 1–4(a). A corresponding signal model that can be used to represent a wide variety of complete amplifier circuits is shown in Figure 1–4(b). We will assume that all passive parameters are resistive in this simplified model. The effects of reactive elements (for example, capacitance and inductance) will be considered in Section 1–7. However, to establish proper notation for later usage, the term *impedance* will be used in reference to the various components. The various parameters relating to amplifier performance will now be discussed.

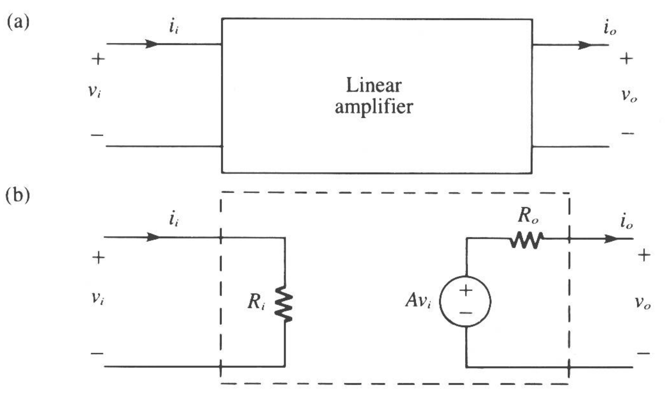

FIGURE 1–4 *Block diagram of a linear amplifier and a common form of a signal model utilizing a VCVS.*

Input Impedance

The input impedance is the effective impedance across the two input terminals as "seen" by a signal source. For the resistive case of Figure 1–4(b), the input impedance is simply R_i. For this resistive case, we can state that

$$R_i = \frac{v_i}{i_i} \tag{1-7}$$

For the more general case with reactive components, transform or phasor voltage and current (rather than instantaneous quantities) must be used in the definition, and a complex input impedance $\overline{Z}_i$ is required in the model.

The input impedance is important in determining the fraction of any available signal voltage that actually appears across the amplifier terminals when the source has an internal impedance. In general, the voltage actually appearing across the amplifier terminals will be lower than the available source voltage due to the interaction between the source and input impedances.

Output Impedance

The output impedance is the impedance portion of the Thevenin or Norton equivalent circuit as viewed at the output terminals. In Figure 1–4(b), a Thevenin form is used for the output portion of the amplifier circuit, and the output impedance is seen to be a resistive value R_o in this case. In the more general case, a complex output inpedance $\overline{Z}_o$ is required in the model.

The output impedance is important in determining the change in output signal as any external load connected to the output terminal changes. Thus, if two amplifier stages are connected, the output impedance of the first stage interacts with the input impedance of the second stage.

Voltage Gain

In the model of Figure 1–4(b), a voltage-controlled voltage source represents the effective voltage amplification of the circuit. With no load connected across the output, the output voltage is A times the input voltage. Thus, the ***open-circuit voltage gain*** is readily determined from the circuit diagram to be A. Under loaded conditions, the voltage gain will be reduced, as will be demonstrated later.

With the given polarity of the controlled source in Figure 1–4(b) and with A positive, the voltage gain is noninverting; that is, the output voltage has the same sign as the input voltage (in phase). However, if *either* the polarity of the controlled source is reversed *or* if A is negative (but not both), the gain is *inverting;* that is, the output voltage is inverted in sign with respect to the input voltage (out of phase).

1–5 CASCADE OF AMPLIFIER STAGES

A model representing a large number of possible linear amplifier circuits was given in the last section. The parameters required to represent an amplifier by this model are the open-circuit voltage gain, the input impedance, and the output impedance. We will now investigate the interaction effects that occur when an amplifier is cascaded with other amplifier circuits, a load, or a source with internal resistance.

First, consider the process of connecting the input terminals of an amplifier to a source with nonzero internal impedance and simultaneously connecting it to a finite load impedance. The connections involved are shown in Figure 1–5(a). An equivalent