HZ BOOKS 华章教育

Mc Graw Hill Education

国外电子与电气工程技术丛书

基于运算放大器的模拟集成电路设计

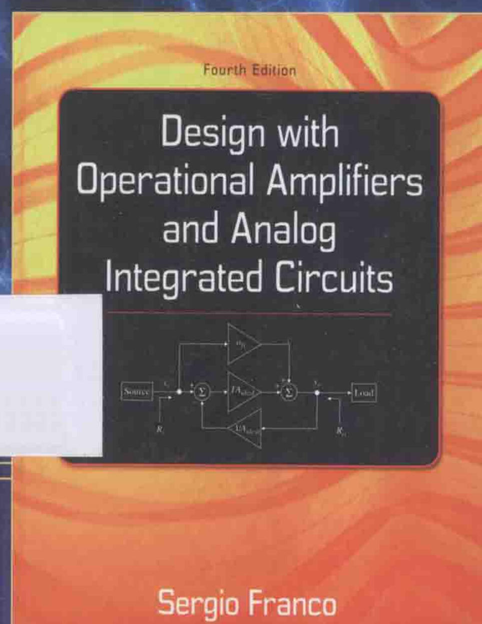
（英文版·第4版）

[美] Sergio Franco 著

何乐年 注释

Design with Operational Amplifiers and Analog Integrated Circuits

Fourth Edition



机械工业出版社
China Machine Press

国外电子与电气工程技术丛书

基于运算放大器的模拟集成电路设计

（英文版·第4版）

[美] Sergio Franco 著
何乐年 注释

机械工业出版社
China Machine Press

图书在版编目（CIP）数据

基于运算放大器的模拟集成电路设计（英文版·第 4 版）/（美）弗兰克（Franco, S.）著；何乐年注释．—北京：机械工业出版社，2015.1
（国外电子与电气工程技术丛书）
书名原文：Design with Operational Amplifiers and Analog Integrated Circuits, Fourth Edition

ISBN 978-7-111-48933-7

I. 基…　II. ① 弗…　② 何…　III. ① 模拟集成电路－电路设计－英文　② 运算放大器－电路设计－英文　IV. ① TN722.702　② TN431.102

中国版本图书馆 CIP 数据核字（2014）第 303199 号

本书版权登记号：图字：01-2014-7782

出版发行：机械工业出版社（北京市西城区百万庄大街 22 号　邮政编码：100037）

责任编辑：谢晓芳　　　　责任校对：殷　虹

印　　刷：北京诚信伟业印刷有限公司　　　　版　　次：2015 年 1 月第 1 版第 1 次印刷

开　　本：186mm×240mm　1/16　　　　印　　张：45.5

书　　号：ISBN 978-7-111-48933-7　　　　定　　价：99.00 元

凡购本书，如有缺页、倒页、脱页，由本社发行部调换

客服热线：(010) 88378991　88361066　　　　投稿热线：(010) 88379604

购书热线：(010) 68326294　88379649　68995259　　　　读者信箱：hzjsj@hzbook.com

出版者的话

文艺复兴以降，源远流长的科学精神和逐步形成的学术规范，使西方国家在自然科学的各个领域取得了垄断性的优势；也正是这样的传统，使美国在信息技术发展的六十多年间名家辈出、独领风骚。在商业化的进程中，美国的产业界与教育界越来越紧密地结合，信息学科中的许多泰山北斗同时身处科研和教学的最前线，由此而产生的经典科学著作，不仅擘划了研究的范畴，还揭示了学术的源变，既遵循学术规范，又自有学者个性，其价值并不会因年月的流逝而减退。

近年，在全球信息化大潮的推动下，我国的信息产业发展迅猛，对专业人才的需求日益迫切。这对我国教育界和出版界都既是机遇，也是挑战；而专业教材的建设在教育战略上显得举足轻重。在我国信息技术发展时间较短的现状下，美国等发达国家在其信息科学发展的几十年间积淀和发展的经典教材仍有许多值得借鉴之处。因此，引进一批国外优秀教材将对我国教育事业的发展起到积极的推动作用，也是与世界接轨、建设真正的世界一流大学的必由之路。

机械工业出版社华章公司较早意识到“出版要为教育服务”。自 1998 年开始，我们就将工作重点放在了遴选、移译国外优秀教材上。经过多年的不懈努力，我们与 Pearson、McGraw-Hill、Elsevier、John Wiley & Sons、CRC、Springer 等世界著名出版公司建立了良好的合作关系，从他们现有的数百种教材中甄选出 Thomas L. Floyd、Charles K. Alexander、Behzad Razavi、John G. Proakis、Stephen Brown、Allan R. Hambley、Albert Malvino、Mark I.Montrose、David A. Johns 、Peter Wilson 、H. Vincent Poor、Dikshitulu K. Kalluri、Bhag Singh Guru、Stephane Mallat 等大师名家的经典教材，以“国外电子与电气工程技术丛书”为总称出版，供读者学习、研究及珍藏。这些书籍在读者中树立了良好的口碑，并被许多高校采用为正式教材和参考书籍。其影印版“经典原版书库”作为姊妹篇也越来越多被实施双语教学的学校所采用。

权威的作者、经典的教材、一流的译者、严格的审校、精细的编辑，这些因素使我们的图书有了质量的保证。随着电气与电子信息学科建设的不断完善和教材改革的逐渐深化，教育界对国外电气与电子信息教材的需求和应用都将步入一个新的阶段，我们的目标是尽善尽美，而反馈的意见正是我们达到这一终极目标的重要帮助。华章公司欢迎老师和读者对我们的工作提出建议或给予指正，我们的联系方法如下：

华章网站：www.hzbook.com
电子邮件：hzjsj@hzbook.com
联系电话：(010) 88379604
联系地址：北京市西城区百万庄南街 1 号
邮政编码：100037

HZ BOOKS 华章教育

华章科技图书出版中心

PREFACE

During the last decades much has been prophesized that there will be little need for analog circuitry in the future because digital electronics is taking over. Far from having proven true, this contention has provoked controversial rebuttals, as epitomized by statements such as "If you cannot do it in digital, it's got to be done in analog." Add to this the common misconception that analog design, compared to digital design, seems to be more of a whimsical art than a systematic science, and what is the confused student to make of this controversy? Is it worth pursuing some coursework in analog electronics, or is it better to focus just on digital?

There is no doubt that many functions that were traditionally the domain of analog electronics are nowadays implemented in digital form, a popular example being offered by digital audio. Here, the analog signals produced by microphones and other acoustic transducers are suitably conditioned by means of amplifiers and filters, and are then converted to digital form for further processing, such as mixing, editing, and the creation of special effects, as well as for the more mundane but no less important tasks of transmission, storage, and retrieval. Finally, digital information is converted back to analog signals for playing through loudspeakers. One of the main reasons why it is desirable to perform as many functions as possible digitally is the generally superior reliability and flexibility of digital circuitry. However, *the physical world is inherently analog,* indicating that there will *always* be a need for analog circuitry to condition physical signals such as those associated with transducers, as well as to convert information from analog to digital for processing, and from digital back to analog for reuse in the physical world. Moreover, new applications continue to emerge, where considerations of speed and power make it more advantageous to use analog front ends; wireless communications provide a good example.

Indeed many applications today are best addressed by mixed-mode integrated circuits (mixed-mode ICs) and systems, which rely on analog circuitry to interface with the physical world, and digital circuitry for processing and control. Even though the analog circuitry may constitute only a small portion of the total chip area, it is often the most challenging part to design as well as the limiting factor on the performance of the entire system. In this respect, it is usually the analog designer who is called to devise ingenious solutions to the task of realizing analog functions in decidedly digital technologies; switched-capacitor techniques in filtering and sigma-delta techniques in data conversion are popular examples. In light of the above, the need for competent analog designers will continue to remain very strong. Even purely digital circuits, when pushed to their operational limits, exhibit analog behavior. Consequently, a solid grasp of analog design principles and techniques is a valuable asset in the design of any IC, not just purely digital or purely analog ICs.

THE BOOK

The goal of this book is the illustration of general analog principles and design methodologies using practical devices and applications. The book is intended as a textbook for undergraduate and graduate courses in design and applications with analog integrated circuits (analog ICs), as well as a reference book for practicing engineers. The reader is expected to have had an introductory course in electronics, to be conversant in frequency-domain analysis techniques, and to possess basic skills in the use of SPICE. Though the book contains enough material for a two-semester course, it can also serve as the basis for a one-semester course after suitable selection of topics. The selection process is facilitated by the fact that the book as well as its individual chapters have generally been designed to proceed from the elementary to the complex.

At San Francisco State University we have been using the book for a sequence of two one-semester courses, one at the senior and the other at the graduate level. In the senior course we cover Chapters 1–3, Chapters 5 and 6, and most of Chapters 9 and 10; in the graduate course we cover all the rest. The senior course is taken concurrently with a course in analog IC fabrication and design. For an effective utilization of analog ICs, it is important that the user be cognizant of their internal workings, at least qualitatively. To serve this need, the book provides intuitive explanations of the technological and circuital factors intervening in a design decision.

NEW TO THE FOURTH EDITION

The key features of the new edition are: *(a)* a complete revision of negative feedback, *(b)* much enhanced treatment of op amp dynamics and frequency compensation, *(c)* expanded coverage of switching regulators, *(d)* a more balanced presentation of bipolar and CMOS technologies, *(e)* a substantial increase of in-text PSpice usage, and *(f)* redesigned examples and about 25% new end-of-chapter problems to reflect the revisions.

While previous editions addressed negative feedback from the specialized viewpoint of the op amp user, the fourth edition offers a much broader perspective that will prove useful also in other areas like switching regulators and phase-locked loops. The new edition presents both two-port analysis and return-ratio analysis, emphasizing similarities but also differences, in an attempt at dispelling the persisting confusion between the two (to keep the distinction, the loop gain and the feedback factor are denoted as L and b in two-port analysis, and as T and β in return-ratio analysis).

Of necessity, the feedback revision is accompanied by an extensive rewriting of op amp dynamics and frequency compensation. In this connection, the fourth edition makes generous use of the voltage/current injection techniques pioneered by R. D. Middlebrook for loop-gain measurements.

In view of the importance of portable-power management in today's analog electronics, this edition offers an expanded coverage of switching regulators. Much greater attention is devoted to current control and slope compensation, along with stability issues such as the effect of the right-half plane zero and error-amplifier design.

The book makes abundant use of SPICE (schematic capture instead of the netlists of the previous editions), both to verify calculations and to investigate higher-order effects that would be too complex for paper and pencil analysis. SPICE is nowadays available in a variety of versions undergoing constant revision, so rather than committing to a particular version, I have decided to keep the examples simple enough for students to quickly redraw them and run them in the SPICE version of their choice.

As in the previous editions, the presentation is enhanced by carefully thought-out examples and end-of-chapter problems emphasizing intuition, physical insight, and problem-solving methodologies of the type engineers exercise daily on the job.

The desire to address general and lasting principles in a manner that transcends the latest technological trend has motivated the choice of well-established and widely documented devices as vehicles. However, when necessary, students are made aware of more recent alternatives, which they are encouraged to look up online.

THE CONTENTS AT A GLANCE

Although not explicitly indicated, the book consists of three parts. The first part (Chapters 1–4) introduces fundamental concepts and applications based on the op amp as a predominantly ideal device. It is felt that the student needs to develop sufficient confidence with ideal (or near-ideal) op amp situations before tackling and assessing the consequences of practical device limitations. Limitations are the subject of the second part (Chapters 5–8), which covers the topic in more systematic detail than previous editions. Finally, the third part (Chapters 9–13) exploits the maturity and judgment developed by the reader in the first two parts to address a variety of design-oriented applications. Following is a brief chapter-by-chapter description of the material covered.

Chapter 1 reviews basic amplifier concepts, including negative feedback. Much emphasis is placed on the loop gain as a gauge of circuit performance. The loop gain is treated via both two-port analysis and return-ratio analysis, with due attention to similarities as well as differences between the two approaches. The student is introduced to simple PSpice models, which will become more sophisticated as we progress through the book. Those instructors who find the loop-gain treatment overwhelming this early in the book may skip it and return to it at a more suitable time. Coverage rearrangements of this sort are facilitated by the fact that individual sections and chapters have been designed to be as independent as possible from each other; moreover, the end-of-chapter problems are grouped by section.

Chapter 2 deals with I-V, V-I, and I-I converters, along with various instrumentation and transducer amplifiers. The chapter places much emphasis on feedback topologies and the role of the loop gain T.

Chapter 3 covers first-order filters, audio filters, and popular second-order filters such as the *KRC*, multiple-feedback, state-variable, and biquad topologies. The chapter emphasizes complex-plane systems concepts and concludes with filter sensitivities.

The reader who wants to go deeper into the subject of filters will find Chapter 4 useful. This chapter covers higher-order filter synthesis using both the cascade and the direct approaches. Moreover, these approaches are presented for both the case of active *RC* filters and the case of switched-capacitor (SC) filters.

Chapter 5 addresses input-referrable op amp errors such as V_{OS}, I_B, I_{OS}, CMRR, PSRR, and drift, along with operating limits. The student is introduced to data-sheet interpretation, PSpice macromodels, and also to different technologies and topologies.

Chapter 6 addresses dynamic limitations in both the frequency and time domains, and investigates their effect on the resistive circuits and the filters that were studied in the first part using mainly ideal op amp models. Voltage feedback and current feedback are compared in detail, and PSpice is used extensively to visualize both the frequency and transient responses of representative circuit examples. Having mastered the material of the first four chapters using ideal or nearly ideal op amps, the student is now in a better position to appreciate and evaluate the consequences of practical device limitations.

The subject of ac noise, covered in Chapter 7, follows naturally since it combines the principles learned in both Chapters 5 and 6. Noise calculations and estimation represent another area in which PSpice proves a most useful tool.

The second part concludes with the subject of stability in Chapter 8. The enhanced coverage of negative feedback has required an extensive revision of frequency compensation, both internal and external to the op amp. The fourth edition makes generous use of the voltage/current injection techniques pioneered by R. D. Middlebrook for loop-gain measurements. Again, PSpice is used profusely to visualize the effect of the different frequency-compensation techniques presented.

The third part begins with nonlinear applications, which are discussed in Chapter 9. Here, nonlinear behavior stems from either the lack of feedback (voltage comparators), or the presence of feedback, but of the positive type (Schmitt triggers), or the presence of negative feedback, but using nonlinear elements such as diodes and switches (precision rectifiers, peak detectors, track-and-hold amplifiers).

Chapter 10 covers signal generators, including Wien-bridge and quadrature oscillators, multivibrators, timers, function generators, and V-F and F-V converters.

Chapter 11 addresses regulation. It starts with voltage references, proceeds to linear voltage regulators, and concludes with a much-expanded coverage of switching regulators. Great attention is devoted to current control and slope compensation, along with stability issues such as error-amplifier design and the effect of the right-half plane zero in boost converters.

Chapter 12 deals with data conversion. Data-converter specifications are treated in systematic fashion, and various applications with multiplying DACs are presented. The chapter concludes with oversampling-conversion principles and sigma-delta converters. Much has been written about this subject, so this chapter of necessity exposes the student only to the fundamentals.

Chapter 13 concludes the book with a variety of nonlinear circuits, such as log/antilog amplifiers, analog multipliers, and operational transconductance amplifiers with a brief exposure to g_m-C filters. The chapter culminates with an introduction to phase-locked loops, a subject that combines important materials addressed at various points in the preceding chapters.

WEBSITE

The book is accompanied by a Website (http://www.mhhe.com/franco) containing information about the book and a collection of useful resources for the instructor. Among the Instructor Resources are a Solutions Manual, a set of PowerPoint Lecture Slides, and a link to the Errata.

ACKNOWLEDGMENTS

Some of the changes in the fourth edition were made in response to feedback received from a number of readers in both industry and academia, and I am grateful to all who took the time to e-mail me. In addition, the following reviewers provided detailed commentaries on the previous edition as well as valuable suggestions for the current revision. All suggestions have been examined in detail, and if only a portion of them has been honored, it was not out of callousness, but because of production constraints or personal philosophy. To all reviewers, my sincere thanks: Aydin Karsilayan, Texas A&M University; Paul T. Kolen, San Diego State University; Jih-Sheng (Jason) Lai, Virginia Tech; Andrew Rusek, Oakland University; Ashok Srivastava, Louisiana State University; S. Yuvarajan, North Dakota State University.

I remain grateful to the reviewers of the previous editions: Stanley G. Burns, Iowa State University; Michael M. Cirovic, California Polytechnic State University-San Luis Obispo; J. Alvin Connelly, Georgia Institute of Technology; William J. Eccles, Rose-Hulman Institute of Technology; Amir Farhat, Northeastern University; Ward J. Helms, University of Washington; Frank H. Hielscher, Lehigh University; Richard C. Jaeger, Auburn University; Franco Maddaleno, Politecnico di Torino, Italy; Dragan Maksimovic, University of Colorado-Boulder; Philip C. Munro, Youngstown State University; Thomas G.Owen, University of North Carolina-Charlotte; Dr. Guillermo Rico, New Mexico State University; Mahmoud F. Wagdy, California State University-Long Beach; Arthur B. Williams, Coherent Communications Systems Corporation; and Subbaraya Yuvarajan, North Dakota State University. Finally, I wish to express my gratitude to Diana May, my wife, for her encouragement and steadfast support.

Sergio Franco
San Francisco, California, 2014

CONTENTS

1

OPERATIONAL AMPLIFIER FUNDAMENTALS

运算放大器（operational amplifier），或者简称 op amp，是在 1947 年由 John R. Ragazzini 命名的，用以代表一种特殊类型的放大器。通过对其外部元件的适当选取，可以构成各种运算，如放大、加、减、微分和积分。运算放大器的首次应用是在模拟计算机中。实现数学运算的能力是由于运算放大器具有高增益并结合负反馈的结果。

早期的运算放大器采用真空二极管实现，因而体积大、耗电并且价格昂贵。第一次显著小型化是由于双极型晶体管（BJT）的出现，促使利用分立 BJT 实现新一代运算放大器。然而，真正的突破出现在集成电路（IC）运算放大器的开发，它的元件是以单片的形式制造在只有针头大小的硅芯片上。第一个这样的器件是在 20 世纪 60 年代初由神童半导体公司（Fairchild Semiconductor

Corporation）的 Robert J. Widlar 研制出的。在 1968 年仙童半导体公司推出了运算放大器从而成为行业标准，这就是流行的 μA741。从那以后，运算放大器的各种系列和制造商急剧涌现。不管怎样，μA741 年无疑是最广泛记载的运算放大器。它的应用普及经久不衰，且当前文献仍有许多拿它作参考，所以无论是从历史观点还是教学角度，它都值得我们学习。

事实上，运算放大器已经持续不断地渗透到模拟和模拟 – 数字混合电子学的每各个方面 [1]。如此广泛地应用得益于价格的急剧下降。今天，批量采购一块运算放大器的价格可以与大多传统元件（如微调电容器、质量好的电容器和精密电阻器）的价格相比拟。事实上，一般把运算放大器看作另一种元件，这对当今我们了解和设计模拟电路具深远影响。

在第 5 章的附录中，图 5A.2 为 μA741 运算放大器的内部电路图。这张电路图或许使你感到畏惧，特别是如果你对 BJT 理解还不够深。然而，设计大量的运算放大器应用电路而无须详细了解运算放大器的内部工作机理是可能的。确实如此，无论运算放大器内部多么复杂，它的输入、输出关系却很简单，可以用黑框表示。你将会看到，这种简化的框图对于大多数情况已经够用了。如果不能满足，可以借助于技术数据，并由此预测电路性能，这同样不需要详细考虑内部工作。

为了提升产品，运算放大器制造商一直将应用部门与产品应用效果维系在一起，并且在商业期刊上利用应用笔记和文章将它们公布出来。当今网站上可以获得许多信息，它们鼓励你利用空闲时间，熟悉起模拟产品数据表和应用笔记。你甚至可以签约参加在线研讨会或网络会议。

运算放大器原理的这种学习被实际试验所证实。你可以在实验室里的一块面包板上组装、调试你的电路，也可以采用现在的各种 CAD/CAE 软件包（如 SPICE）用一台个人电脑对它们进行仿真。最好的效果是两者都做。

本章重点

在简要复习基本运放器的概念后，这一章介绍运算放大器，以及适用于研究各种基本运算放大器电路的分析技术，运放电路包括反相 / 非反相放大器、缓冲放大器、加法 / 差分放大器、微分 / 积分器和负阻转换器。

这些电路的工作核心是负反馈技术。本章介绍二端口网络法和返回比分析法。尤其要指出环路增益是负反馈电路最为重要的特性。（在二端口网络法，环路增益和反馈系数分别表示为 L 与 b，在返回比分析法则分别为 T 与 β）。负反馈的优点被大量实例与 SPICE 仿真证实。

本章最后用某些实际应用问题，如运算放大器的供电问题、内部功耗以及输出饱和（更多细节见第 5 章和第 6 章）。本章大量使用 SPICE 作为手算验证工具，同时也用作教学工具来表达更直接的概念和原则。

1.1 AMPLIFIER FUNDAMENTALS

Before embarking on the study of the operational amplifier, it is worth reviewing the fundamental concepts of amplification and loading. Recall that an amplifier is a two-port device that accepts an externally applied signal, called *input,* and generates a signal called *output* such that *output* = *gain* × *input,* where *gain* is a suitable proportionality constant. A device conforming to this definition is called a *linear amplifier* to distinguish it from devices with nonlinear input-output relationships, such as quadratic and log/antilog amplifiers. Unless stated to the contrary, the term *amplifier* will here signify *linear amplifier.*

An amplifier receives its input from a *source* upstream and delivers its output to a *load* downstream. Depending on the nature of the input and output signals, we have different amplifier types. The most common is the *voltage amplifier,* whose input v_I and output v_O are voltages. Each port of the amplifier can be modeled with a Thévenin equivalent, consisting of a voltage source and a series resistance. The input port usually plays a purely passive role, so we model it with just a resistance R_i, called the *input resistance* of the amplifier. The output port is modeled with a voltage-controlled voltage source (VCVS) to signify the dependence of v_O on v_I, along with a series resistance R_o called the *output resistance.* The situation is depicted in Fig. 1.1, where A_{oc} is called the *voltage gain factor* and is expressed in volts per volt. Note that the input source is also modeled with a Thévenin equivalent consisting of the source v_S and an internal series resistance R_s; the output load, playing a passive role, is modeled with a mere resistance R_L.

We now wish to derive an expression for v_O in terms of v_S. Applying the voltage divider formula at the output port yields

$$v_O = \frac{R_L}{R_o + R_L} A_{oc} v_I \tag{1.1}$$

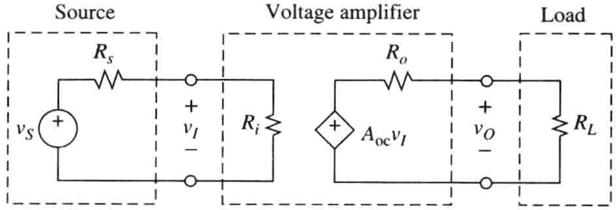


FIGURE 1.1
Voltage amplifier.

We note that in the absence of any load ($R_L = \infty$) we would have $v_O = A_{oc}v_I$. Hence, A_{oc} is called the *unloaded,* or *open-circuit,* voltage gain. Applying the voltage divider formula at the input port yields

$$v_I = \frac{R_i}{R_s + R_i} v_S \tag{1.2}$$

Eliminating v_I and rearranging, we obtain the *source-to-load gain,*

$$\frac{v_O}{v_S} = \frac{R_i}{R_s + R_i} A_{oc} \frac{R_L}{R_o + R_L} \tag{1.3}$$

As the signal progresses from source to load, it undergoes first some attenuation at the input port, then magnification by A_{oc} inside the amplifier, and finally additional attenuation at the output port. These attenuations are referred to as *loading.* It is apparent that because of loading, Eq. (1.3) gives $|v_O/v_S| \le |A_{oc}|$.

EXAMPLE 1.1. (*a*) An amplifier with $R_i = 100\ \text{k}\Omega$, $A_{oc} = 100$ V/V, and $R_o = 1\ \Omega$ is driven by a source with $R_s = 25\ \text{k}\Omega$ and drives a load $R_L = 3\ \Omega$. Calculate the overall gain as well as the amount of input and output loading. (*b*) Repeat, but for a source with $R_s = 50\ \text{k}\Omega$ and a load $R_L = 4\ \Omega$. Compare.

Solution.

(*a*) By Eq. (1.3), the overall gain is $v_O/v_S = [100/(25 + 100)] \times 100 \times 3/(1 + 3) = 0.80 \times 100 \times 0.75 = 60$ V/V, which is less than 100 V/V because of loading. Input loading causes the source voltage to drop to 80% of its unloaded value; output loading introduces an additional drop to 75%.

(*b*) By the same equation, $v_O/v_S = 0.67 \times 100 \times 0.80 = 53.3$ V/V. We now have more loading at the input but less loading at the output. Moreover, the overall gain has changed from 60 V/V to 53.3 V/V.

Loading is generally undesirable because it makes the overall gain dependent on the particular input source and output load, not to mention gain reduction. The origin of loading is obvious: when the amplifier is connected to the input source, R_i draws current and causes R_s to drop some voltage. It is precisely this drop that, once subtracted from v_S, leads to a reduced voltage v_I. Likewise, at the output port the magnitude of v_O is less than the dependent-source voltage $A_{oc}v_I$ because of the voltage drop across R_o.

If loading could be eliminated altogether, we would have $v_O/v_S = A_{oc}$ regardless of the input source and the output load. To achieve this condition, the voltage drops across R_s and R_o must be zero regardless of R_s and R_L. The only way to achieve this is by requiring that our voltage amplifier have $R_i = \infty$ and $R_o = 0$. For obvious reasons such an amplifier is termed *ideal.* Though these conditions cannot be met in practice, an amplifier designer will strive to approximate them as closely as possible by ensuring that $R_i \gg R_s$ and $R_o \ll R_L$ for all input sources and output loads that the amplifier is likely to be connected to.

Another popular amplifier is the *current amplifier.* Since we are now dealing with currents, we model the input source and the amplifier with Norton equivalents, as in Fig. 1.2. The parameter A_{sc} of the current-controlled current source (CCCS)