3: Electrical Measurements Review

Pre-Lab: Read and understand this chapter before coming to lab!
     Complete the following problems: 1a, 3–9, 11, 14–19
     Record the results in your notebook.

Lab: See page 96. Work as individuals!
     Begin lab work: 23 September; Due: 7 October

Reference: Horowitz & Hill, *The Art of Electronics*
     Chapter 1 & Appendix A
     Diefenderfer & Holton, *Principles of Electronic Instrumentation*
     Chapter 6
     Paul Scherz, *Practical Electronics for Inventors*, 2nd edition

Purpose

This review aims to re-familiarize you with the electronic instrumentation you used in Physics 200 lab: components like resistors and capacitors, measuring devices like digital multimeters and oscilloscopes, and electrical sources like function generators and d.c. power supplies. In addition the usual schematic symbols for these devices are presented.

Components

In Physics 200 you learned about three passive, linear components: resistors (R), capacitors (a.k.a., condensers, C) and inductors (a.k.a., chokes or coils, L). These devices are called passive because they require no outside power source to operate (and thus circuits involving just these components cannot amplify: at best power in = power out). These devices are called linear because the current *through* these devices is linearly proportional to the voltage *across* them[1]:

$$I = \frac{1}{Z}V \tag{3.1}$$

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[1]Unless otherwise stated, you should always assume that "voltage" and "current" refers to the root-mean-square (rms) value of that quantity. That is what meters always report. Of course, this equation would also apply to peak or peak-to-peak values as long as they are consistently used.
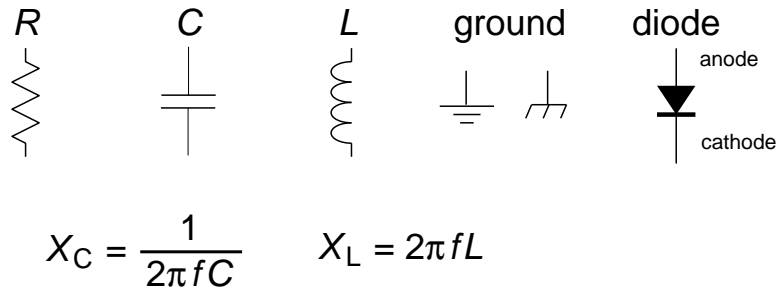
$$X_C = \frac{1}{2\pi f C} \qquad X_L = 2\pi f L$$

Figure 3.1: The schematic symbols for common components including resistors (R), capacitors (C), and inductors (L). For these three "linear" devices there is a linear relationship between the current *through* the device (I) and the voltage *across* the device (V). For resistors, the resistance, $R = V/I$ is constant. For capacitors and inductors the reactance $X = V/I$ depends on frequency (f) as shown above. The two symbols for ground (zero volts) are, respectfully, chassis and earth ground.

The impedance Z (unit: Ω) determines the proportionality constant. Large impedances (think $M\Omega$) mean small currents (think μA) flow from moderate driving voltages. Small impedances (think $1\ \Omega$) mean large currents (1 A) flow from moderate driving voltages. Impedance[2] is an inclusive term: for resistors the impedance is called resistance; for inductors and capacitors the impedance is called reactance. Inductors and capacitors are useful only in circuits with changing voltages and currents. (Note: changing voltage and/or current = alternating current = a.c.; unchanging current/voltage = direct current = d.c..) The reactance (or impedance) of inductors and capacitors depends on the frequency f of the current. A capacitor's impedance is inversely proportional to frequency, so it impedes low frequency signals and passes high frequency signals. An inductor's impedance is proportional to frequency, so it impedes high frequency currents but passes low frequency currents. Recall that current and voltage do not rise and fall simultaneously in capacitors and inductors as they do in resistors. In the inductors the voltage peaks before the current peaks (voltage leads current, ELI). In capacitors the current peaks before the voltage peaks (current leads voltage, ICE).

Diodes are non-linear passive devices. Positive voltages on one terminal (the anode) results in large current flows; positive voltages on the other terminal (the cathode) results in essentially no current flow. Thus the defining characteristic of diodes is easy current flow in only one direction. The arrow on the schematic symbol for a diode shows the easy direction for current flow. On a diode component a white line often marks which terminal allows easy outward flow.

Light Emitting Diodes (LED) are specialized diodes in which part of the electrical power ($I\Delta V$) is dissipated as light rather than heat. The color of the emitted light (from IR to UV) depends on the material and ΔV.

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[2]Impedance is often distinguished as being a complex quantity (as in $Z = a + bi$, where $i = \sqrt{-1}$ and $a, b \in \mathbb{R}$). Resistors then have real impedances whereas Z is purely imaginary for inductors and capacitors. This advanced approach is followed in Physics 338. In Physics 200 this reality is hidden behind 'phasers'.
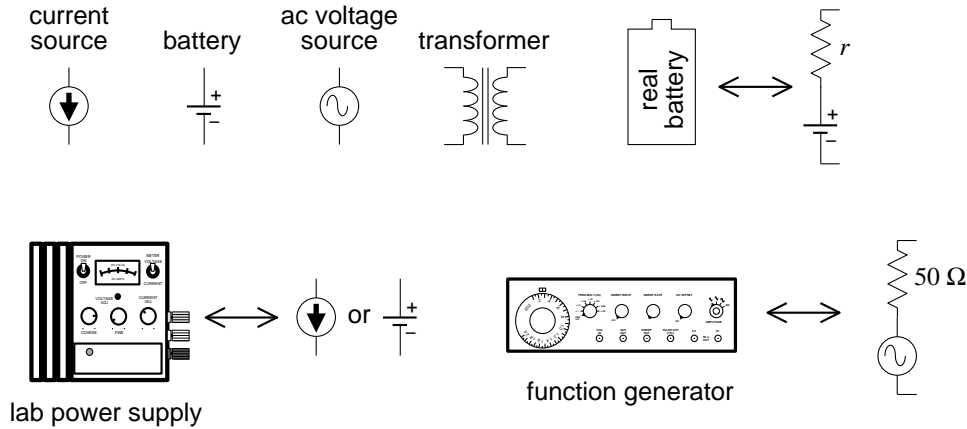
Figure 3.2: The schematic symbols for common electric sources. Real sources can be modeled as ideal sources with hidden resistors. Lab power supplies are fairly close to ideal sources, if operated within specified limits. For example, the Lambda LL-901 specifications report an internal resistance less than 4 mΩ.

Sources

D.C. Current and Voltage Sources

An ideal voltage source produces a constant voltage, independent of the current drawn from the source. In a simple circuit consisting of a voltage source and a resistor, the power dissipated in the resistor (which is the same as the power produced by the voltage source) is V^2/R. Thus as $R \to 0$ infinite power is required. I hope it comes as no surprise that infinite power is not possible, so ideal voltage sources do not exist. Every real voltage source has some sort of current limit built in. (Unfortunately it is not uncommon that the current limiting feature is the destruction the device — beware!!!) Batteries can be thought of as an ideal voltage source in series with a small resistor[3], r, (the internal resistance). The maximum battery current flow (achieved if the external circuit is a "short" i.e., $R \to 0$) is V/r. Laboratory power supplies ("battery eliminators") usually have an adjustable maximum current limit that can be achieved without damaging the device. When this current limit is reached the supplied voltage will be automatically reduced so no additional current will flow. When operating in this mode (current pegged at the upper limit, with actual output voltage varying so that current is not exceeded) the power source is acting as a nearly ideal current source. An ideal current source would produce a constant current, arbitrarily increasing the voltage if that currents meets a big resistance. In a simple circuit consisting of a current source and a resistor, the power dissipated in the resistor (which is the same as the power produced by the current source) is I^2R. Thus as $R \to \infty$ infinite power is required. No surprise: infinite power is not available, so ideal current sources do not exist. Every real current source has some sort of voltage limit built in. Real current sources can be modeled as ideal current sources in parallel with a (large) internal resistance[4].

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[3]Thévenin's Theorem claims most any two terminal device can be thought of this way!
[4]Norton's Theorem claims most any two terminal device can be thought of this way!

A.C. Voltage Sources

A function generator is a common source of a.c. signals. A function generator can produce a variety of wave shapes (sinusoidal, square, triangle, ...) at a range of frequencies, and can even 'sweep' the frequency (i.e., vary the frequency through a specified range during a specified period). Usually the signals are balanced (i.e., produces as much positive voltage as negative), but a d.c. offset can be added to the signal, for example, producing a voltage of the form

$$A\cos(2\pi ft) + B \tag{3.2}$$

(In this case the d.c. offset would be B, the amplitude would be A, and the peak-to-peak voltage would be $2A$.) Most function generators are designed to have an internal resistance of 50 Ω and maximum voltage amplitude of around 10 V. Generally they have a power output of at most a few watts.

Certainly the most common a.c. source is the wall receptacle: 120 V at a frequency of 60 Hz. Transformers can be used to reduce this voltage to less dangerous levels for lab use. A 'variac' (a variable transformer) allows you to continuously vary the voltage: 0–120 V. Relatively large power (> 100 W) and current (> 1 A) can be obtained in this way. Of course the frequency is not changed by a transformer; it would remain 60 Hz.

Electrical Measurement

Digital Multimeter (DMM)

The most common measurement device is the digital multimeter (DMM). Feel free to call these devices 'voltmeters', but in fact they can measure much more than just volts. For example, the Keithley 169 is fairly generic, measuring volts (a.c. and d.c.), amps (a.c. and d.c.), and ohms. The hand-held Metex M-3800 measures the above and adds transistor h_{FE} and diode test. The bench-top DM-441B measures all of the above and frequency too. The ease of switching measurement options should not blind you to the fact that these measurement options put the DMM into radically different modes. If, for example, the DMM is properly hooked up to measure voltage and — without changing anything else — you switch the DMM to measure amps, most likely something will be destroyed: either the DMM or the device it is connected to. Please be careful!

Recall that voltage (or more properly potential difference) is a measurement of the electrical 'push' applied to an electron as it moves through a section of the circuit. It is analogous to water pressure in that the difference in the quantity determines the driving force. (No pressure difference; no net force.) Note that the presence of big 'push', in no way guarantees that there will be a large resulting flow (current). A large resistance (or for a.c. circuits, impedance) can restrict the flow even in the presence of a big push. In fact, large current flows are often driven by very small voltage differences as a very fat (small resistance) wire is provided for the flow. Wires work by having very small resistance; an ideal wire has zero resistance, and hence nearly zero voltage difference between its two ends.

an ammeter acts
like a short circuit

a voltmeter acts
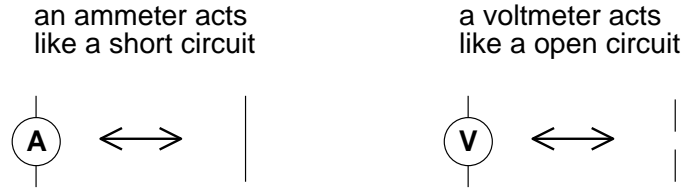like a open circuit

A ⟷

V ⟷

Figure 3.3: The schematic symbols for basic meters. An ammeter must substitute for an existing wire to work properly, whereas a voltmeter can be attached most anywhere.

A voltmeter measures the potential difference across or between the two selected points. A good voltmeter is designed to draw only a small current so it must be equivalent to a large resistance. Modern DDMs typically have input impedances greater than 1 MΩ. Voltmeters with even larger resistance (TΩ) are called electrometers. An ideal voltmeter would draw no current; it would be equivalent to an 'open circuit'. (An open circuit [$R \to \infty$] is the opposite of 'short circuit' [$R \to 0$] which is obtained if the two points are connected by an ideal wire.) Since voltmeters draw only a small current, they should not affect the circuit being measured. This makes the voltmeter an excellent diagnostic tool.
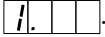
Voltmeters always measure the voltage difference between the two probes (e.g., to measure the 'voltage across' a device place probes at opposite ends of the device), but occasionally you are asked to measure the voltage at a point. Those words imply that the black (a.k.a. common) probe is to be placed at ground. (In fact you'll soon learn that oscilloscopes are designed as one-probe-at-ground voltmeters.)

Measurement of the current flow through a wire, necessarily requires modification of the circuit. The flow normally going through the wire must be redirected so it goes through the ammeter. This requires breaking the path that the current normally uses, i.e., cutting the wire and letting the ammeter bridge the two now disconnected ends. (With luck, the wire may not need to be literately cut, perhaps just disconnected at one end.) Because current measurements require this modification of the circuit under study, one generally tries to avoid current measurements, and instead substitute a voltage measurement across a device through which the current is flowing. Knowledge of the impedance of the device will allow you to calculate the current from the voltage. Because an ammeter substitutes for a wire, it should have a very small resistance. An ideal ammeter would have zero resistance, i.e., be a short circuit between its two leads. (Note that this is the opposite of a voltmeter, which ideally has an infinite resistance between its two leads.) Real ammeters require a small voltage drop (typically a fraction of a volt for a full scale reading) to operate. This small ΔV is called the *voltage burden*.

I say again: converting a DMM from voltmeter to ammeter makes a drastic change from open circuit to short circuit. Making such a switch in a DMM connected to a circuit usually results in damaging something. Poking around in a circuit with a voltmeter is unlikely to cause damage, because the voltmeter acts like a huge resistor (not that different from the air itself). Poking around in a circuit with an ammeter is quite likely to cause damage, as it is linking two points with a wire, i.e., adding short circuits between points in the circuit.

A DMM measures resistance by forcing a current through the leads and, at the same time, measuring the potential difference between the leads. The resistance can then be calculated by the DMM from $R = V/I$. Note that since a DMM in resistance mode is sending a

current through its leads ('sourcing current') and assuming that this current is the only current flowing through the device, you cannot measure the resistance of a powered device. Furthermore, you can almost never use the DMM to measure the resistance of a device attached to an existing circuit because the current injected by the DMM may end looping back through the circuit rather than through the device. (In addition injecting current into a circuit at random places may damage some components in the circuit.) Thus to measure the resistance of something, you almost always have to disconnect at least one end of it from its circuit.

Lab Reminder: For accurate measurement you must use the appropriate SCALE: the smallest possible without producing an overscale. DMM's may report an overscale condition by a flashing display or a nonsense display like: $\boxed{I. \ \ }$. Similarly, for significant DMM measurements you should record in your notebook every digit displayed by the DMM.

A.C. DMM Measurements

Some special considerations are needed when using a DMM to measure a.c. currents or voltages. First, DMMs give accurate readings only for frequencies in a limited range. DMMs fail at low frequencies because DMMs report several readings per second and, in order to be properly measured, the signal needs to complete at least one cycle per reading frame. Thus $f > 20$ Hz or so for accurate readings. At the high frequencies, the input capacitance (~ 100 pF) of the DMM tends to short out the measurement (recall the impedance of a capacitor at high frequency is small). No SJU DMM operates accurately above 0.3 MHz; some DMMs have trouble above 1 kHz. The DMM's manual, of course, reports these specifications.

Recall that a.c. signals are time-variable signals ...there is no steady voltage to report as "the" voltage. The solution is to report root-mean-square ('rms') quantities. (The square root of the average of the square of the voltage.) Since this is a complex thing to calculate, most cheap DMMs assume that the signal is sinusoidal so that there is a relationship between the rms value and the peak value:

$$V_{\mathrm{rms}} = V_{\mathrm{peak}}/\sqrt{2} \tag{3.3}$$

These cheap DMMs find the peak voltage, divide it by $\sqrt{2}$ and report the result as if it were an rms voltage. This of course means the meter reports faulty values if non-sinusoidal signals are applied. "True rms" meters properly calculate the rms quantities.

Oscilloscope

Generally speaking DMMs work in the 'audio' frequency range: 20 Hz – 20 kHz. 'Radio frequency' (rf, say frequencies above 1 MHz) require an alternative measuring device: the oscilloscope (a.k.a., o'scope or scope). Unlike the DMM, the oscilloscope usually measures voltage (not current). Also unlike the DMM, the scope effectively has only one lead: the 'black' lead of the scope is internally connected to ground; the voltage on the 'red' lead is displayed on the screen. (Note: with a DMM you can directly measure the 1 V potential difference between two terminals at 100 V and 101 V. You cannot do this with a scope—its 'black' lead is internally connected to ground so if you connect it's 'black' lead to the 100 V
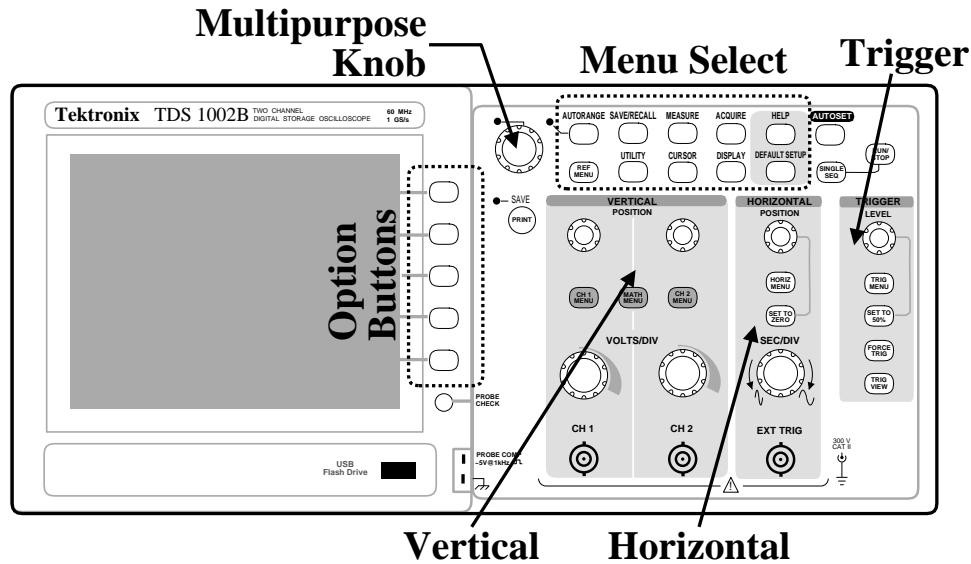
Figure 3.4: The Tektronix TDS 1002B is a two channel digital storage oscilloscope (DSO). Pushing a button in the Menu Select region displays a corresponding menu of the items to be re-configured adjacent to the option buttons. (The multifunction knob allows a continuous variable to be modified.) The VERTICAL region has knobs that control the size (VOLTS/DIV) and POSITION of vertical (y) scales for channel 1 (CH 1) and channel 2 (CH 2). Push buttons in this region control the display of menus for those channels and combinations of those channels (MATH). The HORIZONTAL region has knobs that control the size (SEC/DIV) and POSITION of horizontal (x) scales. In addition to the Main time-base, this dual time-base scope can blow up a selected portion ("Window") of the display. The controls to do this are in the HORIZ MENU. The TRIGGER region has a knob that controls the voltage LEVEL for the triggering and the TRIG MENU button allows the display of configurable options for the trigger. Note particularly the AUTOSET, DEFAULT SETUP, and HELP buttons to the right of the Menu Select region.
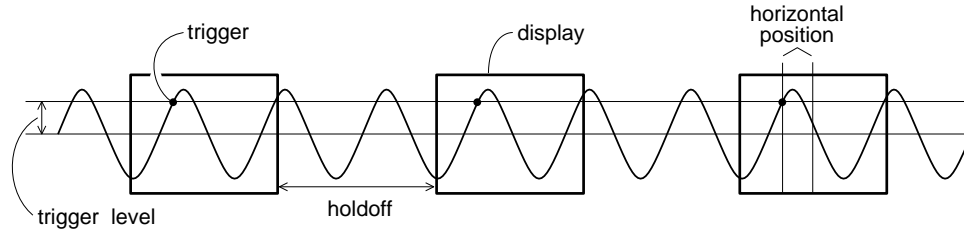
Figure 3.5: An oscilloscope displays one wave-section after another making an apparently steady display. Determining when to start a new wave-section is called triggering. The level and slope of the signal determine a trigger point. The trigger point is placed in the center of the display, but it can be moved using the horizontal POSITION knob. The holdoff is an adjustable dead time following a triggered wave-section.

terminal you will cause a short circuit [the 100 V terminal connected to ground through the scope, which will probably damage either the device or the scope].) While a DMM takes a complex waveform and reduces it to a single number: V_{rms}, a scope displays the graph of voltage vs. time on its screen.

Oscilloscopes are generally used to display periodic signals. Every fraction of a second, a new section of the wave is displayed. If these successively displayed wave-sections match, the display will show an apparently unchanging trace. Thus the TRIGGERing of successive wave-sections is critical for a stable display. And an unsteady display (or a display with 'ghosts') is a sign of a triggering problem. In addition, the scales used for the HORIZONTAL and VERTICAL axes should be in accord with the signal. (That is you want the signal to neither be off-scale large or indistinguishable from zero. A too large time (horizontal) scale will result in displaying hundreds of cycles as a big blur; a too small time scale will result in just a fraction of a cycle being displayed.)

## Oscilloscope Controls and How To Use Them

Pre-lab Exercise   The knob-filled face of an oscilloscope may appear intimidating, but the controls are organized in a logical and convenient way to help you recall their functions. The class web site contains a line drawing of an oscilloscope (`TDS1002Bscope.pdf`). Print out this diagram and have it in hand as you read this section. As each control is discussed below a circled number (e.g., ①) appears. Find this control on the line drawing and label it with that number. Attach your diagram in your notebook. The name of each control or feature will be printed in SMALLCAPS TEXT.

Display Section   The left hand side (lhs) of the scope is dominated by the display or screen ①. Note that there is a USB port ② below the display—this allows you to save scope data and display images on a thumb drive! There is an additional USB port in the back. The power switch is on top of the scope, lhs.
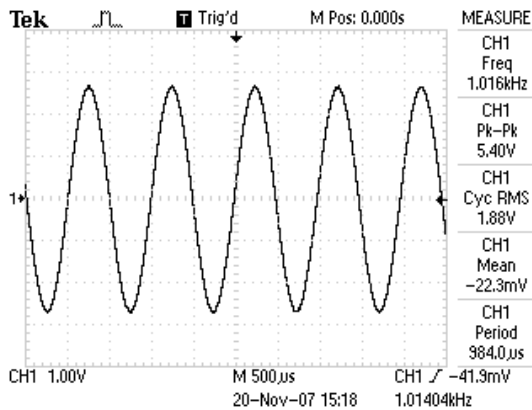
Vertical Sections   Right of the option buttons ㉕ – ㉙ are the knobs and buttons that control the vertical portions of the graph. Typically the display shows a graph of voltage
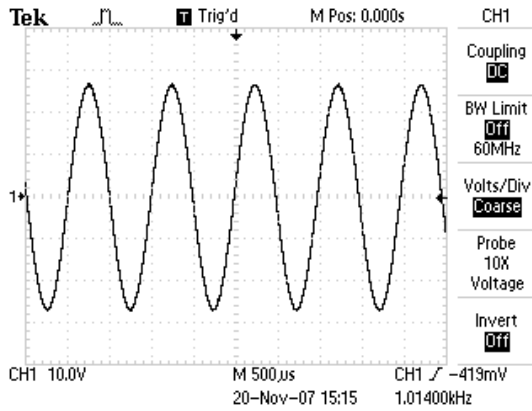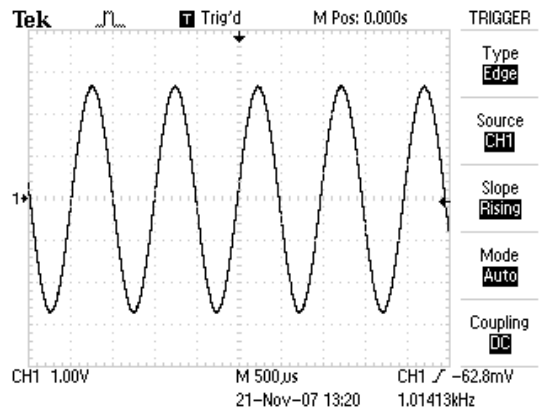
(a) Channel 1 Menu
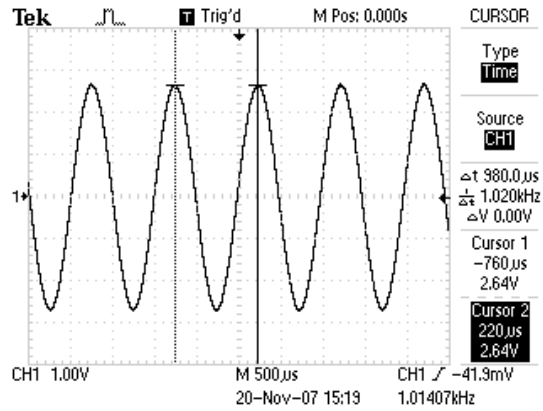
(b) Cursor Menu

(c) Measure Menu

(d) Trigger Menu

Figure 3.6: Buttons (often in the Menu Select region) control which menu appears on the rhs of the display. Here are four examples.

(y or vertical) vs. time (x or horizontal). This scope has two BNC[5] inputs so the vertical section is divided into two sections with identical controls for each input. The inputs are called channel 1 (CH 1) ⑤ and channel 2 (CH 2) ⑩. The scale factor for each input is determined by the corresponding VOLTS/DIV knob ⑥ & ⑪; the vertical location of zero volts on the screen is determined by the corresponding POSITION knobs ⑧ & ⑬. Note that the scale factors and the zero location for the channel traces are independently set. Therefore the graph axes can not show values in physical units (volts), rather the graph is displayed on a 8×10 grid with units called divisions. (Note that a division is about a cm.)

The VOLTS/DIV (or sensitivity) knobs are similar to the range switch on a multimeter. To display a 2 volt signal, set the VOLTS/DIV knob to 0.5 volts/div. A trace 4 div high will then be obtained, since 4 div $\times$ 0.5 V/div = 2 V. The current settings of these sensitivity knobs is displayed in the lower lhs of the display. You should always adjust the sensitivity so that the signal displayed is at least 3 div peak-to-peak.

The traces from the two channels look identical on the screen; the symbols 1-▶ and 2-▶ on the lhs of the display show the position of zero volts for each trace. If you are unsure which trace is which, moving a POSITION knob will immediately identify the corresponding trace.

The CH 1 and CH 2 MENU buttons ⑦ & ⑫ produce menus controlling how the corresponding input is modified and displayed. In addition pushing these menu buttons toggles the display/non-display of the corresponding signal.

The top menu item in CH 1 and CH 2 MENUs, is Coupling, with options: DC, AC, Ground. These options control how the signal supplied to the BNC is connected (coupled) to the scope's voltage measuring circuits. The Ground option means the scope ignores the input and instead the display will graph a horizontal line at zero volts (ground) — this allows you to precisely locate and POSITION the zero volt reference line for that channel on the grid. When AC is selected a capacitor is connected between the inputted signal and scope's electronics. This capacitor prevents any d.c. offset voltage from entering the scope's circuits. Thus any d.c. offset will be subtracted from the signal and the display will show the remaining signal oscillating around a mean of zero volts. The usual selection for Coupling is DC, which means the signal is displayed unmodified.

Proper Practice: Use Coupling▶DC almost always. Exceptional circumstances like a d.c. offset larger than an interesting a.c. signal (i.e., $B \gg A$ in Eq. 3.2) or a requirement to MEASURE an rms voltage in the usual way, i.e., with any d.c. offset removed, may force occasional, brief uses of Coupling▶AC, but don't forget to switch back to Coupling▶DC ASAP.

In between the CH 1 and CH 2 MENU buttons, find the MATH MENU ⑨ button. which is used to display combinations of CH 1 and CH 2 ($+, -, \times$) and Fourier transforms (FFT) of either signal.

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[5]According to Wiki, this denotes "bayonet Neill-Concelman" connector. This coaxial cable connector is very commonly used when signals below 1 GHz are being transmitted. You can also use Wiki to learn about banana connectors and alligator clips (a.k.a. crocodile clips).

Probe   The second item from the bottom in the CH 1 and CH 2 MENUs is Probe. "Probe" is the name for the device/wire that connects the scope to the signal source. In this course most often your probe will be nothing more complex than a wire, so the choice should be 1X Voltage. Note that this is <u>not</u> the factory default choice (which is 10X Voltage). So one of the first things you should do on turning on a scope, is check that the the probe actually attached to the scope matches what the scope thinks is attached to the scope. (If there is a mis-match, all scope voltage measurements will be wrong.) There is a PROBE CHECK button ③ on the scope to help you establish the attenuation of an unlabeled probe, but usually probes are labeled and it is faster just to immediately set the probe type yourself in the corresponding channel menu. Note: most probes used in this class have a switch to select either 10× or 1× attenuation. All SJU probes are voltage probes.
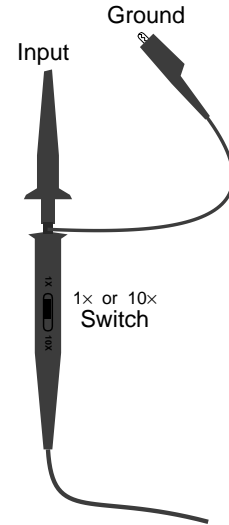
FYI: The name "10×" on a probe is quite confusing: "÷10" would be a better name as the voltage that reaches the scope has been reduced by a factor of 10. Why reduce a signal before measuring it? Because it reduces the probe's impact on the circuit it is connected to. A 10× probe has a larger impedance (smaller capacitance and larger resistance) than a 1× probe and hence affects the circuit less. This is particularly important for high frequency measurements (which are not the focus of this class).

Horizontal Section   In the center-right of the scope face, find the HORIZONTAL section. Just as in the vertical sections, there are knobs that control the horizontal scale (SEC/DIV ⑮) and horizontal POSITION ⑱. In a single time-base scope, all the input channels must be displayed with the same horizontal scale (unlike the vertical scale). In this dual time base scope, a portion of the display can be expanded in a Window. The window controls are found in the HORIZ MENU ⑰. When using the window feature the <u>M</u>ain sec/div setting is labeled M and the <u>W</u>indow sec/div setting is labeled W.

Trigger Section   As you might guess, the process of determining when to trigger and display the next wave-section is the most complex part of a scope. Luckily most often the default settings will work OK. Generally you will want to trigger when the wave has reached a particular LEVEL ㉓. But which wave? The TRIG MENU ㉒ allows you to set the Source: CH1, CH2, Ext (the signal connected to the EXT TRIG BNC ⑭ in the horizontal section), Ext/5 (the same signal, but first attenuated by a factor of 5—useful for larger triggering signals), or AC Line (which uses the 60 Hz, 120 V receptacle power line as the triggering signal—useful for circuits that work synchronously with the line voltage). Just as in the vertical section, the Coupling of this source to the triggering electronics can occur in a variety of ways: subtract the dc offset (AC), filter out (attenuate or remove) high frequency (HF Reject, "high" means > 80 kHz), filter out low frequency (LF Reject, "low" means < 300 kHz), use hysteresis to reduce the effects of noise (Noise Reject), or directly connected (DC). Note: triggering with Coupling▶AC is a common choice as then a LEVEL of zero is sure to match the wave at some point. Similarly Noise Reject is not an uncommon choice. The above options go with Type▶Edge. There are additional sophisticated and useful triggering modes for Type▶Pulse and Type▶Video.

Measure Menu   The MEASURE menu �36 allows up to five measurements to be continuously updated and displayed. Push on one of the option buttons and a new menu is displayed allowing you to set the Source: CH1, CH2, MATH, and the Type: Freq, Period, Mean (voltage), Pk-Pk (peak-to-peak, i.e., the full range of voltage from the lowest valley to the highest peak), Cyc RMS (the root-mean-square voltage of the first complete cycle), Min (minimum voltage), Max (maximum voltage), Rise Time, Fall Time (10% to 90% transitions), Pos(itive) Width, Neg(itive) Width (using the 50% level).

Warning: Unlike a DMM on AC, the option Cyc RMS does not subtract the d.c. offset before calculating rms voltage. You can assure yourself of a DMM-like rms result only if the channel is switched to Coupling▶AC.

If a measurement is displayed with a question mark, try switching scales. (Generally the scope wants signals that are several divisions high and complete at least one—but not too many—cycles in the display.)

Cursor Menu   The CURSOR menu �37 enables a pair of Type▶Amplitude or Type▶Time measuring lines. With Amplitude cursors, a pair of horizontal lines ("cursors") appears. Hitting the appropriate option button allows the multifunction knob to move each cursor up or down to the required place. The voltage for each cursor is displayed along with the difference (ΔV). With Time cursors, a pair of vertical lines appears. Hitting the appropriate option button allows the multifunction knob to move each line (cursor) right or left to the required place. The voltage and time for each cursor is displayed along with the differences (Δt, ΔV), and frequency $1/\Delta t$.

Display Values   The bottom of the display is used to report key numerical values like scale settings.   A typical example:

CH1 500mV   CH2 2.00V   M 1.00ms   CH1 ╱ 0.00V
                                  23-Nov-07 13:03   1.01407kHz

The first two numbers of the first line are the VOLTS/DIV for channels CH1 and CH2, M refers to the main time-base of 1 ms/div, and the final sequence reports that positive edge triggering at a level of 0.00 V is being used with channel 1 as the source. The second line shows the date/time and the frequency of the triggering signal.

Run/Stop   In normal operation, the scope is constantly updating the display. It is possible to freeze the display (i.e., take a snapshot of the voltage vs. time graph) using the RUN/STOP �44 or SINGLE SEQ �43 buttons.

Hit Me First   The scope remembers option settings between uses. Thus unless you are the sole user of the scope it is wise to set it to a well defined initial state before proceeding. The DEFAULT SETUP �41 achieves this goal (but it sets the Probe▶10X Voltage, in the channel menus—which is not usually desired in this class). Similarly the AUTOSET �42 button will attempt to make rational choices for scale factors, etc. given the signals connected to the

scope. If you want you can save commonly used setups using the SAVE/RECALL ㉞ menu button.

Problems

1. (a) A 1.5 V battery can be modeled as an ideal 1.5 V voltage source in series with a 1 Ω resistor. If this battery is connected to a 10 Ω resistor (see below left), what voltage is actually across the 10 Ω resistor?

   (b) A 1 mA current source can be modeled as an ideal 1 mA current source in parallel with a 1 MΩ resistor. If this source is connected to a 10 kΩ resistor (see below right), how much current actually flows through the 10 kΩ resistor.?
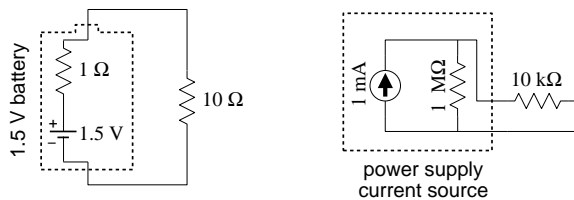
2. (a) A voltage source produces a voltage V when its terminals are disconnected (open circuit). When a device that draws a current I is connected across its terminals, the voltage decreases to $V - \Delta V$. What is the internal resistance?

   (b) A current source produces a current of I when a wire connects the terminals. When a device is instead connected to the terminals the current drops to $I - \Delta I$ and the voltage across the terminals is V. What is the internal resistance?

3. The manual for a stereo amplifier warns that it can be damaged if its "outputs are too heavily loaded". What sort of resistor would constitute a "heavy load": (A) $R = 1$ MΩ or (B) $R = 1$ Ω? Explain!

4. (a) A current of 3 mA flows into a circuit consisting of 3 resistors, and 10 mA flows out (see below left). Report the readings on the three voltmeters. Draw a schematic diagram showing which lead on each voltmeter is the 'red' lead.

   (b) An unknown device is connected in a circuit with a 9 V battery and a 15 kΩ resistor (see below right). The ammeter reads 0.5 mA. What does the voltmeter read?
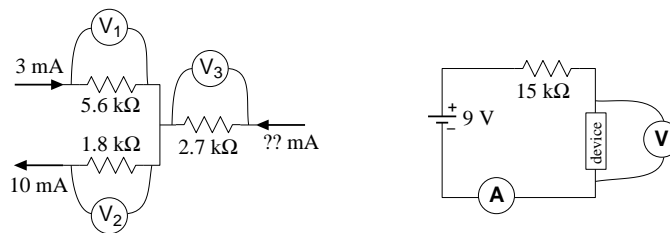
5. What is the resistance (when operating) of a 100 W light bulb operating from a 120 V source?

6. An ideal ammeter should act like a wire and hence have zero volts between its terminals. However real ammeters are less than perfect. The specifications for Keithley 196 in d.c. amps mode reports it has a *voltage burden* of about .15 V when measuring 100 mA on the proper scale. If you use a 196 to measure the current through a 15 Ω resistor powered by a 1.5 V battery, what current does it read?

7. Which light bulb in the below left circuit shines the brightest? Why? Which light bulb shines the dimmest? Why?
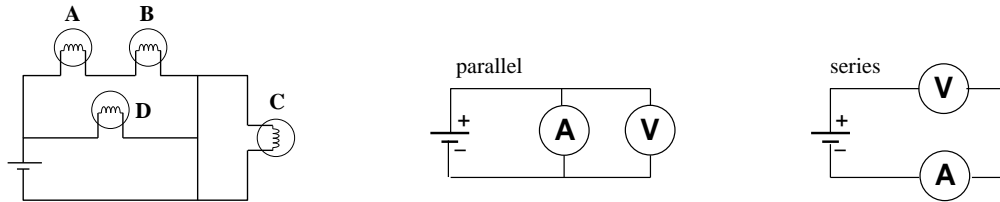

8. (a) An ammeter and a voltmeter are connected is series. Are either likely to be damaged? Why? Will either read the current or voltage of the battery? Why?

   (b) An ammeter and a voltmeter are connected in parallel. Are either likely to be damaged? Why? Will either read the current or voltage of the battery? Why?

9. An ideal voltmeter V_1 is used to measure the voltage across the series combination of a battery and 1 kΩ resistor; an ideal voltmeter V_2 is used to measure the voltage across the battery alone. Which of the below is correct?

   (a) $V_1 > V_2$
   (b) $V_1 = V_2$
   (c) $V_1 < V_2$
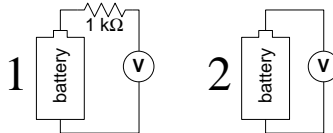
10. The picture (right) shows a circuit in which a battery powers a light bulb.

    (a) Make a careful drawing showing how the voltage produced by the battery could be measured. Include details like exactly where the red and black leads on the voltmeter would be attached.

    (b) Make a careful drawing showing how the current produced by the battery could be measured. Include details like exactly where the red and black leads on the ammeter would be attached.
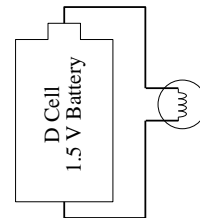
11. The specifications for a Keithley 169 say that, when operating in a.c. volts mode, the inputs look like 1 MΩ in parallel with 100 pF (see right). At what frequency is the current equally shared by the capacitor and the resistor?
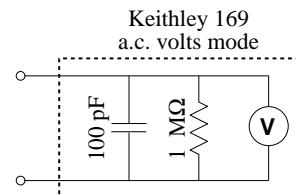
12. A typical lab power supply has knobs labeled VOLTAGE ADJUST and CURRENT ADJUST. If you turn the voltage knob the output voltage changes, but if you turn the current knob nothing seems to change and the current meter continues to read zero. Explain!

13. A function generator has an output impedance of 50Ω and, when unloaded and adjusted to produce its maximum output, produces a voltage amplitude of 10 V. What is the maximum power that can be transferred to an external device attached to the function generator?

14. Oscilloscope — True or False:

    (a) When the vertical input coupling is set to DC mode, the voltage of an a.c. waveform cannot be measured.

    (b) When the vertical input coupling is set to AC mode, the voltage of a battery cannot be measured.

15. A circuit consists of an inductor (inductance L) connected directly to a 120 V, 60 Hz wall receptacle. What is the smallest L you could use and avoid blowing the 20 A fuse? A similar circuit consists of a capacitor connected directly to a wall receptacle. What is the largest C you could use and avoid blowing the fuse?

16. Manufacturers typically report DMM errors as a percentage of the reading plus a certain number of "digits". In this context, one digit means a 1 in the rightmost displayed digit and zeros everywhere else. Consider a DMM display: 0.707. Find the absolute error in this reading if the device is:

    (a) METEX-3800 DC current, 2 mA range.
    (b) METEX-3800 AC current at 500 Hz, 2 A range.
    (c) Keithley 169 resistance, 2 kΩ range.
   (d) Keithley 169 AC volts at 2 kHz, 2 V range.

    The specification sheets can be found posted in the lab or in the manuals in the physics library. Please note that errors should be rounded to one or two significant figures.

17. Work the previous problem assuming the display reads: 0.007

18. The below left diagram shows a single sinusoidal scope trace. Determine: the peak-to-peak voltage, the voltage amplitude, the rms voltage, the wave period and frequency. Assume that the bottom of the scope display reads:

    CH1 500mV   M 1.00ms   Ext ⌐ 0.00V
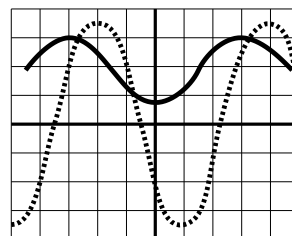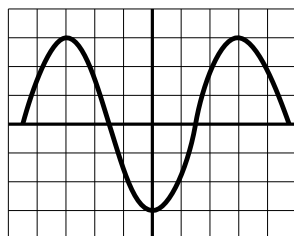
19. The above right diagram shows a pair sinusoidal scope traces. Assume that the scope controls are set as in the previous problem with CH 2 (dotted) and CH 1 (solid) identical. Which trace is lagging: dotted or solid? What is the phase shift in degrees?

20. The section describing oscilloscope controls identified controls with a circled number like: ①. On the class web site, find and print the file `TDS1024Bscope.pdf` which is a line drawing of an oscilloscope. On this hardcopy, locate every control and label each with the appropriate number.

4: Electrical Measurements Lab

Electrical Measurement Lab
DC & AC Measurements
Impedance & Filters
Work individually please!

0. Basic DC measurements.

1. Select a resistor from the "370 Resistors" cup. Sketch your resistor carefully recording the color of the bands on it. Decode the color bands to find the manufacturer's reported resistance.

2. Using a Keithley 169 DMM, measure the resistance of your resistor. Record the result with an error. Using a Metex 3800 DMM, measure the resistance of your resistor. Record the result with an error. Are your results consistent?

3. Find one of the dual battery packs with black and red leads attached. Using a Keithley 169 DMM, measure the voltage of the pack. Record the result with an error. Using a Metex 3800 DMM, measure the voltage of the pack. Record the result with an error. Are your results consistent?

4. Calculation: $R = V/I$

   Measure the voltage across your resistor with a Keithley 169 DMM (record the result with an error). Simultaneously measure the current through the resistor with a Metex 3800 DMM (record the result with an error). Calculate the resistance of the resistor along with its error. Is your calculated resistance consistent with those measured in #2? (If it isn't consult your lab instructor.) I bet the voltage measured here is less than that in #3 above. This is a consequence of the internal resistance of the battery pack that I call *voltage droop* and also related to the *voltage burden* of the ammeter discussed in problem 6 and measured in #8 below. You are now done with the battery pack.
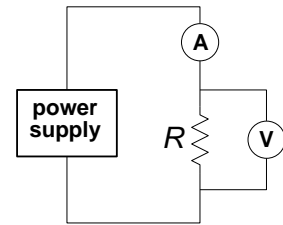
5. Find a LAMBDA power supply. Record its model number. Turn all three of its knobs to mid-range values; leave the terminal plugs unconnected. Notice that the terminal plugs are labeled: + (red), ⊥ (white), − (black). Which terminals should you use to have the power supply function like the battery pack? What is the purpose of the third terminal?

6. Plug-in/turn on the power supply. Switch the METER switch to VOLTAGE and adjust the VOLTAGE ADJ knobs (both COURSE and FINE) until the meter reads approximately the same as #3 above. Now attach a DMM to the power supply. Using the FINE VOLTAGE ADJ knob try again to match the output of the battery pack. (It need not be perfect.)

7. Reform the circuit of #4 now using the power supply adjusted to match the battery pack. Measure of the voltage across and current through your powered resistor and compare to those obtained in #4 above. Why the difference?

8. Voltage Burden of Ammeter. Move the voltmeter in the above circuit so as to measure the voltage drop across the ammeter (rather than your resistor). Report the result.

9. Disconnect the DMMs, and make a circuit where the power supply is directly attached to the resistor. Holding the resistor between your fingers carefully and slowly raise the voltage produced by the power supply. At some point (typically > 20 V) the resistor should start to warm up. Using the power supply meter, record the voltage that produced a noticeable heating effect. Calculate the power (watts) required for this heating effect. (No need to calculate error.)

10. Return the power supply to the approximate voltage level produced by the battery pack and disconnect your resistor. Switch the METER switch to CURRENT. Use a banana plug wire to short circuit the output of the power supply. (Note that short circuiting most devices will result in damage. These lab power supplies are [I hope] an exception to this rule.) Notice that the CURRENT ADJ knob now allows you to set the current through the wire (and of course the voltage across the wire is nearly zero). As long as the output voltage is less than the set voltage limit, the CURRENT ADJ knob is in control. If (as before) the current is below the set current limit, the VOLTAGE ADJ knob is in control. Thus if the voltage limit is set high, you have an adjustable current source; if the current limit is set high, you have an adjustable voltage source.

11. Voltage divider.

    Set up the potentiometer circuit shown and power it with the LAMBDA power supply. Measure V_{out} with a DMM. This is a classic voltage divider. Notice that by adjusting the pot, any fraction of the supplied voltage can be produced.
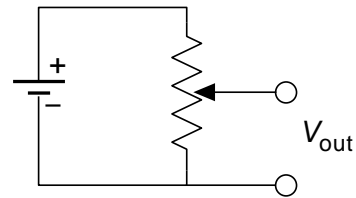
0. Basic AC measurements. For this and following sections you need not report errors in measurements, but always record every digit displayed on the DMM or scope and use devices on proper scales/ranges.

1. WAVETEK 180 as ac power source

    Set up the circuit shown using your resistor and your WAVETEK 180 (as the ac voltage source). Start with all the WAVETEK knobs fully counter-clockwise. (This is basically everything off and sine wave function selected.) Using the big knob and the FREQ MULT knob, set the frequency to 1 kHz. This will also turn on the WAVETEK.
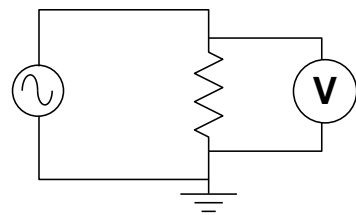
2. Adjusting the AMPLITUDE knob will change the output voltage. What range of voltages can be obtained from the HI BNC output? How about the LO BNC output?

3. Set an output voltage of approximately 1 V. Increase the frequency to find the highest frequency for which the reported voltage remains in the range 0.95–1.05 V (i.e., within 5% of the set value). Report the voltmeter you're using, its reported voltage, and the frequency. Further increase the frequency until the voltmeter reports a voltage under 0.5 V. (Record that frequency.) The apparent change in voltage you are seeing is really mostly due to the failure of the voltmeter to work at high frequency. As you'll see below the WAVETEK's output really is fairly constant as the frequency is varied.

4. With the output voltage still set at approximately 1 V, set the frequency to 100 Hz, and measure the ac current through and the ac voltage across your resistor. (The required circuit is analogous to #4 above. You might want to have your instructor check your circuit before powering up.) Calculate the resistance (no error calculation required). Your result should be consistent with previous resistance measurements. Measure the current again at a frequency of 1 kHz. Does the current (and hence resistance) vary much with frequency?

5. Replace your resistor with a capacitor. With the 100 Hz, 1 V output, measure the current and voltage. Calculate the "resistance" (actually reactance, i.e., V/I). Using your calculated reactance, calculate the capacitance (see Fig. 3.1 on page 80 if you're unsure of the definition of C). Measure again at a frequency of 1 kHz. Does the current (and hence reactance) vary much with frequency? Again calculate the capacitance—it should be nearly the same even though the current should be nearly ten times bigger.

0. Basic scope measurements. **Note:** A "scope trace sketch" should include: horizontal and vertical scale settings (and the size of a DIV on your sketch—this is one place where quad ruled notebook paper helps!), the location of ground (zero volts), and the signal frequency. All of these numbers are on the scope display. In addition report the type of Coupling being used on the displayed channel. Feel free to report "same settings as previous" if that is the case.

1. Set up the scope and a DMM to monitor the function generator as shown. Set the function generator to produce a ∼1 V sine wave at a frequency of ∼1 kHz. Turn on the scope and hit DEFAULT SETUP. You must now change both CH1 and CH2 to 1× probe from the defualt value of 10× probe. Fiddle (or not) with the controls until you have a nice stable display of the signal on the scope. Sketch the scope trace.
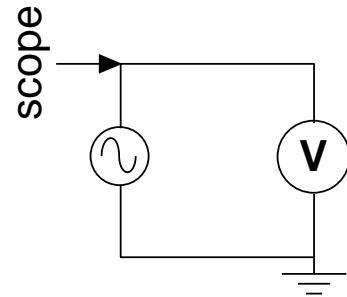
2. Record the size (in units of divisions on the display) for: the peak-to-peak voltage (V_{pp}), the amplitude or peak voltage (V_p), and the period (T) of the wave. Convert these to physical units (volts, seconds) using the scale factors. Calculate the frequency from the period and compare to the set value. Calculate the rms voltage from the peak voltage and compare to the DMM value. Hit the MEASURE menu and arrange the simultaneous display of Freq, Period, Pk-Pk voltage, Cyc RMS voltage, and Max voltage. Compare these values to those you calculated from divisions.

3. Run the function generator frequency up to and beyond the limiting value determined in previous section, #3. Notice that the scope (correctly) shows a constant amplitude even as the voltmeter (incorrectly) shows a varying voltage.

4. Return the frequency to 1 kHz. Vary the function produced by the function generator: try triangle and square waves. For each wave, record the scope-reported peak-to-peak and rms voltages. Also record the rms voltage reported by the DMM. For a square wave: $V_{rms} = V_{pp}/2$; for a triangle wave: $V_{rms} = V_{pp}/2\sqrt{3}$. Compare these calculated rms voltages to those directly reported by the scope and DMM. Which device appears to be a "true rms" meter? Explain.

5. In the MEASURE menu change the measurement of Period to Mean (voltage). Find the DC OFFSET knob on the function generator. Monitor the scope display and produce a ~1 V amplitude sine wave with a ~1 V dc offset. Sketch the resulting scope trace. Record the DMM ac voltmeter reading; record the scope Cyc RMS voltage. Switch the DMM to dc volts and record the dc voltage the reading; record the scope Mean voltage.

   Switch the scope's input to Coupling▶AC, and repeat the above sketches and measurements. Comment on the results.

0. Filters

   In many circumstances in electronics we are concerned with the ratio of voltages (or powers, currents, etc.), e.g., $\mathcal{A} \equiv V_{out}/V_{in}$. For example the aim of an amplifier is to produce a $V_{out} \gg V_{in}$ and one is usually primarily concerned with the amplification (or *gain*), which is that ratio. ($\mathcal{A} > 1$ for amplification.) On the other hand, sunglasses aim to reduce or attenuate light before in enters the eye. ($\mathcal{A} < 1$ for attenuation.) Such ratios are most often reported in *decibels* (dB):

   $$20 \, \log_{10}\left(V_{out}/V_{in}\right) \tag{4.1}$$

   Thus if an amplifier increases the voltage by a factor of 10 (i.e., $\mathcal{A} = 10$), we would say the amplifier has a gain of 20 dB. Some common examples:

amplification		attenuation	
$\mathcal{A}$	dB	$\mathcal{A}$	dB
100	40	$\frac{1}{100}$	-40
10	20	$\frac{1}{10}$	-20
2	6	$\frac{1}{2}$	-6
$\sqrt{2}$	3	$\frac{1}{\sqrt{2}}$	-3
1	0	1	0

   An electronic filter aims to pass certain frequencies and attenuate others. For example, a radio antenna naturally picks up every frequency; an electronic filter must attenuate all but the desired frequency. We start here with a *low pass filter*: a filter that lets low frequencies pass nearly untouched, but attenuates high frequencies. It is impossible to have step changes in attenuation, so as the frequency is increased, $\mathcal{A}$ goes smoothly to zero. Traditionally the curve of $\mathcal{A}$ vs. f is presented as a log-log plot and is called a Bode[1] plot. Filters are usually characterized by their "-3 dB" frequency (f_{-3dB}), i.e., the frequency[2] at which $\mathcal{A} = 1/\sqrt{2} \approx .707$.

   For the following measurements you will use a sinusoidal signal with no dc offset and a very large range of frequencies and voltages: Remember to adjust your scope scales appropriately. Your voltage MEASUREments are most easily done as Pk-Pk or Cyc RMS (it doesn't matter which, just be consistent) with Coupling▶AC.

1. Solder together a lead from your resistor and a lead from your capacitor.

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[1] "Bo–Dee" plots were popularized by Hendrik Wade Bode's book *Network Analysis and Feedback Amplifier Design* 1945. Bode worked at Bell Labs and became head of the lab's Mathematics Department in 1944.

[2] **Note:** The general definition of f_{-3dB} is <u>not</u> that the gain is .707, rather that the gain has <u>changed</u> from some standard value by a factor of .707, i.e., the gain is 3 dB less than 'usual'. In #2 the 'usual' $\mathcal{A}$ is 1, so f_{-3dB} is where $\mathcal{A} = .707$ In #3 the 'usual' $\mathcal{A}$ is .5, so f_{-3dB} is where $\mathcal{A} = .354$

2. *RC* low pass filter.

   Use your *RC* combination to construct the low pass
   filter shown. You will monitor the input to the filter
   (V_{in}) on CH 2 of the scope and the output (V_{out}) on CH
   1. Describe how this filter's 'gain' (but here $\mathcal{A} < 1$,
   so 'attenuation' might be a better word) changes as
   the frequency is varied from 50 Hz to 1 MHz. Find
   the filter's f_{-3dB} (at which $V_{out} = V_{in}/\sqrt{2}$). Make a
   table of attenuation (V_{out}/V_{in}), dB, and f measured
   at frequencies of about 0.1, 0.2, 1, 2, 10, 20, and 100
   times f_{-3dB}. (Note that if, by adjusting the AMPLI-
   TUDE on the Wavetek you make $V_{in} = 1$, you won't
   need a calculator to find V_{out}/V_{in}.) By hand, make
   a log-log graph of attenuation vs. f using the sup-
   plied paper. Check that the filter's Bode-plot slope
   for $f > f_{-3dB}$ is 6 dB per octave (or, equivalently, 20
   dB per decade). Sketch (together) the scope traces
   at f_{-3dB}. Does V_{out} lead or lag V_{in}? (Note: a *RC*
   low pass filter is behind your scope's HF Reject op-
   tion; a *RC* high pass filter is behind your scope's
   Coupling▶AC option.)
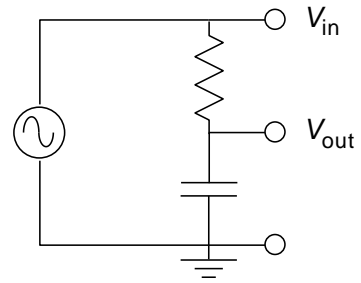
3. *LC* Filter

   I've constructed the beastie shown. (For the curious, it's a 5-pole, low-pass But-
   terworth filter in the π-configuration: see Appendix H of Horowitz and Hill if you
   want more details.) At low frequencies the gain never exceeds about $\frac{1}{2}$; therefore
   f_{-3dB} is defined as the frequency at which $\mathcal{A}$ is .707× its low frequency value, i.e.,
   $\mathcal{A} = .707 \times .5 = .354$. Using a sine wave as input, take data of attenuation vs. fre-
   quency and plot them on log-log paper. Use frequencies of about 0.01, 0.1, 0.2, 0.5, 1,
   2, 4, and 8 times f_{-3dB}. (At high frequencies the attenuation is so large that V_{out} may
   be lost in the noise unless you increase V_{in} to well above 1 V.) How does the steepness
   of this filter's cut-off compare with that of the simple *RC* filter? (I.e., compare the
   dB-per-octave falloff of this filter to the simple *RC* filter.)
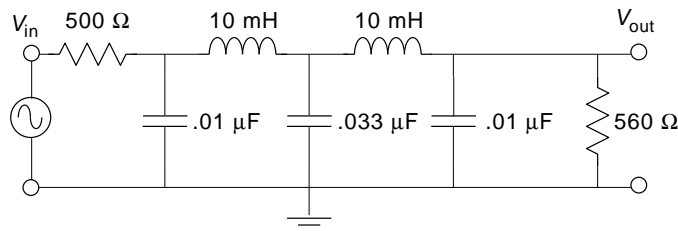
4. Tape your resistor+capacitor combination in your notebook.