

STUDENT MANUAL FOR

THE

影印版

# ART OF ELECTRONICS

## 电子学课程指导与实验

[美] THOMAS C. HAYES  
PAUL HOROWITZ 编著

(哈佛大学)



清华大学出版社

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北京

## **Student Manual for The Art of Electronics**

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Paul Horowitz

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## 写在前面

这本书是与《电子学(The Art of Electronics)》一书配套使用的,包括以下三部分:

- ◆ 实验练习:共有 23 个实验,完成一个实验大约需要 3 个小时。每个实验(除第 23 个外)都要求读者复习课本(《电子学》)上的相关章节。
- ◆ 讲解:每个实验练习或每节课都有与之相配套的讲解材料
- ◆ 实例:共有 20 个验证过的实例

除此以外,本书中包含了一些参考资料:

- ◆ 一些常用术语的词汇表
- ◆ 每章的复习笔记,提醒读者注意该章中最重要的电路和主题
- ◆ 一些精心挑选的器件手册,包括模拟器件和数字器件

## 哪些学生适合学本课程

这些笔记源于哈佛的一门课程,从这些笔记可以看出我们希望在一个学期中教授些什么内容。当然,课程的内容要比书上少。我们只教第一章到第十一章,中间跳过第四章和第七章。即使这样,选择的内容仍比我们要求学生掌握的要多。希望本书能指引学生关注那些最重要的材料。

修本课程的学生主要是那些物理系的大学生,他们希望能学到足够的电子学知识,以便可以在实验室做点有用的工作。但事实上,越来越多非物理系的学生前来听课,研究生也常常出现在课堂上;夏天会有很多高中生来听课,而且有些学得很出色;偶尔会有物理学的教授修本课程(他们也做得很好)。在本课程“扩展”部分的课堂上,可以看到很多想了解在自己机子上到底发生了什么的程序员;也常可看到一些对电子学很好奇的人们。而事实上,这种好奇,是修本课程的惟一要求,而有着这种好奇心的人们才能真正享受这门课程所带来的乐趣。一些寻求工程学课程的人们,可能会觉得我们对课程的处理不很正规,但那些渴望学习如何设计有用电路的人们会喜欢这个课程的。

## 实验练习

本书中的实验是在 Horowitz 和 Robinson 于 1981 年版的《实验手册》中设计的一些实验的基础上修改补充而成的。新的实验将原有的数字电路实验内容都更新了,而且基本上重新设计了关于场效应管和振荡器的相关模拟电路实验。在数字部分,我们采用的器件从 LSTTL 转为 HCMOS,但最大的变化不是这个,而是微处理器在整个数字实验中所占的比重大大增加了,并且从最初的 Z80 处理器变成使用键盘控制的 68008 处理器(完整的原理图参见 Lab15)。

现在的课程中,数字电路那部分内容以微机为重点:我们会遇到一些简单的数字器件——如逻辑门,触发器,计数器,存储器等——因为我们希望读者能够设计小型的数字电路,

并且希望读者能借此更好地理解整个微机的电路。换一种说法,在最后的一系列实验中,微机逐渐成形;而这些实验事实上就是之前遇到的一些单元电路的组合:组合逻辑网络,触发器电路,计数器,存储器,模数转换。模数转换实验内容有所扩展,包括了抽样速率对转换的影响以及用于输入输出端的滤波器的作用。

## 建议:如何使用本书

以下仅仅是建议;当然你也可以找到使用课本、笔记以及其他课程材料的适合个人的方式。下面是使用本书的方法之一:

- ◆ 首先应该完成当天布置的阅读课本相关内容的任务。这些阅读材料中,可能会包含一些你在第一次看课本时疏忽遗漏的小细节。对其中一些要点,你可能会希望看到另一种表述方法来帮助你理解,也可能想看一看相关的范例。在这种特定的好奇心的驱使下,你可以——
- ◆ 看看相关的笔记和实验练习:首先是浏览一下,看看本书上选择了哪些电路和哪些要点。对那些使你感到困惑的地方,要看一看相关的笔记。如果看过笔记依旧觉得迷惑不解,你应重新看一遍课本中的相关内容。
- ◆ 跳过笔记中你已经明白的主题。书中的笔记是为了帮你更好地理解课本而不是为了增加你额外的阅读量:如果你已经阅读并理解了课本中相关主题的内容,跳过笔记中的相应部分并不会使你遗漏任何的知识点。
- ◆ 试着解决相关范例中的题目,至少在脑子里想一想。如果题目看起来很简单,你可以跳过。如果看起来比较难,那么你该试着提出自己的解决方法。如果你在解决该问题的时候,发现自己陷入一大堆计算工作中,很可能你正在做无用功,这时你该看看我们的解决方法。我们希望教给你的是一种解决电路设计难题的方法,而不是一堆特定的法则。假如有两种方法可以设计出优秀的作品,一种繁复而另一种快捷,我们当然希望能引领你走那条捷径。

在这些笔记中,你可能会觉得有些很简单幼稚,而有些则十分地难懂:你的这些感觉反应了你对课本和本书上一些主题的了解程度有深浅之分。比如,在学习本课程中的汇编语言编程的内容时,有些熟练的程序员觉得非常容易,而其他人可能觉得十分难掌握。这没关系。本课程一向以“有趣”著称,从某种意义上讲并不是太难。书中涉及的概念都很浅显,抽象的东西并不多。事实上,实验应该是最好的教师,我们希望课本和本书能在读者做实验时起到指导作用。

## 关于本书的插图和文字

你很快就会发现本书的语言和排版方面都不很“正规”。所有的插图都是手绘的。我们之所以用手绘的插图,除了因为我们觉得手绘的插图好看之外,还因为我们想要鼓励学生们手绘出原理图的草图。有些时候,我们甚至会在电脑上画草图,而最后的版本却用手绘。

编著者



## PREFACE

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This manual is intended to be used along with The Art of Electronics by Horowitz and Hill (Cambridge University Press, New York, 2d ed. 1989) in an introductory electronics course. The manual includes three principal elements:

- laboratory exercises: 23 of these, each meant to occupy a 3-hour lab period; each set of laboratory notes except the last includes a reading assignment in the Text;
- explanatory notes: one for each laboratory exercise or class;
- worked examples: a total of 20: approximately one for each reading assignment.

In addition, we have included some reference materials:

- a glossary of frequently-used terms and jargon;
- review notes for each chapter, noting the most important circuits and topics;
- selected data sheets, analog and digital.

### *The students this course might suit*

These notes arose out of a course at Harvard; they define what we try to teach in that busy term. The course does less than all of Horowitz and Hill, of course. We treat chapters 1-11, omitting Chapter 7, on *Precision Circuits...*, which is more specialized than the rest, and skimming Chapter 4 on *Active Filters and Oscillators*. Even this selection includes more information than we expect students to absorb fully on a first pass through the book. This Manual tries to guide students to the most important material.

The *typical* student that we see—if there really is a typical student—is an undergraduate majoring in Physics, and wanting to learn enough electronics to let him or her do useful work in a laboratory. But we do not assume such background in these notes. Students very different from that typical student thrive in our course. Graduate students in the sciences appear regularly; during the summer we see many high school students, and some of these do brilliantly; now and then a professor of Physics takes the course (and they do all right, too!). In the ‘extension’ version of the course, we see lots of programmers who want to know what’s going on in their machines, and we see people who just happen to be curious about electronics. That curiosity, in fact, is the only prerequisite for this course, and suggests the only good rule to define who will enjoy it. Someone looking for an engineering course will find our treatment oddly informal, but a person eager to learn how to design useful circuits will like this course.

### *Laboratory Exercises*

The laboratory exercises build upon a set of labs that were set out in the 1981 edition of the Laboratory Manual, by Horowitz and Robinson. The new exercises replace all of the original digital labs and substantially revise the analog labs on FET’s and oscillators. In the digital section we have switched over from LSTTL to HCMOS, but the major change has been the enlarged role given to the microprocessor labs, and the shift from the Z80 processor programmed rather laboriously via a DIP switch to a 68008 processor programmed through a keypad. (A complete schematic is included. See Lab 15. Complete keypad units are available through the authors. See Parts list).

We have held to our intention that students should build their computer from the chip level, and that they should not be handed a ROM cleverly programmed by someone else.

We want our students to feel that they know their computer intimately, and that it is fully *their* product.

The digital half of the course now centers on the microcomputer: we meet simpler digital devices—gates, flip-flops, counters, memory—partly because we want to be able to build small digital circuits, but also partly in order to understand the full microcomputer circuit. To put this point another way, the final series of labs, in which the microcomputer gradually takes form, draws together every one of the several circuit elements met earlier: combinational logic networks, flip-flop circuits, counters, memory, and analog/digital conversion. The A-D conversion experiments have been expanded to include the effects of sampling-rate and of filters applied to input and output.

### Notes

The notes that introduce each lab respond to two needs that students often voice:

- The notes *select* a few points from the much broader coverage of the Text; those selected points are, of course, those that we think most important to a student meeting practical electronics for the first time.
- The notes *explain* at length. They do this at a level more basic than the Text's, and they provide explanations in a step-by-step style that the Text cannot afford, given its need to cover far more material.

### A suggestion: how to use the notes

Here's a proposal; you will, of course, find your own way to use Text, Notes and all the other course materials. But here is one way to begin.

- Start by reading the day's assignment in the Text. It will include some material that is subtler than what we expect you to pick up in a first course. You may want to hear some points restated in another way, or you may want to see an example worked. Primed with this specific sort of curiosity, you might then—
- Look at the day's Notes and Lab: scan, first, to see which circuits and which points are selected. Read the Notes on any points that puzzled you; if you still are puzzled, return to the Text for a second look at the topics you now know are most important.
- *Skip* topics in the Notes that you understand already. The Notes are meant to help you, *not* to burden you with additional reading: if you have read and understood the Text's discussion of a topic, you will miss nothing by omitting the corresponding section in the Notes.
- Try the day's worked example, at least in your head. If it looks easy, you may want to skip it. If it looks hard, probably you should try to do your own solution. If you find yourself heading into a lot of work—especially any involved calculations—probably you are doing unnecessary labor, and it is time to peek at our solution. We hope to teach you an approach to problems of circuit design, not just a set of particular rules. If there is a laborious way and a quick way to reach a good design, we want to push you firmly toward the quick way.

We expect that some of these notes will strike you as babyish, some as excessively dense: your reaction naturally reflects the uneven experience you have had with the topics the Text and Manual treat. Some of you are sophisticated programmers, and will sail through the assembly-language programming near the course's end; others will find it heavy going.

That's all right. The course out of which this Manual grew—and, earlier, the Text as well—has a reputation as fun, and not difficult in one sense, but difficult in another: the concepts are straightforward; abstractions are few. But we do pass a lot of information to our students in a short time; we do expect them to achieve literacy rather fast. This course is a lot like an introductory language course, and we hope to teach by the method sometimes called *immersion*. It is the laboratory exercises that do the best teaching; we hope the Text and this Manual will help to make those exercises instructive.

*Why our figures and text look the way they do*

You will discover very quickly that this manual is informal in language and layout. The figures all are hand-drawn. They are done by hand partly because we like the *look* of hand-drawn figures (when they are done right; not all our figures are pretty), and partly because we want to encourage students to do their own free-hand drafting of schematics. In some cases we did *draft* drawings on a computer, then drew the final versions by hand! The text was produced as camera-ready copy, put out by an ordinary PC word processor. So—as writers used to say, long ago—dear reader, look with sympathy, if you can, when you find a typo, or a figure drawn amiss. Don't blame the publisher for corporate sloth. Picture, instead, two fellows hunched over their keyboard and drawing board, late at night and beginning to get drowsy.

*Who helped especially with this book*

Two teaching fellows gave us good advice on uncounted occasions: Shahn Majid, a mathematical Physicist who taught with us for years in the Harvard College course, and Steve Morss, a digital engineer who once took the course and then returned to teach. Steve often would linger late into the night helping to try out a new circuit or analyze an old one. Both of these two could perfectly well have taught the course, and chose nevertheless to linger—Bodhissattva-like—giving their expert help in this quieter way.

A pair of our former students, Jeff Hobson and Wei-Jing Zhu, helped us first by drawing figures—and then gradually turned into this book's godparents, helping in all sorts of ways. Often they would arrive in the evening, at the end of a long day's work, and then would labor to help us organize, check, re-check—and also to make judgments on how to make our points clearly. Often the end of the workday was defined by the departure of the last bus, at 1:00 in the morning. Their devotion to the project was invaluable, and touching.

Finally, Debbie Mills deserves thanks for putting up with her husband Tom's strange, long hours, and then, toward the end, doing much more: providing essential help in organizing, checking, and correcting the growing stacks of printouts and drawings.

Tom Hayes  
Paul Horowitz

Cambridge, Mass.  
July 1989

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## 建议：如何使用本书

以下仅仅是建议；当然你也可以找到使用课本、学习资料以及其他课程材料的适合个人的方式。下面是使用本书的方法之一：

◆首先应该完成当天布置的阅读课本相关内容的任务。这些阅读材料中，可能会包含一些你在第一次看课本时疏忽遗漏的小细节。对其中一些要点，你可能会希望看到另一种表述方法来帮助你理解，也可能想看一看相关的范例。在这种特定的好奇心的驱使下，你可以——

◆看看相关的学习资料和实验练习：首先是浏览一下，看看本书上选择了哪些电路和哪些要点。对那些使你感到困惑的地方，要看一看相关的学习资料。如果看过学习资料依旧觉得迷惑不解，你应重新看一遍课本中的相关内容。

◆跳过学习资料中你已经明白的主题。书中的学习资料是为了帮你更好地理解课本而不是为了增加你额外的阅读量：如果你已经阅读并理解了课本中相关主题的内容，跳过学习资料中的相应部分并不会使你遗漏任何的知识点。

◆试着解决相关范例中的题目，至少在脑子里想一想。如果题目看起来很简单，你可以跳过。如果看起来比较难，那么你该试着提出自己的解决方法。如果你在解决该问题的时候，发现自己陷入一大堆计算工作中，很可能你正在做无用功，这时你该看看我们的解决方法。我们希望教给你的是一种解决电路设计难题的方法，而不是一堆特定的法则。假如有两种方法可以设计出优秀的作品，一种繁复而另一种快捷，我们当然希望能引领你走那条捷径。

在这些学习资料中，你可能会觉得有些很简单幼稚，而有些则十分地难懂：你的这些感觉反应了你对课本和本书上一些主题的了解程度有深浅之分。比如，在学习本课程中的汇编语言编程的内容时，有些熟练的程序员觉得非常容易，而其他人可能觉得十分难掌握。这没关系。本课程一向以“有趣”著称，从某种意义上讲并不是太难。书中涉及的概念都很浅显，抽象的东西并不多。事实上，实验应该是最好的教师，我们希望课本和本书能在读者做实验时起到指导作用。

## 关于本书的插图和文字：

你很快就会发现本手册的语言和排版方面都不很“正规”。所有的插图都是手绘的。我们之所以用手绘的插图，除了因为我们觉得手绘的插图好看之外，还因为我们想要鼓励学生们手绘出原理图的草图。有些时候，我们甚至会在电脑上画草图，而最后的版本却用手绘。

《电子学》出版后获得了巨大成功，本教材是对第一版进行了彻底修订和更新后的第二版。

本教材的第一版被广泛认为是模拟和数字电子电路设计的惟一权威教材和参考书，在全球销售了125000册并被翻译为8种语言。本教材强调设计人员实际中采用的方法，将基本定律、经验定理和大量技巧结合起来，根本改变了电子学课程的教学。这样就产生了一种鼓励对电路的直觉、发散思维以及电路参数和性能的简化计算，主要采用非数学手段的方法。

电子学的发展日新月异，为了适应发展，在全新的第二版中，完全重写了微型计算机和微处理器的章节，充分改写了数字电路、运算放大器及精密电路设计、电路构造技巧等章节，修订书中每个表格，而且还增加了很多表格。

本教材第一版的成功依赖于其平易近人的风格，第二版保留了第一版的这一风格。本教材是科学家和工程师的一本理想的电子学入门教材；对于从事电子电路工作的专业人员或业余爱好者来说，本教材也是一本不可或缺的参考书。

《电子学》完整覆盖了电子学书籍一般涵盖的内容，同时也补充了丰富的重要却被忽视的主题，包括：

- 有用的子电路，例如跟随器，开关，电流源，镜像电流源，差动放大器，推挽电路和级联电路等
- 结型场效应管（JFET）和金属-氧化物-半导体场效应管（MOSFET），场效应管和双极型晶体管设计的比较，静电放电（ESD），放大器辅助设计和模拟开关
- 有源整流器，对数转换器，峰值检测器，介质吸收，单电源运放
- 恒定品质系数（Q）以及恒定带宽滤波器设计，开关电容滤波器，零漂移低通滤波器（zero-offset LPF），单控制端可调陷波器，振荡器
- 分立元件和集成稳压器，安全工作区（SOA），热学设计和散热器，开关电源，短路保护器
- 精密线性电路设计，自动稳零放大器，隔离放大器
- 噪声的产生、测量以及低噪声电路设计，屏蔽与接地技术
- 定时，短脉冲，时钟沿倾斜，单稳态触发器
- 锁相环，光电子电路，总线驱动，容性负载，线缆，信号接口
- IBM-PC和Intel处理器系列，RS-232电缆，串行口，ASC II码，调制解调器，SCSI，IPI，GPIB，并行口，局域网
- 68000系列微处理器，大规模集成电路（LSI）外设芯片，存储器，含有程序的仪器设计
- 定型方法，印刷电路板和绕接线设计，原理图捕获，仪器构造
- 模块化射频器件，高频放大器 and 高速开关电路简化设计
- 电池，太阳能电池，微功率稳压器、运放和微处理器
- 带宽压缩方法，信号平均，多通道缩放，锁定放大器，脉冲幅度分析

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# CHAPTER 1

## Overview

The title of this first chapter, “Foundations,” describes its place pretty well: here you will learn techniques that will underlie circuitry that later produces impressive results. Chapter 1’s circuits are humbler than what you will see later, and the devices you meet here are probably more familiar to you than, say, transistors, operational amplifiers—or microprocessors: Ohm’s Law will surprise none of you;  $I = C \, dV/dt$  probably sounds at least vaguely familiar.

But the circuit elements that this chapter treats—*passive* devices—appear over and over in later *active* circuits. So, if a student happens to tell us, ‘I’m going to be away on the day you’re doing Lab 2,’ we tell him he will have to make up the lab somehow: that the second lab, on RC circuits, is the most important in the course. If you do not use that lab to cement your understanding of RC circuits—especially filters—then you will be haunted by muddled thinking for at least the remainder of *analog* part of the course.

Resistors will give you no trouble; diodes will seem simple enough, at least in the view that we settle for: they are one-way conductors. Capacitors and inductors behave more strangely. We will see very few circuits that use inductors, but a great many that use capacitors. You are likely to need a good deal of practice before you get comfortable with the central facts of capacitors’ behavior—easy to state, hard to get an intuitive grip on: they pass AC, block DC, and *sometimes* cause large phase shifts.

We should also restate a word of reassurance offered by the Text (p. 29), but seldom believed by students: you can manage this course perfectly even if you cannot follow the mathematical arguments that begin in sec. 1.18 (use of complex quantities to represent voltage and current), and even if, after reading the spectacularly-dense *Math Review* in appendix B you feel that *you* must be spectacularly dense. This is the place in the Text and course where the squeamish usually begin to wonder if they ought to retreat to some slower-paced treatment of the subject. Do not give up at this point; hang on until you have seen transistors, at least. The mathematical arguments of 1.18 are not at all characteristic of this Text or of this course. To the contrary, one of the most striking qualities of this Text is its cheerful evasion of complexity whenever a simpler account can carry you to a good design. The treatment of transistors offers a good example, and you ought to stay with the course long enough to see that: the transistor chapter is difficult, but wonderfully simpler than most other treatments of the subject. You will begin designing useful transistor circuits on your first day with the subject.

It is also in the first three labs that you will get used to the lab instruments—and especially to the most important of these, the oscilloscope. It is a complex machine; only practice will teach you to use it well. Do not make the common mistake of thinking that the person next to you who is turning knobs so confidently, flipping switches and adjusting trigger level—all on the first day of the course—is smarter than you are. No, that person has done it before. In two weeks, you too will be making the scope do your bidding—assuming that you don’t leave the work to that person next to you—who knew it all from the beginning.

The images on the scope screen make silent and invisible events visible, though strangely abstracted as well; these scope traces will become your mental images of what happens in your circuits. The scope will serve as a time microscope that will let you see events that last a handful of *nanoseconds*: the length of time light takes to get from you to the person sitting a little way down the lab bench. You may even find yourself reacting emotionally to shapes

on the screen: feeling good when you see a smooth, handsome sine wave; disturbed when you see the peaks of the sine clipped, or its shape warped; annoyed when fuzz grows on your waveforms.

Anticipating some of these experiences, and to get you in the mood to enjoy the coming weeks in which small events will paint their self-portraits on your screen, we offer you a view of some scope traces that never quite occurred, and that nevertheless seem just about right: just what a scope *would* show if it could. This drawing has been posted on one of our doors for years, now, and students who happen by pause, peer, hesitate—evidently working a bit to put a mental frame around these not-quite-possible pictures; sometimes they ask if these *are* scope traces. They are not, of course; the leap beyond what a scope can show was the artist's: Saul Steinberg's. Graciously, he has allowed us to show his drawing here. We hope you enjoy it. Perhaps it will help you to look on your less exotic scope displays with a little of the respect and wonder with which we have to look on the traces below.

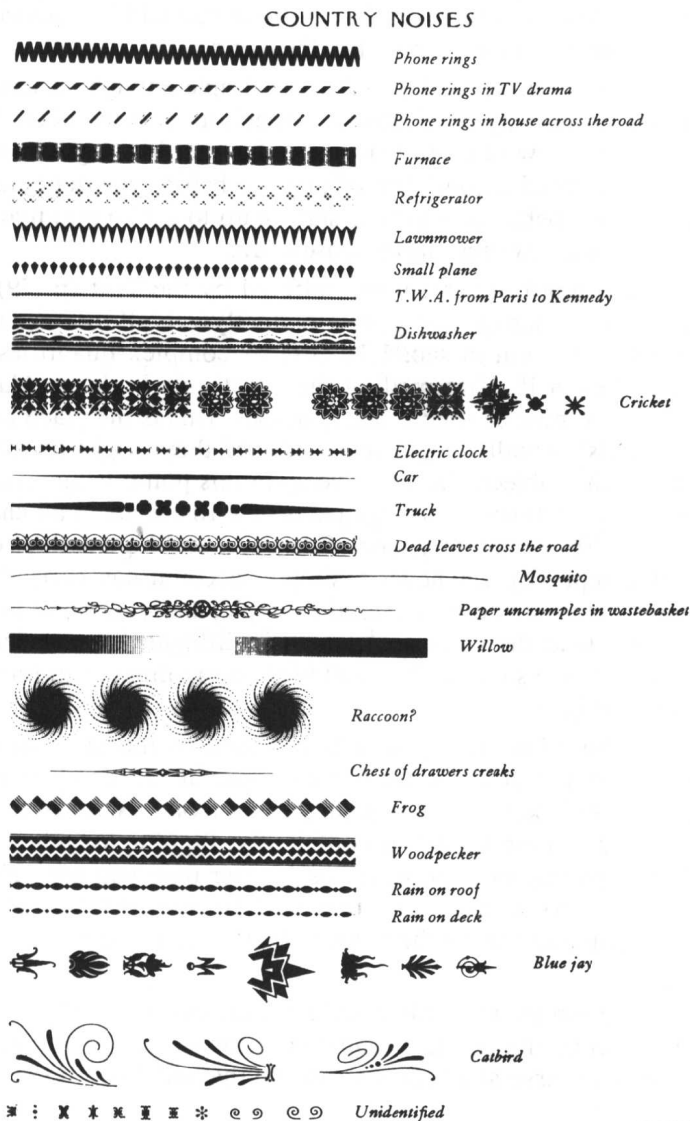


Figure IN1.1: Drawing by Saul Steinberg; copyright 1979 The New Yorker Magazine, Inc.



## Class 1: DC Circuits

### Topics:

- What this course treats: Art? of Electronics

DC circuits

Today we will look at circuits made up entirely of

- DC voltage sources (things whose output voltage is constant over time; things like a battery, or a lab power supply); and
- resistors.

Sounds simple, and it is. We will try to point out quick ways to handle these familiar circuit elements. We will concentrate on one circuit fragment, the voltage divider.

**Preliminary:** What is “the art of electronics?”

Not an art, perhaps, but a craft. Here’s the Text’s formulation of what it claims to teach:

...the laws, rules of thumb, and tricks that constitute the art of electronics as we see it. (P. 1)

As you may have gathered, if you have looked at the text, this course differs from an engineering electronics course in concentrating on the “rules of thumb” and the “tricks.” You will learn to use rules of thumb and reliable tricks without apology. With their help you will be able to leave the calculator-bound novice engineer in the dust!

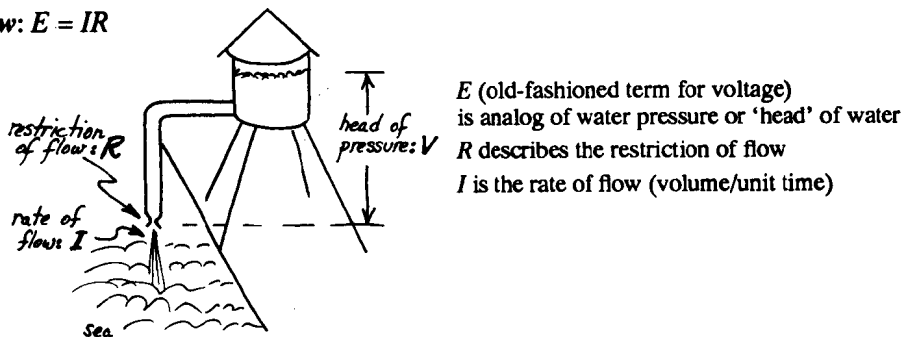
### Two Laws

Text sec. 1.01

First, a glance at two *laws*: Ohm’s Law, and Kirchhoff’s Laws (V,I).

We rely on these rules continually, in electronics. Nevertheless, we rarely will mention Kirchhoff again. We use his observations *implicitly*. We will see and use Ohm’s Law a lot, in contrast (no one has gotten around to doing what’s demanded by the bumper sticker one sees around MIT: *Repeal Ohm’s Law!*)

**Ohm’s Law:**  $E = IR$



**Figure N1.1:** Hydraulic analogy: voltage as head of water, etc. Use it if it helps your intuition

The homely hydraulic analogy works pretty well, if you don’t push it too far—and if you’re not too proud to use such an aid to intuition.

Ohm's is a very useful rule; but it applies only to things that behave like *resistors*. What are these? They are things that obey Ohm's Law! (Sorry folks: that's as deeply as we'll look at this question, in this course<sup>1</sup>.)

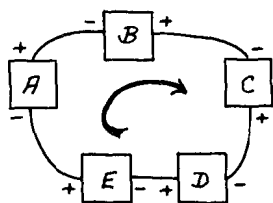
We begin almost at once to meet devices that do *not* obey Ohm's Law (see Lab 1: a lamp; a diode). Ohm's Law describes *one* possible relation between  $V$  and  $I$  in a component; but there are others.

As the text says,

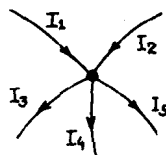
Crudely speaking, the name of the game is to make and use gadgets that have interesting and useful  $I$  vs  $V$  characteristics. (P. 4)

### Kirchhoff's Laws (V,I)

These two 'laws' probably only codify what you think you know through common sense:



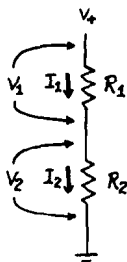
Sum of voltages around loop (circuit) is zero.



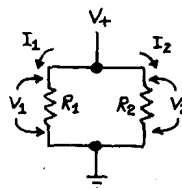
Sum of currents in & out of node is zero (algebraic sum, of course).

Figure N1.2: Kirchhoff's two laws

### Applications of these laws: series and parallel circuits



Series:  $I_{\text{total}} = I_1 = I_2$   
 $V_{\text{total}} = V_1 + V_2$   
 (current same everywhere; voltage divides)



Parallel:  $I_{\text{total}} = I_1 + I_2$   
 $V_{\text{total}} = V_1 = V_2$   
 (voltage same across all parts; current divides)

Figure N1.3: Applications of Kirchhoff's laws: Series and parallel circuits: a couple of truisms, probably familiar to you already

**Query:** Incidentally, where is the "loop" that Kirchhoff's law refers to?

This is *kind of boring*. So, let's hurry on to less abstract circuits: to applications—and tricks. First, some labor-saving tricks.

1. If this remark frustrates you, see an ordinary E & M book; for example, see the good discussion of the topic in E. M. Purcell, *Electricity & Magnetism*, cited in the Text (2d ed., 1985), or in S. Burns & P. Bond, *Principles of Electronic Circuits* (1987).

**Parallel Resistances: calculating equivalent R**

The *conductances* add:

$$\text{conductance}_{\text{total}} = \text{conductance}_1 + \text{conductance}_2 = 1/R_1 + 1/R_2$$

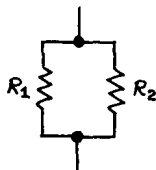


Figure N1.4: Parallel resistors: the *conductances* add; unfortunately, the *resistances* don't

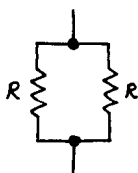
This is the easy notion to remember, but not usually convenient to apply, for one rarely speaks of conductances. The notion "resistance" is so generally used that you will sometimes want to use the formula for the effective resistance of two parallel resistors:

$$R_{\text{tot}} = R_1 R_2 / (R_1 + R_2)$$

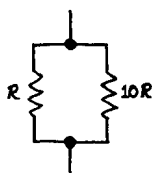
Believe it or not, even this formula is messier than what we like to ask you to work with in this course. So we proceed immediately to some tricks that let you do most work in your head.

Text sec. 1.02

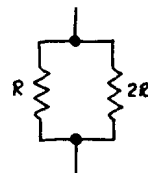
Consider some easy cases:



two equal R's



two very unequal R's



R, 2R

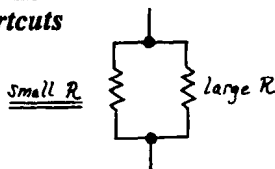
Figure N1.5: Parallel R's: Some easy cases

The first two cases are especially important, because they help one to *estimate* the effect of a circuit one can liken to either case. Labor-saving tricks that give you an estimate are not to be scorned: if you see an easy way to an estimate, you're likely to make the estimate. If you have to work too hard to get the answer, you may find yourself simply *not* making the estimate.

In this course we usually are content with answers good to 10%. So, if two parallel resistors differ by a factor of ten, then we can ignore the larger of the two.

Let's elevate this observation to a rule of thumb (our first). While we're at it, we can state the equivalent rule for resistors in series.

**Parallel resistances: shortcuts**



In a parallel circuit, a resistor much *smaller* than others dominates.  
In a series circuit, the *large* resistor dominates.

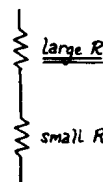


Figure N1.6: Resistor calculation shortcut: parallel, series