Electronics with Discrete Components

Enrique J. Galvez

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Enrique J. Galvez
Department of Physics and Astronomy
Colgate University

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I dedicate this book to Mary, Ricky, Samantha, Daniel, and Elena

PREFACE

This text is designed for a one-semester course on electronics. Its primary audience is second-year physics students, but it can include students from other disciplines or levels who understand elementary notions of circuits and complex numbers. Most physics programs, especially those in liberal arts colleges, can afford only a one-semester course in electronics. Electronics is a vital part of a curriculum because it trains students in a basic skill of experimentation. With this knowledge, students can design circuits to manipulate electronic signals or drive mechanical devices. An electronics course also gives students a basic understanding of the inner workings of electronics instruments. Thus, an electronics course prepares students for advanced laboratories and, ultimately, experimental research.

Because of the nature of the topic, the course must have a huge hands-on component. Electronics is learned by experience. At Colgate University, we have been teaching a course that meets two days a week, with a one-hour lecture followed by a two- to three-hour lab. In the lab, students build circuits that closely follow the topic of the class. We have put special effort into making those labs instructive but at the same time interesting, empowering, and fun. We made a special effort to introduce transducers in the labs, highlighting applications. Today's students live around black boxes, mostly ignorant of the circuits that lie within them. Our recent experience tells us that students find the discovery of how those boxes work, or even the task of building them, extremely interesting, rewarding, and useful. Thus, we can use this "revelation" as a way to motivate students to learn electronics.

Instructors who adopt this text may have labs in place and may not have use for the labs in this book. However, the experiments listed may give instructors ideas to renew or modify the labs in place. In addition to the normal curricular plan, we devote two weeks in the middle of the semester and two weeks at the end of the semester to unscripted projects, in which students design the device of their choice. This is where students learn tremendously and enjoy the experience. Their ambition to build the device of their choice pushes them to invest much energy and time, and along the way, they learn invaluable aspects of building devices, such as creating new designs and troubleshooting. In the first project, students do mostly digital work (more on this choice below), but they still use a little bit of analog, because they need switches or pushbuttons for digital inputs and light-emitting diodes (LED) for digital outputs. In the second project, students do mostly analog work, but they can combine analog and digital electronics. Whatever the case, students end up doing amazing projects. Some of the analog projects can be combined with real computers, but this is an aspect that we do not cover here. If lab PCs have interface cards, the projects will be more powerful. A word of caution from experience: Make sure that the project does not become a computer project. Although knowing programming is not that bad of a goal these days, it is not the objective of this course.

The text is divided into two parts: digital and analog. In each part, we cover the essential components needed to understand and design circuits with discrete components. We cover the digital part first. This may seem like heresy to some instructors, but I urge them to reconsider the concept. Covering digital first makes sense because digital electronics focuses mostly on logic. The topic is not as intellectually demanding as analog. Besides a few rules of thumb for wiring, students have little need to know about the currents that flow through the gates or even the analog circuits that make up those gates. Later in the semester, after covering the analog part, the class revisits the details of gates. The digital part is demanding on wiring practices, but not on conceptual understanding. This way, students get early exposure to demanding circuits and are forced to embrace systematic wiring practices. By the time students reach analog, they no longer have trouble wiring and powering circuits. It makes sense to cover analog after digital because students end with the understanding of the complexity and importance of analog. Otherwise, students would get the wrong message: Since analog is not needed to do digital, it is unnecessary altogether. An instructor who strongly disagrees with this strategy could swap the two parts without major logistic complications, but he or she would have to continue to emphasize analog concepts throughout the digital part.

The content of this text borrows ideas on the organization of topics from two classics in the field: *Digital Design*, by M. Morris Mano, and *The Art of Electronics*, by Paul Horowitz and Winfield Hill. The chapters are designed so that they take an integral number of days. Labs may also extend one day, and in digital, several labs build upon the circuit of the previous lab. The topics of the specific chapters go as follows. The first chapter, "The Basics," reviews the fundamentals of electricity and electrical components. It brings the student, especially the nonphysics major, up to speed with the physics and basics of electric circuits. The second chapter, "Introduction to Digital Electronics," covers digital signals and electronic gates. It is followed by two chapters on combinational logic, namely "Combinational Logic" and "Advanced Combinational Devices." They are followed by a chapter titled "Sequential Logic," which emphasizes counting circuits, and an important application in memory. Throughout this part, we include tables of integrated circuits that are useful for designing circuits. A rack of ICs of various types is vital in an electronics lab. The lab exercises use a "logic board," which is a homemade or commercial box with switches that generate input states, and LEDs to display output states. Appendix A gives the details of this device and its construction. Some versions of these boards are commercially available. If time permits, the instructor may consider other adventures, such as microcontrollers and interfacing using Labview, but such endeavors are specialized to particular equipment for which there is no uniform agreement. Instead of attempting a partial or incomplete description, we do not cover those at all.

The analog part starts with the chapter "AC Signals." It covers a more sophisticated analysis of circuits than the first chapter and centers on the use of complex numbers for defining signals and impedances. We find this advantageous and practical. To complement this, we include a short introduction to complex numbers. It ends with an important concept to students: Thevenin equivalent circuits. Throughout, this part reduces circuits to single-loop modules, building up the concepts of input and output impedance. We follow with the chapter "Filters and the Frequency Domain," where the role of frequency and frequency response comes to the surface. The use of multiple filter stages underscores the role of source and load impedance. At the end of this chapter, we insert a section on Fourier Series. This is important because electronics' processing of signals can be understood easily at the single frequency level. Therefore, knowing the decomposition of a complex signal into its frequency spectrum is vital in understanding the frequency response of a circuit. This part can be skipped if the curriculum already contains Fourier series. The chapter that follows, "Diodes," starts with a physical explanation of semiconductors that gives the student an intuitive and informed basic understanding of the physics of these materials. It emphasizes nonlinear responses and the use of the load line, and ends with an application on the design of power supplies, among other diode tricks. The chapter titled "Transistors," covers both bipolar-junction and field-effect transistors. Because operational amplifiers are much better suited for signal conditioning, we do not cover in detail some of the traditional circuits on biasing the transistor. Increasingly, modern devices use field-effect transistors instead of bipolar transistors, so we give both nearly equal coverage and focus on power drivers, followers, and current sources. These are applications that even operational amplifiers cannot deliver and in which transistors have rightful place. The final part of analog is the experimenters delight: "Operational Amplifiers." We give ample coverage to numerous circuits, plus we use them to smuggle in other interesting topics, such as comparators and feedback. We wrap up with a chapter that interfaces digital and analog signals and transducers, in "Connecting Digital to Analog and to the World."

At the end of most chapters is a section titled "Lab Projects" that contains many interesting circuits that have been proven to work well for instruction. Many of them have interesting twists that make the experience a fun one. I like to follow this motto: "Let the kids have fun." If they do, they will learn electronics. Our tests also have a practical component. When students work in groups there is a danger that they are passive and let their partner(s) do valuable laboratory know-how. To force them to be active participants, we test them individually on building simple circuits. The final section of each chapter is titled "Practicum Test." It gives questions that we have often asked on simple aspects of the lab that students should know. This includes powering components and diagnosing signals with the oscilloscope. The goal is for each student be able to do every task and not leave any activity, and know-how, to his or her partner.

I owe immense gratitude to Joseph Amato. Together we designed this course almost 20 years ago. His prolific expertise and creativity led to the design of a number of lab experiences described in this text. I also want to thank Wes Walters for selling me the idea of covering digital before analog; Dave Glenar, Ken Segall, and Steve Slivan for ideas for labs and problems; Juan Burciaga and Danielle Solomon for useful suggestions and edits; Timothy Kidd, M.K. Kim, Bryan Suits, Christos Velissaris and other anonymous reviewers of the drafts of this book for their valuable advice; and Samantha and Daniel Galvez for helping Dad with aspects of this project.

E.J. "Kiko" Galvez

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CHAPTER 1

THE BASICS

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1.1 FOREWORD: WELCOME TO ELECTRONICS!

This book is primarily geared for physics students, but nonphysics students with some basic physics and math can understand it. Our focus is not physics. We cover the fundamental physics to provide a foundation, but our primary concern is the electronic devices. The good news is that you will learn how some of those black boxes with glitzy lights work and, going beyond that, how to build some of your own boxes. You will discover that the most complicated machines—computers—are as logical as the gears in a bike. Often in this book, we do not approach the subjects as precisely as physicists treat other subjects. For example, using 10 percent accuracies or even factors of 2 for device parameters is usually fine in electronics. Electronics also involves a lot of details, so do not get overwhelmed. Experience will help you distinguish the important details from the less important ones, but still be prepared to take in a lot!

Electronics should be learned from the ground up. Although one can easily go a long way in electronics by knowing some fundamental concepts and understanding how the devices work, a solid foundation in electricity and magnetism is important for an in-depth understanding. The goal of this chapter is to cover the underlying physics, in case the reader lacks a previous foundation in electricity and magnetism. Because electronics is closer to engineering than physics, we are interested less in learning the underlying physical laws as ends in themselves, and more on understanding devices and how they work. Take this course also as an opportunity to learn that every device is based on important physical principles. Knowing those principles will give you an increasing edge in mastering electronics.

We start with fundamental concepts and work our way to devices. As we gain some speed, we will move into elementary circuits.

1.2 CHARGE AND POTENTIAL

Electric charge is a fundamental property of matter that is responsible for most of its structure as we know it. Taking central stage in our electronic world is nature's premier fundamental particle: $\eta\lambda\epsilon\kappa\tau\rho o\nu$. If you have taken enough physics, you will read *electron*. It is the Greek's name for amber, as the ancient Greeks recognized the curious (electrical) properties of amber. Not only do we take for granted the existence of electrons, which are in everything we see and touch (ourselves included), but we "feel" their presence directly with the jolt of static electricity that we get on a dry day. Electrons are simple: They have a mass, and, for the most part, they behave as point particles. Despite trying to find a dimension to them, we have been unsuccessful. Electrons do not always behave like particles: Sometimes they behave as waves. When they do so, people studying them have to figure out not only what the electrons are doing, but what they really are.

Electrons' most important property is their charge. For some fateful reason that originated with the cleverness and wit of Benjamin Franklin, the charge of the electron is labeled as negative. The electron has one unit of elementary charge, which is $q_e = -e$, where $e = 1.6 \times 10^{-19}$ C, with C being the SI unit of the electrical charge, the Coulomb. This value is quite precise and is deemed fundamental by physicists. Do not bother trying to discern the meaning of "fundamental"—it is a physicist's way of saying, "It is what it is and we do not know why." A beautiful story of experimentation involves the measurement of the electronic charge by Robert Millikan. Electrons also have spin, which is at the root of many interesting phenomena, such as magnetism. However, for all purposes that concern us, electrons are simple and have a definite charge.

Atoms have a nucleus that has a charge of the opposite sign: positive. The nucleus is formed by two particles: protons and neutrons. The only exception is the most abundant isotope in the universe, hydrogen, which has only one proton as a nucleus. Protons have a charge, $q_p = +e$, and neutrons have no charge $q_n = 0$. Note that the magnitude of the charge of the protons is *exactly* the same as that of the electron; nature as we know it would not exist if the charges of electrons and protons did not have the exact same magnitude. The properties of matter rely on the exact electrical neutrality of atoms. Protons and neutrons are made of *quarks*, each of which has a fractional charge: The *up* quark has a charge $q_u = +(\frac{2}{3})e$ and the *down* quark has a charge $q_d = -(\frac{1}{3})e$. This way, a proton is made of two ups and one down, and the neutron consists of one up and two downs. Yet for all the fascinating consequences of the existence of quarks, we never see them by themselves because of a strong attractive force that increases with distance. So for all practical purposes, protons and neutrons are whole particles.

Atoms are neutral, but the electrons buzzing around the nucleus follow special rules of behavior dictated by quantum mechanics. We say "buzzing around" because we know they go around the nucleus, but we do not know exactly how. We cannot find out in a deterministic classical way how they move (such as describing nice ellipses). Instead we can only know where they are likely to be, probabilistically; for all we know they can move around in whichever way they please. However, one thing is certain: electrons buzz around always experiencing an attractive force with the positive nucleus and a repulsive force with fellow electrons. Within the nucleus protons still repel each other due to electric forces, but at the short distances within nuclei they are attracted to each other by the stronger nuclear force.

The nucleus is small—100,000 times smaller than the outlying orbits of the electrons in atoms. Atoms are symmetrically neutral when left alone, but when they are pushed against each other the electrons rearrange and atoms are no longer neutrally symmetric: The sides facing each other are more positive on average, and the sides facing away are more negative. A strong repulsion ensues, preventing atoms from getting too close to each other. As a result, matter is mostly made of empty space: Atoms are held away from each other at distances comparable to the sizes of the outer orbits of the electrons, which are point particles, with a tiny nucleus located somewhere inside. This is why neutrons can go a long way through matter without stopping. Electrons' strong interaction with light, an electromagnetic disturbance, makes matter mostly opaque to light (with noted exceptions, such as glass), but electrical forces make matter seem solid when in actuality it is not.

Another property of atoms is that electrons can leave their home atoms to join foreign atoms and make ions (atoms with a net charge). When we rub a plastic (such as a comb or pen) with our sweater on a dry day, we end up with a negatively charged plastic and a positively charged sweater. Electrons from the sweater jump to the plastic when we rub the two together. By applying clever techniques, we can use this effect to charge objects deliberately. Other charged objects in the vicinity then experience forces and react accordingly. Although the concept of force is a useful one to conceptually understand what is happening, it is not convenient for a quantifying the events. It is more practical to use energy arguments: If two objects have the same charge, then as they get close to each other their electrical potential energy increases. If we let them go, they will repel each other, converting the potential energy into kinetic energy and going to places where the potential energy is lower (of course, energy must be conserved).

If we have a charged object in a fixed position and place another charge in its vicinity, then the latter will have a positive potential energy and experience repulsion if it has the same sign as the charge of the fixed object; if it has a charge of the opposite sign, or negative potential energy, it will experience attraction. Thus, the potential energy depends on the charge of the two objects. To separate cause from effect, we define the concept of *electric potential*, or *voltage*. Electric potential is the electrical potential energy per unit charge. To get the potential energy of an object with a charge q at a point with potential V, we use