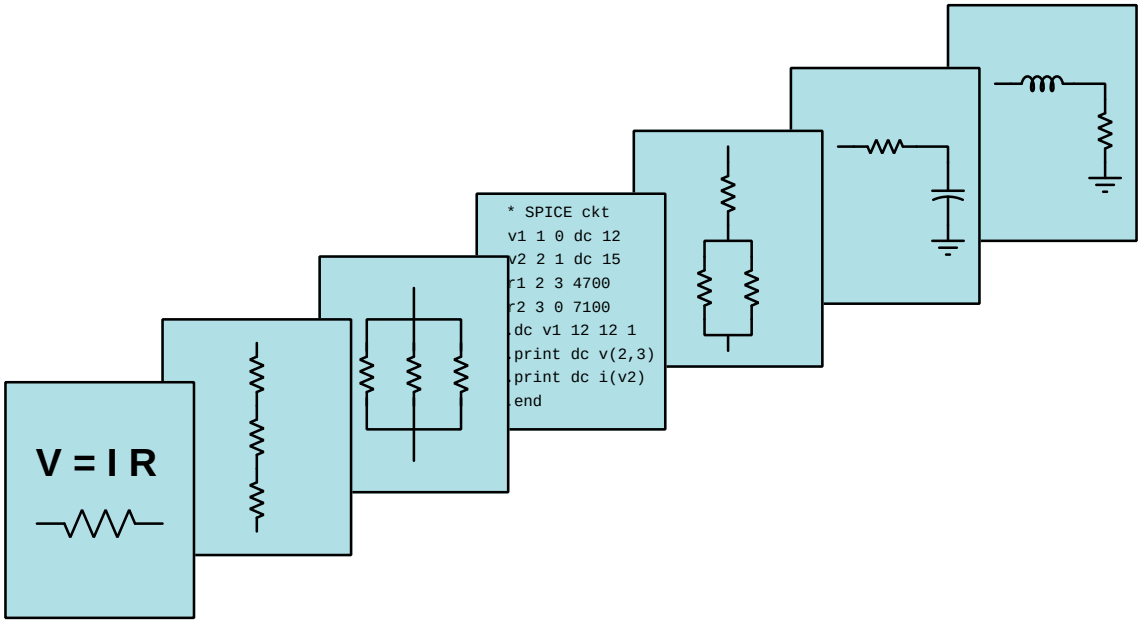
Modular Electronics Learning (ModEL) project



Oscilloscopes

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Chapter 1

Introduction

1.1 Recommendations for students

An *oscilloscope* is perhaps the most useful test tool in the electronic technician's or engineer's collection. Basically a graphing voltmeter, an oscilloscope is able to give a view of electronic signals impossible to see with any other instrument.

Important concepts related to oscilloscopes include **voltage**, **polarity**, **cathode ray tubes**, test **probes**, **capacitance**, **inductance**, **transmission lines**, **parasitic** effects, **sensitivity**, **timebase**, signal **coupling**, **sweep**, **major divisions** and **minor divisions**, **ground**, **ripple**, **ground-referenced** versus **differential** voltage signals, **triggering**, **transient** signals, **switch bounce**, **holdoff**, **phase shift**, **phasors**, **isolation**, **shunt resistor**, **transformer**, **parametric** plot, **Lissajous figures**, **curve tracing**, test probe **compensation**, **RC networks**, **sampling rate**, **aliasing**, and the **Nyquist Sampling Theorem**.

Here are some good questions to ask of yourself while studying this subject:

- How might an experiment be designed and conducted to test whether or not it will be safe to connect a grounded test instrument such as an oscilloscope to a circuit? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What are some practical applications of oscilloscopes?
- What is an oscilloscope able to do that a multimeter cannot?
- What is a multimeter able to do that an oscilloscope cannot?
- What is represented on the vertical axis of an oscilloscope display?
- What is represented on the horizontal axis of an oscilloscope display?
- How can you determine which of two AC signals is leading or lagging the other on an oscilloscope display?

- How can you calculate the amount of phase shift between two AC signals on an oscilloscope display?
- How can you determine the polarity of a DC signal measured by an oscilloscope?
- How can you calculate the frequency of an AC signal on an oscilloscope display?
- How does a $\times 10$ multiplying probe work?
- What are some practical applications for a $\times 10$ multiplying probe?
- What precautions must one take when connecting an oscilloscope to a circuit?
- How do you properly set the vertical sensitivity on an oscilloscope to display a signal?
- How do you properly set the timebase on an oscilloscope to display a signal?
- How do you properly set the trigger controls an oscilloscope to display a signal?
- What does the "holdoff" control do on an oscilloscope?
- What does "DC" coupling do when measuring a signal?
- What does "AC" coupling do when measuring a signal?
- How do the normal, auto, line, and single-sweep triggering modes function?
- In what types of measurement applications might external triggering be useful?
- What are cursors used for on a digital oscilloscope?
- How do you configure an oscilloscope to perform a differential voltage measurement using two channels to measure one signal?
- Where might you need to perform a differential voltage measurement using two channels to measure one signal?
- What are some different applications of X-Y mode?
- What does it mean to "compensate" an oscilloscope probe?
- What is aliasing, and when might it occur on an oscilloscope?
- How may Lissajous figures be used to determine a signal's frequency?

I strongly recommend any serious student of electricity and electronics owning their own oscilloscope. As of this date (2017) it is possible to purchase an entry-level computer-based oscilloscope with free software for less than $150 (US dollars), the oscilloscope interfacing with any personal computer via USB (Universal Serial Bus). Legacy cathode-ray oscilloscopes (CROs) are excellent learning tools, but are practically obsolete compared against computer-based tools.

One of the most challenging features to master on an oscilloscope is *triggering*, and this is best done by viewing a wide diversity of waveforms. The advent of computer-based oscilloscopes

has greatly expanded the palette of triggering functions, and this in turn has made a challenging concept even tougher to master. An essential form of triggering for any modern student to learn is *single-sweep* triggering which may be used to capture a non-repeating waveform. A good source of low-voltage signals to use for such triggering exercises is any form of voltage-based *digital network* such as EIA/TIA-232 or EIA/TIA-485, examples of which are relatively easy to set up in a suitably equipped workshop or lab by an instructor.

1.2 Challenging concepts related to oscilloscopes

The following list cites concepts related to this module's topic that are easily misunderstood, along with suggestions for properly understanding them:

- **Grounded oscilloscope inputs** – oscilloscopes having more than one input "channel" share common ground connections between these channels. That is to say, with two or more input cables plugged into an oscilloscope, the "ground" clip of each input cable is electrically common with the ground clip of every other input cable. This can easily cause problems, as points in a circuit connected by multiple input cable ground clips will be made common with each other (as well as common with the oscilloscope case, which itself is connected to earth ground). One way to avoid unintentional short-circuits through these ground connections is to only connect *one* ground clip of the oscilloscope to the circuit ground, removing or tying back all the other inputs' ground clips since they are redundant.
- **Interpreting oscillograph frequency** – frequency and period are mathematical reciprocals of each other, but the reason for this is not necessarily clear unless and until one closely examines the units of measurement used for each. Frequency is customarily measured in *Hertz*, but what "Hz" really means is *cycles per second*. Period is measured in *seconds*, but what we really mean by this is *seconds per cycle*. Comparing "cycles per second" with "seconds per cycle" makes the reciprocal relationship perfectly clear!
- **Interpreting oscillograph phase shift** – phase shift is typically expressed in degrees, calculated from the shift between two waves' similar peaks as well as their period. Phase shift may be computed from a time-domain oscillograph, as well as from a Lissajous figure.
- **Triggering** – of all the basic oscilloscope controls, triggering is by far the most confusing. One way to understand this better is to find a legacy *analog* (CRO) oscilloscope and set it up for a slow sweep rate measuring a low-frequency AC voltage where you can see the dot rise and fall over time, then by setting the trigger level at different values you can control when the sweep begins at the left-hand edge of the display.

The *Case Tutorial* section "First-time oscilloscope experiment ideas" is an excellent starting-point for any student new to hands-on experimentation with oscilloscopes.

1.3 Recommendations for instructors

This section lists realistic student learning outcomes supported by the content of the module as well as suggested means of assessing (measuring) student learning. The outcomes state what learners should be able to do, and the assessments are specific challenges to prove students have learned.

- **Outcome** – Demonstrate effective technical reading and writing

  Assessment – Students present their outlines of this module's instructional chapters (e.g. Case Tutorial, Tutorial, Historical References, etc.) ideally as an entry to a larger Journal document chronicling their learning. These outlines should exhibit good-faith effort at summarizing major concepts explained in the text.

  Assessment – Students present their "Conceptual Toolbox" Theory Journal entries listing important concepts applied in the Tutorial text(s). A "Conceptual Toolbox" serves as inspiration when solving problems, each concept suggesting a potential problem-solving action. Challenge students to collaboratively generate a Conceptual Toolbox for the day's topic during the class session and then use it when solving problems together, thus fostering the habit of reasoning from principles rather than recalling procedures!

- **Outcome** – Properly interpret oscillograph parameters

  Assessment – Measure signal voltage, frequency, phase shift, rates of rise and fall, etc. from oscillographs; e.g. pose problems in the form of the "Measuring waveform parameters" Quantitative Reasoning question.

- **Outcome** – Demonstrate basic oscilloscope usage in a variety of contexts

  Assessment – Conduct experiments similar to those described in the "First-time oscilloscope experiment ideas" Case Tutorial section.

- **Outcome** – Demonstrate use of and applications for x10 probes

  Assessment – Properly adjust the compensation for a x10 oscilloscope probe.

  Assessment – Measure voltage across one of the resistors of a voltage divider comprised of high-valued resistors (MegaOhms), explaining the discrepancy found between voltage measurement using a x1 probe versus using a x10 probe.

- **Outcome** – Demonstrate differential voltage measurement

  Assessment – Properly configure an oscilloscope to measure the voltage of a source having some common-mode voltage to ground, using two probes in differential mode to reject that common-mode voltage.

- **Outcome** – Prove the concept of Lissajous-figure frequency comparison by experiment

  Assessment – Set up an oscilloscope with two adjustable-frequency signal generators or oscillators and use X-Y mode to set the frequencies to pre-determined ratios, then verify by switching to time-domain mode and measuring the frequency of each signal.

- **Outcome** – Build an LED-array oscilloscope

  Assessment – build a rectangular array of LEDs on a circuit board, the rows and columns driven by comparators comparing input voltages against fixed reference voltages produced by voltage divider networks.

- **Outcome** – Independent research

  Assessment – Locate the technical manual for whatever model of oscilloscope(s) you have access to, and identify within these documents how to use the instrument's basic controls.

Chapter 2

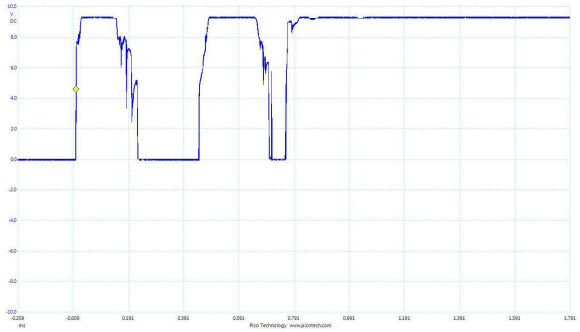
Case Tutorial

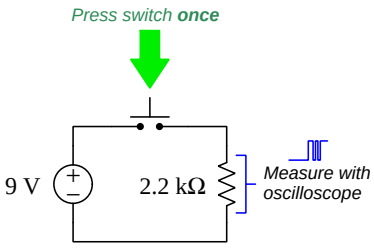
The idea behind a *Case Tutorial* is to explore new concepts by way of example. In this chapter you will read less presentation of theory compared to other Tutorial chapters, but by close observation and comparison of the given examples be able to discern patterns and principles much the same way as a scientific experimenter. Hopefully you will find these cases illuminating, and a good supplement to text-based tutorials.

These examples also serve well as challenges following your reading of the other Tutorial(s) in this module – can you explain *why* the circuits behave as they do?

2.1 Switch contact bounce

When mechanical switch contacts open and close, they tend to do so in a "noisy" fashion, making intermittent contact when opening and when closing. We may capture these intermittent contact events using an *oscilloscope* to graphically plot voltage over time:





This particular oscillograph was captured during the time when the pushbutton switch was pressed a single time. What we see the oscilloscope detect during this time is actually *three* distinct closures of the switch's contacts, with jagged rising and falling edges. The reason we see three closures of the switch over a span of less than 1 millisecond is because the metal contact surfaces are literally *bouncing* of of one another as the pushbutton force acts to press them together. This phenonenon is not unlike dropping a ball on a hard floor surface, the ball bouncing several times before coming to rest on that floor.

Switch bounce is a common problem when any mechanical switch contact generates a signal for the input of a digital counter circuit, the purpose being for that counter to increment or decrement *once* for each switch actuation. "Bouncing" switch contacts will "fool" the counter into counting multiple times per switch actuation instead of just once.

Various techniques exist to mitigate switch bounce:

- **Use mercury-wetted switch contacts** – these are special switch contacts housed in a hermetically-sealed glass tube with a small amount of liquid mercury present. This liquid mercury adheres to the metal switch contact faces, providing a mercury "bridge" maintaining continuity between the contact faces when they are separated by very small distances, thereby maintaining contact during the "bouncing" period.

- **Use an electronic switch** – eliminating mechanical switch contacts altogether is a direct way of solving this problem. "Switches" using magnetic-field sensors and transistors as the switching elements may be used to sense the operation of a pushbutton actuator, and in the case of limit switches used to detect machine motion there exist both inductive-style and capacitive-style proximity switches that will do the same task in a bounce-less manner.

- **Connect a capacitor in the circuit** – inserting a small capacitor into the circuit to stabilize the voltage signal is another way to "de-bounce" mechanical switch contacts, preventing those

contacts from generating transient voltage pulses of too-short duration. This technique works especially well in digital electronic circuits if the capacitor-stabilized voltage signal is sampled by the input of a *Schmitt-trigger* style of logic gate, this type of gate circuit designed to tolerate voltage levels between valid "high" and valid "low" states.

- **Use a shift register** – a digital *shift register* circuit sampling the switch's signal in its serial input terminal, driven by a clock pulse signal of suitable frequency, will populate that register's bits with successive states of the switch. An AND logic function reading all parallel bits from the register then provides a "de-bounced" signal that will be "high" (1) only if *all* previous states of the switch were also "high" (i.e. only if the switch contacts have remained closed for a certain duration of time established by the clock pulse frequency and the number of parallel bits offered by the shift register).

- **Use software sampling** – if the switch's signal goes to the input of a microcontroller or other similarly programmable digital device, that device may be programmed to perform the same repeated sampling and testing of the switch signal described in the shift register technique.

2.2 First-time oscilloscope experiment ideas

One of the most useful test instruments for electronic circuits is the *oscilloscope*, used to create a graphical plot of voltage over time. Oscilloscopes are extremely important for measuring AC (alternating) signals as well as transient (momentary) signals. When first learning the operation of oscilloscopes, it is informative to safely experiment with a real oscilloscope in order to become accustomed to its controls and functionality. Here is a list of experimental ideas that are safe, interesting, and rich with learning opportunities:

- **Measuring battery voltage** – connect an oscilloscope to the terminals of a battery, then interpret that battery's voltage using the divisions on the screen's vertical axis. Note that you will need to have the vertical coupling configured for "DC" in order for this to work!
- **Detecting ambient electric fields** – connect the oscilloscope's probe tip to a long wire and use that wire as a crude antenna to pick up AC electric fields with respect to Earth ground (the oscilloscope will already have an Earth-ground reference from its line power cord).
- **Detecting magnetic fields** – connect the oscilloscope's probe tip and ground clip to a wire coil, then place that coil nearby any AC line-powered device to plot the induced voltage. Note that the coil will be maximally sensitive if it has a large diameter and the multiple loops are close together (i.e. make a "flat" coil rather than a cylindrical coil).
- **Sensing electromagnetic induction** – connect the oscilloscope's probe tip and ground clip to a wire coil, then move a permanent magnet in and out of that coil's center while observing the voltage displayed by the oscilloscope. A large-diameter coil again will work best, and it is recommended to set the timebase to some slow value (e.g. 1 second or more per division) to most easily see the rising and falling voltage signal produced by the magnet's motion.
- **Measuring sound and vibration** – connect the oscilloscope to the terminals of a permanent-magnet loudspeaker, which is also able to function as a simple microphone. Speaking into the loudspeaker's cone will cause its diaphragm to vibrate and thereby produce a weak AC voltage measurable by the oscilloscope. Gently tapping your finger on the cone will produce voltage pulses easily displayed by the oscilloscope. If you configure the oscilloscope for "single-sweep' operation you will be able to capture hand-claps and other transient events.
- **Measuring a 1 kHz square wave signal** – most oscilloscopes provide a test terminal on their front panels outputting a 1 kHz square-wave signal useful for adjusting $\times 10$ probes. However, even with plain $\times 1$ probes this is still a useful test for learning to use an oscilloscope's basic functions. After locking the pulse waveform on the screen, use the vertical and horizontal divisions to verify the signal's magnitude, period, and frequency. The period (i.e. time per cycle) should be 1 millisecond if the frequency is 1000 Hz; i.e. a signal alternating at 1000 cycles per second will take just 1 millisecond to complete one cycle.

- **Measuring rotational speed** – connect the oscilloscope to the terminals of a small induction AC motor. Spinning the motor shaft will produce a small AC voltage due to the residual magnetism of the motor's rotor, and the frequency of this AC voltage will be directly proportional to the shaft's speed. A simple "shaded-pole" AC motor such as the type used for household fans works well for this purpose.

- **Measuring capacitor soakage** – connect the oscilloscope to the terminals of an electrolytic capacitor, a type well-known for a phenomenon called *soakage*. Configure the oscilloscope for "DC" coupling and a very slow timebase (i.e. multiple seconds per division). Short-circuit those terminals and watch the capacitor's voltage fall to zero. When you disconnect the shorting wire, however, you will notice the voltage value slowly rise over time due to this "soakage" effect, where some of the capacitor's stored energy was not dissipated during the short-circuit duration and slowly manifests itself at the capacitor's terminals.

- **Measuring light over time** – connect the oscilloscope to the terminals of a light-emitting diode (LED) which also functions as a simple photovoltaic cell when exposed to light. Point the LED's lens at a light source and measure the effect registered on the oscilloscope's display. This is particularly interesting if the light source happens to *pulse*!

- **Measuring temperature over time** – build a simple series voltage-divider network using one fixed-value resistor and a thermistor (i.e. temperature-dependent resistor) and energize this divider network with a suitable DC voltage source. Measure voltage across either the resistor or the thermistor using an oscilloscope configured for "DC" vertical coupling and set for a very slow timebase (e.g. 1 second per division). This will generate a plot representing temperature changes over time.

- **Measuring voltage noise in a simple DC motor circuit** – connect a DC motor to a battery or other suitable DC voltage source so that the motor runs continuously. Then, connect the oscilloscope probe terminals in parallel with that running motor. If configured for "DC" vertical coupling, you should see the elevated (DC) voltage powering the motor superimposed on a significant amount of jagged "noise" created by the motor's pulsing current draw. Setting the vertical coupling to "AC" allows you to zoom in on that noise while blocking the elevated DC voltage, so that the noise graph remains centered in the screen. You may also try connecting a capacitor in parallel with the running DC motor to see the effect it has in mitigating this voltage "noise".

- **Measuring current pulsations in a simple DC motor circuit** – insert a low-value (1 Ohm or less) *shunt resistor* in series with the DC motor described above, then connect the oscilloscope probe terminals in parallel with that shunt resistor. If configured for "DC" vertical coupling, you should see a graphical representation of that motor's pulsating current as it runs. Instantaneous current may be measured by taking the oscilloscope's voltage measurement at any point in time and dividing that value by the known shunt resistor value (i.e. using Ohm's Law $I = \frac{V}{R}$).

- **Measuring DC motor inrush circuit** – using the same battery-shunt-motor circuit described above, configure the oscilloscope for a slow timebase (e.g. 1 second or more per division) and then have is graph the motor's current when started and stopped by connecting/disconnecting the DC voltage source. Electric motors of all kinds typically draw high current when initially starting to rotate, their current tapering off over time as they come up to normal speed.

- **Measuring various signals in a 555 timer circuit** – consult the datasheet for a simple relaxation oscillator circuit based on a model 555 integrated circuit (IC), build the recommended "astable" test circuit on a solderless breadboard, and use the oscilloscope to measure various pulsating and oscillating voltage signals in the circuit. The same datasheet may also provide sample waveforms which you may compare with your measured oscillographs.

- **Measuring switch contact "bounce"** – connect the oscilloscope in parallel with a resistor that receives power from a DC voltage source through a switch. Configure the oscilloscope for "single-sweep" capture, and use it to display the transient "bouncing" of the switch's contacts as they open and close. Note that you will have to set the timebase to a fairly rapid sweep rate (e.g. 0.2 milliseconds per division or so) in order to successfully capture these rapid closure and opening events.

2.3 Example: measuring signal rates of change

Capacitors and inductors relate voltage to current by rates of change. For a capacitor, the amount of current is proportional to how quickly voltage across that capacitor either rises or falls over time ($I = C\frac{dV}{dt}$). For an inductor, the amount of voltage is proportional to how quickly current through that inductor rises or falls over time ($V = L\frac{dI}{dt}$).

For example, a 330 microFarad capacitor experiencing a voltage increasing at a rate of 45 Volts per second will pass 14.85 milliAmperes. If the voltage happens to decrease at an equivalent rate (i.e. $\frac{dV}{dt} = -45$ Volts per second) then the 14.85 milliAmpere current will reverse direction through the capacitor compared to how it flowed with the increasing voltage.

Similarly, a 100 milliHenry inductor experiencing a current increasing at a rate of 5 Amperes per second will induce a voltage of 500 milliVolts. If the current happens to decrease by an equivalent rate (i.e. $\frac{dI}{dt} = -5$ Amperes per second) then the 500 milliVolt voltage induced across the inductor will reverse polarity from what it was during the period of increasing current.

Not only are rates-of-change important in determining how energy-storing devices such as capacitors and inductors will respond in circuits, but rates-of-change are also important for determining how *parasitic* capacitances and inductances will affect intended circuit behavior. Parasitic capacitance exists between any two conducting surfaces separated by an electrically insulating medium, and parasitic inductance exists along any length of conductor. This means any rate-of-change of voltage over time between two separated conductors will cause some amount of current to "pass"[1] between them, and that any rate-of-change of current over time through any single conductor will cause some amount of voltage to drop across its length. In many circuits these parasitic effects are negligible, but in circuits experiencing extremely fast rates of change for voltage and/or current the effects can be significant or even severe.

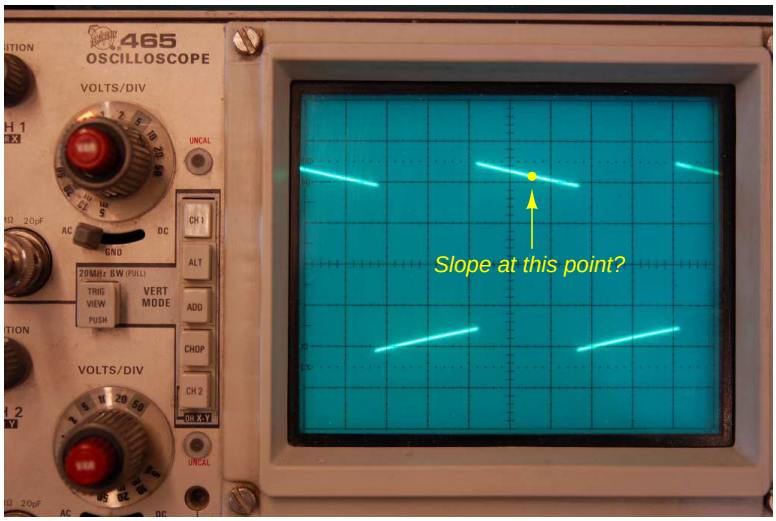
Oscilloscopes are ideal for performing empirical measurements of voltage rates-of-change, and of current rates-of-change given the proper accessories[2]. Some skill is required to do this, though, and here we will explore practical examples to show how it is done.

For any signal plotted in the time domain, where the horizontal axis of the plot is expressed in units of seconds, milliseconds, microseconds, etc., the signal's rate of change at any given point will be the *slope* or *pitch* of the waveform, mathematically defined as its *rise over run*. A great aid to discerning slope at any location on a waveform is to sketch a straight line visually matching the wave's slope at that point, then use locations along that straight line to more easily discern how far it rises (or falls) over some "run" of time. We call this straight line a *tangent line*.

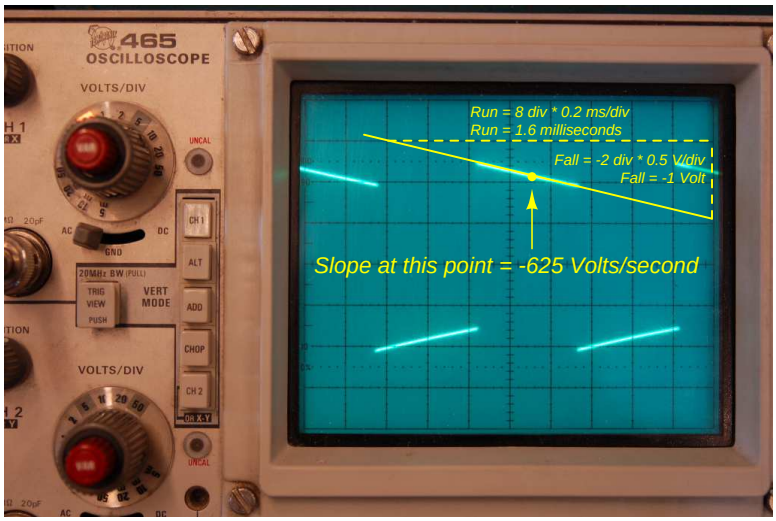
[1] The Scottish physicist James Clerk Maxwell referred to this current as *displacement current*.

[2] For example, a *current probe* converting a sensed current into a voltage the oscilloscope may directly sense, or a *shunt resistor* placed in the circuit developing an oscilloscope-measurable voltage drop for any current passing through.

Here we see an example of a waveform with sloping sections. In the first image we see a specific location on the waveform where we wish to measure voltage rate-of-change ($\frac{dV}{dt}$):



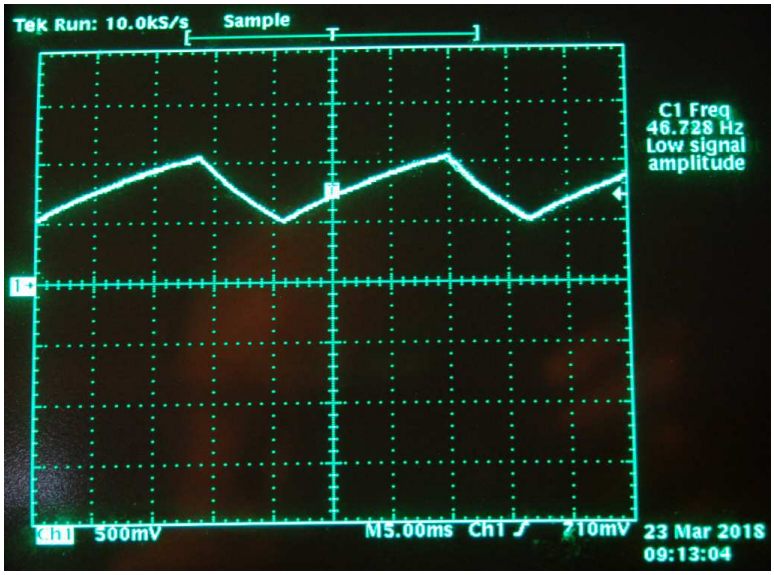
Next we see a tangent line drawn to match the slope of the waveform at the specified location, with convenient points for fall/run measurements taken on that line against the oscilloscope grid's major divisions. In this example, the oscilloscope's vertical sensitivity has been set for 0.5 Volts per division, and the horizontal timebase for 0.2 milliseconds per division:



As we can see, the tangent line falls 2 vertical divisions (-1 Volt) over a timespan of 8 horizontal divisions (1.6 milliseconds), yielding a $\frac{dV}{dt}$ quotient of -625 Volts per second, which may also be expressed as -0.625 Volts per millisecond. The negative sign is important, as it distinguishes this particular rate-of-change as *falling* rather than rising over time.

Such rate-of-change measurements are necessarily approximate, as they require us to visually gauge where a tangent line may be overlaid on the waveform's oscillograph, and also to visually assess the slope of that tangent line using the grid provided on the instrument's display screen. However, in most applications extremely precise rate-of-changes are not necessary, and such techniques suffice quite well.

Below is another example of a waveform with sloping sections, the oscilloscope configured for 500 milliVolts per division on the vertical axis and 5 milliseconds per division on the horizontal:

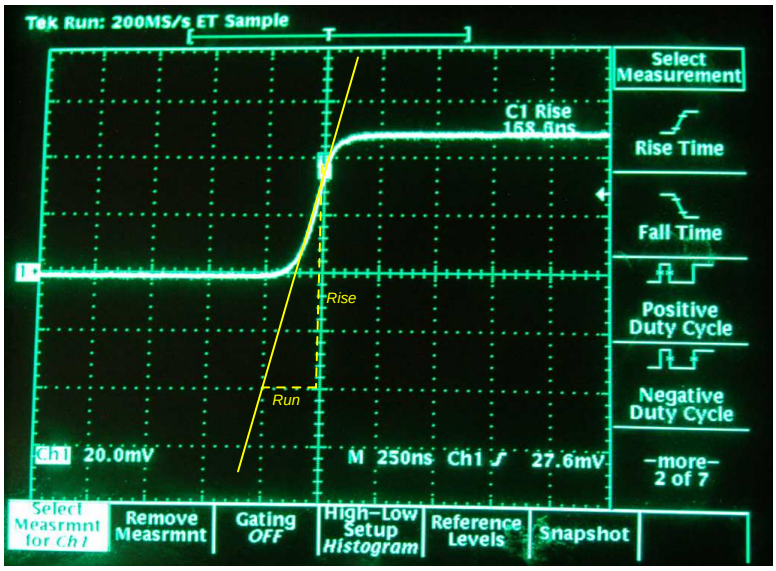


Approximating the slope for each rising section of this wave, we count one division of rise over 2.8 divisions of run, or 500 milliVolts rise over 14 milliseconds of run. This is a rate-of-rise of +35.7 Volts per second.

Approximating the slope for each falling section of this wave, we count one division of fall over 1.4 divisions of run, or −500 milliVolts fall over 7 milliseconds of run. This is a rate-of-fall of −71.4 Volts per second.

If these rates-of-change appear suspiciously large compared to the actual amplitude of the waveform, which barely crests over +1 Volt on the oscillograph, bear in mind that we are calculating *rates of change* for voltage and not absolute values of voltage itself. This is analogous to the distinction between *speed* and *distance*: traveling at a rate of 30 kilometers per hour does not necessarily mean you will travel 30 kilometers, as the actual distance traveled depends on how long that speed is sustained. A voltage rising at a rate of 35.7 Volts per second would indeed rise 35.7 Volts *if given a full second to do so*, but since each rising/falling portion of this waveform is so short in duration the actual amount of rise or fall in each case is only one-half of one Volt. It is therefore perfectly appropriate to consider any $\frac{dV}{dt}$ value as being the *speed* at which a voltage increases or decreases over time, distinct from the actual value of that voltage at any particular moment in time.

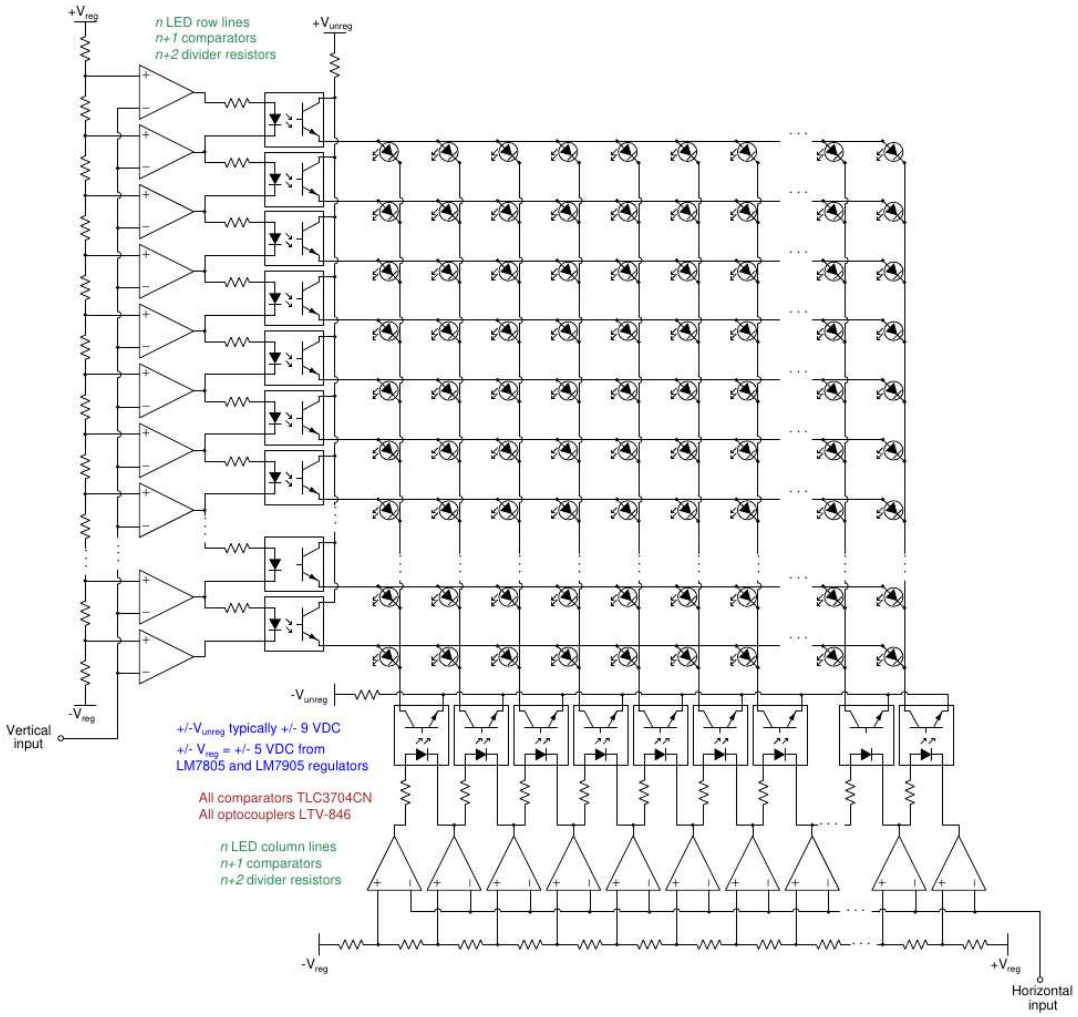
Here we see another oscillograph, this one zoomed into the rising edge of a square wave. For this measurement the oscilloscope was configured for 20 milliVolts per division of vertical sensitivity and a timebase of 250 nanoseconds per division on the horizontal:



The tangent line overlaid on this screenshot for the purpose of measuring the pulse edge's rate-of-change rises approximately 4 vertical divisions over a run of 1 division, which is 80 milliVolts of rise over 250 nanoseconds of run. The pulse edge's rate-of-change, therefore, is approximately +320,000 Volts per second, or +320 Volts per millisecond, or +0.32 Volts per microsecond (all equivalent expressions of $\frac{dV}{dt}$).

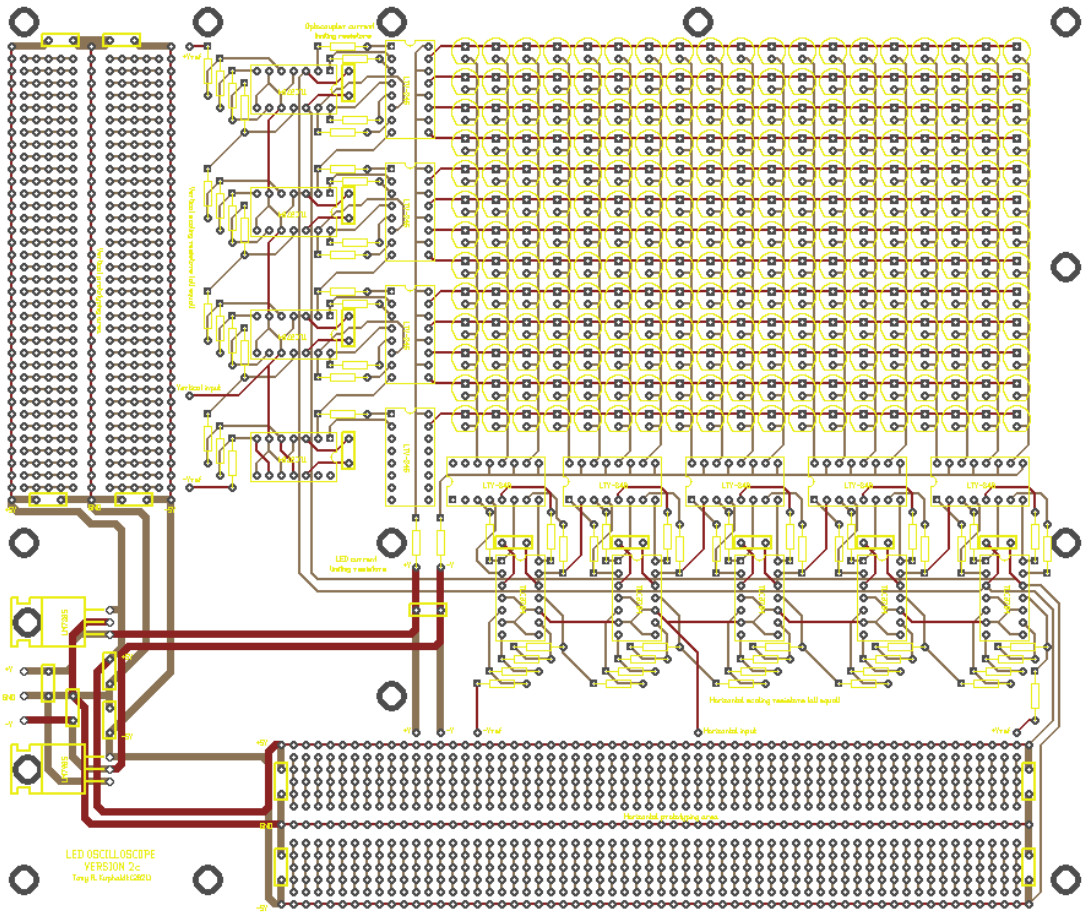
2.4 Example: LED-array oscilloscope project

A great project for learning about oscilloscopes at a detailed level is to *build your own* using an array of LEDs, driven one LED at a time by activating rows and columns. A simple design is shown in schematic form below:



The optoisolators are wired to the comparator outputs such that only one column optoisolator turns on at a time, and only one row optoisolator turns on at a time. This means only one LED in the entire grid ever energizes at any given instant in time. If a sinusoidal voltage is applied to the vertical input terminal (with respect to ground), and another to the horizontal input, the result will be a Lissajous figure shown by the LEDs.

A printed circuit board (PCB) layout is already provided for you on the Modular Electronics Learning Project website in Gerber form suitable for submission to a PCB shop where the boards may be etched for you. After that, the task of populating the PCB with components is at least a full day's worth of soldering:



Uncommitted prototyping areas are provided on this PCB layout for vertical and horizontal drive circuitry, if you wished to add functions such as:

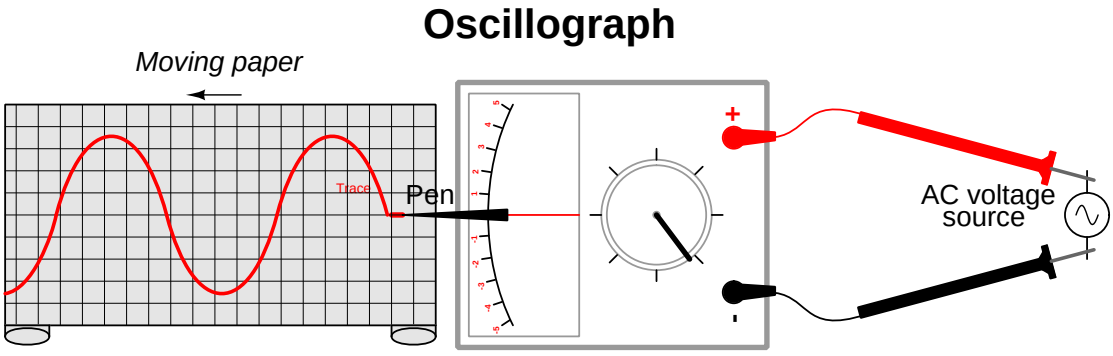
- Vertical sensitivity adjustment
- Horizontal sweep generator and timebase adjustment
- Triggering

Chapter 3

Simplified Tutorial

3.1 A graphical voltmeter

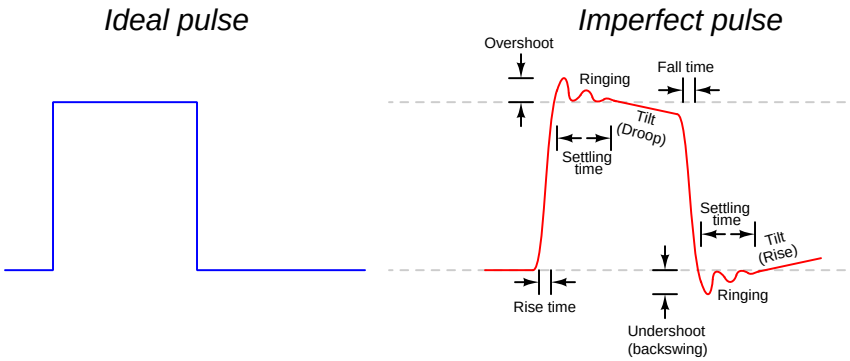
An *oscilloscope* is a graphical voltmeter, displaying a plot of voltage on the vertical axis and time along the horizontal axis of its display. As such, it is useful for measuring voltages that vary rapidly over time, such as alternating current (AC) signals. Modern oscilloscopes use cathode-ray tubes or digital LED-based displays to show the "waveform" of any time-changing voltage signal, but for the sake of conceptually grasping the concept of an oscilloscope we may examine a primitive variant of this test instrument called an *oscillograph*:



As the illustration shows, an oscillograph instrument uses an ink pen attached to the tip of an analog voltmeter's pointer, sketching a plot of voltage on a moving paper strip. As the strip moves in one axis the voltmeter's pointer sweeps along the perpendicular axis to create the two-dimensional plot of voltage over time.

Oscillographs are limited by the speed at which their paper strips can move and the speed at which the voltmeter pointer can swing in response to a changing voltage. For signals alternating more than a few cycles per second such an instrument is impractical. This is where the modern oscilloscope shows its worth: by using an electronic display rather than ink on paper, it is able to plot graphs of voltage over time much faster than any pen-and-paper oscillograph.

In many applications of electronics it is important to analyze the *shape* traced by a voltage or current over time. One such example is in circuits using voltage *pulses*, where voltage rises to some level and then falls to another level repeatedly. An ideal pulse traces a square-cornered shaped on an oscillograph or an oscilloscope screen, but real pulses always deviate to some degree from this ideal. With a graphical voltage-sensing instrument we may closely examine features of a pulse signal to identify imperfections, as these imperfections may cause malfunctions in electronic circuits:



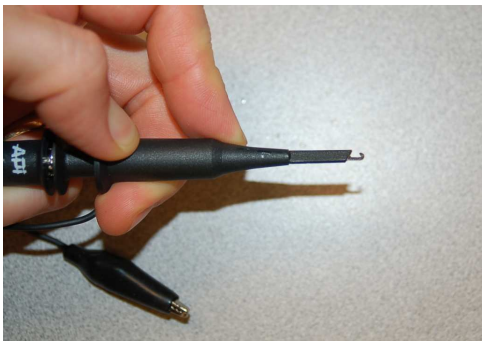
Additionally, with a graphing instrument it becomes possible to identify anomalies such as *transients* (i.e. momentary surges) that may either help identify failures and/or can possibly cause failures. We may also determine such things as *frequency* (the rate at which an alternating voltage or current completes a full cycle), rise and fall times, cross-talk and interference, and other parameters difficult or impossible to discern with non-graphing instruments.

3.2 Oscilloscope probes and grounding

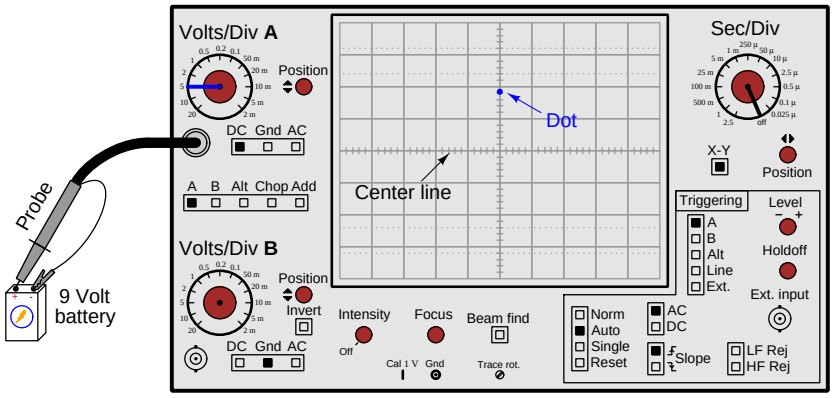
Like any voltmeter, an oscilloscope connects to the circuit under test by way of *two* electrodes, since voltage is fundamentally a relative quantity measured between two points. Instead of red- and black-colored single-wire probes, however, oscilloscopes use coaxial cable probes where both the measurement and reference electrode conductors are contained in a single cable, breaking into separate electrodes at the cable's end. The following photograph shows a general-purpose oscilloscope probe by itself:

A twist-lock "BNC" connector at one end of the probe cable connects to the oscilloscope's input channel, while at the other end of the cable we see a black-handled probe body with a measurement electrode at its tip and a reference electrode in the form of a small "alligator" style clip. You may think of the electrode at the probe's tip as being the *red* test lead of a voltmeter, and the alligator-clip electrode as being the *black* test lead of a voltmeter.

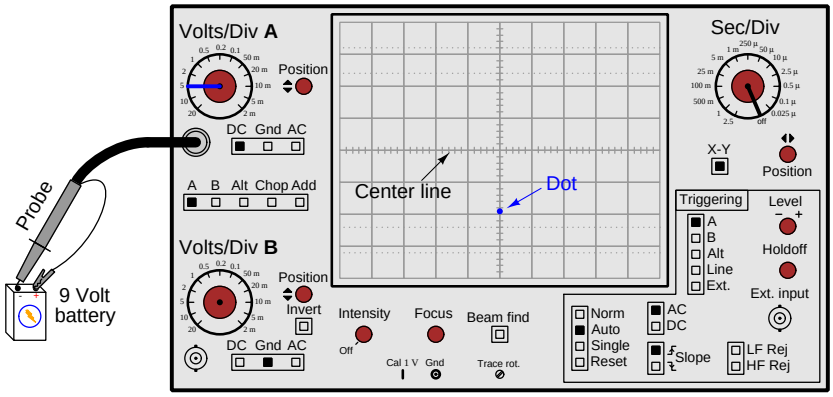
Two photographs shown below reveal the probe tip's construction. The left-hand photograph shows the probe's regular "hook" tip exposed by pulling back the barrel, while the right-hand photograph shows the plastic barrel removed entirely to reveal a sharply-pointed tip and the "reference" ring which is electrically common to the alligator-clip electrode:



If we set up an oscilloscope such that it does not "sweep" from left to right over time as it normally does, we will see nothing but a dot at the center of its screen. This dot moves up when the oscilloscope senses a positive voltage (i.e. + on the "measurement" probe tip and − on the "reference" alligator clip):

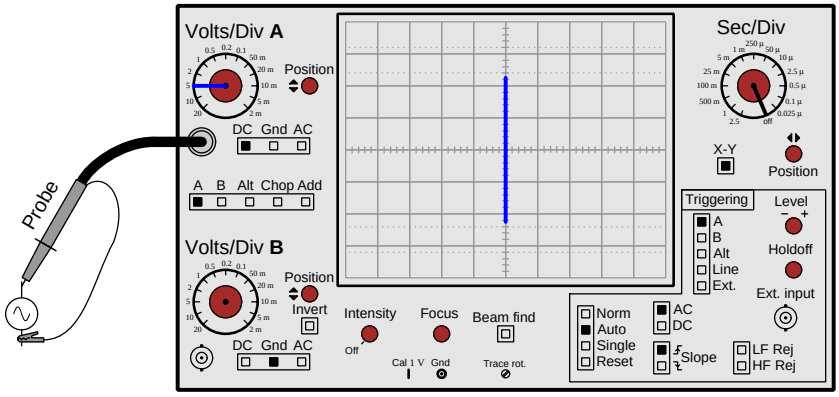


If we reverse the probe connections at the battery's terminals, the oscilloscope's sensed polarity becomes negative and the dot is driven below the center of the screen:



These experiments prove the oscilloscope functions as a graphical voltmeter, with the vertical axis representing voltage magnitude. If we were to continue these experiments with batteries of differing voltage, we would see that the vertical displacement of the dot from the screen's center was directly proportional to the battery's voltage.

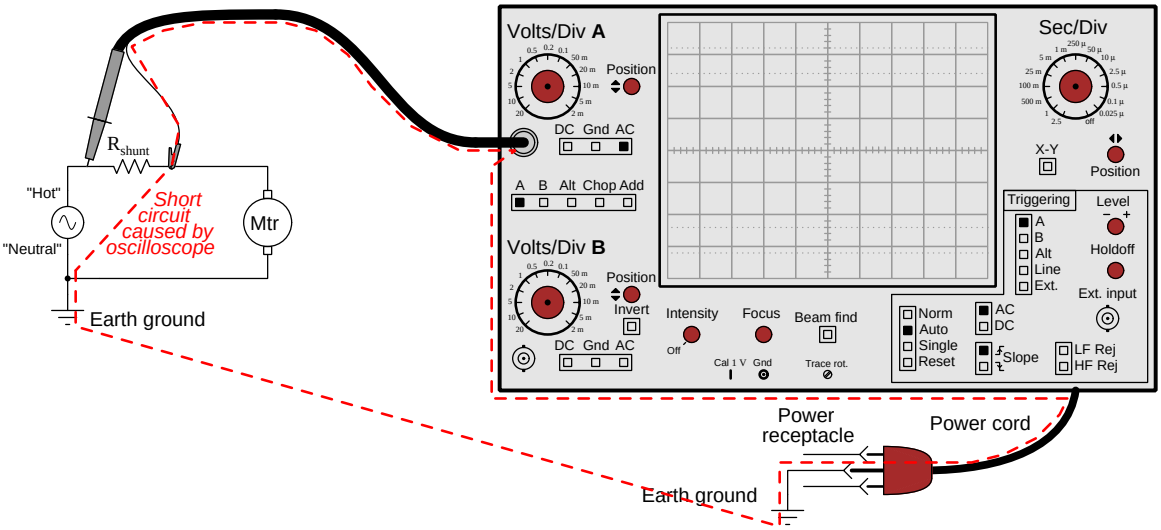
If we were to connect an oscilloscope to an AC voltage source rather than a (DC) battery, we would see the result of the dot sweeping up and down repeatedly: a *vertical line segment* on the screen resulting from the dot's rapid up-and-down retracing of the same path:



As you can see, this re-traced line tells us little about the AC voltage except for its peak-to-peak amplitude. In order to see a plot of the voltage's wave*shape* we would need to activate the oscilloscope's horizontal "sweep" so that the dot traveled from left to right across the screen in addition to moving up and down with the AC voltage signal.

Oscilloscopes are really nothing more than graphical voltmeters, but there is an extremely important caveat one must know about their probe connections in order to connect one safely to a circuit: the "reference" electrode (i.e. the "alligator-clip" lead) always connects to the chassis of the oscilloscope, and for line-powered oscilloscopes the chassis is made electrically common to Earth ground through the power cord's ground prong. This means connecting the reference lead of an oscilloscope to any circuit forces that connected point in the circuit to be at Earth potential.

Failing to recognize this fact of oscilloscope probes may lead to incorrect measurements, damaged circuitry, and even danger to you as you operate the oscilloscope. As an example, consider the following diagram showing an AC line-powered motor with a series *shunt resistor* designed to produce a small voltage drop proportional to motor current. Connecting the oscilloscope in parallel with this shunt resistor will short-circuit past the motor:



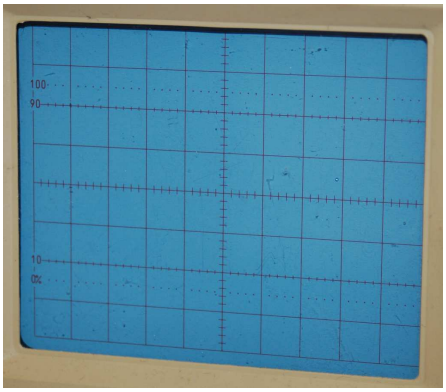
The rule is this: when a single channel of an oscilloscope is connected to any circuit under test, the voltage being measured is *always* ground-referenced. That is to say, the voltage sensed by any oscilloscope channel must be between the probe's measurement tip and Earth ground. This means the reference (alligator-clip) electrode must only ever contact a point in the circuit that is either already at Earth ground potential, or is safe to force to Earth ground potential by connection with the oscilloscope.

Solutions to this problem, for applications where we must use an oscilloscope to measure a "floating" or "differential" voltage signal, are presented in the Full Tutorial of this module.

3.3 Sensitivity and amplitude measurement

Oscilloscopes are akin to graphical voltmeters, but specifically they are graphical *analog* voltmeters. Voltage magnitude is represented by the analog displacement of the trace along the screen's vertical axis, and furthermore the user of the oscilloscope must set the *range* for this vertical axis much like selecting the appropriate range on an analog voltmeter.

An oscilloscope's voltage-measuring range is known as its *vertical sensitivity*. The unit of expression for vertical sensitivity is *Volts per division*: the amount of voltage represented by each square's height on the grid. On legacy oscilloscopes the sensitivity adjustment is a knob which decreases the number of Volts per division when turned clockwise, to "magnify" the waveform along the vertical axis:



As you can see in the left-hand photograph, the center-lines running horizontally and vertically have smaller marks dividing each square into five *minor* divisions to facilitate finer measurements. With analog voltmeters and oscilloscopes alike, the user must choose an appropriate measurement range so that the visible deflection (of meter pointer or oscilloscope dot) is large enough to apprehend but not so large that it exceeds the span of the scale.

Another topic related to the vertical sensitivity of an oscilloscope is *vertical coupling*. Common coupling settings include *DC*, *AC*, and *Ground*. You can see these selectable options on the control panel of this dual-channel oscilloscope, immediately to the right of each channel's vertical sensitivity knob:

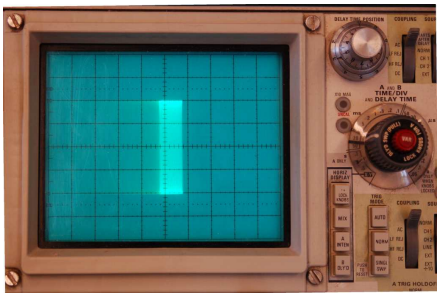
The "DC" coupling option is preferred for general measurements, and it simply means that the voltage signal intercepted by the probe will be *directly* passed on to the oscilloscope's input circuitry for display. By contrast, the "AC" coupling option inserts a capacitor in series with the probe's measurement electrode in order to block any DC bias from reaching the oscilloscope, allowing the oscilloscope to "zoom in" to any AC "ripple" in the measured signal without having the DC component of that signal force the trace completely off the screen[1]. The "Ground" coupling option completely disconnects the oscilloscope's input channel from the probe and shorts that channel's amplifier to ground in order to force a zero-Volt condition for the purpose of calibrating the vertical position of the trace.

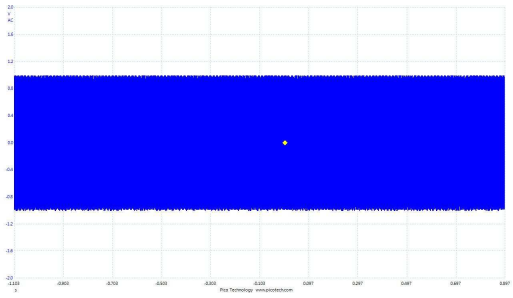
[1] A good illustrative example of this is measuring the output signal of an AC-DC power supply circuit with a 12 Volt DC nominal output and 5 milliVolts of AC "ripple". If we set the coupling for "DC" and the vertical sensitivity (Volts/division) is set high enough to keep the DC trace on the screen, the ripple will be hardly visible. If we decrease the number of Volts per division to magnify that ripple, the DC portion of the signal will force the trace beyond the boundaries of the screen and nothing will remain visible! In order to magnify the ripple so we can see it, we must select "AC" coupling to block the 12 Volt DC component from reaching the oscilloscope's input and only then may we decrease the number of Volts per division to magnify that ripple sufficiently.

3.4 Timebase and frequency measurement

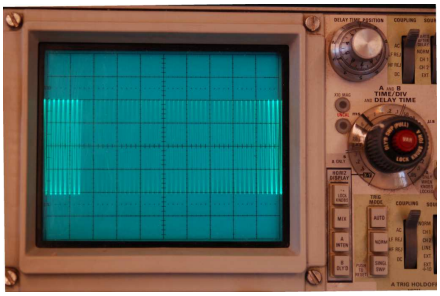
Earlier we saw how connecting an oscilloscope to an AC voltage source while disabling the horizontal "sweep" feature resulted in a vertical line segment on the screen, produced by the dot being repeatedly driven up and down by the alternating polarity of the signal. This representation of an AC signal is not very useful unless all we cared about was measuring its peak-to-peak amplitude.

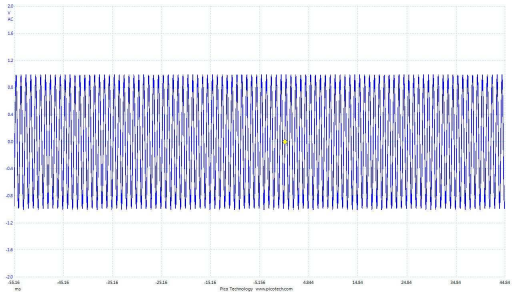
If we activate the horizontal sweep and gradually increase its sweep speed from left-to-right across the screen, we first see the vertical line turn into a solid band of color on the screen. Compare these two real-life oscilloscope displays, one from a CRO (left) and the other from a computer-based oscilloscope (right):

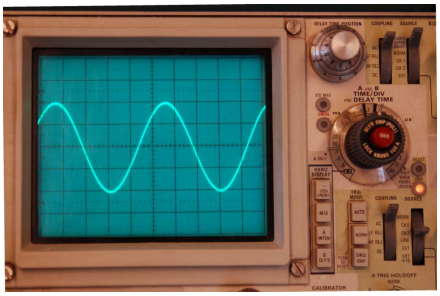


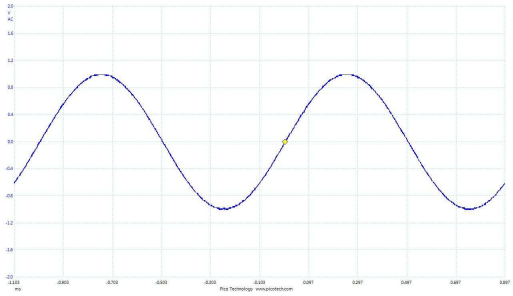


If we continue to increase the horizontal sweep speed, we will be able to discern the shape of the AC signal's waveform:

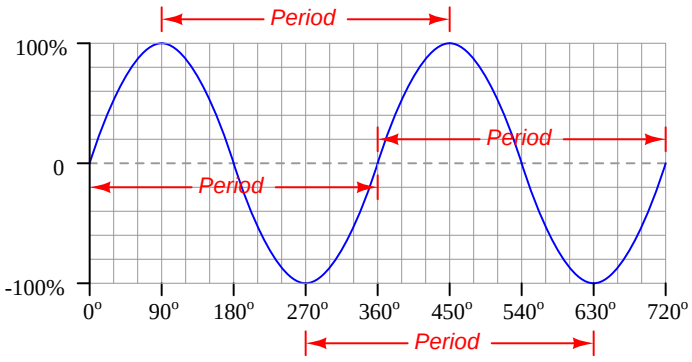








As with the oscilloscope's vertical sensitivity, its horizontal sweep speed (called the *timebase*) is a manually-adjustable setting. Instead of Volts per division, the unit of measurement for timebase is *seconds per division*. Knowing the number of seconds (or milliseconds, or microseconds) represented by each horizontal division on an oscilloscope's display allows us to take measurements of the signal's period (i.e. the amount of time elapsed during one complete cycle of the wave) as shown below:



Supposing this oscilloscope's timebase is set for 5 milliseconds per division, the period of this AC signal must be 60 milliseconds because we count exactly twelve divisions (squares on the screen) between any two points encompassing one full cycle of the wave:

$$\left(\frac{12 \text{ div}}{1}\right)\left(\frac{5 \text{ ms}}{\text{div}}\right) = 60 \text{ ms}$$

Frequency – defined as the number of cycles or periods of the waveform per second – is the reciprocal of the number of seconds per cycle. So, once you read the period of a waveform from an oscilloscope's display you may simply reciprocate that value to compute the signal's frequency. Many years ago it was customary to express frequency in units of *cycles per second* or *cps*, but now we use the name *Hertz* to mean the same thing. In the case of the AC signal having a period of 60 milliseconds, its frequency would be 16.67 cycles per second or 16.67 Hertz.

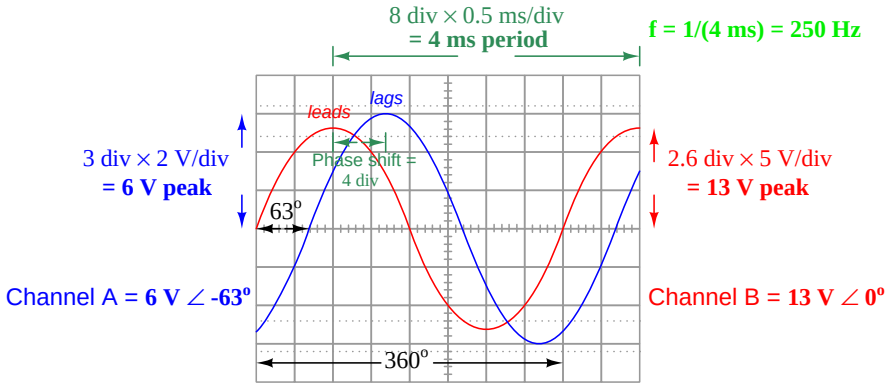
$$f = \frac{1}{t_{period}}$$

$$\frac{1}{\left(\frac{60 \text{ ms}}{\text{cycle}}\right)} = \frac{16.67 \text{ cycles}}{\text{s}}$$

3.5 Multiple traces and phase measurement

A very useful feature of all modern oscilloscopes is the ability to display more than one voltage signal at a time, permitting the simultaneous overlay of multiple signal waveforms on the same screen. This feature is essential for comparing the phase or timing relationship between two or more signals.

The following illustration shows two sinusoidal AC signals simultaneously displayed by an oscilloscope. Channel A is set for 2 Volts per division while channel B is set for 5 Volts per division. Both channels must of course share the same timebase, which in this case is 0.5 milliseconds per division. Calculated values for peak amplitude, period, frequency, and phase shift are all shown below:



Phase shift is a measurement of how far out-of-step two waveforms are from each other. In this example we see a horizontal displacement of 1.4 divisions (one major division plus two minor divisions) separating successive peaks of the two waves, and we also see each wave's period equal to 8 major divisions. Phase shift is most commonly expressed in *degrees*, and we may calculate this shift in degrees using a ratio of the shift versus the total period, in this case $\frac{1.4}{8}$. Since we know that one period of any waveform represents 360^o of rotation, a shift of 1.4 divisions between these two waves is equivalent to $\frac{1.4}{8}$ of 360 degrees, or $\frac{1.4}{8} \times 360^o = 63^o$.

The *trigger* controls of an oscilloscope work to stabilize the display so that it appears stationary on the screen even though it is a moving quantity being re-traced continually over time[2]. In the above example we have triggering based on channel B which "locks" that waveform on the screen beginning at zero Volts rising, while channel A starts at a different point in its waveform due to the phase shift between the two signals. If we arbitrarily consider channel B's signal to be the phase-reference (i.e. having a phase angle of zero degrees), then channel A's signal must have a phase angle of -63^o because it is *lagging* channel B.

[2]To anyone familiar with the use of a *strobe light* to "freeze" the appearance of a rotating object, this concept should be intuitive. The oscilloscope presents the illusion of a "frozen" waveform on its screen by making sure it begins each re-trace of that wave at the same point in the wave's evolution.

Chapter 4

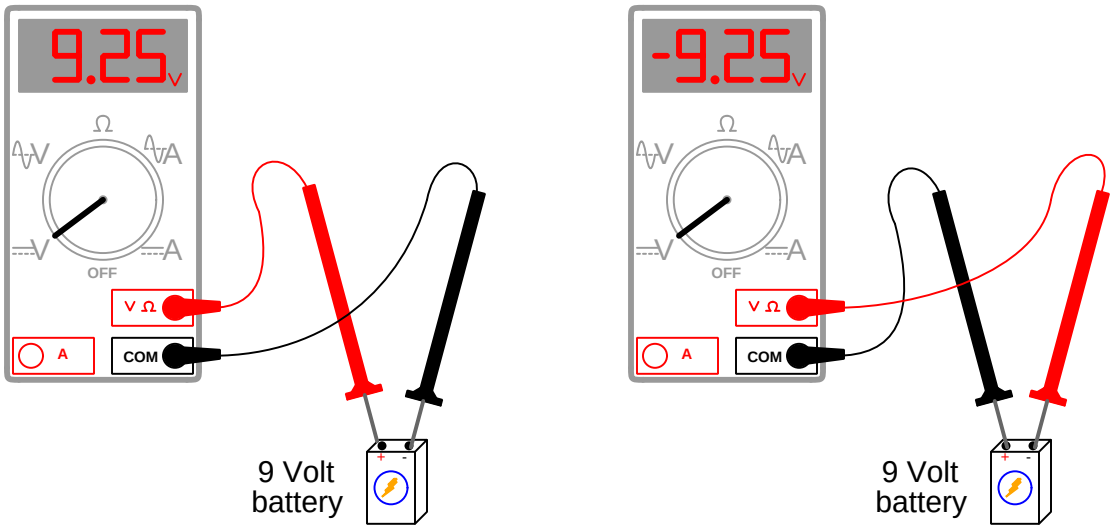
Full Tutorial

The *oscilloscope* is one of the most useful and versatile test instruments for electronic work. A very simple characterization of this instrument is to say that it is a *graphing voltmeter*, plotting a graph of voltage against some other variable (usually time). Oscilloscopes are the preferred instrument for analyzing the amplitude, period, and shape of rapidly-changing electrical signals.

That said, oscilloscopes are challenging to properly configure and use. Modern digital oscilloscope technology has eased this burden somewhat with "Auto Set" features, but oscilloscopes are not intelligent enough to predict which portion of a fast-changing signal you wish to analyze, and therefore even with self-configuring features there is still the need for the human operator to understand what they are doing and how the instrument is supposed to work.

4.1 Voltmeters, oscillographs, and oscilloscopes

A voltmeter is a test instrument designed to measure *voltage*, which we have defined in previous tutorials as the difference in energy possessed by electric charge carriers between two different locations. True to the differential nature of voltage, all voltmeters have *two* test leads: a black-colored lead serving as the reference and a red-colored lead serving as the measurement. If the red test lead contacts a point having greater potential energy per unit charge than the point touched by the black lead, the voltmeter will register a positive value[1]; if the energy levels are reversed, the voltmeter will register a negative value:



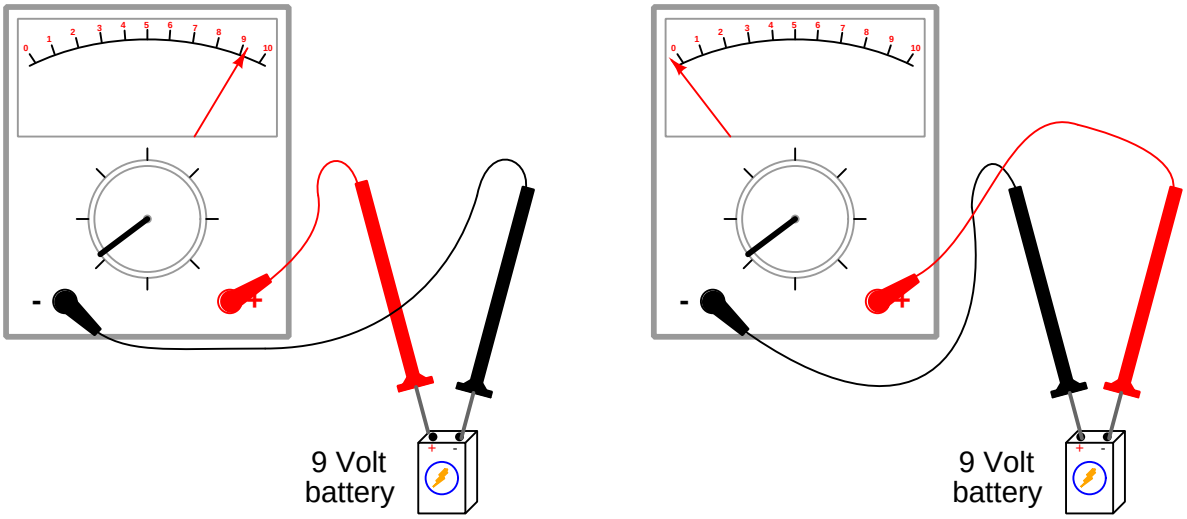
The left-hand voltmeter's positive displayed value indicates a greater potential energy per unit charge at its red (measurement) lead compared to its black (reference) lead. The right-hand voltmeter's negative displayed value indicates a lesser potential energy per unit charge at its red lead compared to its black lead. In both cases, the voltmeter gives a correct indication of voltage, and so it is incumbent upon the person using the voltmeter to properly interpret the meaning of the meter's mathematical sign.

It should be noted that no harm will come to a digital multimeter connected "backwards" across a DC[2] voltage source; the meter will simply register a negative value instead of a positive value.

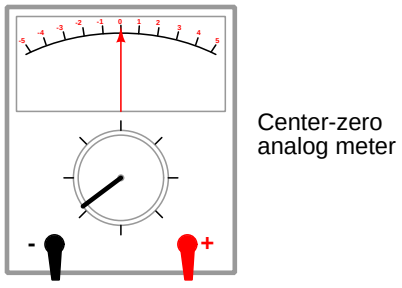
[1] The illustration shows 9.25 Volts measured across the terminals of a "9 Volt" battery, which is typical for batteries: the labeled voltage is a nominal value, with a fresh battery typically outputting slightly more than its advertised rating.

[2] DC, of course, stands for *direct current*, indicating an electrical quantity that does not reverse polarity over time. Even though the letter "C" in DC stands for *current*, the term may be properly applied to either a current or a voltage.

Legacy voltmeters were *analog* in nature, meaning that instead of a digital number displayed for the voltage reading, one had to observe the deflection of a pointer across a printed scale. Most analog voltmeters were arranged such that their indicating scales had zero voltage at the far left and full-range voltage at the far right. Connecting the red test lead to the positive terminal of a voltage source and the black test lead to the negative terminal of the same source would drive the analog voltmeter's pointer to the right; reversing polarity would attempt to drive the pointer to the left, resulting in the pointer moving past the zero mark and resting against a small "peg" to prevent over-travel:

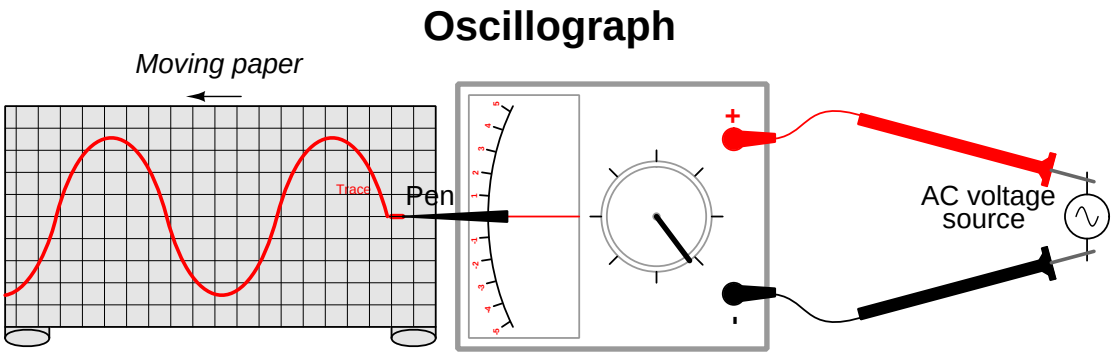


Although an analog voltmeter will likely remain unscathed after being connected backwards across a DC voltage source, it will not yield a usable indication of voltage. If readability of either polarity of DC voltage is desired, a *center-zero* analog voltmeter may be employed for the task. This meter is designed such that the pointer rests in the center of the scale with zero applied voltage, right-hand and left-hand deflection serving to indicate polarity of the voltage under test.



Voltmeters, both analog and digital, are only useful for measuring relatively stable voltages. Even AC voltmeters designed to register the bulk magnitude (e.g. average value, peak value, etc.) of a continuously-alternating voltage cannot display *instantaneous*[3] values for any point in time. For this purpose we need another type of voltage-sensing instrument.

Imagine attaching an ink pen to the tip of the pointer on a center-zero analog voltmeter, and then positioning that assembly above a moving strip of paper[4] whereby the pointer's pen traces along the moving paper. Such a device is called an *oscillograph*, because it is able to sketch a *graph* of a voltage *oscillating* over time:



Given a suitable grid overlaid on the oscillograph's paper, it is now possible to measure two variables with respect to the signal under test: both *instantaneous voltage* (on the vertical axis) and *time* (on the horizontal axis). Any interesting features of the signal's *shape* are also clearly evident with this instrument – data that is indiscernible when using a standard voltmeter.

Oscillographs are useful when a paper copy of the signal's shape (called an *oscillogram*) is necessary for archival purposes. However, in most cases one does not require a permanent record of a measured voltage signal – a temporary measurement is good enough. Furthermore, oscillographs are impractical for signals with high frequency (i.e. a fast rate of oscillation), as the physical speeds necessary for both pen and paper motion exceed practical limits[5].

[3] An "instantaneous" quantity is one at a single point in time, as opposed to an average over a period of time.

[4] A moving strip of paper is relatively easy to arrange, by rolling a long rectangular paper strip around a set of drums. Turning both drums the same direction will cause the paper to unwind off of one drum and wind up on to the other drum like a scroll. If a mechanical clock mechanism or synchronous AC motor is used to rotate the drums, fairly precise timing may be achieved.

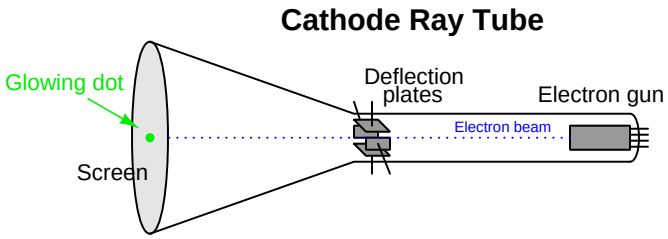
[5] An interesting solution to this problem for high-speed oscillography uses light-sensitive paper, and a narrow beam of light directed at the moving paper by a mirror tilted by the application of voltage. In other words, a mirror took the place of the pointer, and a beam of light took the place of the ink pen. Such instruments required a *triggering signal* to start the paper's motion, because the feed rate of this paper was so high that it was only able to record a fraction of a second's worth of signal before the instrument ran out of paper! One industrial application for this instrument that I am aware of was the recording of nuclear reactor conditions immediately following a scram (emergency shutdown) at a nuclear power plant, where critically important events took place over mere milliseconds' worth of time.

The next logical step in the evolution of voltage-measuring instruments is the elimination of moving parts. Oscillographs, while useful, are limited primarily by the fact that both pen and paper are moving objects possessing mass. If we had a way to sketch a graph of a voltage varying over time, but without using moving parts to do so, the resulting instrument would be much more flexible. This is the definition of an *oscilloscope*: an instrument displaying a virtual graph of voltage.

For many years the standard form of oscilloscope was based on a special component known as a *cathode ray tube*, the same basic type of vacuum tube device used as the centerpiece of early television sets. A cathode ray tube was a long, hollow glass tube evacuated to a state of high vacuum and sealed so air would not leak in. One end of this evacuated tube was wider than the rest and covered internally with *phosphor* powder which would produce a visible glow when struck internally by electrically charged particles. This was the viewing screen area of the tube. At the other end of the cathode ray tube was an assembly of metal pieces known as an *electron gun* which used high-voltage DC and a small heating element to fire a narrow beam of electrons toward the phosphor-coated screen at the other end. When the electron gun assembly was suitably energized, that electron beam struck the phosphor to produce a glowing dot at the center of the viewing screen area.

Metal plates situated about half-way between the electron gun and the screen – one above, one below, and one to either side of the electron beam – allowed the beam to be bent by electrostatic force: applying a voltage across either pair of oppositely-situated plates would cause the electron beam to deflect. This provided a means of controlling exactly where the beam struck the phosphor-coated screen.

A simplified illustration of a cathode ray tube is shown here:



The cathode ray tube thus provided a means of oscillography with no moving parts: the electron beam replaced the ink pen of the oscillograph, while the phosphor-coated screen replaced the scrolling paper strip. The tube's deflection plates provided a nearly perfect means for an applied voltage to move[6] the beam (vertically), rather than an electromagnetic mechanism as used in an analog voltmeter or oscillograph. All that is needed to turn a cathode ray tube into a working oscilloscope is a special electronic "sweep" circuit generating an AC waveform[7] that will deflect the beam from

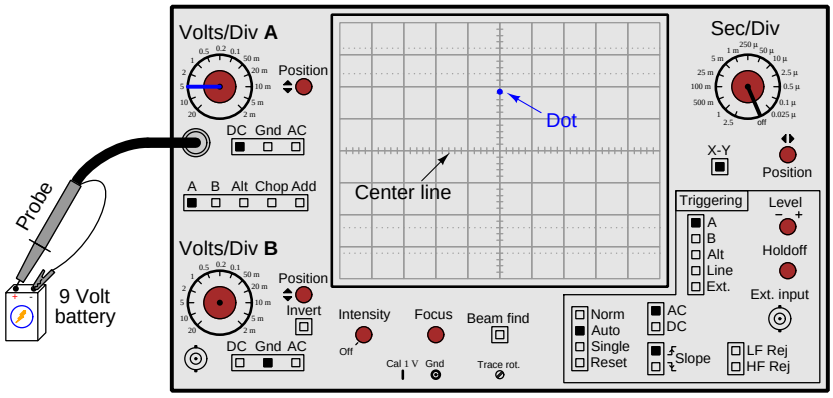
[6] Recall that electrons possess a negative electrical charge, and therefore are influenced by external electric fields. If a pair of metal plates are connected to a DC voltage source, one plate positive and one plate negative so as to form a unidirectional electric field between them, any electron passing through the space between those plates will experience a force pushing away from the negative plate and attracting toward the positive plate.

[7] In particular, this AC waveform must resemble a "ramp" shape gradually increasing in amplitude over time (from a negative value to a positive value) and then quickly descending back down to its starting (negative) value. Such a ramp-shaped AC voltage, when connected across the two horizontal deflection plates, will cause the beam to sweep from left to right across the screen, quickly returning at the end of each sweep to begin again.

left-to-right across the screen's width and then rapidly return the beam to the left-hand side for the next sweep.

Although cathode ray tube technology is all but obsolete at the time of this writing (2017), having been replaced by digitized computer displays, even the most modern oscilloscope emulates the function of this elegantly simple device, and in fact some of the terms originating with the cathode ray tube (e.g. *sweep*) still remain with us. Illustrations of a generic cathode-ray oscilloscope, or *CRO*, will be used throughout this tutorial to illustrate basic oscilloscope operating principles.

A simple illustration of oscilloscope operation is shown in the following illustration, where one channel of the oscilloscope has been connected to a 9 Volt battery:

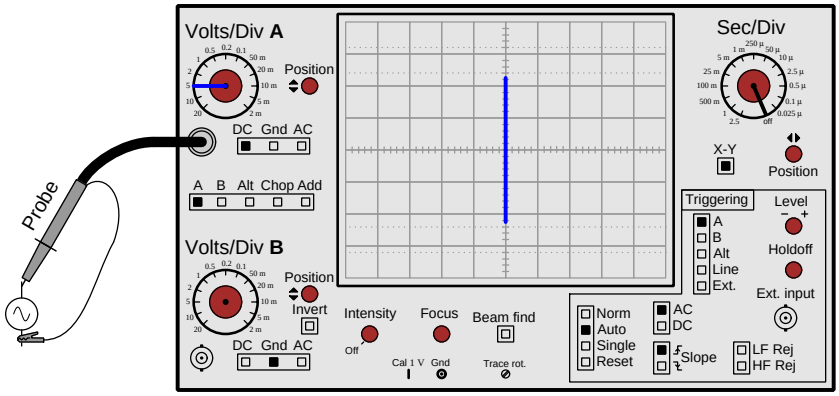


There is no need at this point to focus on all the controls on the front panel of this oscilloscope. We will explore each of them in due time. In this illustration, the horizontal "sweep" function has been turned off so that only a single blue-colored dot appears on the screen. The battery's DC voltage has displaced this blue dot nearly two divisions up from the screen's center, the oscilloscope having been set for a sensitivity of 5 Volts per division.

Note the oscilloscope's *probe*, which takes the place of two test leads commonly used with voltmeters. Many different types of oscilloscope probes exist, but the style of probe shown here is typical for general-purpose use. Oscilloscope probe cables are coaxial[8] in construction, the center conductor of the coaxial cable terminating at a metal tip on the end of the hand-held probe body and the braided conductor of the coaxial cable terminating at the "reference" alligator clip. The oscilloscope's metal probe tip is equivalent to the tip of a voltmeter's red-colored test lead, while the alligator-clip "reference" is equivalent to the tip of a voltmeter's black-colored test lead. Thus, when the probe tip is positive with respect to the reference, the oscilloscope registers a positive (upward) deflection of the dot. Reversing polarity on the oscilloscope probe (i.e. probe tip to the battery's $-$ terminal and reference clip to the battery's $+$ terminal) will case the dot to deflect negatively, below the center line of the screen.

[8] A *coaxial* cable is one where a single conductor is surrounded by insulation and then that insulating layer is itself surrounded by a braided-wire conductive jacket. The whole cable is then covered in another layer of electrically insulating material. The two conductors (single wire and braided tube) share a common axis along the cable's center, hence the name "co-axial".

If we connect this same oscilloscope to an AC voltage source, we will see what appears to be a solid line plotted along the vertical axis of the screen:



This "solid line" is in fact a dot being swept up and down with each cycle of the AC source's voltage. The oscilloscope's phosphor lag plus the persistence of human vision makes this rapidly-moving dot appear as though it were a solid line.

4.2 Probes

An oscilloscope *probe* is the equivalent of a pair of *test leads* for a multimeter: a means to connect the instrument to the circuit under test. Oscilloscope probes commonly use coaxial cable to join the probe's test points to a BNC-style quarter-turn connector. Multimeter test leads are little more than lengths of wire with electrically-insulated safety grips for holding. Oscilloscope probes, by contrast, are engineered electrical networks designed to properly convey a measured signal to the input of an oscilloscope with as little interference and distortion as possible. Coaxial cable is used instead of individual wires in order to reduce noise coupling from external sources to the oscilloscope, as well as to more precisely control the amount of *surge impedance*[9] seen by any signal sent to the oscilloscope's input.

The following photograph shows a general-purpose oscilloscope probe by itself:

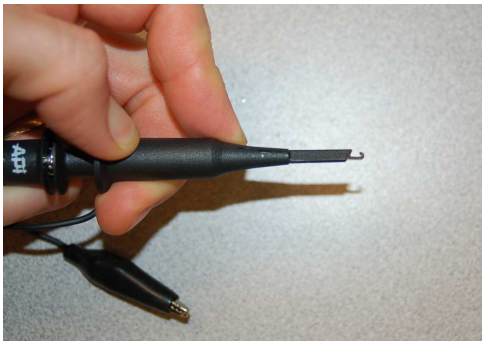
The BNC connector appears at the top of the photograph, terminating one end of the probe's coaxial cable. At the other end of the cable are the test points: one of them being a black alligator clip and the other being a long, black barrel with a hidden hook at the end designed to hold on to a wire or component lead. The alligator clip is the "reference" point, equivalent to the black-colored test lead of a multimeter. The long barrel is the "measurement" point (also called the *tip* of the probe), equivalent to the red-colored test lead of a multimeter.

The hook at the tip of this general-purpose probe may be revealed by pulling back on the black-colored barrel. Releasing the barrel allows it to spring-return to its forward position, thus clamping the test point between the metal hook tip and the plastic end of the barrel. The hook and barrel portion of general-purpose probes such as this may be removed by forcibly pulling it off of the probe

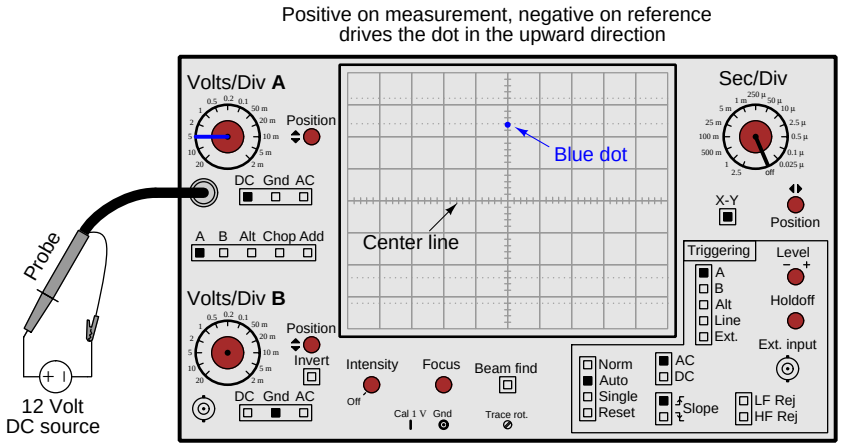
[9] Surge impedance, more commonly called *characteristic impedance* describes the degree to which the intrinsic capacitance and inductance of any passive cable behaves as a temporary load to an impressed signal at one end. This becomes very important when conveying high-frequency and/or extremely short-duration signals, as improper signal impedance can distort the signal. One of the major factors influencing cable surge impedance is the physical separation between conductors, which is precisely controlled by the construction of any coaxial cable. Individual test leads such as those commonly used for multimeters are completely uncontrolled for separation, as the leads are individual and may be moved closer together or farther apart at will.

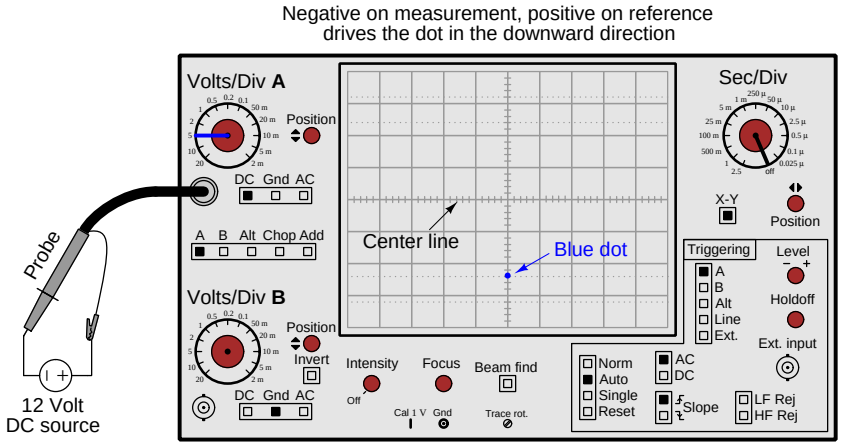
body, revealing a sharply pointed metal pin as the probe's tip. Often, a metal ring coaxial to this tip is also revealed once the barrel has been removed, which serves as an alternate point of contact for the probe's reference terminal.

Two photographs shown below reveal the probe tip's construction. The left-hand photograph shows the probe's regular "hook" tip exposed by pulling back the barrel, while the right-hand photograph shows the plastic barrel removed entirely to reveal a sharply-pointed tip and the "reference" ring:



The measurement (tip) and reference (alligator clip) terminals of an oscilloscope probe work the same as the red and black test leads of a multimeter, respectively, as demonstrated in the following illustrations. Here we see the consequence of connecting the + and − terminals of a DC voltage source to the oscilloscope probe in opposite ways:





Some oscilloscope probes come equipped with a built-in voltage divider network to attenuate the amount of voltage input to the oscilloscope by a certain ratio. Common ratios for "multiplier" probes are 10 and 100. Even though the actual function of the resistive network inside these probes is to *divide* the measured voltage into a lesser quantity, the effect when reading the oscilloscope's screen is that the sensitivity (voltage per division) is *multiplied*. For example, if you read a voltage value of 3.75 Volts while using a x10 probe, the actual circuit voltage being measured is 37.5 Volts.

Multiplier probes are useful for more than one reason. First and most obviously is that a multiplier probe extends the oscilloscope's useful range of voltage measurement, to be able to measure greater voltages than possible with a direct (1:1 ratio) probe. Second, and not so obvious, is the fact that a multiplier probe presents a greater impedance[10] to the circuit under test than a simple 1:1 probe, and in doing so incurs less *loading*[11] of the circuit by the oscilloscope.

Taking this concept one step further is a device called an *active probe*, so named because it contains an electronic amplifier assembly to boost and condition the measured signal prior to being received by the oscilloscope. This permits an even greater level of "loading" impedance (and therefore less loading *effect* on the measured signal) without attenuating the signal strength at the oscilloscope.

It should be obvious that a good-quality test probe should convey the measured voltage signal to the oscilloscope without distorting or otherwise corrupting the integrity of that signal. With DC voltage measurements this is relatively easy to achieve, as any pair of wires will work as test leads to connect the oscilloscope to the circuit. However, in cases where the signal in question is AC of high-frequency (e.g. tens of thousands of Hertz or higher), designing and building a good-quality test probe and cable assembly is far from simple. All cables manifest some amount of *capacitance* within them, owing to the separation of its conductors by layers of electrical insulation. All cables also manifest some amount of *inductance* as well, as any current-carrying conductor will form a magnetic field around it. At high frequencies, the reactance of the cable's intrinsic capacitance and inductance may become significant and function as a load on the measured signal, attenuating it before it even reaches the oscilloscope. Furthermore, where signals of extremely high frequency are concerned, the signal may tend to *echo* back and forth along the probe cable's length, with the probe cable functioning as a *transmission line*[12].

Controlling these parasitic effects is extremely important for faithful reproduction of the measured signal at the oscilloscope's input, and it is what justifies the engineering invested in the design of a high-quality oscilloscope probe. Suffice it to say, an oscilloscope probe is not just a coaxial cable tipped with a test pin and an alligator clip, and it should not be treated as such. Oscilloscope probes

[10] Impedance simply means the degree to which any component or instrument *impedes* the flow of electrical charge carriers. It is a more encompassing term than *resistance*, but for the sake of this discussion means the exact same thing.

[11] An ideal voltage-sensing instrument draws zero current from the circuit while measuring voltage, and therefore has an *infinite* input impedance. Real instruments, however, must by necessity extract at least some amount of energy from the circuit in order to perform the task of measuring, and this means voltage-sensing instruments such as oscilloscopes will in fact draw some current from the circuit and exhibit a finite (albeit very large) amount of input impedance. The greater the level of this input impedance, the less energy extracted from the circuit under test and therefore the less "loading" effect which may corrupt the measurement accuracy.

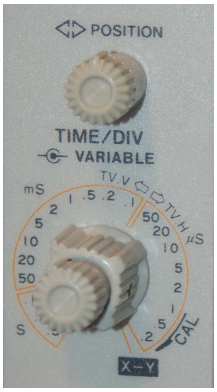
[12] A cable begins to act as a "transmission line" when the time required for a signal to propagate from one end of the cable to the other (at nearly the speed of light) is significant in comparison to the period of its AC cycle. If the alternations of the AC signal evolve faster than the signal can travel down the cable's length, different portions of the cable may simultaneously manifest different amounts of voltage and different amounts of current. Incidentally, this is an interesting exception to *Kirchhoff's Laws*, which are really only "laws" for cases of continuous (DC) electricity.

typically contain precise amounts of added resistance and capacitance in an effort to counter the effects of cable capacitance and inductance. This is why no oscilloscope probe should ever be used for any purpose other[13] than connecting an oscilloscope's input to a measured signal.

4.3 Timebase controls

The previous illustration showing an AC voltage source plotting a vertical line on the oscilloscope's screen is not a very useful application of an oscilloscope, except perhaps to measure the peak-to-peak amplitude of that AC voltage. It is equivalent to a pen-and-paper oscillograph with the paper held still rather than moving. If we wish to view the AC *waveform* rather than just see the extents of its amplitude, we will need to make the oscilloscope *sweep* its dot from left to right rather than maintain a horizontally centered position on the screen.

Every oscilloscope provides a *timebase* adjustment to set the rate at which the dot is swept horizontally across the screen, equivalent to the paper feed rate on an oscillograph. On the illustrated oscilloscope, this is the *Sec/Div* (seconds per screen division) knob, currently switched to its "Off" position. A photograph of a legacy oscilloscope's timebase knob appears in the following photograph:

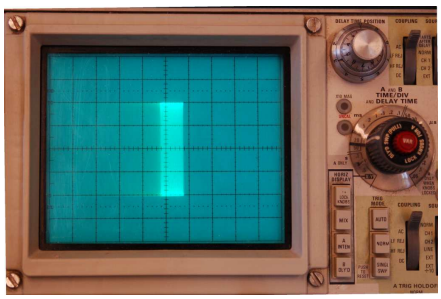


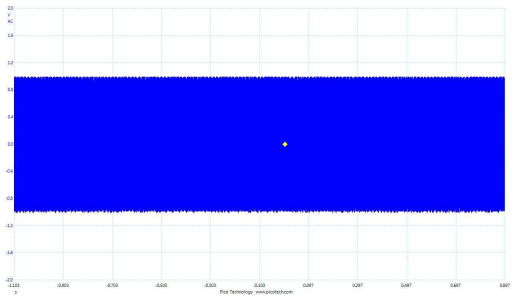
This particular oscilloscope provides a timebase adjustment ranging from 0.5 seconds per division to 0.2 microseconds per division[14]. The "Variable" knob coaxial to the selector knob allows fine control over the timebase for the purpose of esthetically fitting a waveform to the screen (albeit with a loss of calibration in any position but fully clockwise). The left/right "POSITION" centers the trace on the oscilloscope's horizontal axis.

[13] A common mistake made by students new to oscilloscopes is to use oscilloscope probes as signal cables from signal generators and other sources, as though it were a general-purpose cable comprised of nothing but wire.

[14] Cathode-ray oscilloscopes are limited in their timebase ranges because the intensity of the image is an inverse function of sweep: sweep too slowly, and the image merely looks like a moving dot rather than a whole curve because the screen phosphor has limited persistence; sweep too rapidly and the trace becomes too faint to discern. Modern digital oscilloscopes do not suffer this limitation because their traces are plotted by the computer after the data has been buffered in the computer's memory.

If we begin experimenting with this timebase adjustment by setting it to a slow value (i.e. large time value per horizontal division) while an AC voltage is applied to its vertical input. The applied AC voltage sweeps the dot up and down, while the oscilloscope's timebase control sweeps the dot from left to right. At a slow timebase value we will see a vertical "line" slowly move from the left-hand side of the screen to the right-hand side of the screen, then reappear on the left-hand side again. The result, at least for any AC voltage signal of significant frequency, is unimpressive. Compare these two real-life oscilloscope displays, one from a CRO (left) and the other from a computer-based oscilloscope (right):

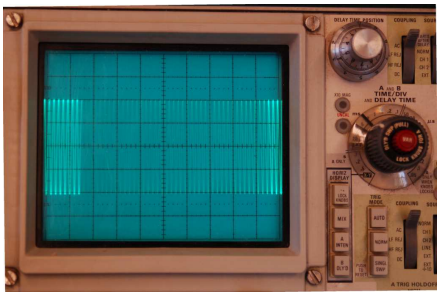


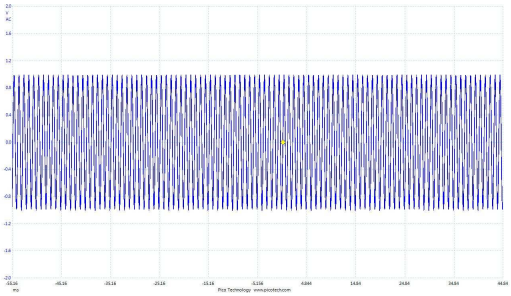


The effect of the CRO's phosphor lag time is evident as the dot oscillates rapidly along the vertical axis and sweeps slowly along the horizontal axis: instead of a single vertical line we see a vertical "band" of color moving to the right with a fading image of itself trailing behind on the left. The computer-based oscilloscope simply shows us a solid swath of color as the moving trace "paints" a path across the screen. Again, this is reminiscent of an oscillograph, this time where the paper is set to move at too slow of a rate to be of any practical use graphing the waveform's shape.

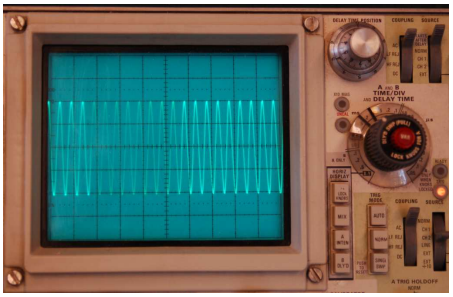
It is worth noting that although a slow timebase setting does nothing to reveal the AC signal's waveshape, having this "band" of color displayed on the screen is useful for precisely measuring the signal's peak-to-peak amplitude.

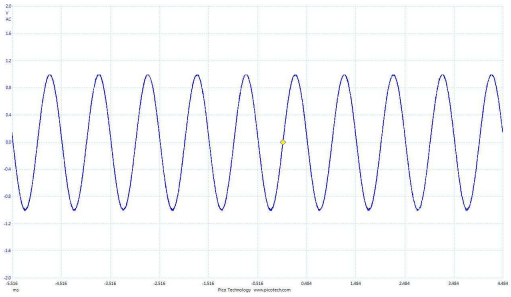
Increasing the oscilloscope's sweep rate by decreasing the timebase setting (i.e. *less* time per division) reveals the trace's true path across the screen: an actual *waveform* with intelligible shape. In each example, the left-hand image is a photograph of the cathode ray oscilloscope while the right-hand image comes from a screenshot of the computer-based oscilloscope:



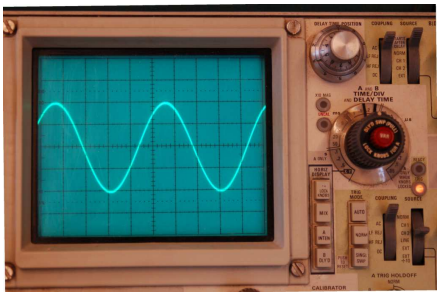


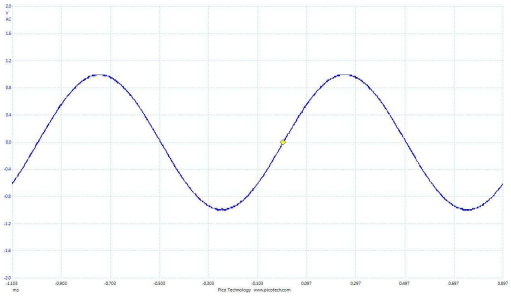
This still isn't as useful to us as it could be, so let's increase the sweep rate even more:





Now the AC signal's waveshape is even more apparent. However, if we increase the sweep rate even more we will be able to improve the view:





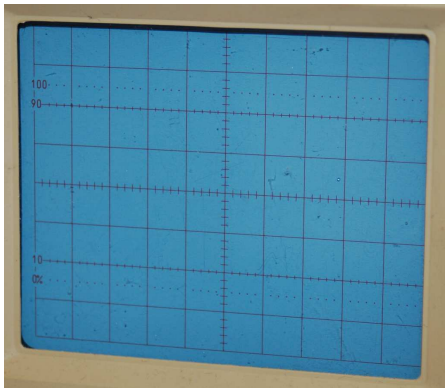
At this final timebase setting, we see approximately two complete cycles of the AC voltage waveform. The shape of this waveform is clearly *sinusoidal*, and we may even measure its period:

from any point on the wave to where the wave repeats itself (horizontal) is approximately 5 divisions on either oscilloscope's screen. Both oscilloscopes are set to a timebase of 0.2 milliseconds per division, which means this waveform's period must be 5 divisions $\times$ 0.2 milliseconds/division = 1.0 millisecond. In other words, one cycle of the waveform occupies 1 millisecond of time. Reciprocating this value to calculate frequency, we get: 1 $\div$ (1 millisecond/cycle) = 1000 cycles per second = 1000 Hertz = 1 kHz.

If we were to increase the sweep rate even more (i.e. decrease the time rating per division), we will come to a point where we see less than a whole cycle of the waveform displayed. Setting the timebase for an oscilloscope, therefore, is a balance between showing too many cycles versus showing too few cycles. Modern digital oscilloscopes generally provide an "auto-set" feature where the machine attempts to determine a good starting value for timebase, but ultimately the correct setting depends on the intent of the human technician or engineer using the oscilloscope: which portion(s) of the waveform hold the greatest interest to us. This, obviously, cannot be guessed by any machine.

4.4 Sensitivity and coupling

An oscilloscope is essentially an analog graphing voltmeter. Like legacy analog voltmeters with a scale of fixed width, the oscilloscope has a screen of fixed height to represent voltage amplitude. Also reminiscent of an analog voltmeter's scale is the grid overlaid on an oscilloscope's screen, each square in this grid representing a *division* of measurement:

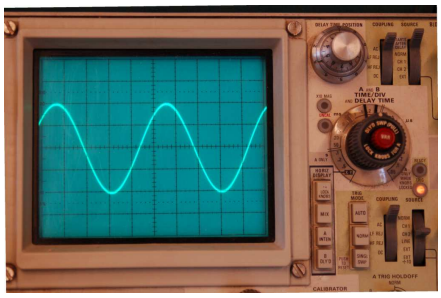


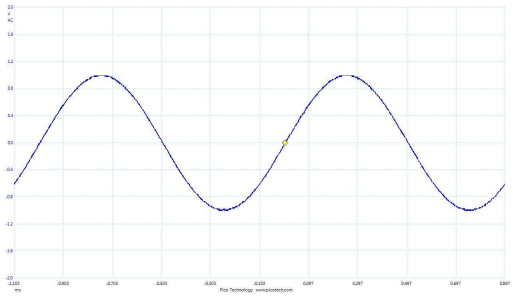
As you can see in this photograph, the center-lines running horizontally and vertically have smaller marks dividing each square into five *minor* divisions to facilitate finer measurements. With analog voltmeters and oscilloscopes alike, the user must choose an appropriate measurement range so that the visible deflection (of meter pointer or oscilloscope dot) is large enough to apprehend but not so large that it exceeds the span of the scale.

Voltage range on an oscilloscope is known by the general phrase *vertical sensitivity*. The unit of expression for vertical sensitivity is *Volts per division*: the amount of voltage represented by each square's height on the grid. On legacy oscilloscopes the sensitivity adjustment is a knob which decreases the number of Volts per division when turned clockwise, to "magnify" the waveform along the vertical axis:

This particular photograph shows an oscilloscope's vertical sensitivity control ranging from 5 Volts/division to 5 milliVolts/division. The orange-colored "Var" knob allows the sensitivity to be finely adjusted for the purpose of esthetically fitting a waveform to the viewing area, but any setting of that "Var" knob other than fully clockwise (to the "CAL'D" position) will result in an uncalibrated Volts-per-division sensitivity. Pulling the "Var" knob out results in a 5-fold magnification of the sensitivity.

Compare the following oscilloscope images, each instrument sensing the same 1 Volt peak sine wave AC signal. The CRO on the left is set for 0.5 Volts per division, while the computer-based oscilloscope on the right is set for 0.4 Volts per division:





Both instruments display the same peak signal voltage, measured either from the center line (0 Volts) up to one of the positive peaks or from the center line down to one of the negative peaks:

- **CRO**: 2 divisions × 0.5 Volt / division = 1.0 Volt peak
- **Computer**: 2.5 divisions × 0.4 Volt / division = 1.0 Volt peak

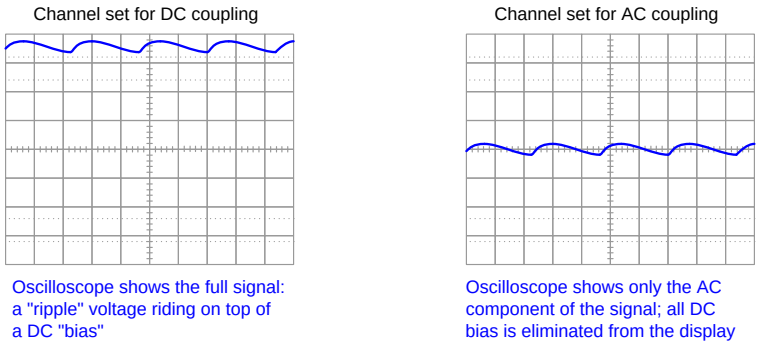
An oscilloscope having four divisions of screen height above and below the center line and a maximum sensitivity setting of 20 Volts per division can therefore display a full waveform no larger than 80 Volts peak (160 Volts peak-to-peak). If signals of greater voltage need to be measured, one option is to use a probe assembly with a built-in voltage divider such that the oscilloscope only experiences a precise fraction of the voltage presented by the circuit under test. ×10 and ×100 probe assemblies are commonly available for oscilloscopes, thus extending their measurement range by orders of magnitude. The use of such a probe, of course, means that the user must bear this multiplier in mind when interpreting voltage. For example, if a signal is measured through a ×10 probe and appears with a peak height of 3.2 divisions with a sensitivity setting of 25 mV/div, the signal's peak value must be:

$$10 \times 3.2 \text{ div} \times \frac{25 \text{ mV}}{\text{div}} = 0.8 \text{ Volts peak}$$

Another important feature of an oscilloscope's vertical controls is the *coupling*. Three basic coupling modes are available: *DC* coupling, *AC* coupling, and *Ground*. In DC coupling mode the input connector is directly connected to the oscilloscope's internal signal processing circuitry so that any DC bias or offset in the measured signal is faithfully represented as a vertical shift of the waveform on the screen. In AC coupling mode the input connected is capacitively coupled to the internal circuitry such that any DC bias or offset becomes blocked and does not appear on the screen. When the coupling is set to "Ground" the input signal is effectively disconnected from the oscilloscope and it registers exactly 0 Volts.

DC coupling is preferable whenever possible, because it gives the truest representation of the signal. AC coupling is used for situations where the DC bias value of the signal is large compared to the peak-to-peak value of the signal, where increasing sensitivity in DC coupling mode to expand the peak-peak waveshape would drive the signal entirely off the screen. An example of this is viewing the *ripple voltage* of a DC power supply circuit, where the amount of "ripple" is quite small compared to the magnitude of the DC voltage. "Ground" coupling is used only when the oscilloscope's vertical position control must be adjusted, and a condition of zero signal is desired to create a flat-line trace on the screen.

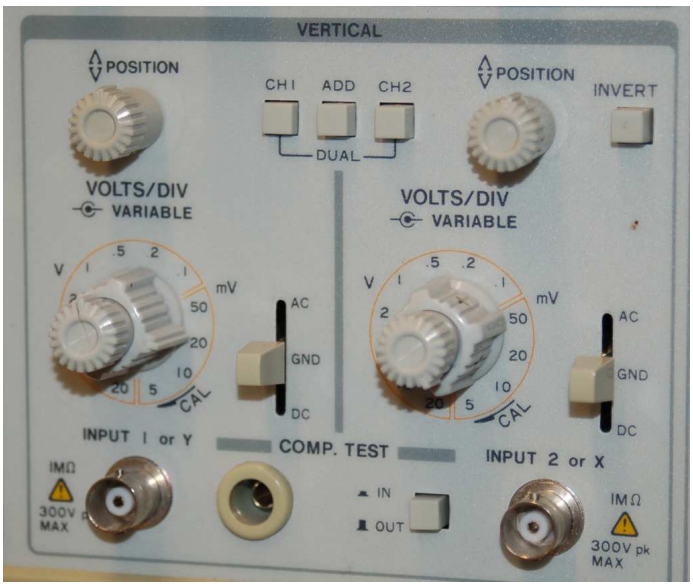
An illustration showing the difference between DC and AC coupling appears here, the signal in question assumed to be the output voltage from an AC-DC power supply circuit:



The vertical sensitivity (Volts per division) is assumed to be the same for both of these coupling settings, which is why the ripple appears equally "tall" in either case. However, AC coupling grants the user freedom to increase vertical sensitivity if desired for the purpose of magnifying only the ripple portion of the waveform for closer inspection. With DC coupling, increased sensitivity will drive the entire trace off of the screen (upwards) where nothing may be viewed.

4.5 Multiple traces

Nearly every oscilloscope has the ability to plot multiple signals, or *traces*, on the same screen. A typical dual-trace CRO control panel is shown here, each of the two vertical inputs having its own sensitivity setting, coupling selector switch, and position adjustment:



A set of three pushbuttons located between the two position adjustments allows the user to select Channel 1 only, Channel 2 only, both channels (both buttons pressed), or the sum of the two signals (Add).

Note that the existence of independent sensitivity selectors allows the two signals to be displayed out of scale with each other. Independent position adjustments also allows those two signals to be displaced vertically from each other if preferred. This flexibility allows the user to position and size the two waveforms arbitrarily.

Computer-based oscillography lends itself very well to plotting multiple signal traces: the computer samples each of the input voltages in rapid succession and simply plots each of them to the screen over the same time domain. Legacy oscilloscopes using cathode-ray tubes (CROs) had to resort to creative techniques to plot more than one signal on the same screen, because a cathode-ray tube has only one electron beam to manipulate and therefore is only capable of generating *one* dot on the screen at any given moment in time.

Two such "tricks" used to display multiple traces on a single cathode-ray tube display included *alternating* sweeps and *chopped* sweeps. In alternating sweep mode, the oscilloscope would alternate between channel 1 and channel 2 when sweeping the dot across the screen. At high sweep speeds (i.e. brief timebase settings) this alternation happened so rapidly that the phosphor lag and persistence of human vision worked to give the illusion of two simultaneous traces on the screen. This technique didn't work so well at slower sweep speeds, as the alternating traces appeared to "flicker" back and forth annoyingly on the screen. Thus, the "chopped" sweep mode was invented to address

this problem: instead of alternating between Channel 1 and Channel 2 every other sweep, the beam would alternate between the two channels many times per sweep, the beam turning off when jumping from one trace to the other so the user never saw the jump. At slow sweep speeds, this gave the illusion of two simultaneous traces plotted to the screen. However, at high sweep speeds the back-and-forth alternation between traces made it appear as though each trace was a broken line instead of a continuous wave.

The following photograph shows the "alternate" and "chopped" mode controls on a legacy dual-trace oscilloscope:

On this particular[15] model, a "slider" style of selector switch determines whether to display just channel 1, just channel 2, the sum of these channels (ADD), or both (DUAL). The pushbutton to the left of this slider switch selects either "alternate" or "chopped" mode for dual-trace operation.

The "Add" mode deserves elaboration. In this mode, the oscilloscope only displays one trace, but that trace is the instantaneous sum of both channel 1 and channel 2 signals. This feature is especially useful when combined with the *invert* feature on the second input channel, which simply displays channel 2's signal upside-down. When "Add" is combined with "Invert" the result is a single trace displayed on the oscilloscope screen that is the mathematical *difference* between the two signals. This is used to perform *differential* signal measurement, which is explained in more detail in a later section of this tutorial.

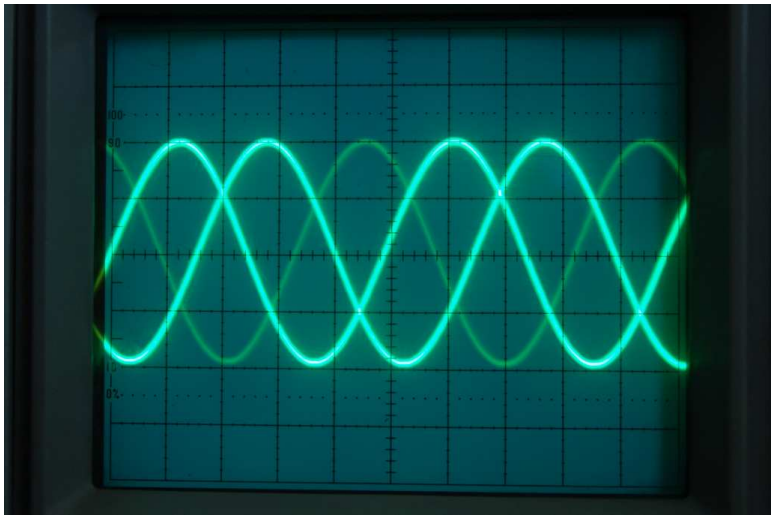
[15] If you haven't guessed by now, there is precious little standardization of controls between different manufacturers and models of oscilloscope. I recall one particularly embarrassing encounter with a new oscilloscope where I searched for *several minutes* trying to locate the on/off power control. Trust me, nothing makes you feel technologically inept like struggling to find the power button on a device. It happened to be a dual function of the *focus* knob – pulling the knob turned the oscilloscope on!

4.6 Triggering

Legacy pen-and-paper oscillographs generated hard-copy records of a measured signal. As such, the only constraints on paper feed rate (i.e. timebase) are the amount of paper one is willing to spill out of the oscillograph during any test and the legibility of the pen's trace. With oscilloscopes, however, we are not tracing waveforms on a (practically) endless strip of paper – instead, we are tracing (and re-tracing) a waveform over the limited width of a graphical screen.

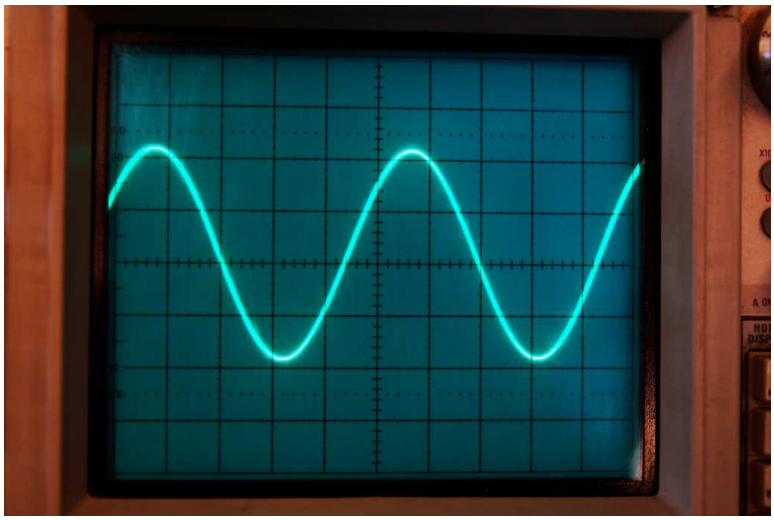
As we have seen, oscilloscopes manage this feat by sending the traveling dot immediately back to the left-hand edge of the screen after it traces its path at the set timebase rate to the right-hand edge of the screen. In this manner, the oscilloscope's display is actually a *continual re-tracing* of the same waveshape. The fact that the waveshape appears to be stationary on the screen of an oscilloscope despite being traced and retraced repeatedly by the sweeping dot is made possible only be beginning each sweep at just the right time.

If we allow an oscilloscope to begin the next sweep immediately after finishing the last, there is no guarantee the dot will trace the same waveshape path. In fact, this will only happen by pure chance, as it is far more probable that the new trace will be out-of-step with the last one. When this happens, the oscilloscope's display will show more of a jumbled mess than a clear waveshape, as is seen here on a 1 kHz sine wave displayed by a legacy cathode-ray oscilloscope (CRO):



The solution to this problem is called *triggering*: intentionally delaying the start of each new sweep until the wave's instantaneous value reaches some pre-determined quantity in a pre-determined direction. With triggering in effect, each and every sweep of the dot begins at the same point on the wave, guaranteeing the wave will re-trace itself across the oscilloscope screen every time.

Applying triggering to the same 1 kHz sine wave, we see a much more stable and legible pattern:



The *trigger level* used in this particular example is a voltage value of 0.5 Volt, with a *rising* slope. Here the oscilloscope display is calibrated such that each vertical division (square on the screen's grid) represents 0.5 Volt of amplitude. The AC voltage being measured has a peak value of 1 Volt, and with the trigger level set to 0.5 Volts we see the wave's trace begin on the left-hand side of the cathode-ray tube's screen approximately at the half-way point between 0 Volts (center) and the positive peak.

We could have just as easily set the trigger level at 0 Volts rising, in which case the waveshape would start its trace on the left-hand side of the cathode ray tube's screen crossing the zero point rather than beginning at the half-way (0.5 Volt) point. Or, we could have set the trigger slope for negative rather than positive, in which case the waveshape would begin in the downward direction rather than in the upward direction.

Legacy CRO triggering controls provide several different modes:

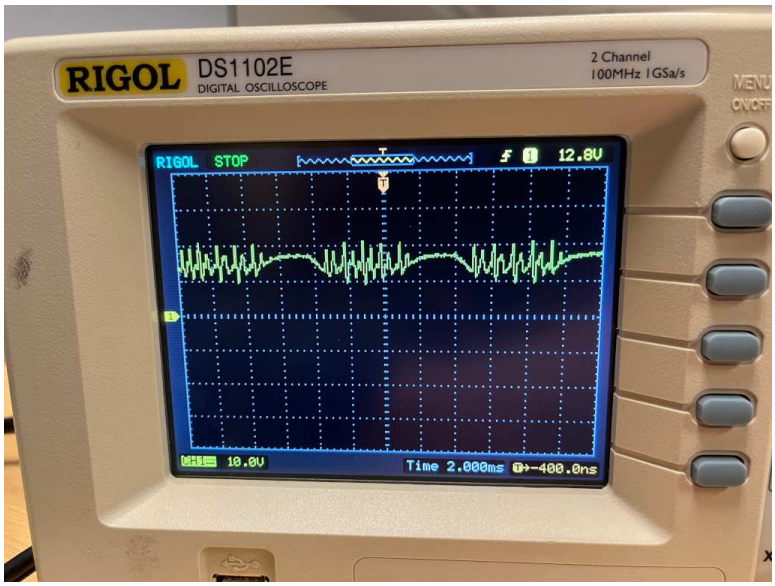
- Normal = Sweeps *only* when triggering criteria (i.e. level and slope) are met
- Auto = Sweeps when triggering criteria met, or after a certain time delay with no sweep
- Line = Sweeps once per cycle of the AC power line frequency
- Single = Sweeps only one time across the screen when triggering criteria met

Normal triggering mode is perhaps the simplest mode to understand: the dot sweeps across the screen if and only if the triggering criteria are met. If the input voltage fails to meet the criteria of sufficient level and slope direction, no sweep will occur and the screen will remain blank. Such triggering can be frustrating for the new oscilloscope user, as the instrument shows absolutely nothing on the screen if there is no input signal, or the triggering level has been set too high or too low.

Auto triggering mode is the best for learning. If the trigger level is incorrectly set or if there is no input signal, the sweeps resume and the screen will display *something* to look at. The "jumbled mess" screenshot shown earlier was taken with the CRO in "auto" triggering mode and the trigger level set too high.

Line triggering mode is useful when the signal you are trying to display happens to be the same frequency as the AC line providing power for the oscilloscope to operate. The AC line power is reliable and strong in amplitude, making it easy for the oscilloscope to "lock in" to it. The signal being measured, by contrast, may be weak or otherwise unreliable. Of course, if the signal of interest isn't at the same frequency as the line power, this mode will result in a jumbled mess because the signal isn't at the same starting point it was when the power line voltage is at the same starting point.

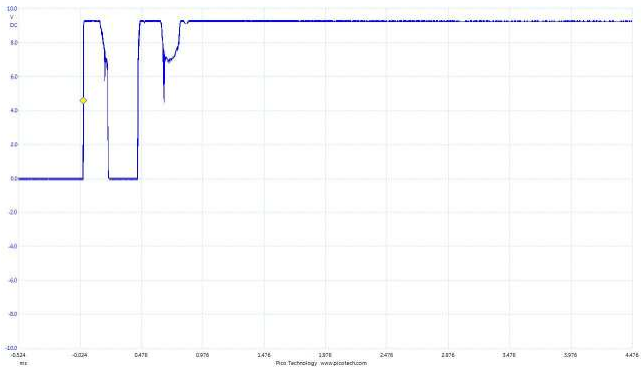
A good use-case for line-triggering is the following waveform measured on an AC-to-DC power supply circuit powering a brush-style permanent magnet DC motor:



Note the "chattering" noise superimposed on the power supply's slow-period waveform by the DC motor's brushes making and breaking contact with the spinning commutator bars. That higher-frequency "chattering" would cause Normal or Auto triggering to randomly pick up on one of those rising or falling edges every sweep, but not the same edge every time, which would mean the waveform could not "lock in" on the waveform and appear stationary as we desire. Knowing that the power supply's relatively low-frequency wave-shape is synchronized to the same AC line power that energizes the oscilloscope, however, means we may use line triggering to very easily stabilize this complex waveform on the screen.

Single-sweep triggering is useful for CROs with delayed phosphor action and/or the legacy technology of photographic camera capture[16]: this is where the sweep does not resume after reaching the right-hand side of the screen, but rather makes a single trace across the screen upon meeting the triggering thresholds. Modern computer-based oscilloscopes do not suffer from the limitations of glowing phosphor, and do an excellent job capturing waveforms using single-sweep mode. Single-sweep triggering requires a *reset* button to prepare the instrument for another sweep.

Single-sweep triggering is necessary when attempting to capture a *transient* event: that is, an event lacking repetition, fleeting or even singular. Modern computer-based oscilloscopes are ideal for capturing such transients because the screen is able to "hold" the image indefinitely, whereas the image presented by a CRO naturally fades within a short period of time. An example of a transient signal captured on a digital oscilloscope using single-sweep triggering is shown in this screenshot, taken of voltage across a 2200 Ω resistor powered by a battery through a normally-open pushbutton switch. The trigger was set for a rising signal at a level of approximately 4.75 Volts[17], designed to sweep once and hold the image upon pressing the pushbutton:



As you can see, the resistor actually energizes and de-energizes a couple of times before the voltage settles at the battery's value (just over 9 Volts). The reason for this is a phenomenon known as *switch bounce*, where the moving metal contacts of a mechanical switch rebound after making first contact. This "bouncing" action, of course, is extremely rapid and requires an instrument such as an oscilloscope to even capture it.

[16] This consisted of a camera with an electronically-triggered shutter mounted firmly to the oscilloscope's bezel so that it viewed the screen and nothing else. When the oscilloscope sweep triggered, the camera's shutter would take a photograph immediately after the one and only sweep, recording that event in film format.

[17] Note the yellow-colored diamond symbol on the trace, denoting both the vertical level of the trigger threshold and the horizontal position of the trigger start point for this particular digital oscilloscope.

So far we have discussed triggering with the assumption that the one signal of interest is the triggering source. With multiple-trace oscilloscopes the user generally has the option of selecting *which* input channel will be used for triggering, so that the display "locks in" to one waveform while displaying the other(s) freely as they relate to the triggered channel. If two AC signals of slightly different frequency are viewed on a dual-trace oscilloscope, the triggered waveform will appear stationary on the screen while the other waveform slowly "drifts" horizontally. The particular channel used as the triggering source may be selected by the trigger Source control on the oscilloscope's faceplate.

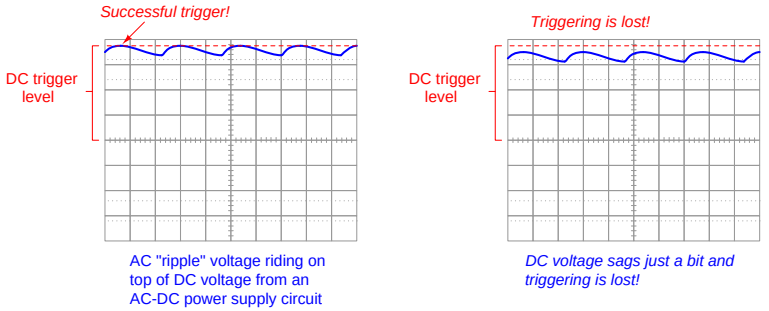
As useful as it is to trigger the sweep based on the signal being measured, this may be problematic if the signal is not perfectly repetitive. A signal that comes and goes, for example, or one that changes shape, will be difficult to use as a reliable trigger basis. For this reason most oscilloscopes provide a means to trigger the sweep based on some signal *other* than the one(s) being displayed.

One such alternative trigger source is an entirely separate input channel provided just for this purpose (called the *external* trigger signal). This additional channel does not generate a visible trace on the screen, but serves only as a signal for the oscilloscope's triggering circuitry to monitor. All displayed channels will sweep when this other input signal matches the triggering threshold. Again, the triggering Source control on the oscilloscope faceplate provides the user with the ability to specify this option, with the Source set for "External" input. Another common triggering source is called *Line*, which uses the AC line power as the triggering signal. This latter option is obviously useful when the signal(s) of interest are synchronized to the power line's frequency.

Another common triggering feature is *coupling*, which is conceptually the same as the coupling option on an oscilloscope's vertical controls. *DC* coupling routes the triggering source signal directly to the triggering circuitry, so that the triggering level is compared directly against that signal source. *AC* coupling blocks any DC bias in the triggering source signal from reaching the triggering circuitry, so that the triggering thresholds apply only to the varying portion of that signal.

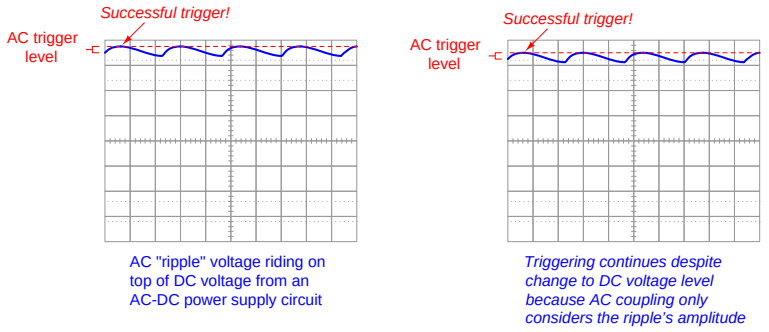
An example of where you might wish to use AC coupling when triggering a signal is if you are triggering off of the *ripple* waveform of a AC-DC power supply where the DC level rises and sags with load variations. If the ripple amplitude is small compared to the DC it's mixed with, just a slight change in DC level may cause triggering to un-lock. If AC coupling is used, triggering never "sees" that DC level, and instead only acts on the ripple voltage.

The following illustrations show how this works when monitoring an AC-DC power supply's output voltage. With the oscilloscope set for DC trigger coupling, the trigger level set such that the "ripple" peaks are just high enough to trigger each sweep, all it takes is a slight reduction in the circuit's DC voltage level to cause triggering to stop:



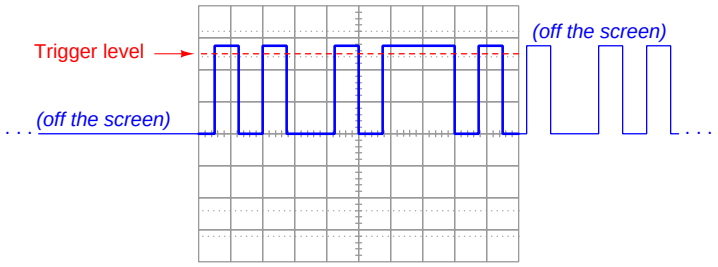
If this happens, and triggering is set to "Normal" mode, there will be no displayed waveform anymore because triggering will not occur. If the triggering mode is set to "Automatic" you will still see a waveform but it will likely be a jumbled mess on the screen because it is no longer synchronized.

Using AC coupling for the triggering signal eliminates this dependency on the signal's DC voltage value:



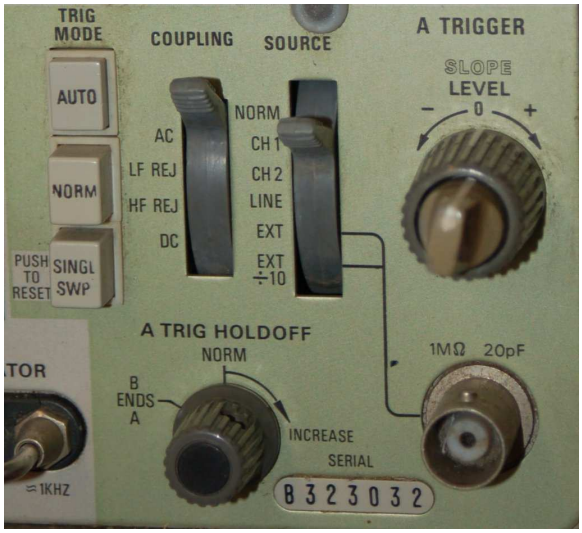
Yet another common triggering control feature is called *holdoff*. This is a time delay within the triggering system, prohibiting the *next* sweep from occurring until after the specified "holdoff" delay time has passed. This is useful when you need to lock in to a feature near the start of a waveform, and must set the timebase such that only the first portion of that wave appears on the screen (i.e. the rest of the waveform is "off the screen"), but you wish to avoid immediate re-triggering on the rest of that waveform. A practical application of this would be locking in to the *first* pulse of a lengthy digital data frame (consisting of a series of "high" and "low" states appearing as a train of pulses) while refusing to re-trigger on any subsequent pulses in that data frame. Setting the holdoff time to wait until the entire data frame completes and be ready to trigger before the next data frame begins, will ensure only the first pulse of that data frame gets displayed on the screen.

The following illustration shows how holdoff may be used to trigger on just the first pulse of a long train:



If not for holdoff, the oscilloscope's triggering system would lock into the next immediate pulse following the end of the sweep. This would re-start the sweep while the pulse train is in the middle of its progression, which would be contrary to our goal of waiting until the pulse train is finished and begins again.

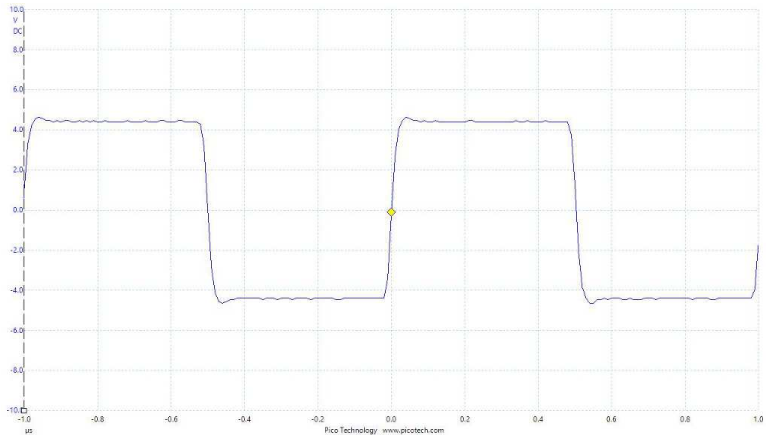
The following image of a CRO's triggering controls appears here:



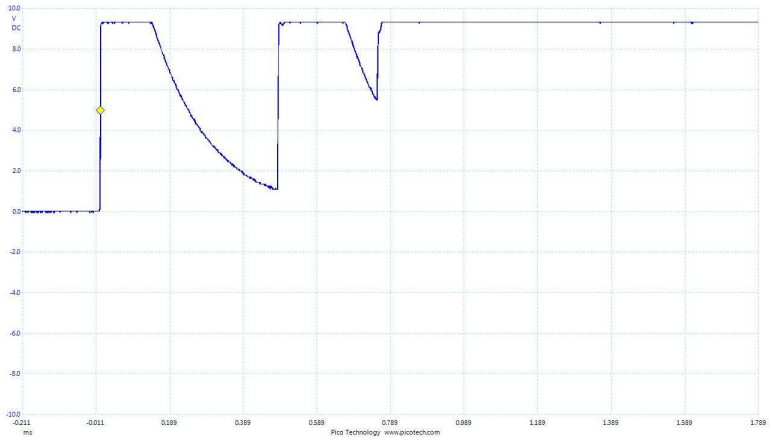
In this photograph you can see three triggering modes (Auto, Normal, and Single Sweep) selected by three pushbuttons. The triggering source (Normal[18], Channels 1 or 2, Line, or External) is set by a multi-position switch. The triggering slope and voltage level are set by a coaxial knob. Holdoff timing is set by a separate knob. Coupling options (AC, DC) are selected by a multi-position switch between the triggering source selector and the triggering mode pushbuttons. A couple of advanced coupling options (low-frequency rejection and high-frequency rejection) are offered by this particular model, which uses high-pass and low-pass filter circuits, respectively, to filter the triggering signal prior to level detection. The end goal of all these controls is to be able to narrowly select *which portion* of a waveform you wish to use as the synchronizing mark for initiating each sweep.

[18] On this particular model of CRO (a Tektronix 465), the "Normal" triggering source is the vertical deflection circuitry controlling the cathode-ray tube. This means the triggering signal will come from whatever is deflecting the electron beam at that moment in time, which covers *both* channels 1 and 2.

Modern digital oscilloscopes provide all these same triggering options, and usually many more as well! One of the immediately noticeable differences between a digital oscilloscope's trigger setting and an analog oscilloscope's (CRO's) trigger setting is that with a digital oscilloscope the trigger's starting time need not be at the left-hand side of the display. In fact, many digital oscilloscopes default to the trigger point being in the *center* of the screen. We see an example of this here, with the digital oscilloscope triggering on the rising edge of a square-wave signal crossing 0 Volts, the trigger point shown on the screen as a yellow-colored diamond symbol:



Next we see a different signal being captured by the oscilloscope, with the triggering point moved up and far to the left from its default center location:



A common control for the trigger point's position on a digital oscilloscope's time (horizontal) axis is the *horizontal position* knob. For other oscilloscopes, you can "drag" the trigger point's location to any arbitrary location on the display, and in so doing set both the start point for the triggered sweep as well as the trigger voltage level.

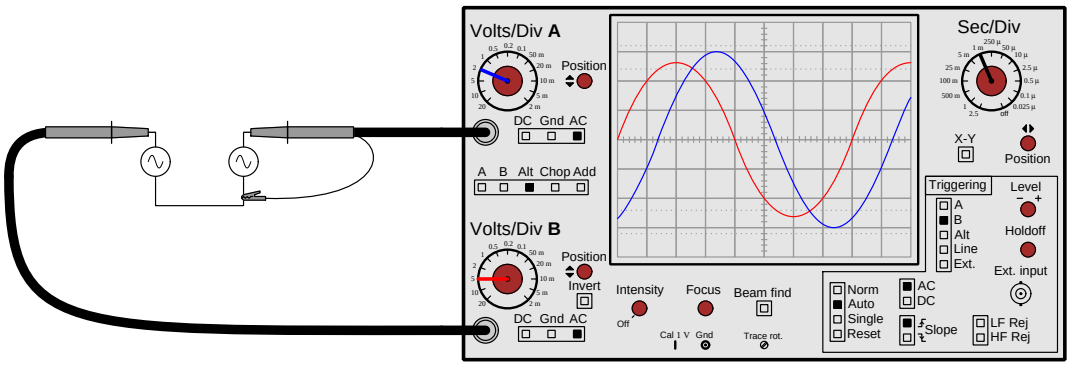
Of all the basic oscilloscope controls, triggering is arguably the most complicated and difficult to master. One of the confounding factors is the *total* lack of standardization between oscilloscope manufacturers (and even between different *models* by the same manufacturer!) with regard to triggering controls. This means you must really learn how triggering works on each and every individual oscilloscope you use.

4.7 Measuring phase shift

Two or more AC quantities at the same frequency may be shifted in phase from one another, which is to say their respective peaks do not occur at the same points in time. *Phase shift* is a very important measurement in AC circuits, and is equivalent to *polarity* for DC quantities.

The most common method of measuring phase shift between two AC quantities is to display them both on a dual-trace oscilloscope, and then measure their displacement on the horizontal (time) axis. One complete cycle represents 360 degrees, and so we may consider the number of horizontal divisions within one cycle to represent 360^o and then calculate phase shift by measuring the number of horizontal divisions separating similar points on the two waves.

Consider this example, where a dual-trace oscilloscope is displaying two AC voltages:



Triggering is based on channel B, and the trigger level set at 0 Volts rising to that that the oscilloscope's sweep from left to right across the screen begins just as the "B" waveform (shown in red) crosses zero in the rising direction. Vertical coupling for both channels has been set for "AC" which eliminates any DC offset and allows for easy centering along the vertical axis. Counting horizontal divisions, we see that each cycle[19] is equal to eight divisions. Calculating the number of degrees per division is a simple matter of dividing 360 degrees by the number of divisions each cycle spans:

$$\frac{360^o}{8 \text{ div}} = 45^o/\text{div}$$

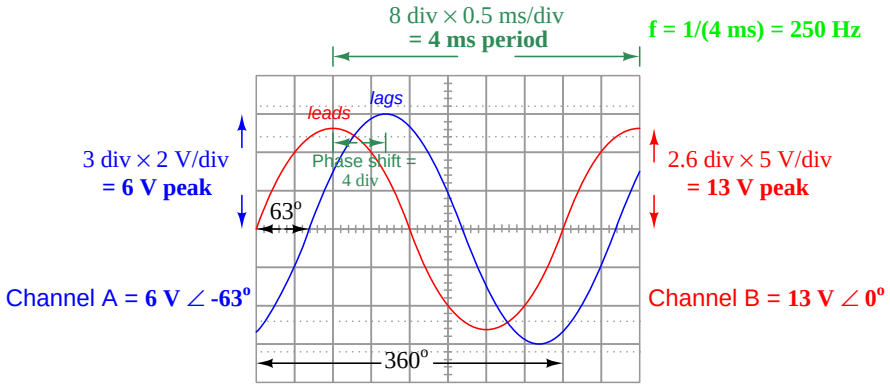
[19] This is the same of both channel A (blue) and channel B (red), since these two waveforms happen to share the same frequency. If the two AC quantities in question have different frequencies, their phase shift will be continuously changing. This means the two waves will "roll" in and out of phase with each other at a rate equal to the difference between their respective frequencies. It is impossible to calculate phase shift in this way for two waveforms at different frequencies because by the time you have finished counting divisions and performing the calculations, the amount of shift has changed.

Now that we know each horizontal division equals 45 degrees for either waveform, we may measure the amount of horizontal shift between them and then multiple that number of divisions by 45^o/div to arrive at degrees of phase shift. In this particular case we see there is approximately 1.4 divisions of displacement between the two waves, most easily counted by noting the horizontal separation between the zero-crossing points[20] for the two sinusoids. Multiplying 1.4 divisions by 45^o/div yields the amount of phase shift between these two AC voltages:

$$\left(\frac{45^o}{\text{div}}\right)(1.4 \text{ div}) = 63^o$$

Furthermore, we may be even more specific by saying that channel A's voltage *lags* channel B's voltage, and/or that channel B's voltage *leads* channel A's voltage. Determining which waveform leads the other is a simple matter of viewing both waves from left to right (in the same direction the oscilloscope "sweeps" the plot across the screen over time) and noting which waveform reaches a particular vertical value first. For example, we could note that the red waveform (B) reaches its positive peak before the blue waveform (A) as the traces progress from left to right, and therefore red (B) leads blue (A).

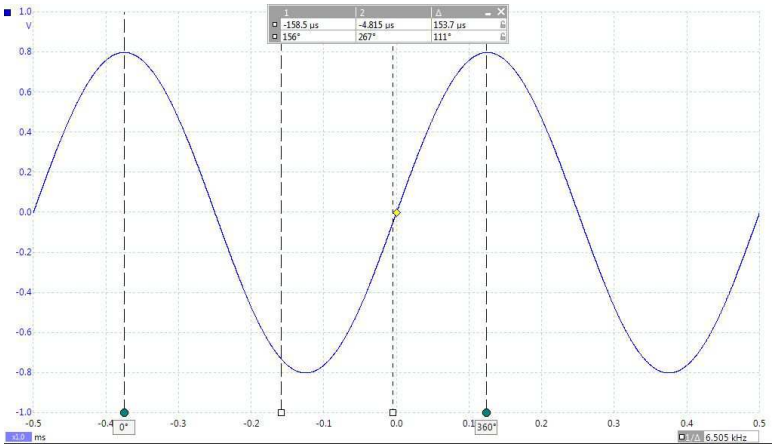
If we wished to describe both of these AC voltages in *phasor* notation, counting channel B's voltage as the phase reference waveform, we could say that channel B is 13 Volts (peak) $\angle$ 0^o and that channel A is 6 Volts (peak) $\angle$ -63^o.



Of course, the choice of phase reference is arbitrary, and therefore we could have just as easily stated channel A as 6 Volts (peak) $\angle$ 0^o and channel B as 13 Volts (peak) $\angle$ $+63^o$.

[20] Any similar points on the two waveforms may be used as markers for measuring phase shift. Positive peaks (or negative peaks for that matter) suffice as well as zero-crossing points. Zero-crossing points (with same slope) are convenient for measurement because they fall along the horizontal axis and are therefore easy to count divisions for, but this is reliable only if the two waveforms are equally centered about the horizontal axis. Any amount of vertical offset between the two waveforms will affect the apparent amount of phase shift at the horizontal axis, although it should be noted that vertical offset does not interfere with the horizontal displacement of peak points.

Digital oscilloscopes provide convenient tools for measuring phase angles, so convenient in fact that the user does not necessarily have to apply any arithmetic to the displayed waveforms. Consider the following screenshot from a PC-based digital oscilloscope showing a single sinusoidal voltage signal with "phase rulers" (green dots) set by the user to define the 0^o and 360^o points on the waveform and "time rulers" (white squares) set at two other points to measure times and phase angles at those points:



A tabular display above the waveform shows both "time ruler" values as both time values (with the trigger point defining $t = 0$) and as phase angle values. A third column in the numerical table shows the difference (Δ) between the time rulers, both as time value and as a phase shift. A single numerical display located in the lower-right corner of the oscilloscope window goes one step further to show the reciprocal of the time difference (as a *frequency*) between the two time rulers. This is useful if the time rulers happen to be set at the starting and ending points of a wave's cycle (i.e. Δt = period of the wave).

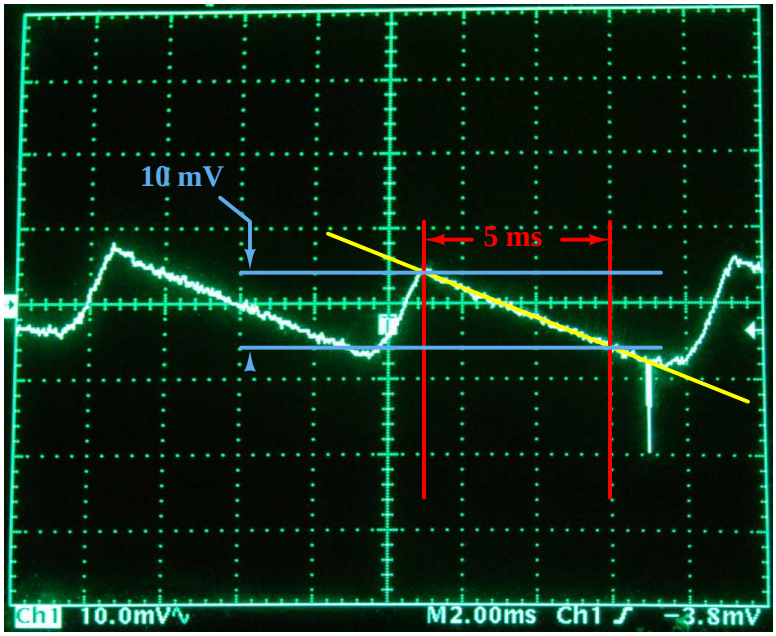
Digital capabilities such as these make analog oscilloscopes all but obsolete.

4.8 Measuring rates of change (slope)

Another important type of measurement possible with an oscilloscope is the *slope* or the *rate-of-change* of a signal over time. For voltage signals, this is mathematically represented by the calculus notation $\frac{dV}{dt}$ which is the instantaneous rate of voltage change over time: the *steepness* of the voltage's rise or fall at a particular instant in time. A very closely related, and more realistic, measurement is $\frac{\Delta V}{\Delta t}$ which is the average rate of voltage change between two specified points in time.

Rate-of-change is an important quantity for many applications. Capacitors, for example, exhibit a current proportional to the rate-of-change of voltage ($I = C\frac{dV}{dt}$). Inductor, similarly, exhibit a voltage proportional to the rate-of-change of current ($V = L\frac{dI}{dt}$). Certain electronic components such as *thyristors* may be falsely triggered into their conductive states by excessive voltage rates-of-change impressed across their terminals. Also, the range of "harmonic" frequencies contained by a pulse signal depends strongly on how rapidly that pulse's edges rise and fall, which may be important for electronic noise mitigation in high-speed digital circuits.

An example of how $\frac{dV}{dt}$ may be estimated for a captured sawtooth waveform appears in this next photograph, the annotations overlaid on the photograph after it was captured on camera:

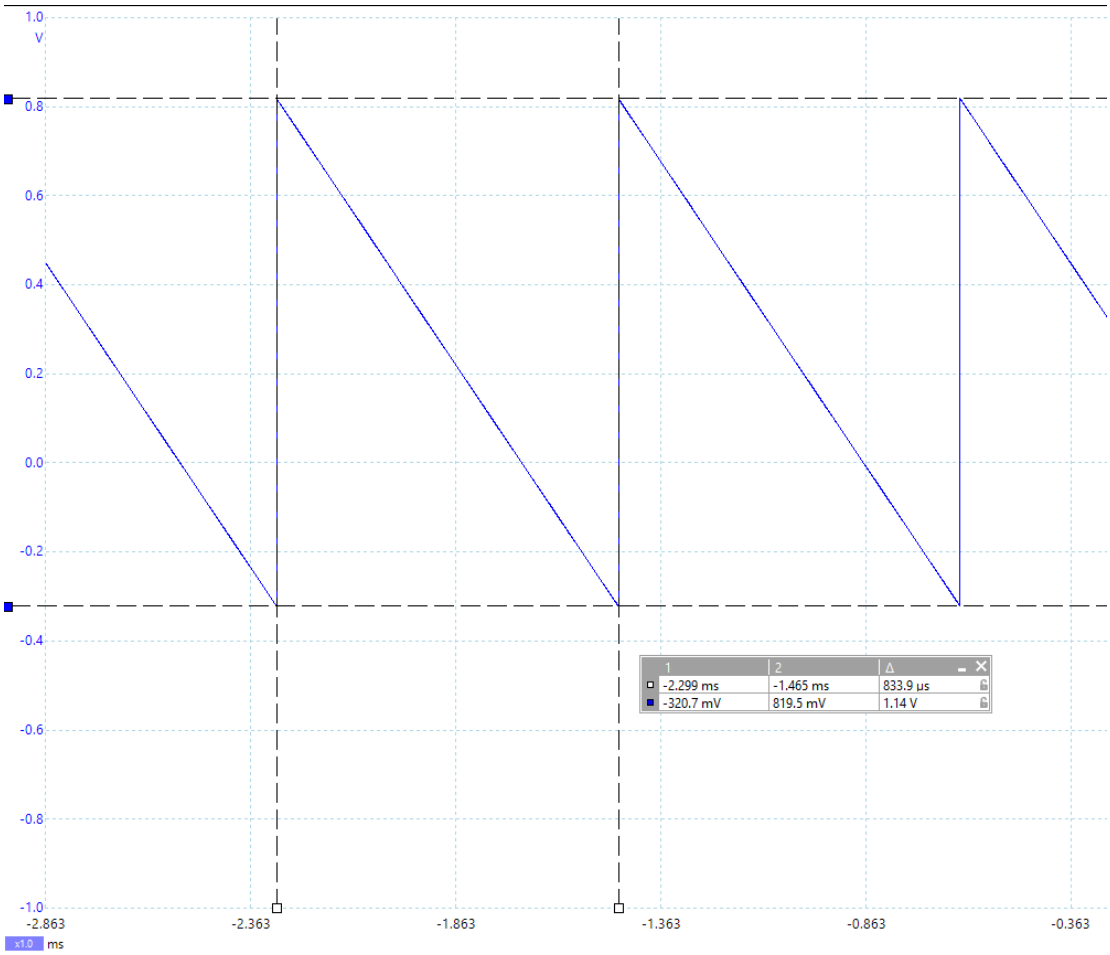


Here the yellow line follows the downward slope of the voltage waveform, while the red lines mark a time interval along that slope and the blue lines mark the voltage fall over that time interval. With the values shown here, -10 milliVolts of fall over 5 milliseconds of time, the estimated $\frac{dV}{dt}$ for this signal's downward slope is -2 Volts per second.

Interestingly, the downward "glitch" seen near the lower-right area of this oscillograph exhibits much larger rates-of-change than the relatively gentle slopes. Even though the vertical height of this transient is not very large, its extremely short timespan means its leading edge will have a large

negative slope ($-\frac{dV}{dt}$) and its trailing edge will have a large positive slope ($+\frac{dV}{dt}$), possibly hundreds or even thousands of *Volts per second* each.

Modern digital oscilloscopes with their "ruler" or "cursor" features allow for this same sort of slope estimation right on the instrument's screen itself. Take for example this screenshot showing voltage cursors (blue squares) and time cursors (white squares) used to define the boundaries of the first complete downward slope captured in this waveform:

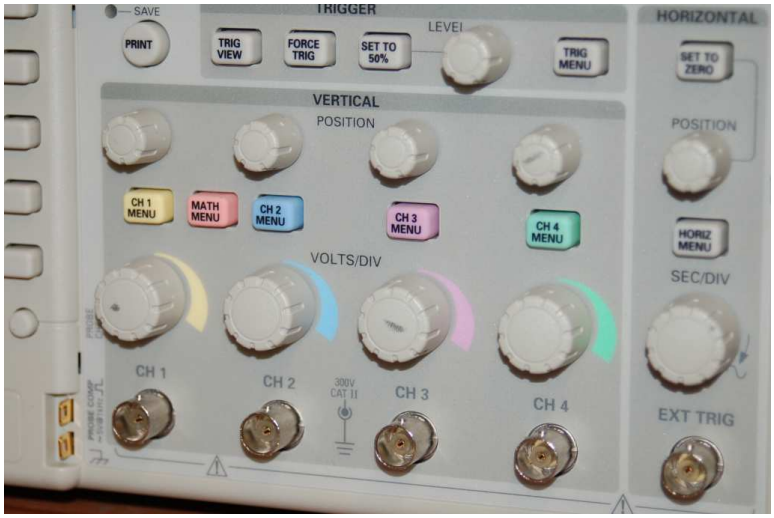


From the positive to the negative peak of this waveform we see a difference of 1.14 Volts, which we will consider to be a negative quantity because the waveform's voltage is falling over that time period. The duration of that period as marked by the time rulers is 833.9 microseconds. This yields a $\frac{dV}{dt}$ value of -1367.07 Volts per second. Do not be surprised or fearful of such a measurement, as -1367.07 Volts/second is not the same thing as -1367.07 *Volts*. The first is simply a rapid rate of fall while the second is a dangerously large potential difference.

4.9 Ground-referencing

Connections to the input channels of an oscilloscope are always made through *BNC* style connectors, which are a coaxial type of electrical connector having an inner female jack (hole) and a circular male body that locks on to the coaxial BNC fitting using a quarter-turn latch mechanism. The circular male body of the BNC connector is both a mechanical support for the coaxial test probe cable and the "ground" or "reference" terminal of the oscilloscope's voltage input, analogous to the black-colored test lead of a multimeter.

The following photograph shows five different channels on a digital oscilloscope: four vertical input channels and one external triggering input channel. Note how each of these channels has its own metal BNC connector below the corresponding adjustment knob:

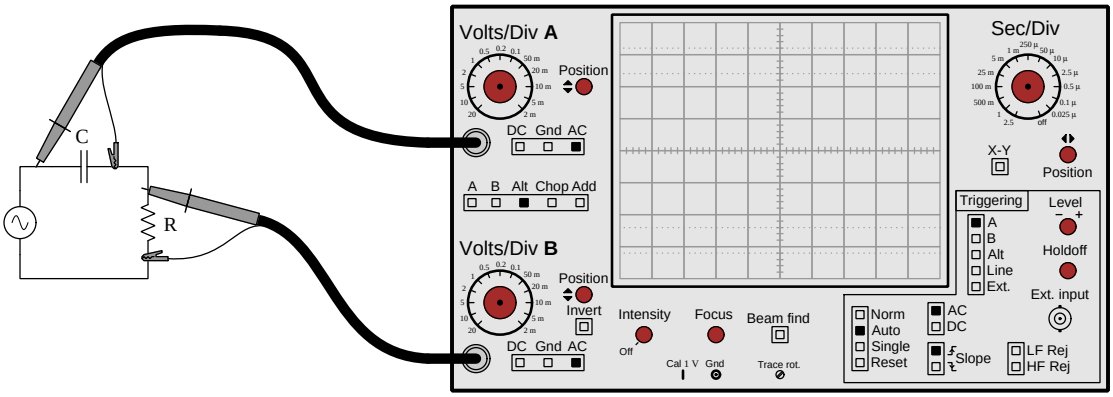


The metal bodies of all these BNC connectors are electrically common with the metal chassis of the oscilloscope, which means they are also equipotential to each other. Even though each probe plugged into a BNC connector has two terminals at its end – a tip and a "reference" alligator clip – for measuring voltage (which of course is *always* measured between two points) the channels are not completely independent of each other. Each and every channel's reference point is connected to the oscilloscope's chassis and is therefore electrically common with every other channel's reference point. It is as if we had a multi-channel voltmeter for measuring multiple voltages simultaneously, where each voltmeter channel had its own pair of red and black test leads, but all the black test leads were common to each other. When using such a voltmeter, we would have to be careful where we connected those black test leads in the circuit, lest we unintentionally short between or more points with those leads.

Furthermore, for line-powered oscilloscopes the metal chassis is also connected to Earth ground through the power cord's grounding prong. This means each and every input channel must measure voltage with reference to ground, and in fact the very act of connecting any probe's reference clip to a point in a circuit forces that point to be electrically common with the Earth!

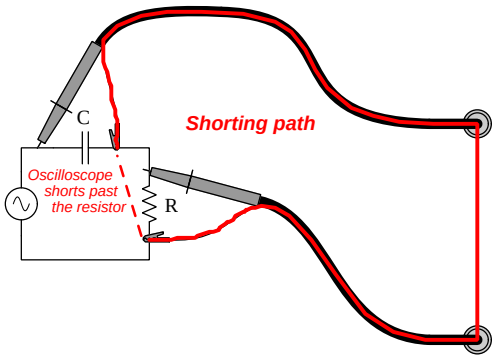
The electrical commonality of all channels' reference points can and does pose practical problems when taking certain measurements using an oscilloscope. We will explore some examples to illustrate both the problem and possible solutions.

First, let us consider the problem of multiple channels sharing a common reference. In the following circuit, a dual-channel oscilloscope is needed to measure the phase shift between two components' voltages in an AC circuit:

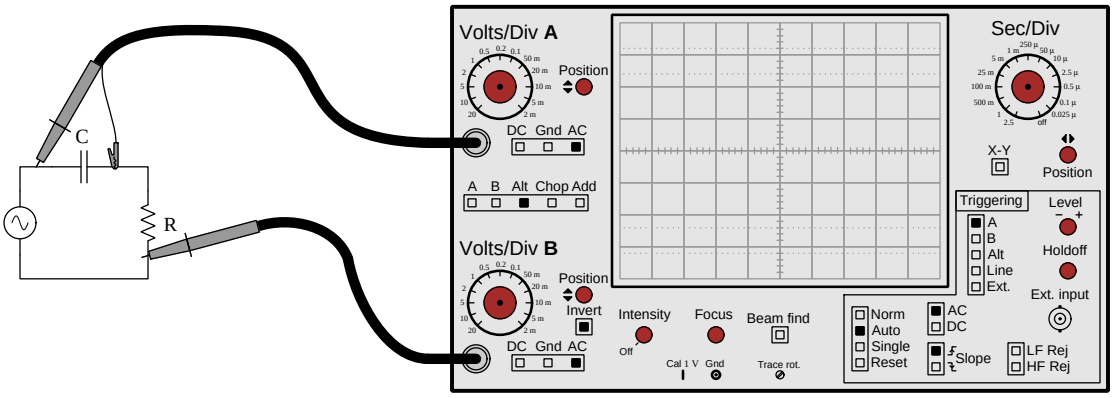


At first this may seem like a reasonable way to connect a dual-trace oscilloscope to such a circuit for the purpose of measuring phase shift. Certainly, when performing voltage drop calculations on an AC capacitor-resistor circuit like this, it is customary to express the phase angle of each voltage assuming polarities as though the circuit were DC (e.g. source + on top and − on bottom; capacitor + on left and − on right; resistor + on top and − on bottom), and it is also customary for technicians to connect the black test lead of their voltmeter to the terminal assumed to be negative (−). Therefore, it may seem a very natural thing to connect each of the oscilloscope's probe references to the assumed negative (−) terminal of each component. However, doing so will not only fail to yield valid results, but it will actually alter the circuit being tested!

Since the two reference clips are electrically common to each other by virtue of both being common with the oscilloscope's chassis, it means any two points we clip them to in the circuit being tested will be "shorted" together through the probe cables and oscilloscope chassis! In this particular case it means the resistor (R) will be shorted past, and the circuit will consist only of the AC source and the capacitor (C). Channel A of the oscilloscope will register full AC source voltage, and channel B will register no voltage at all.



How then may we measure both of these components' voltage drops simultaneously? We must find a way to do so where each of the measured voltages shares a common point, and make that point the one we connect to a probe reference clip. The next illustration shows how to do this:

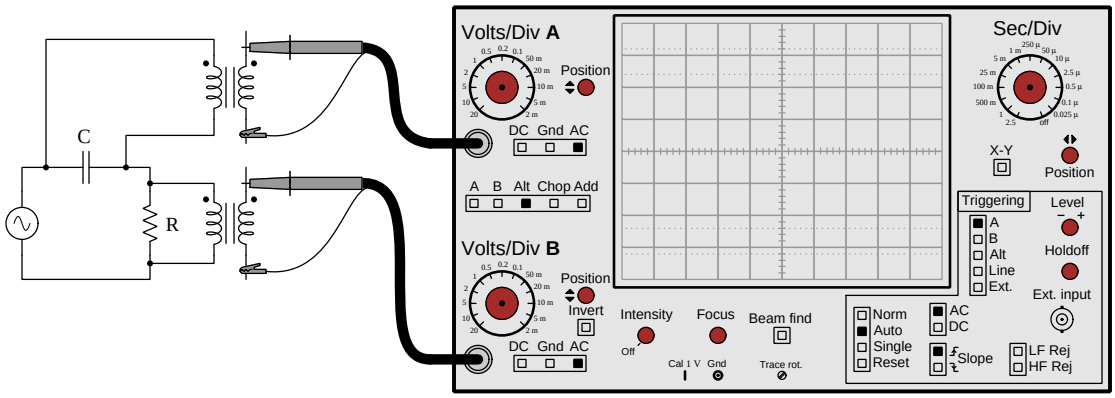


Now channel A senses the capacitor's voltage drop while channel B senses the resistor's, with no shorting past any component in the circuit. Note how we only need one reference clip connected to the circuit (in this case, channel A's reference) because connecting the other probe reference clip to the exact same point in the circuit would be redundant.

Connecting the two oscilloscope channels to the circuit in this manner avoids the shorting problem cause by two reference clips connected to two different points, but it introduces a new problem: now channel B's measurement appears "reversed" in polarity compared to channel A's. The phase shift shown on the oscilloscope's screen will appear 180 degrees off from what we would expect by

mathematical circuit analysis. To counter this inversion, we may use a feature common to most oscilloscopes: the *invert* switch on channel B. Latching this "invert" switch causes the trace for channel B to be inverted, which will un-do the inversion created by our "backward" connection of probe B and allow us to measure the phase shift as expected.

Another solution to the problem of measuring two voltages with different reference points is to use signal transformers to couple the two signals to the oscilloscope's inputs. The purpose of each signal transformers is to provide electrical separation between the circuit and the oscilloscope channel in order to eliminate any conductive pathway between the two[21]:

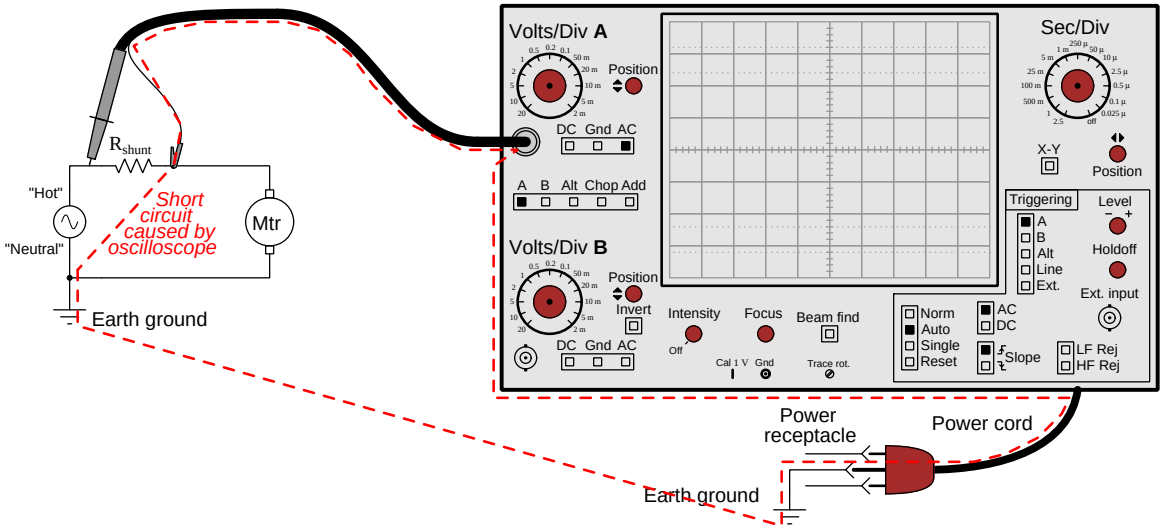


Of course, this may not work well for all applications due to the inevitable distortion and loading each transformer will impose on the circuit's signals. It is well-suited for measurements on electric power systems where the frequency is low, the signals in question are relatively simple (i.e. sinusoidal), and the circuit has a low enough impedance that transformer loading will be negligible. In fact, the freedom to arbitrarily choose transformer step-down ratios makes this solution especially attractive when measuring dangerously high AC voltages, as the transformers will serve the function of reducing signal voltage levels while also providing electrical isolation!

A final solution to the problem of electrically common probe references is to use an oscilloscope with *isolated inputs*. This is a much more expensive option, and one not typically found on general-purpose oscilloscopes. An oscilloscope with isolated input channels provides probe tip and reference clip points for measuring each voltage (between two points), but none of the reference clips are electrically common to each other. Similar to the signal transformer solution, isolated inputs use special electronic circuits to convey the signal information from probe to the oscilloscope's internal amplifiers without direct wire connections between the two.

[21] Technically we could just use one signal isolation transformer to prevent the two oscilloscope channels from shorting past the resistor. However, using two signal transformers makes the two channels comparable in terms of circuit loading which is good for comparative measurements such as this. Also, using two signal transformers completely eliminates potential problems of *grounding* the circuit under test through either channel's reference clip.

Next, let us consider the problem of connecting an oscilloscope to a circuit that is already grounded. In the following example, we see an AC voltage source powering a motor through a low-value resistor called a *shunt*. The source's two terminals are labeled "Hot" and "Neutral" in reference to their relative danger, the "Neutral" being permanently bonded to Earth ground. This makes the "Neutral" conductor safe to touch for anyone standing on the ground, and also makes the "Hot" conductor dangerous to touch (assuming sufficient source voltage to pose a shock hazard). The purpose of this shunt resistor is to drop a measurable voltage for an instrument to measure as a proportionate representation[22] of motor current:

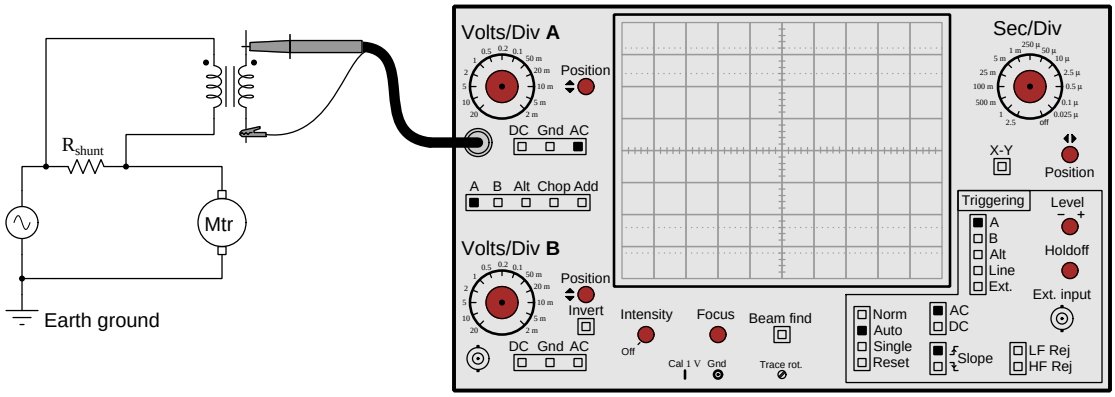


Connecting even just one channel of the oscilloscope across the shunt resistor as shown will create a direct short-circuit between the right terminal of the shunt resistor and Earth ground, since the probe's reference clip is electrically common to the oscilloscope's chassis, and the chassis in turn is bonded to Earth ground through the ground prong of its power cord. The result will be a dangerously high amount of current flowing through the oscilloscope's probe cable and power cable.

A "solution" sometimes employed by foolish technicians is to remove the ground prong from the oscilloscope's power cord, which allows the chassis to become equipotential with the "Hot" conductor connected to the motor. This way, the path for a short-circuit is broken, but the great disadvantage is that the oscilloscope's chassis becomes dangerous to touch! As a general rule, one should *never* disable the safety ground of any piece of equipment for any purpose.

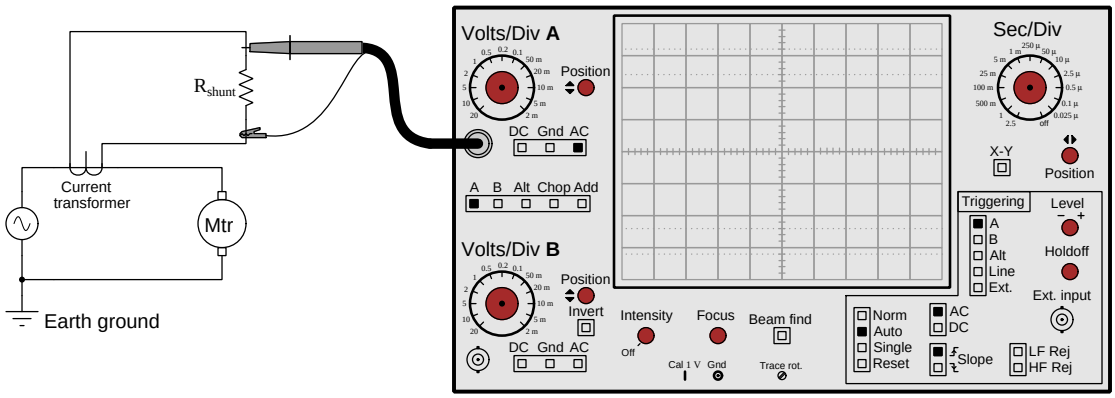
[22] It is important to note that oscilloscopes are designed to measure *voltage* and not *current*. Therefore, if we need to display a current waveform using an oscilloscope, it means we must find some way to faithfully translate the current signal into a voltage signal the oscilloscope will be able to sense.

Installing a signal transformer to isolate the oscilloscope's grounded input channel from the elevated potential of the "Hot" conductor is one solution to this dilemma:



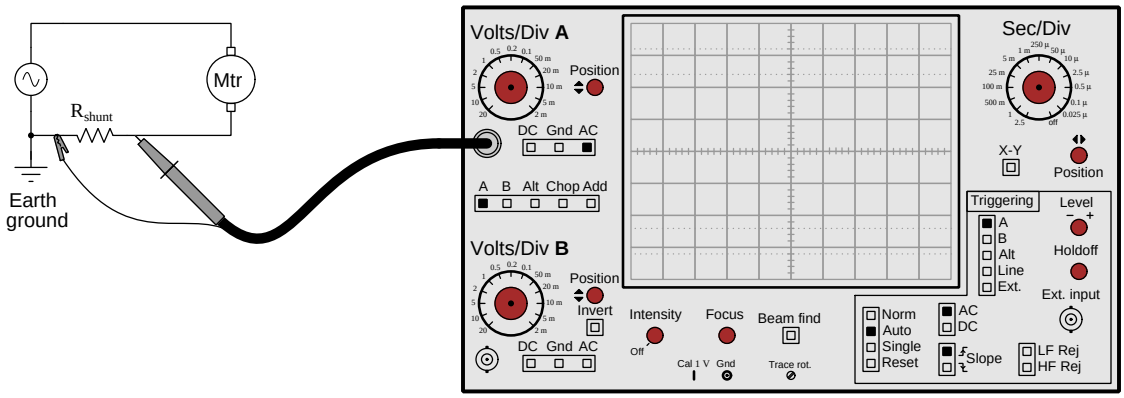
As always, the usual caveats of signal distortion and loading apply to this use of a signal transformer.

Another option well-suited to the measurement of AC current in a power circuit is a special form of transformer called a *current transformer*, most styles consisting of a single winding around a toroidal core, with the power conductor passed through the center of the toroid functioning as a single-turn primary winding. The current transformer steps line current down to a lower level, which may then be passed through a suitable shunt resistor so the oscilloscope may measure voltage across it:



Like the other transformer-based solutions, the current transformer provides isolation (i.e. no electrically-common connections) between the AC circuit and the oscilloscope input.

If appropriate signal/current transformers and isolated input channels are not available, one practical solution may be to re-locate the shunt resistor to the circuit's "Neutral" conductor to make it normally grounded and therefore at the same potential as the channel's reference clip:

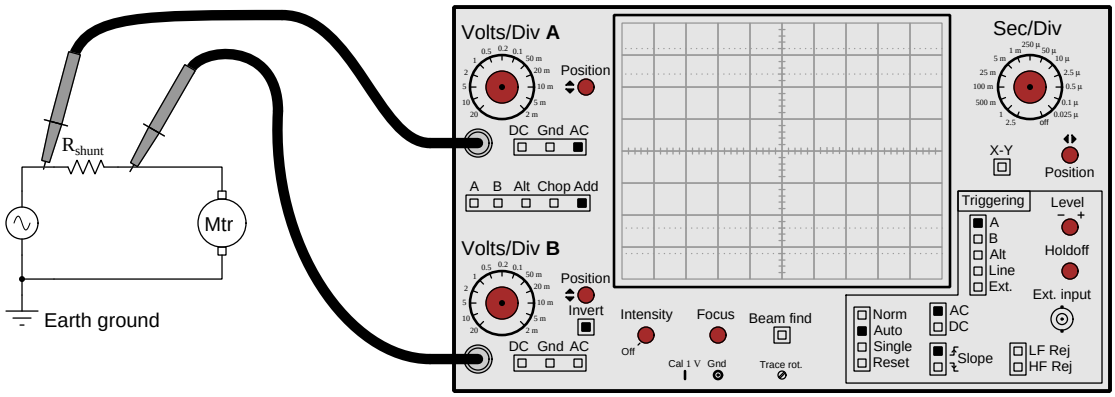


If none of these solutions is practical, there is one more than may be of use. This is called *differential* channel measurement, and is discussed in the next section.

4.10 Differential measurements

As we have seen, the commonality of all oscilloscope input channels' reference terminals, as well as their connection to Earth ground through the oscilloscope's power cord, can pose practical problems for taking specific measurements in circuit. Fortunately, most multi-trace oscilloscopes offer a feature enabling signal measurement without a ground connection at all: *differential measurement*.

The word "differential" refers to a difference, or a mathematical subtraction, between two quantities. In this case, the oscilloscope is set up to subtract one channel's signal value from another channel's signal value and display that result on its screen. In the case of the legacy oscilloscope shown in this illustration, this is done by selecting the "Add" channel option as well as latching the "Invert" button for channel B[23]. The combination of these two options results in the oscilloscope displaying A + (−B), which is the same as A − B. Meanwhile, the probe tips corresponding to these two channels are used as the two test leads for the oscilloscope:



Set up in this manner, the oscilloscope literally measures voltage between channel A's probe tip and Earth ground (via the power plug prong), measures voltage between channel B's probe tip and Earth ground, subtracts the two signals, and displays the result which is mathematically equivalent to the shunt resistor's voltage drop. Since neither probe's reference clip is connected to the circuit at any point, there cannot be any conflict. No signal transformers stand in the way of signal integrity, either.

A couple of caveats are worth mentioning when using differential mode. First, the freedom from probe cable grounding comes at a cost of reducing a dual-trace oscilloscope to a single-trace oscilloscope. If you absolutely need to display two waveforms on the same screen and only have a dual-trace oscilloscope, you cannot use differential mode[24]. Second, when using differential mode, you *must* have both of the channels' vertical sensitivity set precisely equal to one another in order

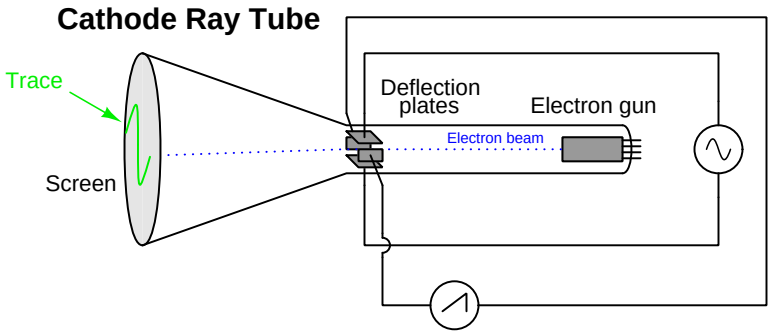
[23] Modern digital oscilloscopes typically offer a "Math" menu within which you will find this same differential mode as a selectable option.

[24] A couple of solutions exist to this problem as well. One is to synchronize two separate oscilloscopes together and use them to each display one of the waveforms. Some oscilloscopes offer a "sync output" connector which may be connected to the "external" trigger input of the next oscilloscope in order that the two instruments may synchronize their triggering and thereby show the two waveforms in the correct perspective to each other. Another solution is to simply purchase an oscilloscope with four or more channels, using pairs of channels as single differential channels!

that the subtraction truly yields the difference of potential between the two probe tips. If channel B, for example, is set to be twice as sensitive as channel A (e.g. 50 mV/div for B and 100 mV/div for A), the displayed result will be A − 2B rather than A − B as it should be.

4.11 X-Y mode

So far our exploration of oscilloscopes has been limited to their use in displaying *time-domain* graphs of voltage; i.e. graphical displays of voltage (vertical axis) over time (horizontal axis). This is a direct consequence of the oscilloscope's origins from oscillographs, where a strip of motor-driven paper provides the timebase and the voltage-driven pen is only free to move vertically. CROs achieve a timebase by sweeping the cathode-ray tube's electron beam from left to right using a sawtooth-shaped AC voltage applied to the horizontal deflection plates: the linear ramp of the "sawtooth" signal drives the dot from left to right across the screen at a set speed, while the much steeper half-cycle returns the dot back to the left-hand side where the sweep will once again resume when triggered.



The use of a sawtooth wave signal to sweep a cathode ray tube's electron beam linearly across the horizontal axis of the screen is merely a way to emulate an oscillograph's constant-speed paper feed rate. A CRO is certainly not limited to displaying time-domain graphs of voltage, though. One may also use a cathode ray tube to display a *parametric*[25] voltage plot, where two external signals drive the glowing dot of the cathode-ray tube, making the plot a function of one signal versus the other rather than one signal versus time. This is sometimes referred to as the X-Y mode of an oscilloscope, because one input voltage signal drives the vertical (x) axis while the other input voltage signal drives the horizontal (y) axis.

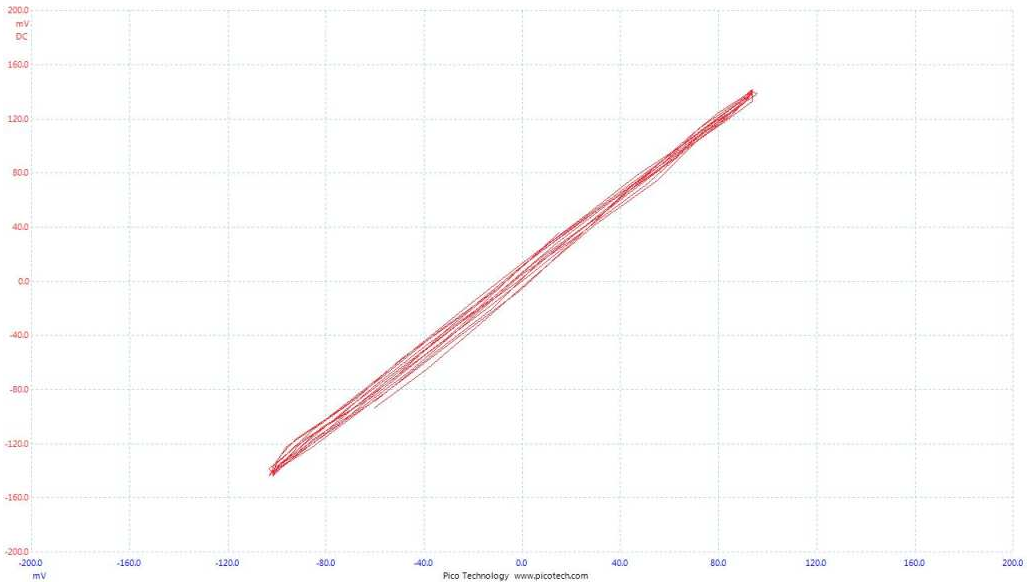
X-Y mode is useful for comparing features of two related signals, especially their frequency ratio or phase shift. It is also useful for displaying the degree of modulation for AM (Amplitude-Modulated) signals. With a very modest collection of external components connected to an oscilloscope, one may use X-Y mode to create a new type of test instrument called a *curve tracer*, useful for displaying the output/input transfer function for any two-terminal electronic component.

[25] In mathematics, a "parametric" plot is one where the x and y axes represent two different dependent variables related to one another by a common dependent variable.

4.11.1 Lissajous figures

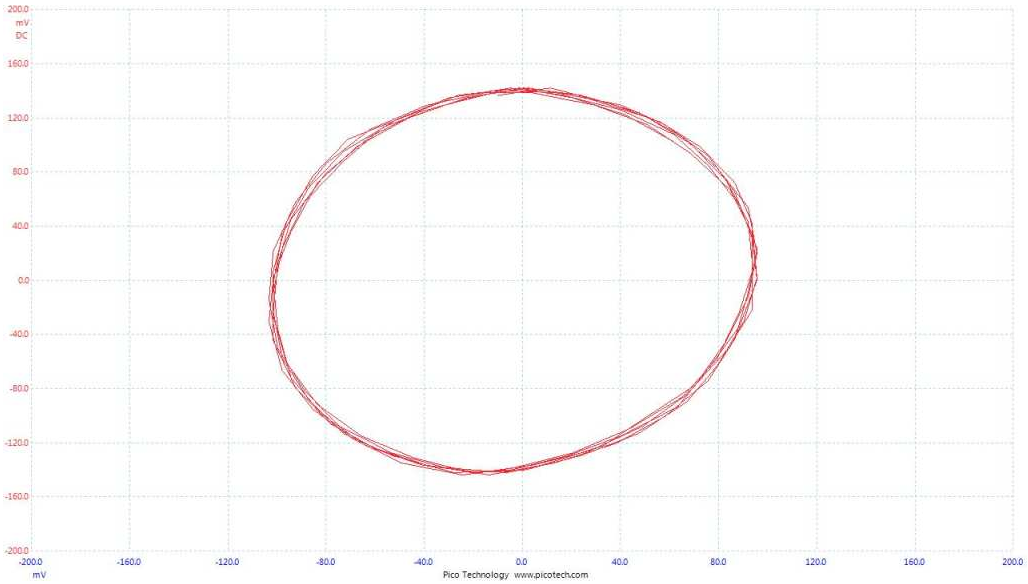
The most basic use of an oscilloscope's X-Y mode is to display *Lissajous* figures, named after Jules Antoine Lissajous, a 19th century French physicist. Lissajous invented an optical apparatus using a pair of *tuning forks* with small mirrors attached, a light beam showing the mechanical vibration of each tuning fork by its deflected angle. The two tuning forks were positioned such that the vibrations of one deflected the light beam horizontally and the vibrations of the other deflected the same light beam vertically, the light beam finally playing on a flat viewing surface. This optical oscillograph therefore plotted one sinusoidal vibration against another, creating complex shapes which came to be known as Lissajous figures. The appearance of these Lissajous figures depends on the frequencies of the two waveforms and also their relative phase shift.

When both the X and Y axes of an oscilloscope are driven by two identical waveforms (i.e. same frequency, same phase shift), the result is a slanted line. The presence of noise in either signal will cause this line to not perfectly re-trace itself as seen in this screenshot of a figure produced by two 60 Hz sine waves from different AC voltage sources, but if the two channels are paralleled to cause them to sense the *exact* same signal the line will be perfect:



The upper-right end-point of this trace represents the dot's position when both sine waves are at their positive peaks (i.e. fully up and fully right); the lower-left point represents the time when both sine waves are at their negative peaks (i.e. fully down and fully left). The middle of this trace represents the point when both signals are zero.

If the two waveforms are 90 degrees phase-shifted from each other, their combined effect will be to draw a *circle* on the oscilloscope's screen: when one wave reaches its peak value the other will be at zero, thus defining the boundaries of that circle[26] on the x and y axes:



Any amount of phase shift between 0 and 90 degrees will result in the plotting of an *ellipse* on the oscilloscope's screen.

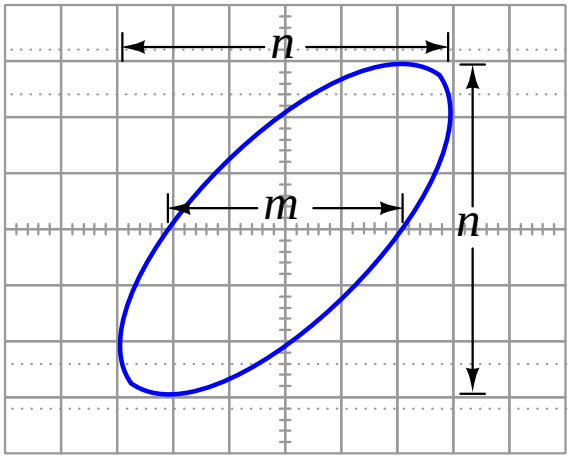
[26] Imagine the x wave at its positive peak while the y wave is at zero: this places the dot at the furthest-right point on the horizontal axis while vertically centered. Now imagine the x wave at zero while the y wave reaches its positive peak: this places the dot fully up, while centered horizontally. Now imagine the x wave at its negative peak while the y wave returns to zero: this places the dot at the far left on the horizontal axis while vertically centered again. Finally, imagine the x wave at zero while the y wave is at its negative peak: now the dot is fully negative on the y axis but centered horizontally. Each of these four conditions together define the right, upper, left, and lower boundaries of the circle, respectively. If this progression continues, the dot will trace a circle in the counter-clockwise direction.

A stable Lissajous figure showing 1:1 frequency ratio is an excellent means of indicating when two AC signals from different sources have the exact same frequency. An example of such a test is shown in the photograph below, where the sinusoidal AC voltage output by a legacy Hewlett-Packard model 200CD oscillator (far right) is compared against the sinusoidal AC voltage output by a Fluke model 5520A multifunction calibrator (far left), the oscilloscope in the center of the photo proving the equality of those two signals' frequencies by a stable circular Lissajous pattern:

It is worth reflecting on the fact that the oscilloscope need not be a precision-calibrated instrument to perform this precise comparison of frequencies. The accuracy of the frequency test is entirely a function of how accurate one of the two frequencies is known. In the case of this test, where the "standard" signal comes from the Fluke 5520A metrology-grade signal source, we have extremely high confidence of the HP 200CD oscillator's output frequency once the oscilloscope shows a frequency match by a stable circular (or linear, or oval) Lissajous figure.

Since phase shift affects the shape of the Lissajous figure formed by two sinusoidal waveforms, we may also use X-Y mode on an oscilloscope to measure *phase shift* between the two signals. Determining the phase shift between the two sinusoidal signals based on the shape of this ellipse is rather simple. First, the vertical and horizontal sensitivity adjustments must be set such that the height and width of the ellipse are equal[27]. Feel free to make fine adjustments to the "Cal" knob on the oscilloscope in order to achieve this equality of width and height[28]. De-calibrating the channels is permissible because we are not trying to accurately measure either signal's amplitude but rather the phase shift between the two signals.

Next, make fine adjustments to the vertical and horizontal position in order to precisely center this ellipse on the oscilloscope screen. Finally, carefully measure the width of the horizontal chord (m) versus either the total width or total height of the ellipse (n):



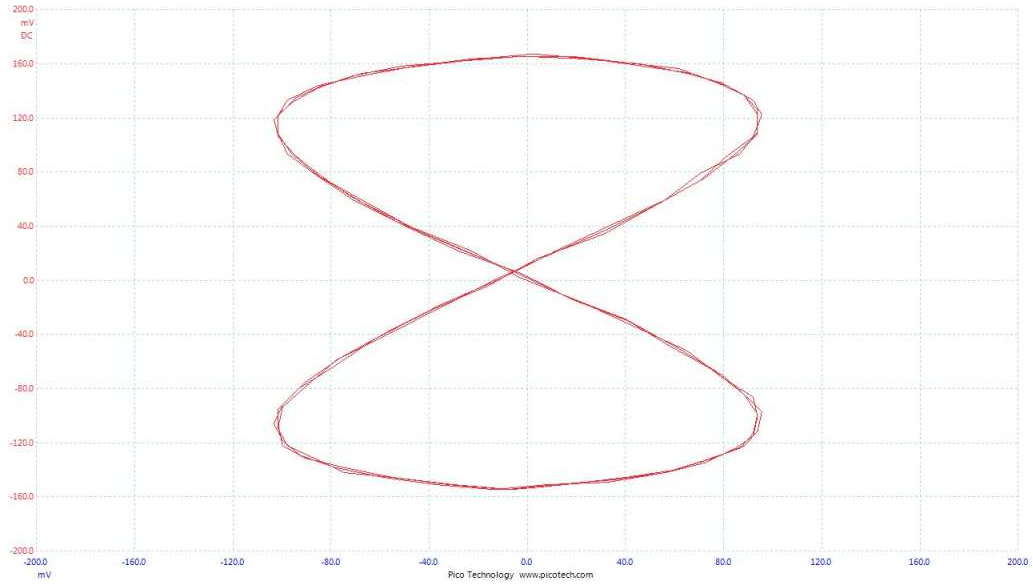
This ratio $\frac{m}{n}$ represents the trigonometric *sine* of the phase angle between the two signals, and therefore the phase angle will be equal to the *arcsine* ($\sin^{-1}$) of this ratio. A diagonal line means m will be equal to zero and $\sin^{-1}(0)$ will be equal to zero degrees of phase shift. A perfect circle means $m = n$ and $\sin^{-1}(1)$ will be equal to 90 degrees of phase shift.

Watching an oscilloscope trace an X-Y plot when viewing two sine waves of slightly differing frequency is highly instructional. As the two signals roll in and out of phase with each other, the Lissajous figure transforms from a straight line (in-phase) to an ellipse (out of phase) to a circle (perfectly 90 degrees out of phase) to another ellipse canted oppositely to the first, and then to a straight line with an opposite slope (perfectly 180 degrees out of phase). Adjusting the frequency of one signal source makes the Lissajous figure progress through this evolution at a different rate. If the two signals' frequencies are precisely equal to each other, the Lissajous figure will maintain a constant shape.

[27] A good way to visualize this is to imagine the ellipse inscribed inside of a perfect *square*.

[28] This is most easily done by switching the oscilloscope out of X-Y mode and back to time-domain mode where the two signals appear as sinusoidal waveforms again. Adjust the "Cal" knob on one or both channels to make the two waveforms have precisely the same height, and ideally matching major division lines on the screen for easy reference. After switching back to X-Y mode the amplitudes of each wave should remain the same, resulting in a Lissajous figure with perfectly balanced height and width.

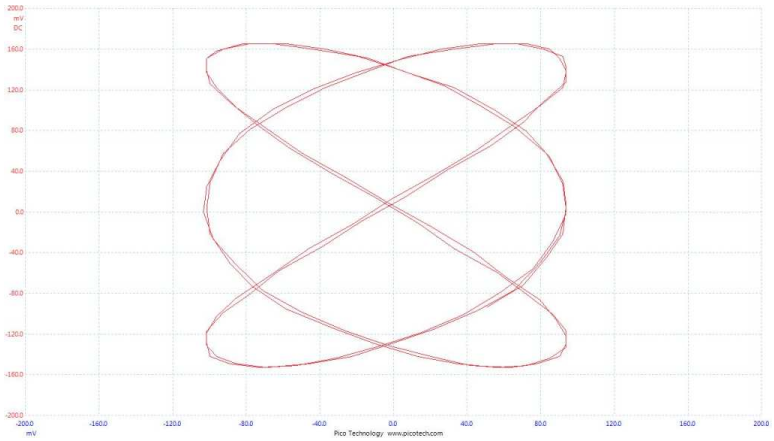
Lissajous figures become even more complex when the two signals are integer ratios of each other. Take for example the following screenshot produced by a 60 Hz sine wave on the horizontal axis and a 30 Hz sine wave on the vertical axis:



What appears to be a "figure eight" plotted on the screen is the result of the dot being cycled horizontally across the screen twice for every one vertical cycle. In fact, it is not difficult to see the sinusoidal shape of the higher-frequency (60 Hz) waveform if you look at this Lissajous figure starting at its top and following down to its bottom along a straight vertical line: you will notice the figure's outline looks similar to a sine wave from the perspective of this vertical axis; then, tracing that same line back up to the top, we see a mirror-image of that same sine wave tracing the other half of the Lissajous figure. This is the shape you get with a 2:1 frequency ratio, and where the higher-frequency wave crosses through zero Volts at the moment the slower-frequency wave reaches its peak value(s).

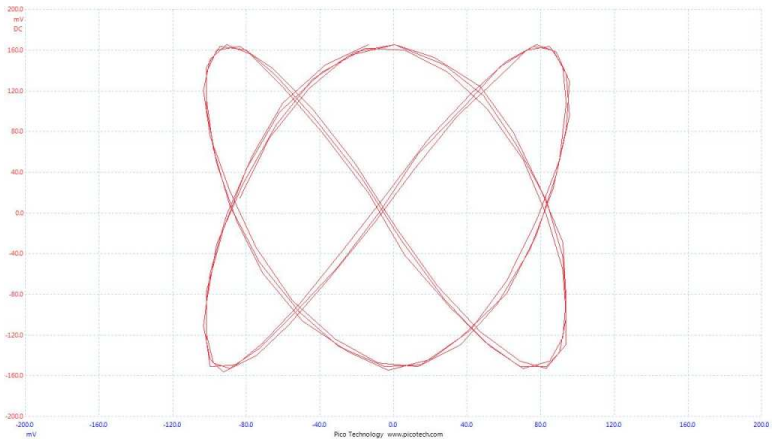
In fact, it is possible to determine the frequency ratio of any two signals creating a Lissajous figure simply by counting the number of "peaks" on each edge of the figure. If you imagine a rectangle just large enough to enclose the Lissajous figure, and then count how many times the curve contacts the boundaries of that tightly-fitted rectangle, you will arrive at the two integers comprising the ratio. In the previous example it should be apparent that the curve contacts the invisible rectangle twice along each vertical edge and only once along each horizontal edge. This tells us the AC signal driving the horizontal axis is oscillating at a frequency of 2 for every 1 cycle of the vertical-axis signal. Of course, these numbers only reflect the *ratio* of frequencies and not the frequencies themselves. For all we know, the two signals creating the previous Lissajous figure could be at 2 kHz and 1 kHz rather than 60 Hz and 30 Hz. Literally *any* 2:1 ratio could be the cause of a "figure eight" Lissajous pattern.

Other examples of Lissajous figures and their ratios are shown here:



With this example we see three peaks along one edge of the figure versus two peaks along a perpendicular edge, revealing a 3:2 frequency ratio. Indeed, this Lissajous figure was created by a 60 Hz sine wave driving the horizontal axis and a 40 Hz sine wave driving the vertical axis.

Here is another example, this time using a 60 Hz sine wave driving the horizontal axis and 90 Hz driving the vertical axis. This is a 2:3 ratio, which "flips" the Lissajous figure 90 degrees compared to the previous example:

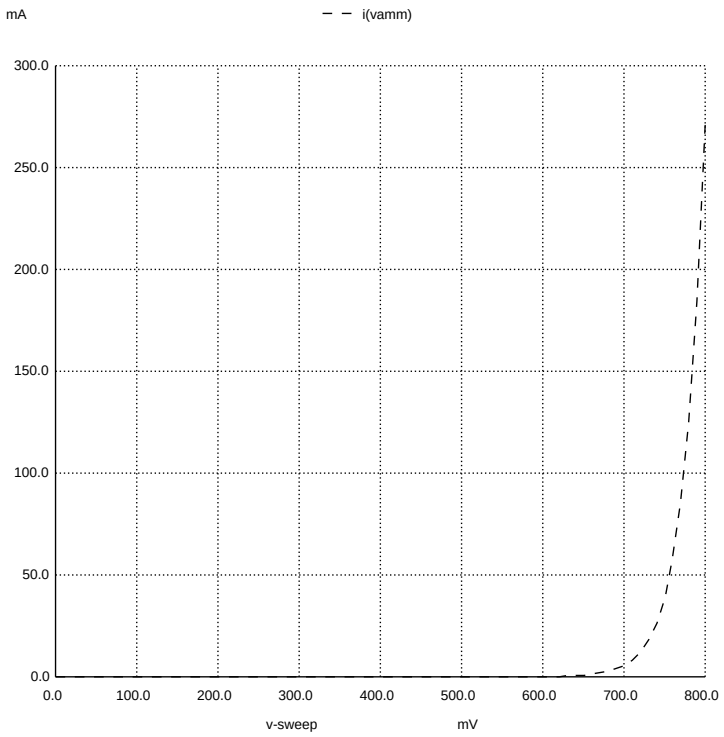


Once again, it is highly instructional to view Lissajous figures plotted by an oscilloscope for two sine-wave signals whose frequencies are not *exactly* fixed to an integer ratio. As the two signals roll in and out of phase with each other, the Lissajous figure will appear to rotate in three dimensions. This effect is not only useful for understanding phase relationships between signals, but also rather mesmerizing to behold.

4.11.2 Curve tracing

Another useful application of X-Y mode on an oscilloscope is *curve tracing*, where the oscilloscope plots a curve on its screen representing the I/V (current over voltage) characteristic curve for a component.

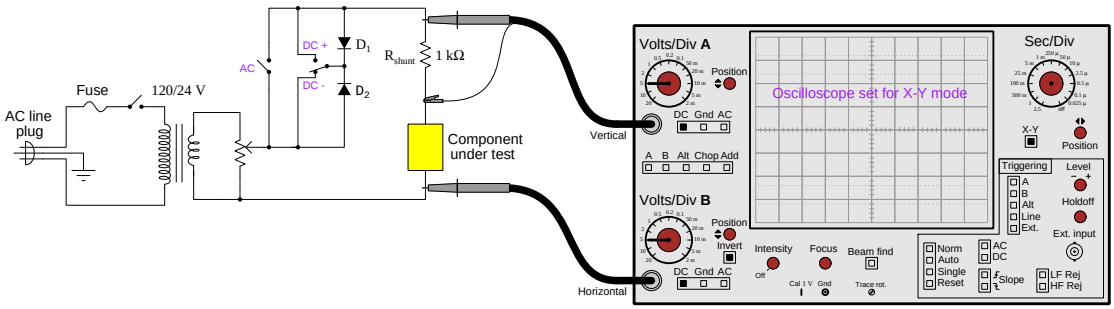
Curve tracing is especially useful for studying the non-linear characteristics of *semiconductor* components. One very common semiconductor component is the *rectifying diode*, used as a sort of one-way valve for electricity. Diodes exhibit an exponential current/voltage curve, as shown in the following graph where the horizontal axis represents applied voltage from 0 to 800 milliVolts and the vertical axis represents diode current from 0 to 300 milliAmperes:



Plotting the current/voltage curve for a component is useful as a learning tool to see how the component responds to changes in applied voltage, as well as a diagnostic tool for assessing the health of a component. If a curve-tracing test yields an unusual plot for a component, it may be a sign that the component in question is faulty. Curve-tracing is also useful for empirically obtaining certain characteristic parameters that may be necessary for circuit design.

A simple curve tracer circuit is shown here, with the component under test represented by a yellow rectangle. A step-down transformer converts AC line voltage from 120 VAC (standard in North America) down to 24 VAC; a potentiometer provides infinitely adjustable levels of voltage between 0 Volts and 24 Volts for testing; a 1000 Ohm "shunt" resistor generates a voltage drop proportional to component current for the oscilloscope's vertical channel to measure; lastly, the oscilloscope's horizontal channel is simply the voltage dropped by the component under test:

Simple curve tracer circuit



It is important that the horizontal channel be *inverted*, since the oscilloscope's reference connection is made between the shunt resistor and the tested component and therefore the measured voltage polarities will be opposite each other so long as both components are behaving as loads. Inverting the horizontal channel allows a standard curve-trace plot to form, where the dot sweeps to the right with increasing component voltage while the dot sweeps upward with increasing component current.

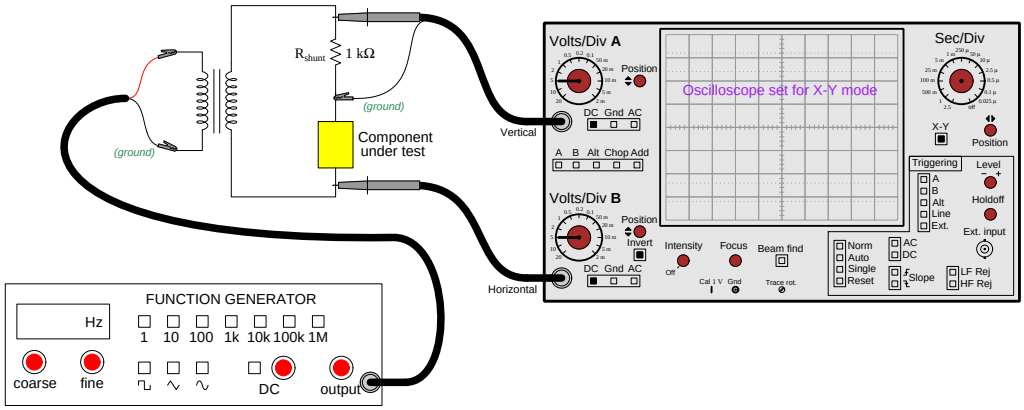
An optional feature of this curve tracer circuit is a pair of diodes and a pair of switches used to control the polarity of voltage applied to the component under test. The SPDT switch controls polarity of DC, while closing the SPST switch applies AC to the tested component.

A more permanent variation of this curve tracer circuit may be built by providing BNC connectors for each of the oscilloscope's channels to connect across the shunt resistor and tested component using plain BNC-to-BNC cables, rather than using standard oscilloscope testing probes. The only spring-clip-style connectors necessary will be a pair of leads used to connect the component under test to the rest of the circuit.

If you have access to a *signal generator* with an ungrounded output[29], this may be used in lieu of the transformer/diode/switch circuit to produce the necessary excitation voltage, which means the curve-tracing circuit may become as simple as a shunt resistor connected in series with the component under test: each channel of the X-Y oscilloscope reading voltage across one of these two components (with the reference lead connected in between) while the signal generator powers the series resistor-component network.

To use a grounded-output signal generator, you must couple it to the tested component and shunt resistor through an isolation transformer:

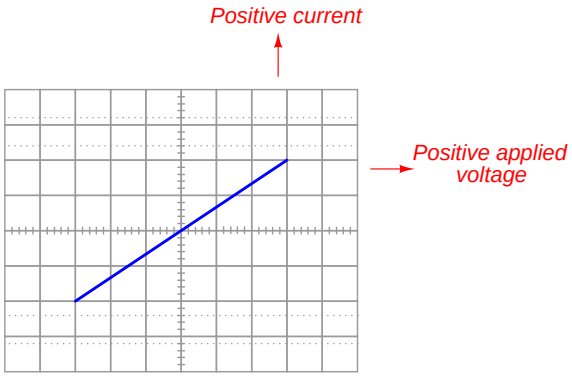
Simple curve tracer circuit using grounded-output signal generator



This isolation transformer allows the signal generator's ground (its black-colored lead) to be electrically distinct from the oscilloscope's ground. A suitable transformer for this application may be formed by using the two primary windings on an industrial control-power transformer (typically rated for 120 Volts AC each), powering one by the signal generator and using the other to deliver power to the shunt resistor and tested device.

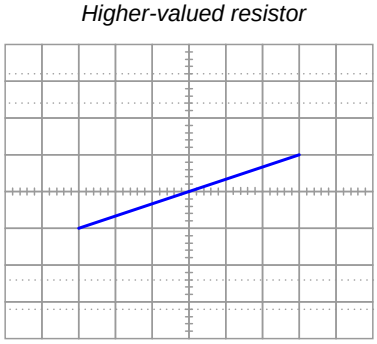
[29] The generator's output *must* be ungrounded, or else either the shunt resistor or the component under test will be shorted past by the grounded reference lead of the oscilloscope! This is why the transformer-based curve tracer circuit is shown as a model: the transformer naturally provides isolation from ground, so that the oscilloscope is free to set the mid-point between the shunt resistor and the component under test as ground.

For example, a simple resistor would generate this[30] oscilloscope display:



It is helpful to keep in mind the meaning of each axis on the oscilloscope's display: vertical being current through the component under test and horizontal being applied voltage across the component under test. Just like a Cartesian coordinate graph, the centerlines intersect at the origin (0,0) of zero current and zero voltage. Areas of the plot to the right of center represent positive applied voltage while areas to the left of center represent negative applied voltage. Areas above center represent positive current while areas below center represent negative current. As the resistor's "curve" shows, current is directly proportional to applied voltage.

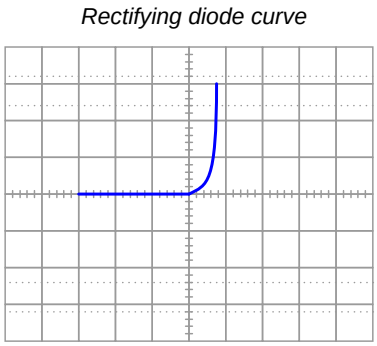
A resistor of greater value (more Ohms of resistance) would generate a characteristic plot with a shallower slope, representing less current for the same amount of applied voltage:



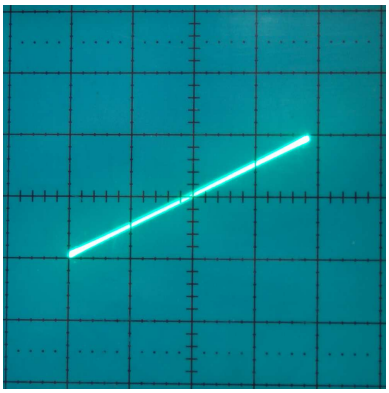
In fact, the *slope* of the linear line segment is a graphical indication of *conductance* (G), which is the reciprocal of resistance, or $\frac{I}{V}$. If you were so inclined, you could swap the X and Y channels of the oscilloscope so that voltage was vertical and current horizontal, and then the slope of the plotted line segment would reflect resistance ($\frac{V}{I}$). However, by convention curve tracers show voltage on the horizontal and current on the vertical.

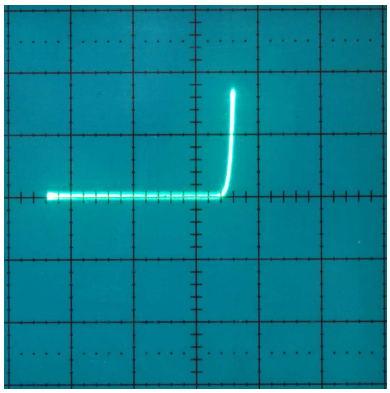
[30] Without inverting the oscilloscope's horizontal channel, the line traced by the screen while testing a resistor will have a negative slope rather than a positive slope as shown here.

A standard rectifying diode produces this characteristic curve, revealing an exponentially-increasing forward current as forward voltage increases (i.e. to the right of the vertical centerline). To the left of the vertical centerline is where the applied voltage is "reverse" and the diode conducts negligible current:



Photographs taken of an oscilloscope functioning as a curve tracer for a 2 kΩ resistor (left) and a 1N4001 rectifying diode (right) show a perfectly linear response for the resistor and the characteristic "hockey-stick" response for the diode. The circuit used for these tests was identical to the one shown previously[31], where a grounded signal generator powers the R_{shunt} / component network through a 1:1 isolation transformer. Vertical and horizontal sensitivities were both 1 Volt per division:





The rectifying diode's "forward" (turn-on) voltage of approximately 0.5 Volts is immediately evident in its curve, as is its blocking characteristic (zero current) when the applied voltage reverses polarity.

[31] Unfortunately, this particular model of oscilloscope – a Tektronix 2213A – only allowed the vertical channel to be "inverted" rather than the horizontal which is what I needed to plot the characteristic curve in the correct orientation (with increasing forward voltage to the right and reverse voltage to the left). To flip the image, I used photo-editing software to manipulate the photograph taken with my digital camera.

Three-terminal devices such as transistors are also testable by a curve tracer, but provisions must be made to "excite" or "stimulate" the third terminal of the device while the curve tracer plots the current/voltage characteristic between the remaining two terminals. On commercial curve-tracing equipment this is a typical feature, often with advanced capabilities such as "stepping" that third terminal's stimulus with every sweep of the trace: this in fact is how characteristic curve *families* are plotted for transistors.

4.12 CRO setup

Cathode-ray oscilloscopes (CROs), being analog devices, require periodic adjustments to correctly display signals on their screens. These adjustments should always be checked when first setting up an oscilloscope for use, and may require additional adjustment during use. Some of the display settings common to most CROs include:

- Focus
- Intensity
- Trace rotation
- Vertical and horizontal position
- Beam find

We will explore each of these settings in order.

Focus sharpens the image created by the electron beam as it "paints" a dot on the oscilloscope screen. Adjustment of focus is rather self-explanatory: simply get any kind of image appearing on the screen, then turn the focus knob until that image appears as "sharp" as possible.

Intensity is also rather self-explanatory: this adjusts the brightness of the image created by the electron beam as it strikes the inner surface of the screen. As a rule, the intensity should be maintained at the lowest practical value which is still readily visible to the user. Excessive electron beam intensity over long periods of time with a constant image can lead to a permanent version of that image being "burned" into the oscilloscope's screen.

Trace Rotation is used to ensure the image's centerline aligns with the horizontal axis of the screen's viewing area. The best way to set this adjustment is to first establish a zero-signal trace by setting the channel's coupling to "Ground" and the triggering to "Auto" to produce a flat-line image. Any deviation of this line from the horizontal axis printed on the screen may then be corrected by turning the trace rotation adjustment. In many cases trace rotation is provided as a screwdriver-driven potentiometer through a hole in the oscilloscope's front panel rather than a regular knob on the front panel. You will find that trace rotation generally does not require adjustment as often as some of the other settings, but should be checked as a matter of habit every time you set up an oscilloscope.

Vertical and Horizontal position controls are also self-explanatory for the most part. Each one sets the default position of the trace on the oscilloscope's screen. Vertical position controls are especially useful for multi-trace oscilloscopes, where it may be advantageous to offset the different waveforms apart from each other in order to clearly view each one. Temporarily setting the coupling control of each trace to "Ground" will plot a straight horizontal line, allowing precise adjustment of each trace to a different division on the grid of the oscilloscope screen so that each trace will have its own "zero" baseline.

Beam Find is a very helpful mode provided by some CROs, intended to help the user locate where the trace is when it appears to be been driven off of the screen by some mis-adjustment

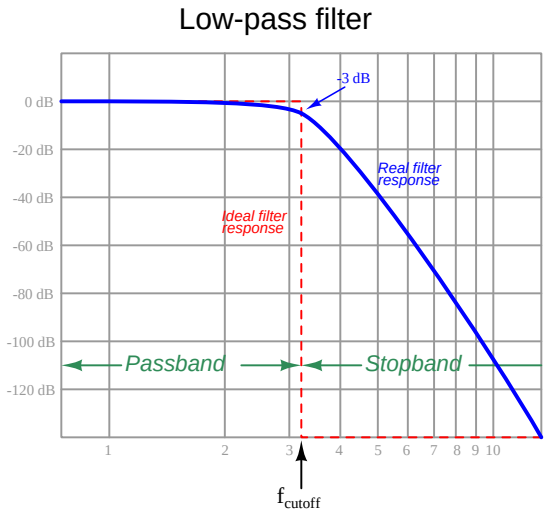
of settings. Pressing the "Beam Find" button causes the cathode ray tube to output a constant (untriggered) electron beam of intense amplitude (so as to be clearly visible), with vertical and horizontal offsets attenuated, as well as vertical and horizontal amplification attenuated in order to shrink the size of the trace and place it in a more centered position on the screen. For example, if the trace were invisible because someone had improperly set the vertical position too high (driving the trace up past the top of the screen), pressing "Beam Find" would show a shrunken version of that trace slightly *above* the screen's center. The above-center location would indicate to the user that the trace is offset in the upward direction. If pressing "Beam Find" displays the shrunken trace centered perfectly on the screen, something else is responsible for its invisibility: perhaps the intensity adjustment is set too low, or there is a problem with triggering.

Users of digital oscilloscopes need not worry about many of the setup concerns facing CRO users. Focus, intensity, and trace rotation are simply not concerns at all with a computer-based digital oscilloscope because the trace image is digitally printed to the screen rather than being the result of an electron beam deflected by analog circuitry.

Some of the other settings, such as vertical and horizontal position, are still present but may be automatically set by engaging the "Auto Set" mode provided by nearly all digital oscilloscopes. "Auto Set" might be thought of as an evolutionary step beyond "Beam Find", not just revealing what is set improperly but also making its own corrections. In addition to correcting vertical and horizontal position problems, "Auto Set" also chooses vertical sensitivity and timebase values as well suited to the signal being captured! Of course, the algorithm used by the digital oscilloscope does not understand the user's intent, and for this reason may not capture the waveform in quite the way the user might wish, but at least "Auto Set" provides a good place to start, with minor adjustments made later by the user to show the waveform as desired.

4.13 Bandwidth

Oscilloscopes, like all measuring instruments, have their limitations, among them being the maximum *frequency* at which it may display an AC signal. All oscilloscopes, analog and digital alike, exhibit a "low-pass" filtered response to signals at their input ports, meaning that AC signals at very high frequency will not be displayed at their true and full magnitude as will low-frequency AC signals. For example, if we were to measure the AC signal output by a perfect AC voltage source (i.e. outputting an AC voltage of constant RMS value regardless of frequency) and gradually increase that frequency of the signal source, the oscilloscope would at some point begin to display a signal of diminishing magnitude even though the true signal's magnitude remained unchanged. Those readers familiar with the concept of *filtering* will recognize this response when plotted on a frequency-domain graph:



The range of frequencies accurately measurable by any oscilloscope is called the *bandwidth* of that instrument. For example, a 100 MHz bandwidth oscilloscope should be able to accurately represent signals anywhere from 0 Hz (DC) to 100 MHz sinusoidal waves, 100 MHz in this case representing the *cutoff frequency* shown in the above plot. This phenomenon is analogous to the high-frequency limitations of human hearing: beyond a certain frequency, sound waves become inaudible to human beings. This high-frequency limit tends to decrease with age, so that younger people on average have higher audio "bandwidth" than older people.

Not only are oscilloscopes limited in their bandwidth capability, but so are the probes used to connect an oscilloscope to a circuit under test. Both parasitic capacitance and dielectric energy dissipation within the probe cable contribute to this "low-pass" filtering behavior, and so oscilloscope probes also come with their own bandwidth ratings. Although it is not strictly necessary to match the bandwidth of a probe to the bandwidth of the oscilloscope it's plugged in to, beware that the effective bandwidth of the entire apparatus is limited by the lowest of these component bandwidths. For example, a probe rated at 20 MHz plugged into an oscilloscope rated at 100 MHz bandwidth forms an apparatus limited to 20 MHz and below; similarly, a 100 MHz probe plugged into a 20

MHz oscilloscope also forms an apparatus limited to 20 MHz and below.

Furthermore, it is important to understand how bandwidth rating relates to non-sinusoidal signals. According to Fourier's Theorem, any non-sinusoidal signal is mathematically equivalent to a series of superimposed sinusoidal signals at different frequencies. A 10 MHz square wave, for example, is equivalent to the sum of a 10 MHz sine wave (its first harmonic, or fundamental frequency) plus a 30 MHz sine wave (third harmonic) at $\frac{1}{3}$ the magnitude of the fundamental plus a 50 MHz sine wave (fifth harmonic) at $\frac{1}{5}$ the magnitude of the fundamental, and so on. If this 10 MHz square wave were viewed on an oscilloscope/probe assembly having a bandwidth of 20 MHz, those higher-order harmonics would be disproportionately attenuated by the low-pass filtering effect which would render a distorted image of the true square wave. Thus, whenever measuring non-sinusoidal signals, one must be sure to use an oscilloscope/cable combination with a bandwidth that is significantly greater[32] than the signal's fundamental frequency.

Closely related to signal frequency limitation is an oscilloscope/probe assembly's ability to accurately display fast *rise* and *fall* times of pulse signals. Since fast-rising and fast-falling signal edges correspond to equivalent high-frequency harmonics (also by Fourier's Theorem), an oscilloscope and/or probe with insufficient bandwidth will also fail to represent the true rate-of-rise/fall for pulse signals, but will instead show a rise or fall rate appearing more gradual than the actual rate-of-change for the pulse signal due to the instrument's attenuation of high-order harmonic frequencies present in the real signal. A recommendation from Tektronix for relating instrument bandwidth to rise/fall-time measurement is shown here:

$$t_{rise/fall} \approx \frac{0.35}{f_{max}}$$

Where,

$t_{rise/fall}$ = Minimum rise or fall time of a signal's edge, in seconds
f_{max} = Bandwidth frequency rating of oscilloscope/probe assembly, in Hertz

For example, an oscilloscope and probe assembly with a bandwidth of 100 MHz should not be expected to accurately represent any pulse edge rising or falling from one voltage level to another in less than 3.5 nanoseconds. Also, if we need to accurately display pulse-edge rise times as rapid as 2 nanoseconds, we must use an oscilloscope/probe assembly with a bandwidth of at least 175 MHz.

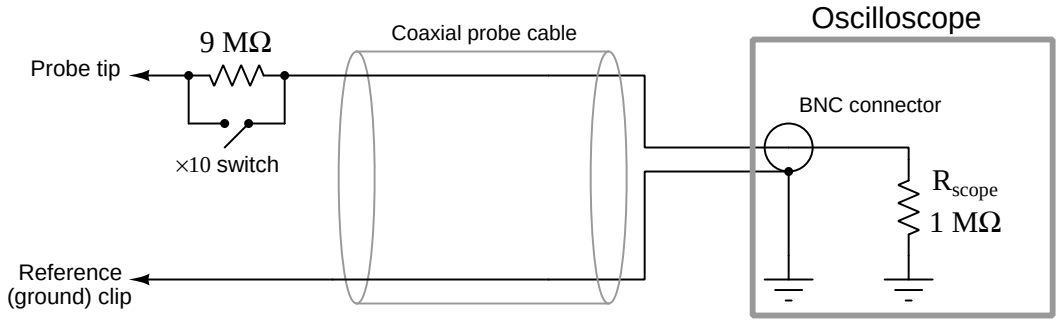
[32] A common recommendation is *5 times greater*; e.g. use an instrument with a bandwidth of at least 50 MHz to measure a 10 MHz square wave with reasonable accuracy.

4.14 x10 probe compensation

As mentioned in a previous section, an oscilloscope probe and cable is a carefully engineered electrical network, not just a set of metal tips attached to the end of a plain coaxial cable. This is especially true of "high-bandwidth" probe assemblies intended to intercept signals of exceptionally high frequency and/or short pulse duration.

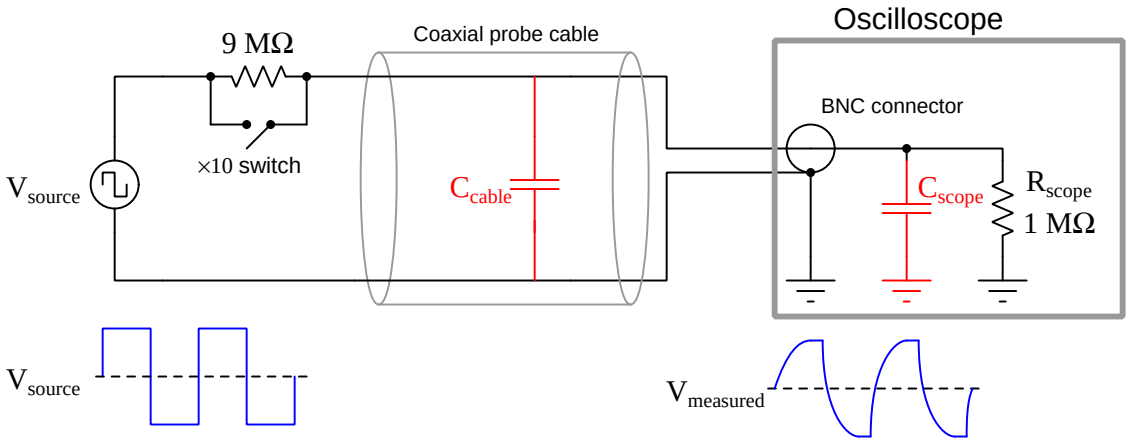
One common feature of general-purpose oscilloscope probes is a ×10 "multiplying" function, consisting of an extra resistance added in series with the probe measurement tip which functions as part of a voltage divider network with the oscilloscope's input impedance (typically 1 MΩ). When engaged, the ×10 feature makes the oscilloscope sense a voltage that is one-tenth the actual signal magnitude. This is useful for extending the voltage-measurement range of the oscilloscope, as well as to reduce resistive loading effects on the circuit being tested.

The voltage-division strategy of a ×10 probe is clear to see in the following diagram, where the oscilloscope input is modeled as a single 1 MΩ resistance. In combination with the 9 MΩ series resistor, the oscilloscope's intrinsic 1 MΩ input resistance forms a 10:1 voltage divider, forcing the oscilloscope to sense just one-tenth the voltage impressed between the probe tip and the reference (ground) clip:

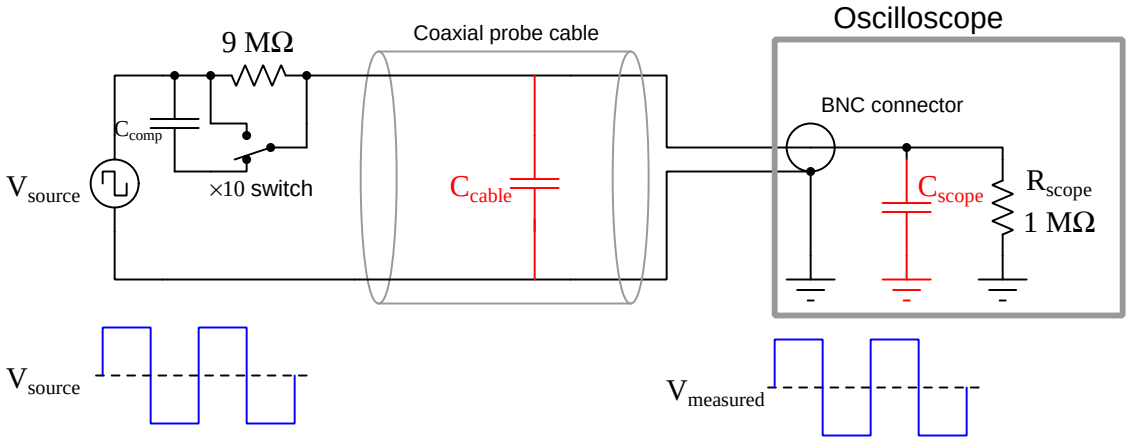


For example, if the probe leads were connected across a 20 Volt source, the oscilloscope would display 2 Volts. The user would either have to mentally multiply any voltage measurements on the oscilloscope display by ten in order to read true voltage, or the oscilloscope would have to be equipped with a ×10 mode to perform this multiplication automatically in conjunction with the 10:1 voltage division ratio of the probe.

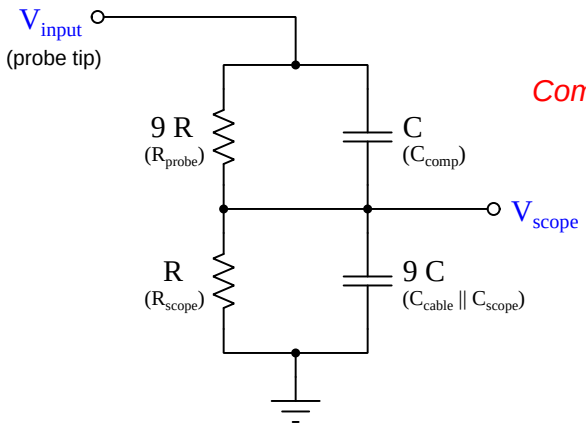
However, an unintended problem arises when we insert this extra resistance into the signal-measurement path, because both the probe cable and the oscilloscope input itself contains parasitic capacitance. If we connect our hypothetical circuit to a square-wave signal source, we will see distortion at the oscilloscope due to the RC time-delay effect of the 9 MΩ "multiplying" resistor and the cable capacitance:



A clever method of compensating for this effect is to connect a proportionately small amount of capacitance in parallel with the 9 MΩ "multiplying" resistor, essentially counter-acting the RC time delay with an inverse RC time delay:

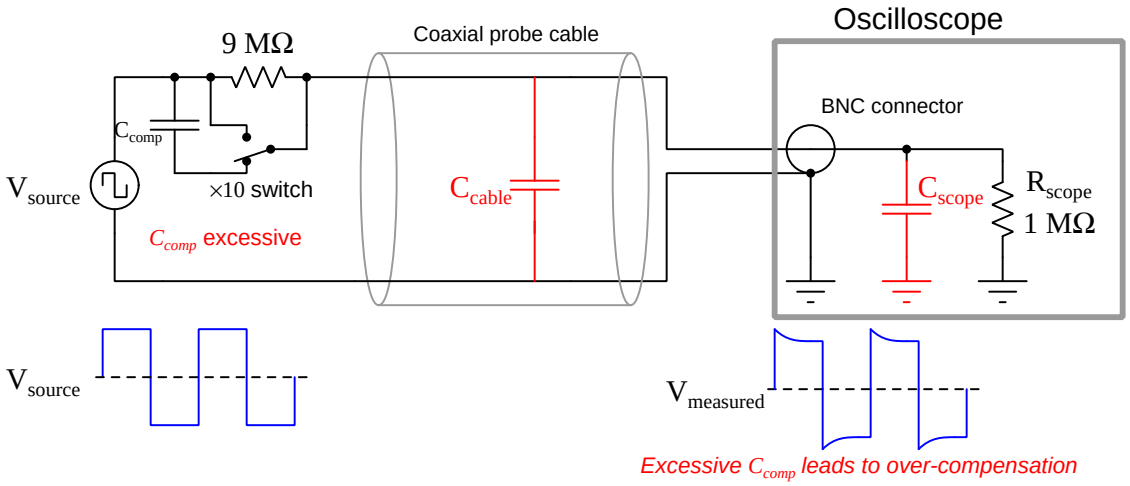


If we re-draw this compensated probe circuit to show the resistor pair and the capacitor pair both working as 10:1 voltage dividers, it becomes clearer to see how the two divider circuits work in parallel with each other to provide the same 10:1 division ratio *only* if the component ratios are properly proportioned:



The series resistor pair forms an obvious 10:1 division ratio, with the smaller of the two resistors being in parallel with the oscilloscope input. The upper resistor, being 9 times larger in resistance value, drops 90% of the voltage applied to the probe tip. The series capacitor pair forms a less obvious 10:1 division ratio, with the cable capacitance being the larger of the two. Recall that the *reactance* of a capacitor to an AC voltage signal is inversely related to capacitance: a larger capacitor will have fewer Ohms of reactance for any given frequency according to the formula $X_C = \frac{1}{2\pi f C}$. Thus, the capacitive voltage divider network has the same 10:1 division ratio as the resistive voltage divider network, even though the capacitance ratios may look "backward" at first glance.

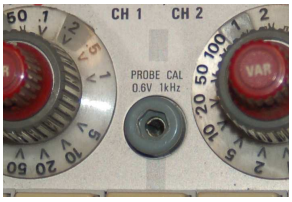
If the compensation capacitor is adjusted to an excessive value, the probe will *overcompensate* for lag (too much lead), resulting in a "spiked" waveform on the oscilloscope display with a perfect square-wave input:

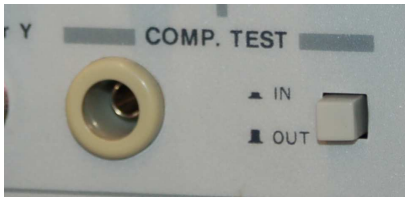


Compensation capacitance inside of a ×10 probe is always *variable*, in order to allow the user adjustment of C_{comp} to avoid under- and over-compensation when connecting to different oscilloscopes which may not all have the same input capacitance rating[33]. A good test for proper probe compensation is to connect the probe to a trusted square-wave signal source and adjust the probe's variable capacitor until a perfect square-wave image appears on the oscilloscope display. A photograph of a ×10 oscilloscope probe showing the range selector switch and the variable capacitance adjustment screw (just below the API brand label) appears in the following photograph:

[33]Interestingly, input resistance is rather well-standardized for oscilloscopes. General-purpose oscilloscopes exhibit a standard resistance of 1 megaOhm (1 MΩ), while some oscilloscopes designed for radio-frequency (RF) measurement applications provide a 50 Ohm input resistance option as well. ×10 probes intended for connection to 50 Ohm oscilloscope inputs are, of course, designed with 450 Ohm internal divider resistors rather than 9 megaOhm divider resistors to achieve the intended 10:1 voltage division ratio.

Adjusting the variable capacitor on a compensated oscilloscope probe is such a commonplace procedure that many oscilloscopes even have a built-in square wave signal generator and test point provided on the face of the instrument just for this purpose:



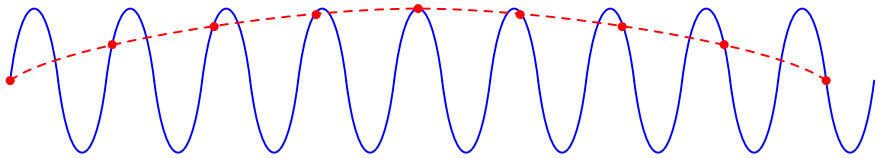


This built-in signal source serves multiple purposes. First, it provides a square-shaped waveform useful for compensation capacitor adjustment. Second, its peak amplitude is precisely regulated in order to serve as a calibration standard for the oscilloscope's vertical sensitivity adjustment. Third, its frequency is also precisely regulated in order to serve as a calibration standard for the oscilloscope's horizontal (timebase) adjustment.

4.15 Digital sampling rate and aliasing

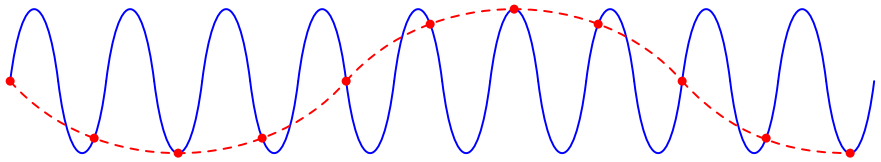
A unique challenge presented by digital oscilloscopes is something called *aliasing* which occurs if the oscilloscope's sampling rate is set too slow for the signal being measured. The fundamental problem is that digital measurement circuits cannot *continuously* sense the input signal, but must take "samples" at discrete points in time. Therefore, a digital measuring instrument such as a digital oscilloscope can never sense the signal in its fullness but must make do with an approximation of that signal comprised of many samples.

If a digital instrument samples a signal at a rate that is slower than the signal's period, the result will be the appearance of a signal at a *much* lower frequency than the signal actually being measured. The following illustration shows this phenomenon, where a set of red dots reveal the points in time where samples are taken:



This false signal, or *alias*, shown by the dashed curve is completely inaccurate but at the same time it may look completely plausible to the oscilloscope user. For this reason, aliasing may not be obvious to detect.

Aliasing may occur even if a digital instrument samples at a rate faster than the signal's period. Note the effect of sampling a sinusoidal signal at a rate slightly faster than the signal's period:



The dashed curve shows the false signal (*alias*) resulting from this sampling pattern.

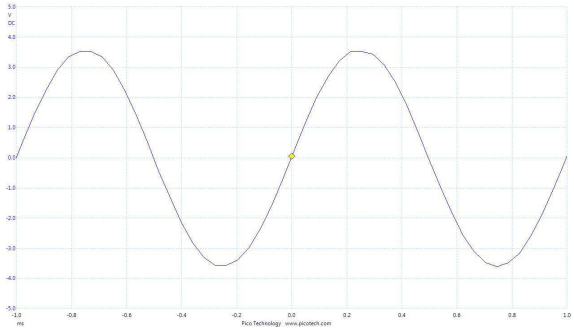
Some references may declare that a digital instrument's sampling rate must be at least twice as fast as the period of the signal in order to avoid aliasing (called the *Nyquist Sampling Theorem*). While this is technically correct, a sampling rate exactly equal to twice the signal frequency is still much too slow to be practical[34]. As a rule, you should always ensure the sampling rate is at least *ten times faster* than the signal's period in order that enough samples are taken within each period to provide at least a fair representation of the signal's shape. If the signal of interest has a complicated wave-shape with fast rise or fall times, an even faster sampling rate may be necessary to capture all the important features.

[34] A simple thought experiment reveals this to be true: imagine the digital oscilloscope sampling at precisely twice the signal frequency, such that the samples occur at the positive and negative peaks of the sinusoidal waveform. With sampling occurring at these points only, the interpreted result will be a *square wave* which is obviously not faithful to the shape of the actual signal. Alternatively, if the oscilloscope samples at precisely twice the signal frequency such that the samples occur at the zero-crossing points, the interpreted result will be a flat line (i.e. no signal at all)!

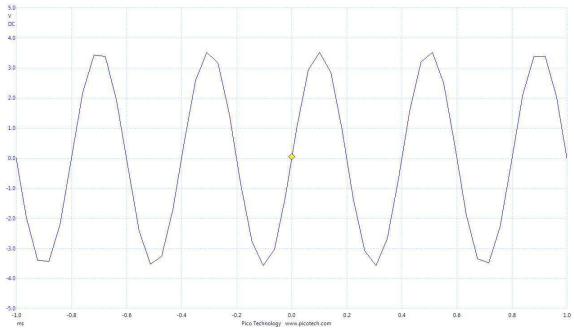
Modern digital oscilloscopes allow the user to select the *sample rate*, making it one more oscilloscope adjustment for the digital oscilloscope user to learn and master. In theory, an infinitely fast sampling rate would be ideal because it would be equivalent to an analog oscilloscope's continuous measurement. However, reduced sampling rates are useful for conserving buffer memory[35] in the digital oscilloscope, and also for filtering out noise which may be superimposed on the signal of interest.

An illustrated example of aliasing appears in the following sequence of screenshots taken from a PC-based digital oscilloscope. The sampling rate was set to the lowest allowed value (50 samples per screen-width), with a constant timebase setting of 0.2 milliseconds per division, while the signal frequency was progressively raised from a starting value of 1 kHz. Examine the following screenshots, noting how the waveform appears as it should at first, then decays in quality as the coarseness of the sampling becomes evident, then turns into a sawtooth waveform when we reach the Nyquist frequency (i.e. sampling exactly twice per cycle), then completely transforms as frequency exceeds the Nyquist limit:

f **= 1 kHz ; samples/cycle = 25** ; oscilloscope faithfully displays signal wave-shape

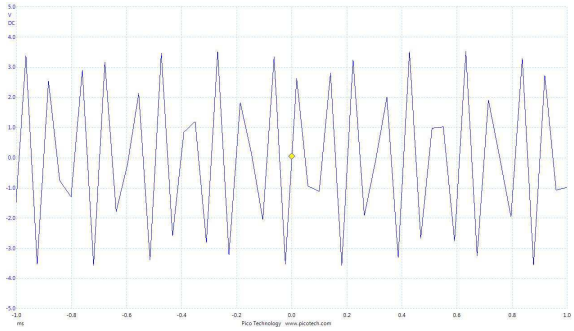


f **= 2.5 kHz ; samples/cycle = 10** ; wave-shape begins to look "rough" due to coarse sampling

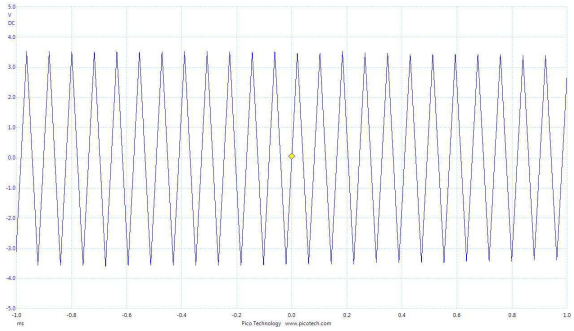


[35] Digital measuring instruments often provide a serial memory bank in order to store the values of successive samples. With digital oscilloscopes this is a necessity because the waveform may only be plotted if all the sample points are thus stored. However, since the amount of buffer memory in any digital instrument is limited, using a faster-than-necessary sample rate limits the number of signal cycles which may be stored. One could imagine a sample rate set so high that the oscilloscope runs out of buffer memory before the signal has even completed one cycle, in which case a complete cycle of the signal waveform could not be displayed on the oscilloscope's screen!

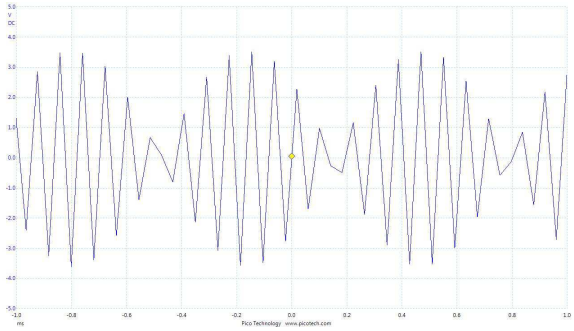
f **= 10 kHz ; samples/cycle = 2.5** ; wave-shape badly distorted



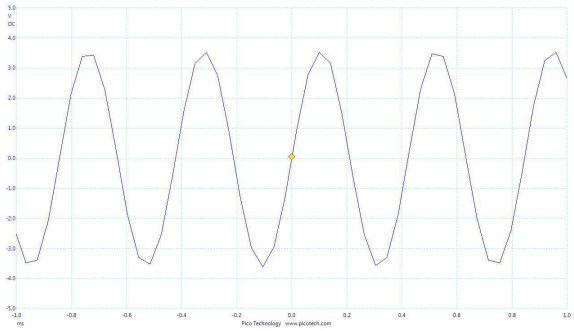
f **= 12.5 kHz ; samples/cycle = 2** (Nyquist minimum rate) ; sinusoid appears to be a triangle wave



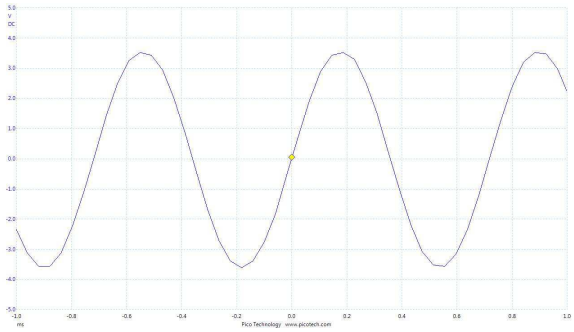
f **= 13 kHz ; samples/cycle = 1.923** ; strange cyclic envelope imposed on the signal



f **= 22 kHz ; samples/cycle = 1.136** ; entirely incorrect frequency (aliased)



f **= 23 kHz ; samples/cycle = 1.087** ; entirely incorrect frequency (aliased)



Pay particularly close attention to the last two displays, showing waveforms with entirely incorrect frequencies. In fact, as the real frequency increases from 22 kHz to 23 kHz, the displayed frequency appears to actually *decrease*! Note how the oscilloscope's timebase setting[36] remains unchanged throughout this experiment, which means the displayed signal should have appeared progressively more "compressed" along the horizontal axis as frequency increased. Instead, though, what we get with aliasing is an entirely wrong waveform with a much lower frequency than the actual signal. The wrong waveforms, however, *look completely plausible*, which is why aliasing is such a thorny problem: if we sample a sinusoidal signal and obtain a sinusoidal display, we might be led to believe that the display must be correct when in fact it could be aliased.

This is a compelling reason to keep any digital oscilloscope's sampling rate as high as practically possible, *at least* ten times faster than the highest expected frequency of our measured signal, just to avoid aliasing.

[36] We cannot see the settings fields in these screenshots, and so we must infer timebase from the display's axis labels. Here we see the horizontal (time) axis extending from -1.0 ms to $+1.0$ ms, and we can count ten divisions along this 2 ms span. Thus, the timebase is 0.2 ms per division.

Chapter 5

Derivations and Technical References

This chapter is where you will find mathematical derivations too detailed to include in the tutorial, and/or tables and other technical reference material.

5.1 Ground in electric and electronic circuits

Ground and *grounding* within both electric power and electronic circuits are commonly misunderstood topics, largely because these terms can often have very different meaning depending on context. Here we will explore some of these different meanings and hopefully eliminate some of the confusion surrounding them.

The very first concept we must understand in order to comprehend what "ground" is in any circuit is that *voltage* is fundamentally a *relative* measurement of potential energy different *between two points*. This is really true of all forms of potential energy, because "potential" means energy that has not yet been put to work setting matter into motion, implying a final state yet to be realized. When we say an electrical charge carrier possesses potential energy (i.e. electrical potential), this means it *could* (potentially) release energy to do work if it were to fall into a lower state of energy. The difference in energy held by that electric charge carrier from its original (high-potential) state to some other lower-potential state will be the amount of energy released by that charge carrier to do work, with that amount of work done dependent on both the charge carrier's initial energy level and its final energy level. *Voltage* is the term we use to describe such a difference in electrical potential.

We say that voltage always exists "between two points" or "between two locations" in a circuit because voltage is the amount of potential energy either lost or gained by electric charge carriers from one position in a circuit to another. It is impossible to quantify how much energy will be gained or lost by charge carriers unless we know both the starting point and the ending point for those charge carriers. In order to quantify the absolute amount of potential energy possessed by anything, we would have to know where or how it could lose every bit of its stored energy to be left with zero capacity to do work[1]. This is really unknowable from a practical perspective, and so the best we can do is quantify gains or losses in potential energy between different states.

This fact about voltage is also why we label it with *pairs* of "+" and "−" symbols, the "+" symbol representing the point of *higher potential* and the "−" symbol representing the point of *lower potential*. We cannot place an absolute value on electrical potential at any single location because no one can say where the location of zero energy is in the universe for electric charges. The best we can do is to rate one location as having higher or lower electrical potential than another, quantifying only the difference in potential between those two locations.

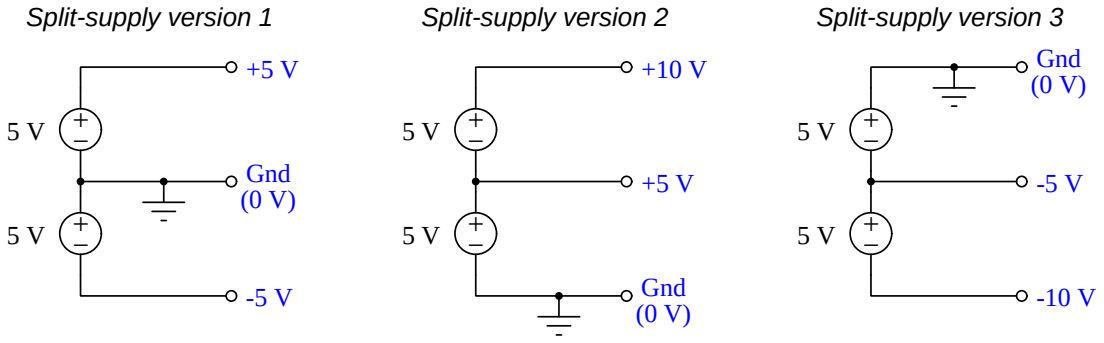
Now that we have reviewed this property of voltage and of potential energy in general, we are ready to explore what is meant by *ground* and *grounding*.

[1] Using gravitational potential energy as an example, a weight hoisted above the Earth's surface certainly possesses potential energy, and we might be tempted to quantify this potential energy by simply measuring its weight and its height above ground level and then multiplying those two quantities (i.e. potential energy equals force times distance). However, there are more places this weight could *potentially* fall than just ground level. That same weight, hoisted above the Earth's surface to the same height, will be assessed to have a far greater amount of potential energy if we consider it potentially falling down a deep hole rather than just falling to ground level. For that matter, one could even argue the weight has a *negative* quantity of potential energy with respect to what it would possess at the summit of the highest mountain! Potential energy, defined as the amount of work that *could* be done, necessarily depends on a system's initial condition *and* any number of different final conditions of which none are known to be truly zero-energy.

How do we rate the height of mountain peaks? Certainly, we may rate one mountain peak as being some number of meters higher or lower than another, but generally what people do instead is measure a mountain's peak height compared to *Mean Sea Level*. Since water is a liquid, and liquid tend to settle at equal heights under the influence of gravity when they are free to move about, the level of oceans throughout the world provide a relatively stable reference point for measurements of altitude. If we imagine a world without oceans, perhaps one with nothing but dry land and no open bodies of water anywhere, people living at different locations in this world would likely choose some flat-land reference points local (to them) for their measurements of nearby mountains, but these localized altitude measurements would be confusing if not meaningless for world-wide comparisons of mountain peaks.

Much the same is true of electrical and electronic circuits, where voltage is an important measure of electrical potential energy as well as a measure of signal strength where electricity is used as an analogue for representing other things[2]. One way to conveniently rate electrical potentials at different points in a circuit is by arbitrarily choosing one of those points to be the "zero-energy" reference point, and calling it *ground*. Ground in an electrical or electronic circuit is analogous to sea level for rating mountain peak heights or a *datum* or *benchmark* used for surveying land: simply a point of reference agreed-upon to be "zero" for the sake of ranking all other potentials to it.

A good example of this is an electrical network popularly known as a *split DC power supply*. Three different versions of this power supply network are shown with the same pair of 5-Volt DC sources, the only difference being the arbitrary location of the "Ground" (Gnd) point:

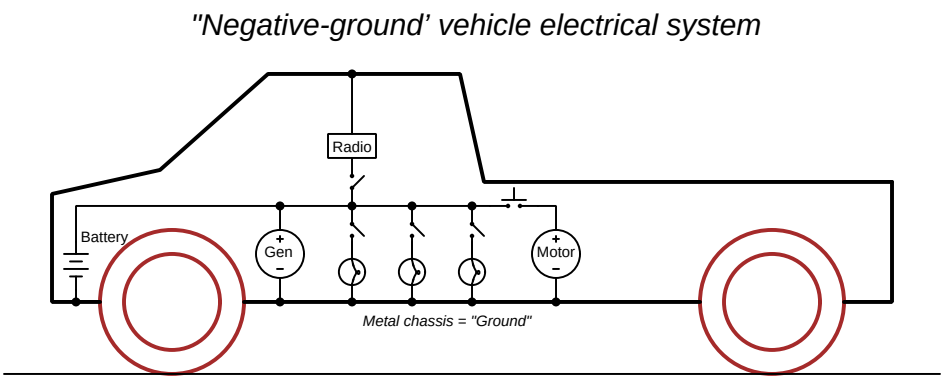


Each terminal's voltage label represents the amount of electrical potential there *relative to the "Ground" terminal*; i.e. "Ground" is simply a "sea-level" reference point against which all other potentials may be measured. The three different versions shown here illustrate just how arbitrary the location of "Ground" really is. Any load connected between the same pairs of terminals on each power supply would experience the same amount of voltage regardless of the "Ground" terminal assignment.

This is one meaning of the word "ground" in electric and electronic circuits: an arbitrary point of reference for the measurement and comparison of electrical power and signal potentials at different locations in the circuit.

[2]Many, many examples exist of voltage being used to represent non-electrical quantities. In digital computer systems, DC voltage levels represent binary "1" and "0" number states. In analog electronic sensor systems, voltage may represent temperature, speed, force, weight, sound pressure, or any number of other physical quantities.

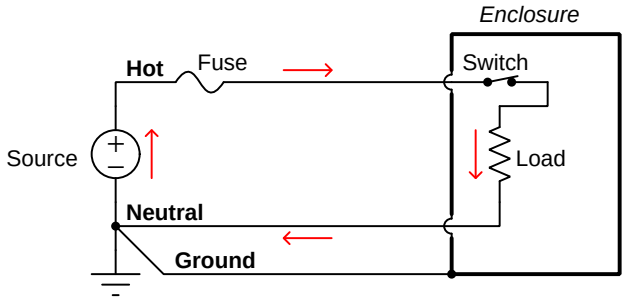
Another meaning of the word "ground" in circuits is a metallic surface used as a common conductor throughout some device or system for reasons of wiring economy. Automobiles with metal frames and chassis typically use their metallic bodies as an electrical conductor for nearly all circuits contained within. Doing so eliminates the need to install separate copper-wire conductors for every source and every load, thereby saving expense and weight:



Modern automotive electrical systems are "negative-ground" which means the vehicle chassis is always the lowest-potential point in any portion of the circuit. Interestingly, some early automobiles used "positive-ground" wiring which simply had the reverse polarity on all sources and loads: the vehicle chassis being the highest-potential point and all other points being either equal to it or at lower (−) potentials. This choice of polarity is really arbitrary, as electric circuits may be designed and built to function just as well either way. The "negative-ground" standardization we see today is really nothing more than automobile manufacturers agreeing to wiring their different vehicles the same way in order to enjoy interoperability of components.

This usage of the word *ground* – describing the metal chassis of some complex system exploited as a common electrical conductor for multiple circuits – is not incompatible with the previous usage of *ground*: a point of reference in a circuit arbitrarily defined to be "zero" potential. An automotive technician troubleshooting circuit faults in a vehicle often connects the black test lead of their voltmeter to the metal chassis, expecting to measure positive or zero voltage values on that meter when probing circuit test points with the red test lead. In a negative-ground electrical system, the chassis' electrical potential is *defined* as zero for the purpose of specifying voltages at other points in the circuit(s).

Yet another electrical meaning of the word "ground" is associated with *safety*, in which one metallic conductor of a power circuit is made electrically common to the Earth through a *grounding rod* buried in the soil. In the following circuit, the ground symbol in the lower-left corner is not merely a reference marker intended for anyone viewing the schematic diagram, but actually represents a metal rod driven deep into the soil and connected to one terminal of the voltage source with intent to achieve equipotentiality with the Earth:



Here the purpose of "grounding" is more important than merely establishing a reference point for voltage measurements. Instead, designating the conductor attached to this metal rod as "Ground" and attaching it to any conductive surface on or around an otherwise energized electrical appliance forces that surface to be equipotential to the same Earth that any humans and animals are standing on. This greatly mitigates the risk of electric shock should there be an internal fault within that appliance by making it impossible to have a difference of potential (i.e. voltage) between the grounded surface and the soil.

The following photograph shows the grounding rod for a commercial building, a large-gauge bare copper conductor clamped to the top of the rod which leads into the building's electrical room:

Ground wires in electric power systems should never carry current during normal operation. In fact, the presence of current through a ground conductor indicates a problem in the system! Note the two current-bearing power conductors in the previous schematic, specifically how the current-carrying conductor made common to Earth ground is called the *neutral*, while the other (non-grounded) power conductors is called *hot* by comparison. The Hot/Neutral designations always refer to which is grounded and which is not, rather than polarity. For example, if we were to reverse

the polarity of the DC voltage source shown in that schematic, the upper conductor (now −) would still be considered "hot" and the lower conductor (now +) would still be considered "neutral".

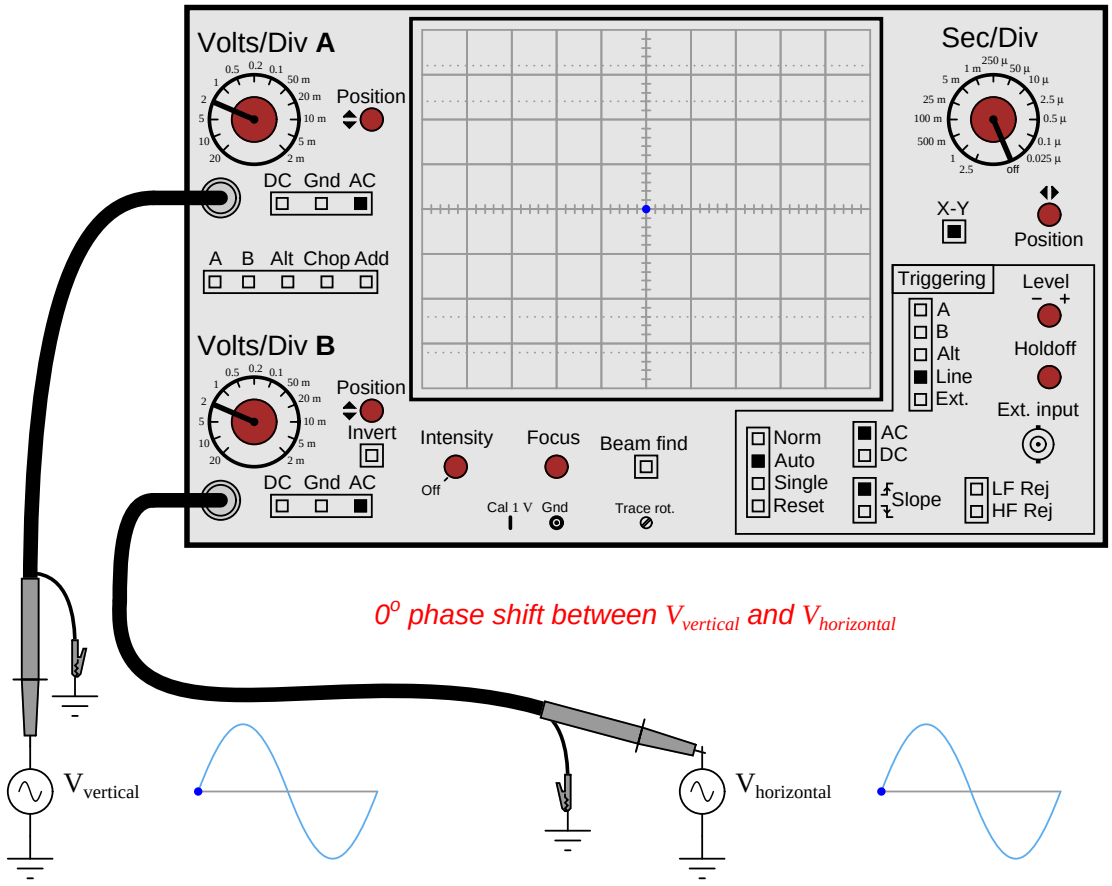
Chapter 6

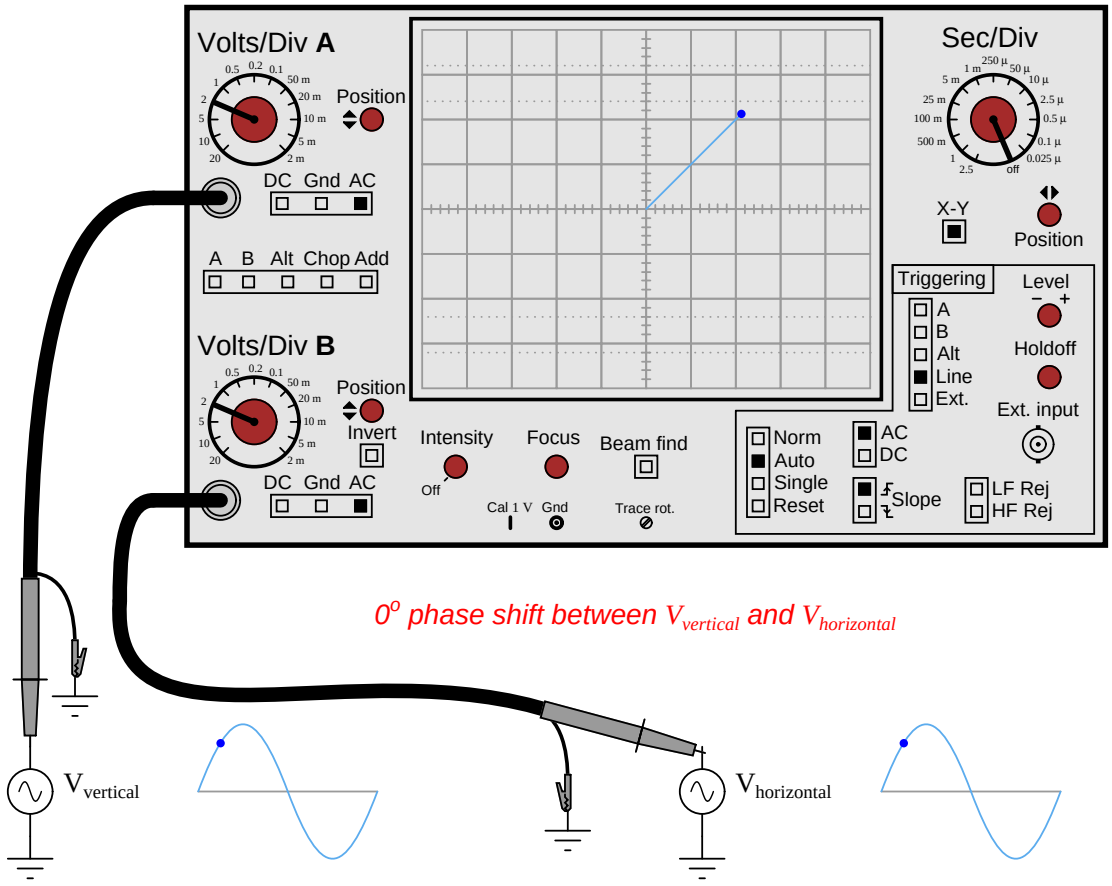
Animations

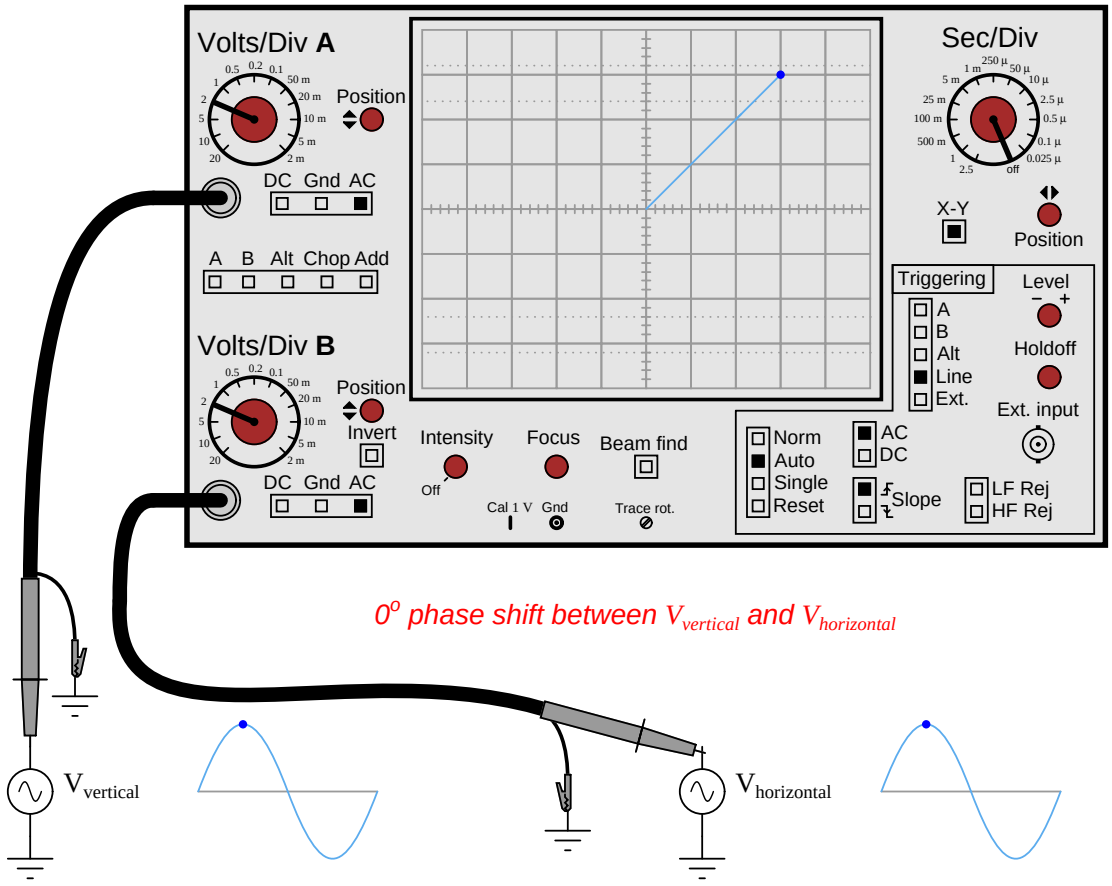
Some concepts are much easier to grasp when seen in *action*. A simple yet effective form of animation suitable to an electronic document such as this is a "flip-book" animation where a set of pages in the document show successive frames of a simple animation. Such "flip-book" animations are designed to be viewed by paging forward (and/or back) with the document-reading software application, watching it frame-by-frame. Unlike video which may be difficult to pause at certain moments, "flip-book" animations lend themselves very well to individual frame viewing.

6.1 Lissajous figure with 0^o phase shift

This animation shows a Lissajous figure being formed on the screen of an oscilloscope from two sinusoidal voltage sources at the same frequency and in-phase (i.e. zero phase shift) with each other.


Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
0^o phase shift between $V_{vertical}$ and $V_{horizontal}$
$V_{vertical}$
$V_{horizontal}$


Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
0° phase shift between V vertical and V horizontal
V vertical
V horizontal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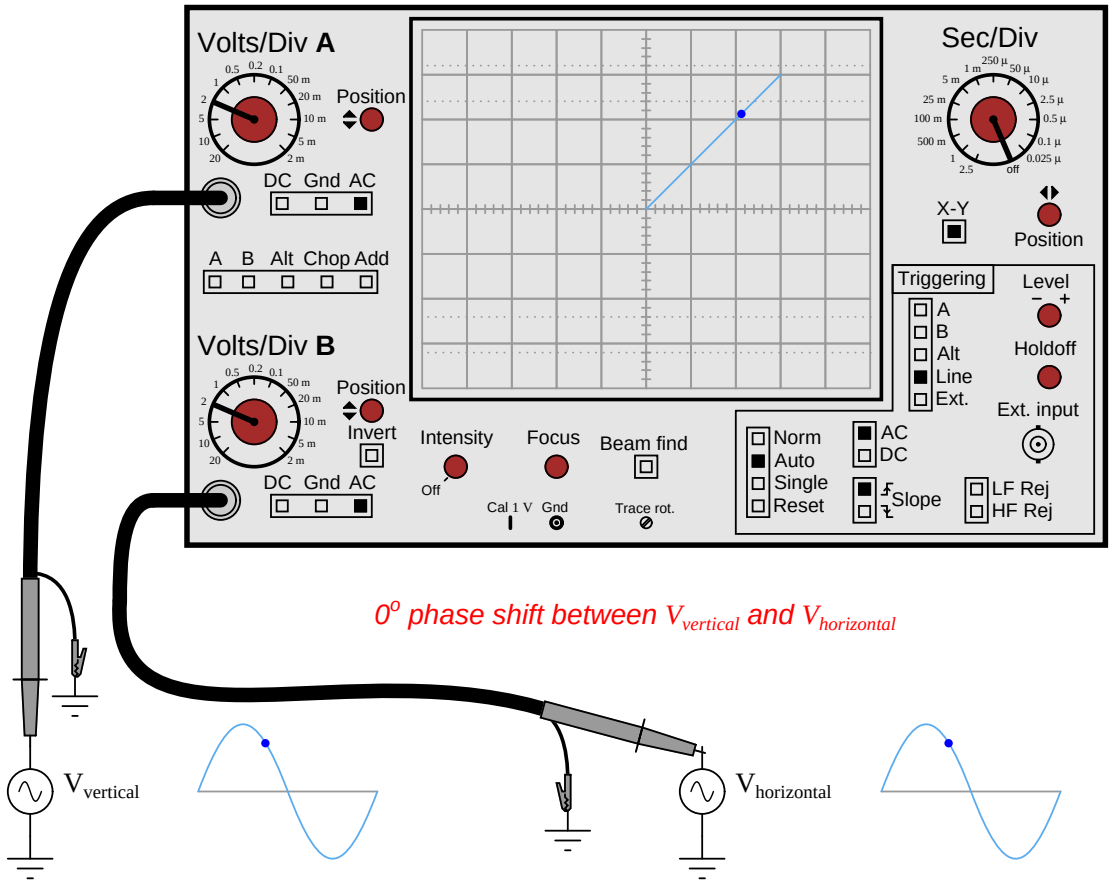
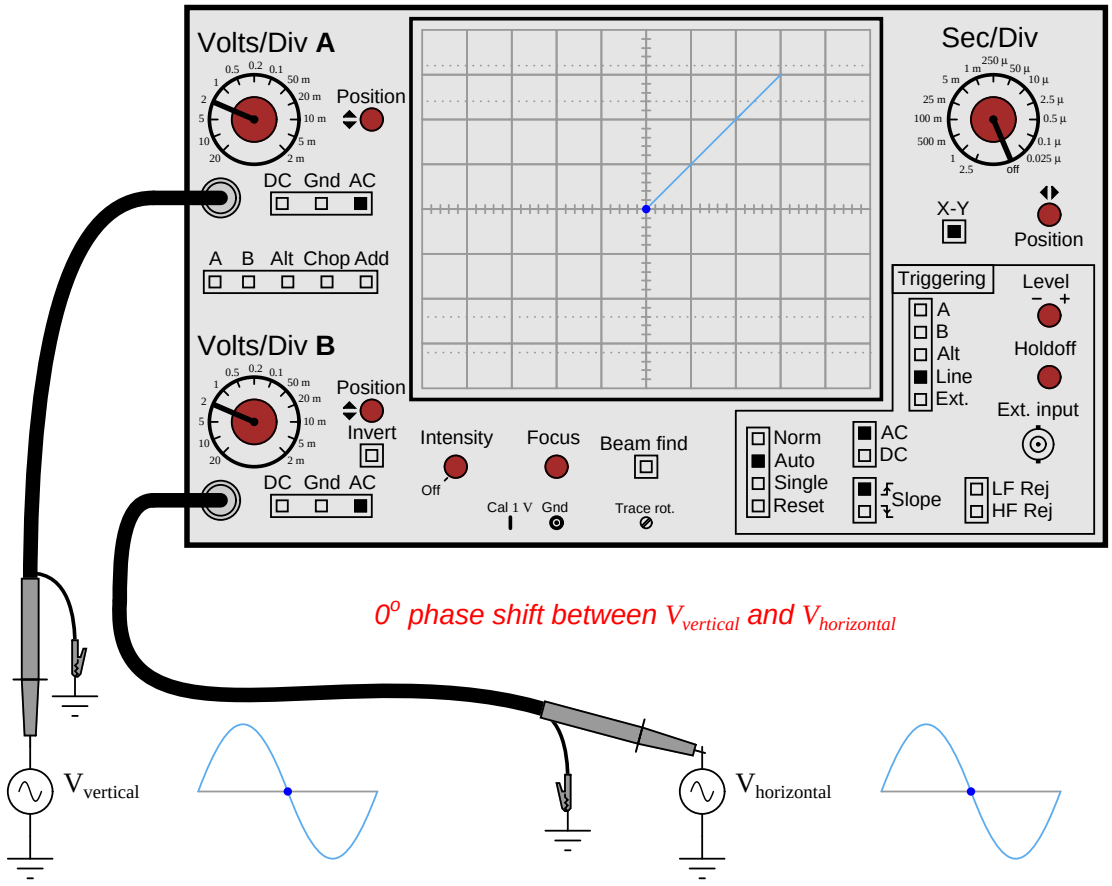
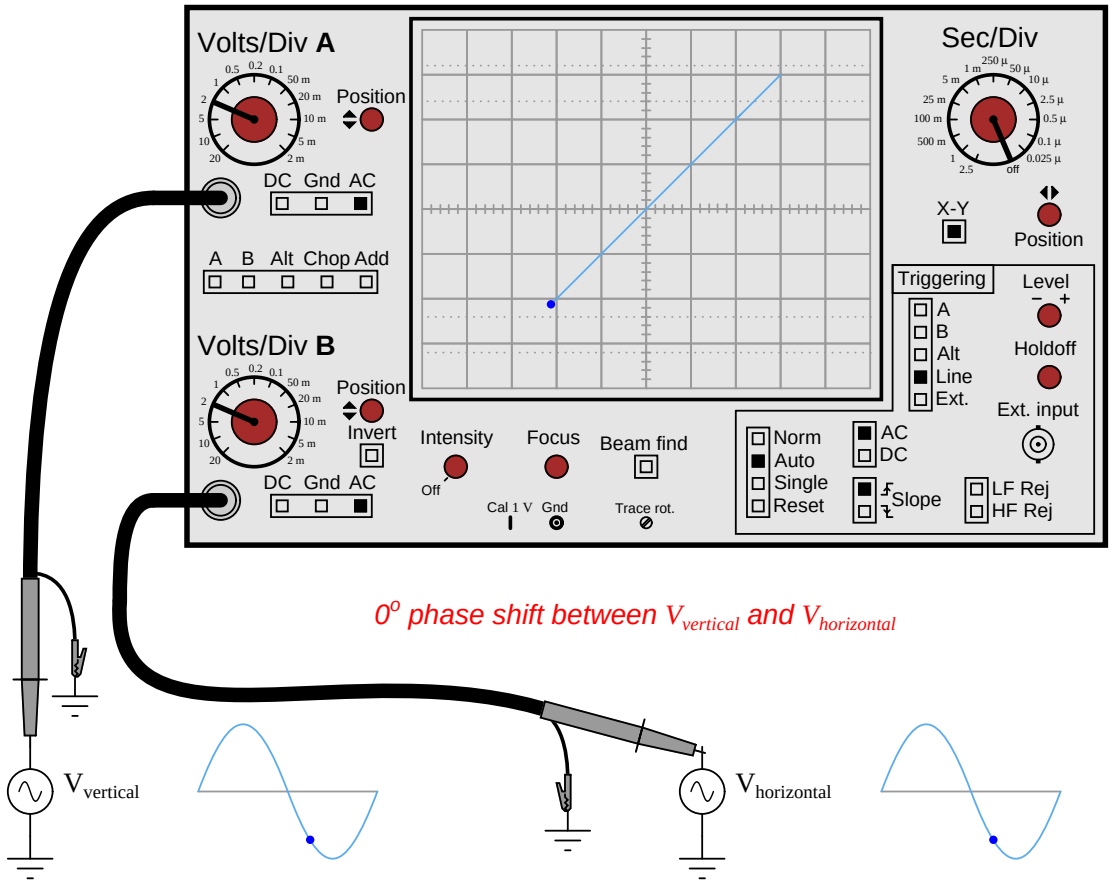
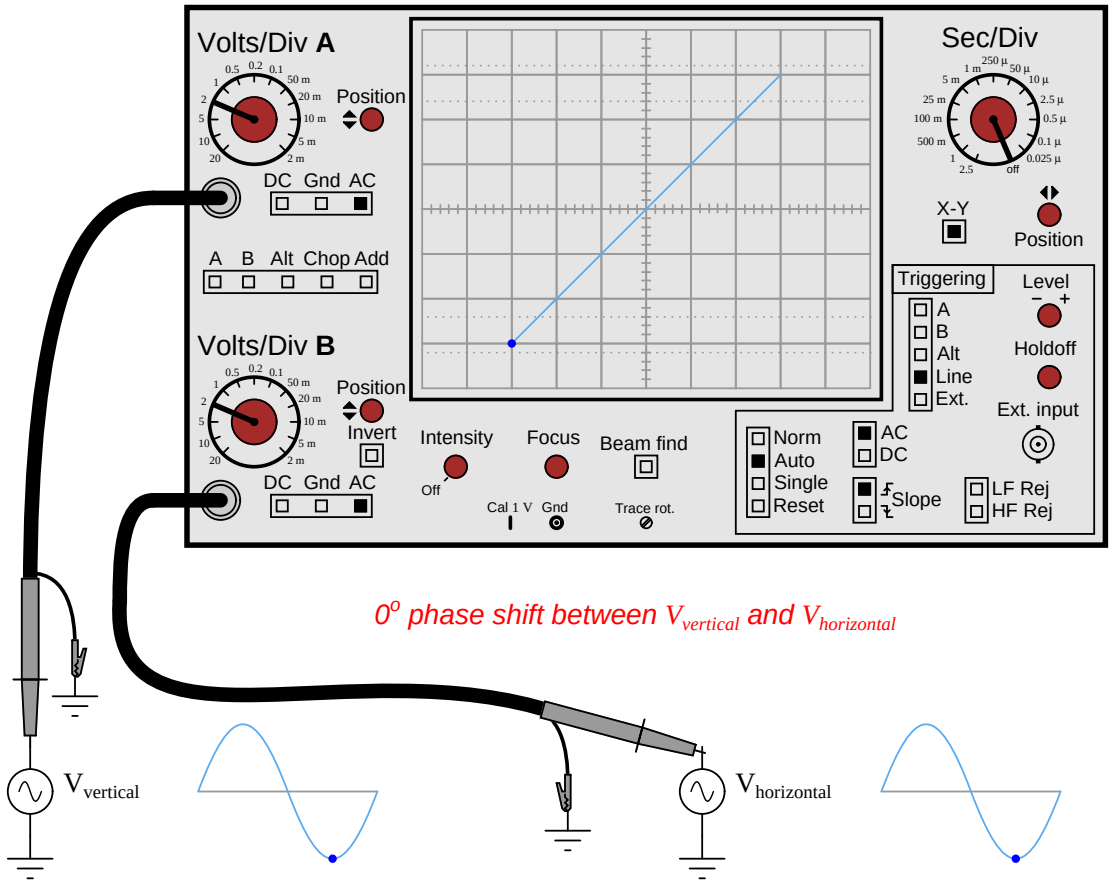
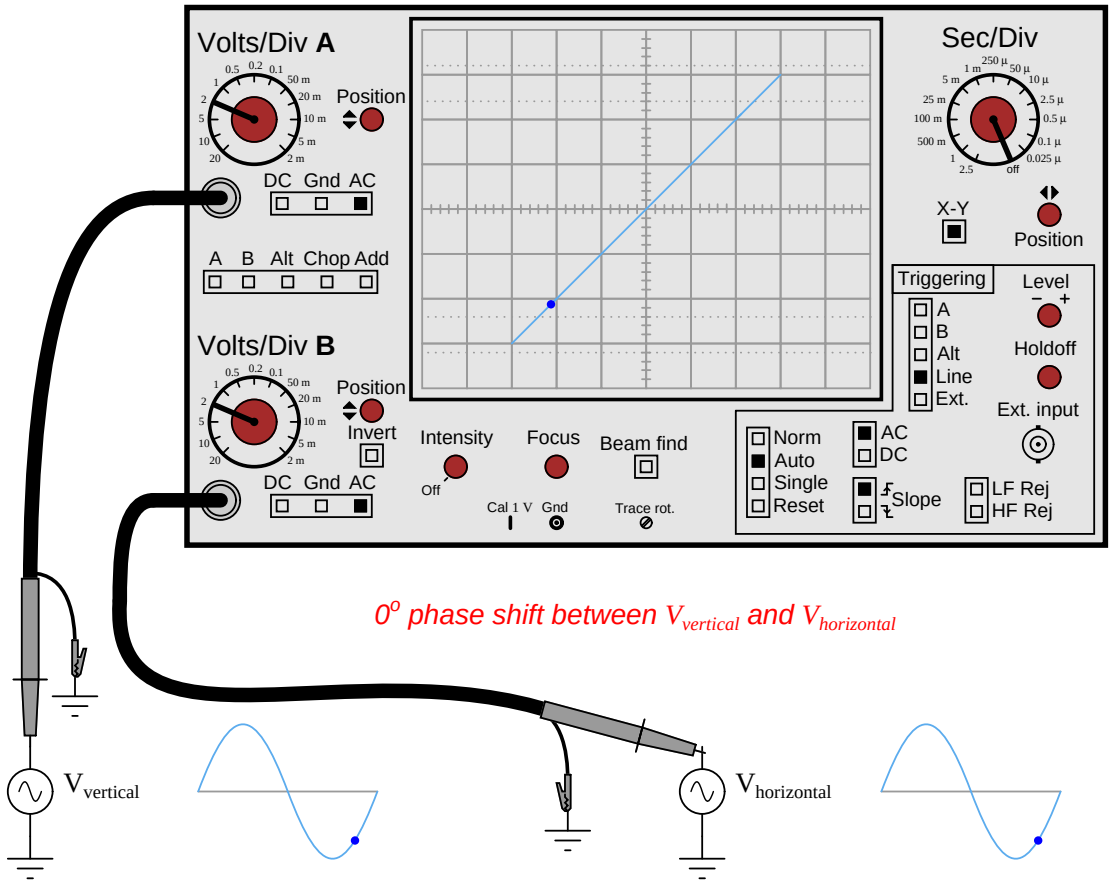
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
0^o phase shift between $V_{vertical}$ and $V_{horizontal}$
$V_{vertical}$
$V_{horizontal}$

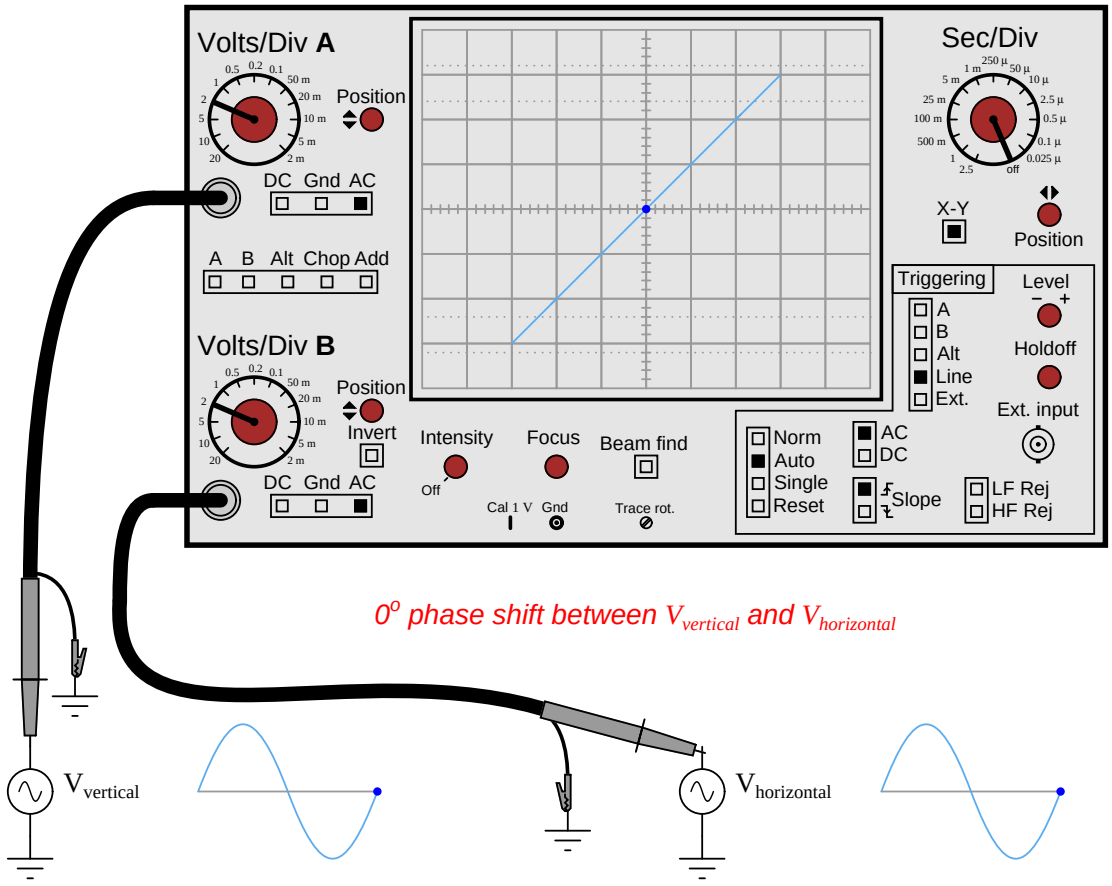

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
0° phase shift between V vertical and V horizontal
V vertical
V horizontal


Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
0^o phase shift between $V_{vertical}$ and $V_{horizontal}$
$V_{vertical}$
$V_{horizontal}$


Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
0° phase shift between V vertical and V horizontal
V vertical
V horizontal

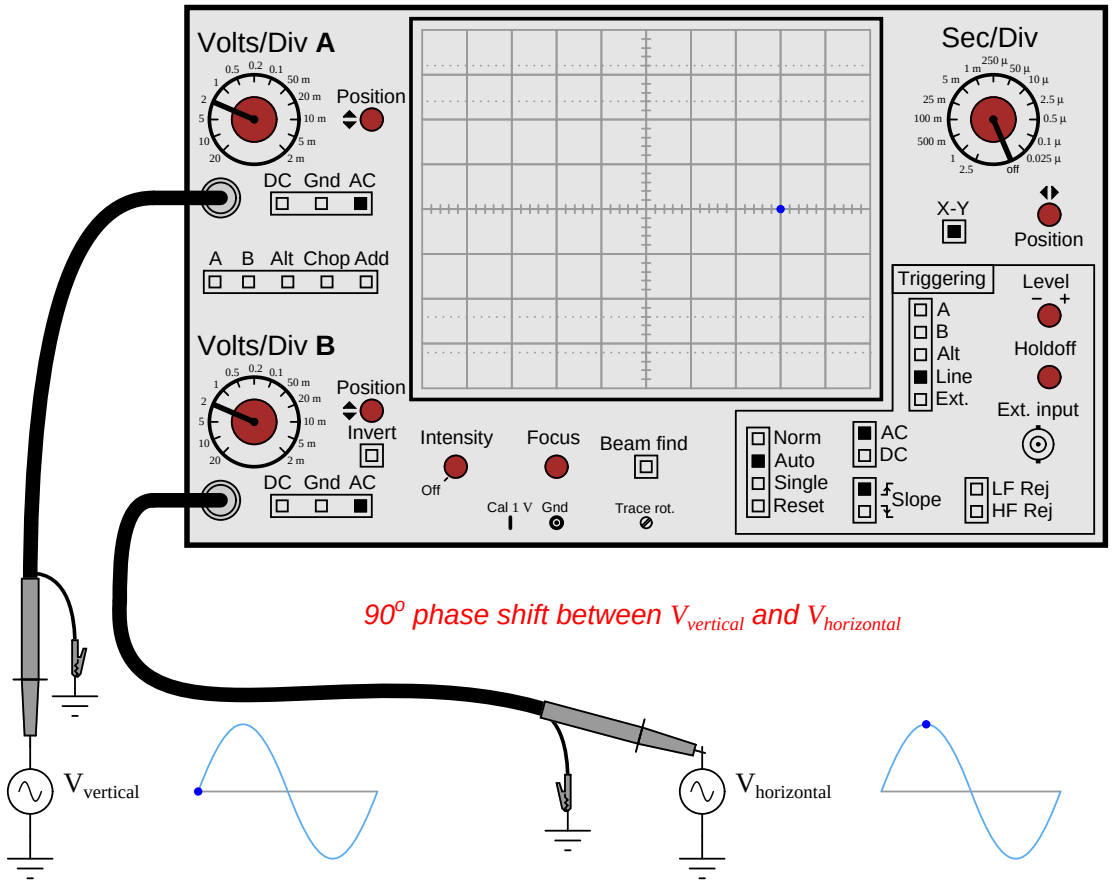

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
0^o phase shift between $V_{vertical}$ and $V_{horizontal}$
$V_{vertical}$
$V_{horizontal}$

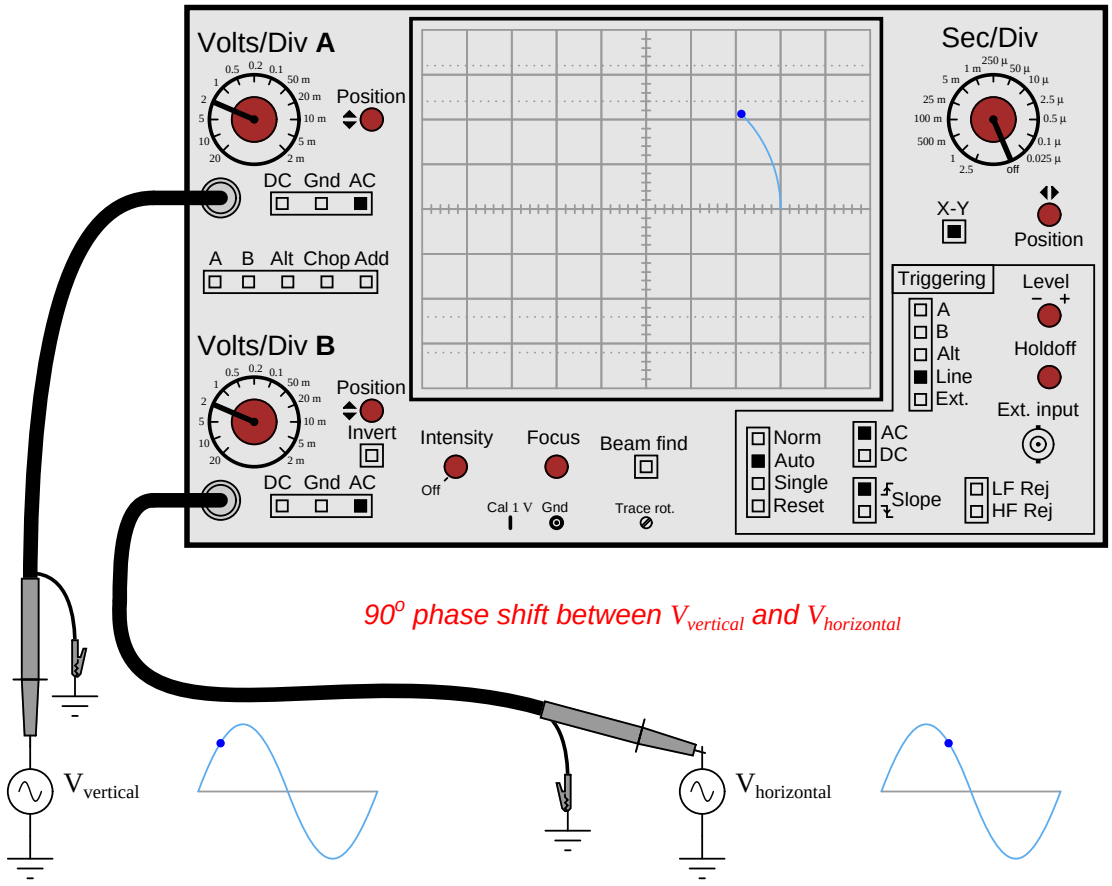

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
0° phase shift between V vertical and V horizontal
V vertical
V horizontal

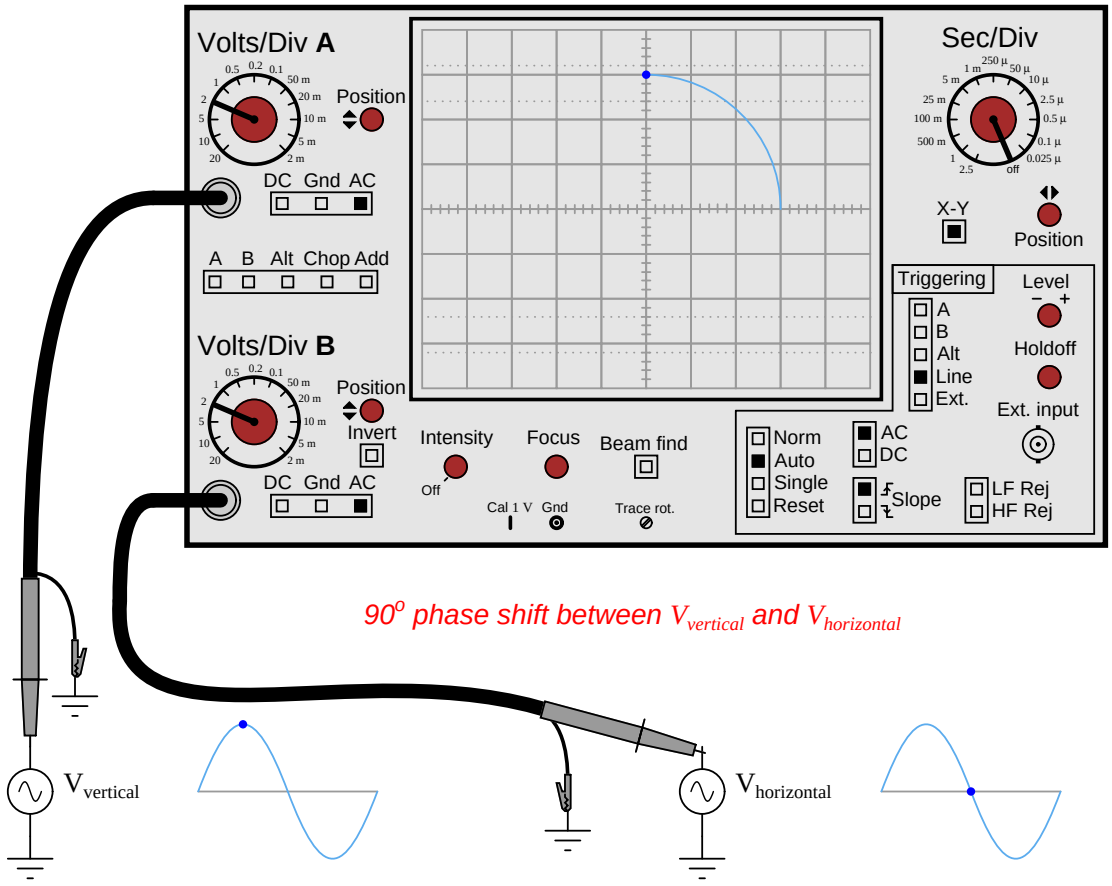

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
0^o phase shift between $V_{vertical}$ and $V_{horizontal}$
$V_{vertical}$
$V_{horizontal}$

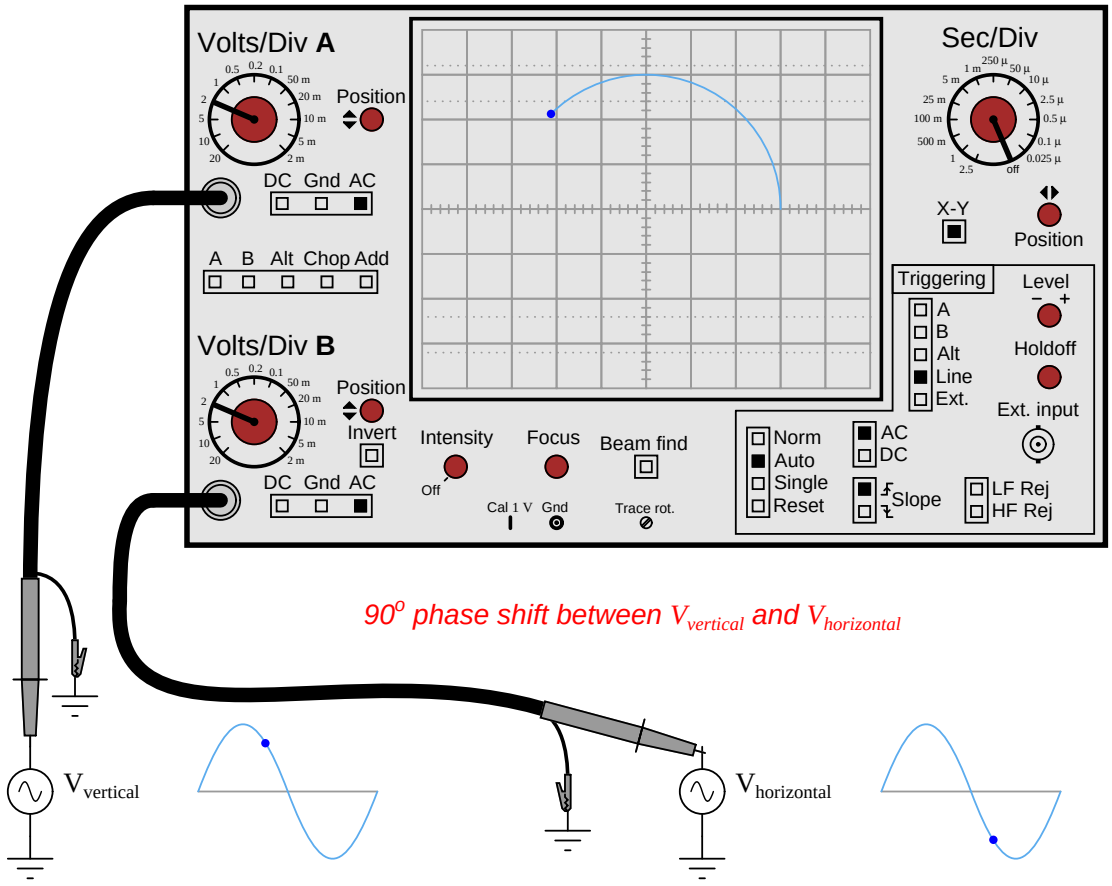
6.2 Lissajous figure with 90^o phase shift

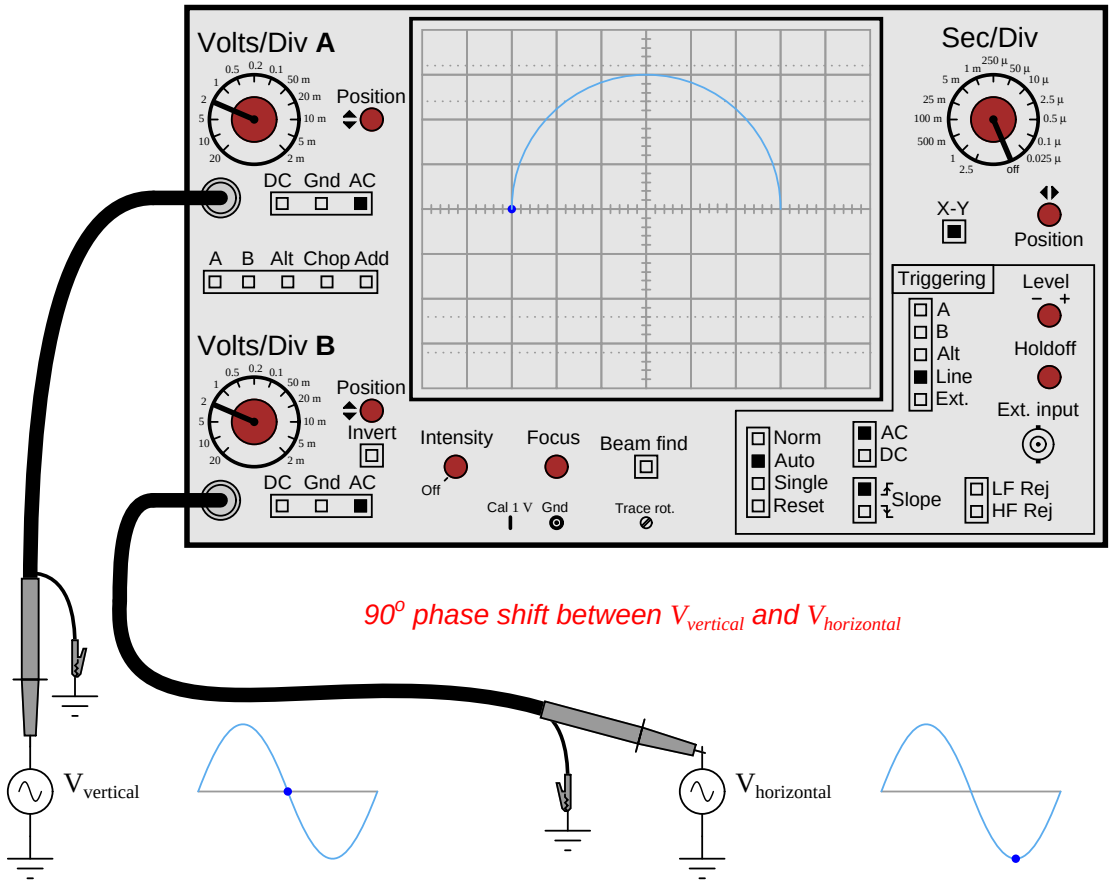
This animation shows a Lissajous figure being formed on the screen of an oscilloscope from two sinusoidal voltage sources at the same frequency and in quadrature (i.e. 90^o phase shift) with each other.

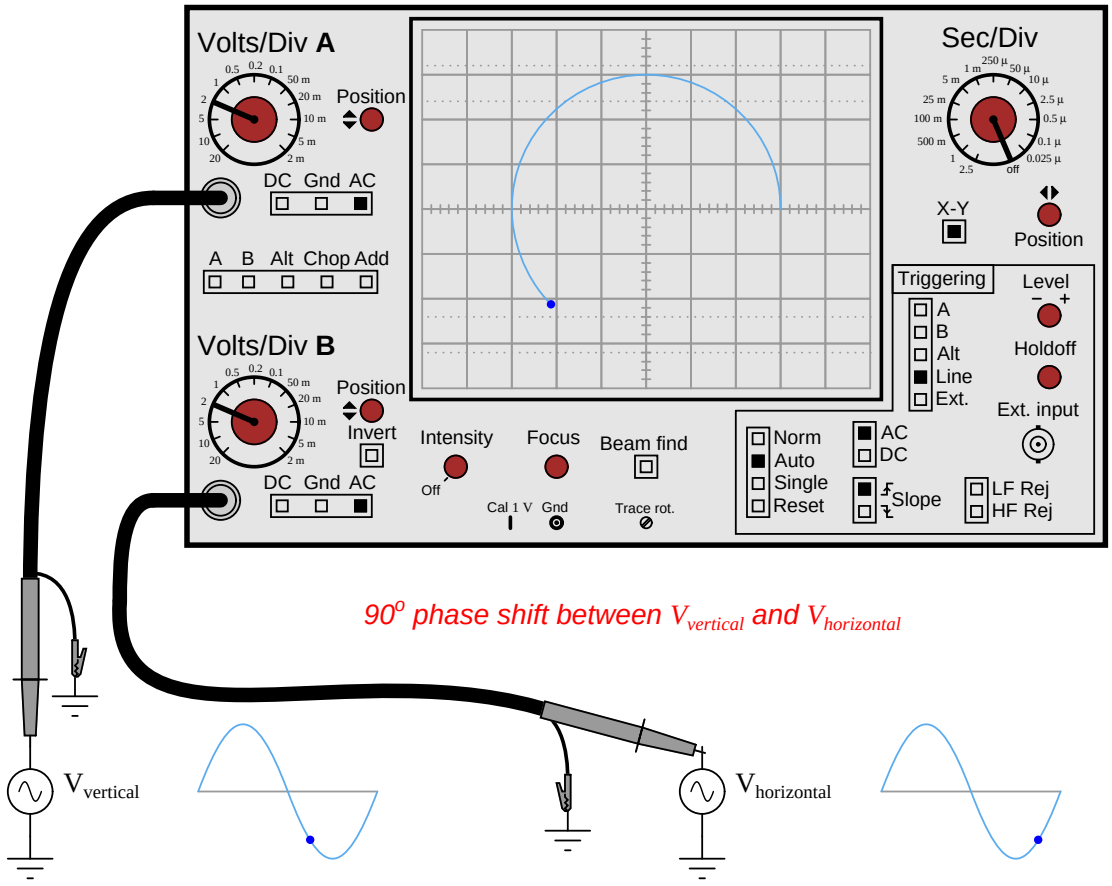

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
90º phase shift between V vertical and V horizontal
V vertical
V horizontal

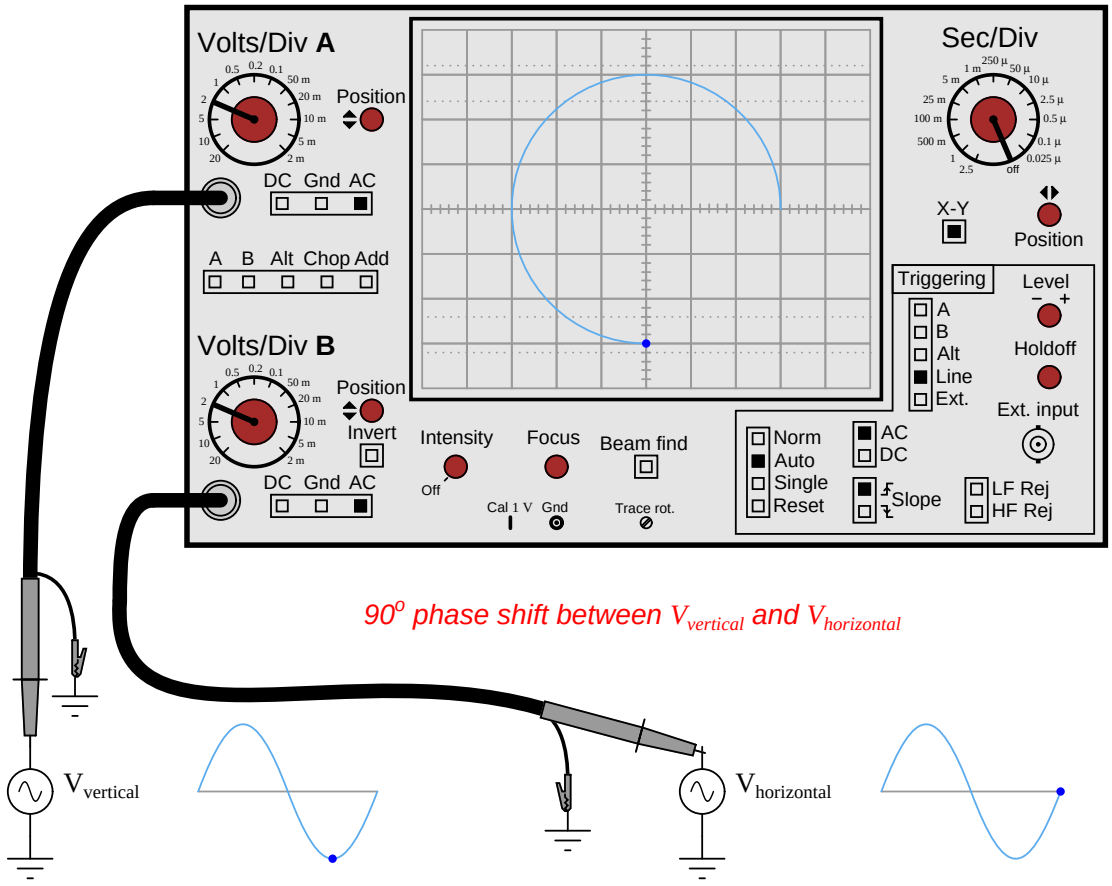

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
90° phase shift between V vertical and V horizontal
V vertical
V horizontal

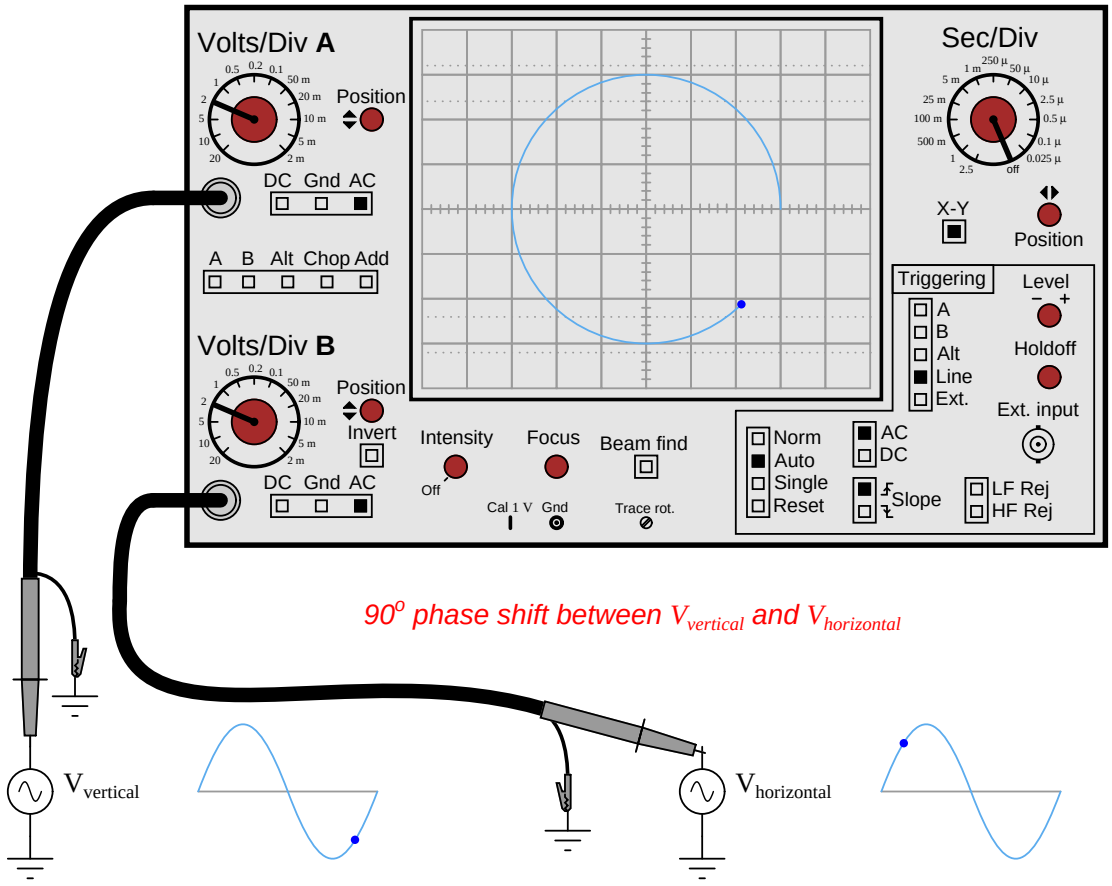

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
90º phase shift between V vertical and V horizontal
V vertical
V horizontal

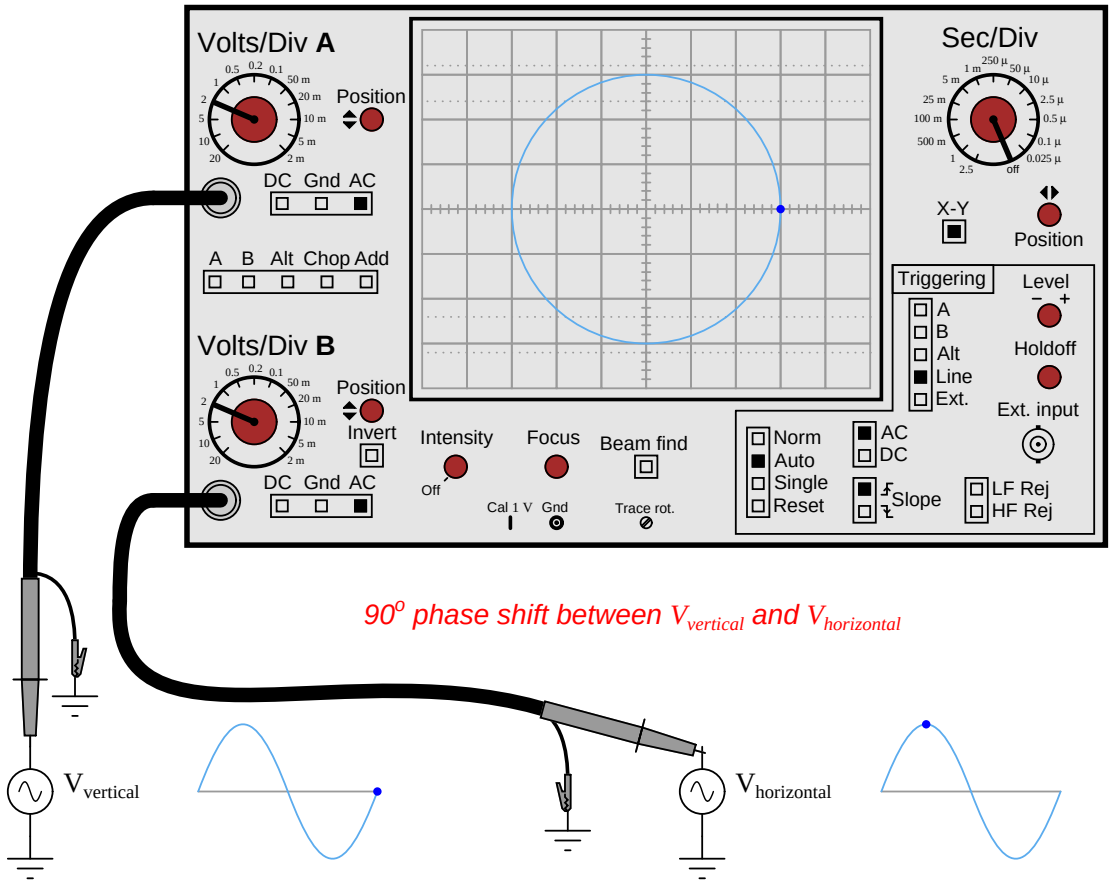

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
90° phase shift between V vertical and V horizontal
V vertical
V horizontal


Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
90º phase shift between V vertical and V horizontal
V vertical
V horizontal


Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
90° phase shift between V vertical and V horizontal
V vertical
V horizontal

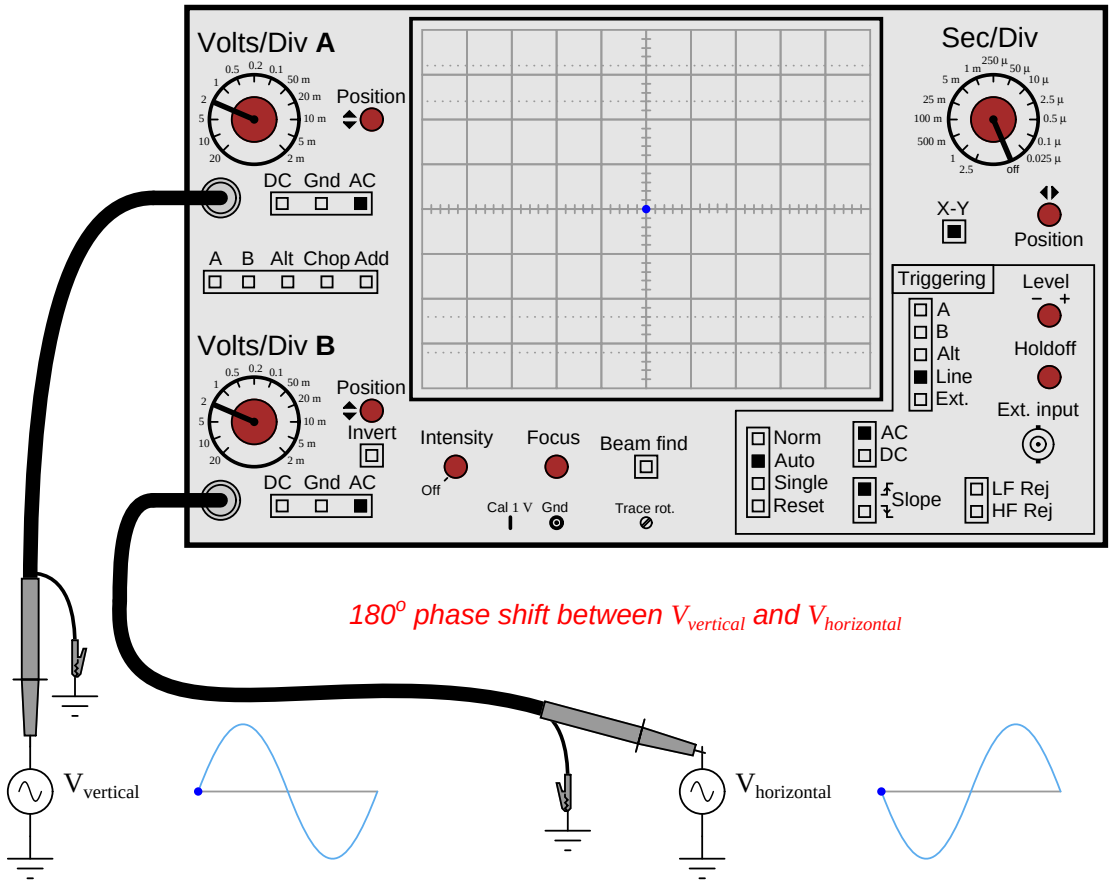

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
90º phase shift between V vertical and V horizontal
V vertical
V horizontal

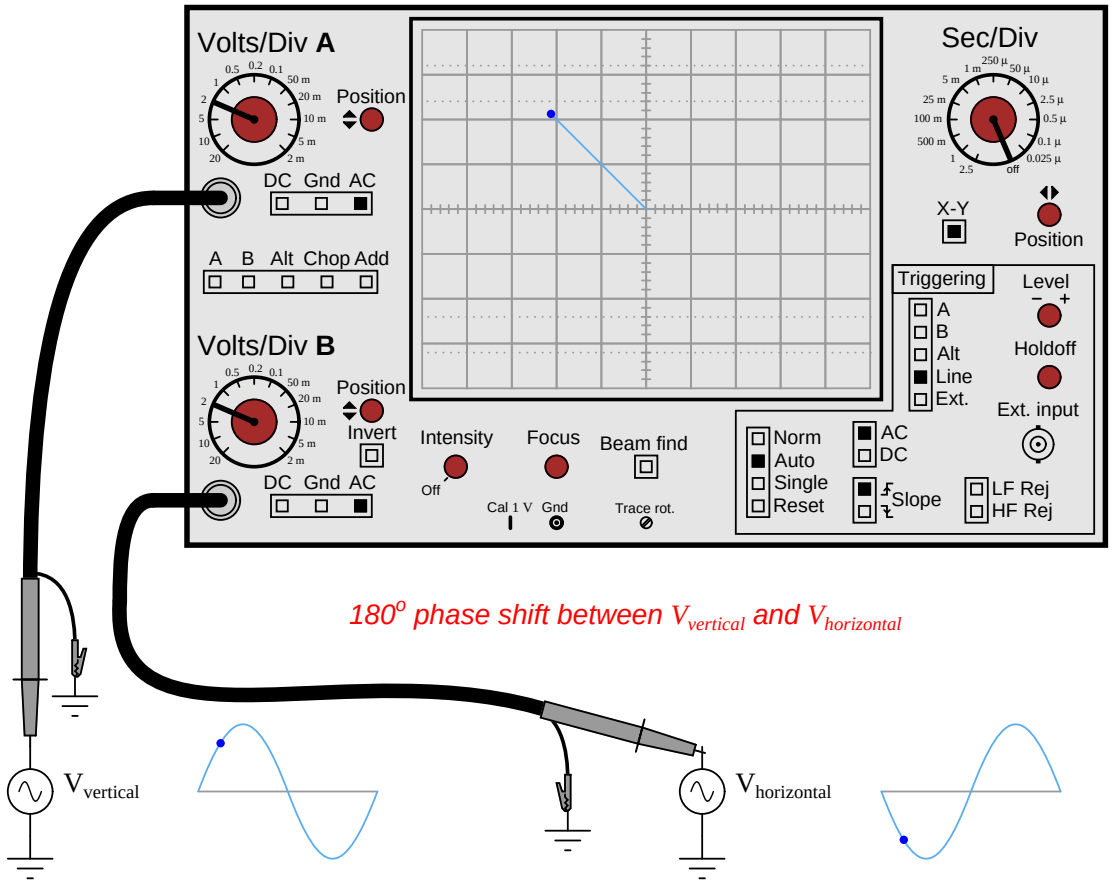

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
90° phase shift between V vertical and V horizontal
V vertical
V horizontal

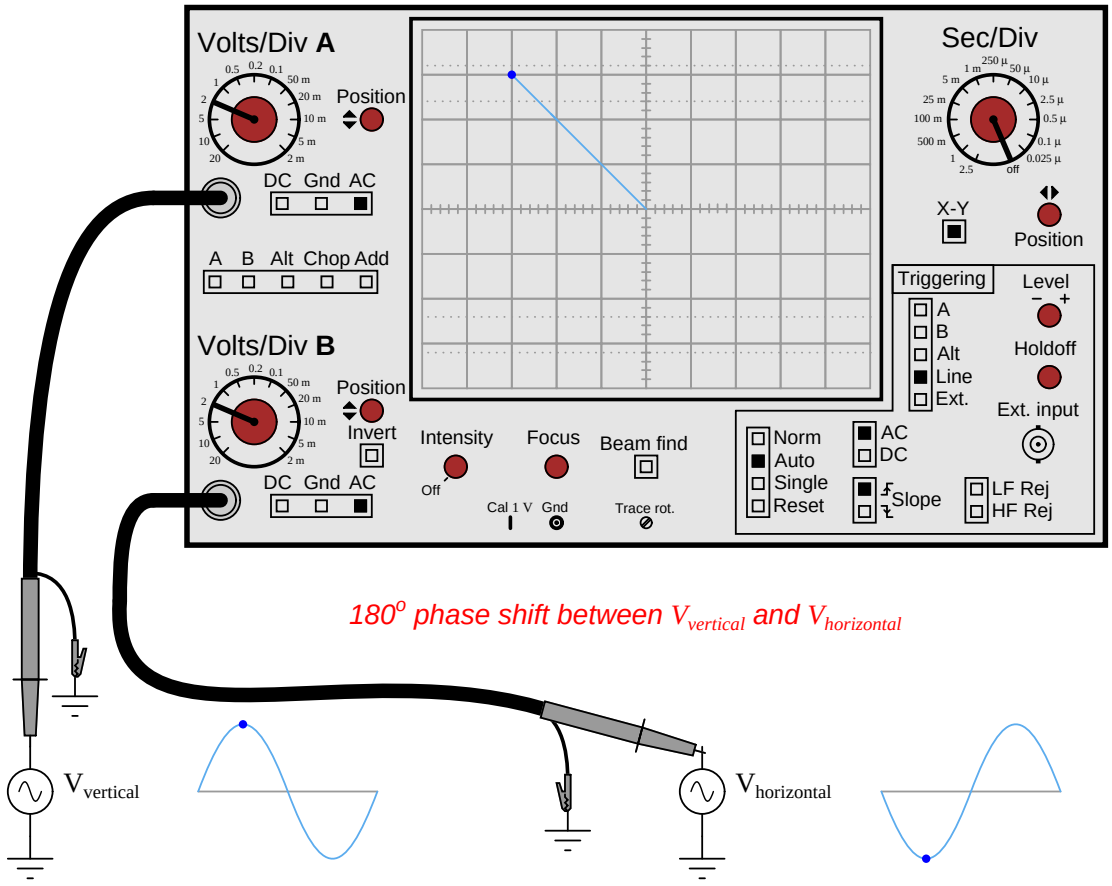

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
90º phase shift between V vertical and V horizontal
V vertical
V horizontal

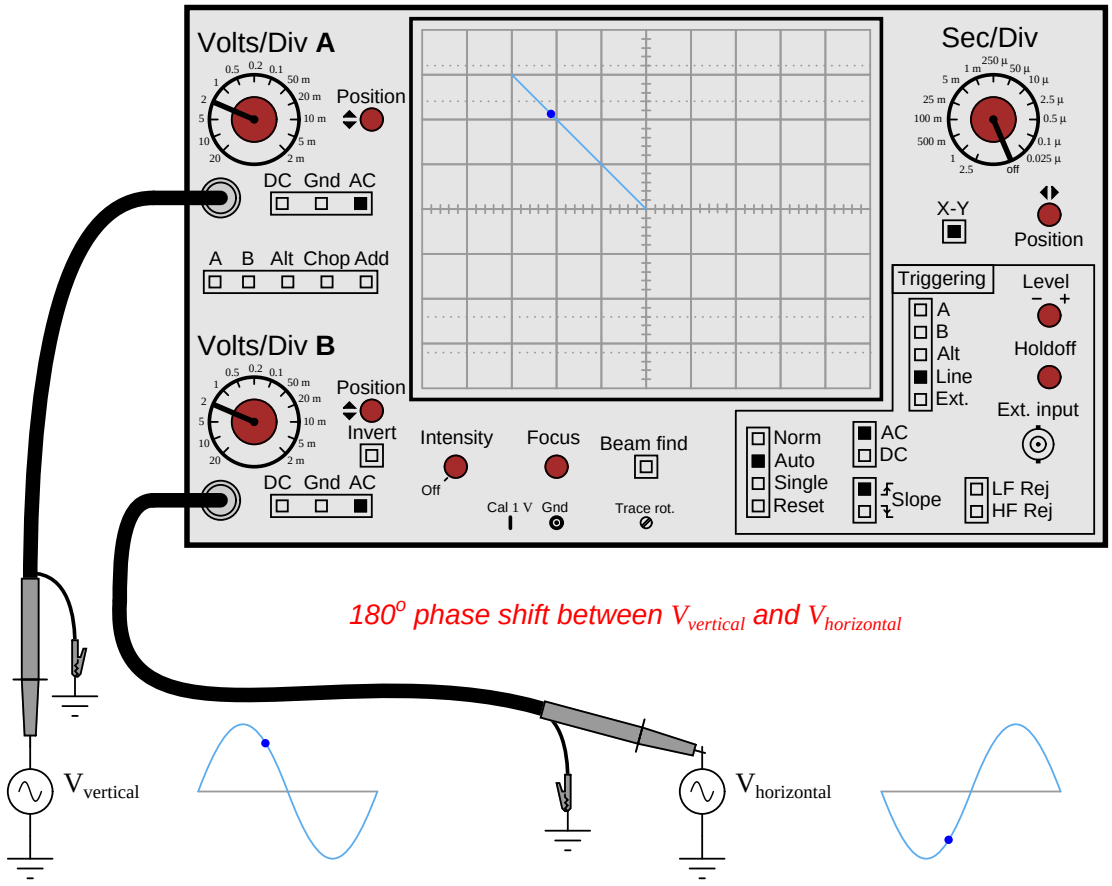
6.3 Lissajous figure with 180^o phase shift

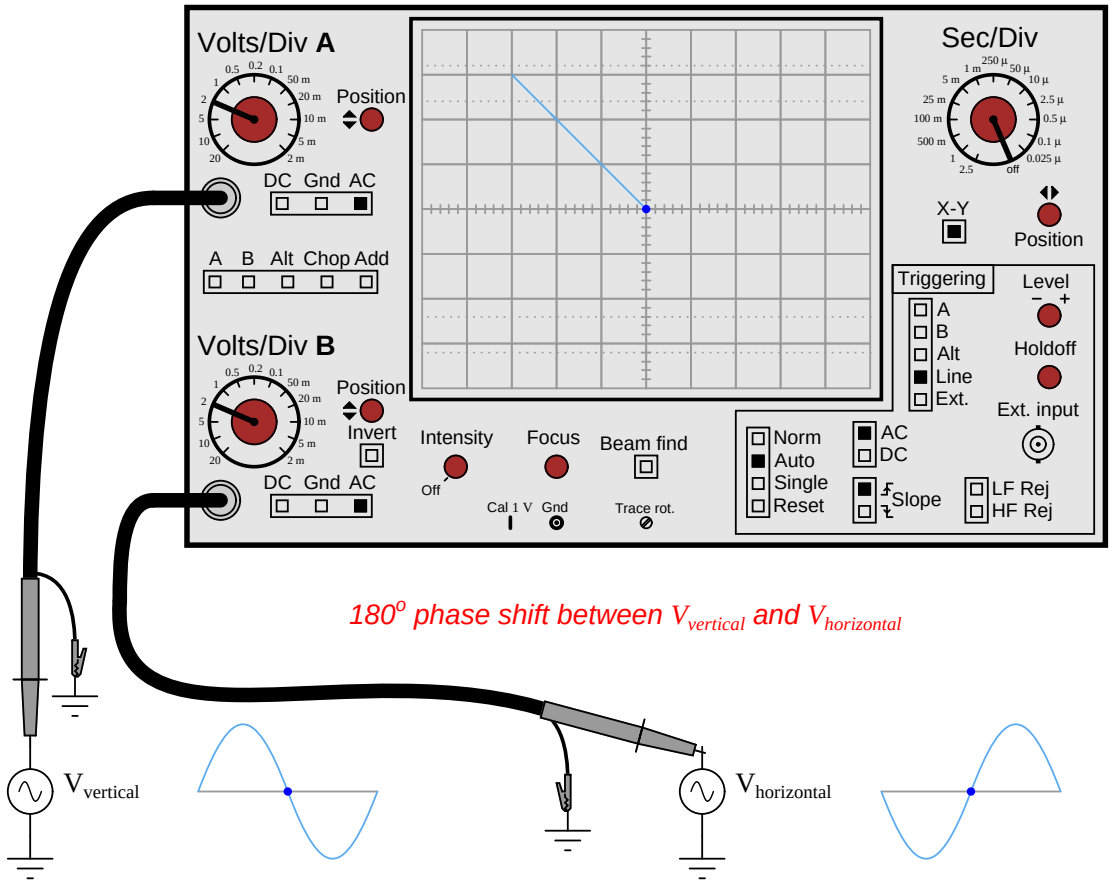
This animation shows a Lissajous figure being formed on the screen of an oscilloscope from two sinusoidal voltage sources at the same frequency and opposite in polarity (i.e. 180^o phase shift) from each other.

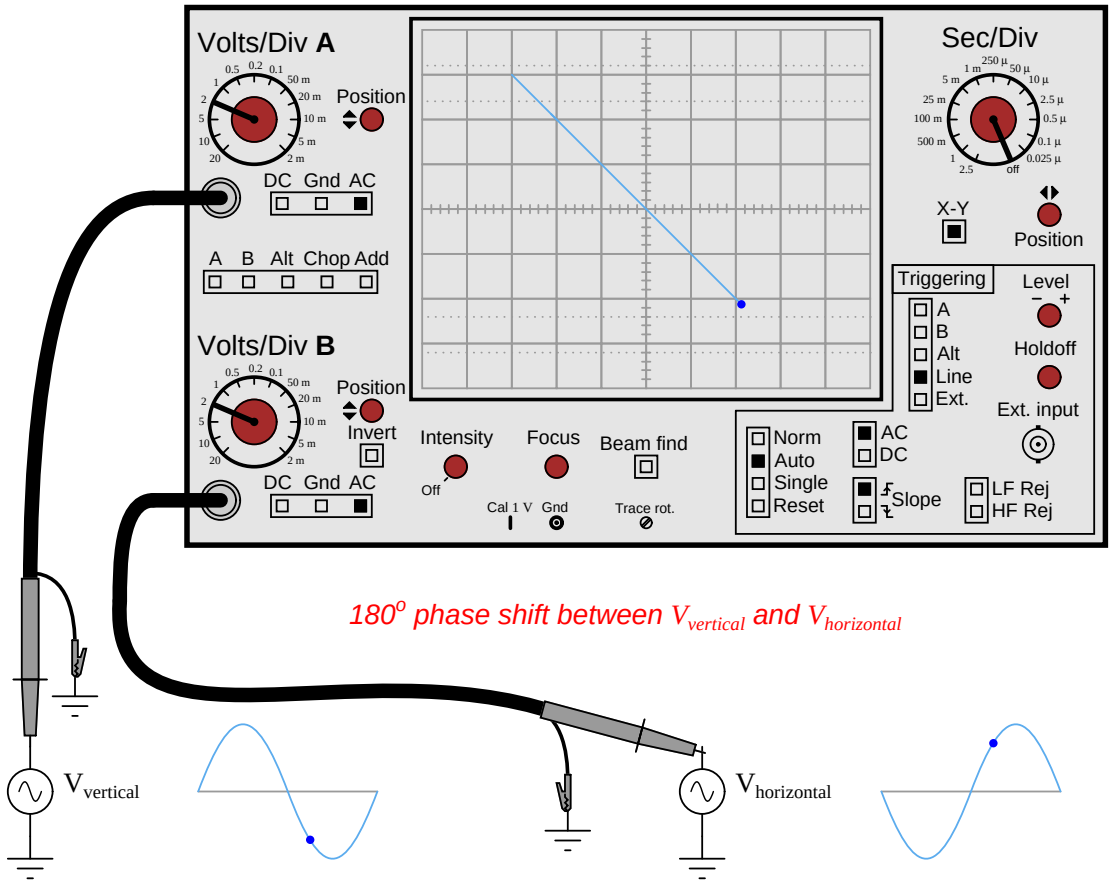

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
180º phase shift between V vertical and V horizontal
V vertical
V horizontal

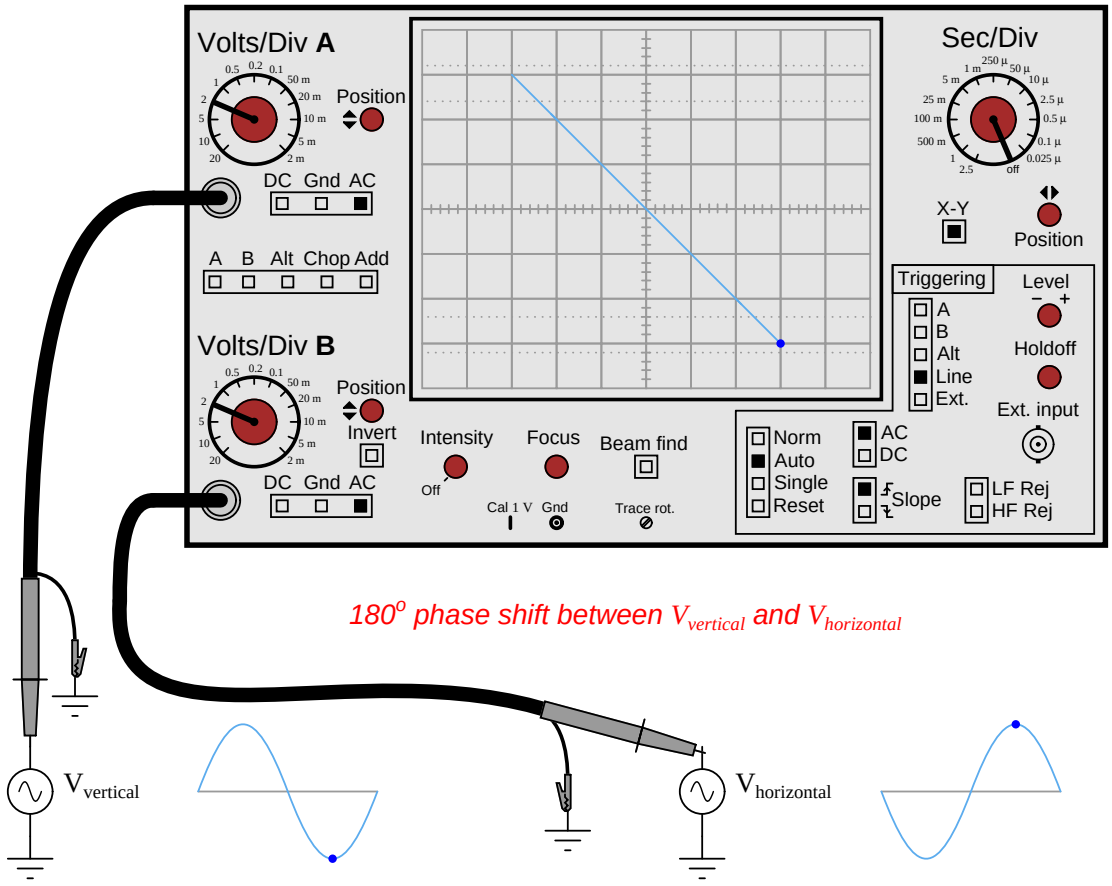

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
180° phase shift between V vertical and V horizontal
V vertical
V horizontal

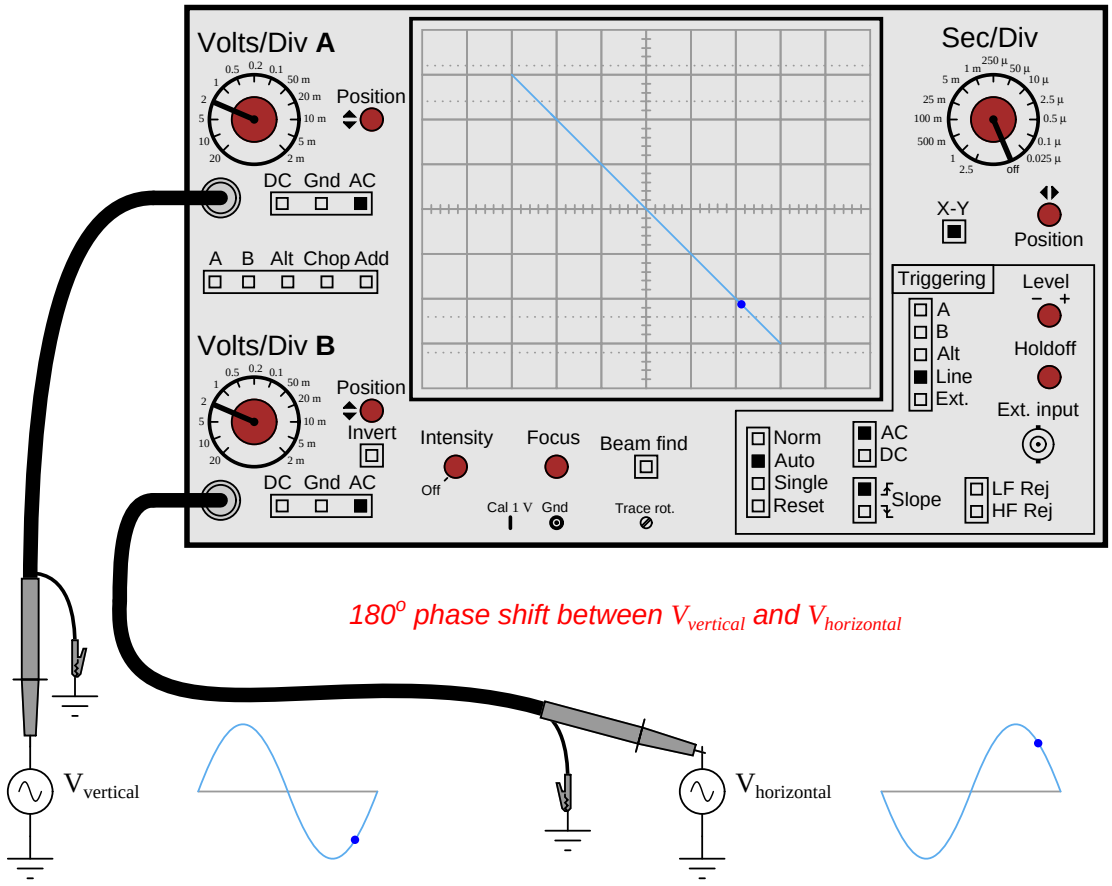

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
180º phase shift between V vertical and V horizontal
V vertical
V horizontal

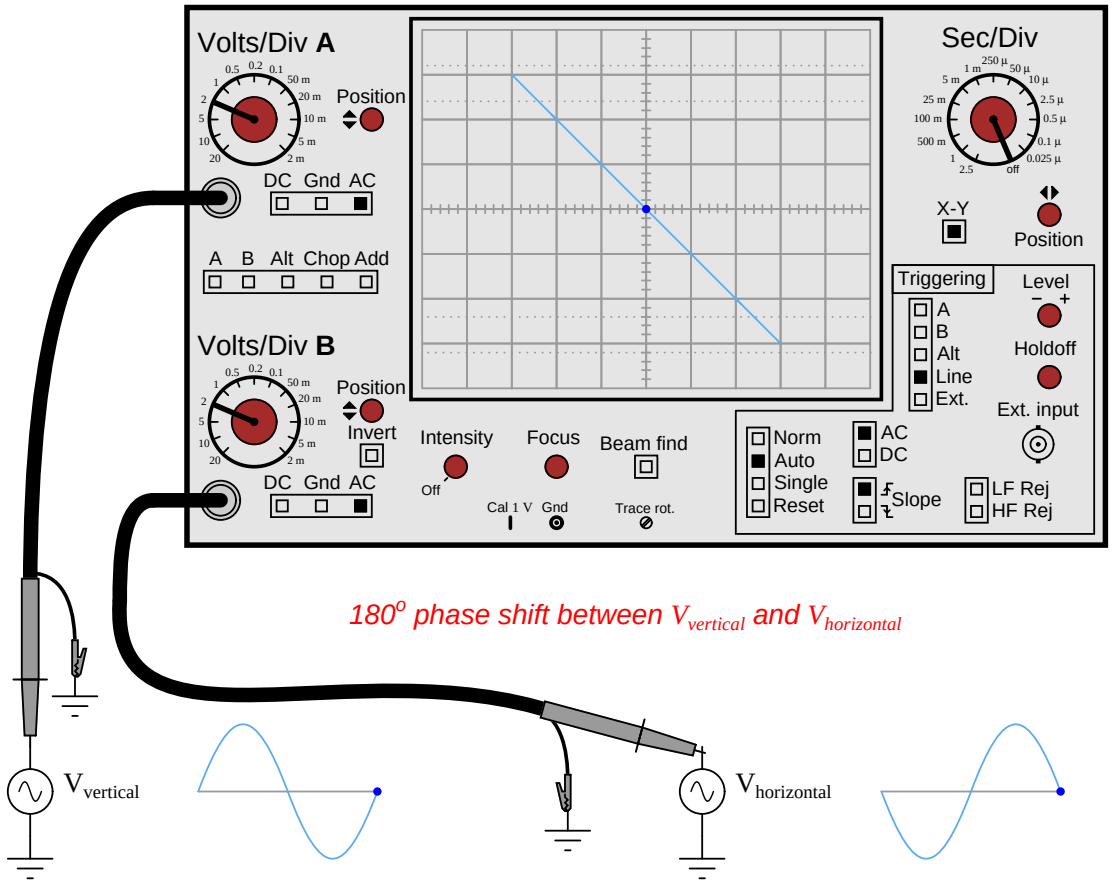

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Cal 1 V Gnd
Beam find
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
180° phase shift between V vertical and V horizontal
V vertical
V horizontal


Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
180º phase shift between V vertical and V horizontal
V vertical
V horizontal


Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
180° phase shift between V vertical and V horizontal
V vertical
V horizontal

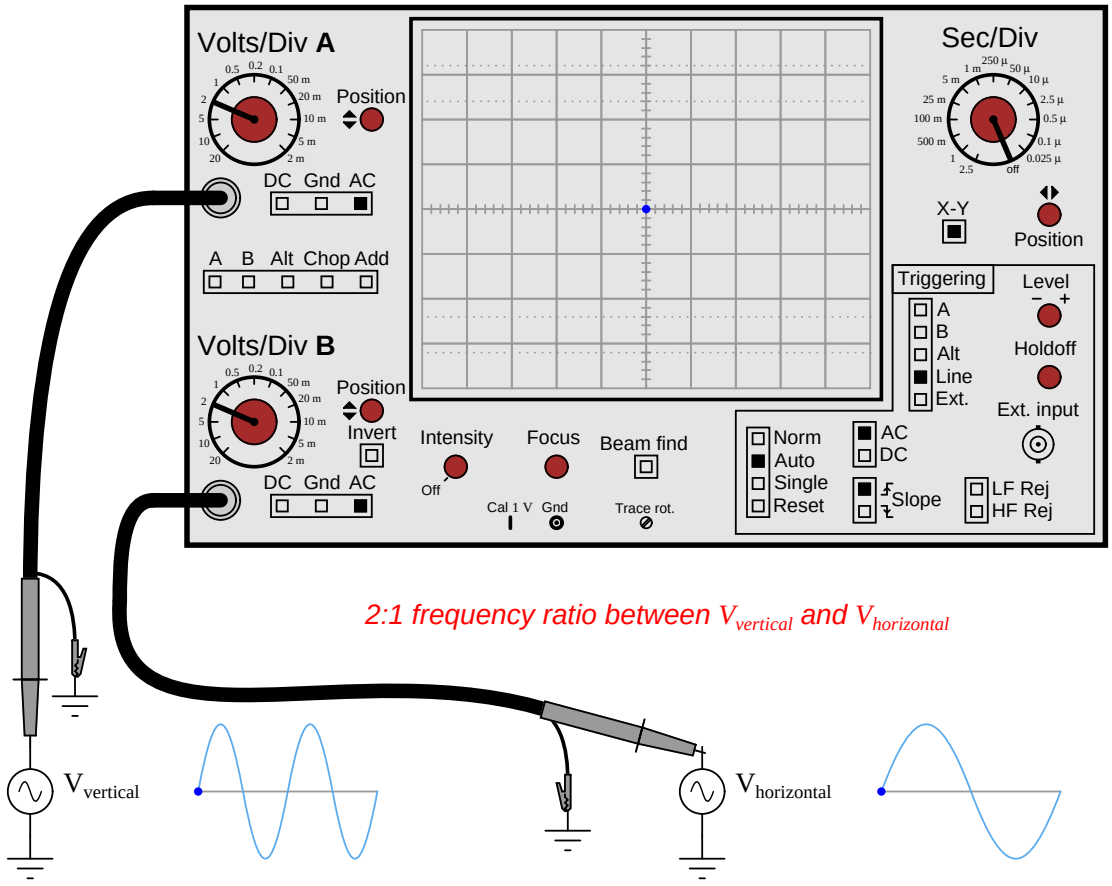

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
180º phase shift between V vertical and V horizontal
V vertical
V horizontal

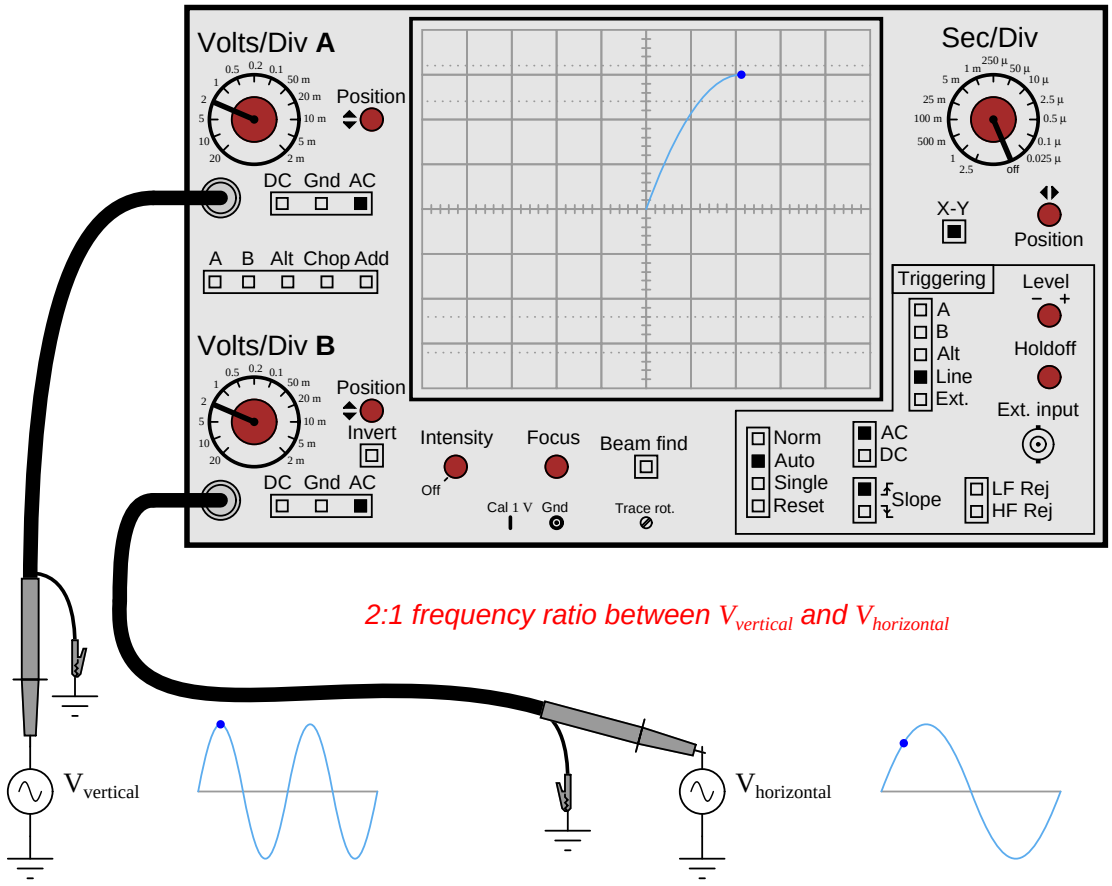

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Cal 1 V Gnd
Beam find
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
180° phase shift between V vertical and V horizontal
V vertical
V horizontal

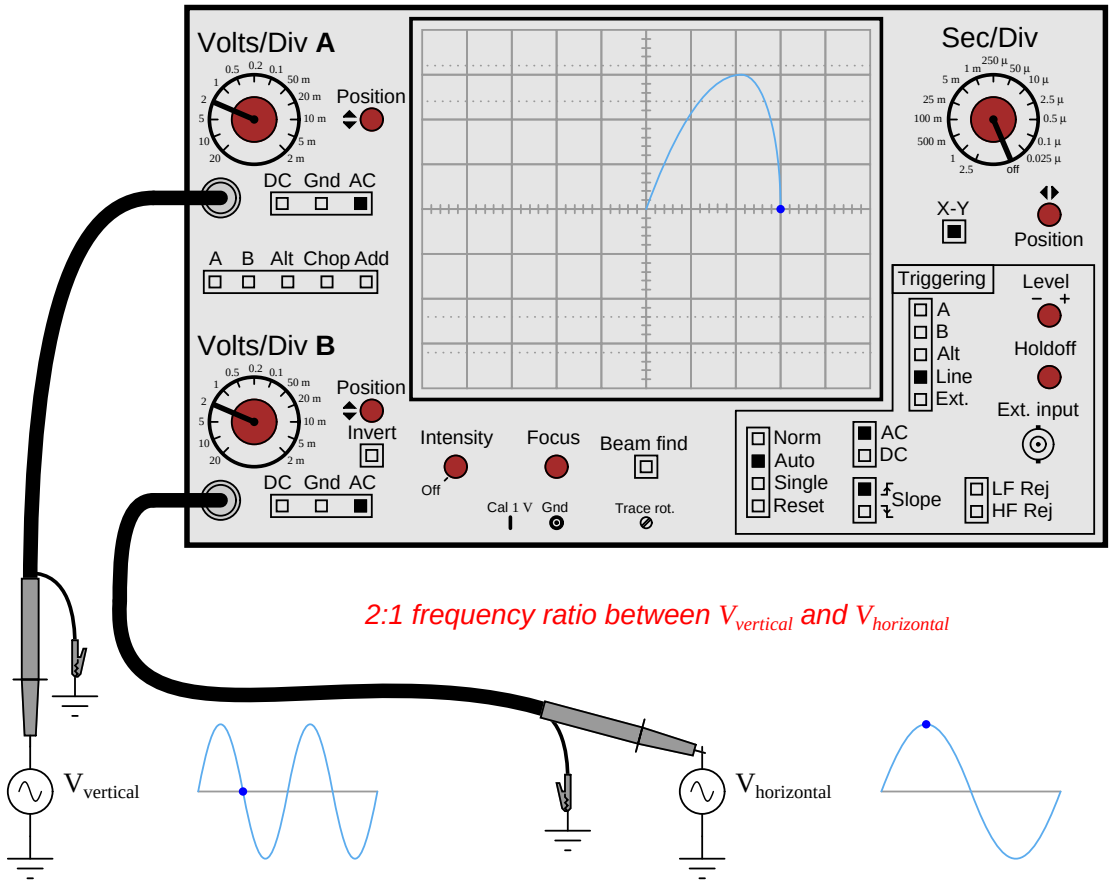

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
180º phase shift between V vertical and V horizontal
V vertical
V horizontal

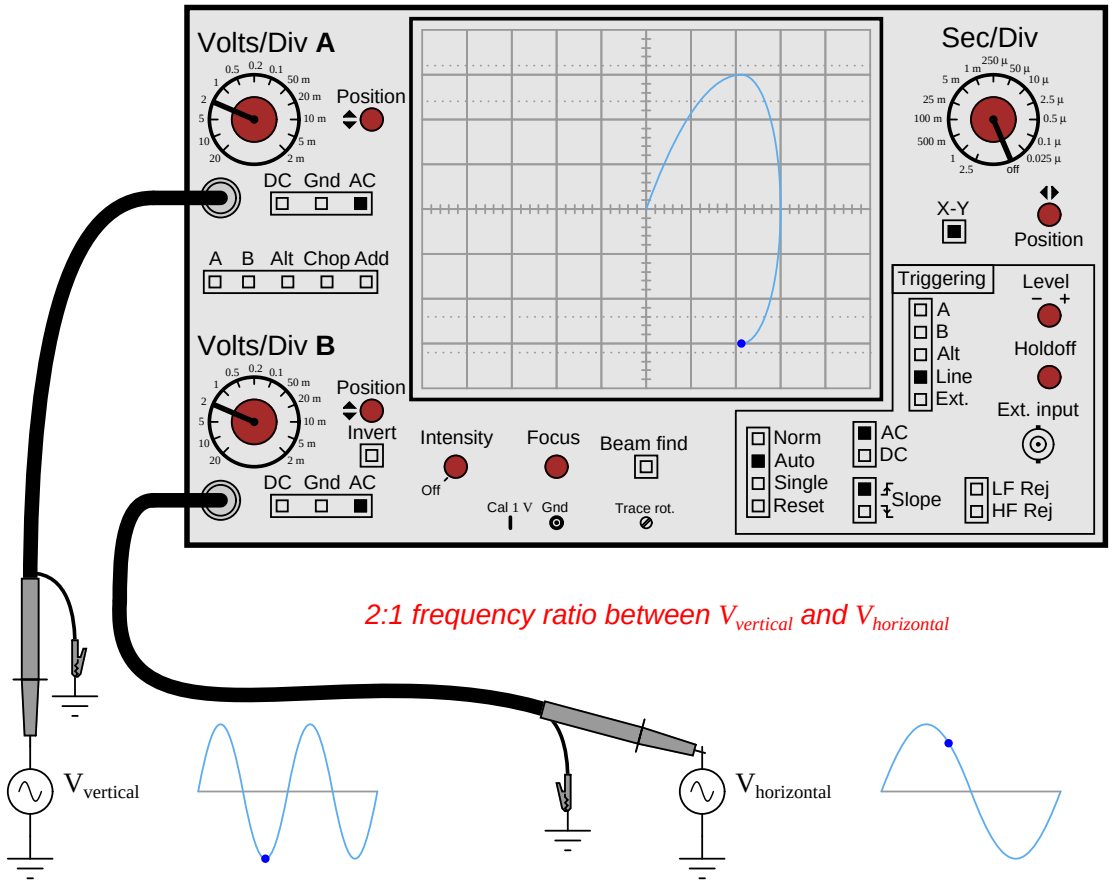
6.4 Lissajous figure with 2:1 frequency ratio

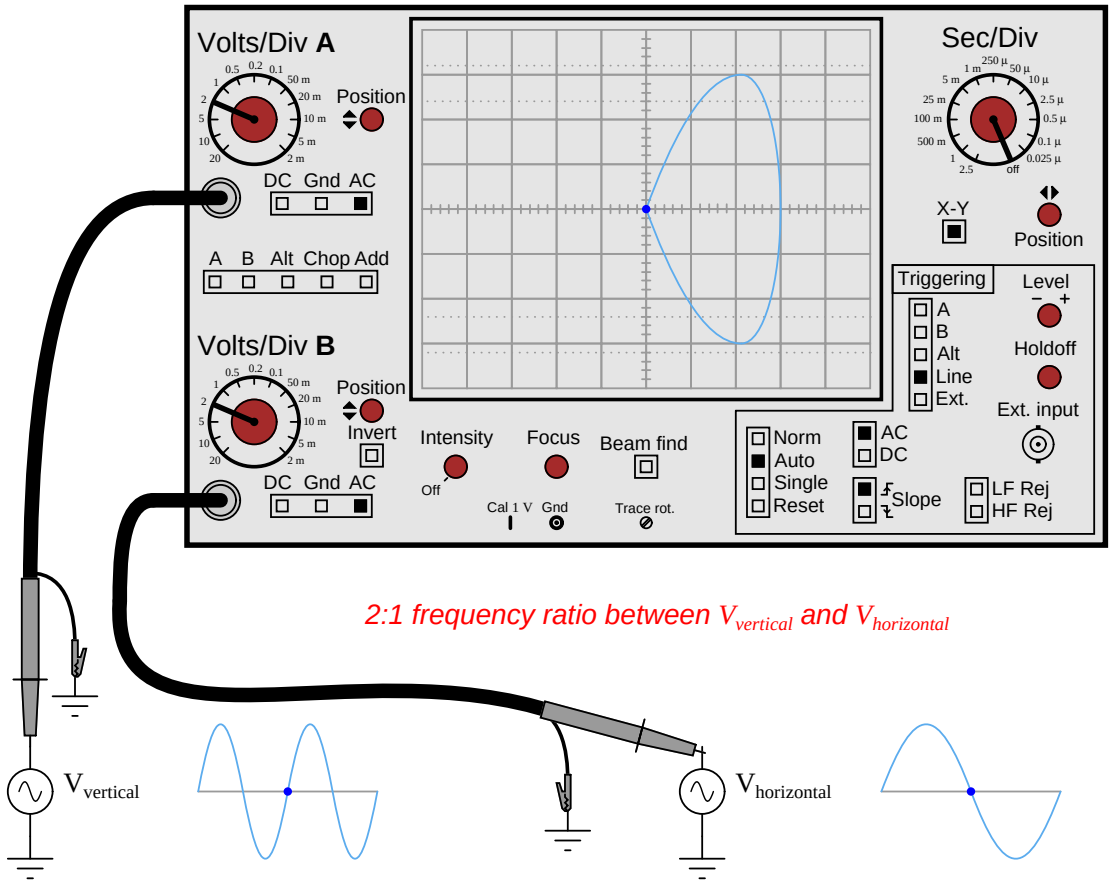
This animation shows a Lissajous figure being formed on the screen of an oscilloscope from two sinusoidal voltage sources with a 2:1 frequency ratio.

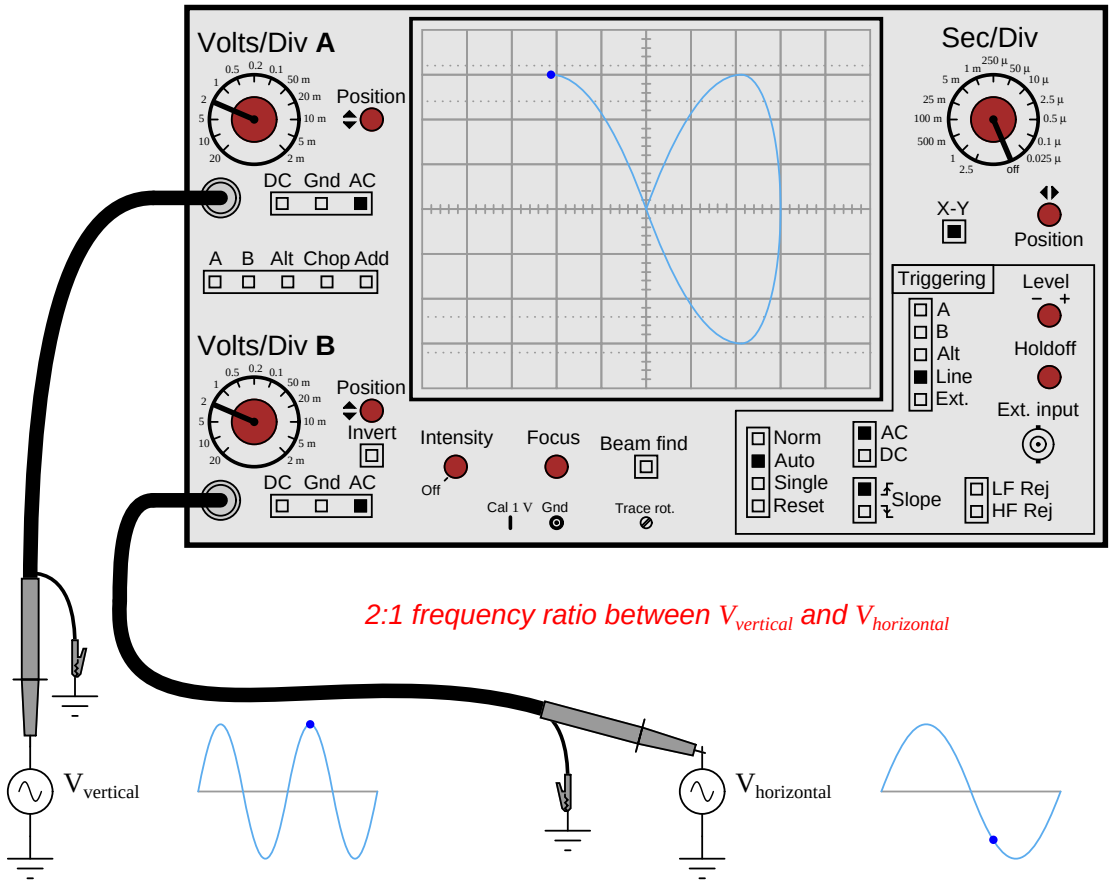

Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V
Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
2:1 frequency ratio between $V_{vertical}$ and $V_{horizontal}$
$V_{vertical}$
$V_{horizontal}$


Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
2:1 frequency ratio between $V_{vertical}$ and $V_{horizontal}$
$V_{vertical}$
$V_{horizontal}$


Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
2:1 frequency ratio between $V_{vertical}$ and $V_{horizontal}$
$V_{vertical}$
$V_{horizontal}$


Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
2:1 frequency ratio between $V_{vertical}$ and $V_{horizontal}$
$V_{vertical}$
$V_{horizontal}$


Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Beam find
Cal 1 V Gnd
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
AC
DC
Slope
LF Rej
HF Rej
2:1 frequency ratio between $V_{vertical}$ and $V_{horizontal}$
$V_{vertical}$
$V_{horizontal}$


Volts/Div A
Position
DC Gnd AC
A B Alt Chop Add
Volts/Div B
Position
Invert
DC Gnd AC
Intensity
Off
Focus
Cal 1 V Gnd
Beam find
Trace rot.
Sec/Div
X-Y
Position
Triggering
A
B
Alt
Line
Ext.
Level
Holdoff
Ext. input
Norm
Auto
Single
Reset
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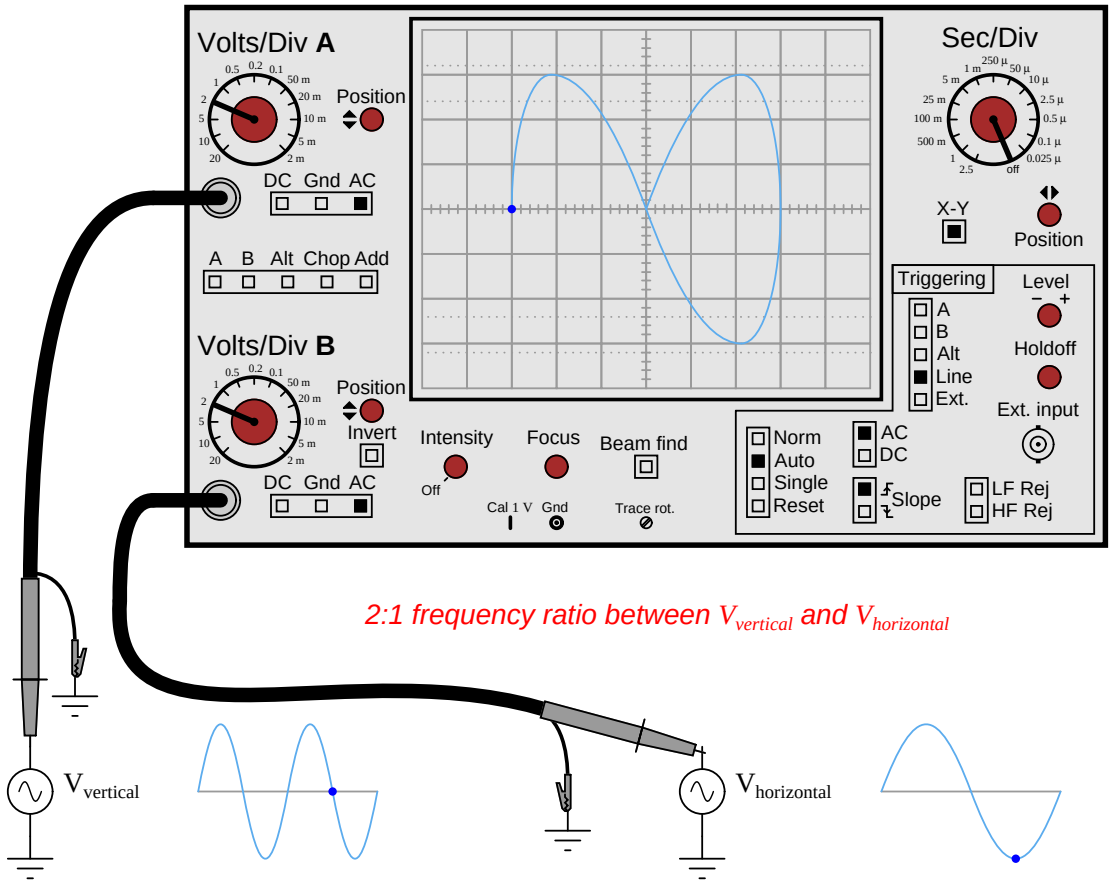
LF Rej
HF Rej
2:1 frequency ratio between $V_{vertical}$ and $V_{horizontal}$
$V_{vertical}$
$V_{horizontal}$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Position
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2:1 frequency ratio between $V_{vertical}$ and $V_{horizontal}$
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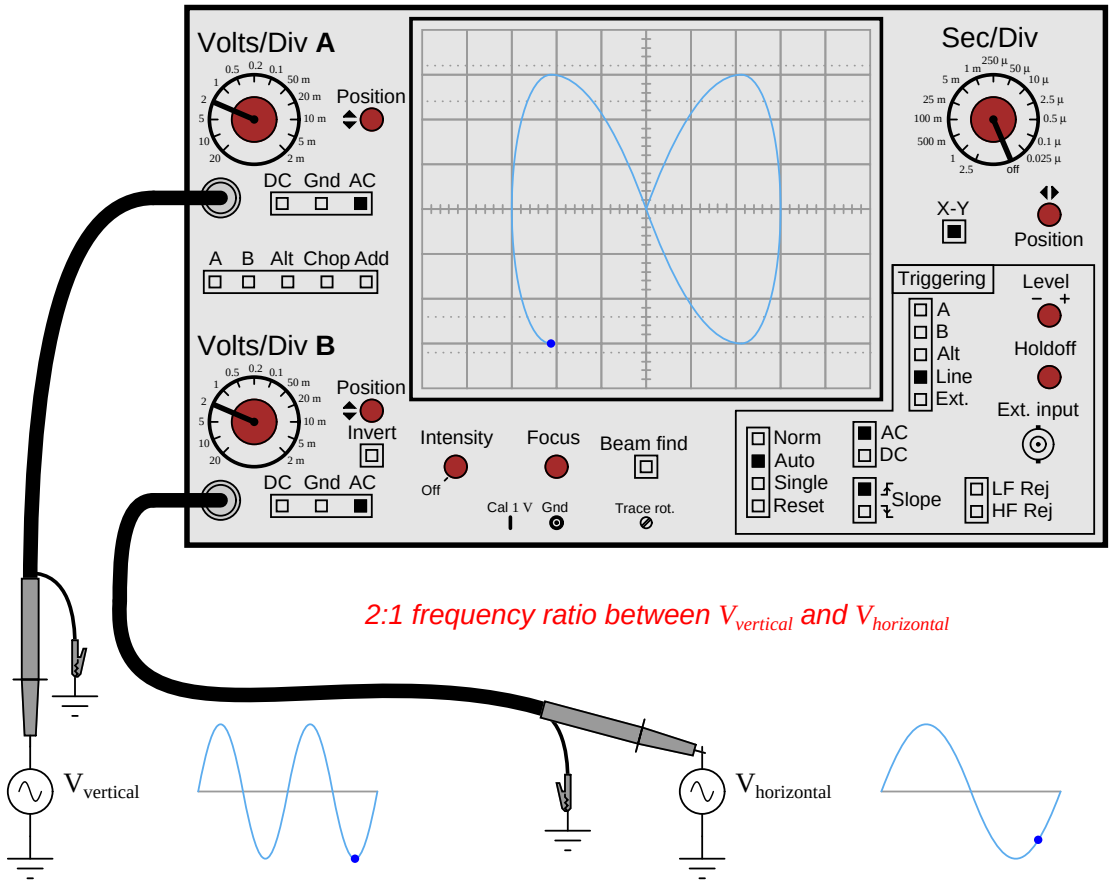
Volts/Div A
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A B Alt Chop Add
Volts/Div B
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DC Gnd AC
Intensity
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Beam find
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2:1 frequency ratio between $V_{vertical}$ and $V_{horizontal}$
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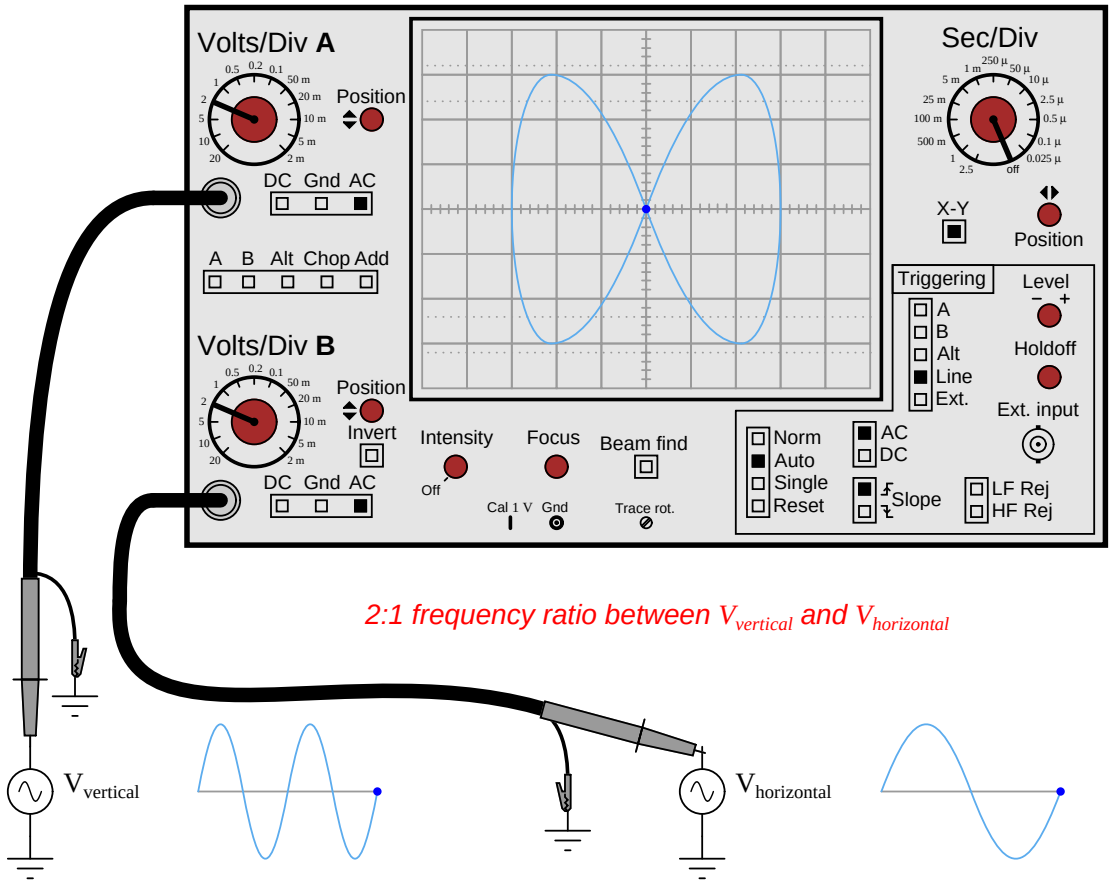
Volts/Div A
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A B Alt Chop Add
Volts/Div B
Position
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DC Gnd AC
Intensity
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Slope
LF Rej
HF Rej
2:1 frequency ratio between $V_{vertical}$ and $V_{horizontal}$
$V_{vertical}$
$V_{horizontal}$

Chapter 7

Questions

7.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking[1]. In a Socratic discussion with your instructor, the goal is for these questions to prompt an extended dialogue where assumptions are revealed, conclusions are tested, and understanding is sharpened. Your instructor may also pose additional questions based on those assigned, in order to further probe and refine your conceptual understanding.

Questions that follow are presented to challenge and probe your understanding of various concepts presented in the tutorial. These questions are intended to serve as a guide for the Socratic dialogue between yourself and the instructor. Your instructor's task is to ensure you have a sound grasp of these concepts, and the questions contained in this document are merely a means to this end. Your instructor may, at his or her discretion, alter or substitute questions for the benefit of tailoring the discussion to each student's needs. The only absolute requirement is that each student is challenged and assessed at a level equal to or greater than that represented by the documented questions.

It is far more important that you convey your *reasoning* than it is to simply convey a correct answer. For this reason, you should refrain from researching other information sources to answer questions. What matters here is that *you* are doing the thinking. If the answer is incorrect, your instructor will work with you to correct it through proper reasoning. A correct answer without an adequate explanation of how you derived that answer is unacceptable, as it does not aid the learning or assessment process.

You will note a conspicuous lack of answers given for these conceptual questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging

[1] *Analytical* thinking involves the "disassembly" of an idea into its constituent parts, analogous to dissection. *Synthetic* thinking involves the "assembly" of a new idea comprised of multiple concepts, analogous to construction. Both activities are high-level cognitive skills, extremely important for effective problem-solving, necessitating frequent challenge and regular practice to fully develop.

questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your conceptual answers, where applicable, is to use circuit simulation software to explore the effects of changes made to circuits. For example, if one of these conceptual questions challenges you to predict the effects of altering some component parameter in a circuit, you may check the validity of your work by simulating that same parameter change within software and seeing if the results agree.

7.1.1 Outline and reflections on the tutorial

"Reading maketh a full man; conference a ready man; and writing an exact man" – Francis Bacon

Francis Bacon's advice is a blueprint for effective education: reading provides the learner with knowledge, writing focuses the learner's thoughts, and critical dialogue equips the learner to confidently communicate and apply their learning. Independent acquisition and application of knowledge is a powerful skill, well worth the effort to cultivate. To this end, students should read these educational resources closely, journal their own reflections on the reading, and discuss in detail their findings with classmates and instructor(s). You should be able to do all of the following after reading any instructional text:

☑ Briefly SUMMARIZE THE TEXT in the form of a journal entry documenting your learning as you progress through the course of study. Share this summary in dialogue with your classmates and instructor. Journaling is an excellent self-test of thorough reading because you cannot clearly express what you have not read or did not comprehend.

☑ Demonstrate ACTIVE READING STRATEGIES, including verbalizing your impressions as you read, simplifying long passages to convey the same ideas using fewer words, annotating text and illustrations with your own interpretations, working through mathematical examples shown in the text, cross-referencing passages with relevant illustrations and/or other passages, identifying problem-solving strategies applied by the author, etc. Technical reading is a special case of problem-solving, and so these strategies work precisely because they help solve any problem: paying attention to your own thoughts (metacognition), eliminating unnecessary complexities, identifying what makes sense, paying close attention to details, drawing connections between separated facts, and noting the successful strategies of others.

☑ Identify IMPORTANT THEMES, especially GENERAL LAWS and PRINCIPLES, expounded in the text and express them in the simplest of terms as though you were teaching an intelligent child. This emphasizes connections between related topics and develops your ability to communicate complex ideas to anyone.

☑ Form YOUR OWN QUESTIONS based on the reading, and then pose them to your instructor and classmates for their consideration. Anticipate both correct and incorrect answers, the incorrect answer(s) assuming one or more plausible misconceptions. This helps you view the subject from different perspectives to grasp it more fully.

☑ Devise EXPERIMENTS to test claims presented in the reading, or to disprove misconceptions. Predict possible outcomes of these experiments, and evaluate their meanings: what result(s) would confirm, and what would constitute disproof? Running mental simulations and evaluating results is essential to scientific and diagnostic reasoning.

☑ Specifically identify any points you found CONFUSING. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.

7.1.2 Foundational concepts

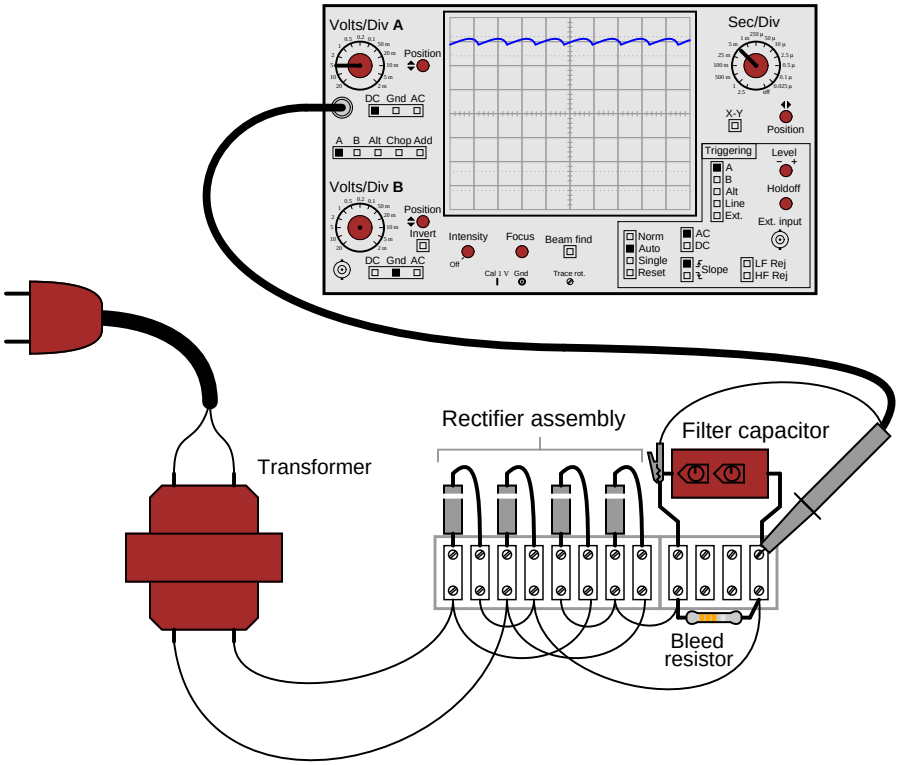
Correct analysis and diagnosis of electric circuits begins with a proper understanding of some basic concepts. The following is a list of some important concepts referenced in this module's tutorial. Define each of them in your own words, and be prepared to illustrate each of these concepts with a description of a practical example and/or a live demonstration.

Voltage

Voltmeter

7.1.3 Measuring ripple voltage

Suppose a technician measures the voltage output by an AC-DC power supply circuit:



The waveform shown by the oscilloscope is mostly DC, with just a little bit of AC "ripple" voltage appearing as a ripple pattern on what would otherwise be a straight, horizontal line. This is quite normal for the output of an AC-DC power supply.

Suppose we wished to take a closer view of this "ripple" voltage. We want to make the ripples more pronounced on the screen, so that we may better discern their shape. Unfortunately, though, when we decrease the number of Volts per division on the "vertical" control knob to magnify the vertical amplification of the oscilloscope, the pattern completely disappears from the screen!

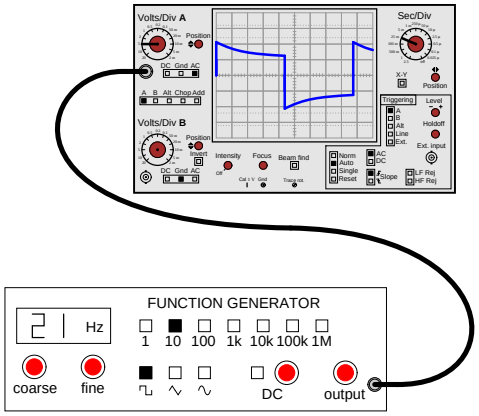
Explain what the problem is, and how we might correct it so as to be able to magnify the ripple voltage waveform without having it disappear off the oscilloscope screen.

Challenges

- Predict the *frequency* of the ripple voltage in this power supply circuit.

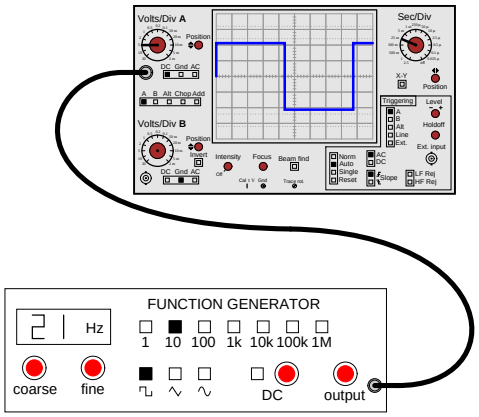
7.1.4 Distorted square wave

A student just learning to use oscilloscopes connects one directly to the output of a signal generator, with these results:



As you can see, the function generator is configured to output a square wave, but the oscilloscope does not register a square wave.

Perplexed, the student takes the function generator to a different oscilloscope. At the second oscilloscope, the student sees a proper square wave on the screen:



It is then that the student realizes the first oscilloscope has its "coupling" control set to AC, while the second oscilloscope was set to DC. Now the student is really confused! The signal is obviously AC, as it oscillates above and below the centerline of the screen, but yet the "DC" setting appears to give the most accurate results: a true-to-form square wave.

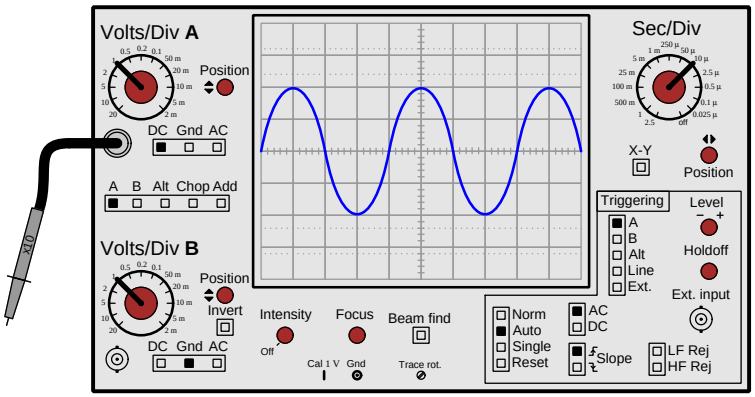
How would you explain what is happening to this student, and also describe the appropriate uses of the "AC" and "DC" coupling settings so he or she knows better how to use it in the future?

Challenges

- Describe a scenario where it would be appropriate to use the AC coupling setting rather than DC.

7.1.5 Uses of a x10 probe

A very common accessory for oscilloscopes is a ×10 probe, which effectively acts as a 10:1 voltage divider for any measured signals. Thus, an oscilloscope showing a waveform with a peak-to-peak amplitude of 4 divisions, with a vertical sensitivity setting of 1 Volt per division, using a ×10 probe, would actually be measuring a signal of *40 Volts* peak-peak:



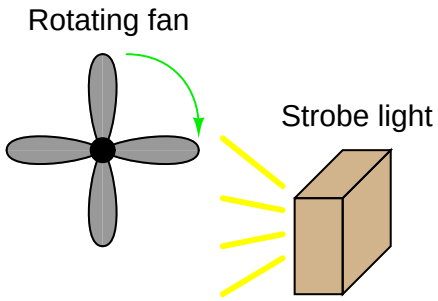
Obviously, one use for a ×10 probe is measuring voltages beyond the normal range of an oscilloscope. However, there is another application that is less obvious, and it regards the input impedance of the oscilloscope. A ×10 probe gives the oscilloscope 10 times more input impedance (as seen from the probe tip to ground). Typically this means an input impedance of 10 MΩ (with the ×10 probe) rather than 1 MΩ (with a normal 1:1 probe). Identify an application where this feature could be useful.

Challenges

- Using a ×10 probe, how much resistive burden does the instrument place on the circuit under test?
- Does the use of a ×10 probe affect the horizontal axis of the oscilloscope's display at all, or just the vertical? Explain why.

7.1.6 Strobe light

A very useful tool for observing rotating objects is a *strobe light*. Basically, a strobe light is nothing more than a very bright flash bulb connected to an electronic pulse generating circuit. The flash bulb periodically emits a bright, brief pulse of light according to the frequency set by the pulse circuit. By setting the period of a strobe light to the period of a rotating object (so the bulb flashes once per revolution of the object), the object will appear to any human observer to be still rather than rotating:

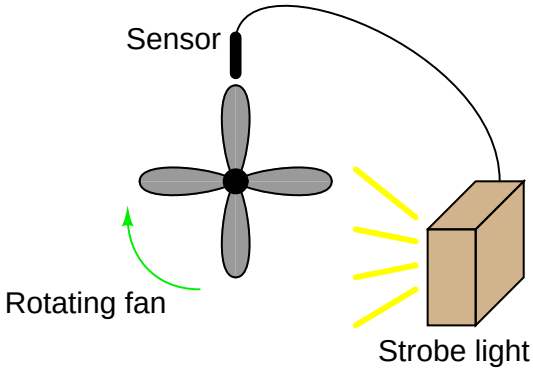


One problem with using a strobe light is that the frequency of the light pulses must exactly match the frequency of the object's rotation, or else the object will not appear to stand still. If the flash rate is mismatched, even by the slightest amount, the object will appear to *slowly* rotate instead of stand still.

Analog (CRT-based) oscilloscopes are similar in principle. A repetitive waveform appears to "stand still" on the screen despite the fact that the trace is made by a bright dot of light constantly moving across the screen (moving up and down with voltage, and sweeping left to right with time). Explain how the sweep rate of an oscilloscope is analogous to the flash rate of a strobe light.

If an analog oscilloscope is placed in the "free-run" mode, it will exhibit the same frequency mismatch problem as the strobe light: if the sweep rate is not *precisely* matched to the period of the waveform being displayed (or some integer multiple thereof), the waveform will appear to *slowly* scroll horizontally across the oscilloscope screen. Explain why this happens.

Now consider a scenario where the strobe light's flashing is triggered by a sensor detecting the passing of fan blades. How would this apparatus differ in behavior from the one where the strobe light was free-running?



How do these two strobe light scenarios relate to an *oscilloscope*?

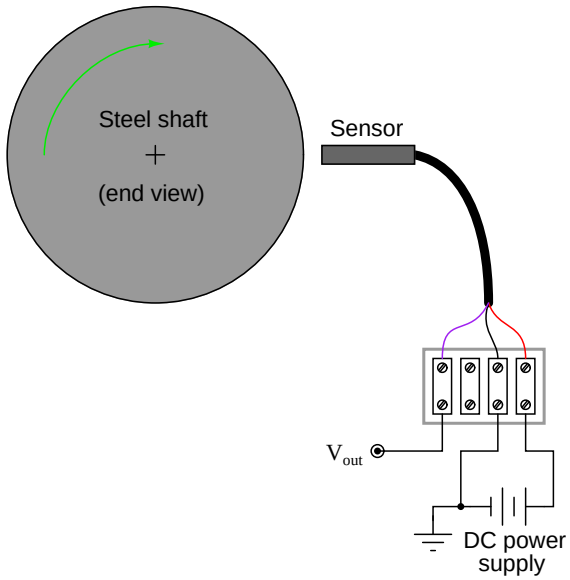
Challenges

- Identify some practical applications of a strobe light.
- Which apparatus (free-running or triggered) most closely resembles a *timing light* of the sort which used to be popular for tuning automobile engines with distributor-based spark ignition?

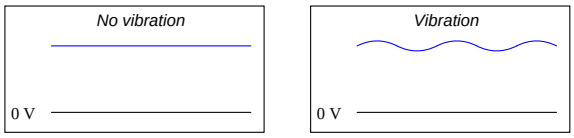
7.1.7 Vibration sensor signal

Large electric motors and other pieces of rotating machinery are often equipped with *vibration sensors* to detect imbalances. These sensors are typically linked to an automatic shutdown system so that the machine will turn itself off it the sensors detect excessive vibration.

Some of the more popular industrial-grade sensors generate a DC voltage proportional to the physical distance between the end of the sensor and the nearest metallic surface. A typical sensor installation might look like this:

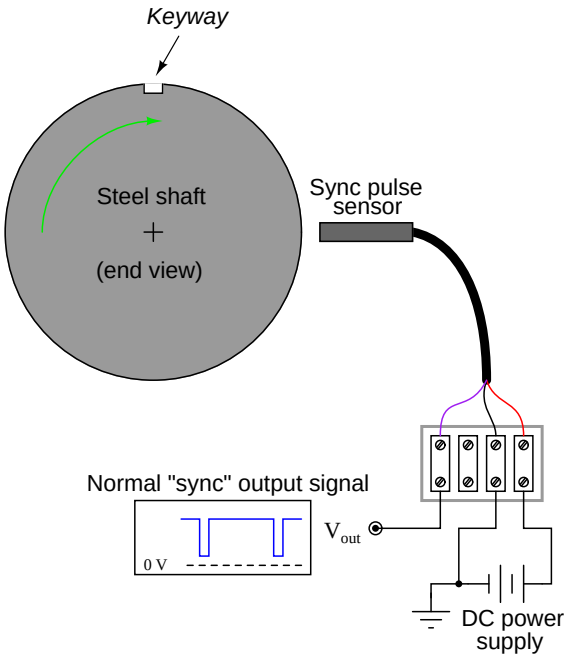


If the machine is running smoothly (or if it is shut down and not turning at all), the output voltage from the sensor will be pure DC, indicating a constant distance between the sensor end and the shaft surface. On the other hand, if the shaft becomes imbalanced it will bend ever so slightly, causing the distance to the sensor tip to periodically fluctuate as it rotates beneath the sensor. The result will be a sensor output signal that is an AC "ripple" superimposed on a DC bias, the frequency of that ripple voltage being equal to the frequency of the shaft's rotation:



The vibration sensing circuitry measures the amplitude of this ripple and initiates a shutdown if it exceeds a pre-determined value.

An additional sensor often provided on large rotating machines is a *sync pulse* sensor. This sensor works just like the other vibration sensors, except that it is intentionally placed in such a position that it "sees" a keyway or other irregularity on the rotating shaft surface. Consequently, the "sync" sensor outputs a square-wave "notch" pulse, once per shaft revolution:



The purpose of this "sync" pulse is to provide an angular reference point, so any vibration peaks seen on any of the other sensor signals may be located relative to the sync pulse. This allows a technician or engineer to determine *where* in the shaft's rotation any peaks are originating.

Your question is this: explain how you would use the sync pulse output to trigger an oscilloscope, so that every sweep of the electron beam across the oscilloscope's screen begins at that point in time.

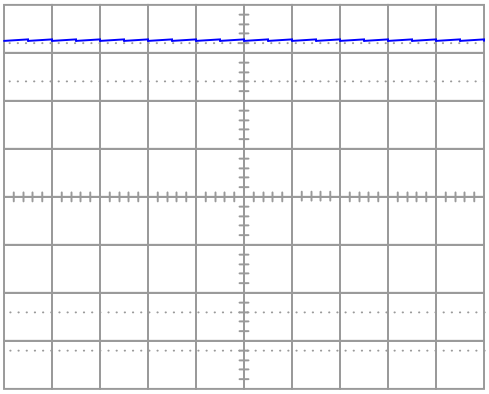
Challenges

- In vibration measurement lingo, the *sync pulse* is often referred to as a *keyphasor*. Explain why this is an appropriate term to describe this signal's purpose.

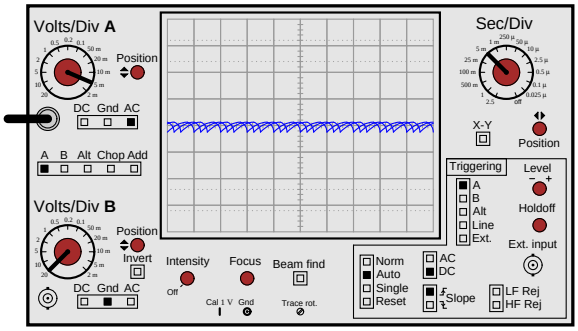
7.1.8 Sudden loss of triggering

A student wants to measure the "ripple" voltage from an AC-DC power supply. This is the small AC voltage superimposed on the DC output of the power supply, that is a natural consequence of AC-to-DC conversion. In a well-designed power supply, this "ripple" voltage is minimal, usually in the range of milliVolts peak-to-peak even if the DC voltage is 20 Volts or more. Displaying this "ripple" voltage on an oscilloscope can be quite a challenge to the new student.

This particular student already knows about the AC/DC coupling controls on the oscilloscope's input. Set to the "DC" coupling mode, the ripple is a barely-visible squiggle on an otherwise straight line:



After switching the input channel's coupling control to "AC", the student increases the vertical sensitivity (fewer Volts per division) to magnify the ripple voltage. The problem is, the ripple waveform is not engaging the oscilloscope's triggering. Instead, all the student sees is a blur as the waveform quickly scrolls horizontally on the screen:



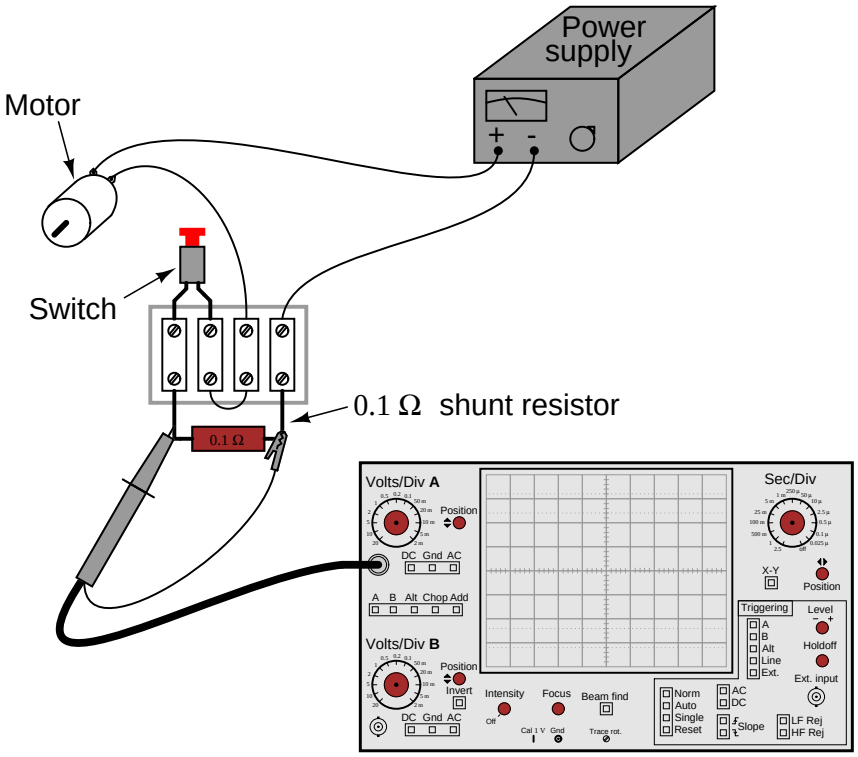
Explain what setting(s) the student can change on the oscilloscope to properly trigger this waveform so it will "hold still" on the screen.

Challenges

- Line-powered oscilloscopes provide at least two different solutions to this particular problem. What is an alternative solution?

7.1.9 Measuring motor inrush current

All electric motors exhibit a large "inrush" current when initially started, due to the complete lack of counter-EMF when the rotor has not yet begun to turn. In some applications it is very important to know how large this transient current is. Shown here is a measurement setup for an oscilloscope to graph the inrush current to a DC motor:



Explain how this circuit configuration enables the oscilloscope to measure motor current, when it plainly is a voltage-measuring instrument.

Also, explain how the oscilloscope may be set up to display only one "sweep" across the screen when the motor is started, and where the vertical and horizontal sensitivity knobs ought to be set to properly read the inrush current.

Challenges

- How would we determine a good size for the shunt resistor, if we had not been instructed to use 0.1 Ω?
- How would we be able to determine a reasonable timebase setting for the oscilloscope to capture the information we care about?

7.2 Quantitative reasoning

These questions are designed to stimulate your computational thinking. In a Socratic discussion with your instructor, the goal is for these questions to reveal your mathematical approach(es) to problem-solving so that good technique and sound reasoning may be reinforced. Your instructor may also pose additional questions based on those assigned, in order to observe your problem-solving firsthand.

Mental arithmetic and estimations are strongly encouraged for all calculations, because without these abilities you will be unable to readily detect errors caused by calculator misuse (e.g. keystroke errors).

You will note a conspicuous lack of answers given for these quantitative questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. My advice is to use circuit simulation software such as SPICE to check the correctness of quantitative answers. Refer to those learning modules within this collection focusing on SPICE to see worked examples which you may use directly as practice problems for your own study, and/or as templates you may modify to run your own analyses and generate your own practice problems.

Completely worked example problems found in the Tutorial may also serve as "test cases[2]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[3] on an answer key!

[2] In other words, set up the circuit simulation software to analyze the same circuit examples found in the Tutorial. If the simulated results match the answers shown in the Tutorial, it confirms the simulation has properly run. If the simulated results disagree with the Tutorial's answers, something has been set up incorrectly in the simulation software. Using every Tutorial as practice in this way will quickly develop proficiency in the use of circuit simulation software.

[3] This approach is perfectly in keeping with the instructional philosophy of these learning modules: *teaching students to be self-sufficient thinkers*. Answer keys can be useful, but it is even more useful to your long-term success to have a set of tools on hand for checking your own work, because once you have left school and are on your own, there will no longer be "answer keys" available for the problems you will have to solve.

7.2.1 Miscellaneous physical constants

Note: constants shown in **bold** type are *exact*, not approximations. Values inside of parentheses show one standard deviation (σ) of uncertainty in the final digits: for example, the magnetic permeability of free space value given as $1.25663706212(19) \times 10^{-6}$ H/m represents a center value (i.e. the location parameter) of $1.25663706212 \times 10^{-6}$ Henrys per meter with one standard deviation of uncertainty equal to $0.0000000000019 \times 10^{-6}$ Henrys per meter.

Avogadro's number (N_A) = **6.02214076** $\times 10^{23}$ **per mole** (mol^{-1})

Boltzmann's constant (k) = **1.380649** $\times 10^{-23}$ **Joules per Kelvin** (J/K)

Electronic charge (e) = **1.602176634** $\times 10^{-19}$ **Coulomb** (C)

Faraday constant (F) = **96,485.33212...** $\times 10^{4}$ **Coulombs per mole** (C/mol)

Magnetic permeability of free space (μ_0) = $1.25663706212(19) \times 10^{-6}$ Henrys per meter (H/m)

Electric permittivity of free space (ϵ_0) = $8.8541878128(13) \times 10^{-12}$ Farads per meter (F/m)

Characteristic impedance of free space (Z_0) = 376.730313668(57) Ohms (Ω)

Gravitational constant (G) = $6.67430(15) \times 10^{-11}$ cubic meters per kilogram-seconds squared ($m^3/kg\text{-}s^2$)

Molar gas constant (R) = **8.314462618... Joules per mole-Kelvin** (J/mol-K) = 0.08205746(14) liters-atmospheres per mole-Kelvin

Planck constant (h) = **6.62607015** $\times 10^{-34}$ **joule-seconds** (J-s)

Stefan-Boltzmann constant (σ) = **5.670374419...** $\times 10^{-8}$ **Watts per square meter-Kelvin**^{4} ($W/m^2 \cdot K^4$)

Speed of light in a vacuum (c) = **299,792,458 meters per second** (m/s) = 186282.4 miles per second (mi/s)

Note: All constants taken from NIST data "Fundamental Physical Constants – Complete Listing", from `http://physics.nist.gov/constants`, National Institute of Standards and Technology (NIST), 2018 CODATA Adjustment.

7.2.2 Introduction to spreadsheets

A powerful computational tool you are encouraged to use in your work is a *spreadsheet*. Available on most personal computers (e.g. Microsoft Excel), *spreadsheet* software performs numerical calculations based on number values and formulae entered into cells of a grid. This grid is typically arranged as lettered columns and numbered rows, with each cell of the grid identified by its column/row coordinates (e.g. cell `B3`, cell `A8`). Each cell may contain a string of text, a number value, or a mathematical formula. The spreadsheet automatically updates the results of all mathematical formulae whenever the entered number values are changed. This means it is possible to set up a spreadsheet to perform a series of calculations on entered data, and those calculations will be re-done by the computer any time the data points are edited in any way.

For example, the following spreadsheet calculates average speed based on entered values of distance traveled and time elapsed:

	A	B	C	D
1	Distance traveled	46.9	Kilometers	
2	Time elapsed	1.18	Hours	
3	Average speed	= B1 / B2	km/h	
4				
5				

Text labels contained in cells `A1` through `A3` and cells `C1` through `C3` exist solely for readability and are not involved in any calculations. Cell `B1` contains a sample distance value while cell `B2` contains a sample time value. The formula for computing speed is contained in cell `B3`. Note how this formula begins with an "equals" symbol (`=`), references the values for distance and speed by lettered column and numbered row coordinates (`B1` and `B2`), and uses a forward slash symbol for division (`/`). The coordinates `B1` and `B2` function as *variables*[4] would in an algebraic formula.

When this spreadsheet is executed, the numerical value `39.74576` will appear in cell `B3` rather than the formula `= B1 / B2`, because 39.74576 is the computed speed value given 46.9 kilometers traveled over a period of 1.18 hours. If a different numerical value for distance is entered into cell `B1` or a different value for time is entered into cell `B2`, cell `B3`'s value will automatically update. All you need to do is set up the given values and any formulae into the spreadsheet, and the computer will do all the calculations for you.

Cell `B3` may be referenced by other formulae in the spreadsheet if desired, since it is a variable just like the given values contained in `B1` and `B2`. This means it is possible to set up an entire chain of calculations, one dependent on the result of another, in order to arrive at a final value. The arrangement of the given data and formulae need not follow any pattern on the grid, which means you may place them anywhere.

[4] Spreadsheets may also provide means to attach text labels to cells for use as variable names (Microsoft Excel simply calls these labels "names"), but for simple spreadsheets such as those shown here it's usually easier just to use the standard coordinate naming for each cell.

Common[5] arithmetic operations available for your use in a spreadsheet include the following:

- Addition (`+`)
- Subtraction (`-`)
- Multiplication (`*`)
- Division (`/`)
- Powers (`^`)
- Square roots (`sqrt()`)
- Logarithms (`ln()` , `log10()`)

Parentheses may be used to ensure[6] proper order of operations within a complex formula. Consider this example of a spreadsheet implementing the *quadratic formula*, used to solve for roots of a polynomial expression in the form of $ax^2 + bx + c$:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

	A	B
1	x_1	= (-B4 + sqrt((B4^2) - (4*B3*B5))) / (2*B3)
2	x_2	= (-B4 - sqrt((B4^2) - (4*B3*B5))) / (2*B3)
3	a =	9
4	b =	5
5	c =	-2

This example is configured to compute roots[7] of the polynomial $9x^2 + 5x - 2$ because the values of 9, 5, and -2 have been inserted into cells `B3`, `B4`, and `B5`, respectively. Once this spreadsheet has been built, though, it may be used to calculate the roots of *any* second-degree polynomial expression simply by entering the new a, b, and c coefficients into cells `B3` through `B5`. The numerical values appearing in cells `B1` and `B2` will be automatically updated by the computer immediately following any changes made to the coefficients.

[5] Modern spreadsheet software offers a bewildering array of mathematical functions you may use in your computations. I recommend you consult the documentation for your particular spreadsheet for information on operations other than those listed here.

[6] Spreadsheet programs, like text-based programming languages, are designed to follow standard order of operations by default. However, my personal preference is to use parentheses even where strictly unnecessary just to make it clear to any other person viewing the formula what the intended order of operations is.

[7] Reviewing some algebra here, a *root* is a value for x that yields an overall value of zero for the polynomial. For this polynomial ($9x^2 + 5x - 2$) the two roots happen to be $x = 0.269381$ and $x = -0.82494$, with these values displayed in cells `B1` and `B2`, respectively upon execution of the spreadsheet.

Alternatively, one could break up the long quadratic formula into smaller pieces like this:

$$y = \sqrt{b^2 - 4ac} \qquad z = 2a$$

$$x = \frac{-b \pm y}{z}$$

	A	B	C
1	x_1	= (-B4 + C1) / C2	= sqrt((B4^2) - (4*B3*B5))
2	x_2	= (-B4 - C1) / C2	= 2*B3
3	a =	9	
4	b =	5	
5	c =	-2	

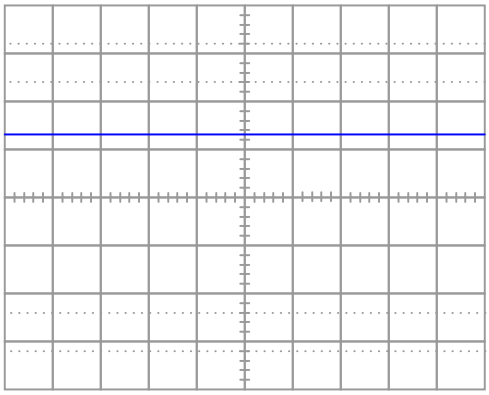
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[8] – all that matters is that they properly reference each other in the formulae.

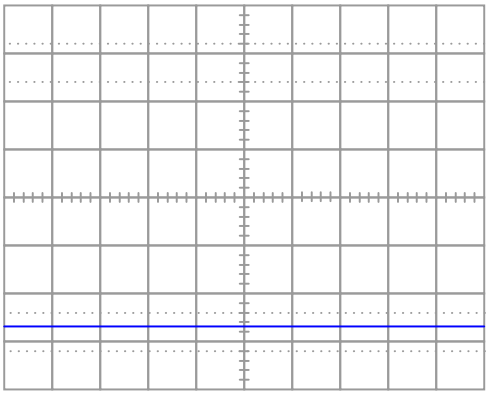
Spreadsheets are particularly useful for situations where the same set of calculations representing a circuit or other system must be repeated for different initial conditions. The power of a spreadsheet is that it automates what would otherwise be a tedious set of calculations. One specific application of this is to simulate the effects of various components within a circuit failing with abnormal values (e.g. a shorted resistor simulated by making its value nearly zero; an open resistor simulated by making its value extremely large). Another application is analyzing the behavior of a circuit design given new components that are out of specification, and/or aging components experiencing drift over time.

[8] My personal preference is to locate all the "given" data in the upper-left cells of the spreadsheet grid (each data point flanked by a sensible name in the cell to the left and units of measurement in the cell to the right as illustrated in the first distance/time spreadsheet example), sometimes coloring them in order to clearly distinguish which cells contain entered data versus which cells contain computed results from formulae. I like to place all formulae in cells below the given data, and try to arrange them in logical order so that anyone examining my spreadsheet will be able to figure out *how* I constructed a solution. This is a general principle I believe all computer programmers should follow: *document and arrange your code to make it easy for other people to learn from it.*

7.2.3 Measuring DC voltages

The following oscilloscope displays are the result of connecting to batteries of unknown voltage. Assuming the oscilloscope display has been properly "zeroed" and the vertical sensitivity is set to 5 Volts per division, determine the voltage of each battery



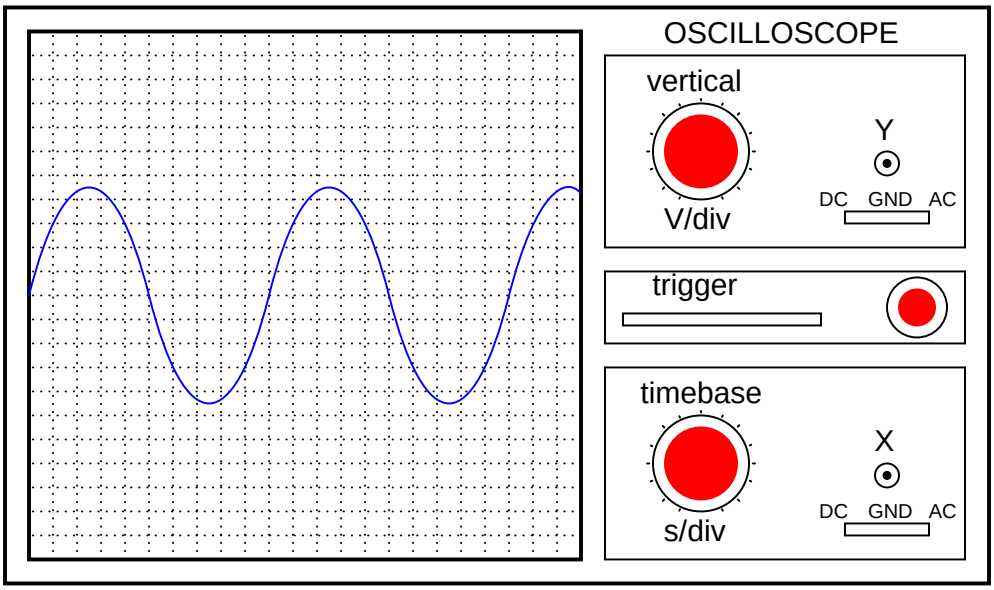


Challenges

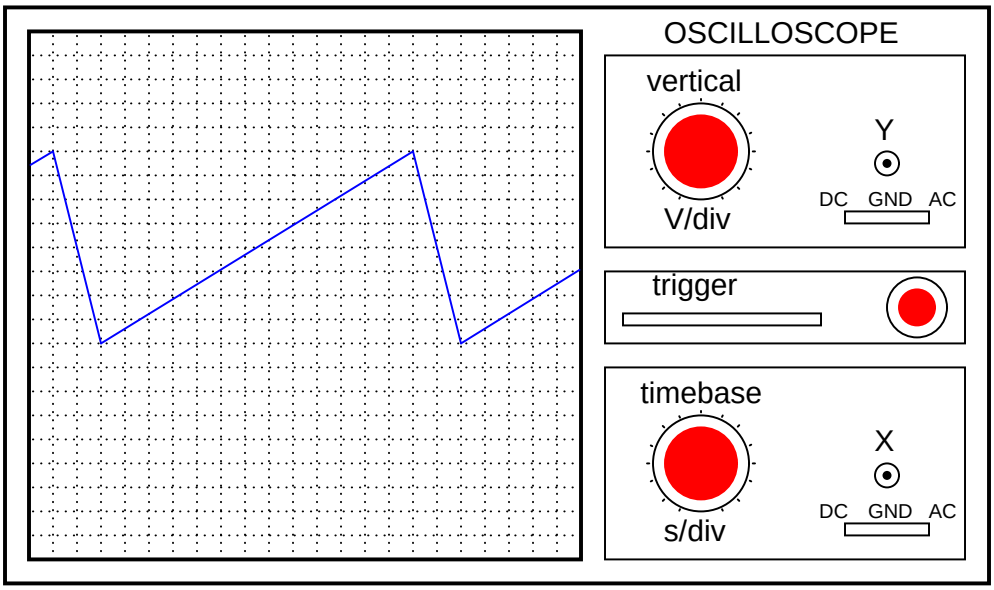
- Why is the oscilloscope's display a flat line?

7.2.4 Measuring AC voltages

Assuming the vertical sensitivity control is set to 0.5 Volts per division, and the timebase control is set to 2.5 ms per division, calculate the amplitude of this sine wave (in Volts peak, Volts peak-to-peak, and Volts RMS) as well as its period and its frequency.



Assuming the vertical sensitivity control is set to 2 Volts per division, and the timebase control is set to 10 μs per division, calculate the amplitude of this "sawtooth" wave (in Volts peak and Volts peak-to-peak) as well as its period and its frequency.



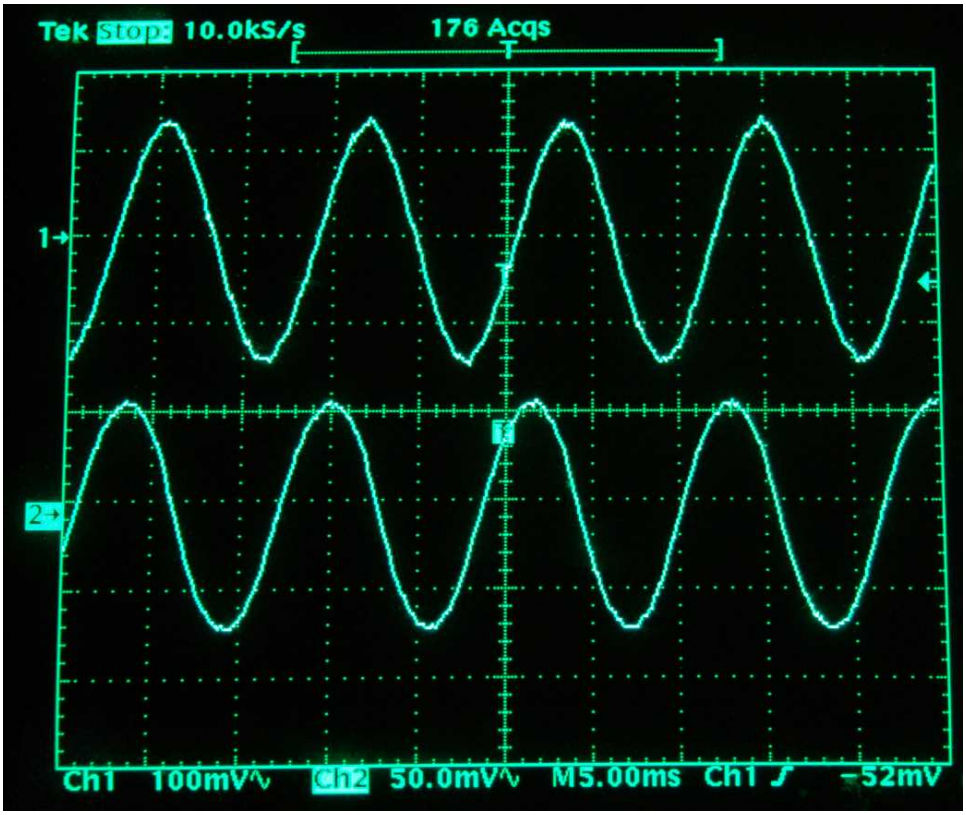
Challenges

- Suppose you were told the oscilloscope probe in each case was set for $\times 10$ operation. How would this affect your determinations of voltage and/or frequency?

7.2.5 Measuring waveform parameters

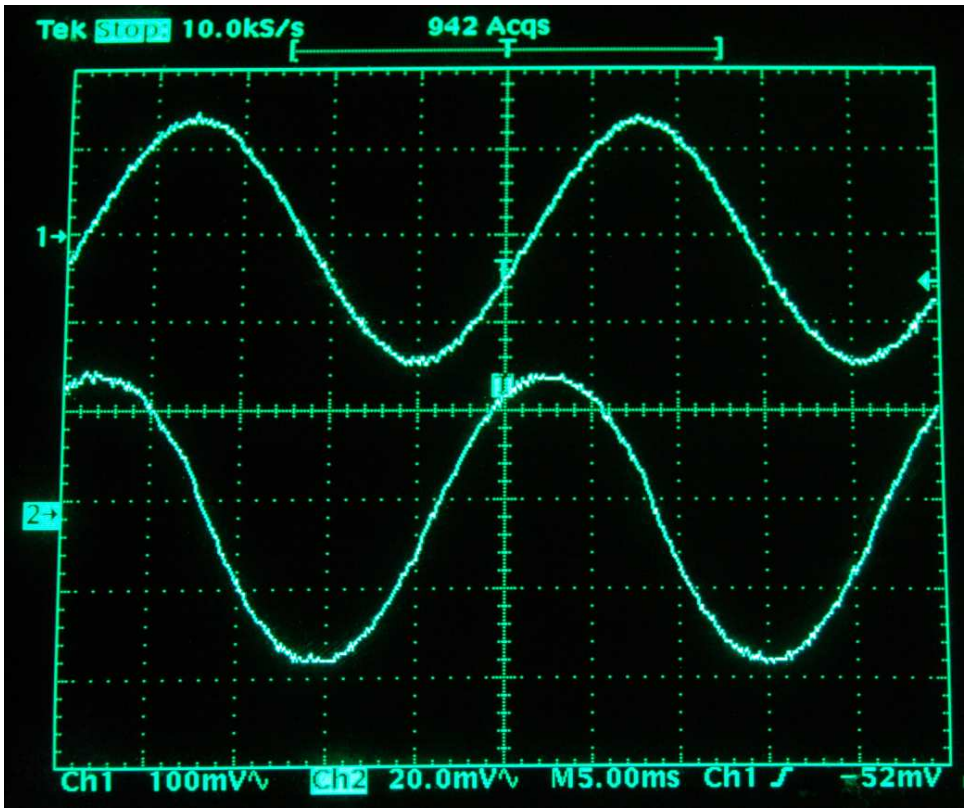
Examine the following oscillographs and determine the listed parameters:

Example #1:



- Signal frequency =
- Channel 1 signal amplitude =
- Channel 2 signal amplitude =
- Phase shift between channels 1 and 2 =
- Channel 1 *leading/lagging* Channel 2 =

Example #2:



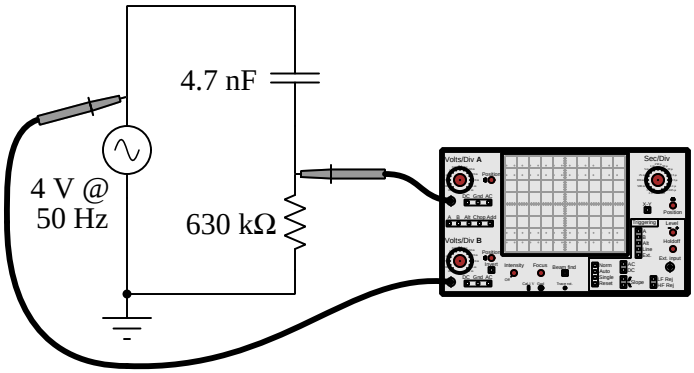
- Signal frequency =
- Channel 1 signal amplitude =
- Channel 2 signal amplitude =
- Phase shift between channels 1 and 2 =
- Channel 1 *leading/lagging* Channel 2 =

Challenges

- Suppose you discovered later that the probe for channel 1 was set to 100:1 instead of 1:1. Which measurements would this affect?

7.2.6 Signal loading

Suppose we wish to connect an oscilloscope across the resistor in this circuit to measure its voltage drop in comparison to the AC source:



Assuming standard 1 MΩ resistive input impedance for the oscilloscope, calculate the voltage magnitudes which will actually be displayed on the oscilloscope, in contrast to their true values with no oscilloscope connected.

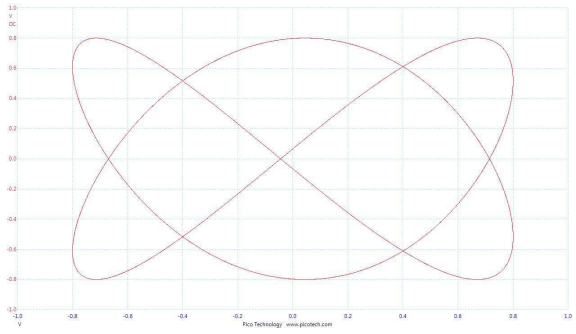
Now, recalculate the measured signal magnitudes assuming both probes are set for $\times 10$ mode.

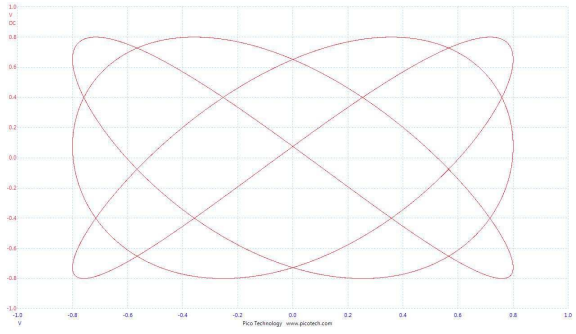
Challenges

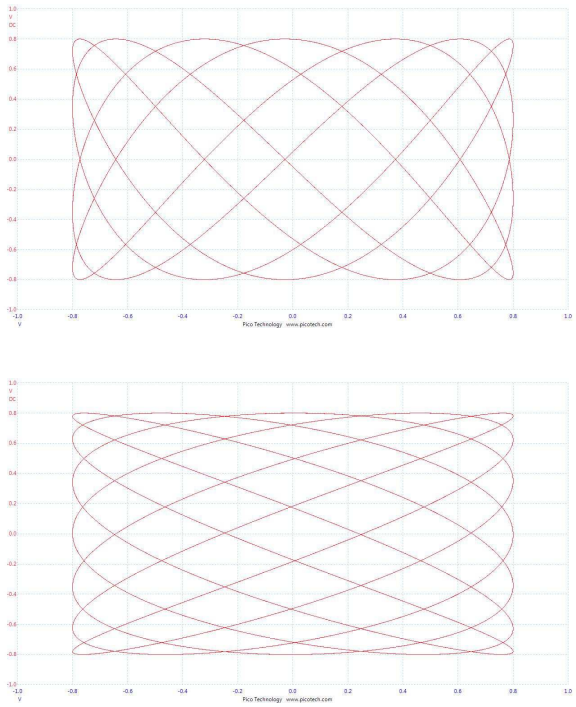
- It is possible for an oscilloscope's loading to only affect voltage magnitude and not phase angle?

7.2.7 Frequency ratios

Examine the following Lissajous figures, and determine the ratio of the two signals' frequencies:







Challenges

- Describe a technique by which you may easily discern the frequency ratio by examination of the Lissajous figure.

7.3 Diagnostic reasoning

These questions are designed to stimulate your deductive and inductive thinking, where you must apply general principles to specific scenarios (deductive) and also derive conclusions about the failed circuit from specific details (inductive). In a Socratic discussion with your instructor, the goal is for these questions to reinforce your recall and use of general circuit principles and also challenge your ability to integrate multiple symptoms into a sensible explanation of what's wrong in a circuit. Your instructor may also pose additional questions based on those assigned, in order to further challenge and sharpen your diagnostic abilities.

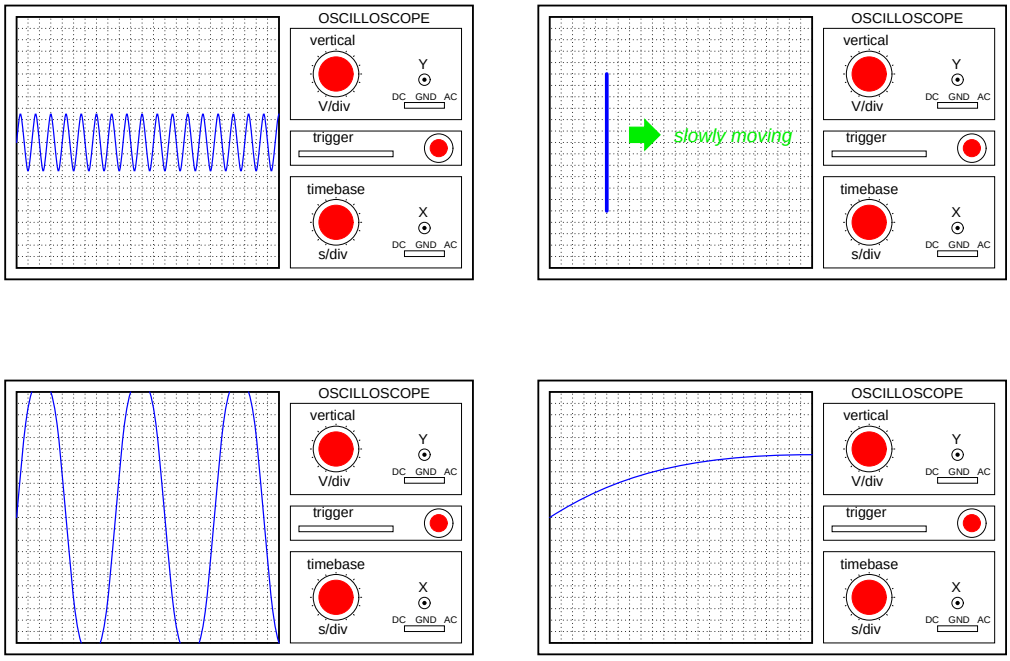
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of the relevant principles and analytical processes in order to ensure you have a strong foundation upon which to build further understanding.

You will note a conspicuous lack of answers given for these diagnostic questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your diagnostic answers, where applicable, is to use circuit simulation software to explore the effects of faults placed in circuits. For example, if one of these diagnostic questions requires that you predict the effect of an open or a short in a circuit, you may check the validity of your work by simulating that same fault (substituting a very high resistance in place of that component for an open, and substituting a very low resistance for a short) within software and seeing if the results agree.

7.3.1 Diagnosing incorrect display settings

In each of the following four oscilloscope screenshots, at least one display setting is improperly set. Ideally, the waveform should fill most of the display, with no more than a few cycles of it visible, in order to capture all the relevant details:

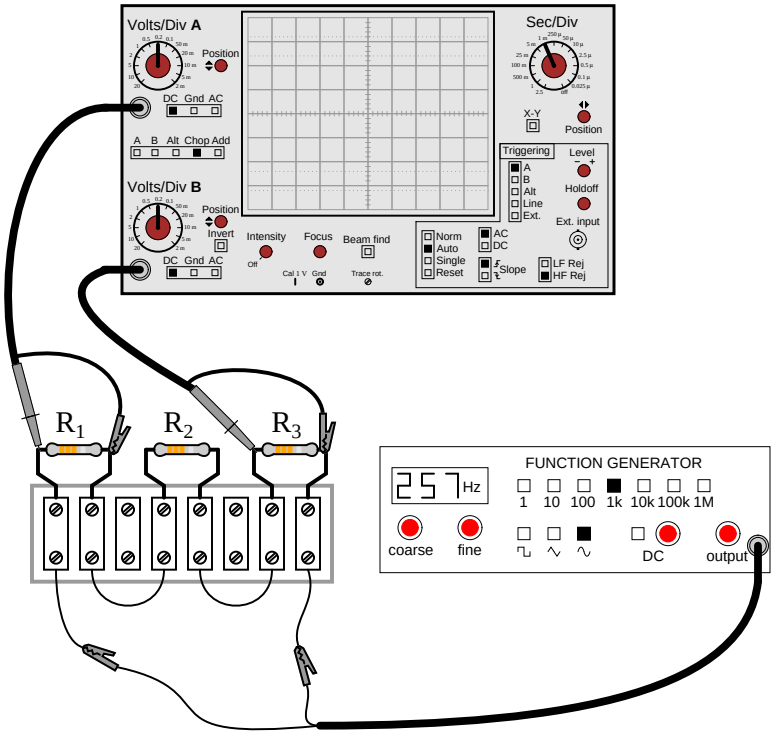


Challenges

- For each of the examples shown, what would the waveform appear as if the Vertical and/or Timebase settings were adjusted even farther in the wrong directions?

7.3.2 Measurement problem in a voltage divider

Explain what sort of problem would be caused by connecting a dual-trace oscilloscope to a circuit in the following manner:



Also, identify how these two signals might be measured without incurring this problem.

Challenges

- If we only measured one voltage drop at a time, would this avoid the measurement problem?

Appendix A

Problem-Solving Strategies

The ability to solve complex problems is arguably one of the most valuable skills one can possess, and this skill is particularly important in any science-based discipline.

- Study principles, not procedures. Don't be satisfied with merely knowing how to compute solutions – learn *why* those solutions work.
- Identify what it is you need to solve, identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and then identify any "missing pieces" to a solution. Annotate all diagrams with this data.
- Sketch a diagram to help visualize the problem. When building a real system, always devise a plan for that system and analyze its function *before* constructing it.
- Follow the units of measurement and meaning of every calculation. If you are ever performing mathematical calculations as part of a problem-solving procedure, and you find yourself unable to apply each and every intermediate result to some aspect of the problem, it means you don't understand what you are doing. Properly done, every mathematical result should have practical meaning for the problem, and not just be an abstract number. You should be able to identify the proper units of measurement for each and every calculated result, and show where that result fits into the problem.
- Perform "thought experiments" to explore the effects of different conditions for theoretical problems. When troubleshooting real systems, perform *diagnostic tests* rather than visually inspecting for faults, the best diagnostic test being the one giving you the most information about the nature and/or location of the fault with the fewest steps.
- Simplify the problem until the solution becomes obvious, and then use that obvious case as a model to follow in solving the more complex version of the problem.
- Check for exceptions to see if your solution is incorrect or incomplete. A good solution will work for *all* known conditions and criteria. A good example of this is the process of testing scientific hypotheses: the task of a scientist is not to find support for a new idea, but rather to *challenge* that new idea to see if it holds up under a battery of tests. The philosophical

principle of *reductio ad absurdum* (i.e. disproving a general idea by finding a specific case where it fails) is useful here.

- Work "backward" from a hypothetical solution to a new set of given conditions.
- Add quantities to problems that are qualitative in nature, because sometimes a little math helps illuminate the scenario.
- Sketch graphs illustrating how variables relate to each other. These may be quantitative (i.e. with realistic number values) or qualitative (i.e. simply showing increases and decreases).
- Treat quantitative problems as qualitative in order to discern the relative magnitudes and/or directions of change of the relevant variables. For example, try determining what happens if a certain variable were to increase or decrease before attempting to precisely calculate quantities: how will each of the dependent variables respond, by increasing, decreasing, or remaining the same as before?
- Consider limiting cases. This works especially well for qualitative problems where you need to determine which direction a variable will change. Take the given condition and magnify that condition to an extreme degree as a way of simplifying the direction of the system's response.
- Check your work. This means regularly testing your conclusions to see if they make sense. This does *not* mean repeating the same steps originally used to obtain the conclusion(s), but rather to use some other means to check validity. Simply repeating procedures often leads to *repeating the same errors* if any were made, which is why alternative paths are better.

Appendix B

Instructional philosophy

B.1 First principles of learning

- **Anyone can learn anything** given appropriate time, effort, resources, challenges, encouragement, and expectations. Dedicating time and investing effort are the student's responsibility; providing resources, challenges, and encouragement are the teacher's responsibility; high expectations are a responsibility shared by both student and teacher.

- **Transfer is not automatic.** The human mind has a natural tendency to compartmentalize information, which means the process of taking knowledge learned in one context and applying it to another usually does not come easy and therefore should never be taken for granted.

- **Learning is iterative.** The human mind rarely learns anything perfectly on the first attempt. Anticipate mistakes and plan for multiple tries to achieve full understanding, using the lessons of those mistakes as feedback to guide future attempts.

- **Information is absorbed, but understanding is created.** Facts and procedures may be memorized easily enough by repeated exposure, but the ability to reliably apply principles to novel scenarios only comes through intense personal effort. This effort is fundamentally creative in nature: casting new concepts in one's own words, running mental experiments to perceive patterns and trends, etc. These acts of making knowledge "one's own" need not be perfect in order to be effective, as the value lies in the activity and not necessarily the finished product. Depth of understanding and permanence of memory are both directly related to mental effort during the learning process – i.e. *easy learning is shallow and fleeting.*

- **Education trumps training.** There is no such thing as an entirely isolated subject, as all fields of knowledge are connected. Training is narrowly-focused and task-oriented. Education is broad-based and principle-oriented. When preparing for a life-long technical career, education beats training every time.

- **Character matters.** Poor habits are more destructive than deficits of knowledge or skill. This is especially true in collective endeavors, where a team's ability to function depends on trust between its members. Simply put, no one wants an untrustworthy person on their team. An essential component of education then, is character development.

- **People learn to be responsible by bearing responsibility.** An irresponsible person is someone who has never *had* to be responsible for anything that mattered enough to them. Just as anyone can learn anything, anyone can become responsible if the personal cost of irresponsibility becomes high enough.

- **What gets measured, gets done.** Accurate and relevant assessment of learning is key to ensuring all students learn. Therefore, it is imperative to measure what matters.

- **Failure is nothing to fear.** Every human being fails, and fails in multiple ways at multiple times. Eventual success only happens when we don't stop trying.

B.2 Proven strategies for instructors

- Assume every student is capable of learning anything they desire given the proper conditions. Treat them as capable adults by granting real responsibility and avoiding artificial incentives such as merit or demerit points.
- Create a consistent culture of high expectations across the entire program of study. Demonstrate and encourage patience, persistence, and a healthy sense of self-skepticism. Anticipate and de-stigmatize error. Teach respect for the capabilities of others as well as respect for one's own fallibility.
- Replace lecture with "inverted" instruction, where students first encounter new concepts through reading and then spend class time in Socratic dialogue with the instructor exploring those concepts and solving problems individually. There is a world of difference between observing someone solve a problem versus actually solving a problem yourself, and so the point of this form of instruction is to place students in a position where they *cannot* passively observe.
- Require students to read extensively, write about what they learn, and dialogue with you and their peers to sharpen their understanding. Apply Francis Bacon's advice that "reading maketh a full man; conference a ready man; and writing an exact man". These are complementary activities helping students expand their confidence and abilities.
- Use artificial intelligence (AI) to challenge student understanding rather than merely provide information. Find productive ways for AI to critique students' clarity of thought and of expression, for example by employing AI as a Socratic-style interlocutor or as a reviewer of students' journals. Properly applied, AI has the ability to expand student access to critical review well outside the bounds of their instructor's reach.
- Build frequent and rapid feedback into the learning process so that students know at all times how well they are learning, to identify problems early and fix them before they grow. Model the intellectual habit of self-assessing and self-correcting your own understanding (i.e. a cognitive *feedback loop*), encouraging students to do the same.
- Use "mastery" as the standard for every assessment, which means the exam or experiment or project must be done with 100% competence in order to pass. Provide students with multiple opportunity for re-tries (different versions of the assessment every time).
- Require students to devise their own hypotheses and procedures on all experiments, so that the process is truly a scientific one. Have students assess their proposed experimental procedures for risk and devise mitigations for those risks. Let nothing be pre-designed about students' experiments other than a stated task (i.e. what principle the experiment shall test) at the start and a set of demonstrable knowledge and skill objectives at the end.
- Have students build as much of their lab equipment as possible: building power sources, building test assemblies[1], and building complete working systems (no kits!). In order to provide

[1] In the program I teach, every student builds their own "Development Board" consisting of a metal chassis with DIN rail, terminal blocks, and an AC-DC power supply of their own making which functions as a portable lab environment they can use at school as well as take home.

this same "ground-up" experience for every new student, this means either previous students take their creations with them, or the systems get disassembled in preparation for the new students, or the systems grow and evolve with each new student group.

- Incorporate external accountability for you and for your students, continuously improving the curriculum and your instructional methods based on proven results. Have students regularly network with active professionals through participation in advisory committee meetings, service projects, tours, jobshadows, internships, etc. Practical suggestions include requiring students to design and build projects for external clients (e.g. community groups, businesses, different departments within the institution), and also requiring students attend all technical advisory committee meetings and to dialogue with the industry representatives at those meetings.
- Repeatedly explore difficult-to-learn concepts across multiple courses, so that students have multiple opportunities to build their understanding.
- Relate all new concepts, whenever possible, to previous concepts and to relevant physical laws. Challenge each and every student, every day, to *reason* from concept to concept and to explain the logical connections between. Challenge students to verify their conclusions by multiple approaches (e.g. double-checking their work using different methods). Ask *"Why?"* often.
- Maintain detailed records on each student's performance and share these records privately with them. These records should include academic performance as well as professionally relevant behavioral tendencies.
- Hold mandatory "check-in" meetings between all program faculty and each new student during their first term. Offer these to all other students as an option, except for any students continuing to manifest unprofessional behaviors, poor academic performance, or who have some other need for a face-to-face meeting with faculty.
- Address problems while they are small, before they grow larger. This is equally true for tutoring technical concepts as it is for helping students build professional habits.
- Build rigorous quality control into the curriculum to ensure every student masters every important concept, and that the mastery is retained over time. This includes (1) review questions added to every exam to re-assess knowledge taught in previous terms, (2) cumulative exams at the end of every term to re-assess all important concepts back to the very beginning of the program, and (3) review assessments in practical (hands-on) coursework to ensure critically-important skills were indeed taught and are still retained. What you will find by doing this is that it actually boosts retention of students by ensuring that important knowledge gets taught and is retained over long spans of time. In the absence of such quality control, student learning and retention tends to be spotty and this contributes to drop-out and failure rates later in their education.
- Finally, *never rush learning.* Education is not a race. Give your students ample time to digest complex ideas, as you continually remind yourself of just how long it took you to achieve mastery! Long-term retention and the consistently correct application of concepts are always the result of *focused effort over long periods of time* which means there are no shortcuts to learning.

B.3 Proven strategies for students

The single most important piece of advice I have for any student of any subject is to take responsibility for your own development in all areas of life including mental development. Expecting others in your life to entirely guide your own development is a recipe for disappointment. This is just as true for students enrolled in formal learning institutions as it is for auto-didacts pursuing learning entirely on their own. Learning to think in new ways is key to being able to gainfully use information, to make informed decisions about your life, and to best serve those you care about. With this in mind, I offer the following advice to students:

- **Approach all learning as valuable**. No matter what course you take, no matter who you learn from, no matter the subject, there is something useful in every learning experience. If you don't see the value of every new experience, you are not looking closely enough!
- **Continually challenge yourself**. Let other people take shortcuts and find easy answers to easy problems. The purpose of education is to stretch your mind, in order to shape it into a more powerful tool. This doesn't come by taking the path of least resistance. An excellent analogy for an empowering education is productive physical exercise: becoming stronger, more flexible, and more persistent only comes through intense personal effort.
- **Master the use of language**. This includes reading extensively, writing every day, listening closely, and speaking articulately. To a great extent language channels and empowers thought, so the better you are at wielding language the better you will be at grasping abstract concepts and articulating them not only for your benefit but for others as well.
- **Do not limit yourself to the resources given to you**. Read books that are not on the reading list. Run experiments that aren't assigned to you. Form study groups outside of class. Take an entrepreneurial approach to your own education, as though it were a business you were building for your future benefit.
- **Express and share what you learn**. Take every opportunity to teach what you have learned to others, as this will not only help them but will also strengthen your own understanding[2].
- Realize that **no one can give you understanding**, just as no one can give you physical fitness. These both must be *built*.
- **Above all, recognize that learning is hard work, and that a certain level of frustration is unavoidable**. There are times when you will struggle to grasp some of these concepts, and that struggle is a natural thing. Take heart that it will yield with persistent and varied[3] effort, and never give up! That concepts don't immediately come to you is not a sign of something wrong, but rather of something right: that you have found a worthy challenge!

[2] On a personal note, I was surprised to learn just how much my own understanding of electronics and related subjects was strengthened by becoming a teacher. When you are tasked every day with helping other people grasp complex topics, it catalyzes your own learning by giving you powerful incentives to study, to articulate your thoughts, and to reflect deeply on the process of learning.

[3] As the old saying goes, "Insanity is trying the same thing over and over again, expecting different results." If you find yourself stumped by something in the text, you should attempt a different approach. Alter the thought experiment, change the mathematical parameters, do whatever you can to see the problem in a slightly different light, and then the solution will often present itself more readily.

B.4 Design of these learning modules

"The unexamined circuit is not worth energizing" – Socrates (if he had taught electricity)

These learning modules, although useful for self-study, were designed to be used in a formal learning environment where a subject-matter expert challenges students to digest the content and exercise their critical thinking abilities in the answering of questions and in the construction and testing of working circuits. Every effort has been made to embed the following instructional and assessment philosophies within:

- The first goal of education is to enhance clear and independent thought, in order that every student reach their fullest potential in a highly complex and inter-dependent world. Robust reasoning is *always* more important than particulars of any subject matter, because its application is universal.
- Literacy is fundamental to independent learning and thought because text continues to be the most efficient way to communicate complex ideas over space and time. Those who cannot read with ease are limited in their ability to acquire knowledge and perspective.
- Articulate communication is fundamental to work that is complex and interdisciplinary.
- Faulty assumptions and poor reasoning are best corrected through challenge, not presentation. The rhetorical technique of *reductio ad absurdum* (disproving an assertion by exposing an absurdity) works well to discipline student's minds, not only to correct the problem at hand but also to learn how to detect and correct future errors.
- Important principles should be repeatedly explored and widely applied throughout a course of study, not only to reinforce their importance and help ensure their mastery, but also to showcase the interconnectedness and utility of knowledge.

These learning modules were expressly designed to be used in an "inverted" teaching environment[4] where students first read the introductory and tutorial chapters on their own, then individually attempt to answer the questions and construct working circuits according to the experiment and project guidelines. The instructor never lectures, but instead meets regularly with each individual student to review their progress, answer questions, identify misconceptions, and challenge the student to new depths of understanding through further questioning. Regular meetings between instructor and student should resemble a Socratic[5] dialogue, where questions serve as scalpels to dissect topics and expose assumptions. The student passes each module only after consistently demonstrating their ability to logically analyze and correctly apply all major concepts in each question or project/experiment. The instructor must be vigilant in probing each student's understanding to ensure they are truly *reasoning* and not just *memorizing*. This is why "Challenge" points appear throughout, as prompts for students to think deeper about topics and as starting points for instructor queries. Sometimes these challenge points require additional knowledge that hasn't been covered in the series to answer in full. This is okay, as the major purpose of the Challenges is to stimulate analysis and synthesis on the part of each student.

The instructor must possess enough mastery of the subject matter and awareness of students' reasoning to generate their own follow-up questions to practically any student response. Even completely correct answers given by the student should be challenged by the instructor for the purpose of having students practice articulating their thoughts and defending their reasoning. Conceptual errors committed by the student should be exposed and corrected not by direct instruction, but rather by reducing the errors to an absurdity[6] through well-chosen questions and thought experiments posed by the instructor. Becoming proficient at this style of instruction requires time and dedication, but the positive effects on critical thinking for both student and instructor are spectacular.

An inspection of these learning modules reveals certain unique characteristics. One of these is a bias toward thorough explanations in the tutorial chapters. Without a live instructor to explain concepts and applications to students, the text itself must fulfill this role. This philosophy results in lengthier explanations than what you might typically find in a textbook, each step of the reasoning process fully explained, including footnotes addressing common questions and concerns students raise while learning these concepts. Each tutorial seeks to not only explain each major concept in sufficient detail, but also to explain the logic of each concept and how each may be developed

[4] In a traditional teaching environment, students first encounter new information via *lecture* from an expert, and then independently apply that information via *homework*. In an "inverted" course of study, students first encounter new information via *homework*, and then independently apply that information under the scrutiny of an expert. The expert's role in lecture is to simply *explain*, but the expert's role in an inverted session is to *challenge*, *critique*, and if necessary *explain* where gaps in understanding still exist.

[5] Socrates is a figure in ancient Greek philosophy famous for his unflinching style of questioning. Although he authored no texts, he appears as a character in Plato's many writings. The essence of Socratic philosophy is to leave no question unexamined and no point of view unchallenged. While purists may argue a topic such as electric circuits is too narrow for a true Socratic-style dialogue, I would argue that the essential thought processes involved with scientific reasoning on *any* topic are not far removed from the Socratic ideal, and that students of electricity and electronics would do very well to challenge assumptions, pose thought experiments, identify fallacies, and otherwise employ the arsenal of critical thinking skills modeled by Socrates.

[6] This rhetorical technique is known by the Latin phrase *reductio ad absurdum*. The concept is to expose errors by counter-example, since only one solid counter-example is necessary to disprove a universal claim. As an example of this, consider the common misconception among beginning students of electricity that voltage cannot exist without current. One way to apply *reductio ad absurdum* to this statement is to ask how much current passes through a fully-charged battery connected to nothing (i.e. a clear example of voltage existing without current).

from "first principles". Again, this reflects the goal of developing clear and independent thought in students' minds, by showing how clear and logical thought was used to forge each concept. Students benefit from witnessing a model of clear thinking in action, and these tutorials strive to be just that.

Another feature of these learning modules is that they do not treat topics in isolation. Rather, important concepts are introduced early in the series, and appear repeatedly as stepping-stones toward other concepts in subsequent modules. This helps to avoid the "compartmentalization" of knowledge, demonstrating the inter-connectedness of concepts and simultaneously reinforcing them. Each module is fairly complete in itself, reserving the beginning of its tutorial to a review of foundational concepts.

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

I am indebted to the developers of many open-source software applications in the creation of these learning modules. The following is a list of these applications with some commentary on each.

You will notice a theme common to many of these applications: a bias toward *code*. Although I am by no means an expert programmer in any computer language, I understand and appreciate the flexibility offered by code-based applications where the user (you) enters commands into a plain ASCII text file, which the software then reads and processes to create the final output. Code-based computer applications are by their very nature *extensible*, while WYSIWYG (What You See Is What You Get) applications are generally limited to whatever user interface the developer makes for you.

The `GNU/Linux` computer operating system

> There is so much to be said about Linus Torvalds' `Linux` and Richard Stallman's `GNU` project. First, to credit just these two individuals is to fail to do justice to the *mob* of passionate volunteers who contributed to make this amazing software a reality. I first learned of `Linux` back in 1996, and have been using this operating system on my personal computers almost exclusively since then. It is *free*, it is completely *configurable*, and it permits the continued use of highly efficient `Unix` applications and scripting languages (e.g. shell scripts, Makefiles, `sed`, `awk`) developed over many decades. `Linux` not only provided me with a powerful computing platform, but its open design served to inspire my life's work of creating open-source educational resources.

Bram Moolenaar's `Vim` text editor

> Writing code for any code-based computer application requires a *text editor*, which may be thought of as a word processor strictly limited to outputting plain-ASCII text files. Many good text editors exist, and one's choice of text editor seems to be a deeply personal matter within the programming world. I prefer `Vim` because it operates very similarly to `vi` which is ubiquitous on `Unix`/`Linux` operating systems, and because it may be entirely operated via keyboard (i.e. no mouse required) which makes it fast to use.

Donald Knuth's TEX typesetting system

Developed in the late 1970's and early 1980's by computer scientist extraordinaire Donald Knuth to typeset his multi-volume magnum opus *The Art of Computer Programming*, this software allows the production of formatted text for screen-viewing or paper printing, all by writing plain-text code to describe how the formatted text is supposed to appear. TEX is not just a markup language for documents, but it is also a Turing-complete programming language in and of itself, allowing useful algorithms to be created to control the production of documents. Simply put, TEX *is a programmer's approach to word processing*. Since TEX is controlled by code written in a plain-text file, this means anyone may read that plain-text file to see exactly how the document was created. This openness afforded by the code-based nature of TEX makes it relatively easy to learn how other people have created their own TEX documents. By contrast, examining a beautiful document created in a conventional WYSIWYG word processor such as Microsoft `Word` suggests nothing to the reader about *how* that document was created, or what the user might do to create something similar. As Mr. Knuth himself once quipped, conventional word processing applications should be called WYSIAYG (What You See Is *All* You Get).

Leslie Lamport's LATEX extensions to TEX

Like all true programming languages, TEX is inherently extensible. So, years after the release of TEX to the public, Leslie Lamport decided to create a massive extension allowing easier compilation of book-length documents. The result was LATEX, which is the markup language used to create all ModEL module documents. You could say that TEX is to LATEX as `C` is to `C++`. This means it is permissible to use any and all TEX commands within LATEX source code, and it all still works. Some of the features offered by LATEX that would be challenging to implement in TEX include automatic index and table-of-content creation.

Tim Edwards' `Xcircuit` drafting program

This wonderful program is what I use to create all the schematic diagrams and illustrations (but not photographic images or mathematical plots) throughout the ModEL project. It natively outputs PostScript format which is a true vector graphic format (this is why the images do not pixellate when you zoom in for a closer view), and it is so simple to use that I have never had to read the manual! Object libraries are easy to create for `Xcircuit`, being plain-text files using PostScript programming conventions. Over the years I have collected a large set of object libraries useful for drawing electrical and electronic schematics, pictorial diagrams, and other technical illustrations.

`Gimp` graphic image manipulation program

Essentially an open-source clone of Adobe's `PhotoShop`, I use `Gimp` to resize, crop, and convert file formats for all of the photographic images appearing in the ModEL modules. Although `Gimp` does offer its own scripting language (called `Script-Fu`), I have never had occasion to use it. Thus, my utilization of `Gimp` to merely crop, resize, and convert graphic images is akin to using a sword to slice bread.

`SPICE` circuit simulation program

`SPICE` is to circuit analysis as TEX is to document creation: it is a form of markup language designed to describe a certain object to be processed in plain-ASCII text. When the plain-text "source file" is compiled by the software, it outputs the final result. More modern circuit analysis tools certainly exist, but I prefer `SPICE` for the following reasons: it is *free*, it is *fast*, it is *reliable*, and it is a fantastic tool for *teaching* students of electricity and electronics how to write simple code. I happen to use rather old versions of `SPICE`, version 2g6 being my "go to" application when I only require text-based output. `NGSPICE` (version 26), which is based on Berkeley `SPICE` version 3f5, is used when I require graphical output for such things as time-domain waveforms and Bode plots. In all `SPICE` example netlists I strive to use coding conventions compatible with all `SPICE` versions.

Andrew D. Hwang's `ePiX` mathematical visualization programming library

This amazing project is a `C++` library you may link to any `C/C++` code for the purpose of generating PostScript graphic images of mathematical functions. As a completely free and open-source project, it does all the plotting I would otherwise use a Computer Algebra System (CAS) such as `Mathematica` or `Maple` to do. It should be said that `ePiX` is *not* a Computer Algebra System like `Mathematica` or `Maple`, but merely a mathematical *visualization* tool. In other words, it won't determine integrals for you (you'll have to implement that in your own `C/C++` code!), but it can graph the results, and it does so beautifully. What I really admire about `ePiX` is that it is a `C++` programming library, which means it builds on the existing power and toolset available with that programming language. Mr. Hwang could have probably developed his own stand-alone application for mathematical plotting, but by creating a `C++` library to do the same thing he accomplished something much greater.

`gnuplot` mathematical visualization software

Another open-source tool for mathematical visualization is `gnuplot`. Interestingly, this tool is *not* part of Richard Stallman's GNU project, its name being a coincidence. For this reason the authors prefer "gnu" *not* be capitalized at all to avoid confusion. This is a much "lighter-weight" alternative to a spreadsheet for plotting tabular data, and the fact that it easily outputs directly to an X11 console or a file in a number of different graphical formats (including PostScript) is very helpful. I typically set my `gnuplot` output format to default (X11 on my Linux PC) for quick viewing while I'm developing a visualization, then switch to PostScript file export once the visual is ready to include in the document(s) I'm writing. As with my use of `Gimp` to do rudimentary image editing, my use of `gnuplot` only scratches the surface of its capabilities, but the important points are that it's *free* and that it *works well*.

`Python` programming language

Both Python and C++ find extensive use in these modules as instructional aids and exercises, but I'm listing Python here as a *tool* for myself because I use it almost daily as a *calculator*. If you open a Python interpreter console and type `from math import *` you can type mathematical expressions and have it return results just as you would on a hand calculator. Complex-number (i.e. *phasor*) arithmetic is similarly supported if you include the complex-math library (`from cmath import *`). Examples of this are shown in the Programming References chapter (if included) in each module. Of course, being a fully-featured programming language, Python also supports conditionals, loops, and other structures useful for calculation of quantities. Also, running in a console environment where all entries and returned values show as text in a chronologically-ordered list makes it easy to copy-and-paste those calculations to document exactly how they were performed.

Appendix D

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Appendix E

References

"ABCs of Probes" primer, document EA 60W-6053-14, Tektronix, 2016.

Appendix F

Version history

This is a list showing all significant additions, corrections, and other edits made to this learning module. Each entry is referenced by calendar date in reverse chronological order (newest version first), which appears on the front cover of every learning module for easy reference. Any contributors to this open-source document are listed here as well.

1-3 February 2026 – error corrections courtesy of Wyatt Gleason.

2 September 2025 – error correction courtesy of Elijah Ross, where "possibly only" needed to be changed to "possible only".

3 September 2024 – added a new photograph to the "Triggering" section of the Tutorial showing a good use-case for Line triggering.

26 August 2024 – added another section to the Introduction chapter specifically for challenges related to this module's topic.

27 June 2024 – clarified units of measurement for frequency in the Simplified Tutorial.

24 June 2024 – divided the Introduction chapter into two sections, one for students and one for instructors, and added content to the instructor section recommending learning outcomes and measures.

4 February 2024 – added a new Case Tutorial section on measuring rates of signal change from oscillograph displays.

29-30 January 2024 – added "Example #1" and "Example #2" labels to the two sub-questions of the "Measuring waveform parameters" problem in the Quantative Reasoning section. Also edited parts of the Simplified Tutorial chapter to clarify the measurement of phase shift.

14 November 2023 – changed title of the "Measuring slope" Tutorial section to "Measuring rates of change (slope)".

13 September 2023 – typo correction in the Full Tutorial chapter courtesy of David Mitchell.

5 September 2023 – added questions to the Introduction chapter.

20 July 2023 – added Technical Reference chapter with a section on grounding in electric and electronic circuits, and made some minor edits to the Simplified Tutorial text defining period and frequency. Also added a Case Tutorial chapter with a section on switch bounce and another section on first-day experimental ideas for exploring the function of oscilloscopes.

9 February 2023 – edited several images (image_1813 and others) and text in the "x10 probe compensation" section of the Full Tutorial to show the oscilloscope's internal capacitance as well as cable capacitance. Also added a Full Tutorial section on bandwidth.

31 January 2023 – minor edit to "x10" text label in image_1807, rotating it for better alignment with probe barrel.

28 November 2022 – placed questions at the top of the itemized list in the Introduction chapter prompting students to devise experiments related to the tutorial content.

27 July 2022 – minor edits to the "Triggering" section of the Full Tutorial to avoid readers being confused by references to "CRO" (cathode-ray oscilloscope).

12 May 2022 – added illustration of pulse imperfections, to show one application of an oscilloscope.

13 April 2022 – added some more explanation, including illustrations and photographs, showing the use of a cathode ray-tube oscilloscope in X-Y mode as a curve tracer.

23 January 2022 – added some clarifying text to the Simplified Tutorial on how to measure a waveform's period, and then how to calculate frequency from that period.

3 December 2021 – capitalized one instance of "Volts" that was previously uncapitalized.

29 October 2021 – added reference in the Full Tutorial to the use of a current transformer to measure AC line current.

2 October 2021 – added a new Tutorial section on $\frac{dV}{dt}$ measurement.

8 May 2021 – commented out or deleted empty chapters.

11 February 2021 – corrected several instances where "Ohms" was uncapitalized.

2 February 2021 – replaced all instances of "volts" with "Volts" (capitalization of units).

20 January 2021 – significantly edited the Introduction chapter to make it more suitable as a pre-study guide and to provide cues useful to instructors leading "inverted" teaching sessions.

13 January 2021 – added some sample curve tracer plots for different components.

4 January 2021 – added a Simplified Tutorial chapter, and made minor edits to the Full Tutorial chapter.

13 May 2020 – added questions regarding the interpretation of waveform amplitude and frequency.

20 October 2019 – added multiple animations showing Lissajous figures formed on an oscilloscope.

13 June 2019 – Corrected a silly typographical error in the *sensitivity and coupling* section of the Tutorial, where I defined a voltmeter as a voltmeter.

12 June 2019 – minor edits to some questions.

2 June 2019 – eliminated mathematical × symbol from section titles, because it does not appear correct in certain PDF viewers' electronic table of contents. Also, added questions.

1 June 2019 – added more questions, and made edits to the Tutorial including probe design, probe compensation, and renaming of the Setup section to be more specific to cathode-ray oscilloscopes (CROs). Added new sections on probe compensation and DSO aliasing.

30 May 2019 – added more questions, and added some content to the Tutorial on probe cable AC effects.

29 May 2019 – added questions.

July 2018 – minor edits made to Tutorial.

June 2018 – added section on measuring phase shift between two sinusoidal waves.

July 2017 – capitalized all instances of the word "Earth".

June 2017 – continued development, adding new sections and new content.

May 2017 – document first published (very incomplete).

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