ME 360: FUNDAMENTALS OF SIGNAL PROCESSING, INSTRUMENTATION AND CONTROL

Experiment No. 1 – Introduction to Laboratory Instruments

1. CREDITS

Originated: N. R. Miller, June 1990
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2. OBJECTIVE

(a) Learn the proper use of the digital multimeter (DMM), function generator, and oscilloscope.
(b) Measure the frequency response (gain and phase shift) of a first-order, low-pass, RC filter.
(c) Determine an unknown capacitance.

3. KEY CONCEPTS

(a) The oscilloscope and digital multimeter are powerful instruments. The oscilloscope is restricted to voltage measurements (AC and DC) but provides better *qualitative* information by allowing one to observe transient waveforms. The multimeter measures current and resistance as well as voltage and typically yields better *quantitative* information than the oscilloscope.
(b) Except in rare circumstances, voltage measurements are *nonintrusive* (do not materially affect normal circuit operation) whereas current and resistance measurements are *intrusive* (the measuring instrument becomes part of the circuit).
(c) A four-wire resistance measurement uses two sets of leads connected between the multimeter and the unknown resistance. One set applies a known current to the resistor. The second set is used solely for voltage measurement with ideally zero current flow. A four-wire resistance measurement eliminates the effect of lead resistance which is important in measuring small resistances.
(d) A first-order system is characterized by two dynamic parameters: (i) the steady-state gain K and (ii) the system time constant τ.
(e) A low-pass RC filter consists of a resistor and capacitor in series. The input voltage is applied across both components in series, and the output voltage is measured across the capacitor.
(f) A low-pass, RC filter behaves as a first-order system with K = 1 and τ = RC.
(g) The key features of a first-order system are:

Governing Equation	$\tau \dfrac{dV_{out}(t)}{dt} + V_{out}(t) = K\ V_{in}(t)$
Transfer Function	$\hat{G}(s) = \dfrac{K}{\tau s + 1}$
Steady-state Response	Input: $V_{in}(t) = V_\infty$ where V_∞ is constant with time Output: $V_{out}(t) = K V_\infty$
Step Response	Input: $V_{in}(t) = V_\infty$ for t > 0 where V_∞ is constant with time Output: $V_{out}(t) = [V_{out}(0) - K V_\infty] \exp(-t / \tau) + K V_\infty$
Sinusoidal Response	Input: $V_{in}(t) = A \cos(\omega t) = A \cos(2 \pi f t)$ where A is amplitude, ω is the angular frequency in rad/s, and f is the frequency in Hz Output: $V_{out}(t) = G(\omega) A \cos[\omega t + \phi(\omega)]$ where $G(\omega)$ is gain and $\phi(\omega)$ is phase shift given by $G(\omega) = \dfrac{K}{\sqrt{1 + (\tau \omega)^2}}$ $\phi(\omega) = -\arctan(\tau \omega)$

(h) In this experiment, we measure (i) the resistance R, (ii) the gain G(ω) and (iii) the phase shift $\phi(\omega)$ of a low-pass RC filter, and then use these values to solve for the time constant τ and the unknown capacitance C.

4. SYNOPSIS OF PROCEDURE

(a) Measure DC voltage using the digital multimeter.

(b) Measure resistance using the digital multimeter (DMM). Compare the measurement with the nominal value coded on the resistor.

(c) Measure current using the digital multimeter. Compare the measurement with the value calculated using Ohm's Law.

(d) Observe a DC waveform on the oscilloscope. Measure the voltage using the on-screen cursors. Compare the oscilloscope measurement with the digital multimeter measurement.

(e) Observe an AC waveform on the oscilloscope. Measure the peak-to-peak voltage, period, and DC offset of the waveform using the on-screen cursors. Compare these results with the values programmed into the function generator.

(f) Measure the RMS voltage of the AC waveform with the digital multimeter. Compare the value obtained with the function generator settings and oscilloscope measurement.

(g) Determine the gain G(ω) and phase shift $\phi(\omega)$ of a low-pass RC filter by comparing the input and output sinusoids on the screen of the oscilloscope.

(h) Determine the gain G(ω) of a low-pass RC filter by taking the ratio of the RMS input and output voltages measured with the digital multimeter.

(i) Use the gain and phase shift to calculate the filter time constant τ. Use the time constant and the measured resistance R to find the unknown capacitance of the filter capacitor.

5. BACKGROUND

In this experiment, we consider three of the most useful general-purpose electronic instruments available; namely, the digital multimeter (DMM), the oscilloscope, and the function generator. Because we use these instruments throughout the semester, we must become familiar with their operation and how to use them efficiently and effectively. Background information on each of these instruments appears in Appendices A, B, and C, respectively.

6. PROCEDURE

Important General Information – Please Read Carefully

*(a) **Always turn off the power supplies when changing connections. Dangling leads can easily contact the metal tabletop creating a short, blowing a fuse, creating an unsafe situation, or damaging the equipment.***

(b) Disconnect the leads from the instruments when not in use. Connect the instruments last after the wiring is checked carefully.

(c) If your station is missing something, ask your Laboratory Assistant to replace it. Do not take items from other stations.

### 6.1 Using the Digital Multimeter (DMM) for DC Voltage Measurement

6.1.1 Station Layout and Initial Setup

(a) In preparation for your laboratory session, review the information on the oscilloscope, digital multimeter, function generator, and patch panel in the appendices. Note the location and organization of the controls for each instrument. Also, understand the use of soft keys on the oscilloscope and the use of setup menus on the digital multimeter and function generator.

(b) In the laboratory, begin by examining the layout of your station. Note the location of the (i) oscilloscope, (ii) function generator, (iii) digital multimeter, (iv) analog computer, (v) patch panel, (vi) rack of leads on the end panel of the station, and (vii) three drawers under the table that contain additional items.

(c) Turn on the power to your station. The main power switch is located on the vertical post next to the analog computer. The switch is lighted in the *on* position.

(d) Power on the (i) oscilloscope, (ii) function generator, and (iii) digital multimeter.

(e) On the patch panel, locate (i) the +5 VDC power supply, (ii) the +10 VDC power supply, and (iii) the -10 VDC power supply. The power supply sockets are at the far left of the patch panel. The following table gives the nominal voltage of each socket with respect to chassis ground.

	"HI"		"LO"	
Power Supply	Color	Potential	Color	Potential
5 VDC	Red	5 VDC	Black	0 VDC
10 VDC	Blue	10 VDC	Black	0 VDC
-10 VDC	Black	0 VDC	Violet	-10 VDC

(f) Observe that the DMM has five input sockets as shown in the diagram below. The two leftmost sockets are used for four-wire resistance measurements. The top and middle right-hand sockets labeled "V Ω ⊷" are used for voltage, resistance, and diode measurements. The bottom and middle right-hand sockets are used for current measurements.
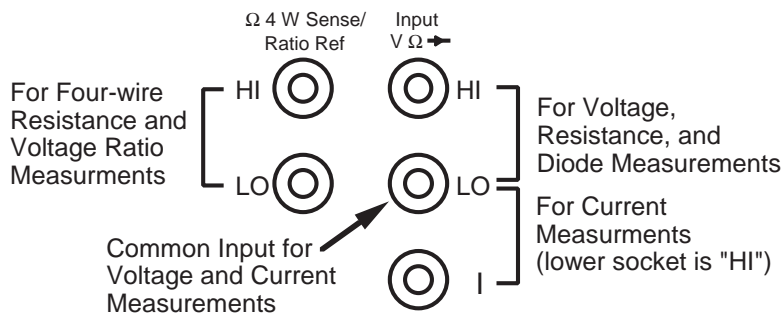
6.1.2 Measure 5 VDC Power Supply Voltages using DMM

(a) Measure the output of the 5 VDC power supply using DMM as shown below. Record the value on the data sheet
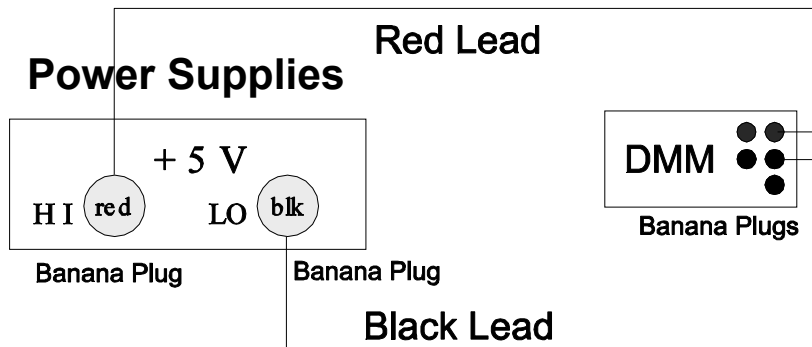
Detailed Procedure for Measuring Fixed Power Supply Voltage

- *Make sure the main power switch on the patch panel is turned off.*
- From the rack of leads on the end panel of your station, select one red lead and one black lead with banana plugs on each end.
- Plug the black lead into the black socket and the red lead into the red socket of the 5 VDC power supply.
- Connect the other end of each lead to the digital multimeter (DMM). For DC voltage measurement, connect the red lead to the top-right-hand socket labeled "HI". Connect the black lead to the middle-right-hand socket labeled "LO".
- Press the "DC V" key to place the DMM in DC-voltage mode.
- Turn on the power supplies using the toggle switch on the far left-hand side of the patch panel.

- Record the voltage output of the 5-VDC supply on the Data Sheet in the table entitled "Power Supply Voltages". Commas in the display are for readability only and do not affect the numerical value.
- If the DMM does not respond, look for "RMT" displayed in the lower left corner. If this reading is present, the DMM has been put into remote control mode by the personal computer. Press the blue "Shift" button to regain local control.

6.1.3   Measure Two Variable Power Supply Voltages using DMM

(a)   Locate the sockets on the patch panel labeled "HP 0 – 20 V" and the associated Hewlett-Packard power supply. Turn the supply on, and set the voltage to 1.123 V. (Detailed procedure is given below.)

(b)   Connect the multimeter to the sockets on the patch panel as shown below.
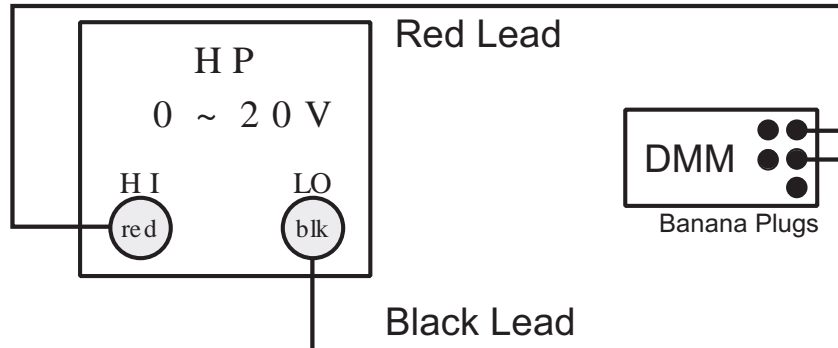
(c)   Measure the voltage using 5-1/2, 6-1/2, and 4-1/2 digits of resolution. Record these values on the Data Sheet.

(d)   Change the voltage on the Hewlett-Packard power supply to 1.234 V, and repeat the measurements for the three different meter resolutions. Record these values on the Data Sheet.

(e)   For each of the six measurements, determine the number of digits displayed.

(f)   After all measurements are taken, set the resolution back to 5-1/2 digits. Turn the Hewlett-Packard power supply   off.

Detailed Procedure for Measuring Variable Power Supply Voltage

- Set the voltage on the Hewlett-Packard power supply to 1.123 VDC by first pressing the "VSET" key, then keying in "1.123", and finally pressing "ENTER". (*Note that the display of the power supply may read a value slightly different than 1.123 V.*)
- Set the meter resolution to 4-1/2 digits by pressing shift then "4" (i. e., the "⌃" key) in the "RANGE / DIGITS" section of the front panel keys on the multimeter.
- Make sure that the instrument is on the most sensitive range for this voltage by pressing the "⌄" key until "OVLD" is displayed and then pressing the "⌃" key once.
- Record the voltage on the Data Sheet in the table entitled "Variable Power Supply Voltage" in the column labeled "DMM – 4-1/2 Digit [V]".
- Repeat the procedure for the 5-1/2 and 6-1/2 digit ranges.
- Change the power supply voltage to 1.234 V, and record the readings for each of the three resolutions.
- *Make sure the multimeter is on the most sensitive range that can be used for the specified voltage as above.*
- After all measurements are taken, cycle power on the DMM to return settings to default.
- Turn off the HP Power supply as we will not use it in the remainder of the lab.

6.2 Using the Digital Multimeter (DMM) for Resistance Measurement

6.2.1   Determine Nominal Resistance Values

(a)   Take the 5-Ω, 510-Ω, and 22.1-kΩ resistors from the parts box in the large drawer at your station. Record the resistance coding information on the Data Sheet in the table entitled "Nominal and Measured
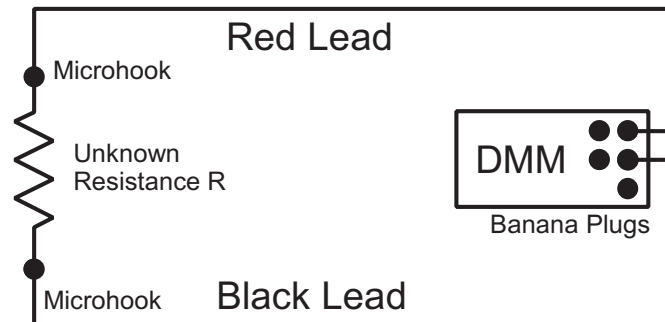
Resistances".

Detailed Procedure for Determining Nominal Resistance Values

- Nominal resistance values and tolerances are specified on the body of a resistor.
- One method is to simply print the values on the resistor. Alternatives include the color coding scheme and military specification summarized in Appendix D.
- The actual resistance varies from the nominal value owing to manufacturing variability. For example, a 10-kΩ resistor with a 10 % tolerance may have a resistance between 9 kΩ and 11 kΩ and still be within manufacturing tolerances.

6.2.2 Measure Resistance of Three Resistors

(b) Using the resistance measurement circuit as shown below, measure the resistance of the three resistors, and record these values on the Data Sheet.
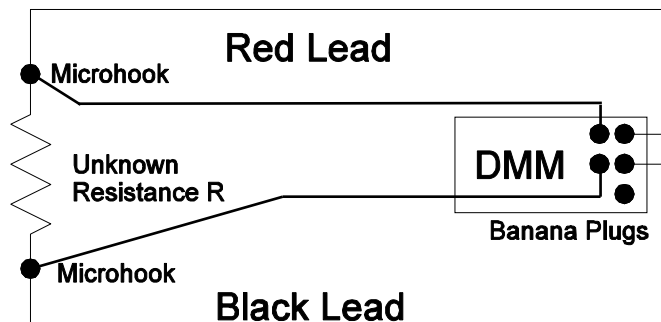

Detailed Procedure for Two-wire Resistance Measurements

- Select red and black leads with microhooks on one end and a banana plugs on the other end.
- Connect the microhooks to the resistor leads and the banana plugs to the DMM as shown above.
- Press the "Ω 2W" key on the DMM to activate two-wire resistance measurement.
- Read the resistance on the display of the DMM and record this value on the Data Sheet in the table entitled "Nominal and Measured Resistances".

(c) Determine the error and percentage error between the nominal and measured values, and record these values on the Data Sheet.

### 6.2.3 Compare Two-wire and Four-wire Resistance Measurements

(a) Set up the four-wire resistance measurement shown below. Measure the resistance of the 5-Ω resistor, and record this value on the Data Sheet. Compute the absolute and percentage difference between the two-wire and four-wire measurements as specified on the Data Sheet.

Detailed Procedure for Four-wire Resistance Measurements

- Select a second pair of red and black leads with microhooks on one end and banana plugs on the other end. Connect this pair of leads between the resistor and the four-wire resistance sockets of the DMM.
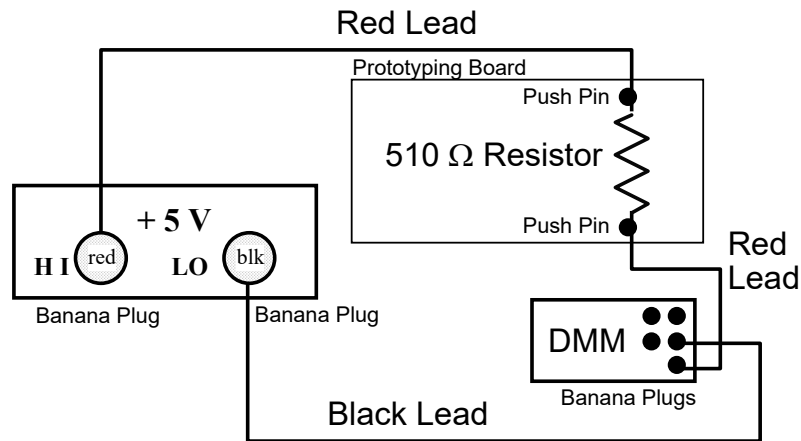
- Activate four-wire resistance mode (designated by "Ω 4W") by first pressing the shift key then the "$\Omega\,2W\,/\,\Omega\,4W$" key.
- A four-wire resistance measurement eliminates the effect of lead resistance as shown below.

Two-wire Resistance Measurement

$$V\,/\,i = R + R_{L1} + R_{L2}$$

Four-wire Resistance Measurement

$$R = V'\,/\,i$$
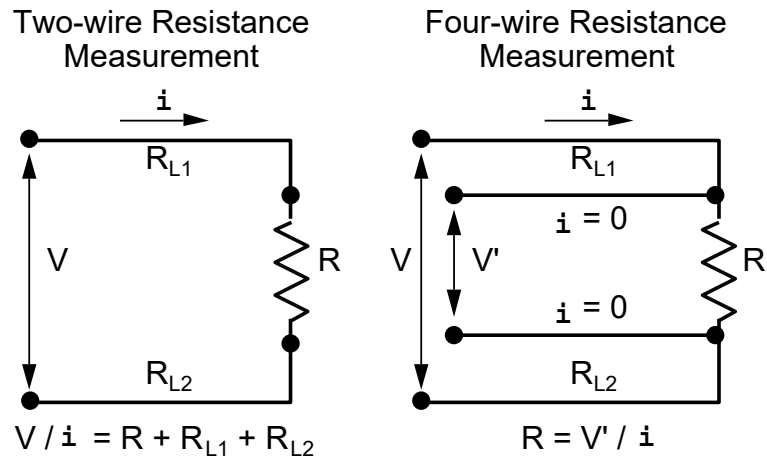
6.3 Using the Digital Multimeter (DMM) for DC Current Measurement

### 6.3.1 Wire Circuit for Current Measurement

(a) Locate the white prototyping board stored in the large drawer at your station. Wire the circuit shown below using the 5 VDC supply, the 510-Ω resistor, and the DMM (set to measure current).

Red Lead

Prototyping Board

Push Pin

510 Ω Resistor

Push Pin

Red Lead

+ 5 V

H I (red)   LO (blk)

Banana Plug   Banana Plug

DMM

Banana Plugs

Black Lead

Detailed Procedure for Making Current Measurements

- The figure below shows the internal connections of the prototyping board.
- The four rows of sockets running the full length of the board are for power and ground buses.
- The many sets of five sockets running in the transverse direction are intended for circuit connections and are referred to here as "connection groups".
- Place the 510-Ω resistor on the board so that its leads are in any two separate connection groups.

For Power and Ground Buses

Connection Groups

Each set of five sockets is used to make a circuit connection

Connection Groups

For Power and Ground Buses
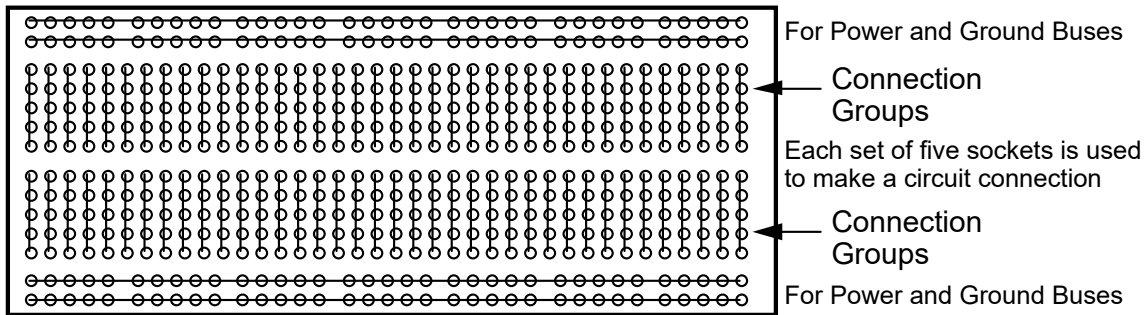
- Make sure the power supply is off.
- Connect a black lead with banana plugs at both ends between the black socket of the power supply and the middle-right-hand "LO" socket of the DMM.
- Select a pair of leads with push pins on one end and banana plugs on other end. Use leads of the same color if red and black leads are not available.
- Connect one of these leads between the bottom-right-hand "I" socket of the DMM (banana plug) and one side of the resistor (push pin).
- Connect the second lead between the "HI" side of the power supply output (banana plug) and the other side of the resistor (push pin).
- Place the DMM in current mode by pressing the shift key then the "DC V / DC I" key.

6.3.2 Measure Current and Compare with Calculated Current

(b) Using (i) the measured output voltage of the 5-V supply and (ii) the measured resistance, calculate the expected current. Record this value on the Data Sheet.

(c) Turn on the power supply, measure the current, and record this value on the Data Sheet. Calculate the error and percentage error, and enter these values on the Data Sheet. Turn the power supply off, and disassemble the circuit. Set the white prototyping board aside for use later.

6.4 Oscilloscope Controls

(a) In the table entitled "Oscilloscope Characteristics" on the Data Sheet, record the following information about the oscilloscope at your station.

(i)   number of input channels (locate input connectors on oscilloscope),

(ii)   range of discrete time-base settings (rotate "Time/Div" knob all the way to the right then all the way to the left and read the time-base settings on the screen),

(iii) range of discrete vertical voltage scale settings (rotate "Volts/Div" knob all the way to the right then all the way to the left and read the vertical voltage scale settings on the screen),

(iv)   input coupling options (press the "1" hard key and read the options on the "Coupling" soft key),

(v)   trigger slope options (press "Edge" hard key in the trigger control section and read the slope options.

6.5 Observing a DC Waveform Using the Oscilloscope

6.5.1   Wire Circuit for DC Voltage Measurement

(a)   Wire the circuit shown below.
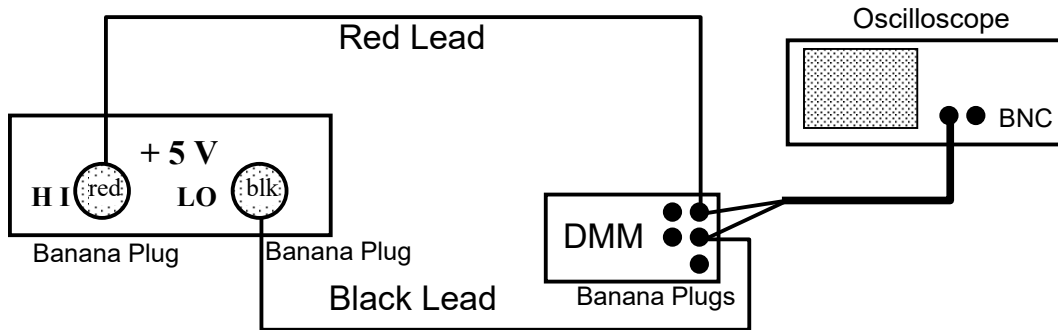
### Detailed Procedure for Wiring Circuit for DC Voltage Measurement

- Connect the output of the +5 VDC supply to the voltage inputs of the multimeter as in Section 6.1 above.
- Next, find a lead with a BNC connector on one end and a pair of banana plugs on the other end.
- Connect the BNC connector to Channel 1 of the oscilloscope and the banana plugs to the voltage inputs of the DMM *through* the banana plugs already installed.
- Check the wiring, and turn the power supply on.

### 6.5.2   Program Oscilloscope for Observing DC Waveform

(b)   Turn on the Channel 1 display, set the volts/division to 2V, set the time/division to 200ms, set the coupling to DC, the trigger source to "1" and the trigger mode to "Auto".

Detailed Procedure for Programming Oscilloscope for DC Voltage Measurement

- *After powering on the Oscilloscope the first thing to do is to have it recall its default settings, because it powers up with the previous user's settings.* Press the "Save/Recall" button and then select the soft key "Default Setup".

- Then press the "1" hard key in the "Analog" control section. This should turn Channel 1 on (if not already), indicated by the button lit yellow. Press the "Coupling" soft key until "DC" is selected. Press the other soft keys as needed to obtain the below desired settings. A filled bullet item means that option is ON. Turn Channel 2 *off* by pressing "2" once or twice to turn off the yellow backlit light.
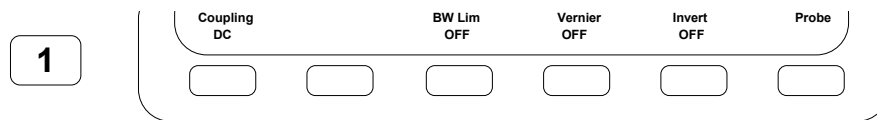
- Adjust channel 1's volt/division knob (larger knob) to set the volt/division to 2V (displayed in the upper left hand corner of the scope display).

- Adjust the time/division knob to set the time/division to 200ms (displayed in the middle of the upper row of the scope display).

- Set the trigger source to "1" by first pressing the "Edge" hard key in the "Trigger" control section and then pressing the "Source" soft key until "1" is selected.
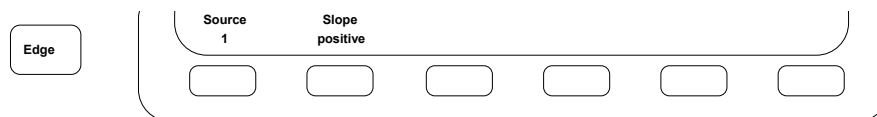
- Set the trigger mode to "Auto" by first pressing the "Mode/Coupling" hard key in the "Trigger" control section and then pressing the "Mode" soft key until "Auto" is selected.

Mode	Coupling	Noise Reject	HF Reject	Holdoff	External
Auto	DC	OFF	OFF		

Mode/
Coupling
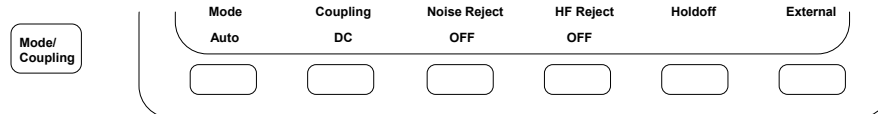
6.5.3   Measure DC Level Using On-screen Cursors

(c)   Activate the on-screen cursor, align it with the DC voltage level, and read the numerical value on the screen. Record this value on the Data Sheet.

Detailed Procedure for Using Cursors to Measure DC Voltage

- Activate the on-screen cursor for measuring the Channel 1 voltage by first pressing the hard key labeled "Cursors" among the general controls, then pressing the "Source" soft key until "1" is selected.
- Press the soft key labeled "X Y" and select Y and then the soft key "Y1" to select the first vertical cursor.
- Adjust the knob just below and slightly to the left of the "Cursors" button to align the cursor with the DC signal.
- Note that the measurement displayed is delta Y. You may have to enable the "Y2" cursor and move it to GND (zero volts) so that your voltage measurement matches the DC input.
- Read the voltage on the screen of the oscilloscope, and record this value in the table entitled "DC Waveform Measurements" on the Data Sheet.

Mode	Source				
Normal	1	X Y	Y1	Y2	Y1 Y2

Cursors
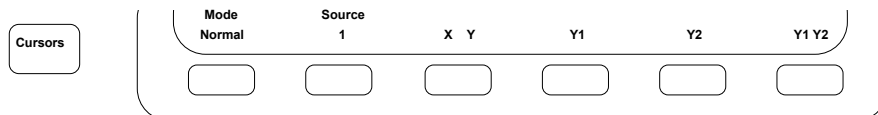
6.5.4   Measure DC Level Using DMM

(d)   Record the reading of the DMM on the Data Sheet.

6.5.5   Observe Effect of Input Coupling

(e)   Press "1" again and change the input coupling to AC. Record the observed effect on the Data Sheet. *Reset the coupling to DC.*

(f)   Turn off the patch panel, and disconnect the leads.

6.6 Using the Oscilloscope to Observe an AC Waveform

6.6.1   Connect Instruments for AC Measurement

(a)   Wire the circuit below for AC waveform measurement shown below.
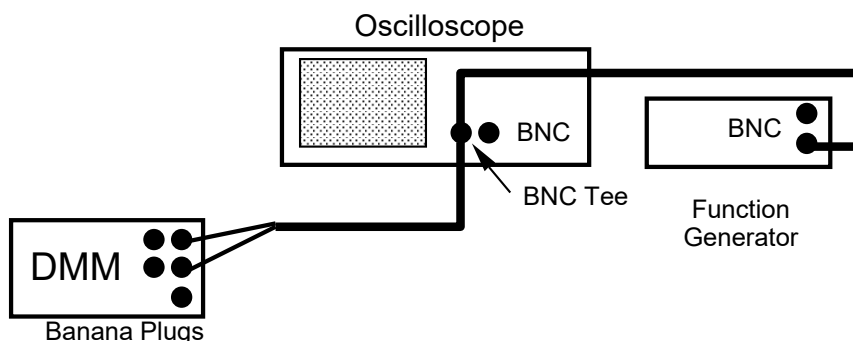
Detailed Procedure for Wiring System for AC Waveform Measurements

- Install a BNC Tee (in the large drawer at the station) on the Channel 1 input of the oscilloscope.
- Connect a lead with a BNC connector on one end and a pair of banana plugs on the other end from one side of the Tee to the DMM.

- Connect a cable with a BNC connector on each end from the other side of the Tee to the "OUTPUT" connector of the function generator.
- Note that the Function Generator has two connectors. *Make sure to use the "OUTPUT" connector and NOT the "SYNC" connector.*

6.6.2   Program Function Generator to Produce a 2 Vp-p, 10-kHz Sinusoid with 1 V Offset

(b)   Program the function generator to output a sine wave at 10 kHz with a peak-to-peak voltage of 2 V and a DC offset of 1 V.

Detailed Procedure for Programming Function Generator

- *Whenever using the Function Generator in lab you will first want to initialize the unit to its 3rd saved state after powering on.* To do this press the "Recall" button, then the arrow up (Λ) key to 3 and finally "Enter".
- Select a sine waveform by pressing the "∿" key.
- Set the frequency to 10 kHz by pressing the "Freq" key, then "Enter Number". The numbers appear next to the keys in small type. Press the "∿" key to enter "1", then the "recall" key to enter "0", and finally the arrow down (V) key for "kHz". The frequency "10.000,000 kHz" should be displayed.
- Set the amplitude to 2 Vp-p by first pressing the "Ampl" key, then "Enter Number", then the "⊓" key for "2", and finally the arrow up (Λ) key for "Vp-p". The amplitude "2.000 Vp-p" should appear on the screen.
- Set the DC offset to 1 V by first pressing the "Offset" key, then adjusting the reading using the large knob next to the display. Compare this method of setting the value with keying in the number directly as was done in (ii) and (iii) above.

6.6.3   Program Oscilloscope for Observing AC Waveform

(c)   Adjust the time base and other controls of the oscilloscope so that two or three periods of the waveform are visible on the screen. Set the Channel 1 coupling to DC, the triggering mode to normal, the trigger slope to "rising", and the coupling to "DC".

Detailed Procedure for Setting Up Oscilloscope for AC Waveform Measurements

- Using button "1", activate Channel 1 with DC coupling.
- Using the "Mode/Coupling" and "Edge" buttons, set the trigger mode to "Normal" and the slope to "rising".
- Turn the trigger level knob so that the trigger voltage is in the range of 0V to 2V. (The trigger level voltage is displayed in the upper right hand corner of the scope's display.) Adjust the trigger level until you see a waveform on the scope. Then adjust the horizontal time base knob so that two or three periods are displayed.

6.6.4   Measure Amplitude, Offset, Period and Frequency

(d)   Use the on-screen voltage and time cursors to measure the amplitude, DC offset, period, and frequency of the sine wave. Record these values on the Data Sheet in the table entitled "AC Waveform Measurements".

6.6.5   Observe Different Waveforms

(e)   Change the waveform using the four waveform function keys on the function generator. Note the results. Return the waveform type to sinusoidal.

6.6.6   Observe Effect of Input Channel Coupling, Trigger Level, and Trigger Slope

(f)   Record the effect of each change listed on the Data Sheet.

Detailed Procedure for Changing Input Coupling, Trigger Level, and Trigger Slope

- Change the Channel 1 coupling to "AC" by first pressing the "1" hard key then pressing the "Coupling" soft key until "AC" is selected. Record what happens on the Data Sheet. (You may have to adjust the trigger level voltage down to a voltage between -1V to 1V to see the waveform.) Set the coupling back to "DC" when finished.
- Adjust the trigger level up and down using the "Level" knob in the "TRIGGER" section of the oscilloscope controls. Record your observations. Take special note of what happens when the trigger level is outside the range of the signal. Return the level to a normal setting between 0V to 2V when finished.
- Change the trigger slope from positive to negative by pressing the "Edge" hard key and then the "Slope" soft key to select a negative (falling) edge. Record your observations. Return to the positive (rising) edge when finished.

6.7 Measuring Gain and Phase Shift of Low-pass, RC Filter

6.7.1   Wire Resistor and Capacitor in Series and Connect the Instruments

(a)   Locate the white prototyping board and the 22.1-kΩ resistor used previously. Find the capacitor in the parts box at the station. Wire the circuit shown below.
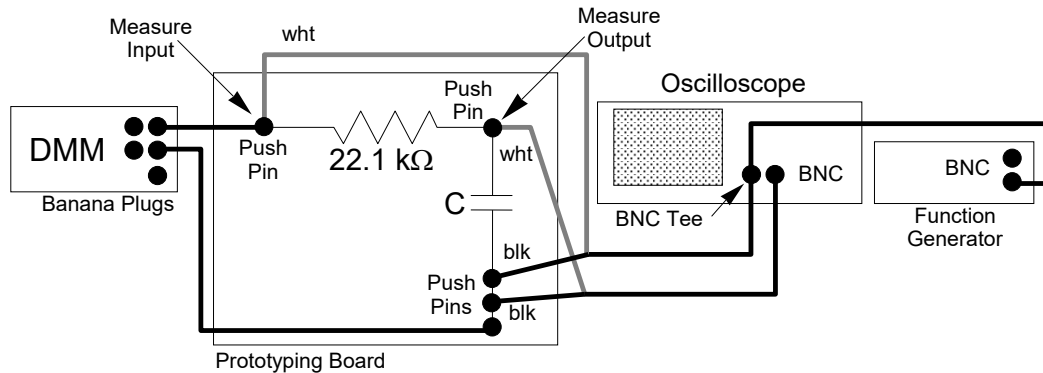
6.7.2   Program Digital Multimeter for AC Voltage Measurement

(b)   Put the multimeter in AC-voltage mode by pressing the "AC V" key.

6.7.3   Program Function Generator for a 2 Vp-p, 1-kHz Sinusoid with 0 VDC Offset

(c)   Program the function generator to produce a sinusoidal waveform at a frequency of 1 kHz, an amplitude of 2 Vp-p, and a 0 VDC offset voltage. (See Detailed Procedure in Section 6.6.2. if needed.)

6.7.4   Program Oscilloscope to Display Filter Input and Output Simultaneously

(d)   Program the oscilloscope to display both the filter input (Channel 1) and the filter output (Channel 2).

Detailed Procedure for Programming Oscilloscope

- Set the horizontal time base to 200 μs/div using the time/division knob.
- Using the "Main/Delayed" button verify that the display mode is set to "Normal".
- Using the "Mode/Coupling" and "Edge" buttons and the trigger level knob, set the trigger mode to "Auto", the trigger coupling to "DC", the edge source to channel "1", the edge slope to "rising", and the trigger level to 0 V.
- Enable both Channels 1 and 2 with DC coupling and "BW Limit", "Fine" and "Invert" all OFF.
- Set the vertical voltage scale to 500 mV/div for each channel.
- Adjust each channel's position knob (smaller knob) so the reference level is centered vertically on the display. Recall that the reference level is indicated by the "⍓" symbol along the left-hand edge of the grid.

### 6.7.5   Measure Gain and Phase Shift Using On-screen Cursors

(e)   Activate the cursors and measure the peak-to-peak voltage of both waveforms. Make sure to switch the cursors "Source" to the appropriate channel. Record these measurements on the Data Sheet.

$$\phi = 360° \, t / T$$

Standard Time Base Mode
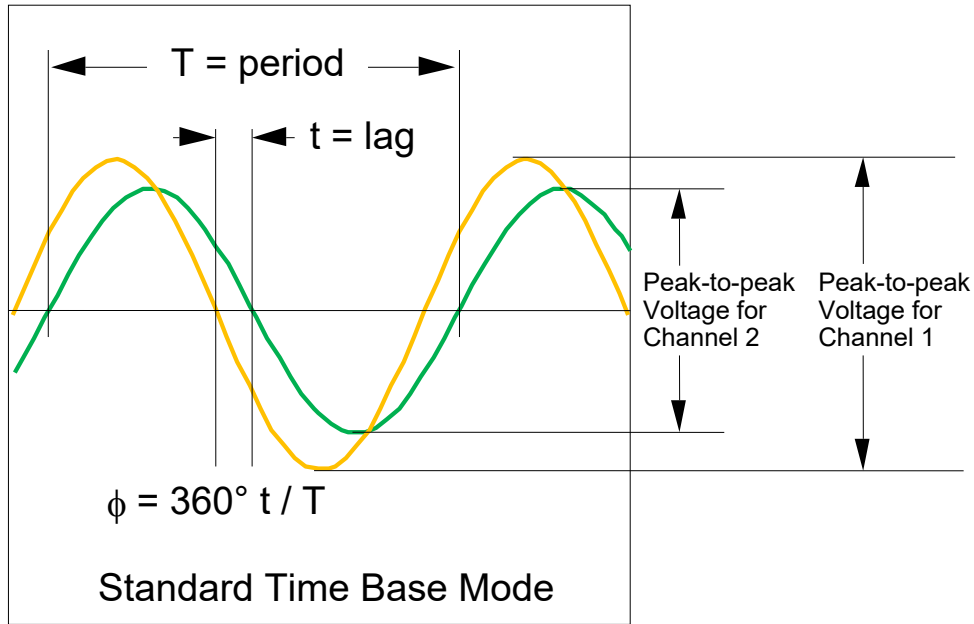
(f)   Use the cursors to measure the time delay between waveforms and the period of each waveform as shown above. Record these measurements on the Data Sheet. Compute the phase shift and capacitance using the equations on the Data Sheet.

6.7.5   Phase Shift Using a Lissajous Pattern

(a)   Change the oscilloscope to XY mode by pressing the "Main/Delayed" hard key followed by the "XY" soft key.

(b)   An elliptical figure known as a Lissajous Pattern should be formed. Center the pattern on the screen with channel 1 and 2's position knobs. Then with the Function Generator's knob adjust the frequency of your input signal and notice how the Lissajous Pattern can be used to measure phase. Switch back and forth between "Main" mode and "XY" mode observing the phase shift. No need to record anything here. Just show your TA the Lissajous changing with frequency.

$$\phi = \arcsin (A / B)$$

x-y Mode
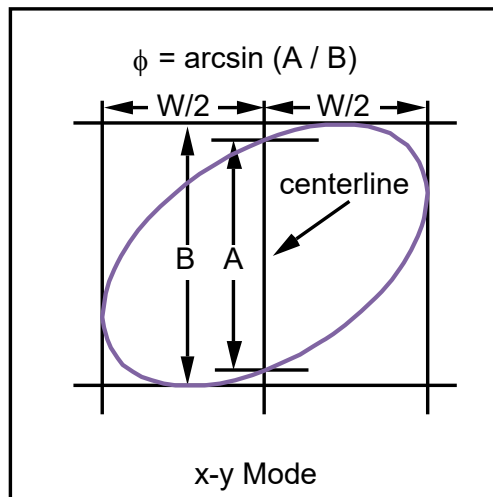
Appendix A. Digital Multimeter (DMM)

The digital multimeter, or DMM for short, is the most common and widely used electronic instrument available today. It can measure both AC and DC voltage and current, resistance and signal frequency. Digital multimeters come in a wide variety of styles and performance levels including battery-powered handheld units intended primarily for field use and AC-powered bench-top units found primarily in the laboratory. Accuracy, measurement capability, and price vary between the different performance levels within each category. Bench-top units are typically more accurate but more costly than handheld instruments although the high end of handheld units overlaps the low end of bench-top models.

The instrument used in our laboratory is the HP 34401A, a 6-1/2 digit, high-performance, digital multimeter.

A.1 General Characteristics of the HP 34401A Digital Multimeter

The general characteristics of the HP 34401A are summarized below. Where appropriate, the specifications of this instrument are compared with those of other high-end units for illustrative purposes.

(a) Definitions: *Resolution* for a DMM is the smallest difference in measurement the meter can display.
$\qquad\qquad\qquad$ *Accuracy* for a DMM is how close the displayed measurement is to the true value.

(b) The maximum resolution of this instrument is achieved in the 6-1/2 digit setting. In this setting the maximum resolution is 1.2 million counts. Or in other words, there are 1.2 million possible measurement readings that the DMM can display given 6-1/2 digits. On the 1-V scale this means that readings between -1.199999 and +1.199999 are possible. A reading of 0.999999 corresponds to 6 full digits of resolution, and the 20 % overrange capability is said to provide an additional 1/2 digit of resolution. This 1/2 digit by convention is the most significant digit of the reading and it can only be a zero or a one. Manufacturers of DMMs came up with this 1/2 digit terminology. In truth there is only $\log_{10}$ (1200000) = 6.08 digits of resolution. Resolution may also be described in terms of percent, parts per million (ppm), or number of bits. Thus, we have

$$\text{resolution as a fraction of full scale} = 1 \text{ part in } 1{,}200{,}000 \approx 1 \text{ ppm} = 0.0001 \text{ \%}$$

$$\text{number of digits of resolution} = \log_{10} (1200000) = 6.08 \text{ digits} \approx 6\text{-}1/2 \text{ digits}$$

$$\text{number of bits of resolution} = \log_2 (1200000) + 1 \text{ sign bit} = 21.19 \approx 21 \text{ bits}$$

Thus, a resolution of 1,200,000 counts, 6-1/2 (6.08) digits, 0.0001 %, 1 ppm, and 21 bits are all roughly equivalent. In contrast, a typical handheld digital multimeter has 3-1/2 or 4-1/2 digits of resolution with the typical upper limit being 50,000 counts. Thus, the resolution of this meter is roughly 30 times better than the best handheld digital multimeter. Typical computer-based data acquisition systems have resolutions ranging from about 8 to 18 bits with values between 12 and 16 bits predominant. Thus, this meter is roughly 10 times better than the best analog-to-digital conversion board and at least 30 times better than the typical board.

The resolution of this instrument can be set at 4-1/2 digits, 5-1/2 digits (the default), or 6-1/2 digits. Lower resolution is used to improve readability or for faster scanning when remote data transfer is used.

(c) Accuracy is far more important than resolution; however, accuracy depends on many factors external to the instrument itself. Accuracy is typically given as the sum of two terms: (i) relative error often expressed as a percent of reading and (ii) absolute error expressed either as a fixed value or as a percent of range. A trait of nearly all digital multimeters is that highest accuracy is realized for DC voltage measurement because additional factors contribute to error for the other measurements. The accuracy of this instrument for DC voltage measurement may be generally rated at 0.005 % of reading (relative error) plus 0.001 % of full scale (absolute error). This accuracy is roughly 10 times better than the best handheld multimeter.

(d) The following measurements are all possible with the HP 34401A multimeter.

(i) DC voltage in five ranges (100 mVDC, 1 VDC, 10 VDC, 100 VDC, and 1000 VDC),
(ii) two-wire resistance measurement in seven ranges (100 Ω, 1 kΩ, 10 kΩ, 100 kΩ, 1 MΩ, 10 MΩ, and 100 MΩ),
(iii) four-wire resistance measurement, a technique to eliminate lead resistance effects in small resistance measurements, over the same seven resistance ranges,
(iv) DC current measurement in four ranges (10 mA, 100 mA, 1 A, 3 A),

(v)   continuity test that produces an audible beep sound when the resistance measured drops below a specified low value, (used for testing circuit connections without having to look at the displayed resistance reading)

(vi)   diode voltage drop with a fixed 1 mA test current and 1 V range with beep for values between 0.3 and 0.8 V,

(vii)   RMS AC voltage in five ranges (100 mVAC, 1 VAC, 10 VAC, 100 VAC, and 750 VAC),

(viii)   RMS AC current in four ranges (10 mA, 100 mA, 1 A, 3 A),

(ix)   frequency from 3 Hz to 300 kHz with an input signal between 100 mVAC and 750 VAC, and

(x)   period from 0.33 µs to 0.33 s with an input signal between 100 mVAC and 750 VAC.

Appendix B. Oscilloscope

The oscilloscope displays voltage waveforms allowing one to easily detect glitches and other waveform anomalies that are virtually impossible to identify with other laboratory instruments. The displayed pattern on the screen of the oscilloscope is known as the *trace*. An oscilloscope can also be used to make AC and DC voltage measurements although typically not as accurately as with a digital multimeter. (A digital oscilloscope like the one in the laboratory combines the elements of both the traditional oscilloscope and the DMM although the accuracy of the DMM function is less that of the dedicated DMM in the laboratory.) Our discussion of oscilloscope principles is divided into three broad areas: (a) horizontal sweep rate and time-base operation, (b) vertical voltage scale, and (c) time-base triggering.

B.1 Horizontal Sweep Rate and Time-base Operation

To display transient waveforms (horizontal mode = main or delayed), time is shown on the horizontal axis and voltage is shown on the vertical axis of the oscilloscope screen. The horizontal scale is calibrated in units of time per screen division, and this value is known as the *time base* or *horizontal sweep rate*. The typical oscilloscope screen is divided into 10 horizontal and 10 vertical divisions. Thus, a sweep rate of 2 ms per division means one division corresponds to 2 ms, and the maximum time slice of a continuous waveform that can be displayed is 20 ms at this sweep rate.

A modern, digital oscilloscope has two functional units. One is devoted to measuring the voltage of the input signal at a given sample interval and storing the values in memory. The other is devoted to displaying the latest time slice of voltage readings stored in memory.

If the scope samples its data without some kind of synchronization the displayed waveforms will start at random voltage locations making the display very hard to read or even useless. Triggering remedies this problem for a periodic waveform by synchronizing the time slices so that they form what appears to be a nearly steady pattern on the screen. Even though the trace may show some jitter, it is generally stable enough for analysis by a human observer. This issue is more fully discussed in Section B.3.

The Agilent DSO6012A oscilloscope at your station also has a "roll" mode (Main/Delayed Menu = Roll) in which voltage measurements are continuously shifted from right to left so that the most recent segment of the waveform is always displayed. This mode tracks the waveform continuously much like a chart recorder, a device that records voltage on paper from a long roll (thus the name "roll" mode). The paper moves at a fixed rate while a pen moves back and forth across the width of the paper marking the instantaneous voltage and thus providing a continuous record of the voltage. Roll mode on the oscilloscope at your station works much the same way except that only that portion of the waveform that fits on the screen can be viewed.

The time base can be set at discrete values such as 2 ms/div, 5 ms/div, and so on. It is not uncommon to have 25 or more such discrete settings ranging from 1 µs/div or less to 10 s/div or more. In addition to these discrete settings, the sweep rate can also be varied between these discrete settings. The oscilloscope at your station uses a knob to adjust this sweep rate. The knob normally varies the time-base setting in large steps; then, in "vernier mode", the same knob varies the time-base setting in smaller steps between the large-step values.

The above discussion assumes that the internal time base drives the horizontal sweep. In "XY" mode (horizontal mode = XY), the Channel 1 or X input defines the horizontal scale, and the Channel 2 or Y input defines the vertical scale. XY mode is used to display the phase shift between two sinusoids with a Lissajous pattern in this experiment.

B.2 Vertical Deflection and Voltage Scale

The oscilloscope at your station has two input channels. As noted above, both channels can be displayed on the vertical axis with time on the horizontal axis, or else Channel 1 or X can drive the horizontal axis and Channel 2 or Y can drive the vertical axis (XY mode). Each channel may be AC coupled or DC coupled. *AC coupling* means that only the AC component of the signal is displayed; the DC portion is filtered out. *DC coupling* means that *both* the AC and DC components are displayed. *Coupling only affects whether the DC component of the waveform is displayed. The AC component is displayed in both modes.*

Each channel also has a position knob that allows the waveform to be moved up or down on the screen for improved viewing. The knob changes the vertical position corresponding to 0 V. The oscilloscope at your station automatically shows the zero point ("⊹") along the left-hand edge of the screen.

The oscilloscope at your station uses a high-speed analog-to-digital converter to realize the above noted oscilloscope functions. Because discrete values are stored in memory, an on-screen cursor can be used to read out voltages and times. This data can be transferred to a computer in digital form for further processing or printing. If the voltage falls outside the range of the measurement, an overrange reading is recorded, and no trace is displayed for that portion of the waveform.

B.3 Time-base Triggering

Triggering establishes t = 0 for the horizontal time base. Triggering options provide flexibility in displaying different waveforms. Important considerations here are the (a) trigger source and coupling, (b) trigger level, (c) trigger slope, and (d) trigger delay. Trigger source simply determines which signal generates trigger events. Trigger source options include (a) one of the two input signals ("1" or "2'), (b) a separate trigger signal "external", or (c) the AC power line ("line"). Trigger coupling can be AC or DC. As before, AC coupling means that the DC component of the trigger signal is filtered out. The trigger level sets the voltage at which potential trigger events are produced. Trigger slope specifies whether positive-going or negative-going transitions generate trigger events. Trigger delay is the time delay between the occurrence of a trigger event and the start of the horizontal sweep. The oscilloscope at your station also has a special feature known as "trigger holdoff". Trigger holdoff keeps the trigger from re-arming for a user-specified length of time ranging from 200 ns to 13.5 s.

With this background on basic terminology, we examine some of the more common situations to see what type of triggering works best.

(a) Periodic Waveforms

For periodic waveforms, the source is almost always the waveform itself. Successive time slices of the waveform are superimposed to produce an apparently continuous pattern on the screen. "Normal" triggering ensures that successive slices lie on top of one another by starting each trace at the same point on the waveform as shown in Fig. B.1.

Starting at the left and moving from left to right in the direction of increasing time, we see that a trigger event occurs when the voltage crosses the trigger level in the positive going direction. This point is indicated by the "X" in Fig. B.1. After a user-specified trigger delay (which is usually zero), the horizontal sweep starts. The linear motion of the trace across the screen is indicated by the saw-tooth waveform shown below the input waveform. The second crossing of the trigger level (indicated by ●) is ignored because the trace is still active. The trace is still active for the third trace as well. The slope is wrong for the fourth crossing even though the trace is no longer active. Finally, the fifth crossing has the correct slope, and the trace is no longer active so a trigger event is generated. This process is repeated continuously, and the successive time slices are superimposed to produce a continuous, ideally stationary pattern on the screen.
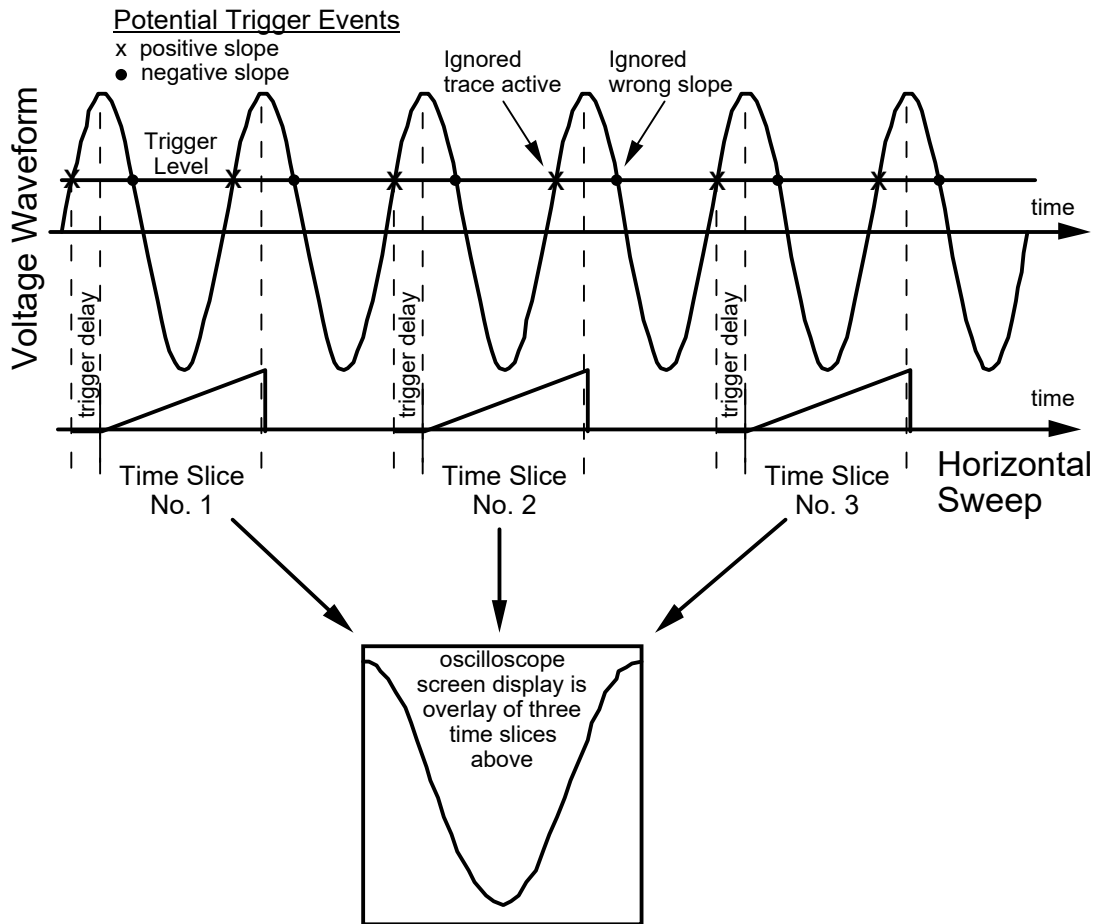
Figure B.1 Illustration of how time-base triggering produces a steady pattern on the oscilloscope screen.

The effect of trigger slope is shown In Fig. B.2. The trigger level is the same in both displays, and the time base is set so that one full period of waveform is displayed. The only difference is that the display on the left is triggered by a positive-going transition whereas the display on the right is triggered by a negative-going transition.
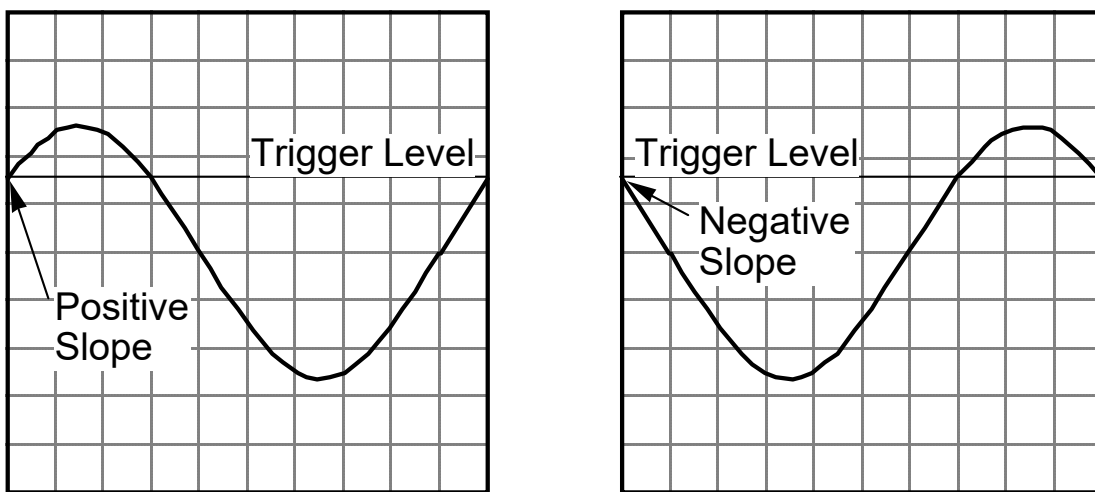
Figure B.2 Effect of trigger slope on waveform display.

The Agilent DSO6012A oscilloscope displays the last digitized waveform until the next trigger event occurs so that rare events are not lost. This behavior can be potentially confusing when the trigger level is too high or too low. One may mistake the last captured waveform for a valid instantaneous waveform. The totally static nature of the image on the screen is the first clue that an incorrect trigger level is being used. The trigger-mode indicator in the upper right-hand corner of the display also flashes. The "Display" then "Clear Display" buttons manually erase the screen and thus remove the captured waveform.

(b) DC Signals

DC signals do not produce trigger events and thus cannot trigger the horizontal trace by themselves. However, because superposition of successive traces is not an issue, any means of triggering the trace is satisfactory. The 60 Hz, AC, power-line voltage provides a convenient source of trigger events for this case. This method of triggering the time base is called "line triggering". If line triggering is used for periodic waveforms, the result will be an incoherent parade of random time slices across the screen known as "garbage".

Both AC and DC waveforms can be viewed in "auto" triggering mode. Auto triggering automatically generates a trigger event if the trigger signal does not generate a trigger event within a certain length of time.

(c) Single-event Triggering

Single-event triggering is used for nonperiodic, transient waveforms. A single event is captured and stored in memory. In single-sweep mode, the time base can be started by a trigger event in the normal manner or by manually pressing a key on the oscilloscope.

Appendix C. Function Generator

A function generator produces a periodic waveform with a user selectable shape, frequency, amplitude, offset, and modulation. The output voltage is given by

$$V_{out}(t) \;=\; V_{DC} + V_{AC}(t) \;=\; V_{offset} + \frac{V_{pp}}{2}\, w(t) \;=\; V_{offset} + A\, w(t)$$

where

$V_{out}(t)$	=	generator output voltage [V],
V_{DC}	=	V_{offset} = DC component of voltage waveform or offset voltage [V],
$V_{AC}(t)$	=	AC component of voltage waveform [V],
$V_{p\text{-}p}$	=	peak-to-peak AC voltage [V] = 2 A,
A	=	amplitude of AC voltage [V] = $V_{p\text{-}p}$ / 2,
$w(t)$	=	periodic waveform normalized so that w(t + T) = w(t), min w(t) = -1, and max w(t) = +1 for all t,
T	=	period of waveform [s], and
f	=	1/T = frequency of waveform [Hz].

A few important terms are further explained below.

Waveform

The function generator at your station can produce the following standard waveform shapes as well as a user-specified "arbitrary" waveform.

Standard Waveform Shapes:　　　sinusoidal　　　square wave　　　triangular　　　ramp

Frequency

Frequency is the rate at which the periodic waveform repeats. Frequency f is expressed in Hz = 1/(seconds) and is the inverse of the waveform period T.

Amplitude

Amplitude can be expressed in terms of the peak-to-peak voltage $V_{p\text{-}p}$, the single-sided amplitude A, or as a root-mean-square (RMS) value V_{rms}.

DC Offset

A periodic waveform may have a constant (DC) offset in addition to the time-varying (AC) component.

Modulation

Modulation means that the amplitude, or frequency, or both are varied by a second waveform. Amplitude modulation is commonly abbreviated AM as in AM radio stations. Similarly, frequency modulation is commonly abbreviated FM as in FM radio stations. Other forms of modulation such as phase modulation are used in communications and other industries. Our use of the function generator is limited in scope and does not involve modulation.

Appendix D. Resistance Coding Schemes

EIA Color-band Resistance Coding Scheme

Band 1 = First Digit
Band 2 = Second Digit
Band 3 = Multiplier
Band 4 = Tolerance
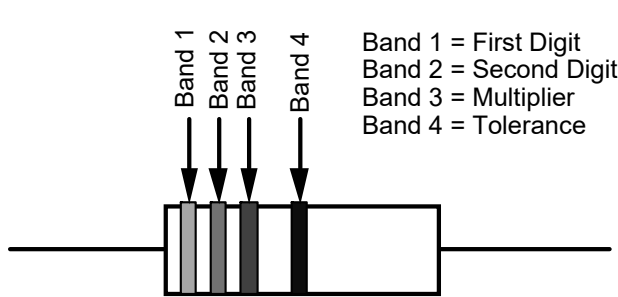
Example
Brown = 1
Black = 0
Red = 100
Red = 2 %

$1000 \, \Omega \pm 20 \, \Omega$

Resistance Color Code

Digit	Color	Multiplier	No. of Zeros
	Silver	0.01	-2
	Gold	0.1	-1
0	Black	1	0
1	Brown	10	1
2	Red	100	2
3	Orange	1K	3
4	Yellow	10K	4
5	Green	100K	5
6	Blue	1M	6
7	Violet	10M	7
8	Gray		
9	White		

Tolerance Code

Color	Tolerance
None	20 %
Silver	10 %
Gold	5 %
Red	2 %
Brown	1 %
Green	0.5 %
Blue	0.25 %
Violet	0.10 %
Gray	0.05 %

(a) The nominal resistance code consists of two or more bands, the typical number being four for standard resistors with 2-% and 5-% tolerance and five for so-called precision resistors with 1-% tolerance. The last band, which may be set slightly apart from the rest, generally signifies resistance tolerance. The next-to-last band is the multiplier and gives the number of zeros following the digits. Occasionally, extra bands after the tolerance band give characteristics like the temperature coefficient of resistance.

(b) Resistance values are usually restricted to the digit combinations given below followed by an appropriate multiplier.

Tolerance	Standard Digit Values
10 % and 20 %	10, 12, 15, 18, 22, 27, 33, 39, 47, 56, 68, 82
2 % and 5 %	10, 11, 12, 13, 15, 16, 18, 20, 22, 24, 27, 30, 33, 36, 39, 43, 47, 51, 56, 62, 68, 75, 82, 91
1 %	100, 102, 105, 107, 110, 113, 115, 118, 121, 124, 127, 130, 133, 137, 140, 143, 147, 150, 154, 158, 162, 165, 169, 174, 178, 182, 187, 191, 196, 200, 205, 210, 215, 221, 226, 232, 237, 243, 249, 255, 261, 267, 274, 280, 287, 294, 301, 309, 316, 324, 332, 340, 348, 357, 365, 374, 383, 392, 402, 412, 422, 432, 442, 453, 464, 475, 487, 499, 511, 523, 536, 549, 562, 576, 590, 604, 619, 634, 649, 665, 681, 698, 715, 732, 750, 768, 787, 806, 825, 845, 866, 887, 909, 931, 953, 976

Examples:

(i) A 2-% tolerance resistor for which the first two bands are yellow and violet may be 4.7 Ω, 47 Ω, 470 Ω, 4.7 kΩ, 47 kΩ, 470 kΩ, 4.7 MΩ, 47 MΩ, or 470 MΩ depending on the third band or multiplier.

(ii) The standard resistance value nearest 500 Ω is 470 Ω in a 10-% or 20-% tolerance resistor, 510 Ω in a 2-% or 5-% tolerance resistor, and 499 Ω in a 1-% tolerance resistor.

Military Specification (Mil-Spec) Coding Scheme

(a) A resistor may alternatively be labeled with a military-type identifier like "RN55D". This specification determines the resistor type, package size, lead configuration, and temperature coefficient. In this case, "RN" signifies a fixed, precision, metal-film resistor, "55" denotes a specific package type and lead configuration, and "D" indicates a temperature coefficient of 100 ppm/°C. The two most common package codes are "55" and "60". Also, "C" denotes a temperature coefficient of 50 ppm/°C, and "E" denotes a temperature coefficient of 25 ppm/°C.

(b) The resistance value is coded with N characters with N typically being 4 or 5. Except as noted below, the first $N-1$ characters are significant digits in the resistance value, and the final character signifies the number of trailing zeros. Thus, "1003" means "100" followed by three zeros which gives "100 000" or 100 kΩ. The letter R may be used instead of a decimal point with the number of trailing zeros omitted. Thus, "49R9" denotes a 49.9 Ω resistor. The letter K may be used to denote both the decimal point and to signify that the value is in kΩ. Thus, "49K9" denotes a 49.9 kΩ resistor. A few more examples serve to illustrate this coding scheme.

R100 = 0.100 Ω	1R00 = 1.00 Ω	10R0 = 10.0 Ω	1000 = 100 Ω	1002 = 10 kΩ
10K0 = 10.0 kΩ	100K = 100 kΩ	2212 = 22.1 kΩ	51R0 = 51.0 Ω	1004 = 1.00 MΩ

(c) A resistance tolerance code may be given after the resistance value as follows: J = 5 %, F = 1 %, D = 0.5 %, C = 0.25 %, B = 0.1 %, A = 0.05 %, Q = 0.02 %, T = 0.01 %, V = 0.005 %, and Y = 0.001 %.

(d) Resistance values are typically restricted to the same standard values listed for the EIA Color-coding Scheme.