Laboratory Exercise 5: RC Transfer Functions

Basic Operation of an Oscilloscope

An oscilloscope is simply a small television set except that the user has control of what is being displayed. An oscilloscope displays a voltage waveform versus time and has the following components:

1) a screen to display a waveform,
2) input jacks for connecting the signal to be displayed, and
3) dials to control how the signal will be displayed.

The Screen

The screen is cathode ray tube found in most television sets where the face of the screen is divided up into a 2 dimensional grid (or axes or scale); say a 10x10 grid. In this example, the vertical grid is divided up into 10 (major) divisions and the horizontal grid is divided into 10 major divisions. To improve the precision, each of these divisions is further broken up into 5 minor divisions.

The horizontal axis (X-axis) represents time and the vertical axis (Y-axis) represents voltage. The scope displays (also called a signal trace or trace) the input signal voltage along the vertical (or Y-axis) while an internally generated signal (called the horizontal sweep or sweep signal) is simultaneously produced along the X-axis creating a 2-dimensional time trace of the input signal.

So if the scope is set to 1 volt/major vertical division and 0.5 seconds/major horizontal division, then a point situated at the 2-dimensional coordinates of 2 major vertical divisions plus 2 minor vertical division and at 3 major horizontal divisions plus 4 minor horizontal divisions would represent a 2.4 volts (or 1 volts/major vertical division times 2 major vertical division plus 1 volts/major vertical division times 2/5 major divisions [which is equal to 2 minor vertical divisions]) at a position of time of 1.9 seconds (or 0.5 seconds/major horizontal division times 3 major horizontal divisions plus 0.5 seconds/major horizontal division times 4/5 major divisions [which is equal to 4 minor horizontal divisions]) from the start of the waveform.

OR

$$\text{Voltage on the vertical scale is } 1\, volts/division \times 2.4\, divisions = 2.4 volts$$

$$\text{Time on the horizontal scale is } 0.5 \sec /division \times 3.8\, divisions = 1.9 \sec$$

Signal Inputs

They are at least one set of connections on each oscilloscope for connecting the external signal to be displayed. Modern scopes can display two or more signals at a time and, therefore, would have a set of jacks for each signal to be displayed. Since our scope is a dual trace scope there are two. These are sometimes called **Y-Inputs**.

Sometimes there are other jacks to connect signals which are used a references but may not be used to display. These inputs are called **Trigger Inputs**. (Certain scopes also support **X-Inputs**, which override the internal sweep signal, and, thereby, Lissajous patterns are displayed. Finally, there may be a **Z-Input** which is directly connected to the gun of the cathode ray tube and is used to modulate the intensity of the beam. These latter two inputs are just mentioned for completeness.)

As part of the **Y-Input** jacks there may be a switch to directly connect (**DC**) or capacitively connect (**AC**) the signal to the scope. For our scope this is a software switch. The latter passes any DC component of the signal while the latter filters out the DC. The latter may be used if the scope is "loading" down the circuit.

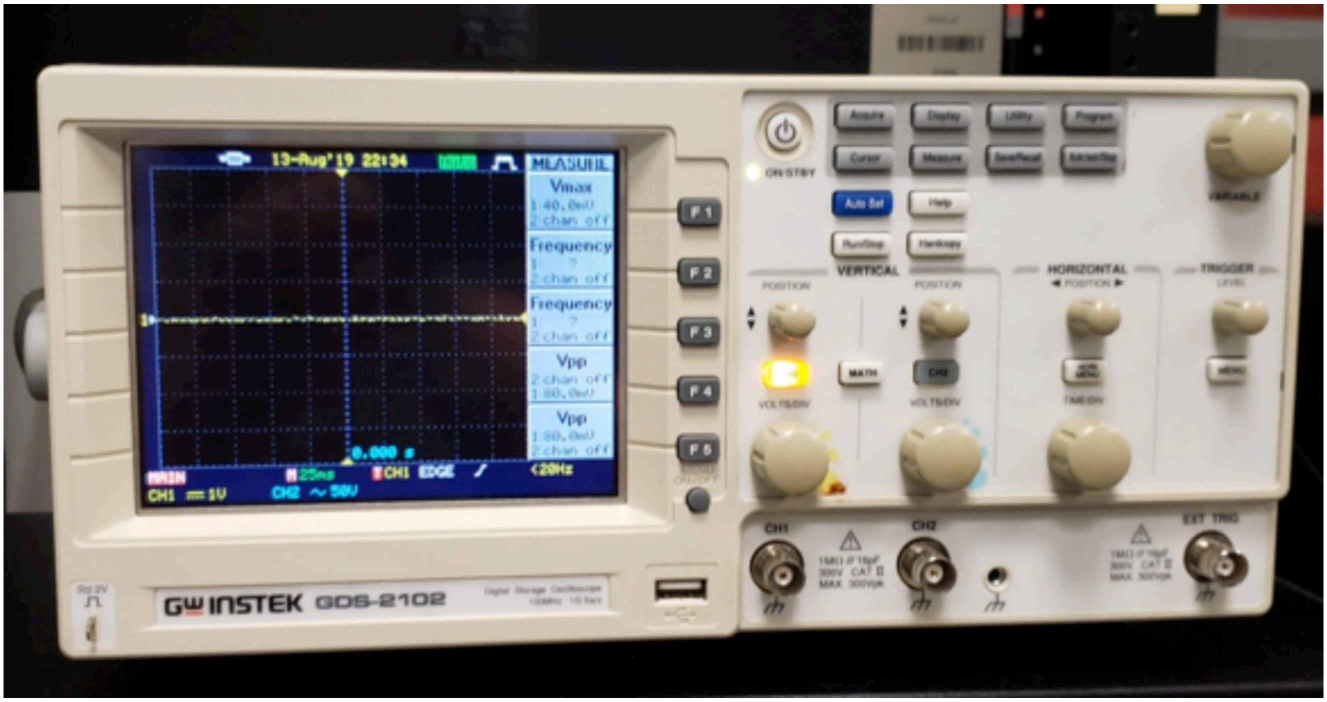
There may also be a calibration (**CAL**) setting on this switch to adjust the oscilloscope parameters.

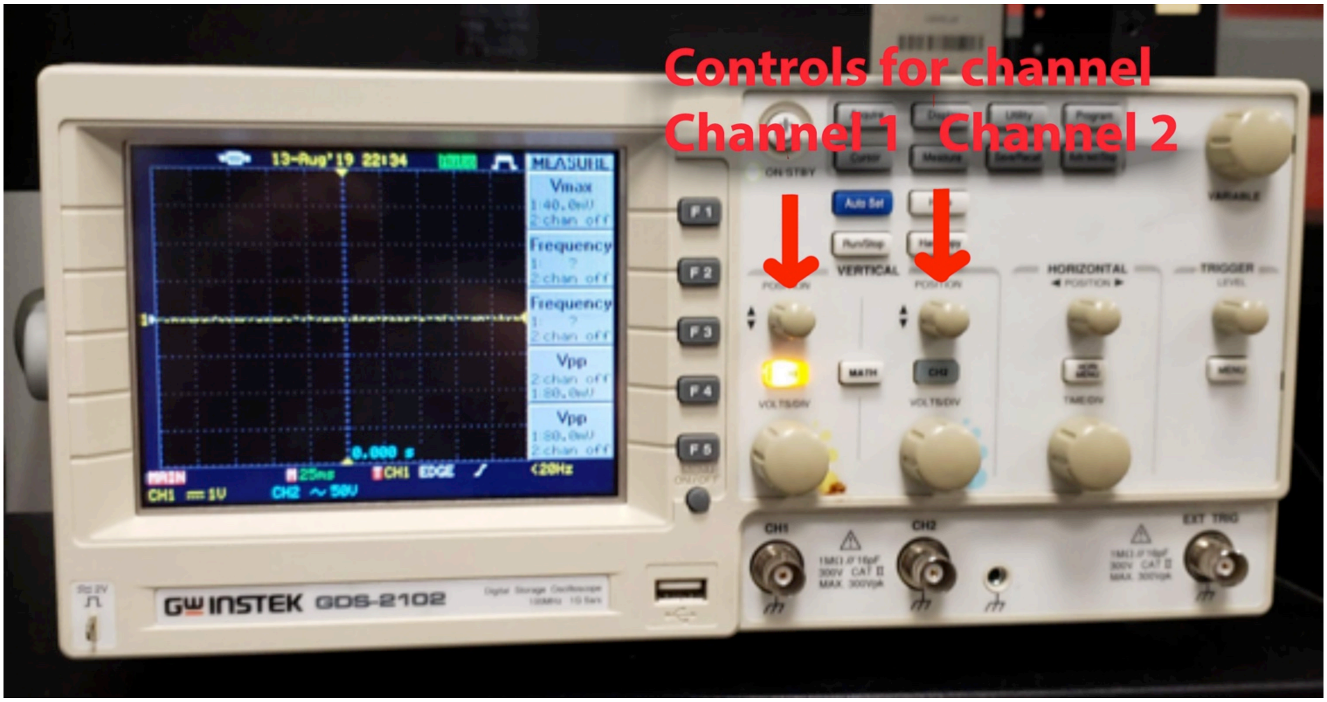
Controls

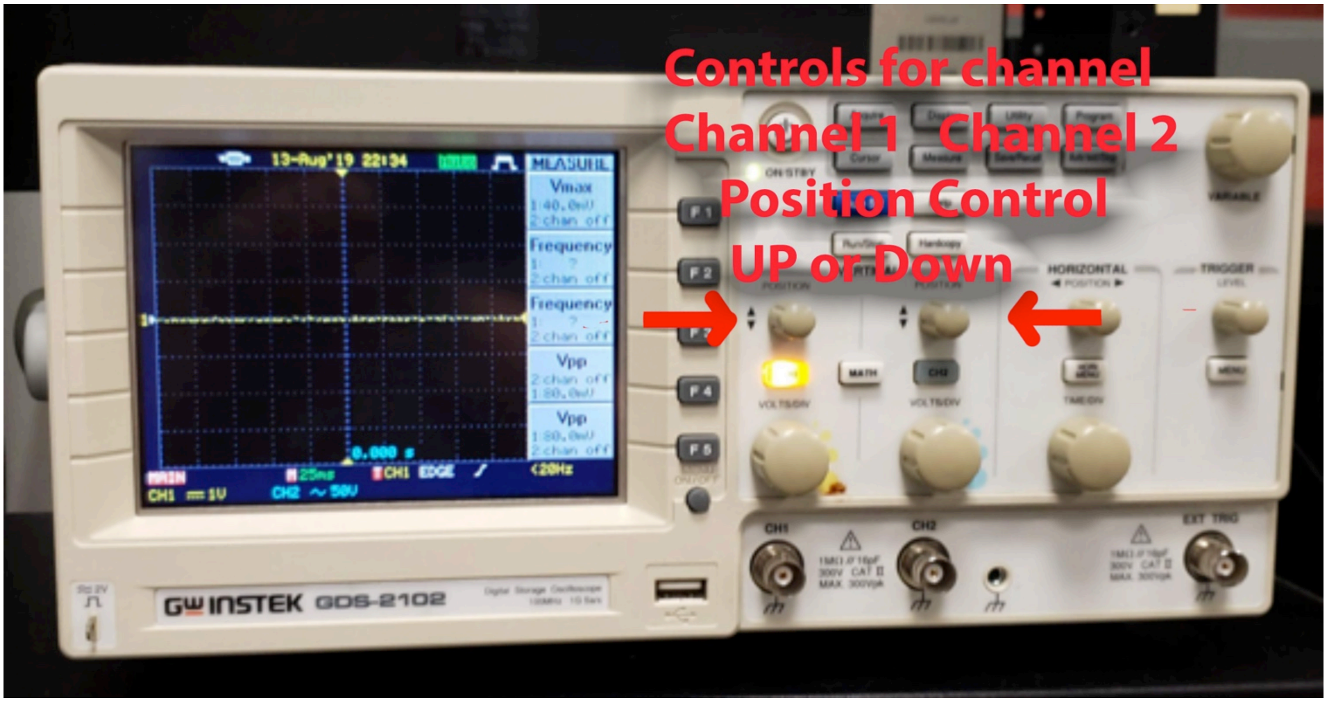
There are several controls on the scope. They include: the vertical grid (or scale) control (**Volts/Div**), vertical position control, the horizontal scale control (**Timebase**), intensity control, **Trigger Level**, **Trigger Source**, etc. There are vertical controls for each **Y-Input** supported by the scope.

The intensity control controls the brightness of the trace and the vertical position control is used to set the zero voltage value of the signal along the Y-axis (e.g., at the center of the grid).

The basic scope controls are the vertical (**Volts/Div**) and horizontal (**Timebase**) controls.




Controls for channel
Channel 1 Channel 2

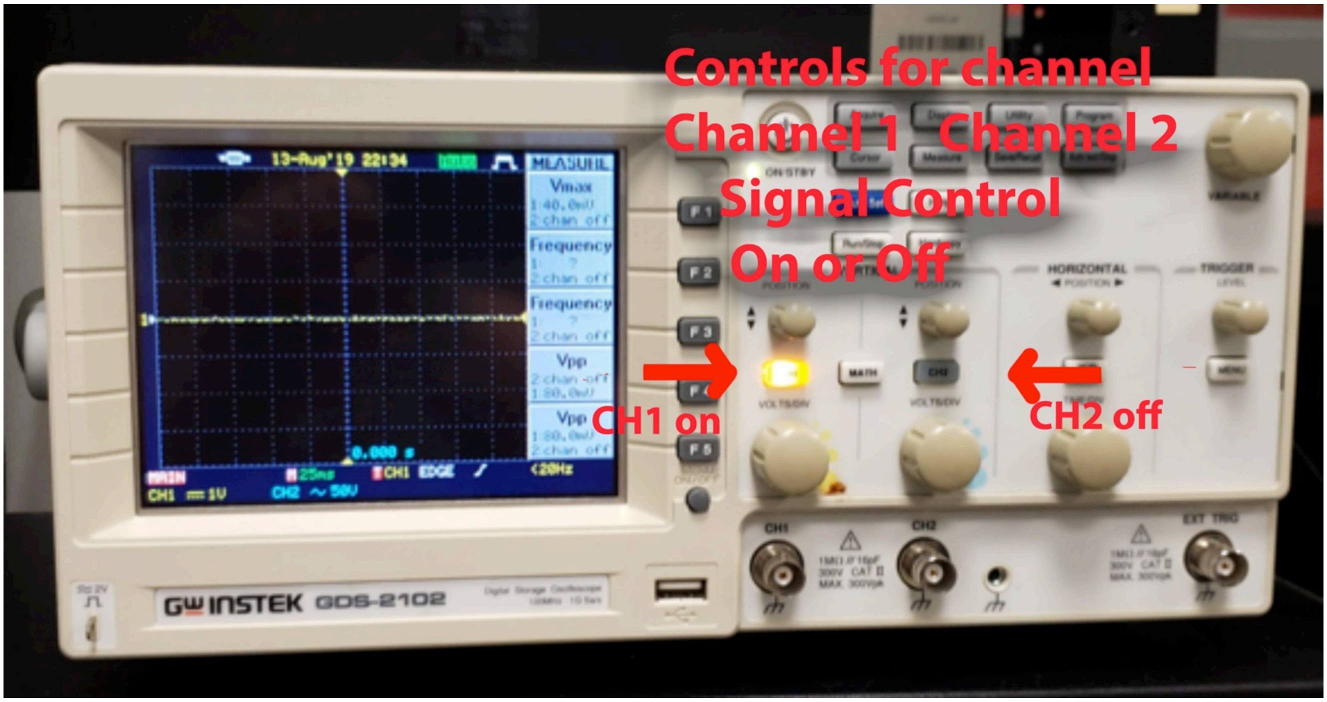


Controls for channel

Channel 1 Channel 2

Position Control

UP or Down



Controls for channel

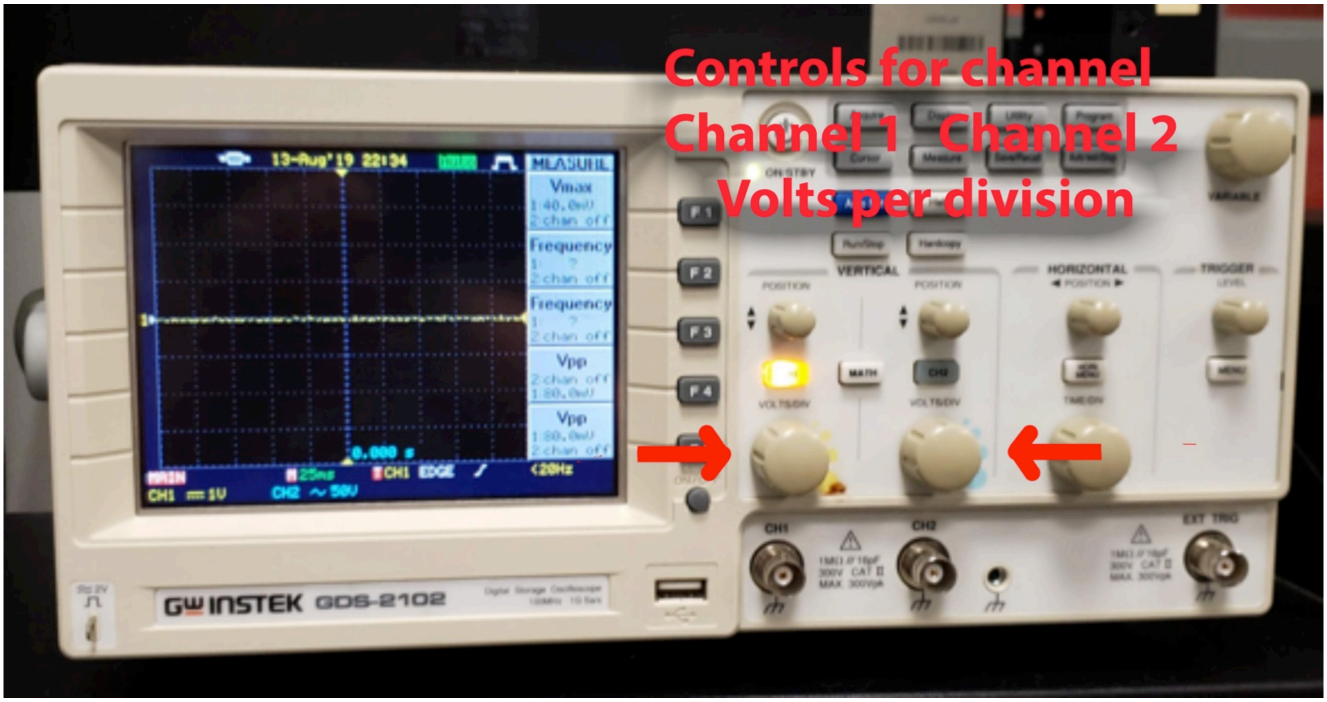
Channel 1 Channel 2

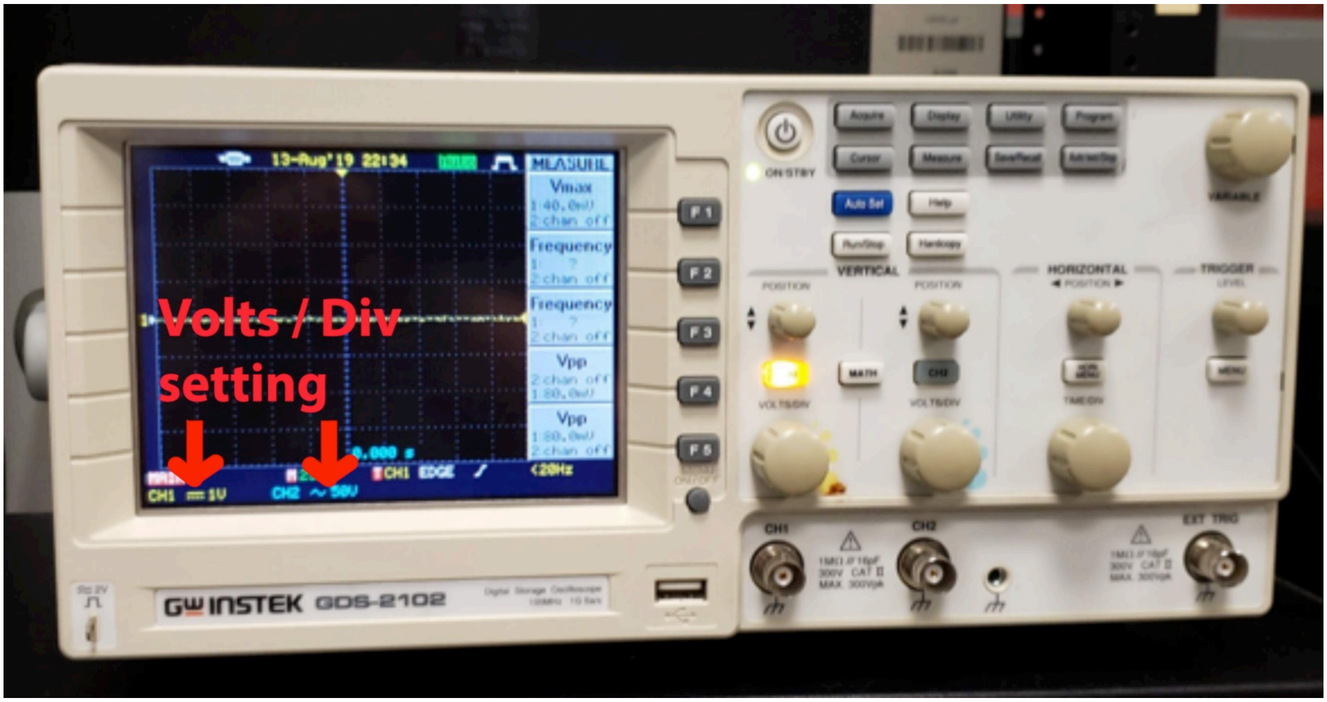
Signal Control

On or Off

CH1 on

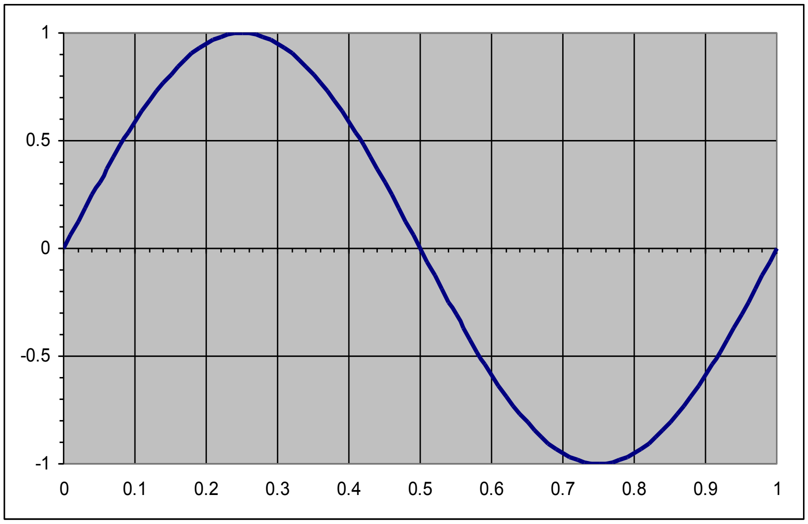
CH2 off


Controls for channel
Channel 1
Channel 2
Volts per division
GW INSTEK GDS-2102

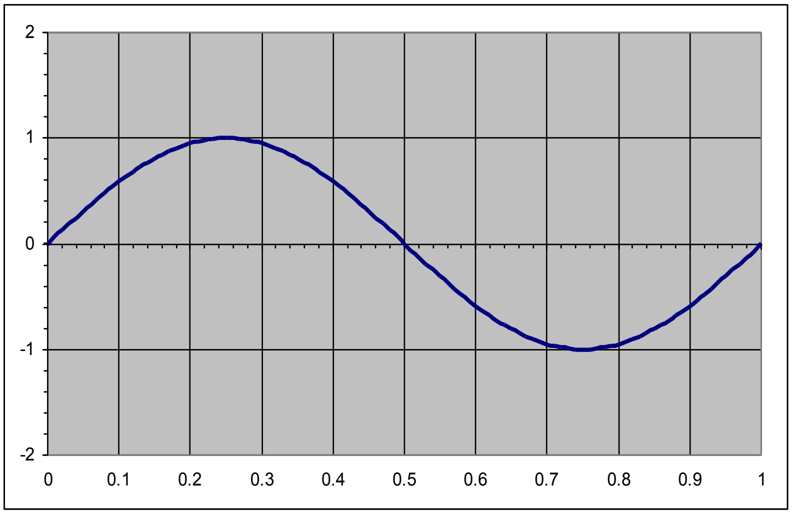

Volts / Div
setting
CH1 ═ 1V
CH2 ∼ 50V
GW INSTEK GDS-2102

Volts/Div

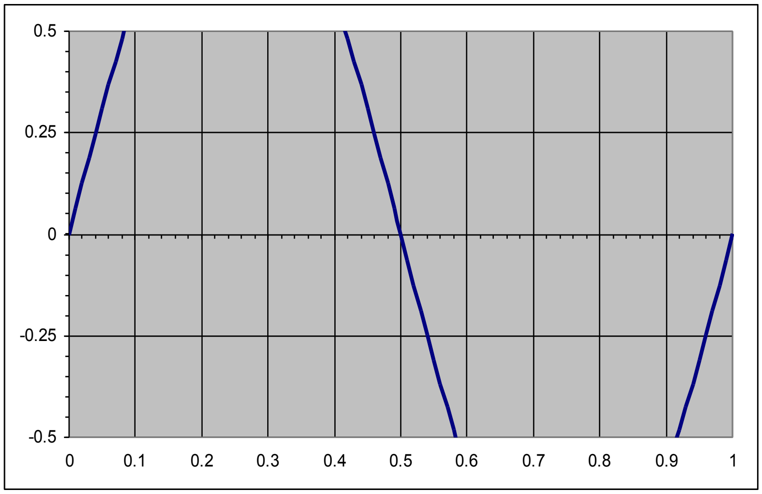
The vertical scale control is used to set how one reads the voltage values from scope's Y-axis grid. This is called the **Volts/Div**. The figure following shows a sine wave with amplitude of 1 volt and the **Volts/Div** is set to 0.5 volts/division. (I am using a 4x10 grid for the display.)



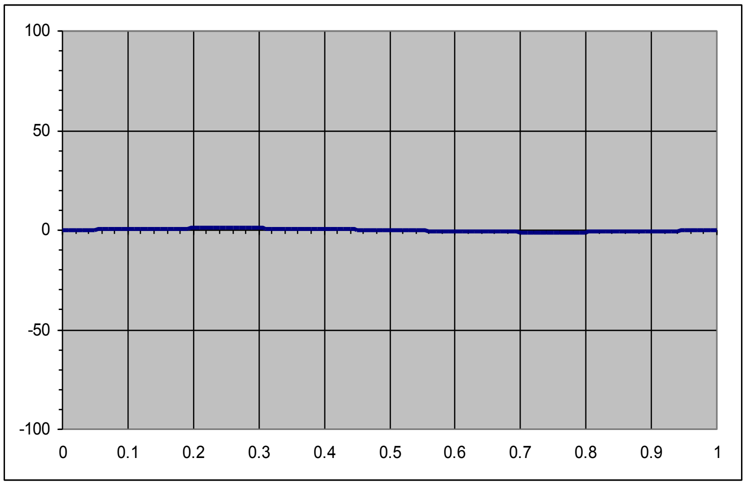
In the following figure, the same sine wave is displayed; however, the **Volts/Div** is set to 1 volt/division.



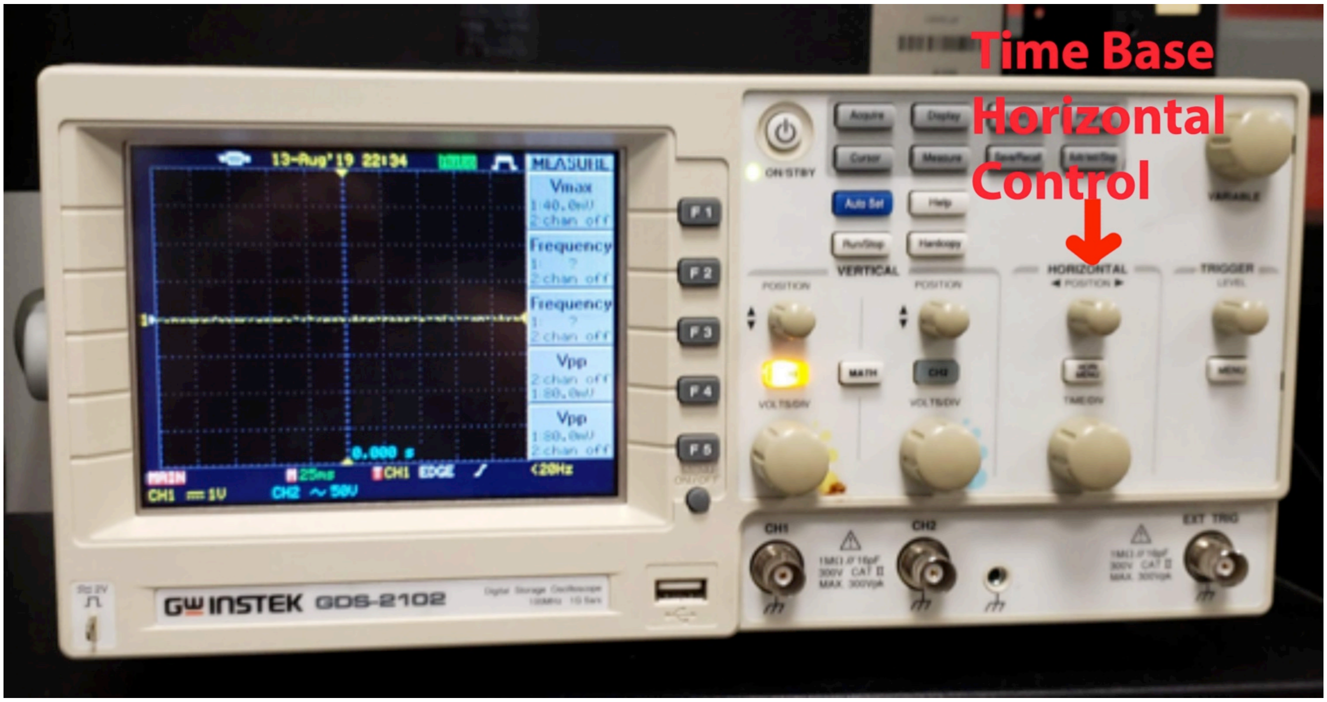
If you set the **Volts/Div** too low, you'll clip the signal. This figure shows the same sine wave with a **Volts/Div** of 250 millivolts/division.

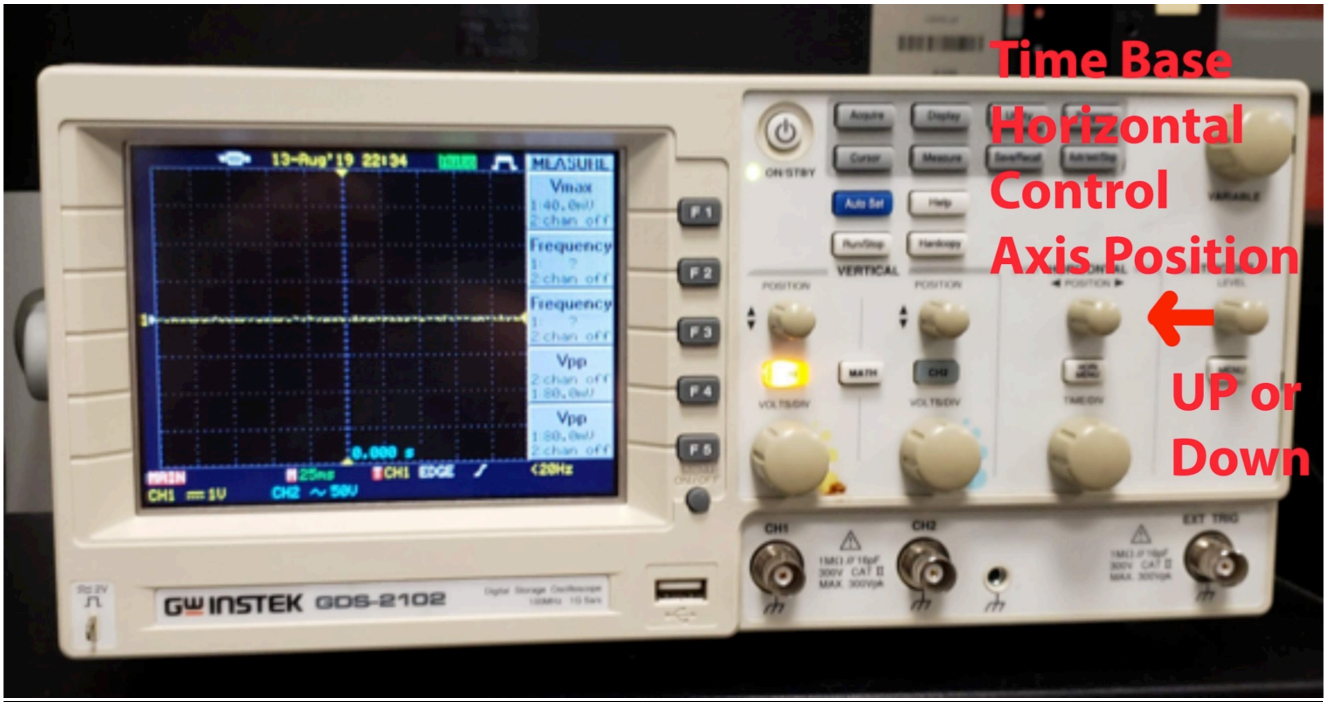


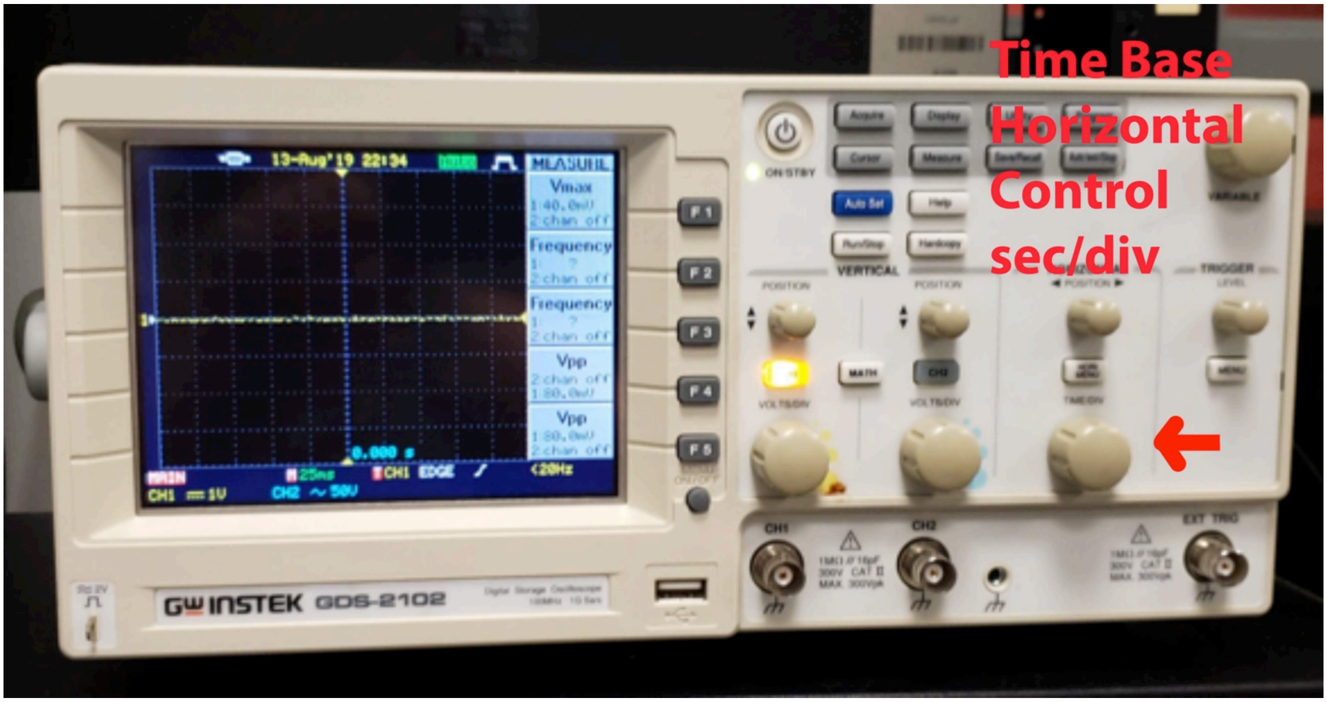
Likewise, setting it too high, and you'll won't find the signal. . This figure shows the same sine wave with a **Volts/Div** of 50 volts/division.

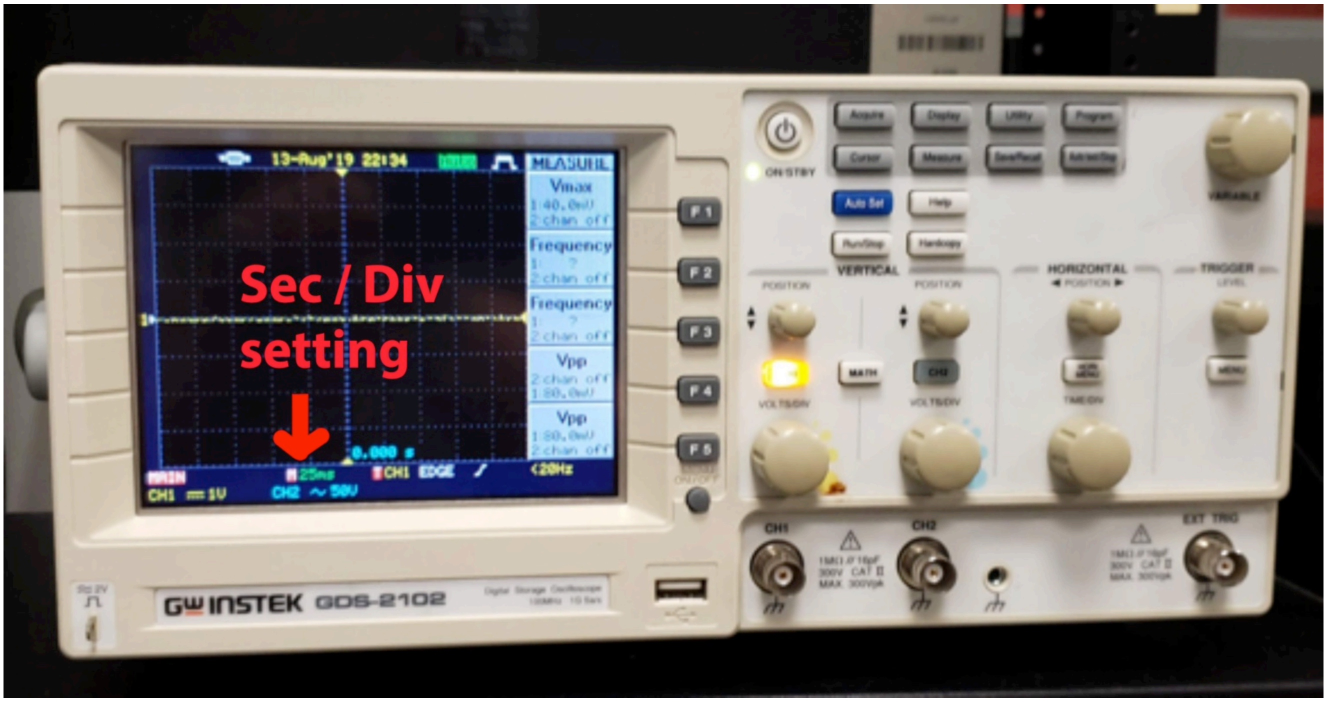


Therefore, knowing the approximate voltage maximums and minimums of the input signal should be the guiding factor for choosing an appropriate value for the ***Volts/Div****.*


Time Base
Horizontal
Control
HORIZONTAL
GW INSTEK GDS-2102

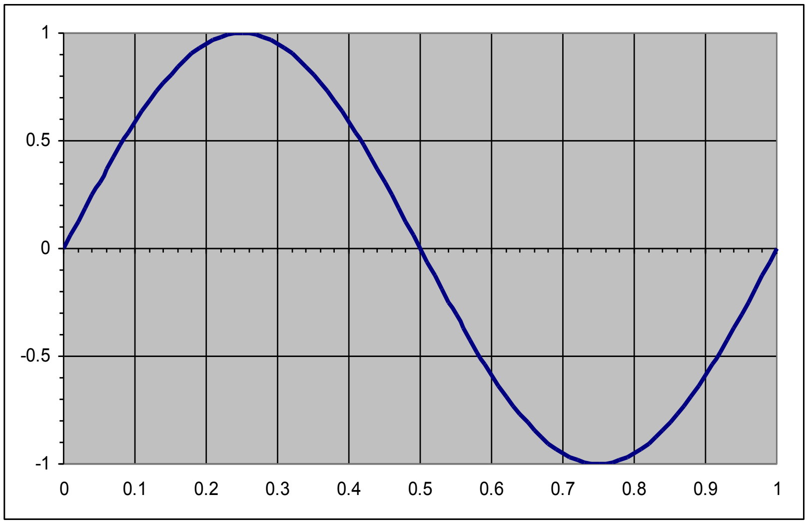

Time Base
Horizontal
Control
Axis Position
UP or
Down
GW INSTEK GDS-2102



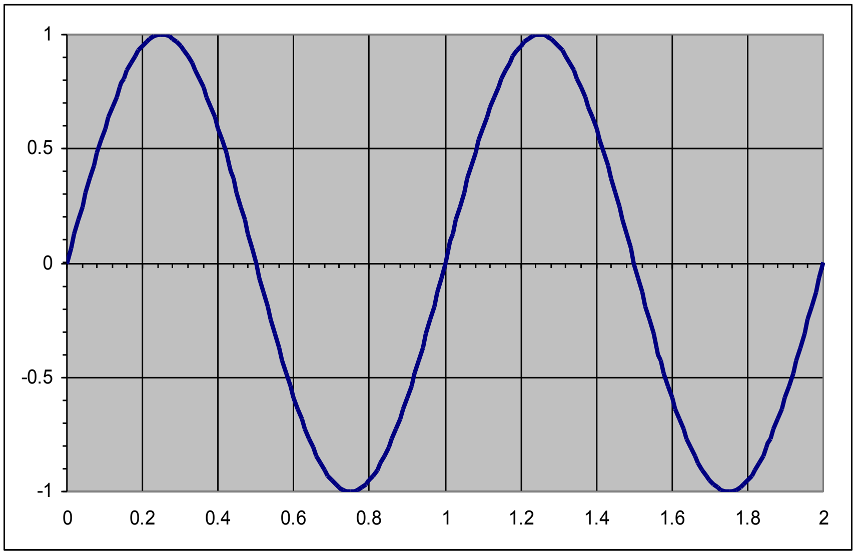


Timebase

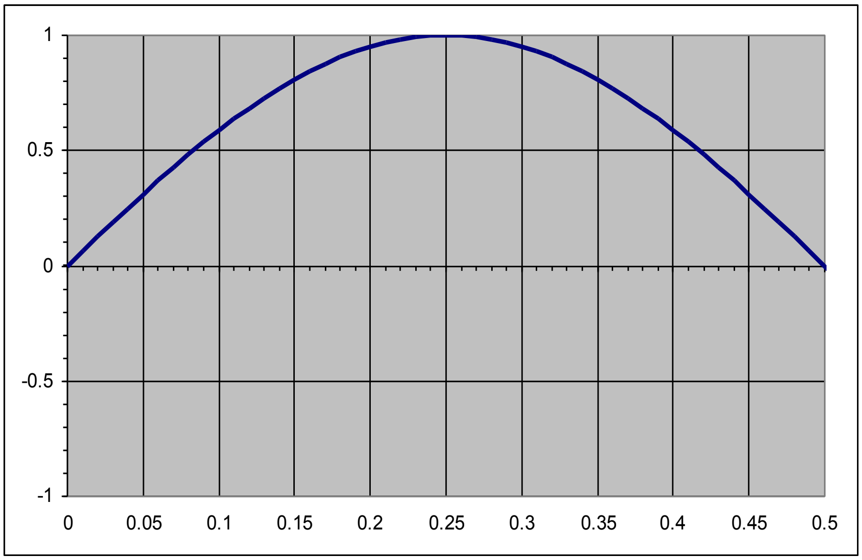
(Assume that **Volts/Div** is set to 500 millivolts/division = .5 volts/division.) The **Timebase** controls how the horizontal (X-axis) is read. In the following figure, a sine wave with frequency 1 Hz is displayed. In this case, the frequency is 1 Hz and its period is 1 complete cycle in 1 second (recall Hz = cycles per second). Since the **Timebase** is set to 0.1 seconds (or 100 milliseconds/division) and there are 10 divisions on the horizontal axis, a second of time spans the full X-axis and, therefore, a full cycle will be displayed.



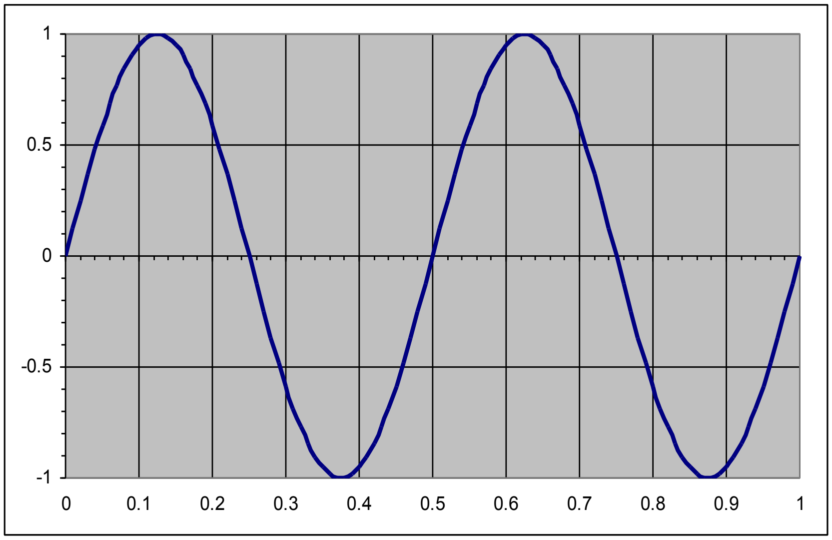
Setting the **Timebase** to 200 milliseconds/division X 10 divisions = 2 seconds will yield a display of 2 cycles.



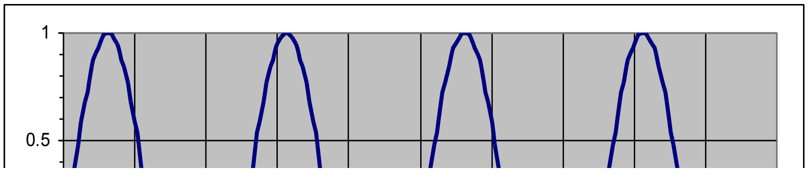
Therefore, increasing the **Timebase** will display more cycles of a periodic signal. Increasing too much will clutter the display. Conversely, reducing the **Timebase,** fewer cycles will be displayed. In the following figure, the **Timebase** is set to 50 milliseconds/division and one half of a cycle is displayed. Reducing is too much may display a useless fragment of a cycle.



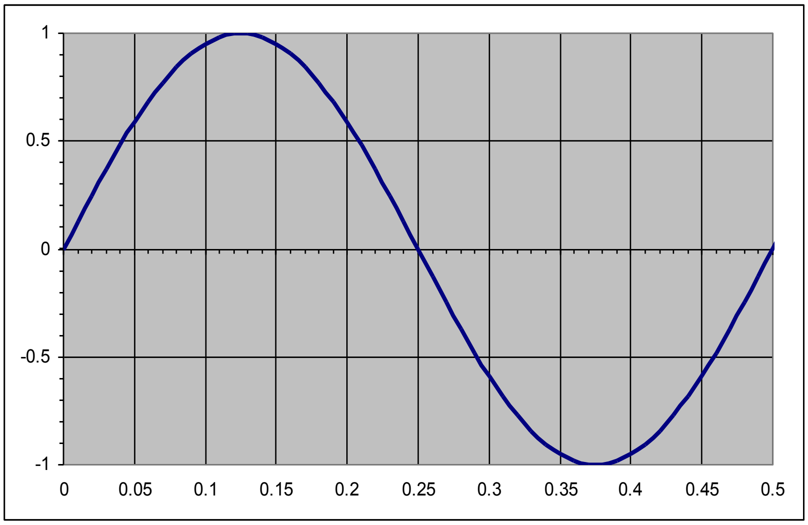
Now, what happens when the frequency changes? For a sine wave with frequency of 2 Hz has a period of 0.5 second (or 500 milliseconds). Therefore, with the **Timebase** set at 100 milliseconds/division, our 10-division scope will display 2 cycles



and with a **Timebase** set at 200 milliseconds/division, 4 cycles will be displayed.



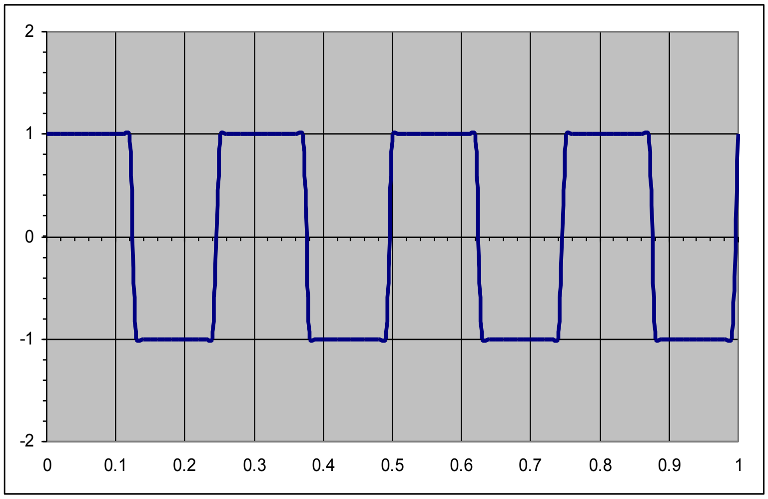
As stated previously, increasing the **Timebase** further will display more cycles. However, to display one cycle of the 2 Hz sine wave, the **Timebase** needs to be reduced to 50 milliseconds/division (since the inverse of the frequency 2 Hz = 0.5 seconds is the signal's period and since our scope has 10 divisions, we have 50 milliseconds).



Therefore, reducing the **Timebase** will support higher frequency periodic signals.

The above discussion is true whether the signal is a sine wave, square wave, or other type of periodic signal.

The following figure shows the trace of a square wave with a frequency of 4 Hz.



Therefore, knowing the approximate maximum frequency of the input signal is the guiding factor for choosing an appropriate value for the ***Timebase****. Recall that the inverse of the maximum frequency of a periodic signal will yield the (time)* ***period*** *of 1 cycle. Therefore, the* ***Timebase*** *should be calculated by taking the* ***period*** *of the signal and dividing it by the number of horizontal X-axis divisions times the desired number of cycles to be displayed.*

How to adjust the Timebase and Volts/Div

When an unknown signal (both in voltage and frequency), one may have to adjust both the **Timebase** and **Volts/Div** in a sequential manner until a clear signal is discerned. For example, if the unknown signal races (moves slowly) across the screen, lower (raise) the **Timebase** until a stationary signal is seen. If the amplitude is low (high), raise (lower) the **Volts/Div.** This may have to be iteratively performed until an acceptable signal is obtained.

Trigger Level and Trigger Source

The trigger is used to determine where (in time) to start of the displayed signal. This feature is used to view the displayed in relation to a secondary signal and is used for timing purposes. For example, one may want to know the relationship of the input signal to the output signal.

First, the **Trigger Source** selects which signal is to be used as the trigger. Typically, the INT is used to select the displayed signal for the trigger (self-trigger), LINE is used to select the 60 Hz line voltage (provided by the electric power company), and EXT is used to select an external signal.

The **Trigger Level** is used to adjust the voltage level of the trigger signal. This is also useful for synchronizing a signal whose frequency is not an exact multiple of the **Timebase**.

Connections

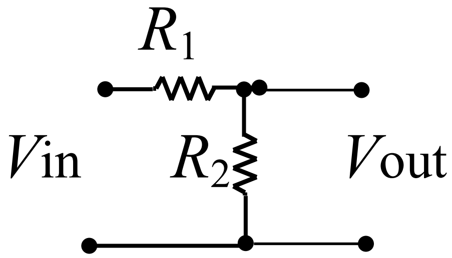
Oscilloscopes and other devices accept as input BNC connectors. BNCs are less noisy because of shielding.

Inside of the BNC is +
And the outside is –

BASIC MEASUREMENTS (Do steps 1 – 2 and consult the Appendices for how to collect and print the data for step 1 and 2. This laboratory requires thoroughness. So take your time.

1. Using the voltmeter, measure the output voltage, V_{out}, vs input voltage, V_{in}, (use the 9 volt batteries for V_{in}) for the following values of R_1 and R_2:

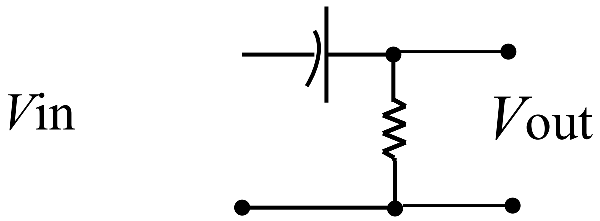
R_1	R_2
10k	10k
10k	1k
1k	10k

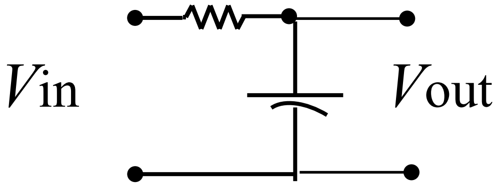


See Appendix A for how to collect and plot this data.

2. For the following circuits using the oscilloscope, determine the transfer function (magnitude and phase angle) for 10 frequencies from 1/100 of the cutoff frequency to about 100 times the cutoff frequency. Choose R and C such that the cutoff frequency is around 200Hz. The cutoff frequency for these circuits is 1/(2*pi*R*C). (For example, R=1k, C=100nf yields a cutoff frequency of 1,592Hz.)

See Appendix B to for how to collect and plot this data. And describe what each is doing as a function of frequency.

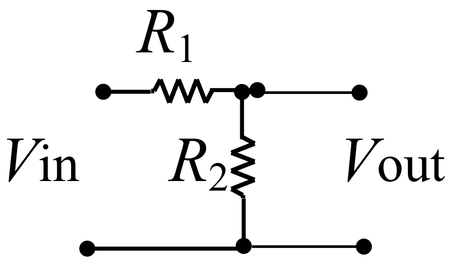




3. Find the 3dB point. Check this value by comparing it to a calculation? The 3dB point occurs at the frequency when Vout/Vin = 0.7 times the maximum value of Vout/Vin.

4. Apply a square wave to these circuits. Describe what happens as the frequency of the square wave changes.

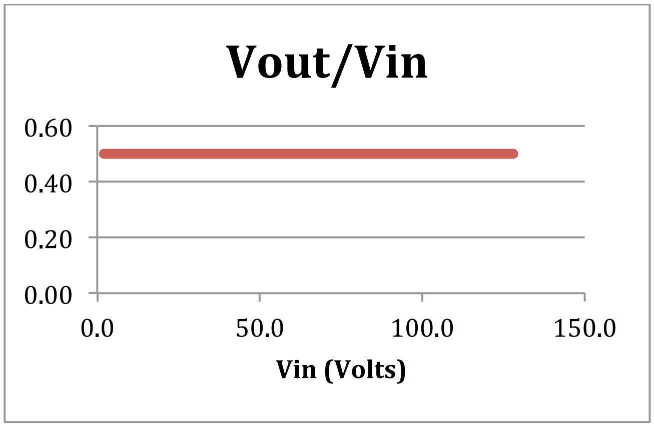
Appendix A: How to collect and plot the transfer function, Vout/Vin, of this resistive circuit.



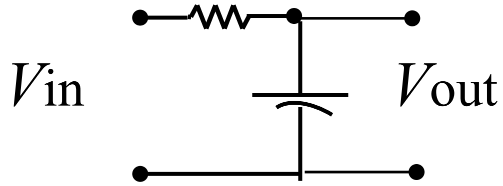
$$Vin = IR_1 + IR_2 = I(R_1 + R_2)$$
$$Vout = IR_2$$
$$\frac{Vout}{Vin} = \frac{IR_2}{I(R_1 + R_2)} = \frac{R_2}{(R_1 + R_2)}$$

Connect the Function Generator to the input of the circuit. Using the Oscilloscope connect Vin to Channel 1 and Vout to Channel 2. Vary the output of the Function Generator to 5 different values of Vin and measure Vin and Vout with the Oscilloscope. Calculate and plot Vout/Vin for the 5 values used. Note this is table is and example for when R1=R2.

Vin	Vout	Vout/Vin
2.0	1.0	0.50
4.0	2.0	0.50
8.0	4.0	0.50
16.0	8.0	0.50
32.0	16.0	0.50
64.0	32.0	0.50
128.0	64.0	0.50



Appendix B: How to collect and plot the transfer function, Vout/Vin, of this RC circuit. Repeat this for the other RC circuit.



$$Vin = IR + IZ_C = I(R + Z_C)$$

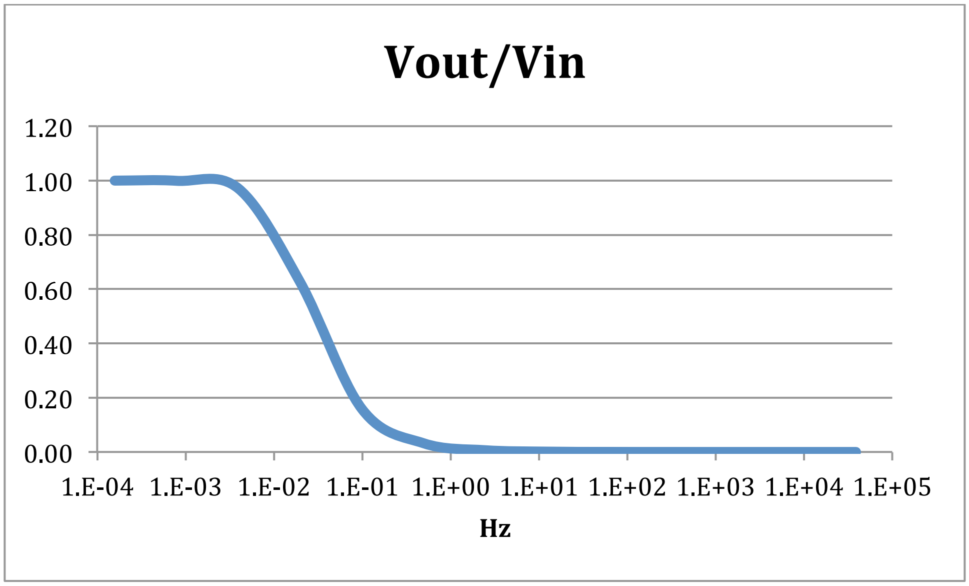
$$Vout = IZ_C$$

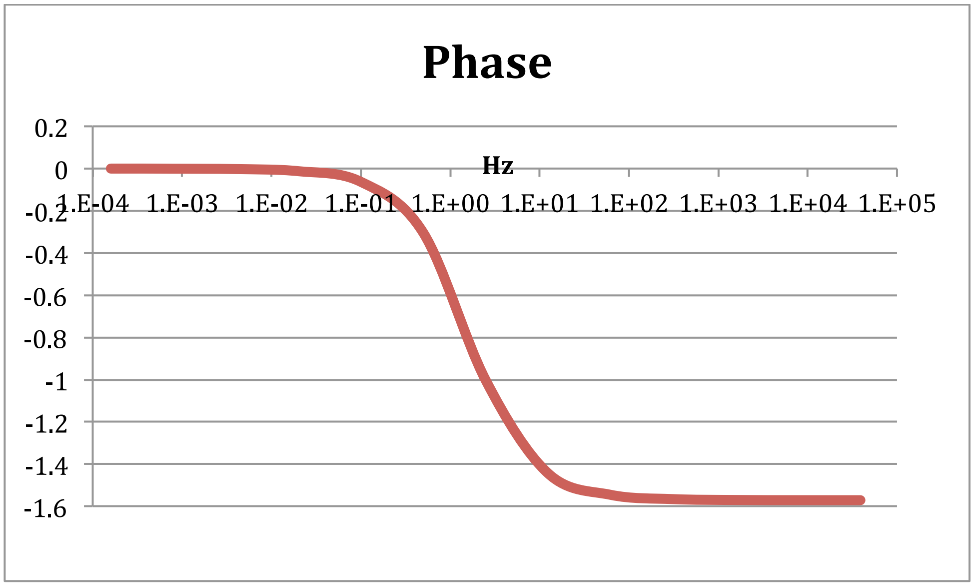
$$\frac{Vout}{Vin} = \frac{IZ_C}{I(R+Z_C)} = \frac{Z_C}{R+Z_C} = \frac{\frac{1}{j\omega C}}{R+\frac{1}{j\omega C}} = \frac{1}{1+j\omega RC}$$

$$= \frac{1}{\sqrt{1+(\omega RC)^2}\angle\tan^{-1}(\omega RC)} = \frac{1}{\sqrt{1+(\omega RC)^2}}\angle-\tan^{-1}(\omega RC)$$

Connect the Function Generator to the input of the circuit. Using the Oscilloscope connect Vin to Channel 1 and Vout to Channel 2. Vary the frequency of the Function Generator to obtain 10 different frequencies from about 1/10 of the cutoff frequency to about 10 times the cutoff frequency and measure Vin and Vout and the time shift between Vin and Vout with the Oscilloscope. 5 of the 10 chosen frequencies should be 2 just below, 2 just above, and 1 at the cutoff frequency. The remainder of the chosen frequency show be several decades below and above the cutoff frequency. Calculate and plot Vout/Vin and the Phase between Vout and Vin for the 10 values used. Note that the Phase is equal to the radian frequency (not Hertz) times the time shift.

Freq	Vin	Vout	Vout/Vin	Time Shift	Phase
0.000	1.00E+00	1.0000	1.000	-1.00E-01	0.000
0.001	2.00E-01	0.2000	1.000	-1.00E-01	0.000
0.004	4.00E-02	0.0400	1.000	-1.00E-01	-0.002
0.020	8.00E-03	0.0080	1.000	-1.00E-01	-0.012
0.099	1.60E-03	0.0016	0.998	-9.99E-02	-0.062
0.497	3.20E-04	0.0003	0.954	-9.69E-02	-0.303
2.487	6.40E-05	0.0001	0.539	-6.41E-02	-1.001
12.434	1.28E-05	0.0001	0.127	-1.85E-02	-1.443
62.170	2.56E-06	0.0001	0.026	-3.96E-03	-1.545
310.849	5.12E-07	0.0001	0.005	-8.02E-04	-1.566
1554.247	1.02E-07	0.0001	0.001	-1.61E-04	-1.570
7771.237	2.05E-08	0.0001	0.000	-3.22E-05	-1.571
38856.187	4.10E-09	0.0001	0.000	-6.43E-06	-1.571


Vout/Vin
1.20
1.00
0.80
0.60
0.40
0.20
0.00
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05
Hz


Phase
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
Hz
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
1.E+01
1.E+02
1.E+03
1.E+04
1.E+05