Physics 364 : Laboratory Electronics

University of Pennsylvania — Spring 2022

- Up-to-date version of this page can be found at http://www.hep.upenn.edu/Classes/Phys364_spring22
  - *shortcut*: http://www.hep.upenn.edu/p364
- Past semesters: 2021c(JK) 2021a(BA) 2020c(JK) 2020a(BA) 2019c(JK) 2019a(BA) 2018(JK)

Contact info

- Bill Ashmanskas — ashmansk@hep.upenn.edu — instructor
- Jose Vithayathil — vithayat@physics.upenn.edu — lab instructor
- Mija Jovchevska — mija@sas.upenn.edu — teaching assistant
- Matija Turcic — matijat@sas.upenn.edu — teaching assistant

Handouts / PDFs

- Homework PDFs, class notes, etc. can be found at http://www.hep.upenn.edu/Classes/Phys364_spring22/files
  - *shortcut*: http://www.hep.upenn.edu/p364/files

Prospectus items

Course ID : PHYS 364-401 2022A

Course description and level

A laboratory-intensive survey of analog and digital electronics, intended to teach students of physics or related fields enough electronics to be effective in experimental research and to be comfortable learning additional topics from reference textbooks. Analog topics include voltage dividers, impedance, filters, operational amplifier circuits, and transistor circuits. Digital topics may include logic gates, finite-state machines, programmable logic devices, digital-to-analog and analog-to-digital conversion, and microcomputer concepts. Recommended for students planning to do experimental work in physical science. Prerequisite: Familiarity with electricity and magnetism at the level of PHYS 102, 141, 151, 171.

Class structure for Spring 2022

We meet TR 1:45–4:45pm in DRL 2N25 (map). Attendance is required, as most of your learning will happen while you work through and discuss each day's lab exercises with your lab partner and the instructors. For rare unavoidable absences due to a red pass, family obligation, etc, we will try to arrange a mutually convenient make-up time in the lab.

The overall course format is somewhat reversed from a typical physics course. You spend 6 hours/week in the lab, briefly jotting down your findings as you go along, so no out-of-class time is needed to write up your labs. To prepare for lab, you spend about 2 hours each weekend reading our notes or a textbook chapter. To help you to assimilate past weeks' lab material, the weekend reading assignment will often contain a single practice problem, which should take under an hour to complete. We will have a final exam, but no midterm exams or quizzes.

Also see workload below.

Schedule

(One schedule change we hope to implement before the end of the term is to reduce by one day the classroom tie spent on the existing FPGA exercises and to add a day spent on serial I/O and register files.)

We meet TR 1:45–4:45pm in DRL 2N25 (map).

Sunday	**Tuesday**	**Thursday**
		Jan 13 (online) Lab 1: introduce lab & equipment; build first circuits; measure some V-vs-I curves lab01 video
Jan 16 Reading 1 due: Thevenin, etc.	**Jan 18** (online) Lab 2a: CircuitLab tutorial, voltage dividers Lab 2b: meter imperfections, Thevenin equivalents lab02b video	**Jan 20** (online) Lab 3: Thevenin, scope intro, AC voltage divider lab03 video

Sunday	Tuesday	Thursday
Jan 23 Reading 2 due: AC circuits, impedance, RC	**Jan 25** Lab 4: scope probe, RC circuits	**Jan 27** Lab 5: RC integrator, RC differentiator, resonant RLC, RL & LR
Jan 30 Reading 3 due: diodes	**Feb 1** Lab 6: diodes 1	**Feb 3** Lab 7: diodes 2 1N914 ds
Feb 6 Reading 4 due: opamp intro	**Feb 8** Lab 8: opamp1: golden rules	**Feb 10** Lab 9: opamp 2 (more golden rules)
Feb 13 Reading 5 (long!): opamp imperfections & comparators	**Feb 15** Lab 10: opamp 3: imperfections	**Feb 17** Lab 11: opamp 4: comparators
Feb 20 Reading 6 due: BJT intro	**Feb 22** Lab 12: opamp 5: AM radio (fun!)	**Feb 24** Lab 13: BJT 1: emitter follower
Feb 27 Reading 7 due: push-pull, mirror, diffamp	**Mar 1** Lab 14: BJT 2: follower, common-emitter amp	**Mar 3** Lab 15: BJT 3: common-emitter amp, current source, push-pull, (switch)
(spring break)		
Mar 13 Reading 8 due: opamp	**Mar 15** Lab 16: BJT 4: diff amp, (switch) (future → circuitlab!)	**Mar 17** Lab 17: BJT 5: home-made opamp
Mar 20 Reading 9 due: PID + group audio proj	**Mar 22** Lab 18: PID controller	**Mar 24** Lab 19: group audio project
Mar 27 Reading 10 due: FETs, digital intro	**Mar 29** Lab 20: FETs	**Mar 31** Lab 21: digital intro

Sunday	Tuesday	Thursday
Apr 3 Reading 11 due: mainly arduino	**Apr 5** Lab 22: arduino 1 CircuitPython version Lab 22p	**Apr 7** Lab 23: arduino 2 CircuitPython version Lab 23p
Apr 10 Reading 12 due: logic, counters, FPGA intro	**Apr 12** Lab 24: flip flop intro	**Apr 14** Lab 25: FPGA 1
Apr 17 Reading 13 due: more FPGA/Verilog	**Apr 19** Lab 26: FPGA 2	**Apr 21** Lab 27: FPGA 3
Apr 24 Reading 14 due: FPGA, FSM *(exam period)*	**Apr 26** Lab 28: FPGA 4 **May 3** (Tuesday) final exam @ DRL A6 noon–2pm **May 10** *spring term ends*	**Apr 28** *(reading days)*

Course policies

Why take this course?

Electronic devices are all around us. A smartphone lets you walk around an unfamiliar city without fear of getting lost, of missing an important message from a friend, or of making the wrong subway connection. Somehow the phone can detect the sound of your voice, can produce both speech and music, can sense Earth's magnetic and gravitational fields, can respond to the swipe of your finger, can record and display images, can exchange radio signals with a distant cell tower, can receive and decode GPS signals from orbiting satellites, and more. Learning a bit of hands-on electronics will give you some intuition for what goes on (at least in principle, if not in detail) inside those electronic gadgets that enrich our lives. So even if you have no practical reason for doing so, spending one semester learning electronics may broaden your view of the world, and thus can be a worthwhile part of your liberal-arts education.

- How a smartphone knows up from down: https://youtu.be/KZVgKu6v808 (4 minutes)

If you work in experimental science, it is likely that some part of your research will involve instruments that turn real-world physical quantities (temperature, pressure, acceleration, light intensity, chemical concentration) into electrical signals that can be measured, recorded, or maybe used in some sort of process control (e.g. turning on and off a laser or a vacuum pump). While many labs primarily use commercial electronics modules for data collection, you may still need to amplify or filter a signal before connecting it to a commercial data-acquisition module. Or perhaps your lab's existing commercial module has a spare output that can be switched on or off under computer control, but you need to amplify that output with a circuit that can provide enough current to drive the stepper motor that moves your experiment back and forth on the tabletop. Understanding the building blocks of electronics can give you more flexibility in how you carry out experiments in your own research.

In some fields of research, experiments require huge numbers of custom-designed electronics modules. The High-Energy Physics group here at Penn has designed key parts of the readout electronics for the CDF experiment at Fermilab (e.g. discovery of top quark), the ATLAS experiment at CERN (discovery of Higgs boson), and the SNO experiment in Sudbury, Canada (resolution of solar neutrino puzzle). These experiments could not be done without teams of scientists who understand electronics (and the associated particle-detection instruments, which are also custom-designed). So knowing something about electronics can be pretty handy if you work in experimental particle physics, radio astronomy, etc.

Synopsis of course content

In the first few weeks, we will become familiar with the lab equipment as we study circuits built entirely from passive two-terminal components: resistors, capacitors, inductors, diodes, and LEDs. Then we will study opamps (operational amplifiers), which are essentially the Swiss-army-knife of analog electronics. Opamps will allow us to accomplish so many useful tasks (including mathematical "operations") that we will find them almost magical. To show off our new skills for an afternoon, we will combine these quasi-magical components into a simple home-made AM radio receiver.

Having seen how handy opamps can be, we will then learn just enough about Bipolar Junction Transistors (BJTs) to be able to see how, in principle, an opamp is implemented — and we'll test this understanding by building our own simplified opamp. We will also apply our opamp and transistor skills to make an analog P-I-D controller ("proportional, integral, derivative"), as shown in this Phys364 video.

Then we will study Field-Effect Transistors (FETs) as a segue between analog and digital electronics. From there, we will study digital logic gates and Arduino microcontrollers (tiny computers that interact with their surroundings). After seeing how handy it is to be able to program a little computer to be able to interact with the world, we will briefly study Field Programmable Gate Arrays (FPGAs) as a mechanism for building up more complicated digital circuits, such as arithmetic operations, memories, and Finite State Machines. Finally, we will see that the microprocessor that powers a computer is, in principle, just a Finite State Machine with attached memory.

In summary, we will learn to use the magic of opamps to solve useful problems in analog electronics — then learn how opamps are built up out of transistors (BJTs). Then we will build up digital logic gates out of transistors (FETs) and learn to use logic gates and tiny Arduino computers to carry out useful tasks in digital electronics — then learn how a simple computer can be built up (inside an FPGA) out of logic gates. Our hope is that this process will both leave you with useful skills and help to demystify the electronic devices that power our modern world.

Grading

- 50% — lab write-ups (work in class & submit scanned PDF on Canvas at end of each day that we meet)
  - Don't spend time at home making your lab look good. Just scan it right away to a PDF and upload it to Canvas.
  - Most labs contain some "optional/extra-credit" material, which you are not required to do. But your doing some of the optional parts of the labs will earn you "free points" (in proportion the the total number of optional lab exercises you complete) that will reduce the weight of any points that you may lose on the final exam.
  - So if you don't have time for the optional parts of the labs, don't let them worry you. But to the extent that your time and interest allow, you can use the optional lab material as insurance against possible future mistakes made on exam problems.
- 25% — in-person final exam — (date tbd)
  - Note that points earned by completing "optional/extra-credit" lab exercises (usually at the end of each lab) will proportionally reduce the weight of any mistakes you may make on the final exam.
- 15% — email/online responses to weekly reading assignments
  - Most questions will simply be to motivate you to think about the reading that you just did, and to demonstrate to me that you read it carefully.
- 10% — one (!) homework problem a week, which you will turn in with your weekly reading assignment
- up to 5% extra credit — final project, if you choose to do it
  - Main reason to do a project is if you think you'll enjoy the challenge of making your own idea work in the lab.
  - Your having done an interesting project provides me with good material if you later ask me for a letter of recommendation.

- If you finish the course with a cumulative score of 80% or more, your letter grade will be no lower than a straight B.
- If your cumulative score is 90% or more, then your letter grade will be no lower than an A–.
- If your cumulative score exceeds 100% (which requires doing some sort of final project as well as doing an excellent job on all of your regular work) you can earn an A+. Penn only counts it as 4.0, but it will still make you smile every time you see it.

Textbook

- Required text: *Basic Electronics for Scientists and Engineers*, by D. Eggleston
  - https://www.amazon.com/Electronics-Scientists-Engineers-Dennis-Eggleston/dp/0521154308
  - available in Penn bookstore and on amazon (about $55 new, about $40 used, or $33 for the Kindle edition)
  - If you prefer not to own your own textbook, our classroom (DRL 2N25) has several reserve copies that can be signed out. (Beware: we won't give you a grade for the course until you return or replace any books you borrow! But so far nobody has ever failed to return a book.)
  - We will provide the first 1 or 2 chapters on Canvas so that you have time to order your own copy of the book.
- We will supplement Eggleston's textbook with our own written notes.

Work load

- 6 hours/week in lab
  - Regular class meeting time is TR 1:45-4:45pm, in DRL 2N25. If you need more time, you can stay a bit late, you can arrive a bit early, or you can schedule extra time with us.
  - You'll turn in a scanned PDF of your written record of your lab work at the end of each class (or once you get home to your computer that evening), which will mainly consist of filling in blank spaces on the day's lab handout.
  - Your lab write-up doesn't need to be beautiful — it just needs to convince us that you did the work and honestly took the time to think about the questions posed in the lab handout.
- 2 hours/week on reading textbook/notes (due each Sunday night)
  - Includes answering some straightforward questions by email, to convince me that you've done the reading, and to let me know what we may need to supplement in class or in future weeks' reading.

- 1 hour/week on a practice problem (typically a calculation or a CircuitLab simulation based on a lab you've recently completed) to help you to assimilate each week's ideas.
- So the total weekly time commitment is about the same as that of a typical physics course, but in Physics 364 you'll spend a larger fraction of those hours in class. (We estimate that a "typical" physics course requires 3-4 hours in class plus 6-8 hours outside of class per week.)
- There will also be one in-class final exam. (No midterm exams.)
- Optional final project (for extra credit), if you wish.
  - A final project is a fun way to reinforce what you have learned, makes you a potential contender to distinguish yourself with an "A+" grade, and provides me with some excellent material to use if you later ask me for a letter of recommendation. But it is not necessary: you can fully meet our expectations simply by doing a good job on all of the *required* coursework.

Academic integrity and honesty

- The University of Pennsylvania takes academic integrity very seriously.
  - *Every member of the University community is responsible for upholding the highest standards of honesty at all times.*
  - Both gaining and helping someone else to gain unfair advantage constitute academic dishonesty: *Facilitating academic dishonesty: knowingly helping or attempting to help another violate any provision of the Code*
- As a bright and creative person, you too should take seriously the honest representation of what is and what is not your own work.
- What honesty implies for this course is that we don't want you simply to copy down other people's answers (or our answers). But we do want you to learn from your classmates, to discuss physics together, and to work cooperatively in the lab.
- On labs and on homework problems, work cooperatively, but what you turn in must be the product of your own mind's reasoning. **Copying someone else's work onto your own paper without proper attribution is never acceptable.**

Links to related courses

- Physics 364, fall 2021 (Kroll): http://www.hep.upenn.edu/Classes/Phys364_fall21/
- Physics 364, fall 2016: http://www.hep.upenn.edu/Classes/Phys364_fall16/
- Physics 364, fall 2014: http://positron.hep.upenn.edu/wja/p364/2014/

- Harvard's Physics 123: http://www.people.fas.harvard.edu/~thayes/phys123/
- Berkeley's Physics 111: http://instrumentationlab.berkeley.edu/