PRINCETON UNIVERSITY   **PHYSICS 104 LAB**
Physics Department   **Week #7**

EXPERIMENT VI
OSCILLOSCOPE, SIGNAL GENERATOR AND FILTERS

Introduction. Work in any electronics lab relies heavily on the use of the digital multi-meter (DMM), the oscilloscope, and the signal generator. You have already gained some experience with the DMM; this week we want you become familiar the oscilloscope and the signal generator. In most cases, the best way to become proficient in the use of an instrument is to: 1) understand its basic principles, 2) break these down (in your mind) into functional units, and 3) hack. You should work in pairs, so that everyone gets a chance to be the knob twister. If you merely watch most of the time, you won't get it.

Basic Principles of the oscilloscope. The sketch below shows a block diagram of an analog oscilloscope. The cathode-ray tube (CRT) is the central element. It's very similar to the one in a TV set or a computer monitor. The electron gun forms a narrow beam of electrons which passes through two sets of deflection plates on its way to a phosphorescent screen. The screen emits light where the beam hits. The horizontal and vertical amplifiers apply voltages to the deflection plates. The resulting **E** fields from these voltages deflect the beam to any position on the screen. Thus, a saw-tooth voltage on the horizontal plates causes the spot to sweep at a constant speed from left to right across the screen making the horizontal position proportional to time. If simultaneously there is a vertical voltage of (say) $V_0 \sin(2\pi t/T)$, a sine wave will be drawn on the screen. But there's a catch. Unless the saw-tooth and the sine voltage are *synchronized*, successive wave forms will not be superimposed on the screen. That's the job of the trigger (time base) circuit. When on "internal" (which yours will always be on), it starts each saw-tooth sweep at the same voltage level of the vertical signal, thus the two are synched and the pattern on the screen is stationary.

Oscilloscope cut-away box drawing

2
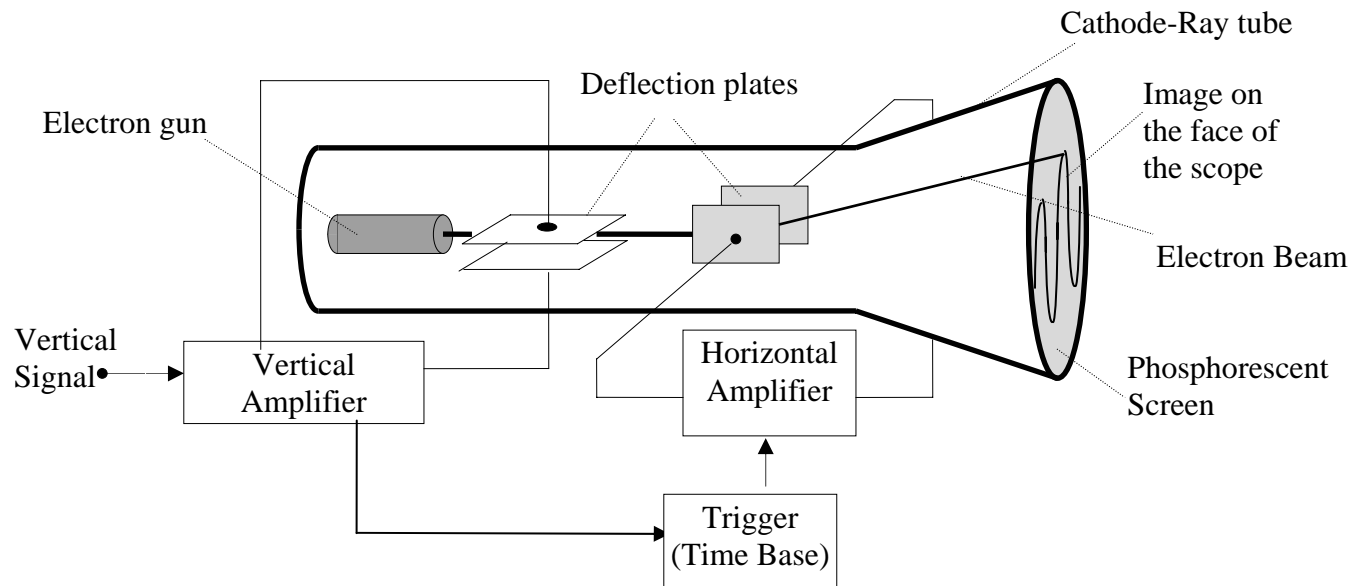
Oscilloscope Operation. If you haven't used a scope before, don't be dismayed by the density of knobs and switches on the front. Most of the time you only use a few. Ignore the rest of the controls which have been preset. You can divide the face of the oscilloscope into three functional sections, as marked on the scope. Looking from left to right there are the VERTICAL, HORIZONTAL, and TRIGGER controls. Below you will find some drawings for these sections which include ONLY the controls that you will use. You will be using a Tektronix model 2225 oscilloscope.
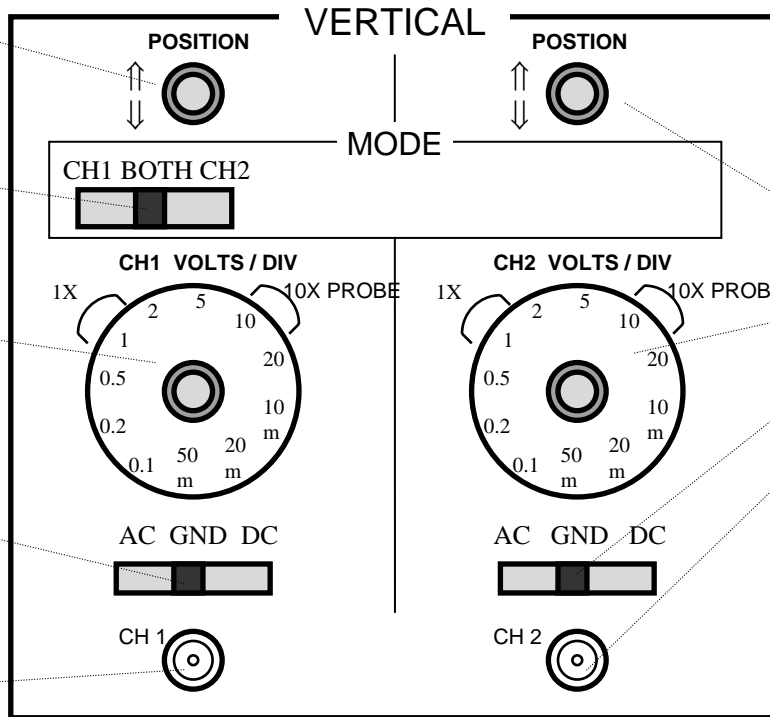
Moves CH(annel) 1 Trace up and down the screen.

This lets you look at CH 1, CH 2 or both.

Adjusts the vertical scale of CH 1 (in Volts).

Sets the CH 1 input to look at AC only, AC and DC together, or grounds it.

Input to CH 1

VERTICAL

POSITION

POSTION

MODE

CH1 BOTH CH2

CH1 VOLTS / DIV

1X   10X PROBE
  2   5
1   10
0.5   20
0.2   10 m
0.1   50 20
      m m

AC GND DC

CH 1

CH2 VOLTS / DIV

1X   10X PROBE
  2   5
1   10
0.5   20
0.2   10 m
0.1   50 20
      m m

AC GND DC

CH 2

These controls do the same things for CH 2.

HORIZONTAL

⇐ POSITION ⇒

COARSE   FINE

SEC / DIV

ms
10 5 2 1 .5 .2
.20   .1
50   50
           20 μs
.1   10
.2   5
sec .5   .5 1 2
     xy

Move the trace left and right on the screen

Adjusts the horizontal scale of both channels (in seconds)

TRIGGER

MODE

P-P
Auto

SOURCE

CH1
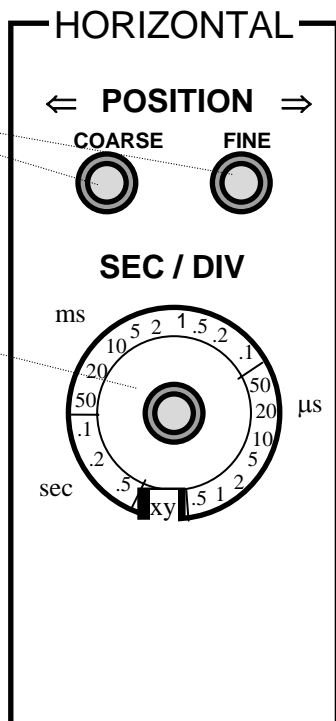
When on P-P Auto the signal triggers automatically

When on CH1, the scope is triggered using the timing of the signal inputted to CH1
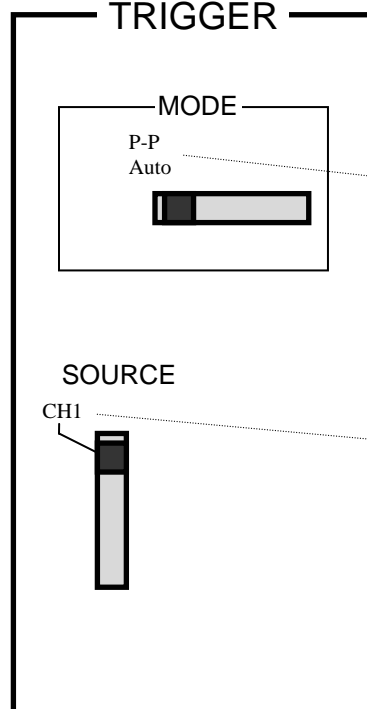
Take some time and study the figures on p. 2 and familiarize yourself with the functions of the oscilloscope.

Basic Principles of the Signal Generator. You will be using a Wavetek model 19 signal generator. The signal generator can produce periodic signals of varying frequency, amplitude, and shape.

FREQUENCY RANGE Hz menu on the panel of the generator allows you to choose the frequency range for the output signal.

FUNCTION menu lets you choose the shape of the wave you wish to generate.

FREQUENCY (START) knob on the left of the panel can be used to vary the frequency from zero to the maximum of the selected range. (i.e. if you have chosen the 2k button on the FREQ. RANGE menu, you can use the large knob to generate waves from zero hertz to 2000 hertz).

AMPLITUDE knob allows you to vary the peak to peak voltage of the output wave signal. The maximum output of the generator is 20 p-p volts.

DC OFFSET knob can be used to introduce a DC level on 'top' of which the AC signal is generated.

DISPLAY SELECT button switches the display between frequency, output voltage, and DC offset.

MAIN OUT connector on the front panel is the output of the generator.

You will not be using any of the other knobs or controls on the panel. The figure below shows all the knobs and the buttons you need to be familiar with in order to effectively use the generator.
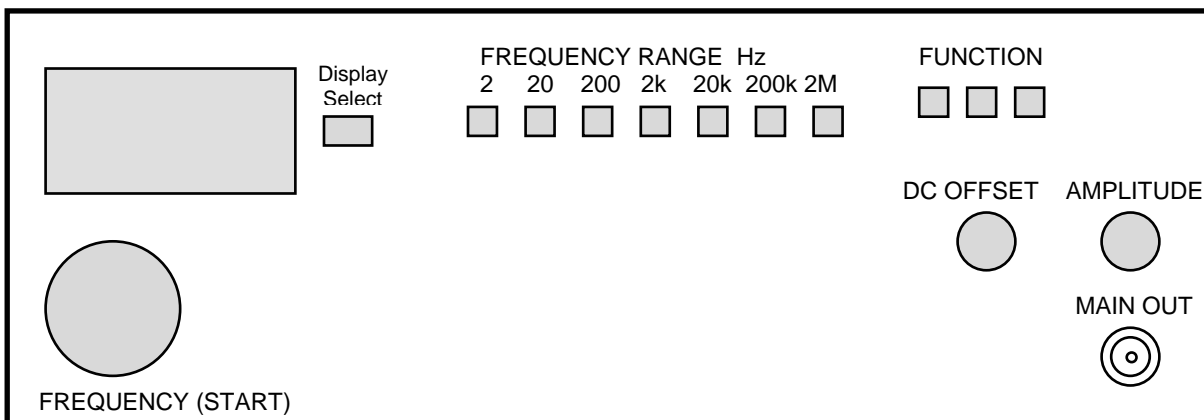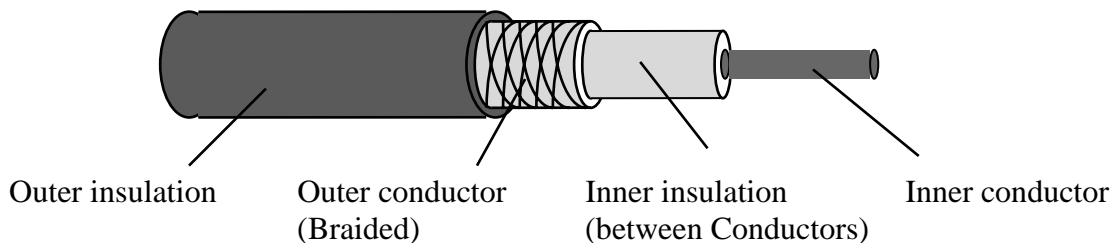

Become familiar with the signal generator. Connect the MAIN OUT of the generator to CH1 of the scope using a coaxial cable with twist-on "BNC" connectors. Generate the following signals with the signal generator and then use the scope to observe the frequency, the peak-to-peak voltage, and the DC level for each waveform.

Briefly note this activity in your lab notebook, and move on to experiments 1-6, which are the primary content of this Lab.

Wave Shape	Signal Frequency	Signal Peak-to-peak voltage	Signal DC level
Sinusoidal	1000 Hz (1 KHz)	1 Volt	0 Volt
Sinusoidal	1000000 Hz (1MHz)	5 Volts	+1 Volt
Triangular	50000 Hz (50 KHz)	2.5 Volts	-2 Volts
Square	20000 Hz (20 KHz)	10 Volts	0 Volts

Coaxial cables. As a sidebar, consider the cables you are using for this experiment. They are called coaxial cables, and they contain two coaxial conductors (hence the name). The center (or inner) conductor carries the signal and the outer conductor is typically connected to ground at one or both ends of the cable. The drawing below shows a cross section of a coaxial cable. When the outer conductor is connected to an external ground, the inner conductor is "shielded" from electric and magnetic effects due to sources outside your circuit. This is in contrast to connections via a pair of wire that form a loop, through which external magnetic fields may be changing, in which cause additional voltages will be induced in your circuit that may confuse your measurements. Properly grounded coaxial cables are immune to this type of "interference".

Outer insulation   Outer conductor   Inner insulation   Inner conductor
(Braided)   (between Conductors)

1. The Black Box. After you have spent some time with the signal generator and have become familiar with the scope, turn off the generator and disconnect it from the scope. Next turn on the Black Box. There are 12 BNC connectors on the front panel, each with a different output signal. Your job is to measure and record the signal characteristics of each output (sketch it, and describe it in your notebook). You should look for a *DC level* and one or more *AC signals* riding on top of the DC level. Characterize the AC signals by their *shape*, *frequency* (in hertz, kilohertz or megahertz), and *peak to peak amplitude* (V $_{p-p}$).

Note: Make sure to record the black box number in your notebook. This number is found on the top left of the black box face.

If you have difficulty displaying a waveform, you may need to make adjustments to the HORIZONTAL sweep rate, or even the TRIGGER of the scope. A useful strategy is to begin the study of an unknown waveform with the VERTICAL scale on a coarse setting, such as 5 V; switch to a more sensitive setting only if the waveform appears to have a small vertical extent. To avoid possible initial confusion due to the presence of a DC level, you can begin study of a new signal with the AC/GND/DC switch of the VERTICAL section of the scope set to AC. Then, once you have understood the oscillatory part of the waveform, change the AC/GND/DC switch to DC; if the waveform shifts vertically on the scope, a DC level is present.

2. *RC* "High-Pass" Filter. The function of the circuit shown below is to block low frequency components of the input signal from the output, but to "pass" high frequency signals.

$$C = 0.01\mu F$$

From signal gen. V_{in} I $R = 500\,\Omega$ V_{out} To scope using 10X probe
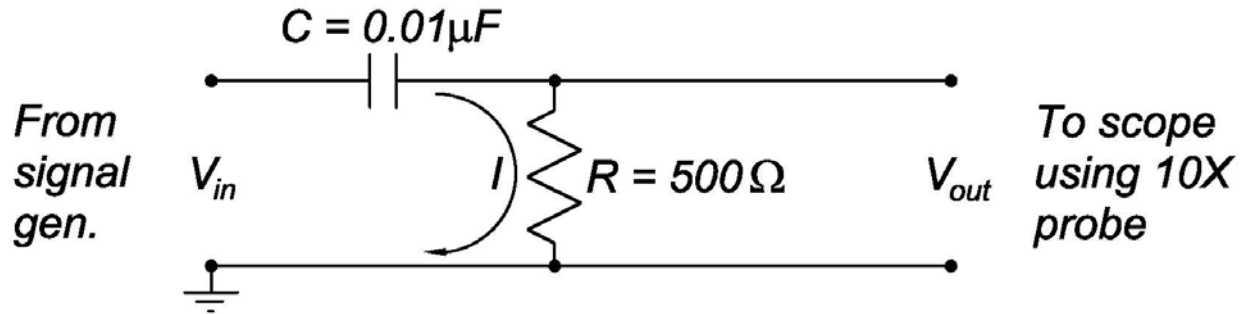
The capacitor blocks low-frequencies, but transmits high frequencies. "High" and "low" are defined relative to the characteristic frequency $\omega_{char} = 2\pi f_{char}$ f_{char} of the circuit, which in inversely related to the RC time constant the you explored in Lab 3:

$$\tau = RC \quad \text{or} \quad \omega_{char} = \frac{1}{\tau_{char}} = \frac{1}{RC}, \text{ and } f_{char} = \frac{\omega_{char}}{2\pi} = \frac{1}{2\pi RC}.$$

As you can see, the circuit shown in the diagram above is a kind of voltage divider, which differs from the one in Lab 3 in that one of the two elements—the capacitor—has a (complex) impedance whose value depends on frequency $Z_C = \dfrac{1}{i\omega C}$. Since the capacitor is in series with the resistor (of impedance $Z_R = R$), the total (complex) impedance of this filter is $Z = Z_R + Z_C = R + \dfrac{1}{i\omega C}$. The current I in the circuit is given by Ohm's law: $V_{in} = IZ$, and the output voltage across the resistor is given by $V_{out} = IZ_R = IR$. Hence the ratio of the output to the input voltage is

$$\frac{V_{out}}{V_{in}} = \frac{Z_R}{Z} = \frac{Z_R}{Z_R + Z_C}.$$

This has the same form as does a resistive voltage divider, except that one of the resistors has been replaced by a capacitor. Since the impedance of the capacitor is high at low frequencies, the ratio V_{out}/V_{in} will be low there; conversely, the impedance of the capacitor is low at high frequencies, to the ratio V_{out}/V_{in} approaches unity here. The circuit is a high-pass filter.

We can make a detailed analysis of the ratio V_{out}/V_{in} using complex numbers:

$$\frac{V_{out}}{V_{in}} = \frac{R}{R + \dfrac{1}{i\omega C}} = \frac{1}{1 - \dfrac{i}{\omega RC}} = \frac{1}{\sqrt{1 + \left(\dfrac{1}{\omega RC}\right)^2}} e^{-i\tan^{-1}\frac{1}{\omega RC}} = \frac{e^{i\tan^{-1}\frac{1}{\omega RC}}}{\sqrt{1 + \left(\dfrac{1}{\omega RC}\right)^2}} = \frac{e^{i\tan^{-1}\frac{\omega_{char}}{\omega}}}{\sqrt{1 + \left(\dfrac{\omega_{char}}{\omega}\right)^2}} = \frac{e^{i\tan^{-1}\frac{f_{char}}{f}}}{\sqrt{1 + \left(\dfrac{f_{char}}{f}\right)^2}}.$$

Thus, the output voltage of the filter depends on frequency f. When $f \ll f_{char}$, we see that $|V_{out}|/|V_{in}| \ll 1$ (because the capacitor blocks the current at low frequencies), while

when $f \gg f_{char}$, we see that $|V_{out}|/|V_{in}| \approx 1$. When $f = f_{char}$, then $|V_{out}| = |V_{in}|/\sqrt{2}$. Only frequencies higher than f_{char} propagate easily through the filter!

[This analysis assumes that the output voltage is across a high-impedance device, so that negligible current flows in the output leads. The impedance of your oscilloscope probe is greater than 1 MΩ, so this condition is well satisfied in this Lab.]

Confirm the behavior of the filter by observing the ratio of the amplitude of the output voltage to the amplitude of input voltage as you change the input frequency, *i.e.*, observe $|V_{out}|/|V_{in}|$ as a function of frequency f. (Optional: keep track of the phase relation between V_{out} and V_{in} as well.)

> *Hint:* If you put the generator input (*i.e.*, V_{in}) on CH1 and trigger the scope from it, you can put the output of the circuit (*i.e.*, V_{out}) on CH2 and compare the two signals directly.

Start with the Wavetek generator on a frequency range that includes the characteristic frequency f_{char} that you expect for the filter. Then "sweep" the frequency control knob from one extreme to another over a few seconds, while watching the signals on the oscilloscope. If your setup is correct, you should see that $|V_{out}|/|V_{in}|$ is small for frequencies f below f_{char}, and unity when $f \gg f_{char}$. Try to identify f_{char} as the frequency at which $|V_{out}|/|V_{in}| = 0.707$.

Once you have observed the resonance curve qualitatively, make and <u>plot</u> a set of quantitative measurements of $|V_{out}|$ over a broad range of frequencies, both above and below the characteristic frequency, such as between $0.1 f_{char}$ to $10 f_{char}$. Three or four measurements on each side of f_{char} and one at f_{char} ought to be enough to tell you where the interesting frequencies are in terms of the behavior of V_{out}. For this reason it is a good idea to plot as you go.

Your plot could be of $|V_{out}|/|V_{in}|$ as a function of frequency f, but given the very broad range of f you would be well advised to plot $|V_{out}|/|V_{in}|$ as a function of $\log f$ or to use the three cycle semi-log paper, with f along the log side. You might then want to take several more readings in the vicinity of the interesting parts of the plot. You are not asked to make error calculations in this part of the experiment.

3. *RC* "Low-Pass" Filter. In a "low-pass" filter, high frequencies should be shorted to ground. This can be accomplished by placing a capacitor between the signal line and ground (plus a resistor to define the characteristic cutoff frequency $f_{char} = 1/2\pi RC$). Here, the capacitor shorts the current from the signal generator to ground at high frequencies
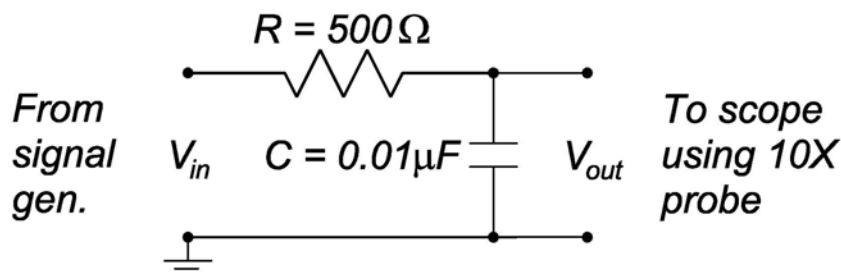
Make a frequency sweep as in part 2, and deduce the resonant frequency f_{char} from your observations of $|V_{out}|$ and $|V_{in}|$. You do not need to make detailed plots as a function of frequency in this part (nor in the following two parts).

4. *LR* "Low-Pass" Filter. There is a "theorem" that the functionality of any filter that can be built with resistors and capacitors could also be obtained in an appropriate circuit of resistors and inductors. Inductors block high frequencies but pass low frequencies, so a simple *LR* low-pass filter could be built as shown below. Do your agree that in this case the characteristic cutoff frequency is $f_{char} = R / 2 \pi L$?
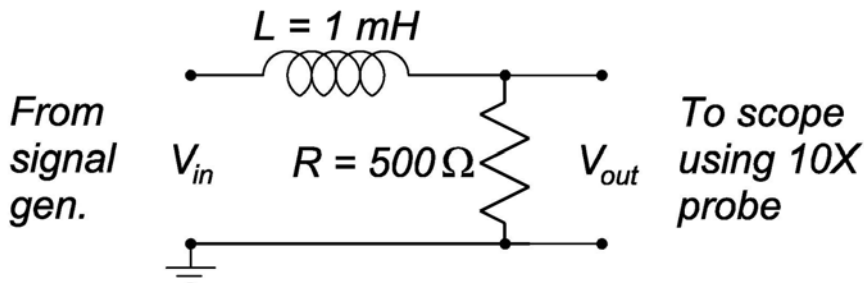
Make a frequency sweep of the Wavetek generator to estimate the resonant frequency of this filter.

5. *LR* "High-Pass" Filter. If you reverse the resistor and inductor in part 4, you should obtain a high-pass filter, as shown below, since now the inductor shorts low frequencies to ground.
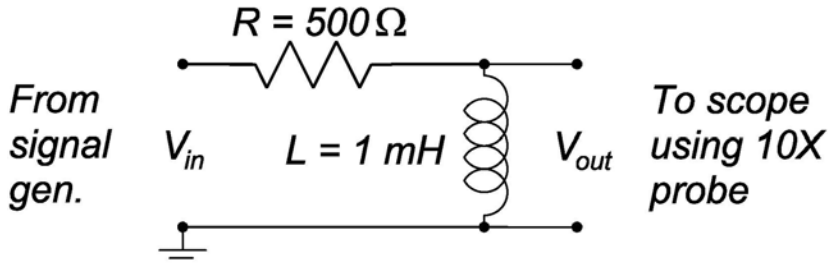
Again, make a frequency sweep to estimate the resonant frequency of this filter.

6. Lissajous Figures (Optional, but very entertaining).

Your oscilloscope has another mode of operation, called "x-y display". Activate this mode by turning the knob in the HORIZONTAL control panel to "x-y". Then the signal on CH1 drives the horizontal deflection plates of the scope, and the signal in channel 2 drives the vertical plates. For example, connect Ch 12 of the Black box to scope CH1, and connect the MAIN out of the Wavetek generator (when in sinewave mode) to CH2 of the scope. If the frequencies of the two input signals are identical, a stable circle will be displayed on the scope. If you have trouble tweaking the fine frequency knob on the Wavetek generator in sufficiently small steps, you might try fine tuning the black box instead, by using a small screwdriver applied (carefully!) to the recessed trimpot on the front face of the black box. Some patience is required to "tune" your Lissajous figures.

Try tuning to various frequencies f_1 and f_2 that are in small integer ratios: 1/2, 2/3, 5/4, …. Describe the stable patterns that you observe. Also, try using Black Box CH11 in scope CH2 instead of the Wavetek generator.

PRINCETON UNIVERSITY   **PHYSICS 104 LAB**
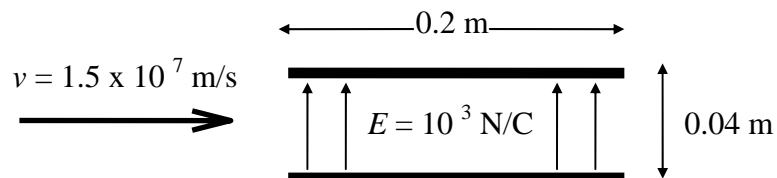**Physics Department**   **Week #7**
Name:_____   **Date/Time of Lab:**_____

EXPERIMENT VI   PRELAB PROBLEM SET

1. An electron (mass = 9.1 x 10^{-31} kg, charge = -1.6 x 10^{-19} C) is projected into a region of uniform electric field 0.2 m long with velocity v = 1.5 x 10^7 m/s, as shown in the figure below.

How long will the electron be in the uniform field between the two plates?

What will be its acceleration? Will you need to consider the effect of gravity on the electron?

What is the angle between its velocity when it leaves the region of electric field and its original direction?

What is the vertical deflection of the beam from its undeflected location, if it is viewed on a phosphorescent screen 20 cm away from the field region.

Continued on reverse

2. Suppose you see the following trace on your oscilloscope. You have set the vertical scale to 1 Volt per square and the horizontal to 10 µs per square. Report the frequency, peak-to-peak voltage, and the DC level of the curve.
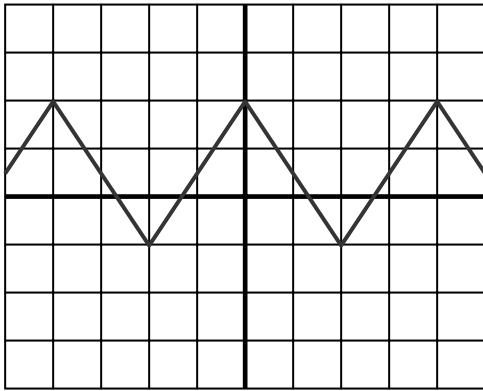
3. Analyze the high-pass *LR* filter circuit shown below to find a (complex) expression for V_{out} / V_{in} as a function of the frequency f of the signal generator. Identify the characteristic frequency $f_{\text{char}} = \omega_{\text{char}} / 2\pi$. (See part 2 of the lab for the case of a high-pass *RC* filter. Note that the complex impedance of an inductance L at angular frequency ω is $Z_L = i\omega L$.)