# Electronics Segment Handout

**AST351** **Spring 2004**

## 1. Background

Before photons become numbers, they become electrons. Almost all modern detectors convert incoming photons into charge. This charge has to be held, maneuvered, and manipulated with analog electronics and then converted to digital form. You can't always buy this stuff from the store and even if you can, you can't always find somebody to repair it for you at four in the morning on top of Mont Blanc.

## 2. Goals

At the end of this segment, you should know...

(1) How to design and analyze analytically the DC and AC performance of circuits containing resistors and capacitors.

(2) How to design and analyze analytically the performance of simple circuits using operational amplifiers, including amplifiers and filters.

(3) How to implement in hardware and test the passive circuits and op-amp circuits using standard laboratory equipment.

(4) How to design and simulate the performance of circuits using the CAD program CircuitMaker.

(5) Know where to begin when you need to learn more about new kinds of circuits.

## 3. What to Do

You are encouraged to work together on any and all aspects of the assignment. The only thing you need to do on your own is to write up the problem set. You can work together to figure out the problems, but we think you'll learn more if you write up your solutions independently.

(1) Start by reading the assigned parts of Chapters 1 and 4 of the Art of Electronics. The other reading contains information that will be valuable to you in parts of this segment or in the project. Skim through it when you have finished the first part of the reading so that you will know what to find where.

(2) When you have finished the basic reading, do the problem set.

(3) Go through the On-Line tutorials for Circuit Maker and play with the program a bit. (Note: A student version of Circuit Maker is downloadable for free from www.microcode.com. You can use it to try out the assignments at home.)

(4) Become familiar with the laboratory test equipment and with the circuit breadboards.

(5) Do the laboratory/CAD exercises.

## 4. Reading Assignments

**(1) General Electronics**:
**The Art of Electronics** pp. 1-44, 175-209
**Building Scientific Apparatus** pp. 463-465 (2nd ed.), 530-537 (3rd ed.),

**(2) Electronics CAD**:
**CircuitMaker User Manual**. There are copies on the shelf in the lab. Please do not take them out of the room.

**(3) Electronics Fabrication**:
**Building Scientific Apparatus** pp. 470-490 (2nd ed.), 537-559 (3rd ed.), Identifying resistors and capacitors: 367-370 (2nd ed.), 424-430 (3rd ed.).

**The Art of Electronics** pp. 827-840, 860-61, Resistor Code: p. 1053.

**(4) Oscilloscopes**:
**The Art of Electronics** Appendix A: 1045-1049

## 5. Supplementary Material

### 5.1. Safety Tips

Working with electronics can be quite safe, as long as you use a little common sense and don't mess with anything you don't understand. First and foremost, you need to make sure you don't do anything to endanger yourself. Second, with detector chips now costing in excess of $100,000, you need to make sure that you do nothing that can damage valuable components. Here are a few tips for your own safety:

(1) Be a bad ground. Wear rubber soled shoes. When working on high voltage equipment, whenever possible, work with one hand in the apparatus and the other in your pocket (i.e. not holding onto a metal tabletop.

(2) Turn things off and unplug them before you handle their insides. Unless you absolutely need to have the circuit powered up, this step will make you more secure. Note, however, that

capacitors with high shunt resistances bleed charge very slowly, especially when the ground has been floated by unplugging. Some older high voltage power supplies (including those in old TV sets) have whomping big capacitors in them. The high voltage section of these devices can be deadly, even when unplugged.

(3) Always know what's what before you go sticking a probe someplace. Look at the circuit diagram or take time to recognize the parts of the circuit. Generally, the most dangerous part of any circuit is the 110 volt supply line. Take extra care in wiring this up and in insulating the connectors. One particularly important spot is the on-off switch where you often have exposed pins with line voltage on them.

Here are a few tips to help protect your equipment.

(1) Wear a grounding strap and work on an anti-static mat when working with static sensitive low-voltage devices, such as our detectors. These gadgets won't kill you but you may kill them.

(2) Use sharp enough probes to avoid accidental short circuits during testing.

(3) Remember that an Ohmmeter sources current. Don't use it if you are not sure what the current will do to the part of the circuit you are testing.

## 5.2. Tools of the Trade

The **digital multimeter** or **DMM** is your all-purpose testing tool. It allows you to measure DC voltages, AC voltages, currents, and resistances. If nobody in your segment group knows how to use all of the features, fool with it and look at the manual. If that's not enough, get one of us to give you a demo.

The lab is equipped with several stand-alone **DC power supplies**. These can output up to 20 V. In addition, the electronic breadboards have fixed $\pm 5$ and $\pm 12$ volt supplies. If it matters for what you are doing, don't trust the nominal supply voltage or the meter on the front of the power supply. Use the DVM to measure the output.

The lab also has an **oscilloscope**. This is your most important diagnostic tool for any kind of AC circuit. It is worth knowing how to use one properly. Read the appropriate pages in Horowitz and Hill, look at the manual, and play with the oscilloscope. One good way to do this is to use it to learn about the signal generator. One important thing to note is that oscilloscopes do not have infinite input impedance. This means that they can draw curent out of the circuits you are testing, and so can change their properties. This is most likely to occur if the resistors in your circuit are comparable to or larger than the input impedance of the scope. Take a look at the manual to find out how much of a problem this will be for the scope you are using. **Note: The oscilloscope probe is 10x, so the scope should be set to 10x when using it. For other test leads, make sure you set the scope probe setting to 1x.**

There are **signal generators** and signal generators. Ours is of the cheap variety. It will put out a range of waveforms over a range of frequencies. As a rule, it is a good idea to measure the output frequency and voltage with the oscilloscope if these quantities are important in your application.

### 5.3. Troubleshooting Electronics

You may not have to build the electronics you use. Just because other people built it, however, doesn't mean it's any more reliable than the stuff you built yourself. Here are a few hints, based on much painful experience, about where to look for the trouble in other people's equipment.

1) Note the safety hints above, both for your sake and for the sake of the equipment.

2) You never seem to have the circuit diagram when you need it. Think about what the device does and try to identify the various sub-components.

3) The most likely problem is that something is loose. In most cases, this means the edge connector on a printed circuit board or another kind of connector. With the power off, re-seat loose-feeling boards and wiggle your connectors.

4) Look around for loose wires, screws or bits of loose solder that may have shorted something. If your problem is intermittent, it is often a bad solder joint with a crack. Heating or cooling will then cause changes. Look the board over carefully. Sometimes you get lucky and spot it.

5) Dumb as this sounds, you may have blown a fuse. Check near the power supply for the on-board fuses. Do not replace fast blow with slow blow or low amperage with high. Never jumper the fuse. If you don't see any shorts, you may want to conclude that your fuse was zapped by a surge and try with a new one. If it blows, there is still a short (sorry).

6) Most of the time, when a component goes bad due to shocks or a surge, it is the first input or output amplifier. In many circuits, especially digital circuits, this is a unity-gain stage put into the circuit to protect everything else. Replace these first.

7) If you need to get going in a hurry, you are better off if you have spare boards and can swap the bad ones out.

## 6. Reference Material

Data sheets and application notes for many op-amps and other integrated circuits are available from the manufacturers. We list here some URL's for companies making op-amps:

www.datasheets.com – has got info about all kinds of boards and devices.

www.analog.com
www.burr-brown.com
www.nsc.com
www.temic.com
www.semi.harris.com
www.hp.com

There are some materials in the 3-ring binder in the lab as well. In particular, you will find pin diagrams for some of our op-amps in the binder.

## 7. Problem Set

1. I have a supply of one megohm resistors. I have a 10V battery. (a) Draw a circuit, using as few resistors as possible, that shows test points where a voltmeter would measure 0,4,6, and 10 volts. (b) How much current flows through this circuit? (c) How much power is dissipated in the stage between 4 and 6 volts?

2. A photovoltaic detector receives a high enough photon flux to cause it to generate $10^5$ electrons per second. The equivalent circuit for the detector is an ideal current source in parallel with a 10 pF capacitor. If the detector starts with zero volts across its capacitor, how long does it take the output voltage to reach one volt?

3. When the detector in problem 2 reaches one volt, we reset it by flipping a switch and allowing the charge to bleed to ground through a one megohm resistor. How long must the switch remain closed before the output voltage is reset close enough to zero (say, to less than 1mV)?

4. (a) Draw a low-pass filter using a capacitor and a resistor that produces a 1 KHz 1V sine wave at its output given a 1 KHz 10V sine wave at its input. Be sure to assign values for C and R. Show your work. (b) What would the output look like if the input had been a 1 KHz square wave ? Explain.

5. Draw an op-amp circuit with unity gain using negative feedback. Explain in words how the circuit functions.

6. Draw a circuit with a single op-amp and a switchable gain of -1,-10, or -100.

7. Draw a circuit using an op-amp and resistors and capacitors, which filters out both low and high frequencies (3db points at 200 Hz and 5 kHz) and has a gain of 100 near 1 kHz. Suppose you want your circuit to remove noise from pickup at 60 Hz. How well will it do this?

8. You have three op-amps with identical gain-bandwidth products but different noise characteristics. Suppose you are going to build a high-gain amplifier with three stages. Discuss and explain the strategy for the correct order in which to place the amplifiers in the circuit.

## 8. Laboratory Assignment

In the initial exercise below, you will first draw the circuit on paper and calculate some of its basic characteristics. You will then breadboard the circuit and test it. Finally, you will construct a model of the circuit in CircuitMaker and explore the effects of modifications to the circuit design. Once you have been through the process, you may modify it to suit your group's working style. In every case, however, you need to try at least some of the steps out in hardware. Pay close attention to how the real-world circuit's characteristics differ from those of the sim-circuit. At the end of each exercise, you should understand the workings of an ideal circuit of the type you are working with and something of the foibles of real circuits.

**Assignment:** Your group should take notes on what it does and produce a report on the outcome of your simulations and real-world tests. This report does not have to be terribly detailed, but should include at least some discussion of each of the exercises outlined below. If you work separately, get together at the end of each exercise and combine your wisdom for the report. The report should address the questions raised in each of the exercises.

### 8.1. Passive Circuits

**Design it On Paper**:
Look over the available resistors and capacitors in the lab. Using these "passive" components, design (on paper) a voltage divider that outputs 1/4 of the input DC voltage and serves as a low-pass filter with a cutoff frequency between 1 and 10 kHz, depending on which resistors and capacitors are available. Calculate the cutoff frequency and plot the response versus frequency for the device.

**Build it and Test It**:
Using one of the electronics breadboards, wire together the circuit you have drawn. Test its DC properties using the power supply on the breadboard and the DMM. Be sure to use the ohmmeter to determine the resistance of each resistor you use. Do the measurements confirm your design?

Now get out the signal generator and oscilloscope. Measure the voltage level and frequency of the input signal. For your circuit, measure the voltage gain ($V_{out}/V_{in}$) versus frequency over its interesting range and plot this quantity. Calculate the actual capacitance of the capacitor or capacitor network you are using. Does it agree with the nominal value to within the errors?

**Model It and Vary It**:
Now build the same circuit in CircuitMaker. Use a battery and the probe tool to confirm that it has the same DC characteristics as the circuit you built. Use the signal generator to replicate one of the AC measurements you made. Now use the AC analysis feature of CircuitMaker to measure the frequency response of your circuit. Does it behave like the real circuit did?

Again, using CircuitMaker, take your passive circuit and modify the parameters of some of the components. Run the DC and AC simulations and confirm that the circuit behaves as you would expect.

## 8.2. Op-Amp Circuits

**Follower**:
1. Design a fairly high impedance passive DC voltage divider (say 100 kΩ for each of the resistors). What voltage do you measure at the junction between the two resistors using the oscilloscope when you put in a 1 kHz sine wave at 1V? What does this say about the input impedance of the oscilloscope?

2. Place a smaller resistor (say 10 kΩ) across the output of your divider. What does your design say the output voltage should be, given the same input from the signal generator? What do you measure?

3. Put a unity gain op-amp amplifier circuit (Figure 4.8 of Horowitz and Hill) across the output of your original circuit. Be sure to check out the characteristics of your circuit before you use it). Place your 10 kΩ resistor across the output of your op-amp. What is the output voltage now? How do you explain the difference?

4. Play around with this basic circuit. How effectively can you buffer a high impedance input against the droop of a low impedance output? Is there another type of op-amp which might do a better job than what you are using?

**Amplifier**:
1. Start with a simple design for an inverting amplifier using an op-amp. Plan, build and test an amplifier with a gain of around 100 from DC up. At what frequency does the amplifier gain begin to decrease? Why is this? Does your CircuitMaker model do this? Play with your circuit a bit. What happens if you ground the inputs? What should happen in the ideal case? Try AC coupling the input.

**Differential Amplifier**:
Modify your circuit to accept a differential input. Evaluate, test and modify the circuit as you did for the previous amplifier. What is the point of the differential amp?

**Filters**:
Come up with a design for an op-amp circuit with a well-defined cuton and cutoff frequency. Try alternative designs in simulation. Try out at least one of them on the breadboard. Input a sine wave below the cuton frequency and above the cutoff frequency. Note how much the signal is attenuated relative to the signal in the center of the filter. Input a square wave with the same frequency as each sine wave. What does the output waveform look like? Why?

Note: If you want to learn more about filters, you should continue your reading in Horowitz and Hill through Chapter 5. Decent filter design may be an important aspect of getting your spectrometer to work well when you build it.

## 9. Deliverables

**Each Student:**
Problem Set
**Group:**
Lab Report