Oscilloscopes

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Chapter 1

Introduction

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:

• 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 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?
CHAPTER 1. INTRODUCTION

• 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 normal, auto, line, and single-sweep triggering modes function?
• 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?

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.
Chapter 2

Simplified Tutorial
2.1 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 having frequencies greater than a few cycles per second (i.e. a few Hertz) 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 oscillograph.
In many applications of electronics it is important to analyze the \textit{shape} traced by a voltage or current over time. One such example is in circuits using voltage \textit{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:

\begin{itemize}
  \item \textit{Ideal pulse}
  \item \textit{Imperfect pulse}
\end{itemize}

Additionally, with a graphing instrument it becomes possible to identify anomalies such as \textit{transients} (i.e. momentary surges) that may either help identify failures and/or can possible cause failures. We may also determine such things as \textit{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.
2.2 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:

![Oscilloscope probe](image)

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:

![Probe tip construction](image)
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.
2.3 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.
2.4 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:
2.4. TIMEBASE AND FREQUENCY MEASUREMENT

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 as shown below:

Supposing this oscilloscope’s timebase is set for 5 millisecond 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, being 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 in Hertz. In the case of the AC signal having a period of 60 milliseconds, its frequency would be 16.67 Hertz.

\[
f = \frac{1}{t_{\text{period}}} = \frac{1}{\left( \frac{60 \text{ ms}}{\text{cycle}} \right)} = \frac{16.67 \text{ cycles}}{\text{s}}
\]
2.5 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:

Channel A = 6 V ∠ -63°

Channel B = 13 V ∠ 0°

Of these measurements, phase shift is the most complex. We see a horizontal displacement of 1.4 divisions (one major division plus two minor divisions) separating the two waves, and we also see a period equal to 8 major divisions. Since we know that one period represents 360° of rotation for the wave, a shift of 1.4 divisions must be \( \frac{1.4}{8} \) of 360 degrees, or 63°.

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. 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° because it is lagging channel B.

\[ f = \frac{1}{0.5 \text{ ms/ division}} = 2000 \text{ Hz} \]

\[ f = \frac{1}{4 \text{ ms/ division}} = 250 \text{ Hz} \]

\[ 8 \text{ div} \times 0.5 \text{ ms/ division} = 4 \text{ ms period} \]

\[ 3 \text{ div} \times 2 \text{ V/ division} = 6 \text{ V peak} \]

\[ 2.6 \text{ div} \times 5 \text{ V/ division} = 13 \text{ V peak} \]

\[ 360° \]

\[ 63° \]

\[ 0° \]

\[ 1.4 \text{ divisions} \]

\[ 8 \text{ major divisions} \]

\[ 360° \]

\[ \frac{1.4}{8} \]

\[ 63° \]

\[ 0° \]

\[ 250 \text{ Hz} \]

\[ 2000 \text{ Hz} \]

\[ \text{To anyone familiar with the use of a strobe light to “freeze” the appearance of a rotating object, this concept should be intuitive. The oscilloscope presents the illusion of a “frozen” waveform on its screen by making sure it begins each re-trace of that wave at the same point in the wave’s evolution.} \]
Chapter 3

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.
3.1 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:

\[ \text{COM} \quad -9.25 \] \[ \text{A} \quad + 
\]

\[ \text{COM} \quad 9.25 \] \[ \text{V} \quad V \]

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:

![Oscillograph Diagram]

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\(^5\).

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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 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 that will deflect the beam from...
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:

![Oscilloscope Illustration](image)

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.

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\(^8\)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.
3.2 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 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.

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:

Positive on measurement, negative on reference drives the dot in the upward direction

Negative on measurement, positive on reference drives the dot in the downward direction
3.2. PROBES

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 to the circuit under test than a simple
1:1 probe, and in doing so incurs less loading\textsuperscript{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\textsuperscript{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 pins and an alligator clip, and it should not be treated as such. Oscilloscope probes

\textsuperscript{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.

\textsuperscript{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.

\textsuperscript{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 added 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 than connecting an oscilloscope’s input to a measured signal.

3.3 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:

![Timebase Knob](image)

This particular oscilloscope provides a timebase adjustment ranging from 0.5 seconds per division to 0.2 microseconds per division. 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.
3.3. TIMEBASE CONTROLS

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):

![CRO Display](image1.png) ![Computer-based Display](image2.png)

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:
3.3. **TIMEBASE CONTROLS**

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 × 0.2 milliseconds/division = 1.0 millisecond. Reciprocating this value to calculate frequency, we get: 1 ÷ (1 millisecond/cycle) = 1000 cycles/second = 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.
3.4 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:

![Grid Image]

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:

![Sensitivity Knob Image]

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.
3.4. SENSITIVITY AND COUPLING

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:

\[
10 \times 3.2 \text{ div} \times \frac{25 \text{ mV}}{\text{div}} = 0.8 \text{ Volts peak}
\]
CHAPTER 3. FULL TUTORIAL

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 connector 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.
3.5 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 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.

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

![Sine wave on oscilloscope screen](image)

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 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 begin at the zero point rather than begin 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
3.6. TRIGGERING

“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.

Single-sweep triggering is useful for CROs with delayed phosphor action and/or the legacy technology of photographic camera capture\textsuperscript{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\textsuperscript{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.

\textsuperscript{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.

\textsuperscript{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:

![Diagram showing holdoff in a digital data frame](image)

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.
3.6. TRIGGERING

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\textsuperscript{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.

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.

\textsuperscript{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.
3.7 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° 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:

![Oscilloscope Display]

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 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:

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

---

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.
3.7. MEASURING PHASE SHIFT

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 multiply that number of divisions by 45°/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 for the two sinusoids. Multiplying 1.4 divisions by 45°/div yields the amount of phase shift between these two AC voltages:

\[
\left(\frac{45^\circ}{\text{div}}\right) (1.4 \text{ div}) = 63^\circ
\]

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) \(\angle 0^\circ\) and that channel A is 6 Volts (peak) \(\angle -63^\circ\).

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

---

\(20\) 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.
CHAPTER 3. FULL TUTORIAL

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° and 360° 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 ($\Delta$) 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. $\Delta t =$ period of the wave).

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

Another important type of measurement possible with an oscilloscope is the \textit{slope} or the \textit{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 \textit{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 \textit{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 the next photograph, the annotations overlaid on the photograph after it was captured on camera:

![Image of oscilloscope waveform with annotations](image)

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 \(\left(+\frac{dV}{dt}\right)\), 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.
3.9 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!
3.9. GROUND-REFERENCING

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.

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.

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

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22It 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.
3.9. GROUND-REFERENCING

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.
3.10 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. 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. Second, when using differential mode, you must have both of the channels’ vertical sensitivity set precisely equal to one another. Modern digital oscilloscopes typically offer a “Math” menu within which you will find this same differential mode as a selectable option.

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.

### 3.11 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* 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.

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25In 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.
3.11.1 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:

![Lissajous Figure Example](image)

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 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.

Since phase shift affects the shape of the Lissajous figure formed by two sinusoidal waveforms, we may use X-Y mode on an oscilloscope to measure phase shift between the two signals.

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26Imagine 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.
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. Feel free to make fine adjustments to the “Cal” knob on the oscilloscope in order to achieve this equality of width and height. 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 \(n\):

\[
\frac{m}{n}
\]

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. If the Lissajous figure is a straight line, \(m\) will be equal to zero and \(\sin^{-1}(0)\) will be equal to zero degrees of phase shift. If the Lissajous figure is a perfect circle, \(m = n\) 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.
3.11. X-Y MODE

Lissajous figures become even more complex when the two signals are not at the same frequency, but 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:

![Lissajous figure screenshot](image)

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.
3.11.2 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:

![Graph of a diode's I/V curve](image)

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:

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:

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.

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\(^{29}\)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 oscilloscope display:

![Oscilloscope Display](image)

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:

![Higher-valued Resistor](image)

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.

---

\[^{30}\text{Without inverting the oscilloscope’s horizontal channel, the line traced by the screen while testing a resistor will have a negative slope rather than a positive slope as shown here.}\]
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\(^\text{31}\), where a grounded signal generator powers the \(R_{\text{shunt}}\) / 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.

\(^\text{31}\)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.
### 3.12 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.
CHAPTER 3. FULL TUTORIAL

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.
3.13  \( x_{10} \) 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 \( \times 10 \) “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 M\( \Omega \)). When engaged, the \( \times 10 \) 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 \( \times 10 \) probe is clear to see in the following diagram, where the oscilloscope input is modeled as a single 1 M\( \Omega \) resistance. In combination with the 9 M\( \Omega \) series resistor, the oscilloscope’s intrinsic 1 M\( \Omega \) 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:

![Diagram of probe compensation](image)

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 \( \times 10 \) 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 the probe cable contains capacitance between its conductors. 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:

\[ V_{\text{input}} \quad (\text{probe tip}) \]

\[ \begin{align*}
9R & \quad \text{(Rprobe)} \\
C & \quad \text{(Ccomp)} \\
R & \quad \text{(Rscope)} \\
9C & \quad \text{(Cable)} \\
V_{\text{scope}} & \quad \text{(scope)}
\end{align*} \]

**Compensation is effective because**

\[ (9R)(C) = (R)(9C) \]

\[ \tau_1 = \tau_2 \]

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 \( X_C = \frac{1}{\pi f C} \). 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:

Capacitor-compensated oscilloscope probes provide variable capacitors for user-adjustment of $C_{\text{comp}}$ to avoid under- and over-compensation. 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 $\times 1/10$ oscilloscope probe showing the range selector switch and the variable capacitance adjustment screw (just below the API brand label) appears in the following photograph:
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.
3.14 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:

![Aliasing Illustration]

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:

![Aliasing Illustration]

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\(^{32}\). 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.

\(^{32}\)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\(^{33}\) 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:

\[
f = 1 \text{ kHz} \; ; \; \text{samples/cycle} = 25 \; ; \; \text{oscilloscope faithfully displays signal wave-shape}
\]

\[
f = 2.5 \text{ kHz} \; ; \; \text{samples/cycle} = 10 \; ; \; \text{wave-shape begins to look “rough” due to coarse sampling}
\]

\(^{33}\) 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!
$f = 10 \text{ kHz} \; ; \; \text{samples/cycle} = 2.5 \; ; \text{wave-shape badly distorted}$

$f = 12.5 \text{ kHz} \; ; \; \text{samples/cycle} = 2 \; (\text{Nyquist minimum rate}) \; ; \text{sinusoid appears to be a triangle wave}$

$f = 13 \text{ kHz} \; ; \; \text{samples/cycle} = 1.923 \; ; \text{strange cyclic envelope imposed on the signal}$
3.14. DIGITAL SAMPLING RATE AND ALIASING

\[ f = 22 \text{ kHz} \; \text{samples/cycle} = 1.136 \; \text{entirely incorrect frequency (aliased)} \]

\[ f = 23 \text{ kHz} \; \text{samples/cycle} = 1.087 \; \text{entirely incorrect frequency (aliased)} \]

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 \textit{decrease}! Note how the oscilloscope’s timebase setting\[^{34}\] 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, \textit{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, \textit{at least} ten times faster than the highest expected frequency of our measured signal, just to avoid aliasing.

\[^{34}\]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 4

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.
4.1 Lissajous figure with 0° 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.
4.1. LISSAJOUS FIGURE WITH 0° PHASE SHIFT

0° phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
0° phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
4.1. LISSAJOUS FIGURE WITH $0^\circ$ PHASE SHIFT

$0^\circ$ phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
0° phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
4.1. LISSAJOUS FIGURE WITH 0° PHASE SHIFT

0° phase shift between \( V_{\text{vertical}} \) and \( V_{\text{horizontal}} \)
0° phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
4.1. LISSAJOUS FIGURE WITH $0^\circ$ PHASE SHIFT

$0^\circ$ phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
$0^\circ$ phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
4.1. LISSAJOUS FIGURE WITH $0^\circ$ PHASE SHIFT

$0^\circ$ phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
4.2 Lissajous figure with 90° 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° phase shift) with each other.
4.2. LISSAJOUS FIGURE WITH 90° PHASE SHIFT

90° phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
CHAPTER 4. ANIMATIONS

90° phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
4.2. LISSAJOUS FIGURE WITH 90° PHASE SHIFT

90° phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
90° phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
4.2. LISSAJOUS FIGURE WITH 90° PHASE SHIFT

90° phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
90° phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
4.2. LISSAJOUS FIGURE WITH 90° PHASE SHIFT

$90^\circ$ phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
90° phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
4.2. LISSAJOUS FIGURE WITH 90° PHASE SHIFT

90° phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
4.3 Lissajous figure with 180° 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° phase shift) from each other.
4.3. LISSAJOUS FIGURE WITH 180° PHASE SHIFT

$180^\circ$ phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
180° phase shift between $v_{\text{vertical}}$ and $v_{\text{horizontal}}$
4.3. **LISSAJOUS FIGURE WITH 180° PHASE SHIFT**

*180° phase shift between $V_{vertical}$ and $V_{horizontal}$*
180° phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
4.3. LISSAJOUS FIGURE WITH $180^\circ$ PHASE SHIFT

$180^\circ$ phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
180° phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
4.3. LISSAJOUS FIGURE WITH $180^\circ$ PHASE SHIFT

$180^\circ$ phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
180° phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
4.3. LISSAJOUS FIGURE WITH $180^\circ$ PHASE SHIFT

180° phase shift between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
4.4 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.
4.4. LISSAJOUS FIGURE WITH 2:1 FREQUENCY RATIO

2:1 frequency ratio between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
2:1 frequency ratio between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
4.4. LISSAJOUS FIGURE WITH 2:1 FREQUENCY RATIO

2:1 frequency ratio between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
2:1 frequency ratio between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
4.4. LISSAJOUS FIGURE WITH 2:1 FREQUENCY RATIO

2:1 frequency ratio between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
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2:1 frequency ratio between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
4.4. LISSAJOUS FIGURE WITH 2:1 FREQUENCY RATIO

2:1 frequency ratio between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
2:1 frequency ratio between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
4.4. LISSAJOUS FIGURE WITH 2:1 FREQUENCY RATIO

2:1 frequency ratio between $V_{\text{vertical}}$ and $V_{\text{horizontal}}$
Chapter 5

Questions

5.1 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.
5.1. CONCEPTUAL REASONING

5.1.1 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, write their own outline and 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 OUTLINE THE TEXT, as though you were writing a detailed Table of Contents. Feel free to rearrange the order if it makes more sense that way. Prepare to articulate these points in detail and to answer questions from your classmates and instructor. Outlining is a good self-test of thorough reading because you cannot outline what you have not read or do 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.
5.1.2  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
5.1.3 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.
5.1.4 Distorted square wave

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

![Oscilloscope and Function Generator Diagram]

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:

![Second Oscilloscope Diagram]

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?
5.1. CONCEPTUAL REASONING

**Challenges**

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

5.1.5 Uses of a x10 probe

A very common accessory for oscilloscopes is a x10 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 x10 probe, would actually be measuring a signal of 40 Volts peak-peak:

![Oscilloscope display with x10 probe settings](image)

Obviously, one use for a x10 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 x10 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 x10 probe) rather than 1 MΩ (with a normal 1:1 probe). Identify an application where this feature could be useful.

**Challenges**

- Using a x10 probe, how much resistive burden does the instrument place on the circuit under test?

- Does the use of a x10 probe affect the horizontal axis of the oscilloscope’s display at all, or just the vertical? Explain why.
5.1.6 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?
5.1.7 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 if 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.
5.1.8 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?
5.1.9 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?
5.2 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" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely on an answer key!

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2In 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.

3This 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.
5.2.1 Miscellaneous physical constants

Note: constants shown in bold type are exact, not approximations. Values inside of parentheses show one standard deviation ($\sigma$) of uncertainty in the final digits: for example, Avogadro’s number given as $6.02214179(30) \times 10^{23}$ means the center value ($6.02214179 \times 10^{23}$) plus or minus $0.00000030 \times 10^{23}$.

Avogadro’s number ($N_A$) = $6.02214179(30) \times 10^{23}$ per mole (mol$^{-1}$)

Boltzmann’s constant ($k$) = $1.3806504(24) \times 10^{-23}$ Joules per Kelvin (J/K)

Electronic charge ($e$) = $1.602176487(40) \times 10^{-19}$ Coulomb (C)

Faraday constant ($F$) = $9.64853399(24) \times 10^4$ Coulombs per mole (C/mol)

Magnetic permeability of free space ($\mu_0$) = $1.25663706212(19) \times 10^{-6}$ Henrys per meter (H/m)

Electric permittivity of free space ($\epsilon_0$) = $8.8541878128(13) \times 10^{-12}$ Farads per meter (F/m)

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

Gravitational constant ($G$) = $6.67428(67) \times 10^{-11}$ cubic meters per kilogram-seconds squared (m$^3$/kg-s$^2$)

Molar gas constant ($R$) = $8.314472(15)$ Joules per mole-Kelvin (J/mol-K) = $0.08205746(14)$ liters-atmospheres per mole-Kelvin

Planck constant ($h$) = $6.62606896(33) \times 10^{-34}$ joule-seconds (J-s)

Stefan-Boltzmann constant ($\sigma$) = $5.670400(40) \times 10^{-8}$ Watts per square meter-Kelvin$^4$ (W/m$^2$-K$^4$)

Speed of light in a vacuum ($c$) = **299792458 meters per second** (m/s) = 186282.4 miles per second (mi/s)

Note: All constants taken from NIST data “Fundamental Physical Constants – Extensive Listing”, from [http://physics.nist.gov/constants](http://physics.nist.gov/constants), National Institute of Standards and Technology (NIST), 2006; with the exception of the permeability of free space which was taken from NIST’s 2018 CODATA recommended values database.
5.2. QUANTITATIVE REASONING

5.2.2 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:

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Distance traveled</td>
<td>46.9</td>
<td>Kilometers</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Time elapsed</td>
<td>1.18</td>
<td>Hours</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Average speed</td>
<td>= B1 / B2</td>
<td>km/h</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 variables⁴ 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.

⁴Spreadsheets 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\textsuperscript{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\textsuperscript{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 \( ax^2 + bx + c \):

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

<table>
<thead>
<tr>
<th>( A )</th>
<th>( B )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( x_{-1} = (-B4 + \text{sqrt}((B4^2) - (4<em>B3</em>B5))) / (2*B3) )</td>
</tr>
<tr>
<td>2</td>
<td>( x_{+2} = (-B4 - \text{sqrt}((B4^2) - (4<em>B3</em>B5))) / (2*B3) )</td>
</tr>
<tr>
<td>3</td>
<td>( a = )</td>
</tr>
<tr>
<td>4</td>
<td>( b = )</td>
</tr>
<tr>
<td>5</td>
<td>( c = )</td>
</tr>
</tbody>
</table>

This example is configured to compute roots\textsuperscript{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.

\textsuperscript{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.

\textsuperscript{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.

\textsuperscript{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:

\begin{align*}
y &= \sqrt{b^2 - 4ac} \\
x &= \frac{-b \pm y}{2a}
\end{align*}

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.

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\(^8\)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.
5.2.3 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?
5.2.4 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 \( \mu \text{s} \) 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?
5.2.5 Measuring waveform parameters

Examine the following oscillographs and determine the listed parameters:

- Signal frequency = 
- Channel 1 signal amplitude =
- Channel 2 signal amplitude =
- Phase shift between channels 1 and 2 =
- Channel 1 *leading/lagging* Channel 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?
5.2.6 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 ×10 mode.

**Challenges**

- It is possible for an oscilloscope’s loading to only affect voltage magnitude and not phase angle?
5.2.7 Frequency ratios

Examine the following Lissajous figures, and determine the ratio of the two signals' frequencies:
5.2. QUANTITATIVE REASONING

Challenges

- Describe a technique by which you may easily discern the frequency ratio by examination of the Lissajous figure.
5.3 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.
5.3.1 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:

![Oscilloscope Screenshots]

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?
5.3.2 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?
Chapter 6

Projects and Experiments

The following project and experiment descriptions outline things you can build to help you understand circuits. With any real-world project or experiment there exists the potential for physical harm. *Electricity can be very dangerous in certain circumstances, and you should follow proper safety precautions at all times!*

### 6.1 Recommended practices

This section outlines some recommended practices for all circuits you design and construct.
Safety first!

Electricity, when passed through the human body, causes uncomfortable sensations and in large enough measures\(^1\) will cause muscles to involuntarily contract. The overriding of your nervous system by the passage of electrical current through your body is particularly dangerous in regard to your heart, which is a vital muscle. Very large amounts of current can produce serious internal burns in addition to all the other effects.

Cardio-pulmonary resuscitation (CPR) is the standard first-aid for any victim of electrical shock. This is a very good skill to acquire if you intend to work with others on dangerous electrical circuits. You should never perform tests or work on such circuits unless someone else is present who is proficient in CPR.

As a general rule, any voltage in excess of 30 Volts poses a definitive electric shock hazard, because beyond this level human skin does not have enough resistance to safely limit current through the body. “Live” work of any kind with circuits over 30 volts should be avoided, and if unavoidable should only be done using electrically insulated tools and other protective equipment (e.g. insulating shoes and gloves). If you are unsure of the hazards, or feel unsafe at any time, stop all work and distance yourself from the circuit!

A policy I strongly recommend for students learning about electricity is to never come into electrical contact\(^2\) with an energized conductor, no matter what the circuit’s voltage\(^3\) level! Enforcing this policy may seem ridiculous when the circuit in question is powered by a single battery smaller than the palm of your hand, but it is precisely this instilled habit which will save a person from bodily harm when working with more dangerous circuits. Experience has taught me that students who learn early on to be careless with safe circuits have a tendency to be careless later with dangerous circuits!

In addition to the electrical hazards of shock and burns, the construction of projects and running of experiments often poses other hazards such as working with hand and power tools, potential

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\(^1\)Professor Charles Dalziel published a research paper in 1961 called “The Deleterious Effects of Electric Shock” detailing the results of electric shock experiments with both human and animal subjects. The threshold of perception for human subjects holding a conductor in their hand was in the range of 1 milliampere of current (less than this for alternating current, and generally less for female subjects than for male). Loss of muscular control was exhibited by half of Dalziel’s subjects at less than 10 milliamperes alternating current. Extreme pain, difficulty breathing, and loss of all muscular control occurred for over 99% of his subjects at direct currents less than 100 milliamperes and alternating currents less than 30 milliamperes. In summary, it doesn’t require much electric current to induce painful and even life-threatening effects in the human body! Your first and best protection against electric shock is maintaining an insulating barrier between your body and the circuit in question, such that current from that circuit will be unable to flow through your body.

\(^2\)By “electrical contact” I mean either directly touching an energized conductor with any part of your body, or indirectly touching it through a conductive tool. The only physical contact you should ever make with an energized conductor is via an electrically insulated tool, for example a screwdriver with an electrically insulated handle, or an insulated test probe for some instrument.

\(^3\)Another reason for consistently enforcing this policy, even on low-voltage circuits, is due to the dangers that even some low-voltage circuits harbor. A single 12 Volt automobile battery, for example, can cause a surprising amount of damage if short-circuited simply due to the high current levels (i.e. very low internal resistance) it is capable of, even though the voltage level is too low to cause a shock through the skin. Mechanics wearing metal rings, for example, are at risk from severe burns if their rings happen to short-circuit such a battery! Furthermore, even when working on circuits that are simply too low-power (low voltage and low current) to cause any bodily harm, touching them while energized can pose a threat to the circuit components themselves. In summary, it generally wise (and always a good habit to build) to “power down” any circuit before making contact between it and your body.
6.1. RECOMMENDED PRACTICES

contact with high temperatures, potential chemical exposure, etc. You should never proceed with a project or experiment if you are unaware of proper tool use or lack basic protective measures (e.g. personal protective equipment such as safety glasses) against such hazards.

Some other safety-related practices should be followed as well:

- All power conductors extending outward from the project must be firmly strain-relieved (e.g. “cord grips” used on line power cords), so that an accidental tug or drop will not compromise circuit integrity.

- All electrical connections must be sound and appropriately made (e.g. soldered wire joints rather than twisted-and-taped; terminal blocks rather than solderless breadboards for high-current or high-voltage circuits). Use “touch-safe” terminal connections with recessed metal parts to minimize risk of accidental contact.

- Always provide overcurrent protection in any circuit you build. Always. This may be in the form of a fuse, a circuit breaker, and/or an electronically current-limited power supply.

- Always ensure circuit conductors are rated for more current than the overcurrent protection limit. Always. A fuse does no good if the wire or printed circuit board trace will “blow” before it does!

- Always bond metal enclosures to Earth ground for any line-powered circuit. Always. Ensuring an equipotential state between the enclosure and Earth by making the enclosure electrically common with Earth ground ensures no electric shock can occur simply by one’s body bridging between the Earth and the enclosure.

- Avoid building a high-energy circuit when a low-energy circuit will suffice. For example, I always recommend beginning students power their first DC resistor circuits using small batteries rather than with line-powered DC power supplies. The intrinsic energy limitations of a dry-cell battery make accidents highly unlikely.

- Use line power receptacles that are GFCI (Ground Fault Current Interrupting) to help avoid electric shock from making accidental contact with a “hot” line conductor.

- Always wear eye protection when working with tools or live systems having the potential to eject material into the air. Examples of such activities include soldering, drilling, grinding, cutting, wire stripping, working on or near energized circuits, etc.

- Always use a step-stool or stepladder to reach high places. Never stand on something not designed to support a human load.

- When in doubt, ask an expert. If anything even seems remotely unsafe to you, do not proceed without consulting a trusted person fully knowledgeable in electrical safety.
6.1.2 Other helpful tips

Experience has shown the following practices to be very helpful, especially when students make their own component selections, to ensure the circuits will be well-behaved:

- Avoid resistor values less than 1 kΩ or greater than 100 kΩ, unless such values are definitely necessary\(^4\). Resistances below 1 kΩ may draw excessive current if directly connected to a voltage source of significant magnitude, and may also complicate the task of accurately measuring current since any ammeter’s non-zero resistance inserted in series with a low-value circuit resistor will significantly alter the total resistance and thereby skew the measurement. Resistances above 100 kΩ may complicate the task of measuring voltage since any voltmeter’s finite resistance connected in parallel with a high-value circuit resistor will significantly alter the total resistance and thereby skew the measurement. Similarly, AC circuit impedance values should be between 1 kΩ and 100 kΩ, and for all the same reasons.

- Ensure all electrical connections are low-resistance and physically rugged. For this reason, one should avoid compression splices (e.g. “butt” connectors), solderless breadboards\(^5\), and wires that are simply twisted together.

- Build your circuit with testing in mind. For example, provide convenient connection points for test equipment (e.g. multimeters, oscilloscopes, signal generators, logic probes).

- Design permanent projects with maintenance in mind. The more convenient you make maintenance tasks, the more likely they will get done.

- **Always document and save your work.** Circuits lacking schematic diagrams are more difficult to troubleshoot than documented circuits. Similarly, circuit construction is simpler when a schematic diagram precedes construction. Experimental results are easier to interpret when comprehensively recorded. Consider modern videorecording technology for this purpose where appropriate.

- **Record your steps** when troubleshooting. **Talk to yourself** when solving problems. These simple steps clarify thought and simplify identification of errors.

\(^4\)An example of a necessary resistor value much less than 1 kΩ is a *shunt resistor* used to produce a small voltage drop for the purpose of sensing current in a circuit. Such shunt resistors must be low-value in order not to impose an undue load on the rest of the circuit. An example of a necessary resistor value much greater than 100 kΩ is an electrostatic *drain resistor* used to dissipate stored electric charges from body capacitance for the sake of preventing damage to sensitive semiconductor components, while also preventing a path for current that could be dangerous to the person (i.e. shock).

\(^5\)Admittedly, solderless breadboards are very useful for constructing complex electronic circuits with many components, especially DIP-style integrated circuits (ICs), but they tend to give trouble with connection integrity after frequent use. An alternative for projects using low counts of ICs is to solder IC sockets into prototype printed circuit boards (PCBs) and run wires from the soldered pins of the IC sockets to terminal blocks where reliable temporary connections may be made.
6.1. RECOMMENDED PRACTICES

6.1.3 Terminal blocks for circuit construction

Terminal blocks are the standard means for making electric circuit connections in industrial systems. They are also quite useful as a learning tool, and so I highly recommend their use in lieu of solderless breadboards\(^6\). Terminal blocks provide highly reliable connections capable of withstanding significant voltage and current magnitudes, and they force the builder to think very carefully about component layout which is an important mental practice. Terminal blocks that mount on standard 35 mm DIN rail\(^7\) are made in a wide range of types and sizes, some with built-in disconnecting switches, some with built-in components such as rectifying diodes and fuseholders, all of which facilitate practical circuit construction.

I recommend every student of electricity build their own terminal block array for use in constructing experimental circuits, consisting of several terminal blocks where each block has at least 4 connection points all electrically common to each other\(^8\) and at least one terminal block that is a fuse holder for overcurrent protection. A pair of anchoring blocks hold all terminal blocks securely on the DIN rail, preventing them from sliding off the rail. Each of the terminals should bear a number, starting from 0. An example is shown in the following photograph and illustration:

Screwless terminal blocks (using internal spring clips to clamp wire and component lead ends) are preferred over screw-based terminal blocks, as they reduce assembly and disassembly time, and also minimize repetitive wrist stress from twisting screwdrivers. Some screwless terminal blocks require the use of a special tool to release the spring clip, while others provide buttons\(^9\) for this task which may be pressed using the tip of any suitable tool.

\(^6\)Solderless breadboards are preferable for complicated electronic circuits with multiple integrated “chip” components, but for simpler circuits I find terminal blocks much more practical. An alternative to solderless breadboards for “chip” circuits is to solder chip sockets onto a PCB and then use wires to connect the socket pins to terminal blocks. This also accommodates surface-mount components, which solderless breadboards do not.

\(^7\)DIN rail is a metal rail designed to serve as a mounting point for a wide range of electrical and electronic devices such as terminal blocks, fuses, circuit breakers, relay sockets, power supplies, data acquisition hardware, etc.

\(^8\)Sometimes referred to as equipotential, same-potential, or potential distribution terminal blocks.

\(^9\)The small orange-colored squares seen in the above photograph are buttons for this purpose, and may be actuated by pressing with any tool of suitable size.
The following example shows how such a terminal block array might be used to construct a series-parallel resistor circuit consisting of four resistors and a battery:

- **Series-parallel resistor circuit**
  - `v1 1 0 dc 6`
  - `r1 2 5 7100`
  - `r2 5 8 2200`
  - `r3 2 8 3300`
  - `r4 8 11 4700`
  - `rjmp1 1 2 0.01`
  - `rjmp2 0 11 0.01`
  - `.op`
  - `.end`

Note the use of “jumper” resistances `rjmp1` and `rjmp2` to describe the wire connections between terminals 1 and 2 and between terminals 0 and 11, respectively. Being resistances, SPICE requires a resistance value for each, and here we see they have both been set to an arbitrarily low value of 0.01 Ohm realistic for short pieces of wire.

Listing all components and wires along with their numbered terminals happens to be a useful documentation method for any circuit built on terminal blocks, independent of SPICE. Such a “wiring sequence” may be thought of as a *non-graphical description* of an electric circuit, and is exceptionally easy to follow.

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10SPICE is computer software designed to analyze electrical and electronic circuits. Circuits are described for the computer in the form of *netlists* which are text files listing each component type, connection node numbers, and component values.
6.1. RECOMMENDED PRACTICES

An example of a more elaborate terminal block array is shown in the following photograph, with terminal blocks and “ice-cube” style electromechanical relays mounted to DIN rail, which is turn mounted to a perforated subpanel. This “terminal block board” hosts an array of thirty five undedicated terminal block sections, four SPDT toggle switches, four DPDT “ice-cube” relays, a step-down control power transformer, bridge rectifier and filtering capacitor, and several fuses for overcurrent protection:

Four plastic-bottomed “feet” support the subpanel above the benchtop surface, and an unused section of DIN rail stands ready to accept other components. Safety features include electrical bonding of the AC line power cord’s ground to the metal subpanel (and all metal DIN rails), mechanical strain relief for the power cord to isolate any cord tension from wire connections, clear plastic finger guards covering the transformer’s screw terminals, as well as fused overcurrent protection for the 120 Volt AC line power and the transformer’s 12 Volt AC output. The perforated holes happen to be on \( \frac{1}{4} \) inch centers with a diameter suitable for tapping with 6-32 machine screw threads, their presence making it very easy to attach other sections of DIN rail, printed circuit boards, or specialized electrical components directly to the grounded metal subpanel. Such a “terminal block board” is an inexpensive yet highly flexible means to construct physically robust circuits using industrial wiring practices.

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\(^{11}\) An electrical subpanel is a thin metal plate intended for mounting inside an electrical enclosure. Components are attached to the subpanel, and the subpanel in turn bolts inside the enclosure. Subpanels allow circuit construction outside the confines of the enclosure, which speeds assembly. In this particular usage there is no enclosure, as the subpanel is intended to be used as an open platform for the convenient construction of circuits on a benchtop by students. In essence, this is a modern version of the traditional breadboard which was literally a wooden board such as might be used for cutting loaves of bread, but which early electrical and electronic hobbyists used as platforms for the construction of circuits.

\(^{12}\) At the time of this writing (2019) the cost to build this board is approximately $250 US dollars.
6.1.4 Conducting experiments

An experiment is an exploratory act, a test performed for the purpose of assessing some proposition or principle. Experiments are the foundation of the scientific method, a process by which careful observation helps guard against errors of speculation. All good experiments begin with an hypothesis, defined by the American Heritage Dictionary of the English Language as:

An assertion subject to verification or proof, as (a) A proposition stated as a basis for argument or reasoning. (b) A premise from which a conclusion is drawn. (c) A conjecture that accounts, within a theory or idealational framework, for a set of facts and that can be used as a basis for further investigation.

Stated plainly, an hypothesis is an educated guess about cause and effect. The correctness of this initial guess matters little, because any well-designed experiment will reveal the truth of the matter. In fact, incorrect hypotheses are often the most valuable because the experiments they engender lead us to surprising discoveries. One of the beautiful aspects of science is that it is more focused on the process of learning than about the status of being correct\(^\text{13}\). In order for an hypothesis to be valid, it must be testable\(^\text{14}\), which means it must be a claim possible to refute given the right data. Hypotheses impossible to critique are useless.

Once an hypothesis has been formulated, an experiment must be designed to test that hypothesis. A well-designed experiment requires careful regulation of all relevant variables, both for personal safety and for prompting the hypothesized results. If the effects of one particular variable are to be tested, the experiment must be run multiple times with different values of (only) that particular variable. The experiment set up with the “baseline” variable set is called the control, while the experiment set up with different value(s) is called the test or experimental.

For some hypotheses a viable alternative to a physical experiment is a computer-simulated experiment or even a thought experiment. Simulations performed on a computer test the hypothesis against the physical laws encoded within the computer simulation software, and are particularly useful for students learning new principles for which simulation software is readily available\(^\text{15}\).

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\(^{13}\) Science is more about clarifying our view of the universe through a systematic process of error detection than it is about proving oneself to be right. Some scientists may happen to have large egos – and this may have more to do with the ways in which large-scale scientific research is funded than anything else – but scientific method itself is devoid of ego, and if embraced as a practical philosophy is quite an effective stimulant for humility. Within the education system, scientific method is particularly valuable for helping students break free of the crippling fear of being wrong. So much emphasis is placed in formal education on assessing correct retention of facts that many students are fearful of saying or doing anything that might be perceived as a mistake, and of course making mistakes (i.e. having one’s hypotheses disproven by experiment) is an indispensable tool for learning. Introducing science in the classroom – real science characterized by individuals forming actual hypotheses and testing those hypotheses by experiment – helps students become self-directed learners.

\(^{14}\) This is the principle of falsifiability: that a scientific statement has value only insofar as it is liable to disproof given the requisite experimental evidence. Any claim that is unfalsifiable – that is, a claim which can never be disproven by any evidence whatsoever – could be completely wrong and we could never know it.

\(^{15}\) A very pertinent example of this is learning how to analyze electric circuits using simulation software such as SPICE. A typical experimental cycle would proceed as follows: (1) Find or invent a circuit to analyze; (2) Apply your analytical knowledge to that circuit, predicting all voltages, currents, powers, etc. relevant to the concepts you are striving to master; (3) Run a simulation on that circuit, collecting “data” from the computer when complete; (4) Evaluate whether or not your hypotheses (i.e. predicted voltages, currents, etc.) agree with the computer-generated results; (5) If so, your analyses are (provisionally) correct – if not, examine your analyses and the computer simulation again to determine the source of error; (6) Repeat this process as many times as necessary until you achieve mastery.
6.1. RECOMMENDED PRACTICES

Thought experiments are useful for detecting inconsistencies within your own understanding of some subject, rather than testing your understanding against physical reality.

Here are some general guidelines for conducting experiments:

• The clearer and more specific the hypothesis, the better. Vague or unfalsifiable hypotheses are useless because they will fit any experimental results, and therefore the experiment cannot teach you anything about the hypothesis.

• Collect as much data (i.e. information, measurements, sensory experiences) generated by an experiment as is practical. This includes the time and date of the experiment, too!

• Never discard or modify data gathered from an experiment. If you have reason to believe the data is unreliable, write notes to that effect, but never throw away data just because you think it is untrustworthy. It is quite possible that even “bad” data holds useful information, and that someone else may be able to uncover its value even if you do not.

• Prioritize quantitative data over qualitative data wherever practical. Quantitative data is more specific than qualitative, less prone to subjective interpretation on the part of the experimenter, and amenable to an arsenal of analytical methods (e.g. statistics).

• Guard against your own bias(es) by making your experimental results available to others. This allows other people to scrutinize your experimental design and collected data, for the purpose of detecting and correcting errors you may have missed. Document your experiment such that others may independently replicate it.

• Always be looking for sources of error. No physical measurement is perfect, and so it is impossible to achieve exact values for any variable. Quantify the amount of uncertainty (i.e. the “tolerance” of errors) whenever possible, and be sure your hypothesis does not depend on precision better than this!

• Always remember that scientific confirmation is provisional – no number of “successful” experiments will prove an hypothesis true for all time, but a single experiment can disprove it. Put into simpler terms, truth is elusive but error is within reach.

• Remember that scientific method is about learning, first and foremost. An unfortunate consequence of scientific triumph in modern society is that science is often viewed by non-practitioners as an unerring source of truth, when in fact science is an ongoing process of challenging existing ideas to probe for errors and oversights. This is why it is perfectly acceptable to have a failed hypothesis, and why the only truly failed experiment is one where nothing was learned.
The following is an example of a well-planned and executed experiment, in this case a physical experiment demonstrating Ohm’s Law.

Planning Time/Date = 09:30 on 12 February 2019

HYPOTHESIS: the current through any resistor should be exactly proportional to the voltage impressed across it.

PROCEDURE: connect a resistor rated 1 k Ohm and 1/4 Watt to a variable-voltage DC power supply. Use an ammeter in series to measure resistor current and a voltmeter in parallel to measure resistor voltage.

RISKS AND MITIGATION: excessive power dissipation may harm the resistor and/or pose a burn hazard, while excessive voltage poses an electric shock hazard. 30 Volts is a safe maximum voltage for laboratory practices, and according to Joule’s Law a 1000 Ohm resistor will dissipate 0.25 Watts at 15.81 Volts ($P = V^2 / R$), so I will remain below 15 Volts just to be safe.

Experiment Time/Date = 10:15 on 12 February 2019

DATA COLLECTED:

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000 V</td>
<td>0.000 mA</td>
</tr>
<tr>
<td>2.700 V</td>
<td>2.603 mA</td>
</tr>
<tr>
<td>5.400 V</td>
<td>5.206 mA</td>
</tr>
</tbody>
</table>

Analysis Time/Date = 10:57 on 12 February 2019

ANALYSIS: current definitely increases with voltage, and although I expected exactly one milliAmpere per Volt the actual current was usually less than that. The voltage/current ratios ranged from a low of 1036.87 (at 8.1 Volts) to a high of 1037.81 (at 14 Volts), but this represents a variance of only -0.0365% to +0.0541% from the average, indicating a very consistent proportionality -- results consistent with Ohm’s Law.

ERROR SOURCES: one major source of error is the resistor’s value itself. I did not measure it, but simply assumed color bands of brown-black-red meant exactly 1000 Ohms. Based on the data I think the true resistance is closer to 1037 Ohms. Another possible explanation is multimeter calibration error. However, neither explains the small positive and negative variances from the average. This might be due to electrical noise, a good test being to repeat the same experiment to see if the variances are the same or different. Noise should generate slightly different results every time.
The following is an example of a well-planned and executed virtual experiment, in this case demonstrating Ohm’s Law using a computer (SPICE) simulation.

Planning Time/Date = 12:32 on 14 February 2019

HYPOTHESIS: for any given resistor, the current through that resistor should be exactly proportional to the voltage impressed across it.

PROCEDURE: write a SPICE netlist with a single DC voltage source and single 1000 Ohm resistor, then use NGSPICE version 26 to perform a "sweep" analysis from 0 Volts to 25 Volts in 5 Volt increments.

* SPICE circuit
v1 1 0 dc
r1 1 0 1000
dc v1 0 25 5
.print dc v(1) i(v1)
.end

RISKS AND MITIGATION: none.

DATA COLLECTED:
DC transfer characteristic Thu Feb 14 13:05:08 2019

<table>
<thead>
<tr>
<th>Index</th>
<th>v-sweep</th>
<th>v(1)</th>
<th>v1#branch</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.000000e+00</td>
<td>0.000000e+00</td>
<td>0.000000e+00</td>
</tr>
<tr>
<td>1</td>
<td>5.000000e+00</td>
<td>5.000000e+00</td>
<td>-5.000000e-03</td>
</tr>
<tr>
<td>2</td>
<td>1.000000e+01</td>
<td>1.000000e+01</td>
<td>-1.000000e-02</td>
</tr>
<tr>
<td>3</td>
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<td>1.500000e+01</td>
<td>-1.500000e-02</td>
</tr>
<tr>
<td>4</td>
<td>2.000000e+01</td>
<td>2.000000e+01</td>
<td>-2.000000e-02</td>
</tr>
<tr>
<td>5</td>
<td>2.500000e+01</td>
<td>2.500000e+01</td>
<td>-2.500000e-02</td>
</tr>
</tbody>
</table>

Analysis Time/Date = 13:06 on 14 February 2019

ANALYSIS: perfect agreement between data and hypothesis -- current is precisely 1/1000 of the applied voltage for all values. Anything other than perfect agreement would have probably meant my netlist was incorrect. The negative current values surprised me, but it seems this is just how SPICE interprets normal current through a DC voltage source.

ERROR SOURCES: none.
As gratuitous as it may seem to perform experiments on a physical law as well-established as Ohm’s Law, even the examples listed previously demonstrate opportunity for real learning. In the physical experiment example, the student should identify and explain why their data does not perfectly agree with the hypothesis, and this leads them naturally to consider sources of error. In the computer-simulated experiment, the student is struck by SPICE’s convention of denoting regular current through a DC voltage source as being negative in sign, and this is also useful knowledge for future simulations. Scientific experiments are most interesting when things do not go as planned!

Aside from verifying well-established physical laws, simple experiments are extremely useful as educational tools for a wide range of purposes, including:

- Component familiarization (e.g. Which terminals of this switch connect to the NO versus NC contacts?)
- System testing (e.g. How heavy of a load can my AC-DC power supply source before the semiconductor components reach their thermal limits?)
- Learning programming languages (e.g. Let’s try to set up an “up” counter function in this PLC!)

Above all, the priority here is to inculcate the habit of hypothesizing, running experiments, and analyzing the results. This experimental cycle not only serves as an excellent method for self-directed learning, but it also works exceptionally well for troubleshooting faults in complex systems, and for these reasons should be a part of every technician’s and every engineer’s education.

### 6.1.5 Constructing projects

Designing, constructing, and testing projects is a very effective means of practical education. Within a formal educational setting, projects are generally chosen (or at least vetted) by an instructor to ensure they may be reasonably completed within the allotted time of a course or program of study, and that they sufficiently challenge the student to learn certain important principles. In a self-directed environment, projects are just as useful as a learning tool but there is some risk of unwittingly choosing a project beyond one’s abilities, which can lead to frustration.

Here are some general guidelines for managing projects:

- Define your goal(s) before beginning a project: what do you wish to achieve in building it? What, exactly, should the completed project do?
- Analyze your project prior to construction. Document it in appropriate forms (e.g. schematic diagrams), predict its functionality, anticipate all associated risks. In other words, plan ahead.
- Set a reasonable budget for your project, and stay within it.
- Identify any deadlines, and set reasonable goals to meet those deadlines.
- Beware of scope creep: the tendency to modify the project’s goals before it is complete.
- Document your progress! An easy way to do this is to use photography or videography: take photos and/or videos of your project as it progresses. Document failures as well as successes, because both are equally valuable from the perspective of learning.
6.2 Experiment: first explorations with a digital oscilloscope

Set up a PC-based digital oscilloscope to measure a signal coming from a signal generator (or alternatively, use the PC software to simulate measurement of a signal), and explore the following features of the oscilloscope:

- Vertical sensitivity
- Timebase settings
- Triggering options
  - Positive and negative slope
  - Auto, Single, etc.
- Sample rate
- Saving screenshots as graphic image files

Challenges

- ???.
- ???.
- ???.
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

“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.

The following principles inform the instructional and assessment philosophies embodied in these learning modules:

• 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\(^1\) 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\(^2\) 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\(^3\) 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

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\(^1\)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.

\(^2\)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.

\(^3\)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 characteristic of these learning modules is a lack of step-by-step instructions in the Project and Experiment chapters. Unlike many modern workbooks and laboratory guides where step-by-step instructions are prescribed for each experiment, these modules take the approach that students must learn to closely read the tutorials and apply their own reasoning to identify the appropriate experimental steps. Sometimes these steps are plainly declared in the text, just not as a set of enumerated points. At other times certain steps are implied, an example being assumed competence in test equipment use where the student should not need to be told again how to use their multimeter because that was thoroughly explained in previous lessons. In some circumstances no steps are given at all, leaving the entire procedure up to the student.

This lack of prescription is not a flaw, but rather a feature. Close reading and clear thinking are foundational principles of this learning series, and in keeping with this philosophy all activities are designed to require those behaviors. Some students may find the lack of prescription frustrating, because it demands more from them than what their previous educational experiences required. This frustration should be interpreted as an unfamiliarity with autonomous thinking, a problem which must be corrected if the student is ever to become a self-directed learner and effective problem-solver. Ultimately, the need for students to read closely and think clearly is more important both in the near-term and far-term than any specific facet of the subject matter at hand. If a student takes longer than expected to complete a module because they are forced to outline, digest, and reason on their own, so be it. The future gains enjoyed by developing this mental discipline will be well worth the additional effort and delay.

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.

This methodology of assigning text-based modules to students for digestion and then using Socratic dialogue to assess progress and hone students’ thinking was developed over a period of several years by the author with his Electronics and Instrumentation students at the two-year college level. While decidedly unconventional and sometimes even unsettling for students accustomed to a more passive lecture environment, this instructional philosophy has proven its ability to convey conceptual mastery, foster careful analysis, and enhance employability so much better than lecture that the author refuses to ever teach by lecture again.

Problems which often go undiagnosed in a lecture environment are laid bare in this “inverted” format where students must articulate and logically defend their reasoning. This, too, may be unsettling for students accustomed to lecture sessions where the instructor cannot tell for sure who comprehends and who does not, and this vulnerability necessitates sensitivity on the part of the “inverted” session instructor in order that students never feel discouraged by having their errors exposed. Everyone makes mistakes from time to time, and learning is a lifelong process! Part of the instructor’s job is to build a culture of learning among the students where errors are not seen as shameful, but rather as opportunities for progress.
To this end, instructors managing courses based on these modules should adhere to the following principles:

- Student questions are always welcome and demand thorough, honest answers. The only type of question an instructor should refuse to answer is one the student should be able to easily answer on their own. Remember, the fundamental goal of education is for each student to learn to think clearly and independently. This requires hard work on the part of the student, which no instructor should ever circumvent. Anything done to bypass the student’s responsibility to do that hard work ultimately limits that student’s potential and thereby does real harm.

- It is not only permissible, but encouraged, to answer a student’s question by asking questions in return, these follow-up questions designed to guide the student to reach a correct answer through their own reasoning.

- All student answers demand to be challenged by the instructor and/or by other students. This includes both correct and incorrect answers – the goal is to practice the articulation and defense of one’s own reasoning.

- No reading assignment is deemed complete unless and until the student demonstrates their ability to accurately summarize the major points in their own terms. Recitation of the original text is unacceptable. This is why every module contains an “Outline and reflections” question as well as a “Foundational concepts” question in the Conceptual reasoning section, to prompt reflective reading.

- No assigned question is deemed answered unless and until the student demonstrates their ability to consistently and correctly apply the concepts to variations of that question. This is why module questions typically contain multiple “Challenges” suggesting different applications of the concept(s) as well as variations on the same theme(s). Instructors are encouraged to devise as many of their own “Challenges” as they are able, in order to have a multitude of ways ready to probe students’ understanding.

- No assigned experiment or project is deemed complete unless and until the student demonstrates the task in action. If this cannot be done “live” before the instructor, video-recordings showing the demonstration are acceptable. All relevant safety precautions must be followed, all test equipment must be used correctly, and the student must be able to properly explain all results. The student must also successfully answer all Challenges presented by the instructor for that experiment or project.
Students learning from these modules would do well to abide by the following principles:

• No text should be considered fully and adequately read unless and until you can express every idea in your own words, using your own examples.

• You should always articulate your thoughts as you read the text, noting points of agreement, confusion, and epiphanies. Feel free to print the text on paper and then write your notes in the margins. Alternatively, keep a journal for your own reflections as you read. This is truly a helpful tool when digesting complicated concepts.

• Never take the easy path of highlighting or underlining important text. Instead, summarize and/or comment on the text using your own words. This actively engages your mind, allowing you to more clearly perceive points of confusion or misunderstanding on your own.

• A very helpful strategy when learning new concepts is to place yourself in the role of a teacher, if only as a mental exercise. Either explain what you have recently learned to someone else, or at least imagine yourself explaining what you have learned to someone else. The simple act of having to articulate new knowledge and skill forces you to take on a different perspective, and will help reveal weaknesses in your understanding.

• Perform each and every mathematical calculation and thought experiment shown in the text on your own, referring back to the text to see that your results agree. This may seem trivial and unnecessary, but it is critically important to ensuring you actually understand what is presented, especially when the concepts at hand are complicated and easy to misunderstand. Apply this same strategy to become proficient in the use of circuit simulation software, checking to see if your simulated results agree with the results shown in the text.

• 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 effort, and never give up!

Students interested in using these modules for self-study will also find them beneficial, although the onus of responsibility for thoroughly reading and answering questions will of course lie with that individual alone. If a qualified instructor is not available to challenge students, a workable alternative is for students to form study groups where they challenge one another.

To high standards of education,

Tony R. Kuphaldt

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4 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.

5 Avoid the temptation to simply share answers with study partners, as this is really counter-productive to learning. Always bear in mind that the answer to any question is far less important in the long run than the method(s) used to obtain that answer. The goal of education is to empower one’s life through the improvement of clear and independent thought, literacy, expression, and various practical skills.
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 $\LaTeX$ 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. $\LaTeX$ 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, $\LaTeX$ is a programmer’s approach to word processing. Since $\LaTeX$ 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 $\LaTeX$ makes it relatively easy to learn how other people have created their own $\LaTeX$ 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 $\LaTeX$

Like all true programming languages, $\LaTeX$ is inherently extensible. So, years after the release of $\LaTeX$ 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 $\LaTeX$ is to $\LaTeX$ as $C$ is to $C++$. This means it is permissible to use any and all $\LaTeX$ commands within $\LaTeX$ source code, and it all still works. Some of the features offered by $\LaTeX$ that would be challenging to implement in $\LaTeX$ 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.
APPENDIX C. TOOLS USED

**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

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.

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 $\times$ 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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