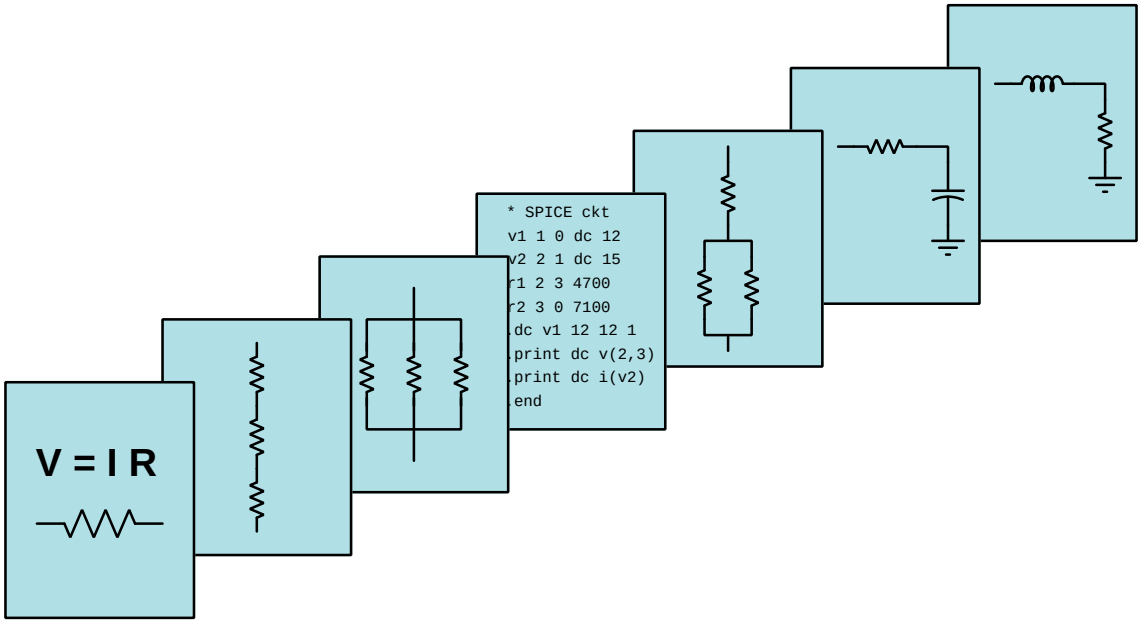
Modular Electronics Learning (ModEL) project



Brute-Force Power Supplies

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Chapter 1

Introduction

1.1 Recommendations for students

Power supplies are circuits designed to condition electricity from some specified source into a form suitable for powering an otherwise incompatible load. In most cases this means converting from AC to DC and also reducing voltage. This module focuses on the most simplistic of these power supply circuits, called a *brute force* power supply.

Important concepts related to brute-force power supplies include **DC** versus **AC** electricity, electromagnetic **induction**, **transformers**, **diodes**, **rectifier** circuits, winding **tap**, **capacitors**, **ripple**, and **filter circuits**.

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

- What does the term "brute force" mean for a power supply circuit design?
- What factors influence the amount of ripple voltage output by a brute-force power supply?
- What factors influence the output voltage of a transformer?
- What components and materials go into the making of a power transformer?
- What purpose does a rectifier serve in a power supply circuit?
- What are some different types of rectifier circuits?
- What is a *block diagram*, and how does one differ from a schematic diagram?
- What distinguishes the primary winding from the secondary winding of a transformer?
- How do voltage and current relate to each other in a capacitor?
- Why is the ripple voltage waveform shaped asymmetrically as it is?
- What gets simplified in the method of approximating ripple voltage magnitude described in the Tutorial?

- Why is ripple voltage generally a bad thing for electronic circuits?
- What purpose does a filter network serve in a power supply circuit?
- Why are transformers suitable for AC only and not DC?
- Which transformer has a more stable output voltage, one with an 8% regulation rating or one with a 3% regulation rating?
- Why do some transformers have multiple primary and multiple secondary windings rather than just one of each?
- How might an experiment be designed and conducted to measure the ripple voltage amplitude for a power supply?

1.2 Recommendations for instructors

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

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

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

  Assessment – Students show how ripple voltage quantitative estimations were obtained by the author in the Tutorial chapter's examples.

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

- **Outcome** – Apply the relationship of current and voltage rate-of-change for a capacitor to output voltage ripple approximations

  Assessment – Given a schematic diagram and average DC load current, calculate the amount of peak-to-peak ripple voltage expected at the output of a brute-force power supply circuit.

- **Outcome** – Design a brute-force power supply circuit

  Assessment – Sketch a schematic diagram complete with component part numbers for a brute-force power supply circuit given AC input voltage, desired DC output voltage, maximum desired ripple voltage, and expected DC load current.

- **Outcome** – Independent research

  Assessment – Locate a brute-force power supply manual and properly interpret some of the information contained in that document.

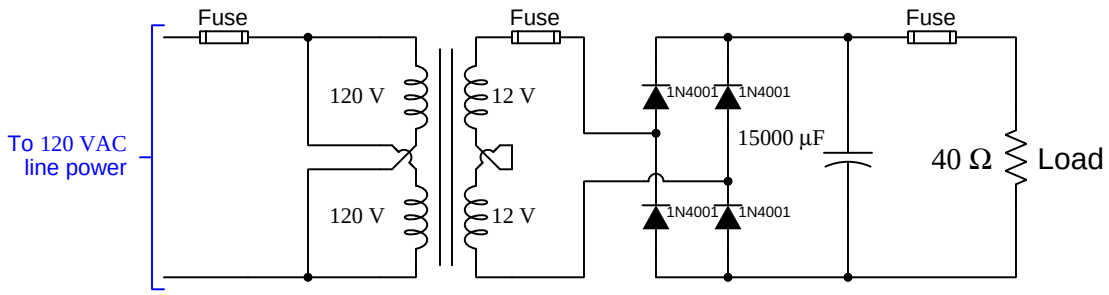
Chapter 2

Case Tutorial

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

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

2.1 Example: simple power supply calculations



Calculations:

$V_{primary} = 120$ Volts RMS

$V_{secondary} = 24$ Volts RMS

$V_{secondary(peak)} = (24)\sqrt{2} = 33.94$ V

$V_{rectified(peak)} = (24)\sqrt{2} - 1.4 = 32.54$ V

$I_{load(peak)} = \frac{V_{rectified(peak)}}{R_{load}} = \frac{32.54}{40} = 0.8135$ A

$f_{ripple} = 120$ Hz (two pulses per line cycle)

$V_{ripple} \approx \left(\frac{I_{load}}{C}\right)\left(\frac{1}{f_{ripple}}\right) = \left(\frac{0.8135}{15000 \times 10^{-6}}\right)\left(\frac{1}{120}\right) = 0.452$ Volts peak-to-peak

These calculations assume the transformer's full-load current rating is equal to (or very nearly equal to) the load current. If load current is substantially less than the transformer's rated full-load output current, secondary voltage will be greater than 24 Volts RMS, based on the transformer's voltage regulation rating:

$$\text{Voltage regulation } \% = \frac{V_{no-load} - V_{full-load}}{V_{full-load}} \times 100\%$$

For example, if we assume this transformer has a voltage regulation rating of 10%, and we were to disconnect the load:

- Secondary RMS AC voltage would rise to 26.4 Volts
- Secondary peak voltage would rise to 37.34 Volts
- DC output would rise to 35.94 Volts and have zero ripple

2.2 Example: measuring signal rates of change

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

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

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

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

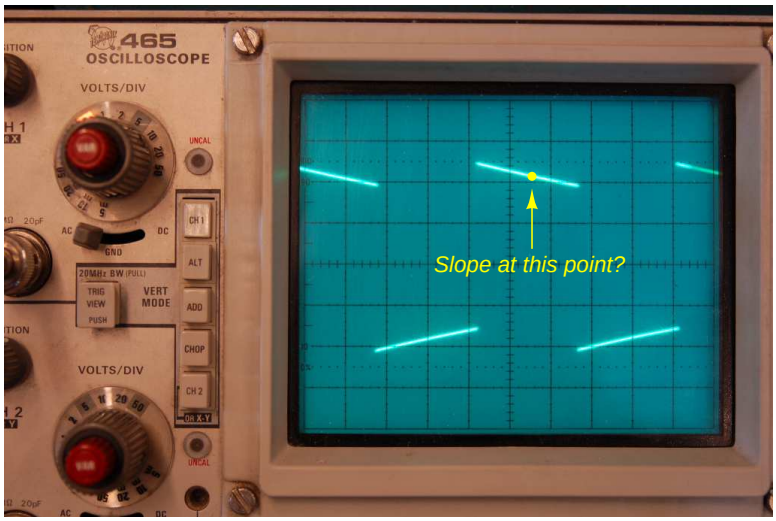
Oscilloscopes are ideal for performing empirical measurements of voltage rates-of-change, and of current rates-of-change given the proper accessories[2]. Some skill is required to do this, though, and here we will explore practical examples to show how it is done.

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

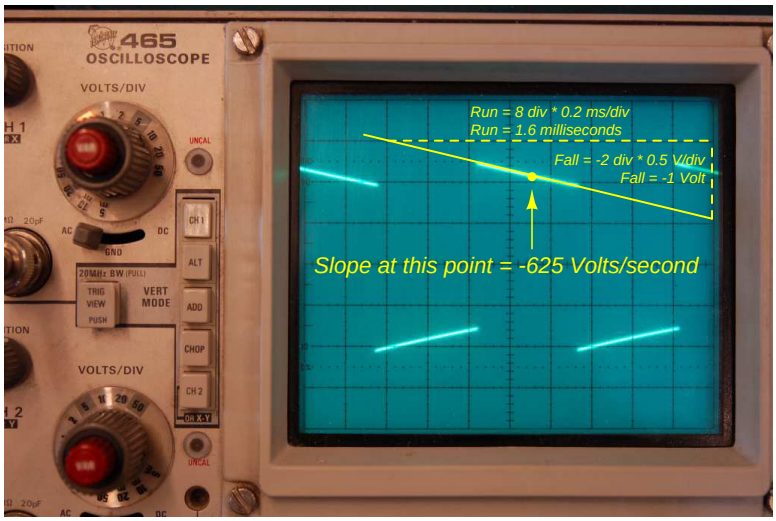
[1] The Scottish physicist James Clerk Maxwell referred to this current as *displacement current*.

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

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



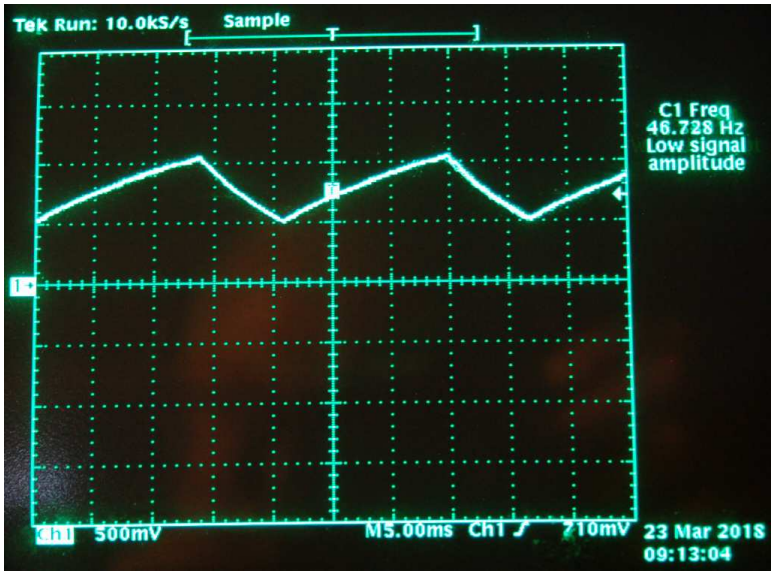
Next we see a tangent line drawn to match the slope of the waveform at the specified location, with convenient points for fall/run measurements taken on that line against the oscilloscope grid's major divisions. In this example, the oscilloscope's vertical sensitivity has been set for 0.5 Volts per division,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



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

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

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

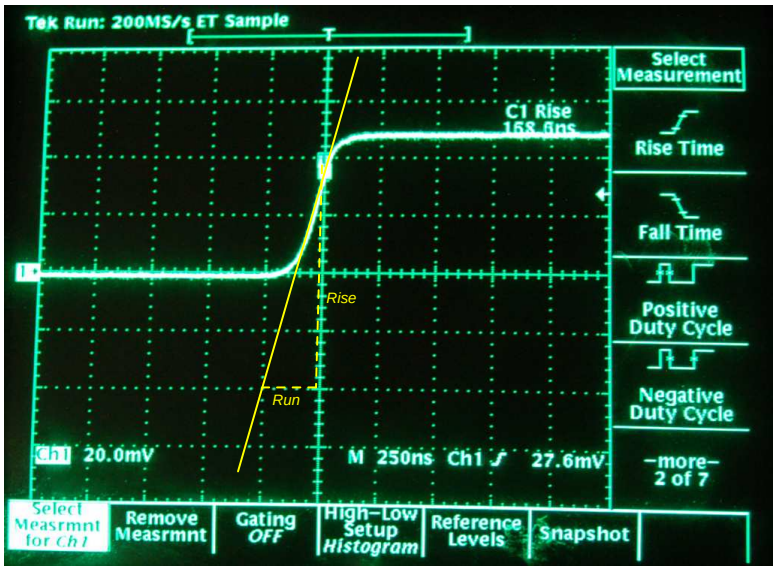


Approximating the slope for each rising section of this wave, we count one division of rise over 2.8 divisions of run, or 500 milliVolts rise over 14 milliseconds of run. This is a rate-of-rise of +35.7 Volts per second.

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

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

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



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

Chapter 3

Tutorial

A *power supply* is a circuit designed to convert electrical energy from a source into voltage and/or current levels suitable for a load that would otherwise be mis-matched to that source. Usually this means converting 120 Volts AC into low-voltage DC appropriate for powering electronic circuits, but of course this is not always the case. Some power supply circuits output more voltage than they take in; some power supplies convert from DC to DC rather than AC to DC, etc.

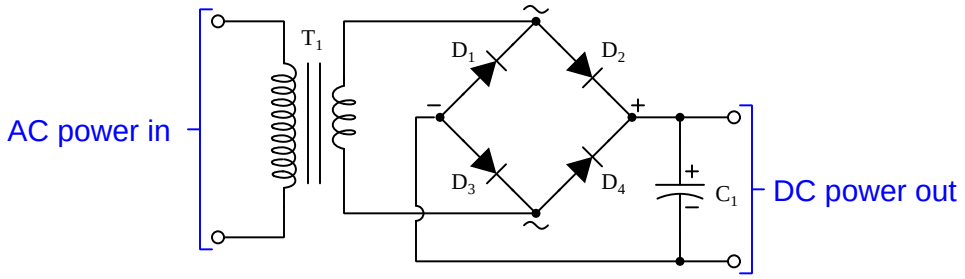
For the vast majority of power supplies, however, the task is to convert AC line power into DC at some voltage level appropriate to a specific DC load. Several different power supply circuit designs are available to choose from, but the simplest of these is the so-called *brute force* power supply which offers no voltage or current regulation but enjoys a high degree of reliability due to its design simplicity. This Tutorial explains the operation of typical brute-force AC/DC power supply designs.

3.1 Design overview

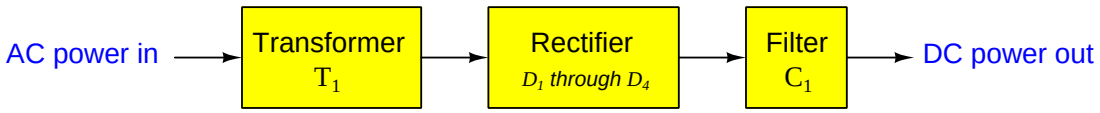
Most electronic circuits require low-voltage, direct-current (DC) electrical energy in order to function properly. Most electrical power systems, by contrast, operate at dangerously high voltages and are usually alternating-current (AC) rather than direct-current (DC). In order to bridge high-voltage AC electrical energy sources to low-voltage DC loads we must use a special circuit known as a *power supply*.

As one might guess, there exist many different types and designs of power supply, each suited to a different application or need. In this Tutorial we will focus on the simplest possible power supply design, often referred to as a *brute-force power supply*. These circuits feature a bare minimum of components and maintain reliable output voltage by sheer force of ratio between source voltage and load voltage. They are often over-built in the sense that their components are able to handle greater output power than the load typically demands, both to maximize reliability and to maintain more stable output voltage as load current varies.

A simple brute-force AC-DC power supply is shown in the following schematic diagram:



Another way to view this power supply circuit is as a series of blocks, each block serving a distinct purpose:



Component T_1 is a *transformer*, consisting of two wire coils wrapped around a common iron core. Electric current passing through the larger coil from the AC input power creates an alternating magnetic field in the iron core, and this alternating magnetic field induces a smaller AC voltage across the smaller coil. Thus, the transformer performs the function of reducing the dangerous AC line voltage to a lower level that will be safer for powering electronic circuits and also for any person working on or near those circuits. In the act of reducing voltage, this transformer also boosts current such that the smaller coil outputs more Amperes of current than the larger coil takes in from the AC source.

Components D_1 through D_4 are called *diodes*, and they act as one-way directional "valves" for electric current. By arranging four of them as shown, the alternating current (AC) output by the transformer's smaller coil will be directed in such a way that it always flows the same direction coming out of the four-diode array. Thus, the diodes perform the function of *rectification*, or converting AC into DC. This particular arrangement of four diodes is called a *bridge rectifier*, typically available in the form of an integrated circuit with all four diodes contained within a common package.

Component C_1 is a *capacitor* and serves to "smooth" (filter) the strongly pulsating DC output by the rectifier into gently "rippling" DC more suitable for powering electronic circuits.

Variations exist for the basic brute-force power supply design, but this is one of the most elementary, and in fact will serve well to power a wide range of electronic circuits. Beginning students of electricity and electronics would do well to build their own brute-force power supply as a valuable learning experience.

The next few sections of this Tutorial will explain the role of each "block" in more detail.

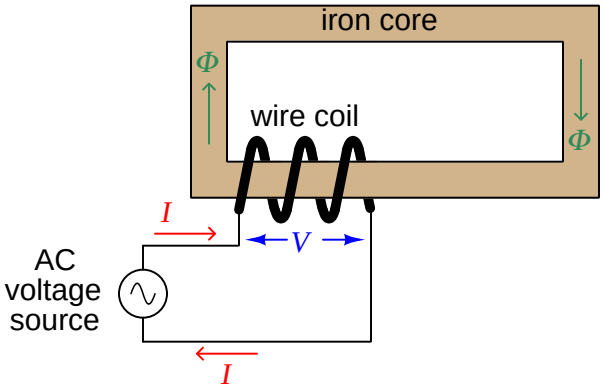
3.2 Transformers

Faraday's Law of Electromagnetic Induction states that the voltage induced in any coil of wire by a varying magnetic field is proportional to the number of turns in that coil as well as the rate at which the magnetic flux varies. When a single coil of wire is wrapped around an iron core and energized with AC, the voltage across that coil is directly related to this rate-of-change of the alternating magnetism in the core:

$$V = N\frac{d\Phi}{dt}$$

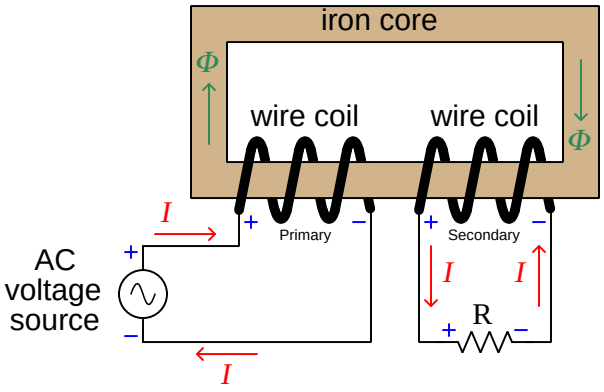
Where,

V = Voltage applied to the coil or induced by the coil (Volts)
N = Number of turns of wire
$\frac{d\Phi}{dt}$ = Rate of change of magnetic flux (Webers per second)



For any single wire coil, this is called *self-induction*: voltage induced in the coil as a result of the magnetic field produced[1] by the coil's own current.

A second wire coil wrapped around the same iron core experiences the same magnetic flux as the first coil, and therefor experiences an induced voltage as well. The following illustration shows a two-coil system with the second coil connected to a resistance, with current directions and voltage polarities labeled at a particular instant in time:



Carefully note the current arrows and voltage polarity (+ and −) symbols for the AC source, for each coil, and for the resistor. From these we can see that the AC source is indeed behaving as a *source*[2] and the resistor as a *load*[3]. The two coils have opposing roles: the coil connected to the AC source is functioning as a load, while the coil connected to the resistor is functioning as a source.

What we see happening in this illustration is a transfer of energy, from the AC source to the first coil, from the first coil to the magnetic field, from the magnetic field to the second coil, and finally from the second coil to the resistor. The Law of Energy Conservation states that energy cannot be created or destroyed, but that it can change forms, and this is what is happening here. In honor of this we call such a two-coil component a *transformer*, transforming energy from electrical to magnetic and back to electrical.

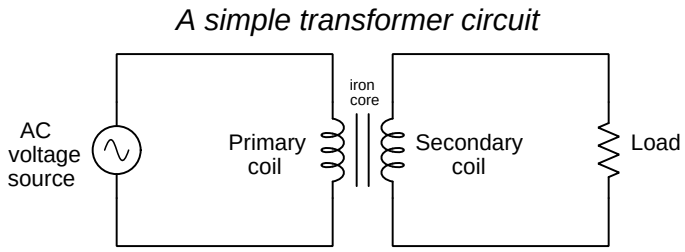
Faraday's Law tells us magnetic flux must vary in strength over time in order to induce a voltage, and so transformers require a time-varying current through their primary windings in order to function. This is why *transformers are only only useful in AC or pulsed DC applications.*

[1] The intensity of the magnetic flux (ϕ) is a direct function of coil current, and is relatively linear. Nonlinearities are chiefly due to the ferromagnetic core material, some materials being less linear than others.

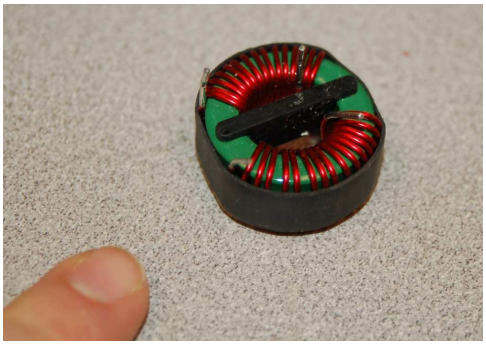
[2] Charge carriers entering the lower-potential (−) terminal and exiting the higher-potential (+) terminal because they have acquired some energy passing through the source.

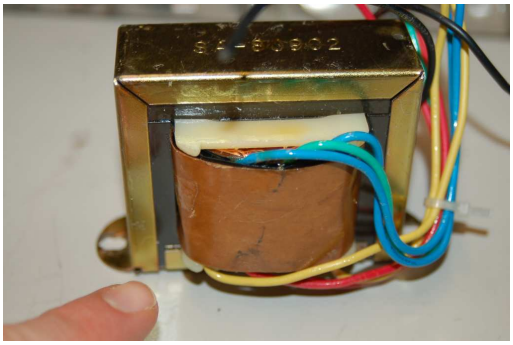
[3] Charge carriers entering the higher-potential (+) terminal and exiting the lower-potential (−) terminal because they have released some of their energy passing through the load.

Transformers are typically drawn as a set of coils (commonly called *windings*) sharing a common core. The coil connected to an electrical source is called the *primary* winding, while the coil connected to an electrical load is called the *secondary* winding. If the core is ferromagnetic, it is shown as a set of parallel lines between the coils:



The following pair of photographs show two small transformers: the left-hand image shows a transformer intended for use in a computer power supply with the two coils (colored red, with 15 turns each) clearly visible around a green-colored toroidal core; the right-hand image shows a slightly larger transformer with a different core configuration and multiple coils:





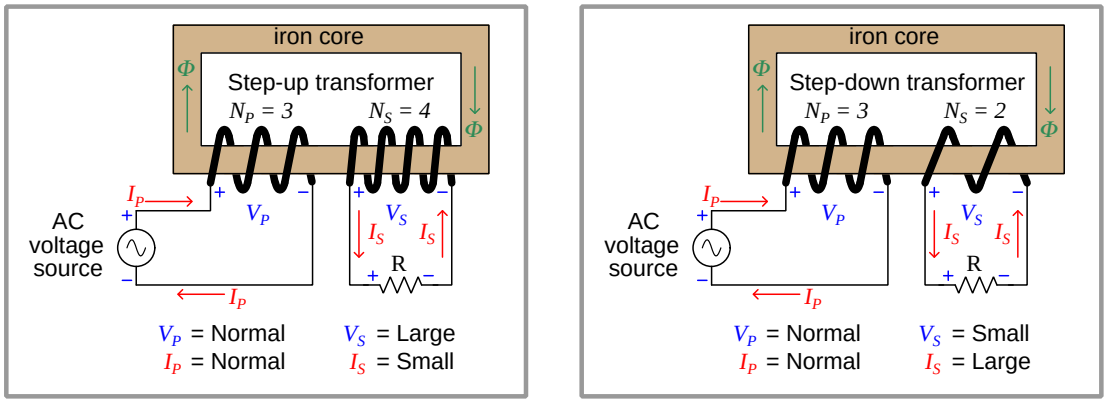
Even the largest transformers used in electric power systems operate on the same fundamental principle, and share very similar designs: a set of wire coils wrapped around a shared core material experiencing a common magnetic flux. This core is commonly comprised of laminated sheets of high-silicon alloy steel, the purpose of the laminations[4] being to minimize induced electric currents in the core material.

[4]Laminated iron is where the core's thickness is comprised of multiple layers of thin iron sheet, each sheet electrically insulated with a thin coating to prevent sheet-to-sheet electrical conductivity. Just as the windings wrapped around the iron core experience induced voltage across their circumferential length, a solid iron core would experience circular currents within its bulk if not for the impediment posed by the laminations. These insulated laminations make the iron core electrically insulating across its width while diminishing none of its magnetic properties.

If a transformer is constructed with windings having different numbers of turns, the amount of voltage induced in the secondary will not be the same as the voltage impressed across the primary. This follows Faraday's Law: if both windings share the same magnetic flux by virtue of being wrapped around the same core, but they have differing numbers of turns (N), their voltages must differ proportionally. We may express this as a ratio of voltages and a ratio of turns:

$$\frac{V_P}{V_S} = \frac{N_P}{N_S}$$

This is perhaps the most useful property of electrical transformers: the ability to increase or decrease AC voltage simply by building coils with different numbers of turns.



In a brute-force power supply circuit, the transformer's turns ratio is the primary factor in determining the power supply's output voltage. For example, if the transformer turns ratio is 10:1 and it is energized by a 120 VAC source, its output voltage should be 12 Volts AC. So long as the source's voltage (120 VAC) remains unchanged and the transformer's turns ratio is fixed, the output voltage should ideally remain fixed at or near 12 VAC by "brute force" of these parameters.

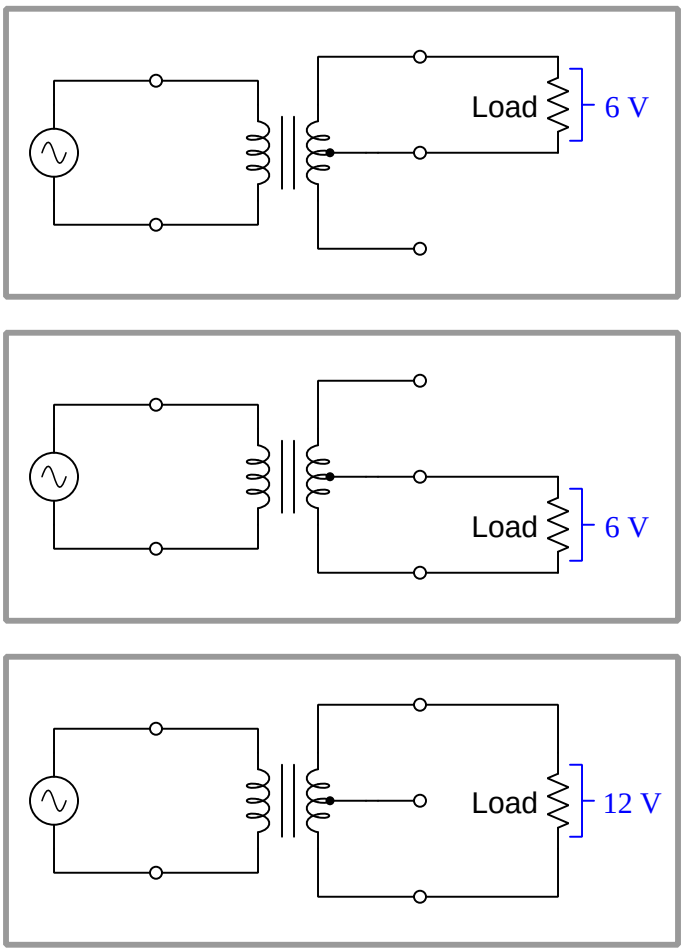
In reality, voltage output by a transformer actually varies slightly with load current: as the load draws more current, the secondary winding's voltage will "sag" below its open-circuit voltage even if the primary winding voltage remains unchanged. The degree to which transformer's output voltage sags is called its *voltage regulation percentage*[5]:

$$\text{Voltage regulation } \% = \frac{V_{no-load} - V_{full-load}}{V_{full-load}} \times 100\%$$

For example, if a power transformer has a full-load rated output voltage of 12 Volts and a regulation of 8%, it means its unloaded output voltage will rise by 8% (of 12 Volts) to become 12.96 Volts.

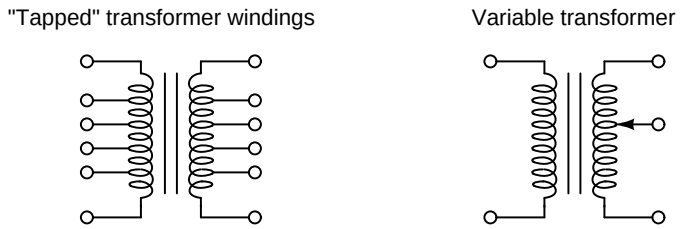
[5]This same figure is also known as the transformer's *impedance percentage*.

Some transformers designed for power applications provide different voltage ratio options to the user, either in the form of *tapped* windings or *multiple* windings. For example, a transformer with a "12 Volt center-tapped" secondary winding provides either 6 or 12 Volts of output depending on which two terminals you connect to the load:

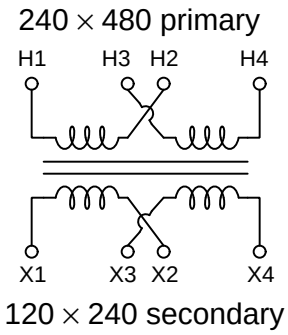


Voltage, as we know, is always *relative* between two points. There is no such thing as voltage existing at any single point, and so to speak of voltage we must always specify which *two* points we are measuring between. This "12 Volt center-tapped" secondary winding provides 12 Volts between the outer-most terminals, and 6 Volts between the center terminal and either of the outer terminals.

The principle of "tapping" a transformer winding is not limited to merely the center turn of the winding, or limited to just the secondary winding. On the left we see a transformer with multiple taps on both the primary and secondary windings; on the right we see a transformer with a movable tap (called a *wiper*) on one winding:

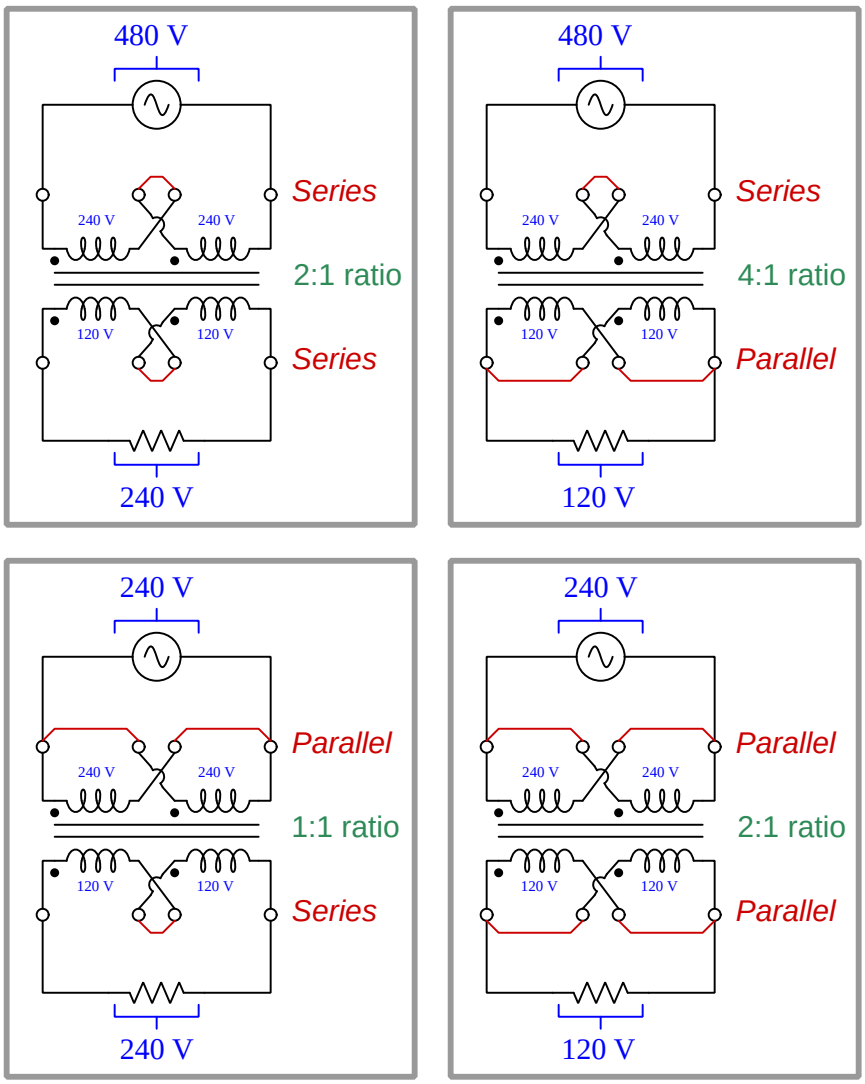


A very common design for industrial "control power" transformers provides two separate primary windings and two separate secondary windings, these pairs of windings intended to be connected in either series or parallel as necessary to obtain the desired step-down ratio:



Each of the individual primary windings is rated at a maximum voltage of 240 Volts, but by connecting them in either series or parallel with each other we may energize the transformer from either a 480 Volt or 240 Volt AC source, respectively. Similarly, the transformer may output either 240 Volts or 120 Volts to a load depending on whether we connect the two secondary windings in series with each other or in parallel with each other, respectively.

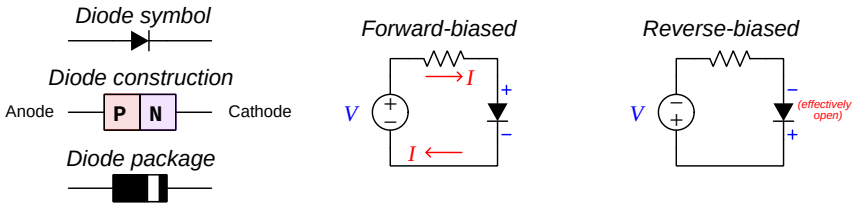
Four possible combinations of "jumper" wires configure this transformer for different step ratios:



In every configuration, each primary winding receives 240 Volts across it and each secondary winding produces 120 Volts. When connecting windings in series the total voltage becomes the sum of the individual winding voltages, and when connecting in parallel the total voltage is the same as the individual winding voltages (but the individual winding *currents* add to make the total current).

3.3 Diodes and rectifiers

Semiconductor diodes are simple, two-terminal devices with *anode* and *cathode* terminals. The most common material from which diodes are constructed is *silicon*, specially alloyed with other elements to form "P" and "N" types of silicon, which when joined together to form a "PN junction" exhibits one-way conduction. Its symbol is an arrowhead meeting with a perpendicular line. The arrowhead points in the direction of "conventional flow" current notation. A colored stripe toward one end of the physical device marks the cathode terminal:

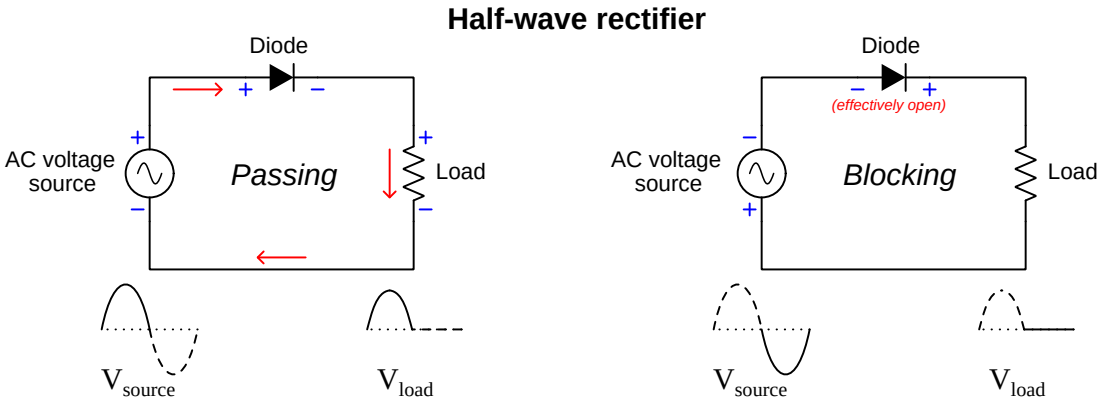


If an external voltage is applied to a PN junction such that the diode's N-type side is negative and its P-type side is positive (i.e. the polarity necessary for conduction), the diode enters a state referred to as *forward-bias*. Applying the opposite voltage polarity causes that same diode to become *reverse-biased* where it prevents conduction and functions as an "open". All diodes drop a small amount of voltage while conducting current in the forward-biased direction. For PN-junction diodes made of silicon semiconductor material this *forward voltage drop* varies between approximately 0.5 Volts to 0.7 Volts. Interestingly, this voltage drop does not vary linearly with current as is the case with resistors, which is to say that diodes do not obey Ohm's Law. A common "simplifying assumption" for diode circuit analysis is that silicon PN-junction diodes drop a constant 0.7 Volts when conducting regardless of the amount of current.

In the reverse-biased mode a diode effectively functions as an *open* and blocks electric current. This means regardless of the reverse-bias voltage drop, it dissipates no power in this mode since $P = IV$ (Joule's Law) and current is zero ($I = 0$). When forward-biased, however, the small amount of voltage ($\approx$ 0.7 Volts) means it will dissipate some power ($P \approx 0.7I$). Like resistors, diodes are rated for power dissipation capability, and this maximum power rating must be respected in the design of any diode-based circuit to ensure the diode(s) will not overheat. Semiconductor devices are especially susceptible to thermal damage, much more so than resistors!

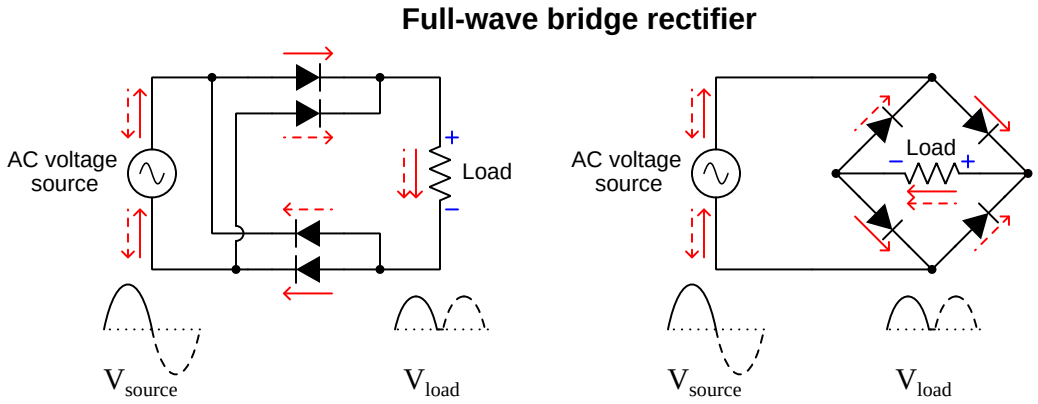
Any circuit utilizing diodes to convert alternating current electricity (AC) into direct current electricity (DC) is called a *rectifier*. Several types of rectifier circuits exist, and we will explore just a few of them.

The simplest form of rectifier circuit is one where a single diode placed in series between an AC voltage source and load allows current during one half-cycle but blocks it during the other half-cycle. This is known as a *half-wave rectifier* for the rather obvious reason that only half of the AC wave gets applied to the load while the other half is blocked. The following diagrams show voltage polarities and currents for both half-cycles of the AC source:



Notice how the diode experiences a voltage across it in both half-cycles. This is the *forward voltage* mentioned previously, typically 0.7 Volts for a silicon rectifying diode. When blocking, the diode's voltage will be equal to the full voltage of the AC source at any given instant during the blocked half-cycle. The existence of the diode's forward voltage drop means the load cannot receive the full output voltage of the AC source during the conducting half-cycle, but will always be slightly less. In order to calculate the peak value of this rectified voltage based on the RMS value of the sinusoidal AC input, we multiply the AC's RMS voltage value by $\sqrt{2}$ in order to calculate the unrectified waveform's peak value, then subtract the diode's forward voltage drop from that value.

Half-wave rectification is adequate for any application where the load is not adversely affected by *pulsating* DC and where the load does not require more than one-half of the source's full power rating. Most brute-force power supplies, however, benefit from being able to rectify both halves of the AC power cycle, and for this purpose we generally use *full-wave* rectifier circuits. A common full-wave rectifier design takes the form of *bridge network* using four diodes:

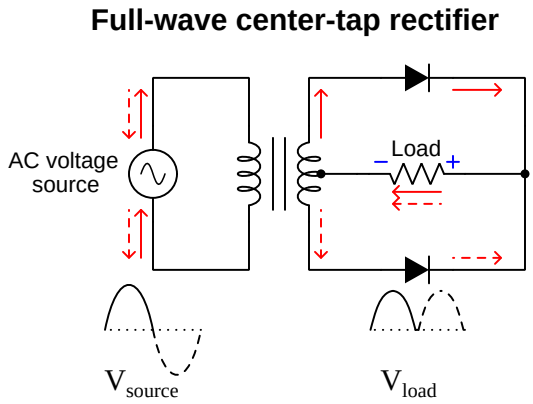


The two schematic diagrams shown above represent the exact same circuit, just drawn differently. While the diamond-shaped circuit on the right is the more conventional way to represent a bridge network, the "rectangular" shaped circuit on the left is just as valid, and may help in clarifying how full-wave rectification takes place.

Since load current must flow through *two* diodes rather than one diode at any given time in a full-wave bridge rectifier circuit, a greater voltage drop "penalty" is incurred than with a half-wave rectifier. At any moment when conduction occurs, the load's voltage will be less than the AC source's voltage by *two* diode forward voltage drops (e.g. 1.4 Volts for standard silicon diodes). Peak rectified voltage will be the sinusoidal AC's RMS voltage multiplied by $\sqrt{2}$ minus 1.4 Volts.

To see a flip-book animation of a full-wave bridge rectifier in action, turn to section 5.1 beginning on page 44.

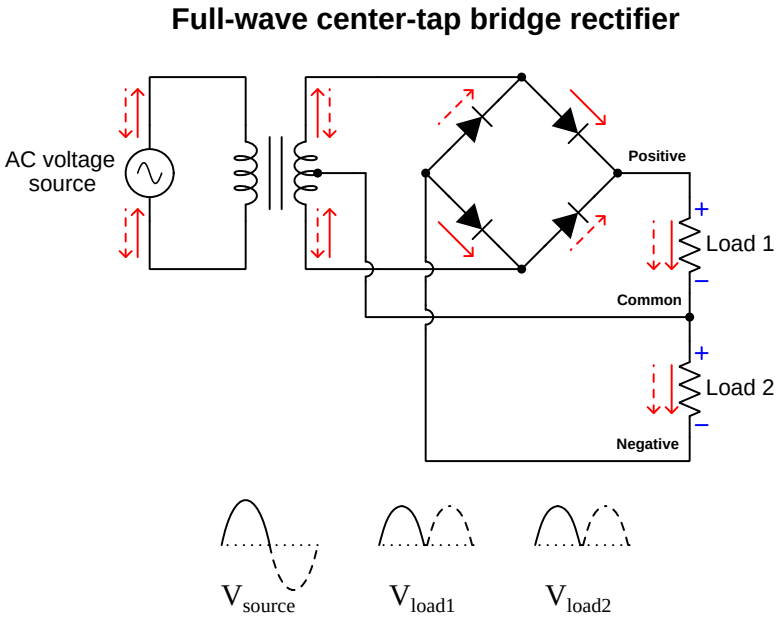
In a brute-force power supply circuit the AC source shown in these rectifier schematics would actually be the secondary winding of the transformer. This leads us to another design possibility, namely exploiting certain properties of transformers to form a rectifier circuit requiring fewer diodes. The key to this alternative full-wave rectifier design is to use a transformer with a *center-tapped* secondary winding, as shown below:



A clear advantage of this rectifier design is that it only needs two diodes rather than four to achieve full-wave rectification. However, this advantage comes at the expense of only utilizing half of that transformer's power and secondary voltage capability, since only one-half of its secondary winding is doing work at any given time. This center-tap rectifier configuration used to be more popular in AC-DC power supply circuit designs when diodes were more expensive and exhibited higher forward voltage drops than today[6]. Peak rectified voltage is equal to the peak AC voltage value for *half* the transformer's secondary winding (RMS voltage multiplied by $\sqrt{2}$) minus one diode voltage drop.

[6] A prime example of this design preference may be found by examining the power supply circuits of antique *vacuum tube* radios and televisions. It was common practice in those times to use vacuum tube diodes rather than solid-state diodes because solid-state diodes at that time did not have the power-handling capabilities of vacuum tubes. Like all vacuum tubes, diode tubes of that era were physically fragile, dropped more voltage when conducting than semiconductor diodes (typically *dozens* of Volts rather than fractions of a Volt), and each required power to energize a "heater" filament to bring the device up to its proper operating temperature. It is no wonder then that rectifier circuits of that era favored two-diode designs over four-diode designs.

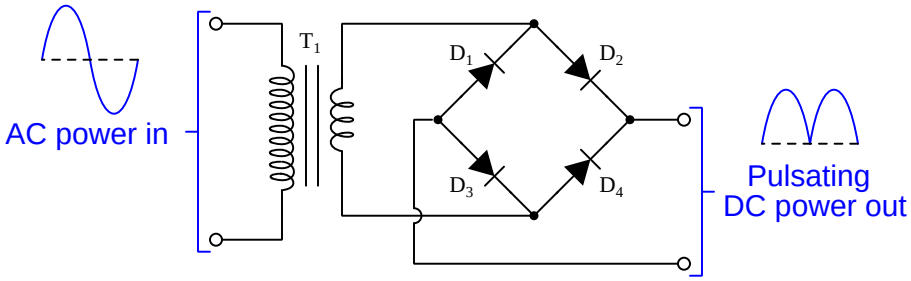
It is even possible to combine the center-tap rectifier principle with the bridge rectifier principle into a single circuit providing a "split" DC power supply having a positive terminal, a negative terminal, and a third terminal common to both:



These so-called "split" DC power supplies are quite common in a variety of electronics applications, especially where the circuit(s) powered must handle AC signals where the signal polarity alternates between + and − at different times with respect to ground. Audio amplifiers handling speech and music signals, for example, often require split DC power supplies for this reason.

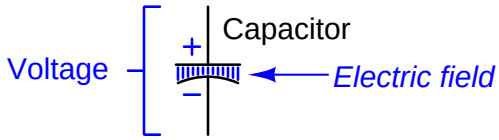
3.4 Filters

A power supply consisting only of a transformer and full-wave rectifier is incomplete because its DC output will be *pulsating* rather than steady over time. Most electronic circuits require constant DC voltage for proper operation, and will not take well to this pulsating power:



What we need to "smooth" or *filter* this rectified DC power so that it remains more steady over time is to equip the power supply circuit with a component capable of storing energy during the pulsation peaks and releasing energy during the pulsation valleys. One such device is called a *capacitor*, which uses the electric field between two conductive plates to store energy.

The fundamental behavior of a capacitor is that it stores energy in an electric field, and that the intensity of that field (and therefore the amount of energy it stores) is a direct function of voltage between the conductive plates:



The amount of current flowing into or out of this capacitance is a direct function of how quickly voltage varies over time. This may be expressed using calculus "derivative" notation:

$$I = C\frac{dV}{dt}$$

Where,

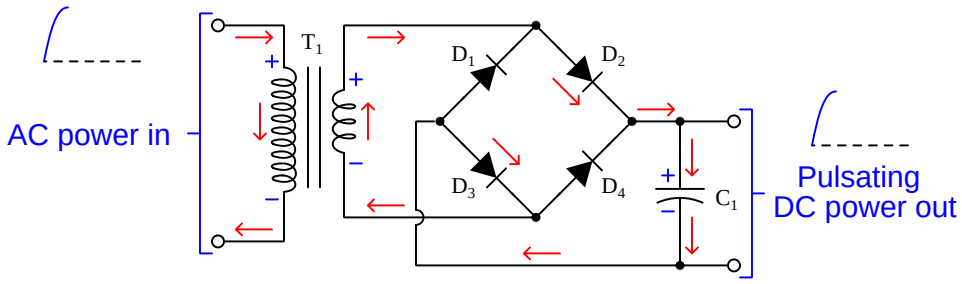
I = Current (Amperes)

C = Capacitance (Farads)

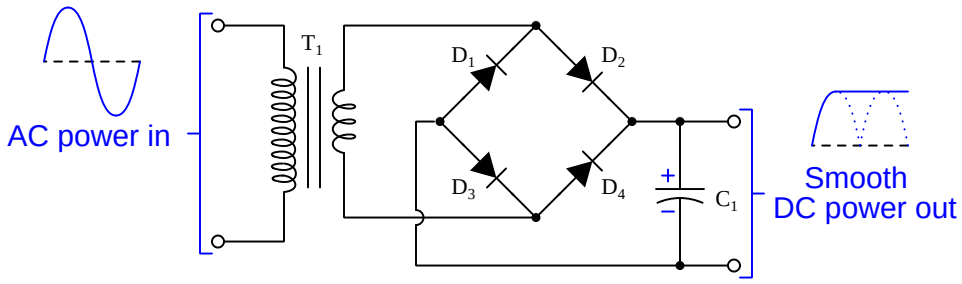
$\frac{dV}{dt}$ = Rate of voltage rise/fall over time (Volts per second)

Unlike current through a resistance, which is a simple proportion ($I = \frac{V}{R}$), current through a capacitance is a function of *time*. When the voltage is steady ($\frac{dV}{dt} = 0$) there will be zero current. When voltage rises ($\frac{dV}{dt} = +$), current flows as through a load. When voltage falls ($\frac{dV}{dt} = -$), current flows as through a source.

If we connect a capacitor between the output terminals of a transformer-rectifier power supply and energize the transformer with AC, we will see that the capacitor's voltage rises right along with the pulsating DC output of the rectifier for the rising quarter-cycle of the AC. During this time the capacitor experiences a rising voltage, and responds by accepting current as a load. The rising voltage means a growing electric field inside the capacitor, which means the capacitor is absorbing energy from the rectifier and transformer, which means it must act as a load:

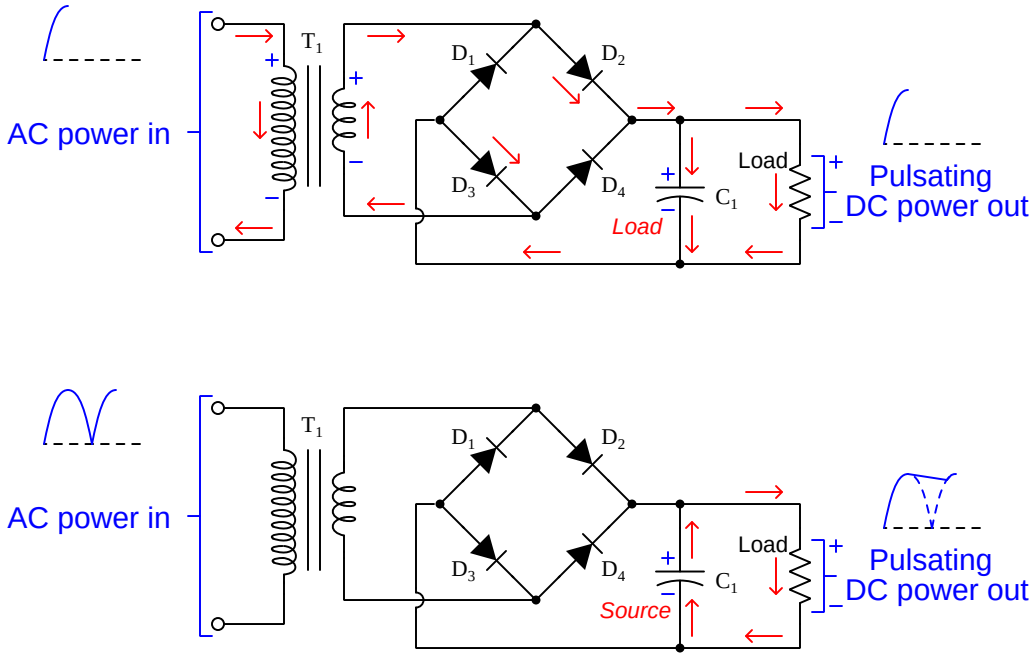


After that first voltage peak, however, something interesting happens. The rectifier on its own would begin to output less voltage as the AC waveform returns to zero, and if the capacitor were to follow suit it would mean it must release energy (as a source) because a reduction in voltage would mean a weakening electric field inside the capacitor, which would mean the capacitor is releasing energy to the rest of circuit as a source. However, this is impossible due to the diodes. In order for the capacitor to act as a source to decrease its voltage, capacitor current would have to reverse direction and flow *up* rather than down. Diodes D_2 and D_4 prevent any upward-flowing current from exiting the top of the capacitor, and diodes D_1 and D_3 prevent any upward-flowing current from entering the bottom of the capacitor. Therefore, the capacitor cannot release any of its stored energy, and as a result its voltage remains constant as the AC source continues its cycle:



In other words, the addition of a capacitor to this circuit "captures" the peak output voltage of the rectifier and provides a perfectly steady, pulsation-less, DC voltage to the power supply's output terminals. This also results in an apparent "boost" to the power supply's output voltage compared to its performance with no capacitor installed. Any voltmeter connected to the output terminals will now register the rectified DC's *peak* voltage rather than its *RMS* value when it was pulsating.

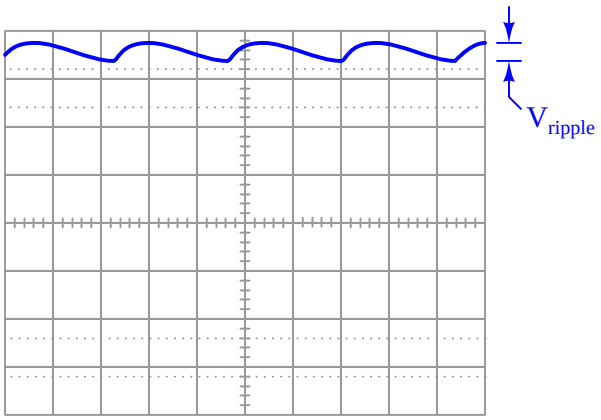
Despite what the previous explanation might suggest, though, capacitive filtering is not perfect. The DC output voltage from our brute-force power supply will be perfectly "flat" over time only if the power supply is not delivering energy to any load. Once we install a load in the circuit we will find that the capacitor's voltage no longer remains steady during the off-peak moments of the AC waveform:



An interesting point to mention here is that a secondary-cell (i.e. rechargeable) battery is a respectable substitute for a filtering capacitor. Rather than using an electric field to store energy as a capacitor does, a battery uses chemical bonds to do the same. During each "peak" period of the AC waveform the battery functions as a load and stores that energy in chemical form, then during the "off-peak" periods the battery functions as a source to maintain a nearly constant voltage. In fact, this is precisely what happens in an automotive electrical power system as the engine runs and spins an *alternator*, which is a combination of AC generator and full-wave rectifier. The vehicle's battery is usually the only filtering component in the power system, providing fairly "smooth" DC to the vehicle's loads without any help from capacitors.

3.5 Ripple

The fluctuations in output voltage resulting from the capacitor (or battery) alternately acting as a load and a source is called *ripple voltage*, and when viewed on the display of an oscilloscope its shape betrays the steep rising-edge of the rectified waveform prior to each shallow decay period where the capacitor fills in as a temporary source:



Ripple voltage amplitude depends on two factors: how much current the load draws from the power supply, and the amount of capacitance offered by the filter capacitor. Recall the mathematical relationship between current and voltage for any capacitance:

$$I = C\frac{dV}{dt}$$

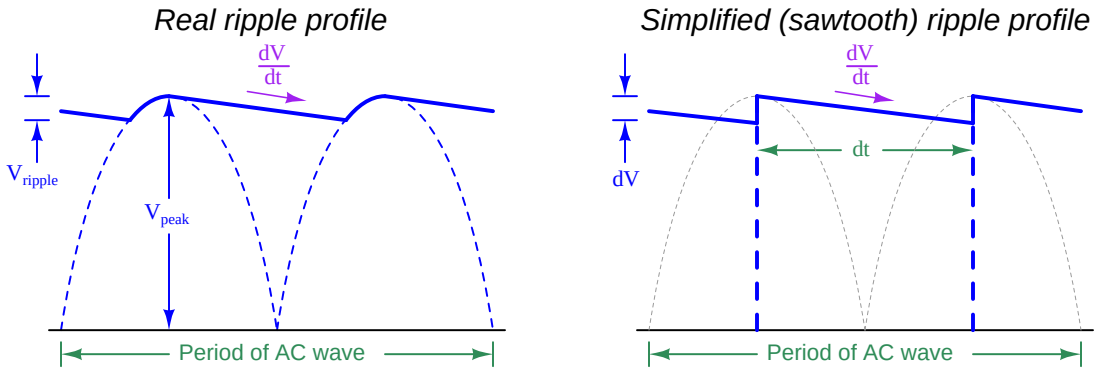
Where,
I = Current (Amperes)
C = Capacitance (Farads)
$\frac{dV}{dt}$ = Rate of voltage rise/fall over time (Volts per second)

During the off-peak periods of the AC waveform, I is the amount of current draw from the capacitor by the load. C of course is the capacitor's capacitance. $\frac{dV}{dt}$ is the rate at which voltage ramps downward over time. The greater $\frac{dV}{dt}$, the farther voltage will "fall" between AC peaks, increasing the depth of the ripple. Therefore, greater ripple will result from greater I (load current) and/or smaller C (capacitance).

Ripple may be reduced but never completely eliminated, since the capacitor's voltage *must* decrease as it releases energy to the load during the AC's off-peak moments. Complete elimination of ripple is possible only by adding more stages to the power supply (specifically, a circuit called a *voltage regulator*), but by definition brute-force power supplies do not have regulator circuits and so these will be discussed in a separate module.

When selecting filter capacitors for brute-force power supply circuits, the question of ripple is always "how much can the load tolerate?" Once we know the maximum tolerable[7] ripple voltage it becomes possible to choose an adequate filter capacitor size. Some loads such as incandescent lamps, electric motors, and heating elements tolerate large amounts of ripple – so much so that filter capacitors may not even be necessary at all! Other loads such as electronic amplifiers and digital semiconductor logic circuits have maximum tolerable ripple voltage values measured in *milli*Volts.

One method for estimating the amount of ripple output by a brute-force power supply is to simplify the capacitor's charging/discharging profile to be a *sawtooth* waveform. This requires we visualize the rectified AC peaks as single impulses rather than half-sine waves:



$\frac{dV}{dt}$ is simply the *slope*[8] of the ripple voltage profile. By simplifying the profile's shape to be a sawtooth waveform, we make dV equal to the ripple voltage and dt equal to one-half of the AC waveform's period[9]. For 60 Hz AC power, the AC waveform's period is $\frac{1}{60}$ of a second (16.667 milliseconds) which makes dt equal to 8.333 milliseconds.

For example, if a load draws 240 mA of current from a brute-force power supply with a filter capacitor of 4700 μF, the approximate rate of voltage fall will be 51.1 Volts per second. Over the half-period time of 8.333 ms (assuming 60 Hz line frequency) a rate of 51.1 V/s results in voltage falling by 426 mV, which will be the approximate peak-to-peak ripple voltage for the brute-force power supply.

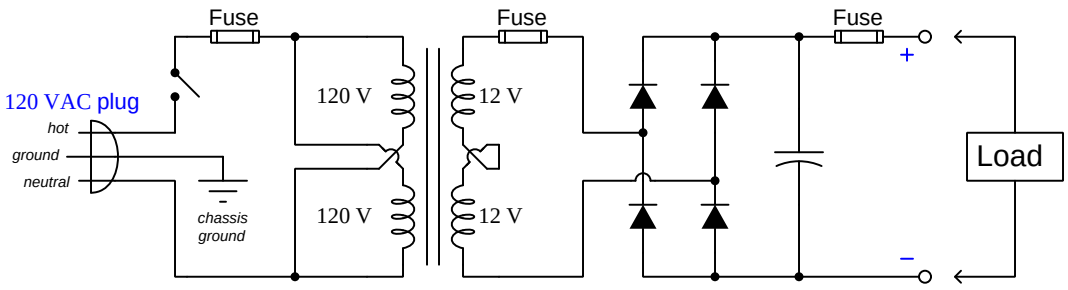
[7] There is no simple answer to calculating this maximum ripple voltage for any particular load, because the deleterious effects of ripple vary widely from one application to another. For an audio amplifier, power supply ripple voltage translates into an audible "hum" on the amplified signal, and so the criterion for maximum ripple will be the amount of "hum" the listener deems tolerable. For a digital logic circuit power supply ripple may cause indeterminate output signal states, inconsistent delay (signal propagation) times, etc., and so the criterion for maximum ripple will be the tolerable unreliability of the logic circuit's function (i.e. how often can we afford to have this circuit "glitch" and produce the wrong result?). For loads that are completely intolerant of any ripple, we must abandon brute-force power supply design by adding a voltage regulator stage, but even then voltage regulators have their own ripple tolerance for the preceding (brute-force) stages of the power supply circuit to meet.

[8] Any slope is mathematically defined as *rise* (or *fall*) over *run*. In this case, dV is the fall and dt is the run, with the quotient of those two values being the slope.

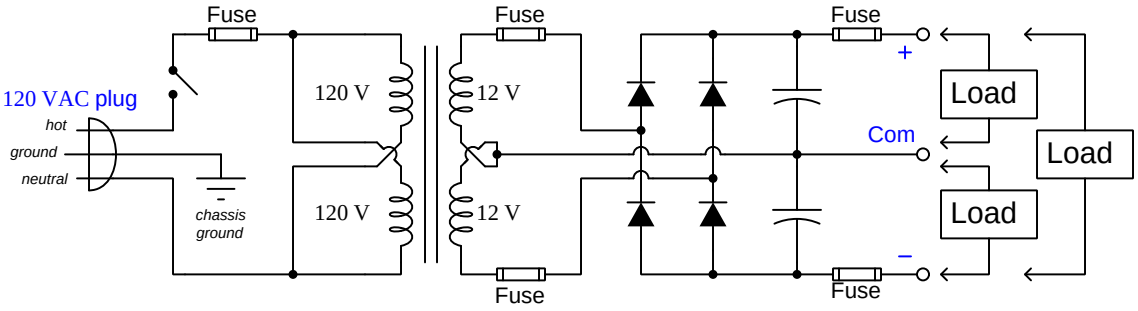
[9] The *period* of an AC waveform is the amount of time required to complete one whole cycle. Since we are using full-wave rectification, we get *two* DC pulsation peaks for every one AC cycle, which means the dt shown in the graph is one-half the time of a whole AC cycle.

3.6 Practical power supply designs

A simple brute-force power supply design is shown below, stepping 120 VAC line voltage down to 24 VAC which is then rectified and filtered to output approximately 32 Volts unloaded:



A variation on this design provides "split" +V and −V outputs (± 12 Volts DC nominal, but more realistically ± 16 Volts DC unloaded) with three connection terminals for loads:



Both of these designs employ more fuses than are strictly necessary, but for student-built power supplies I recommend zealous overcurrent protection for reasons of safety as well as fault diagnosis[10].

[10] Different faults will cause different fuses to blow, thus aiding the troubleshooting process if any fault were to occur either with the load(s) or with any of the internal components of the power supply itself

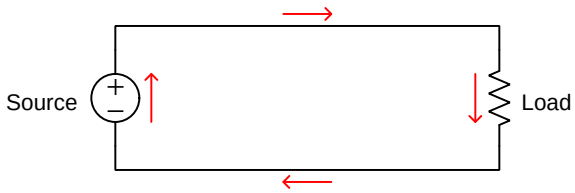
Chapter 4

Derivations and Technical References

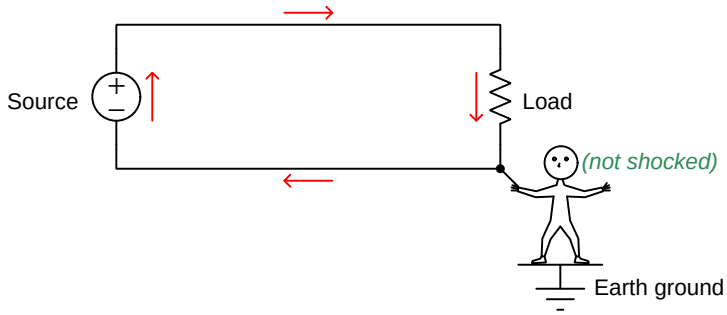
This chapter is where you will find mathematical derivations too detailed to include in the tutorial, and/or tables and other technical reference material.

4.1 Hot, neutral, and ground power conductors

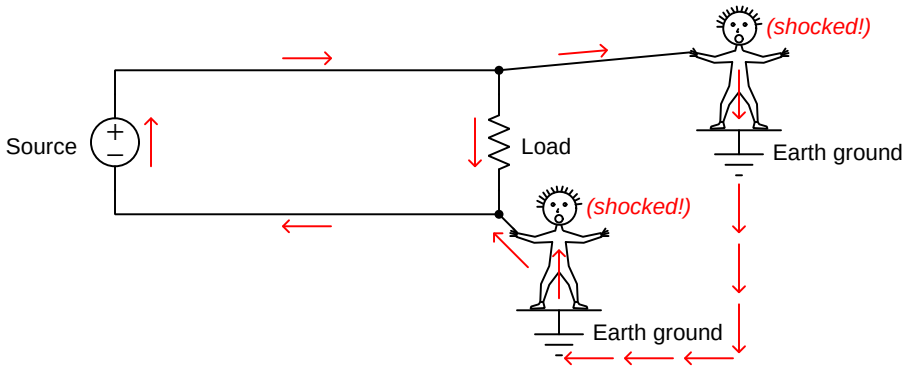
An elementary electric circuit needs just two conductors to convey electrical energy to a load:



If a person standing on bare Earth happens to make physical contact with either of these conductors, they would not be shocked or burned because the circuit is *ungrounded* or *floating*, and as such there is no complete path for current to pass through the person's body via the Earth:

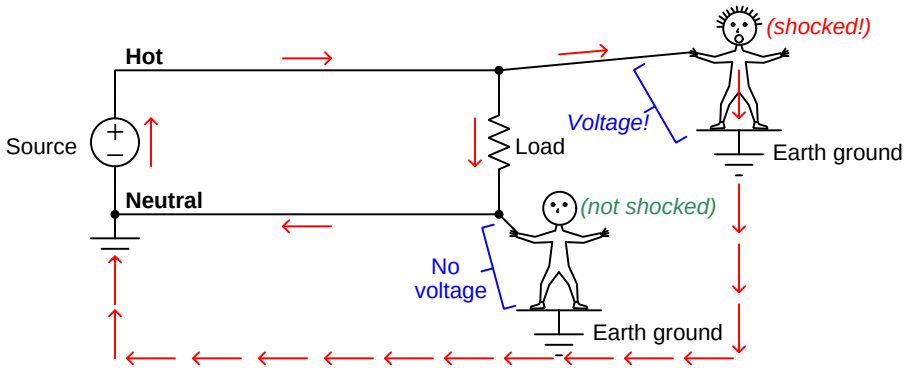


In principle, the foot-grounded person ought to be able to touch *any* conductor in this circuit with no risk for the same reason. However, this assumes the circuit has no other connection to Earth ground. If, for example, *two* people happened to touch opposite conductors simultaneously, a path for shock current would be formed through ground. Given sufficient source voltage, *both* people would be shocked:



In fact, *any* unintentional connection to Earth ground of either conductor in this circuit will make the other conductor dangerous to touch. For this and other[1] reasons it is standard practice to intentionally "ground" one of the conductors in a power circuit at the power source.

When we bond one of the conductors to ground – and it doesn't matter which one! – that grounded conductor is now electrically common to the Earth, and therefore must be equipotential to ground. This means there will be negligible voltage between that conductor and the Earth, therefore making it safe for a grounded person to touch. Conversely, the *other* conductor in the circuit is now guaranteed to have full source voltage between it and ground, and would be dangerous to touch. In honor of these facts, we refer to the grounded power conductor as the *neutral* and the non-grounded power conductor as the *hot*:



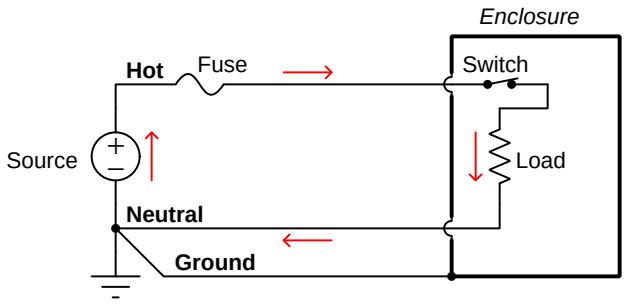
In a simple two-conductor circuit such as this, an interruption anywhere halts current everywhere. The location of a power switch or fuse may seem irrelevant given this fact, but once we commit to "hot" and "neutral" conductor identities via intentional Earth-grounding this is no longer an arbitrary decision. Knowing that the Earth ground connection makes the "hot" conductor intrinsically more dangerous than the "neutral" it now makes sense to only locate disconnection devices on the "hot" side. The rationale is simple: when a switch or a fuse opens, *it makes sense to disconnect the dangerous conductor from the load and leave the safe conductor connected*. This minimizes the probability of electric shock from accidental personal contact anywhere at the load.

An important yet non-obvious point to make about safety grounding in electric power circuits is that there should only be *one* connection between the neutral conductor and Earth ground, and that connection should be located at the *source* and not the load. The rationale for the source-location of this bond is to ensure the integrity of this grounding in the event no matter how many or how few loads connect to that source. Bonding the neutral conductor to Earth ground at a single point (at the source) as opposed to at multiple points in the circuit avoids *ground loops* which may cause other problems[2].

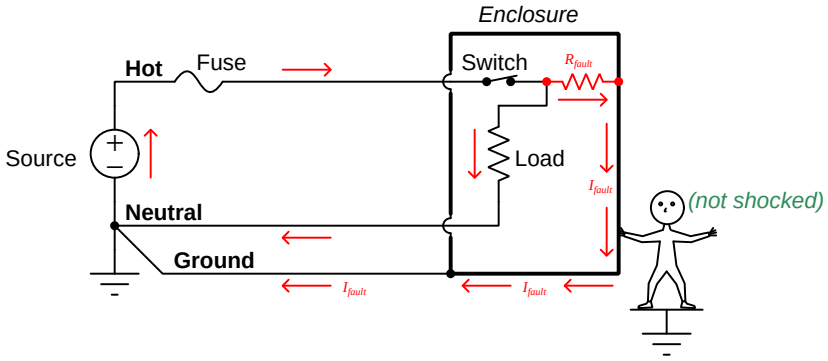
[1] Another good reason to intentionally ground one of the conductors within an electric power circuit is to prevent unintended safety hazards resulting from *lightning strikes*. This is especially relevant since most electrical power transmission and distribution conductors are overhead, suspended from insulators on tall tower or pole structures, and as such are susceptible to lightning. Grounding one of the power conductors helps ensure normal (i.e. modest) electrical potentials between each conductor and Earth ground. Otherwise, a lightning strike to any conductor in a power circuit would elevate the electrical potential of *all* conductors dramatically, and the point at which that potential "flashed over" to Earth ground would be unpredictable.

[2] The Earth is a relatively poor conductor of electricity, and so any current passing from one grounding point to

Many electrical loads have their energized components housed inside of rugged metal enclosures. In the unlikely event that a component fails and/or a conductor detaches from its normal connection point and makes contact with the metal enclosure, it is desirable to ensure the metal enclosure remains at Earth potential. For this reason, metal-clad loads use a third conductor to make the metal enclosure electrically common with the Earth. This third conductor is called the *ground*, *Earth*, or *Protective Earth* (PE) conductor:



Note how this protective ground conductor carries no load current. It exists only to bond the metal enclosure to Earth, in the unlikely event that an accidental connection might be made between that metal enclosure and the "hot" conductor. In the next diagram we see what would happen in a circuit with a properly grounded metal-clad load and an internal "ground fault" where the hot conductor makes accidental contact with that metal cladding:



The ground conductor maintains the load's metal enclosure equipotential with the Earth, keeping it safe for the grounded person to touch. If the ground fault has a low resistance, the resulting fault current will cause the fuse to blow, disconnecting the "hot" conductor from the load entirely and ensuring safety.

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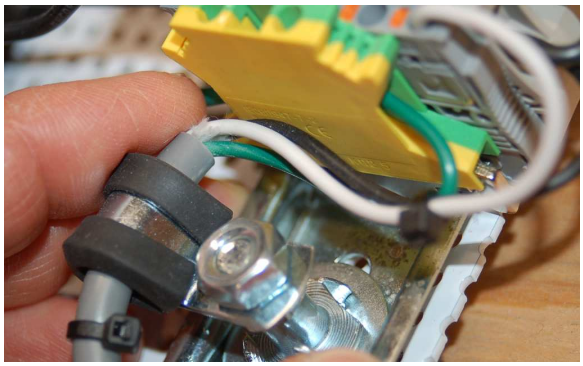
another will develop a voltage drop between those points, just like current passing through a resistor, which would make those points no longer equipotential with each other. Also, ground currents can, over time, cause corrosion of the metal grounding rod as it chemically interacts with ions in the soil, and this will increase its contact resistance to make it a poorer ground connection. Finally, ground loops invite electrical noise, as they constitute a physically large circuit which may experience induced currents from magnetic fields perpendicular to that loop. This noise may compromise the integrity of electronic signals with connections to the power circuit.

Alternatively, the load's metal enclosure may be replaced by a sturdy plastic (electrically insulating) enclosure, in which case we would refer to the load as being *double-insulated*.

Properly identifying the hot, neutral, and ground conductors is obviously important for anyone tasked with connecting loads to grounded power sources. For this reason, *color codes* exist to clearly distinguish these conductors from one another. Not surprisingly there exist multiple color code standards[3], the two most common shown here for simple two-conductor ("single-phase") AC power circuits:

Conductor	**US standard**	**European standard**
Hot	Black	Brown
Neutral	White	Blue
Ground/PE	Green, Green/Yellow, or bare	Green/Yellow

The 120 Volt AC power cord shown in the photograph below has a black wire ("hot"), a white wire ("neutral"), and a green wire ("ground" or "potential Earth"):

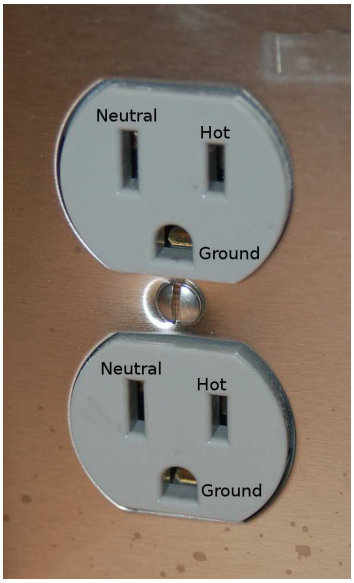


In this photograph we see the green ground wire terminate at a green/yellow-colored "grounding" terminal block[4]. The white neutral wire terminates at a regular terminal block adjacent to the grounding block. The black hot wire disappears out of the camera's view but terminates immediately at a *fuse-holding* terminal block. Note also how this cable is properly strain-relieved by the rubber-grommeted clamp so that the conductors themselves bear no mechanical tension applied to the cable.

[3] The wonderful thing about standards is that there are so many to choose from!

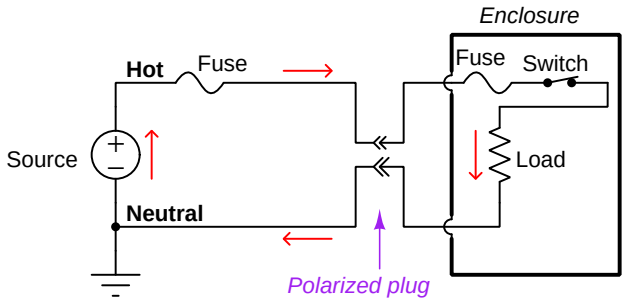
[4] This is a terminal block with a metal clamp base making solid electrical contact between the terminal and the metal DIN rail the block mounts to.

Similarly, the hot, neutral, and ground conductors are all visually distinct by the shapes of their respective jacks on a standard (US) power receptacle:

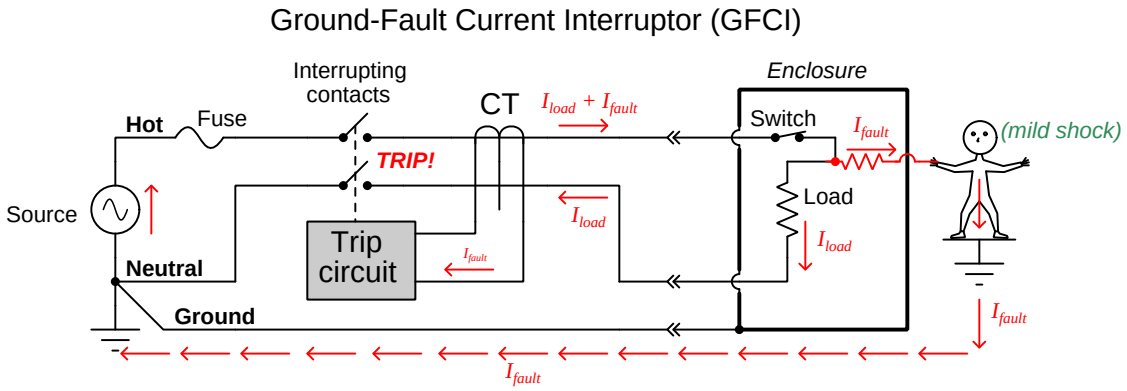


The small size difference between the hot and neutral jacks is not just for visual indication, but also for *polarized* two-prong power plugs where there is no ground conductor. On such a plug the hot and neutral "stabs" themselves are slightly different in size, such that it simply will not fit in the wrong direction.

Appliances using such a "polarized" power plug rely on the plug's polarization to ensure it is always the "hot" conductor and never the "neutral" that is disconnected by means of an internal overcurrent device (e.g. fuse, breaker) and/or power switch:



In scenarios where electrical shock via connection to the Earth is more likely, an additional form of protection against electric shock exists called *ground fault protection*, also called *residual current detection*. In the United States, the National Electrical Code requires such protection in residential circuits supplying electrical power to potentially wet zones such as bathrooms and outdoor work areas. The principle of operation for ground fault protection is to monitor current traveling to and from the load, and to automatically trip a disconnecting switch in the event that any *difference* in current is detected between those two conductors, as would happen if a person standing on the ground were to somehow come into contact with the "hot" conductor inside the load enclosure:



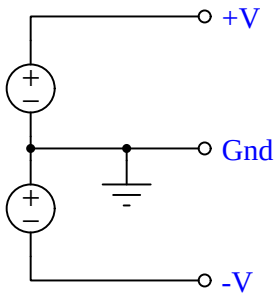
A device called a *current transformer* (CT)[5] surrounds the hot and neutral conductor, and generates an electrical signal proportional to any difference in current through those two conductors. If any imbalance is detected, a sensitive "trip circuit" signals a pair of switch contacts to automatically open ("trip") and thus completely disconnect the load from the source. The CT and trip circuit are quite sensitive, capable of detecting current imbalances in the milliAmpere range and tripping the disconnect switch in mere fractions of a second.

GFCI-equipped power receptacles are easily identified by the presence of "Test" and "Reset" pushbuttons. GFCI circuit breakers also have "Test" pushbuttons. For both devices pressing the "Test" switch inserts a resistive ground fault into the circuit to test that the tripping circuit and interrupting contacts function as designed:

[5] Current transformers only work on alternating current (AC), but since most electrical power systems are already AC for other practical reasons this is not a barrier to application. This entire discussion on "hot" and "neutral" wires is valid regardless of whether the circuit in question is DC or AC, the basic safety principles being identical for each.

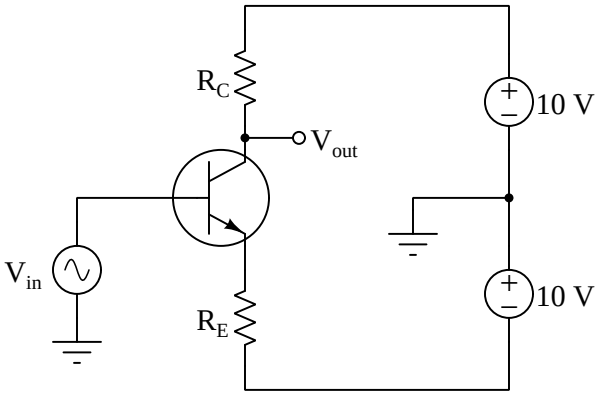
4.2 Split DC power supplies

A popular way to allow electronic amplifier circuits to input and output truly AC (alternating current) signals, as well as handle "bipolar" DC signals (i.e. signals having either positive or negative potential with respect to ground) is to power them using a *split* DC source. This is a DC power supply configuration providing three points of connection and three different voltage levels as shown below:

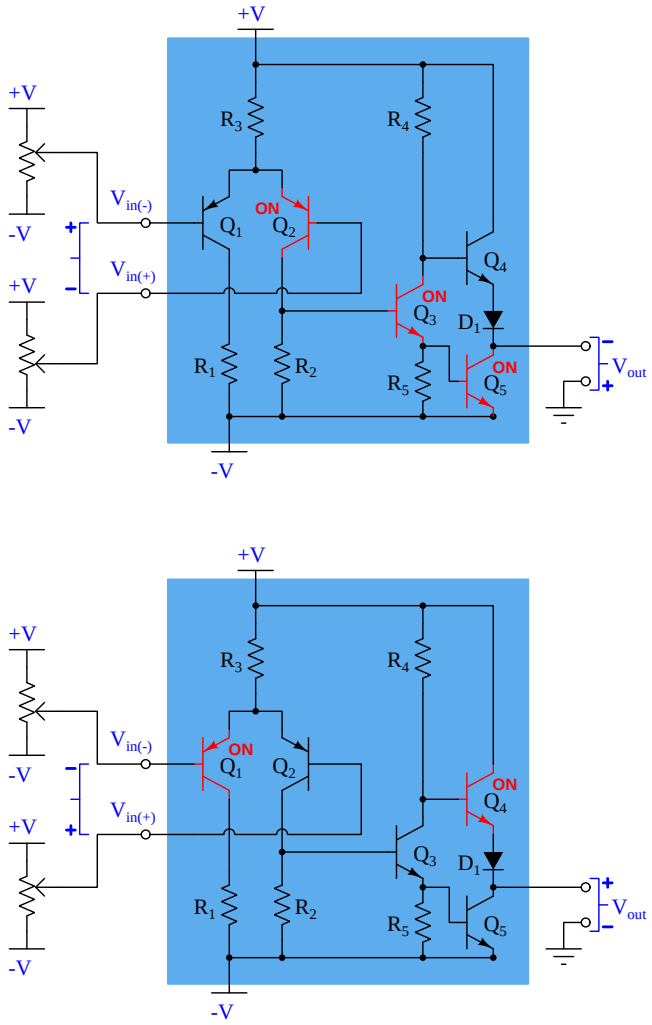


From +V to Ground we measure the voltage of the upper source; from −V to ground we measure the negative voltage of the lower source; between +V and −V we measure those sources' voltage sum. Typical split DC supplies are symmetrical, meaning that +V and −V have the same absolute values.

If we consider a common-emitter BJT amplifier energized by such a supply, we see it becomes possible to achieve Class-A amplification of an AC signal source without the need for biasing resistors anywhere. Moreover, the output voltage is capable of achieving true AC status as well, alternating positive and negative with respect to ground, all because of the split power supply:



In the following diagrams we show the simplified internal schematic diagram of a comparator powered by a split supply, in two "limiting case" conditions. In keeping with the problem-solving strategy of "limiting cases" we will assume all transistor states to be either fully on (saturated) or fully off, marking those saturated-on transistors in red:



In the upper scenario we see the comparator subjected to a negative differential voltage input (i.e. inverting terminal more positive than noninverting), and this causes its output to saturate low by turning on transistor Q_5. With Q_5 on, the output terminal is nearly equipotential with the negative supply rail ($-$V), and so is negative with respect to ground.

In the lower scenario the comparator experiences a positive differential input (noninverting terminal more positive than inverting), causing Q_4 to saturate on. With Q_4 fully, on the output terminal is nearly equipotential with the positive rail (+V), and so is positive with respect to ground.

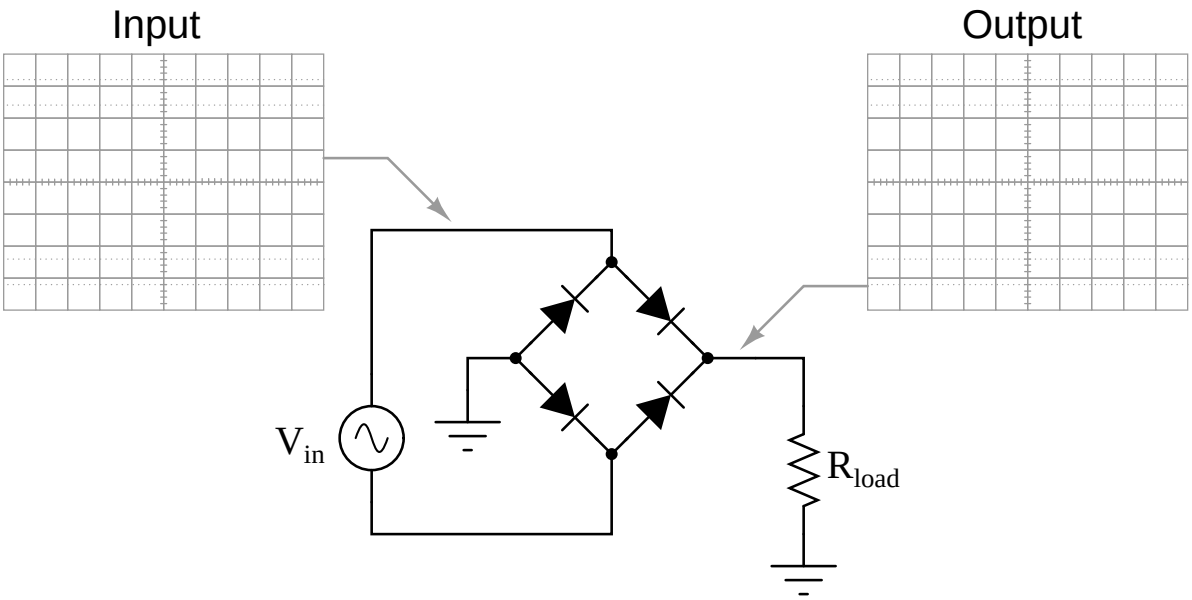
Chapter 5

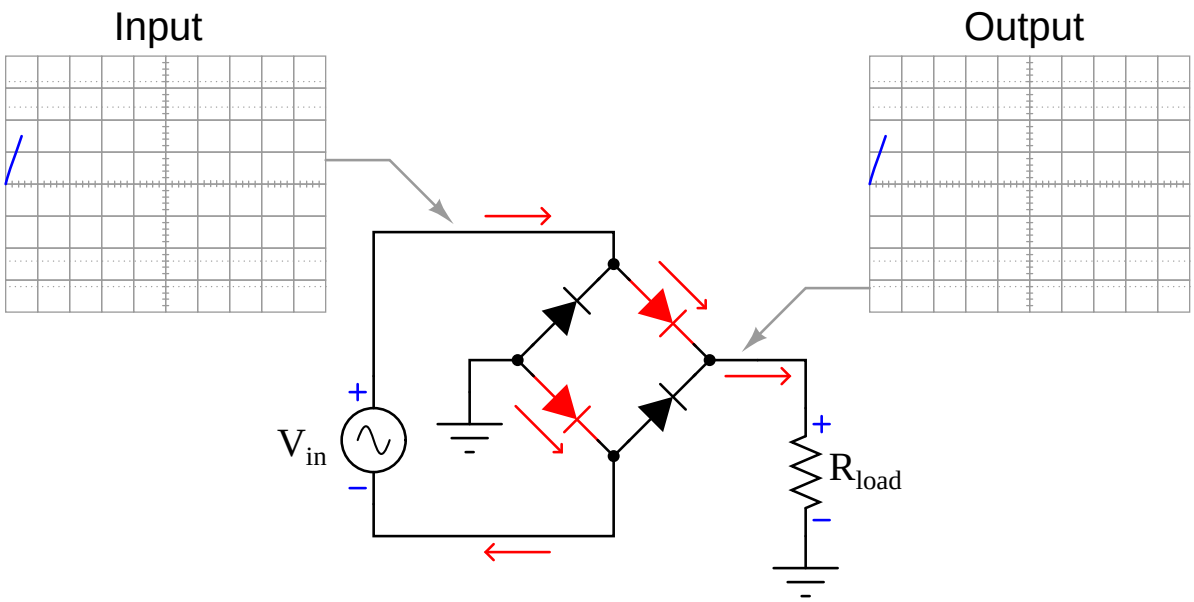
Animations

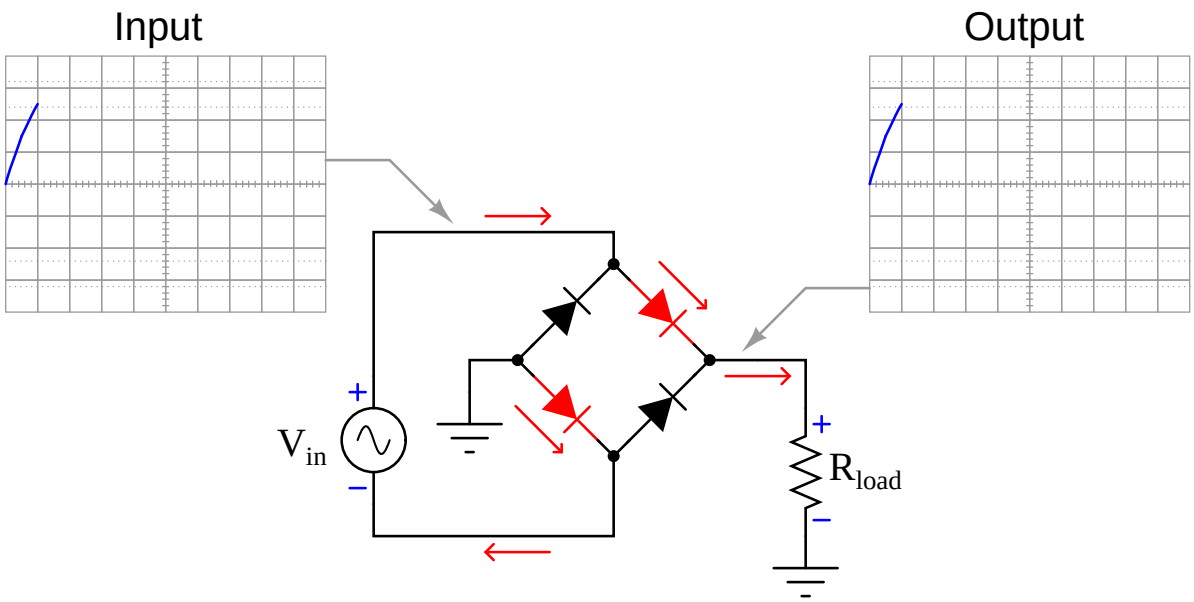
Some concepts are much easier to grasp when seen in *action*. A simple yet effective form of animation suitable to an electronic document such as this is a "flip-book" animation where a set of pages in the document show successive frames of a simple animation. Such "flip-book" animations are designed 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.

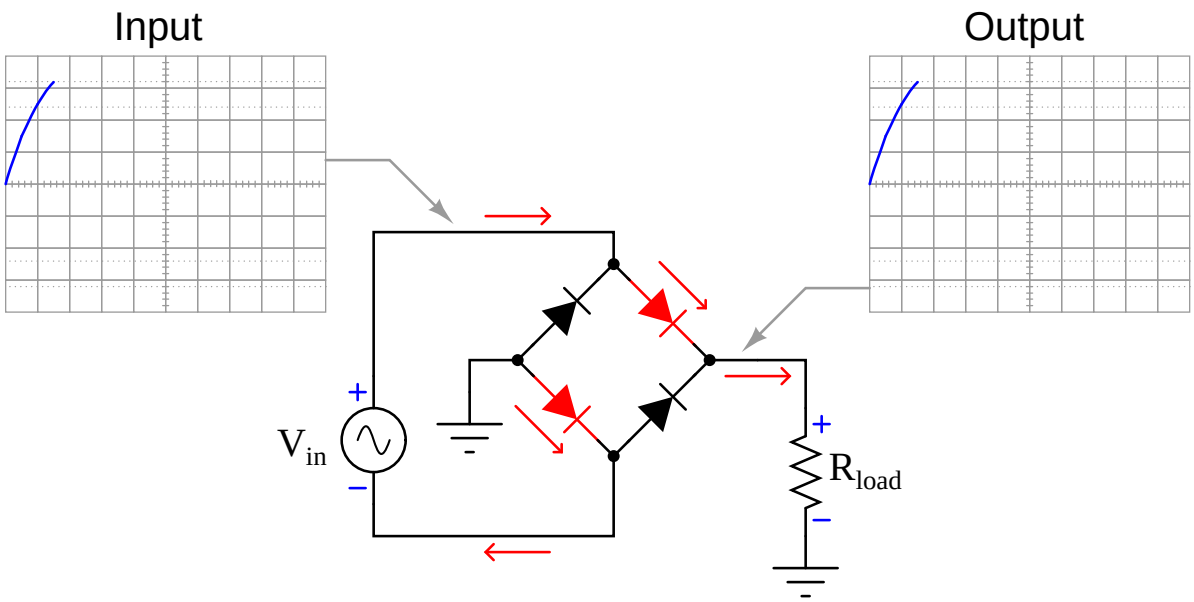
5.1 Full-wave bridge rectifier with ideal diodes

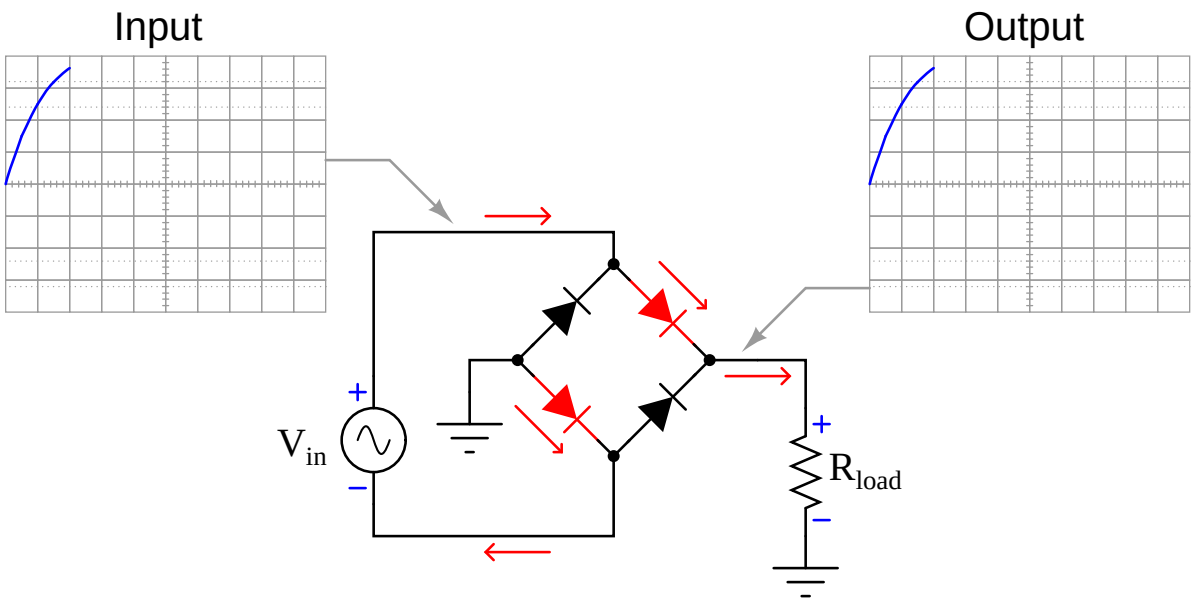
The following animation shows a full-wave, single-phase bridge rectifier using ideal diodes (with no forward voltage drop). Oscillographs show the input (AC) and output (rectified DC) of the rectifier circuit, with forward-biased diodes colored red.

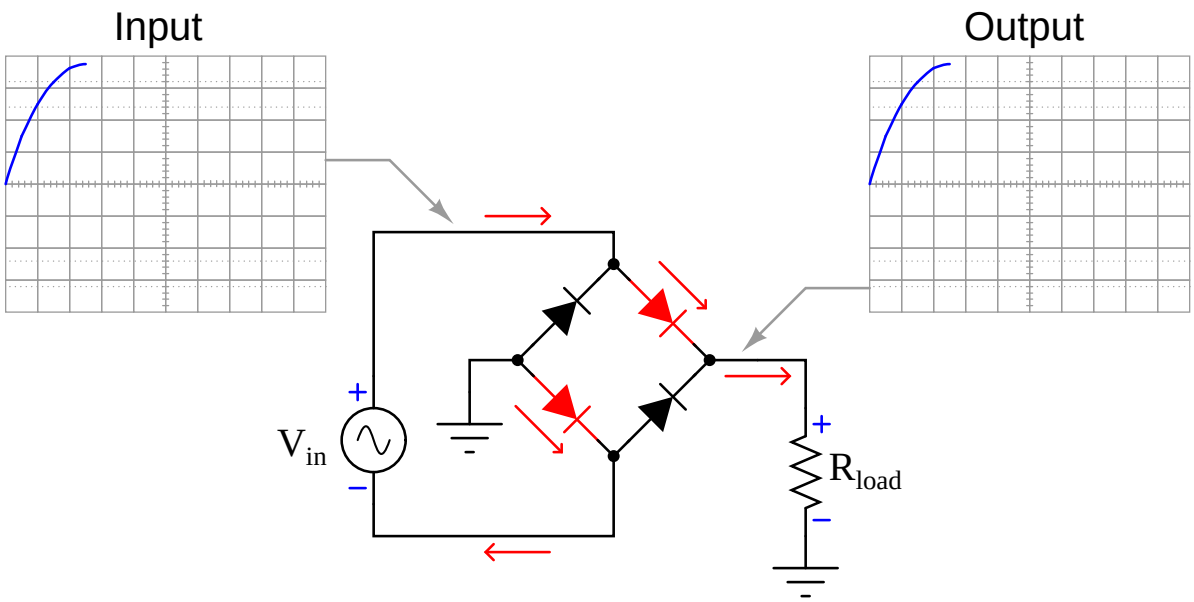

Input
Output
V_{in}
R_{load}

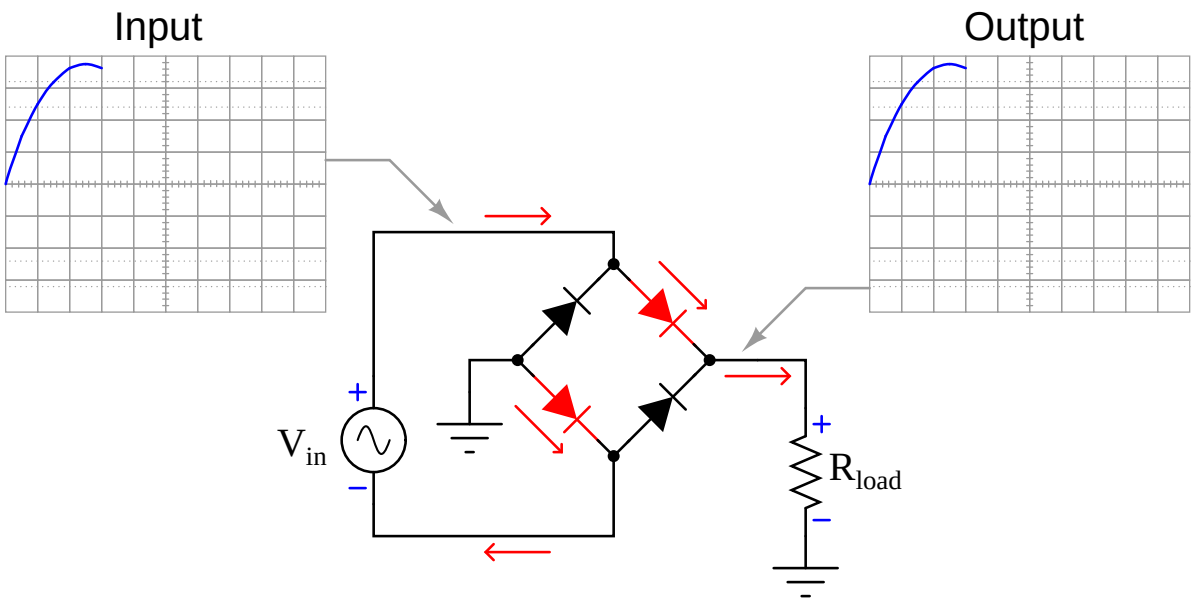

Input
Output
+
V_{in}
−
+
R_{load}
−

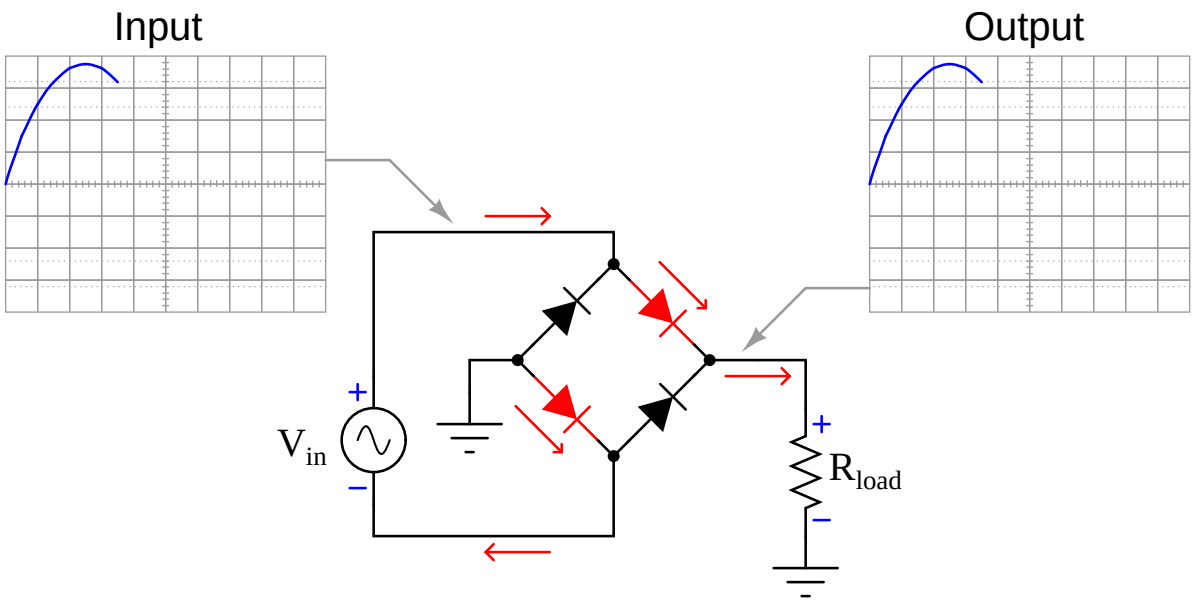

Input
Output
+
V_{in}
−
+
R_{load}
−

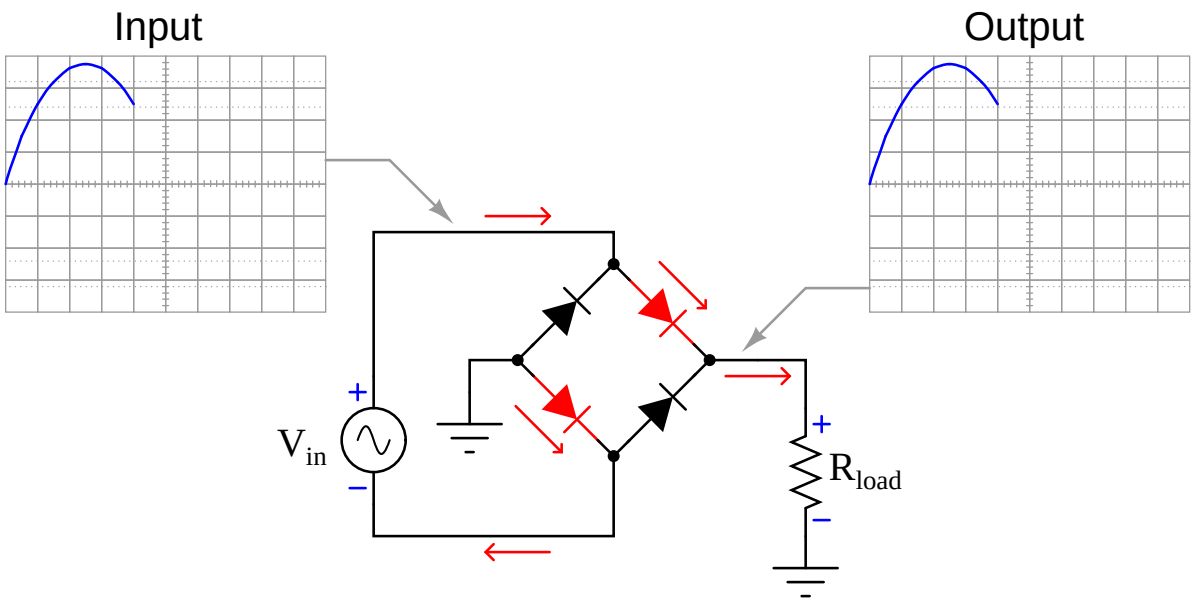

Input
Output
+
V_{in}
−
+
R_{load}
−

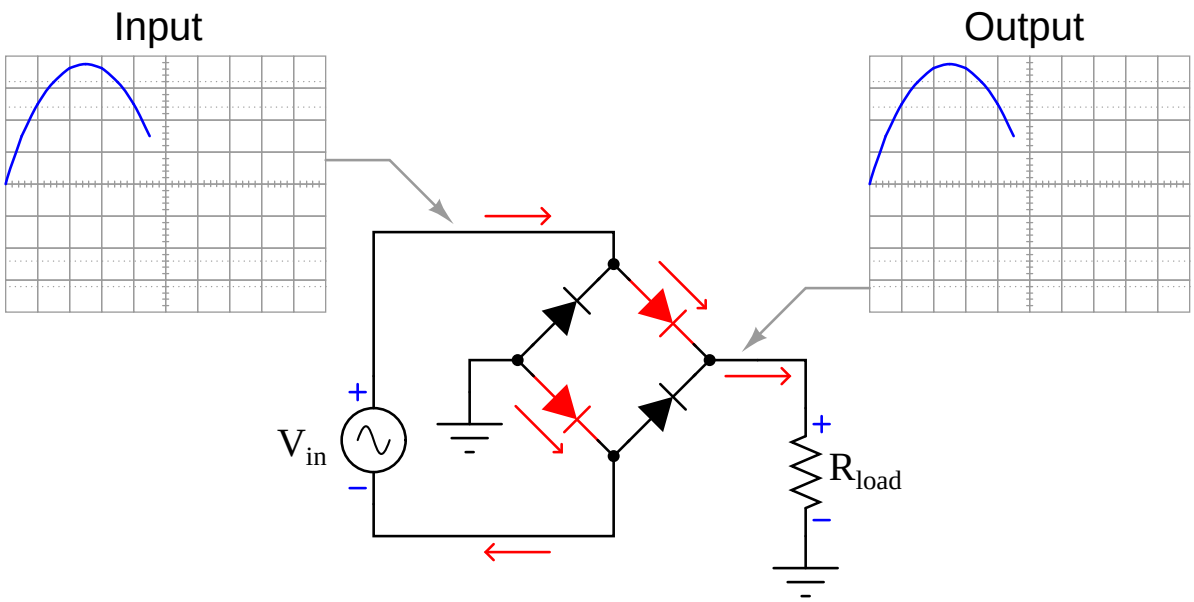

Input
Output
+
V_{in}
−
+
R_{load}
−

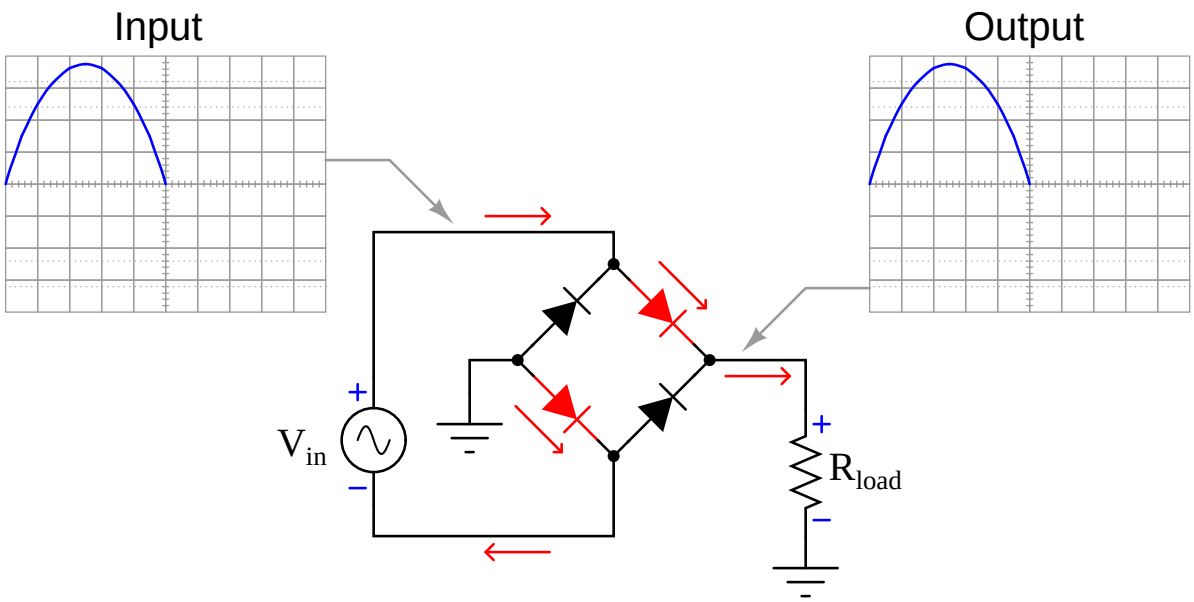

Input
Output
+
V_{in}
−
+
R_{load}
−

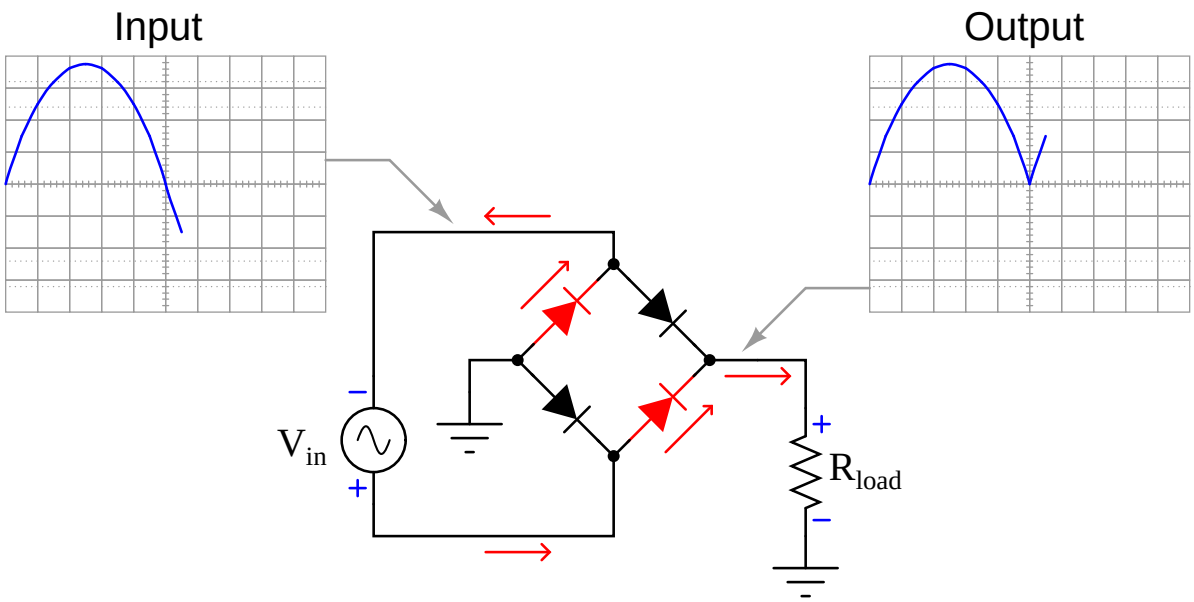

Input
Output
+
V_{in}
−
+
R_{load}
−

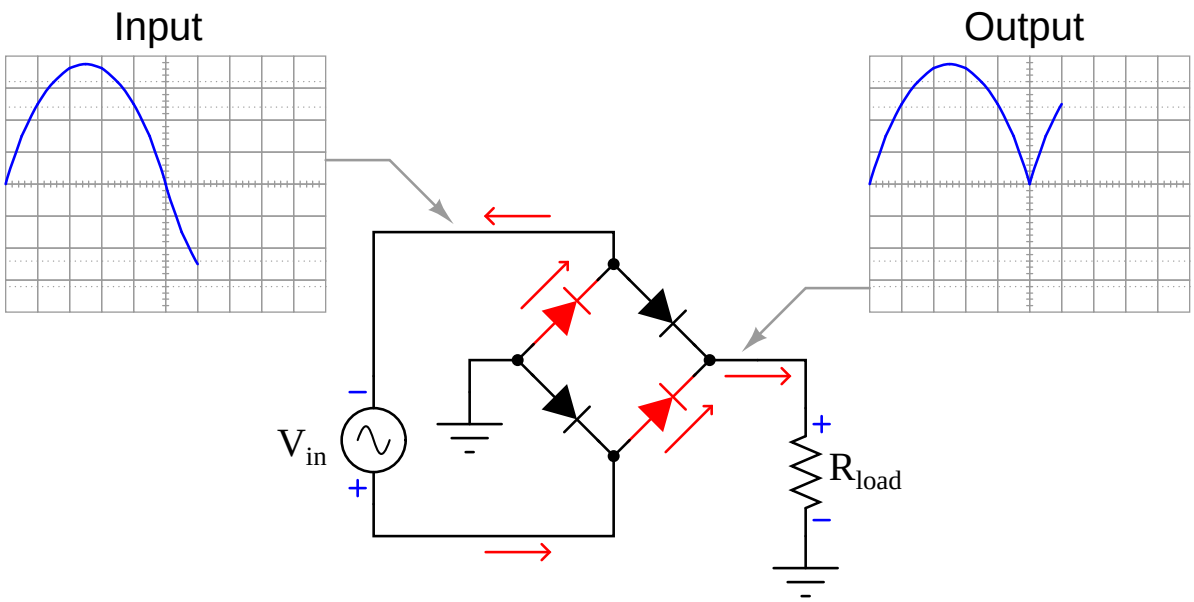

Input
Output
+
V_{in}
−
+
R_{load}
−

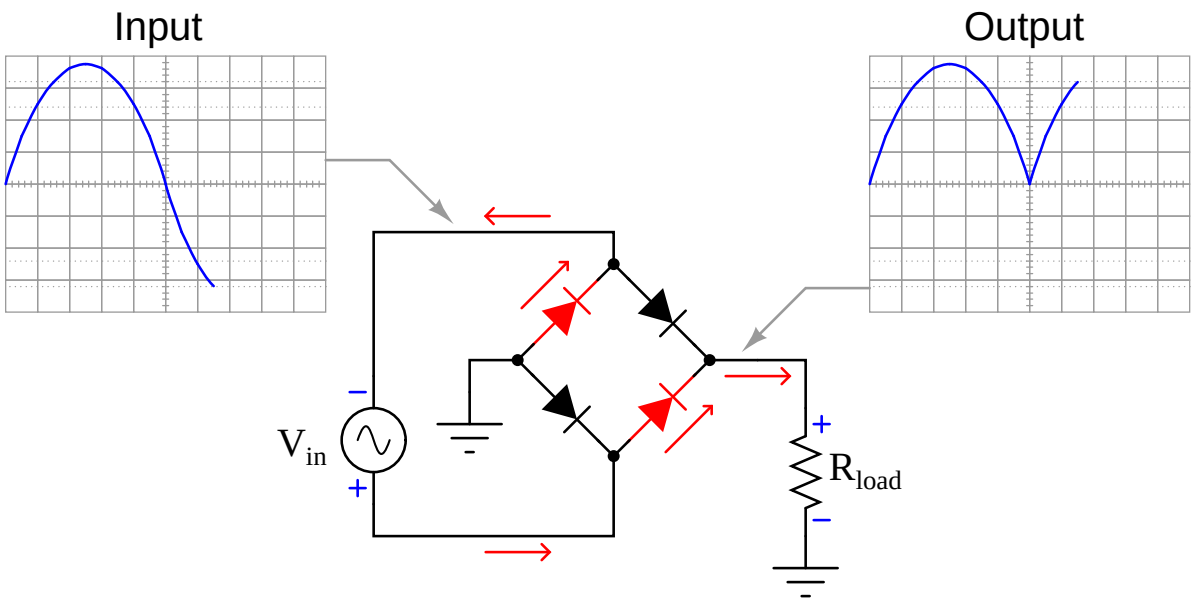

Input
Output
+
V_{in}
−
+
R_{load}
−

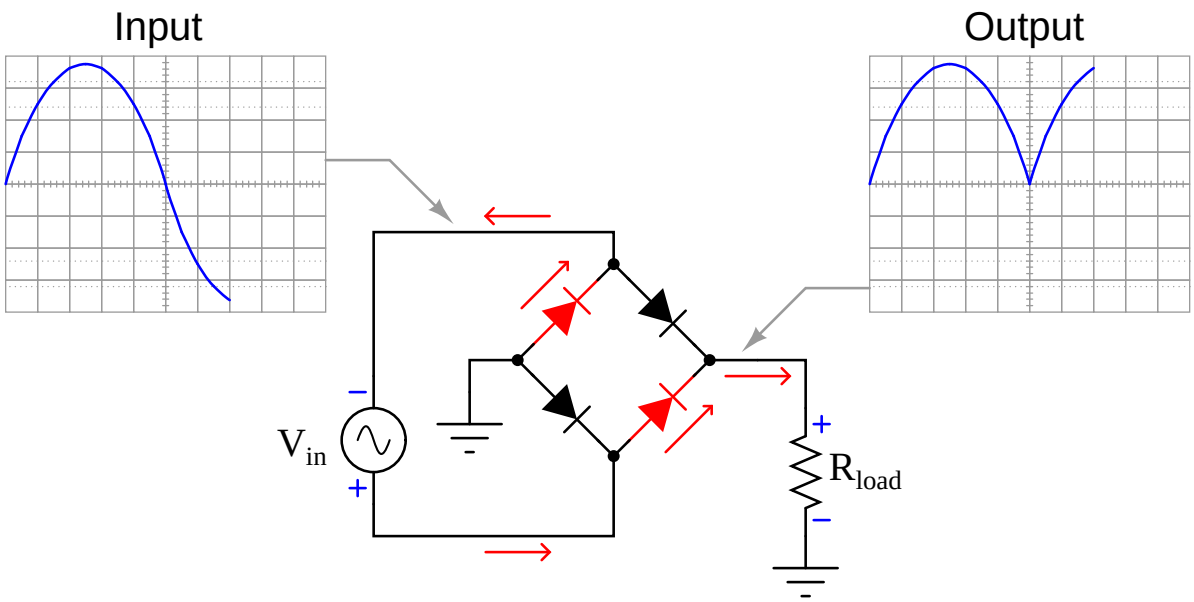

Input
Output
+
V_{in}
−
+
R_{load}
−

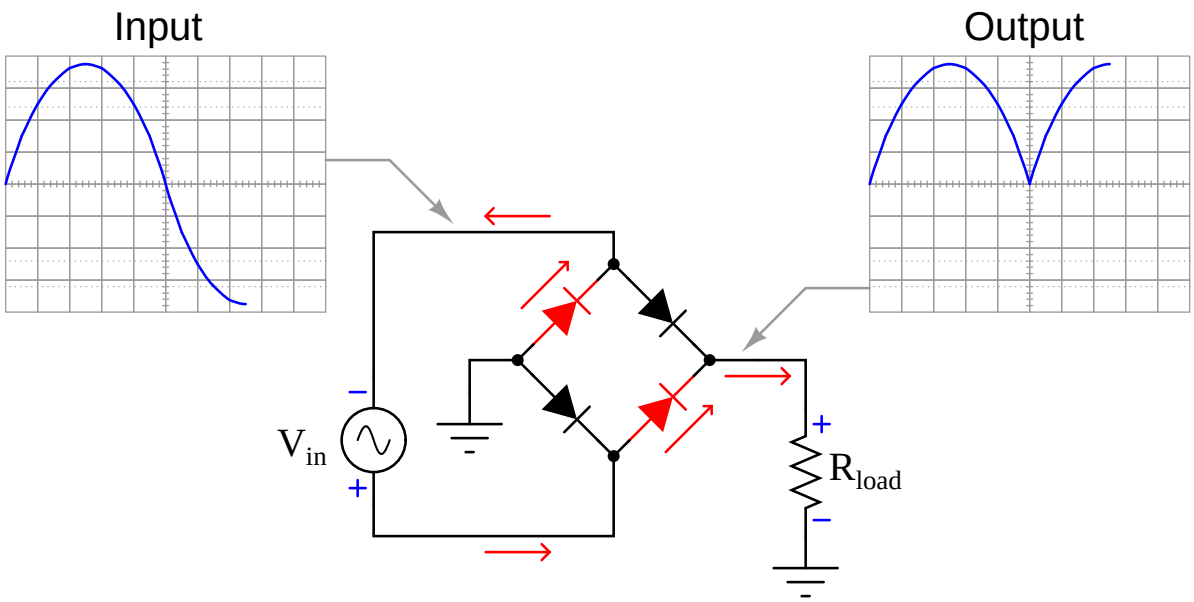

Input
Output
+
V_{in}
−
+
R_{load}
−

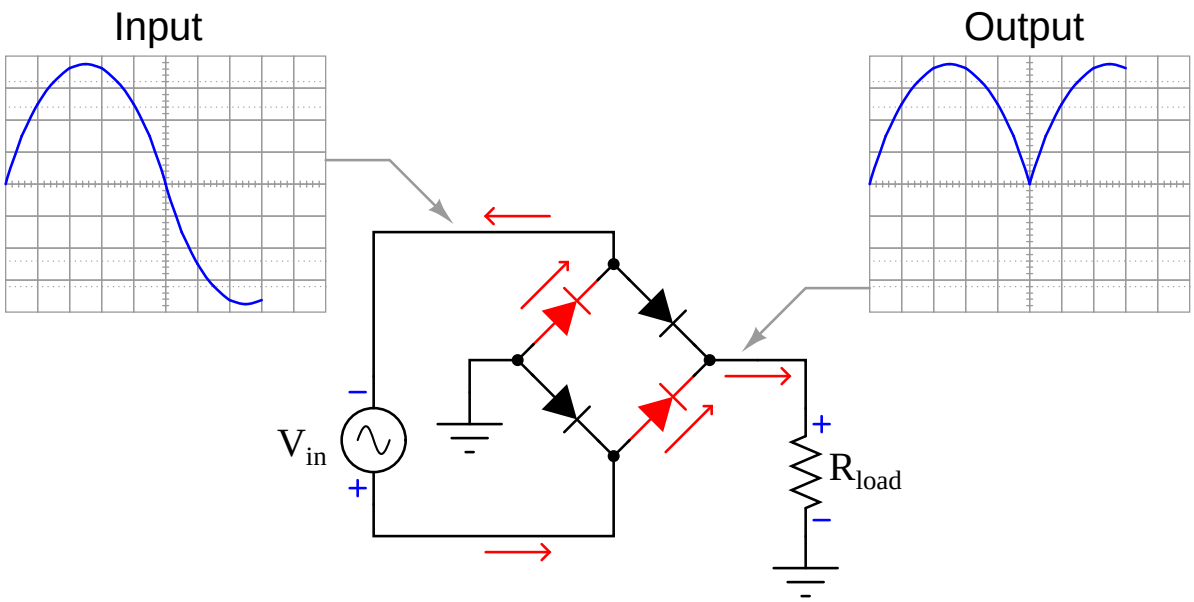

Input
Output
V in
R load

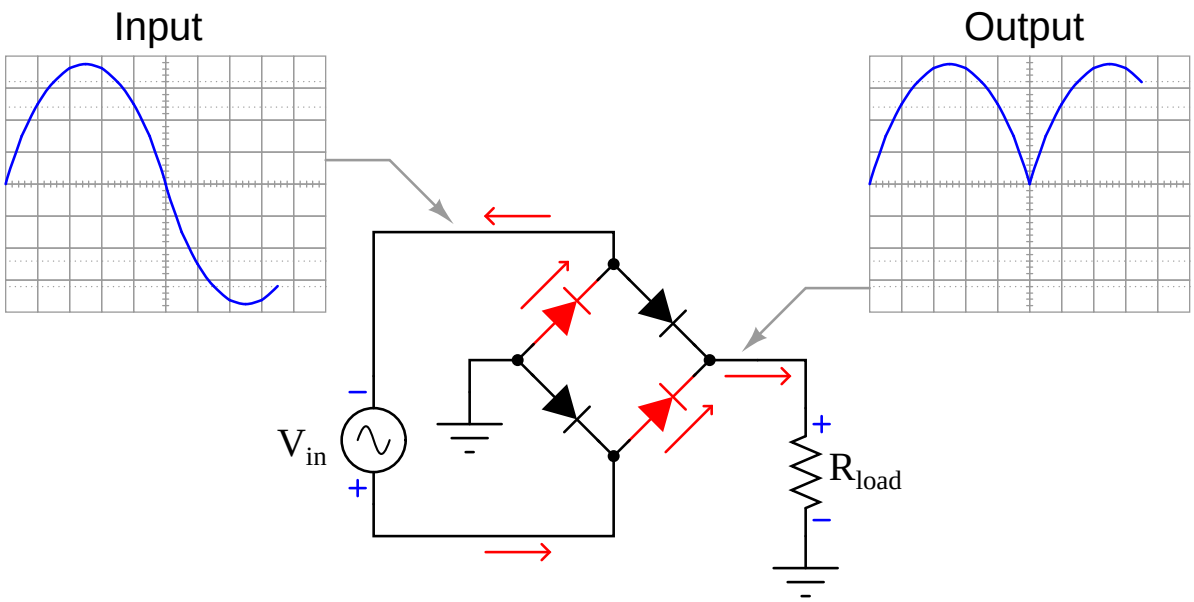

Input
Output
V in
R load

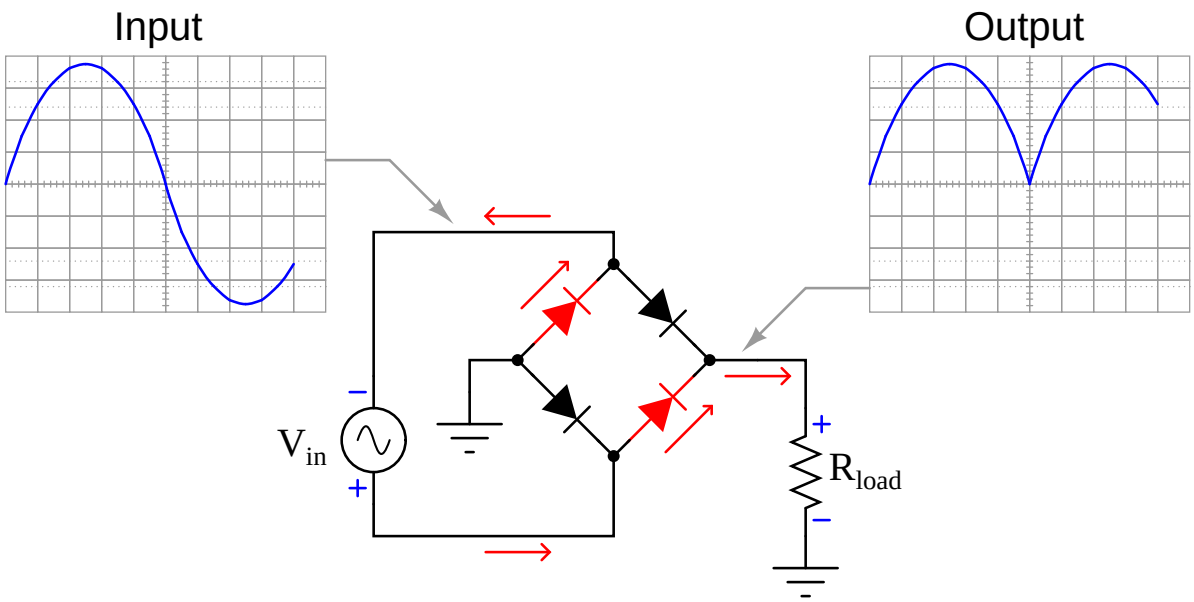

Input
Output
V in
R load

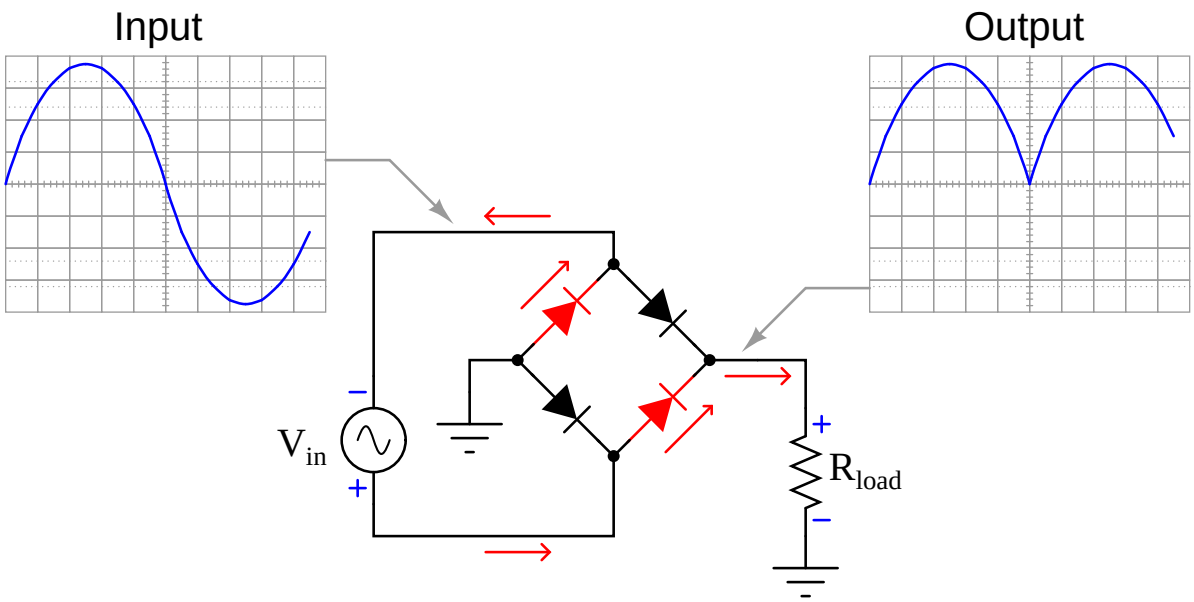

Input
Output
V in
R load

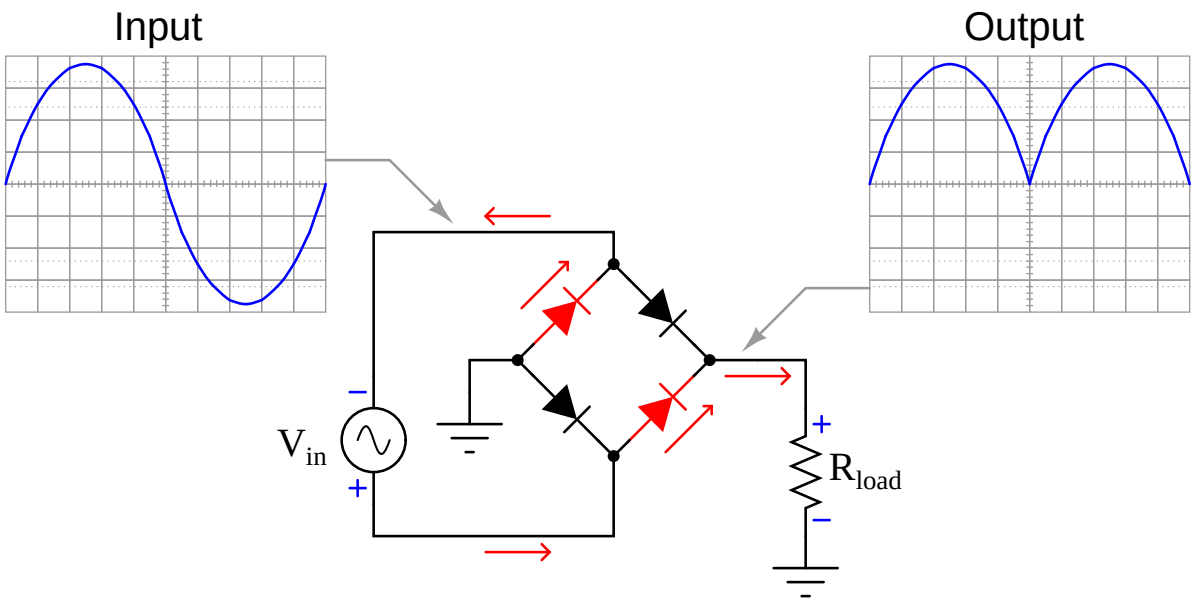

Input
Output
V in
R load


Input
Output
V in
R load


Input
Output
V in
R load

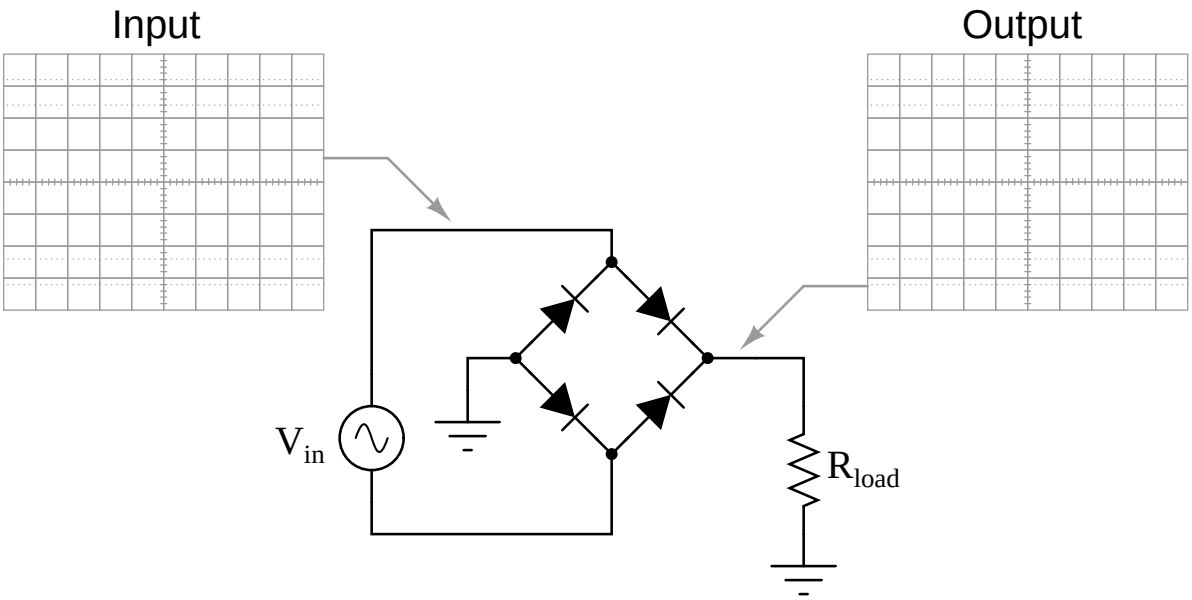

Input
Output
V in
R load

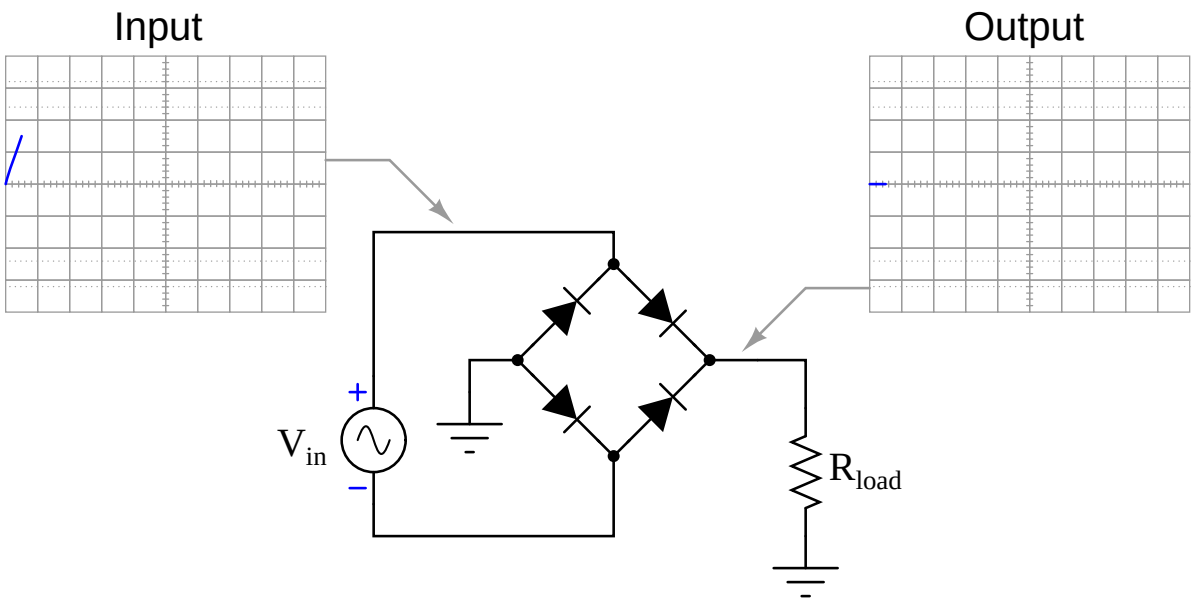

Input
Output
V in
R load

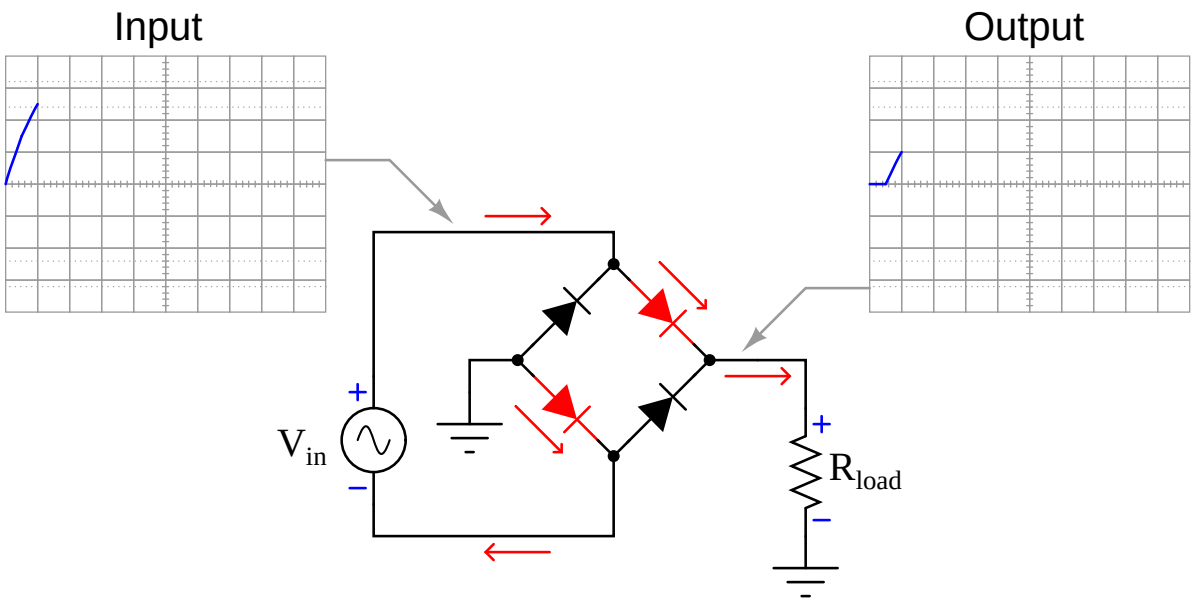

Input
Output
V in
R load

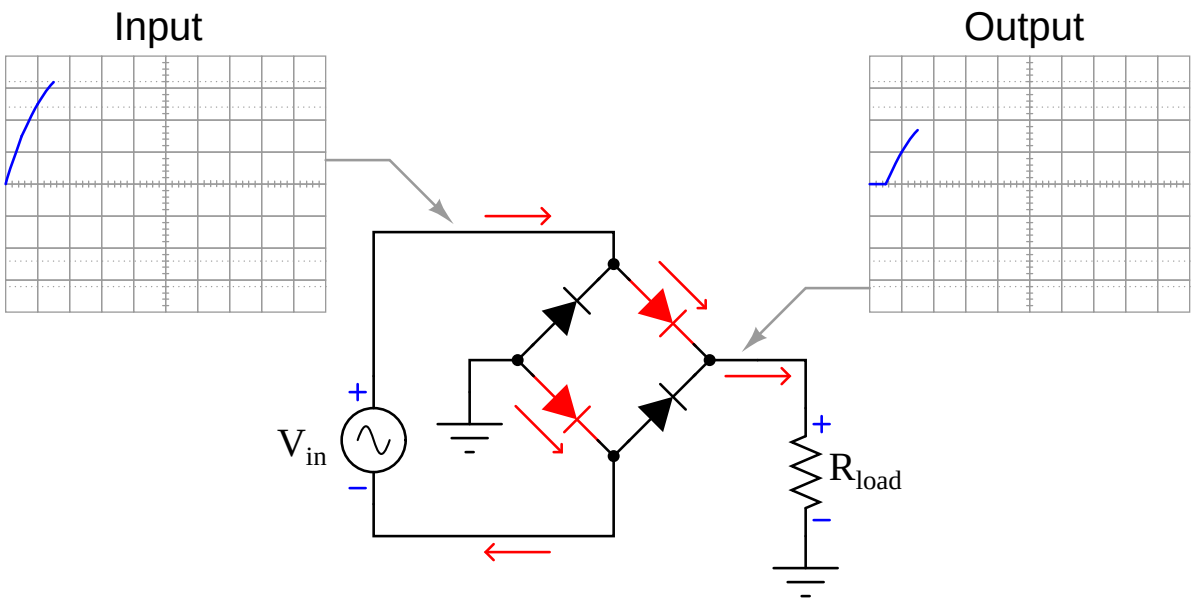
5.2 Full-wave bridge rectifier with real diodes

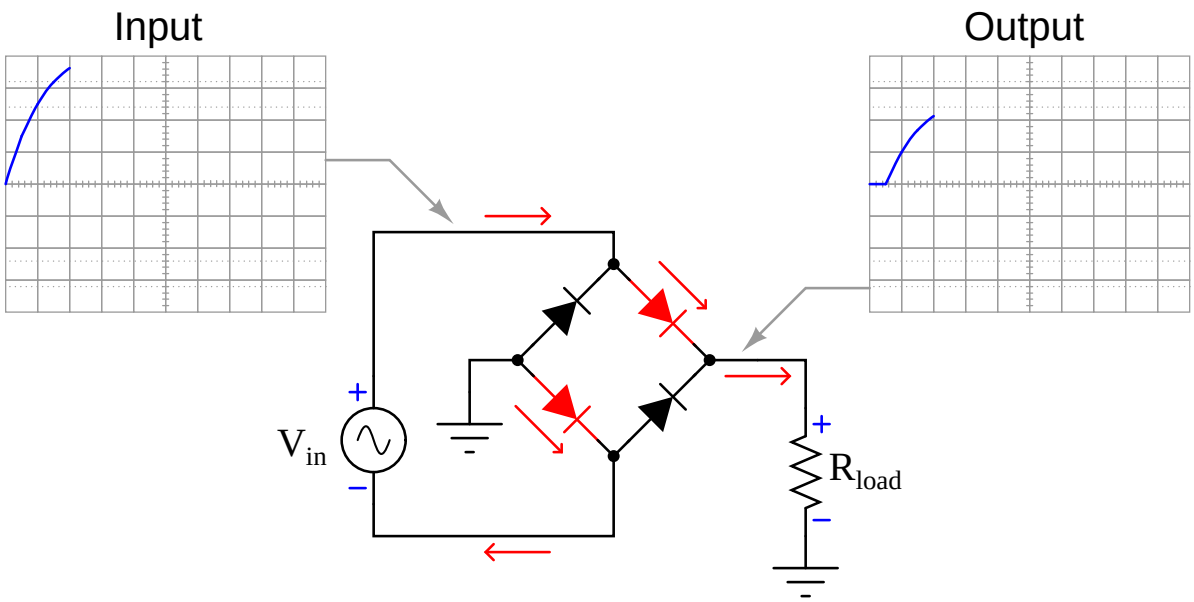
The following animation shows a full-wave, single-phase bridge rectifier using real diodes (with some forward voltage drop). Oscillographs show the input (AC) and output (rectified DC) of the rectifier circuit, with forward-biased diodes colored red.

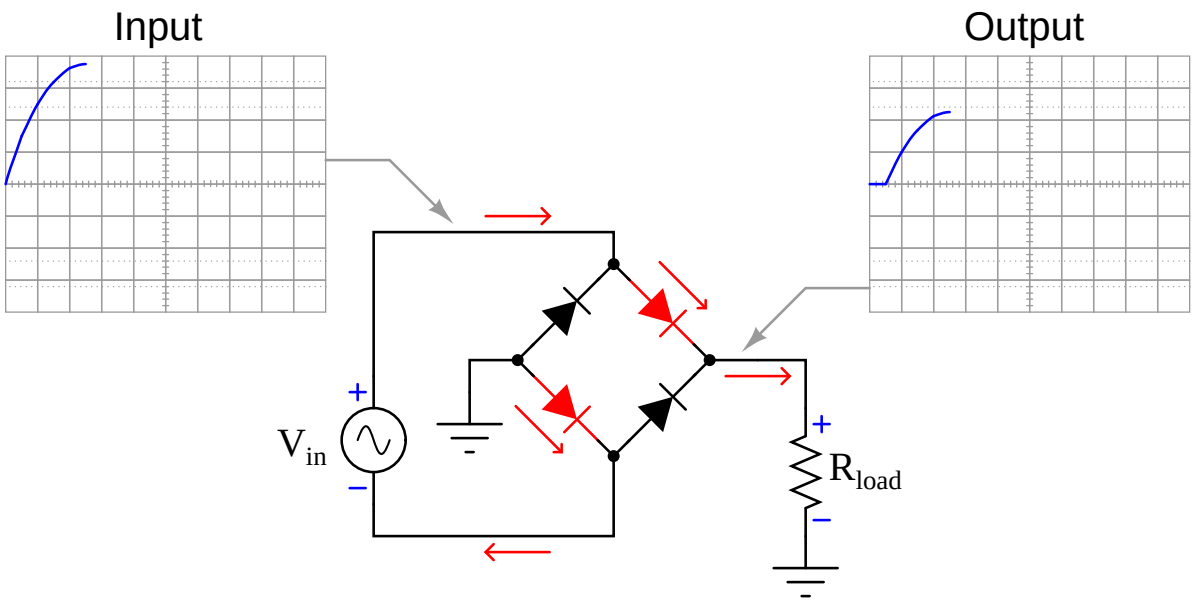

Input
Output
V_{in}
R_{load}


Input
Output
+
V_{in}
−
R_{load}


Input
Output
+
V_{in}
−
+
R_{load}
−


Input
Output
+
V_{in}
−
+
R_{load}
−


Input
Output
+
V_{in}
−
+
R_{load}
−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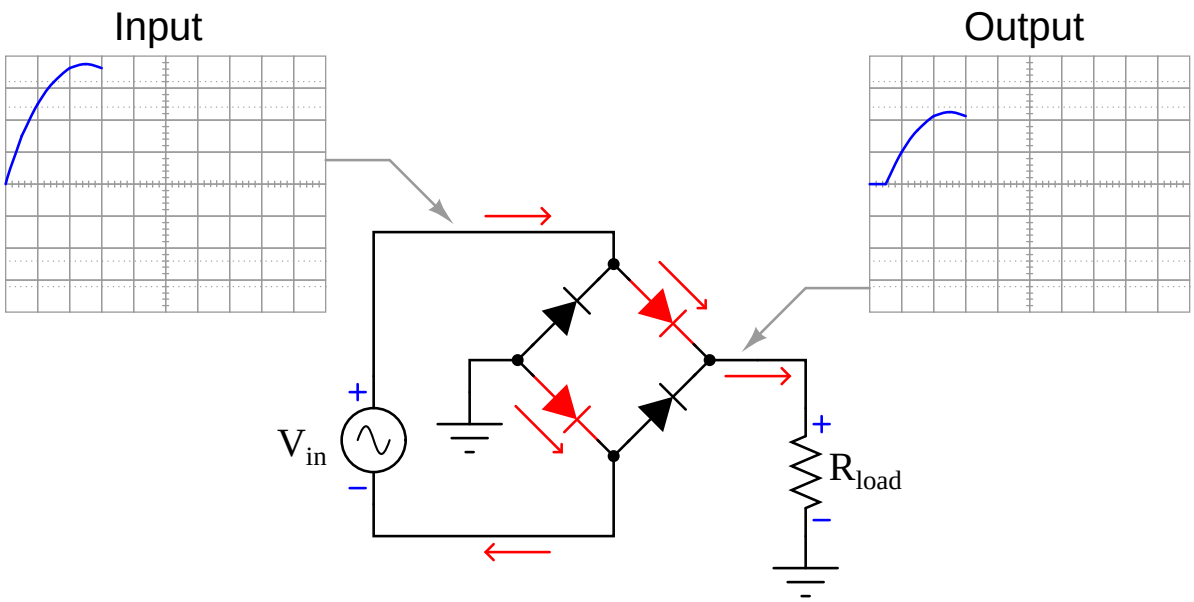
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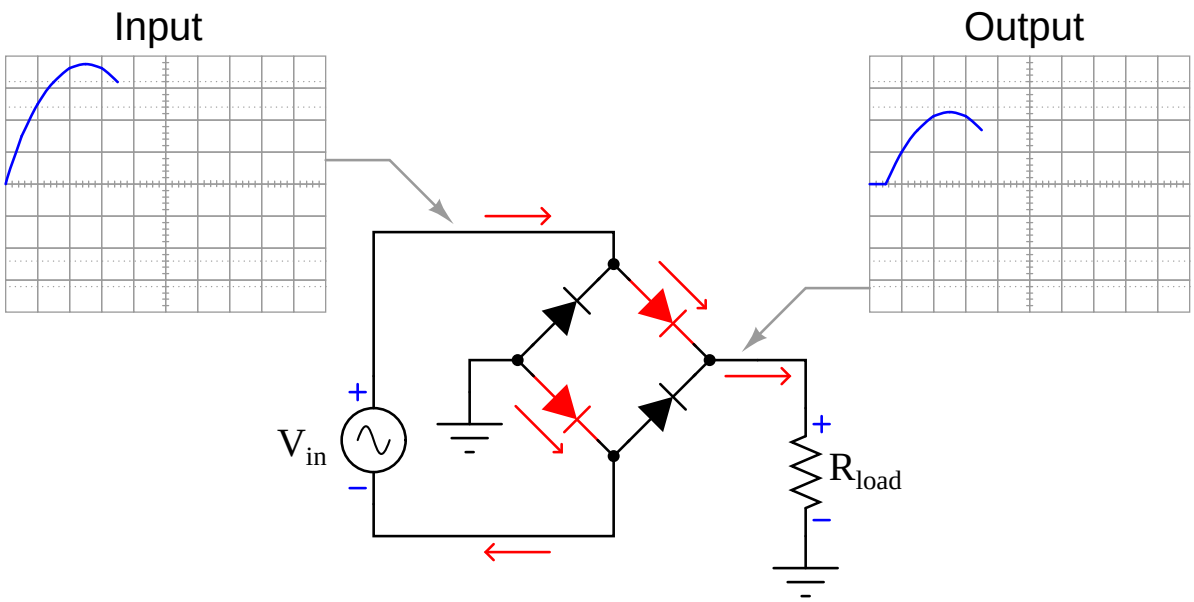
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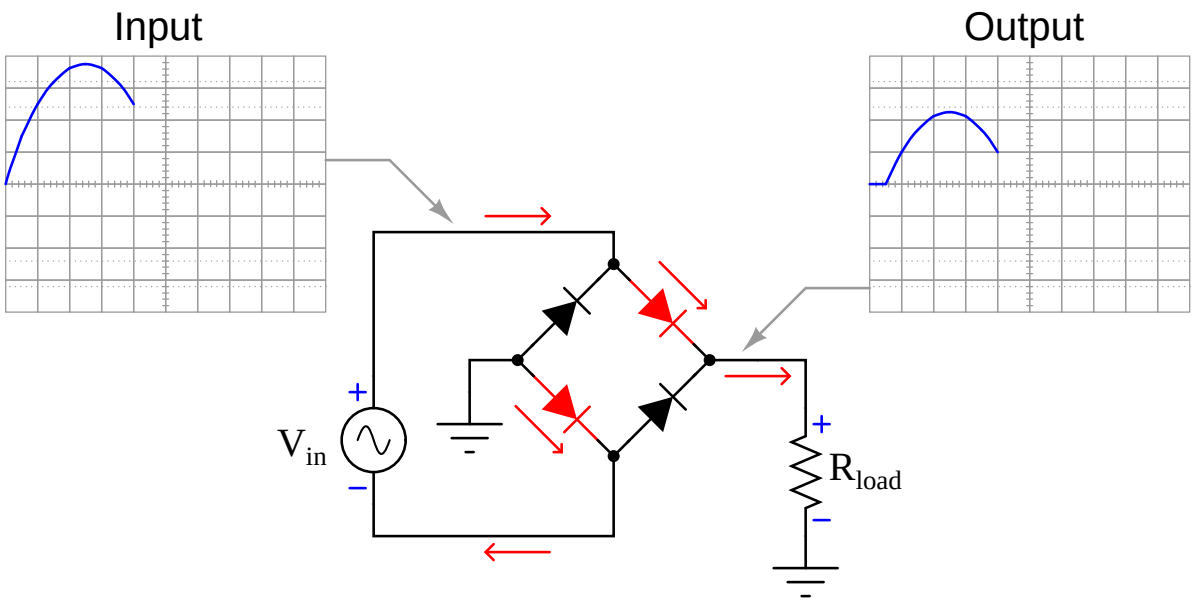
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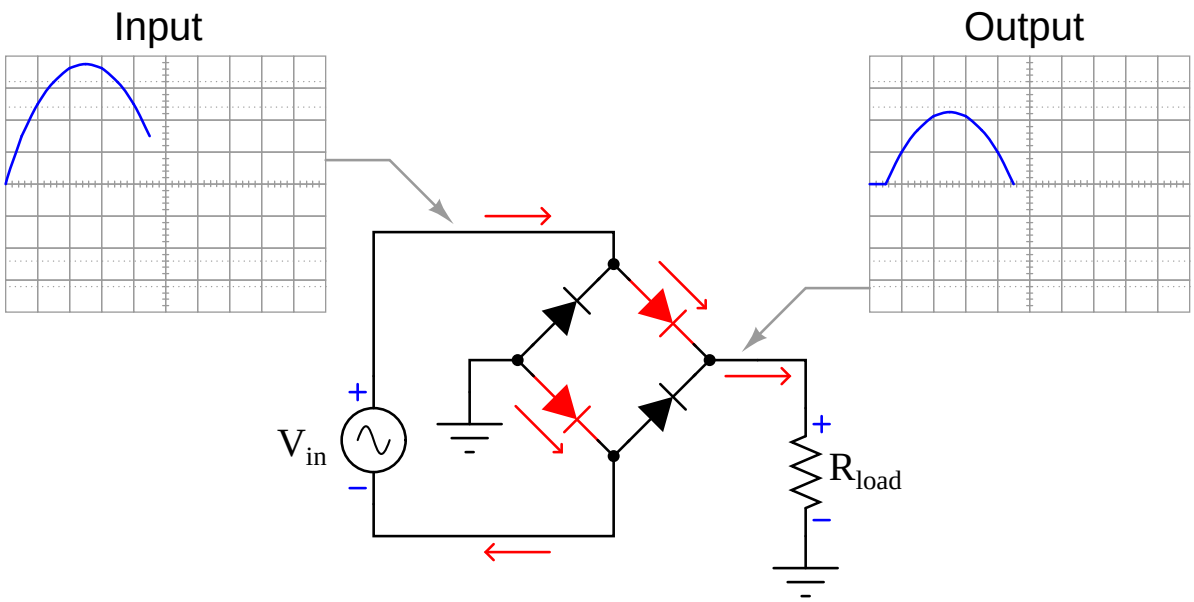
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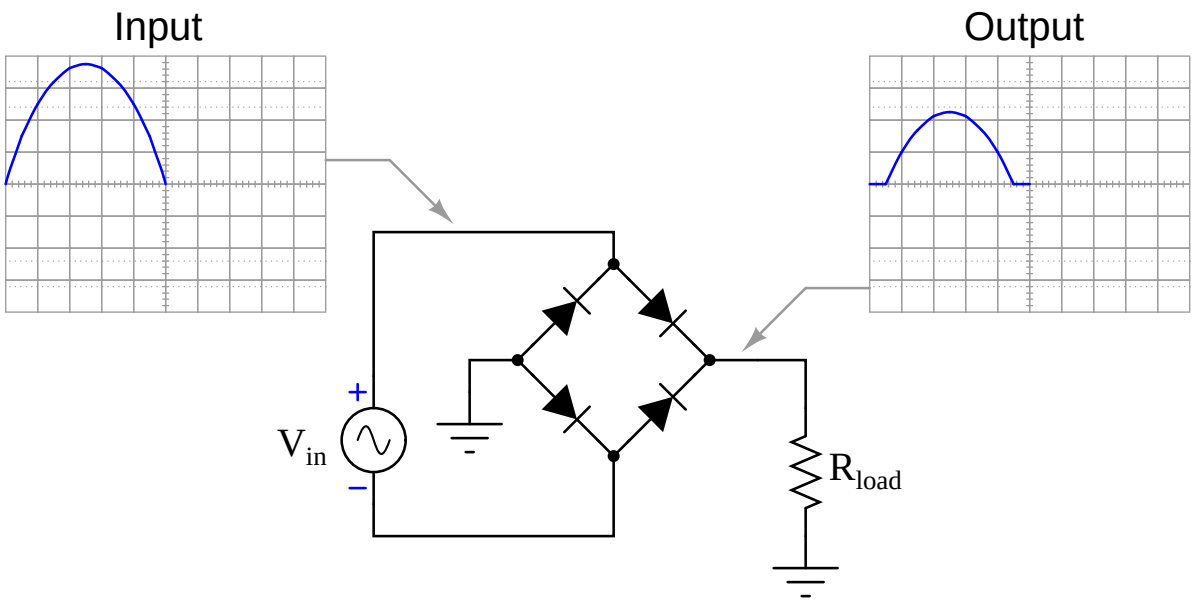
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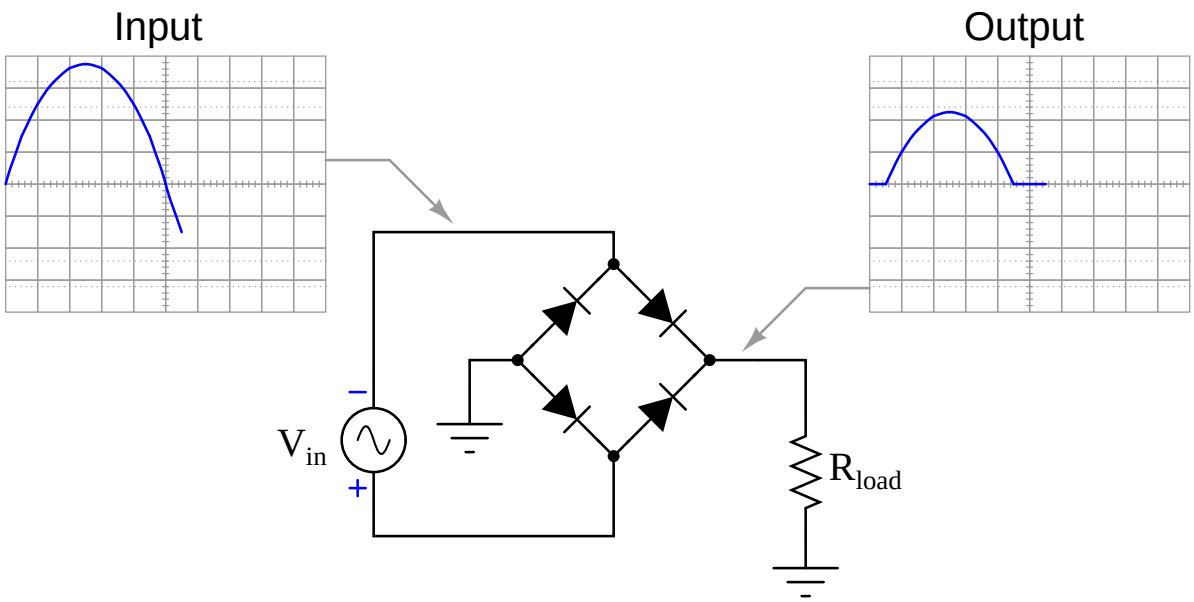
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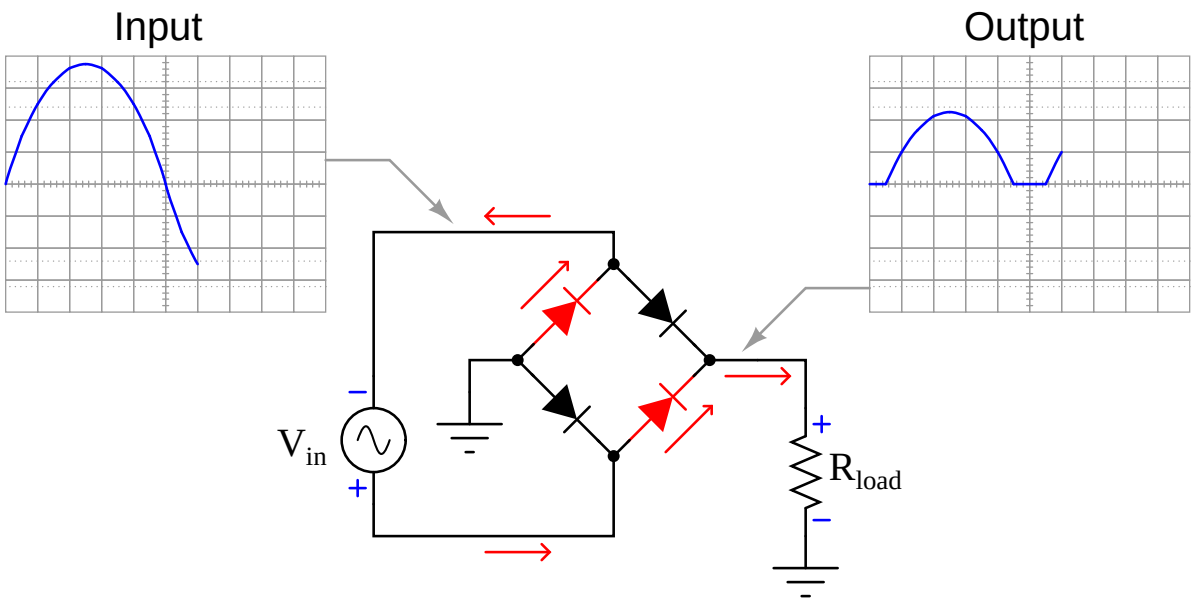
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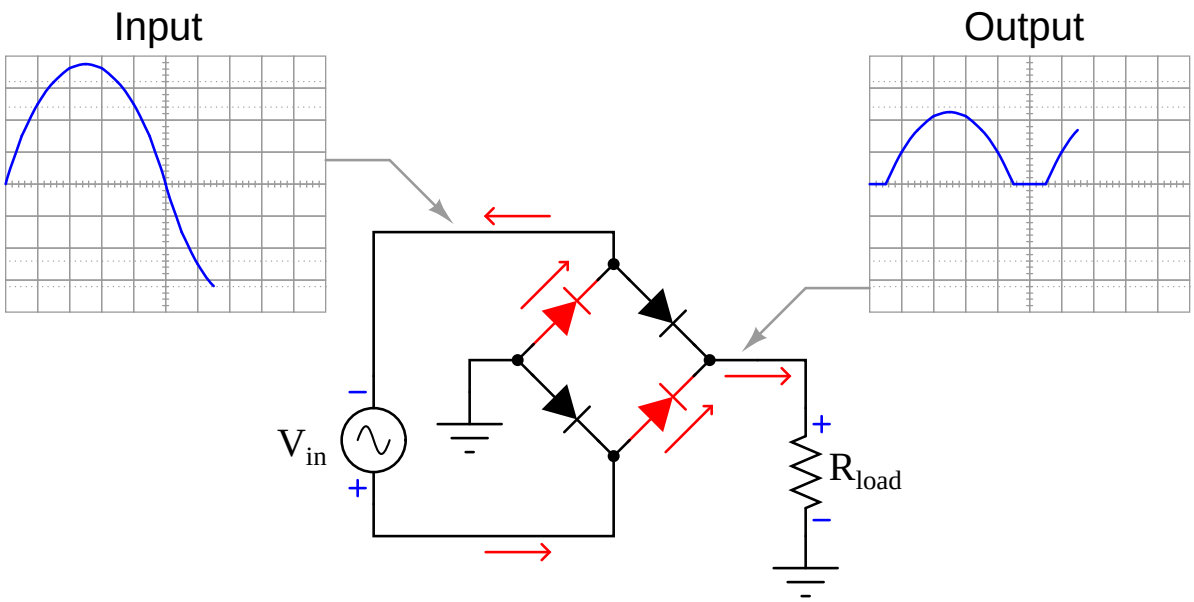
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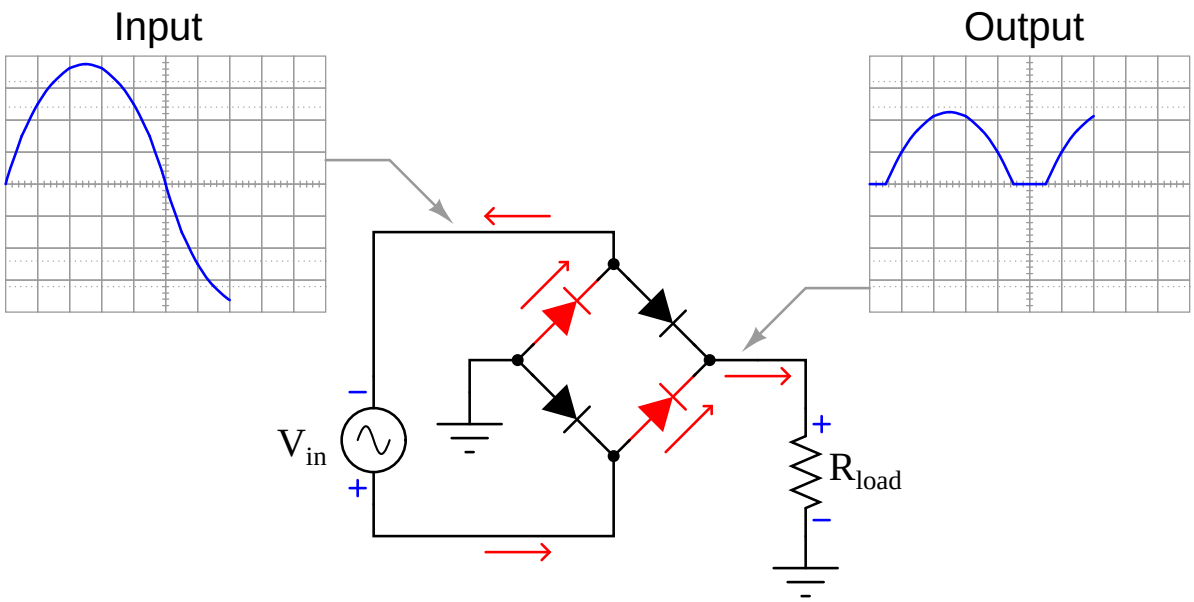
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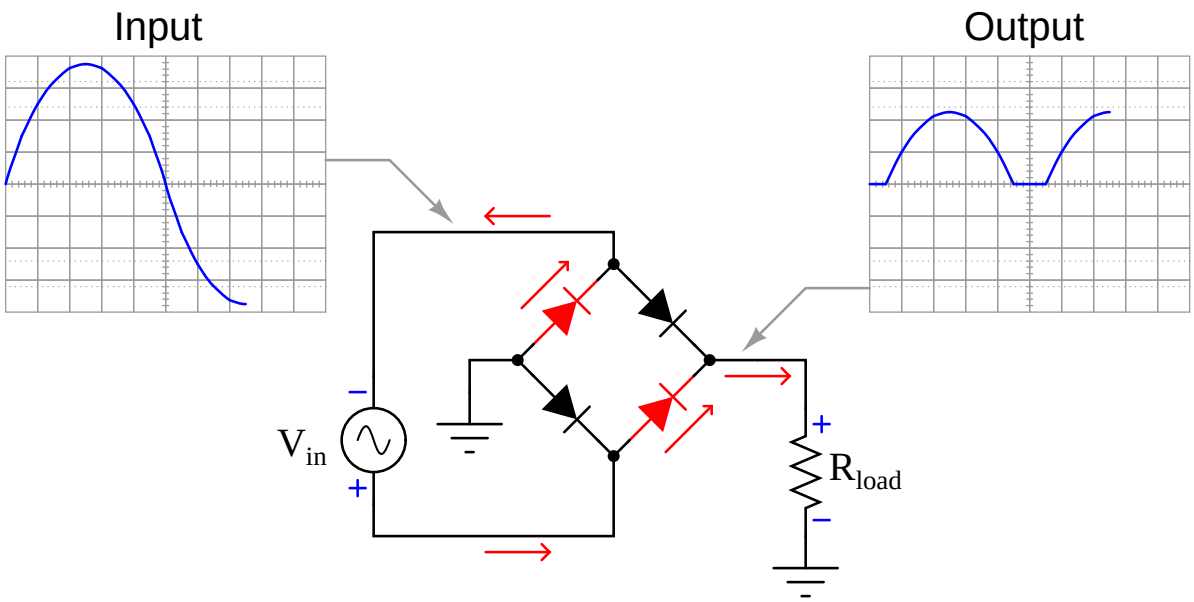
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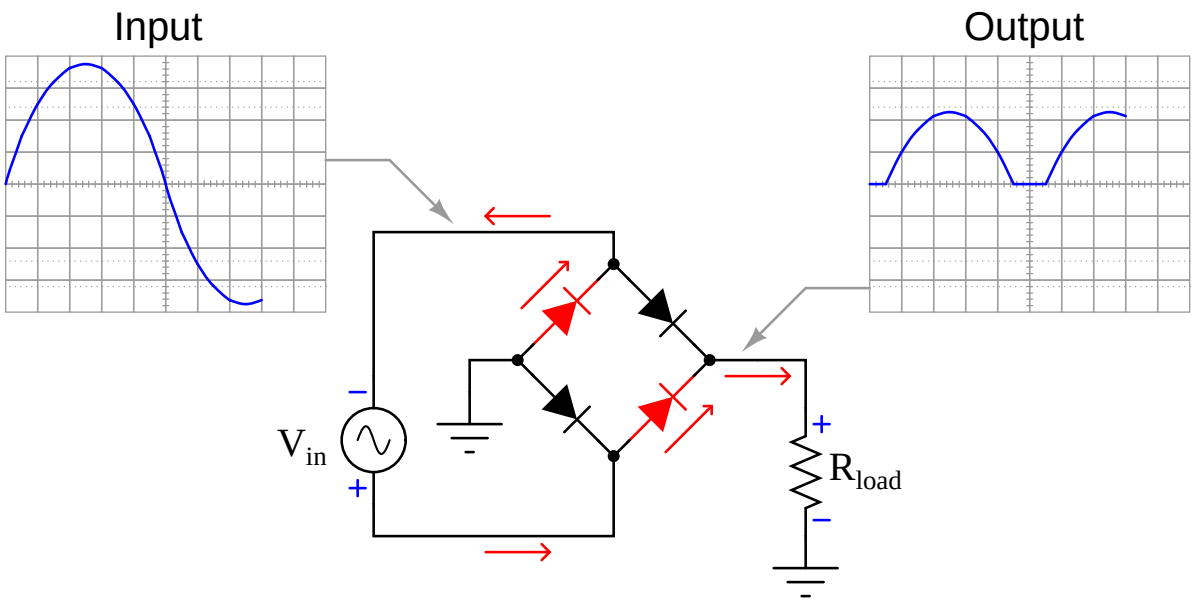
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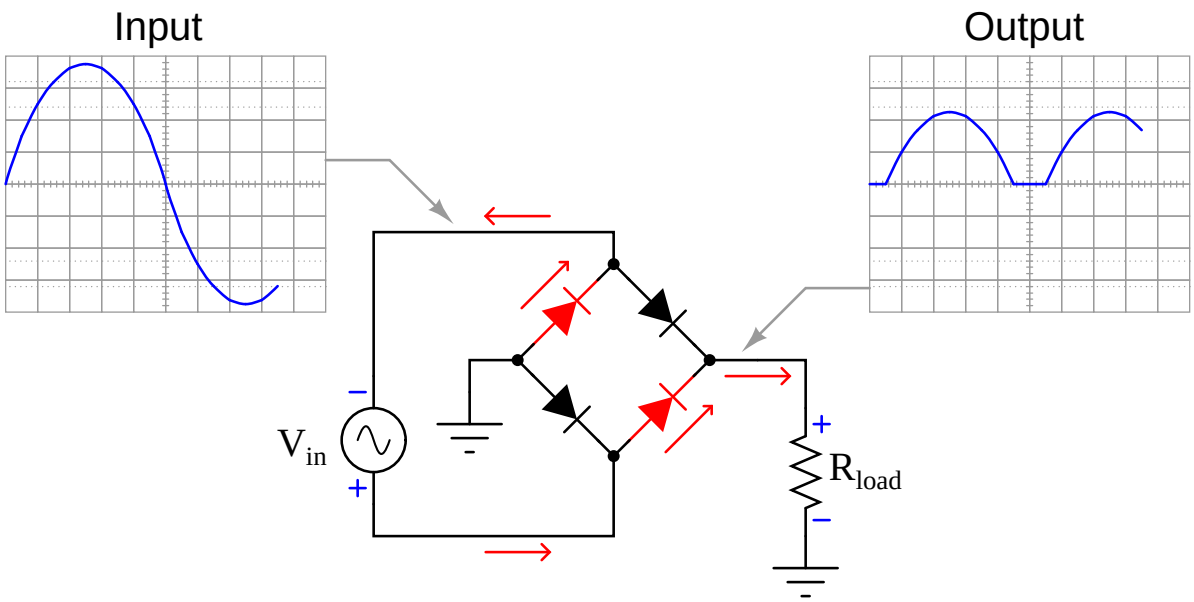
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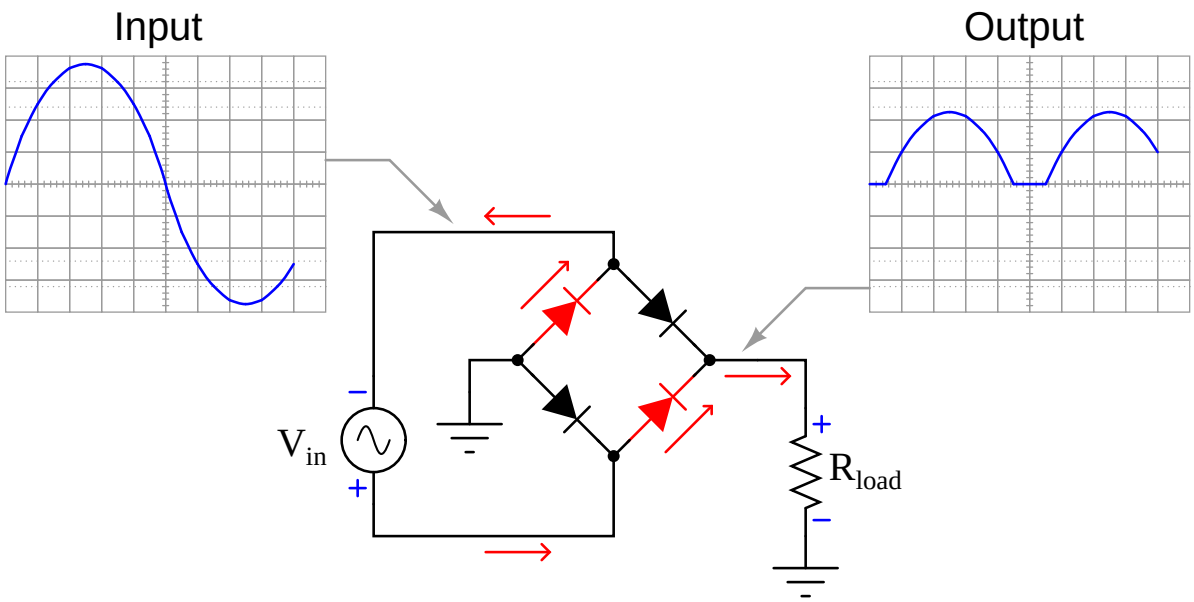
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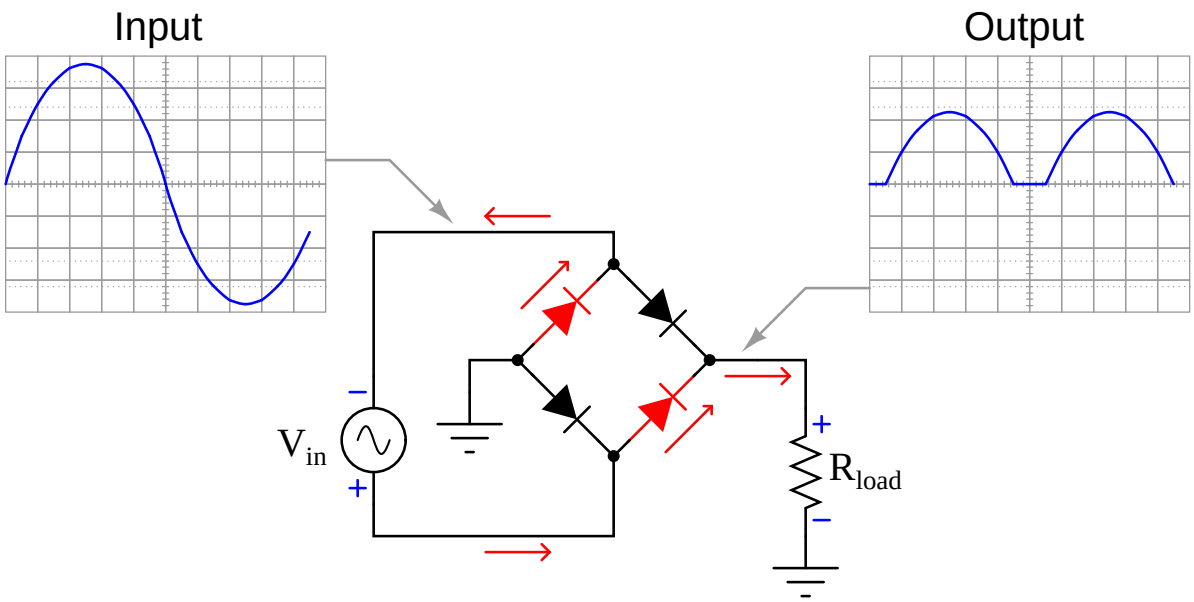
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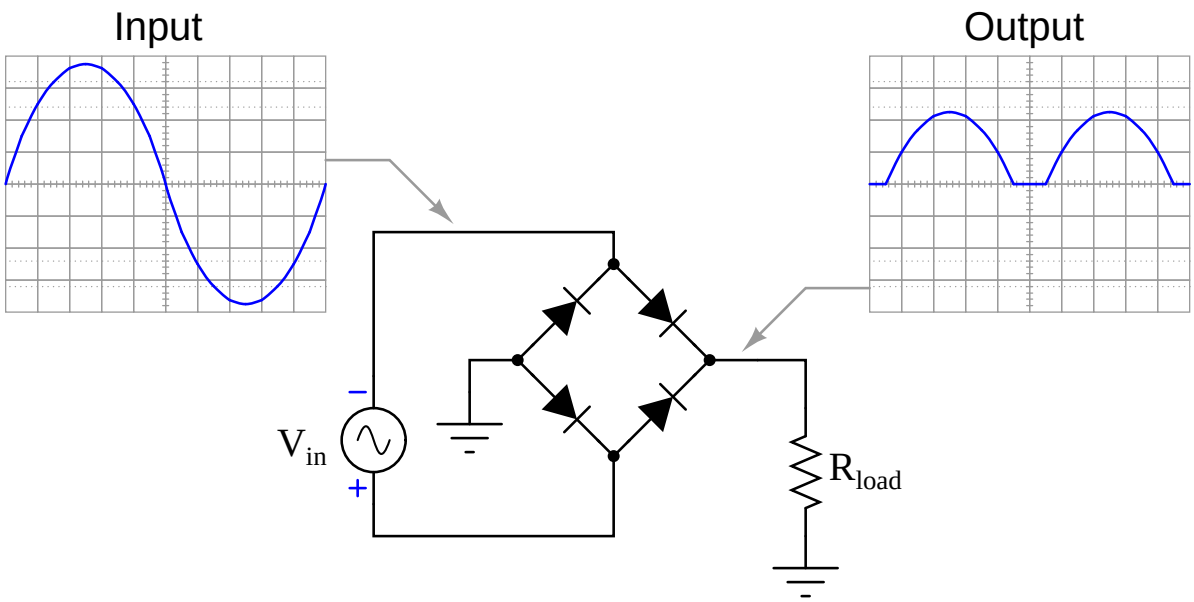
Input
Output
V in
R load

Chapter 6

Questions

This learning module, along with all others in the ModEL collection, is designed to be used in an inverted instructional environment where students independently read[1] the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture[2], the instructor engages with students in Socratic-style dialogue, probing and challenging their understanding of the subject matter through inquiry.

Answers are not provided for questions within this chapter, and this is by design. Solved problems may be found in the Tutorial and Derivation chapters, instead. The goal here is *independence*, and this requires students to be challenged in ways where others cannot think for them. Remember that you always have the tools of *experimentation* and *computer simulation* (e.g. SPICE) to explore concepts!

The following lists contain ideas for Socratic-style questions and challenges. Upon inspection, one will notice a strong theme of *metacognition* within these statements: they are designed to foster a regular habit of examining one's own thoughts as a means toward clearer thinking. As such these sample questions are useful both for instructor-led discussions as well as for self-study.

[1] Technical reading is an essential academic skill for any technical practitioner to possess for the simple reason that the most comprehensive, accurate, and useful information to be found for developing technical competence is in textual form. Technical careers in general are characterized by the need for continuous learning to remain current with standards and technology, and therefore any technical practitioner who cannot read well is handicapped in their professional development. An excellent resource for educators on improving students' reading prowess through intentional effort and strategy is the book textitReading For Understanding – How Reading Apprenticeship Improves Disciplinary Learning in Secondary and College Classrooms by Ruth Schoenbach, Cynthia Greenleaf, and Lynn Murphy.

[2] Lecture is popular as a teaching method because it is easy to implement: any reasonably articulate subject matter expert can talk to students, even with little preparation. However, it is also quite problematic. A good lecture always makes complicated concepts seem easier than they are, which is bad for students because it instills a false sense of confidence in their own understanding; reading and re-articulation requires more cognitive effort and serves to verify comprehension. A culture of teaching-by-lecture fosters a debilitating dependence upon direct personal instruction, whereas the challenges of modern life demand independent and critical thought made possible only by gathering information and perspectives from afar. Information presented in a lecture is ephemeral, easily lost to failures of memory and dictation; text is forever, and may be referenced at any time.

General challenges following tutorial reading

- Summarize as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an intelligent child: as simple as you can without compromising too much accuracy.
- Simplify a particular section of the text, for example a paragraph or even a single sentence, so as to capture the same fundamental idea in fewer words.
- Where did the text make the most sense to you? What was it about the text's presentation that made it clear?
- Identify where it might be easy for someone to misunderstand the text, and explain why you think it could be confusing.
- Identify any new concept(s) presented in the text, and explain in your own words.
- Identify any familiar concept(s) such as physical laws or principles applied or referenced in the text.
- Devise a proof of concept experiment demonstrating an important principle, physical law, or technical innovation represented in the text.
- Devise an experiment to disprove a plausible misconception.
- Did the text reveal any misconceptions you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.
- Describe any useful problem-solving strategies applied in the text.
- Devise a question of your own to challenge a reader's comprehension of the text.

General follow-up challenges for assigned problems

- Identify where any fundamental laws or principles apply to the solution of this problem, especially before applying any mathematical techniques.
- Devise a thought experiment to explore the characteristics of the problem scenario, applying known laws and principles to mentally model its behavior.
- Describe in detail your own strategy for solving this problem. How did you identify and organized the given information? Did you sketch any diagrams to help frame the problem?
- Is there more than one way to solve this problem? Which method seems best to you?
- Show the work you did in solving this problem, even if the solution is incomplete or incorrect.
- What would you say was the most challenging part of this problem, and why was it so?
- Was any important information missing from the problem which you had to research or recall?
- Was there any extraneous information presented within this problem? If so, what was it and why did it not matter?
- Examine someone else's solution to identify where they applied fundamental laws or principles.
- Simplify the problem from its given form and show how to solve this simpler version of it. Examples include eliminating certain variables or conditions, altering values to simpler (usually whole) numbers, applying a limiting case (i.e. altering a variable to some extreme or ultimate value).
- For quantitative problems, identify the real-world meaning of all intermediate calculations: their units of measurement, where they fit into the scenario at hand. Annotate any diagrams or illustrations with these calculated values.
- For quantitative problems, try approaching it qualitatively instead, thinking in terms of "increase" and "decrease" rather than definite values.
- For qualitative problems, try approaching it quantitatively instead, proposing simple numerical values for the variables.
- Were there any assumptions you made while solving this problem? Would your solution change if one of those assumptions were altered?
- Identify where it would be easy for someone to go astray in attempting to solve this problem.
- Formulate your own problem based on what you learned solving this one.

General follow-up challenges for experiments or projects

- In what way(s) was this experiment or project easy to complete?
- Identify some of the challenges you faced in completing this experiment or project.

- Show how thorough documentation assisted in the completion of this experiment or project.
- Which fundamental laws or principles are key to this system's function?
- Identify any way(s) in which one might obtain false or otherwise misleading measurements from test equipment in this system.
- What will happen if (component X) fails (open/shorted/etc.)?
- What would have to occur to make this system unsafe?

6.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking[3]. 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 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.

[3] *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.

6.1.1 Reading outline and reflections

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

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

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

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

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

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

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

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

6.1.2 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 full 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.

Conservation of Energy

Simplification as a problem-solving strategy

Annotating diagrams as a problem-solving strategy

Direct current

Alternating current

RMS

Block diagram

Electromagnetism

Electromagnetic induction

Faraday's Law of Electromagnetic Induction

Transformer

Primary winding

Secondary winding

Turns ratio

Diode

N-type semiconductor

P-type semiconductor

Rectifier

Capacitance

Ripple

Filter

6.1.3 First conceptual question

Challenges

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

6.1.4 Second conceptual question

Challenges

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

6.2 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[4]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[5] on an answer key!

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

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

6.2.1 Miscellaneous physical constants

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

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

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

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

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

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

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

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

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

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

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

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

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

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

6.2.2 Introduction to spreadsheets

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

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

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

Text labels contained in cells `A1` through `A3` and cells `C1` through `C3` exist solely for readability and are not involved in any calculations. Cell `B1` contains a sample distance value while cell `B2` contains a sample time value. The formula for computing speed is contained in cell `B3`. Note how this formula begins with an "equals" symbol (`=`), references the values for distance and speed by lettered column and numbered row coordinates (`B1` and `B2`), and uses a forward slash symbol for division (`/`). The coordinates `B1` and `B2` function as *variables*[6] 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.

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

Common[7] 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[8] proper order of operations within a complex formula. Consider this example of a spreadsheet implementing the *quadratic formula*, used to solve for roots of a polynomial expression in the form of $ax^2 + bx + c$:

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

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

This example is configured to compute roots[9] 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.

[7] 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.

[8] 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.

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

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

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

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

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

Note how the square-root term (y) is calculated in cell `C1`, and the denominator term (z) in cell `C2`. This makes the two final formulae (in cells `B1` and `B2`) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – 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.

[10] 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.*

6.2.3 First quantitative problem

Challenges

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

6.2.4 Second quantitative problem

Challenges

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

6.3 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.

6.3.1 First diagnostic scenario

Challenges

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

6.3.2 Second diagnostic scenario

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

B.1 First principles of learning

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

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

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

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

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

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

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

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

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

B.2 Proven strategies for instructors

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

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

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

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

B.3 Proven strategies for students

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

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

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

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

B.4 Design of these learning modules

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

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

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

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

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

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

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

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

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

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

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

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

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

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

The `GNU/Linux` computer operating system

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

Bram Moolenaar's `Vim` text editor

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

Donald Knuth's TEX typesetting system

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

Leslie Lamport's LATEX extensions to TEX

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

Tim Edwards' `Xcircuit` drafting program

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

`Gimp` graphic image manipulation program

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

`SPICE` circuit simulation program

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

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

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

`gnuplot` mathematical visualization software

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

`Python` programming language

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

Appendix D

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Appendix E

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.

30-31 August 2024 – added a third fuse to the example power supply schematic shown in Case Tutorial section "Example: simple power supply calculations" (image_5343). Also added a new Tutorial section showcasing this practical design.

18 July 2024 – added polarity dots to all the transformer windings shown in image_5408.

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

3 February 2024 – added helpful clarifications for students brand-new to power supply circuits, specifically to help students building their first power supply in the IETTI-102 Projects course I teach.

14 November 2023 – added a new Case Tutorial section on empirically determining signal rates of change.

31 July 2023 – updated the Tutorial section on rectifier circuits with improvements made to mod_rectifier's tutorial. Also added a Technical Reference to split DC power supply circuits.

27 January 2023 – added secondary-side fuse to Case Tutorial schematic diagram (image_5343).

8 January 2023 – added example of bridge rectifier with center tap.

28 July 2022 – minor additions to the Tutorial on diode power dissipation.

26 July 2022 – added "primary" and "secondary" labels to more transformer diagrams for clarity.

25 July 2022 – added more questions to the Introduction chapter.

20 June 2022 – edited image_5343 to include a fuse on the AC line power, shown in the Case Tutorial chapter.

10 September 2021 – added Technical Reference on hot, neutral, and ground power conductors.

27 June 2021 – added Tutorial content discussing multi-winding transformers.

23 June 2021 – added Tutorial content discussing voltage regulation.

11-16 June 2021 – added content to the document, including an Introduction chapter, an Animations chapter with full-wave rectifier behavior shown.

10 June 2021 – document first created.

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