SYLLABUS

Boston University CAS PY 371A1

"Physical Electronics for Scientists - eLab"
Winter/Spring 2020

ALL STUDENTS ARE REQUIRED TO PERUSE & AND ASSIMILATE THIS BEFORE THE FIRST SESSION. Please come with any questions; otherwise we'll dedicate our precious time in the lab working with your equipment.

Laboratory - PRB 364 (617) 358-5216

Open times: Winter 2019: Mondays 10am - 7pm, Thursdays 11am-1:30pm and 3:30-5pm & by appointment

Winter 2020: to be determined by registrants schedules, providing a minimum of 8 open hours for each

eLab Director
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Office Hours: Monday 9 am - 7 pm, any time eLab is open, and by appointment or by phone anytime.

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Consultants for eLab Projects:
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Course Website
physics.bu.edu/adlab_and_elab

Prerequisites
Curiosity and an eagerness to design, construct, and evaluate an instrument to measure or control something. No past experience or course work.

Cohort

Interns from freshman to 3rd year of grad school have enjoyed this course.

Course credit

If you are an undergrad, desiring credit to apply to grad school, you can register for PY681 grad credit, rather than PY371. Please obtain the Directors' endorsement.

Course Objectives

The eLab experience consists of hands-on construction and analysis of classic electronic circuits giving the student a thorough understanding of the “art” of electronics. As in any industrial or national lab, each intern has her/his own workstation, complete with microprocessor, some 40 transducers and actuators, scope, VOMs, DVMs, signal generator, power supplies, transformer, batteries, electronic developer’s breadboard, and parts (ICs, transistors, diodes, resistors, capacitors, chokes, LEDs, bulb *etc.*).

This electronics laboratory gives you experiential understanding of electronic circuits, components, manufacturers and choices about building or purchasing solutions to state-of-the-art problems that face researchers. Interns in the lab learn the realities and limitations of devices and circuits that do not follow the (mathematical) rules; everyone learns why the recommended text carries the word “art.” Many tools required to advance the “art” simply do not exist off the shelf and have to be built, often from scratch. Measuring, monitoring, examining and recording data is the essence of successful invention. This course provides a thorough understanding of the circuits and tools that can be constructed to solve a myriad of problems that scientists face daily in the real world.

Each week we meet in the lab for 8 hours. Time is allocated for lunch and to compensate for conflicts with the any concurrent class. The typical uninitiated student must prepare for ~2 hours before each session to be ready to construct the circuits of each lab session. You prepare by reading the lab manual well before entering the lab; a short quiz at the beginning of each session ensures that you know the concepts to be addressed. After the quiz, the lab director reviews the critical concepts. Throughout the session, the senior staff answer, on the fly, questions that inevitably arise while your construction the circuits and performing the lab measurements. Teaching moments for all hands occur quite often during the day in the lab.

eLab Open and Make-up Times …

are determined to fit all registrants to avoid class conflicts, giving each students at least 8 hours/week to work on their projects.

At a common hour when all students can be present we discuss the challenges of the session, the homework, and the quiz. Time to catch up or to have extra fun can be arranged at any time with the e-Lab Director.

All students MUST BE PRESENT at each session, and especially at the common overlap time. A minimum of 2 experimenters are in the lab at any one time for security.

If you cannot come to lab and take the quiz, you must contact the Lab Director before the lab session. We will schedule makeup time upon your request.

Course Materials and Communication

You will find all course material at the course website. You are required to check your e-mail daily for messages from eLab staff.

Lab Manual and Web Notes

Hayes & Horowitz, *Student Manual for the Art of Electronics,* 2nd edition, is required for the first half semester of the course, which is dedicated to analog electronics. A .pdf is available on the web. It is referred to as H&H below in homework assignments.

The second half of the course, focusing on digital electronics, follows web notes by Hazen and Gastler. They are perpetually being upgraded to keep up with the state of the art. For this part of the course, the intern will learn to program an Arduino microprocessor in C, and to configure it as the data acquisition system for an experiment or project of her/his choice.

Although the University has standardized on Python coding, the language of microprocessor and of essentially all physics research is C. Hence, if you are an undergrad, this course is likely to enhance measurably your coding talents.

Recommended for the super serious student is Horowitz & Hill, *The Art of Electronics*. This is the best resource in the business. You may need to use it to answer questions and to explore concepts mention in the *Student Manual,* but insufficiently developed there. This reference book is rigorous, providing a challenge even for those who are already familiar with electronics. It is a good reference for many projects that researchers will encounter throughout their career.

Both books are on reserve at the Science and Engineering Library, and copies of both are in eLab for consultation.

Lab Notebook

You are required to record all you do in your personal Lab Notebook, written in ink, dated and initialed on each page. You should use it for the rest of your life, as Feynman did. In all industrial and national labs you are required by contract to keep such a book for patent purposes, as well as for claiming credit. You must keep clear notes in this, your formal laboratory notebook, including what you did, what the expected results should have been, and an explanation of what "went wrong," if so. Your homework should be written in this logbook too. It will be regularly inspected by the eLab director. The lab staff will be looking over your shoulder to help you make sure that you are doing the work properly. However, we will not be constructing the circuits for you.

Presenting your final project at Annual eLab Open House

To perfect your science communication, you will often be called upon to present your current work to the Department Chairman, outside departmental visitors, etc. You will also describe your final project to attendees at our annual eLab Open House.

Grading Scheme

The lab is divided into two halves, *analog* and *digital,* of 7 weeks each. Each half counts approximately 50% of your grade. Each of the following activities factor into your grade:

lab book entries	10%,
quizzes at the beginning of each session	20%
class participation	20%
digital coding	15%
final project	20%
final practical exercise	15%

The final is conducted in the lab during the last session. It includes 1) analog, 2) digital concepts, and 3) evaluating your proficiency with the equipment. No preparation is necessary for 3).

PY371 targets undergraduates who have minimal hardware experience. PY681 is designed for graduate students, from whom we expect more theoretical insight. We pair each with a different undergrad on each experiment so that the grad student can develop his mentorship skills.

Academic honesty is controlled by your signature; initialing each lab page is your assurance that you understand and are abiding by Boston University's policy. Otherwise, you are encouraged to work with one another in realizing your projects.

Recommended Ways to Organize your Work

Before coming to the lab, read the appropriate section of the Student Lab Manual (It will take about 2 hours). The manual has many questions for you to think about and answer. If you cannot figure out an answer, at least try to formulate an approach to tackle the problem posed by the question; then ask one of the lab instructors.

During the lab, try to associate the material you have read with the equipment at your workstation. Follow the directions in the Student Lab Manual (which often may require reading several times) and attempt to finish all of each assignment. If you get stuck for even 10 minutes, please ask for help. Do not let the lab exercises or homework pile-up.

"Read" means to *scan through* the material without stopping for points you do not understand immediately. *"Study"* means to *dwell on and assimilate* each sentence you read. If you find unknown terms, find what they mean in the text or on the web.

Course Schedule by Week

The specific dates and days of the week below are for an earlier year, and therefore will vary from year to year.

ANALOG ELECTRONICS

Mon. Jan 16   Martin Luther King Holiday - no classes

Week 1

Required HW1: read H&H 1-31

Mon. Jan 23   Thevenin equivalent circuit, voltage divider & your scope, signal generator, breadboard, power supply, VOM

H&H Lab 1

Week 2

Required HW2: read H&H pps 32-81, focusing on pps 46-59 & 71-83

Mon. Jan 30   Low & hi-pass filters, 6dB/octave, RC time constant, 3dB point, integrators & differentiators; Diodes

H&H Lab 2, Ignoring phase shifts & L2-9

H&H Lab 3, Ignoring L3-1, 3-8

Week 3

Required HW3: read H&H pps 82 to 123

Mon. Feb 6   Bipolar Transistors : gain (beta), V-I curves

H&H Labs 4 & 5, Ignoring 4-8, 5-3 B, 5-4, If time, 4-5, 4-9, 5-6

Week 4

Required HW4: read H&H pps 124 to 162

Mon Feb 13   Differential Amps; FET's (field effect transistors)

H&H Labs 6 & 7, Ignoring 6-2 to 3, & 7-3c, 7-4 know most terms on pps 140-1
If time, 6-4 to 5

Mon Feb 20 Presidents' Day Holiday; Lab on Tues instead…more prep time

Week 5
Required HW5: read H&H pps 163 to 206
Tues Feb 21 Op Amps, the Golden Rule
H&H Labs 8-1 to 5 & 9-1a,9-2 to 3
If time, 9-4,5,6 or 7, your choice.

Week 6
Required HW6: read H&H pps 207 to 266, ignoring 224-226. Know most terms on p 243 and on pp 265-6.
Mon Feb 27 Op Amps Applications: oscillators, Schmidt triggers, etc.; FETs II
H&H Labs 10-1, 2, 3 or 4, 7, & 11-1a), 2, 3, 5

***DIGITAL ELECTRONICS* -** This half of the course is detailed at http://edf.bu.edu/PY371.

Mar. 6-10 Spring Break - take your Arduino home

Follow Dan Gastler's Crash Course in C lecture slides:
https://docs.google.com/presentation/d/18sV6cQqeDFwiH5KBWFixevLTHqkzHcVgzM-WMMHFghs/edit?usp=sharing

Download Arduino software to your laptop; do the "blink" tutorial at http://arduino.cc/en/Tutorial/Foundations

Week 7
Required HW7: read H&H pps 281 to 319; must bring laptop, cable, and Arduino to lab.
Mon Mar 13 µ0: Digital Gates, Combinational Logic, D&RS Flip-Flops, Latches, & Shift Registers

H&H Labs 13-1 (but not b 1), 2, 4, 5; Lab 14-1, -2, -5-b
If time do 13-6, 14-6

Read Eric Hazen's microprocessor page: http://edf.bu.edu/PY371 for homework.

10am. Special Lecture in class: "Intro to Arduino and Programming it in simplified C", Dan Gastler

Week 8
Required HW8, µ1: Basic I/O, driving an LED display, digital voltmeter and thermometer
Mon Mar 20 HW on Arduino: do coding exercises - masking & shifting bits, loops.

Week 9
Required HW9, µ2: Analog output: PWM, serial DAC, waveform generator. Timer interrupts. Function generator (sine, square, ramp)
Mon Mar 27 Read H&H p. 372 to understand keypads

Week 10
Required HW10, µ3: Signal generator enhancements: active filter, lookup tables; Stepping Motor Controller
Draft Proposal for Project due, including web reference & price for any components not likely in eLab.
Mon. Apr 3 If you haven't done it yet: H&H Lab 14-1, -2, -5-b . If you have time do, 14-6.

Week 11
Required HW11, μ4: Catching up and Playing Around
Final Proposal for Project due. including web reference & price for any components not likely in eLab.
Mon. Apr 10 Finish Lab 14, if not yet done. Start working on your final project if you have time.

Mon Apr 17 Patriots' Day Holiday, extra time to prepare before Wednesday

Week 12
Required HW12, μ5: Teaming up your computer with an Arduino: DIY Oscilloscope
Wed. Apr 19

Week 13
Required HW13, μ6: Storage Scope; Interrupts and Other Exceptions.
Mon. Apr 24
Dedicated time working on your project.

Week 14
Required HW14, μ7: All Physics Open House: Demonstration and discussion of your project with visitors
Mon. May 1
Finish final project
Check out: Make sure all needed equipment is at your station. Leave all cables, probes etc. hooked up. If you have anything extra, return to storage racks, shelves, bins, etc.. All must be tidy for your successor before exam starts.

Final Practical Exercise
Part 1: Written Portion
Part 2: Hand-on skills: facility with all your diagnostic equipment

e-Lab Annual Lunch, Larry's house & garden, 111 Carlton at Ivy Street

HOW MIGHT "ELECTRONICS FOR SCIENTISTS" EARN YOU HUB CREDITS?

SCIENTIFIC AND SOCIAL INQUIRY
Scientific Inquiry I (SI1)
Scientific Inquiry II (SI2)

Scientific I Outcome 1
Students will identify and apply the major concepts involved in the operation of physical electronics, ubiquitous in our technological world. By manipulating the innards of electronic devices and circuits, students themselves learn the inner workings, capabilities, and limitations of cell phones, microprocessors, drones, control circuits, computers...basic technical literacy which all college educated scientists and engineers should have in their "tool boxes".

Scientific II Outcome 1
This course and its experience include an introduction to the way scientists and engineers develop complex electronic systems, such as the internet.

Researching, proposing, designing, building, programming and evaluating a microprocessor based control system is the heart of what Silicon Valley has taught us. In setting up their own microprocessor to realize a project of their choice, interns learn to code in a simplified version of the ubiquitous computer language C, the most common technical programming language these days.

Scientific II Outcome 2

In manipulating their world with their own sensors, electronic brain, and actuators, interns have to think of the consequences on their world. The eLab world, for example, has other students sensitive to loud noise, a drone flying inside the lab room, electronic components on fire, etc.

Safety in the lab, for each intern, and for their fellow interns, is paramount. The eLab safety course, for example, includes: eye wash, fire extinguishers, treating radioactive sources (e.g. in smoke detectors).

For each sensor and each actuator, the intern must research and peruse the specification sheets to make sure they are using each within its safe operating dynamic range.

COMMUNICATION

Digital/Multimedia Expression (DME)
Oral and/or Signed Communication (OSC)

Oral/Signed Outcome 1

Sporadically, every hour or so, a burnt out component, an odor and smoke, a circuit on fire, a blown fuse, or an expletive generated by an insurmountable hurdle becomes a "learning moment". The instructor stops all in whatever they are doing at their station to hear the "perpetrator" share with the entire lab what has happened, in a clear and coherent oral manner, and what lesson is to be learned. The instructor enhances the "lesson" as appropriate. The goal is to inform and instruct "perpetrators" peers to avoid further experiences of the same kind. Because the laboratory space and number students is small (12-15) and because each of the students is likely run across the same problem, these interactive sessions involve all the students in the class. It is an impromptu, unrehearsed opportunity for each student to learn to form coherent arguments under pressure and speaking extemporaneously about their experience in a field previously foreign to them.

Because the class consists almost exclusively of laboratory work in tight working space, a wide range of communication skills is mandatory. In dealing with both their peers and teaching staff, students will learn how to ask and answer questions effectively, modifying their approach with the audience. Indeed, in a creative but highly energetic environment like the eLab, students must learn to appreciate non-verbal cues such as tone of voice and body language, from a diverse group of classmates and teaching staff. Without those hard to define skills, it is difficult to maintain a peaceful, working, creative environment.

Oral/Signed Outcome 2

At the annual eLab "Open House" each intern presents his final project to the class and the attendees invited from the entire Physics Department, including faculty. Fielding questions and demonstrating the performance of her/his electronics creation is critical to their final grade. In addition, they know that their public presentation serves to attract other students to this very challenging but rewarding course.

The elements of this oral presentation include
1) realizing the design,
2) assembling the circuit with its sensor(s) and actuator(s),
3) coding the microprocessor,
4) justifying the project, and
6) evaluating the circuitry,

To enhance the presentation, the student is aided by projecting her/his poster describing the project.

Oral/Signed Outcome 3

As part of each final design project, the student writes and signs a proposal for her/his invention, researches the required components and equipment needed, develops the parts list, and outlines the procedure she/he proposes. This is typical of all research labs. Each proposal is reviewed by the eLab staff, and given back to each intern to improve in coming up with a final, doable electronic project. The components of the proposal include

1) realizing a design,
2) assembling the circuit with it's sensor(s) and actuator(s),
3) coding the microprocessor,
4) justifying the project to the eLab Director, the Advanced Labs Manager, and the Teaching Fellow
5) writing the "Users Manual",
6) evaluating the performance of the circuitry,
7) posting the project and photos of it on the eLab website, and
8) preparing the text of a poster to be projected in eLab during the annual eLab open house.

Digital/Multimedia Outcome 1

Students craft and deliver their electronic demonstrations using the media of their own digital microprocessor, which always is visual and active, using sensors and actuators of their choice, controlled by the software they write for their microprocessor. Their processor is often electronically coupled to the overhead projector, especially for their presentation at the annual open house.

Digital/Multimedia Outcome 2 As part of each final design project, the student digitally prepares a proposal for the work, researches the required components and equipment needed on the web, develops the parts list with costs from the lowest priced vendor, and outlines the procedure she/he proposes in

1) realizing a design,
2) assembling the circuit with it's sensor(s) and actuator(s),
3) coding the microprocessor,
4) justifying the project to the eLab Director, the Advanced Labs Manager, and the Teaching Fellow
5) writing the "Users Manual",
6) evaluating the performance of the circuitry,
7) posting the project and photos of it on the eLab website, and
8) preparing the text of a poster to be projected in eLab during the annual eLab open house.

All of the above is digital work.

Digital/Multimedia Outcome 3

Students will add photos they take and electronic schematic diagram descriptions of their invention to the eLab website, http://physics.bu.edu/AdLab_and_eLab/

This combines the experience of projected media, oral 1-1 presentation using digital aids, electronically composing and printing their poster, and forming her/his own eLab web page consistent with the style and character of the Boston University and eLab website. Hence, interns use various communication technologies to get their points across.

Hence, audio-visual representation of both qualitative and quantitative data (graphs, oscilloscope traces, etc.) of the performance of electronic circuits is inherent in the eLab experience. Many of the intern demonstrations are time-based or interactive.

INTELLECTUAL TOOLKIT
Creativity/Innovation (CRI)
Critical Thinking (CRT)
Research and Information Literacy (RIL)
Teamwork/Collaboration (TWC)

Critical Thinking Outcome 1

To propose a final electronic project requires critically evaluating what problem the intern proposes to attack with his microprocessor, how to build it, what will it cost, how long will it take to build. Then she/he must write it up, defend it, modify it to meet constraints. This is quite a challenge, even to a budding entrepreneur.

Critical Thinking Outcome 2

After developing each proposed final project, the intern presents it to the entire eLab and staff, using multimedia means, and defends it with the required participation of each of the members of the lab. The goal for the student reviewers is to critically challenge the project and sharpen it.

Research Outcome 1

For their final design project, interns must research the electronic literature in designing and proposing their project...it must be doable in a constrained period of time with a constrained budget.

Research Outcome 2

The interactive nature of eLab...discovering problems, asking questions as to why, involving other interns, student "experts" in the lab, and consulting with the lab staff are all part of the eLab experience...occurring many times each day.

Teamwork Outcome 1

During the first half of the term, each student proceeds to build and evaluate the performance of each of some 100 classic circuits, concurrent with some 13 other students, each at his own work station, dealing with the same circuit. When one student finds a vexing problem, almost always another in the room has encountered the same challenge. To avoid student frustration and discouragement, after struggling for at most ~10 min with the problem, each intern is expected to involve the instructor, who shouts out the problem to all in the lab, and asks for a volunteer to come over and assist the student in trouble. This develops empathy, cooperative learning, and teamwork, which are so critical to the productive workplace today.

Teamwork Outcome 2

Leading up to the final design project for the last half of the semester, interns naturally learn to work in a team to solve challenging design or implementation problems. Each student becomes facile at a particular skill, e.g. soldering, coding in C, etc. During the realization of each students individual project, they learn to make good use of the skills of the other in the lab...that is, the lab functions as a whole organism. We call this coopetition, for the synergism of cooperation and competition coexisting side by side. This is the model of American high tech, both in a lab, and between independent labs.

Creativity Outcome 1

By creating some 100 different circuits and a final "invention", eLab interns learn how to think in new ways, both as if they were an engineer designing a new widget or a programmer a coding a microprocessor dedicated to a specific task, e.g. an application-specific machine. Interns must imagine a new possibility for their final project and discover a new approach when, most likely, the first, or the second, does not work out. Although the students must acquire a basic understanding of analog and digital electronics and learn standard analysis and testing technique, their final project is a new thing. This process turns out, at first, to be frustrating, but eventually becomes a source of deep satisfaction. Their creation is generally a product that could be patented for the common good.

Any intern completing this course could, as many have, immediately enter into the technically skilled electronics workforce. These interns will have the personal experience of taking risks (blowing fuses, smoking resistors, burning themselves on a soldering iron), failing and trying again, probably ten times in each e-Lab session. In this way, they will have learned the importance of taking both risks and criticism. They will have developed the patience and persistence that allows their own creativity to bear fruit. They will also gain an understanding of the delicate balance between freedom and traditional technical wisdom in which true creativity can thrive.

Creativity Outcome 2

Electronics for scientists features a capstone project in which students design, build, test, perfect and demonstrate to a large audience an original circuit/invention. Their work is showcased in the annual Open House at the end of the semester, to which all members of Physics are invited.

12/18/19