

Operational Amplifiers and Linear ICs

THIRD EDITION

DAVID A. BELL

*Lambton College of Applied Arts and Technology
Sarnia, Ontario, Canada*

OXFORD
UNIVERSITY PRESS

OXFORD
UNIVERSITY PRESS

YMCA Library Building, Jai Singh Road, New Delhi 110001

Oxford University Press is a department of the University of Oxford.
It furthers the University's objective of excellence in research, scholarship,
and education by publishing worldwide in

Oxford New York
Auckland Cape Town Dar es Salaam Hong Kong Karachi
Kuala Lumpur Madrid Melbourne Mexico City Nairobi
New Delhi Shanghai Taipei Toronto

With offices in
Argentina Austria Brazil Chile Czech Republic France Greece
Guatemala Hungary Italy Japan Poland Portugal Singapore
South Korea Switzerland Thailand Turkey Ukraine Vietnam

Oxford is a registered trade mark of Oxford University Press
in the UK and in certain other countries.

Published in India
by Oxford University Press

© Oxford University Press 2011

The moral rights of the author have been asserted.

Database right Oxford University Press (maker)

First published 2011

All rights reserved. No part of this publication may be reproduced,
stored in a retrieval system, or transmitted, in any form or by any means,
without the prior permission in writing of Oxford University Press,
or as expressly permitted by law, or under terms agreed with the appropriate
reprographics rights organization. Enquiries concerning reproduction
outside the scope of the above should be sent to the Rights Department,
Oxford University Press, at the address above.

You must not circulate this book in any other binding or cover
and you must impose this same condition on any acquirer.

ISBN-13: 978-0-19-569613-4
ISBN-10: 0-19-569613-1

Typeset in Times New Roman
by Anvi Composers, New Delhi 110063
Printed in India by Chaman Enterprises, Delhi 110002
and published by Oxford University Press
YMCA Library Building, Jai Singh Road, New Delhi 110001

CONTENTS

<i>Preface</i>	<i>iii</i>
Chapter 1 Introduction to Operational Amplifiers	1
1-1 IC Operational Amplifier	1
<i>Circuit Symbol and Terminals</i>	1
<i>Basic Op-Amp Circuit</i>	2
1-2 The Voltage Follower Circuit	4
1-3 The Noninverting Amplifier	6
1-4 The Inverting Amplifier	8
Chapter 2 Operational Amplifier Parameters and Performance	13
2-1 Ideal and Practical Operational Amplifiers	14
<i>Op-Amp Model</i>	14
<i>Currents and Impedances</i>	14
<i>Voltage Gain</i>	15
<i>Ideal Op-Amp</i>	16
2-2 Basic Op-Amp Internal Circuitry	17
<i>Current Mirror</i>	17
<i>Complementary Emitter Follower</i>	18
<i>Level Shifting Stage</i>	19
<i>Representative IC Op-Amp</i>	19
2-3 Input, Output, and Supply Voltages	22
<i>Supply Voltage Options</i>	22
<i>Input Voltage Range</i>	22
<i>Output Voltage Range</i>	23
<i>Common Mode Rejection</i>	23
<i>Power Supply Rejection</i>	25
2-4 Offset Voltages and Currents	27
<i>Input and Output Offset Voltages</i>	27
<i>Input Bias Current Effects</i>	27
<i>Input Offset Current</i>	29
<i>Combined Effect of Input Error Sources</i>	29
<i>Offset Nulling</i>	30
2-5 Input and Output Impedances	31
<i>Input Impedance</i>	31
<i>Output Impedance</i>	32
2-6 Slew Rate and Frequency Limitations	34
<i>Slew Rate</i>	34
<i>Frequency Limitations</i>	35

2-7	Op-amp Classification	36
	<i>Packages</i>	36
	<i>Op-Amp Identification Numbers</i>	36
	<i>Temperature Range</i>	37
	<i>Classification</i>	37
	<i>Op-Amp Selection</i>	38
Chapter 3 Op-Amps as DC Amplifiers		42
3-1	Biasing Op-Amps	43
	<i>Bias Current Paths</i>	43
	<i>Bias Circuit Resistor Values</i>	43
	<i>Voltage Divider Bias</i>	44
	<i>Biasing BIFET Op-Amps</i>	45
3-2	Direct-Coupled Voltage Follower	46
	<i>Performance</i>	46
	<i>Voltage Follower Compared to an Emitter Follower</i>	48
3-3	Direct-Coupled Noninverting Amplifiers	48
	<i>Design</i>	48
	<i>Performance</i>	51
	<i>Computer Analysis of a Noninverting Amplifier</i>	52
3-4	Direct-Coupled Inverting Amplifiers	52
	<i>Design</i>	52
	<i>Performance</i>	54
	<i>Computer Analysis of an Inverting Amplifier</i>	55
3-5	External Nulling Methods	55
3-6	Summing Amplifiers	57
	<i>Inverting Summing Circuit</i>	57
	<i>Noninverting Summing Circuit</i>	59
3-7	Difference Amplifier	61
	<i>Circuit Operation</i>	61
	<i>Input Resistances</i>	63
	<i>Common Mode Voltages</i>	63
	<i>Output Level Shifting</i>	64
	<i>Circuit Design</i>	64
	<i>Computer Analysis of a Difference Amplifier</i>	66
3-8	Instrumentation Amplifier	66
	<i>Differential Input/Output Amplifier</i>	66
	<i>Complete Instrumentation Amplifier</i>	68
	<i>Computer Analysis of an Instrumentation Amplifier</i>	72
	<i>Integrated Circuit Instrumentation Amplifier</i>	72
Chapter 4 Op-Amps as AC Amplifiers		78
4-1	Capacitor-Coupled Voltage Follower	79
4-2	High Z_{in} Capacitor-Coupled Voltage Follower	82
	<i>Computer Analysis</i>	85
4-3	Capacitor-Coupled Noninverting Amplifier	85
4-4	High Z_{in} Capacitor-Coupled Noninverting Amplifier	88
	<i>Computer Analysis</i>	90

4-5	Capacitor-Coupled Inverting Amplifier	92
4-6	Setting the Upper Cutoff Frequency	92
	<i>Computer Analysis</i> 94	
4-7	Capacitor-Coupled Difference Amplifier	95
4-8	Use of a Single-Polarity Supply	96
	<i>Voltage Follower</i> 96	
	<i>Noninverting Amplifier</i> 98	
	<i>Inverting Amplifier</i> 100	

Chapter 5 Operational Amplifier Frequency Response and Compensation 105

5-1	Op-Amp Circuit Stability	106
	<i>Loop Gain and Loop Phase Shift</i> 106	
	<i>Single-Stage BJT Amplifier Gain and Phase Responses</i> 107	
	<i>Uncompensated Op-Amp Gain and Phase Response</i> 108	
	<i>Phase Margin</i> 110	
5-2	Frequency Compensation Methods	112
	<i>Phase-Lag and Phase-Lead Compensation</i> 112	
	<i>Miller Effect Compensation</i> 113	
	<i>Manufacturer's Recommended Compensation</i> 114	
5-3	Internally Compensated Op-amps	116
	<i>Compensated Op-Amp Gain and Phase Response</i> 116	
	<i>Amplifier Stability and Gain</i> 117	
5-4	Circuit Bandwidth and Slew Rate	118
	<i>Lower and Upper Cutoff Frequencies</i> 118	
	<i>Gain-Bandwidth Product</i> 120	
	<i>Full-Power BW and Slew Rate</i> 121	
5-5	Stray and Load Capacitance Effects	123
	<i>Effects of Stray Capacitance on Circuit Stability</i> 123	
	<i>Effects of Load Capacitance on Circuit Stability</i> 126	
5-6	Circuit Stability Precaution	129
	<i>Power Supply Decoupling</i> 129	
	<i>Stability Precautions</i> 130	

Chapter 6 Noise in Op-Amp Circuits 134

6-1	Thermal Noise	135
	<i>Resistors Noise</i> 135	
	<i>Noise Gain</i> 136	
6-2	Shot Noise	137
6-3	Op-Amp Noise	139
6-4	Signal-to-Noise Ratio	141
6-5	Minimizing Noise	143
	<i>Grounding and Screening</i> 143	

Chapter 7 Miscellaneous Op-Amp Linear Applications 147

7-1	Voltage Sources	148
	<i>Positive and Negative Voltage Source</i> 148	

<i>Computer Analysis of Voltage Source</i>	150	
7-2 Current Sources and Current Sinks		152
<i>Current Sources</i>	152	
<i>Current Sinks</i>	154	
<i>Computer Analysis of a Current Sink</i>	156	
7-3 Current Amplifiers		157
<i>Current-to-Voltage Converter</i>	157	
<i>Current Amplifier</i>	157	
<i>Computer Analysis of a Current Amplifier</i>	159	
7-4 DC Voltmeter Circuit		159
7-5 Linear Ohmmeter Circuit	161	
<i>Computer Analysis of the Linear Ohmmeter</i>	164	
7-6 Log and Antilog Amplifiers		165
<i>Basic Log Amplifier</i>	165	
<i>Basic Antilog Amplifier</i>	166	
<i>Temperature Compensation</i>	167	
Chapter 8 Switching, Differentiating, and Integrating Circuits		173
8-1 Op-Amps in Switching Circuits		174
<i>Output Voltage Swing</i>	174	
<i>Maximum Differential Input Voltage</i>	174	
<i>Slew Rate</i>	175	
<i>Frequency Compensation</i>	176	
8-2 Voltage Level Detectors		176
<i>Zero Crossing Detector</i>	176	
<i>Level Detector</i>	178	
<i>Voltage Level Monitor</i>	178	
<i>Computer Analysis</i>	181	
8-3 Inverting Schmitt Trigger Circuit		182
<i>Circuit Operation</i>	182	
<i>Positive Feedback</i>	183	
<i>Triggering Points</i>	183	
<i>Voltage Waveforms</i>	183	
<i>Hysteresis</i>	184	
<i>Input/Output Characteristic</i>	184	
<i>Circuit Design</i>	185	
<i>Adjusting the Trigger Points</i>	186	
8-4 Noninverting Schmitt Trigger Circuit		187
<i>Circuit Operation</i>	187	
<i>Adjusting the Trigger Points</i>	188	
<i>Computer Analysis</i>	190	
8-5 IC Voltage Comparator		191
<i>Comparator Operation</i>	191	
<i>Comparator Specification</i>	192	
<i>Comparator Level Detectors</i>	192	
<i>Window Detector</i>	194	
<i>Comparator as a Schmitt Trigger</i>	195	
<i>Computer Analysis</i>	196	

8-6	Differentiating Circuits	197
	<i>Differentiating Circuit Waveforms</i>	197
	<i>Basic Differentiating Circuit</i>	198
	<i>Practical Op-Amp Differentiating Circuit</i>	200
	<i>Differentiator Circuit Design</i>	200
	<i>Differentiator Performance</i>	202
	<i>Sine Wave Response</i>	202
8-7	Integrating Circuits	204
	<i>Integrating Circuit Waveforms</i>	204
	<i>Basic Integrating Circuit</i>	205
	<i>Practical Op-Amp Integrating Circuit</i>	206
	<i>Integrator Circuit Design</i>	206
	<i>Integrator Performance</i>	207
	<i>Sine Wave Response</i>	208
Chapter 9 Signal Processing Circuits		214
9-1	Precision Half-Wave Rectifiers	215
	<i>Saturating Precision Rectifier</i>	215
	<i>Nonsaturating Precision Rectifier</i>	216
	<i>Two-Output Precision Half-Wave Rectifier</i>	218
9-2	Precision Full-Wave Rectifiers	219
	<i>Half-Wave Rectifier and Summing Circuit</i>	219
	<i>Computer Analysis</i>	221
	<i>High Input Impedance Precision Full-Wave Rectifier</i>	221
9-3	Limiting Circuits	224
	<i>Peak Clipper</i>	224
	<i>Dead Zone Circuit</i>	226
	<i>Precision Clipper</i>	227
	<i>Computer Analysis</i>	228
	<i>Precision Plus/Minus Clipping Circuit</i>	228
9-4	Clamping Circuits	231
	<i>Diode Clamping Circuit</i>	231
	<i>Precision Clamping Circuit</i>	232
	<i>Computer Analysis</i>	235
9-5	Peak Detectors	235
	<i>Precision Rectifier Peak Detector</i>	235
	<i>Voltage Follower Peak Detector</i>	237
9-6	Sample-and-Hold Circuits	239
	<i>Op-Amp Sample-and-Hold</i>	239
	<i>IC Sample-and-Hold</i>	242
Chapter 10 Signal Generators		247
10-1	Astable Multivibrator	248
	<i>Circuit Operation</i>	248
	<i>Astable Design</i>	249
10-2	Monostable Multivibrator	251
	<i>Monostable Operation</i>	251
	<i>Recovery Time</i>	253

	<i>Monostable Design</i>	253
	<i>Triggering the Monostable</i>	255
	<i>Computer Analysis</i>	257
10-3	Triangular Wave Generator	258
	<i>Schmitt-Integrator Combination</i>	258
	<i>Design Calculations</i>	259
10-4	Modifications to the Triangular Wave Generator	260
	<i>Frequency and Duty-Cycle Adjustment</i>	260
	<i>Voltage-Controlled Oscillator Modification</i>	263
	<i>Computer Analysis</i>	265
10-5	Signal Generator Output Controls	266
10-6	555 Timer Monostable	268
	<i>Timer Block Diagram</i>	268
	<i>Timer Monostable Circuit</i>	269
	<i>Designing a 555 Monostable</i>	270
	<i>Modifications to the Basic 555 Monostable</i>	271
	<i>Timing and Frequency Limitations</i>	272
10-7	Timer Pulse and Square Wave Generators	273
	<i>Astable Multivibrator</i>	273
	<i>555 Astable Design</i>	274
	<i>Computer Analysis</i>	275
	<i>Square Wave Generator</i>	275
	<i>Another Square Wave Generator Circuit</i>	276
	<i>Computer Analysis</i>	278
10-8	Miscellaneous Timer Circuits	278
	<i>Voltage-Controlled Oscillator</i>	278
	<i>Delay Timers</i>	280
	<i>Sequential Timers</i>	281
	<i>Pulsed-Tone Oscillator</i>	282
	<i>The 7555 CMOS Timer</i>	283
Chapter 11 Sinusoidal Oscillators		289
11-1	Phase Shift and Quadrature Oscillators	290
	<i>Phase Shift Oscillator Circuit</i>	290
	<i>Phase Shift Oscillator Design</i>	291
	<i>Quadrature Oscillator</i>	292
11-2	Colpitts and Hartley Oscillators	293
	<i>Colpitts Oscillator</i>	293
	<i>Circuit Design</i>	295
	<i>Hartley Oscillator</i>	296
11-3	Wein Bridge Oscillator	297
11-4	Oscillator Amplitude Stabilization	300
	<i>Output Amplitude</i>	300
	<i>Diode Stabilization</i>	300
	<i>Computer Analysis</i>	302
	<i>Voltage Divider Stabilization</i>	302

<i>Computer Analysis</i>	305	
<i>FET Stabilization Circuit</i>	305	
11-5 IC Function Generator		307
<i>Functional Block Diagram</i>	307	
<i>Supply Voltage and Output Amplitude</i>	308	
<i>Basic 8038 Function Generator</i>	309	
<i>Adjusting the Frequency</i>	311	
<i>Output Parameters</i>	313	
Chapter 12 Active Filters		317
12-1 Filter Types and Characteristics		317
<i>Low-Pass</i>	318	
<i>High-Pass</i>	318	
<i>Band-Pass</i>	318	
<i>Notch</i>	318	
<i>Fall-Off Rate</i>	319	
<i>Filter Design Categories</i>	320	
12-2 First-Order Active Filters		321
<i>First-Order Low-Pass Filter</i>	321	
<i>Filter Characteristics</i>	321	
<i>Design Calculations</i>	323	
<i>First-Order High-Pass Filter</i>	324	
12-3 Second-Order Filters		326
<i>Second-Order Low-Pass Filter</i>	326	
<i>Second-Order High-Pass Filter</i>	328	
12-4 Third-Order Filters		331
<i>Third-Order Low-Pass Filter</i>	331	
<i>Computer Analysis</i>	333	
<i>Third-Order High-Pass Filter</i>	333	
12-5 Band-Pass Filters		335
<i>Multistage Band-Pass Filter</i>	335	
<i>Single-Stage Band-Pass Filter</i>	336	
<i>Bandwidth</i>	338	
<i>Narrowband Single-Stage Band-Pass Filter</i>	340	
12-6 Notch Filters		341
12-7 All-Pass Phase Shifting Circuits		343
<i>Phase-Lag Circuit</i>	343	
<i>Phase-Lead Circuit</i>	346	
12-8 State-Variable Filter		347
<i>Computer Analysis</i>	350	
12-9 IC Switched-Capacitor Filters		350
<i>Switched-Capacitor Resistor Simulation</i>	350	
<i>IC Filter Circuit</i>	352	
Chapter 13 DC Voltage Regulators		359
13-1 Voltage Regulator Basics		360
<i>Regulator Action</i>	360	
<i>Source Effect</i>	361	

	<i>Load Effect</i>	361
	<i>Ripple Rejection</i>	361
13-2	Op-Amp Series Voltage Regulator	362
	<i>Basic Circuit</i>	362
	<i>Series Regulator Design</i>	364
	<i>Series Regulator Performance</i>	366
13-3	Adjustable Output Regulators	367
	<i>Output Voltage Adjustment</i>	367
	<i>High Output Current Circuit</i>	368
	<i>Computer Analysis</i>	370
13-4	Output Current Limiting	371
	<i>Short-Circuit Protection</i>	371
	<i>Fold-Back Current Limiting</i>	373
13-5	IC Linear Voltage Regulators	376
	<i>723 IC Regulator</i>	376
	<i>LM317 and LM337 IC Regulators</i>	379
	<i>LM340 Regulators</i>	381
13-6	Switching Regulators	381
	<i>Switching Regulator Operation</i>	381
	<i>Comparison of Linear and Switching Regulators</i>	383
	<i>Step-Down Converter</i>	384
	<i>Step-Down Converter Equations</i>	384
	<i>Step-Up Converter</i>	388
	<i>Inverting Converter</i>	390
13-7	Switching Regulator Controller	392
	<i>Function Block Diagram</i>	392
	<i>Step-Down Converter Using an MC34063</i>	393
	<i>Variable Off Time Modulator</i>	394
	<i>Catch Diode Selection</i>	395
	<i>Diode Snubber</i>	395
	<i>High Power Converters</i>	395

Chapter 14 Audio Power Amplifiers 400

14-1	BJT Power Amplifier With Op-Amp Driver	401
	<i>Op-Amp Power Amplifier</i>	401
	<i>Resistor Calculations</i>	403
	<i>Capacitor Calculations</i>	404
	<i>Transistor Specifications</i>	404
	<i>Op-Amp Specification</i>	404
	<i>Diodes</i>	405
	<i>Computer Analysis</i>	408
14-2	Power Amplifier Performance Improvement	409
	<i>Darlington-Connected Output Transistors</i>	409
	<i>Quasi-Complementary Output Stage</i>	412
	<i>Output Current Limiting</i>	413
	<i>V_{BE} Multiplier</i>	413
	<i>Use of Bootstrapping Capacitors</i>	415
	<i>Load Compensation</i>	420
	<i>Power Supply Decoupling</i>	420

14-3	IC Power Amplifier Driver	421
14-4	MOSFET Power Amplifier With Op-Amp Driver	424
	<i>Advantages of MOSFETs</i> 424	
	<i>Power Amplifier with MOSFET Output Stage</i> 424	
	<i>Output Voltage Swing</i> 426	
	<i>MOSFET Power Amplifier Design</i> 427	
	<i>Computer Analysis</i> 430	
	<i>Bias Control</i> 432	
	<i>Complete Op-Amp MOSFET Power Amplifier</i> 433	
14-5	IC Power Amplifiers	434
	<i>250 mW IC Power Amplifier</i> 434	
	<i>Bridge-Tied Load Amplifier</i> 435	
	<i>2.5 W IC Power Amplifier</i> 437	
	<i>7 W IC Power Amplifier</i> 441	
	<i>68 W IC Power Amplifier</i> 441	

Chapter 15 Digital-to-Analog and Analog-to-Digital Conversion **447**

15-1	Analog/Digital Conversion Basics	448
	<i>Resolution</i> 448	
	<i>Analog-to-Digital Conversion</i> 449	
	<i>LSB and MSB</i> 449	
	<i>Digital-to-Analog Conversion</i> 450	
	<i>Settling Time</i> 451	
	<i>Monitonicity</i> 451	
	<i>Accuracy</i> 451	
15-2	Digital-to-Analog Conversion	451
	<i>Weighted Resistor DAC</i> 451	
	<i>R-2R DAC</i> 454	
	<i>Multiplying DAC</i> 456	
	<i>Integrated Circuit 8-Bit DAC</i> 457	
	<i>Computer Analysis</i> 457	
15-3	Parallel ADC	459
	<i>Simple 3-Bit Parallel ADC</i> 459	
15-4	ADC Counting Methods	461
	<i>AND Gate</i> 461	
	<i>Flip-Flops</i> 462	
	<i>Counting Registers</i> 464	
	<i>Frequency Division</i> 465	
	<i>Linear Ramp ADC</i> 465	
	<i>Dual-Slope Integrator ADC</i> 467	
	<i>Digital Ramp ADC</i> 468	
	<i>Successive Approximation ADC</i> 470	

Chapter 16 Phase-Locked Loop **473**

16-1	Basic Phase-Locked Loop System	474
16-2	PLL Components	476

<i>Phase Detector</i>	476	
<i>Phase/Frequency Detector</i>	478	
<i>Filter</i>	479	
<i>Amplifier</i>	479	
VCO	479	
16-3 PLL Performance Factors		479
<i>Loop Gain</i>	479	
<i>Tracking Range</i>	481	
<i>Capture Range</i>	482	
<i>Frequency Synthesis</i>	484	
16-4 PLL Frequency Response and Compensation		485
<i>System Characteristics</i>	485	
<i>VCO as an Integrator</i>	485	
<i>Instability</i>	487	
<i>Compensation</i>	488	
16-5 Integrated Circuit PLL		488
Appendix A IC Data Sheets		494
A-1 741 Op-amp		494
A-2 LM709 Operational Amplifier		498
A-3 108 and 308 Op-amp		499
A-4 353 Op-amp		503
Appendix B Standard Value Components		506
Table B-1 Typical Standard-Value Resistors		506
Table B-2 Typical Standard-Value Capacitors		508
Appendix C Answers to Odd-Numbered Problems		509
<i>Index</i>		515

CHAPTER 1

Introduction to Operational Amplifiers

Objectives

After studying this chapter, you will be able to

- 1 Sketch the circuit symbol for an operational amplifier (op-amp) and identify all terminals.
- 2 Draw a basic (three bipolar junction transistor) op-amp internal circuit diagram. Identify all terminals, and explain the circuit operation.
- 3 Sketch an op-amp voltage follower circuit. Explain its operation.
- 4 Draw the diagram for an op-amp noninverting amplifier. Explain the circuit operation, and calculate the voltage gain for given resistor values.
- 5 Draw the diagram for an op-amp inverting amplifier. Explain the circuit operation, and calculate the voltage gain for given resistor values.

INTRODUCTION

Operational amplifiers (op-amps) are very high gain amplifier circuits with two high-impedance input terminals and one low-impedance output. The input terminals are identified as *inverting input* and *noninverting input*. The basic op-amp circuit consists of a differential amplifier input stage, a level shifting intermediate stage, and an emitter-follower output stage. Operational amplifiers can be employed for a great many circuit applications by using various combinations of externally connected components. The simplest of these are the voltage follower, the noninverting amplifier, and the inverting amplifier.

1-1 IC OPERATIONAL AMPLIFIER

Circuit Symbol and Terminals

The circuit symbol for an op-amp, illustrated in Fig. 1-1, shows that there are two input terminals, one output terminal, and two supply terminals. Plus-minus supply voltages ($+V_{CC}$ and $-V_{EE}$) are normally used and these typically range from ± 5 to ± 22 V. The input terminals are designated as *inverting input* (minus sign) and *noninverting input* (plus sign). A positive-going voltage applied to the inverting input produces a negative-going (inverted)

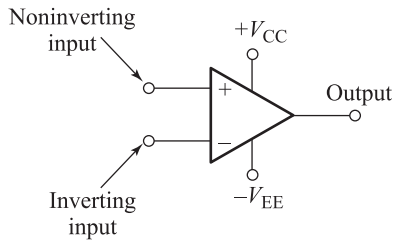


Figure 1-1 Operational amplifier circuit symbol. There are two supply terminals ($+V_{CC}$ and $-V_{EE}$), two input terminals (inverting and noninverting), and one output.

output, and a positive-going signal at the noninverting input generates a positive-going (noninverted) output.

Basic Op-amp Circuit

The basic circuit of an IC op-amp consists of a bipolar junction transistor (BJT) differential amplifier input stage combined with an emitter follower output. This is illustrated in Fig. 1-2. Note the plus—minus supply ($+V_{CC}$ and $-V_{EE}$), which is normally used. Transistors Q_1 and Q_2 together with resistors R_E and R_C constitute a differential amplifier, which produces a voltage change at the collector of Q_2 when a voltage difference is applied to the bases of Q_1 and Q_2 . The Q_2 collector voltage is passed to the voltage divider (R_a and R_b), which shifts the dc voltage level down to approximately half-way between $+V_{CC}$ and $-V_{EE}$. This voltage is then applied to the output via the emitter follower consisting of transistor Q_3 and emitter resistor R_{E3} .

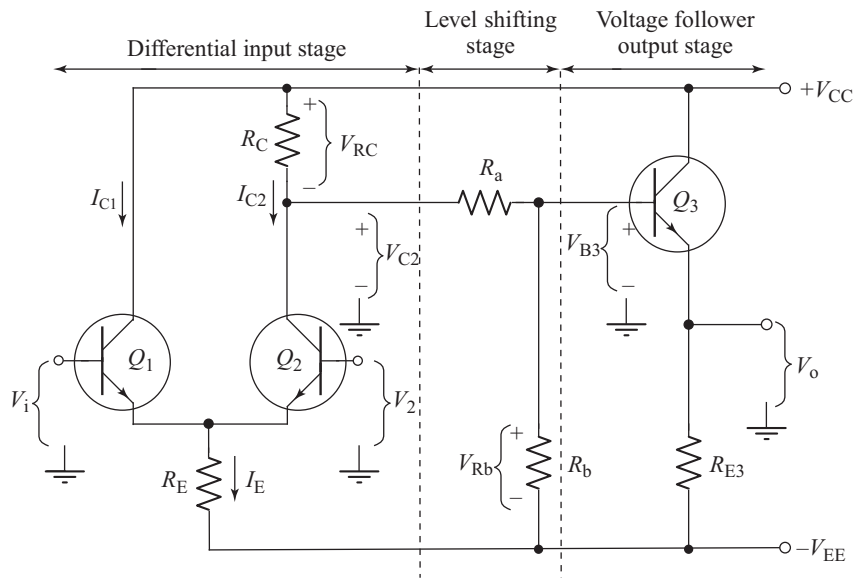


Figure 1-2 An op-amp circuit consists basically of a differential amplifier input stage, a level shifting intermediate stage, and an emitter follower output.

Example 1-1

Calculate the voltage and current levels for the circuit shown in Fig. 1-2 if $V_{CC} = \pm 10$ V, $V_i = V_2 = 0$, and the components are $R_a = 47$ k Ω , $R_b = 100$ k Ω , and $R_C = R_E = R_{E3} = 4.7$ k Ω . For simplicity, assume that Q_1 and Q_2 are

perfectly matched, that the current through R_a and R_b has no effect on the voltage drop across R_C , and that the Q_3 base current has no effect on the voltage divider.

Solution

$$\begin{aligned} V_{RE} &= V_{B1} - V_{BE} - V_{EE} \\ &= 0 - 0.7 \text{ V} - (-10 \text{ V}) \\ &= 9.3 \text{ V} \end{aligned}$$

$$\begin{aligned} I_E &= \frac{V_{RE}}{R_E} = \frac{9.3 \text{ V}}{4.7 \text{ k}\Omega} \\ &= 1.98 \text{ mA} \end{aligned}$$

$$I_{C1} = I_{C2} = \frac{I_E}{2} = 0.99 \text{ mA}$$

$$\begin{aligned} V_{RC} &= I_{C2} \times R_C \\ &= 0.99 \text{ mA} \times 4.7 \text{ k}\Omega \\ &= 4.65 \text{ V} \end{aligned}$$

$$\begin{aligned} V_{RaRb} &= V_{CC} - V_{EE} - V_{RC} \\ &= 10 \text{ V} - (-10 \text{ V}) - 4.65 \text{ V} \\ &= 15.35 \text{ V} \end{aligned}$$

$$\begin{aligned} V_{Rb} &= \frac{V_{RaRb} \times R_b}{R_a + R_b} \\ &= \frac{15.35 \text{ V} \times 100 \text{ k}\Omega}{100 \text{ k}\Omega + 4.7 \text{ k}\Omega} \\ &= 10.4 \text{ V} \end{aligned}$$

$$\begin{aligned} V_o &= V_{EE} + V_{Rb} - V_{BE} \\ &= -10 \text{ V} + 10.4 \text{ V} - 0.7 \text{ V} \\ &= -0.3 \text{ V} \end{aligned}$$

To further investigate the operation of the circuit in Fig. 1-2, suppose that a positive input ($+V_i$) is applied to the base of Q_1 and that the Q_2 base is held at ground level. This produces an increase in I_{C1} and a decrease in I_{C2} , resulting in a decreased voltage drop across resistor R_C . Consequently, V_{C2} and V_{B3} are increased, producing a positive-going output voltage. If the input to Q_1 base is negative ($-V_i$) instead of positive, I_{C1} is decreased and I_{C2} is increased, resulting in an increase in V_{RC} , a decrease in V_{B3} , and a consequent negative-going output.

It is seen that a positive-going input at the base of Q_1 produces a positive-going output at the Q_3 emitter, and that a negative-going input to Q_1 gives a negative-going output. This means that an input voltage applied to Q_1 base results in an output having the same polarity as the input (a noninverted output). Thus, the terminal at the base of Q_1 is the *noninverting input*.

Now assume that Q_1 base is maintained at ground level while a positive input ($+V_2$) is applied to the base of Q_2 . In this case I_{C1} is decreased and I_{C2} is

increased, producing an increased voltage drop across R_C and a consequent negative-going output. When the input to Q_2 base is negative ($-V_2$) instead of positive, I_{C2} is decreased, I_{C1} is increased, V_{RC} is decreased, and the output is positive-going. So, an input voltage to Q_2 base results in an output having the opposite polarity to the input (an inverted output). So, the terminal at the base of Q_2 is the *inverting input*.

The differential amplifier stage offers high input impedance (Z_i) at the BJT bases. The emitter follower output stage gives a low output impedance (Z_o). The input stage also provides voltage gain, and the more complex circuitry of a practical IC op-amp produces much higher gain than would be available from the simple differential amplifier stage illustrated. As with all amplifiers, the voltage gain is the output voltage divided by the input voltage. In this case, the input voltage is the difference between the two input terminal voltages (V_D). Where no negative feedback is involved, the voltage gain is termed the *open-loop voltage gain* (A_{OL}) (or $A_{v(OL)}$). When negative feedback is employed, the voltage gain becomes the *closed-loop gain* (A_{CL}). The high input impedance and the low output impedance are also enhanced by the practical op-amp circuitry, and they are both very much improved by the use of negative feedback in typical op-amp applications.

Section Review

- 1-1.1 Sketch the graphic symbol for an op-amp and identify all of the terminals.
 1-1.2 Sketch the basic (three BJT) internal circuit for an op-amp. Identify the inverting and noninverting terminals and briefly explain the circuit operation.

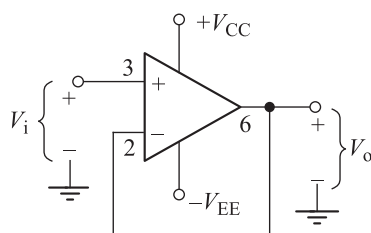
Practice Problem

- 1-1.1 Calculate V_o for the circuit in Example 1-1 when the supply is $V_{CC} = \pm 15$ V and R_C and R_E are changed to 5.6 k Ω .

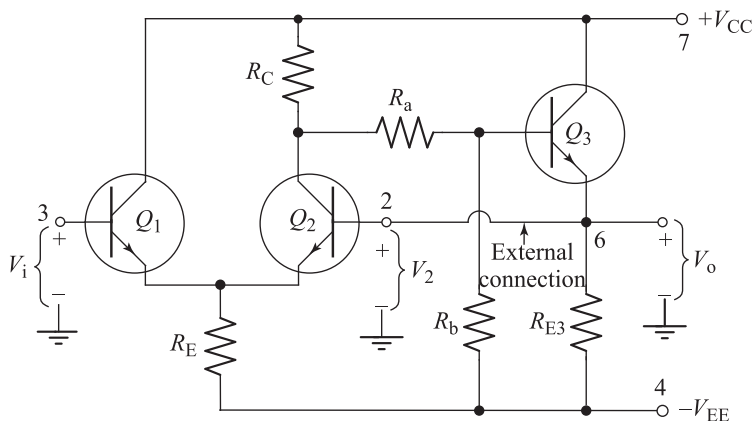
1-2 THE VOLTAGE FOLLOWER CIRCUIT

The IC op-amp lends itself to a wide variety of applications. The very simplest of these is the *voltage follower* shown in Fig. 1-3(a). The output terminal is connected directly to the inverting input terminal, the signal is applied to the noninverting input, and the load is directly coupled to the output. The output voltage now follows the input, giving the circuit a voltage gain of 1, a very high input impedance, and a very low output impedance.

To understand how the voltage follower operates, consider the basic op-amp circuit reproduced in Fig. 1-3(b). As in Fig. 1-3(a), the output (terminal 6) is connected to the inverting input terminal (terminal 2). With terminal 3 grounded, terminal 2 and the output must also be at ground level. If the input voltage (V_i) is increased above ground level, I_{C1} is increased and I_{C2} is decreased, causing V_{C2} to be decreased and thus producing an increase in V_o , which brings V_2 back to equality with V_i . If V_2 were somehow to go above the level of V_i , I_{C2} would be increased to produce a drop in V_o , which would



(a) Voltage follower circuit



(b) Basic op-amp circuit connected as a voltage follower

Figure 1-3 In a voltage follower circuit, the op-amp output is connected directly back to the inverting input terminal. When the input voltage changes, the output changes to keep the inverting input terminal voltage equal to the voltage at the noninverting input.

drive V_2 back to equality with V_i . It is seen that there is 100% negative feedback (NFB), which maintains the output voltage equal to the input. The output always *follows* the input; hence the name *voltage follower*.

The output of a voltage follower does not perfectly follow the input, because there has to be a very small difference between the two input terminals (a *differential input*, V_D) to produce the output voltage change. This depends on the op-amp amplification without feedback, known as the *open-loop voltage gain* (A_{OL} or $A_{v(OL)}$). When negative feedback is employed, the voltage gain becomes *closed-loop gain* (A_{CL}).

The voltage follower has a high input impedance, a low output impedance, and a closed-loop voltage gain of 1. This is similar to a BJT emitter follower. However, the difference between the dc input and output voltages with a voltage follower is typically less than 50 μV compared to 0.7 V for an emitter follower. As will be demonstrated, the voltage follower also has a much higher input impedance and a much lower output impedance than the emitter follower.

Example 1-2

Calculate the difference between the input and output voltages for a voltage follower with a 3 V input if the op-amp has $A_{OL} = 200\,000$.

Solution

$$V_D = \frac{V_o}{A_{OL}} = \frac{3 \text{ V}}{200\,000} = 15 \mu\text{V}$$

Practice Problems

- 1-2.1** Calculate the precise peak output voltage levels when a ± 100 mV signal is applied as input to a voltage follower that uses an op-amp with $A_{OL} = 100\,000$.
- 1-2.2** The output of a voltage follower is to follow the input within $20 \mu\text{V}$. Determine the minimum open-loop gain of the amplifier if the maximum input is ± 5 V.

1-3 THE NONINVERTING AMPLIFIER

The *noninverting amplifier* circuit shown in Figs. 1-4(a) and (b) behaves in a similar way to a voltage follower, except that the output voltage is divided by resistors R_1 and R_2 before being fed back to the inverting terminal. Consider the conditions that exist when the noninverting input is grounded. As is the case of the voltage follower, the inverting input terminal must also be at (or very close to) ground, and thus the junction of R_1 and R_2 is also at ground level. With both ends of resistor R_2 at ground level, there is no current flow through R_2 , and so (neglecting the very small bias current into terminal 2) there is no current through R_1 and no voltage drop across R_1 . Consequently, the circuit output voltage equals the input, which is at ground level.

Now suppose that a $+100$ mV input is applied to terminal 3. As explained, the output will move to a level that makes the feedback voltage (to terminal 2) equal to the voltage at terminal 3. The feedback voltage is developed across resistor R_2 , and the output appears across $R_1 + R_2$. So,

$$V_{R2} = V_i = I_1 R_2$$

and

$$V_o = I_1 (R_1 + R_2)$$

giving a *closed-loop voltage gain*

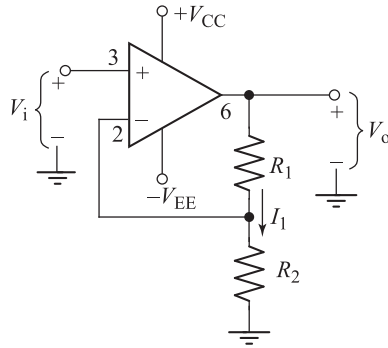
$$A_{CL} = \frac{V_o}{V_i} = \frac{I_1 (R_1 + R_2)}{I_1 R_2}$$

or,

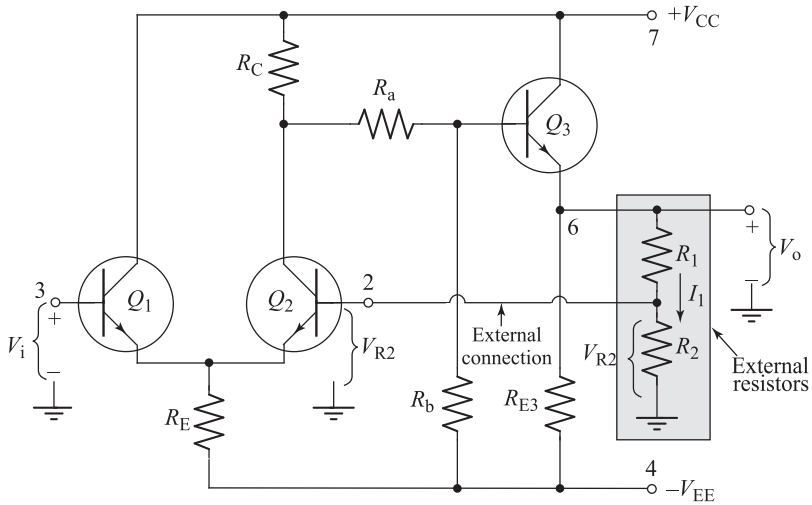
$$A_{CL} = \frac{R_1 + R_2}{R_2} \quad (1-1)$$

Example 1-3

A noninverting amplifier, as in Fig. 1-4, has $R_1 = 8.2 \text{ k}\Omega$ and $R_2 = 150 \Omega$. (a) Calculate the voltage gain. (b) Determine a new resistance for R_2 to give $A_{CL} = 75$.



(a) Noninverting amplifier circuit



(c) Basic op-amp circuit connected as a noninverting amplifier

Figure 1-4 A noninverting amplifier operates in the same way as a voltage follower except that the output voltage is divided before it is fed back to the inverting input terminal. The circuit closed-loop voltage gain is $A_{CL} = (R_1 + R_2)/R_2$.

Solution

(a) From Eq. 1-1

$$A_{CL} = \frac{R_1 + R_2}{R_2} = \frac{8.2 \text{ k}\Omega + 150 \text{ }\Omega}{150 \text{ }\Omega} = 55.7$$

(b) Again from Eq. 1-1

$$A_{CL} = \frac{R_1 + R_2}{R_2} = \frac{R_1}{R_2} + 1$$

giving

$$R_2 = \frac{R_1}{A_{CL} - 1} = \frac{8.2 \text{ k}\Omega}{75 - 1} = 111 \text{ }\Omega$$

Practice Problems

- 1-3.1** For cases (a) and (b) in the circuit in Example 1-3, calculate the voltages across resistors R_1 and R_2 when a +50 mV signal is applied as input.
- 1-3.2** A noninverting amplifier, as in Fig. 1-4, has $R_1 = 4.7 \text{ k}\Omega$ and $R_2 = 220 \Omega$. (a) Determine the closed-loop voltage gain. (b) Calculate the difference between the two input terminal voltages for a 300 mV input if the op-amp has $A_{OL} = 100\,000$.

1-4 THE INVERTING AMPLIFIER

The circuit shown in Fig. 1-5(a) is essentially the same as the noninverting amplifier in Fig. 1-4(a) with the important exception that the noninverting terminal is grounded and the input voltage is applied to resistor R_2 . In this case, a positive-going input voltage produces a negative-going output and vice versa. So, the circuit is an *inverting amplifier*. Figure 1-5(b) shows the way the circuit is usually drawn. Note that the junction of the two resistors is connected to the op-amp inverting input terminal, the noninverting terminal is grounded, and the input is applied between R_2 and ground, exactly as in Fig. 1-5(a).

Figure 1-5(c) shows the basic op-amp circuit connected as an inverting amplifier. When a positive-going input is applied to R_2 , I_{C2} is increased, thus increasing the voltage drop across R_C and driving the output voltage down. Because the base of Q_1 is grounded, the base of Q_2 will always be maintained at ground level (by negative feedback) regardless of the level of V_i . Thus, when V_i is applied, the output voltage moves to the level that keeps the inverting input terminal at ground. For this reason, the inverting input terminal in this type of circuit is referred to as a *virtual ground* or *virtual earth*.

Note from the above explanation that V_o is moved in a negative direction when V_i is positive. Similarly, when V_i is negative, V_o has to move in a positive direction to keep the op-amp inverting input terminal at ground level.

Now return to Fig. 1-5(b) and recall that the voltage at the inverting input terminal always remains close to ground because the noninverting terminal is grounded. Thus, the junction of R_1 and R_2 always remains at ground level. With V_i at one end of R_2 and ground at the other end, V_i appears across R_2 , as illustrated. Also, with V_o at one end of R_1 and ground at the other end, V_o is seen to be developed across R_1 . Ignoring the very small bias current flowing into the op-amp inverting input terminal, the current I_1 effectively flows through both R_1 and R_2 . The input and output voltages can now be expressed as

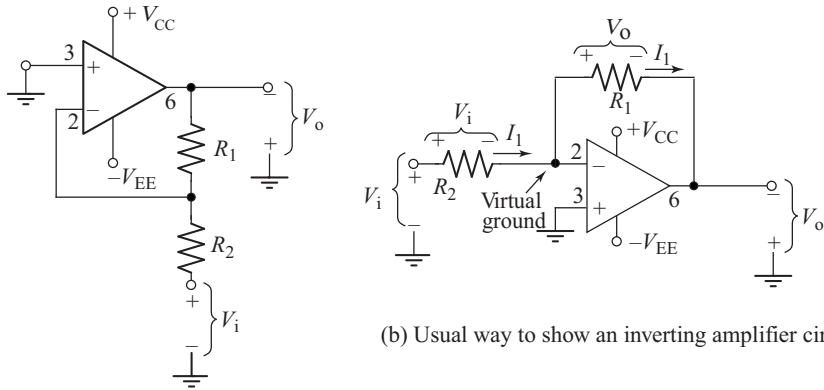
$$V_i = I_1 R_2$$

and

$$V_o = -I_1 R_1$$

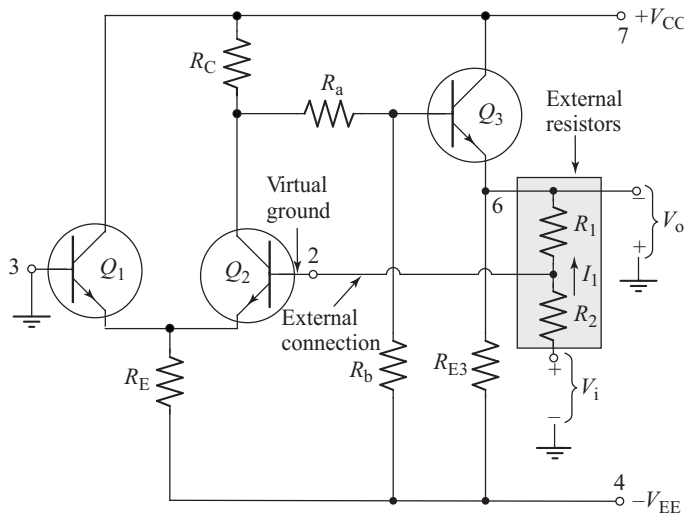
The closed-loop voltage gain is

$$A_{CL} = \frac{V_o}{V_i} = \frac{-I_1 R_1}{I_1 R_2}$$



(a) Inverting amplifier circuit

(b) Usual way to show an inverting amplifier circuit



(c) Basic op-amp circuit connected as an inverting amplifier

Figure 1-5 In an inverting amplifier the input is applied via resistor R_2 to the inverting input. This is essentially the same as a noninverting amplifier with the noninverting terminal grounded and the signal applied to the voltage divider. The circuit closed-loop voltage gain is $A_{CL} = -R_1/R_2$.

or,

$$A_{CL} = -\frac{R_1}{R_2} \tag{1-2}$$

The minus sign in Eq. 1-2 indicates that the output is inverted with respect to the input.

Example 1-4

An inverting amplifier, as in Fig. 1-5, has $R_1 = 8.2 \text{ k}\Omega$ and $R_2 = 270 \text{ }\Omega$. (a) Determine the voltage gain. (b) Calculate a new resistance for R_2 to give $A_{CL} = 60$.

Solution

(a) From Eq. 1-2

$$A_{CL} = -\frac{R_1}{R_2} = -\frac{8.2 \text{ k}\Omega}{270 \text{ }\Omega}$$

$$= -30.4$$

(b) From Eq. 1-2

$$R_2 = \frac{R_1}{A_{CL}} = \frac{8.2 \text{ k}\Omega}{60}$$

$$= 137 \text{ }\Omega$$

Practice Problems

- 1-4.1** For cases (a) and (b) in the circuit in Example 1-4, calculate the current through resistors R_1 and R_2 when a +100 mV signal is applied as input.
- 1-4.2** An inverting amplifier, as in Fig. 1-5, has $R_1 = 3.9 \text{ k}\Omega$ and $R_2 = 180 \text{ }\Omega$. (a) Determine the voltage gain. (b) If the op-amp has $A_{OL} = 200\,000$, calculate the voltage difference between the op-amp input terminals when a 200 mV input is applied.

Review Questions**Section 1-1**

- 1-1** Sketch the circuit symbol for an op-amp and identify all terminals.
- 1-2** Draw a basic (three BJT) op-amp internal circuit diagram. Identify the inverting input, noninverting input, and output terminals. Explain the circuit operation.

Section 1-2

- 1-3** Draw a circuit diagram for a voltage follower (a) using an op-amp graphic symbol and (b) using the basic three BJT op-amp circuit. Discuss the voltage follower operation.

Section 1-3

- 1-4** Draw a circuit diagram for a noninverting amplifier (a) using an op-amp graphic symbol and (b) using the basic three BJT op-amp circuit. Explain the circuit operation, and write the equation for the closed-loop voltage gain.

Section 1-4

- 1-5** Draw a circuit diagram for an inverting amplifier (a) using an op-amp graphic symbol and (b) using the basic three BJT op-amp circuit. Explain the circuit operation, and write the equation for the closed-loop voltage gain. Explain the term virtual ground.

Problems**Section 1-1**

- 1-1** Recalculate the circuit current and voltage levels for the basic three BJT op-amp circuit in Example 1-1 when the output is directly connected to the inverting input terminal.

- 1-2 A basic op-amp circuit as in Fig. 1-2 has the following components: $R_C = R_E = R_{E3} = 6.8 \text{ k}\Omega$, $R_a = 56 \text{ k}\Omega$, and $R_b = 120 \text{ k}\Omega$. The supply is $V_{CC} = \pm 12 \text{ V}$. Calculate the circuit current and voltage levels when the output is directly connected to the inverting input terminal. Assume that Q_1 and Q_2 are perfectly matched and that I_{B3} has no effect on the voltage divider.

Section 1-2

- 1-3 A 741 op-amp (Data Sheet A-1 in Appendix A) is connected as a voltage follower. If $V_i = 750 \text{ mV}$ and the amplifier open-loop gain is the only error source, calculate the precise level of V_o for (a) the specified minimum voltage gain and (b) for the specified typical gain.
- 1-4 An LM308 op-amp (Data Sheet A-3 in Appendix A) is substituted in place of the 741 in Problem 1-3. Calculate the output voltages for cases (a) and (b) once again.
- 1-5 An op-amp voltage follower with a 200 mV minimum input signal is to have 0.005% maximum output error. Determine the amplifier minimum open-loop gain.
- 1-6 A voltage follower using an LM308 op-amp is to reproduce the input with a maximum error of 10 μV due to the op-amp open-loop gain. Calculate the acceptable minimum input voltage.

Section 1-3

- 1-7 An op-amp noninverting amplifier, as in Fig. 1-4, has $R_1 = 22 \text{ k}\Omega$ and $R_2 = 120 \Omega$. Calculate the output voltage produced by a 75 mV input.
- 1-8 An op-amp noninverting amplifier is to have a voltage gain of 101. If $R_2 = 180 \Omega$ in Fig 1-4, determine a suitable resistance value for R_1 .
- 1-9 A 120 mV signal is to produce a 12 V output from an op-amp noninverting amplifier. If a 15 k Ω resistor is to be used for R_1 (as in Fig. 1-4), determine a suitable resistance value for R_2 .
- 1-10 Calculate the closed-loop gain for a noninverting amplifier, as in Fig. 1-4, with $R_1 = 27 \text{ k}\Omega$ and $R_2 = 390 \Omega$. Determine the voltage gain that results if the resistor positions are reversed.

Section 1-4

- 1-11 An op-amp inverting amplifier, as in Fig. 1-5(b), has $R_2 = 120 \Omega$ and $R_1 = 22 \text{ k}\Omega$. Calculate the output voltage produced by a 50 mV input.
- 1-12 An op-amp inverting amplifier is to have a voltage gain of 150. If $R_1 = 33 \text{ k}\Omega$ in Fig 1-5(b), determine a suitable resistance value for R_2 .
- 1-13 Calculate the closed-loop voltage gain for an inverting amplifier, as in Fig. 1-5(b), which has $R_1 = 39 \text{ k}\Omega$ and $R_2 = 680 \Omega$. Determine the new voltage gain if the resistor positions are reversed.
- 1-14 An op-amp inverting amplifier, as in Fig. 1-5(b), is to have a 0.5 V input signal and a 9 V output. Determine a suitable resistance value for R_2 if $R_1 = 12 \text{ k}\Omega$.

Practice Problem Answers

- 1-1.1 -0.2 V
- 1-2.1 $\pm(100\text{ mV} - 0.1\text{ }\mu\text{V})$
- 1-2.2 $250\ 000$
- 1-3.1 $(50\text{ mV}, 2.7\text{ V}), (50\text{ mV}, 3.69\text{ V})$
- 1-3.2 $22.4, 67\text{ }\mu\text{V}$
- 1-4.1 $370\text{ }\mu\text{V}, 730\text{ }\mu\text{A}$
- 1-4.2 $-21.7, 21.7\text{ }\mu\text{V}$