1. **Voltage Divider** Select two resistors, with \( R_1 \) approximately equal to \( 2 R_2 \). Use resistors in the 500 Ohm to 10Kohm range. Build a “voltage divider” as shown below. See also Appendix B for notes on the drawing convention used.

![Voltage Divider Diagram]

a) Make a table and record \( V_{out} \) for 3 values of \( V_{in} \). What is the ratio? What did you expect?

b) Hook your function generator up to supply \( V_{in} \) to your voltage divider. Look at \( V_{in} \) and \( V_{out} \) simultaneously on Ch1 and Ch2 of the oscilloscope, driving the circuit with a 1Khz sine wave. Graph what you see and interpret it.

2. **Low-pass filter** Construct the circuit below, using approximately \( R_1 = 10 \) Kohm, \( C_1 = 0.01 \) uF. (Record the actual values you use in your lab book).

![Low-pass Filter Diagram]

a. Driving the circuit with an input (\( V_{in} \)) sine wave, scan in frequency from very low frequency to very high frequency, and qualitatively describe the behavior. Why is this called a “low pass filter”?

b. For a sinusoidal frequency \( \omega \), write down an expression for \( V_{out}/V_{in} \). Calculate the “3dB” frequency of the low-pass filter – this is the frequency for which \( V_{out}/V_{in} = 1/\sqrt{2} \) (See Appendix C). Verify this by direct measurement. (Remember that \( \omega = 2\pi f \).)
c. **Record the amplitudes of** $V_{in}$, $V_{out}$ **of these waves at different frequencies.** Include several measurements near the transition frequency, as well as at least one frequency well above and well below the transition.

d. **In what frequency limit does the phase shift** $\phi$ **approach zero degrees? 90 degrees?** Note that the phase angle is calculated as the $360^\circ$ times the time shift divided by the wave period.

3. **Integrator** Using the same circuit (and same values of $R_I$ and $C_1$) as #2, Drive $V_{in}$ with a 500Hz square wave and **graph the input and output.** What is happening?

Increase the frequency until the output looks like a triangle wave. (Graph $V_{in}$ and $V_{out}$ of course.) The circuit is now acting like an “integrator”; **explain how this works.**

Drive it with a triangle wave at the same high frequency, and **graph the results.** Given your knowledge of calculus, **what is the mathematical form of the output?**

4. **High-pass filter** Construct the circuit below, using approximately $R_I = 10$Kohm, $C_1 = 0.01$uF. (Record the actual values you use in your lab book). **Write down an expression for** $V_{out}/V_{in}$. **Calculate the “3dB point” of this filter,** and then send sine waves into $V_{in}$, and vary the input frequency from well above to well below the filter transition. **Record the amplitude of** $V_{out}$ **for values where** $V_{out}$ **is approximately equal to** $V_{in}$, and then a few values down to where $V_{out}$ **is about 0.1** $V_{in}$. **Find the frequency at which** $(V_{out}/V_{in}) = 0.7 = 1/\sqrt{2}$; **does it agree with your calculation from component values?**

5. **Differentiator.** Using the same circuit architecture as #4, change to $C_1 = 100$pF and $R_I = 100$ Ohms or so. Drive this (and **record the waveforms and explain the output**) with

   a. a 100 KHz square wave
   b. a 100 KHz triangle wave
   c. a 100 KHz sine wave
Appendix A. A note on $f$, $T$, $\omega$, and $\tau$.

For a capacitor, $V=Q/C$, but we usually need the current $I=dQ/dt$. With all signals sinusoidal, we write:

\[
\begin{align*}
V &= V_0 e^{i\omega t} \\
I &= I_0 e^{i\omega t} \\
Q &= Q_0 e^{i\omega t}
\end{align*}
\]

where $V_0$, $I_0$, etc., are constants. Then we have, simply, $I=i\omega Q$, $dV/dT=i\omega V_0$, etc., and the circuit can be readily analyzed algebraically. Note that, mathematically, $\omega$ is introduced as an arbitrary constant, but it has a definite interpretation: the period of the sinusoid, $T$, is defined by the condition that all signals are the same at times $t$ and $t+T$. This requires $\omega T = 2\pi$. The frequency is defined as $1/T$, so $\omega = 2\pi f$, and we call $\omega$ the angular frequency. Note that $\omega$ and $f$ differ by a factor of $2\pi \approx 6$.

The transient behavior of many circuits involves some combination of $R$, $C$ and $L$ forming a time constant $\tau$, that governs an exponential decay or rise. For example, in an RC circuit, we often have terms $e^{-t/(RC)} = e^{-t/\tau}$ where $\tau=RC$. This time constant $\tau$, will be a rise or fall time if the circuit is pulsed. Thus, in an RC circuit where the characteristic (“3 dB”) frequency is given by $f_o=\omega_0/(2\pi)=1/(2\pi RC)$, the rise or fall time is given by $\tau=1/(RC)$. Note that $\tau$ is $2\pi$ times faster than $T=1/f_o$. For example, a signal with a very fast rising edge, put through a low-pass filter with a 3db point of $f_0=1\text{MHz}$ will emerge with a rise time rolled-off to $\tau \sim 160 \text{nsec} \leftrightarrow 1/(6.2 \text{MHz})$. 
Appendix B. Comments on circuit diagram conventions

In the above circuits, we use a common type of circuit drawing convention where the input and output are represented as simple lines running into and out of the circuit, and one or more grounded points are represented by triangles. This might be confusing – all valid circuits must have a loop. Where are the loops above?

Here we redraw the first circuit in this lab. Note two things: (1) The input voltage is created by some device, generically thought of as a “voltage source” that outputs a voltage relative to some ground, and similarly the output is measured relative to ground by some device (scope or DMM). (2) In terms of a set of loops, the various “local” grounds of the circuit should be tied together, and then the overall ground tied at one point to a true “Earth” ground which is often plumbing, or a rod driven into the ground. The Earth ground symbol is different that the triangles representing a local ground. The circuit shown is the ideal case where there is only one Earth ground. A single Earth ground is required to get the lowest levels of noise, but is usually not attained in simple practice. For instance, the output shield on the BNC from most function generators is connected to Earth ground via the power cord for the function generator. However most scopes have a “floating” input shield. In any case, it is important for the experimenter to establish an explicit ground connection in the circuit.

This circuit is often drawn as:

Here we see three separate local grounds. It is implied that these are tied together, and that ultimately these are connected to Earth ground. In practice in this lab, this means you must connect the breadboard circuit ground to the BNC shields, which tie together the shields or grounds of the various instruments. Since we are not terribly concerned about noise, it is ok that
such a circuit can have multiple Earth ground connections. The circuits in the writeup above are like this second drawing, but omit the local grounds at the instruments.

Appendix C: decibels and 3dB

For two signals with powers $P_1$ and $P_2$, or voltages $V_1$ and $V_2$, where $P \sim V^2$, the difference between the signals is described in decibels as:

$$dB = 10 \log_{10} \left( \frac{P_1}{P_2} \right) = 20 \log_{10} \left( \frac{V_1}{V_2} \right)$$

Note that we often encounter electronics circuits with a “single pole” transfer function of the form:

$$\frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{1 + \left( \frac{f}{f_o} \right)^2}}$$

In this case, with $f = f_0$, $V_{out}/V_{in} = 1/\sqrt{2}$, which, from the above formula, gives $dB = -3$ decibels, thus the condition $f = f_0$ is often referred to as the 3 dB point.