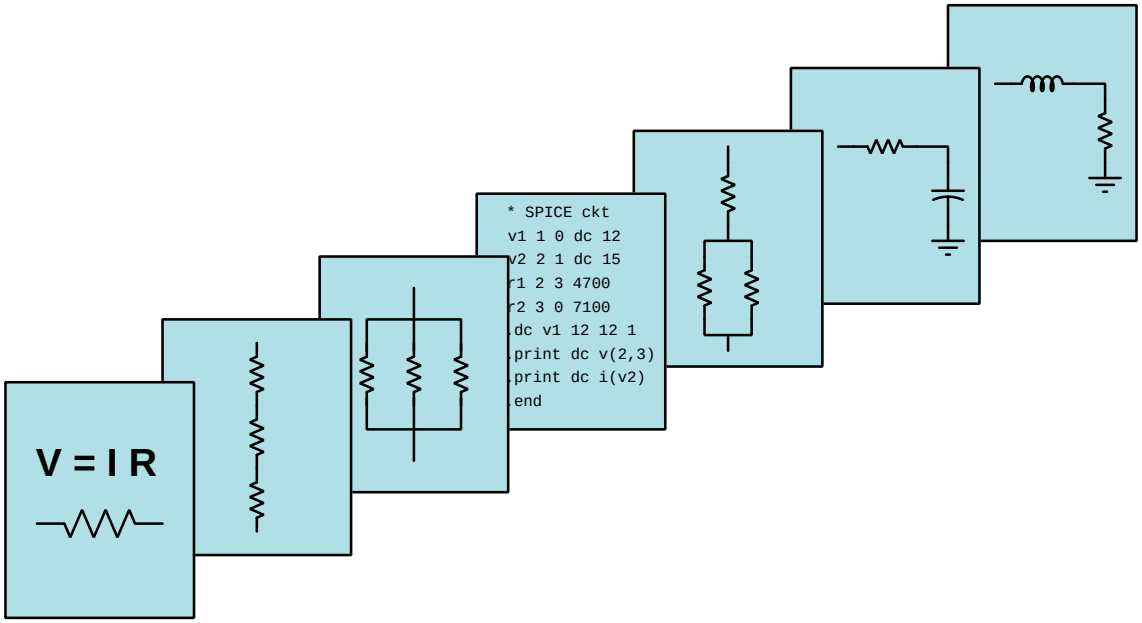
Modular Electronics Learning (ModEL) project



Rectifier Circuits

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Chapter 1

Introduction

1.1 Recommendations for students

A *rectifier* is simply a circuit designed to convert AC (alternating current) into DC (direct current), based on the principle of unidirectional components (i.e. diodes) alternately passing and blocking electric current based on polarity. Several different rectifier circuit configurations exist, and are the subject of this learning module.

Important concepts related to rectifier circuits include **AC** versus **DC** electricity, **diode** function, **waveforms**, **biasing**, **forward voltage drop**, **bridge** networks, **transformers**, **frequency**, **ripple**, **filtering**, **polyphase** AC circuits, and **phase shift**.

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

- How might an experiment be designed and conducted to measure the forward voltage drop of a PN junction? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What are some practical applications of PN-junction electronic devices?
- Why is electric power typically distributed in AC form rather than DC?
- What is the function of a diode?
- How was AC converted to DC before the advent of diodes?
- How does half-wave rectification compare with full-wave?
- How is frequency quantified?
- How do each of the rectifier circuits work to convert AC into DC?
- How does three-phase AC differ from single-phase AC?
- What causes "ripple" in a rectifier's output?
- What undesirable effects might ripple have on a circuit powered by an unfiltered rectifier?

1.2 Challenging concepts related to rectifiers

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

- **Hot chassis phenomenon** – although modern televisions no longer rectify line AC voltage for direct powering of internal circuitry, the so-called "hot chassis" effect is found in any rectifier circuit where line AC is rectified. This voltage is simply the drop across one of the diodes in the bridge rectifier network, which for half of one cycle will be the diode's drop as it blocks current.

1.3 Recommendations for instructors

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

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

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

  Assessment – Students show how current directions were determined by the author in the Tutorial chapter's rectifier circuit 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 concept of ripple and RMS-vs-peak voltages to the calculation of rectifier circuit output

  Assessment – Given AC input frequency and RMS voltage, determine peak output voltage and ripple frequency for any style of rectifier circuit; e.g. pose problems in the form of the "Rectified peak voltage and ripple frequency" Quantitative Reasoning question.

- **Outcome** – Design a rectifier circuit from a schematic diagram

  Assessment – Sketch wire placement in a pictorial diagram for a rectifier given a desired schematic diagram; e.g. pose problems in the form of the "Terminal block construction of a bridge rectifier" Conceptual Reasoning question.

- **Outcome** – Independent research

  Assessment – Read and summarize in your own words reliable source documents on the subject of early AC-to-DC rectifier circuits. Recommended readings include *Hawkins Electrical Guide Number Five* published in 1917.

  Assessment – Locate diode and rectifier datasheets and properly interpret some of the information contained in those documents including average current rating, peak current rating, peak inverse voltage rating, typical forward voltage drop, etc.

Chapter 2

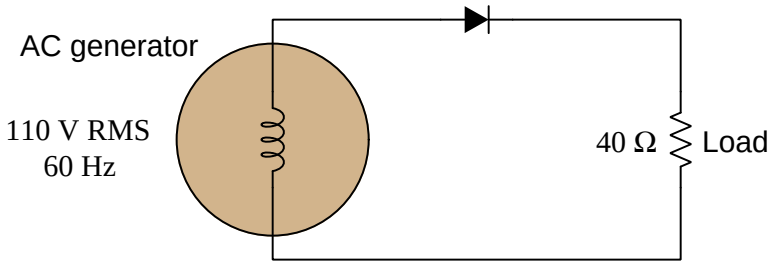
Case Tutorial

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: single-phase, half-wave rectifier

Otherwise known as a *single-phase, single-pulse* (1Ph1P) rectifier circuit:



Calculations:

$V_{generator(peak)} = (110)\sqrt{2} = 155.56$ V

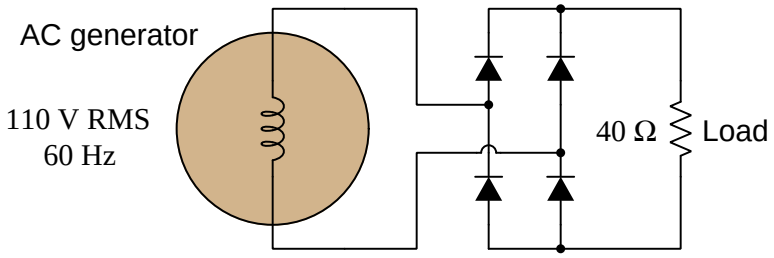
$V_{load(peak)} = (110)\sqrt{2} - 0.7 = 154.86$ V

$I_{load(peak)} = \frac{V_{load(peak)}}{R_{load}} = \frac{154.86}{40} = 3.8716$ A

$f_{ripple} = 60$ Hz (one pulse per generator cycle)

2.2 Example: single-phase, full-wave rectifier

Otherwise known as a *single-phase, two-pulse* (1Ph2P) rectifier circuit:



Calculations:

$V_{generator(peak)} = (110)\sqrt{2} = 155.56$ V

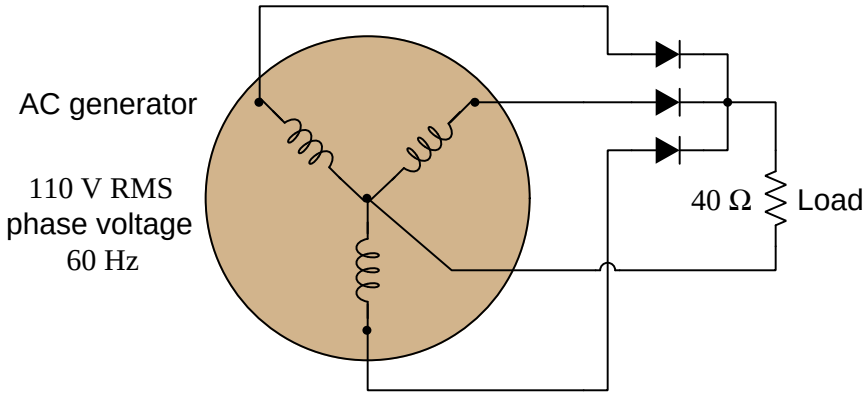
$V_{load(peak)} = (110)\sqrt{2} - 1.4 = 154.16$ V

$I_{load(peak)} = \frac{V_{load(peak)}}{R_{load}} = \frac{154.16}{40} = 3.8541$ A

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

2.3 Example: three-phase, half-wave rectifier

Otherwise known as a *three-phase, three-pulse* (3Ph3P) rectifier circuit:



Calculations:

$V_{phase(peak)} = (110)\sqrt{2} = 155.56$ V

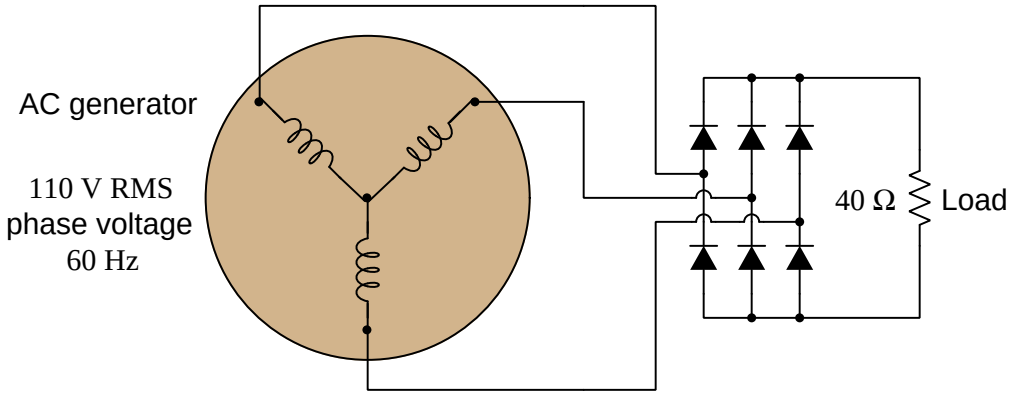
$V_{load(peak)} = (110)\sqrt{2} - 0.7 = 154.86$ V

$I_{load(peak)} = \frac{V_{load(peak)}}{R_{load}} = \frac{154.86}{40} = 3.8716$ A

$f_{ripple} = 180$ Hz (three pulses per generator cycle)

2.4 Example: three-phase, full-wave rectifier

Otherwise known as a *three-phase, six-pulse* (3Ph6P) rectifier circuit:



Calculations:

$V_{phase(peak)} = (110)\sqrt{2} = 155.56$ V

$V_{line(peak)} = V_{phase(peak)}\sqrt{3} = 269.44$ V

$V_{load(peak)} = V_{line(peak)} - 1.4 = 268.04$ V

$I_{load(peak)} = \frac{V_{load(peak)}}{R_{load}} = \frac{268.04}{40} = 6.7011$ A

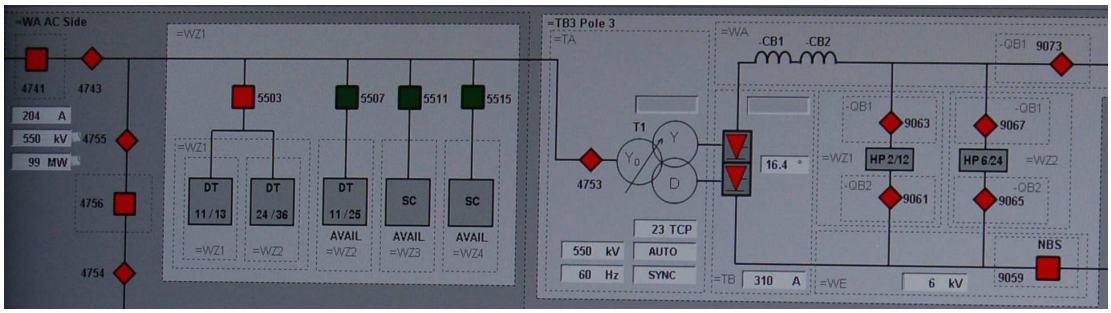
$f_{ripple} = 360$ Hz (six pulses per generator cycle)

2.5 Example: HVDC harmonic filters

Some large-scale electric power grids benefit from transmission of power via DC rather than AC. Alternating current (AC) came to dominate power grid technology because AC induction motors and generators were simpler and much more reliable than DC brush-type motors and generators, and also because *transformers* allowed reliable and efficient transformation between different levels of voltage and current than possible with DC. However, modern semiconductor device technology now permits reliable and efficient conversion from AC to DC and also from DC to AC. Such technology, when applied to high-voltage DC transmission of electric power, is commonly referred to by the acronym *HVDC*, which stands for *High Voltage Direct Current*.

One challenge of semiconductor-based AC/DC conversion, though, is the creation of harmonic frequencies in power network voltages and currents. These harmonics, if not attenuated, create problems ranging from excessive component heating to electromagnetic interference with other systems, and so must be mitigated through the use of filter networks installed at HVDC substation facilities.

In the following single-line diagram we see the layout of a very large[1] AC-to-DC converter system where three-phase AC power at a fundamental frequency of 60 Hz gets rectified to DC using a twelve-pulse semiconductor rectifier network. "Twelve-pulse" simply means that for every one cycle of the 60 Hz AC there will be twelve distinct pulses applied to the DC bus. This unavoidably creates a strong 12th harmonic, or 720 Hz, on the DC side of the system. However, other harmonics result from semiconductor switching, including strong 11th and 13th harmonics on the AC side of an HVDC system, which is why we see multiple filters represented in this single-line diagram:



Each filter appears in this diagram as a grey-colored box with the harmonic numbers represented within. For example, the left-most grey box with "DT 11/13" written inside is a filter network designed to attenuate the 11th and 13th harmonics. Immediately to the right of that filter network is another ("DT 24/36") designed to attenuate the 24th and 36th harmonics. Another to the right of that one marked "DT 11/25" attenuates the 11th and 25th harmonics. These three filter networks exist on the AC side of the converter system operating at a nominal system voltage of 550 kiloVolts. On the DC (right-hand) side of this converter system we see another pair of filter networks: one filtering out the 2nd and the 12th harmonics, and another one filtering the 6th and 24th harmonics.

These harmonic numbers all relate to the AC side's fundamental frequency of 60 Hz, and the particular harmonics generated in this HVDC converter system are a function of the number of

[1] This particular HVDC converter facility has a full-power rating in excess of 3000 MegaWatts!

switching elements in the converter (in this case, twelve) and the pattern in which they are switched.

Harmonic filters designed for this purpose consist of resistor-inductor-capacitor networks where the L and C values are "tuned" to resonate together at such frequencies as to attenuate the undesired harmonics from the power circuit. In the photographs shown below we see two views of such a filter network belonging to the DC side of a HVDC converter system, each filter operating at a potential of 550 kV with respect to Earth ground:

In the left-hand photo we see the tall tower-like structure holding the filter's capacitors, and in the background we see the filter's cylindrical air-core inductors, all of them suspended above the Earth on porcelain insulator stacks. The capacitor assembly consists of multiple capacitors connected in series so as to divide the impressed voltage across them rather than have the full 550 kV across any single capacitor's dielectric layer. In the right-hand photo we see a sign on the security fence declaring this filter network to be tuned to the 6th and 24th harmonics (of 60 Hz), screening out those harmonics created by the twelve-pulse thyristor array from reaching the DC power transmission line.

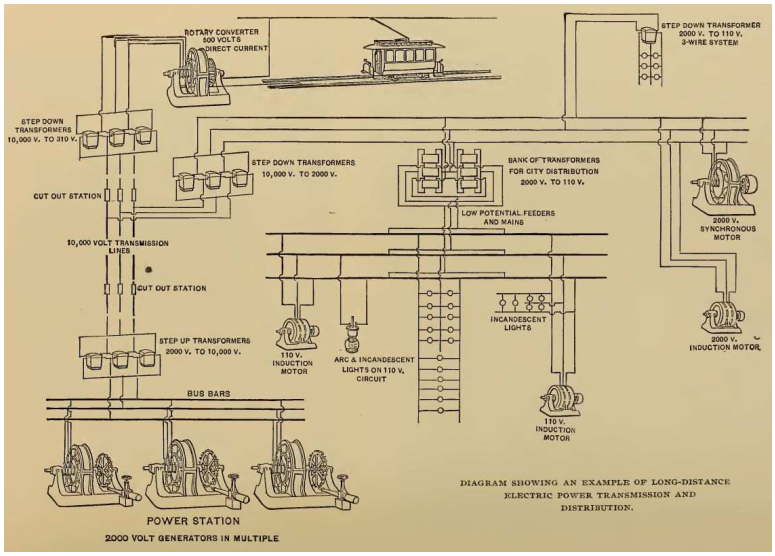
Chapter 3

Tutorial

3.1 AC-DC power conversion

Electric power is more often than not generated as *alternating current* (AC) rather than *direct current* (DC), for reasons of simplicity and efficiency[1]. However, a great many electrical and electronic loads require[2] DC for their proper operation, thereby necessitating ways to convert AC into DC.

A legacy method for performing this conversion was to mechanically couple an AC motor to a DC generator, so that energy would be converted from electrical to mechanical (at the AC motor) and then from mechanical to electrical (in the DC motor). A simplified schematic diagram from the year 1895 shows electrical power distribution from generators located at Niagara Falls to several different loads located miles away in urban and industrial areas, and in this diagram we see an example of a *rotary converter* (i.e. AC motor/DC generator combination) providing 500 Volt DC electricity to electric trolley cars[3]:



[1] AC permits the use of *transformers* which have the ability to step voltage up and current down, or vice-versa. This allows the sources and loads to operate at (safe) low voltages while the power lines operate at very high voltage (and correspondingly low current) in order to use thin wires which are less costly than thick wires. No DC technology of the time was capable of performing this degree of voltage/current shifting at reasonable efficiency levels.

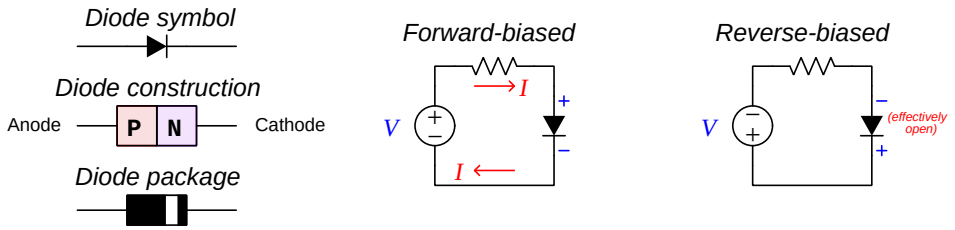
[2] Virtually all *amplifier* circuits operate on DC power, and the same is true for virtually all digital logic circuitry.

[3] At that time, the most efficient type of electric motor for variable-speed traction applications (i.e. propelling a vehicle) was a DC motor rather than an AC motor. This is why a rotary converter was necessary, to provide DC power to the trolley system from an AC source at the hydroelectric dam.

3.2 Diodes

Rotary converters, however, are inefficient machines and prone to failure due to their wearing parts. A non-mechanical solution to the problem of converting AC electricity into DC electricity is therefore advantageous. With the advent of *diodes*, which function by allowing electric current to pass through in one direction but not the other, the potential for non-mechanical AC-DC power conversion became a reality. For those familiar with hydraulic systems and plumbing, the diode is the electrical equivalent of a *check valve*: a unidirectional flow device permitting flow in one direction but not the other.

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:



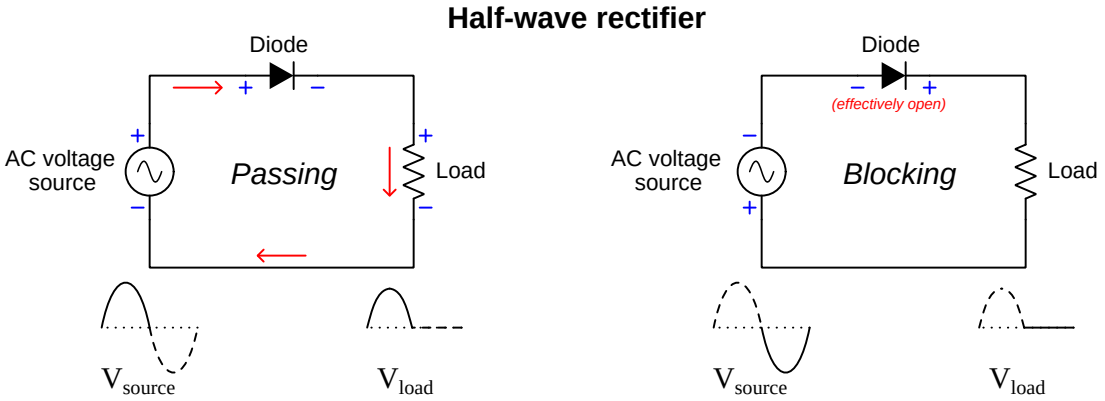
If an external voltage is applied to a PN junction such that the diode's N-type side is negative and its P-type side is positive (i.e. the polarity necessary for conduction), the diode enters a state referred to as *forward-bias*. Applying the opposite voltage polarity causes that same diode to become *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, which we will explore throughout the rest of this Tutorial.

3.3 Simple rectifier circuits

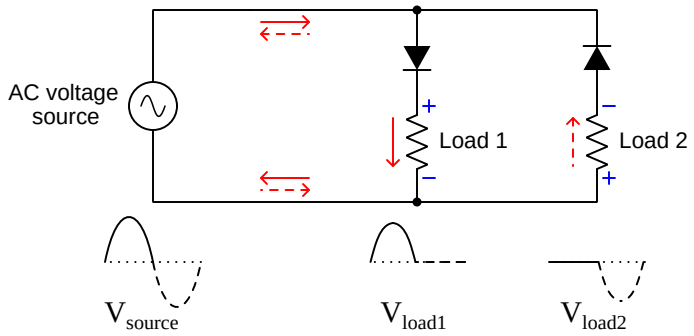
The simplest form of rectifier circuit is one where a single diode placed in series between an AC voltage source and load allows current during one half-cycle but blocks it during the other half-cycle. This is known as a *half-wave rectifier* for the rather obvious reason that only half of the AC wave 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 accordance with Kirchhoff's Voltage Law. 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.

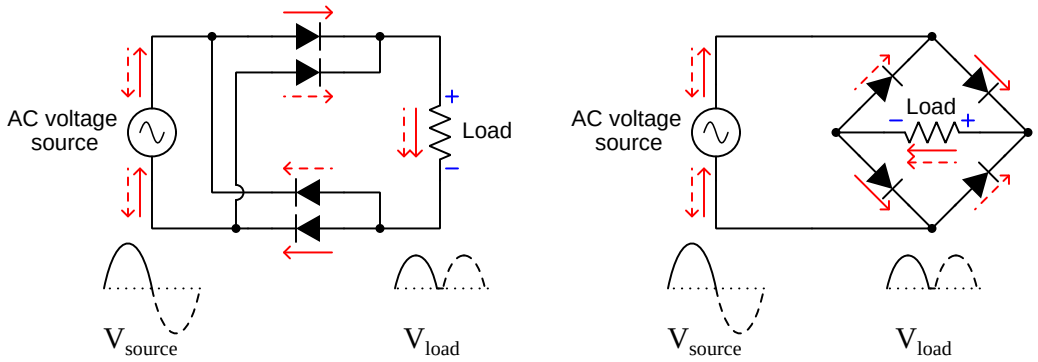
Half-wave rectification is adequate for any application where the load is not adversely affected by *pulsating* DC and where the load does not require more than one-half of the source's full power rating. In applications where *two* such loads exist, fuller use of the AC source's power capability may be realized by operating a pair of half-wave rectifiers in parallel with each other:

Dual half-wave rectifiers



This technique for using both half-cycles of the AC source's output should make the reader wonder if it might be possible to use multiple diodes to create a *full-wave rectifier*, where both half-cycles of AC get routed in the same direction through a single load. Indeed, such a circuit does exist, as a form of *bridge* network:

Full-wave bridge rectifier



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.

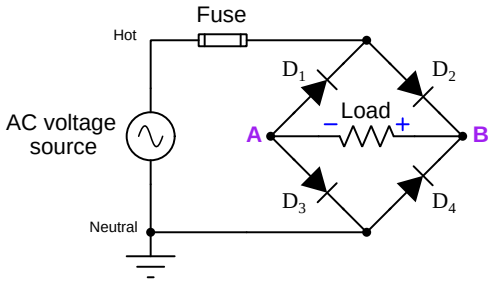
Since load current must flow through *two* diodes rather than one diode at any given time in a full-wave bridge rectifier circuit, a greater voltage drop "penalty" is incurred than with a half-wave rectifier. At any moment when conduction occurs, the load's voltage will be less than the AC source's voltage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

with Kirchhoff's Voltage Law. Peak rectified voltage will thus be the sinusoidal AC's RMS voltage multiplied by $\sqrt{2}$ minus 1.4 Volts.

3.4 Bridge rectifier potentials

An interesting phenomenon unique to bridge rectifier circuits is that both the positive and negative DC terminals of the rectifier's output have different electrical potentials than either of the AC terminals on the rectifier's input. This may be problematic for circuits where the voltage is high enough to pose an electric shock hazard, and where Earth-grounding is necessary to ensure safety.

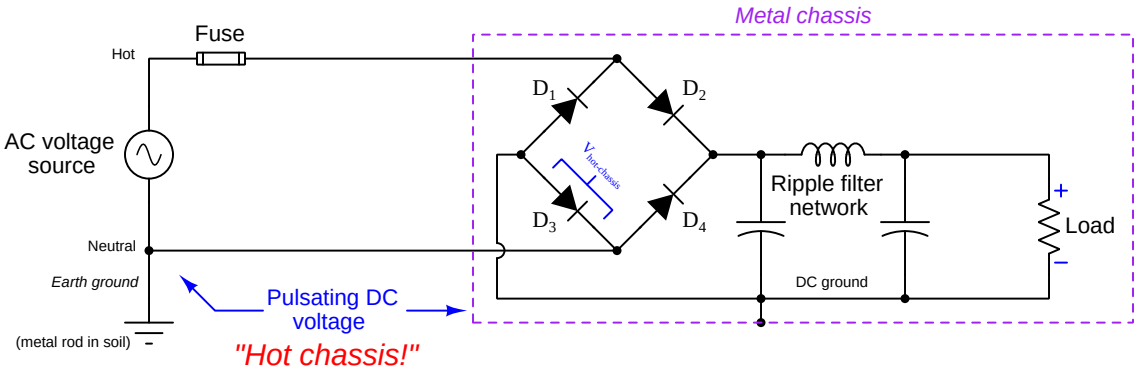
For example, consider the following circuit where the AC voltage source supplying electrical energy to a full-wave bridge rectifier is made electrically common to the Earth on one terminal. As per convention, this grounded terminal of the AC voltage source is called *neutral* while the ungrounded terminal is called *hot*. The "hot" conductor is the one protected from overcurrent by a fuse, so that if the fuse blows it will only be the "hot" (dangerous) conductor disconnected from the rest of the circuit and not the "neutral" (safe) conductor:



If we were to connect an AC voltmeter between the "hot" conductor and Earth ground, we would measure the full AC source voltage. That same meter should register zero voltage between "neutral" and Earth ground because the neutral conductor has been made electrically common to ground. However, a voltmeter connected between either points A and ground or B and ground would register significant voltage, about half of the AC source's value. The reason for this becomes easy to see once you identify which component the voltmeter would be in parallel with: connected between point A and ground, the voltmeter would be in parallel with diode D_3; connected between point B and ground, the voltmeter would be in parallel with diode D_4. As each of these diodes turns off to block current through the opposite half-cycle, they will drop approximately half of the source's voltage. This is why points A and B will operate at non-Earth potentials.

One of the confusing aspects of electrical terminology is the multiple meanings of the word "ground". In the sense we just described, "ground" refers to the intentional connection of a circuit conductor to Earth, usually using a metal rod driven deep into the soil, for the purpose of electrical safety to ensure that conductor has negligible potential compared to any other floor or ground surface where someone might be standing or kneeling. However, the word "ground" can also refer to some arbitrary point in a circuit designated as the point of reference for all potential measurements. Electronic circuits often (but not always!) deem the negative terminal of the main DC voltage source to be this "ground" reference point.

Consider what will happen if we locate the rectifier assembly and all DC-powered components within their own metal chassis (enclosure) and happen to connect the negative terminal of the rectifier's output to that metal frame. If we do so, we will find that there is substantial voltage between this metal chassis' "ground" and Earth "ground" because those two "ground" points are not actually electrically-common to each other but actually span across diode D_3 of the bridge rectifier. This means that metal chassis will technically be "hot" (with as much voltage as is dropped across D_3), though not quite as "hot" as the ungrounded AC power conductor! We can see this in the following schematic:

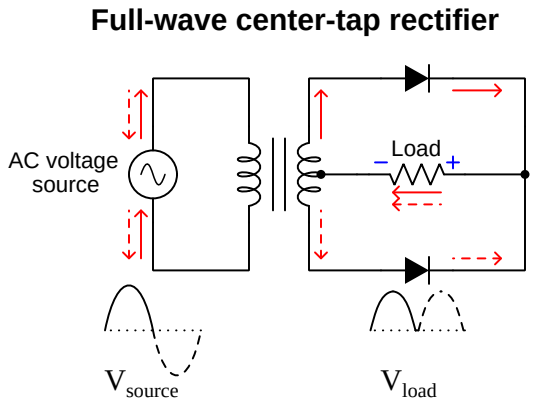


In early television receiver designs, DC power supply circuits converting 120 Volt AC line power to DC suitable for powering the television set's internal circuitry were often built this way, with much of that internal DC-powered circuitry mounted to a metal sub-chassis that itself rested on insulating posts separating it electrically from the Earth-grounded frame of the television's case. This was called a *hot chassis* design, in an effort to warn any unsuspecting electronics technicians of the electric shock hazard posed by making skin contact with the DC chassis while standing on an Earth-potential floor.

Even though analog television receivers are now considered an obsolete technology, and much has improved in design safety standards for consumer appliances, the same fundamental "hot chassis" phenomenon exists whenever AC is rectified into DC using a full-wave bridge diode network: there will be one diode's worth of voltage existing between either of the AC input terminals and either of the DC output terminals. One modern application where we still see "hot chassis" voltage is in switch-mode AC-to-DC power converters where AC line power is first rectified into DC before being converted to different DC voltage levels by means of DC-DC converter circuitry: here, the "ground" trace on the rectifier's printed circuit board will be "hot" with one diode's worth of voltage compared to Earth ground.

3.5 Center-tapped transformer rectifiers

A different style of full-wave rectifier uses a transformer with a center-tapped secondary winding, as shown below:

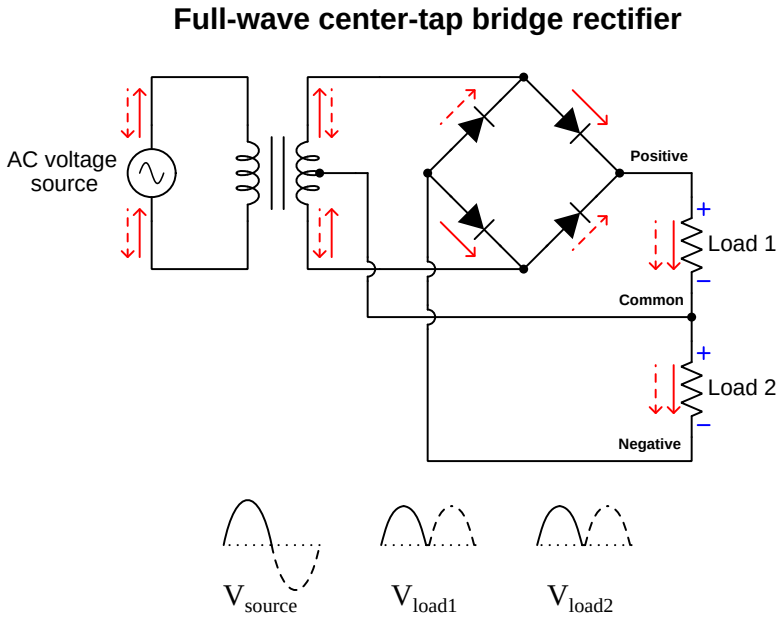


One advantage of this rectifier design is that it requires only two diodes rather than four to achieve full-wave rectification. However, this advantage comes at the expense of requiring a transformer, and only using half of that transformer's power and secondary voltage capability, since only one-half 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[4]. 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.

Another advantage of the center-tapped full-wave rectifier is that the DC load and AC source (i.e. transformer secondary) share a mutual connection at the transformer's center-tap terminal. One may optionally connect this shared terminal to Earth ground to ensure a "neutral" conductor if the secondary voltage is high enough to constitute a shock hazard. Alternatively, you can connect this shared terminal to the metal chassis of the device, and there will be no "hot chassis" phenomenon between the secondary winding's AC and the rectified DC because that chassis-grounded point will be shared in common.

[4] 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:



Again, it is possible to bond that "Common" conductor to Earth ground if desired for safety to ensure zero electrical potential between that point in the circuit and the Earth so that it will always be safe to touch, and/or bond that "Common" conductor to the device's metal chassis, and there will never be any "Hot chassis" phenomenon between the secondary winding's AC voltage and the DC load voltages to cause problems.

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.

3.6 Ripple

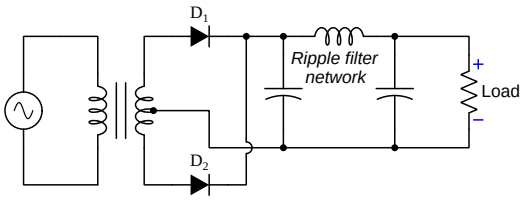
Given that the purpose of a rectifier is to take alternating current (AC) and convert it into direct current (DC), it stands to reason that the ultimate goal would be to output DC that is as continuous as that coming from a chemical battery, photovoltaic panel, or other intrinsically DC energy source. Of the AC-to-DC converter techniques we have explored thus far, the rotary converter (i.e. motor-generator set) comes closest to achieving this ideal. Diode-based rectifier circuits output a strongly *pulsing* form of DC which may not be suitable for all purposes.

A common term for this pulsation is *ripple*. Ripple amplitude is typically specified as a *peak-to-peak* quantity: the amount of voltage variation from the highest point on the waveform to the lowest point. Ripple frequency is specified in *Hertz* (i.e. cycles per second) just like any AC frequency. It should be evident that the ripple amplitude for both half-wave and full-wave rectifier circuits is equal to the waveform's peak value, since the rectified DC waveform dips down all the way to zero every time the AC input crosses through zero. The frequency for half-wave DC is equal to the frequency of the AC source, but the frequency for full-wave DC is *twice* that of the AC source because the full-wave repeats itself twice for every one cycle of the AC.

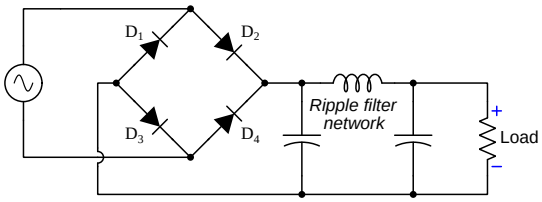
Ripple in rectified DC is often a source of problems for sensitive electronic circuits. In audio circuits, ripple often manifests as an ever-present "buzzing" noise heard from the loudspeakers. In analog signaling and computation circuits, ripple is a form of dynamic error forcing the signal to deviate from its desired value. For this reason, most AC-to-DC power conversion circuits also contain *filtering* components to attenuate this ripple and provide a "smoother" DC output to the load. However, if there is a way to reduce or eliminate ripple at the source by way of a better rectification technique, this is preferred to adding filtering.

One way to mitigate this ripple is to connect capacitors and/or inductors between the rectifier and the DC load. Capacitors connected in parallel with the rectifier's DC output act to stabilize the DC voltage, and inductors connected in series with the DC load's current act to stabilize that current. Here are examples of capacitor-inductor ripple filters used on both bridge and center-tapped full-wave rectifiers:

Filtered center-tap rectification

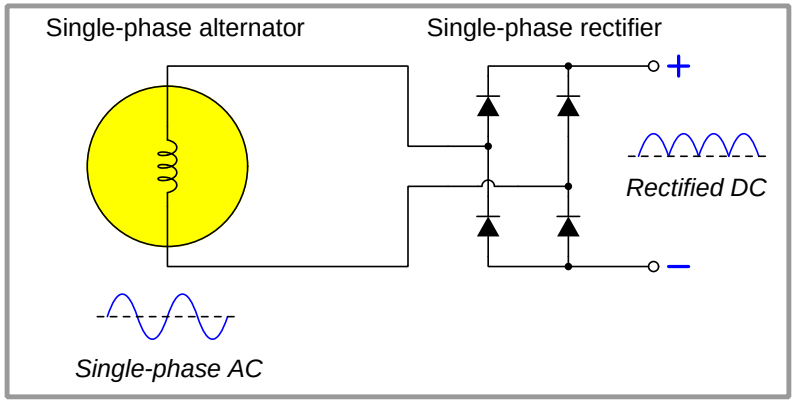


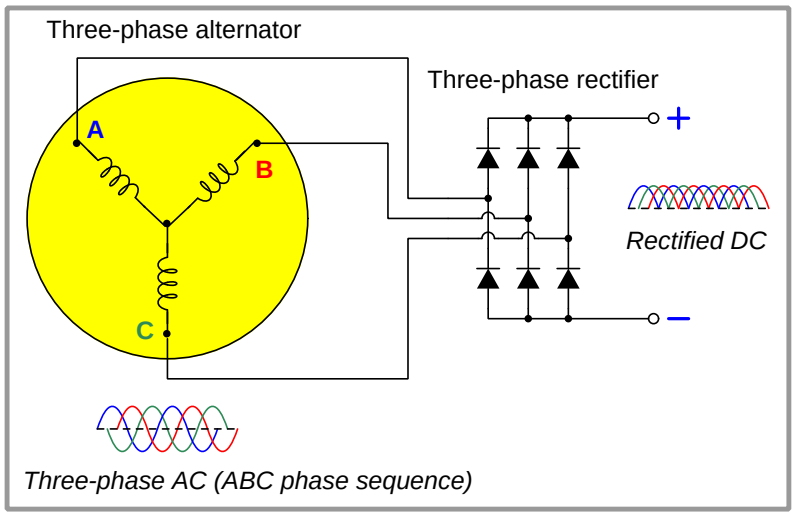
Filtered bridge rectification



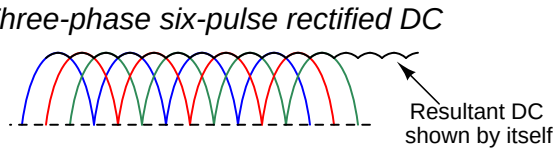
3.7 Polyphase rectifiers

Another effective strategy for mitigating ripple in rectification circuits is to utilize *polyphase* AC sources rather than *single-phase* AC sources. With multiple AC waveforms to rectify, the effect at the DC load will be an overlapping of rectified pulses resulting in a much "smoother" final result than rectified single-phase. Consider the following examples, where a single-phase AC generator ("alternator") is contrasted against a three-phase machine, both rectifiers designed for full-wave rectification:





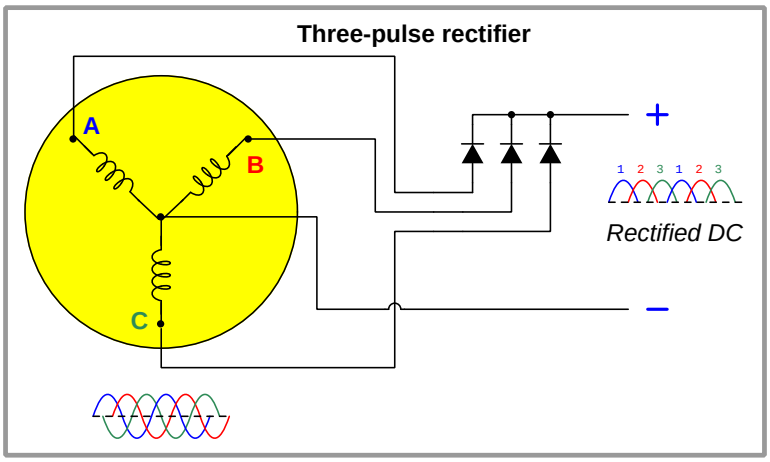
This three-phase, full-wave circuit is commonly known as a *six-pulse* rectifier, because the rectified DC output has six distinct peaks within one complete cycle of the AC source. Compared to the *two-pulse* rectifier (i.e. single-phase, full-wave rectifier) circuit, the DC load connected to the output of the six-pulse rectifier experience *only* the peaks of the overlapping waves and none of the valleys, the result being a much "smoother" and more continuous voltage applied to the load than any single-phase rectified DC:

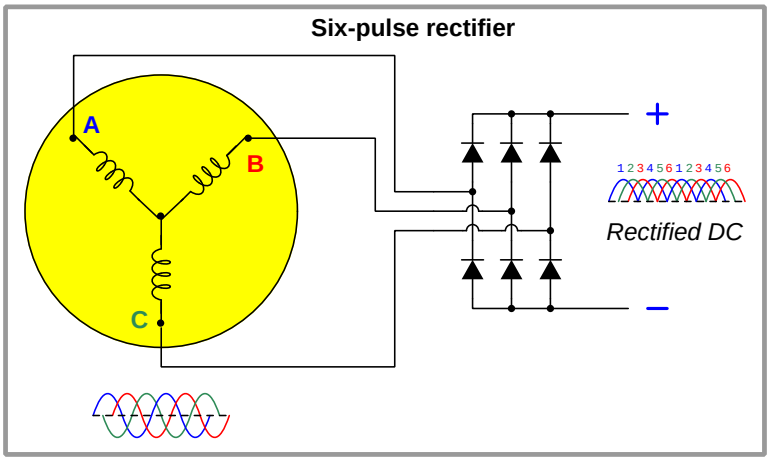


The ripple amplitude is *far* less than the peak amplitude of each rectified phase, and the ripple frequency is now *six times* greater than the AC source's frequency thanks to the three sets of overlapping waveforms.

From the perspective of filtering – should we ever add a filter to the output of a rectifier to achieve the smoothest possible DC – a higher ripple frequency is better than a lower ripple frequency. AC-DC converter filtering requires a *low-pass* filter characteristic, where DC (zero frequency) needs to be passed and anything higher than zero frequency should be blocked. The higher the ripple frequency, the further it is from the desired frequency of zero, and therefore the more effective any low-pass filtering scheme will be in achieving this goal.

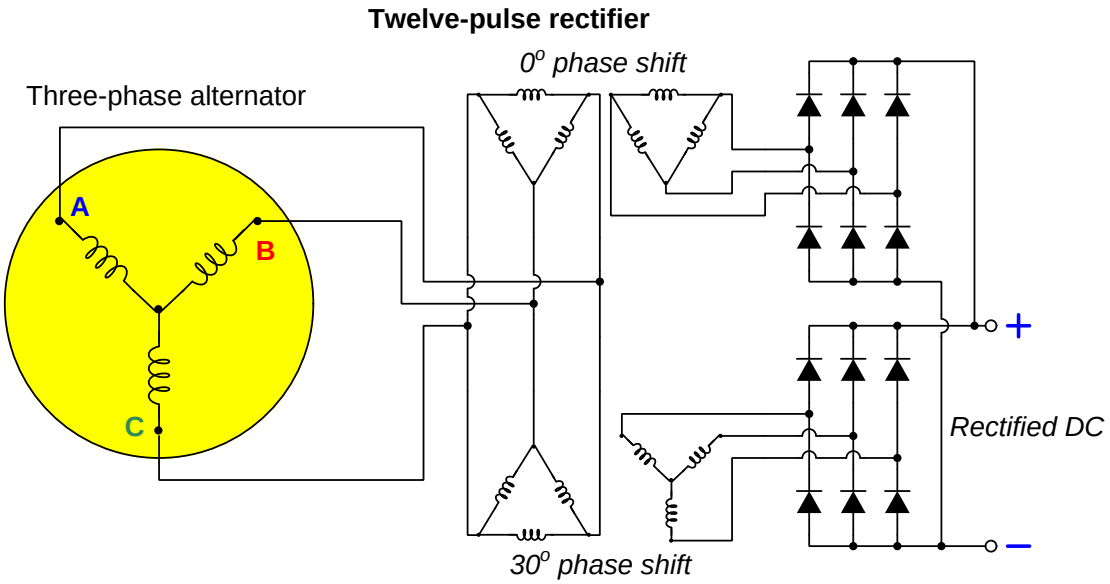
Half-wave rectification of three-phase AC is also possible, and is more commonly known as *three-pulse rectification* because the resulting ripple voltage has three distinct pulses per cycle of the original AC. Here we see three-pulse versus six-pulse rectification of three-phase AC, the three-phase circuit requiring a Wye-connected AC source with a center conductor:



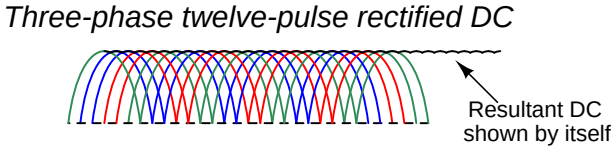


Of course, ripple voltage is greater for a three-pulse rectifier than it is for a six-pulse rectifier, but even three-pulse rectification creates less ripple than two-pulse rectification which is the best we can do with single-phase AC.

If an even "smoother" ripple voltage is desired from the rectification process, it is possible to use multiple banks of six-pulse rectifiers fed by three-phase transformers with different primary-secondary winding configurations. Different combinations of Wye and Delta windings result in phase-shifts from primary to secondary, and these phase shifts may be exploited to minimize rectification ripple. Consider the following example, where the lower transformer bank introduces a 30 degree phase shift compared to the upper bank, resulting in a *twelve-pulse rectifier* circuit:



The result of paralleling two six-pulse rectifiers is called, unsurprisingly, *twelve-pulse* rectification:



Ripple amplitude is even less than it was for six-pulse rectification, and the ripple frequency is now *twelve times* greater than the AC source's frequency thanks to the six sets of overlapping waveforms.

With further extension of this strategy, even more pulses per cycle may be obtained. Eighteen-pulse, twenty-four-pulse, and even higher pulse count rectifiers exist for three-phase AC-to-DC conversion. However, such high pulse-count schemes are limited in application due to the expense of the transformers providing the necessary phase-shifting for each of the six-pulse rectifier networks. Of course, it is also possible to combine capacitive/inductive ripple filtering with polyphase rectification to achieve very low levels of ripple in the DC output.

Chapter 4

Historical References

This chapter is where you will find references to historical texts and technologies related to the module's topic.

Readers may wonder why historical references might be included in any modern lesson on a subject. Why dwell on old ideas and obsolete technologies? One answer to this question is that the initial discoveries and early applications of scientific principles typically present those principles in forms that are unusually easy to grasp. Anyone who first discovers a new principle must necessarily do so from a perspective of ignorance (i.e. if you truly *discover* something yourself, it means you must have come to that discovery with no prior knowledge of it and no hints from others knowledgeable in it), and in so doing the discoverer lacks any hindsight or advantage that might have otherwise come from a more advanced perspective. Thus, discoverers are forced to think and express themselves in less-advanced terms, and this often makes their explanations more readily accessible to others who, like the discoverer, comes to this idea with no prior knowledge. Furthermore, early discoverers often faced the daunting challenge of explaining their new and complex ideas to a naturally skeptical scientific community, and this pressure incentivized clear and compelling communication. As James Clerk Maxwell eloquently stated in the Preface to his book *A Treatise on Electricity and Magnetism* written in 1873,

> It is of great advantage to the student of any subject to read the original memoirs on that subject, for science is always most completely assimilated when it is in its nascent state . . . `[page xi]`

Furthermore, grasping the historical context of technological discoveries is important for understanding how science intersects with culture and civilization, which is ever important because new discoveries and new applications of existing discoveries will always continue to impact our lives. One will often find themselves impressed by the ingenuity of previous generations, and by the high degree of refinement to which now-obsolete technologies were once raised. There is much to learn and much inspiration to be drawn from the technological past, and to the inquisitive mind these historical references are treasures waiting to be (re)-discovered.

4.1 Electromechanical rectifiers

One way to rectify AC into DC using mechanical components is to design set of a magnetically-actuated switches that open and close in time with the half-cycles of the AC waveform, effectively "steering" the source's alternating current to a DC load. This rectifier design's voltage and current ratings are limited by the wear incurred at the switch contacts, which must operate at the AC line frequency. One such design of switching-type rectifier is shown here, from page 1528 of *Hawkins Electrical Guide Number Five* (published in 1917):

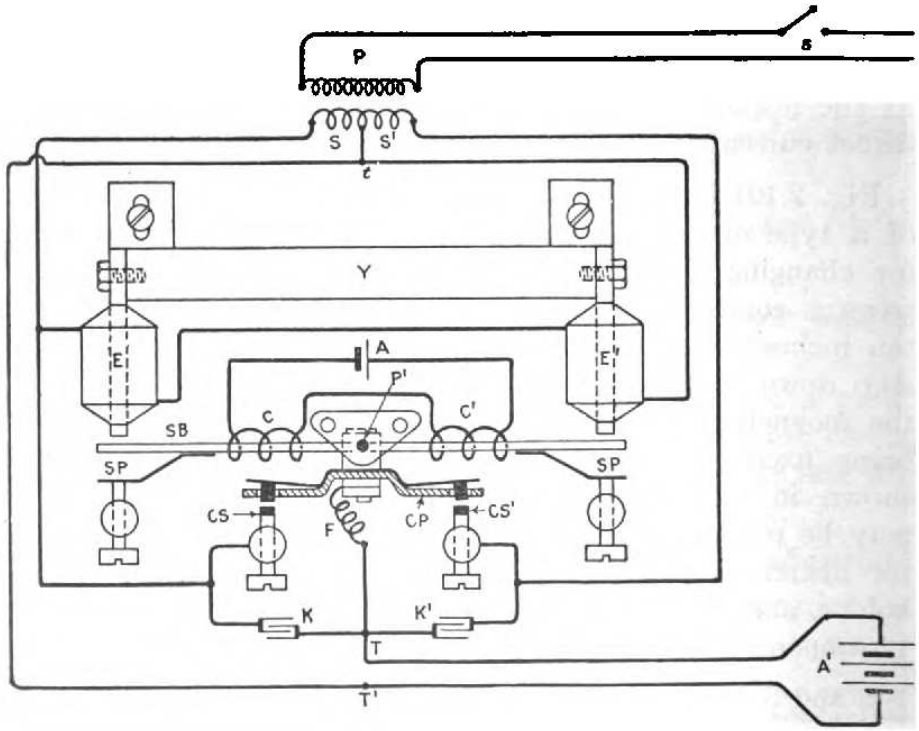
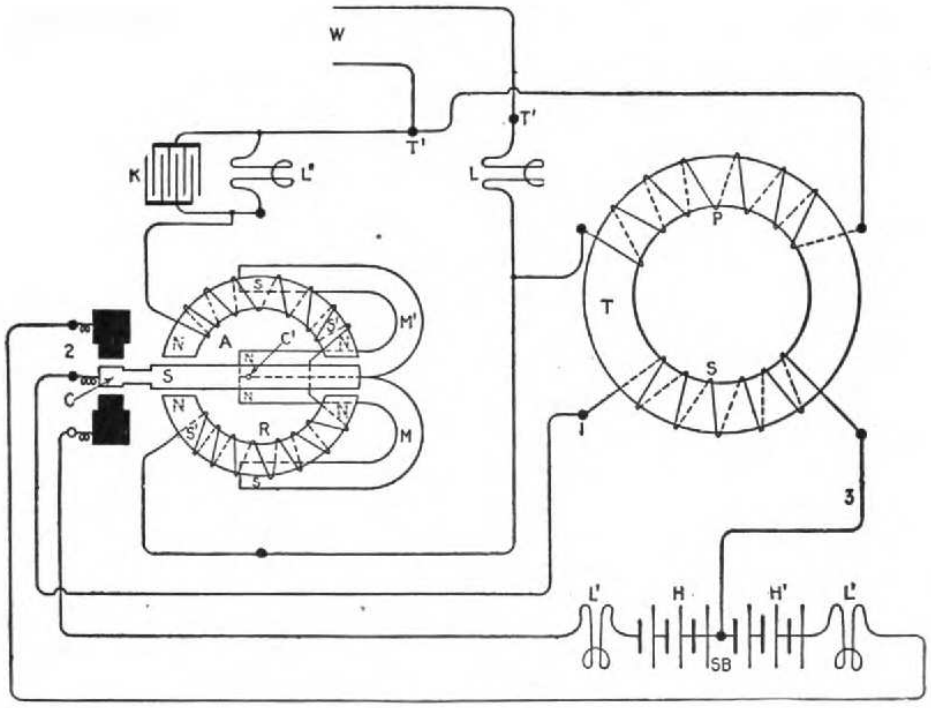


Fig. 2,121.—Diagram showing essential features of Premier Ampero electromagnetic rectifier. Details of construction and principles of operation are given in the accompanying text.

This particular rectifier, manufactured by Premier Ampero in two different sizes, was rated at either 6 or 12 Amperes at 20 Volts. The heart of the mechanism was a steel bar (labeled *SB*) magnetized by a polarizing current supplied by a small battery (*A*) through two coils (*C* and *C'*). Two electromagnet coils (*E* and *E'*) energized by the AC source. This steel bar would rock to and fro as the AC-excited coils alternately attracted and repelled its two ends. Contacts *CS* and *CS'* alternately close to connect the positive terminal of the DC load (here, a secondary-cell battery labeled *A'*). A pair of capacitors (called *condensers* as was customary for that era) labeled *K* and *K'* connected in parallel with these switch contacts helped to reduce contact arcing.

As is evident from the transformer at the top of this diagram which routed the AC power to the rectifier, this is a single-phase, one-way, two-pulse (1P1W2P) design, similar in operation to a full-wave center-tap diode rectifier.

A variation on this design theme is seen in the General Electric "Batten" model of electromechanical rectifier, the following schematic diagram taken from page 1529 of *Hawkins Electrical Guide Number Five*:



As with the Premier Ampero design, the General Electric unit uses a magnetically-actuated steel bar to alternately make and break a pair of switch contacts at line frequency. Here, the bar (labeled S in the diagram) is magnetically polarized by a pair of horseshoe-style permanent magnets (*M* and *M'*). Perhaps the most interesting feature of this rectifier is that it requires a center-tapped *battery* (*SB*, divided into two halves labeled *H* and *H'*) rather than using a center-tapped transformer winding and a regular battery. That is to say, it functions by applying charging current to one-half of the secondary-cell battery at any given time. Incandescent lamps (all *L* and *L'*) serve as resistances to limit current.

A rotary style of electromechanical rectifier (simply called a "mechanical" rectifier by the authors of *Hawkins Electrical Guide Number Five*) uses a set of slip rings and commutators mounted on the shaft of an electric motor spinning at synchronous speed (i.e. in-step with the AC source frequency) to rapidly switch polarities in order to supply full-wave rectified DC to any load. The following illustration (from page 1497) shows the slip ring, commutator, and brushes for this rectifier. The reader is left to their own imagination in visualizing the rotating shaft supporting these ring structures, and the other motor components (e.g. armature and field windings) connected to that shaft:

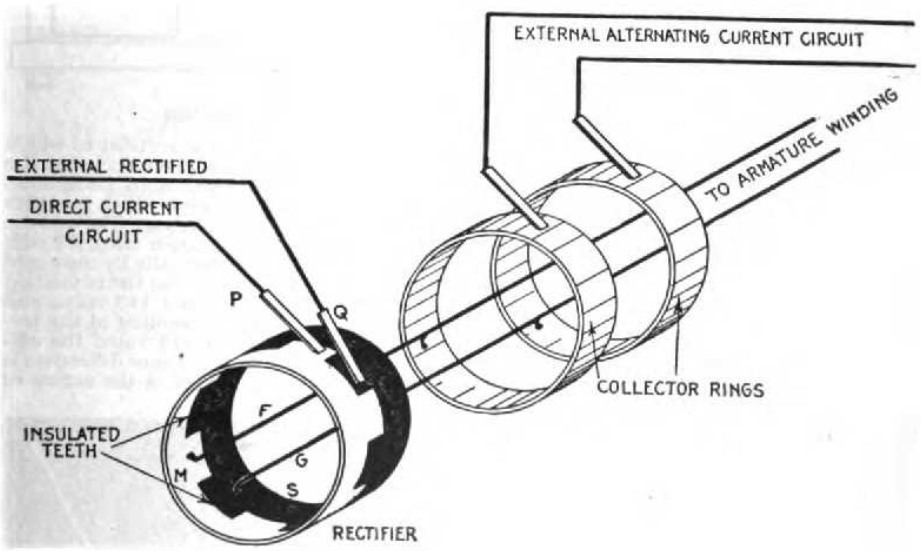


FIG. 2,079.—Mechanical rectifier. The rectifier consists of two castings M and S with teeth which fit together as shown, being insulated so they do not come in contact with each other. Every alternate tooth, being of the same casting, is connected together, the same as though joined by a conducting wire. There are as many teeth as there are poles. The part M of the rectifier is connected to one of the collector rings by F, and the part S to the other ring by G.

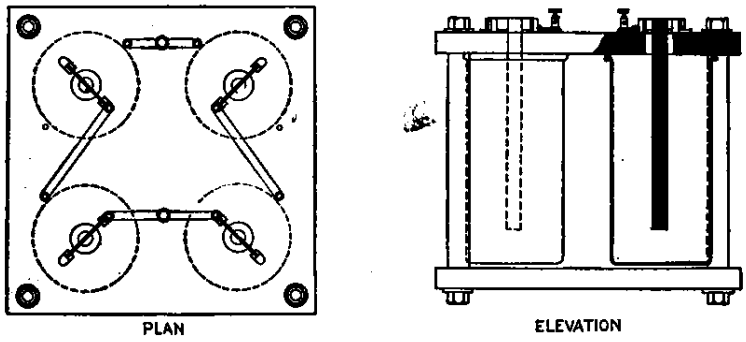
An advantage of this design over the rocking-bar style of electromechanical rectifier is that the physical brush contact with slip rings and commutator was continuous, and thus less prone to arcing and impact-related mechanical wear. It also leveraged the high degree of technological refinement[1] in brush and commutator design from DC electric motors and generators common to that era.

[1] It may seem strange to speak of century-old technology as being "highly refined", but for certain technologies now considered obsolete it is actually quite typical to find those once-prevalent technologies had been developed to an impressive degree prior to being displaced by some different technology. The fact that we don't use many brush-style DC motors and generators anymore is a testament to the limitations of brushes and commutators in general, but that does not mean brushes and commutators of that day were necessarily primitive. Here we see a case where the relatively advanced brush/commutator technology of that time was applied to solve the non-motor problem of rectification. In fact, such lessons and insights are a major reason why Historical References such as this are included in these learning modules along with tutorials on modern circuit technology: there is much we can learn from the past regarding design solutions and the often non-linear evolution of technology.

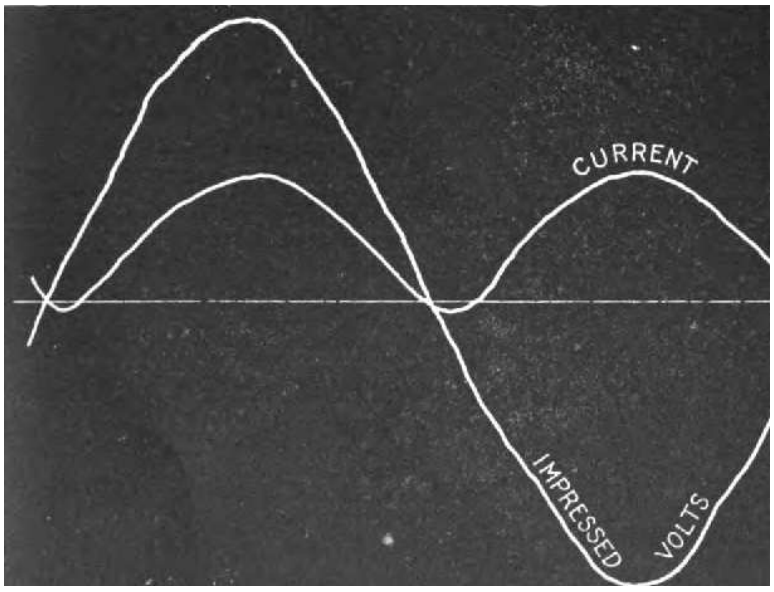
4.2 Electrochemical rectifiers

Another legacy technology for rectification was *electrochemical*. These devices were constructed similar to batteries, with conductive electrodes made of different materials immersed in a liquid electrolyte solution. The chemical action between the dissimilar electrodes and the electrolyte facilitated passage of electric current in one direction more readily than the other. These "liquid diodes" could then be used singly for half-wave rectification or connected in networks for full-wave rectification.

One such rectifier was manufactured under the name *Nodon*, using four electrolytic cells each with an aluminum cathode and lead anode immersed in a liquid ammonium phosphate solution. A thin film of aluminum hydroxide formed on the surface of the aluminum-metal cathode was responsible for each cell's diode action. The four cells were connected in a standard bridge network (called the *Gratz* connection by the authors of *Hawkins Electrical Guide Number Five* in 1917), as shown in the following illustration from page 1498:

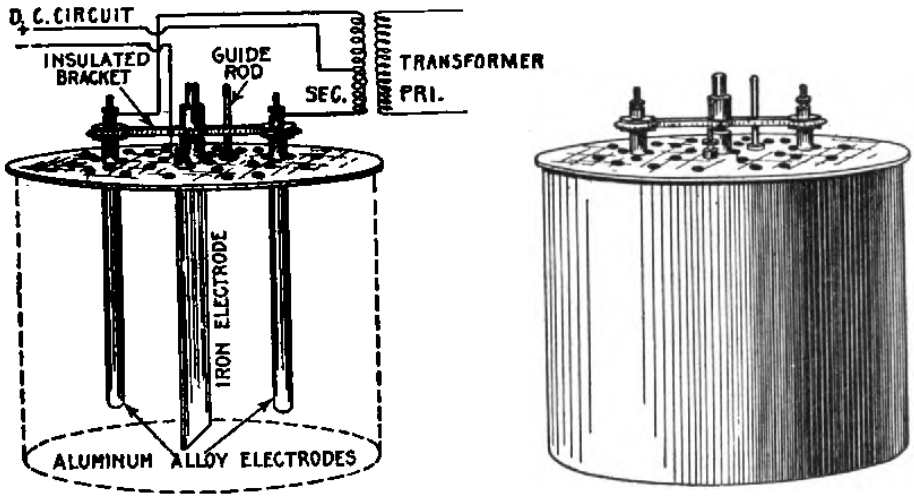


An oscillograph of this rectifier's operation shows full-wave rectification of the AC power, also taken from page 1498 of *Hawkins Electrical Guide Number Five*:



Typical operating voltage was less than 140 Volts, and typical operating current was 5 Amperes. As you can see from the oscillograph, the rectification is not perfect: the "DC" output current actually does reverse direction for short periods of time as evidenced by the current trace dipping slightly below the zero line, immediately following the zero-crossing of the AC source voltage. Efficiency was rather low – reaching a maximum of only 75% – largely owing to resistive energy losses in the electrochemical cells (both resistance of the aluminum hydroxide film when forward-biased as well as bulk resistance of the ammonium phosphate solution).

A different model of electrochemical rectifier of that era was manufactured under the brand *Mohawk*, shown here on page 1501 of *Hawkins Electrical Guide Number Five*:



FIGS. 2,085 and 2,086.—Mohawk electrolytic rectifier. To put in commission, clean out the jar. Fill with distilled or rain water. Add six pounds of electro salts, stir and after all salts are dissolved place the cover in position. The specific gravity of the solution should be 1.125. The middle iron electrode must hang straight down in the solution and not touch either of the other aluminum alloy electrodes. The aluminum alloy electrodes are mounted on an insulated bracket that slides up and down on a ¼" rod. This rod screws in the hole taped in the middle of the cover. The electrodes give the best results only when perfectly smooth. Should they get rough, covered with a deposit or a white coating remove from the solution, and clean with fine sand paper. Finish with fine sand paper. Form the film again and the electrodes will be as good as new. Clean iron electrode occasionally.

As this schematic diagram shows, this is another "one-way" circuit providing full-wave rectification to the DC load, requiring a center-tapped transformer winding.

Rather than aluminum and lead electrodes as was the case with the Nodon model, the Mohawk uses aluminum and iron electrodes. Interestingly the aluminum hydroxide film accounting for the cells' diode action would slowly dissolve over time if the rectifier was not in active use. That film could be preserved over periods of non-use by removing the electrodes from the liquid electrolyte and drying them off.

The caption is included for historical reference, as it gives some indication of the routine maintenance associated with these rectifiers. Additionally, the operating inefficiency of these rectifiers meant the liquid solution could become quite warm with use, leading to evaporation of water from the electrolyte solution and thereby necessitating period replenishment with distilled water.

4.3 Vacuum tube rectifiers

One of the pivotal discoveries in the history of electronics is the *Edison effect*. Thomas Edison, while developing a reliable incandescent electric lamp, discovered the passage of a small electric current (in one direction only) between the hot filament wire of the lamp and a cold metal wire also located within the lamp's evacuated glass envelope. This effect was at the time noted as a curiosity, but later developed by others[2] into practical applications bearing little relation to electric illumination. The ability of vacuum tubes to exert control over the flow of electricity led to them being called *valves*, analogous to mechanical valves used to throttle fluids through pipes.

An illustration of a demonstration device for the Edison effect appears below, from page 1502 of *Hawkins Electrical Guide Number Five* (published in 1917), with accompanying caption describing how this vacuum-based diode could be used to drive a (DC) galvanometer detector from an AC signal:

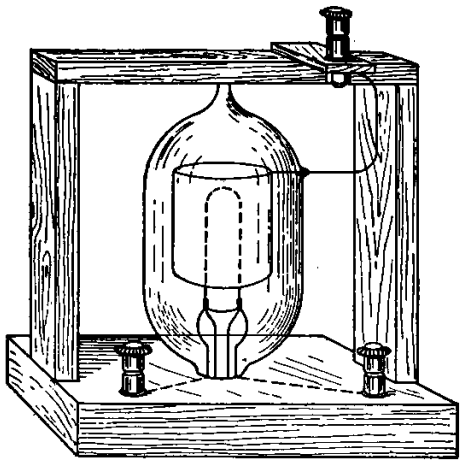


FIG. 2,087.—The Fleming oscillation valve. It depends for its action on the well-known Edison effect in glow lamps. The valve consists of a carbon filament glow lamp with a simple central horseshoe filament. Around this filament inside the exhausted bulb is fixed a small cylinder of nickel, which is connected by means of a platinum wire sealed through the bulb to a third terminal. **The valve is used as follows:** *The carbon loop is made incandescent by a suitable battery. The circuits in which the oscillations are to be detected is joined in series with a sensitive mirror galvanometer, the nickel cylinder terminal and the negative terminal of the filament of the valve being used.* The galvanometer will then be traversed by a series of rapid discharges all in the same direction, those in the opposite direction being entirely suppressed.

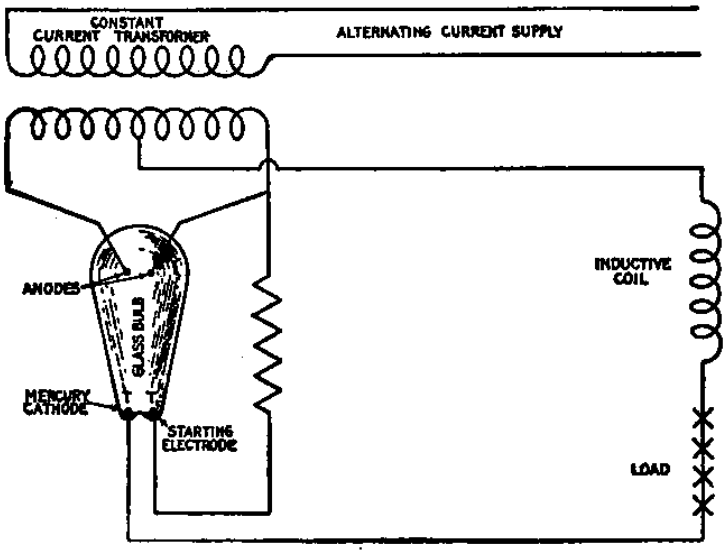
Although vacuum tube rectifiers were quite limited in their ability to carry current (measured in milliAmperes rather than Amperes) – since that current is comprised entirely of electrons driven into the vacuum space of the tube by the heat of the glowing filament – they excelled at rectifying AC signals of extremely high frequency. Electromechanical rectifiers were limited by their inability to physically *move* fast enough to handle high AC frequencies, and electrochemical rectifiers were limited by the speeds of ions at the electrode surfaces. Free electrons within a vacuum space, however, are capable of *extremely* fast motion. As a result, vacuum tube rectifiers could, at least in theory, rectify AC signals in the range of *millions* of Hertz (cycles per second), making them more practical for *signal* applications than for *power* applications.

[2] John Ambrose Fleming, the English electrical engineer, is notable as an early developer of vacuum tube technology, which is why this caption reads "Fleming oscillation valve".

4.4 Mercury arc rectifiers

A rectification technology closely related to vacuum tubes is *mercury arc* or *mercury vapor* rectifiers. Instead of thermally-emitted electrons within an evacuated glass tube, these rectifiers used mercury metal *vapor* inside of an airtight enclosure. Similar to the history of the vacuum tube rectifier, where the fundamental "Edison effect" principle was discovered while developing incandescent electric lamps, the fundamental principle of mercury arc rectification was discovered while developing mercury-vapor discharge lamps. An American electrical engineer named Peter Cooper Hewitt was experimenting with electric arcs in low-pressure mercury vapor as a source of light, and in the course of those experiments identified the phenomenon of diode action within mercury lamps when one of the two electrodes was a pool of liquid mercury at the bottom of the tube. This phenomenon was exploited to create mercury vapor diodes which could be used for power rectification. Like the vacuum tubes that preceded, mercury rectifiers were commonly referred to as *valves*.

An illustration[3] from page 1508 of *Hawkins Electrical Guide Number Five* (published in 1917) shows a simple full-wave center-tap rectifier circuit using a dual-anode mercury vapor element:



Mercury vapor tubes were capable of conducting *far* more current than vacuum tubes, owing to the much greater density of charge carriers[4] in the glass envelope's space. For this reason, mercury

[3] One detail seen in this diagram is that the transformer is designed to output a *constant current*. This is a rather unusual transformer design, where one winding is movable and suspended on a counterweighted beam so that it moves closer to or farther from the other winding based on magnetic attraction, the force of which is a function of load current. The purpose for using a constant-current transformer is unrelated to the mercury rectifier, but instead represents the peculiar operating characteristics of arc (discharge) lamps which function better when current is constant and voltage is variable. This, in fact is why multiple "X" symbols are used for the load in this schematic diagram: the intended load in this case is a series-connected string of arc lamps.

[4] In a vacuum tube, the only charge carriers are electrons thermally emitted from a heated filament. In a mercury vapor tube, an immense quantity of ionized mercury atoms are emitted from the liquid mercury pool, those positive ions and their dissociated electrons comprising a relatively dense field of charge carriers for conducting electric current.

arc rectifiers saw much longer[5] use than any of the other power rectification technologies listed in this chapter. Later developments in this technology led to *steel tank* designs rather than glass bulbs, and with water cooling systems these massive rectifiers could be designed to handle over 1000 Amperes of current. Other developmental directions for mercury rectifiers in the 1960's focused on extremely high voltage applications for use in long-distance power transmission using DC rather than AC[6] to avoid problems with line reactance.

A schematic diagram of a three-phase mercury rectifier circuit with accompanying caption appears below, from page 1509 of *Hawkins Electrical Guide Number Five*:

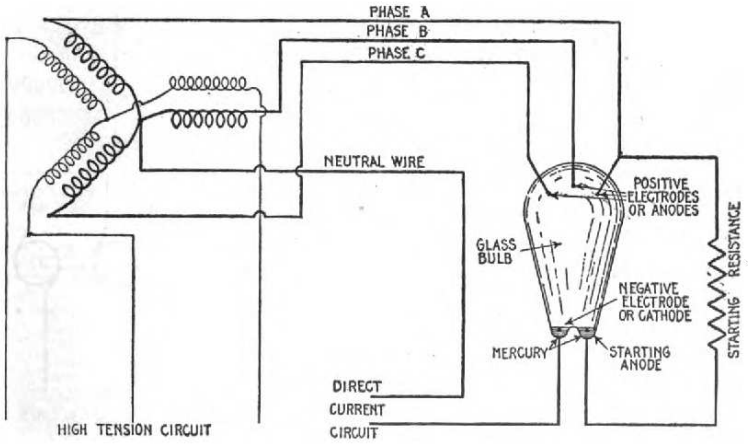


FIG. 2,095.—Three phase mercury arc rectifier. The rectifier bulb is provided with three positive electrodes or anodes, a negative electrode or cathode, and a starting anode, as shown. The three phase leads are connected to the anodes at the top of the bulb, a branch from one phase being brought down to the starting anode, a resistance being placed in the circuit to prevent excessive current on account of the proximity of the two lower electrodes. Since there is always a pressure on one of the three anodes in the right direction, a reactance coil is not necessary. The apparatus is started in the usual way by tilting.

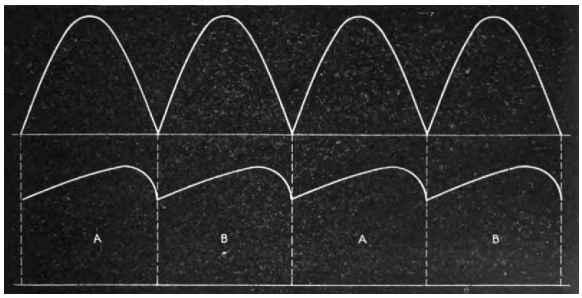
Note the use of a triple-anode mercury "valve" in this circuit, where three anodes share a common cathode. A couple of noteworthy characteristics of mercury rectifiers is evident from this illustration's caption, (1) the need for continuous current to maintain mercury ionization, and (2) cold start-up procedures. These characteristics will be described in the following two paragraphs.

The operation of a mercury arc rectifier depends on there being plentiful mercury metal ions within the otherwise empty space of the tube, and this continuous state of ionization requires continuous (i.e. non-pulsing) current through the tube. With a three-phase rectifier this is not a problem since at least one of the three phases is guaranteed to be conducting in the desired direction at any given time, but in a single-phase rectifier some means must be provided to maintain current when the AC waveforms crosses through zero. In the diagram from page 1508 of *Hawkins*

[5]Some notable installations in high-voltage DC power transmission circuits saw use into the 21st century. The DC converter station operated by Bonneville Power Administration in Celilo, Oregon, for example, replaced the last of its mercury arc rectifiers in 2004.

[6]A so-called *DC link* is a two-wire DC transmission line linking different AC power grids. At each end of the line, a *converter station* using these mercury rectifiers would either convert AC into DC (rectification) or DC into AC (inversion), typically using the same mercury devices for both operations. The design details of these multi-use mercury elements were more complex than for simple rectification, but the basic concept was the same: control conduction of electricity between anode and cathode using a "cloud" of mercury metal ions.

you can see the solution employed: an inductive coil connected in series with the DC load. The magnetic field generated by the inductor stores energy necessary to maintain an arc in the tube during those brief moments in time when the AC source no longer supplies current. Interestingly, this is the reason mercury rectifiers were never used for single-phase, *half-wave* rectification: the time delay between successive pulses would have been far too long to sustain an arc inside the tube without using an enormous amount of inductive reactance. An oscillograph showing the current-sustaining effect of this series inductance for single-phase[7], full-wave rectification appears below, from page 1521 of *Hawkins Electrical Guide Number Five*:



If the power arc within a mercury rectifier ever ceases, it must be restarted somehow. A "starting anode" is provided for this purpose, with its own small pool of liquid mercury positioned near the main cathode. A "starting resistance" connects this second anode to the other anode(s) of the tube. In order to start up such a mercury rectifier, it must be gently *shaken* to cause liquid mercury to splash between the cathode pool and the starting anode pool. As comical as it may sound, some mercury rectifiers actually used a small electric motor and crank mechanism to physically shake a cold mercury tube until it ionized!

Once operating, the excitation caused by the electric arc through the mercury vapor causes the vapor to glow, just as it does in a mercury vapor lamp. This is plainly evident in transparent (i.e. glass-envelope) mercury rectifiers. A photograph[8] showing this effect appears here:

[7] The annotations A and B denote the respective half-cycles of the single-phase AC source.
[8] This photograph was made public-domain courtesy of Timberwind.

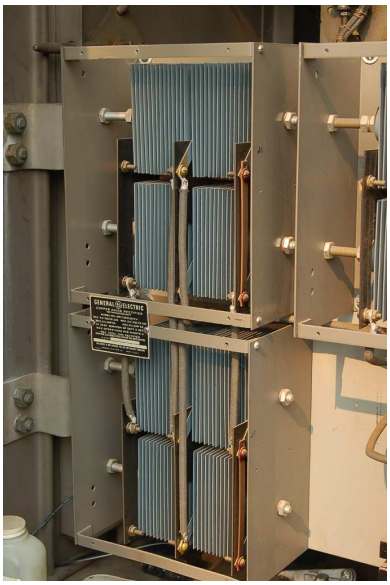
An actual photograph of a dual three-phase mercury-arc rectifier assembly (decommissioned) appears with permission from Neil Probert who saw this working as a Power Engineering Specialist in the United Kingdom. According to the nameplate on this assembly, it was rated at 400 Volts AC input, 3-phase at 50 cycles per second (50 Hz), outputting 230 Volts DC at a maximum of 435 Amperes, or 100 kiloWatts. The manufacturer was a company called the Electric Construction Company, abbreviated *ECC*:

Note also the open-air contact circuit breaker (with magnetic trip coils) on the front of this enclosure, in all its hazardous glory! No safety protections of any kind on this circuit breaker preventing someone from making accidental contact with live copper terminals, nor from being scorched by arc flash in the event of manually interrupting too high of a current! The probability of arc flash is even more apparent when you consider the number of poles on this circuit breaker – two poles, not three poles – suggesting it was for the DC and not the AC side of this rectifier circuit. Since the rectified output of this assembly is more or less continuous owing to the inductor previously mentioned, any arc produced at the breaker's contacts would also be continuous and therefore more difficult to extinguish than an AC arc which naturally commutates 100 times per second at 50 Hz.

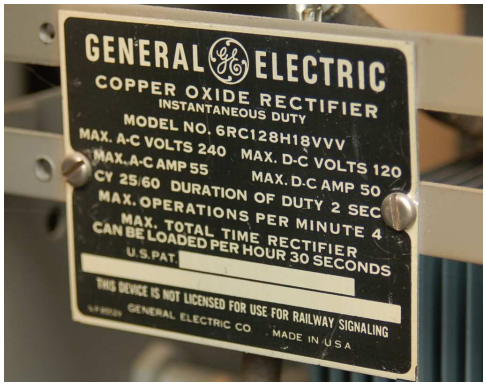
4.5 Copper oxide and selenium rectifiers

Before the commercial availability of silicon and germanium semiconductor materials, some manufacturers produced rectifying diodes using junctions of copper and copper-oxide, or iron and selenium. Both types of metal-based rectifiers were built as "stacks" with multiple series-connected junctions to attain practical reverse-bias breakdown voltage ratings.

A photograph of a copper oxide rectifier is seen here, part of an antique General Electric circuit breaker. Each "fin" represents a single diode junction:



A close-up photo of this rectifier's nameplate shows it suitable for "instantaneous" rather than "continuous" duty:



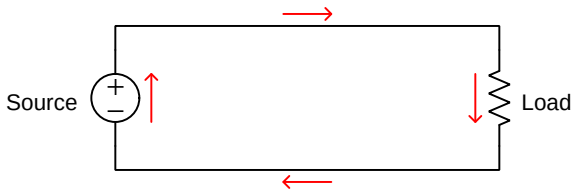
Chapter 5

Derivations and Technical References

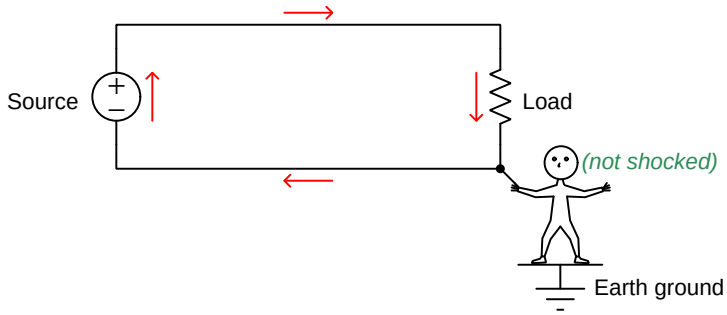
This chapter is where you will find mathematical derivations too detailed to include in the tutorial, and/or tables and other technical reference material.

5.1 Hot, neutral, and ground power conductors

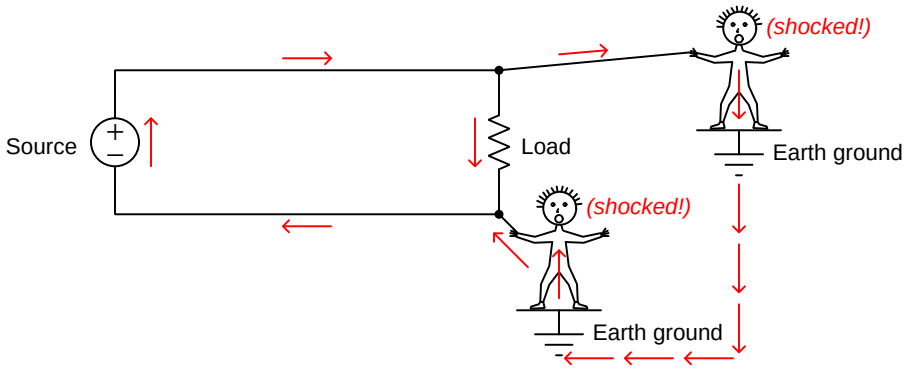
An elementary electric circuit needs just two conductors to convey electrical energy to a load:



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:

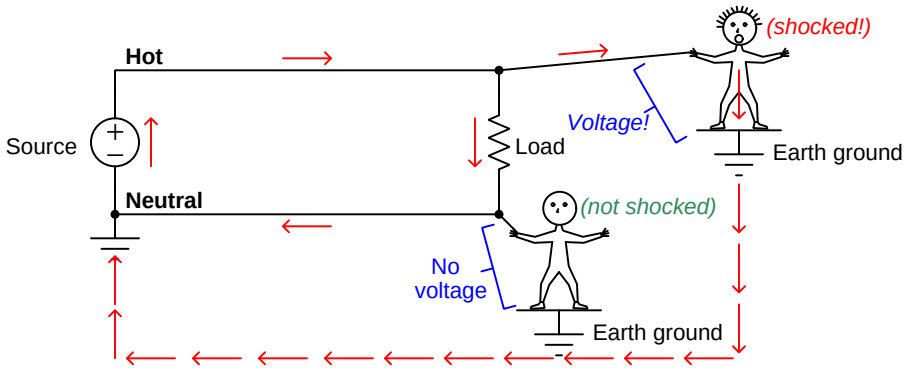


In principle, the foot-grounded person ought to be able to touch *any* conductor in this circuit with no risk for the same reason. However, this assumes the circuit has no other connection to Earth ground. If, for example, *two* people happened to touch opposite conductors simultaneously, a path for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



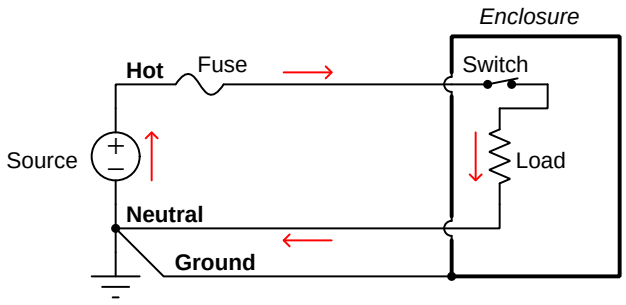
In a simple two-conductor circuit such as this, an interruption anywhere halts current everywhere. The location of a power switch or fuse may seem irrelevant given this fact, but once we commit to "hot" and "neutral" conductor identities via intentional Earth-grounding this is no longer an arbitrary 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].

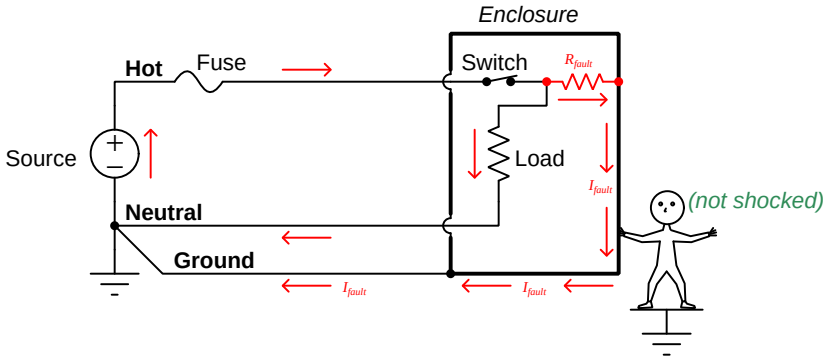
[1] Another good reason to intentionally ground one of the conductors within an electric power circuit is to prevent unintended safety hazards resulting from *lightning strikes*. This is especially relevant since most electrical power transmission and distribution conductors are overhead, suspended from 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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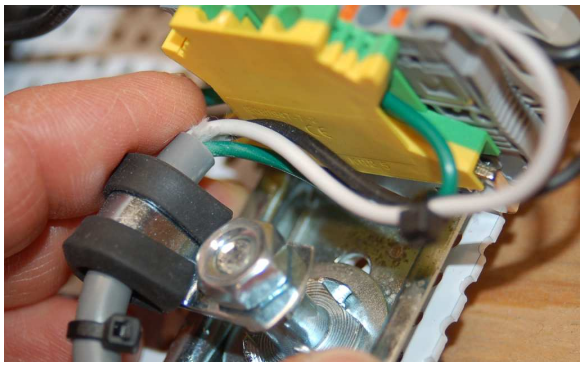
another will develop a voltage drop between those points, just like current passing through a resistor, which would make those points no longer equipotential with each other. Also, ground currents can, over time, cause corrosion of the metal grounding rod as it chemically interacts with ions in the soil, 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"):

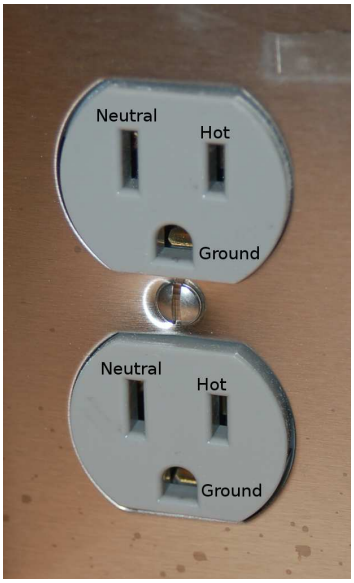


In this photograph we see the green ground wire terminate at a green/yellow-colored "grounding" terminal block[4]. The white neutral wire terminates at a regular terminal block adjacent to the grounding block. The black hot wire disappears out of the camera's view but terminates immediately at a *fuse-holding* 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!

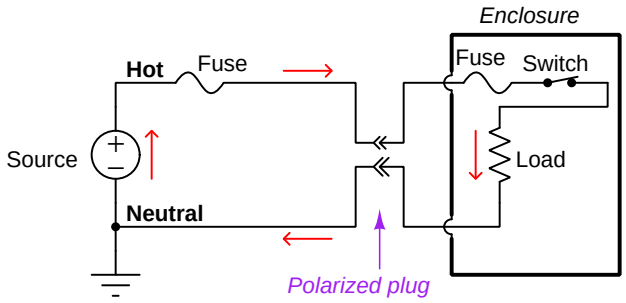
[4] This is a terminal block with a metal clamp base making solid electrical contact between the terminal and the metal DIN rail the block mounts to.

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

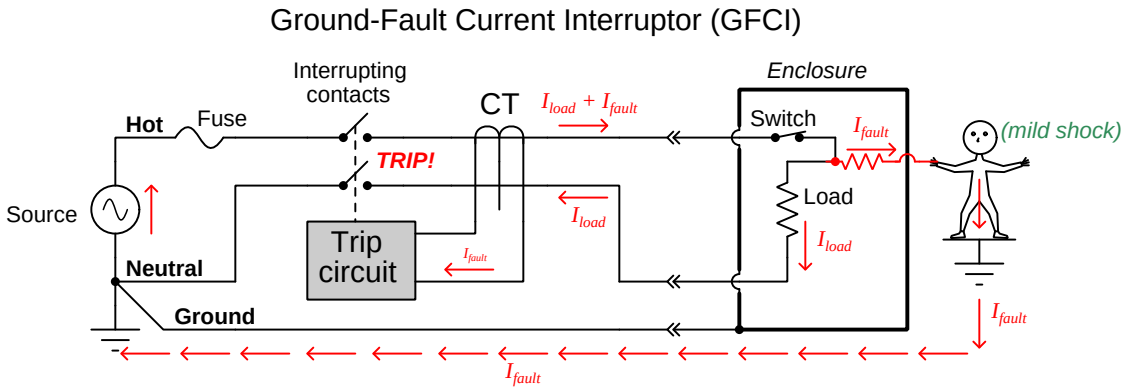


The small size difference between the hot and neutral jacks is not just for visual indication, but also for *polarized* two-prong power plugs where there is no ground conductor. On such a plug the hot and neutral "stabs" themselves are slightly different in size, such that it simply will not fit in the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

5.2 Ground in electric and electronic circuits

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

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

We say that voltage always exists "between two points" or "between two locations" in a circuit because voltage is the amount of potential energy either lost or gained by electric charge carriers from one position in a circuit to another. It is impossible to quantify how much energy will be gained or lost by charge carriers unless we know both the starting point and the ending point for those charge carriers. In order to quantify the absolute amount of potential energy possessed by anything, we would have to know where or how it could lose every bit of its stored energy to be left with zero capacity to do work[6]. This is really unknowable from a practical perspective, and so the best we can do is quantify gains or losses in potential energy between different states.

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

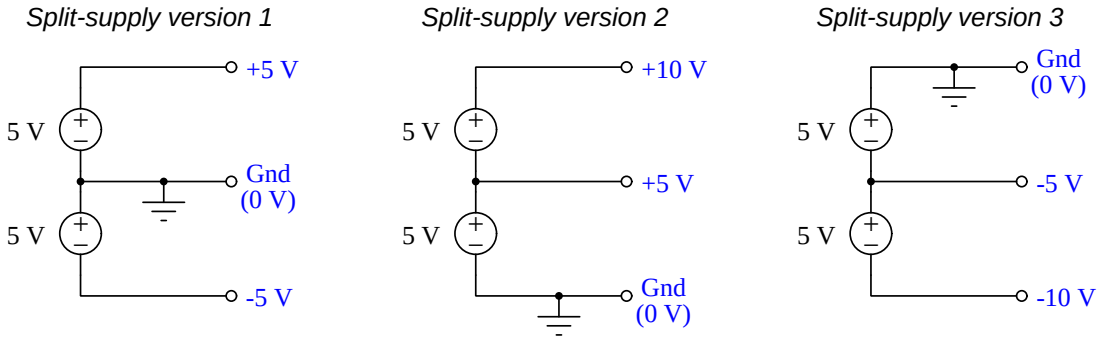
Now that we have reviewed this property of voltage and of potential energy in general, we are ready to explore what is meant by *ground* and *grounding*.

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

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

Much the same is true of electrical and electronic circuits, where voltage is an important measure of electrical potential energy as well as a measure of signal strength where electricity is used as an analogue for representing other things[7]. One way to conveniently rate electrical potentials at different points in a circuit is by arbitrarily choosing one of those points to be the "zero-energy" reference point, and calling it *ground*. Ground in an electrical or electronic circuit is analogous to sea level for rating mountain peak heights or a *datum* or *benchmark* used for surveying land: simply a point of reference agreed-upon to be "zero" for the sake of ranking all other potentials to it.

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

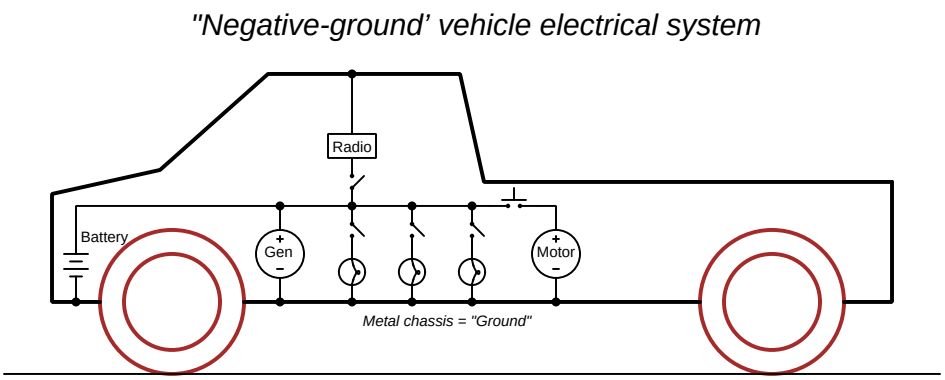


Each terminal's voltage label represents the amount of electrical potential there *relative to the "Ground" terminal*; i.e. "Ground" is simply a "sea-level" reference point against which all other potentials may be measured. The three different versions shown here illustrate just how arbitrary the location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

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

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

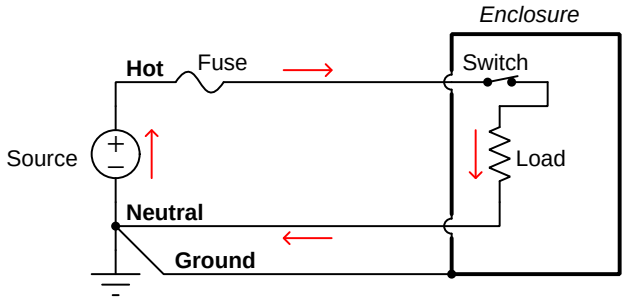
Another meaning of the word "ground" in circuits is a metallic surface used as a common conductor throughout some device or system for reasons of wiring economy. Automobiles with metal frames and chassis typically use their metallic bodies as an electrical conductor for nearly all circuits contained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



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

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

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



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

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

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

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

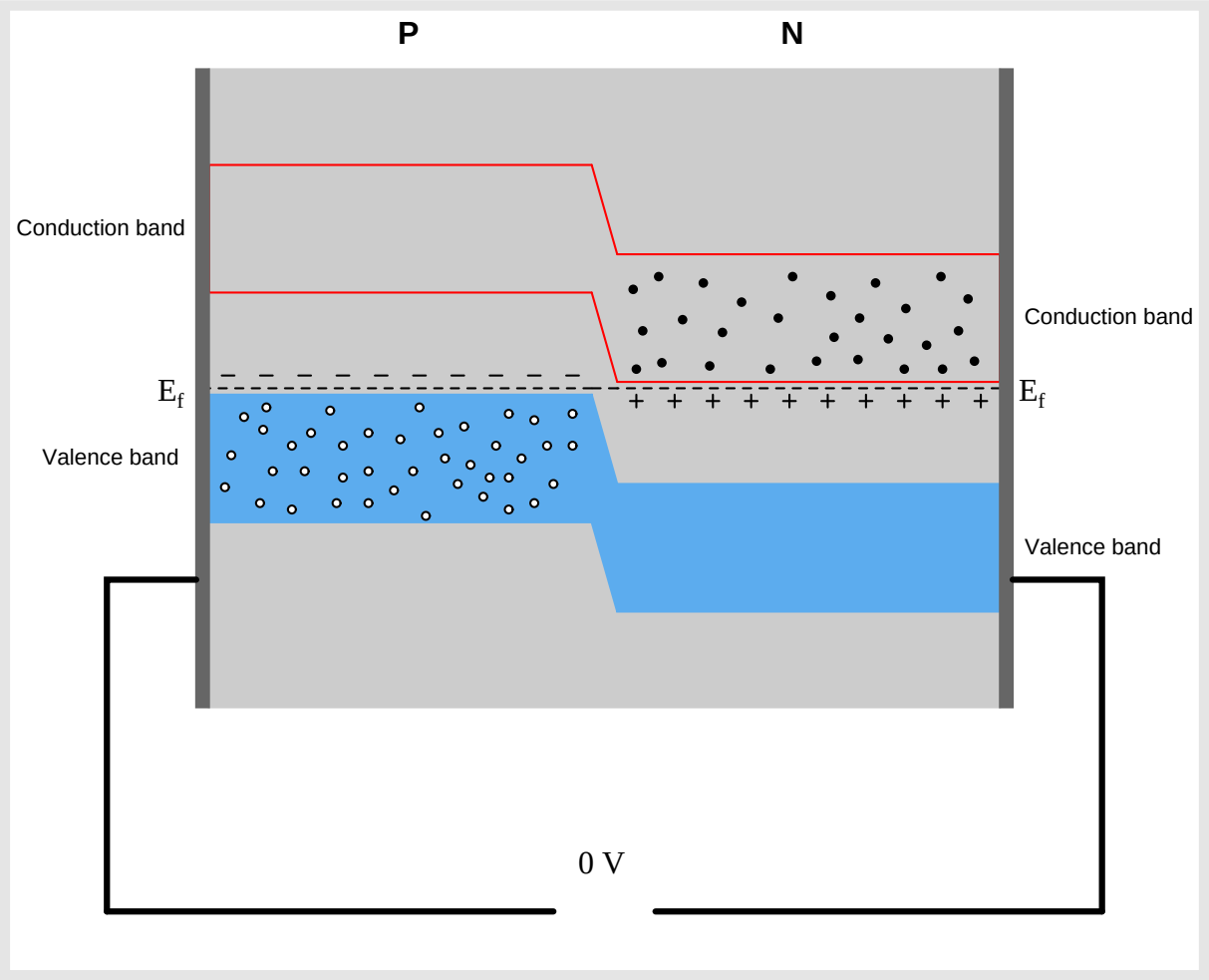
Chapter 6

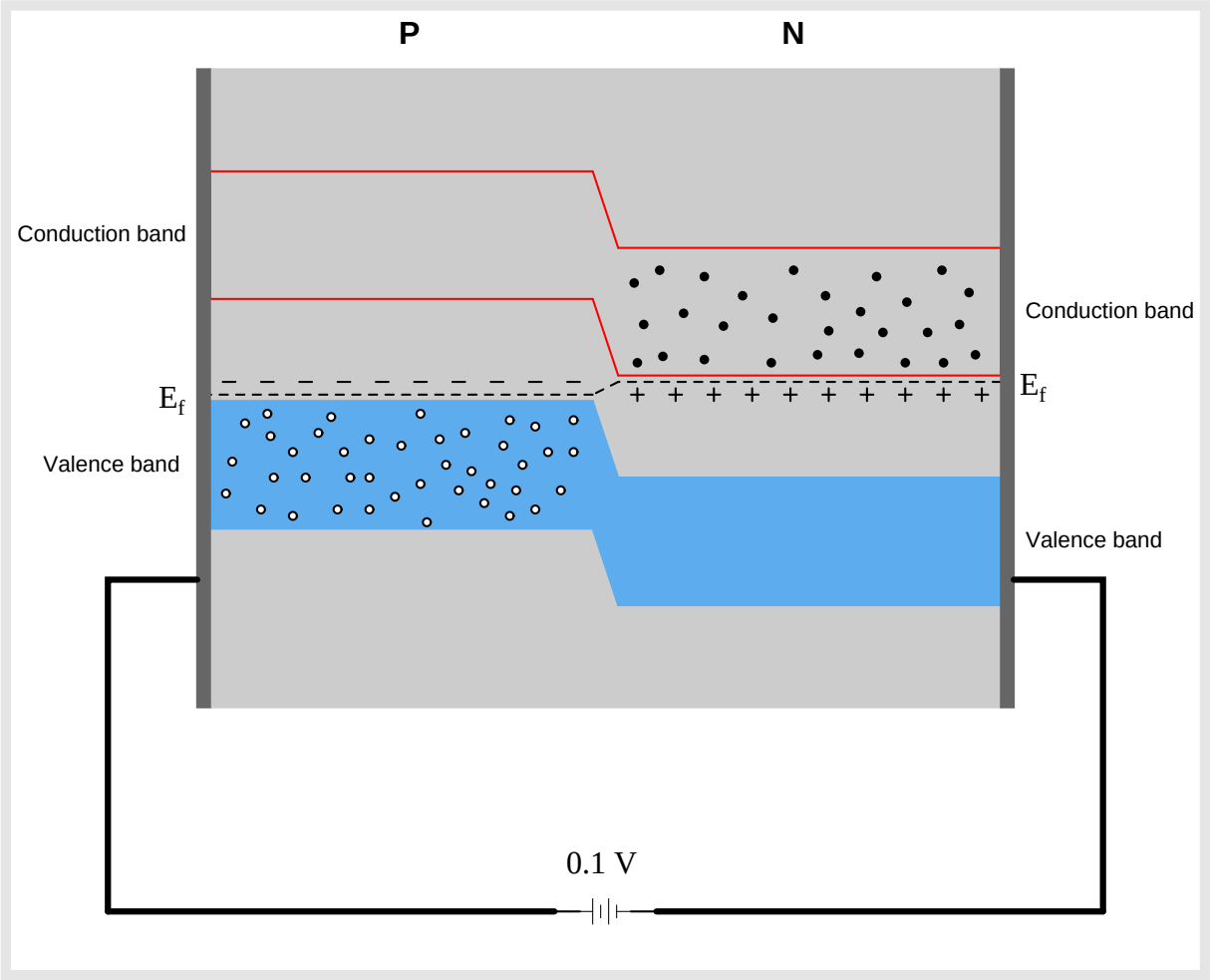
Animations

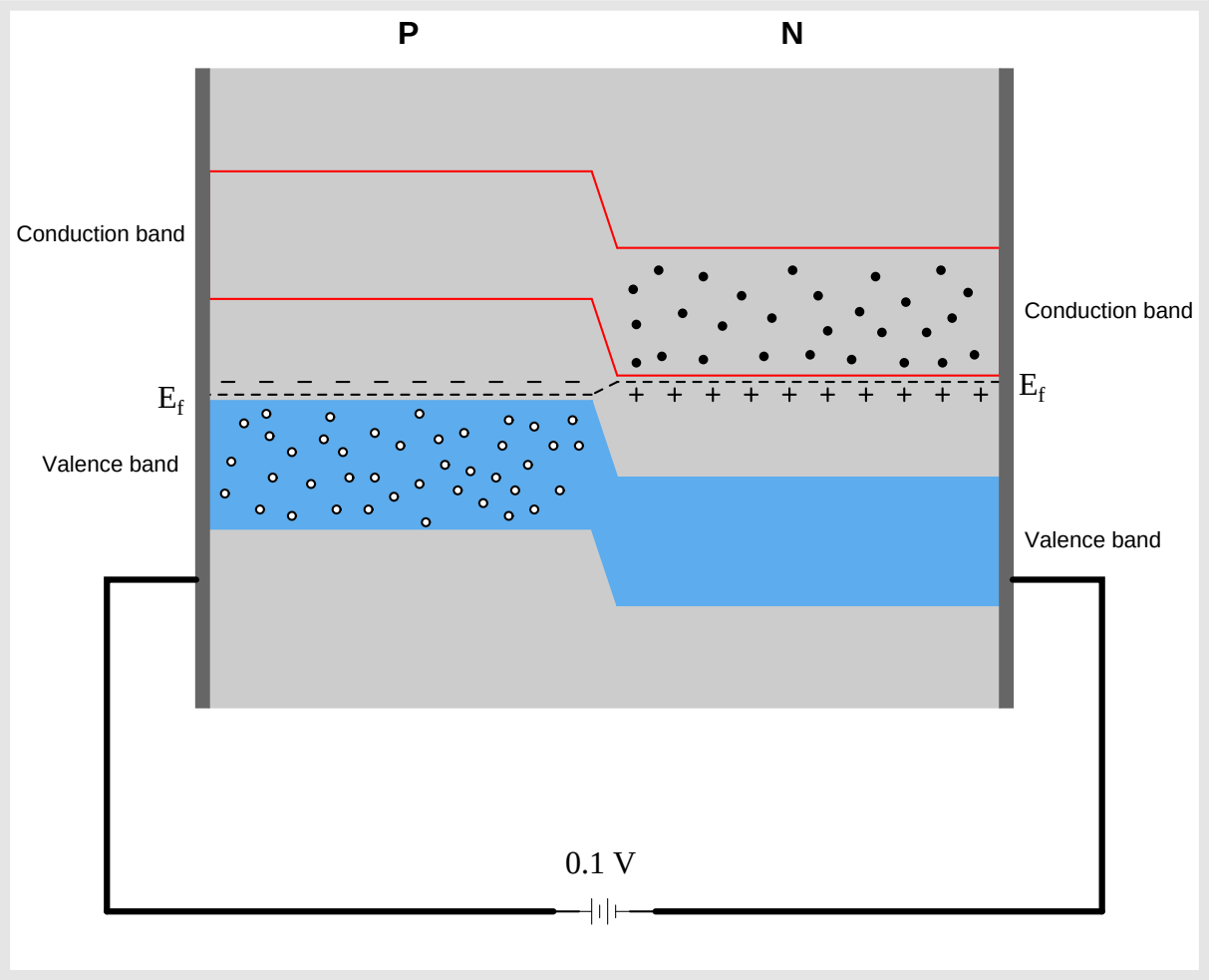
Some concepts are much easier to grasp when seen in *action*. A simple yet effective form of animation suitable to an electronic document such as this is a "flip-book" animation where a set of pages in the document show successive frames of a simple animation. Such "flip-book" animations are designed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

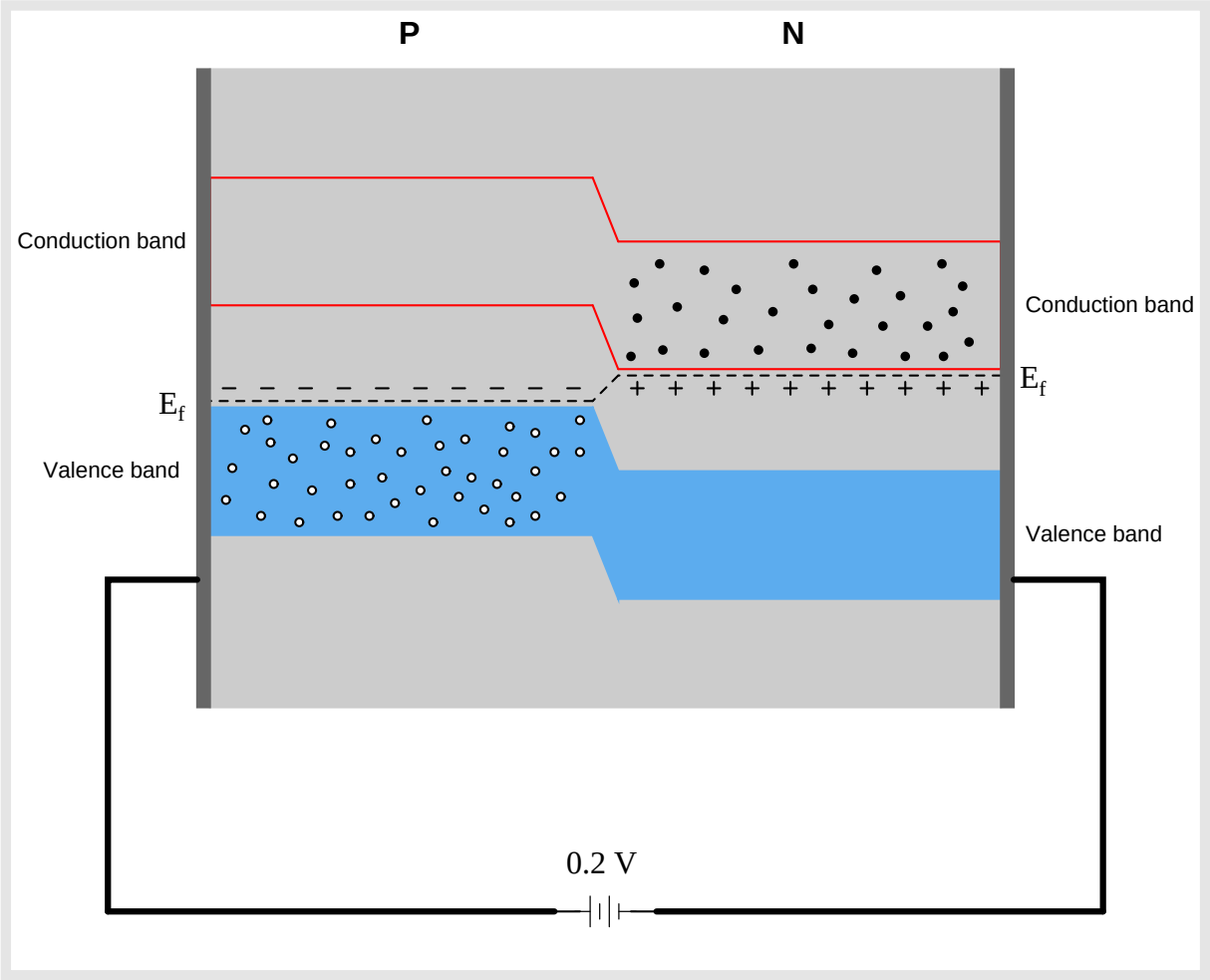
6.1 Animation of a forward-biased PN diode junction

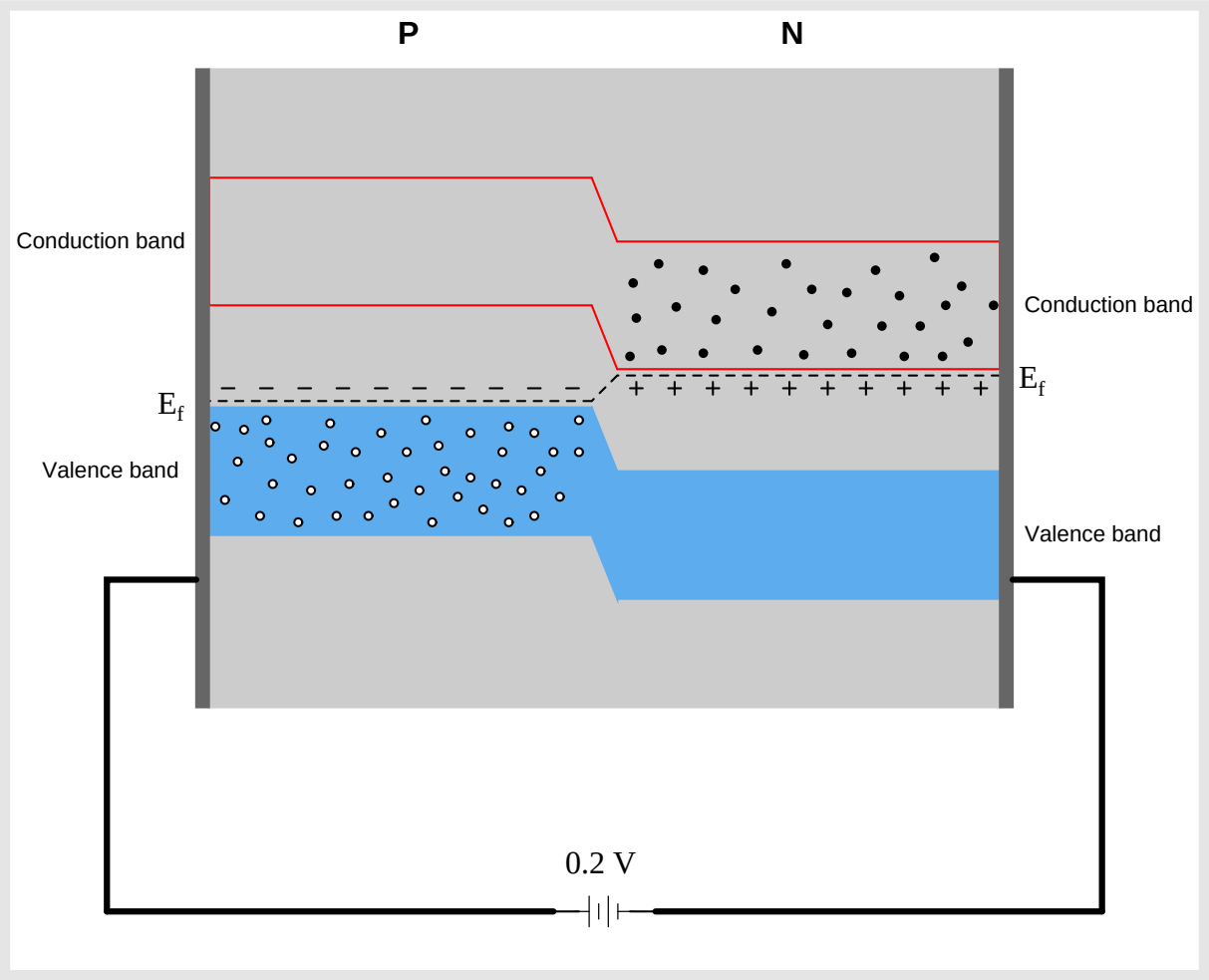
The following animation illustrates the behavior of charge carriers inside a semiconductor diode junction. A DC voltage source provides forward-biasing voltage to the PN junction, and this voltage source's value is progressively raised until the diode begins to conduct. Energy levels within the diode's semiconductor halves are shown relative to one another by means of height in the illustration.

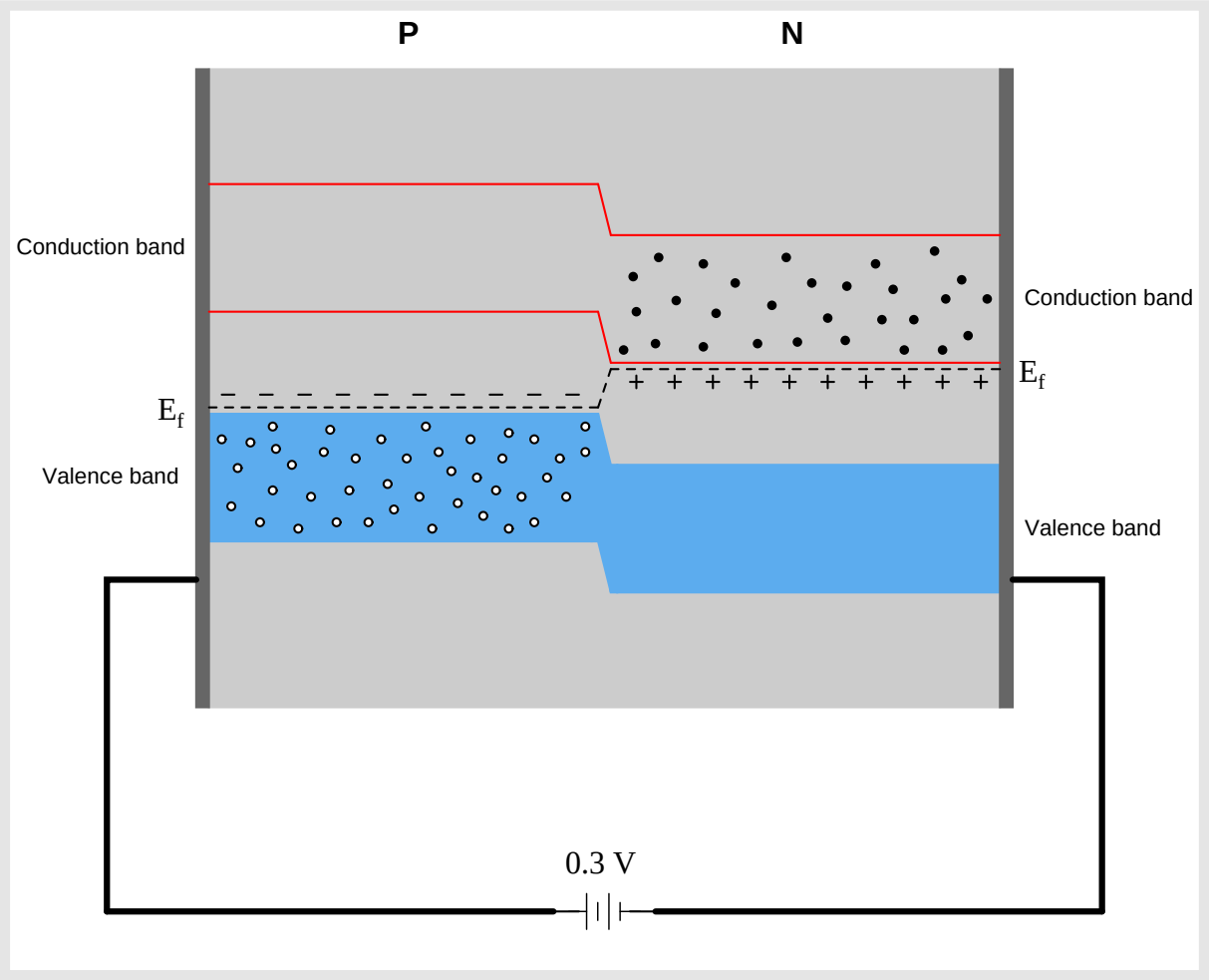

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0 V

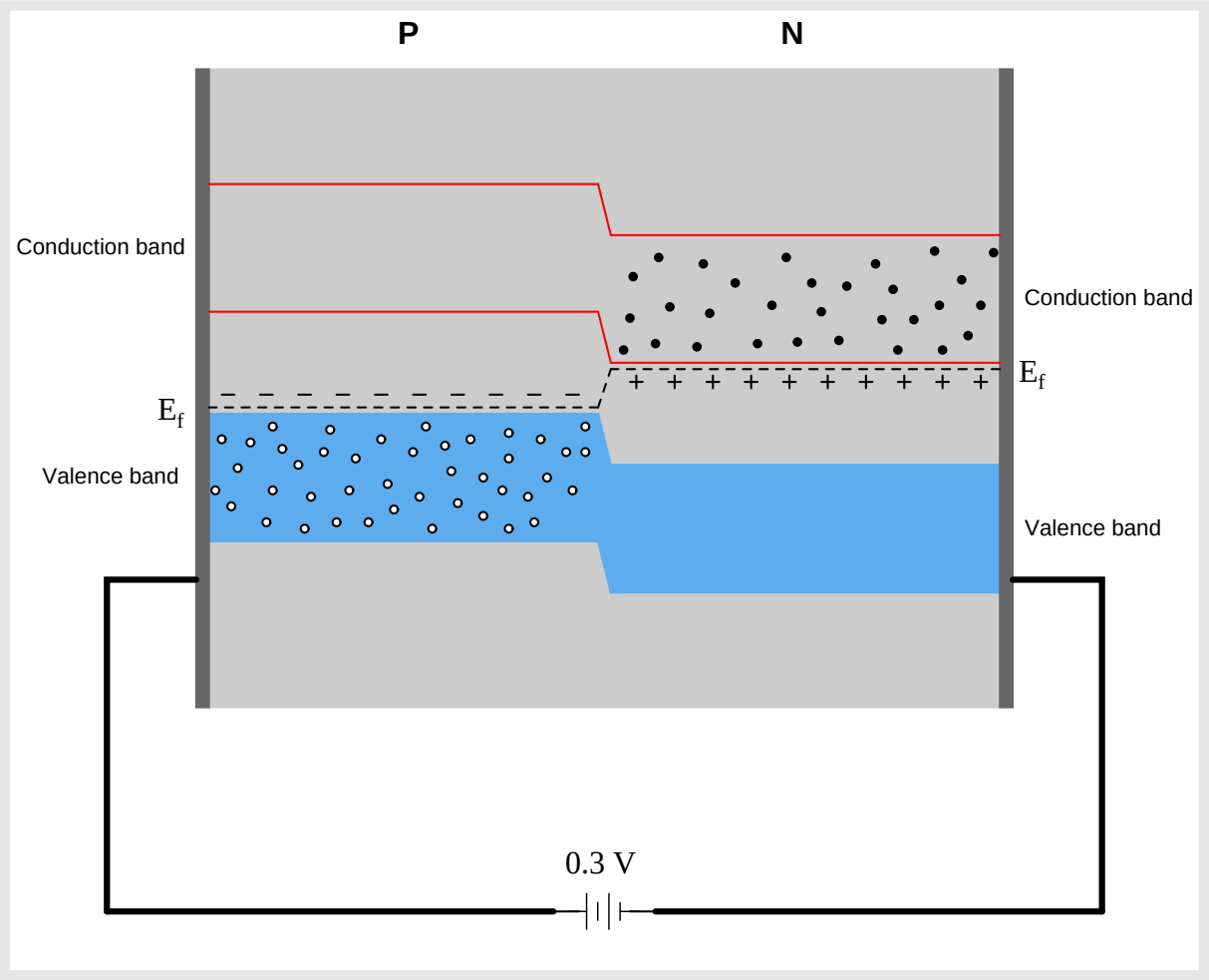

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.1 V

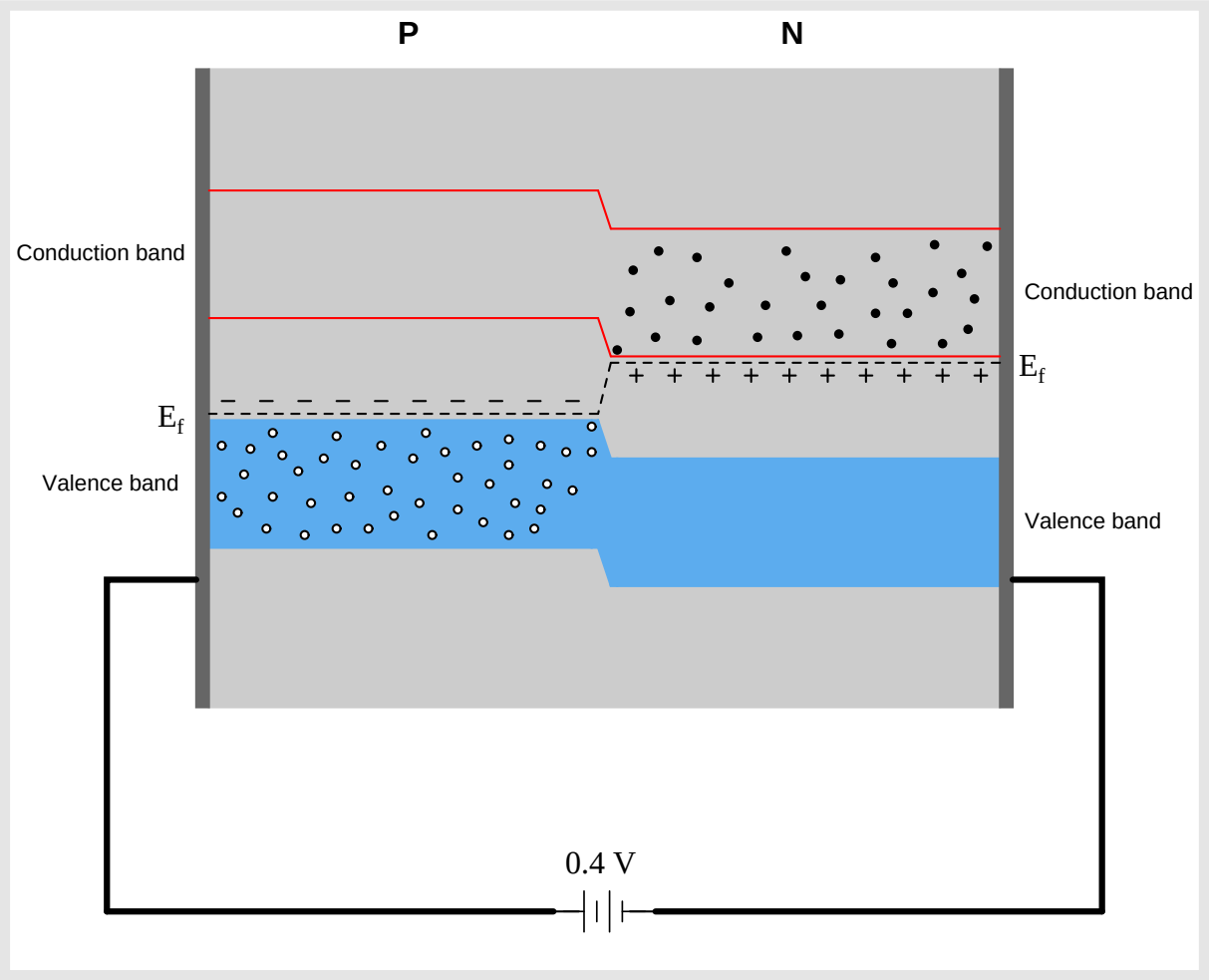

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.1 V

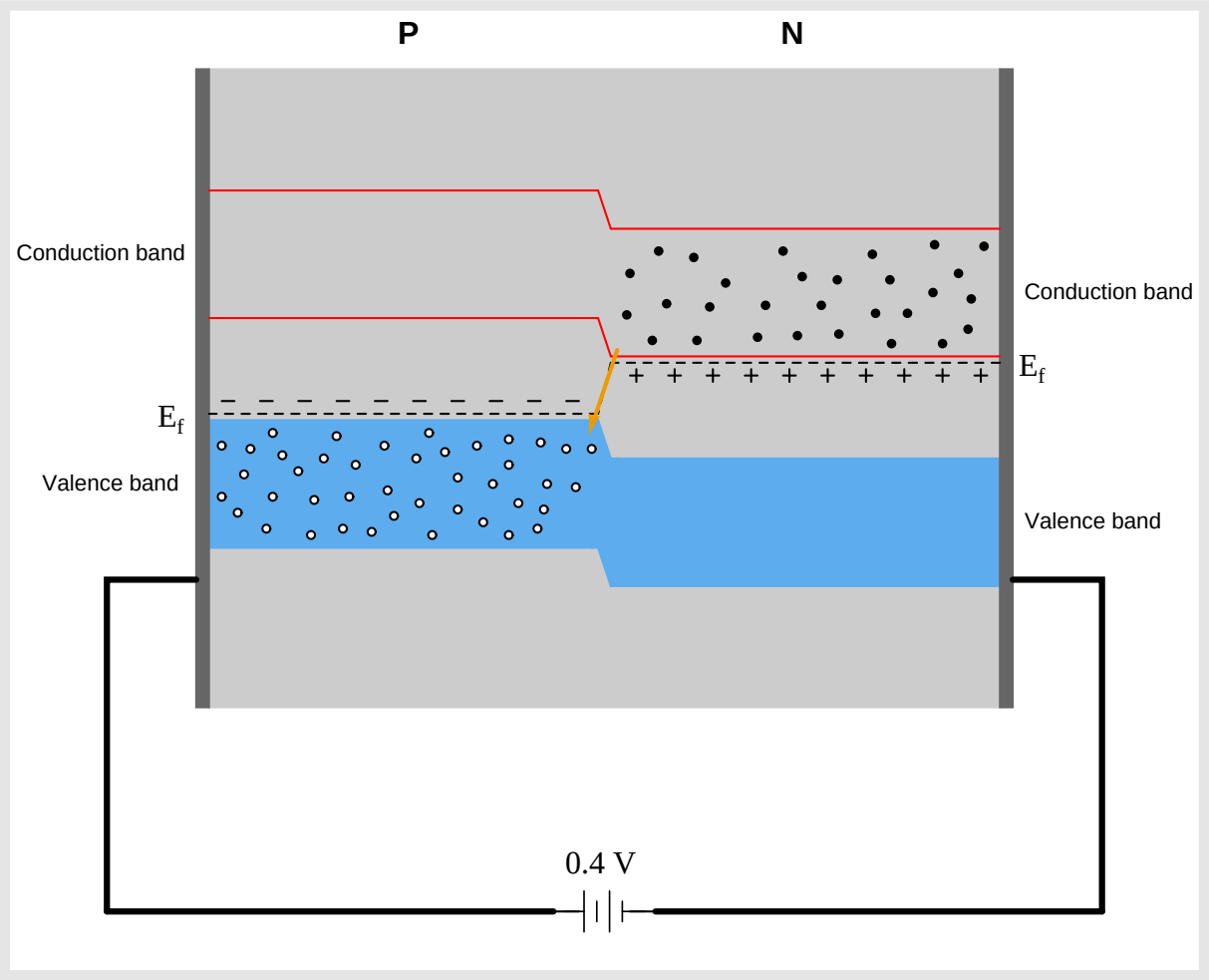

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.2 V

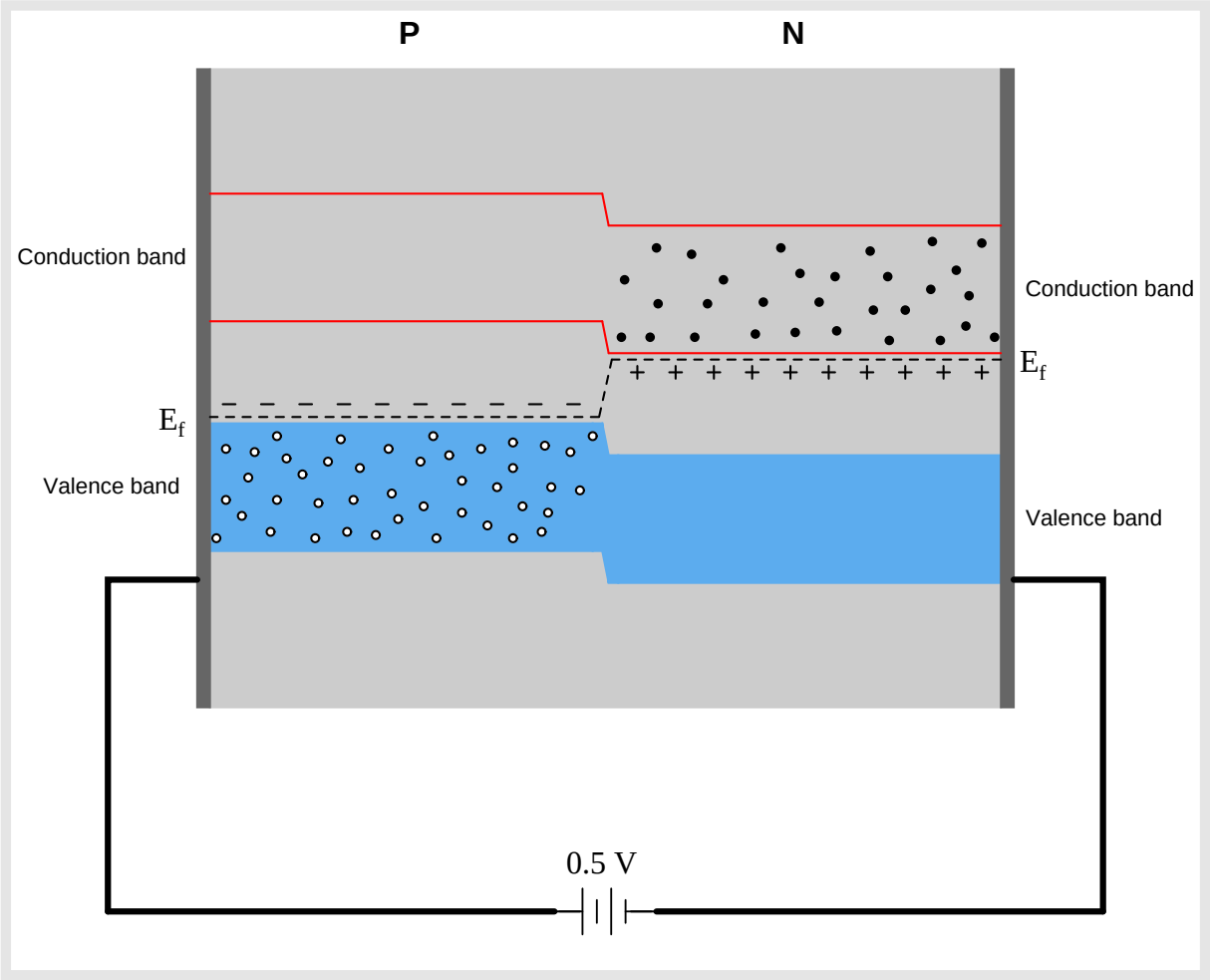

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.2 V

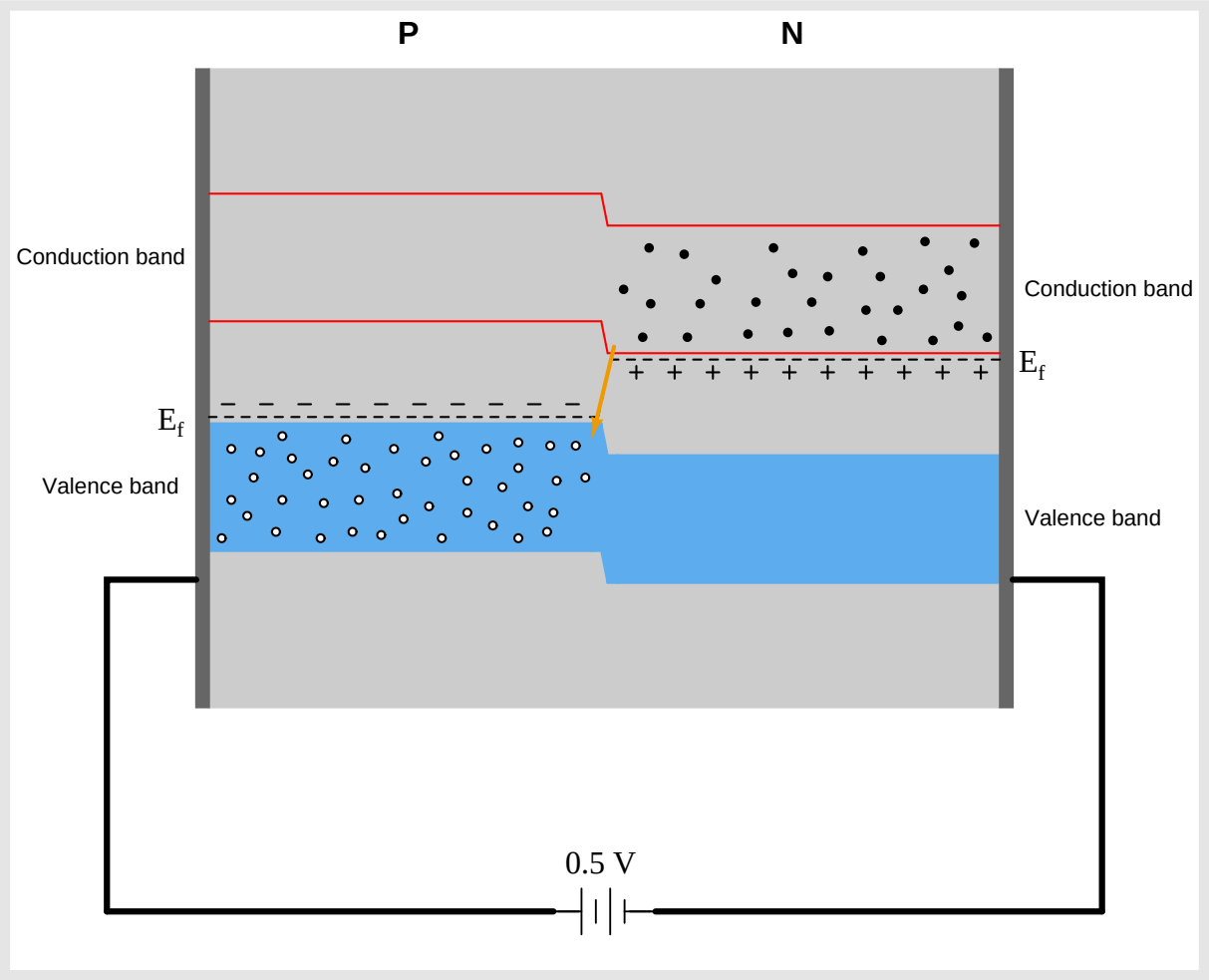

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.3 V

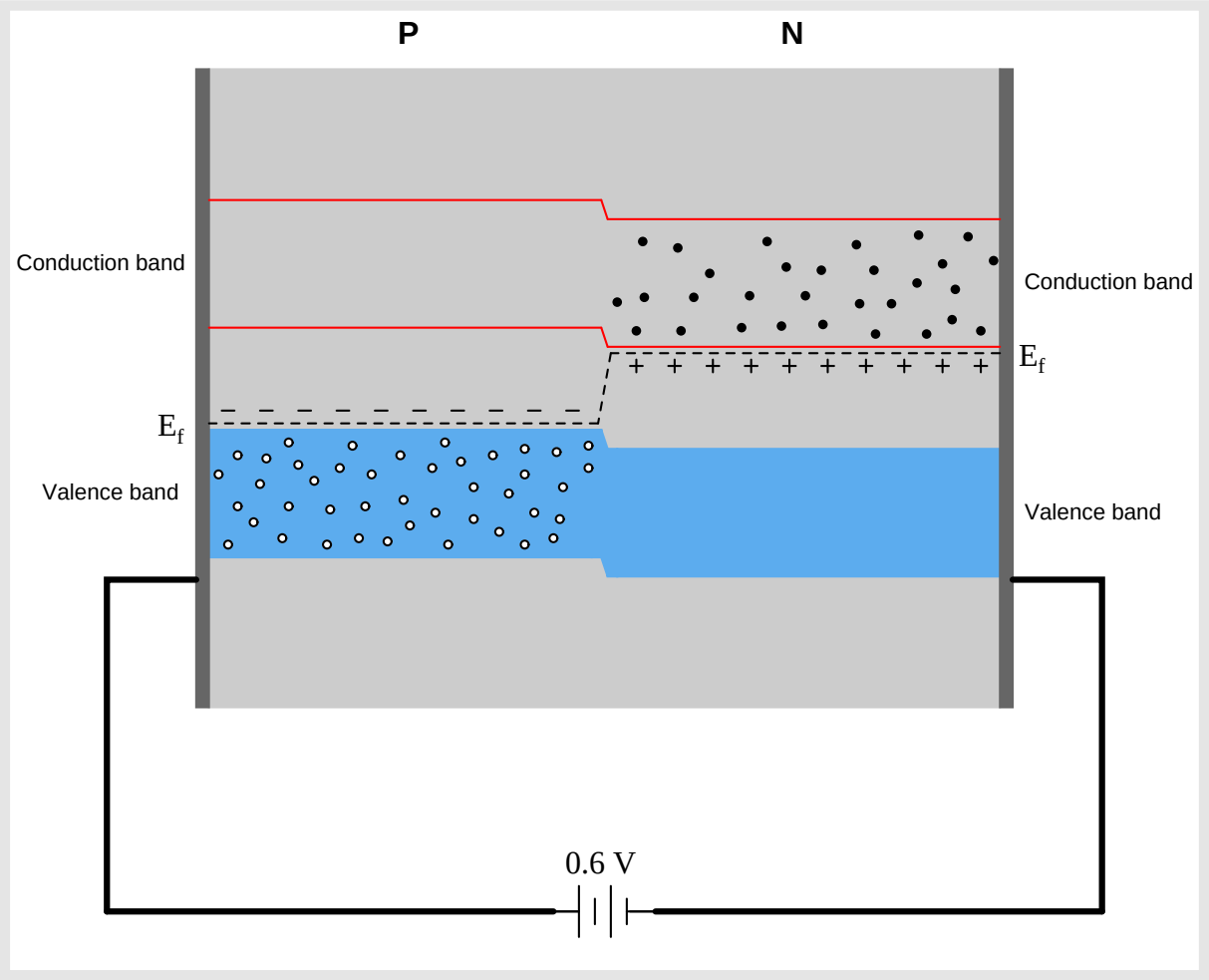

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.3 V

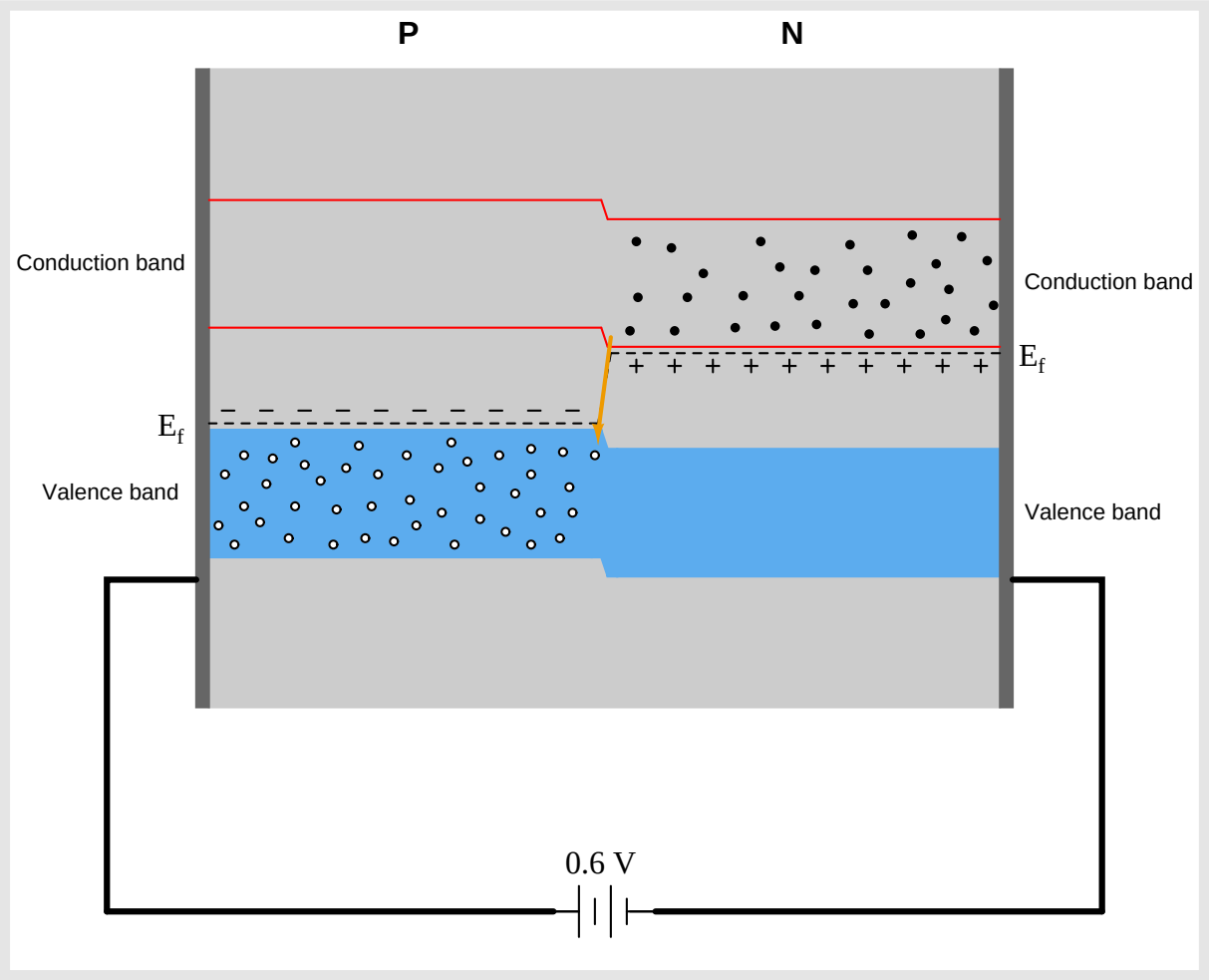

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.4 V

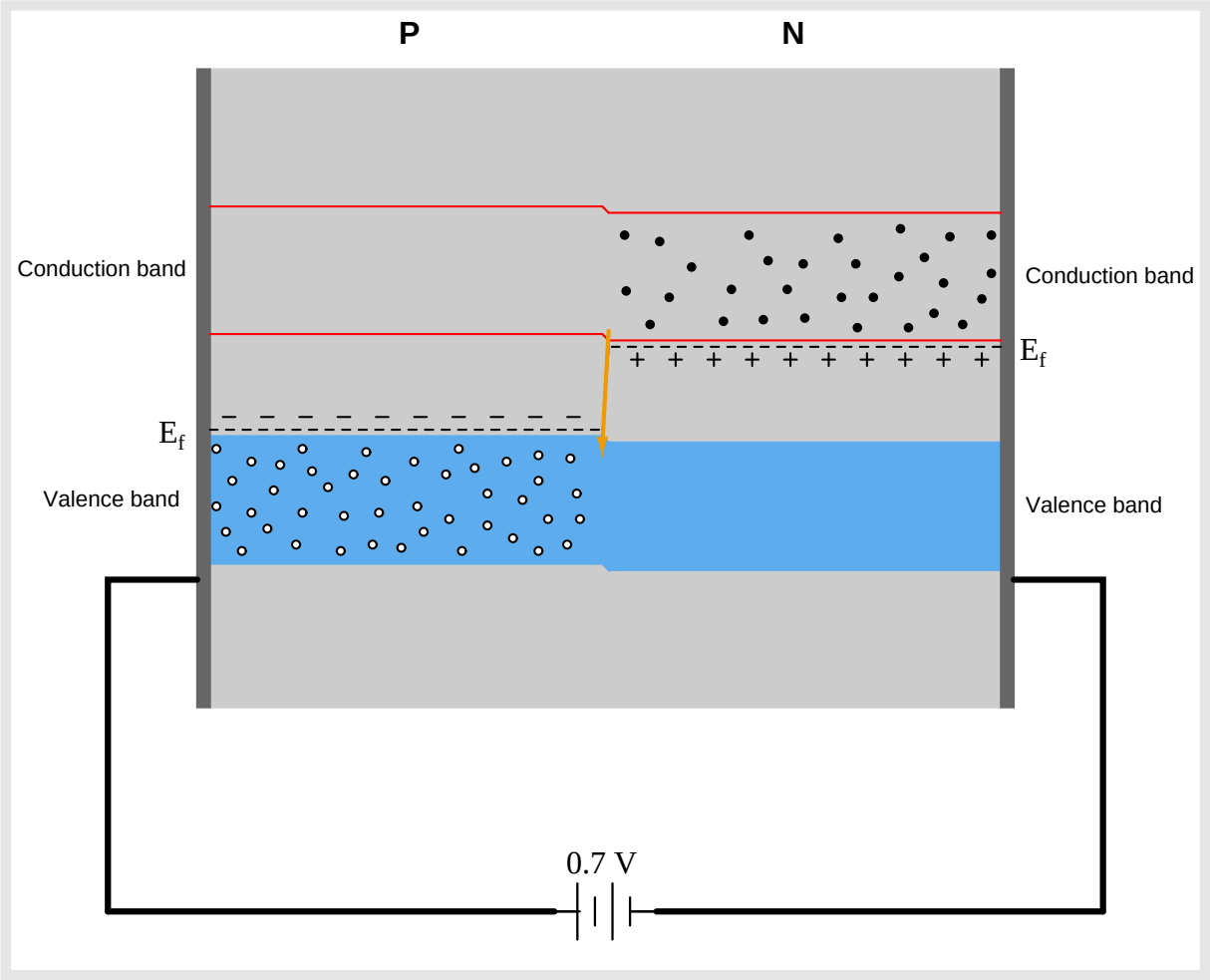

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.4 V

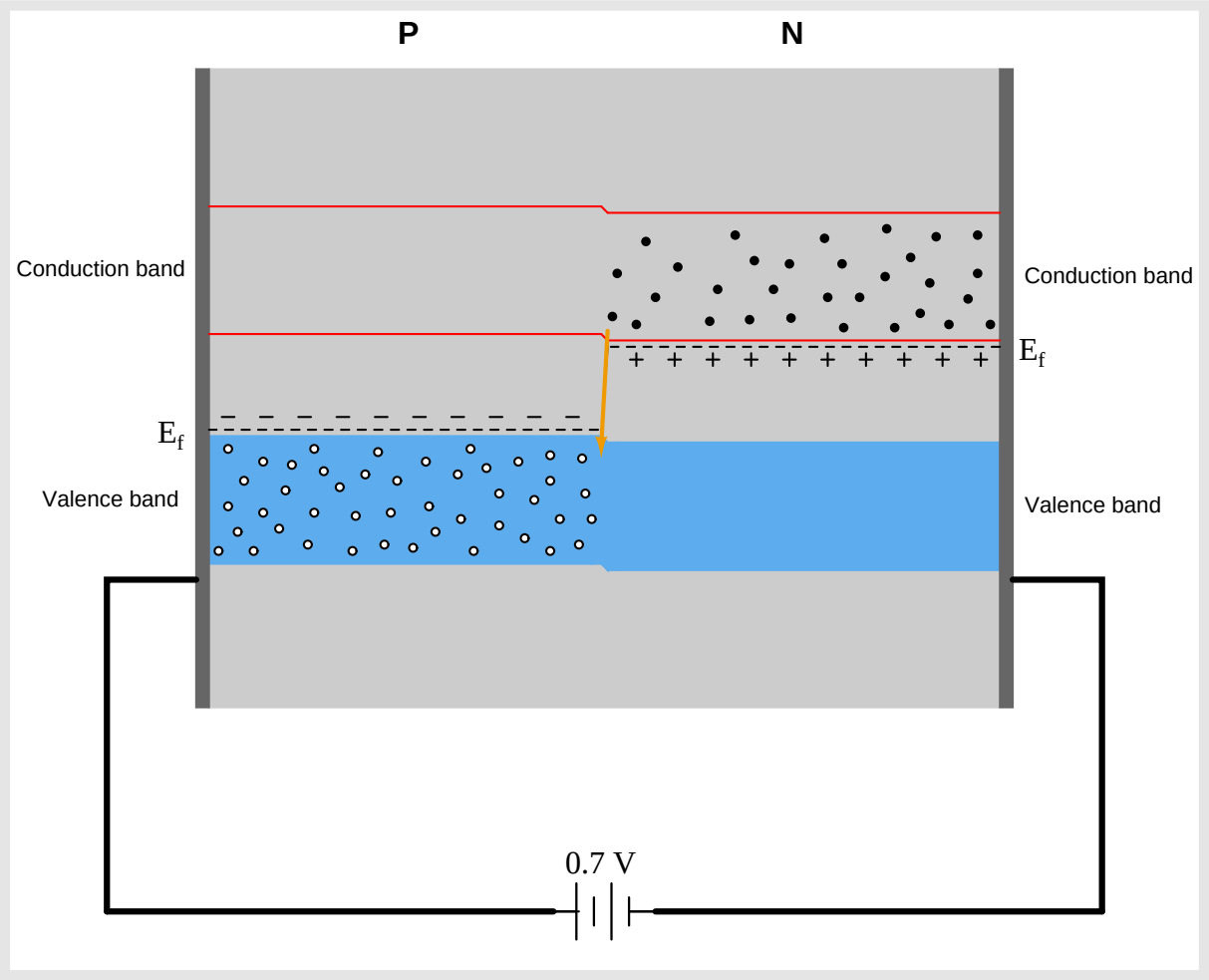

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.5 V

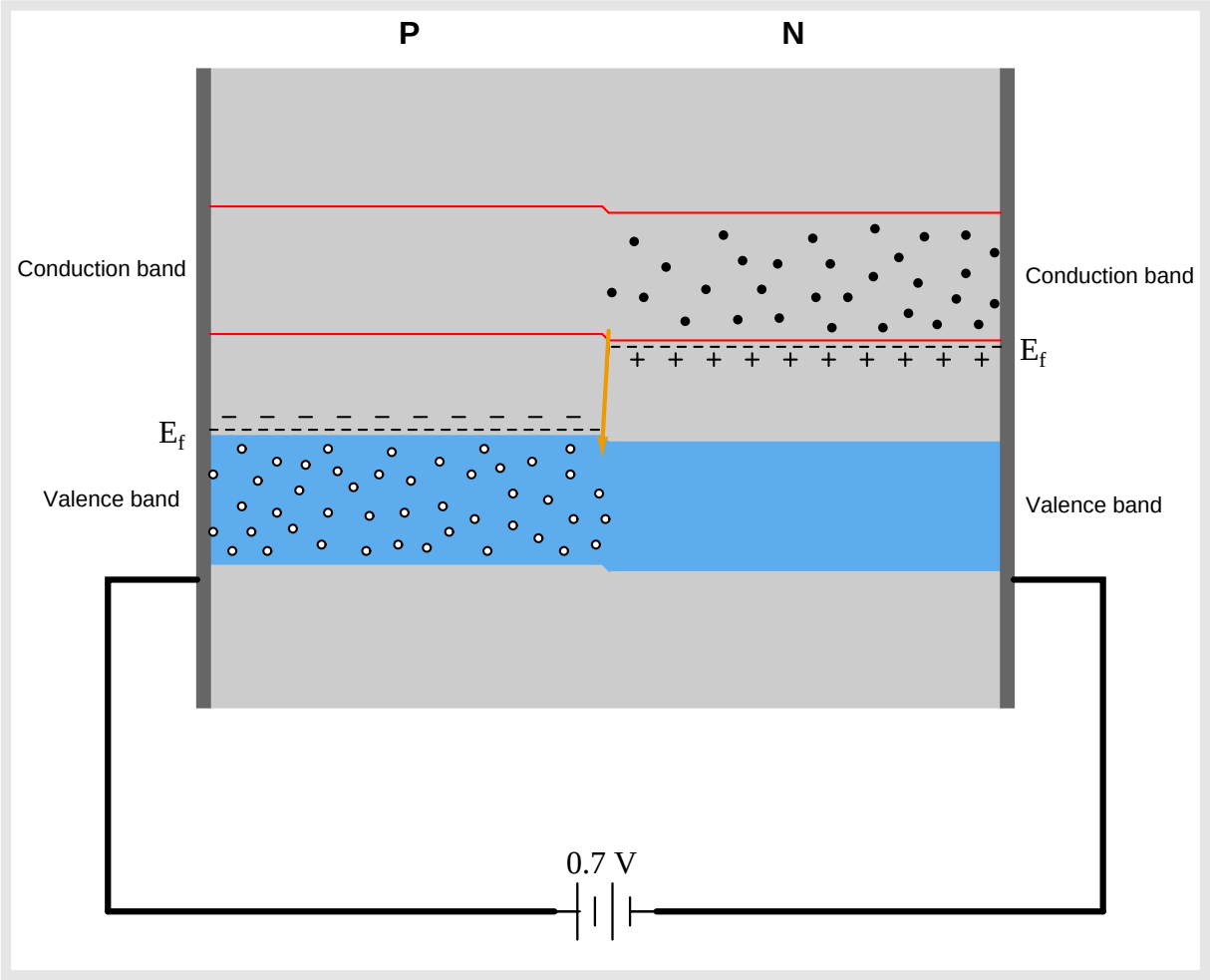

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.5 V

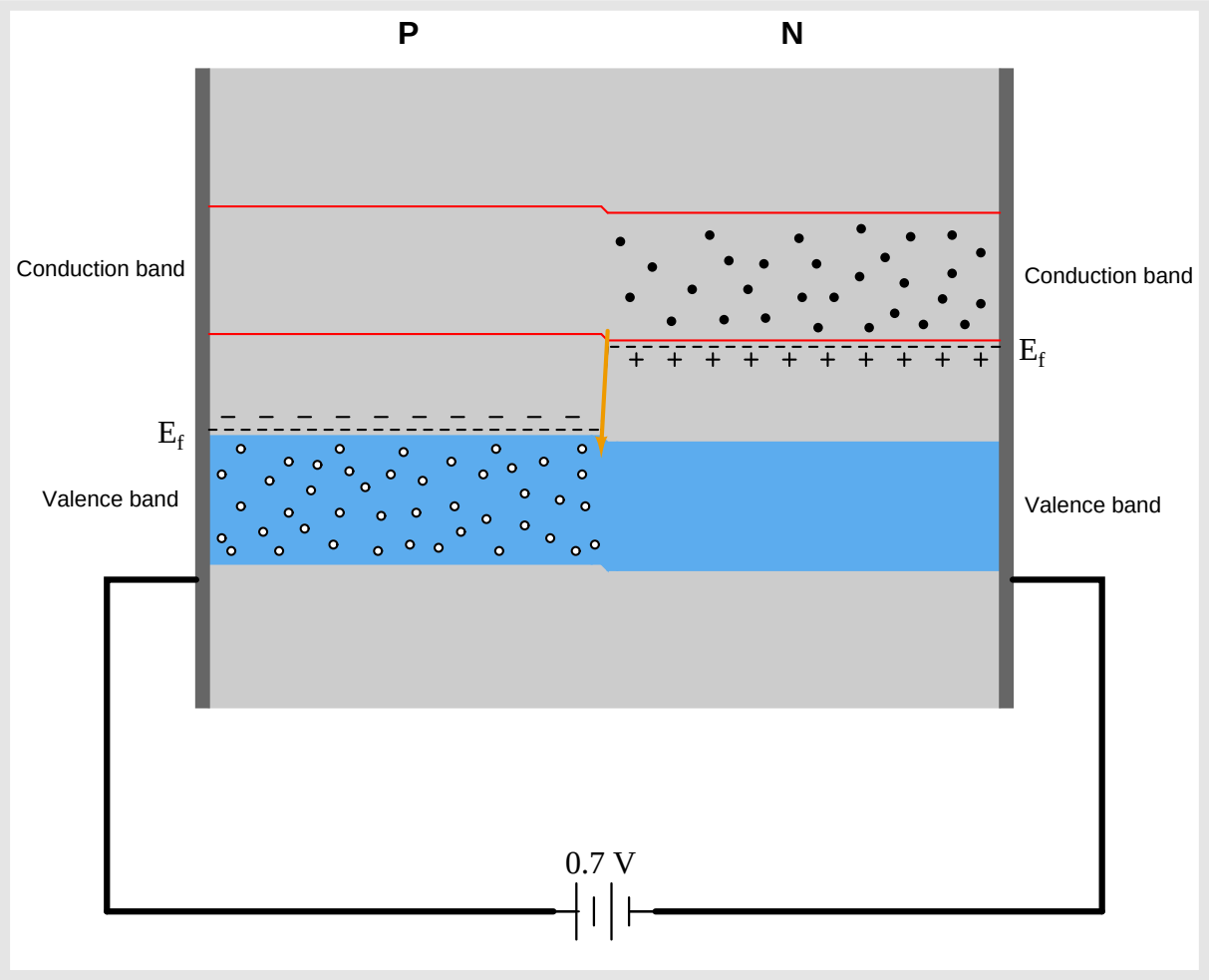

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.6 V

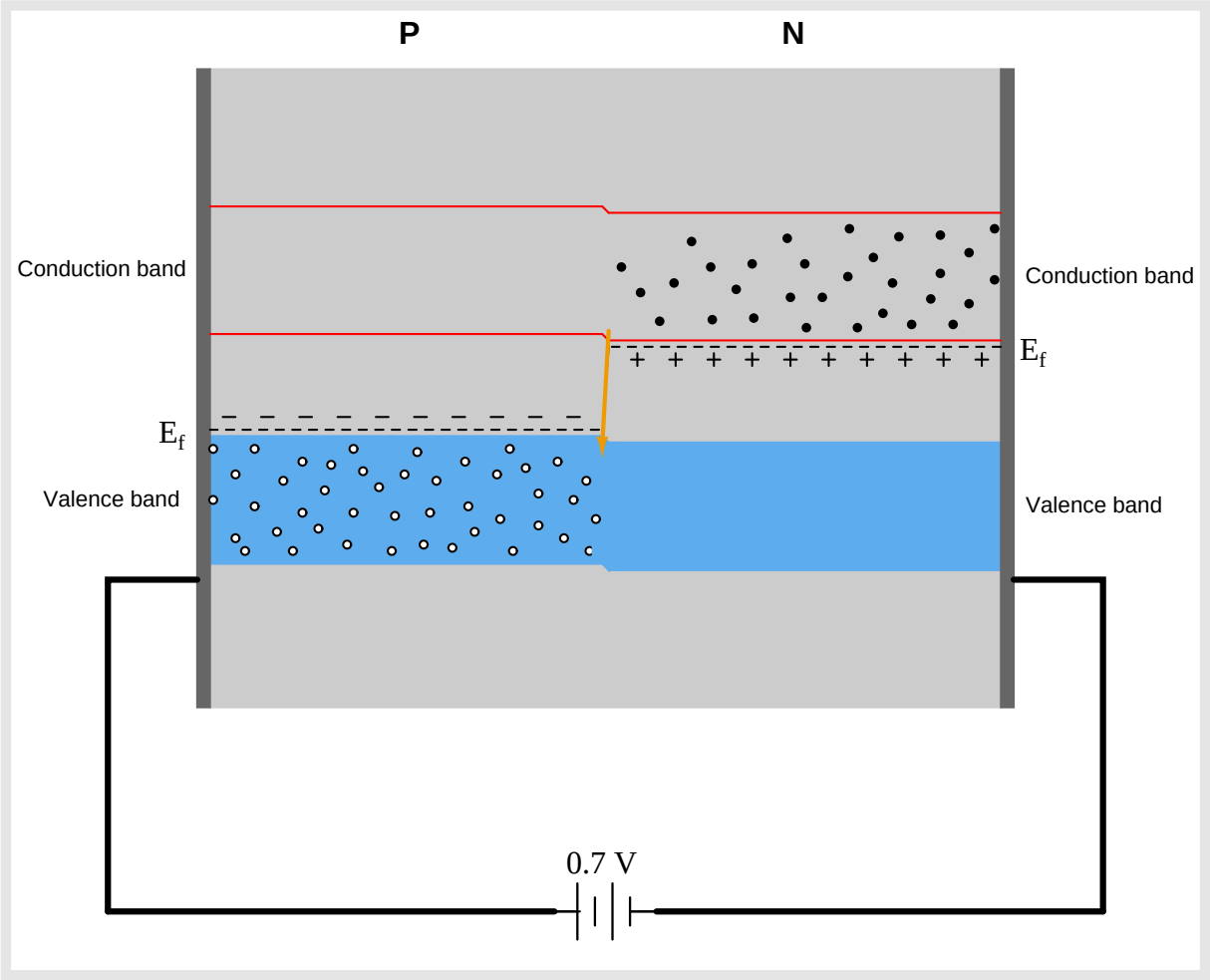

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.6 V

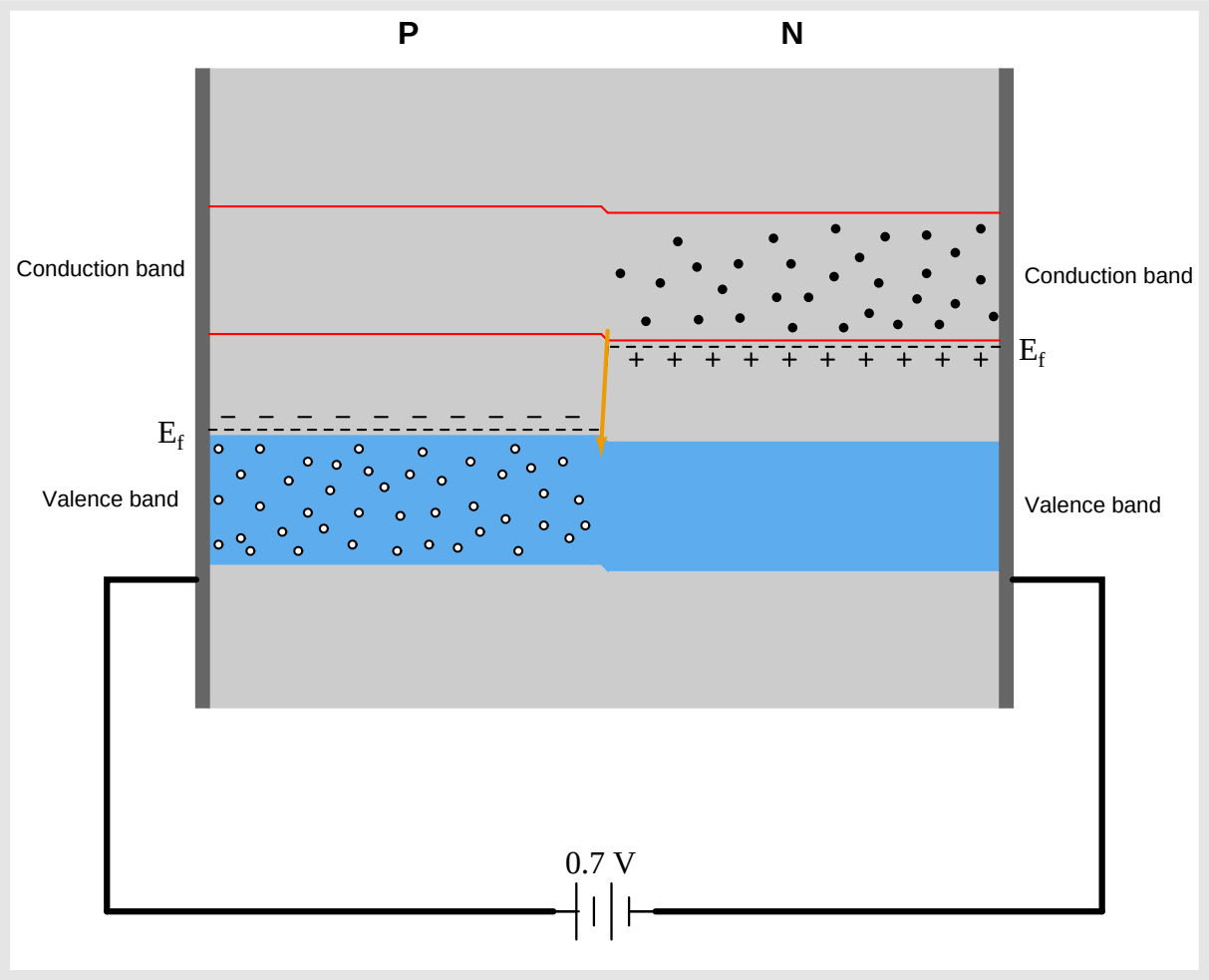

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.7 V

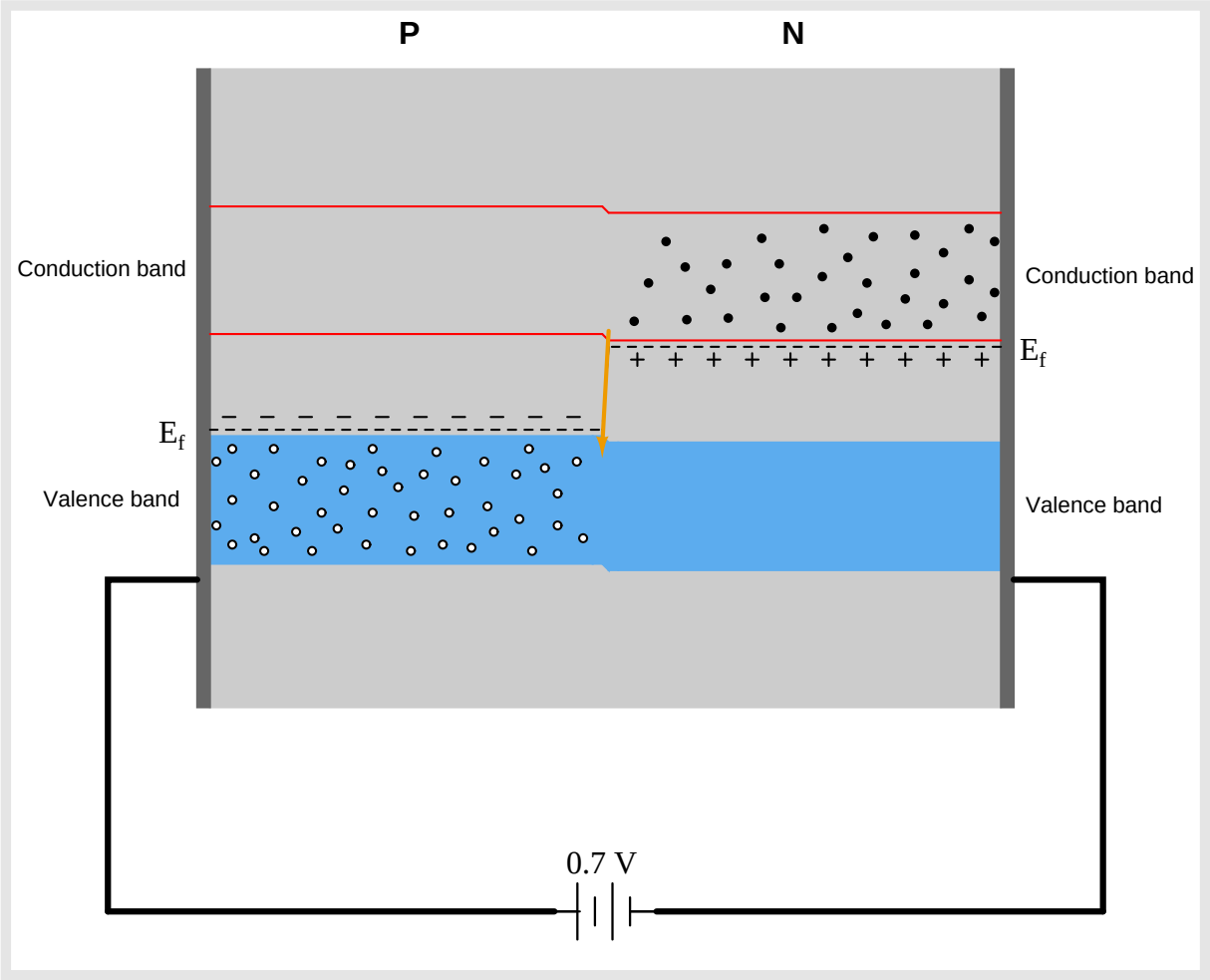

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.7 V

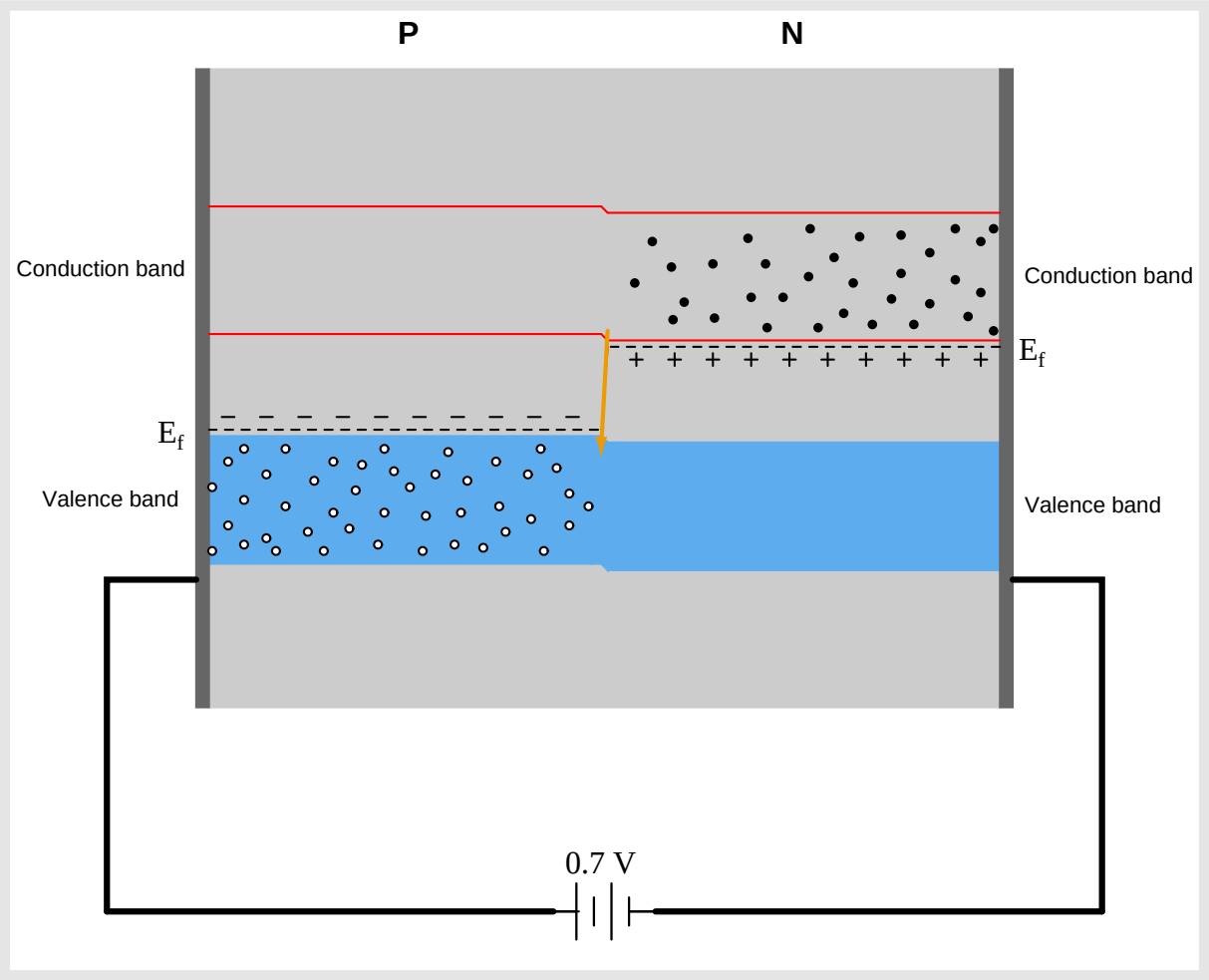

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.7 V

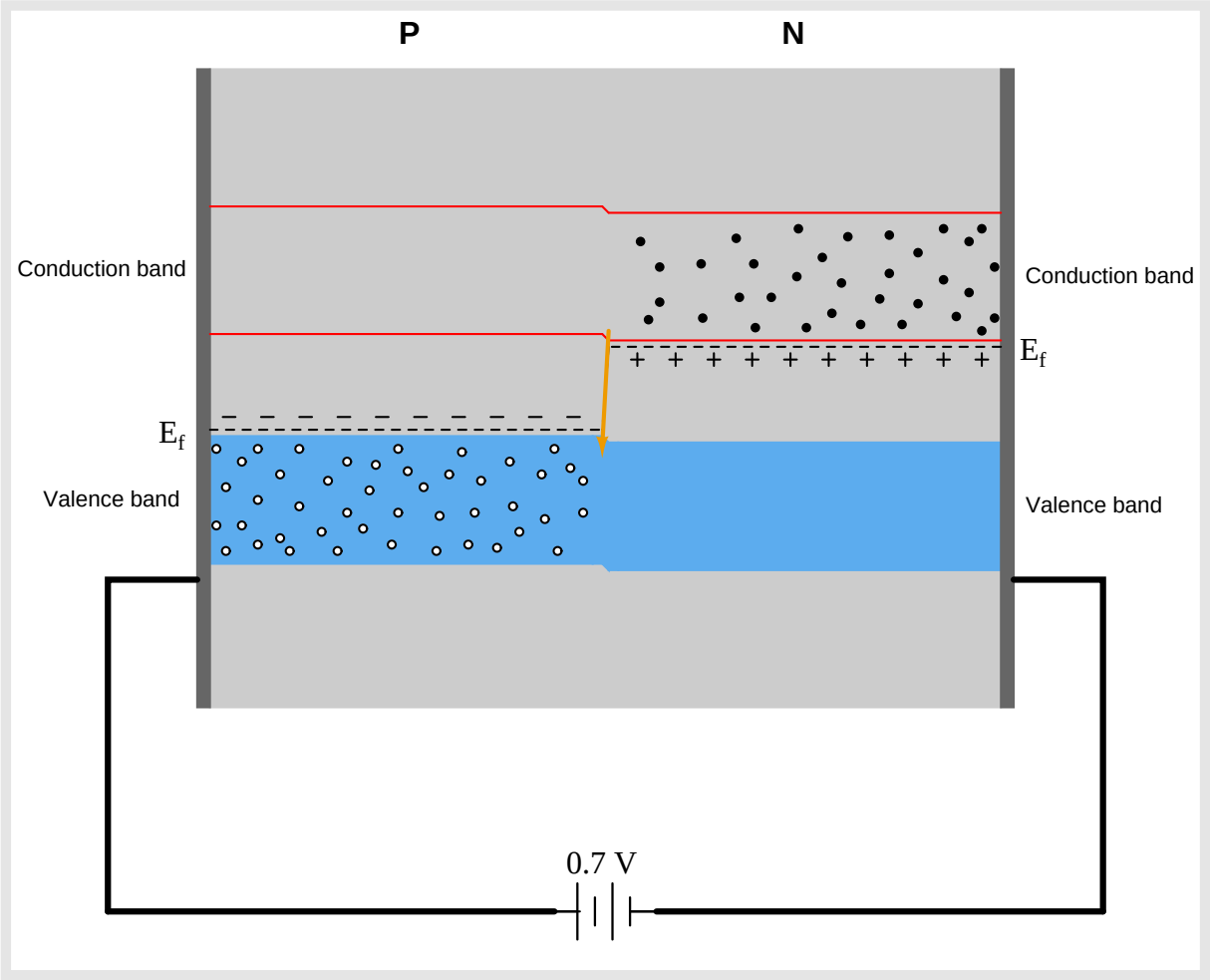

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.7 V

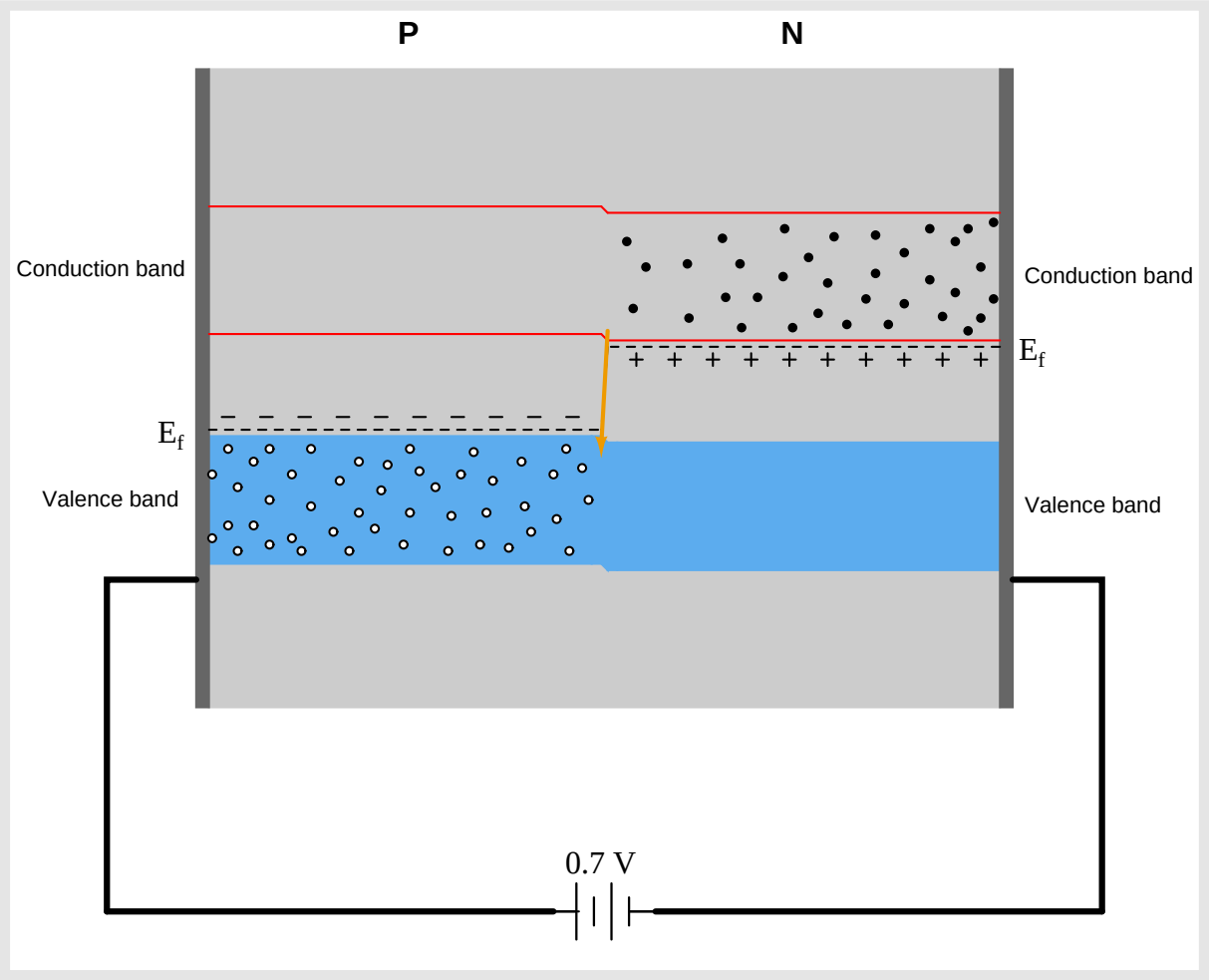

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.7 V


P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.7 V


P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.7 V

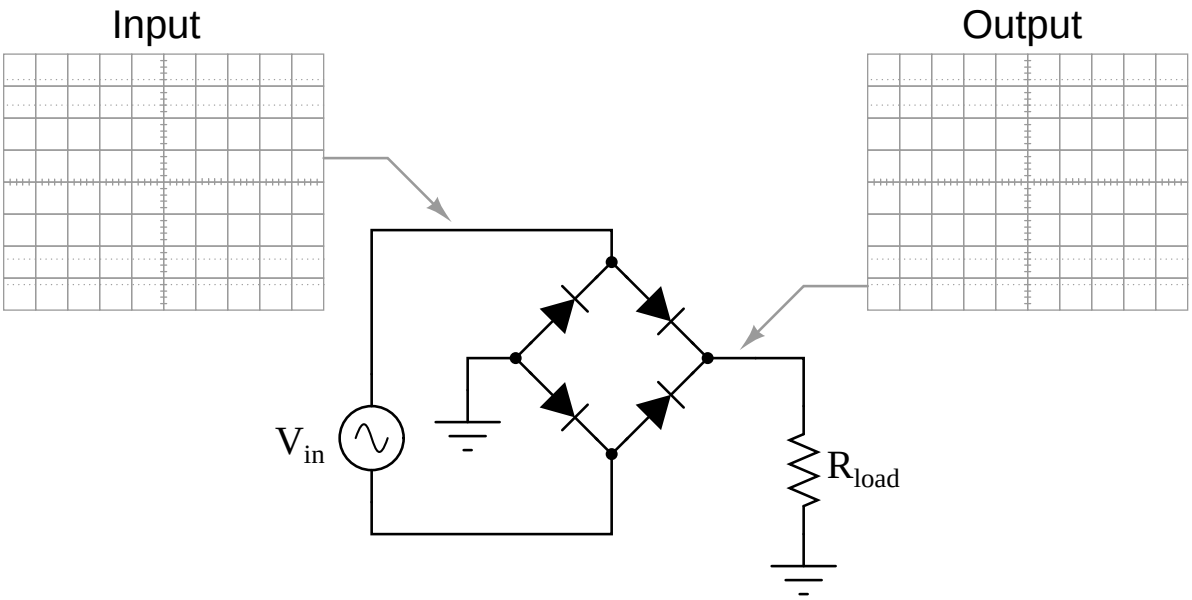

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.7 V

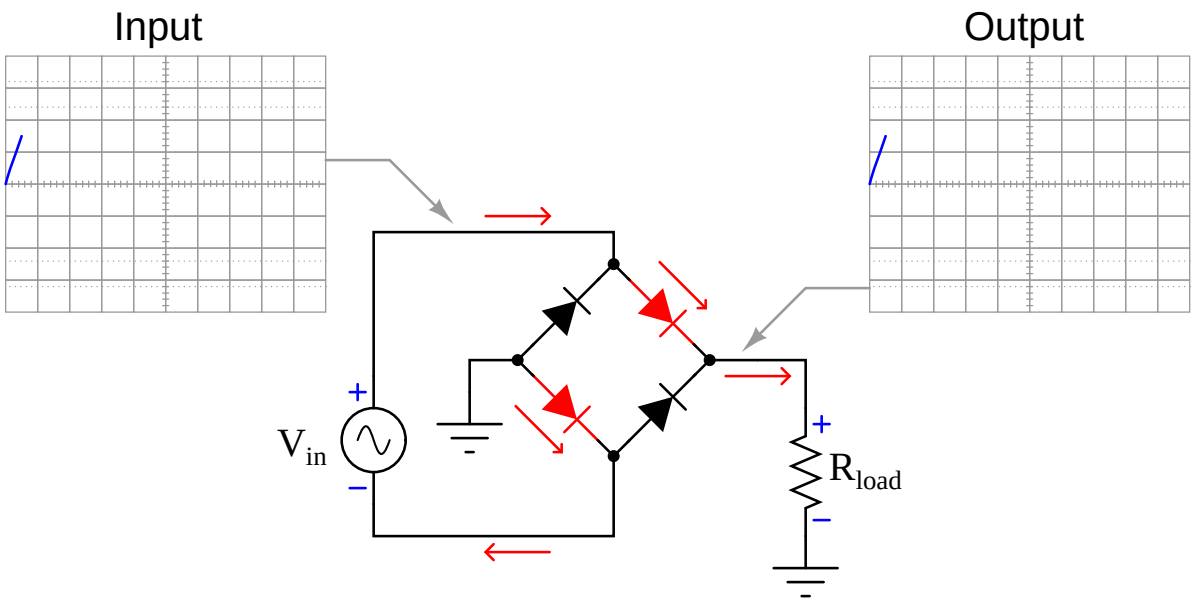

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.7 V

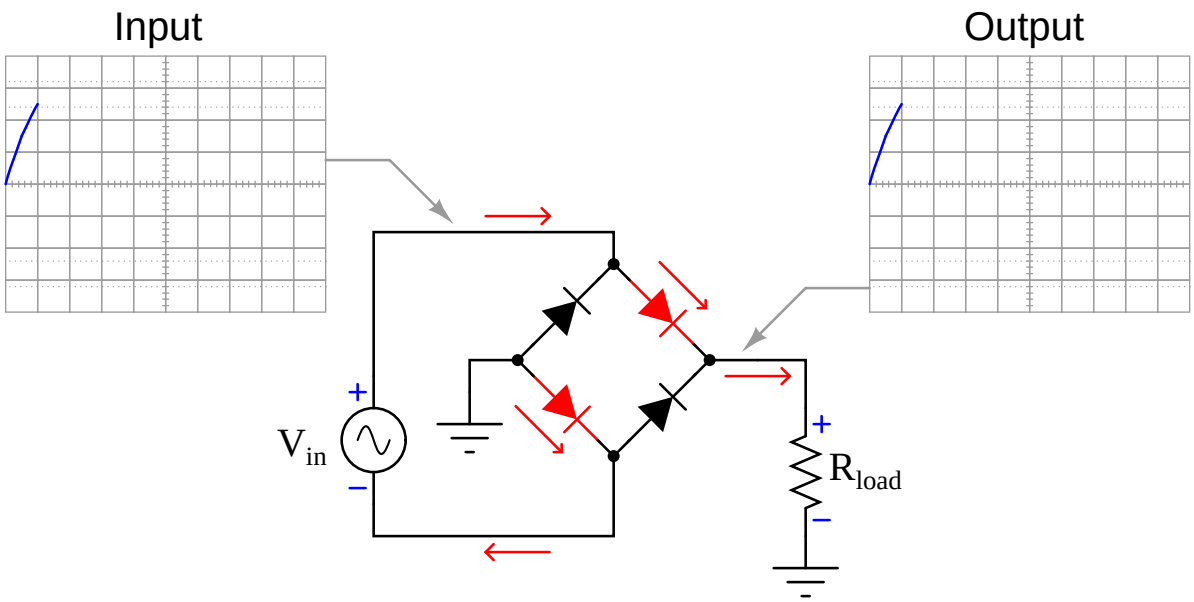

P
N
Conduction band
Conduction band
E_f
E_f
Valence band
Valence band
0.7 V

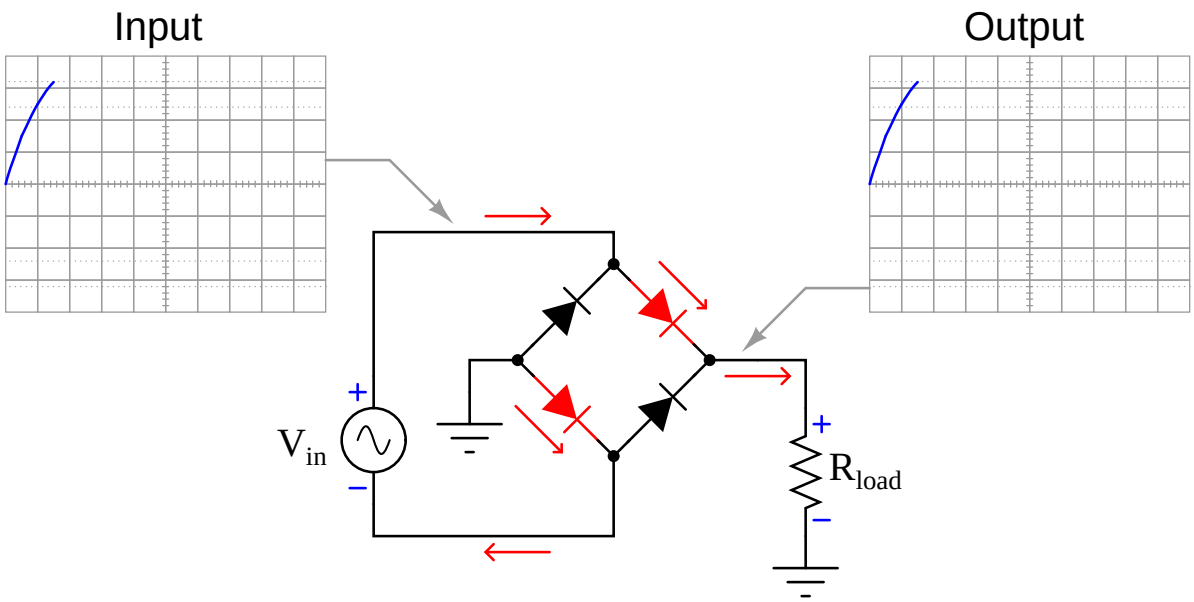
6.2 Full-wave bridge rectifier with ideal diodes

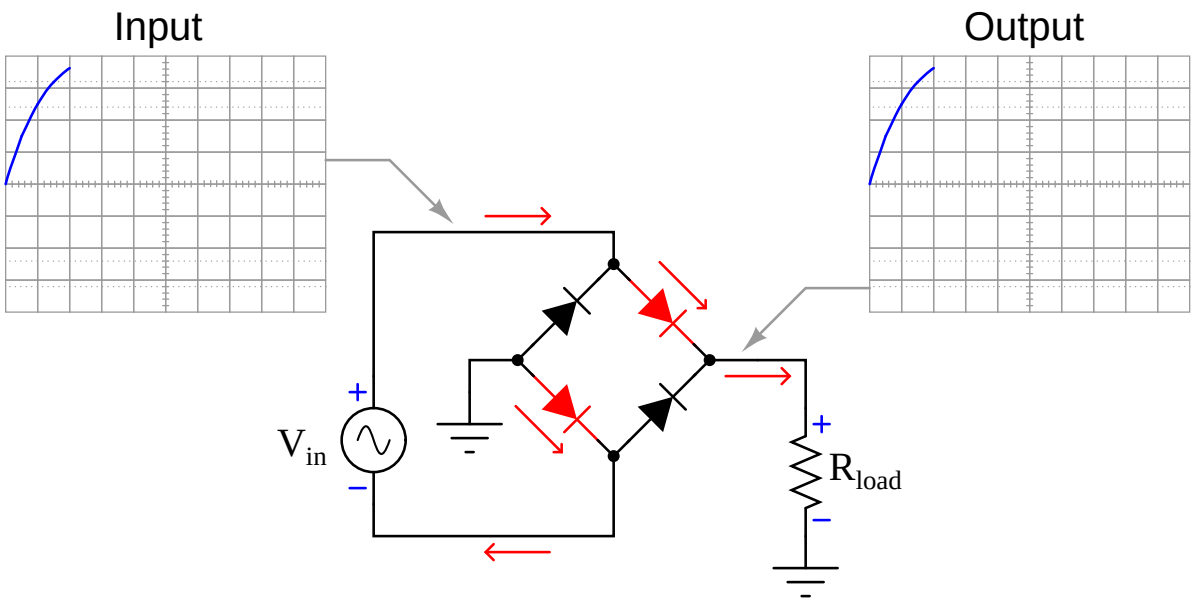
The following animation shows a full-wave, single-phase bridge rectifier using ideal diodes (with no forward voltage drop). Oscillographs show the input (AC) and output (rectified DC) of the rectifier circuit, with forward-biased diodes colored red.

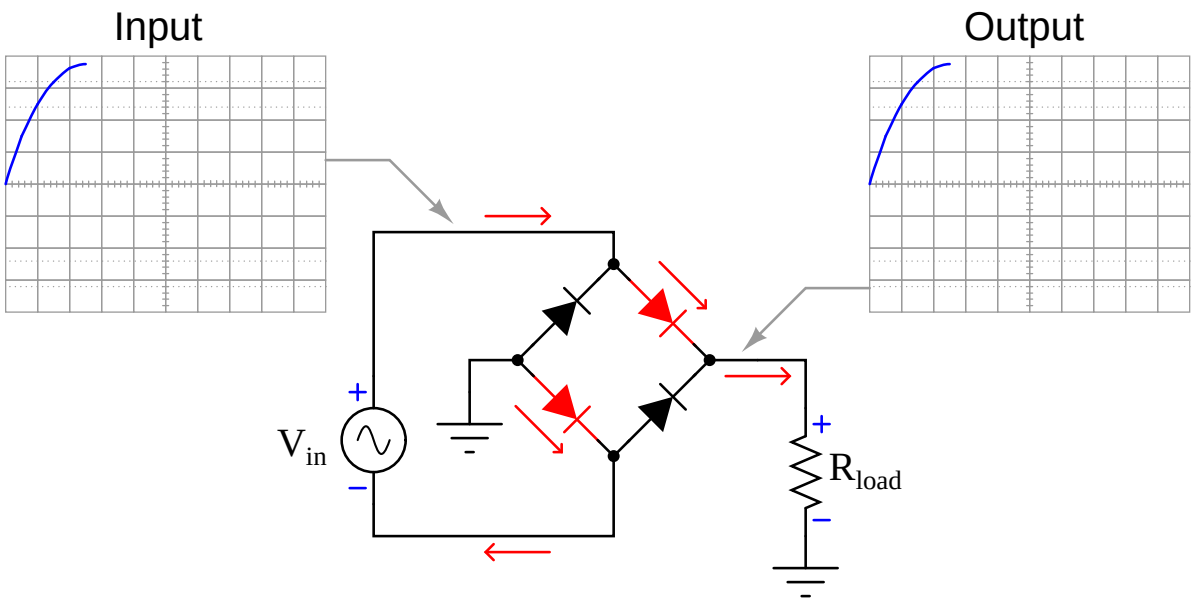

Input
Output
V_{in}
R_{load}

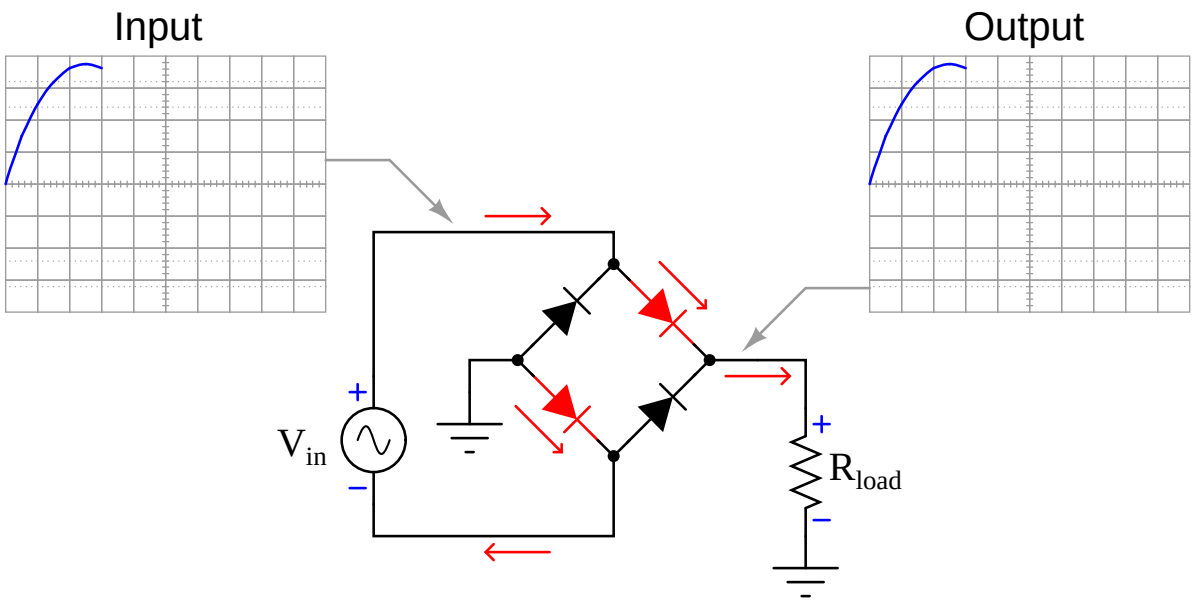

Input
Output
+
V_{in}
−
+
R_{load}
−

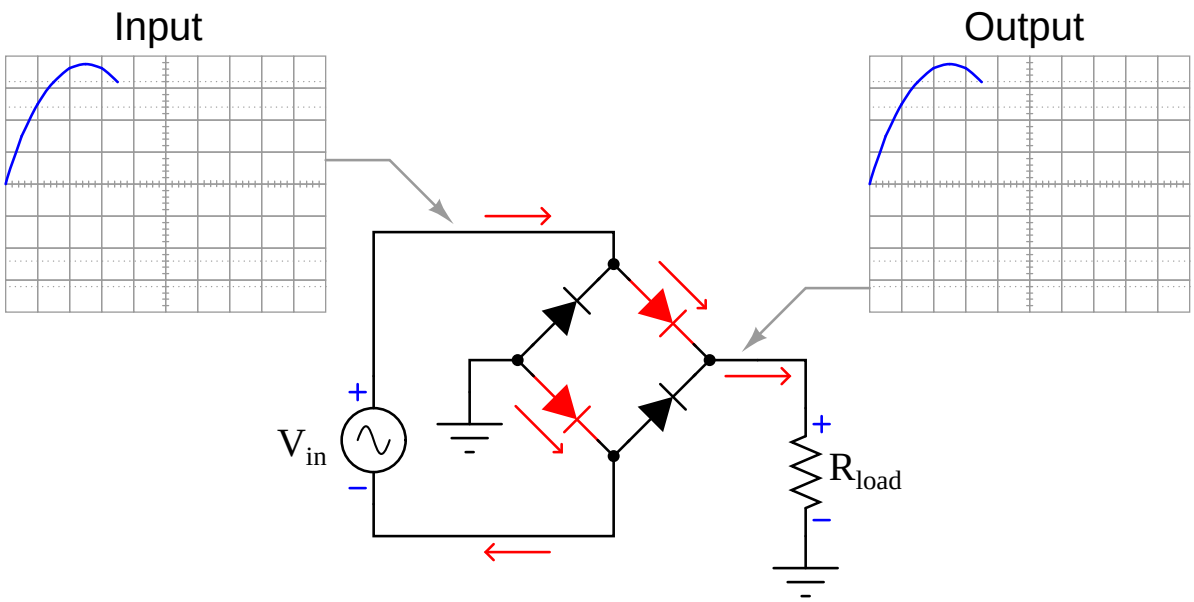

Input
Output
+
V_{in}
−
+
R_{load}
−

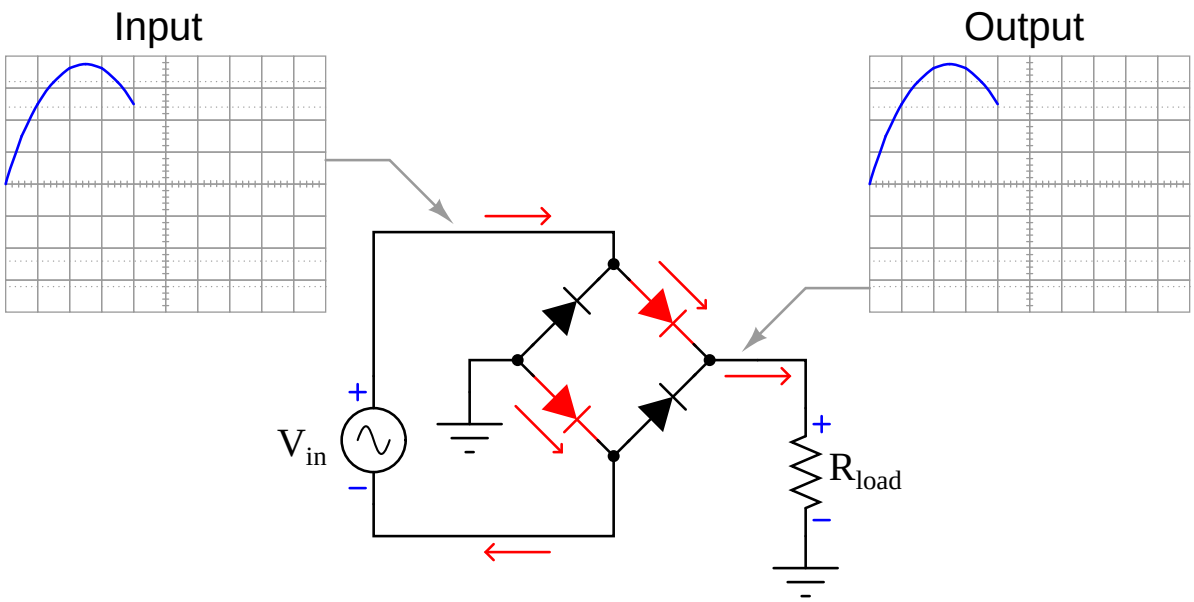

Input
Output
+
V_{in}
−
+
R_{load}
−

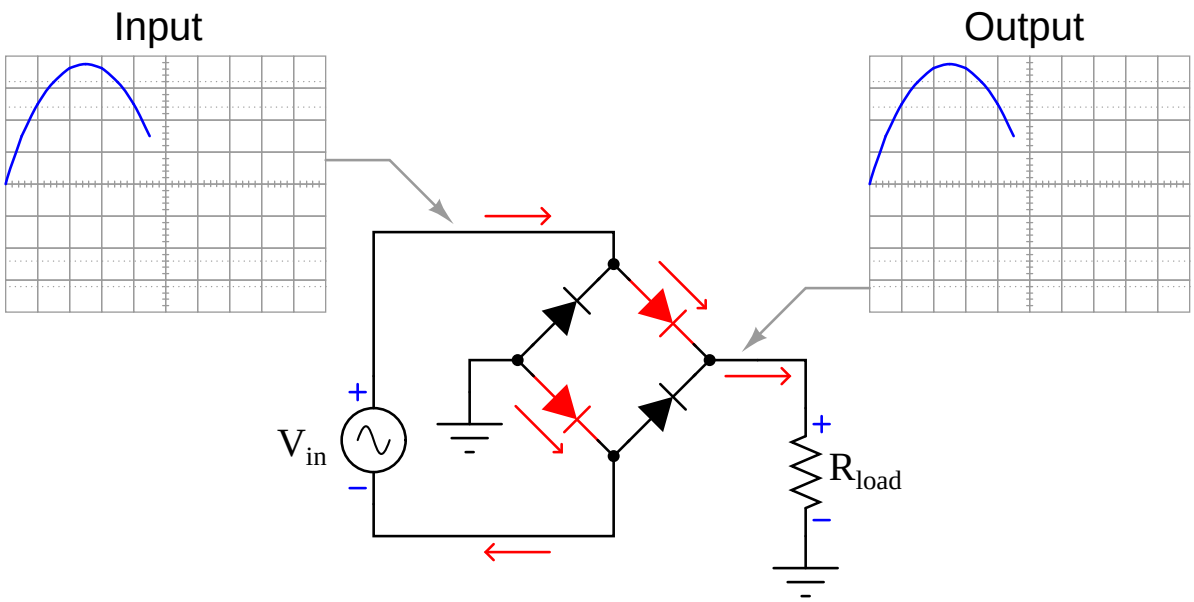

Input
Output
+
V_{in}
−
+
R_{load}
−

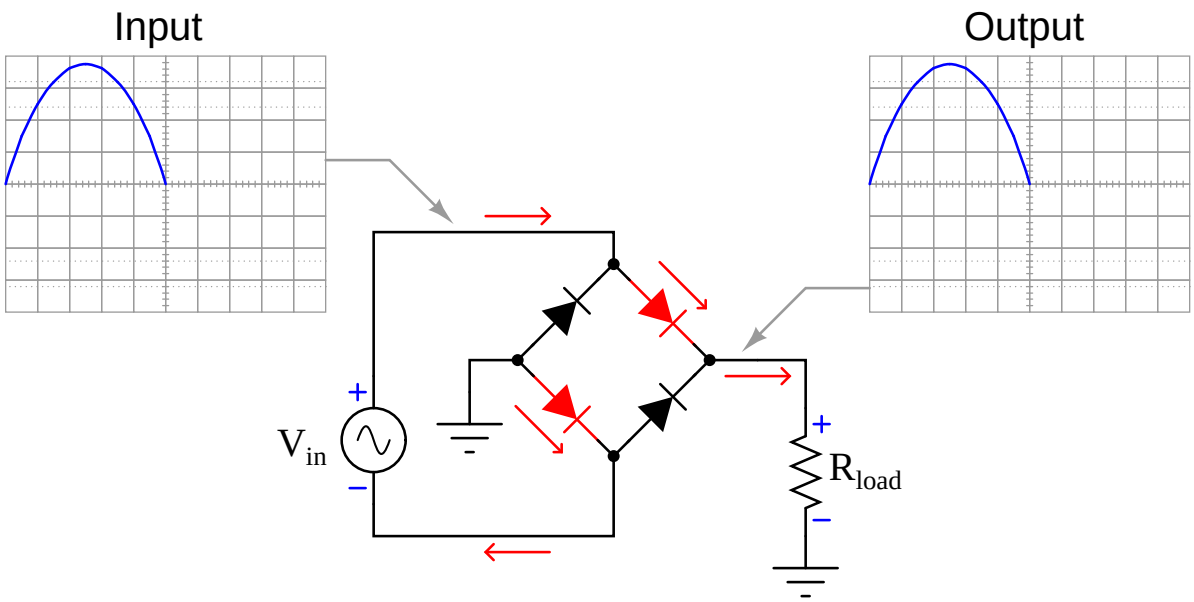

Input
Output
+
V_{in}
−
+
R_{load}
−

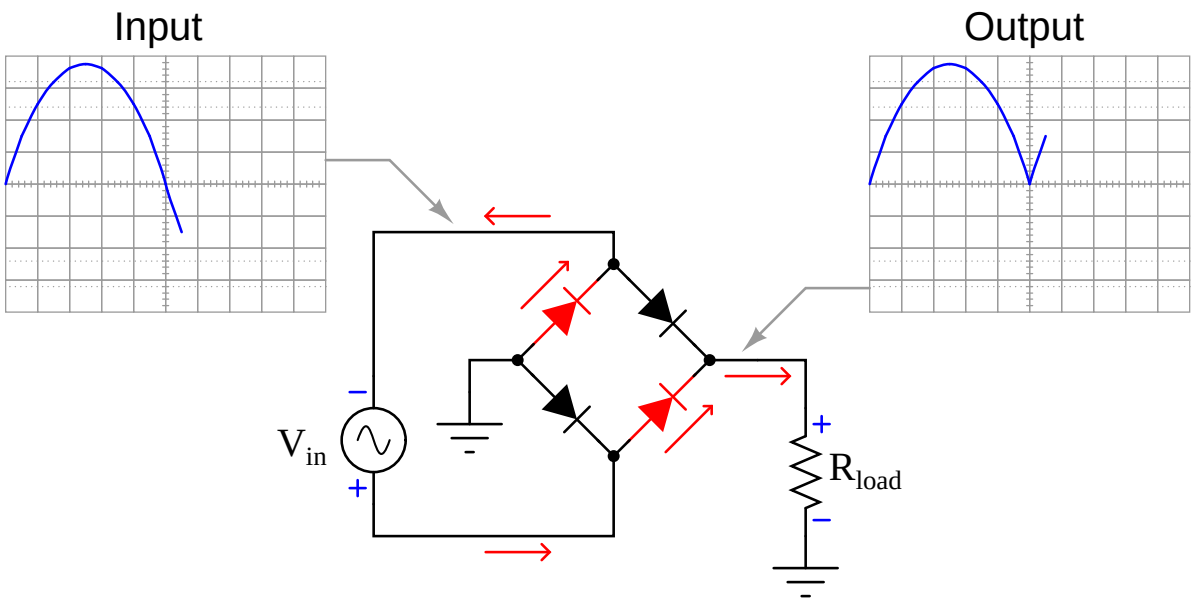

Input
Output
+
V_{in}
−
+
R_{load}
−

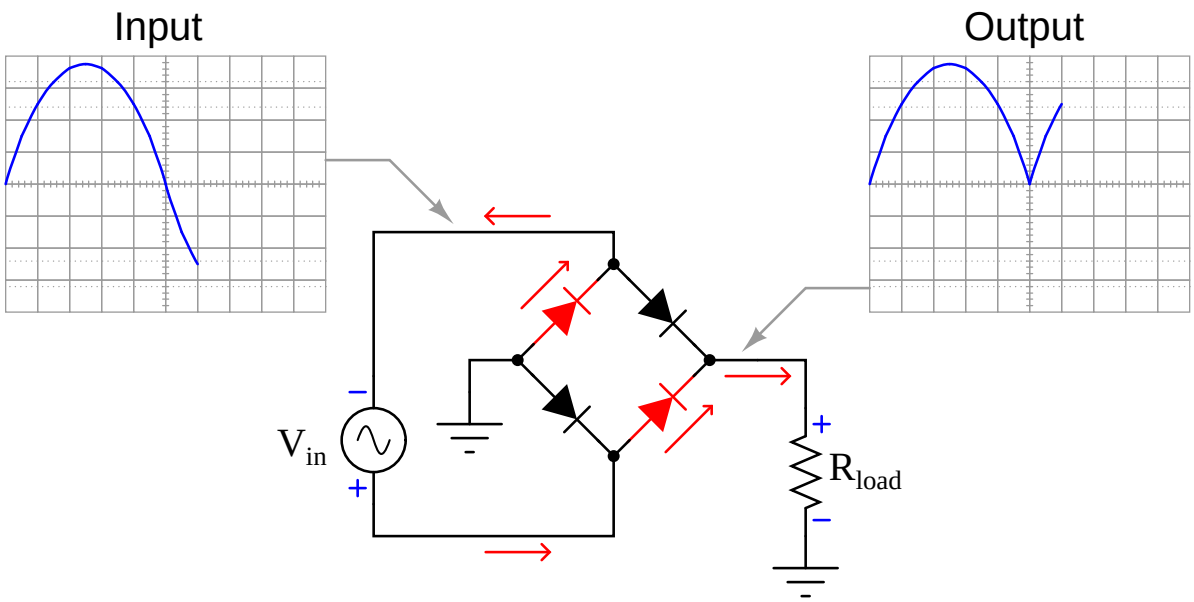

Input
Output
+
V_{in}
−
+
R_{load}
−

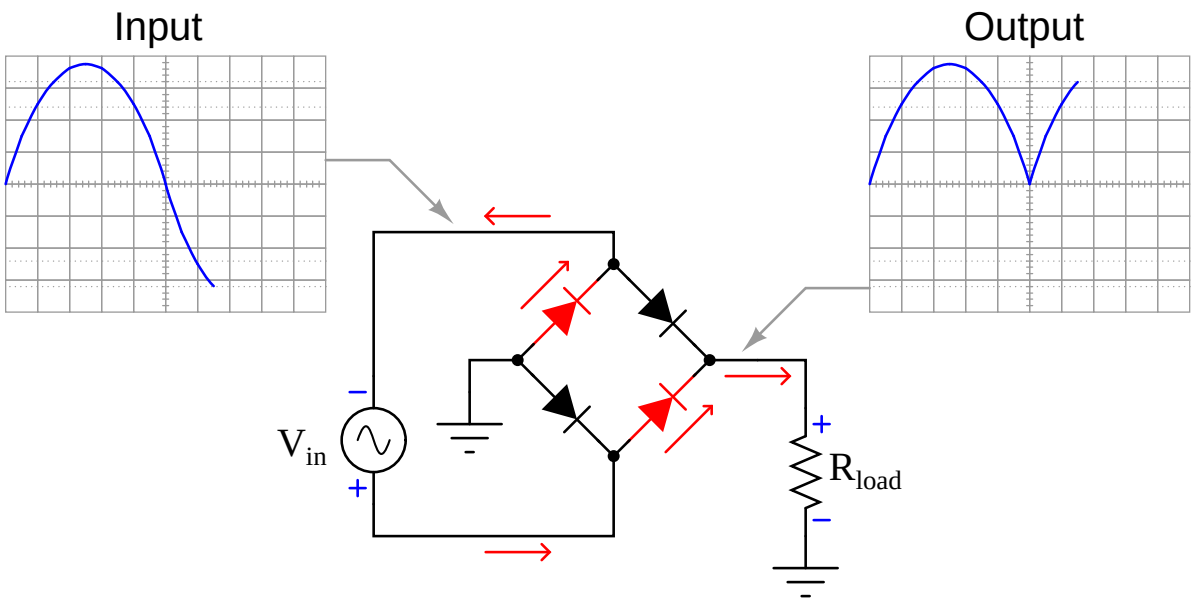

Input
Output
+
V_{in}
−
+
R_{load}
−

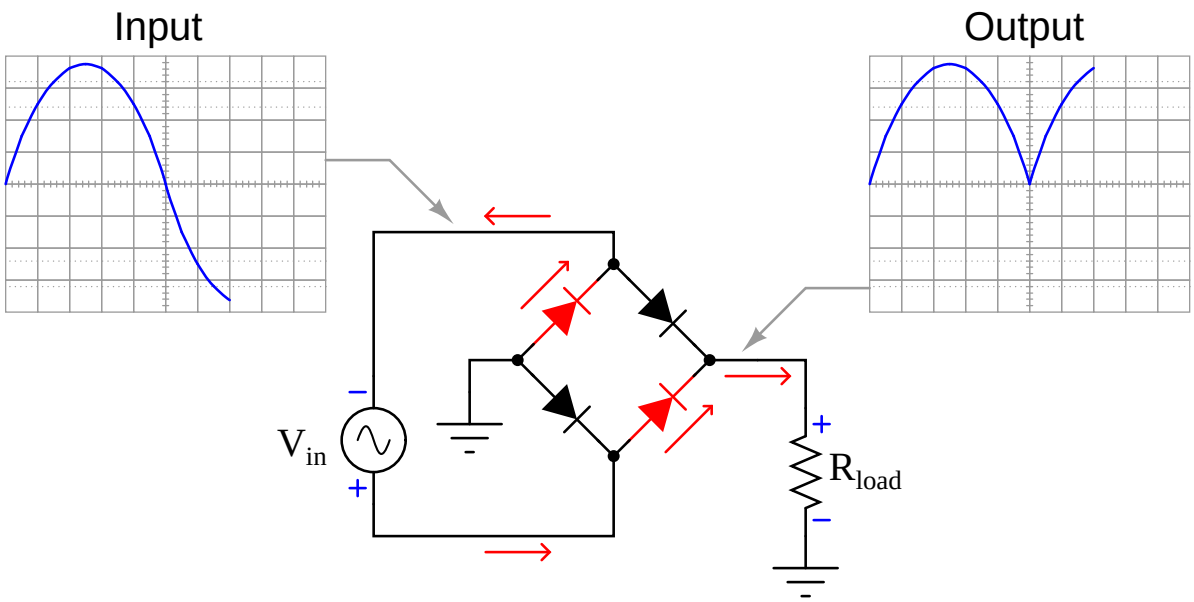

Input
Output
+
V_{in}
−
+
R_{load}
−

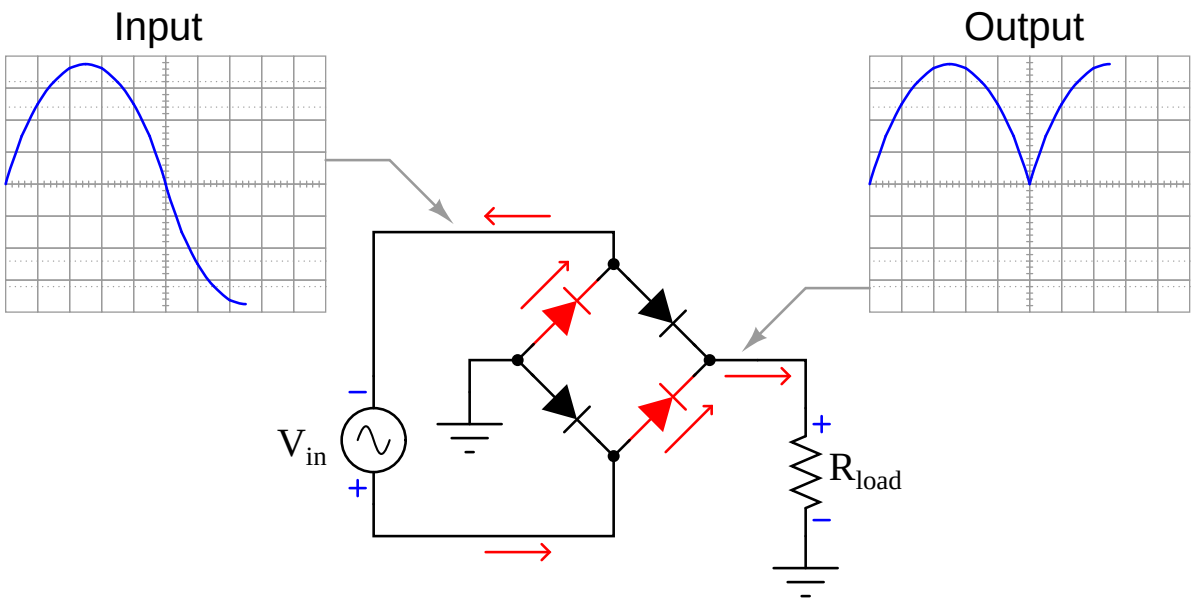

Input
Output
+
V_{in}
−
+
R_{load}
−

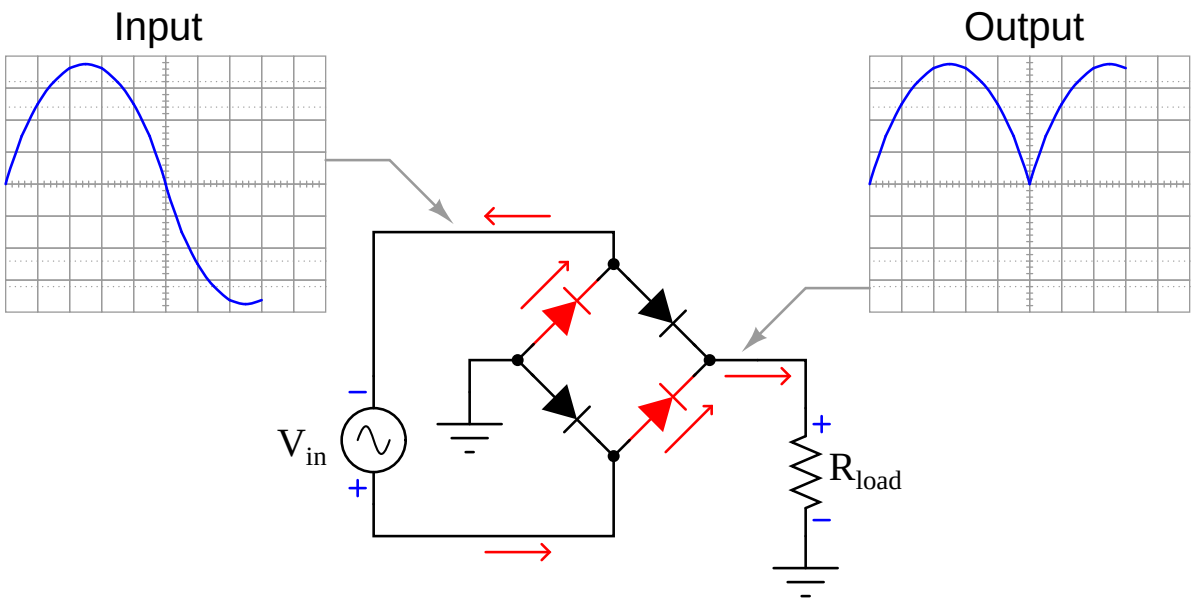

Input
Output
V in
R load

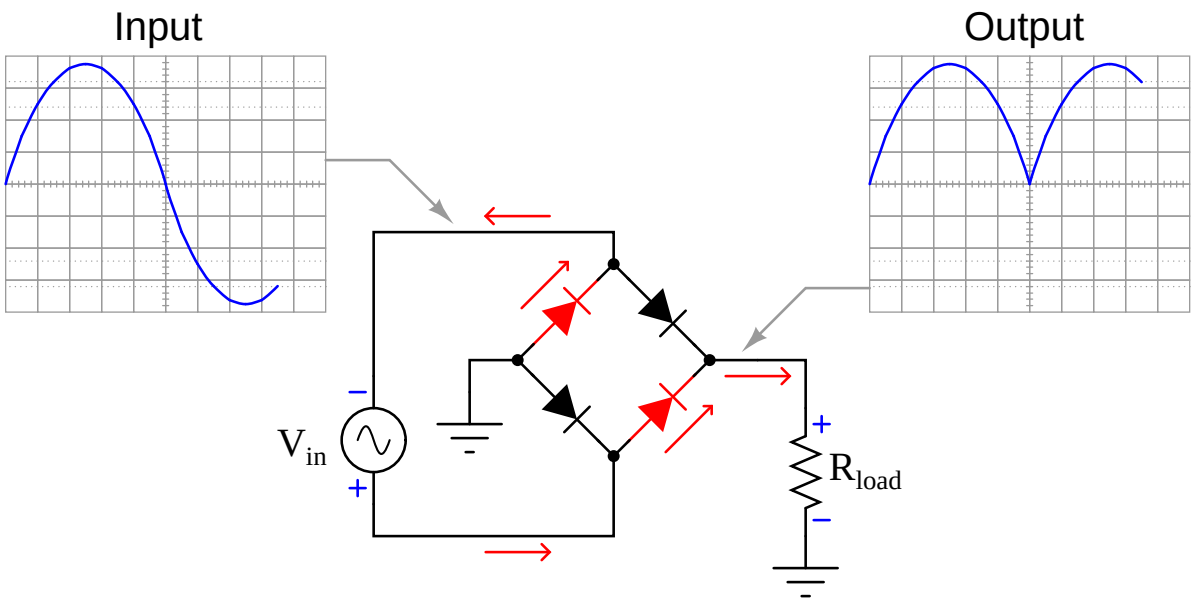

Input
Output
V in
R load

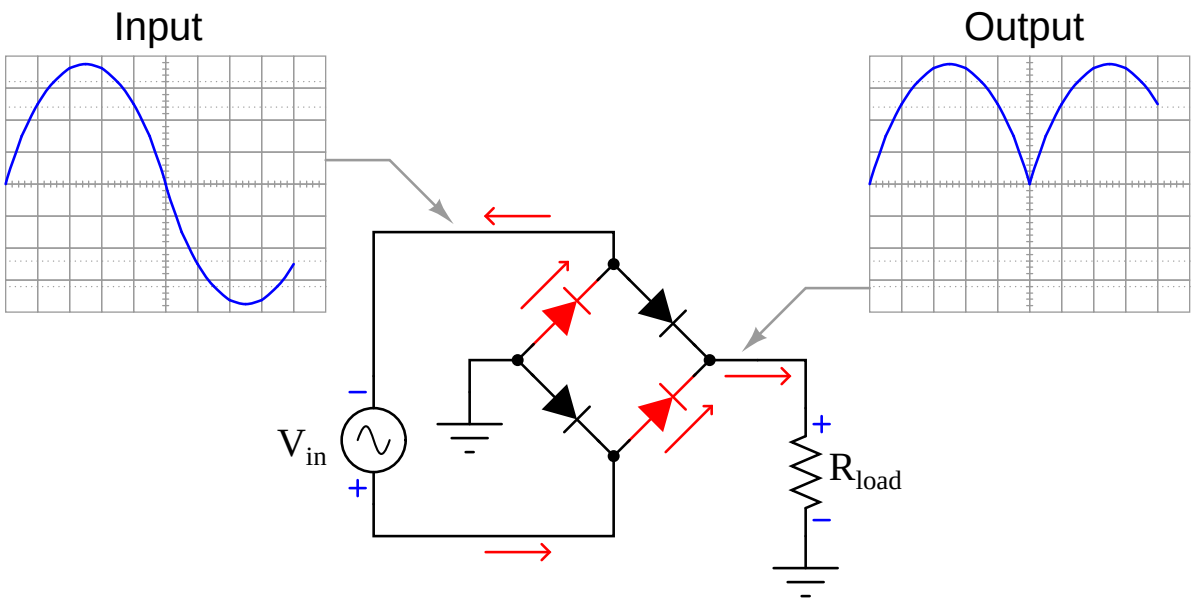

Input
Output
V in
R load

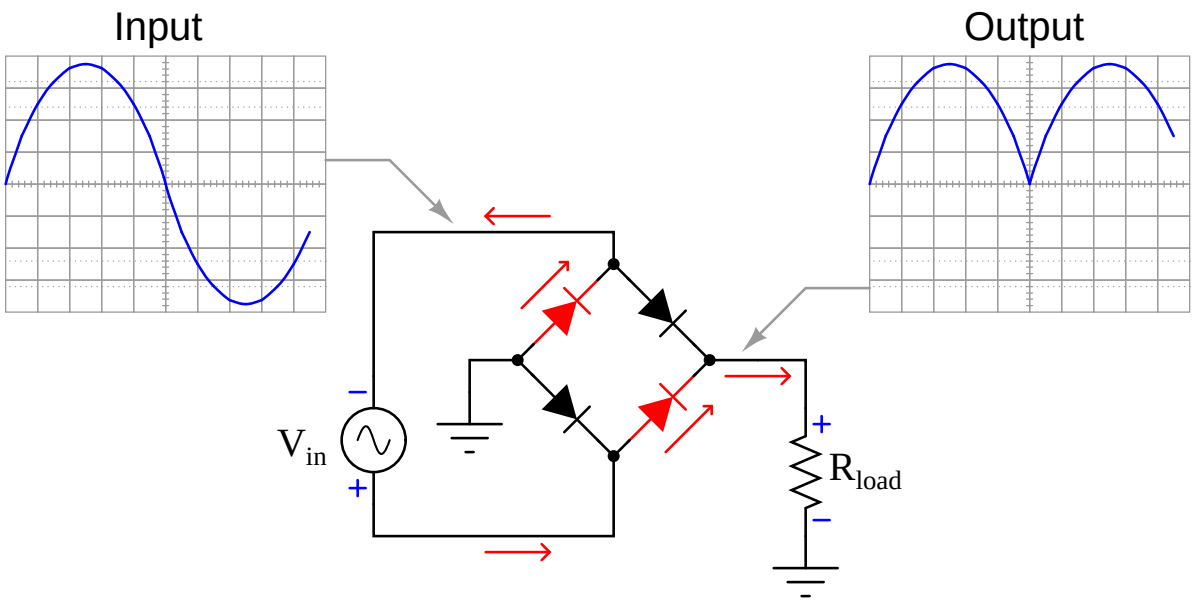

Input
Output
V in
R load

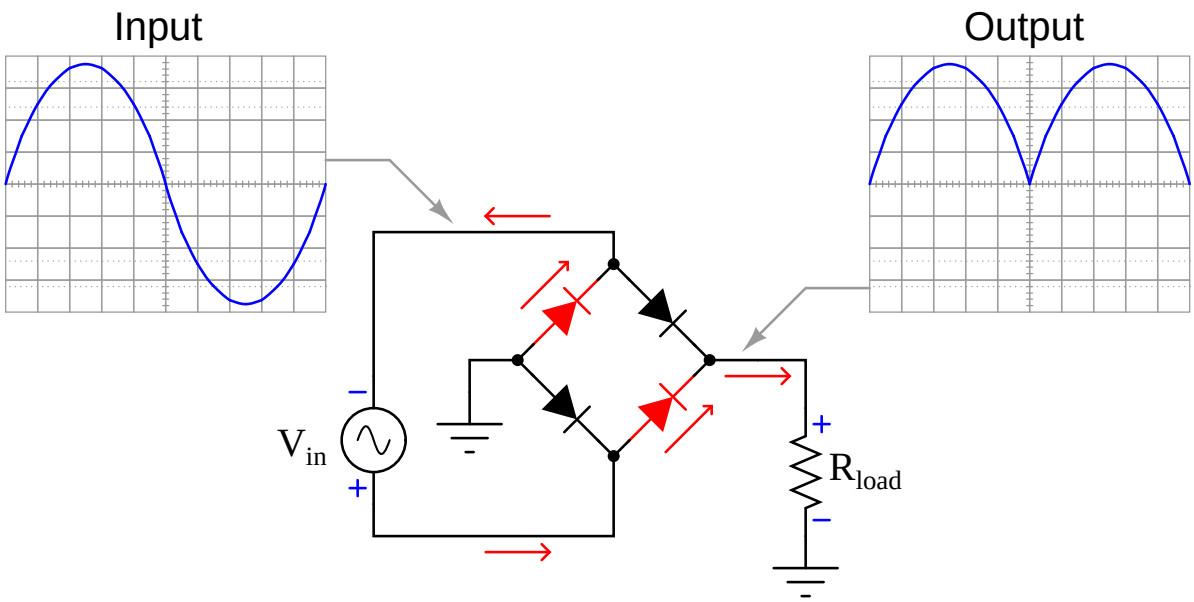

Input
Output
V in
R load


Input
Output
V in
R load


Input
Output
V in
R load

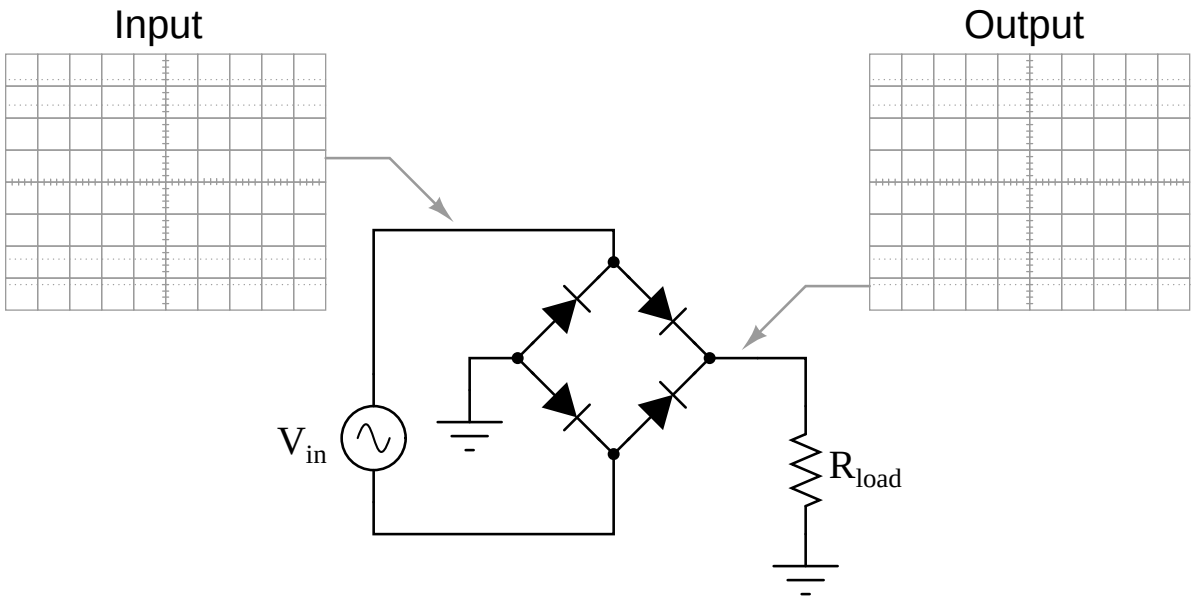

Input
Output
V in
R load

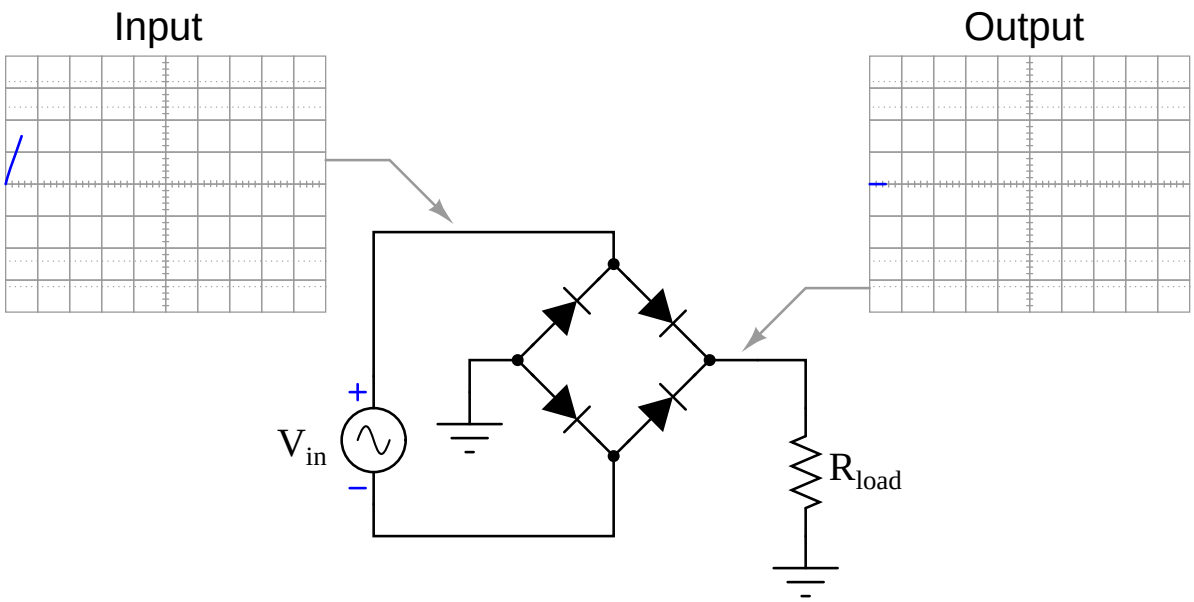

Input
Output
V in
R load

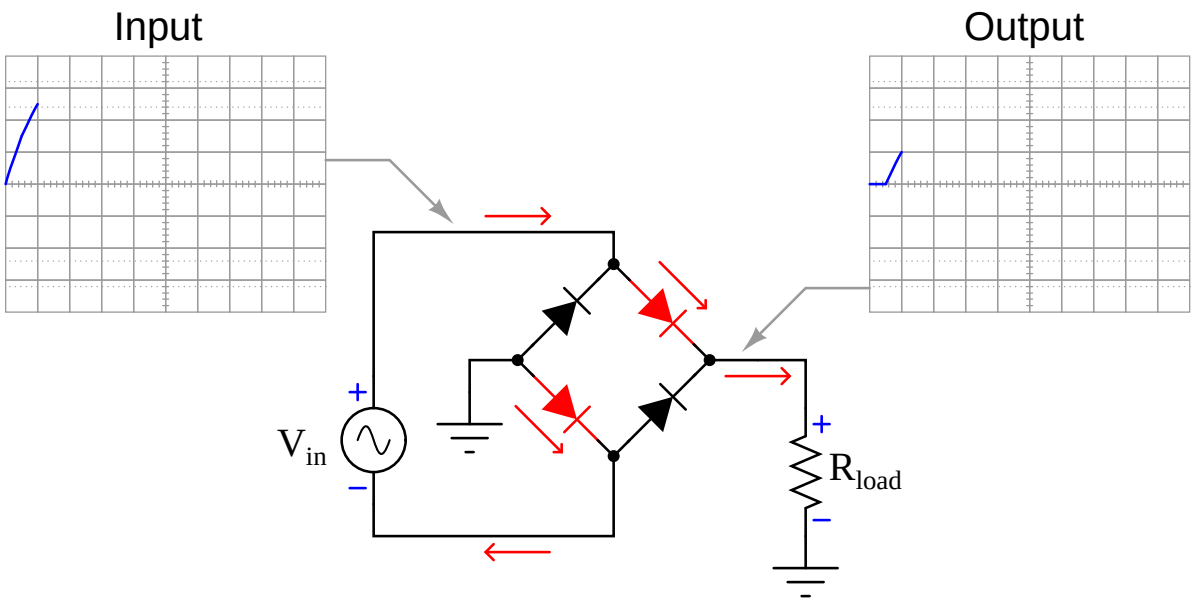

Input
Output
V in
R load

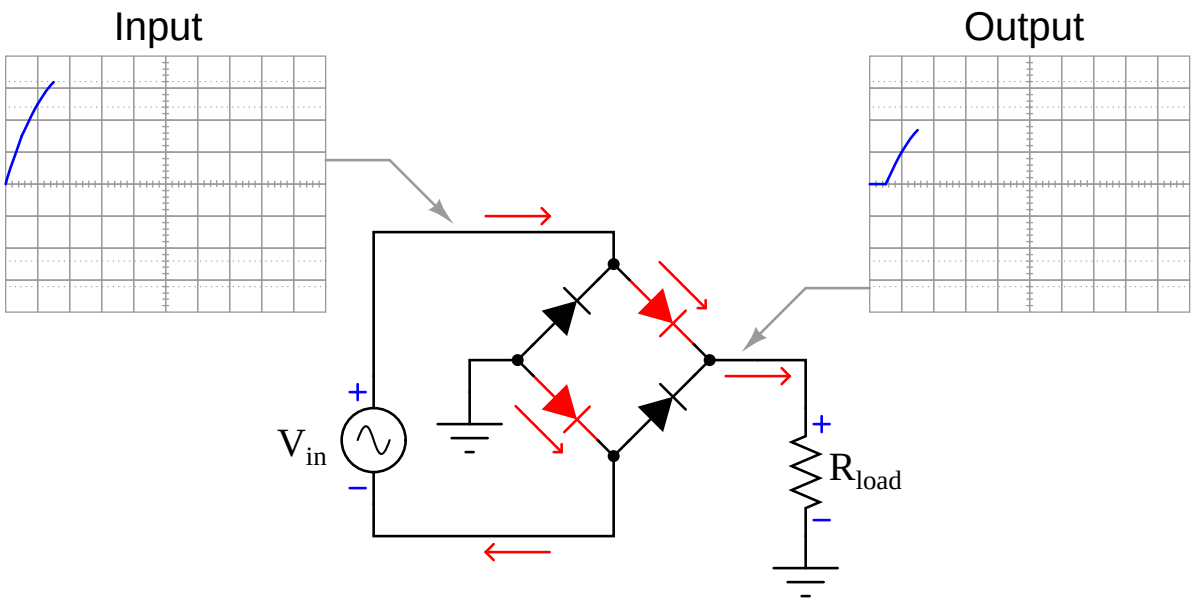
6.3 Full-wave bridge rectifier with real diodes

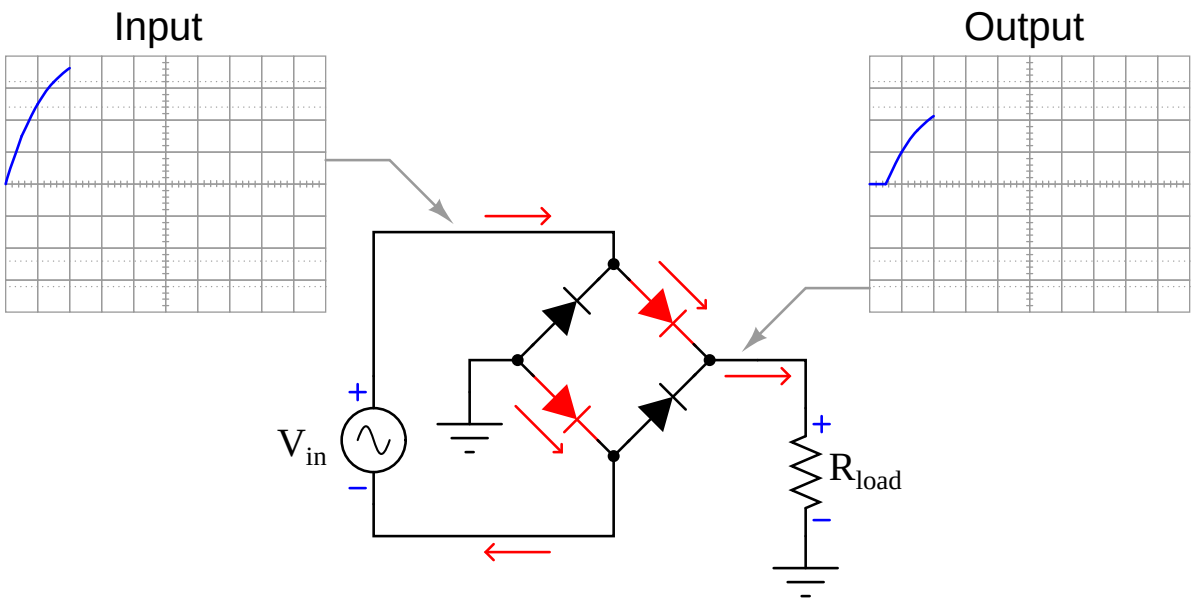
The following animation shows a full-wave, single-phase bridge rectifier using real diodes (with some forward voltage drop). Oscillographs show the input (AC) and output (rectified DC) of the rectifier circuit, with forward-biased diodes colored red.

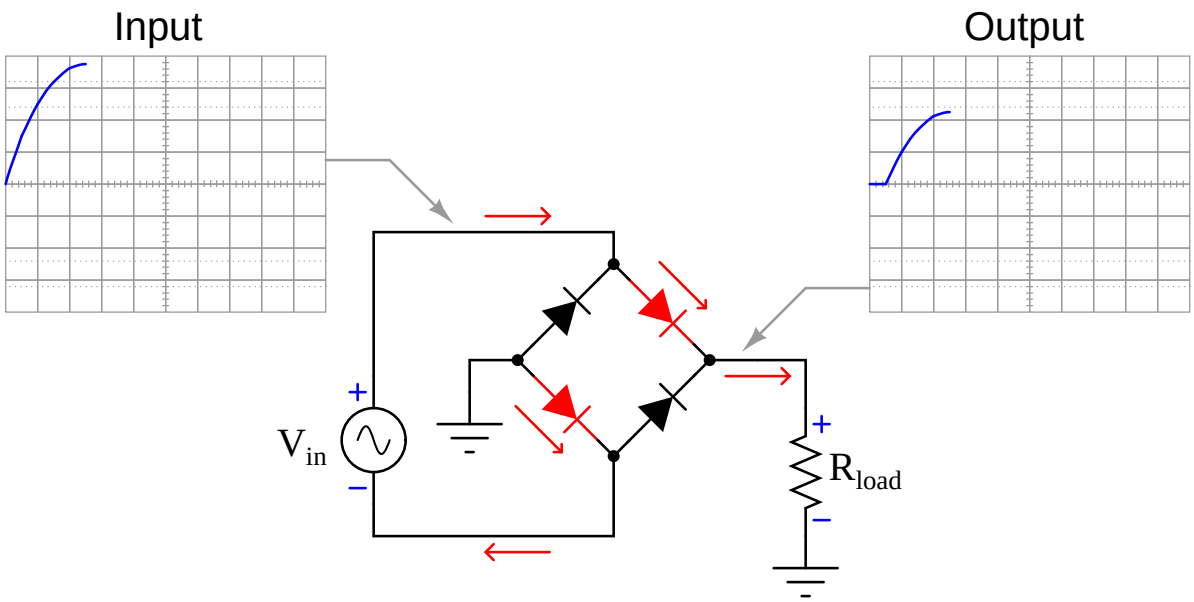

Input
Output
V_{in}
R_{load}

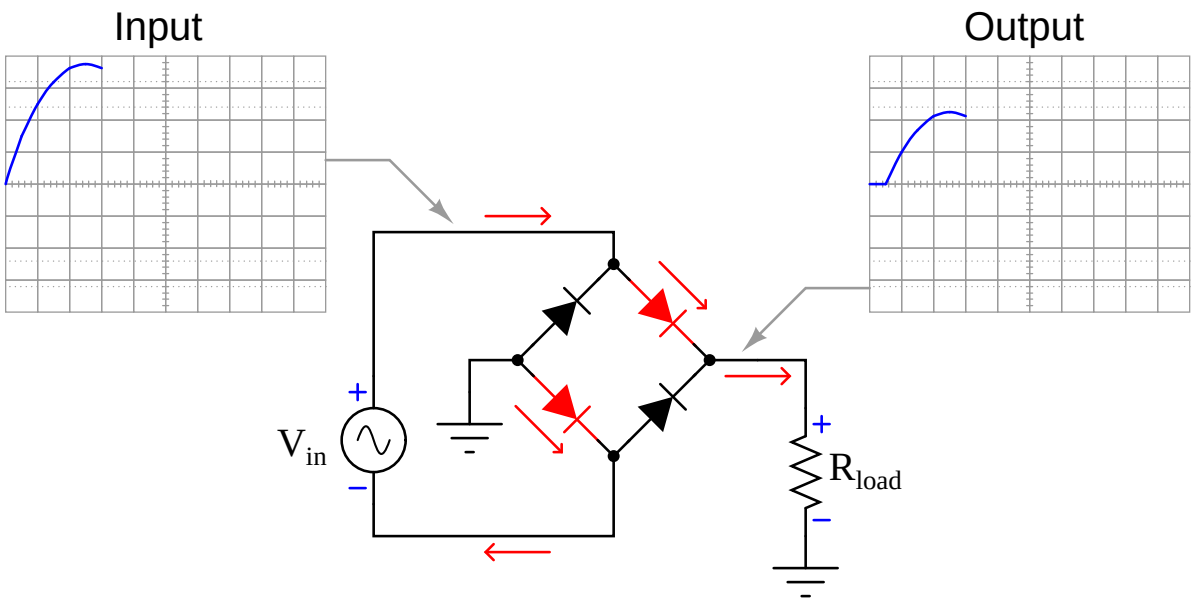

Input
Output
+
V_{in}
−
R_{load}

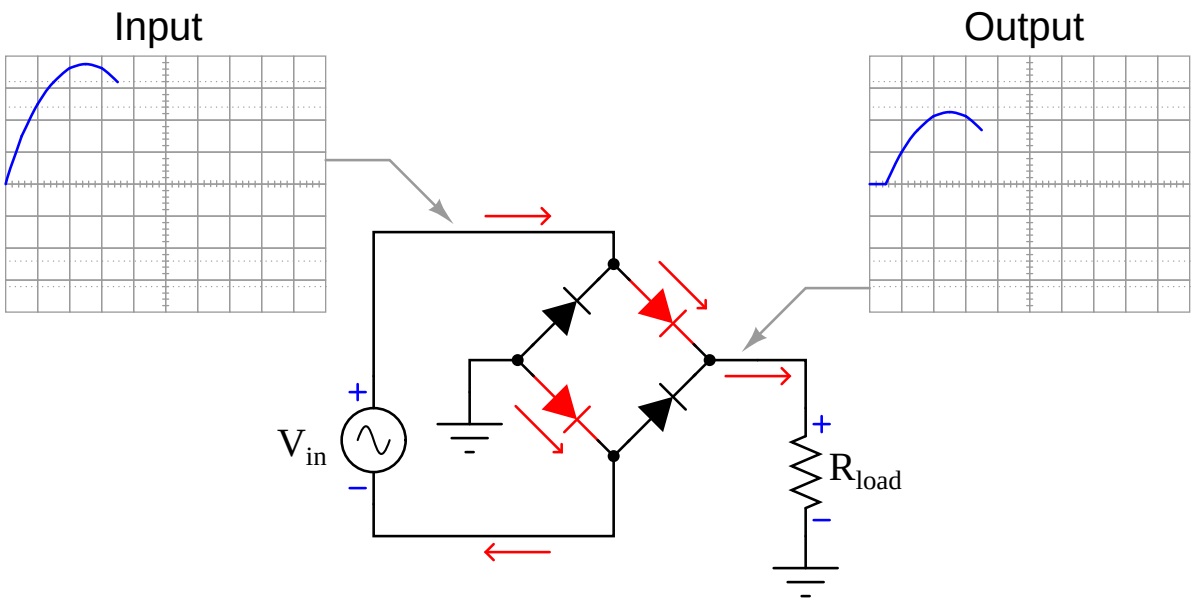

Input
Output
+
V_{in}
−
+
R_{load}
−

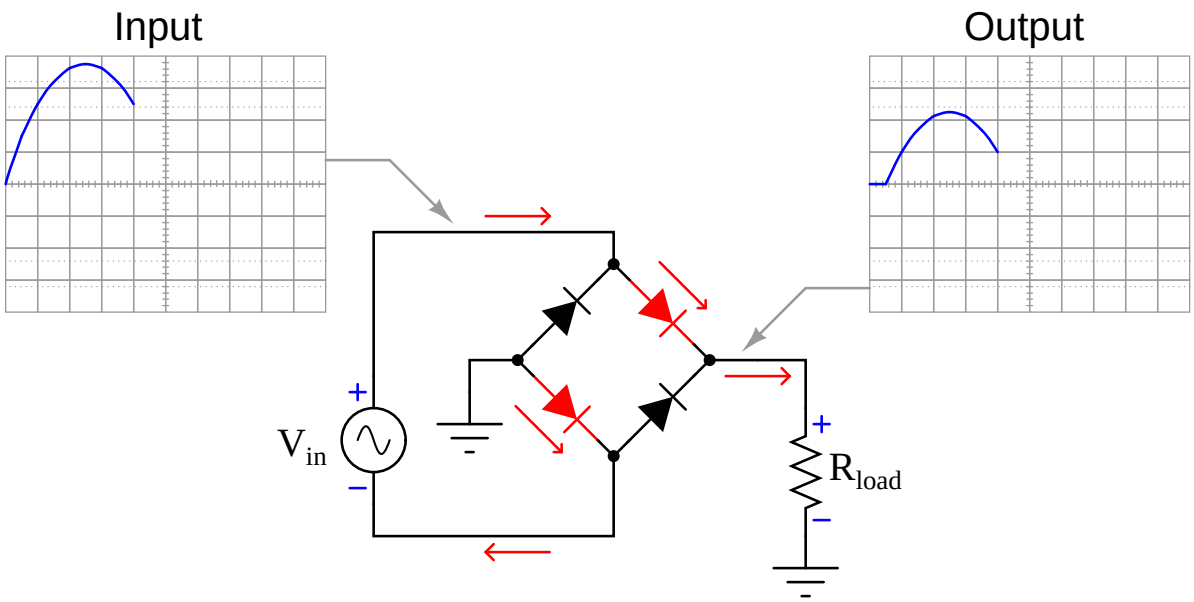

Input
Output
+
V_{in}
−
+
R_{load}
−

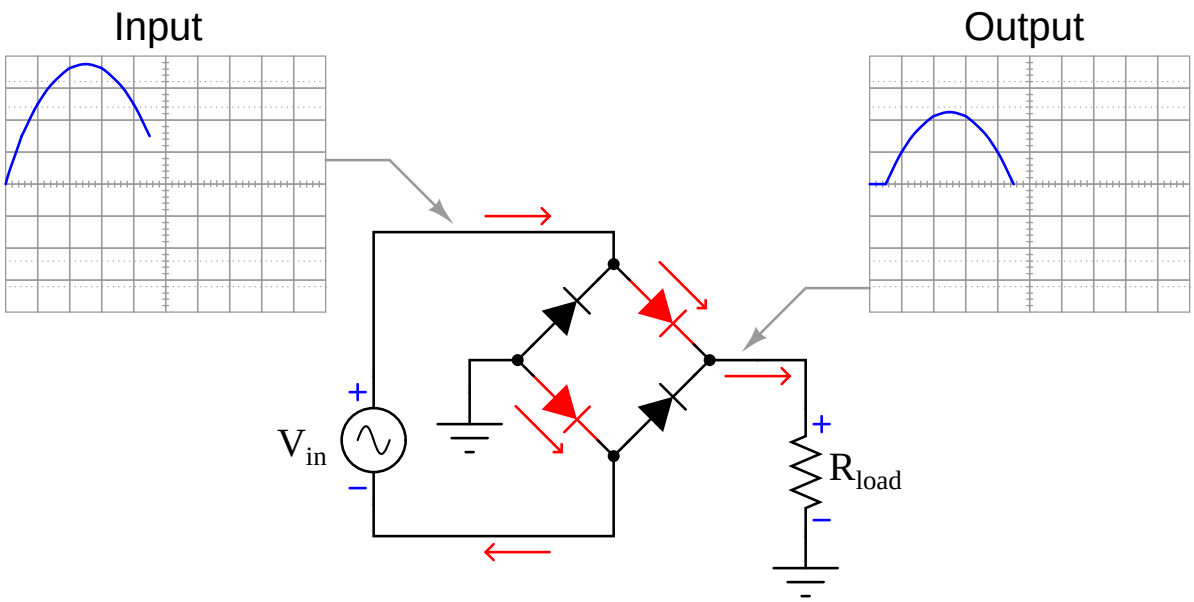

Input
Output
+
V_{in}
−
+
R_{load}
−

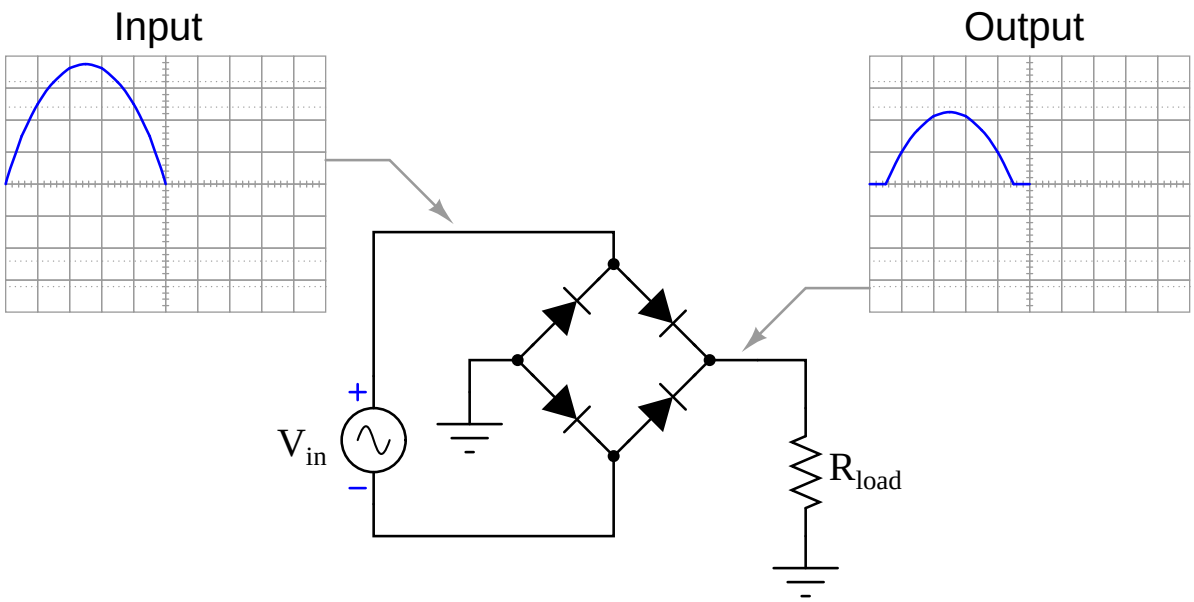

Input
Output
+
V_{in}
−
+
R_{load}
−

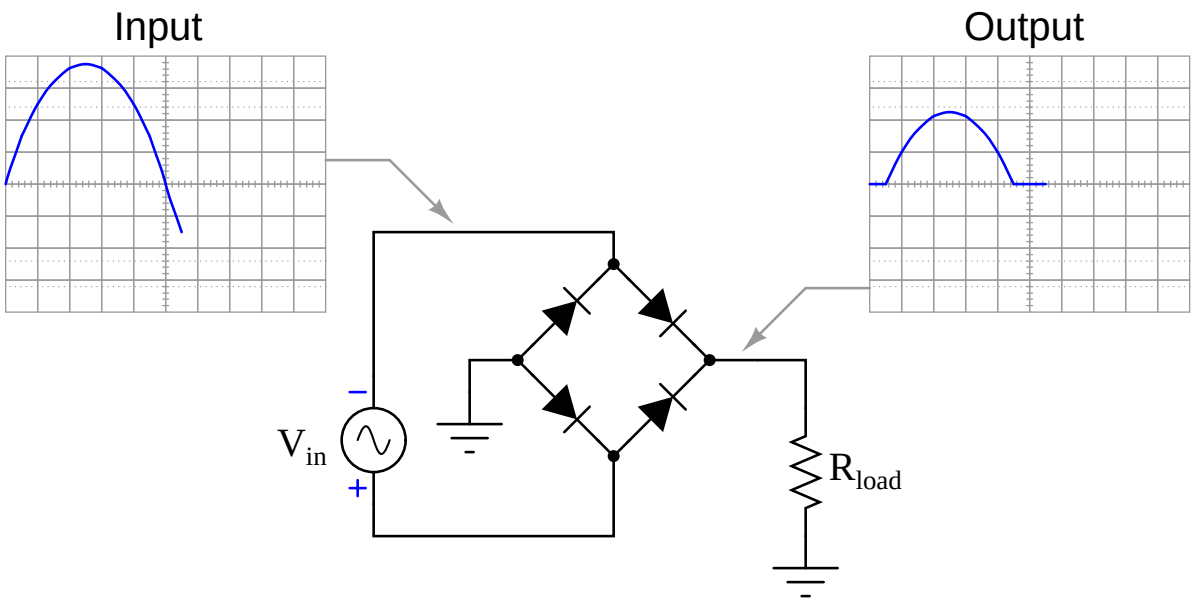

Input
Output
+
V_{in}
−
+
R_{load}
−

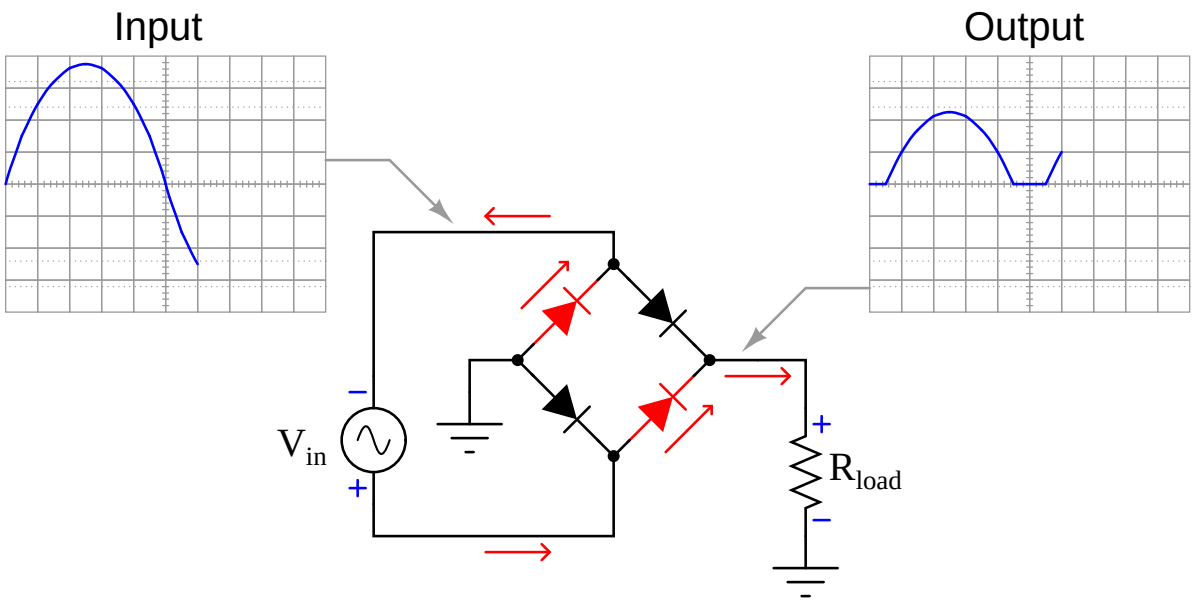

Input
Output
+
V_{in}
−
+
R_{load}
−

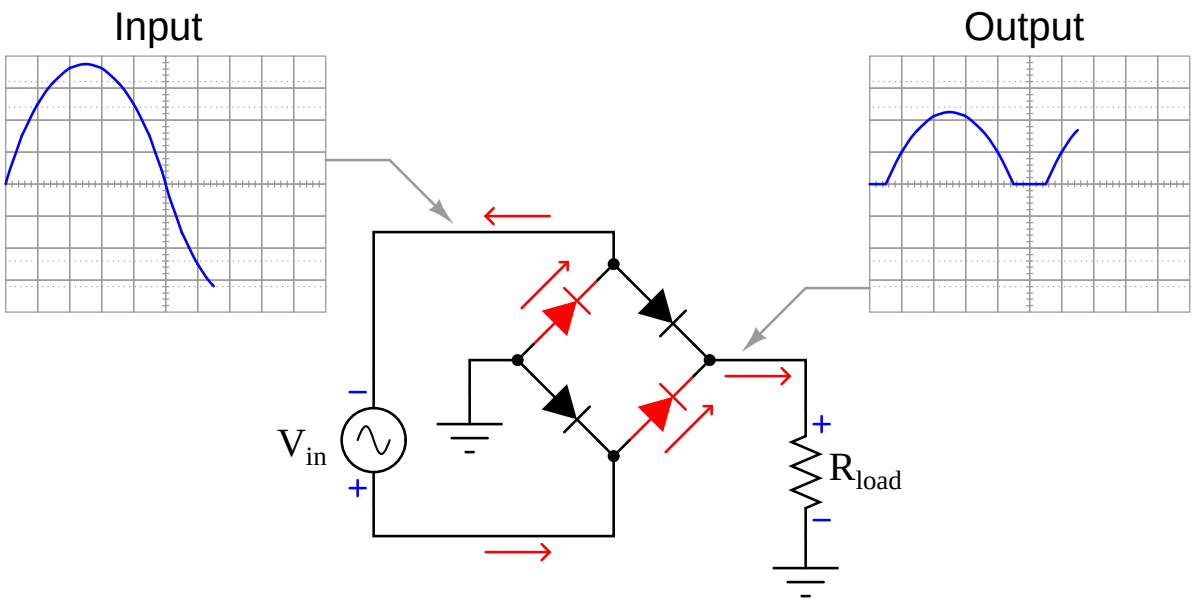

Input
Output
+
V_{in}
−
+
R_{load}
−

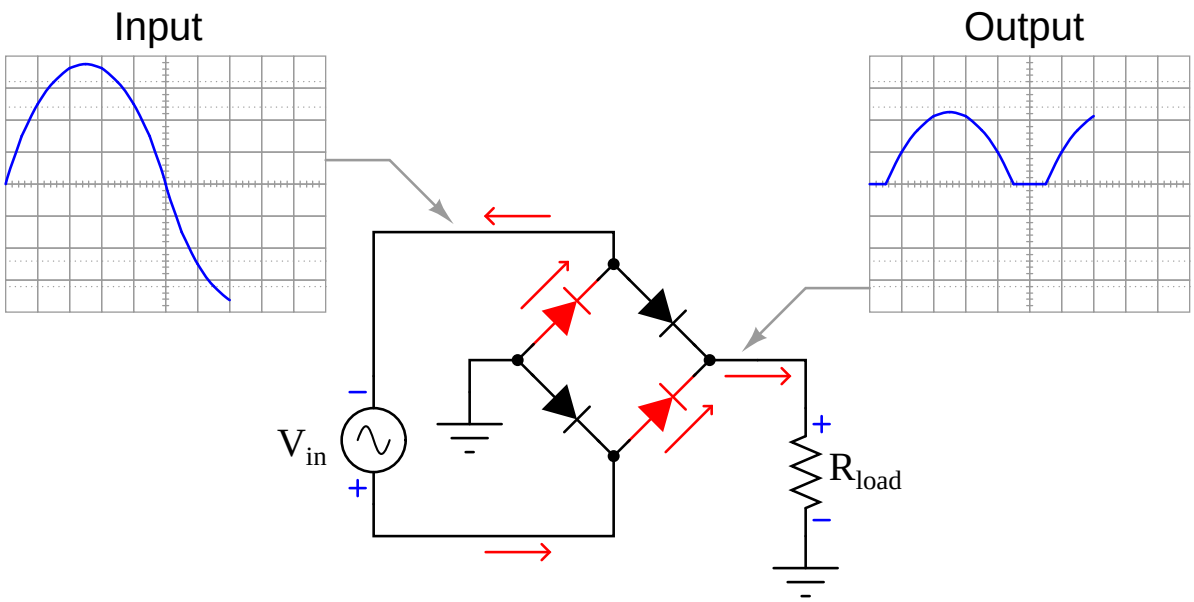

Input
Output
+
V_{in}
−
+
R_{load}
−

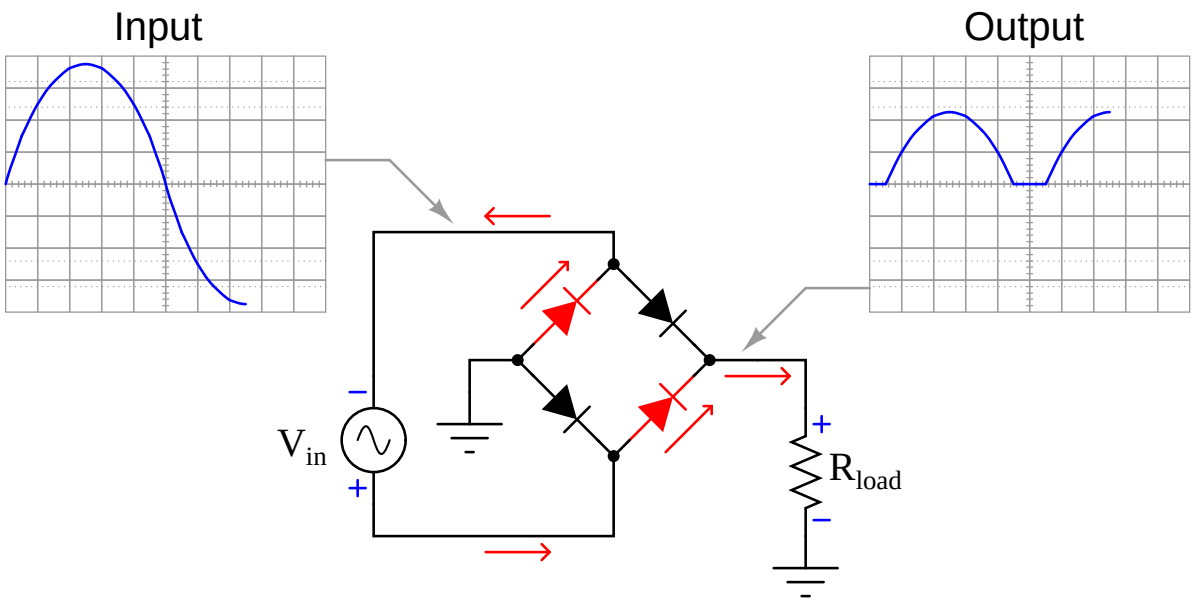

Input
Output
+
V_{in}
−
R_{load}

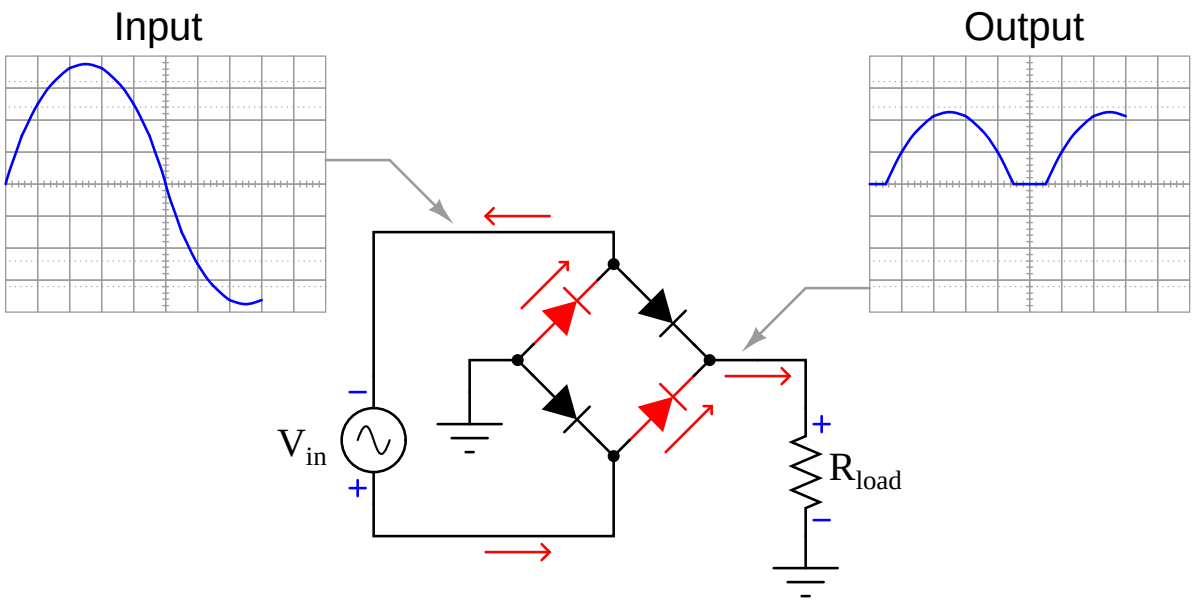

Input
Output
V in
R load

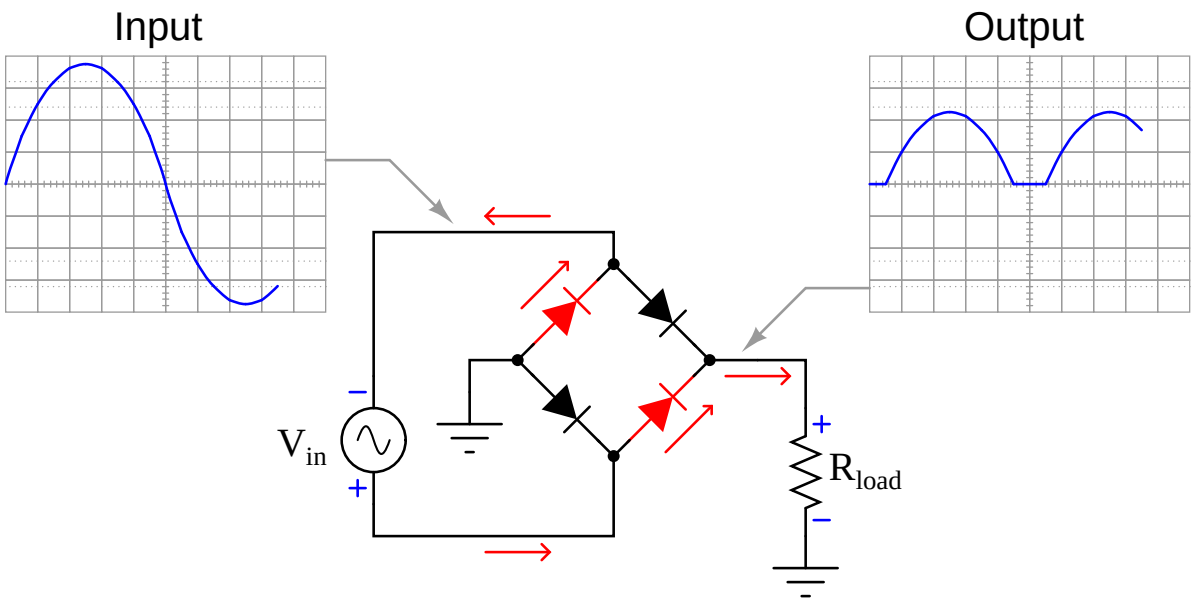

Input
Output
V in
R load

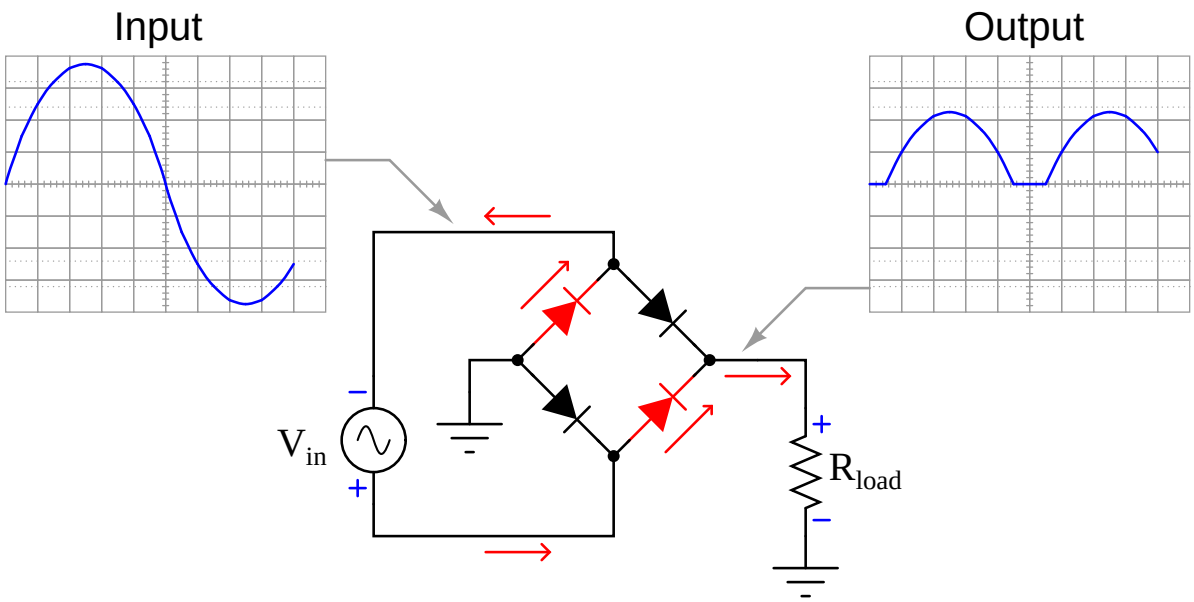

Input
Output
V in
R load

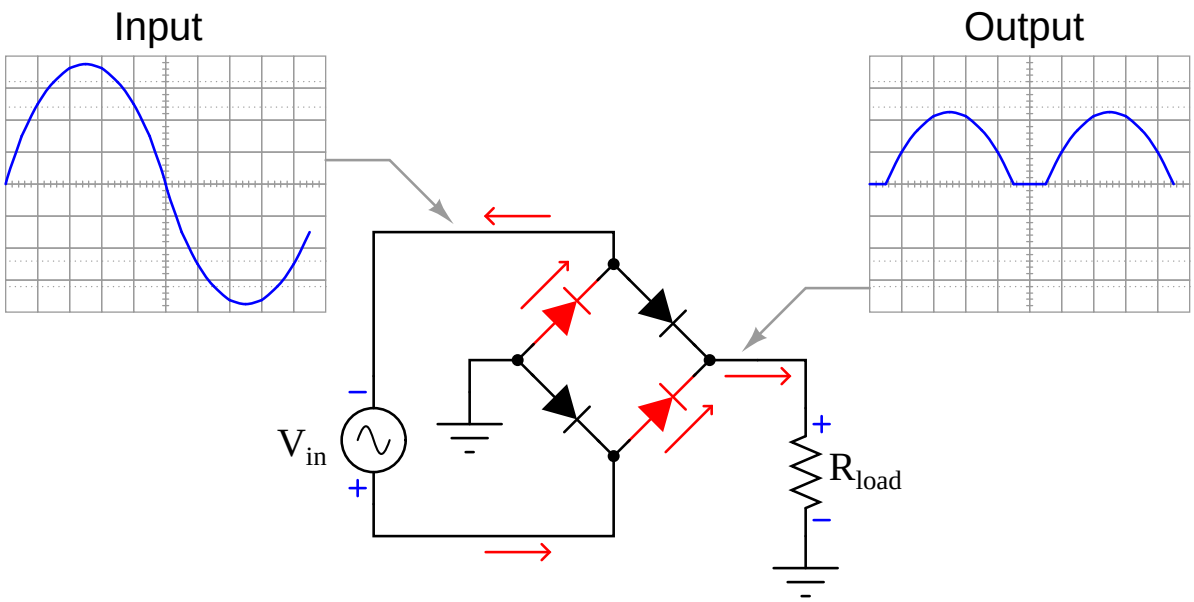

Input
Output
V in
R load

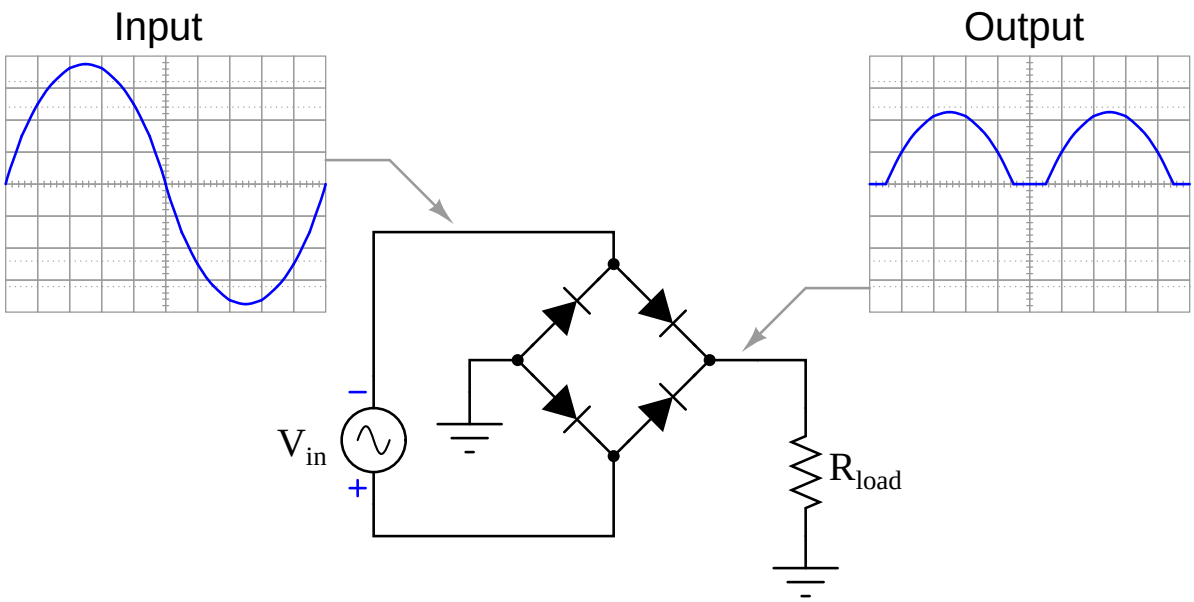

Input
Output
V in
R load


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}

Chapter 7

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?

7.1 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.

7.1.1 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.

7.1.2 Foundational concepts

Correct analysis and diagnosis of electric circuits begins with a proper understanding of some basic concepts. The following is a list of some important concepts referenced in this module's 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.

Direct Current (DC)

Alternating Current (AC)

Energy

Conservation of Energy

Energy conversion

Rectification

Diode

Forward-biasing

Reverse-biasing

Forward voltage drop

Bridge network

Transformer

Ripple

Filter

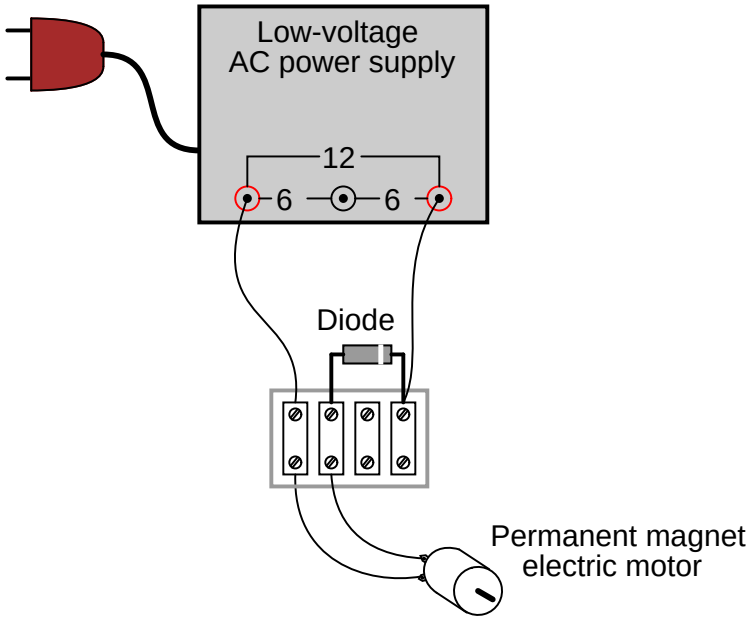
Advantages of polyphase electrical systems

Rectifier pulse number

Phase shift

7.1.3 Powering a DC motor

How would this permanent-magnet DC behave if powered by the following circuit? Assume that the "Low-voltage AC power supply" is nothing more than a step-down transformer rated for standard line voltage (120 VAC in the United States) on the primary winding, having a center-tapped secondary winding outputting 6 or 12 Volts:

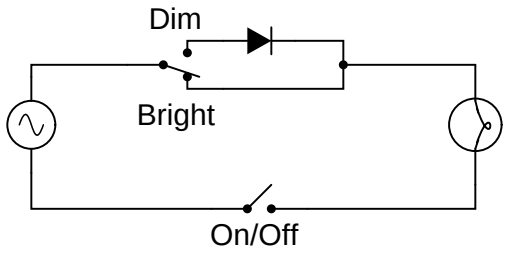


Challenges

- Identify the polarity of the DC voltage between the motor terminals.
- If a DC voltmeter were connected in parallel with the motor terminals, how much voltage would you suppose it would register?

7.1.4 Simple lamp dimmer

A simple form of "dimmer" control for an incandescent electric lamp uses a diode as shown below:



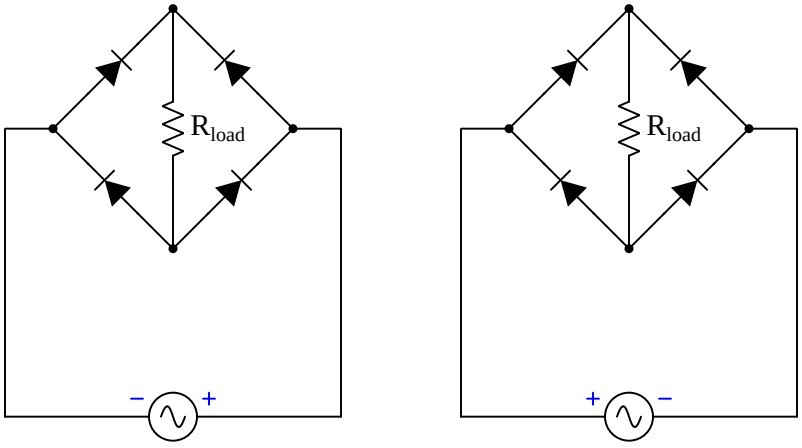
Explain how this circuit is able to make the lamp glow brighter and dimmer.

Challenges

- What would be the consequence of the diode failing open?
- What would be the consequence of the diode failing shorted?

7.1.5 Bridge rectifier currents

Trace all currents through these identical rectifier circuits at a moment in time when the AC source's polarity is as shown:



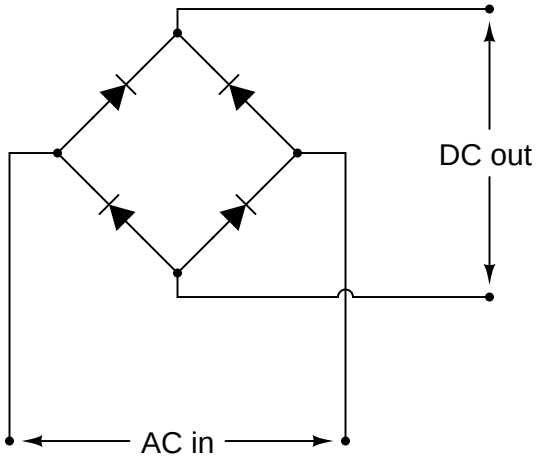
Also, mark the polarity of the voltage drop across R_{load}.

Challenges

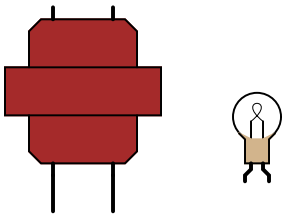
- What would be the consequence of the upper-left diode failing open?
- What would be the consequence of the upper-right diode failing open?
- What would be the consequence of the lower-right diode failing shorted?

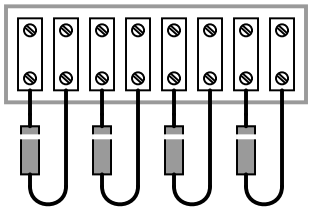
7.1.6 Terminal block construction of a bridge rectifier

A very common form of full-wave rectifier circuit is the *bridge rectifier*. Typically, it is drawn as a "diamond" of four diodes:



Draw the connections in this illustration to form a bridge rectifier circuit, receiving power from the transformer and delivering power to the lamp:



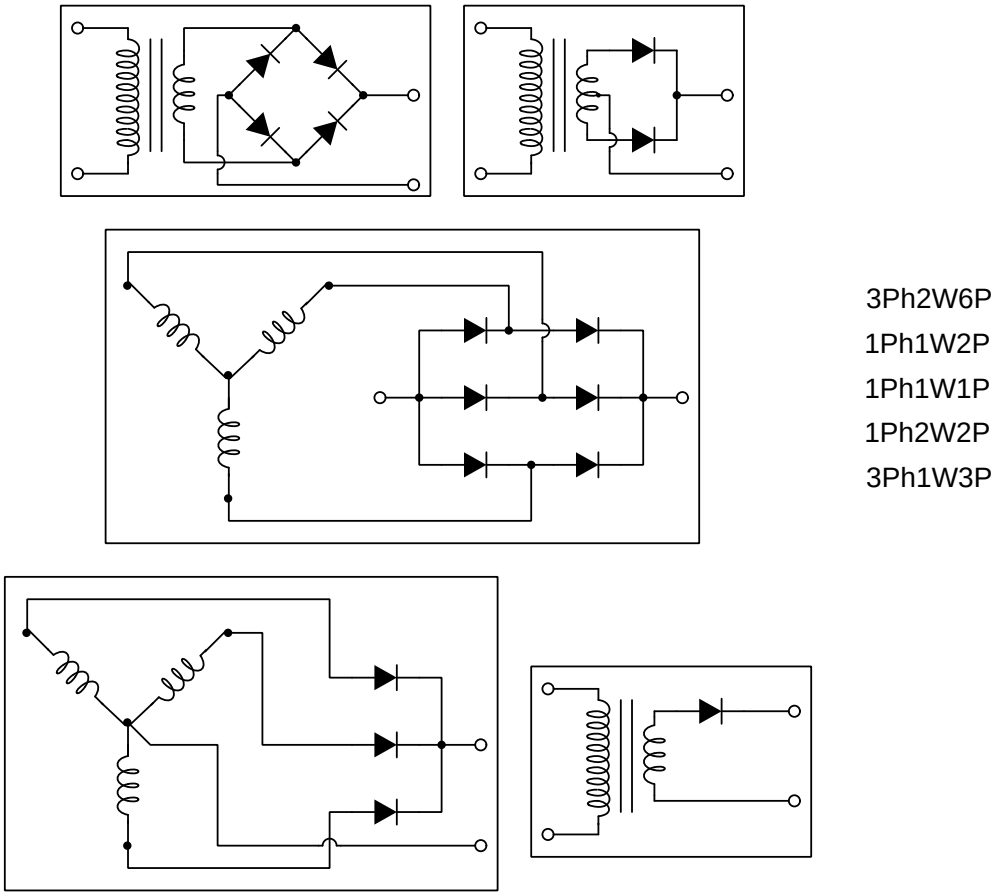


Challenges

- Sketch the direction of currents through the bridge rectifier for each half-cycle of the AC power source, and determine the DC voltage polarity across the lamp terminals.

7.1.7 Rectifier pulse identifications

Power rectifier circuits are often classified according to their number of *phases*, *ways*, and *pulses*. Match the following rectifier circuits to the Phase/Way/Pulse labels given in this illustration:

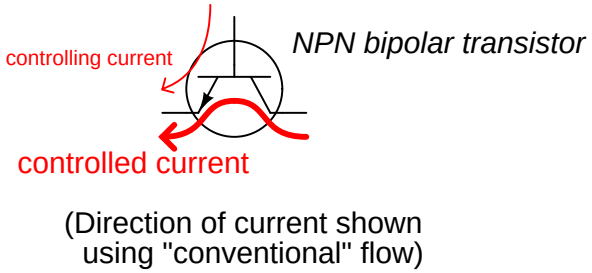


Challenges

- Identify the effect of a diode failing *open* in any one of the rectifier circuits shown.
- Identify the effect of a diode failing *shorted* in any one of the rectifier circuits shown.
- Identify the DC polarity of the output terminals for each of the rectifier circuits shown.
- Describe how to reverse the polarity of each of the rectifier circuits shown.

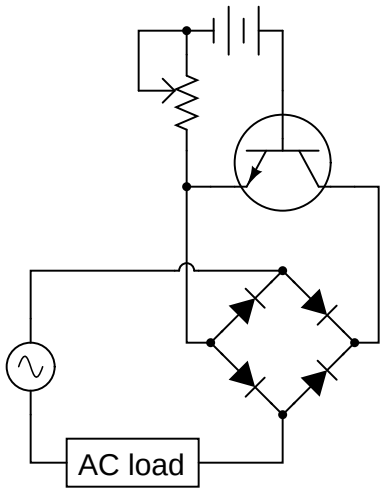
7.1.8 Transistor controlling an AC load

Bipolar transistors are extremely useful devices, allowing a small electric current to control the flow of a much larger electric current:



These devices would be even more useful to us if they were able to control alternating current (AC), but they cannot. Bipolar transistors are polarized (one-way-only) devices.

This fact does not prevent us from using bipolar transistors to control AC. We just have to be clever about how we do it:



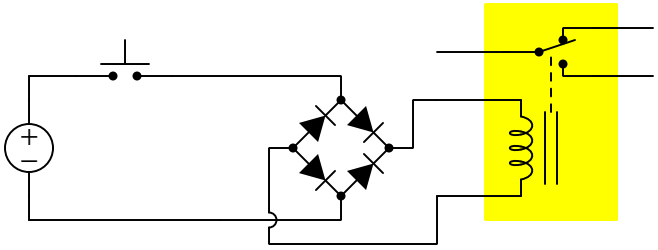
Explain how this circuit functions. How is the transistor (a DC-only device) able to control alternating current (AC) through the load?

Challenges

- Is it necessary to understand how a transistor works to answer this question? Why or why not?

7.1.9 Bridge rectifier commutation

A very unconventional application of a bridge rectifier appears in the following diagram, where it functions as a commutating diode network for a relay coil:



Trace the path of current through the diodes in the bridge, both when the pushbutton switch is pressed and when it is released.

Bridge rectifiers have several advantages over single diodes for the purpose of commutating the current of a de-energizing inductance. Explain *why* each of the following advantages is true:

- A bridge rectifier results in a decay time approximately twice as rapid as a single diode.
- A bridge rectifier provides redundancy in the event of any one diode failing open.
- A bridge rectifier successfully commutates a relay coil when energized by either an AC or a DC source.

Challenges

- Explain why a "commutating" diode is useful and/or necessary in a relay circuit.

7.2 Quantitative reasoning

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

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

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

Completely worked example problems found in the Tutorial may also serve as "test cases[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.

7.2.1 Miscellaneous physical constants

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

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

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

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

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

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

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

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

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

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

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

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

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

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

7.2.2 Introduction to spreadsheets

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

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

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

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

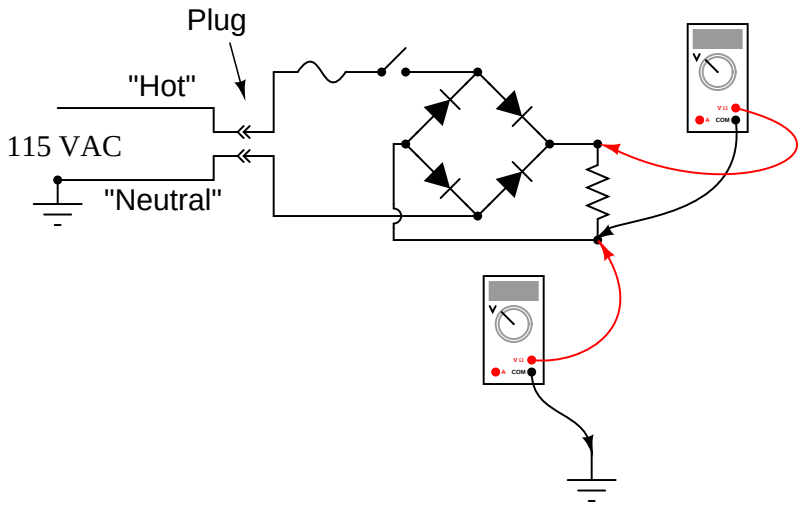
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference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

7.2.3 Line-powered rectifier

Determine the approximate amount of voltage each voltmeter in this circuit will indicate when the switch is closed:



Challenges

- Do either of these measured voltages pose a safety hazard?

7.2.4 Rectified peak voltage and ripple frequency

Calculate the peak rectified voltage and ripple frequency output by a single-phase, full-wave bridge rectifier assuming an AC input voltage of 35 Volts (RMS) at 60 Hz, and using silicon rectifying diodes.

Calculate the peak rectified voltage and ripple frequency output by a single-phase, half-wave rectifier assuming an AC input voltage of 220 Volts (RMS) at 50 Hz, and using a silicon rectifying diode.

Calculate the peak rectified voltage and ripple frequency output by a three-phase, three-pulse rectifier assuming an AC input voltage of 480 Volts (RMS) at 60 Hz, and using silicon rectifying diodes.

Calculate the peak rectified voltage and ripple frequency output by a three-phase, six-pulse rectifier assuming an AC input voltage of 220 Volts (RMS) at 50 Hz, and using silicon rectifying diodes.

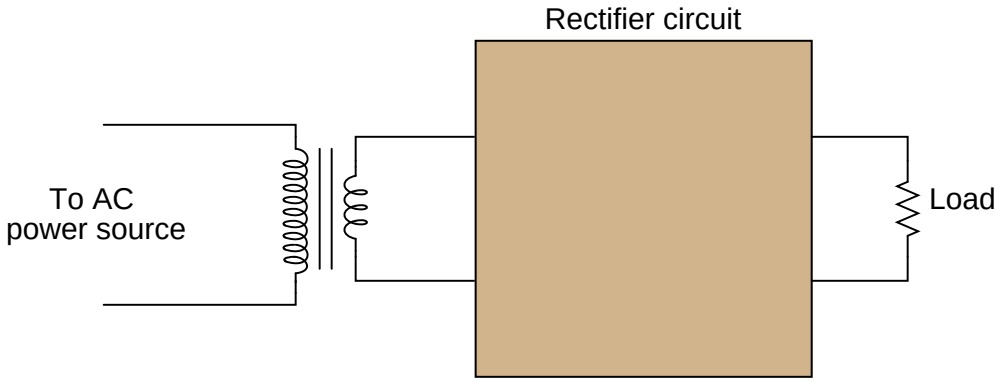
Calculate the peak rectified voltage and ripple frequency output by a single-phase, full-wave rectifier assuming an AC input voltage of 180 Volts (peak) at 60 Hz, and using silicon rectifying diodes.

Challenges

- What advantages or disadvantages are there to using a full-wave versus half-wave rectifier circuit?

7.2.5 Heavy-duty rectifier design

Suppose you need to build a full-wave bridge rectifier with a current rating of 2.5 Amperes, but only have model 1N4001 diodes to build it with. Draw a schematic diagram of the circuit, showing how multiple 1N4001 diodes could be connected together to accomplish this:



Challenges

- What would be the consequence of any single diode failing open in your proposed circuit?

7.3 Diagnostic reasoning

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

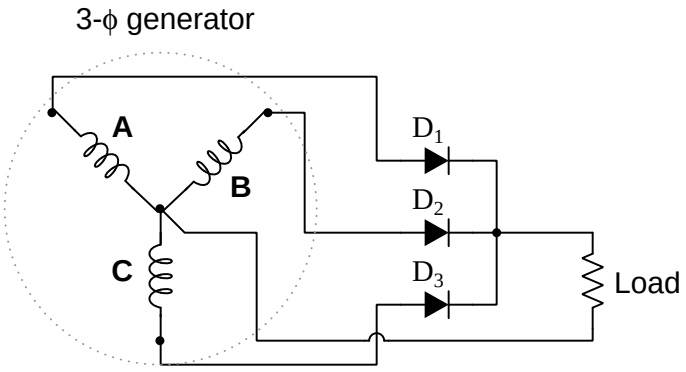
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

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

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

7.3.1 Faults in a three-pulse rectifier

Predict how all component voltages and currents in this circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no coincidental faults):



- Diode D_1 fails open:
- Generator winding **C** fails open:
- Center connection joining generator windings fails open:

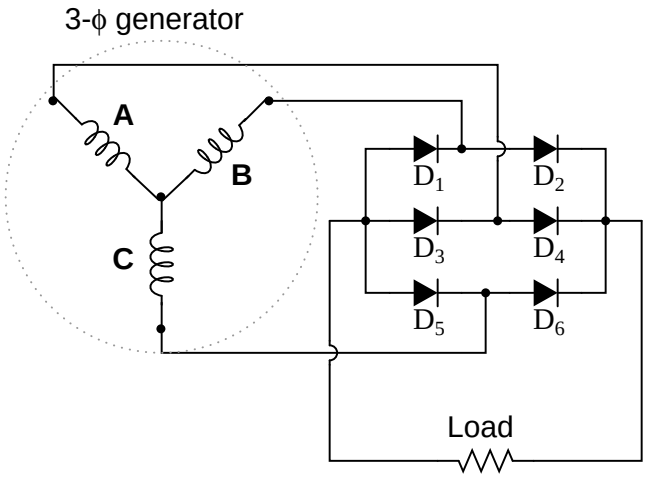
For each of these conditions, explain *why* the resulting effects will occur.

Challenges

- Identify the voltage polarity and current direction for the load.

7.3.2 Faults in a six-pulse rectifier

Predict how all component voltages and currents in this circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no coincidental faults):



- Diode D_3 fails open:
- Generator winding **C** fails open:
- Center connection joining generator windings fails open:

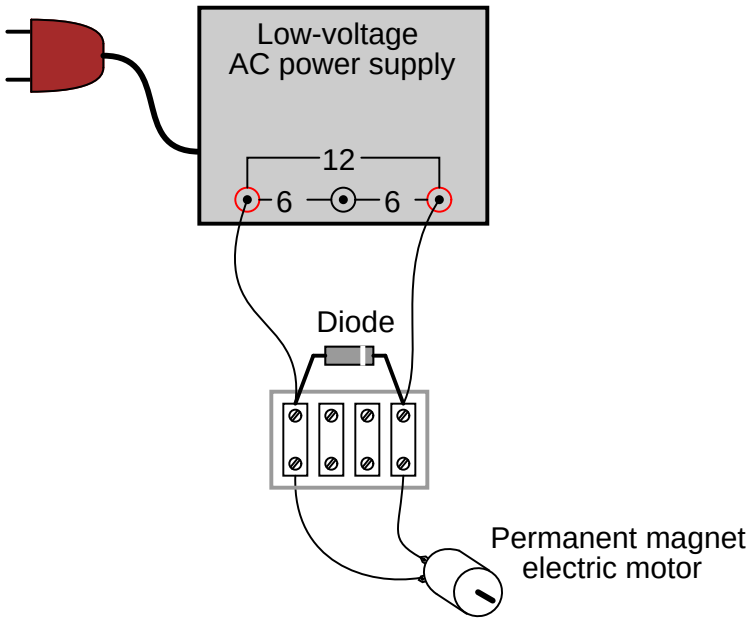
For each of these conditions, explain *why* the resulting effects will occur.

Challenges

- Identify the voltage polarity and current direction for the load.

7.3.3 How not to power a DC motor with an AC source

A technician attempting to energize a DC electric motor using an AC voltage source decides to connect these two components to each other and to a diode as shown below:



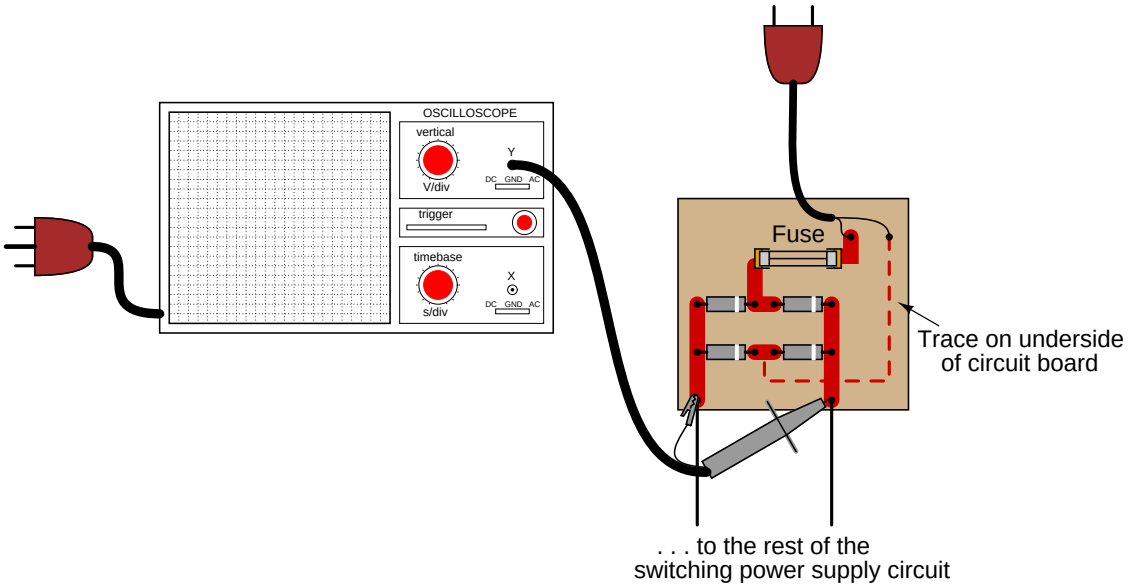
Explain why this circuit is destined to fail.

Challenges

- During the brief period of time prior to catastrophic failure, identify (if possible) the DC polarity of voltage across the motor's terminals.

7.3.4 How not to connect an oscilloscope to a rectifier

A technician decides to measure the output voltage of a bridge rectifier circuit using an oscilloscope. This particular bridge rectifier is the front-end of a *switching power supply circuit*, and directly rectifies the incoming 120 Volt AC power, with no transformer:



However, the technician is surprised to find that the fuse blows every time she turns the power on to the circuit. When the oscilloscope is disconnected from the circuit, the fuse does not blow, and everything works fine. What is wrong? Why does the oscilloscope cause a fault in the circuit?

Here is another interesting symptom: if just the probe tip is touched to one of the rectifier circuit's output terminals, the oscilloscope shows a half-wave rectified waveform, without the ground clip being connected to anything!

Challenges

- Trace a possible path for fault current in this circuit with the oscilloscope's ground clip attached.

Appendix A

Problem-Solving Strategies

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

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

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

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

Appendix B

Instructional philosophy

B.1 First principles of learning

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

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

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

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

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

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

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

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

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

B.2 Proven strategies for instructors

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

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

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

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

B.3 Proven strategies for students

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

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

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

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

B.4 Design of these learning modules

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

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

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

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

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

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

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

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

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

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

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

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

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

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

The `GNU/Linux` computer operating system

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

Bram Moolenaar's `Vim` text editor

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

Donald Knuth's TEX typesetting system

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

Leslie Lamport's LATEX extensions to TEX

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

Tim Edwards' `Xcircuit` drafting program

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

`Gimp` graphic image manipulation program

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

`SPICE` circuit simulation program

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

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

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

`gnuplot` mathematical visualization software

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

`Python` programming language

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

Appendix D

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Appendix E

References

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Appendix F

Version history

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

22 March 2026 – typographical error correction courtesy of Wyatt Gleason, where I cited 600 Volts instead of the proper 500 Volts for DC electric trolley car motors in the simplified schematic (circa 1895) for the Niagara Falls power system.

22 October 2025 – typographical error correction courtesy of Caleb Wing.

17 April 2025 – included new photographs of an old mercury-arc rectifier courtesy of Neil Probert, a Power Engineering Specialist working in Newport, Wales, UK, into the "Mercury arc rectifiers" section of the Historical References chapter. Also shortened one sentence in the "Vacuum tube rectifiers" Historical References section so that the entire section occupies just one page in the PDF document. Also made a minor clarifying addition to the "Electrochemical rectifiers" section of the Historical References chapter.

11 October 2024 – added a new "Challenging concepts" section to the Introduction chapter.

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.

27 October 2023 – made clarifications to the concept of grounding and to the concept of "hot chassis" voltage in the Tutorial, including to image_5125. Also added a Derivations and Technical References chapter with sections on hot/neutral/ground conductors and ground definitions.

30 July 2023 – edited comments in the Tutorial about PN junction diodes being forward- versus reverse-biased, after some students mistakenly thought those terms referred to different types of diodes.

28 July 2023 – edited image_5125 and image_5126 to fix small errors where wire-lines were not extended fully into their respective connection points (nodes).

13 May 2023 – added Case Tutorial section on harmonic filters in HVDC substations.

22 March 2023 – added "published in 1917" to the *Hawkins Electrical Guide Number Five* book citations in *all* the Historical References sections, as some were missing this date reference. Also changed the title of the "Peak rectified voltage" Quantitative Reasoning question to "Rectified peak voltage and ripple frequency", as well as added "and ripple frequency" that was missing in several of the sub-questions. Also added comments in the Tutorial about grounding options for center-tapped full-wave rectifier networks.

7-8 March 2023 – error correction in instructor notes in the "Peak rectified voltage" Quantitative Reasoning question. Also added another sub-question to that, and elaborated on rectifier circuits in the Tutorial.

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

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

28 July 2022 – minor edits to the Tutorial chapter.

14 May 2022 – added a new Historical References section on copper oxide rectifiers.

10-11 June 2021 – divided Tutorial into sections, and made minor edits to it including adding some footnotes.

11 May 2021 – added some review of semiconductor diodes to the Tutorial.

9 May 2021 – commented out or deleted empty chapters.

30 March 2021 – added more sub-questions to the "Peak rectified voltage" Quantitative Reasoning question. Also added a Case Tutorial chapter with four example rectifier circuits.

24 March 2021 – corrected capitalization on the word "volt" and also added content to the Tutorial discussing the "hot chassis" phenomenon with bridge rectification.

30 August 2020 – significantly edited the Introduction chapter to make it more suitable as a pre-study guide and to provide cues useful to instructors leading "inverted" teaching sessions.

11 February 2020 – corrected minor typographical error in equation (instructor's notes) of the "Peak rectified voltage" Quantitative Reasoning problem.

23 January 2020 – added Foundational Concepts to the list in the Conceptual Reasoning section.

18 December 2019 – minor edits to diagnostic questions, replacing "no multiple faults" with "no coincidental faults".

20 October 2019 – added bridge rectifier circuit animations.

27 September 2019 – added another form of electromechanical rectifier to the Historical References chapter.

26 September 2019 – eliminated Case Tutorial chapter (no content yet). Added content to the Historical References chapter.

24 September 2019 – continued writing Tutorial.

23 September 2019 – document first created.

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