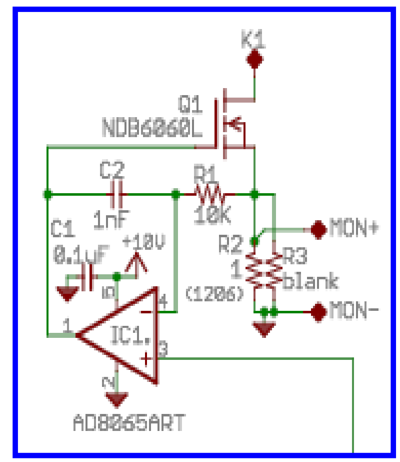
Physics 252: Electronics I
Introduction to Analog Circuits

Prerequisites: PHYS 102 or PHYS 108.

Introduction to analog electronics. Theory, design, and application of circuits using passive and active components.

… or how to understand and design circuits like these



Small print: *If you haven't had some circuits in an introductory physics course you should talk to me after class.*

Instructors

Prof. Seth Aubin

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Matthew Simons **(Tuesday section)**

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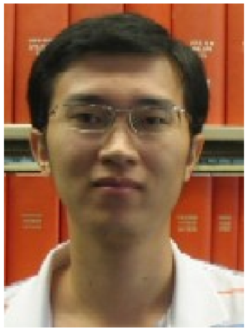


Guangzhi Qu **(Wednesday section + grading)**

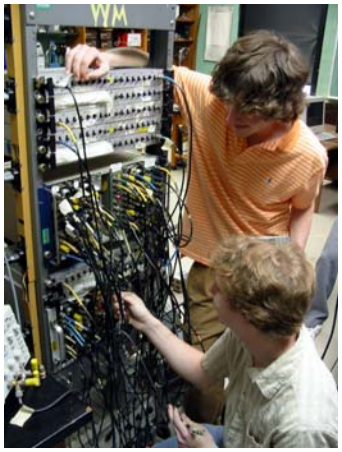
Office: room 243, tel: 1-3570

Office hours:

Friday	11am – noon (Aubin)
Monday	3:30 pm – 4:30 pm (Simons)
Thursday	3 pm – 4 pm (Qu)

Electronics Engineering

Why Electronics ?

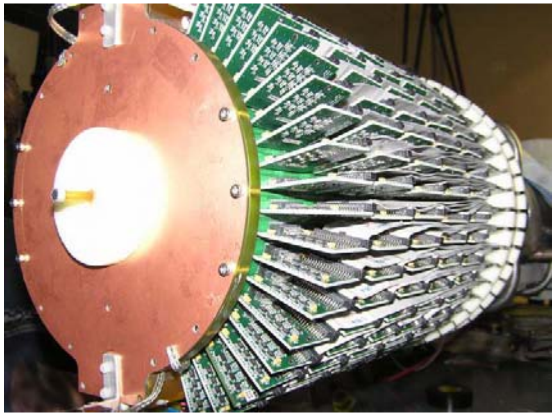


Almost all signals are acquired, transmitted, modified, and analyzed electronically.

Why Engineering?

- Experimental physicists make most of their own equipment, because it does not exist yet.

- Roughly 50% of experimental physics consists of designing, constructing, debugging, and testing an apparatus or instrument.

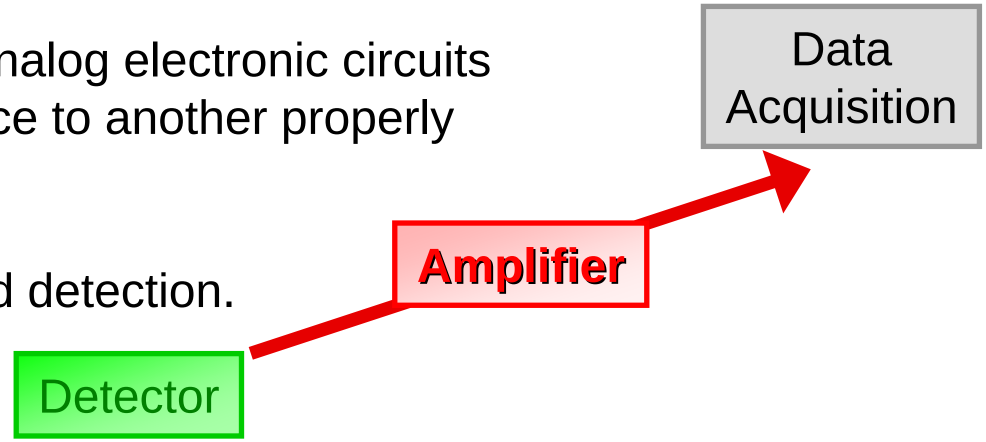


- The other 50% are spent taking data and analyzing it.

Course Objectives

Primary: Design and test basic analog electronic circuits for connecting one device to another properly and efficiently.

Secondary: Signal acquisition and detection.



Important Concepts:

- Impedance
- Amplification
- Frequency analysis
- Feedback

Important Components and Equipment:

- Resistors, capacitors, inductors.
- Diodes, photo-diodes, transistors, FETs.
- Op-amps, comparators.
- Multimeters, oscilloscopes, function generators.
- Breadboards and soldering irons.
- Modern circuit design and lay-out software.

Textbook

Posted over the weekend.

→ Read before class

Chapter 1: DC circuit basics

Overview

Electrical circuit design depends first and foremost on understanding the basic quantities used for describing electricity: Voltage, current, and power. In the simplest circuits these are related by Ohm's law. After defining and understanding these quantities, we will begin a discussion of network analysis and look at a few examples.

Voltage

Voltage (measured in volts, V) is measured between two points in a circuit. It is the amount of potential energy delivered per unit charge as a charge flows along the circuit. You measure a voltage by connecting the two terminals of a voltmeter to the two points in your circuit. You must measure the voltage while your circuit is operating. If you have a good *voltmeter* (defined in week 2), your measured voltage will be the same as the voltage was before you connected the voltmeter. A voltage decrease in the direction of current flow represents energy flowing out of the circuit (usually into heat). Voltage sources, such as batteries and power supplies, produce voltage increases along the direction of current flow.

Current

Current (measured in amperes or amps, A, which is equivalent to Coulombs/second) is measured at a single point in a circuit. It is the rate at which charge flows along the circuit. To measure a current with a *current meter* (or *ammeter*) you must break the circuit at that point and connect each end to one of the terminals of the ammeter. Current can only flow in complete circuits. That's why a switch stops an electrical circuit – it breaks the circuit and interrupts the current flow.

Power

Power (measured in Watts, W) is the rate at which electrical energy is converted into heat or some other form of energy. Since we all know that energy is conserved, a circuit needs a *power supply* or battery, which converts another form of energy into electrical energy, in order for it to operate. The power consumed is the product of the current flowing through an element times the voltage drop across the element

$$P = IV$$

Where P is the power, I is the current, and V is the voltage.

IV Characteristic

We can completely characterize any element that has two terminals by its "IV" characteristic (i.e. how much current flows through it when a given voltage is put across it?). The IV characteristic is given by the functions I(V) or V(I) and is frequently defined graphically.

Textbook

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Ground

Ground is the name given to the V=0 reference point. This makes it easier to refer to voltages, since you can generally assume that the 2nd point is ground if it is not explicitly stated. We will also use it to represent the implied completion of a circuit, even when we do not explicitly show a wire connection between different places in a circuit, since all ground connections are connected together.

Resistance

A *resistor* is a two-terminal device that converts a voltage into a current or converts a current into a voltage. The current through a resistor is always related to the voltage drop across the resistor by Ohm's Law

$$V = IR$$

where R is the resistance (measured in Ohms, Ω) This also means that a resistor generates heat when a current flows given by:

$$P = IV = I^2R = V^2/R.$$

Each of these expressions give the same answer but one or the other will be easier to use, depending on what you know about the circuit (I or V, or both).

It may seem silly to have a device that just turns electrical energy into heat, but resistors actually perform many important roles:

1. They turn electrical energy into heat. This can be useful if you want to make an electrical heater, or (more likely) a light bulb. Light is just a form of heat given off by a very hot source. Sometimes you must dissipate power somewhere. For example, if you want to deliver 100 mA current at 12 Volts to part of your circuit, but your power supply only gives you 15 Volts, then the extra power

   300mW = (100mA) (15V - 12V)

   must go somewhere. You dissipate it in a resistor rather than by heating your sensitive transistors.
2. If you have a voltage source and you want a specific amount of current then a resistor does the job. It converts a voltage difference between two points into a current flowing through the resistor. Sometimes, you will add a resistor in series in a circuit to prevent the power supply from delivering too much current in case you short the output lines together. This is called a *current limiting resistor*.
3. If you have a current flowing and you want to convert it into a voltage then a resistor is again the solution. This might seem a little more far-fetched, because you may not be familiar with constant *current sources*. When we begin studying transistors we will find that they will behave as current sources. So we will use a resistor on the output to convert the current into a voltage.

When we consider capacitors, in week three, we will generalize resistance for AC circuits by allowing for phase shifts. We will call this generalization to the complex plane *impedance*. For this week we will assume resistance and impedance to mean the same thing.

Textbook

Posted over the weekend.

→ Read before class

Network Analysis

If you connect one power supply and lots of resistors together in a complicated network, then currents will flow through all the various elements so as to insure that charge is conserved, energy is conserved, and Ohm's Law is satisfied. Simultaneously satisfying all these conditions will give you exactly one solution. We will start with two resistors and then proceed to more complicated systems. Specifically, two resistors in series will draw the same current as an equivalent resistor with resistance. This is stated mathematically as:

$$R_S = R_1 + R_2.$$

Alternatively, two resistors in parallel will draw current equivalent a resistor with resistance

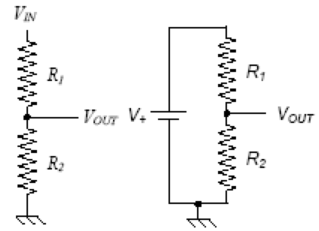
$$\frac{1}{R_{//}} = \frac{1}{R_1} + \frac{1}{R_2} \text{ or } R_{//} = \frac{R_1 R_2}{R_1 + R_2}$$

Note that the resistance of 2 resistors in parallel is always less than the smaller, but not less than half of that smaller resistance. If the two resistors differ by a large factor, then you can ignore the larger resistor. For example, a 1KΩ in parallel with 1MΩ is within 999Ω or very close to 1KΩ.

Standard resistors come in a few dozen difference ratings (more on this in lab). So in general one can get any particular value one wants. One can make up an equivalent resistor using a few resistors in series and parallel combinations to get a much larger range of options. In Design Exercise 1-1, we have you design a network to have a specific net resistance given a very limited set of resistances.

Voltage Dividers

By far, the most useful thing you can do with two resistors is to make a *voltage divider*, which is just two resistors in series. Voltage dividers are shown here schematically in two slightly different but equivalent representations. It "divides" a total voltage into two parts with each part proportional to the resistance in that leg. So, if you know the starting voltage and the target voltage, then you can calculate the required ratio of the two resistors.

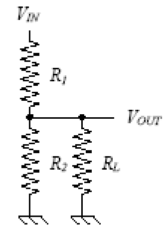


$$V_{OUT} = V_{IN}\left(\frac{R_2}{R_1 + R_2}\right)$$

In Design Exercise 1-2 you get to derive this relationship.

A Loaded Voltage Divider

Of course, the way you will use V_{OUT} from a voltage divider is to connect it to something, usually another resistor. This then changes the equivalent resistance in the lower leg, and therefore changes the voltage across that leg!



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Remember to do the Design Exercises before Lab !!!

To choose the actual resistor values, you have two competing concerns: (1) low resistance makes the divider less sensitive to loading when you use the target voltage (i.e. "stiffer"); and (2) high resistance draws less current, and therefore uses less power. We'll spend more time on this and become more formal in the coming weeks.

For now, let's just consider what happens to our voltage divider when we connect a load resistance (R_L) from its output to ground. In this case we can replace the R_2 from the expression for the unloaded divider with an equivalent resistance of R_2 and R_L in parallel. This gives us a voltage across R_L of:

$$\begin{aligned} V_{OUT,LOADED} &= V_{IN}\frac{R_{2//L}}{R_1 + R_{2//L}} \\ &= V_{IN}\left(\frac{\frac{R_L R_2}{R_L + R_2}}{R_1 + \frac{R_L R_2}{R_L + R_2}}\right) \\ &= V_{IN}\frac{R_L R_2}{R_1 R_2 + R_L R_1 + R_L R_2} \\ &= V_{IN}\frac{R_2}{R_1 + R_2}\frac{R_L}{R_{1//2} + R_L} \\ &= V_{UNLOADED}\frac{R_L}{R_{1//2} + R_L} \end{aligned}$$

where $R_{2//L}$ is the equivalent resistance of R_2 and R_L in parallel, $R_{1//2}$ is the equivalent resistance of R_1 and R_2 in parallel, and $V_{UNLOADED}$ is the output voltage of the unloaded voltage divider. From the last expression it is clear that the loaded voltage is always less that the loaded voltage. The smaller the load the larger the difference between loaded and unloaded, while large load resisters do not affect the output significantly.

So, if you want to ensure that you do not affect the output of a device, you would like to have the input of your device to look like a large resistor and the output look (in this case $R_{P1,2}$) look like a small resistance. Next week we'll show that this is a general conclusion and more formally define these concepts.

Design Exercises

Design Exercise 1-1: Use only 1kΩ resistors to create a network with an equivalent resistance of 667Ω. What is the minimum number of required resistors?

Design Exercise 1-2: Use network analysis and Ohm's Law to derive a formula for V_{OUT} for an unloaded voltage divider.

Design Exercise 1-3: Assuming that R_1, R_2 and R_L are 1kΩ resistors and V_{IN} is 10V, compute V_{OUT} for both a loaded voltage divider and an unloaded voltage divider. How much does the output voltage change when it is loaded?

Evaluation

The following components will be used to evaluate your performance this semester:

➢ Lab book	(30%)
➢ Quizzes/participation	(15%)
➢ Lab reports	(20%)
➢ Midterm	(15%)
➢ Final	(20%)

Only for guidance, actual formulation might change somewhat

Participation, enthusiasm, & "artistic simplicity" of your circuits (i.e. is it a rat's nest or can I figure out what you're trying to do?) also help to decide the actual grades

Lab book I

- In science your notebook becomes the official record of your research.
  - Record everything you do in your notebook so anyone could understand your measurement & repeat them if necessary (i.e. If you get run over by a bus).
  - Methods & results are carefully recorded in a notebook (and supplemental computer files)
  - They form the basis for later research publication
  - They would also establish your legal claim for a patent

AKA a logbook, lab journal …

Lab book II

- You do not need to take lecture notes in your lab book, though this is recommended.

- The lab book should be a bound notebook (i.e no spiral).
  - → A composition notebook (available at bookstore) or
  - → Engineering computation book (available from Staples)

- If you end up with loose papers (e.g. graphs) related to your work, you should staple or tape them into the book.

- Make sure you have it for the 2nd lab.

- Leave the first few pages blank for an updated Table of Contents.

Lab book III

What should you put in your lab book?

Write down basically everything !

- **What you did**.
  - **How you did it** (e.g. circuit diagrams).
  - How you made measurements (which test equipment and how they were connected).
  - Your **data** & enough information to tell us what that data is.
  - **What you observed**.
  - Your **calculations** (including scratch work).
  - **Plots**.
  - Answers to questions & justifications for your answers.
  - If you end up with loose papers (e.g. graphs) related to your work, you should staple or scotch tape them into the book.

Lab book IV

Completeness before neatness…

… but still well kept !!!

Due Dates

- **Lab books**

  Lab books are due by 5pm 2 days after lab & will be returned by the next lab period:

  → Thursdays for the Tuesday class
  → Fridays for the Wednesday class

- **Reports**

  - Reports are due in class (Monday) the following week

  - Late reports or logbooks will have points deducted

  - Max length of 3 pages, but less is better !

  - Important measured numbers should include an ***estimated uncertainty***.

Quizzes

- Most weeks will include a short quiz or activity based on recent topics.

- They can either be in the lab or lecture depending on the specific topic.

- Next week's will be on learning resistor codes (we'll do it in lab).

- Quizzes will be about 5 minutes long at the beginning of class/lab … don't be late!

Weekly Topics

Week 0: 1/16 **NO CLASS**

Week 1: 1/22-23 **DC Circuits Basics**
Ohm's Law, Power, network analysis, voltage divider, measurements

Week 2: 1/28-30 **Kirchhoff's Law's and Thevenin's Theorem**
Impedance Matching, Thevenin's Theorem

Week 3: 2/4-6 **Capacitors, Inductors, and Complex Impedance**
Capacitors, inductors, complex impedance, transformers, resonators

Week 4: 2/11-12 **Passive Filters and Transmission Lines**
Filters (RC, Chebychev, Butterworth, etc…), coaxial cables, AM and FM modulation, ground loops

Week 5: 2/18-20 **Diodes**
MIDTERM TEST, diodes, rectifiers, LEDs.

Week 6: 2/25-27 **Transistors 1: BJTs**
Transistors 1: BJTs, gain, amplifiers

-------------------------------- Spring Break --------------------------------

Week 7: 3/10-12 **Transistors 2: More BJTs**
Transistors 2: BJTs continued, amplifiers, FETs

Week 8: 3/17-19 **Transistors 3: FETs**
Transistors 3: FETs continued, amplifiers

Week 9: 3/24-26 **Op-Amps 1: Introduction to Op-Amps**
Op-amps 1: Golden rules of op-amps, integrated circuits, simple circuits

Week 10: 3/31-4/2 **Op-Amps 2: detectors, filters, power amplifiers**
Op-amps 2: Op-amp limitations, important circuits

Week 11: 4/7-9 **PID Control Theory**
Feedback: Control theory, PID control

Week 12: 4/14-16 **Electronic Circuit Design Tools**
Design tools (Spice and Eagle).

Week 13: 4/21-23 **Comparators**
Important complex op-amp circuits (comparators, triggers, etc …)

Week 14: 4/29 **(Tuesday, 1:30-4:30)** **FINAL EXAM**

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Resistor Examples

Standard Resistors

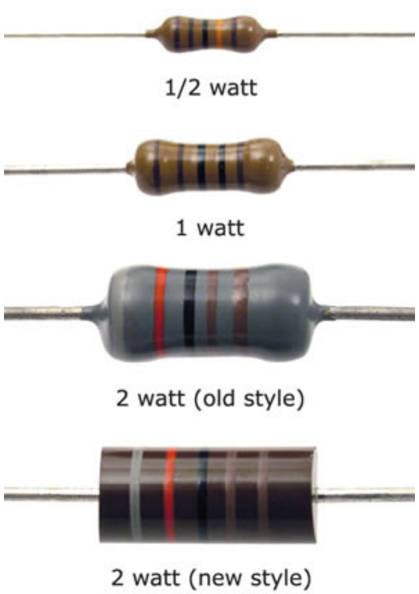


Image from
www.audionote.co.uk

Power Resistor

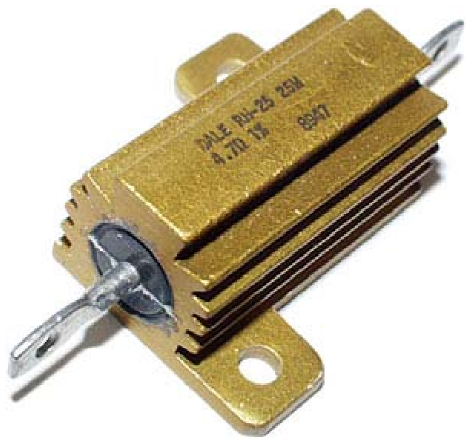


Image from
www.dansdata.com

Surface-Mount
Resistor

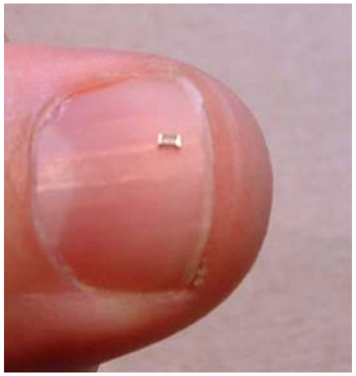
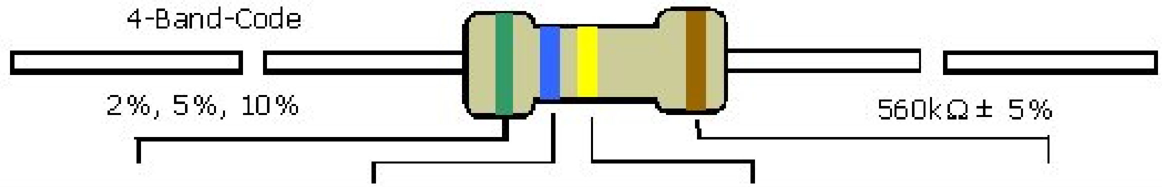
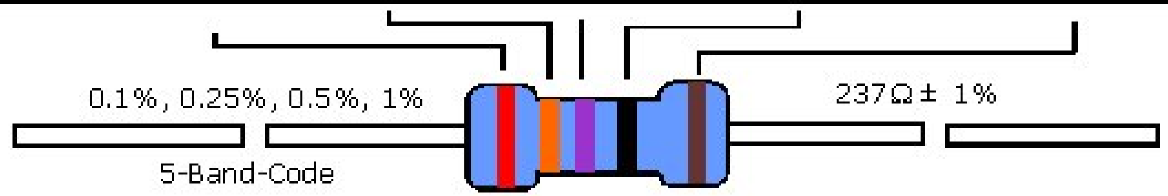


Image from
www.seed-solutions.com

Resistor Code



COLOR	1st BAND	2nd BAND	3rd BAND	MULTIPLIER	TOLERANCE	
Black	0	0	0	1Ω		
Brown	1	1	1	10Ω	± 1%	(F)
Red	2	2	2	100Ω	± 2%	(G)
Orange	3	3	3	1KΩ		
Yellow	4	4	4	10KΩ		
Green	5	5	5	100KΩ	±0.5%	(D)
Blue	6	6	6	1MΩ	±0.25%	(C)
Violet	7	7	7	10MΩ	±0.10%	(B)
Grey	8	8	8		±0.05%	
White	9	9	9			
Gold				0.1	± 5%	(J)
Silver				0.01	± 10%	(K)



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