Laboratory 3

The Oscilloscope

Required Components:
- 1 10Ω resistor
- 2 100Ω resistors
- 2 1kΩ resistors
- 1 2kΩ resistor
- 2 4.7MΩ resistors
- 1 0.022µF capacitor
- 1 0.1µF capacitor
- 1 1.0µF capacitor

3.1   Objectives

In the previous laboratory exercise you learned about the basic operation of the oscilloscope. This laboratory exercise is designed to give you a more in-depth understanding of the proper use of the oscilloscope and its range of applications.

The oscilloscope is probably one of the most widely used electrical instruments and is one of the most misunderstood. During the course of this laboratory exercise you will become familiar with the proper methods of connecting inputs, grounding, coupling, and triggering the oscilloscope. Also during the course of this experiment you will learn the proper use of the oscilloscope attenuator probe.

3.2   Introduction

3.2.1   AC and DC Signals

An AC signal varies with time, and its deterministic expression contains time as the independent variable. For example,

$$F_1(t) = 2.0 \sin 5t \tag{3.1}$$

$$F_2(t) = 3.1 \cos 5t + 5.1 e^{-3.0t} \tag{3.2}$$

A DC signal on the other hand does not vary with time, hence t does not appear in its expression:

$$F_3(t) = 1.0 \tag{3.3}$$

$$F_4(t) = 5.63 \tag{3.4}$$

Now what if our signal can be written:

$$F_5(t) = 2.0 + 1.0\sin 5t \qquad (3.5)$$

Is it AC or DC? Well, we say it is AC (1.0 sin 5 t) with a DC offset (2.0). We can see this if we plot the signal below:
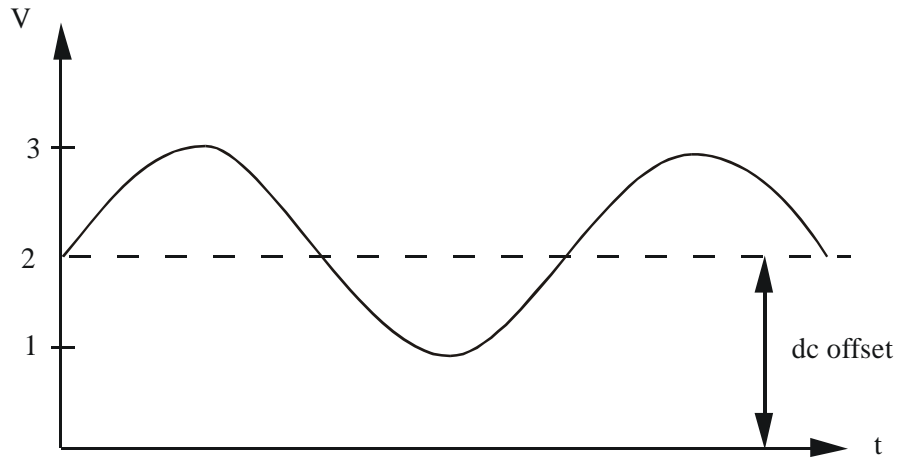

Figure 3.1 AC Signal with DC Offset

This difference between an AC and DC signal is important when understanding oscilloscope coupling.

3.2.2   AC and DC Coupling

Most oscilloscopes are provided with a switch to select between AC or DC coupling of a signal to the oscilloscope input amplifier. When AC coupling is selected, the DC component of the signal is blocked by a capacitor inside the oscilloscope that is connected between the input terminal and the amplifier stage. Both AC and DC coupling configurations are illustrated in Figure 3.2. R_{in} is the input resistance (impedance) and C_{in} is the input capacitance. C_c is the coupling capacitor that is present only when AC coupling is selected.
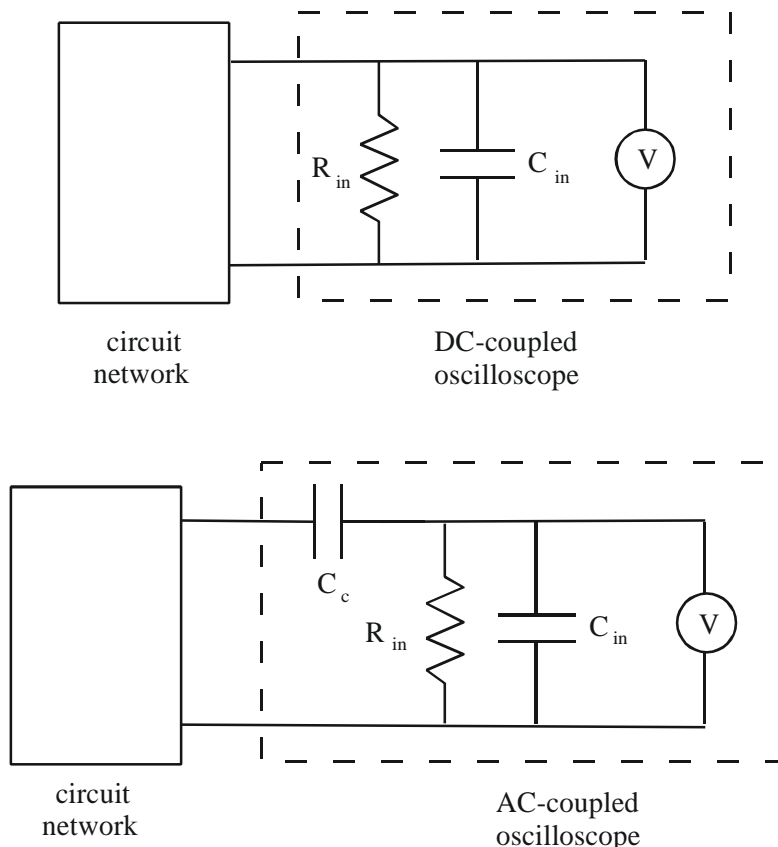
Figure 3.2 Oscilloscope Coupling

AC Coupling

AC coupling must be selected when the intent is to block any DC component of a signal. This is important, for example, when measuring small AC spikes and transients on a 5 V TTL (transistor-transistor logic) supply voltage. However, it must be kept in mind that with AC coupling:

- One is not aware of the presence of any DC level with respect to ground.

- The lower frequency components of a signal are attenuated.

- When the oscilloscope is switched from DC to AC coupling, it takes a little time before the display stabilizes. This is due to the time required to charge the coupling capacitor C_c to the value of the DC component (average value) of the signal.

- Sometimes the input time constant ($\tau = R_{in}C_c$) is quoted among the oscilloscope specifications. This number is useful, because after about five time constants (5τ), the displayed signal is stable.

AC coupling can be explained by considering the impedance of the coupling capacitor as a

function of frequency:

$$Z = \frac{1}{j\omega C} \tag{3.6}$$

where j represents the imaginary number $\sqrt{-1}$. With a DC voltage ($\omega = 0$) the impedance of the capacitor is infinite, and all of the DC voltage at the input terminals of the oscilloscope will appear across the capacitor. Thus, AC-coupling the oscilloscope will eliminate any DC offset present in the voltage appearing across the input terminals of the oscilloscope. For AC signals, the impedance is less than infinite, resulting in attenuation of the input signal dependent upon the frequency. As the input frequency increases the attenuation decreases to zero. The coupling mode is selected using the input selectors on the front panel of the oscilloscope. Generally, if the signal type is unknown, DC coupling is the first choice for observing the signal.

3.2.3   Triggering the Oscilloscope

Triggering refers to an event at the input terminals of the oscilloscope that causes the electron beam to sweep across the screen and display the terminal voltage. The oscilloscope may be level triggered either in the AC or DC mode, and the level of the magnitude is adjustable using the trigger level control. The slope (+ or –) of the terminal voltage also affects when the beam is triggered. This slope is selected either positive or negative.

Another triggering option available is that of line triggering. Line triggering uses the AC power input to synchronize the sweep. Thus, any terminal voltage synchronized with the line frequency of 60Hz or multiples of 60Hz can be triggered in this mode. This is useful to detect if 60 Hz noise from various line related sources is superimposed on the signal.

3.2.4   Grounding Source and Scope

Normally, all measurement instruments, power sources, and signal sources in a circuit must be referenced to a common ground as shown in Figure 3.3.
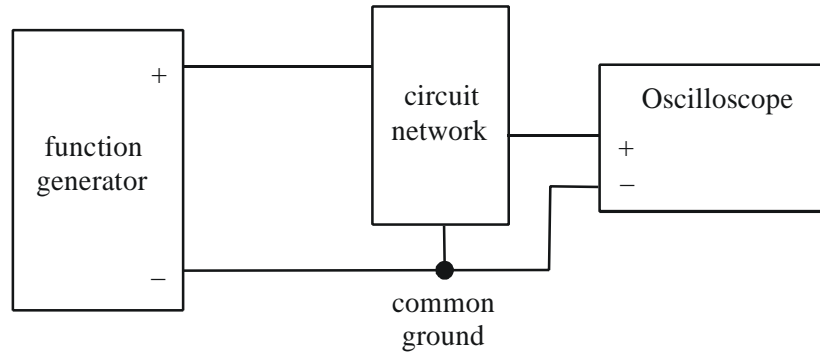
Figure 3.3 Common Ground Connection

However, as can be seen from Figure 3.4, if we wish to measure a differential voltage ΔV, it is correct to connect the scope as shown. Note that the oscilloscope signal ground and external network ground are not common. This type of connection allows us to measure a potential difference anywhere in a circuit.
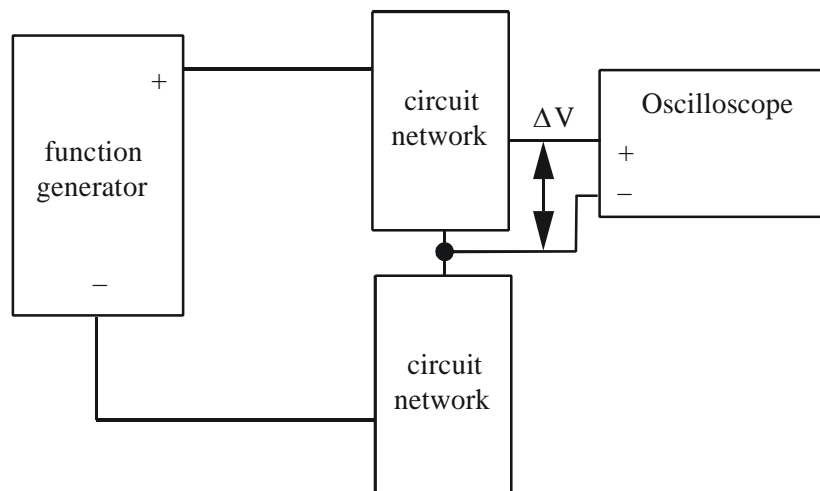

Figure 3.4 Relative Ground Connection

NOTE - In many oscilloscopes, including the HP54602A, each channel's "–" signal reference is attached to chassis ground, which is attached to the ac line ground. Therefore, to make a differential voltage measurement, you must use the "Ch1 – Ch2" signal difference feature, using the "+" leads of each channel. An alternative for dc circuits is to measure the voltage at each node separately, relative to ground, and then manually subtract the voltage readings.

3.2.5   Properly Grounding the Oscilloscope to the Wall Socket

As with most of the instruments you will be using in the laboratory the oscilloscope is equipped with a 3-pronged plug (see Figure 3.5) for safety purposes. The two flat prongs of this plug complete the circuit for alternating current to flow from the wall socket to the instrument. The

round prong of the plug is connected only to the chassis and not to the signal ground. This is important to protect the operator if there is a short circuit inside the oscilloscope. Otherwise, a high voltage can occur on the chassis jeopardizing the safety of the user.
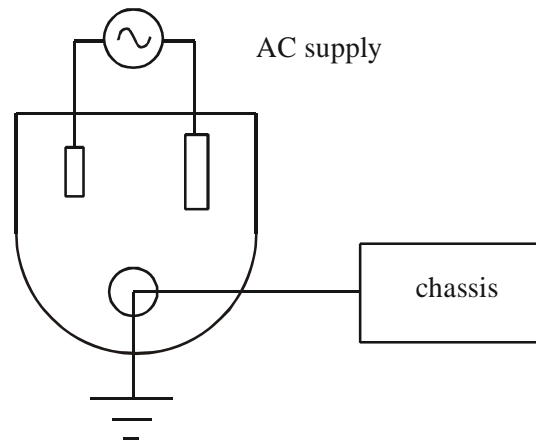

Figure 3.5 Three-prong AC Power Plug

3.3   Using the Attenuator Probes

In a previous laboratory exercise you determined the input impedance of the oscilloscope, and you should have found it to be approximately 1MΩ. An input impedance of 1MΩ is large and in most cases can be considered infinite. However, when measuring the voltage drop across an element whose impedance is of an order of magnitude of 1 MΩ or larger, the input impedance can induce serious error in the measurement. To avoid this problem, the input impedance of the oscilloscope must be increased. One method of increasing the oscilloscope input impedance is the use of an attenuator probe. The use of an attenuator probe will increase the input impedance by some known factor but will at the same time decrease the amplitude of the input signal by the same factor since the current into the oscilloscope is limited by the input impedance. Thus a 10X probe will increase the magnitude of the input impedance of the oscilloscope by a factor of 10, but the displayed voltage will be only 1/10 of the amplitude of the actual terminal voltage. **Most oscilloscopes offer an alternative scale to be used with a 10X probe (or it is done is software, for example with the NI ELVIS).** A simple schematic of the oscilloscope input terminals with the probe attached is presented in Figure 3.6.
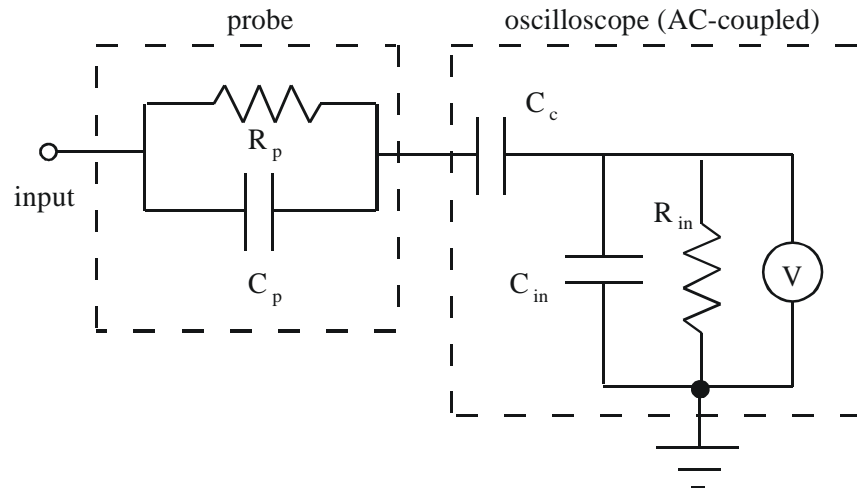
Figure 3.6 Simple Model of Oscilloscope and Probe

Note that the addition of the attenuator probe to the input terminals of the oscilloscope not only changes the resistive characteristics of the terminals but the capacitive characteristics as well. A complete model for the oscilloscope, the cable connections and the attenuator probe is shown in Figure 3.7.
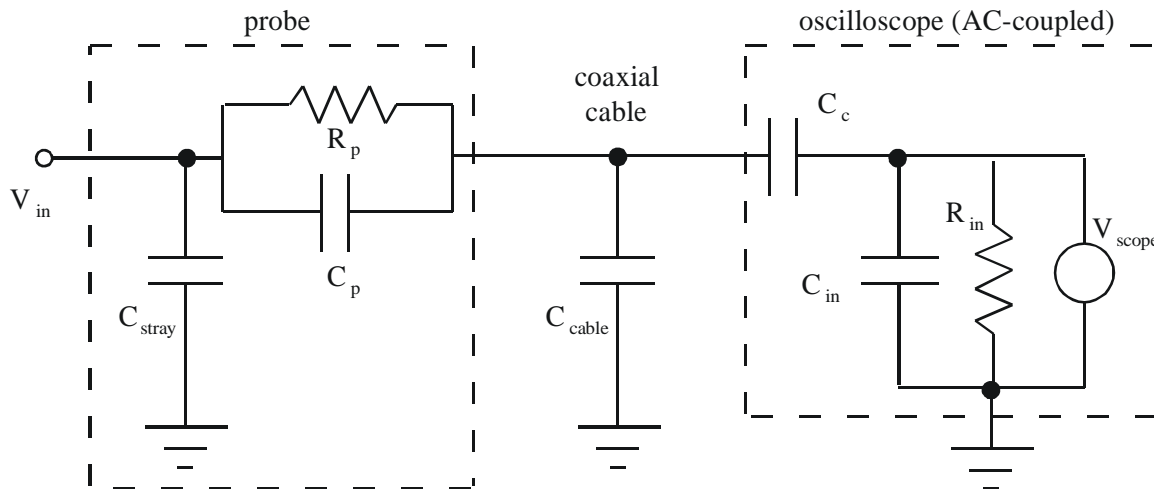

Figure 3.7 Complete Model of Oscilloscope, Probe, and Cable

Due to the collection of complex impedances between the input (V_{in}) and the oscilloscope voltage measuring device (V_{scope}), the voltage reading will depend on the frequency components of the input (in addition to the input voltage magnitude). However, by adjusting C_p, this dependence can be minimized. **If using the HP 54602A Oscilloscope, C_p can be adjusted by turning the small screw in the attenuator probe and monitoring a square wave output from the probe adjust port on the front panel of the oscilloscope. The diagram given in Figure 3.8 will help you when tuning the probe.**
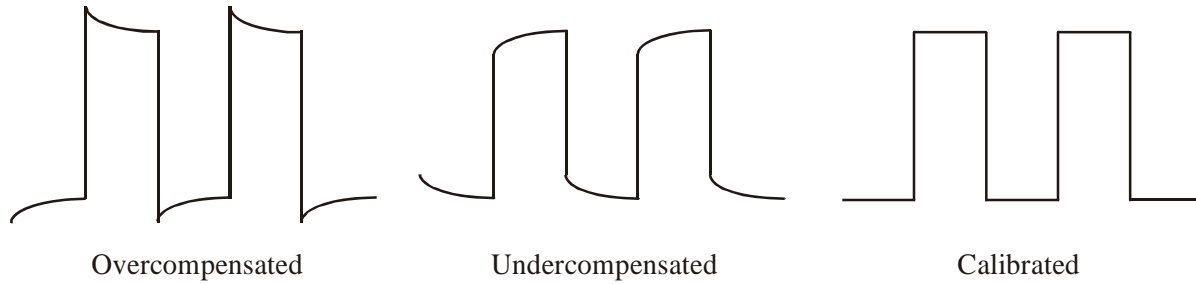
| Overcompensated | Undercompensated | Calibrated |

<u>Figure 3.8</u> Attenuator Probe Calibration

The use of C_p to minimize the frequency dependence can be understood by looking at the impedances in the model. To simplify the analysis we will assume that the effects of C_{stray} and C_c are negligible, so the impedances of the circuit sections are

$$Z_{scope} = \frac{R_{in}}{j\omega R_{in}C_{in} + 1} \tag{3.7}$$

$$Z_{scope + cable} = \frac{R_{in}}{j\omega R_{in}(C_{in} + C_{cable}) + 1} \tag{3.8}$$

$$Z_{probe} = \frac{R_p}{j\omega R_p C_p + 1} \tag{3.9}$$

and from voltage division, the resulting voltage input-output relationship is

$$\frac{V_{scope}}{V_{in}} = \frac{Z_{scope + cable}}{Z_{probe} + Z_{scope + cable}} = \frac{\dfrac{R_{in}}{j\omega R_{in}(C_{in} + C_{cable}) + 1}}{\dfrac{R_p}{j\omega R_p C_p + 1} + \dfrac{R_{in}}{j\omega R_{in}(C_{in} + C_{cable}) + 1}} \tag{3.10}$$

Now it is clear that if we adjust C_p so $R_p C_p = R_{in}(C_{in} + C_{cable})$, the frequency dependence will be eliminated.

3.4   Specific Background Information on Using an HP54602A Oscilloscope

Looking at the front of the scope you can see that it contains a screen and a number of buttons and knobs. The screen displays the output of the oscilloscope. Just below the screen are six 'soft' buttons. The function of these buttons will change depending upon menu selections. The current function of each button is displayed directly above the button on the bottom of the screen.

3.4.1　The Screen

The screen is divided into eight vertical and ten horizontal divisions. Typical information displayed on the screen includes:

The Y-Axis Scale: The Y-Axis scale is located in the upper left hand corner of the screen. Each channel can have a different scale. For example if the screen reads: 1 2V 2 200mV, it means that channel one has a scale of 2 volts per division, while channel two has a scale of 200 millivolts per division.

The Time Scale: The time scale is located in the upper right side of the screen. Each channel has the same time scale. For example, 10ms/ means 10 milliseconds per division.

Delay: The time delay indicator is located in the upper middle section of the screen. This displays whether the signal is shifted left or right. Typically this should be reading 0.00 s.

Trigger information:　 The current trigger mode is in the upper right hand corner of the screen. It is displayed either as an up arrow or as a down arrow indicating positive or negative slope triggering.

Channel Grounds: Along the right hand side of the display there will be a channel ground indicator (a ground symbol with the channel number next to it). It shows where the ground for that channel is with respect to the displayed grid. If the ground is off the screen there will be an arrow with the channel number at the top or bottom of the screen to indicate where the ground is.

Along the bottom of the screen there is room for addition information to be displayed. The very bottom of the screen indicates the current functions of the soft buttons. These functions change depending upon which menu button has been selected.

3.4.2　Buttons and Dials

The buttons and dials on the oscilloscope are separated into five groups: Vertical (outlined in blue), Horizontal (outlined in gray), Trigger (outlined in green), Storage (outlined in gray) and an unnamed group (also outlined in gray). The unnamed group contains the Measure and Save/ Recall sub-groups as well as the Autoscale, Display, and Print/Utility buttons.

3.4.3　Vertical

The vertical group contains four columns, one for each channel. Each column contains a coaxial input port. Above the input port is a dial labeled "Level." This dial can be used to adjust the location of the ground on the screen. Above the "Level" knob there is a button with the channel number on it. Pressing this button will call up a menu that can be accessed with the soft buttons located just below the screen. For channels 1 and 2 this menu includes:

Off On: Selecting this will toggle the trace of the selected channel on and off

Coupling: Allows switching between AC and DC coupling.

BW Limit: Allows limiting the bandwidth of the signal displayed (helps to reduce noise).

Vernier: Leave off.

Probe: This indicates to the oscilloscope if an attenuation probe is attached. The scope will multiply the incoming signal by the selected value before displaying it.

Channels 3 and 4 have less extensive capabilities:

Off On: Same function as channels 1 and 2

Coupling: Only DC coupling is available for channels 3 and 4

V/div: Channels three and four are limited to 2 possible voltage scales

Probe: Same as channels one and two

Between the channel 1 and channel 2 buttons, there is a button with a plus and a minus on it. This button will bring up a menu that allows you to perform math on the signals. You can add, subtract and multiply signals together or perform and display the results (spectrum) of a Fast Fourier Transform (FFT).

For channels 1 and 2 there is also a large green knob. This knob will change the Y-axis scale on the screen.

3.4.4 Horizontal

The horizontal control group contains one large knob (Time/Div), one small knob (Delay), and one button labeled Main/Delay. The large knob is used to adjust the time scale on the screen. This will allow you to zoom in on sections of the signal. The small knob labeled "Delay" allows you to move the signal left and right so you can inspect different areas of the signal. The button brings up a menu that allows you to choose one of four horizontal modes and switch the location of your time reference from the center of the screen to the left of the screen.

The four horizontal modes are:

Main: This is the normal or default setting you will usually use.

Delayed: This splits the screen vertically into two windows. On the top you will see a large section of your signal separated by two vertical lines. On the bottom window you will see an expanded version of the signal that lies within the two vertical lines on the upper window. By adjusting the delay knob you can move left and right through the signal. Adjusting the Time/Div changes the spacing between the two vertical lines and thus the amount of "zoom."

XY: This allows you to use channel 1 as the x-axis instead of time.

Roll: In this mode the scope just displays the current signal without 'trying' to maintain a steady display.

3.4.5 Trigger

Triggering ensures that the display of a signal will be stable for direct observation.

Triggering is the event that causes the scope to start scanning the electron beam creating the displayed signal called a trace. The scope starts the trace at the left and moves to the right at a speed determined by the time scale. For example, if the time scale is 200ms/division it will take the scope 2 ms (200ms/division times ten divisions) to complete the trace. Once the trace has reached the end of the screen the scope waits for another triggering event to initiate the trace again. The triggering event can be adjusted by the knobs and buttons in the trigger menu.

The trigger group contains two knobs and three buttons:

Source: This button allows you to choose which channel will be used as the trigger. In addition to the four input channels, the line can also be used as a trigger. This means the scope will trigger based on the voltage coming from the AC power source. This is useful when looking for noise caused by electrical interference.

Mode: You should usually select the normal mode

Slope/Coupling: This button will bring up a menu that allows you to select the slope of the trigger. You can either trigger on the signal when it is going up or going down (up arrow, down arrow) depending on how you want the signal displayed. This menu also contains features that will help you trigger on a noisy signal

Level: This knob allows you to adjust the voltage level at which triggering occurs. Combined with the slope this is how triggering is adjusted. For example, if you have the level set to zero and the slope set to + (up arrow) you will be triggering every time the signal goes from below zero volts to above zero volts. The level is very important when you are dealing with signals that have been rectified (by a diode). A rectified signal may never have a value of less than zero, and if you leave the level at zero, the scope may never trigger, and no signal will be displayed.

Holdoff: You should not need to use this.

3.4.6   Storage

The scope has the ability to store signals for later display and comparison.

3.4.7   Measure

There are three buttons and some knobs in the measure sub-group:

Voltage: pressing this button brings up a menu that will allow you to make a variety of voltage measurements.

By selecting the appropriate soft button you can display just about any information that you want. For example, if you want to know the RMS voltage of the signal on channel 2, you should push the left-most soft button until the number 2 is highlighted and then press the Vrms button. The RMS voltage will appear near the bottom of the screen.

Time: Similar to the voltage button, this displays a menu that will allow you to make a variety of time measurements. You can measure frequency, period, rise time, etc.

Cursors: This button allows you to make manual measurements of a signal. It will bring up

a window with the following options.

Source: Allows you to change the channel you are measuring.

Active Cursor: You will be able to have four cursors on the screen at once. Two are vertical labeled V1 and V2, and two are horizontal labeled T1 and T2. Using the unlabeled knob just below and to the right of the cursors button you will be able to move the active cursor around. While you are moving the cursor the screen will display its position relative to ground (or zero time) and also relative to the other cursor. This allows you to measure the voltage difference for any specific part of the signal.

3.4.8   Save/Recall

This group contains two buttons:

Trace: This allows you to save a trace so you can look at it later.

Setup: This button brings up a menu that allows you to save the setup of your voltage and time scales as well as your triggering. This may be useful if you have a particular setup you like. Also in this menu is an Undo Autoscaling button that will be useful if you press the Autoscale button by accident and lose your signal.

Autoscale

This is probably the most useful button on the scope. Pressing this button will automatically setup the voltage scales, time scale, and triggering so you produce a stable display. Although it is very helpful, it is not perfect for every application. It is easy to overuse this button. Here are some things to watch out for:

(1)   If you have a relatively low frequency signal (less than 50 Hz) Autoscale will not find the signal.

(2)   If you have a DC signal, Autoscale may not find the signal. If so, try switching your trigger source to line if you cannot get a DC signal displayed.

(3)   If you are using more than one channel Autoscale will set the vertical scales differently and adjust the ground levels so each signal is displayed separately.

Display

This button will bring up a menu with the following options:

Display Mode [normal, peak detect, average]: Leave this on normal

Vernier: Leave this off

Grid: Pressing this will let you turn the grid on and off

3.4.9 How to Find a Signal on an HP54602A Oscilloscope

Use the following procedure to display an unknown input signal on the oscilloscope:

(1) Optional: It is a good practice to reset the settings of the scope to default settings before beginning because you might not know what state the scope was left in by previous users. To do this, press the "Setup" buton in the "Save/Recall" button group. Then select "Default Setup" with the below-screen button.

(2) First try pressing the Autoscale button. Often this will automatically scale and display the signal. If the signal is not displayed (e.g., when a signal has a low frequency or is dc), continue with the remaining steps below.

(3) Make sure the desired channel is on and set up properly.

- Press the number button corresponding to the channel you want to observe

- Turn the channel on by pressing the left-most "soft" button.

- With the right-most 'soft' button, select the type of probe you are using.

- If it is possible that your signal could have a large DC offset, select AC coupling with the second-to-left below-screen button. This will remove the DC offset and bring the pure AC portion of the signal into range.

- Make sure BW Lim, Invert, and Vernier are off.

(4) Move the channel ground to the center of the display.

- There should be a ground symbol on the right hand side of the screen.

- If the ground is off the screen there will be an arrow in either the upper or lower right hand corner pointing to it.

(5) You can move the ground up and down with the small, light colored, "position" knob. Make sure the trigger is set up correctly.

- Press the 'source' button and then select the appropriate channel

- Press the 'mode' button and select "Auto Lvl"

- Adjust the level knob until the level is within the range of the signal

- If you have a noisy signal press the Slope/Coupling button and turn the "Noise Rej" on.

(6) Set the Vertical scale.

- The vertical scale is displayed in the upper left corner of the screen

- Turn the Volts/Div knob (above Channel 1) until the vertical scale is about half of the amplitude of the signal.

(7) Set the Time scale.

- The time scale is displayed at the top of the screen (just right of center)

- Turn the Time/Div knob until the time scale is about ½ of the period of the signal.

3.5   Laboratory Procedure / Summary Sheet

Group: _____   Names: _____   _____

_____   _____

(1)   In this step you will examine the effects of AC coupling of an oscilloscope.

Set the function generator to produce a 5 V_{pp} 1kHz sinusoidal output. To do this, press the Vpp button, enter 5, and press Enter. The "Not Entered" light should go off when you press Enter; otherwise, press it again more firmly and squarely.

Display the sinusoid on the oscilloscope with a sensitivity of 1 V/div. Make sure the triggering source is set to the proper "channel" (and not "line" triggering). **NOTE - If using the Philips PM5193 function generator, be sure to connect to the lower "OUTPUT" jack** (not the upper "TTL OUT" jack).

Adjust the triggering level and notice what effect it has.

Use the +/– trigger selector (press the slope button and toggle between positive and negative edge triggering) and notice what effect it has.

Refer back to Figure 3.2 for details on the impedances within the oscilloscope. We can simulate an AC coupled oscilloscope by adding an external coupling capacitor to a DC coupled oscilloscope. To do this, build the circuit shown in Figure 3.9. Using the function generator Vdc button, add a 5 Vdc offset to the 5V_{pp} 1kHz signal (by entering 5 and pressing Enter).

Be sure to select DC coupling on the oscilloscope. Use a 0.022 µF coupling capacitor ($C_{coupling}$) and note the resulting output. Then try a 0.1 µF and a 1 µF capacitor (refer back to Section 1.4 in Lab 1 for info on how to read capacitor values). **Note carefully what happens to the oscilloscope display when you <u>first</u> attach the scope 1X probe (or banana cable with alligator clip) to measure V_o for each case.** Make sure you discharge the coupling capacitor by shorting its leads before you attach the probe to measure the voltage. How do the results change with the capacitance value?

What is the effect of the function generator output impedance R_o on the measured voltage V_o?

Now remove the coupling capacitor and toggle the oscilloscope between DC coupling and AC coupling and note what you observe in the measured voltage signal. Which of the three external coupling capacitors that you tried most closely approximates what you think the actual coupling capacitance of the oscilloscope is?
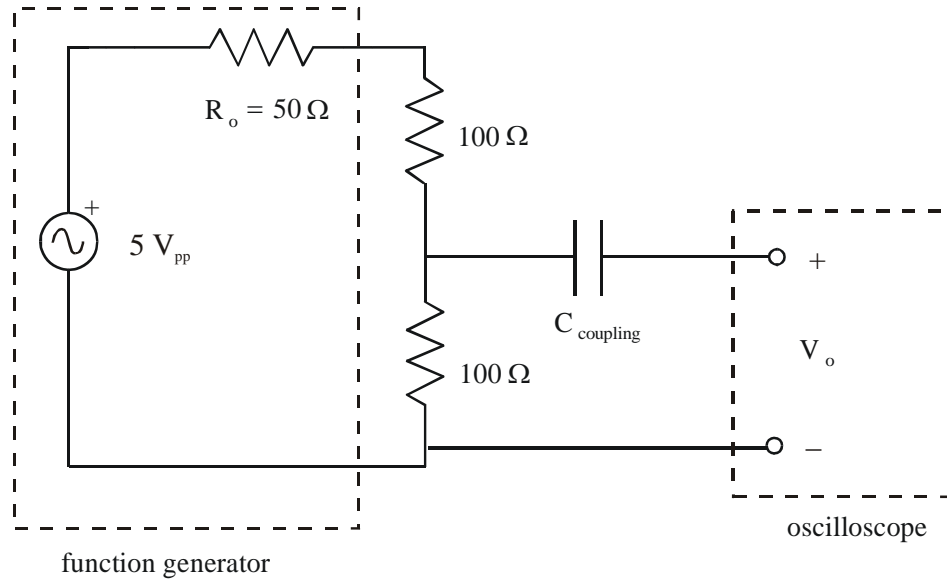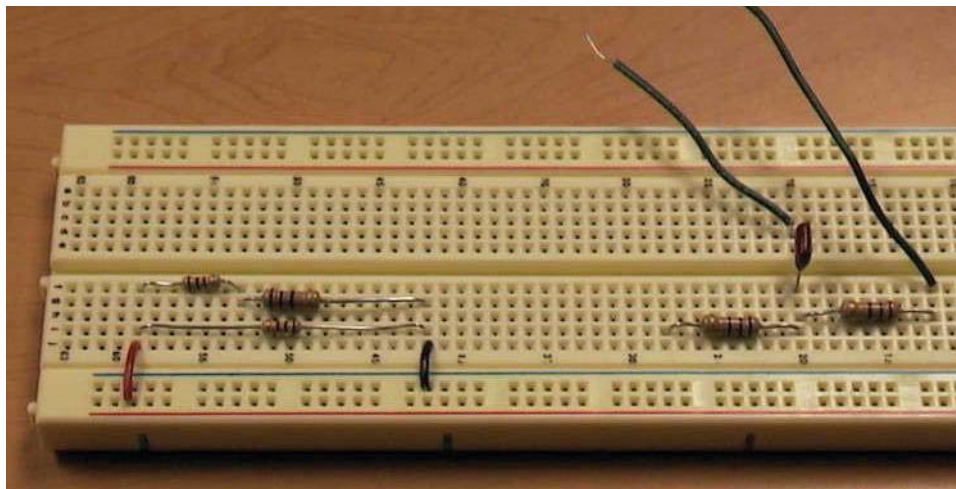
Figure 3.9 Coupling Capacitor Effects

Figure 3.10 Circuits for Steps 1 (right) and 4 (left)

(2)   In this step and the next you will study the effects of oscilloscope input impedance. You will be using an oscilloscope 10X probe to increase the input impedance and note the consequences. **Before continuing, read through the probe calibration procedure described in Section 3.3**.

Connect a 10X attenuator probe to channel 1 and calibrate the probe. Use the probe adjust port on the oscilloscope.

Construct the circuit shown below with $R_1 = R_2 = 1 \, k\Omega$ and set V_i to a $6V_{pp}$, 1kHz sine wave.
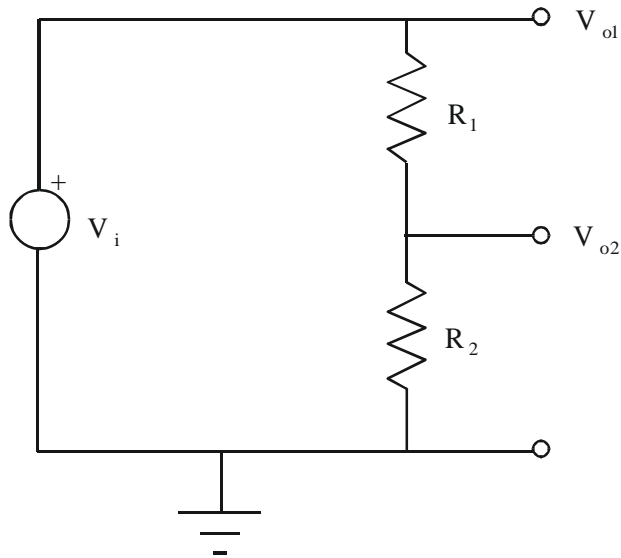

Figure 3.11 Probe Measurements

Using the attenuator probe, determine each of the voltages V_{o1} and V_{o2} for the circuit above and record the **peak-to-peak values** in the following table. Be sure that nothing is connected to Channel 2. Note that the voltages V_{o1} and V_{o2} labeled in the figure are node voltages defined relative to ground, and not "across" voltages, so the probe ground clip should be attached to the ground of your circuit. V_{o2} happens to also be the voltage across R_2, but V_{o1} is not the voltage across R_1

$R_1 = $ _____

$R_2 = $ _____

.

	Calculated	Measured with 1X probe*	% Error	Measured with 10X probe	% Error
V_{o1}					
V_{o2}					

*: Alternatively, you can use a plain banana plug wire with a BNC adapter.

(3) Repeat Part 2 for $R_1 = R_2 = 4.7$ MΩ and record the values V_{o1} and V_{o2} in the following table.

$R_1 = $ _____

$R_2 = $ _____

	Calculated	Measured with 1X probe	% Error	Measured with 10X probe	% Error
V_{o1}					
V_{o2}					

(4) Although the oscilloscope is primarily a voltage measuring instrument it can be used to indirectly measure current by inserting a small value resistor in the circuit branch of interest (unless there is a resistor in the branch already). In order to measure the current we use the oscilloscope to measure the voltage drop across this resistor and then the current through it can be calculated using Ohm's Law.

For the network shown below determine the current I by inserting resistor R of various values (see below) and measuring the voltage drop across it in each case.
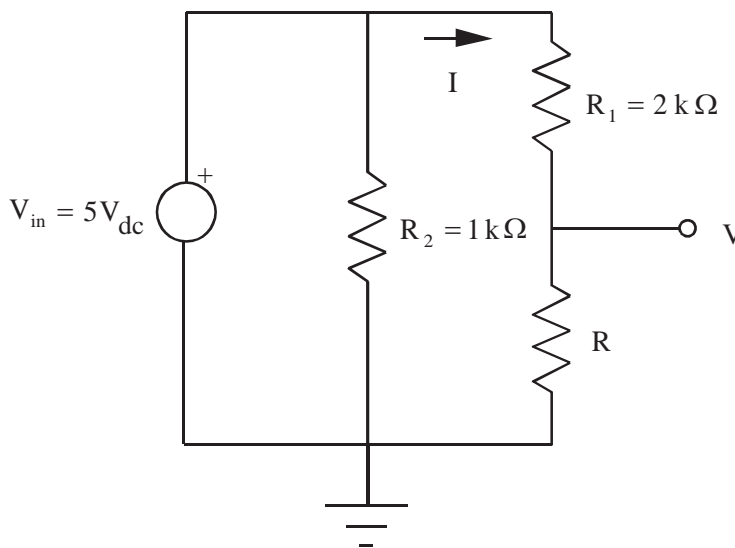

Figure 3.12 Measuring Current

Record the exact (measured) resistance values for R_1 and R_2:

R_1 = _____

R_2 = _____

For each resistance value below, measure the voltage (V) across resistor R. **NOTE** - when measuring small voltages with the oscilloscope, you might need to adjust the voltage scale manually to get accurate readings.

R	Measured with 1X probe	Measured with 10X probe
10 Ω		
100 Ω		
1 KΩ		

Record the exact (measured) resistance values for each of the three R resistors used:

R (10 Ω) = _____

R (100 Ω) = _____

R (1 kΩ) = _____

Calculate the expected current through R (for each value) using the actual values for R_1 and R. Then calculate currents from the measured voltage values above (using Ohm's Law), and compare them to the expected current values:

R	expected (calculated) current	I via the 1X probe measurement	% Error	I via the 10X probe measurement	% Error
10 Ω					
100 Ω					
1 KΩ					

LAB 3 QUESTIONS

Group: _____   Names: _____   _____

_____   _____

(1)   From the data obtained for V_{o2} in step 3 of the procedure, determine the input impedance of the oscilloscope with the 10X attenuator probe attached (see Section 2.2.8 in Lab 2).

(2)   How does the input impedance of the oscilloscope with the 10X attenuator probe compare to the input impedance with the 1X probe?

(3)   By what factor is the input voltage attenuated when the 10X probe is used with the oscilloscope?

(4)   When is it advantageous to use the oscilloscope attenuator probe?

(5)   You have a 4 V$_{pp}$, 100 Hz sine wave, and I wish it to be displayed on the oscilloscope as shown below. Indicate what values to set for the vertical amplifier (voltage divisions), time base, and trigger.
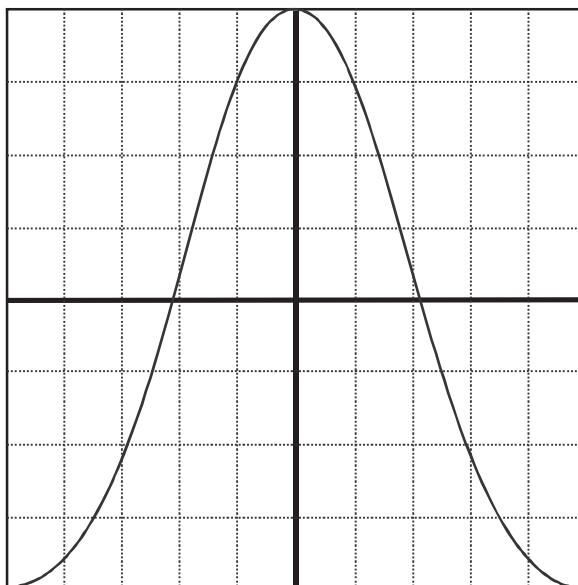

Figure 3.13 Oscilloscope Sine Wave Display

(6)   What is the effect of AC coupling when a signal with a DC offset is displayed on an oscilloscope?

(7)   In part 4, what effect does the inserted resistor have on the current measured?