

EDWARD STERNIN, WITH

SOPHIE DELLA MANNA & FULVIO BOSEGLAV



INTRODUCTORY
ELECTRONICS
FOR SCIENTISTS

VOLUME I

PHYSICS@BROCKU.CA

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Brock University, Physics Department, 1812 Sir Isaac Brock Way, St. Catharines, Ontario, Canada L2S 3A1

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Foreword

Why bother?

It is important to remember why we consider Electronics an essential part of education in Physics and other natural sciences. Namely, the omnipresence of electronic devices in the tools and instruments used by today's scientists. Precise measurements are impossible today without highly sophisticated electronic instruments. The sensitivity and speed that modern electronic instruments possess open up experimental possibilities that were simply unavailable to previous generations of scientists. To a time traveller from only a few decades ago, the technology we routinely have at our disposal today would appear magical. Still, even these modern instruments have their limitations and can mislead the experimenter if used improperly. To be a competent scientist, one needs to understand this "magic" of today's electronics, its capabilities and limitations. This need will make our approach different from that of engineering: we will focus on *analysis*, on understanding the operation of existing electronic devices, and not on the design of new ones.

To understand [physics] measurements, we need to know the limitations of [electronic] instruments. On the other hand, to build better [electronic] instruments, we need to understand the underlying [physics] phenomena on which these devices are built. This course will try to walk the boundary between Physics and Electronics, hopefully to the mutual benefit of both.

To the student

This is an unusual book. In the world of instant ubiquitous access to information, one easily falls into a trap of seemingly having all the necessary *information* at one's fingertips. Information is not *knowledge*, rather, it's only the beginning and the foundation of it. The core of knowledge lies in the relationships between pieces of information. Using a poetic metaphor: knowledge is in the skills that allow one to both build bridges between isolated islands of information and to navigate the open seas beyond.

In the past, the only way to read a physics textbook was to take a piece of paper, cover each solved example in the book, and work your own way through the example, revealing what's underneath one line at a time as needed to get unstuck. In this way, working through every solved example in the book, one acquires the skill of facing a new problem without having the solution. This is still the best way to read textbooks, but it is rarely practised. Online video tutorials and AI summaries of helpful online advice is what today's students turn to when encountering a difficulty or needing a hint. They are flashy,

Any sufficiently advanced technology is indistinguishable from magic.

A.C. Clarke

colourful, and compete for your attention on your computer and your phone. The problem is, they create an illusion of knowledge. When one follows someone else's solution, it seems simple and clear, but try it with a blank sheet of paper only a minute later and the certainty seems to vanish and even starting on the first line of the solution seems like an insurmountable barrier. If you ever found yourself in a situation like that, and immediately *reached for an online search* to help you, you have a problem that Richard Feynman called "fragility of knowledge". Yes, you understood the explanation at the time you were hearing it, but you did not make it your own.

This book is an attempt to help you make your knowledge more robust. Each short chapter contains just the bare minimum of a description, often more like a set of lecture notes than a complete textbook. It is a skeleton for you to add to. Make it your own: write margin notes, insert citations and references, treat it as a workbook, and not a revered text. The additional sources are plentiful on the internet, in the library, and in the lab. Electronics especially evolves rapidly, so do not hesitate to reach to the raw technical documentation and application notes provided by the manufacturers of electronic components for the latest information.

Electronics laboratory

Most importantly, electronics cannot be learned without getting your hands dirty. Every other chapter in the book is devoted to a lab that is designed to illustrate and complement the theoretical chapter that precedes it. Here, too, you will not receive specific instructions (those are available online on the course web page, with step-by-step instructions and suggestions), but instead it contains questions you want to be asking yourself before (pre-lab), during, and after the lab, when preparing your discussion and conclusions for submission. Always try to reflect on why we chose this particular lab at this point in the course and how it is related to the material just covered. We believe that the labs will help you solidify your *knowledge*, adding layers of visceral, hands-on, feeling for the concepts covered on the page.

We chose a single continuous theme for all of the labs. After you familiarize yourself with the environment of your workstation and its instruments during the orientation lab, we will begin by assembling a "mystery circuit". You will follow the assembly instructions and by the end of the first lab, your circuit will work as intended. The real fun will begin after that: over the course of several labs you will examine what the circuit is doing and how, what role different components and blocks within the circuit play, how it could have been

done differently, *etc.* You will continually break apart and reassemble parts of your mystery circuit, making note of your observations — again, directly in this workbook. Text in red highlights places where you need to make your contributions (write directly into the book!). Along the way, your TA will review and initial your completed tasks, marking out the checkpoints for your learning. Your lab reports will be very easy to write after that, as we will only require you to provide a brief (approximately 400 words, or slightly more if the material requires) summary of your observations, of what was learned, and how it relates to the material in the course. No Introduction, no Theory, just Discussion and Conclusions. We know you have other classes and their homework to complete.

What skills to bring into the class

This is a second-year class, so the prerequisite of completing the standard complement of first-year Introductory Physics and Calculus are assumed. We will try to make the course as self-contained as possible, bringing in the physics and mathematics concepts as we need them, but we have to start somewhere. You are expected to know:

Terminology:

charge: q

Coulomb: $F_{12} = k \frac{q_1 q_2}{r_{12}^2}$

current: $I = \frac{dq}{dt}$, or the rate of flow of charge over time

Units set the scale of things.

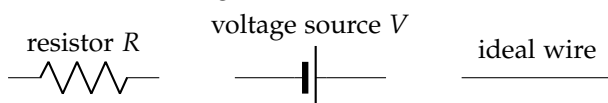
A unit of charge, one Coulomb, is *very* large. Two one-Coulomb charges one meter apart interact with a *very* large force of 8.987552×10^9 N. *Elementary* charge, $e^- = 1.6 \times 10^{-19}$ C is *very* small, and negative by a historical convention.

Easy to remember, $k = 9 \times 10^9 \text{ N} \cdot \text{m}^2 \cdot \text{C}^{-2}$

AC/DC is more than a rock band.

DC = direct current, *i.e.* charges move in one direction; *AC* = alternating current, *i.e.* charges move back-and-forth.

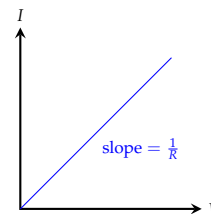
Symbols used in circuit diagrams:



Ohm's Law is a linear dependence of current *through* a resistor on the voltage applied *across* it:

$$I = \frac{V}{R} \quad \text{or} \quad I = \frac{1}{R}V \quad \text{or} \quad V = IR$$

The slope of the plot of current *I* vs. voltage *V* is $1/R$, where *R* is the resistance. This graph is the so-called *VI*-characteristic (pronounced "volt-amp characteristic") diagram of a simple resistor.



Resistivity: The resistive property of the material is defined by

$$R = \rho \frac{L}{A},$$

where ρ is the *resistivity*, a property of the material, and because $\rho = \rho(T)$ is temperature-dependent, so is the resistance:

$$R(T) = R_0 [1 + \alpha(T - T_0)],$$

with the dependence approximately linear for small variations in temperature, $(T - T_0)$ about T_0 .

If you need to review these concepts, a re-reading of your first-year notes or textbook might be helpful at this point.

How to succeed in this class

This is a one-semester introductory course, covering both analog and digital electronics, that is not enough time to give a comprehensive coverage to either. At the same time, it's a transition course, from the elementary treatment in the first year to a more mathematically rigorous treatment, using differential equations and elements of linear algebra. The "formulae" you may need for the analysis of the measurements you perform in the lab may need to be derived, they will not always be provided in the lab manual. The critical evaluation of your work (error bars on all measurements, deficiencies of procedure, fit methods) is *required* when submitting when submitting your lab reports for evaluation. This course should orient you in the subject of electronics, and to equip you for a future deeper dive into the subject.

At Brock, PHYS 3P92 is an advanced electronics lab course, available to those interested in pursuing the subject further.

Math skills:

- algebra and elementary trigonometry;
- the following three identities:

$$\begin{aligned} \sin 2\alpha &= 2 \sin \alpha \cos \alpha \\ \cos 2\alpha &= \cos^2 \alpha - \sin^2 \alpha \\ 1 &= \cos^2 \alpha + \sin^2 \alpha \end{aligned}$$

No kidding, learn these by heart! Yes, you will be tested.

- linear algebra (solving systems of equations);
- differential equations describing a simple harmonic oscillator (SHO), up to and including a damped, periodically driven harmonic oscillator typically taught in calculus-based introductory mechanics courses;
- complex numbers. This will be reviewed within this course, as some first-year pathways may miss this material, but the idea of a complex plane and basic algebra of complex numbers, up to the Euler's formula, will be required.

Marks:

Component	Worth	Comments
Homework	20%	Expect a homework assignment every week or so; full marks given for demonstrated effort. Late penalty is a sinking cap of 15%/day.
Labs	32%	All labs must be completed, and all lab reports submitted.
Midterm	10%	An in-class written test: problems similar to homework, full marks require correct answers.
Final	30%	A written final: problems similar to homework, full marks require correct answers. 50% minimum to pass the course.
Lab final	8%	A lab test: analysis of a "black-box" (unknown) circuit.

Table 1: Grade composition

As you can see from Table 1, our grading scheme for the course tries to balance a variety of components. Ultimately, a success in a physics course — achieving the desired *learning outcomes* — comes down to being able to solve physics problems on a blank sheet of paper, without assistance, on the final exam. Attending lectures, actively participating in the discussions in-class, and homework are the primary means of preparing for the final exam, though there are differences between the ongoing work, where demonstrated effort is more important than the correct answer, measuring the progress in the learning process itself. Exams (the midterm and the final) are different, they are designed to demonstrate a completion of this process, and correct answers are required. An allowance is made for the midterm: if the final exam mark is higher than the midterm mark, the latter is ignored and the weight of the final increases and covers the equivalent worth of both.

Of course, the experimental (lab) component is an integral part of electronics, and the grade composition reflects that by assigning a significant weight to the lab work.

Textbook:

This workbook is your primary source, but plenty of excellent textbooks on Electronics exist. Several have been used in the past,

and several copies are available on the shelf in the lab, and to borrow in the Physics office, and in the library. And, of course, online. To orient you in your additional reading, on occasion you will see pointers to roughly which section in one of the two most popular textbooks you should be visiting for additional insight.

DH will refer to Diefenderfer and Holton, and S will refer to Simpson, see **Bibliography** in the back of the book.

To the instructor

This book was born as an attempt to address a fundamental change in the university students that seems to have gradually taken place after 2020, namely in the transition of the primary approach to learning away from a written word. The instantaneous, ubiquitous access to information (call it the “iPad effect”) coupled with the dominance of pedagogical theories that emphasize “conceptual learning” over so-called “memorization” seems to have diminished the importance of information in the eyes of learners. This, of course, is a completely false dichotomy. In science, learning (memorizing!) the facts underpins acquisition of abstract concepts and frees the necessary mental space for processing new ideas. Developing conceptual breadth creates a structure that helps to make sense of the experimental evidence. One supports the other; one is impossible without the other.

The pace of information flow has increased dramatically in the XXI century, and students develop rational strategies for coping with such information overload: they learn how to “surf” what was once quaintly referred to as the “information superhighway”, optimizing for speed and not for the depth of coverage. As a result, long texts developed by the authors of the previous generation are missing the mark completely: the students are not reading them from the first word to the last, re-reading if portions are not clear. Instead, they scan through those texts for keywords, then enter them into AI tools and search engines to get a quick summary response for difficult parts. Academic success is seen as *finding* the right words and transferring them into the homework assignment or lab report. The problem is, this approach creates an illusion of learning the subject matter. Faced with a blank page on the final exam, in the absence of familiar search tools, the students tend to have tremendous difficulties reading and comprehending the problem and starting a solution from scratch. If a final exam prepared in the 1990s is offered to the 2020s students, the results are catastrophic: the exam is written in a language that is completely foreign to today’s students.

Addressing the “reluctant learner”

To an instructor, this inability, or perhaps a refusal to read finely crafted paragraphs seems almost offensive, a reluctance to learn. The gap between what the instructors think their texts are conveying and what the students are getting from those texts is widening. Students in this generation are as smart as they have always been, but the way they view and deal with written words is quite different from that of the previous generations.

What to do? It is possible that a new generation of instructors will find a way to replace the written word with some other means of conveying the skills and wisdom to future generations of learners. In the meantime, several approaches may help to bridge the gap. One, curiously enough, may be to adopt a form of deliberately “muddled teaching”: a somewhat disjointed presentation, focusing on the clarity of small segments, but lacking the overall structure and connections between the segments. In the past, this would be considered poor instruction, but the effect of adopting such a teaching style is to force the learner to make the connections on their own, thus encouraging them to engage with the material more than they would if the entire presentation was a clear, linear, and polished moving picture that only needs to be watched, but not necessarily engaged with. In a word, the worse you teach, the better they learn, although this may result in terrible teaching evaluations from students. Anecdotally, this author has seen such a positive effect in COVID-affected cohorts of students, but this hypothesis still awaits a systematic examination, in part because it seems irresponsible to deliberately teach “worse” than one is capable of.

Integration with laboratories

Another alternative, and the one that this book embodies, is to broaden the engagement surface across lectures, own work, and hands-on laboratories, tightly coupling all three and making them a part of one highly structured learning pathway. It is no secret that scheduling difficulties and variations in lecture flow virtually ensure that the labs are only loosely related to the lecture material, and many instructors rely on the lab demonstrators to take care of the student learning in the labs. We are attempting to do the opposite: to make the labs a seamlessly integral part of the learning pathway, and to strongly synchronize lectures and labs. Every second chapter in this book is a lab, and while the specific instructions on performing the lab experiments are left for the online resources (text, images, videos), the lessons learned are meant to be *recorded* directly in this book, becoming an integral part of the learners’ pathway through

the material. The act of *writing in a book* is meant to change the relationship with the book, and encourage making it one's own. The text — the lecture component — is also deliberately presented with very wide margins, to encourage the reader making additional margin notes and clarifications, and in some strategic places additional blank space is inserted for the same purpose.

The “mystery” circuit

To motivate learners, it's important to make them aware of — and hungry for — the ultimate learning goal. Beginning skiers will progress much faster if, on their first day, the instructor arranges for a visit to the top of the mountain, even if the descent back down is via a chairlift: the vistas that open up at the top are breathtaking and will inspire faster learning. In the same way, we choose here to reverse the traditional bottom-up approach to the labs (starting from simple building blocks and building up to more and more complex circuits). Instead, we begin by building a reasonably complex circuit that does something, even though the assembly instructions are followed fairly blindly, and then begin a detailed block-by-block analysis of what different segments of this circuit do in subsequent labs. We chose our “mystery circuit” carefully to include both purely analog elements and the interface to the digital domain. As the course progresses, each step in the analysis of the circuit closely mirrors the development of the course material in the intervening chapters. The final “reveal” of what the circuit is and how else one could implement similar functionality occurs near the end of the course, and brings a sense of reward. We suggest that the students do not rush ahead and look up this “punchline” before the preceding labs are completed, it will make the process feel less satisfactory. And we appeal to the instructors: do not rob the learners of the joy of that discovery by telling them too much too early.

