Lab Unit 1: Measurement, Passive Filtering, and Transmission of Signals

This lab unit is devoted to the measurement, passive filtering, and transmission of signals. In Part I you will become acquainted with the various test instruments you will be using throughout the course to measure signals. In Part II of this lab unit you will use the oscilloscope to study passive RC filters – high pass, low pass, and band pass. Finally, in Part III you will measure the input and output impedance of a filter and investigate the effects of characteristic impedance on the transmission of signals.

I. TEST INSTRUMENTS

Although you probably won't fully understand how to use all of functions of the test instruments without more experience and background material, this lab will get you familiar with the most basic (and most useful) functions. While doing the activities in this section, feel free to explore and fiddle with all the various knobs and buttons so that you can learn what they all do. You can also refer to the specific manual for each instrument for details of operation. Several copies of the instrument manuals are available in the laboratory.

A. OSCILLOSCOPE AND WAVEFORM GENERATOR

The #1 rule of electronics is: **The Oscilloscope is Your Best Friend.** It is the best way to visualize the electrical signals that you will be working with. It may look daunting at first, but every oscilloscope performs the same function: to show you an electrical signal as a function of time. If you take the time to learn how to use the oscilloscope now, you will save yourself endless hours later on wondering if your measurements are good or not. Nothing can replace "seeing" the signals!

- **Inspect the various controls on the oscilloscope**. The operator's manual for the TDS 2000 series oscilloscopes will give you more information on the features of the scope.

- **Attach a P220 oscilloscope probe to Channel 1 of the scope**. Scope probes are available and are used for most measurements. These probes have a "1X" or "10X" switch that determines the attenuation of the probe. The 10X notation means that the signal is *attenuated* by a factor of 10. Connect the probe to the PROBE COMP terminal on the front of the scope. Push the AUTOSET button and verify that you see a 5 V peak to peak square wave at 1 kHz. If the square wave is distorted, adjust the probe as described in the oscilloscope user manual.

- **Inspect the various controls on the waveform generator**. Refer to the operating instructions (pages 9-10) of the Exact Model 502SL for a description of the features and function of all the knobs and buttons. Set the waveform generator to output a sine wave with a frequency of your choice. Connect a BNC with a clip lead connector to the MAIN OUTPUT.

- **Hook up the "main output" of the waveform generator to Channel 1 of the scope**. Place two small wires in separate locations on the breadboard; one is for signal and the other for ground. Attach the scope probe and the waveform generator to the wires. Adjust the vertical settings (voltage/div), the horizontal settings (time/div), and trigger settings on the scope so that you can see the sine wave.

- **Use the oscilloscope to study various waveforms from the waveform generator over a wide range of frequencies.** Observe the effect of the amplitude knob and attenuator buttons on the waveform generator.

- **Experiment with the various controls on the oscilloscope until you can use them effectively.** Vary the "source", "slope", and "level" of the trigger controls. Experiment with triggering on "AC line", "CH1" and "Ext". When using the Ext trigger, attach the SYNC OUT of the function generator to EXT TRIG of the scope. Compare internal and external triggering for a < 20 mV_{pp} signal. (You can use all three attenuator buttons to get the low signal) Note that the scope display will remain stable over a wide range of output signal levels, including virtually unobservable signals. You can look at the trigger waveform using the TRIG VIEW button. Make sure you understand the idea of "triggering".

- **Explore the difference between AC and DC input coupling on the scope inputs.** In the AC mode, a capacitor is inserted in series with the input. Apply a DC offset to the signal with the appropriate knob on the waveform generator. Try both AC and DC input coupling on the scope. When the scope is on DC input, note that there is a saturation problem when large offset voltages are combined with large time-varying output signals. Note the effect of AC and DC input coupling on the waveform for a low frequency square wave signal.

- **Measure the frequency and V_{pp} of a sine wave on the oscilloscope**. Record the relevant settings of the waveform generator in your notebook. Note the time scale and voltage scale settings on the scope. Measure the frequency and V_{pp} of the signal using the scales on the scope. Now experiment with the MEASURE function of the scope. Note the effects that the "amplitude" knob and "attenuator" buttons on the signal generator have on your measurement.

- **Use two channels of the scope to measure phase shifts.** You can use a phase shifting network as shown in Figure 1 to shift the phase of an output signal. Practice measuring phase shifts between the two signals by using two channels on the oscilloscope. It is usually easiest to compare the phase by looking at the two signals where they cross zero, rather than trying to identify the shift in their maxima. Note that the *sign* of the phase angle is important. If we have an input signal $\cos(\omega t)$, the shifted signal is at $\cos(\omega t+\phi)$. So a signal with a *positive* phase shift occurs at a slightly *earlier* time than one with no phase shift and shows up farther to the left on the oscilloscope. This is sometimes called a "leading" phase shift. A waveform that has a negative phase shift reaches its maximum further to the right on the screen and is said to be a "lagging" because it occurs later in time.

Measure the voltages and phase shifts at least three frequencies less than 1 kHz. Be sure to measure the exact frequency on the oscilloscope and not just read it from the waveform generator dial.

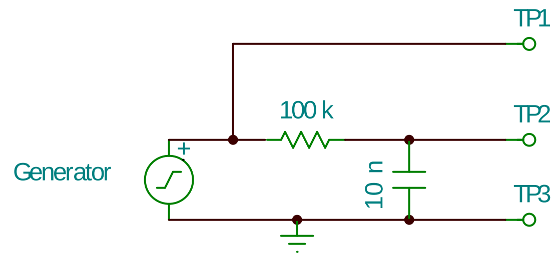

Figure 1. Phase Shifting Network

- **Learn to set a Zoom Window** The Window feature of the scope allows you to look at the same waveform at two different time scales, which is useful for zooming in to see interesting features of the waveform. **Change the capacitor of the phase shift network to 1 nF and apply a 100 Hz square wave to the circuit.** Set the time scale to capture about 5 cycles of the waveform. Use the HORIZ MENU button and switch between “Main” and “Window”. The size and location of the window is changed using the “Window Zone” in combination with the horizontal position and time scale knobs. Experiment with these controls by capturing the rising edge of the phase shifted signal. Once you capture the edge, use the MEASURE tool to determine its rise time. If you are interested**,** A more detailed way to manually make a rise time measurement is described on p 47 of the scope manual.

B. DIGITAL MULTIMETER (DMM)

- **Build the voltage divider shown in Figure 2 on your breadboard.** Measure (with the DMM) and record the resistance of each resistor before hooking it up to the circuit. Also measure the effective resistance of the R2/R3 parallel combination. You can use the +5V DC voltage from the IDL-800 Digital Lab for your voltage source.

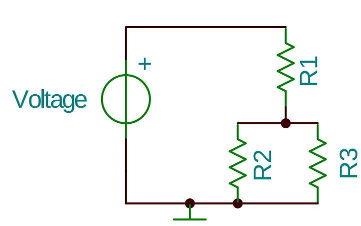

Figure 2. Voltage Divider

- **Use the DMM** to measure the voltage drop across resistors 1 and 2 and the current through resistors 1, 2 and 3. Recall that when measuring voltages the meter is placed in *parallel* with the circuit and when measuring current the meter is placed in *series* with the circuit. Confirm that your measurements are consistent with Ohm's and Kirchoff's Laws.

- **Investigate the AC and DC settings of the DMM.** Set the waveform generator to output a waveform with Vpp = 4.0 volts as viewed on the oscilloscope. Apply a 2.0 volt DC offset to the signal. Now look at the signal with the DMM set to DC and AC. Record your results and explain them.

II. CHARACTERISTICS OF PASSIVE FILTERS

One of the major challenges in electrical measurement is optimizing the signal-to-noise ratio. In many case, the signal of interest A_1 lies at one particular frequency ω_1, while the noise A_2 may be at a different frequency ω_2 or distributed over many different frequencies, ω_2. The total signal that you measure is the sum of these, $S(t) \sim A_1\cos(\omega_1 t) + A_2\cos(\omega_2 t)$. In most measurements, what matters most is the signal-to-noise ratio. While amplifying a signal will usually amplify the signal and the noise, in many cases you can improve the signal-to-noise ratio by selectively attenuating certain frequencies. Note that one important point here is that most simple electronic circuits are **linear**. For a linear system, we can take a complex signal S(t), break it up into its different frequency components (sums of sines and cosines with different amplitudes, phases, and frequencies), and then look at how the filter affects each frequency component individually. We will look at this in more detail later in the context of Fourier analysis.

The simplest way of attenuating certain frequencies is with a filter. Most common filters are made from resistors, capacitors, and possibly inductors. Inductors show up primarily in high-frequency circuits, so we will focus primarily on resistors and capacitors. Filters made from resistors, capacitors, and inductors are called **passive** filters. Later when we work with op-amps we will look at **active** filters. When constructing a filter we will usually use discrete devices called resistors and capacitors that are (reasonably) ideal. However the electrical behavior of many important physical systems (electrical double-layers, ionic solutions, monolayer films, nanowires etc) that many of you will be working with, can also be thought of in terms of resistors and capacitors. Understanding the behavior of circuits containing both resistors and capacitors is also important for many instruments, not only because of the use of these components for low- and high-pass filters, but also because there are capacitances present even in circuits that do not contain capacitors.

In general, we can characterize the property of any circuit component using four parameters. These are:

a) **Transfer Function**: The transfer function tells the magnitude of the output signal divided by the size of the input signal. $T>1$ implies amplification, $T<1$ implies attenuation, and T is usually a function of frequency.

$$T = \frac{\text{RMS Output Voltage}}{\text{RMS Input Voltage}}.$$

b) **Phase shift**: For a sinusoidal input, the phase shift is a measure of how much the output signal leads or lags the input signal.

c) **Input impedance**: The input impedance is measured in ohms. It gives an indication of how much current is drawn by the inputs to a circuit. Lower input impedances will draw more current.

d) **Output impedance:** Output impedance is also measured in ohms. It gives an indication of how much the output voltage changes when the output is connected to something else. When you connect two electronic "modules" together, you will want to know the output impedance of the first device and the input impedance of the second device.

In this next part of the lab, you will look at the transfer functions and phase shifts of several different passive filters. Later in this lab, you will study input and output impedances of these filters. You will also investigate another type of impedance that is often critical in measurements – the "characteristic impedance". The characteristics impedance tends to be a property of cables, transmission lines, and other things that are used to connect different circuit components together.

A. LOW-PASS FILTERS

A resistor placed in series with a capacitor as shown in Figure 3 is a simple low-pass filter. The phase shifter circuit in Figure 1 is also a low pass filter. Low pass filters are often used to remove high-frequency noise in electrical measurements. The input is applied to the circuit and the response is monitored across the capacitor. For low-frequency input signals the output will be close in magnitude and phase to the input signal; for high-frequency signals the output will be attenuated and shifted in phase. For a complex input signal, the low-frequency signals are "passed" through, while the high-frequency components are attenuated.

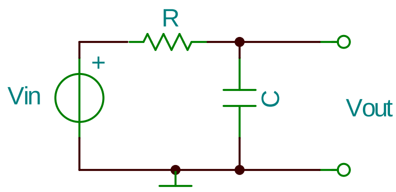

Figure 3. Low Pass Filter

- Examine quantitatively the response characteristics of a low-pass RC filter by constructing the filter with a a 1000 Ω resistor with a 0.1μF ceramic capacitor. Make sure you measure the values of the resistance and capacitance. Make measurements of the input and output signal amplitudes and relative phase at as many frequencies as are necessary to quantitatively demonstrate the filter characteristics. Try to choose values covering at least 6 orders of magnitude in frequency; choosing values 10x different in frequency is usually good. Be sure to write down these numbers (including the frequency as measured on the oscilloscope), as you will need them in your report. Try to accurately identify at what input frequency you see a phase shift of 45 degrees. This is often the easiest way to identify the characteristic "cut-off" frequency of the filter. Again, be sure to write down this number, as you will need it later.

- Finally, look briefly at how the behavior of the filter is changed when it is “loaded” by a 100 Ω resistor and then by 10 kΩ. Does the loading change the cutoff frequency significantly?

B. HIGH-PASS FILTERS

The high-pass filter looks similar to the low-pass filter, but with the position of resistor and capacitor reversed. In the high-pass filter the output is measured across the resistor instead of across the capacitor. The high-pass filter is often used to remove low-frequency (and DC) voltages. Here, high frequencies are "passed" without change in amplitude or phase, while the low frequencies are attenuated and shifted in phase. The capacitor in this circuit is also called a "blocking" capacitor because it blocks any DC voltage at the input from being passed to the output.

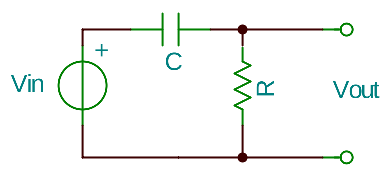

Figure 4. High Pass Filter

- Examine quantitatively the response characteristics of a high-pass RC filter. Use a 1000 Ω resistor with a 0.1 μF ceramic capacitor. Make sure you measure the values of the resistor and capacitor. Make measurements of the input and output signal amplitudes and relative phase at as many different frequencies as are necessary to quantitatively demonstrate the filter characteristics, and try to identify at what input frequency you see a phase shift of 45 degrees. This will determine the characteristic "cut-off" frequency of the filter. Also study the filter loaded by 100 ohms and compare results to the unloaded case. Do the cutoff frequency and peak output voltage change? Compare the measured filter characteristics with your quantitative theoretical predictions.

➢ Remove the load and look at the shape of the output when square and triangle waves covering the same frequency range as above are applied to the circuit. Sketch both input and output waveforms in your notebook above, below, and at the cut-off frequency. Explain your observations, paying particular attention to the relationship of the curve shape to the period of the waveform and the time constant of the filter.

C. BANDPASS FILTERS

After having gone through the exercises above, it is reasonable to assume that a bandpass filter can be created by combining a high-pass and a low-pass filter so that the circuit passes a band of frequencies. This can in fact be done, but the form of the response function depends on the manner in which the high-pass and low-pass filters are cascaded. You have already seen that adding loads to the filters changes their cutoff frequencies and output voltages. Cascading two filters usually adds a load to the first filter, so we need to consider the effect of loading to predict the properties of a bandpass filter.

Figure 5 shows two ways of creating a bandpass filter. The figure on the left is a low-pass filter followed by a high-pass filter; on the right is a high-pass followed by a low-pass. Even if we restrict ourselves to keeping the same RC time constant for both parts of the filter, there are many possible combinations of R and C which we can use. You will look at just one of the possibilities.

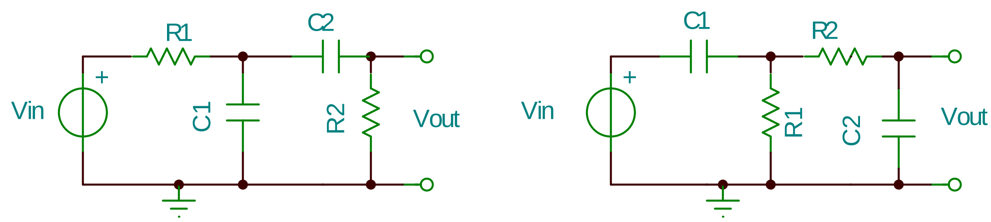

Figure 5. Band Pass Filters

➢ Set up one of the bandpass filters shown above, using R_1 = 1 kΩ, C_1 = 0.1 μF, R_2 = 100 kΩ, and C_2 = 0.001 μF. First find the center of the bandpass, where the relative phase of the output is 0°. Then measure the response function for your filter and compare this with your theoretically predicted filter behavior (magnitude and phase). Also, note the full-width-at-half-maximum (FWHM) of your filter. Determine the upper frequency limit by measuring the magnitude of the output voltage at the center of the bandpass and increasing the frequency until the magnitude is reduced to 0.707 of the maximum. The lower frequency limit is determined the same way, except you decrease the frequency. The FWHM is the difference in these frequency limits.

III. MEASUREMENT OF INPUT, OUTPUT, AND CHARACTERISTIC IMPEDANCES

In addition to the transfer function, every electronic circuit (such as your filters) is characterized by two more parameters: output impedance, Z_o, and input impedance, Z_i. Here, you will look at the output and input impedance of the high-pass filter you studied earlier. You will then look at characteristic impedance of a transmission line.

A. OUTPUT IMPEDANCE

The output impedance Z_o is usually assumed to appear in the instrument as shown in Figure 6. At low enough frequencies, the output impedance will be dominated by the resistor R. At higher frequencies, the inductor and capacitor will become important.

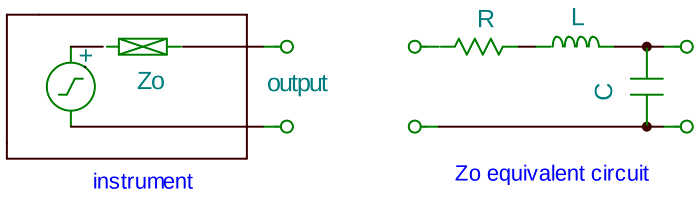

Figure 6. Output Impedance

- Set up a high-pass filter using a 1000 Ω resistor and a 0.1 µF ceramic capacitor. Connect up the waveform generator to the input and look at the output on the oscilloscope. Set the waveform generator to some reasonably low frequency (maybe 100 Hz or so) and measure the output amplitude on the oscilloscope. Next, insert a decade resistor box in parallel with the oscilloscope as shown in Figure 7, and adjust the resistance until the signal magnitude has declined to exactly half the original value. The resistance necessary to cut the signal in half is output impedance. Repeat this at a couple other frequencies above and below the cutoff frequency of the filter.

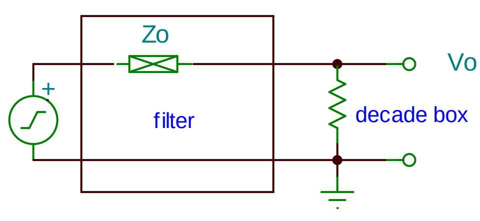

Figure 7. Measurement of Output Impedance

B. INPUT IMPEDANCE

Now, you will measure the input impedance. The input impedance of any instrument or circuit, Z_i, can be represented as shown in Figure 8.

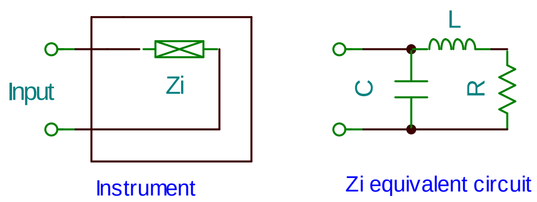

Figure 8. Input Impedance

- To measure the input impedance, connect the waveform generator to your high-pass filter, putting a decade resistor box in series with the waveform generator (Figure 9). Connect the oscilloscope to the circuit so that you measure the total voltage (channel 1) and the voltage across the filter input (channel 2). Start with a very small value of resistance, and then increase this resistance until the signal on channel 2 is half the value of channel 1. At this point, the voltage drop across the resistor and the filter (Z_i) are the same, so their impedances are also the same. Note that we have made an approximation here that voltage and current are in phase with one another; this can cause an error of as much as $\sqrt{2}$ in the value determined in this way. However, for now this is good enough.

  Again, measure the impedance at a few values above and below the cutoff frequency of the filter. Choose values about a factor of 10 apart in frequency and try to cover ~6 orders of magnitude in frequency.

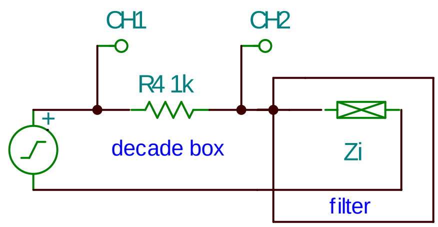

Figure 9. Measurement of input impedance

C. CHARACTERISTIC IMPEDANCE

In addition to input impedance and output impedance, there is a third kind of impedance that you need to know about: this is the *characteristic* impedance, or sometimes called the "transmission line impedance". While the input and output impedances are properties of individual instrument components, the characteristic impedance is usually used to describe the properties of the *cables* that we use to connect the individual modules together.

When connecting two instruments together, we typically use some type of cable or wiring. Especially at high frequencies, these can also affect the measurement. The characteristic impedance of a transmission line tells us what happens to a high-frequency or a pulsed signal that is propagating from one instrument to another through the cable. Most cables and connecting wires can be though of in terms of their inductance and capacitance. Both the capacitance and inductance both change the relationship between current and voltage, so that the cable introduces a phase shift. For the transmission line, we think about what happens to a signal that is propagating down the cable. When the signal gets to the end of the cable, it will tend to generate a reflection back. For a sinusoidal signal, this generates standing waves in the cable. The situation is exactly analogous to light passing from one medium to another having a different index of refraction. If the indices of refraction are different, then a reflection is generated. The sign of the reflection (i.e., if the reflected wave has the same sign or the opposite sign as that at of the incoming wave) depends on whether the index of refraction increases or decreases. The situation with electrical signals is identical: when a signal encounters a change in the characteristic impedance, it generates a reflection.

- To see the effect, use the nanosecond pulse generator to launch a short pulse down a coaxial cable. The cable should be at least 10 feet long to see this easily on our oscilloscopes. Use a "tee" to split the pulse out so that it goes to the scope and to the long cable. You can then put a resistor at the end, between the central conductor and the "shield" of the cable, as shown in Figure 10.

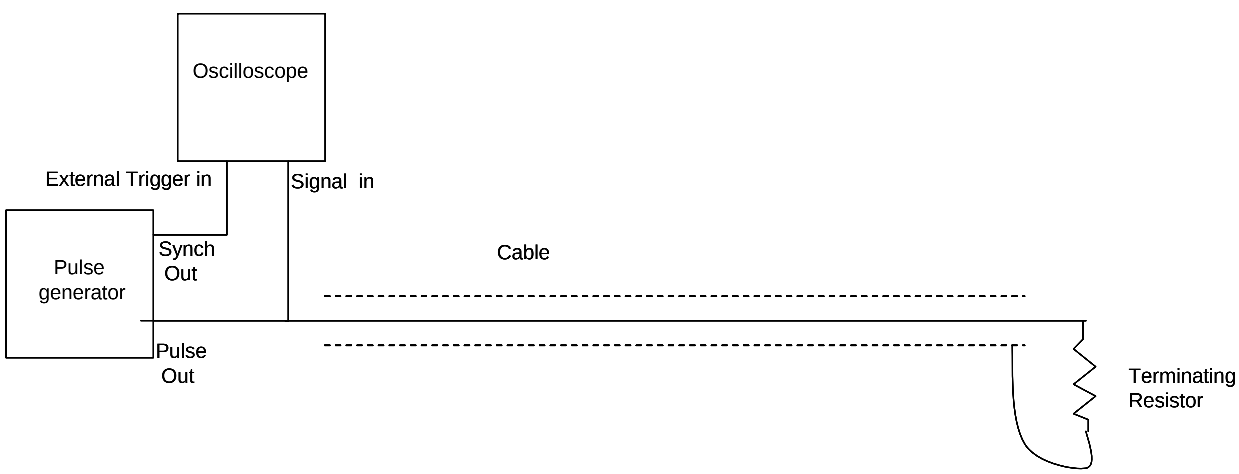

Figure 10. Setup for viewing pulses

In electronics jargon, you are "terminating the cable with an xx-ohm load". Set up the scope so that it triggers from the rising edge of the "synch out" from the pulser board. If everything is adjusted properly, you should now see a short pulse (~10 nanoseconds wide) on the scope, and you will also see some "ringing" around it. Your result might look something like the graph in Figure 11.

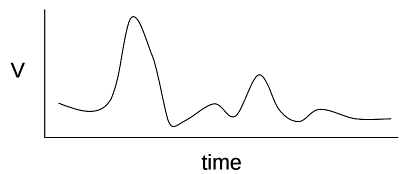

Figure 11. Pulse with ringing

- Now, connect different values of resistance to the far end of the cable. Try values of 0 ohms (completely shorted cable), high values, and something close to 50 ohms. How does the reflected signal change as you change the value of the terminating resistor? You should be able to see that the reflected signal has one sign when the terminating resistance is large, it should flip upside down when the terminating resistance is small, and the reflection should vanish (leaving you with a nice clean pulse on the oscilloscope) when the terminating resistance is close to 50 ohms. In this case, 50 ohms is the characteristic impedance of the cable. By definition, the characteristic impedance of a cable means that if we terminate the cable in that value of resistance, no reflections will be generated. Matching the impedance of a cable to the value of a resistor on either end is called "impedance-matching". An important property of impedance matching is that it also corresponds to the condition where the maximum power is transferred down the cable.

- Now, try using a longer cable. Measure the round-trip time for an electrical signal passing down the cable and back. Based on this, calculate the speed of the signal going down the cable.

LAB REPORT

Each person will submit their own informal lab report. When you have completed the activities, ask for the Report Sheet. The Report Sheet (actually several sheets), will contain questions for you to answer and tables to fill in based on your results. Many of the questions can be answered right on the report sheet you will be given. A few will require a separate sheet and you will need to attach any relevant plots and sketches. Much of what is asked for in the report should already be written in your lab notebook and you will be able to pull results from there. The summaries and questions in the report are intended to help solidify your understanding of what you did in lab.