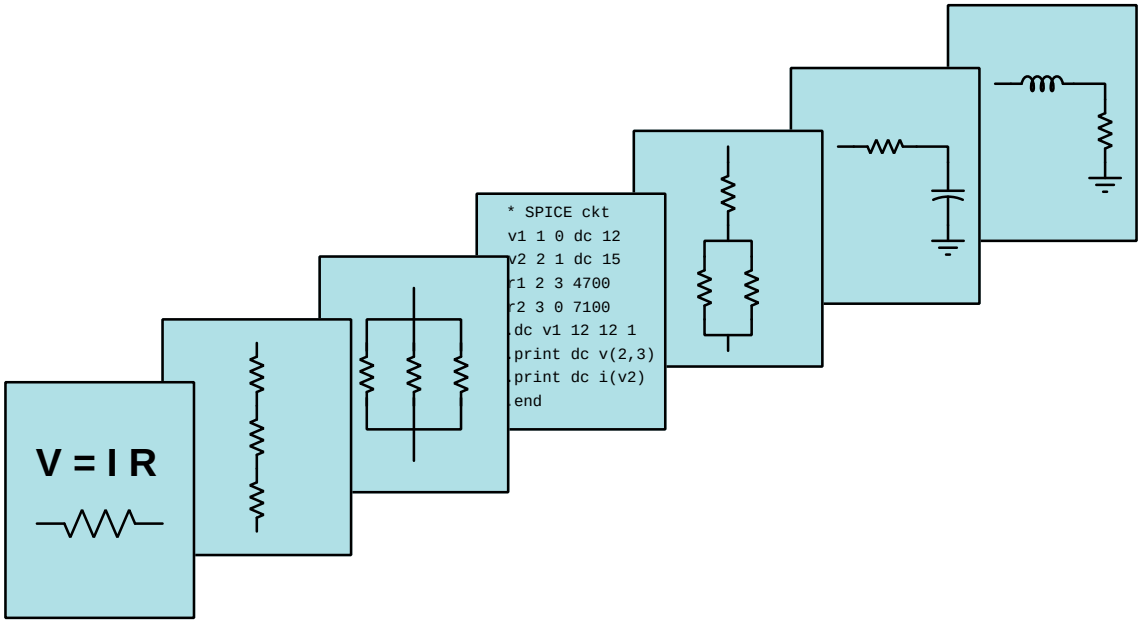
Modular Electronics Learning (ModEL) project



Superposition Theorem

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Contents

1 Introduction **3**
- 1.1 Recommendations for students . . . 3
- 1.2 Challenging concepts related to the Superposition Theorem . . . 5
- 1.3 Recommendations for instructors . . . 6

2 Tutorial **7**
- 2.1 Review of ideal and real sources . . . 8
- 2.2 The Superposition Theorem . . . 10
- 2.3 Example: Series-aiding voltage sources . . . 11
- 2.4 Example: Series-opposing voltage sources . . . 12
- 2.5 Example: Two paralleled batteries . . . 13
- 2.6 Example: Voltage source and current source . . . 16

3 Derivations and Technical References **19**
- 3.1 Superposition of AC signals . . . 20

4 Questions **23**
- 4.1 Conceptual reasoning . . . 27
  - 4.1.1 Reading outline and reflections . . . 28
  - 4.1.2 Foundational concepts . . . 29
  - 4.1.3 1-5 VDC versus 4-20 mA signaling . . . 30
  - 4.1.4 Mixed AC/DC network . . . 32
- 4.2 Quantitative reasoning . . . 34
  - 4.2.1 Miscellaneous physical constants . . . 35
  - 4.2.2 Introduction to spreadsheets . . . 36
  - 4.2.3 Two-source, three-resistor network . . . 39
  - 4.2.4 Wind turbine and battery network . . . 40
  - 4.2.5 Two generators powering a heating element . . . 41
  - 4.2.6 Two generators powering a motor . . . 42
  - 4.2.7 One generator and two batteries . . . 43
- 4.3 Diagnostic reasoning . . . 44
  - 4.3.1 Actually disabling a source . . . 45

5 References **47**

6 Version history **49**

Index **50**

Chapter 1

Introduction

1.1 Recommendations for students

A *network theorem* is a useful tool for simplifying the analysis of some system, provable on the basis of more fundamental principles and/or theorems. Network theorems are proven tools useful for quickly and easily analyzing complex electrical networks without being limited to fundamental rules such as Ohm's Law and Kirchhoff's Laws.

The *Superposition Theorem* is one of those network theorems. It is, perhaps, the easiest network theorem to understand: the amount of voltage or current in any given portion of a multi-source electrical network is the sum total (i.e. superposition) of the individual effects of each source (considered one at a time) at that portion. To summarize, the whole is equal to the sum of its parts.

Important concepts related to the Superposition Theorem include **voltage sources**, **current sources**, **internal resistance**, the effects of **opens** versus **shorts**, **light** versus **heavy** load conditions, **Ohm's Law**, **Joule's Law**, **linear** versus **non-linear** functions, **equivalent** electrical networks, and **substitution** of source resistances.

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

- In what ways do voltage sources differ from current sources?
- How much internal resistance does an ideal voltage source possess?
- How much internal resistance does an ideal current source possess?
- What defines the "heaviness" of a load, for voltage sources and current sources alike?
- How would you describe the application of the Superposition Theorem to any given circuit, in your own words?
- What parameters in a circuit is the Superposition Theorem useful in solving for?
- What parameters in a circuit is the Superposition Theorem *not* useful in solving for?

- What does it mean for a mathematical function to be linear?
- Why did the Tutorial apply the Superposition theorem to circuits so elementary that they did not require any network theorems to analyze? What educational value is there in doing that?
- What must be done with all unused sources when applying the Superposition Theorem to a network?
- What is the definition of a series network?
- What is the definition of a parallel network?
- What do we replace a voltage source with when "disabling" it during Superposition analysis, and why?
- What do we replace a current source with when "disabling" it during Superposition analysis, and why?
- What is meant by the phrase "exchanging tedium for complexity" in regard to problem-solving strategies?
- How might an experiment be designed and conducted to demonstrate the Superposition Theorem?

1.2 Challenging concepts related to the Superposition Theorem

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

- **Equivalent electrical networks** – the possibility that completely different networks of components may nevertheless *behave* identically from the perspective of two or more connection terminals is non-intuitive for many students new to electric circuits. However, there are many analogues in life that may be used to help explain. For example, a box containing an unknown assortment of items may have precisely the same weight as a different box containing something completely different from the first: i.e. from the perspective of weight sense at the handle when lifting each box, the boxes may behave the same even though their contents may be wholly different. Quite often when using the Superposition Theorem we must model real voltage and current sources as being collections of idealized components.

- **Schematic annotation as a problem-solving tool** – as an instructor you will find most students new to the study of electronics attempt to solve circuit-analysis problems by inspection, or by plugging given values into familiar equations until something resembling an answer emerges. Such efforts are usually fruitless because it is difficult to track the real-world context of every circuit parameter doing things this way. You will need to demonstrate, encourage, and at times *require* your students to apply the alternative strategy of first sketching a schematic diagram of the circuit and then annotating it with all known values. Once the given information gains context through this annotation, appropriate principles (e.g. Ohm's Law, KVL, KCL) are much easier to identify and then properly apply for that circuit. Then, as calculated values get annotated on the same schematic diagram the next logical steps to follow become easier and easier to identify. I recommend using different colors to label different parameters (e.g. blue for voltage, red for current, black for component values, green for power). Students should have blank "scratch" paper and writing instruments with them at all times, even during discussions, so as to neatly organize information and to articulate and focus their thoughts!

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 quantitative results were obtained by the author in the Tutorial chapter's examples.

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

- **Outcome** – Apply the Superposition Theorem to the analysis of multi-source circuits

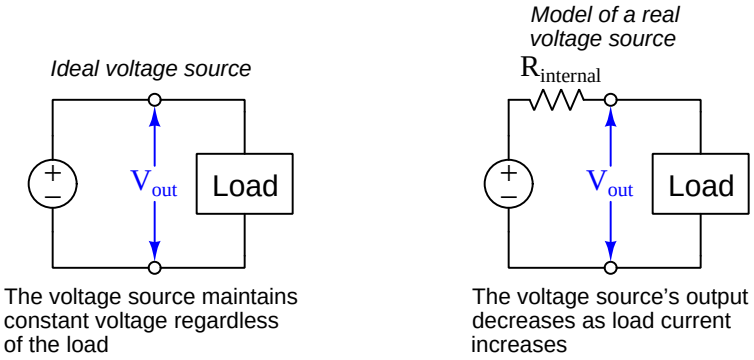
  Assessment – Calculate circuit conditions given a schematic diagram of a multi-source circuit.

Chapter 2

Tutorial

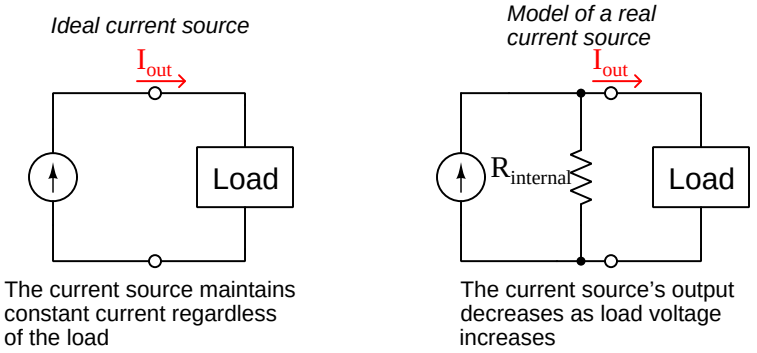
2.1 Review of ideal and real sources

A perfect voltage source outputs constant voltage regardless of how much or little current passes through it: no matter the rate of electrical charge carriers flowing through a perfect voltage source, each charge carrier gains the exact same amount of energy from the source. Real voltage sources cannot maintain absolutely constant voltage over wide variations in current, and so we often model real voltage sources as ideal voltage sources connected in series with internal resistance:



The closer to ideal a voltage source is, the less its internal resistance. An ideal voltage source is considered to have zero internal resistance.

Similarly, a perfect current source outputs constant current regardless of how much or little voltage appears across its terminals: no matter how much energy is given to each electrical charge carrier as it passes through the source, the rate that charge carriers move through will remain constant. Real current sources cannot maintain absolutely constant current over wide variations in voltage, and so we often model real current sources as ideal current sources connected in parallel with internal resistance:



The closer to ideal a current source is, the more its internal resistance. An ideal current source is considered to have infinite internal resistance.

Real sources, both voltage and current, approach ideal behavior as less power is drawn from them, and deviate more from ideal behavior when more power is demanded. Common terms for describing the relative power demanded from a source are "heavy" for high-power loads and "light" for low-power loads, evocative of a person exerting energy to hoist a heavy object versus a light object. For a voltage source, a "light" load is one drawing little or no current, such as an open-circuit, because less current for any given voltage results in less power. For a current source, a "light" load is one dropping little to no voltage, such as a short-circuit, because less voltage for any given current also results in less power. If you examine the schematic models of real voltage and current sources previously shown, and imagine their respective minimum-power load conditions (i.e. open load for the voltage source and shorted load for the current source) you will see that in both cases the internal resistance becomes irrelevant. For the voltage source, a load drawing no current means that the source's $R_{internal}$ drops no voltage, leaving full source voltage at the output terminals. For the current source, a load dropping no voltage means that the source's $R_{internal}$ passes no current, leaving full source current at the output terminals.

While the internal resistances of real voltage and current sources have many practical implications, the important point to recognize for this tutorial is that *voltage sources ideally have no internal resistance while current sources ideally have infinite internal resistance.* In particular, some electrical network theorems require this knowledge to apply, as one must consider the internal resistance of each source as a factor in the theorem.

2.2 The Superposition Theorem

One network theorem particularly useful for circuits containing more than one electrical source is the *Superposition Theorem*. It may be stated as such:

Superposition Theorem

> Any given voltage or current in a multi-source network is equal to the sum (superposition) of that same voltage or current resulting from each source considered one at a time.

Suppose you are tasked with determining some voltage or current quantity in a complex multi-source network. According to the Superposition Theorem, all you have to do is treat that network as though it only has one source component (necessarily simplifying the network) for as many times as there are sources, and add the voltage/current values computed while each of those sources was in effect. In other words, we regard a multi-source electrical network as the *superposition* of multiple single-source networks analyzed one source at a time.

There is one important caveat for the Superposition Theorem, namely that it only applies to *linearly proportional quantities*. Networks comprised exclusively of components obeying Ohm's Law are a good fit for Superposition because Ohm's Law implies a direct proportionality between voltage and current. Many types of semiconductor components, by contrast, are *nonlinear*[1] and therefore unsuitable for the Superposition Theorem. Likewise, certain quantities such as power (P) do not lend themselves to the Superposition Theorem because it scales nonlinearly as a function of voltage or current ($P = I^2R$ and $P = \frac{V^2}{R}$).

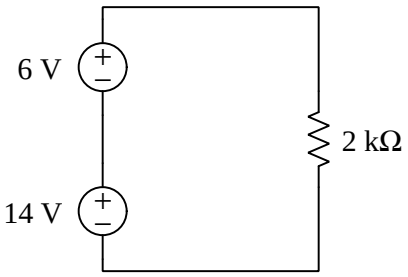
Another important consideration when applying the Superposition Theorem is that all the *other* sources in the circuit must be replaced by their equivalent internal resistance values when analyzing the circuit one source at a time. This is why the tutorial began with a discussion of ideal versus real voltage and current sources, and their corresponding internal resistance values. One must know that voltage sources have low internal resistance (ideally zero) and that current sources have high internal resistance (ideally infinite) in order to properly perform these substitutions.

We will explore the application of the Superposition Theorem to various resistor-source networks in the following sections.

[1] For the purpose of this discussion, a "nonlinear" component is one where voltage and current are *not* directly proportional to each other at any portion of the component's range. Another way to consider this characteristic would be to think of such components as having unstable resistance values. Not only are semiconductor PN junctions quite nonlinear, but so are some non-semiconductor devices such as incandescent lamps (where filament resistance changes with temperature, which in turn is affected by voltage and current). Some texts also add the condition of *bilateral symmetry* to the use of the Superposition Theorem, meaning that components must behave the same when energized in both polarities. However, the concept of linearity applied across a range of values both positive and negative covers this criterion. If a component does not exhibit bilateral symmetry, then it cannot be linear across its *entire* range of permitted values.

2.3 Example: Series-aiding voltage sources

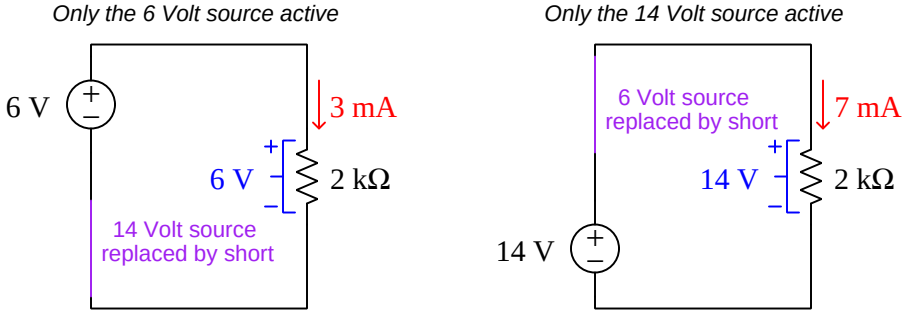
The following circuit is so simple it doesn't require the use of the Superposition Theorem, but we will begin with this anyway because it will make the concept easy to understand:



It should be obvious upon first inspection that the 2 kΩ resistor will experience a total voltage of 20 V from the two series-aiding sources, and that it will therefore pass 10 mA of current:

$$I = \frac{V_T}{R} = \frac{6\ \text{V} + 14\ \text{V}}{2000\ \Omega} = 10\ \text{mA}$$

Let us now prove we can get the same results using the Superposition Theorem. What we must do is analyze how this circuit would function *with just one source active at a time*, the other source "disabled" by replacing it with its equivalent internal resistance. Since these are voltage sources, and we have not been instructed that they are anything but *ideal* voltage sources, we will substitute a short-circuit (i.e. a length of wire) in place of each being disabled:

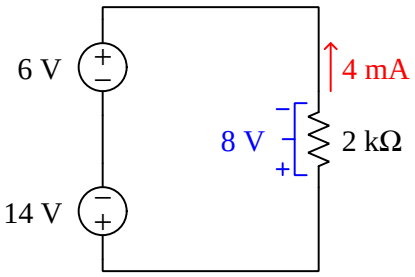


In each analysis, we use Ohm's Law to calculate current ($I = \frac{V}{R}$), 3 mA resulting from the 6 V source and 7 mA resulting from the 14 V source. *Superimposing* these two currents – 3 mA and 7 mA both flowing in the same direction (down) – we get a sum of 10 mA (down), just as we expected. Resistor voltage drops also superimpose correctly, with 6 V (+ on top and − on bottom) and 14 V (+ on top and − on bottom) summing to make 20 V (+ on top and − on bottom).

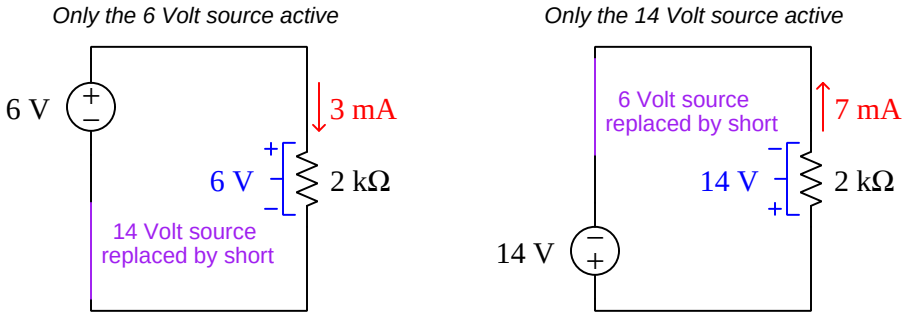
Note how power dissipations do *not* superimpose correctly. Using $P = IV$ we get 18 mW with just the 6 V source and 98 mW with just the 14 V source, but much more than the sum (a true value of 200 mW versus a superimposed sum of only 116 mW) with both sources active. Superposition does not work here because power is *nonlinear* with respect to applied voltage in a resistive network.

2.4 Example: Series-opposing voltage sources

Our next circuit is also simple enough that the Superposition Theorem is unnecessary, but again it should prove instructive:



With the two voltage sources opposing, the net voltage experienced by the resistor will be 8 V, resulting in a current of 4 mA (flowing up). Now that we know the correct result for resistor voltage and resistor current in this dual-source circuit, let us apply Superposition Theorem to verify we get the same results:

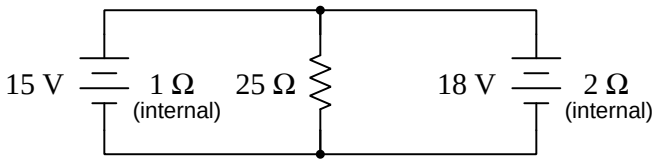


- Superimposing currents: 3 mA down plus 7 mA up = **4 mA up**
- Superimposing voltages: 6 V (+ top) plus 14 V (− top) = **8 V (− top)**

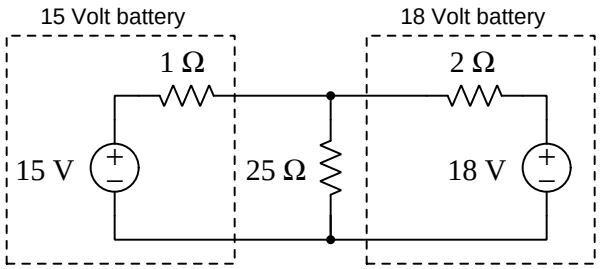
Power dissipations once again do *not* superimpose correctly. The single-source dissipation values of 18 mW and 98 mW (negative power?) most certainly do not add up to (−)80 mW, as we know the true power dissipation with both sources active will be 32 mW ($P = IV$ with 8 V and 4 mA at the resistor)!

2.5 Example: Two paralleled batteries

Having applied the Superposition Theorem to two simplistic circuits, let us now apply it to a circuit worthy of the theorem. We will choose for our example a circuit where one resistive load is powered by two parallel-connected batteries. The batteries' voltages are unequal, as are their internal resistances:



If we re-draw the circuit to model each real battery as a combination of an ideal voltage source with a series-connected resistance, we will see why we need the Superposition Theorem to calculate voltages and currents:



A simplifying Theorem is necessary to analyze this circuit because no two resistances are directly in series or directly in parallel with each other[2], and therefore we cannot compute a total resistance. While it should be clear that both batteries contribute to the powering of the resistor, it is not intuitive exactly how much of a contribution each battery makes.

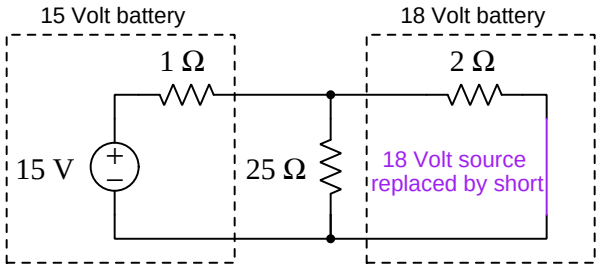
Our analysis of this circuit will proceed similarly to the previous examples: we will consider the effects of each voltage source one at a time on circuit voltages and currents, then algebraically sum those voltages and currents to determine voltage and current in the circuit with both sources active. Since the batteries are real and not ideal voltage sources, when we disable each one we will maintain its internal resistance in place while shorting the ideal-source portion of the model.

Despite the fact that our basic procedure for applying Superposition Theorem to this circuit will remain the same as the prior examples, more calculations will be necessary simply due to the fact that this circuit contains more resistors than either of the previous examples. May this stand as a general caveat: just because a network theorem simplifies the *complexity* of a problem, doesn't mean the solution will not be *tedious*. In fact, a great many problem-solving techniques function by

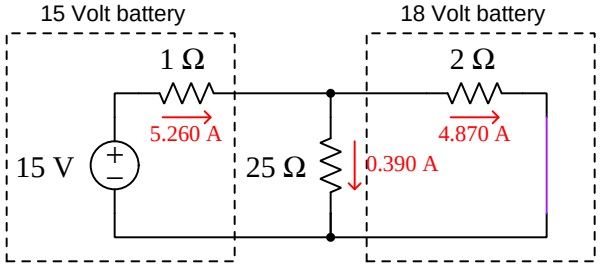
[2]Recall that the definition of a series network is one where all components constitute a single path for current (i.e. all components are connected *in-line* with each other). Recall as well that a parallel network is one where all components span the same two sets of electrically-common points (i.e. all components are connected *across* one another). The resistors in this dual-battery circuit fail to meet either criterion, and so are neither in series nor in parallel with each other.

substituting tedium for complexity, converting a problem too difficult for you to solve at all into a series of smaller problems you *can* solve.

First, we will analyze this circuit with just the 15 V battery active:



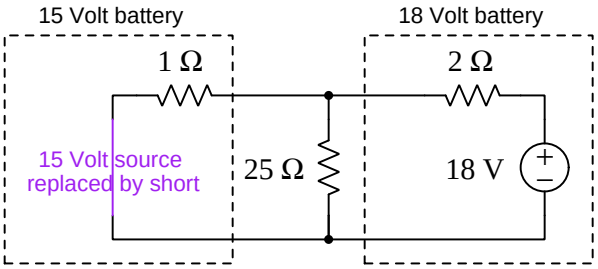
With the 18 V source disabled, the three resistors form a series-parallel network with the 25 Ω and 2 Ω in parallel, and the 1 Ω in series with that parallel subnetwork, all powered by the 15 V source. We could calculate all voltage drops and all currents, but for the sake of simplicity we will only calculate currents. Once we superimpose all the calculated current values, we will be able to determine voltage drops from those:



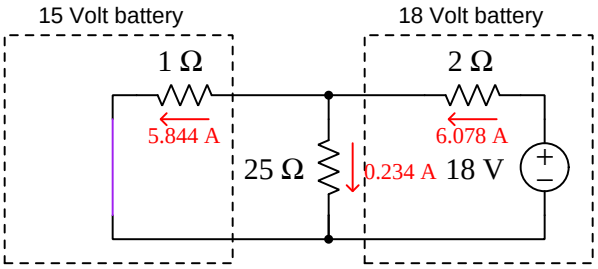
Summarizing the results:

- Current through 15 V battery = 5.260 A (right)
- Current through 18 V battery = 4.870 A (right)
- Current through 25 Ω load = 0.390 A (down)

Next, we will analyze this circuit with just the 18 V battery active:



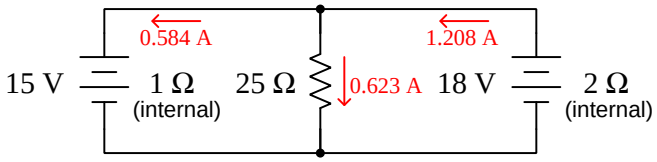
With the 15 V source disabled, the three resistors form a different series-parallel network with the 25 Ω and 1 Ω in parallel, and the 2 Ω in series with that parallel subnetwork, all powered by the 18 V source. Calculating currents as before:



Superimposing these results with the previous:

- Current through 15 V battery = 5.844 A (left) − 5.260 A (right) = 0.584 A (left)
- Current through 18 V battery = 6.078 A (left) − 4.870 A (right) = 1.208 A (left)
- Current through 25 Ω load = 0.390 A (down) + 0.234 A (down) = 0.623 A (down)

Annotating our original schematic diagram with these currents, we see that the 15 V battery actually functions as a *load* while the 18 V battery is the only operating *source* in the circuit[3]:

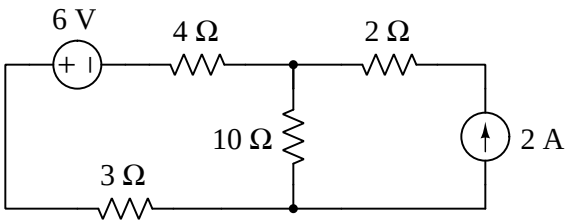


Terminal voltage for both batteries, equal to load voltage assuming connecting wires of negligible resistance, will be 15.584 Volts as predicted by Ohm's Law ($V = IR = (0.623\ \text{A})(25\ \Omega) = 15.584\ \text{V}$).

[3]Recall the functional definition of an electrical load, where electric charge carriers enter at higher energy (+) than they exit (−). A source draws charge carriers in at lower energy (−) and ejects them out at higher energy (+). In this dual-battery circuit, the 18 V "source" battery is depleting its internal energy reserve as it discharges, while the 15 V "load" battery is being *charged* by the 18 V battery.

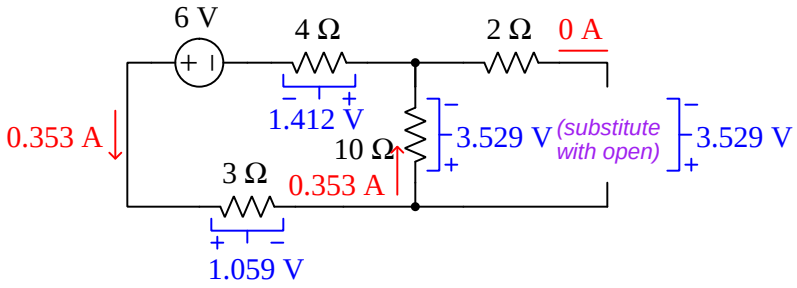
2.6 Example: Voltage source and current source

The last example circuit we will examine is the following, containing both a voltage source and a current source:

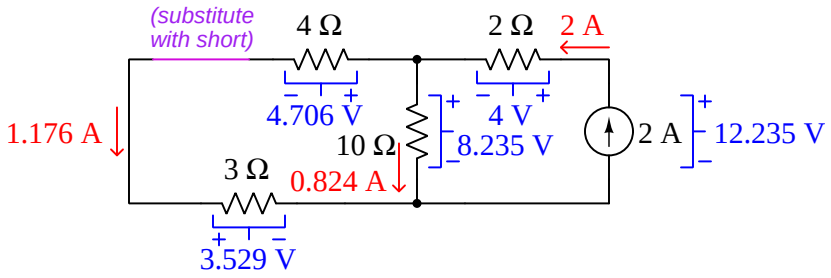


As with the "Two paralleled batteries" example, this circuit really demands a network theorem, as it is impossible to regard it as a simple series-parallel network. With both sources in place, it is impossible to condense all resistances into a single equivalent resistance as we would do in a normal series-parallel resistor network.

For our first step, we will analyze the circuit with only the voltage source active, replacing the current source with its equivalent internal resistance (i.e. open). Another way to conceptualize the de-activation of a current source is to set its current value to zero, and since we know the guaranteed effect of an *open* is to prevent current, replacing the current source with an open ensures zero current there. Note the careful marking of voltage polarities and current arrow directions as well as magnitudes, as these will become important when we superimpose the calculated quantities:



Next, we will analyze the circuit with only the current source active, replacing the voltage source with its equivalent internal resistance (i.e. short). Another way to conceptualize the de-activation of a voltage source is to set its voltage value to zero, and since we know the guaranteed effect of a *short* is to prevent voltage, replacing the voltage source with a short ensures zero voltage there:

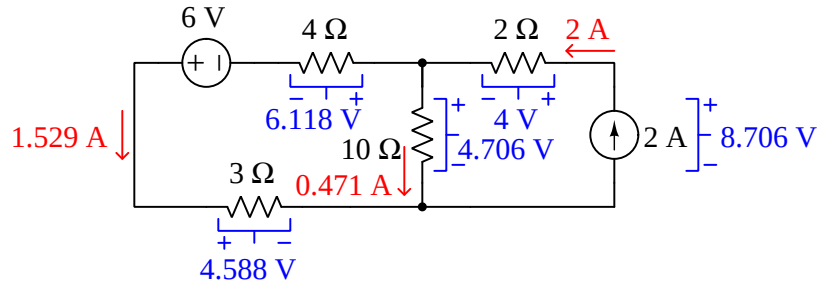


Superimposing the calculated currents:

- 6 V source: 1.176 A (left) + 0.353 A (left) = **1.529 A** (left)
- 2 A source: 0 A + 2 A (up) = **2 A** (up)
- 10 Ω resistor: 0.824 A (down) − 0.353 A (up) = **0.471 A** (down)

Superimposing the calculated voltages:

- 2 A source: 12.235 V (+ up) − 3.529 V (+ down) = **8.706 V** (+ up)
- 4 Ω resistor: 1.412 V (+ right) + 4.706 V (+ right) = **6.118 V** (+ right)
- 3 Ω resistor: 1.059 V (+ left) + 3.529 (+ left) = **4.588 V** (+ left)
- 10 Ω resistor: 8.235 V (+ up) − 3.529 V (+ down) = **4.706 V** (+ up)
- 2 Ω resistor: 0 V + 4 V (+ right) = **4 V** (+ right)



Tedious though the solution may be, at least each step of it is *possible* with just the tools of series-parallel circuit analysis. As was mentioned previously, this is the hallmark of many problem-solving techniques: exchanging tedium for complexity. It should be evident just *why* the Superposition

Theorem made this formerly intractable problem amenable to ordinary series-parallel analysis as we examine the schematic diagram at each step: by disabling all but one source at a time, *the circuit contains fewer components and therefore becomes simpler*.

Chapter 3

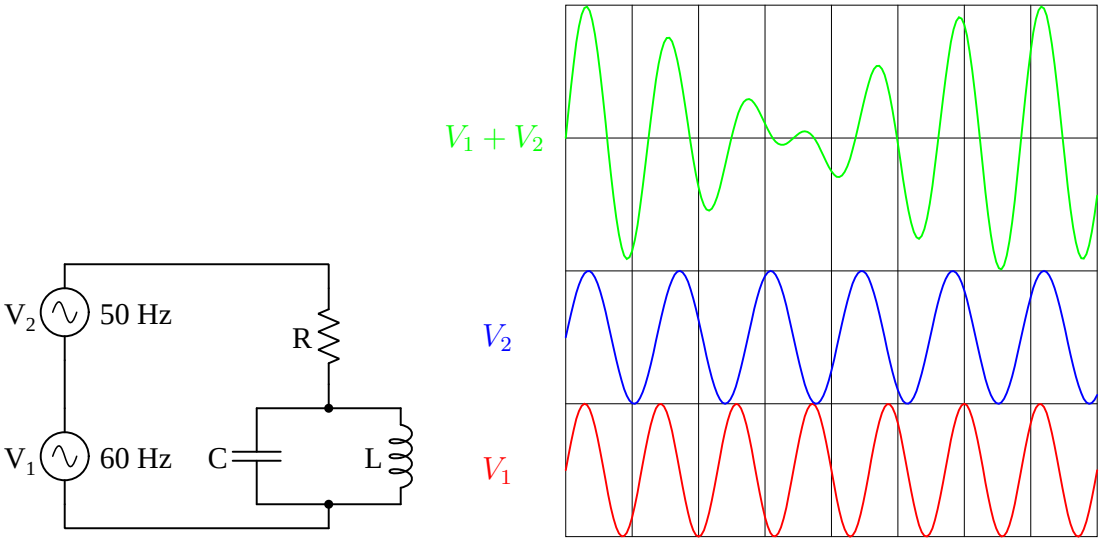
Derivations and Technical References

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

3.1 Superposition of AC signals

This module's Tutorial has focused on Superposition as a concept within DC circuits, whereby DC voltages and/or currents resulting from multiple sources may be superimposed to obtain the aggregate result of those sources working simultaneously. However, the Superposition Theorem is not limited to direct-current (DC) circuits, but also applies to alternating-current (AC) circuits as well, so long as the components in question behave linearly.

Consider a simple AC circuit powered by two series-connected sinusoidal voltage sources *of differing frequency*. The sum of these two AC sources will *not* be sinusoidal, and this complicates analysis of the circuit:



Computing voltages and currents in any resistor-capacitor-inductor network is easy enough using *phasor* mathematics to represent simple sine-shaped AC waveforms. However, as we see in the graphical plot, the sum $V_1 + V_2$ is most definitely *not* a simple sine wave and so phasor techniques fail.

However, since we know resistors and capacitors and inductors are all *linear* components, we know that the Superposition Theorem applies. This means we may calculate any voltage or current in this network by calculating that voltage or current twice (once for each of the two AC sources considered by itself with the other source disabled) and then summing the results of those two calculations. The resulting AC voltage or current, like $V_1 + V_2$, will not be a simple sine wave, but at least we are able to compute it using mathematical techniques that work *only* with simple sine waves.

This basic concept of superimposed sinusoidal AC voltages/currents has many theoretical and practical applications, including the following:

- The **Fourier series** – This is the theoretical equivalence between *any* repeating ("periodic") function and the sum (i.e. superposition) of multiple sinusoidal functions of integer-multiple frequencies to the original waveform's over-all period. For example, a square-wave function is mathematically equivalent to $\sin(\omega t) + \frac{1}{3}\sin(3\omega t) + \frac{1}{5}\sin(5\omega t) + \cdots + \frac{1}{n}\sin(n\omega t)$. The remarkable thing about the Fourier series is that, at least in theory, we may simulate *any* periodic waveform whatsoever as a particular series of sine and cosine functions at different frequencies and amplitudes. Some of these series may be infinite, as for square waves, but others are not.

- **Harmonics** – This is really just an expression of the Fourier series. Any non-sinusoidal voltage or current waveform in a circuit acts like the sum (i.e. superposition) of multiple sinusoidal waveforms at different amplitudes and frequencies. A remarkable phenomenon is when some change made to a single-source AC circuit distorts the wave-shape of an AC voltage or current so that it no longer resembles a perfect sinusoid, that circuit begins to behave as through it is being powered by *multiple* superimposed AC sources at different frequencies and amplitudes rather than by a single source! A computational technique called a *Fourier Transform* (FT) is able to compute those sinusoidal signals, thereby "separating" a non-sinusoidal signal into a collection of definite sinusoidal signals.

- **Symmetrical components** – This is the theoretical equivalence between an imbalanced set of phasors in a three-phase AC circuit and the sum (i.e. superposition) of *three* sets of balanced phasors with specific properties: one set rotating the normal direction, another set rotating backwards, and a third set where all three phasors share the same angle. Similar to harmonics, these "other" phasor sets "appear" any time a circuit alteration causes the normally-balanced phasors to become imbalanced (e.g. during fault conditions in a three-phase AC power network).

- **Biasing** – This is where a DC "offset" or "bias" signal is added to (i.e. superimposed with) an AC signal, usually for the purpose of "tricking" some semiconductor device to remain in its conductive state throughout the AC signal's waveform.

- **Audio mixing** – An electronic device used in many professional audio performance and recording settings is a *mixing console*, whereby AC signals from a variety of individual sound sources are summed together to produce a "mixed" signal representing the whole audio experience. The audio signals originate from such devices as microphones and musical instrument "pickup" sensors, with the relative "weighting" of each signal manually adjusted by manually-adjusted potentiometers. A person with the title of *sound engineer* makes adjustments to these potentiometers to achieve the over-all desired effect, which is an aesthetically proper balance of sound sources. The audio power signal sent to the loudspeakers (or to the recording device) represents a superposition of every audio channel's signal fed to the mixing console, the result (ideally) being the same as though every audience member were simultaneously listening to each sound produced by the performers.

Chapter 4

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?

4.1 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.

4.1.1 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.

4.1.2 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.

Network theorem

Series

Parallel

Electrical source

Electrical load

Voltage source

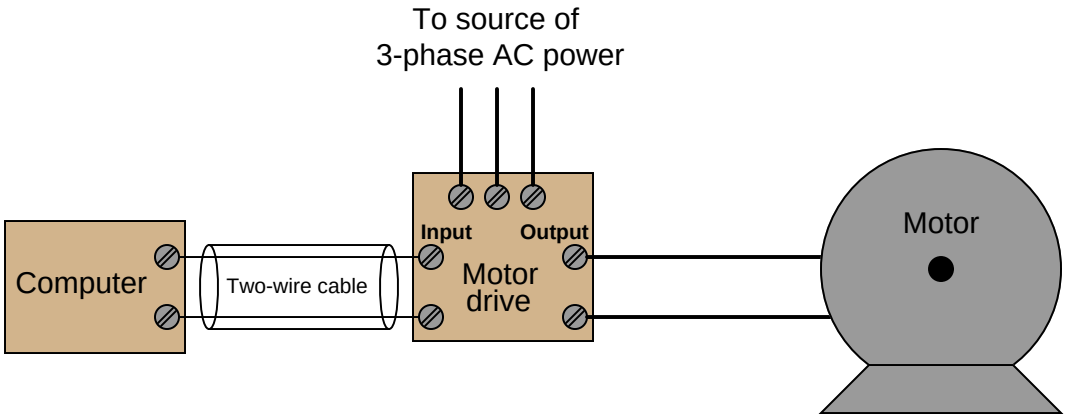
Current source

Strategy for analyzing a series-parallel resistor circuit

Superposition

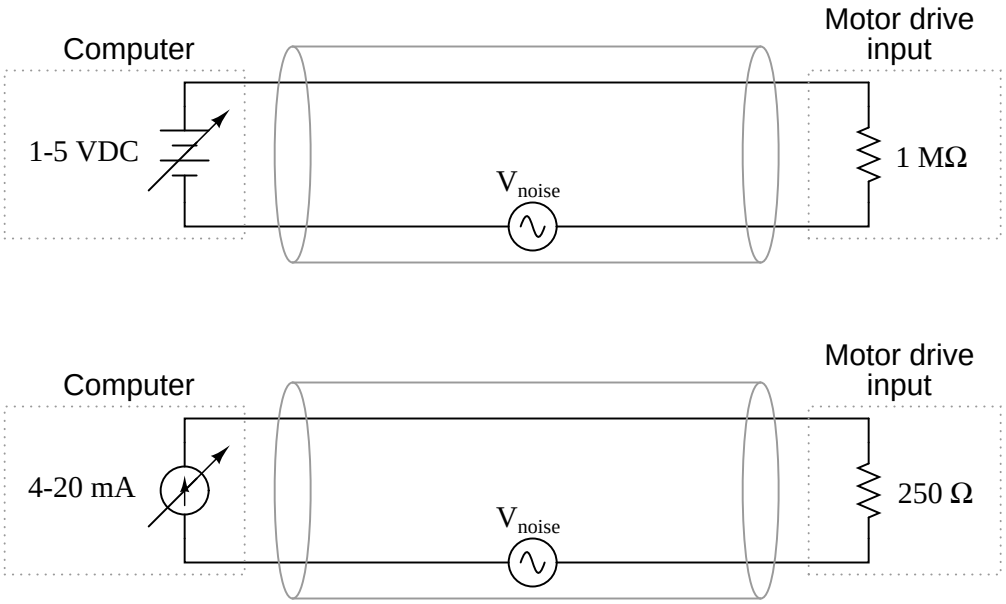
4.1.3 1-5 VDC versus 4-20 mA signaling

Electrical signals are frequently used in industrial control applications to communicate information from one device to another. An example of this is motor speed control, where a computer outputs a speed command signal to a motor "drive" circuit, which then provides metered power to an electric motor:



Two common standards for analog control signals are 1-5 Volts DC and 4-20 mA DC. In either case, the motor will spin faster when this signal from the computer grows in magnitude (1 Volt = motor stopped, 5 Volts = motor runs at full speed; or 4 mA = motor stopped, 20 mA = motor runs at full speed).

At first, it would seem as though the choice between 1-5 Volts and 4-20 mA as control signal standards is arbitrary. However, one of these standards exhibits much greater immunity to induced noise along the two-wire cable than the other. Shown here are two equivalent schematics for these signal standards, complete with an AC voltage source in series to represent the "noise" voltage picked up along the cable's length:



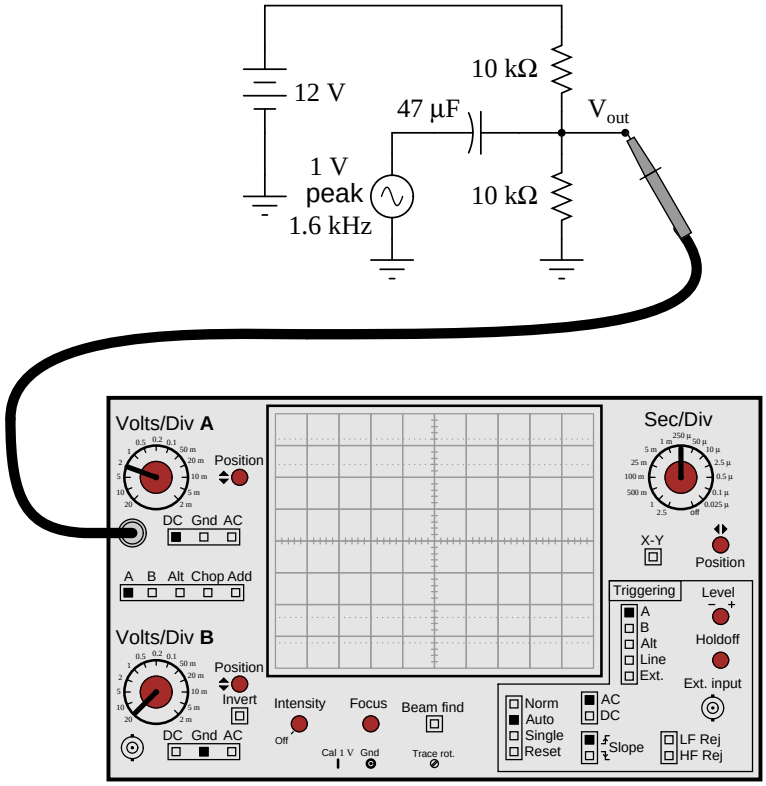
Use the Superposition Theorem to qualitatively determine which signal standard drops the greatest amount of noise voltage across the motor drive input's resistance, thereby most affecting the motor speed control.

Challenges

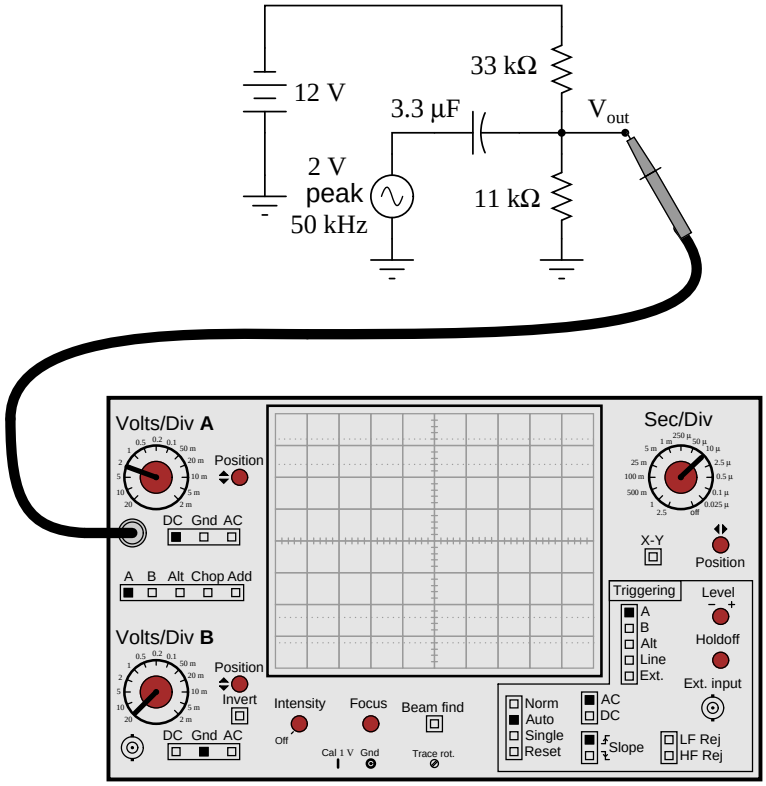
- What undesirable effects do you think noise superimposed on the DC signal cable would have on motor speed control?
- Why do you suppose the 1-5 Volt signal system requires a much greater input impedance (1 MΩ) than the 4-20 mA signal system? What might happen to the voltage signal received at the motor drive's input terminals if the input resistance were much less?

4.1.4 Mixed AC/DC network

Sketch the approximate waveform of this circuit's output signal (V_{out}) on the screen of the oscilloscope:



Sketch the approximate waveform of this circuit's output signal (V_{out}) on the screen of the oscilloscope:



Challenges

- Explain why it is acceptable to use a polarized (polarity-sensitive) capacitor in this circuit when it is clearly connected to a source of AC. Why is it not damaged by the AC voltage when used like this?

4.2 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.

4.2.1 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.

4.2.2 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	

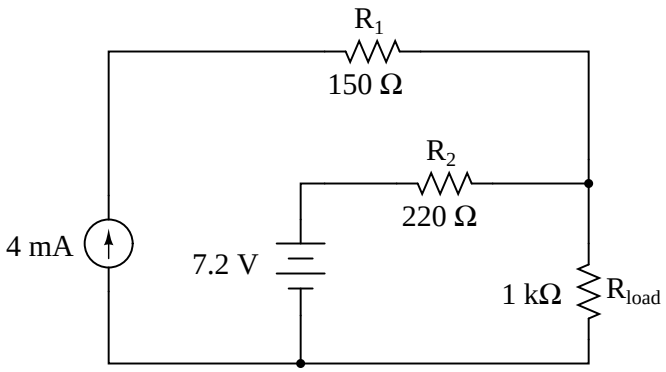
Note how the square-root term (y) is calculated in cell `C1`, and the denominator term (z) in cell `C2`. This makes the two final formulae (in cells `B1` and `B2`) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly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

4.2.3 Two-source, three-resistor network

Explain in your own words how to apply the *Superposition Theorem* to calculate the amount of current through the load resistor in this circuit, and calculate its value:

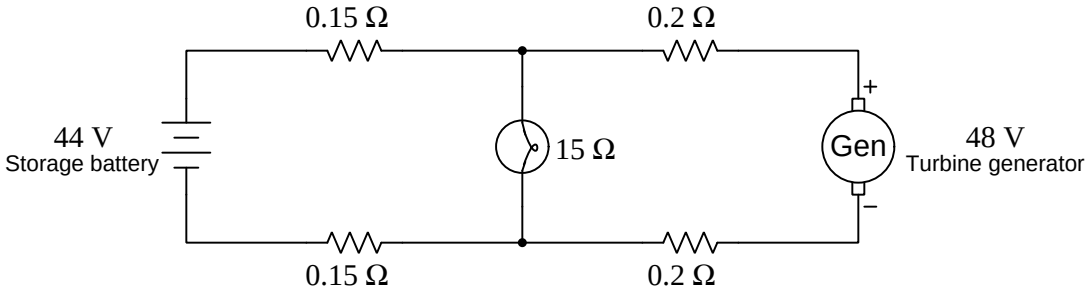


Challenges

- Describe how the voltage source and current source are regarded differently from one another in your application of the Superposition Theorem.
- Is either source in this circuit actually functioning as a load? How can we tell?

4.2.4 Wind turbine and battery network

A wind turbine generator and a storage battery work together to supply DC power to an electric lamp. Calculate the amount of current through each of these three components, given the values shown in the schematic diagram. Assume internal resistances of the generator and battery to be negligible:



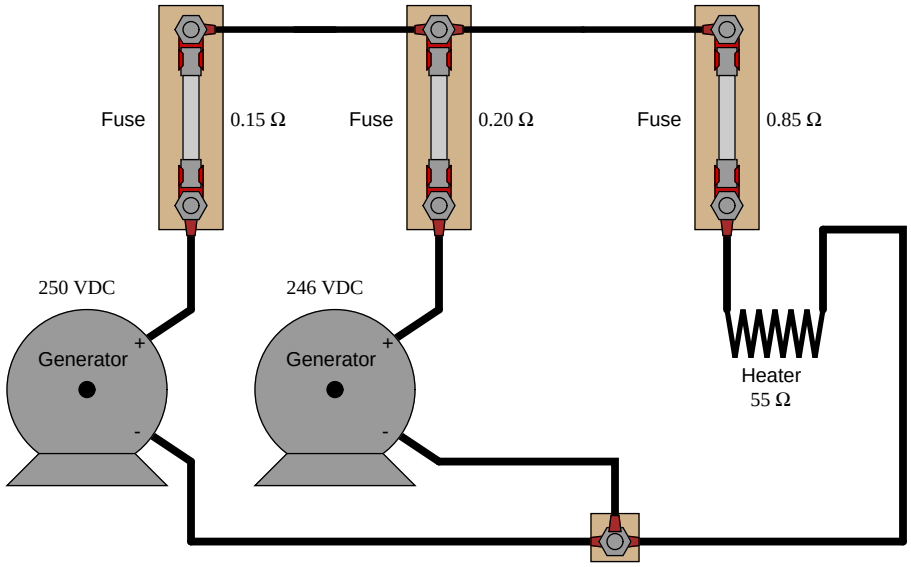
$I_{batt} =$ $I_{bulb} =$ $I_{gen} =$

Challenges

- Is either the generator or the battery in this circuit functioning as a load? How can we tell?
- Would we ever desire the battery to function as a load?
- Would we ever desire the generator to function as a load?

4.2.5 Two generators powering a heating element

Use the Superposition Theorem to calculate the amount of current going through the 55 Ω heater element. Ignore all wire and connection resistances, only considering the resistance of each fuse in addition to the heater element resistance:

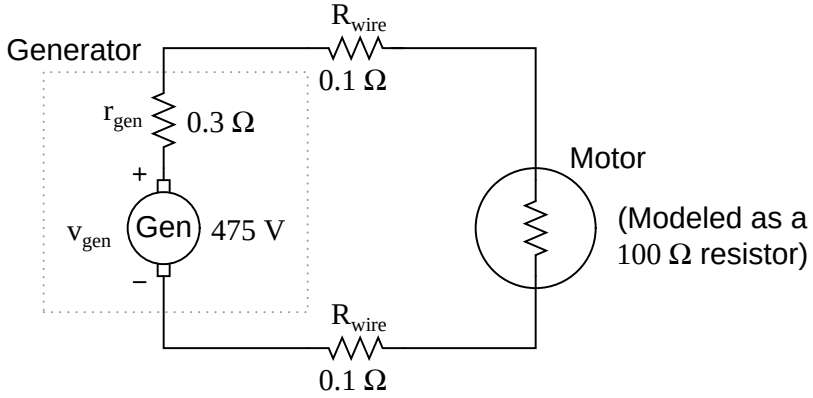


Challenges

- Explain how you could use the Superposition Theorem to calculate current going through the short length of wire connecting the two generator fuses together.
- Is either generator in this circuit functioning as a load? How can we tell?

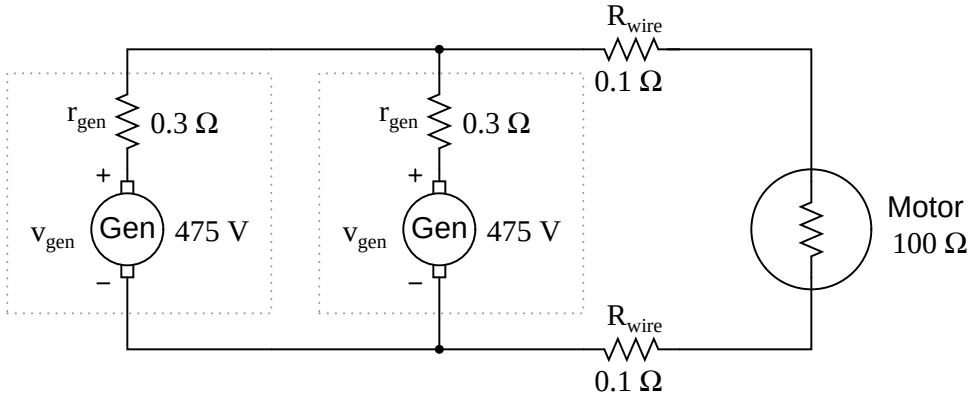
4.2.6 Two generators powering a motor

Suppose a DC generator is powering an electric motor, the latter we will model as a 100 Ω resistor:



Calculate the amount of current this generator will supply to the motor and the voltage measured across the motor's terminals, taking into account all the resistances shown (generator internal resistance r_{gen}, wiring resistances R_{wire}, and the motor's equivalent resistance).

Now suppose we connect an identical generator in parallel with the first, using connecting wire so short that we may safely discount its additional resistance:



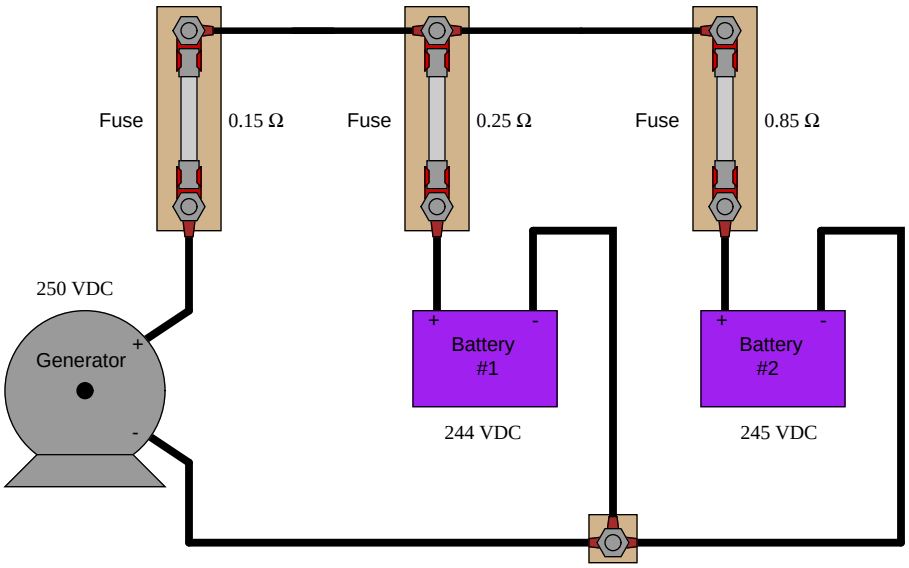
Use the Superposition Theorem to re-calculate the motor current and motor terminal voltage, commenting on how these figures compare with the first calculation (using only one generator).

Challenges

- How much current does each generator supply to the circuit when there are two generators connected in parallel?
- Is either generator in this circuit functioning as a load? How can we tell?

4.2.7 One generator and two batteries

Calculate the current through each battery using the Superposition Theorem. Feel free to ignore all wire and connection and battery internal resistances – only consider the resistance of each fuse:



Challenges

- Identify any safety hazards that could arise as a result of excessive resistance in the fuse holders (e.g., corrosion build-up on the metal tabs where the fuse clips in to the fuse-holder).
- Are the two batteries behaving as loads, sources, or one of each?

4.3 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.

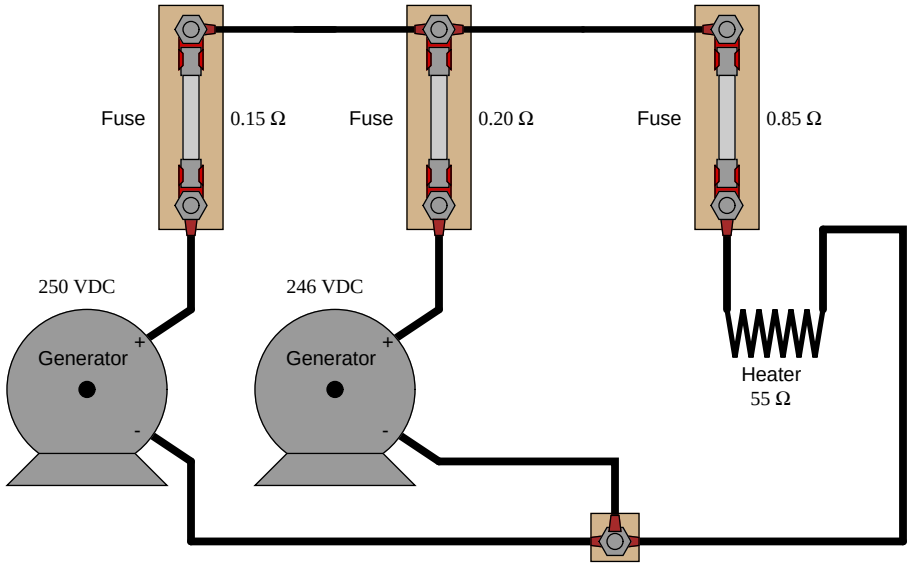
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of 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.

4.3.1 Actually disabling a source

When applying the Superposition Theorem, we consider how a multi-source circuit will behave while only being powered by one source at a time. Identify a realistic fault that could result in this circuit *actually* having only one active source (while the other source is disabled in the same manner as we assume for Superposition analyses):



Challenges

- What would happen if the heater element failed open?

Chapter 5

References

Chapter 6

Version history

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

1 October 2025 – added a frameboxed title for the Superposition Theorem. Also corrected a typographical error courtesy of Wyatt Gleason.

2 March 2025 – minor edits to the Tutorial.

2 October 2024 – added another "Challenging concepts" bullet-item to the list in the Introduction chapter.

23 September 2024 – divided the Introduction chapter into sections, one with recommendations for students, one with a listing of challenging concepts, and one with recommendations for instructors. Also eliminated the Projects and Experiments chapter.

10-11 October 2022 – minor additions to the Tutorial chapter, providing alternative conceptualizations for the disabling of current sources and voltage sources in Superposition analysis. Also changed a few instances of "volts" to "Volts".

7 March 2022 – added some questions to the Introduction chapter.

11 October 2021 – added some instructor notes.

9 July 2021 – replaced some TeX-style italicizing markup with LaTeX-style.

18 March 2021 – minor additions to the Introduction, and minor edits to the Tutorial. Also added some labels to image_2033.

8 October 2020 – minor additions to the Introduction, and minor edits to the Tutorial.

29 September 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.

17 April 2020 – added more sections to the Tutorial.

12 September 2019 – altered capitalization of "Theorem" in two places.

11 September 2019 – added Technical Reference on superposition as a concept applicable to AC signals of differing frequency. Also added another Example circuit to the Tutorial, and corrected some typographical errors.

5 September 2019 – completed Tutorial and began adding questions.

3 September 2019 – continued writing Tutorial.

30 August 2019 – document first created.

Index

Audio mixer, 21

Biasing, 21

Fourier series, 21
Fourier transform, 21

Greenleaf, Cynthia, 23

Harmonics, 21
Heavy versus light load, 9

Isosceles Triangle Theorem, 3

Linear component, 10
Load, heavy versus light, 9

Metacognition, 28
Mixing, audio, 21
Murphy, Lynn, 23

Nonlinear component, 10

Ohm's Law, 10
Open, 16

Parallel network, 13

Reading Apprenticeship, 23

Schoenbach, Ruth, 23
Scientific method, 28
Series network, 13
Short, 17
SPICE, 23
Superposition theorem, 10
Symmetrical components, 21

Theorem, Isosceles Triangle, 3
Transform, Fourier, 21