APPENDIX D

DISCUSSION OF ELECTRONIC INSTRUMENTS

DC POWER SUPPLIES

We will discuss these instruments one at a time, starting with the DC power supply. The simplest DC power supplies are batteries which supply an essentially constant voltage as long as the output current isn't too large. The unit of voltage is typically 1.5 V, which corresponds to the chemical potential difference of the battery active material. Battery elements can be hooked in series to supply larger voltages (N x 1.5 V) at the same current. To a good approximation a battery can be considered to be a constant voltage source in series with an internal resistance r_i (for a "D" cell $r_i = 1\ \Omega$ and a typical 12 V automobile battery has $r_i = 1\ m\Omega$) . Batteries have the property that they supply a potential difference with no reference to ground: if you ground the positive terminal, the battery supplies a negative voltage with respect to ground; that is, current flows into the negative terminal from ground through whatever resistive network you have connected between the battery and ground. Some power supplies do not have this property: they come with one of the outputs connected to ground and the other output at either $+V$ or $-V$.

The DC power supply we use in the lab provides 3 outputs: $+$, $-$, and ground. The output voltage appears between the $+$ and $-$ terminals and either one (**never both**) can be connected to ground or some other common voltage reference point. Now you need not do this, but if you are measuring voltages in a circuit with, for example, an oscilloscope you must connect the common reference point to ground since the oscilloscope measures voltages with respect to ground only! If the circuit uses only a single polarity voltage it is good practice to ground one side of the power supply by connecting either the $+$ or $-$ terminal to the ground terminal at the supply and then connect the ground of the power supply to the ground of the oscilloscope with a wire (do not rely on the ground connection made through the AC wiring!). If the circuit requires both voltage polarities, use two supplies: one with the $+$ terminal grounded, the other with the $-$ terminal grounded. The power supplies used in the lab have adjustable voltage and current controls which act as upper limits: they work the following way. If you adjust the controls to their midpoint the power supply will supply about 10 V or 1 A; that is, for currents less than 1 A the supply will furnish whatever current is required at 10 V (a constant voltage source) but above 1 A the output voltage will decrease (to 0 if necessary) to keep the current constant at 1 A (a constant current source). The maximum output voltage and current are each independently adjustable. The output resistance (the internal resistance r_i discussed above) is $\sim 1\ m\Omega$.

It is good practice to turn on the power supply before you connect it to the circuit and adjust the voltage to the desired value. The current adjustment control should normally be set to one quarter of full scale ($= 0.5$ A) when you are using the supply as a constant voltage source.

FUNCTION GENERATOR and AC LINE VOLTAGE

A function generator should be considered a variable frequency, variable voltage AC (bipolar) power supply. With the DC offset turned off the average value of the output is = 0 V, but the DC offset control can be used to adjust the average value (so that the output voltage never goes below 0 VDC, for example). The output connectors are called BNC's (bayonet connectors) and are meant to be connected to coaxial cables, although adapters are available to connect the output to banana plugs. The output impedance is typically 50 ohms. The waveforms available from function generators are typically sine, square, and triangle waves, and sometimes pulses with variable width and frequency. Some function generators provide the capability of automatically sweeping the frequency over a limited range.

Since we're talking about AC power supplies we sometimes use a 6 V transformer as a 60 Hz power supply, so a few words now about the AC that comes out of plugs in the wall. For historic reasons, this power is said to be supplied by or come from "the mains". Standard AC power in the US is 120 V_{RMS}, 60 Hz. This means we can write V(t) as V(t) = 170 V x sin(120πt). The output of a 6V transformer (actually 6.3V) is V(t) = 8.9 V x sin(l20πt), so the transformation is from 120 V_{RMS} to 6.3 V_{RMS} at 60Hz. Nov the 60Hz is really a pretty good sine wave and it really is 60 Hz to fantastic accuracy (parts in 10^7/year) but the 120V is a dream (you can easily measure 110 to 125 V depending on the time of day and year). DC power supplies often compensate for the variation in line voltage (see the specifications above). Most AC power plugs have three outputs: ground, which is in fact attached to ground and is usually connected with green wires; common or neutral, which is usually not at zero volts (but typically less than a volt or so off ground), is returned to the generator without (supposedly) touching ground, and is usually connected with white wires; and, hot, which is at nominally 170 VAC and is usually connected with black or red wires. The transformer discussed above does more than reduce the amplitude of the AC voltage: it electrically isolates the output from the input. You must never ground the common side of the AC main, but you can ground one side of the output of a transformer which electrically isolates the output from the input. Not all transformers provide isolation: variable transformers, which are often called autotransformers or Variacs (a trade name), have AC common connected to both the input and output. One last point about transformers. The 6.3 V transformer discussed above is called a step down transformer for an obvious reason. Step up transformers are used to increase the output voltage, and isolation transformers do not change the amplitude of the voltage at all, but permit you to ground one side of the output.

Most plugs on the wall provide 1 phase and neutral of AC mains power. Power companies manufacture and distribute AC power in 3 phases, each 120° out of phase from the other 2. The figure to the left below shows the 3 phases A, B, and C each connected to the neutral N by a resistor R. You can show that the current at N (which is called a summing junction) equals zero. Power companies make use of this; power is distributed to a localized area in such a way that the current in each of the 3 phases is approximately equal, so the current flowing back to the generator through the neutral is small, and as a consequence the voltage drop across the neutral is also small. Now this doesn't work if the loads are not purely resistive, but contain reactive elements like inductors and capacitors. You can read about this under the topic "power factor" in a textbook. This scheme of power manufacture has another advantage. The figure to the right below shows the resistors R connected between 2 phases. You can

show that the 2 phase voltage is approximately 208 V_{RMS}. The relationship between the voltages in the figures shown below are an example of an AC Δ-Y transformation.
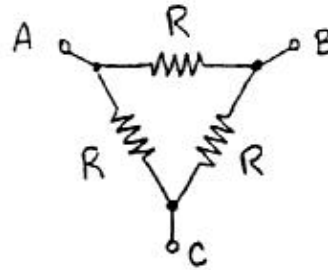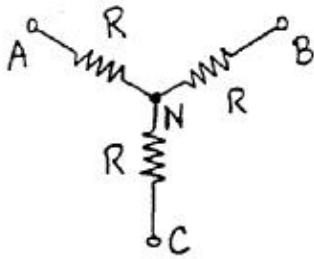
ANALOG MULTIMETERS

The next instrument to discuss is the VOM, the Volt-Ohm-Milliammeter. VOM's are now often replaced by digital meters, but they are still in common use and have some desirable features: they are noiseless and do not require power to measure voltages and currents. Some pointers on using VOM's follow.

1. To protect the meter from accidental abuse, leave it set to read the highest normal voltage scale (usually 1000 V) when not in use. If you need to transport the meter or zero the movement, set it to read the highest normal current scale (usually 500 mA).

2. Normal connection to the meter is made to the two inputs labelled COMMON and + (positive) located at the lower-left on the meter (see the specifications above). You will sometimes use the 50 µA and COM inputs to measure small currents. The label + tells you where to connect relatively positive potentials and currents.

3. Mechanical meters often change their reading when they are rotated between horizontal and vertical, so place the meter in the most convenient position for reading, disconnect all inputs, and then set the meter movement to zero using the adjustment screw located just below the meter face. If you are using the meter to measure resistance, first zero the meter movement, set the selector switch to the resistance scale you are going to use, short the COM and + input terminals with a wire, and use the resistance "zero adjust" knob to give a reading of 0 Ω.

4. Do not trust AC voltage readings below 0.2V; you will see why when we discuss diode rectifier circuits. (See the discussion on waveforms below.)

5. To understand the influence the meter has on the circuit it is being used to measure, first realize that for each different full scale setting the metering circuit has a different resistance. When measuring DC voltages, the resistance of the meter, R, is the series resistance of the meter movement r_g (typically 5 kΩ) and a "multiplier resistor" R_M and that R is given by the sensitivity times the voltage which gives full scale deflection; e.g., R = 20 kΩ/V x 10 V_{FS} =

200 kΩ. As a consequence, a VOM typically draws a current of 50 μA when it indicates a full scale voltage. The voltage read is correct to the accuracy of the meter, but the voltage across the circuit element being examined may change when the meter is removed because the meter steals current from the circuit (e.g., 20 μA when reading l V on the 2.5 V_{FS} scale).

Similarly, when you use a VOM to measure current the meter resistance R is the parallel resistance of the meter movement r_g and a "shunt resistor" R_S and that R is given by the current sensitivity divided by the current which gives full scale deflection; e.g., R = 0.25 ΩA/1 mA = 250 Ω. As a consequence, a VOM typically drops a voltage of 0.25 V when it indicates full scale current. The current read is correct to the accuracy of the meter, but the current through the circuit element being examined may change when the meter is removed because the meter steals voltage from the circuit (e.g., 0.1 V when reading 4 mA on the 10 mA scale). It is often necessary to correct a measurement for the load an analog meter presents to a circuit. You will get some practice doing this and learn ways to minimize the perturbation introduced by a measuring device.

DIGITAL MULTIMETERS

Digital Multimeters usually have a sufficiently high input impedance (e.g. 10 MΩ) that you don't need to be concerned with the current drawn when making voltage measurements. In addition, these instruments use active element rectifier circuits (using operational amplifiers) so that AC voltages smaller than about 1 mV can be measured; note that these meters only give accurate readings for frequencies below some maximum value for sine waves (see the specifications above and the discussion on waveforms, below). Some digital multimeters have the capability of measuring AC and DC currents. Typically these meters drop about 0.1 V across the input when measuring full scale current, not a big improvement over the VOM.

ELECTROMETERS

Electrometers are very useful instruments for measuring voltages while drawing almost no current (10^{-14} A at 1V) and for measuring very small currents (~ 1 pA). The voltage drop across the ammeter depends on the multiplier setting.

1. If you measure 0.5 nA on the 10^{-9} A scale with the multiplier on x1, the voltage drop across the meter is 0.5 V and the deflection is half scale.

2. If you measure 0.5 nA on the 10^{-6} A scale with the multiplier on x0.00l, the voltage drop is 5 mv and the deflection is still half scale.

MEASUREMENT OF WAVEFORMS OTHER THAN SINE WAVES

The oscilloscope is an example of an instrument that measures the amplitude of waveforms for sine wave frequencies < 100 MHz or risetimes < 5 ns. Most other instruments have a more restricted frequency range. Life is yet more complicated in that that some meters (e.g. the Keithley 175 DMM) measure the true RMS average voltage, whereas others measure some different sort of average, but may (as in the case of the Keithley 178 DMM) be calibrated so that for some particular waveform (usually sine waves) what you read is the RMS voltage. Consequently for waveforms other than sine waves it may be necessary to convert the meter reading to an understandable quantity. For some simple waveforms the conversion is straightforward. If we define V_0 to be half the peak-to-peak voltage, then the true RMS voltage for square, sine, and triangle waves is V_0, $V_0/\sqrt{2}$, and $V_0/\sqrt{3}$, respectively. So if you have waveforms with $V_0 = 7.07$ V, a meter that measures the true RMS voltage should read 7.07, 5.00, and 4.08 V_{RMS} for square, sine, and triangle waves, respectively. For meters which measure some other average, the readings depend on how the averaging is done! The table below gives actual measurements made with two different voltmeters. The waveforms all had $V_0 = 7.07$ V as measured on a Tektronix 2213A oscilloscope. All readings are in volts. This table should convince you that you must understand an instrument if you are to make use of the readings it gives. Note however that the DMM is within its guaranteed accuracy for sine waves with $f < 20$ kHz.

frequency (Hz)	sine wave		square wave		triangle wave	
	Simpson VOM	Keithley 178 DMM	Simpson VOM	Keithley 178 DMM	Simpson VOM	Keithley 178 DMM
100	4.81	4.99	7.84	7.60	3.85	4.07
1k	4.78	4.99	7.60	7.85	3.85	4.08
10k	4.80	4.97	7.58	7.80	3.85	4.08
100k	4.62	5.15	7.00	7.60	3.80	4.19
1M	3.80	1.66	7.65	2.36	3.00	1.36
True RMS	5.00		7.07		4.08	