

## Physics 123/223, ES 153: Introduction, Fall 2016

REV 0; July 19, 2016.

### What's in This Handout

- A brief description of the course and some course policies.
- A schedule

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## 1 Course Format and Goals

This course tries to teach you enough electronics so that you can do useful design work in a laboratory. The course achieves this very broad coverage at the expense of depth. But that does not mean that your designs will be second-rate: the premise of Horowitz & Hill's text is that a person need not go through the rigors of three or four terms at engineering school before designing a good amplifier, an integrator, or a board that's to feed a computer with a signal from some odd transducer. For a nice balanced response to the book, see <http://www.eevblog.com/?p=89>.

At term's end you will have seen a lot of standard circuits, and will have programmed a tiny computer to control a variety of peripherals. You will be a novice, but a novice well-equipped to continue learning. Databooks that now are opaque to you should, by term's end, be intelligible. Lots of scary schematics will have ceased to scare you.

We will meet twice each week, devoting the first part of the afternoon (till  $\approx$  3p.m.) to classroom discussion of the current topics, which are defined in part by the lab exercises and in part by the reading. The small class size permits us to work in an informal seminar-like atmosphere. After the hour of talk, you will spend the remainder of the afternoon building circuits on the "breadboard" gizmos (you can't learn electronics without actually doing it).

The course is not hard but does take a lot of time. It has the reputation of being equivalent to 1.5 to 2 full courses. The work is so different from what you are asked to do in an ordinary Physics course, however, that you may find it restful: an afternoon of occupational therapy, spent pushing little wires into holes: building things—then finding out why they don't work.

This course resembles Engineering Sciences 52 in its hands-on quality, and in its emphasis on practical design rather than theory. It differs from ES-52 in covering a broader set of topics, but we do not provide the continual project-building experience of ES-52. Until late in the course, each circuit that you build will require no more than perhaps 20 minutes to build and try. A few labs ask you to do more: Lab 5, in which you can wire an operational amplifier from individual transistors; Lab 12, the group audio-project; Lab 18a, in which you build a digital circuit that you designed earlier; and the final microcontroller lab, in which you implement a design of your own.

Compared to a course like Engineering Sciences 154 (electronic devices and circuits<sup>1</sup>) Physics 123 is both broader and shallower. It tries to do "all of electronics" in one term. At the start, we remind you of Ohm's Law; by the end you are programming a microcontroller (or a home-made microcomputer if you take that branch, in the micro section of the course).

Physics 123 qualifies as a General Education course, in the category, "Science of the Physical Universe."

### Note for Engineers

Undergraduate engineering students, and particularly SB (Bachelor of Science) concentrators, should enroll in the Engineering Sciences course number (ES-153). This will ensure the course counts as an engineering elective toward concentration requirements. Requirement questions should be directed toward an engineering Assistant Director of Undergraduate Studies (ADUS).

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<sup>1</sup>154 Course Description: "Design of analog integrated circuits using semiconductor transistors. Emphasis on intuitive design methods, and analytical and simulation-based circuit analysis. Topics: the physics of semiconductors; operating principles of bipolar transistors and field effect transistors; bias circuits and active loads; single- and multi-stage amplifiers; operational amplifiers; frequency responses and stability; noise; switched capacitor circuits and comparators; data converters."

This is a graded course. We don't allow students to take it Pass/Fail and we don't accept auditors. (And there are exceptions to every rule.)

## 2 A Rough Map of the Course Schedule

Here is a sketch of the course topics:

- Analog (13 labs)
  - Passive Circuits** 3 labs: DC, RC Circuits, Diode Circuits
  - Discrete Transistors** 2 labs: simplest view, differential and operational amplifier
  - Operational Amplifier Circuits** 5 labs: idealized, departures from ideal, oscillators, nasty positive feedback, PID loop
  - Analog Wrapup** 3 labs: voltage regulators, MOSFET switches, group analog project
- Digital (13 labs)
  - Logic** 5 labs: Gates, Flip-flops, Counters & PLD's (programmable logic devices), Memory, Project
  - Conversion** 1 lab: Analog $\Leftrightarrow$ Digital
  - Microcontroller** 7 labs

## 3 Staff

### 3.1 Lecturers (except that we don't really lecture):

Bradley Hubbard-Nelson

EEmail: bradhn@mindspring.com

Tom Hayes

EEmail: hayes@physics.harvard.edu

Jefferson 258; office: 495-4740

Office, Jefferson 258, is in the old brick building behind the Science Center, first door on right if you enter Jefferson at its westernmost doorway.

Whichever section you're in, you'll see both of us: we both teach both sections.

### 3.2 Teaching Assistants:

Jake Connors Email: jconnors@physics.harvard.edu Ann Wang Email: annwang@g.harvard.edu

Harneke Gulati Email: harnekgulati@college.harvard.edu Aun Zaidi Email: zaidi01@college.harvard.edu

### Office Hours

Brad Hubbard By appointment: send me an email

Tom Hayes Drop in any morning; or call up and make a date. You can call my office phone to make sure I'm in.

### Teaching Assistants:

Weekend free labs do double duty, as office hour and free lab session. These sessions run most weekends, Sunday, 3-6 p.m.

### Extra Lab Time

See “office hours,” above: if no one shows up at a Sunday session, the person in charge will leave after perhaps 15 minutes (this occurs approximately never).

If you need extra time in lab, we can lend you a key for the off hours, which include every morning.

## 4 Problem Sets, Quizzes & Midterm

A midterm will cover the *analog* material of the course. The final will cover all course material, analog and digital, but will give slightly more than half its attention to digital.

### 4.1 Quizzes

Not really—but often you can expect to be asked to try a task that does not count at all for a grade. It cannot count, because the quizzes are *anonymous*. See § 7.2 on page 8, below.

### 4.2 Homeworks

We will give out xeroxed homework assignments, approximately one per week. Homeworks are due *Mondays* (though not quite *every* Monday, as you'll gather from the schedule: we skip a homework around midterm week, and after Thanksgiving vacation). Homeworks are due by 5 p.m. in the lobby outside Sci Center 110b. There's a Physics 123 drop box, first on the right as you walk into the little lobby.

**MIT people** are invited to email their HW's. Email scanned work to the homework “drop-box,” [harvardphysics123@gmail.com](mailto:harvardphysics123@gmail.com). (Note that this is only for homework submission; this is not the email to use for asking questions.) Check that your scanned document is readable, please, before you send it.

Harvard people, please do not email your submissions—unless you've warned us beforehand that you have a special reason to do so, such as going out of town.

Extensions: We are generous with extensions, if you ask Tom before the assignment is due. We are much grumpier when you offer an excuse after you're late. When you have put a late homework into the box, be sure to email Tom to say you've done this—lest the document languish, unnoticed.

Homeworks Late Without an Extension: We'll keep some discretion, here. But our usual policy is to give a maximum of 50% of the points you would otherwise have earned, so long as it appears that you did the homework without use of our solutions.

### 4.3 Collaboration on Homework Assignments

We hope that you will discuss homework questions with one another. Such discussions are the principal activity at our Sunday sessions, for many students. Since we assume such collaboration, you need not announce it on the work that you submit—**but...**

because homework scores get considerable weight in the course grade, and because we don't believe you can learn the material without practicing on problems, we do not allow one person simply to copy the work done by another. If someone explains to you how to approach a problem, fine. But write out your own answer—and often a good answer will include some explanation of your method. We will look with disfavor on submissions that match, word-for-word. In some rare cases it may be appropriate to acknowledge that a problem stumped you, so that you must give credit to someone who told you how to solve it.

We recognize that these judgments are subtle, and matters of degree. We don't want to distract you with writing lawyer-like acknowledgments. We do want you to worry a bit about the issue.

Here is a relevant excerpt from the FAS "Student Handbook:"

students must acknowledge any collaboration and its extent in all submitted work; however, students need not acknowledge discussion with others of general approaches to the assignment....

To the extent that our discussion of collaboration seems to modify this policy, our discussion controls.

## 5 Grading

The course grade rests on roughly the following basis:

- *Homeworks*: 30%
- *Midterm*: 25%
- *Final exam*: 40%
- *Class & Lab performance*: 5% (just our subjective impression)
- *Final project*: (Optional): up to 5% "extra-credit" boost

It is only in recent years that we have given any explicit weight to our impression of your class and lab work. We're trying this in the hope that it will let us reward the diligent (and will help us to lure in the occasional student who is inclined to skip labs). We give little weight to this subjective judgment. We give little weight partly because we doubt our judgment, but also partly because we don't want to corrupt the labs: we like the idea that you're doing the labs not to please us but in order to learn, and we want you to feel that, too. The final project can help, a little, but we never recommend that you do a project in order to maximize your grade: reviewing old exams usually pays better, per-hour.

## 5.1 Lab reports? NO!

We do not expect lab reports, and we barely grade lab performance (see just above). But we do expect you to do all the labs. *If you don't do the labs, you can't pass the course.*<sup>2</sup>

## 6 Texts

### 6.1 The main text

This is a book that embodies the course, in day-by-day doses: Learning the Art of Electronics by Tom Hayes with Paul Horowitz (2016). We'll refer to this book as "LAoE."

Each daily dose includes...

**class notes** These present the day's topics much as the live in-class talk does—but the typed class notes are much tidier and more complete. These you ought to read before coming to class.

**lab** There is one for each of our meetings. You should flip through this so that you know what you'll be doing in lab. The building of circuits goes much more smoothly when you can anticipate what you'll be doing. And knowing what's in the lab will let you make choices about what parts of a lab to hurry on to, in the event (not rare) that you find yourself strapped for time.

**supplementary notes** these you can read or ignore. They treat a topic, offering an explanation that you may or may not find necessary. For example, on day 1 you'll find a handout on reading resistors. If you're familiar with this process, skip this handout entirely.

**worked examples** these are design problems, and may not interest you much as you prepare for class—but can become keenly interesting when you're working on a design for homework.

### 6.2 An Excellent Reference Book (*not required*)

Horowitz & Hill, The Art of Electronics, (Third Edition, 2015). This is a *great* reference book—almost surely the best general trove of circuit-design wisdom that you will find. But you don't need it to get through this course happily. After the course, you will appreciate its depth and comprehensiveness. During the course, you'll probably feel busy enough just reading the xeroxed handouts. We'll refer to this book as "AoE."

### 6.3 Other Electronics Resources You Might Find Helpful

#### 6.3.1 Books

We don't recommend paralleling your reading in LAoE or AoE with reading another, more conventional electronics textbook. You'd end up spending a good deal of energy translating from the terms

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<sup>2</sup>Does this remark seem silly, because the point goes without saying? Well, the remark honors an original fellow of some years ago who came to the organizing meeting at term's start, heard us say 'No lab reports,' and then did not reappear until the day of the exam. We don't like that way of doing the course.

of one into the terms of the other. The engineers' treatment would be much more mathematical than ours (and, we think, less helpful for development of intuition).

But if you'd like a second source...

- ... here is one recommended by David Abrams, who teaches SEAS' introductory electronics course, Eng Sci 52:

Scherz & Monk, *Practical Electronics for Inventors*, (Third Edition, 2013)

ISBN-13: 978-0071771337 ISBN-10: 0071771336

This book is available at the Coop and for online order at Amazon , Barnes & Noble , Walmart , Alibris , AbeBooks , and other vendors. The list price for the book is \$40.

If s/he has access to the Harvard Library site, it is available online.

- Some books for hobbyists and tinkerers can help to fill in background that we forget to explain: how instruments work, for example. Here are three that looked good, to our hasty appraisal, plus one conventional treatment of electronics, in the style of an ordinary engineering course:
  - “Electronics: circuits, amplifiers and gates,” by D. V. Bugg (2d ed., 2006), on reserve in Physics Research Library. Good on introductory topics, especially passive devices.
  - “Practical Electronics for Inventors,” by Paul Scherz (McGraw Hill, 2007; 934 pages, \$40). This is a sort of encyclopedia of standard circuits and also pithy explanations of technology—how a Liquid Crystal Display works, for example.
  - “Intuitive Analog Electronics,” by Thomas M. Frederiksen (McGraw Hill, 1989). Good explanations of basic concepts like voltage, engineering notation, and other topics that we tend to skip. The author is a very knowledgeable person who works in the semiconductor industry (at National Semiconductor). He has written a half dozen similar books, all quite good, and all with titles that begin, “Intuitive...”: re: CMOS, op amps, digital, computers.
  - “Microelectronic Circuit and Devices” (2nd Edition), by Mark N. Horenstein. This is a conventional engineering treatment (an overpriced paperback, at more than \$100—but available at Cabot Science Library)—and explains points from which our course averts its eyes, such as the physics of a semiconductor junction. Some people may yearn for this sort of explanation, which they will never hear from us.

### 6.3.2 Simulators

Former students passed on to us links to two good simulators:

**Analog** The analog simulator shows currents flowing—kind of like what a science museum's interactive demo might show:

<http://www.falstad.com/circuit/e-index.html>

#### Digital

The digital is pretty good, too:

<http://joshblog.net/projects/logic-gate-simulator/Logicly.html>

## 7 A Few Innovations, in recent years:

### 7.1 Usually, we post our daily handwritten notes

We'll use Canvas.

### 7.2 frequent “anonymous quizzes”

On many class days you will be asked to try a short quiz—without putting your name to the paper. We'll talk about one or two of your responses in class. These quizzes are meant to let you—and your teachers—test whether ideas and skills are getting through to you. Since these quizzes are anonymous, they really test the teachers rather than you.

We *may* occasionally make a quiz *not anonymous* and assign it small weight—perhaps 5 points, like a quarter of a homework. Last term, we noticed that some students habitually failed to do preparatory reading. The class meetings and lab are more fruitful if you do the reading, even hastily. So, we may try some incentives.

### 7.3 Problem solutions and old exams on the web

Raggedy solutions to problems in earlier editions of AoE—some appearing also in the current edition—are now on the Web (along with some recent exams and solutions; we expect you won't be interested in the exams for a while). On our web page you will find a link to these so-called “electronic reserves.” No username or password is required. If you prefer to go direct, the URL for these reserves is

<http://www.courses.fas.harvard.edu/~phys123/solutions/>

### 7.4 *Lab Design Exercises added*

We have inserted small design exercises into most of the labs, so that you will have the pleasure of building something of your own design at almost every session. We get a kick out of building our own designs, and figure you will, too.

- *Some More Complex Lab Circuits, used to Pull Together Fragments*

Students have told us that they like to make a circuit that *does* something, rather than always build circuit fragments. So, we have added several such labs:

- The second discrete-transistor lab asks you to put together multiple familiar stages so as to form an operational amplifier.
- On a larger scale, the motor-control lab (called “PID”<sup>3</sup>) incorporates many operational-amplifier circuit fragments that you have met in earlier labs.
- A group design-and-build project concludes the analog section of the course. This is a circuit that transmits music using infrared “light,” frequency-modulated.

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<sup>3</sup>This is an acronym for the conventional name of this sort of circuit: “Proportional, Integral, Derivative. . . .”



### 7.4.1 New Analog Labs:

- *PID motor control lab* This is an involved circuit, but gratifying to see in action. It makes vivid the problem of maintaining stability in a feedback loop: it's borderline-spooky to see a little motor rocking and fussing as it tries to find its resting position. It's a cool lab—but we have relegated it to *optional* status, as a Saturday class, because Armistice Day knocked a day out of our course schedule.
- *Analog design lab* We will devote a lab to letting the whole class build an analog circuit you have *designed*, at the end of the analog part of the course. Students regularly devise digital projects; they have not had a chance to try building their own analog designs, until we introduced this project. This exercise is fun—and also provides a pretty good review of lots of what you'll have learned to that point in the course.

### 7.5 Less(!) discrete transistor material

Recently, we at last took something *out* of the course, whereas normally we just keep stuffing in new topics. We have minimized what we think is the hardest part of discrete bipolar transistor design: the so-called “Ebers-Moll” model, and some subtleties such as Early Effect, Miller Effect and current-mirror designs. We have also cut out a day we used to devote to linear applications of FETs (field effect transistors; we'll meet FETs only as switches).

### 7.6 An Odd Option: We offer Two Alternative Sets of Microcontroller Labs

For the past 30 years or so we have been building up a computer from parts. We still offer a set of labs in which you can do this—and far more than half of our students, last term, chose this path. A few years ago we offered, for the first time, an alternative scheme using a microcontroller in a more conventional way: a single-chip controller stands alone. A laptop PC communicates with the IC, programming the device and monitoring its operation.

The two ways of treating the microcontroller lead to the same results. All of you will conclude the course by using a controller “standalone,” to do something of your own choice.

### 7.7 PLDs

Programmable Logic Devices (PALs and GALs). We will devote class and homework time, though not a lab session, to these gadgets. We'll give you a chance to “burn” a PLD, after you have written its design.

- We will use homework assignments to try to get you used to designing in terms these chips understand (or, more precisely, used to designing in terms a *logic compiler* understands). PLDs provide an efficient way to make complex logic circuits with very little strain on either your brain or fingers (nothing to wire!).
- You can download the logic compiler to your PC. We will use a “Hardware Design Language” (HDL) called Verilog. We will learn only as much Verilog as we need to design fairly-simple circuits: counters, combinational networks, small state machines. Verilog's versatility can

make it overwhelming. We won't attempt to make you expert in its use, but want you to get comfortable with the language, so that later you will not be scared to take advantage of its further powers.

### **7.7.1 A digital project lab**

Struck by students' enthusiasm for the analog project lab—in which you do the designing, and get some impressive results—we now give a day to a somewhat-similar digital lab exercise. It is not a group exercise, but something each person or pair of lab partners will design, and then build. In recent terms, these individual designs have included a) a sine generator using a phase-locked loop and active filter, b) an oscilloscope multiplexer, c) a reaction timer, and d) a capacitance meter.

### **7.8 Microcomputer Breadboards that can ease your wiring work**

We have fabricated curious custom microcomputer breadboards, boards that can speed up your wiring work in some of the early digital labs: wiring counters and memory, particularly. These breadboards include a printed circuit that connects displays and keypad directly to the computer's *buses*.

## **8 Schedule**

The course schedule follows. On the web, it is a separate document.

## Physics 123 Schedule, Fall 2016

REV 0; July 18, 2016.

<u>MON</u>	<u>TUES</u>	<u>WED</u>	<u>THU</u>	<u>FRI</u>
<u>September</u>				
			1-Lab 1	2
5-(Holiday)	6-L2	7 <i>(a quiz or two, on Labs 2 &amp; 3?)</i>	8-L3	9
12-PS1	13-L4(Q I)	14	15-L5(Q II)	16
19-PS2	20-L6(op I)	21	22-L7(op II)	23
26-PS3	27-L8(Op III)	28	29-L9(Op IV)	30
<u>October</u>				
3-PS5	4-L10(PID)	5	6-L11(reg'ltrs)	7
10 (Holiday)	11-L12(FETs)	12	13-L13: PROJECT	14
<b>MIDTERM:</b> Mon. eve, Oct. 17				
17-test	18-D1	19	20-D2	21
24-PS6	25-D3	26	27-D4(Digital Project)	28
31-PS7				
<u>November</u>				
	1-D5	2	3- $\mu$ 1	4
7-PS8	8- $\mu$ 2	9	10- $\mu$ 3	11
14-PS9	15- $\mu$ 4	16	17- $\mu$ 5	18
21-PS10	22- $\mu$ 6	23, 24, 25: Thanksgiving holiday		
28 (no PS)	29-free lab, projects	30- $\mu$ 6		
<u>December</u>				
			1-free lab, projects	2
(Reading period begins Dec. 3)				
5-PS11	6-A visiting lecturer, then free lab, projects, through this week		7	8
				9
(Exams begin Dec. 10)				