

**Recommended schedule**

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Day 1

Topics: *Parallel circuits, current sources, and troubleshooting*

Questions: *1 through 20*

Lab Exercises: *Parallel resistances (question 61)*

**Demo: Show how to set up regulated power supply for sourcing fixed amount of current**

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Day 2

Topics: *Parallel circuits, Kirchhoff's Current Law, and chemical batteries*

Questions: *21 through 40*

Lab Exercise: *Parallel DC resistor circuit (question 62)*

**MIT 6.002 video clip: Disk 1, Lecture 2; Kirchhoff's Current Law 10:36 to 12:51**

**MIT 8.02 video clip: Disk 2, Lecture 10; Battery demonstration 11:38 to 15:00**

**MIT 8.02 video clip: Disk 2, Lecture 10; Shorting a 9-V battery 26:47 to 28:29**

**MIT 8.02 video clip: Disk 2, Lecture 10; Shorting a 12-V car battery 29:22 to 31:18**

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Day 3

Topics: *Parallel circuits, current divider circuits, and temperature coefficient of resistance*

Questions: *41 through 60*

Lab Exercise: *Parallel DC resistor circuit (question 63)*

**Demo: Measure resistance of a magnet wire spool, both cold and room temperature**

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Day 4

Exam 3: *includes Parallel DC resistor circuit performance assessment*

**Troubleshooting assessment due: Simple lamp circuit**

Question 64: Troubleshooting log

Question 65: Sample troubleshooting assessment grading criteria

**Project due: Solder-together electronic kit**

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Troubleshooting practice problems

Questions: *66 through 75*

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General concept practice and challenge problems

Questions: *76 through the end of the worksheet*

Skill standards addressed by this course section

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*EIA Raising the Standard; Electronics Technician Skills for Today and Tomorrow, June 1994*

**B Technical Skills – DC circuits**

- B.02** Demonstrate an understanding of principles and operation of batteries.
- B.03** Demonstrate an understanding of the meaning of and relationships among and between voltage, current, resistance and power in DC circuits.
- B.05** Demonstrate an understanding of application of Ohm's Law to series, parallel, and series-parallel circuits.  
*Partially met – parallel circuits only.*
- B.11** Understand principles and operations of DC parallel circuits.
- B.12** Fabricate and demonstrate DC parallel circuits.
- B.13** Troubleshoot and repair DC parallel circuits.

**B Basic and Practical Skills – Communicating on the Job**

- B.01** Use effective written and other communication skills. *Met by group discussion and completion of labwork.*
- B.03** Employ appropriate skills for gathering and retaining information. *Met by research and preparation prior to group discussion.*
- B.04** Interpret written, graphic, and oral instructions. *Met by completion of labwork.*
- B.06** Use language appropriate to the situation. *Met by group discussion and in explaining completed labwork.*
- B.07** Participate in meetings in a positive and constructive manner. *Met by group discussion.*
- B.08** Use job-related terminology. *Met by group discussion and in explaining completed labwork.*
- B.10** Document work projects, procedures, tests, and equipment failures. *Met by project construction and/or troubleshooting assessments.*

**C Basic and Practical Skills – Solving Problems and Critical Thinking**

- C.01** Identify the problem. *Met by research and preparation prior to group discussion.*
- C.03** Identify available solutions and their impact including evaluating credibility of information, and locating information. *Met by research and preparation prior to group discussion.*
- C.07** Organize personal workloads. *Met by daily labwork, preparatory research, and project management.*
- C.08** Participate in brainstorming sessions to generate new ideas and solve problems. *Met by group discussion.*

**D Basic and Practical Skills – Reading**

- D.01** Read and apply various sources of technical information (e.g. manufacturer literature, codes, and regulations). *Met by research and preparation prior to group discussion.*

**E Basic and Practical Skills – Proficiency in Mathematics**

- E.01** Determine if a solution is reasonable.
- E.02** Demonstrate ability to use a simple electronic calculator.
- E.05** Solve problems and [sic] make applications involving integers, fractions, decimals, percentages, and ratios using order of operations.
- E.06** Translate written and/or verbal statements into mathematical expressions.
- E.12** Interpret and use tables, charts, maps, and/or graphs.
- E.13** Identify patterns, note trends, and/or draw conclusions from tables, charts, maps, and/or graphs.
- E.15** Simplify and solve algebraic expressions and formulas.
- E.16** Select and use formulas appropriately.
- E.17** Understand and use scientific notation.

**Common areas of confusion for students**

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**Difficult concept:** *Using Ohm's Law in context.*

When applying Ohm's Law ( $E = IR$  ;  $I = \frac{E}{R}$  ;  $R = \frac{E}{I}$ ) to circuits containing multiple resistances, students often mix contexts of voltage, current, and resistance. Whenever you use any equation describing a physical phenomenon, be sure that each variable of that equation relates to the proper real-life value in the problem you're working on solving. For example, when calculating the current through resistor  $R_2$ , you must be sure that the values for voltage and resistance are appropriate for that resistor and not some other resistor in the circuit. If you are calculating  $I_{R_2}$  using the Ohm's Law equation  $I = \frac{E}{R}$ , then you must use the value of *that resistor's* voltage ( $E_{R_2}$ ) and *that resistor's* resistance ( $R_2$ ), not some other voltage and/or resistance value(s). Some students have an unfortunate tendency to overlook context when seeking values to substitute in place of variables in Ohm's Law problems, and this leads to incorrect results.

**Difficult concept:** *The path of least resistance.*

A common electrical adage is that "Electricity always follows the path of least resistance." This is only partly true. Given two or more paths of differing resistance, more current will flow through the path of least resistance, but this does not mean there will be zero current through the other path(s)! The saying should probably be revised to state that "Electricity *proportionately* favors the path of least resistance." Be careful not to blindly follow some truism about electricity, but always think quantitatively about voltage and current values if possible! Perform some Ohm's Law calculations on parallel circuit branches to convince yourself of how current "favors" lesser resistances, or measure currents in your own safe, low-voltage circuits to see firsthand how it works.

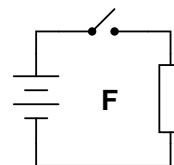
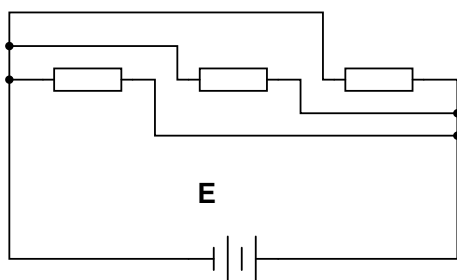
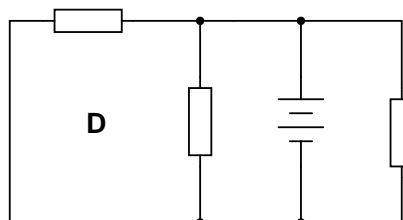
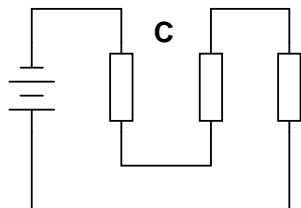
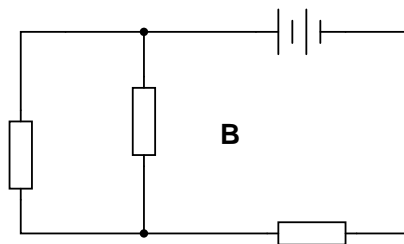
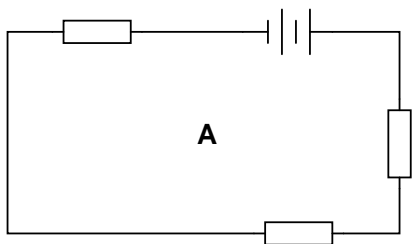
**Difficult concept:** *Parallel resistances diminishing.*

Series resistances are easy to conceptually manage: it just makes sense that multiple resistors connected end-to-end will result in a total resistance equal to the sum of the individual resistances. However, parallel resistances are not as intuitive. That some total quantity (total resistance) actually *decreases* as individual quantities accumulate (resistors connected in parallel) may seem impossible, usually because the word "total" is generally associated with addition.

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Question 1

Identify which of these circuits is a *parallel* circuit (there may be more than one shown!):



file 01718

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Answer 1

Circuits **D** and **E** are *parallel* circuits.

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Notes 1

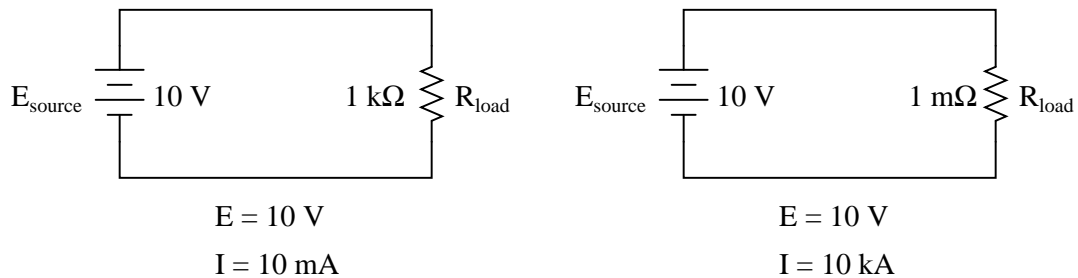
The purpose of this question is to get students to identify what distinguishing characteristic uniquely identifies a circuit as being "parallel." Once this has been identified, there are several conclusions which may be deduced (regarding voltage drops, currents, resistances, etc.).

Some students may have difficulty distinguishing that circuit **E** is a parallel circuit, but it is!

## Question 2

A *voltage source* is a source of electricity that (ideally) outputs a constant voltage. That is, a perfect voltage source will hold its output voltage constant regardless of the load imposed upon it:

### *Ideal voltage sources assumed*



In real life, there is no such thing as a perfect voltage source, but sources having extremely low internal resistance come close.

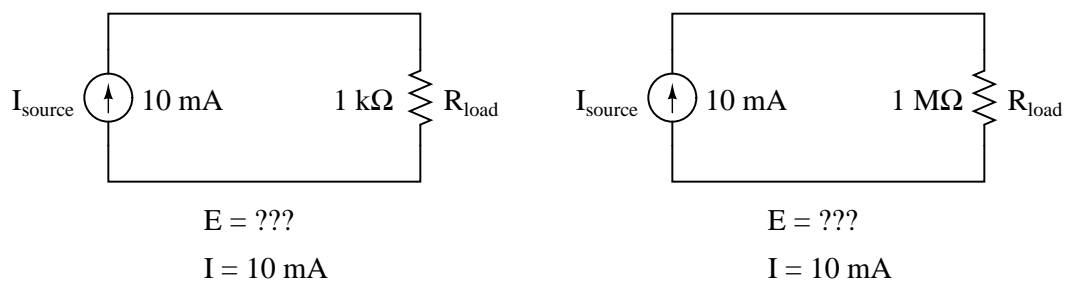
Another type of electricity source is the *current source*, which (ideally) outputs a constant current regardless of the load imposed upon it. A common symbol for a current source is a circle with an arrow inside (always pointing in the direction of conventional flow, not electron flow!). Another symbol is two intersecting circles, with an arrow nearby pointing in the direction of conventional flow:

### *Current sources*



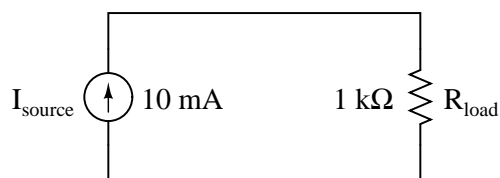
Predict how an ideal current source would behave for the following two load scenarios:

### *Ideal current sources assumed*

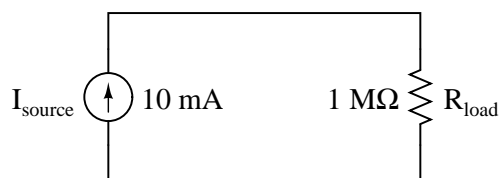


file 01735

*Ideal current sources assumed*



$E = 10 \text{ V}$   
 $I = 10 \text{ mA}$



$E = 10 \text{ kV}$   
 $I = 10 \text{ mA}$

Follow-up question: identify the polarity of the voltage drops across the resistors in the circuits shown above.

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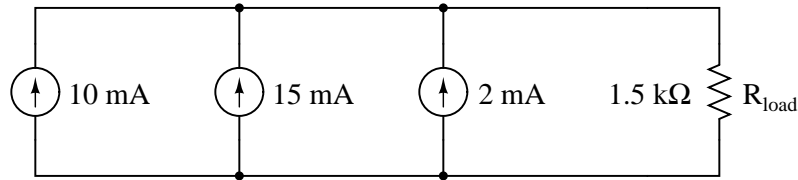
Notes 2

Let students know that there really is such a thing as a perfect current source, just as there is no such thing as a perfect voltage source. However, there are devices that closely approximate ideal current sources (current transformers in AC circuits and "current mirror" DC transistor circuits, for example).

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Question 3

Calculate the total current output to the load resistor by this set of parallel-connected current sources:



Also, calculate the voltage dropped across  $R_{\text{load}}$ .  
[file 01736](#)

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Answer 3

The total current in this circuit is 27 mA, and the load voltage is 40.5 volts.

Follow-up question: trace the direction of current through all three sources as well as the load resistor. Compare these directions with the polarity of their shared voltage. Explain how the relationship between voltage polarity and current direction relates to each component's identity as either a *source* or a *load*.

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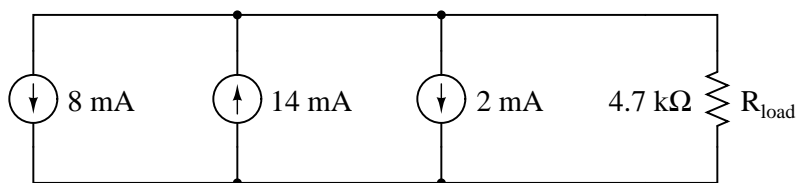
Notes 3

Have your students collectively agree on a procedure they may use to accurately discern series voltage sums and polarities. Guide their discussion, helping them identify principles that are true and valid for all series circuits.

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Question 4

Calculate the total current output to the load resistor by this set of parallel-connected current sources:



Also, calculate the voltage dropped across  $R_{\text{load}}$ .

file 01737

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Answer 4

The total current in this circuit is 4 mA, and the load voltage is 18.8 volts.

Follow-up question: indicate the polarity of the voltage across the load resistor with "+" and "-" symbols.

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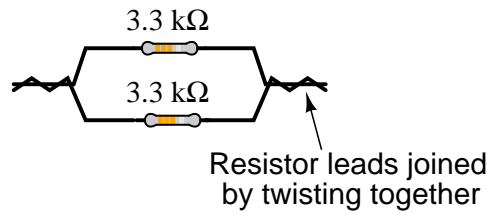
Notes 4

Have your students collectively agree on a procedure they may use to accurately discern series voltage sums and polarities. Guide their discussion, helping them identify principles that are true and valid for all series circuits.

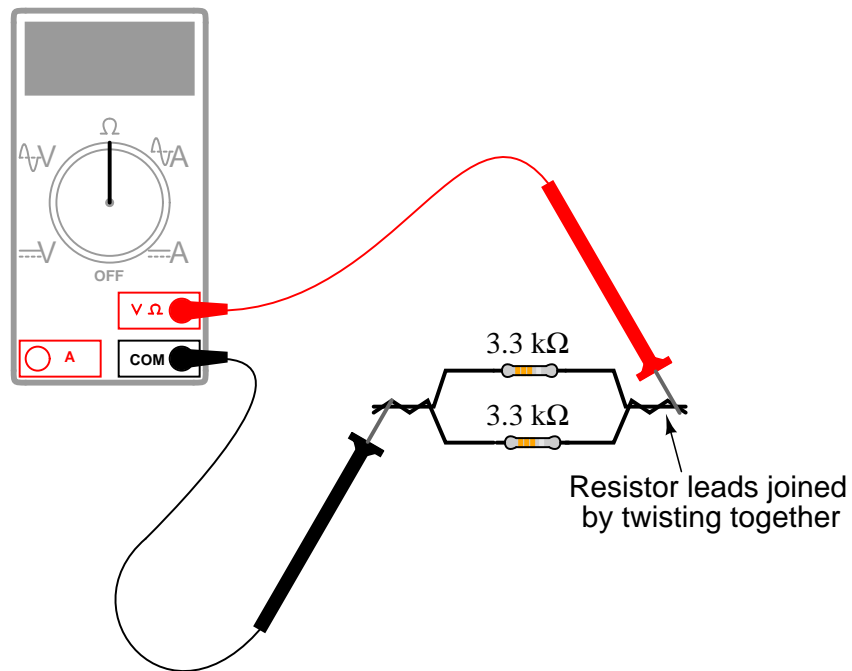


Question 5

Suppose I connect two resistors in parallel with one another, like this:

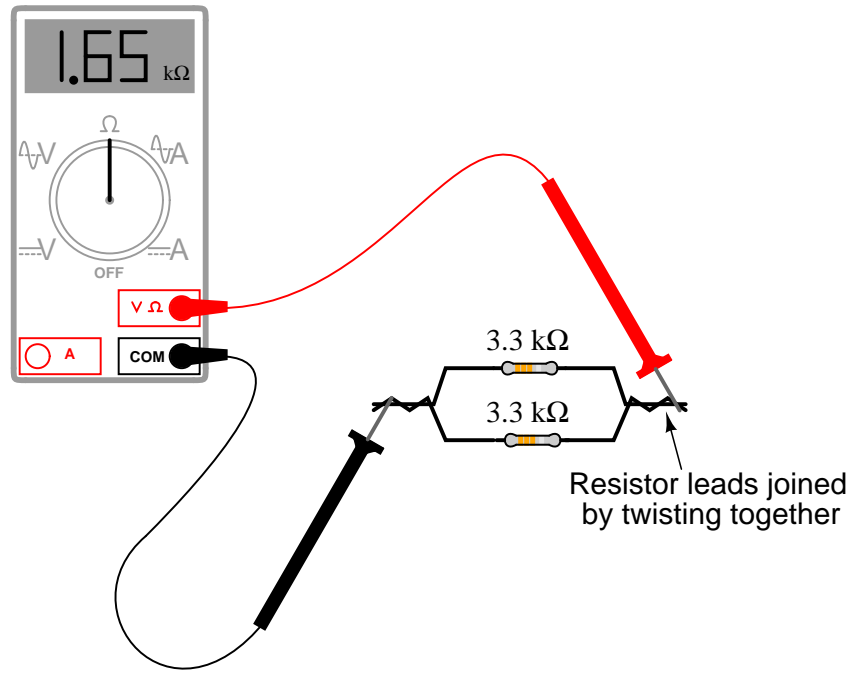


How much electrical resistance would you expect an ohmmeter to indicate if it were connected across the combination of these two parallel-connected resistors?



Explain the reasoning behind your answer, and try to formulate a generalization for all combinations of parallel resistances.

[file 01731](#)



Follow-up question: how much resistance would you expect the ohmmeter to register if there were *three* similarly-sized resistors connected in parallel instead of two? What if there were *four* resistors?

Notes 5

The concept of parallel (total) resistance, in relation to individual resistances, often confuses new students. Be sure to allow plenty of discussion time to work through the conceptual difficulties with them.

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Question 6

There are two well-known formulae for calculating the total resistance of parallel-connected resistances. One of these works only for two resistances, while the other works for any number of parallel resistances. Write these two formulae, and give examples of their use.

[file 01733](#)

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Answer 6

$$R_{parallel} = \frac{R_1 R_2}{R_1 + R_2}$$

$$R_{parallel} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \cdots + \frac{1}{R_n}}$$

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Notes 6

Although I typically use the lower formula exclusively in my teaching, the upper formula is often useful for situations where a calculator is not handy, and you must estimate parallel resistance.

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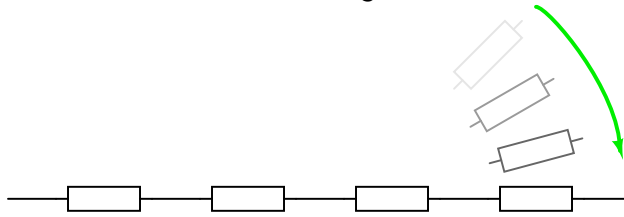
Question 7

A quantity often useful in electric circuit analysis is *conductance*, defined as the reciprocal of resistance:

$$G = \frac{1}{R}$$

In a series circuit, resistance increases and conductance decreases with the addition of more resistors:

*Adding successive resistors in series*

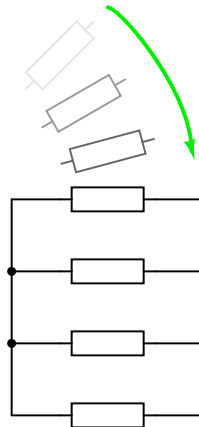


R increases with more resistors

G decreases with more resistors

Describe what happens to total resistance and total conductance with the addition of *parallel* resistors:

*Adding successive resistors in parallel*



file 01734

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Answer 7

When successive resistors are connected in parallel, total resistance *decreases* while total conductance *increases*.

Follow-up question: what is the exact formula that describes total conductance in a network of parallel conductances?

$$G_{total} = ???$$

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Notes 7

Once students recognize the mathematical relationship between resistance and conductance ( $G = \frac{1}{R}$ ), and they realize that parallel conductances add just like series resistances add, it is but a short exercise in algebra to develop the parallel resistance formula ( $R_{parallel} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n}}$ ).

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Question 8

The equation for calculating total resistance in a parallel circuit (for any number of parallel resistances) is sometimes written like this:

$$R_{total} = (R_1^{-1} + R_2^{-1} + \dots + R_n^{-1})^{-1}$$

Re-write this equation in such a way that it no longer contains any exponents.

[file 00297](#)

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Answer 8

$$R_{total} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n}}$$

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Notes 8

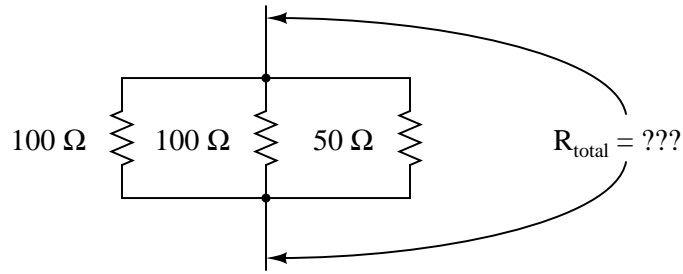
This question is an exercise in basic algebra, specifically the meaning of negative exponents.

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Question 9

There is a simple equation that gives the equivalent resistance of two resistances connected in parallel. Write this equation.

Secondly, apply this two-resistance equation to the solution for total resistance in this three-resistor network:



No, this is not a "trick" question! There *is* a way to apply a two-resistance equation to solve for three resistances connected in parallel.

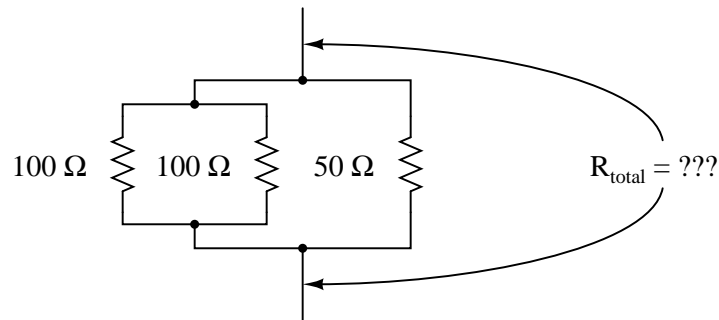
[file 00298](#)

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Answer 9

$$R_{total} = 25 \Omega$$

In case you are still unsure of how to apply the "two-resistance" parallel equation to this network, I'll give you a hint: this equation gives the *equivalent resistance* of two parallel-connected resistors. Examine this modified version of the original schematic diagram:



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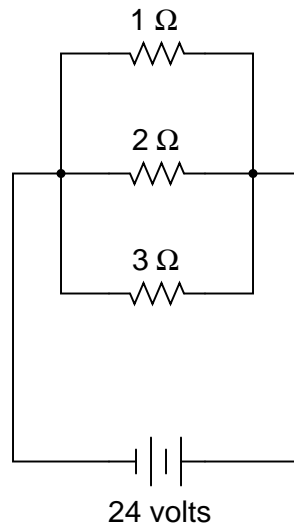
Notes 9

And who said technological work never involves creativity? This question challenges students to apply an equation to a problem that it is not ideally suited for. The basic principle used in the solution of the problem is very practical. It involves the *substitution* of an equivalent component value in place of multiple components, which is a problem-solving technique widely applied in electrical network analysis, as well as other forms of mathematical analysis.

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Question 10

In this circuit, three resistors receive the same amount of voltage (24 volts) from a single source. Calculate the amount of current "drawn" by each resistor, as well as the amount of power dissipated by each resistor:



file 00089

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Answer 10

$$I_{1\Omega} = 24 \text{ amps}$$

$$I_{2\Omega} = 12 \text{ amps}$$

$$I_{3\Omega} = 8 \text{ amps}$$

$$P_{1\Omega} = 576 \text{ watts}$$

$$P_{2\Omega} = 288 \text{ watts}$$

$$P_{3\Omega} = 192 \text{ watts}$$

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Notes 10

The answers to this question may seem paradoxical to students: *the lowest value of resistor dissipates the greatest power*. Math does not lie, though.

Another purpose of this question is to instill in students' minds the concept of components in a simple parallel circuit all sharing the same amount of voltage.

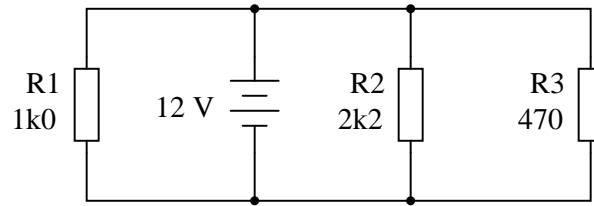
Challenge your students to recognize any mathematical patterns in the respective currents and power dissipations. What can be said, mathematically, about the current drawn by the 2 Ω resistor versus the 1 Ω resistor, for example?

You might want to mention that in electrical parlance, a "heavy" load is one that draws a large amount of current, and thus has a large resistance. This circuit, which shows how the lowest resistance in a parallel circuit consumes the most power, gives practical support to the term "heavy" used to describe loads.

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Question 11

Explain, step by step, how to calculate the amount of current ( $I$ ) that will go through each resistor in this parallel circuit, and also the voltage ( $V$ ) dropped by each resistor:



file 01550

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Answer 11

$$\begin{aligned} I_{R1} &= 12 \text{ mA} ; V_{R1} = 12 \text{ V} \\ I_{R2} &= 5.45 \text{ mA} ; V_{R2} = 12 \text{ V} \\ I_{R3} &= 25.5 \text{ mA} ; V_{R3} = 12 \text{ V} \end{aligned}$$

Follow-up question: trace the direction of current through all three resistors as well as the power supply (battery symbol). Compare these directions with the polarity of their shared voltage. Explain how the relationship between voltage polarity and current direction relates to each component's identity as either a *source* or a *load*.

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Notes 11

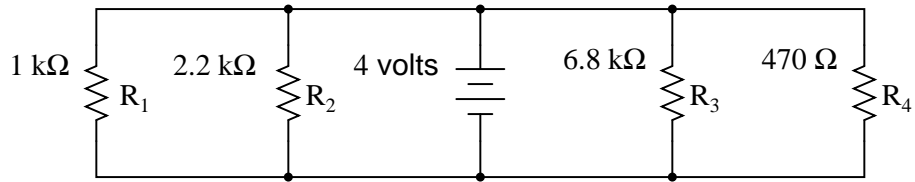
Students often just want to memorize a procedure for determining answers to questions like these. Challenge your students to not only understand the procedure, but to also explain *why* it must be followed.

Something your students will come to realize in discussion is that there is more than one way to arrive at all the answers! While some of the steps will be common to all calculation strategies, other steps (near the end) leave room for creativity.



Question 12

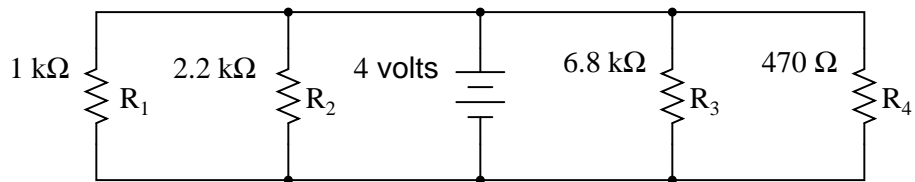
Complete the table of values for this circuit:



	$R_1$	$R_2$	$R_3$	$R_4$	Total
V					
I					
R	1 k $\Omega$	2.2 k $\Omega$	6.8 k $\Omega$	470 $\Omega$	
P					

[file 01732](#)

Answer 12



	$R_1$	$R_2$	$R_3$	$R_4$	Total
V	4 V	4 V	4 V	4 V	4 V
I	4 mA	1.82 mA	588.2 $\mu$ A	8.51 mA	14.92 mA
R	1 k $\Omega$	2.2 k $\Omega$	6.8 k $\Omega$	470 $\Omega$	268.1 $\Omega$
P	16 mW	7.27 mW	2.35 mW	34.0 mW	59.67 mW

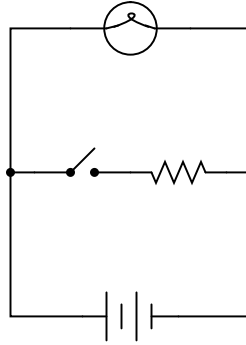
Notes 12

Discuss with your students what a good procedure might be for calculating the unknown values in this problem, and also how they might check their work.

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Question 13

What will happen to the brightness of the light bulb if the switch in this circuit is suddenly closed?



file 00103

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Answer 13

Ideally, there will be no change whatsoever in the light bulb's brightness when the switch is closed, because voltage sources are supposed to maintain constant voltage output regardless of loading. As you might have supposed, though, the additional current "drawn" by the resistor when the switch is closed might actually cause the lamp to dim slightly, due to the battery voltage "sagging" under the additional load. If the battery is well oversized for the application, though, the degree of voltage "sag" will be inconsequential.

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Notes 13

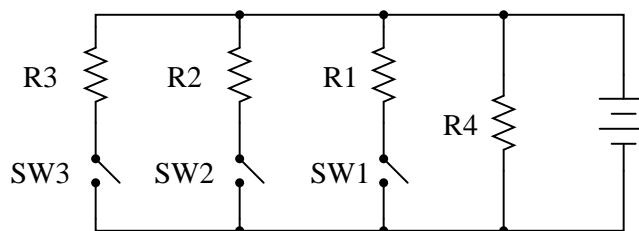
This question illustrates a disparity between the ideal conditions generally assumed for theoretical calculations, and those conditions encountered in real life. Truly, it is the purpose of a voltage source to maintain a constant output voltage regardless of load (current drawn from it), but in real life this is nearly impossible. Most voltage sources exhibit some degree of "sag" in their output over a range of load currents, some worse than others.

In this example, it is impossible to tell how much the voltage source's output will "sag" when the switch is closed, because we have no idea of what the resistor's current draw will be compared to that of the light bulb, or what the voltage source's rated output current is. All we can say is that theoretically there will be no effect from closing the switch, but that in real life there will be some degree of dimming when the switch is closed.

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### Question 14

What will happen in this circuit as the switches are sequentially turned on, starting with switch number 1 and ending with switch number 3?



Describe how the successive closure of these three switches will impact:

- The voltage drop across each resistor
- The current through each resistor
- The total amount of current drawn from the battery
- The total amount of circuit resistance "seen" by the battery

file 00296

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### Answer 14

I won't explain what happens when each of the switches is closed, but I will describe the effects of the first switch closing:

As the first switch (SW1) is closed, the voltage across resistor R1 will increase to full battery voltage, while the voltages across the remaining resistors will remain unchanged from their previous values. The current through resistor R1 will increase from zero to whatever value is predicted by Ohm's Law (full battery voltage divided by that resistor's resistance), and the current through the remaining resistors will remain unchanged from their previous values. The amount of current drawn from the battery will increase. Overall, the battery "sees" less total resistance than before.

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### Notes 14

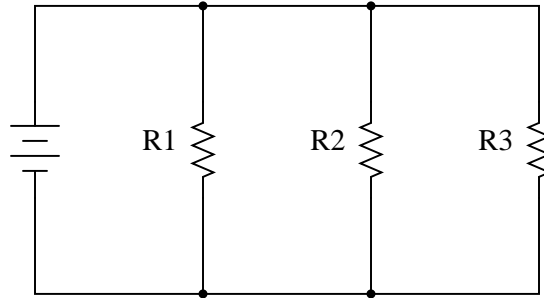
One problem I've encountered while teaching the "laws" of parallel circuits is that some students mistakenly think the rule of "all voltages in a parallel circuit being the same" means that the amount of voltage in a parallel circuit is fixed over time and cannot change. The root of this misunderstanding is memorization rather than comprehension: students memorize the rule "*all voltages are the same*" and think this means the voltages must remain the same before and after any change is made to the circuit. I've actually had students complain to me, saying, "But you told us all voltages are *the same* in a parallel circuit!", as though it were my job to decree perfect and universal Laws which would require no critical thinking on the part of the student. But I digress . . .

This question challenges students' comprehension of parallel circuit behavior by asking what happens after a change is made to the circuit. The purpose of the switches is to "add" resistors from the circuit, one at a time, without actually having to insert new components.

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Question 15

What will happen to the current through R1 and R2 if resistor R3 fails open?



[file 00367](#)

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Answer 15

If you think the currents through R1 and R2 would increase, think again! The current through R1 and the current through R2 both remain the same as they were before R3 failed open.

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Notes 15

A *very* common mistake of beginning electronics students is to think that a failed resistor in a parallel circuit supplied by a voltage source causes current through the other resistors to change. A simple verification using Ohm's Law will prove otherwise, though.

If this mistake is revealed during discussion, ask the class this very important question: "What assumption has to be made in order to conclude that the other two currents will change?" Invariably, the assumption is that the source outputs a constant *current* rather than a constant *voltage*.

Another common mistake of beginning electronics students is to think that the position of the failed resistor matters. Ask your students to determine what will happen to the current through R2 and R3 if R1 were to fail open instead. If there are any misunderstandings, use the discussion time to correct them and improve everyone's comprehension of the concept.

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### Question 16

In a parallel circuit, certain general rules may be stated with regard to quantities of voltage, current, resistance, and power. Express these rules, using your own words:

"In a parallel circuit, voltage . . ."

"In a parallel circuit, current . . ."

"In a parallel circuit, resistance . . ."

"In a parallel circuit, power . . ."

For each of these rules, explain *why* it is true.

file 00292

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### Answer 16

"In a parallel circuit, voltage *is equal across all components.*"

"In a parallel circuit, currents *add to equal the total.*"

"In a parallel circuit, resistances *diminish to equal the total.*"

"In a parallel circuit, power *dissipations add to equal the total.*"

---

### Notes 16

Rules of series and parallel circuits are very important for students to comprehend. However, a trend I have noticed in many students is the habit of memorizing rather than understanding these rules. Students will work hard to memorize the rules without really comprehending *why* the rules are true, and therefore often fail to recall or apply the rules properly.

An illustrative technique I have found very useful is to have students create their own example circuits in which to test these rules. Simple series and parallel circuits pose little challenge to construct, and therefore serve as excellent learning tools. What could be better, or more authoritative, than learning principles of circuits from real experiments? This is known as *primary research*, and it constitutes the foundation of scientific inquiry. The greatest problem you will have as an instructor is encouraging your students to take the initiative to build these demonstration circuits on their own, because they are so used to having teachers simply *tell* them how things work. This is a shame, and it reflects poorly on the state of modern education.

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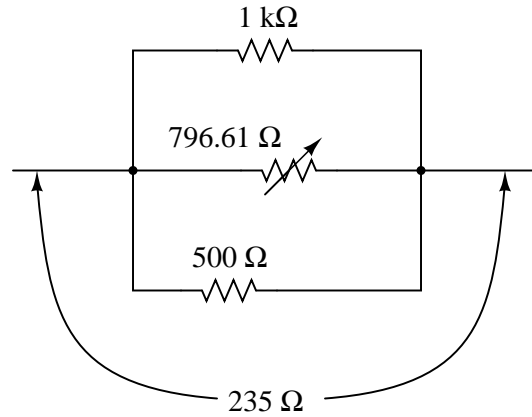
Question 17

Suppose you needed a resistance equal to precisely  $235\ \Omega$  for the construction of a precision electrical meter circuit. The only resistors available to you are two  $1\ \text{k}\Omega$  resistors, one  $500\ \Omega$  resistor, and a rheostat variable between  $600$  and  $1000$  ohms. Design a parallel resistor network using any combination of these components that will yield a total resistance of  $235\ \Omega$ . If you use the rheostat in your design, specify its resistance setting.

[file 00335](#)

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Answer 17



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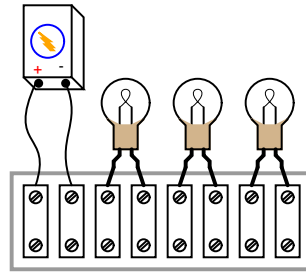
Notes 17

This problem is an exercise in estimation, and algebraic equation manipulation. Estimation will reveal which resistors should be combined together, and algebraic manipulation will give the exact values needed.

---

Question 18

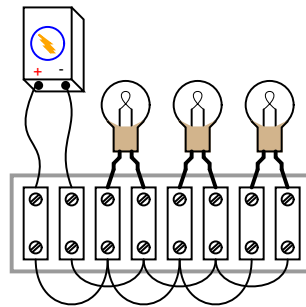
Draw the connecting wires on this terminal strip so that the three light bulbs are wired in parallel with each other and with the battery.



[file 01738](#)

---

Answer 18



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Notes 18

One of the more difficult visualization tasks for new students of electronics is translating schematic diagrams to physical layouts, and visa-versa. This, sadly, is a skill that I don't see emphasized nearly enough in most basic electronics curricula. It seems the majority of class time is spent mathematically analyzing useless resistor networks, and not enough time is invested building students' spatial relations skills.

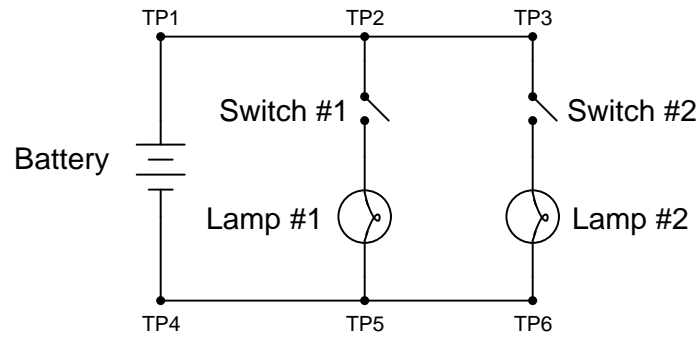
While series connections are very easy to visualize on terminal strips, parallel connections are more difficult. Work with your students through this question helping those who lack the innate spatial relations ability to see the solution quickly.

A "trick" I often use to help students build this skill is to have them first draw a nice, clean schematic diagram. Then they over-trace each wire in the diagram as they draw it in the pictorial diagram. In this way, they make sure not to overlook connections in the pictorial diagram.

---

### Question 19

The following circuit has a problem. Switch #1 is able to control lamp #1, but lamp #2 never comes on no matter what is done with switch #2:



Identify which of these hypothetical faults could account for this problem, and which could not account for the problem. In other words, which of these faults are possible, and which are not possible, given the symptoms exhibited by the circuit? Consider each of these hypothetical faults one at a time (no multiple, simultaneous faults):

- Battery is dead
- Switch #2 failed open
- Switch #2 failed shorted
- Switch #1 failed open
- Switch #1 failed shorted
- Open wire between test points 1 and 2 (between TP1 and TP2)
- Open wire between test points 5 and 6 (between TP5 and TP6)

[file 03298](#)

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### Answer 19

- Battery is dead: *Not possible*
- Switch #2 failed open: *Possible*
- Switch #2 failed shorted: *Not possible*
- Switch #1 failed open: *Not possible*
- Switch #1 failed shorted: *Not possible*
- Open wire between test points 1 and 2 (between TP1 and TP2): *Not possible*
- Open wire between test points 5 and 6 (between TP5 and TP6): *Possible*

Follow-up question: if we allow ourselves to consider more than one fault occurring at the same time, which of these scenarios becomes possible? Explain why.

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### Notes 19

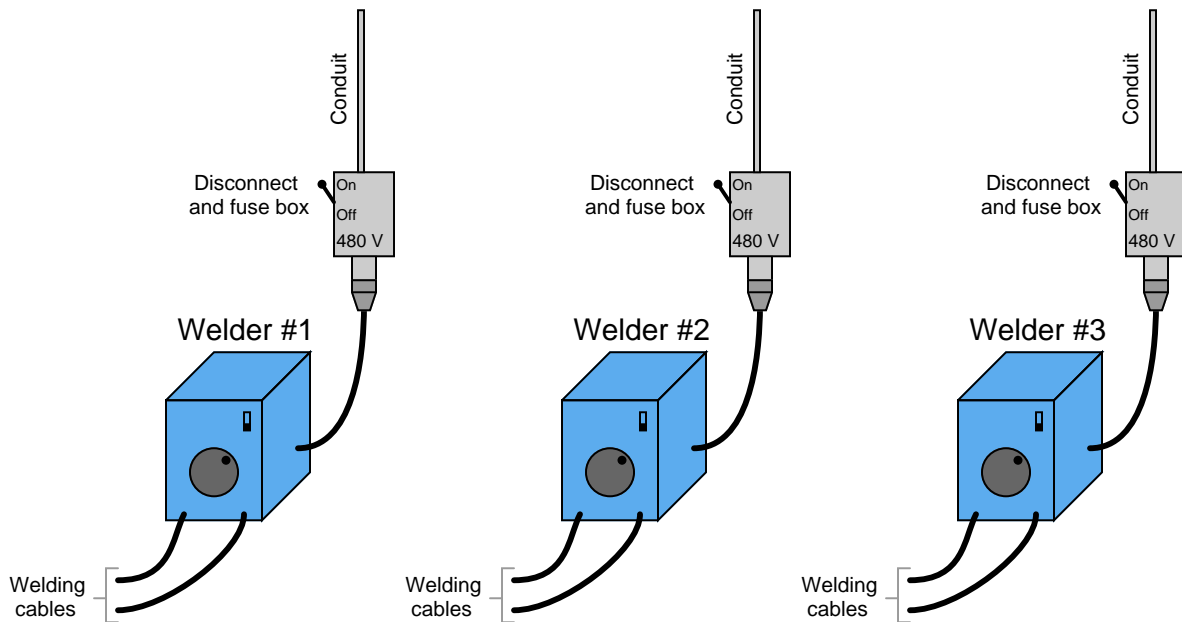
This question helps students build the skill of eliminating unlikely fault possibilities, allowing them to concentrate instead on what is more likely. An important skill in system troubleshooting is the ability to formulate probabilities for various fault scenarios. Without this skill, you will waste a lot of time looking for unlikely faults, thereby wasting time.

For each fault scenario it is important to ask your students *why* they think it is possible or not possible. It might be that some students get the right answer(s) for the wrong reasons, so it is good to explore the reasoning for each answer.



Question 20

At a construction site, several electric "arc" welders are plugged into 480 volt receptacles. Each receptacle has its own safety disconnect switch and fuse overcurrent protection:



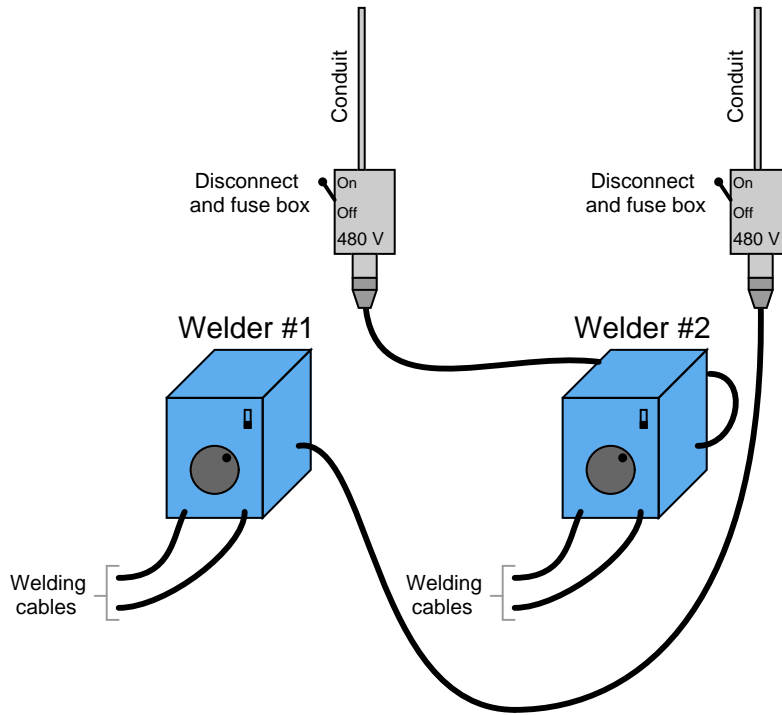
You, as an electronics technician working at the job site, happen to be walking past these welders when one of the welding personnel stops you to ask for help.

“You’re an electrician, right?”

“Not exactly,” you reply, “but maybe I can help you anyway.”

“My welder’s dead – it doesn’t even turn on. Can you check it out?”

You didn’t bring your multimeter or any other test equipment, so you can’t check for voltage at the receptacle. As you look around the job site, you notice that no one is using welder #2. When you flip its power switch on, welder #2 turns on just like it should. Deciding to apply your “swap interchangeable components” troubleshooting strategy, you turn off both welders’ power switches, then turn off the disconnect switches at both receptacles and swap the power cables between receptacles:



When you turn the disconnect switches on and try to start both welders, you find that *neither* one turns on now! Switching the power cables back to their original receptacles doesn't make things better, either. Both welders #1 and #2 are still "dead," which is a worse situation than what you first encountered. This is not good, because the person who called you for help is beginning to cast angry looks in your direction, and you are fairly sure the operator of welder #2 won't be much happier when he returns to find his welder non-functional as well.

Identify the most likely location of the fault in this system, and explain why the "swap interchangeable components" strategy got you into trouble.

[file 01572](#)

Answer 20

The likely location of the fault is in welder #1. I'll let you determine what the nature of this fault most likely is, and why the strategy employed in this scenario probably wasn't the wisest.

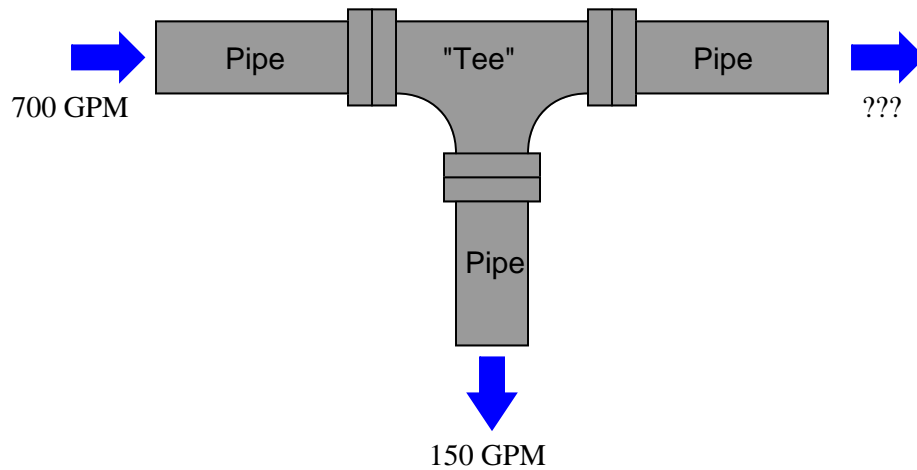
Notes 20

This situation is very realistic, and underscores the need for careful thinking on the part of the troubleshooter when deciding what specific troubleshooting strategy to apply. Despite the undeniable power of the "swap interchangeable components" strategy, it is not fool-proof.

---

Question 21

How much water *must* flow out of the pipe with the question-mark symbols next to it?



Explain how this hydraulic example relates to Kirchhoff's Current Law (KCL) in an electric circuit.  
[file 00350](#)

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Answer 21

550 gallons per minute ("GPM"), assuming no leaks in the pipe.

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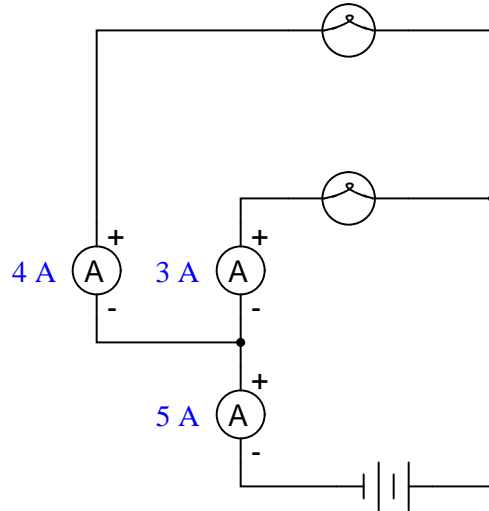
Notes 21

Ask your students to draw an electric circuit schematic showing how the same principle illustrated in the hydraulic system would apply to electric current, with "flow rates" of 700 amps, 150 amps, and 550 amps, respectively.

---

Question 22

In this circuit there is at least one ammeter that is not reading correctly:



Apply Kirchhoff's Current Law to this circuit to prove why all three current measurements shown here cannot be correct.

[file 01742](#)

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Answer 22

Kirchhoff's Current Law renders this scenario impossible: "the algebraic sum of all currents at a node *must* be zero."

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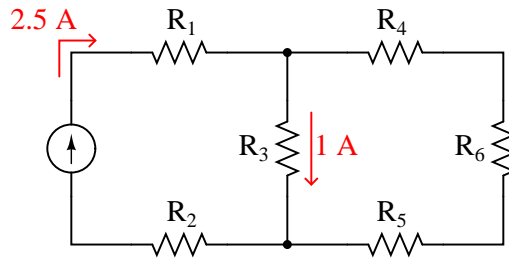
Notes 22

Another way of stating KCL is to say, "What goes in must come out." When continuous DC currents are involved, this law is really nothing more than a restatement of the Conservation of Charge. Of course, there are transient exceptions to this law (static electric charge and discharge, for example) as well as interesting AC exceptions (current "through" a capacitor), so a hard-literal interpretation of KCL may cause confusion later on. However, it is a fairly intuitive Law to grasp, and consequently I seldom find students experiencing difficulty with it.

---

Question 23

Use Kirchhoff's Current Law to calculate the magnitude and direction of the current through resistor  $R_4$  in this resistor network:

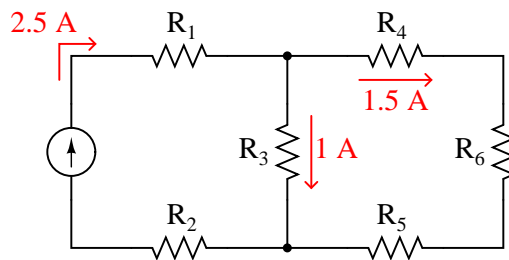


*Note: all current arrows point in the direction of conventional flow!*

file 01740

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Answer 23



*Note: all current arrows point in the direction of conventional flow!*

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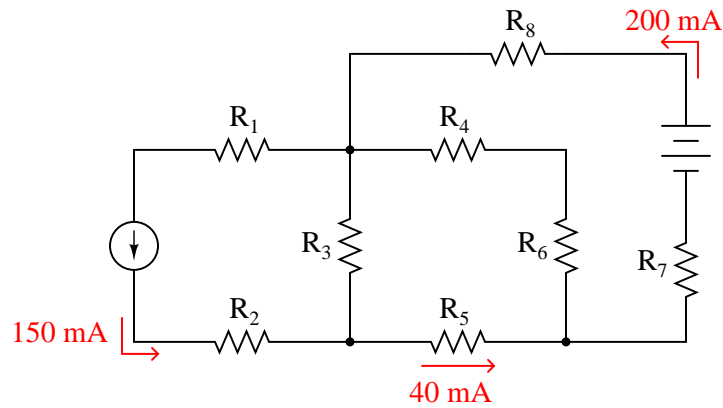
Notes 23

It is not necessary to know anything about series-parallel or even parallel circuits in order to solve the  $R_4$ 's current – all one needs to know is how to use Kirchhoff's Current Law.

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Question 24

Use Kirchhoff's Current Law to calculate the magnitudes and directions of currents through *all* resistors in this circuit:

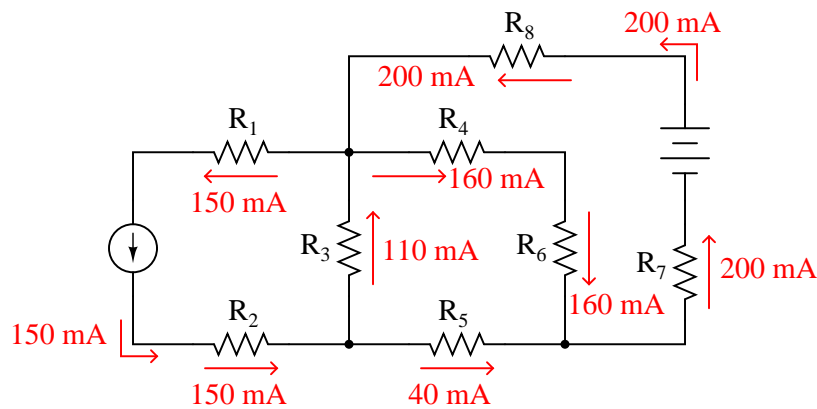


*Note: all current arrows point in the direction of conventional flow!*

file 01741

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Answer 24



*Note: all current arrows point in the direction of conventional flow!*

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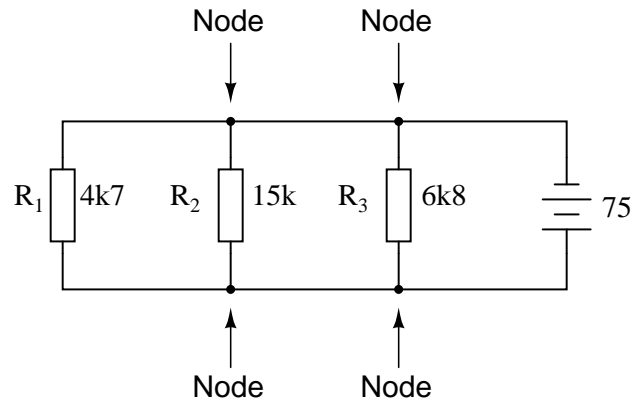
Notes 24

It is not necessary to know anything about series-parallel or even parallel circuits in order to solve the  $R_4$ 's current – all one needs to know is how to use Kirchhoff's Current Law.

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Question 25

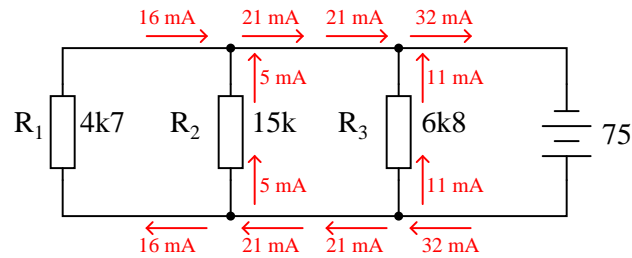
Calculate and label the currents at each node (junction point) in this circuit:



file 01744

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Answer 25



*Currents shown according to conventional notation*

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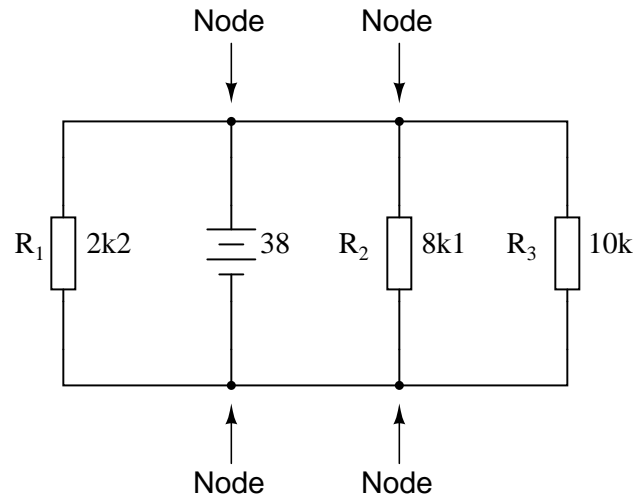
Notes 25

Discuss with your students techniques for calculating the node currents. What Laws did your students apply, and more importantly, in *what order* did they apply them?

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Question 26

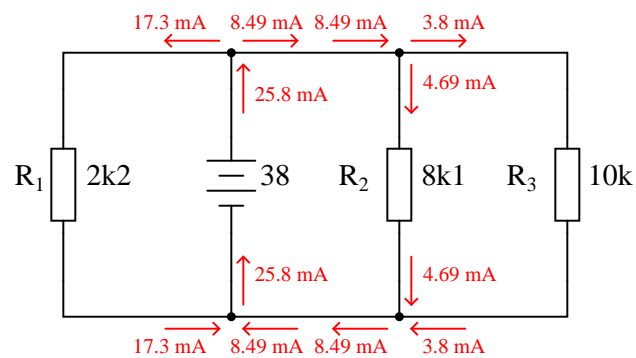
Calculate and label the currents at each node (junction point) in this circuit:



file 01746

---

Answer 26



*Note: all arrows point in the direction of conventional flow!*

---

Notes 26

Discuss with your students techniques for calculating the node currents. What Laws did your students apply, and more importantly, in *what order* did they apply them?



---

Question 27

If I wanted to build a battery-powered electric drill, would it be better to use *primary* cell batteries, or *secondary* cell batteries? Explain your answer.

[file 00408](#)

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Answer 27

”Secondary” cell batteries would be better to use for an application such as an electric drill, because it would be wasteful to have to discard so many primary-cell batteries at the rate they would be ”consumed” powering such a device.

---

Notes 27

Basically, the point of this question is to get students to research what the difference is between a primary and a secondary cell. Framing the question in a practical context makes it more interesting, and involves other practical issues as well (economics, conservation, etc.).

---

Question 28

Identify some common "primary" cell types, as well as some common "secondary" cell types. For each of these battery types, identify their standard output voltages.

[file 00519](#)

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Answer 28

Primary cell types and voltages:

- Carbon-zinc: 1.5 volts
- Alkaline: 1.5 volts
- Lithium: 1.8 to 3.65 volts, depending on exact chemical makeup
- Mercuric-oxide: 1.35 to 1.4 volts

Secondary cell types and voltages:

- Lead-acid: 2.1 volts
- Nickel-cadmium: 1.2 volts
- Silver-zinc: 1.5 volts

Follow-up question: what are some of the safety and environmental concerns regarding the chemical substances used in batteries, both primary and secondary types?

---

Notes 28

Challenge your students to list a few cell types other than what is listed in the answer section.

Note: data for typical cell output voltages taken from chapter 20 of the *Electronic Engineer's Reference Book*, 5th edition (edited by F. Mazda).

---

Question 29

Batteries store energy in the form of chemical bonds between atoms. When a complete circuit is connected to the terminals of a battery, a current begins inside the battery and through the circuit. Chemical reactions begin inside the battery at the same time the circuit is formed, fueling this current. When all the chemicals have been depleted, though, the current will cease. This is what happens when a battery "dies."

Explain what takes place when a battery is *recharged*, and what electrical device(s) must be connected to a battery to recharge it. Be as specific as possible in your answer.

file 01745

---

Answer 29

*Recharging* is a reversal of the chemical reactions taking place during the discharge of a battery. In order for this to occur, some external source of energy must force current *backward* through the battery.

---

Notes 29

It is important to note to your students that not all battery types lend themselves to recharging, even though many "primary" cells can be rejuvenated a small degree by being put through a charging (reverse-current) cycle.

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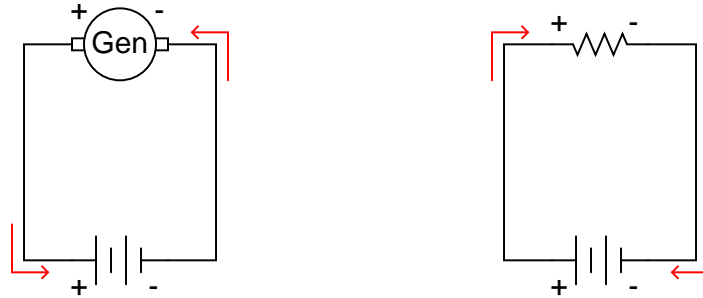
Question 30

Draw a schematic diagram showing a DC generator charging a battery, and another schematic showing a battery discharging into a resistive load. Be sure to include arrows in your drawing showing the direction of charging current.

file 00520

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Answer 30



*All arrows pointed in the direction  
of conventional flow!*

Follow-up question #1: how must the battery and generator voltages compare in order for the battery to have current forced "backward" through it?

Follow-up question #2: which is the *source* component, and which is the *load* component in a circuit where a generator charges a secondary-cell battery? Explain your reasoning.

---

Notes 30

It is very important for students to understand the direction of current through a battery, both when charging and when discharging. A helpful perspective on this topic is to think of the battery either as being a *source* of electrical energy versus being a *load*. Under which conditions (charging or discharging) is the battery playing the role of source versus load?

---

Question 31

What does the *amp-hour* capacity of a chemical battery represent? What does it mean if a battery is rated at, say, 150 amp-hours?

[file 01743](#)

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Answer 31

The amp-hour rating of a battery is an approximate indication of its useful lifespan per charge.

Follow-up question: why not just rate batteries in terms of hours, instead of amp-hours? Since time is the value we are most likely interested in, why bother to refer to current (amps) at all?

---

Notes 31

Although the basic concept of an amp-hour battery rating is simple, it is important to realize that real battery discharge characteristics are very nonlinear, and therefore the simple "amps times hours" approach may yield grossly inaccurate predictions regarding battery life.

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Question 32

What is the best-performing secondary cell technology today, in terms of energy stored per unit mass?  
[file 00410](#)

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Answer 32

There is no point in giving an answer here, as it will change as battery technology evolves. However, in your answer you need to specify an actual numerical figure for energy density, for comparison against other classmates' research!

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Notes 32

Questions like this are fun, because they allow the students to do research on state-of-the-art technology. Ask them where they obtained their information for the answer!

---

Question 33

Suppose I desired to power the light bulbs in a remote cabin with solar power, charging a large battery bank. The battery bank needs to be able to power ten 60-watt light bulbs for eight hours without being recharged. The system voltage is 115 volts. How large must the battery bank be, in total amp-hours?

file 00409

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Answer 33

At least 41.7 amp-hours of capacity is needed, at 115 volts.

---

Notes 33

Ask your students what they would recommend for a battery bank capacity if they were designing this system. Would they specify 41.7 amp-hours exactly? Why or why not?

---

#### Question 34

Some brands of dry-cell batteries come equipped with a built-in charge indicator in the form of a thermal strip along one side. Pressing two white dots closes a circuit, which heats up the strip and indicates battery charge by changing color.

Compare the accuracy of a charge indicator of this general design against using a voltmeter to measure open-circuit battery voltage. Which method of measurement is a more accurate indication of battery charge, and why?

[file 00518](#)

---

#### Answer 34

The thermal strip charge indicator is actually a more accurate indication of battery charge than an open-circuit voltage test.

Challenge question: in the absence of such a "charge indicator" on the side of a battery, how could you perform an accurate assessment of battery charge?

---

#### Notes 34

This question is practical because I've seen students measure the open-circuit voltage of a battery and declare it "good" when it is really past the end of its useful life. This is not to say that a plain voltmeter is useless for determining battery charge. Obviously if an open-circuit voltage test yields abnormally low voltage, we know the battery is dead. The question is, under what condition(s) is a "good" voltage measurement a reliable indicator of adequate battery charge?



---

Question 35

An important equation in predicting the capacity of a lead-acid cell is called *Peukert's formula*:

$$I^n t = C$$

Where,

$I$  = Discharge current, in amps

$n$  = Constant, particular to the cell (typically between 1.1 and 1.8)

$t$  = Time of discharge

$C$  = Constant, particular to the battery (varies with the amp-hour capacity)

Explain how Peukert's formula relates to the simpler "amp-hour" formula.

Also, calculate the discharge time for a battery with an  $n$  value of 1.2 and a  $C$  value of 200, given a discharge current of 25 amps.

[file 00516](#)

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Answer 35

The "amp-hour" formula is linear, while Peukert's formula is not (at least for values of  $n$  not equal to unity).

The discharge time for the example problem is 4.2 hours.

---

Notes 35

Ask one of your students to write Peukert's equation on the whiteboard in front of class, along with the standard amp-hour formula. Viewed side-by-side, there is but one difference between the two equations, and it is the exponent  $n$ .

---

Question 36

A battery has an advertised capacity of 600 amp-hours, taken from tests performed over an 8-hour period (where capacity in amp-hours =  $It$ ). According to Peukert's formula, what rate of current discharge will result in the battery fully discharging in 3 hours (assume an  $n$  value of 1.35)?

file 00517

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Answer 36

155 amps

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Notes 36

Ask your students to calculate the amount of current predicted by the "simple" amp-hour equation for a discharge time of 3 hours. In your students' estimation, which is a more realistic prediction, Peukert's formula or the amp-hour ( $It$ ) formula?

---

Question 37

An oft-repeated claim is that lead-acid batteries self-discharge at a greater rate while sitting on a concrete floor, than when installed in an automobile, or on a shelf, or in some other place where there is no direct contact with a concrete surface. Is this claim true, or not?

Design an experiment to test the veracity of this claim, and design it in such a way that a single instance of a defective battery does not skew the results of the test.

[file 00521](#)

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Answer 37

This is a fun topic to discuss! Do your research, and come to discussion time prepared with ideas on how to test this claim.

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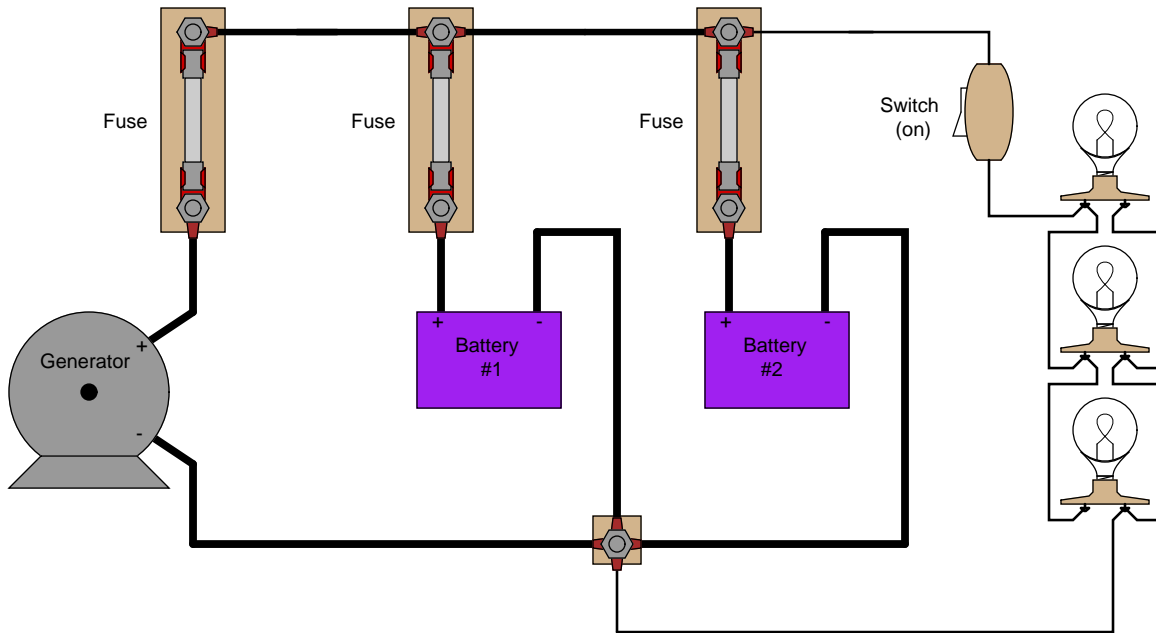
Notes 37

I have heard this claim many, many times, but I have not yet been in such a position where I could test it myself. Even if I had tested it, I still wouldn't give away the answer! There are many practical matters that must be addressed in the setup and testing of batteries for self-discharge. This question provides an excellent opportunity to discuss scientific method with your students, including such principles as *double-blind* testing, *test* and *control* groups, and statistical correlation.

---

Question 38

Determine the current through battery #2 in this power system, if the generator is outputting 50 amps, battery #1 is charging at a rate of 22 amps, and the light bulbs draw 5 amps of current each. Be sure to indicate whether battery #2 is charging or discharging:



file 00351

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Answer 38

Battery #2 is charging at a rate of 13 amps.

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Notes 38

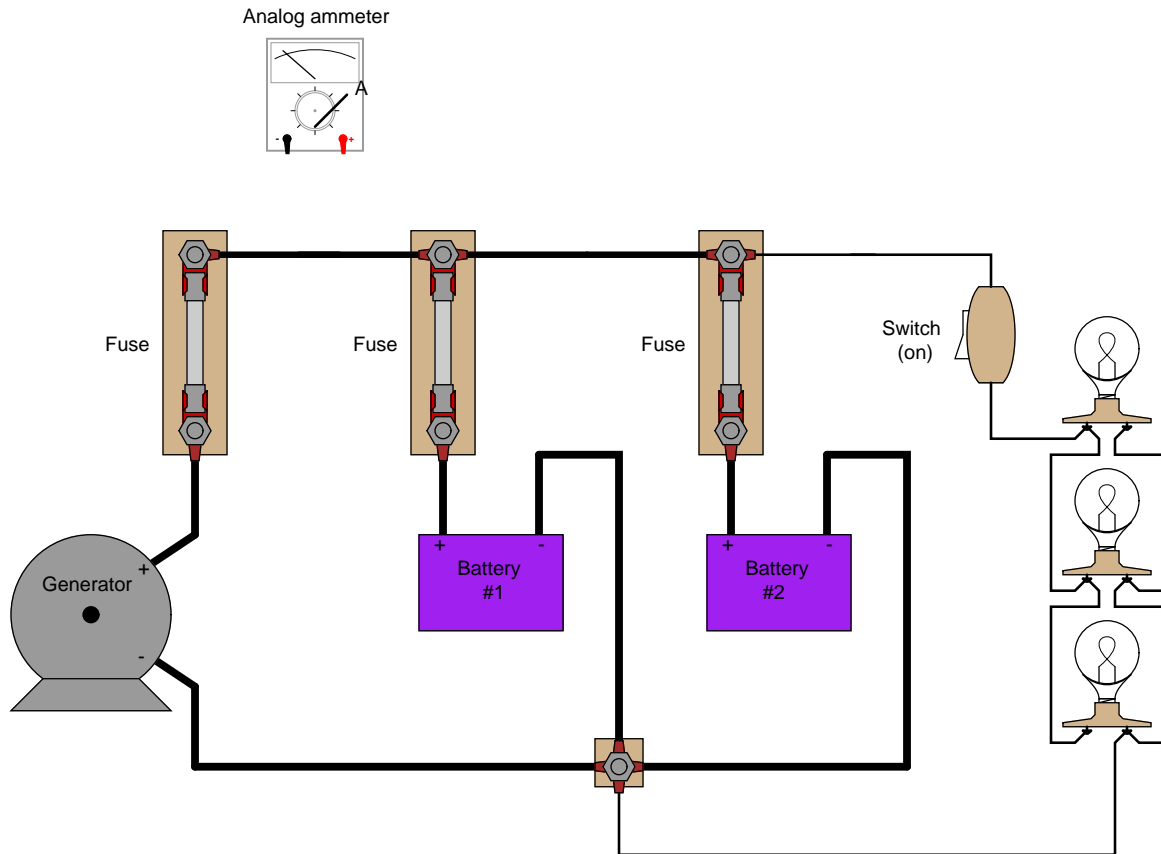
Perhaps the most difficult portion of this question for students to figure out is which way current goes when a battery is charging, versus when it is discharging. Thus, it is a good review for students on secondary battery theory!

Another challenge for students might be where to label a "node" for the algebraic summation of currents. Do not simply tell them, but rather let them choose the node.

---

Question 39

Explain how an analog ammeter could be used to measure the current output of the generator in this circuit, as it charges the two batteries and energizes the three light bulbs. Be sure to connect the ammeter in the circuit in such a way that the meter needle does not drive "downscale"!



file 00352

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Answer 39

To measure generator output current, remove the fuse and connect the ammeter test leads to the two "clips" of the empty fuse holder, the red lead on the clip connecting to the generator, and the black lead on the clip connecting to the battery.

Follow-up question: describe any relevant safety procedures and considerations necessary prior to performing this task.

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Notes 39

Be sure to reinforce the safety aspects of this task. Although the primary focus of this question is most definitely Kirchhoff's Current Law, that is no excuse to avoid discussing electrical safety!

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Question 40

A very powerful method for discerning cause-and-effect relationships is *scientific method*. One commonly accepted algorithm (series of steps) for scientific method is the following:

1. Observation
2. Formulate an hypothesis (an educated guess)
3. Predict a unique consequence of that hypothesis
4. Test the prediction by experiment
5. If test fails, go back to step #2. If test passes, hypothesis is provisionally confirmed.

This methodology is also very useful in technical troubleshooting, since troubleshooting is fundamentally a determination of cause for an observed effect. Read the following description of an experienced troubleshooter diagnosing an automotive electrical problem, and match the troubleshooter's steps to those five steps previously described for scientific method:

One day a car owner approached a mechanic friend of theirs with a problem. The battery in this car seemed to be dying, requiring frequent jump-starts from other vehicles, or the application of a battery charger overnight, to be able to start reliably. "What could be the problem?" asked the car owner to the mechanic.

The mechanic considered some of the options. One possibility was that a parasitic load was draining the battery of its charge when the car was shut off. Another possibility was that the car's charging system (the engine-driven generator and its associated circuitry) was faulty and not charging the battery when the engine was running. A third possibility was that the battery itself was defective, and unable to hold a charge.

"Let's check the battery voltage with the engine stopped, and with the engine running," said the mechanic. The two walked over to the car and opened the hood, then the mechanic connected a voltmeter to the battery's terminals. It read 11.3 volts DC. This was a 12-volt (nominal) battery.

"Start the car," said the mechanic, still watching the voltmeter. As the electric starting motor labored to turn the engine, the voltmeter's reading sagged to 9 volts. Once the engine started and the electric starter disengaged, the voltmeter rebounded to 11.2 volts.

"That's the problem!" shouted the mechanic. With that, the owner stopped the car's engine.

Explain which of the three hypotheses was confirmed by the voltmeter's reading, and how the mechanic was able to know this.

[file 01577](#)

Steps in the scientific method are indicated by superscript numbers at the end of sentences in the original narrative:

One day a car owner approached a mechanic friend of theirs with a problem. The battery in this car seemed to be dying, requiring frequent jump-starts from other vehicles, or the application of a battery charger overnight, to be able to start reliably.<sup>1</sup> “What could be the problem?” asked the car owner to the mechanic.

The mechanic considered some of the probable causes. One possibility was that a parasitic load was draining the battery of its charge when the car was shut off.<sup>2</sup> Another possibility was that the car’s charging system (the engine-drive generator and its associated circuitry) was faulty and not charging the battery when the engine was running.<sup>2</sup> A third possibility was that the battery itself was defective, and unable to hold a charge.<sup>2</sup>

“Let’s check the battery voltage with the engine stopped, and with the engine running,” said the mechanic.<sup>(3)</sup> The two walked over to the car and opened the hood, then the mechanic connected a voltmeter to the battery’s terminals. It read 11.3 volts DC. This was a 12-volt (nominal) battery.

“Start the car,” said the mechanic, still watching the voltmeter. As the electric starting motor labored to turn the engine, the voltmeter’s reading sagged to 9 volts. Once the engine started and the electric starter disengaged, the voltmeter rebounded to 11.2 volts.<sup>4</sup>

“That’s the problem!” shouted the mechanic.<sup>(5)</sup> With that, the owner stopped the car’s engine.

Steps 3 and 5 are labeled parenthetically because the story does not tell what the mechanic was thinking. It doesn’t indicate, for example, what the mechanic’s prediction was when deciding to do a voltage check of the battery with the engine stopped and with the engine running. I’ve left these steps for *you* to elaborate.

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Notes 40

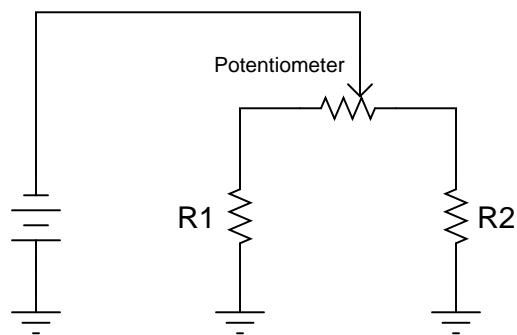
Once students have successfully identified the mechanic’s reasoning, ask them to explain how the prediction of battery voltage *uniquely* relates to only one of the three hypotheses stated.

Also, discuss whether this concludes the diagnostic procedures, or if there is more troubleshooting left to do. What steps are recommended to take next, if any?

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Question 41

Which way would you have to move the potentiometer wiper, to the left or to the right, in order to increase current through resistor R1?



file 01747

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Answer 41

You would have to move the potentiometer wiper to the *left*.

Follow-up question: what would happen to the current through resistor R2 as you moved the wiper in that direction (closer to resistor R1)?

---

Notes 41

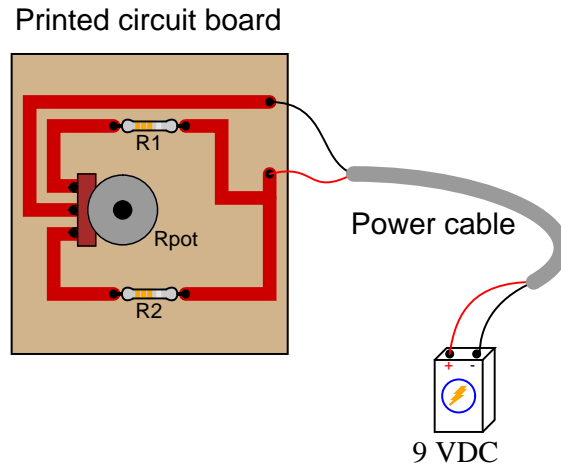
This circuit is fairly self-explanatory.



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Question 42

Which way would you have to twist the potentiometer shaft in order to increase current through resistor R1, clockwise or counter-clockwise? Explain your answer.



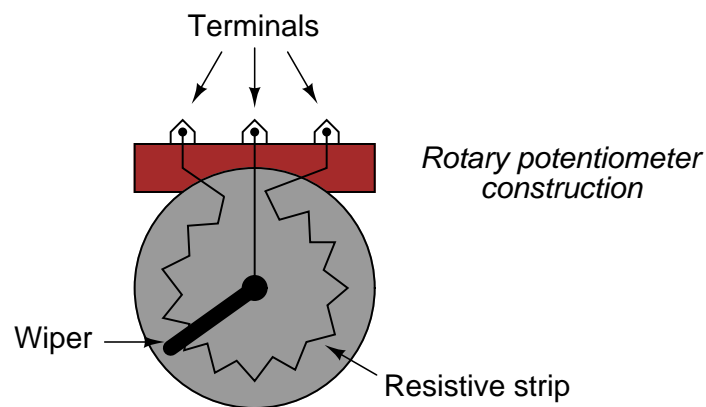
[file 01748](#)

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Answer 42

You would have to twist the potentiometer shaft *counter-clockwise*.

Here's a hint for those unfamiliar with the internal construction of rotary potentiometers:



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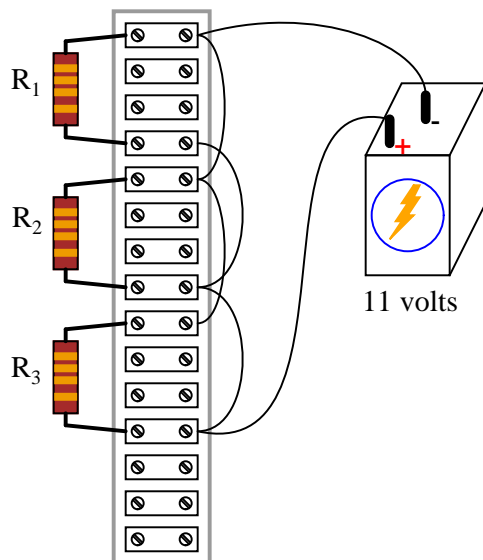
Notes 42

This circuit is fairly self-explanatory, but getting the answer correct requires that you understand how a rotary potentiometer is constructed inside.

---

Question 43

Determine the amount of current conducted by each resistor in this circuit, if each resistor has a color code of Org, Org, Red, Gld (assume perfectly precise resistance values – 0% error):



Also, determine the following information about this circuit:

- Voltage across each resistor
- Power dissipated by each resistor
- Ratio of each resistor's current to battery current ( $\frac{I_R}{I_{bat}}$ )
- Ratio of total circuit resistance to each resistor's resistance ( $\frac{R_{total}}{R}$ )

[file 00365](#)

---

Answer 43

Current through each resistor = 3.33 mA

Voltage across each resistor = 11 V

Power dissipated by each resistor = 36.67 mW

Current ratio =  $\frac{1}{3}$

Resistance ratio =  $\frac{1}{3}$

---

Notes 43

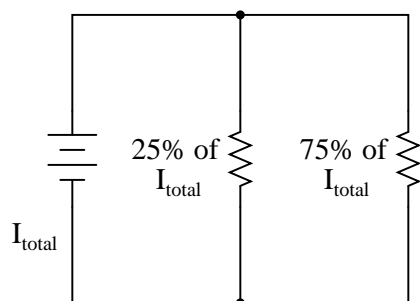
When performing the mathematical analysis on this circuit, there is more than one possible sequence of steps to obtaining the solutions. Different students in your class may very well have different solution sequences, and it is a good thing to have students share their differing problem-solving techniques before the whole class.

An important aspect of this question is for students to observe the identical ratios (current versus resistance), and determine whether or not these ratios are equal by chance or equal by necessity. Ask your students, "What kind of evidence would prove these ratios were merely equal by chance?" Setting mathematics aside and viewing this circuit from a purely experimental point of view, ask your students what data could possibly prove these ratios to be equal by chance in this particular case? Hint: it would only take a single example to prove this!

---

Question 44

Calculate the necessary resistor values to produce the following percentage splits in current:



Hint: one resistor carries three times the current of the other.

[file 01428](#)

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Answer 44

There are many different sets of resistor values that will achieve this design goal!

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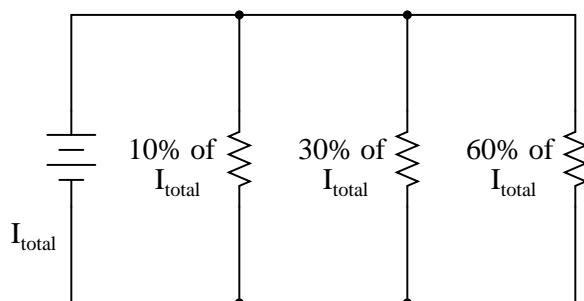
Notes 44

Different students will likely arrive at different solutions for this design task. Have your students share their differing solutions, emphasizing that there is often more than one acceptable solution to a problem!

---

Question 45

Calculate one possible set of resistor values that would produce the following percentage splits in current:



[file 00366](#)

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Answer 45

There are many different sets of resistor values that will achieve this design goal! I'll let you try to determine one of your own.

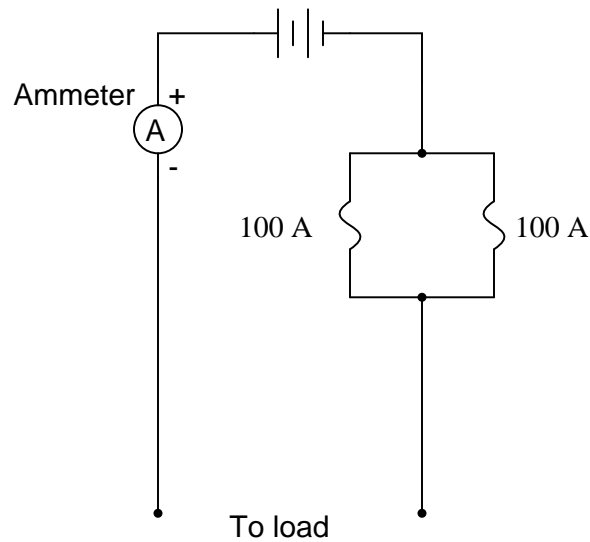
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Notes 45

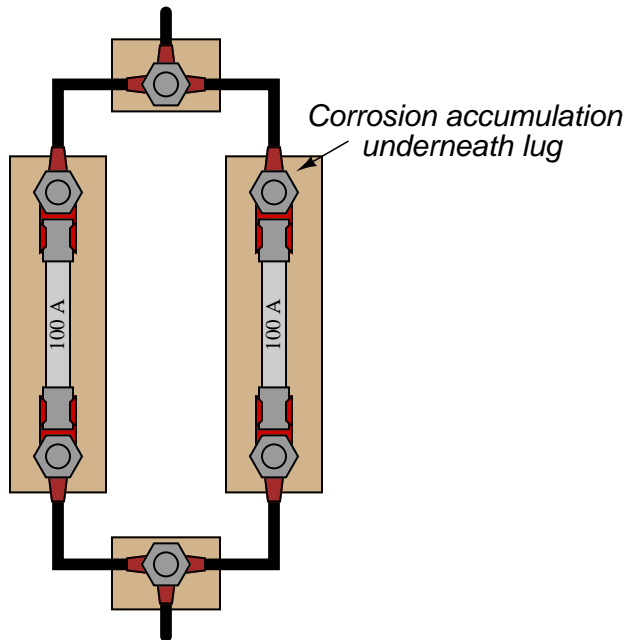
Different students will likely arrive at different solutions for this design task. Have your students share their differing solutions, emphasizing that there is often more than one acceptable solution to a problem!

Question 46

In an effort to obtain greater overcurrent ratings than a single fuse can provide, an engineer decides to wire two 100 amp fuses in parallel, for a combined rating of 200 amps:



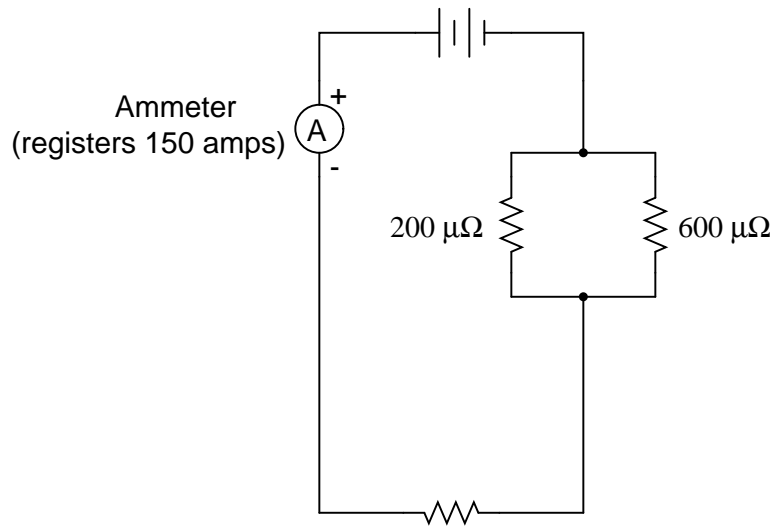
However, after a few years of operation, the system begins blowing fuses even when the ammeter registers less than 200 amps of load current. Upon investigation, it is found that one of the fuse holders had developed corrosion on a terminal lug where one of the wires connects:



Explain how a small accumulation of corrosion led to this condition of fuses blowing when there was no overcurrent condition (load current less than 200 amps), and also why connecting fuses in parallel like this is generally not a good idea.

[file 00334](#)

Here is an electrical calculation to help explain the fuse-blowing problem. Calculate the current through each resistor in this circuit:



---

Notes 46

Ask your students to explain what happens to current in a circuit when it branches from one path into two or more parallel paths. Discuss how the proportionality of the current "split" between those paths depends on the relative resistances of those two paths.

Even if your students have not yet studied current divider circuits, this question provides an excellent opportunity to explore the concept.

Incidentally, it is now common for some manufacturers of residential power distribution equipment to "gang" circuit breakers together in parallel for added overcurrent capacity. This engineering practice is questionable for the exact same reason it is questionable with the fuses in this scenario: any amount of corrosion or other infiltration of electrical resistance into one of the parallel "legs" offsets the split of current between the paralleled overcurrent protection devices, forcing one of them to handle a disproportionately large share of the total current (and therefore trip sooner).

---

Question 47

We know that the voltage in a parallel circuit may be calculated with this formula:

$$E = I_{total}R_{total}$$

We also know that the current through any single resistor in a parallel circuit may be calculated with this formula:

$$I_R = \frac{E}{R}$$

Combine these two formulae into one, in such a way that the  $E$  variable is eliminated, leaving only  $I_R$  expressed in terms of  $I_{total}$ ,  $R_{total}$ , and  $R$ .

file 00368

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Answer 47

$$I_R = I_{total} \left( \frac{R_{total}}{R} \right)$$

How is this formula similar, and how is it different, from the "voltage divider" formula?

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Notes 47

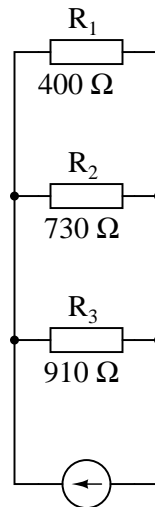
Though this "current divider formula" may be found in any number of electronics reference books, your students need to understand how to algebraically manipulate the given formulae to arrive at this one.

At first it may seem as though the two divider formulae (voltage versus current) are easy to confuse. Is it  $\frac{R}{R_{total}}$  or  $\frac{R_{total}}{R}$ ? However, there is a very simple way to remember which fraction belongs with which formula, based on the numerical value of that fraction. Mention this to your students and at least one of them will be sure to recognize the pattern.

---

Question 48

Calculate the percentage of total current for each resistor in this parallel circuit:



file 01750

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Answer 48

$R_1 = 50.3\%$  of total current

$R_2 = 27.6\%$  of total current

$R_3 = 22.1\%$  of total current

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Notes 48

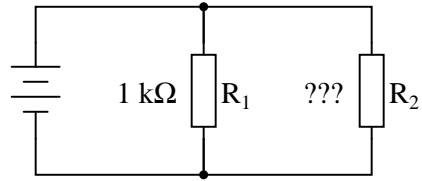
Nothing to comment on here, really. Just a straight-forward current divider formula problem!



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Question 49

Calculate the proper value of resistance  $R_2$  needs to be in order to draw 40% of the total current in this circuit:



file 01749

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Answer 49

$$R_2 = 1.5\text{ k}\Omega$$

Follow-up question: explain how you could arrive at a rough estimate of  $R_2$ 's necessary value without doing any algebra. In other words, show how you could at least set limits on  $R_2$ 's value (i.e. "We know it has to be less than . . ." or "We know it has to be greater than . . .").

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Notes 49

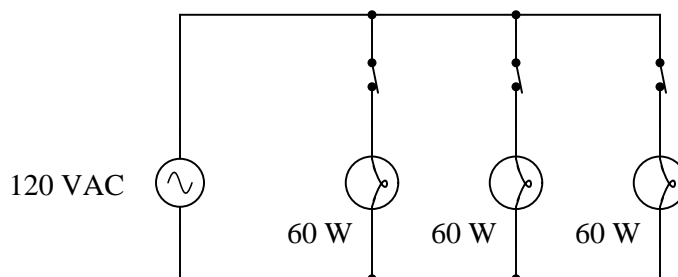
This is an interesting problem to solve algebraically from the current divider formula. I recommend using the product-over-sum formula for parallel resistance if you plan on doing this algebraically. The estimation question (in the follow-up) is also very good to discuss with your students. It is possible to at least "bracket" the value of  $R_2$  between two different resistance values without doing any math more complex than simple (fractional) arithmetic.

Of course, a less refined approach to solving this problem would be to assume a certain battery voltage and work with numerical figures – but what fun is that?

---

Question 50

A student is trying to use the "current divider formula" to calculate current through the second light bulb in a three-lamp lighting circuit (typical for an American household):



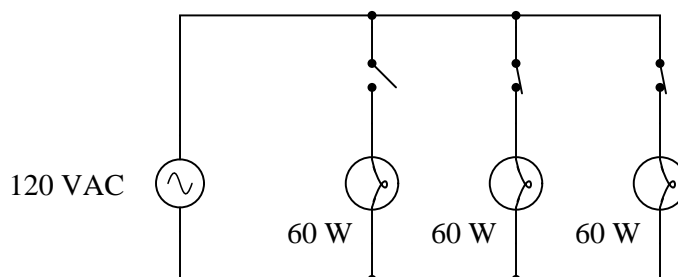
The student uses Joule's Law to calculate the resistance of each lamp ( $240 \Omega$ ), and uses the parallel resistance formula to calculate the circuit's total resistance ( $80 \Omega$ ). With the latter figure, the student also calculates the circuit's total (source) current: 1.5 A.

Plugging this into the current divider formula, the current through any one lamp turns out to be:

$$I = I_{total} \left( \frac{R_{total}}{R} \right) = 1.5 \text{ A} \left( \frac{80 \Omega}{240 \Omega} \right) = 0.5 \text{ A}$$

This value of 0.5 amps per light bulb correlates with the value obtained from Joule's Law directly for each lamp: 0.5 amps from the given values of 120 volts and 60 watts.

The trouble is, something doesn't add up when the student re-calculates for a scenario where one of the switches is open:



With only two light bulbs in operation, the student knows the total resistance must be different than before:  $120 \Omega$  instead of  $80 \Omega$ . However, when the student plugs these figures into the current divider formula, the result seems to conflict with what Joule's Law predicts for each lamp's current draw:

$$I = I_{total} \left( \frac{R_{total}}{R} \right) = 1.5 \text{ A} \left( \frac{120 \Omega}{240 \Omega} \right) = 0.75 \text{ A}$$

At 0.75 amps per light bulb, the wattage is no longer 60 W. According to Joule's Law, it will now be 90 watts (120 volts at 0.75 amps). What is wrong here? Where did the student make a mistake?

[file 01739](#)

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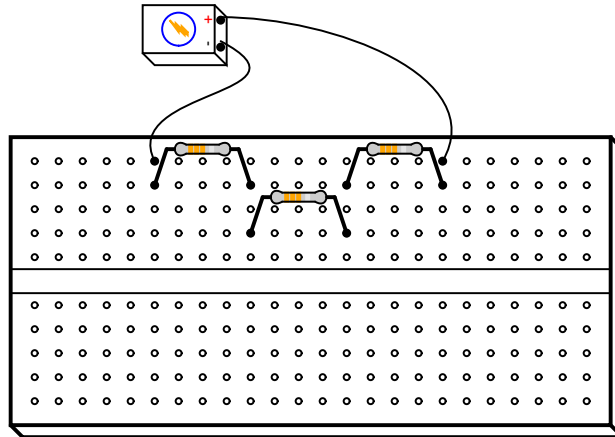
Answer 50

The student incorrectly assumed that total current in the circuit would remain unchanged after the switch opened. By the way, this is a *very* common conceptual misunderstanding among new students as they learn about parallel circuits!

I am surprised how often this principle is misunderstood by students as they first learn about parallel circuits. It seems natural for many of them to assume that total circuit current is a constant when the source is actually a constant-*voltage* source!

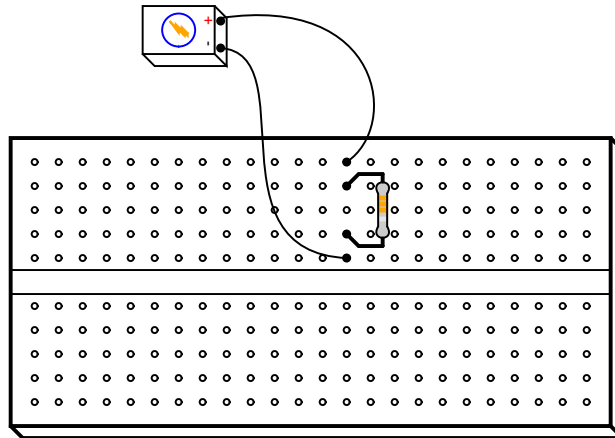
Question 51

*Solderless breadboards* provide convenient means for electronics hobbyists, students, technicians, and engineers to build circuits in a non-permanent form. The following illustration shows a three-resistor series circuit built on a breadboard:



The interconnections between the metal spring clips within the holes of the breadboard allow continuity between adjacent leads of the resistors, without the resistor leads having to be jammed into the same hole.

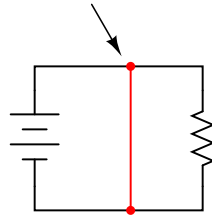
However, new students often get themselves into trouble when first learning how to use solderless breadboards. One common mistake is shown here, where a student has attempted to create a simple single-resistor circuit:



What the student has actually created here is a *short circuit*. Re-draw this circuit in schematic form, and explain why this circuit is faulty.

[file 01761](#)

"Short circuit" caused  
by breadboard interconnections



Follow-up question #1: explain what might happen if a large battery or high-current power supply were powering this short circuit.

Follow-up question #2: show how the single-resistor circuit *should* have been built on the breadboard so as to avoid a short circuit.

---

Notes 51

Situations such as this are *very* common among new students! Be sure to discuss the significance of "short circuits" as well as how to avoid them.

---

### Question 52

An electronics instructor wants to demonstrate to his students the effect of electrical resistance changing with temperature. To do this, he selects a carbon resistor about 3 centimeters in length and 5 millimeters in diameter, black in color, with a wire at each end, and connects it to an ohmmeter. Whenever he grasps the resistor between his fingers, the ohmmeter instantly responds by showing a greatly reduced resistance.

What is wrong with this experiment?

[file 00507](#)

---

### Answer 52

If the change in resistance is truly due to a change in resistor temperature, it should not be *instant*.

---

### Notes 52

I must confess, the genesis of this question was an experience from my own education. This really happened! I still remember staring at the demonstration, perplexed that the resistance would change so quickly and so greatly when the instructor grasped the resistor. I also recall the mild insult the instructor directed at me as I attempted to communicate my confusion: "What's the matter? Too complicated for you?" Please, never treat your students like this.

Some students may believe the experiment is flawed because they expect the resistance to rise with increased temperature, rather than fall. This, however, makes a fundamental assumption about the nature of temperature-induced resistance changes, which is a bad thing in science. Let the experimental evidence tell you how the phenomenon works, don't tell it what it should do!

Discuss with your students what they think the *real* mechanism of resistance change is in this experiment, and how they might modify the experiment so as to isolate temperature as the only changing variable.

---

Question 53

If we were to plug an electric saw into a very long extension cord, and then plug the other end of the cord into a power receptacle, we would notice a decreased level of performance from the saw, as compared with how it performs when directly plugged into the same receptacle (with no extension cord).

Determine if the saw's performance becomes better or worse as the ambient temperature increases, and explain your answer.

[file 00508](#)

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Answer 53

The saw's performance worsens as ambient temperature increases.

---

Notes 53

Discuss the nature of the problem, with reference to Ohm's Law. Ask your students to explain the effect in terms of Ohm's Law, and the cord's ability to deliver electrical power to the saw motor.

---

Question 54

The electrical resistance of a conductor at any temperature may be calculated by the following equation:

$$R_T = R_r + R_r\alpha T - R_r\alpha T_r$$

Where,

$R_T$  = Resistance of conductor at temperature  $T$

$R_r$  = Resistance of conductor at reference temperature  $T_r$

$\alpha$  = Temperature coefficient of resistance at reference temperature  $T_r$

Simplify this equation by means of factoring.

[file 00509](#)

---

Answer 54

$$R_T = R_r[1 + \alpha(T - T_r)]$$

Follow-up question: when plotted on a graph with temperature ( $T$ ) as the independent variable and resistance ( $R_T$ ) as the dependent variable (i.e. a two-axis graph with  $T$  on the horizontal and  $R$  on the vertical), is the resulting plot linear? Why or why not? How is it possible to tell just by looking at the equation, prior to actually plotting on a graph?

---

Notes 54

Just an exercise in algebra here!



---

Question 55

Write an equation solving for the temperature of a conductor ( $T$ ), given its resistance at that temperature ( $R_T$ ), its resistance at a standard reference temperature ( $R_r$  @  $T_r$ ), and its temperature coefficient of resistance at that same reference temperature ( $\alpha$  @  $T_r$ ).

file 00510

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Answer 55

$$T = \frac{\frac{R_T}{R_r} - 1}{\alpha} + T_r$$

---

Notes 55

Students may be able to find this equation in a textbook somewhere, but the point of this question is really to have them perform algebraic manipulation to derive this equation from another.

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Question 56

Precision wire-wound resistors are often made of a special metal alloy called *manganin*. What is it about this alloy that makes it preferable for use in precision resistor construction?

[file 00511](#)

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Answer 56

The  $\alpha$  value of manganin alloy is nearly zero.

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Notes 56

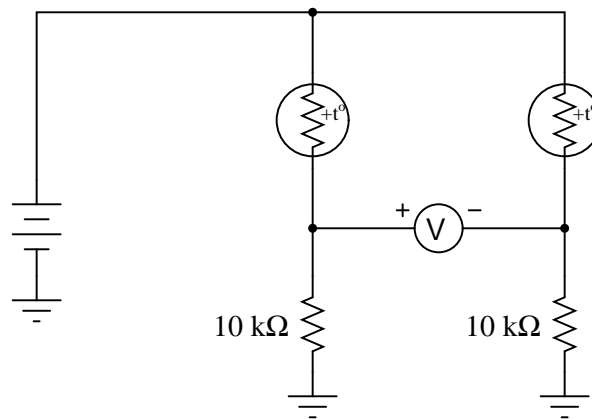
Ask your students what a wire-wound resistor made of copper or iron wire might do, if subjected to changes in temperature.

An historical side-note: during World War II, allied forces made extensive use of *analog computers* for directing the firing of projectiles and the dropping of bombs. Unlike digital computers, which perform mathematical operations using on/off signals and are thus immune to errors caused by slight changes in component value, electronic analog computers represent physical variables in the form of continuous voltages and currents, and depend on the precision of its constituent resistors to produce precise results. I remember reading one of the pioneering engineers in that field describe great gains in accuracy being due mostly to improvements in resistor construction. Without some crucial improvements in resistor accuracy and stability, analog computers of the war-time era would have suffered from substantial inaccuracies. Of all things, the lowly *resistor* was an influential piece of the allied war effort!

---

Question 57

A *thermistor* is a special resistor that dramatically changes resistance with changes in temperature. Consider the circuit shown below, with two identical thermistors:



The "+t" label in each one shows that they both have positive  $\alpha$  coefficients.

How much voltage would you expect the voltmeter to register when the two thermistors are at the exact same temperature? Which thermistor would have to become hotter in order to cause the voltmeter to read a significant *negative* voltage?

[file 01751](#)

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Answer 57

If the two thermistors are at equal temperature, the voltmeter should register 0 volts. To get the voltmeter to register negative, the left-hand thermistor would have to be warmer than the right-hand thermistor.

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Notes 57

This circuit may be viewed from the perspective of it being two voltage dividers, or from the perspective of being a current divider. Either way, it is a good exercise for you and your students to explore how it functions.

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### Question 58

Calculate the resistance of each of these specimens, given their resistance at the reference temperature ( $R_r @ T_r$ ), and their present temperatures ( $T$ ):

- Specimen 1: Copper ;  $R_r = 200 \Omega @ T_r = 20^\circ\text{C}$  ;  $T = 45^\circ\text{C}$  ;  $R_T =$
- Specimen 2: Copper ;  $R_r = 10 \text{ k}\Omega @ T_r = 20^\circ\text{C}$  ;  $T = 5^\circ\text{C}$  ;  $R_T =$
- Specimen 3: Aluminum ;  $R_r = 1,250 \Omega @ T_r = 20^\circ\text{C}$  ;  $T = 100^\circ\text{C}$  ;  $R_T =$
- Specimen 4: Iron ;  $R_r = 35.4 \Omega @ T_r = 20^\circ\text{C}$  ;  $T = -40^\circ\text{C}$  ;  $R_T =$
- Specimen 5: Nickel ;  $R_r = 525 \Omega @ T_r = 20^\circ\text{C}$  ;  $T = 70^\circ\text{C}$  ;  $R_T =$
- Specimen 6: Gold ;  $R_r = 25 \text{ k}\Omega @ T_r = 20^\circ\text{C}$  ;  $T = 65^\circ\text{C}$  ;  $R_T =$
- Specimen 7: Tungsten ;  $R_r = 2.2 \text{ k}\Omega @ T_r = 20^\circ\text{C}$  ;  $T = -10^\circ\text{C}$  ;  $R_T =$
- Specimen 8: Copper ;  $R_r = 350 \Omega @ T_r = 10^\circ\text{C}$  ;  $T = 35^\circ\text{C}$  ;  $R_T =$
- Specimen 9: Copper ;  $R_r = 1.5 \text{ k}\Omega @ T_r = -25^\circ\text{C}$  ;  $T = -5^\circ\text{C}$  ;  $R_T =$
- Specimen 10: Silver ;  $R_r = 3.5 \text{ M}\Omega @ T_r = 45^\circ\text{C}$  ;  $T = 10^\circ\text{C}$  ;  $R_T =$

[file 00512](#)

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### Answer 58

- Specimen 1:  $R_T = 220.2 \Omega$
- Specimen 2:  $R_T = 9.394 \text{ k}\Omega$
- Specimen 3:  $R_T = 1.681 \text{ k}\Omega$
- Specimen 4:  $R_T = 23.35 \Omega$
- Specimen 5:  $R_T = 679 \Omega$
- Specimen 6:  $R_T = 29.18 \text{ k}\Omega$
- Specimen 7:  $R_T = 1.909 \text{ k}\Omega$
- Specimen 8:  $R_T = 386.8 \Omega$
- Specimen 9:  $R_T = 1.648 \text{ k}\Omega$
- Specimen 10:  $R_T = 3.073 \text{ M}\Omega$

---

### Notes 58

Students may find difficulty obtaining the proper answers for the last three specimens (8, 9, and 10). The key to performing calculations correctly on these is the *assumed temperature* at which the  $\alpha$  figure is given for each metal type. This reference temperature may not be the same as the reference temperature given in the question!

Here are the  $\alpha$  values I used in my calculations, *all at a reference temperature of 20° Celsius*:

- Copper = 0.004041
- Aluminum = 0.004308
- Iron = 0.005671
- Nickel = 0.005866
- Gold = 0.003715
- Tungsten = 0.004403
- Silver = 0.003819

Your students' sources may vary a bit from these figures.

---

Question 59

A spool of #10 AWG aluminum wire is 500 feet long. If the ambient temperature is 80° F, what is its end-to-end electrical resistance? Explain all the calculations necessary to solve this problem.

file 00513

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Answer 59

0.7899  $\Omega$

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Notes 59

Solving this problem requires several concepts be integrated: calculating the resistance of a wire given its metal type, length, and gauge; converting between different temperature units; and calculating shift in resistance due to temperature.

---

Question 60

An incandescent light bulb has a filament resistance of  $5.7 \Omega$  when at room temperature ( $20^\circ \text{C}$ ), but draws only 225 mA when powered by a 12 volt DC source. Given that the filament is made out of tungsten metal, calculate its temperature in degrees F when powered by the 12 VDC source.

[file 00514](#)

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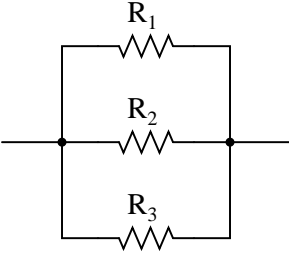
Answer 60

$$T = 3,484^\circ\text{F}$$

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Notes 60

Solving this problem requires several concepts be integrated: Ohm's Law, converting between different temperature units, and calculating temperature from shift in resistance.

Competency: <b>Parallel resistances</b>	Version:						
<b>Schematic</b> 							
<b>Given conditions</b> $R_1 =$ $R_2 =$ $R_3 =$							
<b>Parameters</b> <table><thead><tr><th></th><th>Predicted</th><th>Measured</th></tr></thead><tbody><tr><td><math>R_{total}</math></td><td><input type="text"/></td><td><input type="text"/></td></tr></tbody></table>			Predicted	Measured	$R_{total}$	<input type="text"/>	<input type="text"/>
	Predicted	Measured					
$R_{total}$	<input type="text"/>	<input type="text"/>					
<b>Analysis</b> Equation used to calculate $R_{total}$ :							

---

Answer 61

Use circuit simulation software to verify schematic diagram. Your real circuit will verify the pictorial diagram.

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Notes 61

Specify standard resistor values, all between 1 k $\Omega$  and 100 k $\Omega$  (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.).

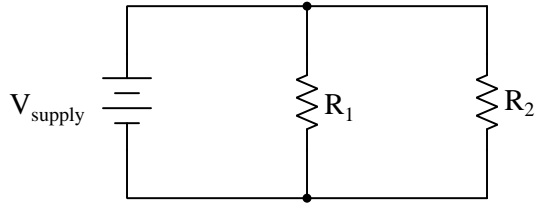
**General concepts and principles to emphasize**

- How to use a multimeter to accurately measure resistance
- How to read resistor color codes
- The effect of adding resistances in parallel with each other

**Suggestions for Socratic discussion and experimentation**

- Does the polarity of the ohmmeter matter when measuring the resistance of a network such as this? Why or why not?
- What would the total resistance formula look like for a 4-resistor parallel network? How about a 5-resistor parallel network?
- Does an “open” fault in a resistor result in its resistance increasing or decreasing?
- Does a “shorted” fault in a resistor result in its resistance increasing or decreasing?



<b>Competency: Parallel DC resistor circuit</b>	<b>Version:</b>																								
<b>Schematic</b>																									
																									
<b>Given conditions</b>																									
$V_{\text{supply}} =$	$R_1 =$	$R_2 =$																							
<b>Parameters</b>																									
<table style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 15%;"></th> <th style="width: 20%; text-align: center;">Predicted</th> <th style="width: 20%; text-align: center;">Measured</th> <th style="width: 15%;"></th> <th style="width: 20%; text-align: center;">Predicted</th> <th style="width: 20%; text-align: center;">Measured</th> </tr> </thead> <tbody> <tr> <td style="padding-right: 10px;"><math>I_{\text{supply}}</math></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="padding-right: 10px;"><math>I_{R1}</math></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> </tr> <tr> <td style="padding-right: 10px;"><math>V_{R1}</math></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="padding-right: 10px;"><math>I_{R2}</math></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> </tr> <tr> <td style="padding-right: 10px;"><math>V_{R2}</math></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td style="border: 1px solid black; width: 60px; height: 25px;"></td> <td></td> <td></td> <td></td> </tr> </tbody> </table>		Predicted	Measured		Predicted	Measured	$I_{\text{supply}}$			$I_{R1}$			$V_{R1}$			$I_{R2}$			$V_{R2}$						
	Predicted	Measured		Predicted	Measured																				
$I_{\text{supply}}$			$I_{R1}$																						
$V_{R1}$			$I_{R2}$																						
$V_{R2}$																									
<b>Analysis</b>																									
Relationship between resistor (branch) currents and total current:																									
<b>Fault analysis</b>																									
Suppose component <input style="width: 40px; height: 20px;" type="text"/> fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted																									
What will happen in the circuit? <small>Write "increase", "decrease", or "no change" for each parameter:</small>																									
$I_{\text{supply}}$		$I_{R1}$																							
$V_{R1}$		$I_{R2}$																							
$V_{R2}$																									

---

**Answer 62**

Use circuit simulation software to verify your predicted and measured parameter values.

---

**Notes 62**

Use a variable-voltage, regulated power supply to supply any amount of DC voltage below 30 volts. Specify standard resistor values, all between 1 k $\Omega$  and 100 k $\Omega$  (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k, 47k, 68k, etc.).

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

**General concepts and principles to emphasize**

- Electricity can only travel continuously when there is a *complete circuit* (i.e. a conductive “loop”)
- The distinction between electrical *sources* and electrical *loads*
- Voltage must be the same across all components in a parallel circuit
- Qualitative analysis using Ohm's Law (i.e. how to analyze *increases* and *decreases* without the use of numerical quantities)

**Suggestions for Socratic discussion and experimentation**

- Sketch the direction of current in this simple circuit. Also sketch the + and – symbols marking voltage polarity across each component in the circuit. Explain why the relationship between the power supply's voltage polarity and current direction is different than the relationship between each resistor's voltage polarity and current direction. Identify whether each of the components in this circuit is an electrical *source* or an electrical *load*.
- If just one of these resistor's resistance happens to increase, how will this change affect all the other electrical quantities in the circuit?
- If just one of these resistor's resistance happens to decrease, how will this change affect all the other electrical quantities in the circuit?
- If the power supply's voltage happens to increase, how will this change affect all the other electrical quantities in the circuit?
- Demonstrate how to measure voltage across different pairs of points in the circuit. Do you get different measured values, or the same value? Explain the results.
- Demonstrate how to measure current at different points in the circuit. Do you get different measured values, or the same value? Explain the results.

<b>Competency: Parallel DC resistor circuit</b>		Version:	
<b>Schematic</b>			
<b>Given conditions</b>			
$V_{\text{supply}} =$	$R_1 =$	$R_2 =$	$R_3 =$
<b>Parameters</b>			
	Predicted	Measured	
$I_{\text{supply}}$			$I_{R1}$
$V_{R1}$			$I_{R2}$
$V_{R2}$			$I_{R3}$
$V_{R3}$			
<b>Analysis</b>			
Relationship between resistor (branch) currents and total current:			
<b>Fault analysis</b>			
Suppose component <span style="border: 1px solid black; display: inline-block; width: 30px; height: 15px; vertical-align: middle;"></span> fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted			
What will happen in the circuit? <small>Write "increase", "decrease", or "no change" for each parameter:</small>			
$V_{R1}$		$I_{\text{supply}}$	
$V_{R2}$		$I_{R1}$	
$V_{R3}$		$I_{R2}$	
		$I_{R3}$	

---

**Answer 63**

Use circuit simulation software to verify your predicted and measured parameter values.

---

**Notes 63**

Use a variable-voltage, regulated power supply to supply any amount of DC voltage below 30 volts. Specify standard resistor values, all between 1 k $\Omega$  and 100 k $\Omega$  (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 8k2, 10k, 22k, 33k, 39k, 47k, 68k, 82k, etc.).

An extension of this exercise is to incorporate troubleshooting questions. Whether using this exercise as a performance assessment or simply as a concept-building lab, you might want to follow up your students' results by asking them to predict the consequences of certain circuit faults.

**General concepts and principles to emphasize**

- Electricity can only travel continuously when there is a *complete circuit* (i.e. a conductive “loop”)
- The distinction between electrical *sources* and electrical *loads*
- Voltage must be the same across all components in a parallel circuit
- Qualitative analysis using Ohm's Law (i.e. how to analyze *increases* and *decreases* without the use of numerical quantities)

**Suggestions for Socratic discussion and experimentation**

- Sketch the direction of current in this simple circuit. Also sketch the + and – symbols marking voltage polarity across each component in the circuit. Explain why the relationship between the power supply's voltage polarity and current direction is different than the relationship between each resistor's voltage polarity and current direction. Identify whether each of the components in this circuit is an electrical *source* or an electrical *load*.
- If just one of these resistor's resistance happens to increase, how will this change affect all the other electrical quantities in the circuit?
- If just one of these resistor's resistance happens to decrease, how will this change affect all the other electrical quantities in the circuit?
- If the power supply's voltage happens to increase, how will this change affect all the other electrical quantities in the circuit?
- Demonstrate how to measure voltage across different pairs of points in the circuit. Do you get different measured values, or the same value? Explain the results.
- Demonstrate how to measure current at different points in the circuit. Do you get different measured values, or the same value? Explain the results.



---

Answer 64

I do not provide a grading rubric here, but elsewhere.

---

Notes 64

The idea of a troubleshooting log is three-fold. First, it gets students in the habit of documenting their troubleshooting procedure and thought process. This is a valuable habit to get into, as it translates to more efficient (and easier-followed) troubleshooting on the job. Second, it provides a way to document student steps for the assessment process, making your job as an instructor easier. Third, it reinforces the notion that each and every measurement or action should be followed by reflection (conclusion), making the troubleshooting process more efficient.

---

Question 65

NAME: \_\_\_\_\_ **Troubleshooting Grading Criteria**

You will receive the highest score for which *all* criteria are met.

100 % (*Must meet or exceed all criteria listed*)

- A. Absolutely flawless procedure
- B. No unnecessary actions or measurements taken

90 % (*Must meet or exceed these criteria in addition to all criteria for 85% and below*)

- A. No reversals in procedure (i.e. changing mind without sufficient evidence)
- B. Every single action, measurement, and relevant observation properly documented

80 % (*Must meet or exceed these criteria in addition to all criteria for 75% and below*)

- A. No more than one unnecessary action or measurement
- B. No false conclusions or conceptual errors
- C. No missing conclusions (i.e. at least one documented conclusion for action / measurement / observation)

70 % (*Must meet or exceed these criteria in addition to all criteria for 65%*)

- A. No more than one false conclusion or conceptual error
- B. No more than one conclusion missing (i.e. an action, measurement, or relevant observation without a corresponding conclusion)

65 % (*Must meet or exceed these criteria in addition to all criteria for 60%*)

- A. No more than two false conclusions or conceptual errors
- B. No more than two unnecessary actions or measurements
- C. No more than one undocumented action, measurement, or relevant observation
- D. Proper use of all test equipment

60 % (*Must meet or exceed these criteria*)

- A. Fault accurately identified
- B. Safe procedures used at all times

50 % (*Only applicable where students performed significant development/design work – i.e. not a proven circuit provided with all component values*)

- A. Working prototype circuit built and demonstrated

0 % (*If any of the following conditions are true*)

- A. Unsafe procedure(s) used at any point

file 03932

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Answer 65

Be sure to document all steps taken and conclusions made in your troubleshooting!

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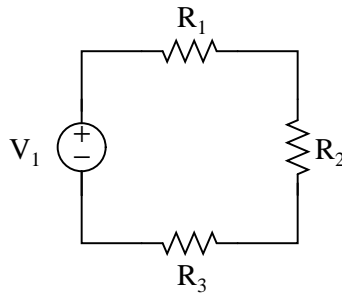
Notes 65

The purpose of this assessment rubric is to act as a sort of “contract” between you (the instructor) and your student. This way, the expectations are all clearly known in advance, which goes a long way toward disarming problems later when it is time to grade.

---

### Question 66

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 multiple faults):



- Voltage source  $V_1$  fails with increased output:
- Solder bridge (short) across resistor  $R_1$ :
- Solder bridge (short) across resistor  $R_2$ :
- Resistor  $R_3$  fails open:

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

[file 03935](#)

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### Answer 66

- Voltage source  $V_1$  fails with increased output: *All resistor currents increase, all resistor voltages increase, current through  $V_1$  increases.*
- Solder bridge (short) across resistor  $R_1$ : *All resistor currents increase, voltage across resistors  $R_2$  and  $R_3$  increase, voltage across resistor  $R_1$  decreases to zero, current through  $V_1$  increases.*
- Solder bridge (short) across resistor  $R_2$ : *All resistor currents increase, voltage across resistors  $R_1$  and  $R_3$  increase, voltage across resistor  $R_2$  decreases to zero, current through  $V_1$  increases.*
- Resistor  $R_3$  fails open: *All resistor currents decrease to zero, voltages across  $R_1$  and  $R_2$  decrease to zero, voltage across  $R_3$  increases to equal  $V_1$ .*

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### Notes 66

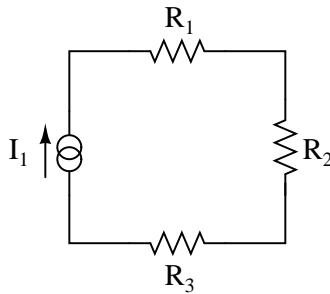
The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of knowing what the fault is, rather than only knowing what the symptoms are. Although this is not necessarily a realistic perspective, it helps students build the foundational knowledge necessary to diagnose a faulted circuit from empirical data. Questions such as this should be followed (eventually) by other questions asking students to identify likely faults based on measurements.



---

Question 67

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 multiple faults):



- Current source  $I_1$  fails with increased output:
- Solder bridge (short) across resistor  $R_1$ :
- Solder bridge (short) across resistor  $R_2$ :
- Resistor  $R_3$  fails open:

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

[file 03934](#)

---

Answer 67

- Current source  $I_1$  fails with increased output: *All resistor currents increase, all resistor voltages increase, voltage across  $I_1$  increases.*
- Solder bridge (short) across resistor  $R_1$ : *All resistor currents remain unchanged, voltage across resistor  $R_1$  decreases to zero, voltage across  $I_1$  decreases by the amount  $R_1$  previously dropped.*
- Solder bridge (short) across resistor  $R_2$ : *All resistor currents remain unchanged, voltage across resistor  $R_2$  decreases to zero, voltage across  $I_1$  decreases by the amount  $R_2$  previously dropped.*
- Resistor  $R_3$  fails open: *Theoretically, all resistor currents remain unchanged while a large arc jumps across the failed-open  $R_3$  (and possibly across  $I_1$  as well). Realistically, all resistor currents will decrease to zero while the voltages across  $R_3$  and  $I_1$  will increase to maximum.*

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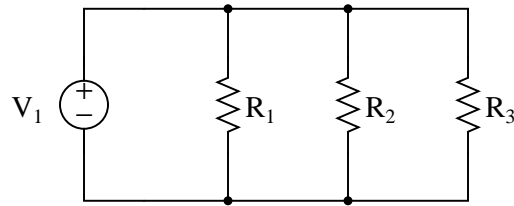
Notes 67

The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of knowing what the fault is, rather than only knowing what the symptoms are. Although this is not necessarily a realistic perspective, it helps students build the foundational knowledge necessary to diagnose a faulted circuit from empirical data. Questions such as this should be followed (eventually) by other questions asking students to identify likely faults based on measurements.

---

### Question 68

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 multiple faults):



- Voltage source  $V_1$  fails with increased output:
- Resistor  $R_1$  fails open:
- Resistor  $R_3$  fails open:
- Solder bridge (short) across resistor  $R_2$ :

For each of these conditions, explain *why* the resulting effects will occur.  
[file 03936](#)

---

### Answer 68

- Voltage source  $V_1$  fails with increased output: *All resistor currents increase, all resistor voltages increase, current through  $V_1$  increases.*
- Resistor  $R_1$  fails open: *All resistor voltages remain unchanged, current through  $R_1$  decreases to zero, currents through  $R_2$  and  $R_3$  remain unchanged, current through  $V_1$  decreases by the amount that used to go through  $R_1$ .*
- Resistor  $R_3$  fails open: *All resistor voltages remain unchanged, current through  $R_3$  decreases to zero, currents through  $R_1$  and  $R_2$  remain unchanged, current through  $V_1$  decreases by the amount that used to go through  $R_3$ .*
- Solder bridge (short) across resistor  $R_2$ : *Theoretically, all resistor voltages remain unchanged while a near-infinite amount of current goes through the shorted  $R_2$ . Realistically, all resistor voltages will decrease to nearly zero while the currents through  $R_2$  and  $V_1$  will increase dramatically.*

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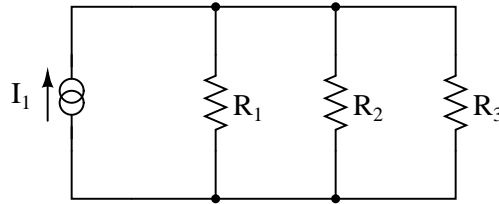
### Notes 68

The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of knowing what the fault is, rather than only knowing what the symptoms are. Although this is not necessarily a realistic perspective, it helps students build the foundational knowledge necessary to diagnose a faulted circuit from empirical data. Questions such as this should be followed (eventually) by other questions asking students to identify likely faults based on measurements.

---

Question 69

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 multiple faults):



- Current source  $I_1$  fails with increased output:
- Resistor  $R_1$  fails open:
- Resistor  $R_3$  fails open:
- Solder bridge (short) across resistor  $R_2$ :

For each of these conditions, explain *why* the resulting effects will occur.  
[file 03937](#)

---

Answer 69

- Current source  $I_1$  fails with increased output: *All resistor currents increase, all resistor voltages increase, voltage across  $I_1$  increases.*
- Resistor  $R_1$  fails open: *All resistor voltages increase, current through  $R_1$  decreases to zero, currents through  $R_2$  and  $R_3$  increase, current through  $I_1$  remains unchanged, voltage across  $I_1$  increases.*
- Resistor  $R_3$  fails open: *All resistor voltages increase, current through  $R_3$  decreases to zero, currents through  $R_1$  and  $R_2$  increase, current through  $I_1$  remains unchanged, voltage across  $I_1$  increases.*
- Solder bridge (short) across resistor  $R_2$ : *All resistor voltages decrease to zero, currents through  $R_1$  and  $R_3$  decrease to zero, current through shorted  $R_2$  increases to equal  $I_1$ , current through  $I_1$  remains unchanged, voltage across  $I_1$  decreases to zero.*

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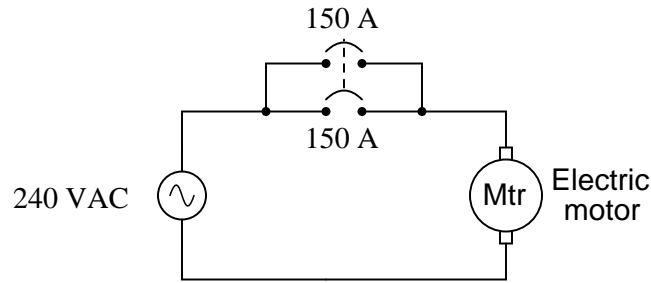
Notes 69

The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of knowing what the fault is, rather than only knowing what the symptoms are. Although this is not necessarily a realistic perspective, it helps students build the foundational knowledge necessary to diagnose a faulted circuit from empirical data. Questions such as this should be followed (eventually) by other questions asking students to identify likely faults based on measurements.

---

Question 70

Two 150-amp circuit breakers are connected in parallel to obtain a total ampacity of 300 amperes for an electric motor service. The system works just fine for several years, but then both breakers begin to spuriously trip:



An electrician measures motor current using a clamp-on ammeter, and discovers the motor's current is no more than 228 amperes at full mechanical load. Describe what might possibly be wrong that is causing both circuit breakers to trip.

[file 03938](#)

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Answer 70

One of the circuit breakers has probably developed more resistance in its parallel branch than the other (contact resistance, resistance at the wire connection points, etc.). I will let you explain why this causes false trips.

---

Notes 70

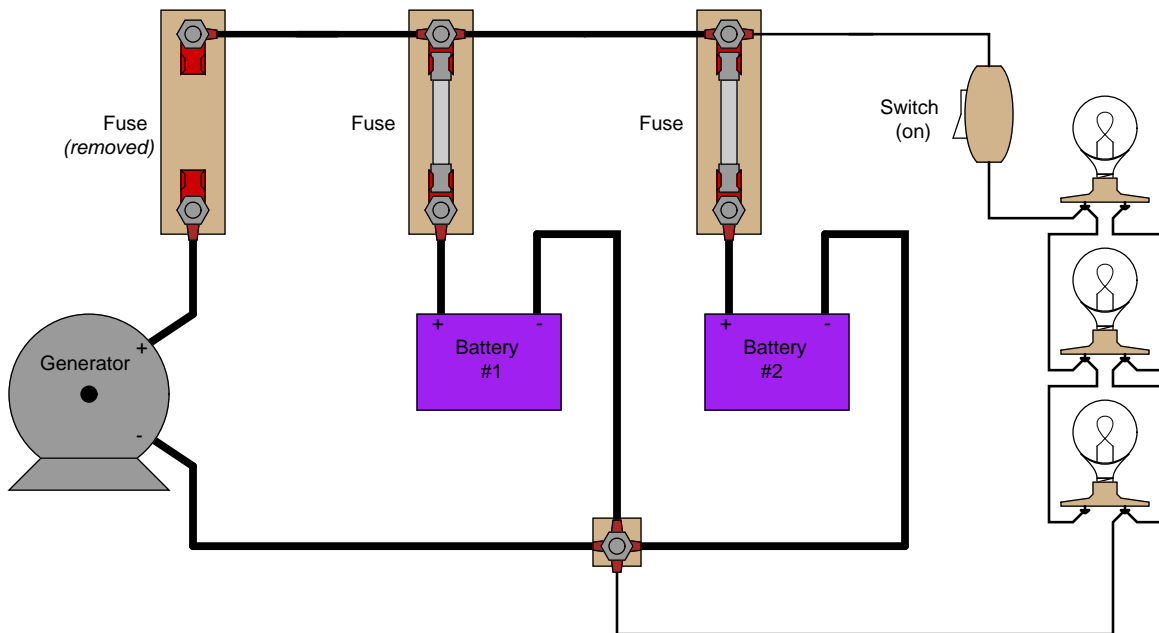
This is a very practical problem, directly dealing with parallel resistances. Unfortunately, I have seen residential circuit breaker panels new from the manufacturer, equipped with paralleled breakers! Bad idea . . . baaaaaad idea.

Something worthwhile to note as a possible cause of the tripping is a spurious motor problem. Perhaps the circuit breakers are sharing current equally after all, but the motor is occasionally drawing more than 300 amps of current! Just because an electrician measured less than 300 amps at full load does not mean the motor *never* draws more than 300 amps. There may be another problem after all. Discuss this with your students, asking them how they would identify such a problem after having determined the two circuit breakers were doing their job correctly.

---

Question 71

The generator in this power system is disconnected for routine servicing by removing its fuse, leaving the two batteries to supply all power to the bank of light bulbs:



The two batteries are rated such that they are supposed to provide at least 10 hours of back-up power in the event of a generator "outage" such as this. Unfortunately, the light bulbs begin to dim much sooner than expected. Something is wrong in the system, and you are asked to figure out what.

Explain what steps you would take to diagnose the problem in this circuit, commenting on any relevant safety measures taken along the way.

[file 03940](#)

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Answer 71

One simple procedure would be to connect a voltmeter in parallel with the light bulb bank, then remove the fuse for battery #1 and note the decrease in bus voltage. After that, replace the fuse for battery #1 and then remove the fuse for battery #2, again noting the decrease in bus voltage. If there is a problem with one of the batteries, it will be evident in this test. If both batteries are in good condition, but simply low on charge, that will also be evident in this test.

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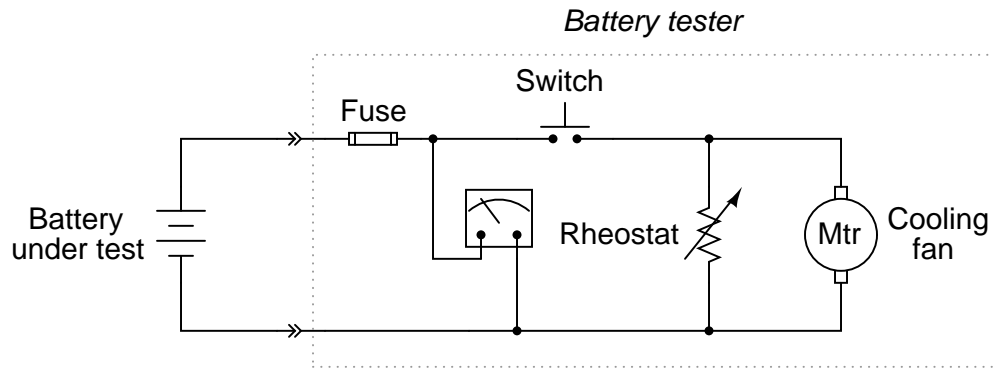
Notes 71

I purposely avoided giving away explicit answers in the Answer section of this question, electing instead to simply provide a sound procedure. The point here is for students to figure out on their own what the voltmeter indications would mean with regard to battery condition.

---

Question 72

This heavy-duty battery test circuit seems to have a problem. Instead of the voltmeter drooping when the test switch is closed, it remains steady regardless of switch state. This happens even when the battery under test is known to be weak:



Other clues to the problem include the fact that rheostat setting seems to make no difference in the voltmeter's indication, and also that the cooling fan motor does not come on when the switch is pressed.

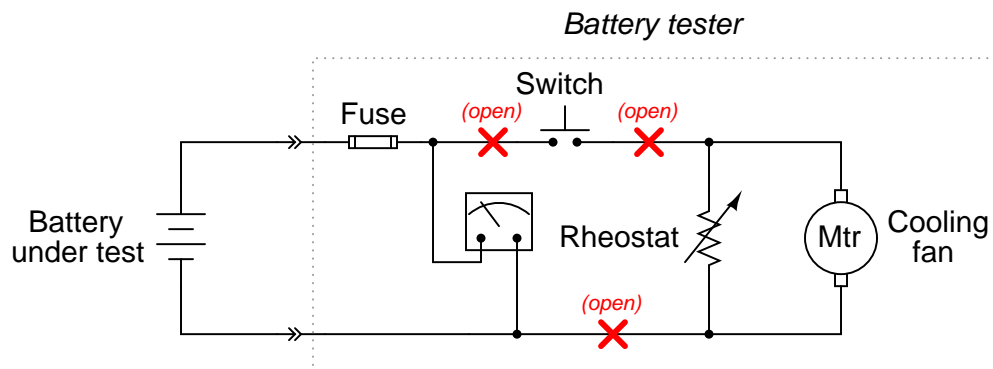
Identify possible faults in this circuit that could account for the symptoms listed here. Also, explain *why* each of your proposed faults would cause the observed symptoms.

[file 03941](#)

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Answer 72

Possible faults include broken wires or open connections at the following points in the circuit (marked with "X"):



Note: there is one more fault possibility that I have not listed here!

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Notes 72

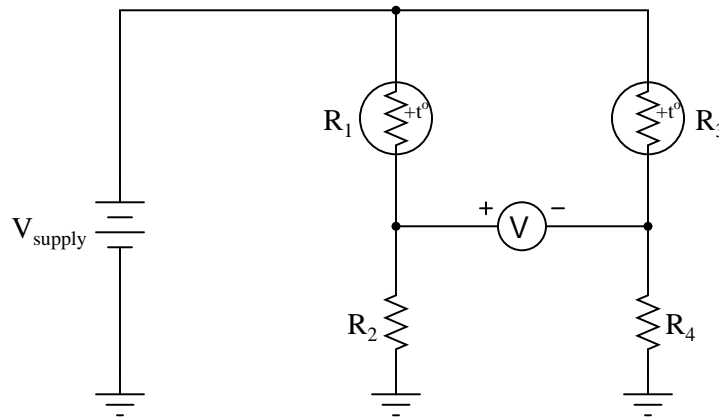
Discuss this simple circuit with your students, asking them how they diagnosed the problem and what possible faults could account for it. Encourage them to explore more than one possibility in their diagnoses!

In case a student happens to ask what the cooling fan is there for, tell them that it is there to provide cooling to the rheostat when in use.

---

### Question 73

Predict how the operation of this thermistor bridge circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):



- Thermistor  $R_1$  fails open:
- Thermistor  $R_3$  fails open:
- Solder bridge (short) across thermistor  $R_3$ :
- Resistor  $R_2$  fails open:
- Resistor  $R_4$  fails open:

For each of these conditions, explain *why* the resulting effects will occur.  
[file 03939](#)

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### Answer 73

- Thermistor  $R_1$  fails open: *Voltmeter "pegs" in the negative direction.*
- Thermistor  $R_3$  fails open: *Voltmeter "pegs" in the positive direction.*
- Solder bridge (short) across thermistor  $R_3$ : *Voltmeter "pegs" in the negative direction.*
- Resistor  $R_2$  fails open: *Voltmeter "pegs" in the positive direction.*
- Resistor  $R_4$  fails open: *Voltmeter "pegs" in the negative direction.*

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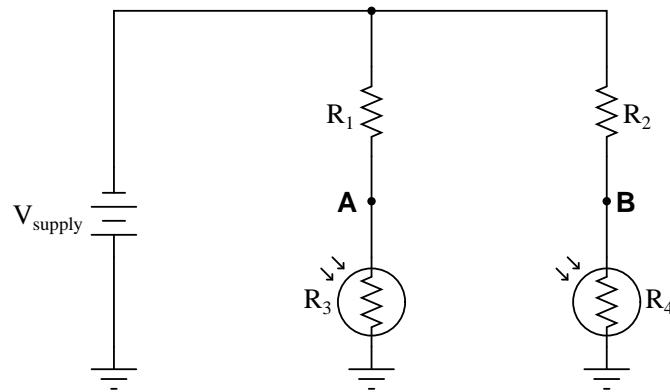
### Notes 73

The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of knowing what the fault is, rather than only knowing what the symptoms are. Although this is not necessarily a realistic perspective, it helps students build the foundational knowledge necessary to diagnose a faulted circuit from empirical data. Questions such as this should be followed (eventually) by other questions asking students to identify likely faults based on measurements.

---

### Question 74

Predict how the voltage polarity between test points **A** and **B** will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):



- Photoresistor  $R_4$  fails open:
- Photoresistor  $R_3$  fails open:
- Solder bridge (short) across photoresistor  $R_4$ :
- Resistor  $R_2$  fails open:
- Resistor  $R_1$  fails open:

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

[file 03944](#)

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### Answer 74

- Photoresistor  $R_4$  fails open: *Test point B will be positive with respect to test point A (negative).*
- Photoresistor  $R_3$  fails open: *Test point A will be positive with respect to test point B (negative).*
- Solder bridge (short) across photoresistor  $R_4$ : *Test point A will be positive with respect to test point B (negative).*
- Resistor  $R_2$  fails open: *Test point A will be positive with respect to test point B (negative).*
- Resistor  $R_1$  fails open: *Test point B will be positive with respect to test point A (negative).*

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### Notes 74

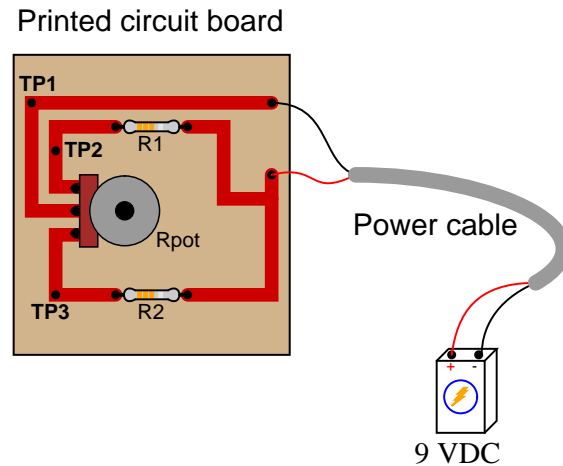
The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of knowing what the fault is, rather than only knowing what the symptoms are. Although this is not necessarily a realistic perspective, it helps students build the foundational knowledge necessary to diagnose a faulted circuit from empirical data. Questions such as this should be followed (eventually) by other questions asking students to identify likely faults based on measurements.



---

Question 75

This current divider circuit has a problem. The voltage between test points TP2 and TP1 varies with the potentiometer position, but the voltage between test points TP3 and TP1 remains at 0 volts no matter where the potentiometer is set:



Identify the most likely fault which would account for these measurements.  
[file 03943](#)

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Answer 75

There is an "open" fault in resistor  $R_2$ , or somewhere in series with  $R_2$  (bad solder connection, open trace, etc.).

Follow-up question: identify which direction of potentiometer shaft motion (clockwise or counter-clockwise) should increase the voltage between test points TP2 and TP1.

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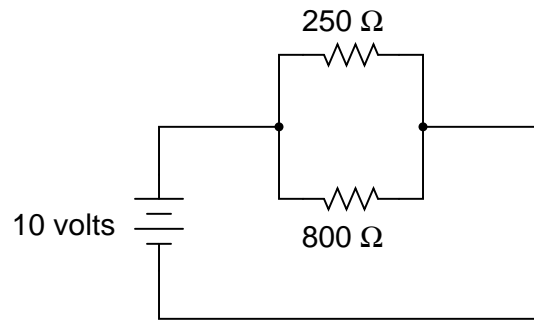
Notes 75

Discuss with your students how they determined the identity of the fault. Also, be sure to discuss the follow-up question with them: how to determine the proper direction to turn the potentiometer shaft in order to increase  $V_{TP2-TP1}$ . It is important that your students realize how a 3/4 turn potentiometer works, and what to expect when the shaft is turned.

---

Question 76

A common saying about electricity is that "it always takes the path of least resistance." Explain how this proverb relates to the following circuit, where electric current from the battery encounters two alternate paths, one being less resistive than the other:



[file 00085](#)

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Answer 76

The 250 Ω resistor will experience a current of 40 mA, while the 800 Ω resistor will experience a current of 12.5 mA.

---

Notes 76

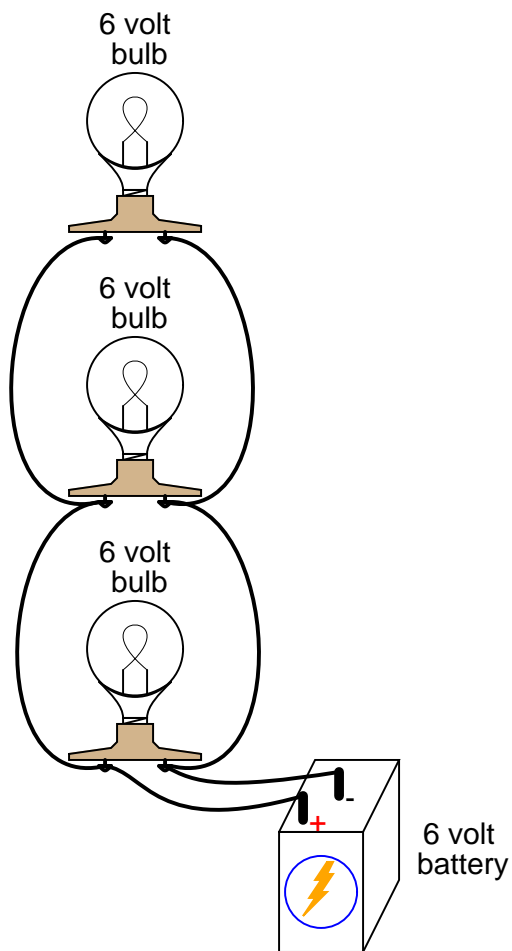
As an instructor, I was very surprised to hear many beginning students claim that *all* current would go through the lesser resistor, and *none* through the greater resistor! The proverb about "takes the path of least resistance" really should be understood as "*proportionately* taking paths of lesser resistance." People new to the study of electricity often misunderstand such basic principles, their errors usually based on folk wisdom like this. It is imperative to break through these myths with hard fact. In this case, Ohm's Law serves as a mathematical tool we can use to dispel false ideas.

Of course, a circuit as simple as this may be readily assembled and tested in class, so that all may see the truth for themselves.

---

Question 77

Qualitatively compare the voltage and current for each of the three light bulbs in this circuit (assume the three light bulbs are absolutely identical):



file 00037

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Answer 77

The voltage dropped across each of the lights bulbs is guaranteed to be equal. The current through each of the light bulbs, in this particular case (with identical bulbs), happens to be equal.

---

Notes 77

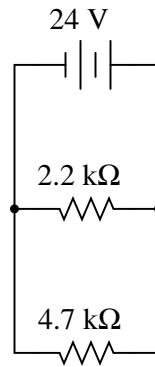
Here, the important principles of voltage and current in a parallel circuit are highlighted. This question serves to further define, in practical ways, what the term "parallel" really means.

An important lesson of this question is the distinction between measurements which are *guaranteed* to be equal versus measurements which just *happen* to be equal for a given selection of components.

---

Question 78

According to Ohm's Law, how much current goes through each of the two resistors in this circuit?



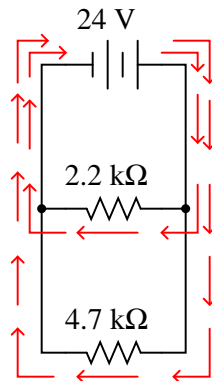
Draw the paths of all currents in this circuit.  
file 01963

---

Answer 78

$$I_{R(2.2k)} = 10.91 \text{ mA}$$

$$I_{R(4.7k)} = 5.11 \text{ mA}$$



*All arrows drawn in the direction  
of conventional flow!*

Follow-up question: how much *total* current does the battery supply to the circuit, given these individual resistor currents?

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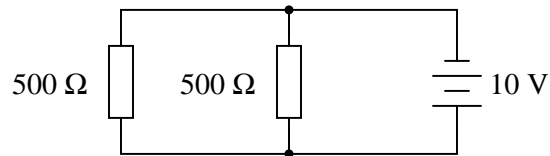
Notes 78

A key element to this question is the plotting of currents. Students need to see how individual resistor currents graphically relate to the total source current in a parallel circuit, because this has direct bearing on the calculation of total current, and also to an understanding of total resistance in parallel circuits.

---

Question 79

Calculate the total amount of current that the battery must supply to this parallel circuit:



Now, using Ohm's Law, calculate total resistance ( $R_{total}$ ) from total (source) voltage  $V_{total}$  and total (source) current  $I_{total}$ .  
[file 01964](#)

---

Answer 79

$$I_{total} = 40.0 \text{ mA}$$

$$R_{total} = 250 \Omega$$

Follow-up question: without appealing to Ohm's Law, explain why the total resistance is one-half as much as either of the individual resistances.

---

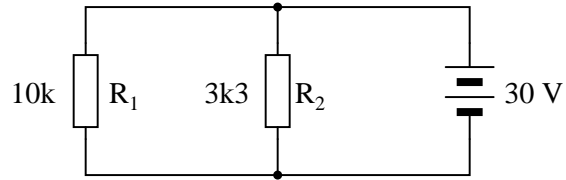
Notes 79

While some students seem able to immediately grasp the concept of parallel resistances diminishing in (total) value, it is worthwhile to approach it from an Ohm's Law perspective as well to give other students a more formal rationale for this effect.

---

Question 80

Complete the table of values for this circuit:



	R <sub>1</sub>	R <sub>2</sub>	Total
V			
I			
R			
P			

[file 03399](#)

---

Answer 80

	R <sub>1</sub>	R <sub>2</sub>	Total
V	30 V	30 V	30 V
I	3 mA	9.09 mA	12.09 mA
R	10 kΩ	3.3 kΩ	2.481 kΩ
P	90 mW	272.7 mW	362.7 mW

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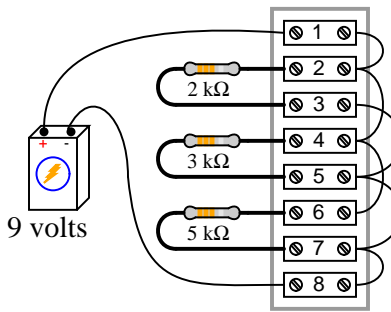
Notes 80

Discuss with your students what a good procedure might be for calculating the unknown values in this problem, and also how they might check their work.

---

Question 81

The circuit shown here is commonly referred to as a *current divider*. Calculate the voltage dropped across each resistor, the current drawn by each resistor, and the total amount of electrical resistance "seen" by the 9-volt battery:



- Current through the 2 k $\Omega$  resistor =
- Current through the 3 k $\Omega$  resistor =
- Current through the 5 k $\Omega$  resistor =
- Voltage across each resistor =
- $R_{total}$  =

Can you think of any practical applications for a circuit such as this?

[file 00294](#)

---

Answer 81

- Current through the 2 k $\Omega$  resistor = 4.5 mA
- Current through the 3 k $\Omega$  resistor = 3 mA
- Current through the 5 k $\Omega$  resistor = 1.8 mA
- Voltage across each resistor = 9 volts
- $R_{total}$  = 967.74  $\Omega$

How much current is drawn from the battery in this circuit? How does this figure relate to the individual resistor currents, and to the total resistance value?

---

Notes 81

Some students may find the diagram hard to follow, and so they will find the task of analysis helped by drawing an equivalent schematic diagram for this circuit, with all terminal points labeled. I recommend you not suggest this solution immediately, but rather challenge your students to think of problem-solving techniques on their own. Surely, someone in the class will have thought of doing this, and the impact of such a suggestion coming from a peer is greater than if it came from you, the instructor.

Be sure to ask your students this question: "Why is this type of circuit commonly called a *current divider*?"

---

Question 82

Manipulate this equation to solve for resistor value  $R_1$ , given the values of  $R_2$  and  $R_{parallel}$ :

$$R_{parallel} = \frac{R_1 R_2}{R_1 + R_2}$$

Then, give an example of a practical situation where you might use this new equation.  
[file 01988](#)

---

Answer 82

$$R_1 = \frac{R_2 R_{parallel}}{R_2 - R_{parallel}}$$

I'll let you figure out a situation where this equation would be useful!

---

Notes 82

This question is really nothing more than an exercise in algebraic manipulation.



---

Question 83

The formula for calculating total resistance of three parallel-connected resistors is as follows:

$$R = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

Algebraically manipulate this equation to solve for one of the parallel resistances ( $R_1$ ) in terms of the other two parallel resistances ( $R_2$  and  $R_3$ ) and the total resistance ( $R$ ). In other words, write a formula that solves for  $R_1$  in terms of all the other variables.

[file 03067](#)

---

Answer 83

$$R_1 = \frac{1}{\frac{1}{R} - \left(\frac{1}{R_2} + \frac{1}{R_3}\right)} \quad \text{or} \quad R_1 = \frac{1}{\frac{1}{R} - \frac{1}{R_2} - \frac{1}{R_3}}$$

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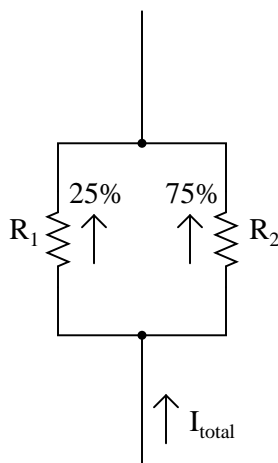
Notes 83

This question is nothing more than practice algebraically manipulating equations. Ask your students to show you how they solved it, and how the two given answers are equivalent.

---

Question 84

Choose two resistor values such that one resistor passes 25% of the total current, while the other resistor passes 75% of the total current:



file 00336

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Answer 84

There are many combinations of resistor values that will satisfy these criteria.

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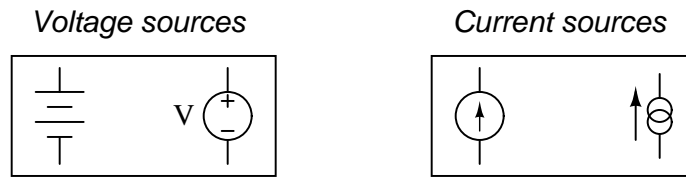
Notes 84

This is a fine example of a question with multiple correct answers. No matter how many unique combinations students invent, they may all be verified by a few simple Ohm's Law calculations.

---

Question 85

Ideal *voltage sources* and ideal *current sources*, while both being sources of electrical power, behave very differently from one another:



Explain how each type of electrical source would behave if connected to a variable-resistance load. As this variable resistance were increased and decreased, how would each type of source respond?

[file 03226](#)

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Answer 85

An ideal voltage source will output as much or as little current as necessary to maintain a constant voltage across its output terminals, for any given load resistance. An ideal current source will output as much or as little voltage as necessary to maintain a constant current through it, for any given load resistance.

---

Notes 85

Ask your students to think of a few "thought experiment" scenarios where voltage and current sources could be put to test. Have them invent voltage and current values for these voltage and current sources, respectively, then calculate all other circuit parameters given several different values of load resistance.

---

Question 86

Although the voltage divider and current divider equations are very useful in circuit analysis, they are easily confused for one another because they look so similar:

$$V_R = V_{total} \left( \frac{R}{R_{total}} \right) \qquad I_R = I_{total} \left( \frac{R_{total}}{R} \right)$$

Specifically, it is easy to forget which way the resistance fraction goes for each one. Is it  $\frac{R}{R_{total}}$  or is it  $\frac{R_{total}}{R}$ ? Simply trying to memorize which fraction form goes with which equation is a bad policy, since memorization of arbitrary forms tends to be unreliable. What is needed is recognition of some sort of *principle* that makes the form of each equation sensible. In other words, each equation needs to make sense *why* it is the way it is.

Explain how one would be able to tell that the following equations are wrong, without referring to a book:

$$V_R = V_{total} \left( \frac{R_{total}}{R} \right) \qquad \text{Wrong equations!} \qquad I_R = I_{total} \left( \frac{R}{R_{total}} \right)$$

[file 03443](#)

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Answer 86

The resistance fraction must always be less than 1.

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Notes 86

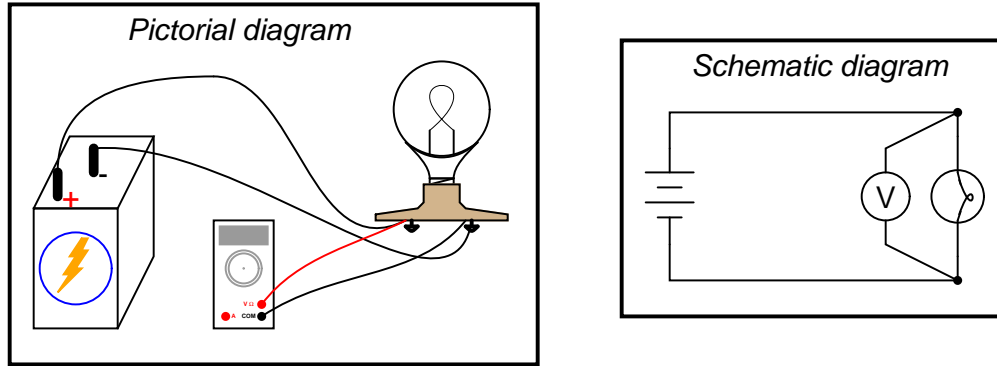
Note that I do not explain why the fraction is less than 1 for each equation. I leave it to the students to figure out that  $R < R_{total}$  for series circuits and  $R_{total} < R$  for parallel circuits.

Many students have the unfortunate tendency to *memorize* in favor of *understand*, especially when it comes to equations. Comprehension is, of course, far superior, and exercises like this one help students build comprehension of the formulae they use in electronics.

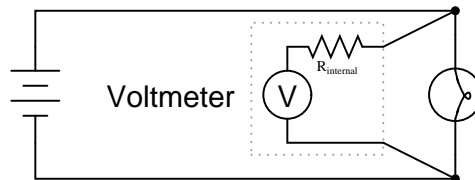
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Question 87

Voltmeters must be connected in *parallel* with the voltage to be measured:



In order to practically function, an voltmeter must have some finite amount of internal resistance. It is usually a very large amount, but less than infinite. It should be apparent to you that the presence of this resistance will have some effect on the circuit voltage, when compared to the amount of voltage in the circuit without any meter connected, due to the fact that real voltage sources tend to “sag” when subjected to additional loads:



Explain why it is usually safe to ignore the internal resistance of an voltmeter, though, when it is in a circuit. A common term used in electrical engineering to describe this intentional oversight is *swamping*. In this particular circuit an engineer would say, “The resistance of the light bulb *swamps* the internal resistance of the voltmeter.”

[file 03639](#)

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Answer 87

When one quantity “swamps” another, we mean that its effect is huge compared to the effect of the other, so much so that we may safely ignore it in our calculations and still arrive at a reasonably accurate result.

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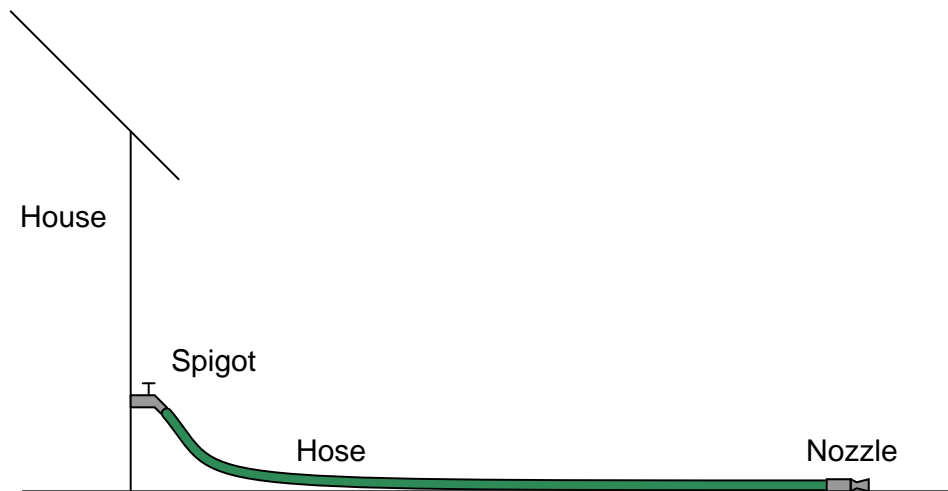
Notes 87

I have found that the concept of “swamping” is extremely useful when making estimations. To be able to ignore the values of some components allows one to simplify a great many circuits, enabling easier calculations to be performed.

---

Question 88

One day you decide to water your garden, using a garden hose that is already connected to a spigot on the side of your house:



When you turn on the valve at the spigot, though, no water comes out the nozzle at the other end of the hose. Explain the steps you would take to troubleshoot this problem.

[file 01568](#)

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Answer 88

This is an excellent question for discussion amongst your classmates! Two things I recommend, though:

- Identify some probable sources of trouble in this garden hose "system."
- Proceed in a logical manner to find the trouble as efficiently as possible.

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Notes 88

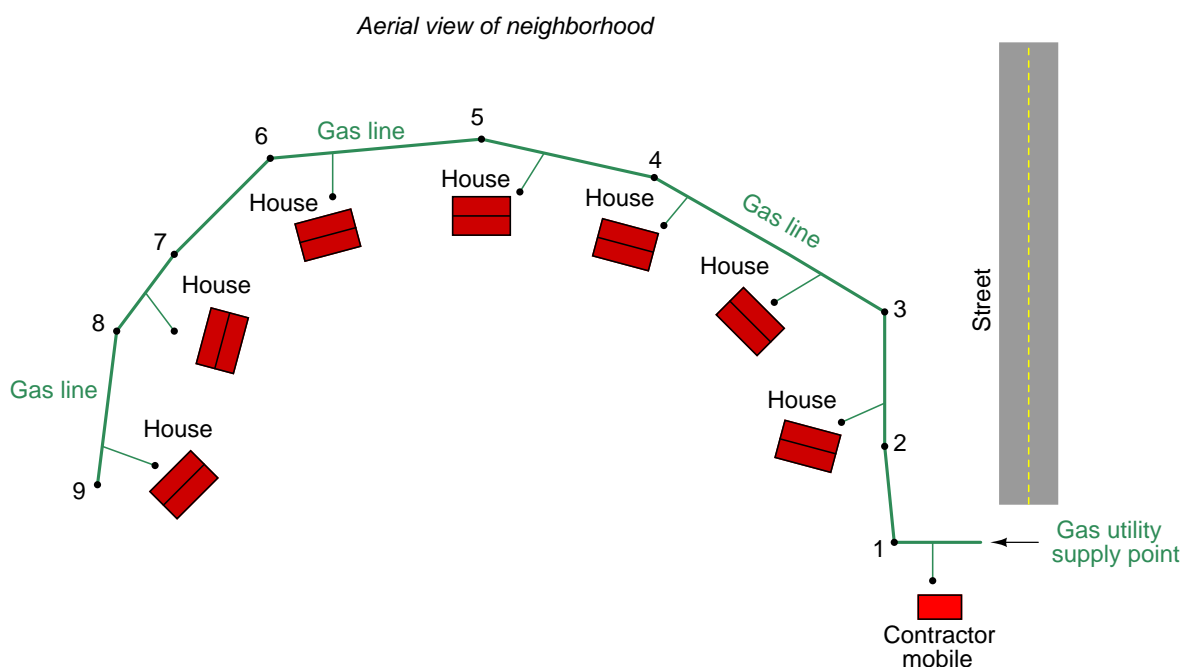
Discuss with your students both probable causes of this problem as well as strategies for locating the problem. Encourage students to analyze the system by dividing it into sections. Since garden hoses easily detach from spigots and nozzles alike, they lend themselves well to the so-called "divide-and-conquer" method of troubleshooting.

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Question 89

A new residential neighborhood is being built, and you are working as a member of the construction crew. One day, when the heating technicians are on-site doing checks of the gas furnaces in each new house, they report that the last house in the neighborhood does not have natural gas. The piping is installed, of course, but when they turn the gas valve on nothing comes out.

The gas pipeline servicing these houses is laid out in the following manner:



Each black dot on the diagram is a shutoff valve, used for isolating different sections of the service pipeline. Based on the heating technician's report, you conclude that the service pipeline going up to that house must not be "live," and that one of the numbered valves was probably left in the *off* position. But which one could it be?

You know that the main utility connection at the street is "live," because the gas heater in the contractor mobile building is working just fine. You decide to go to valve #8 and check for gas pressure at that point in the pipeline with a portable pressure gauge, then checking the pressure at each valve location down the pipeline until you find where there is good gas pressure. However, before you step out of the room to go do this, one of your co-workers suggests you start your search at the middle point of the pipeline instead: at the location of valve #4.

Explain why your co-worker's idea is better, and also what your next step would be if: (a) you did find pressure at that point, and (b) if you did *not* find pressure at that point.

[file 01595](#)

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Answer 89

Your co-worker's strategy is based on the principle of dividing the gas pipeline into halves, and checking for pressure at the half-way point. This troubleshooting strategy is sometimes referred to as the "divide-and-conquer" method, because it divides the system into small sections to optimize troubleshooting time and effort.

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Notes 89

This problem gives students a chance to explore the "divide and conquer" strategy of troubleshooting in a context that is very simple and does not require knowledge of electricity.

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### Question 90

As a technician, you are sent to troubleshoot a complex piece of electronic equipment that has stopped working. Upon opening the cabinet door for this equipment, your nose is greeted by the pungent odor of burnt circuit board (a smell you are unlikely to forget, once having experienced it). What does this simple fact indicate (or possibly indicate) about the nature of the equipment's fault?

[file 01576](#)

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### Answer 90

The fact that you can *smell* trouble indicates you are most likely dealing with a catastrophic failure caused by (or resulting in) excessive current. When components have been heated to such a degree that they emit strong odors, the damage is often visible as well, which makes it easier to locate problem areas.

Follow-up question: upon further investigation, you locate the charred remains of an electronic component, located on one of the system's circuit boards. Is this the only fault, being that it is the only component visibly damaged? Explain why or why not.

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### Notes 90

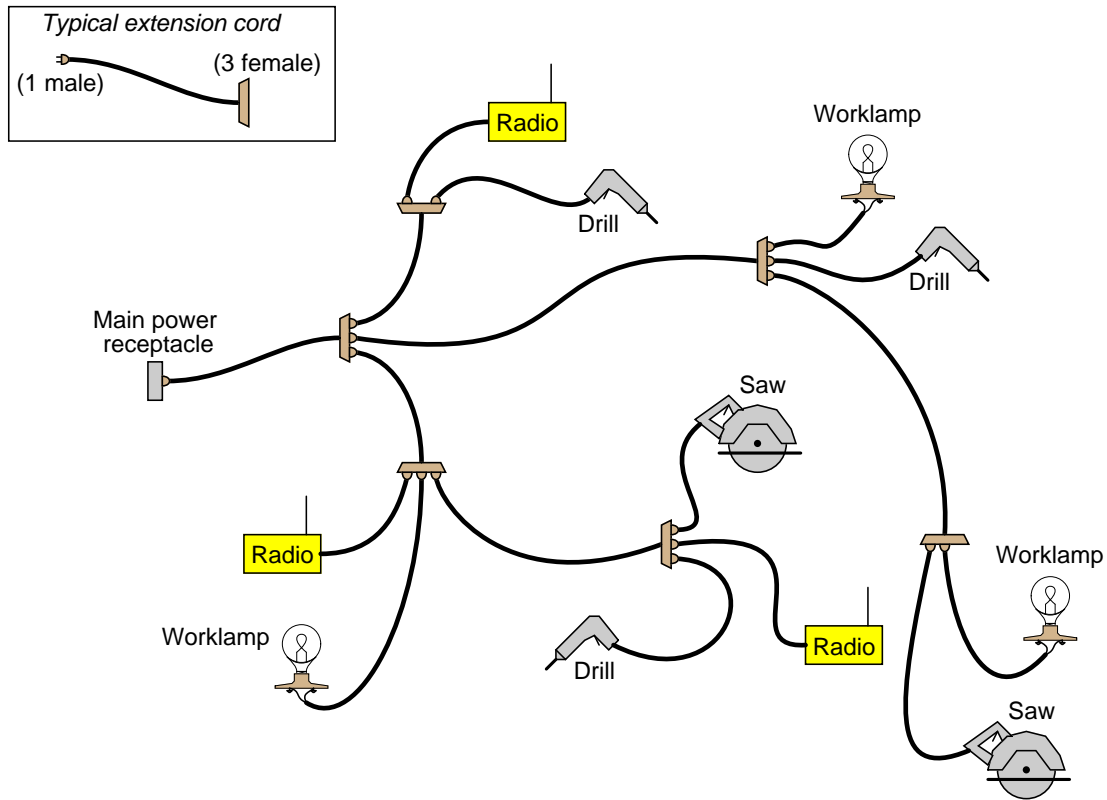
It is important for students to understand that not all faults become visible, even if catastrophic!

Be sure to discuss with your students that the burnt component may very well be a *victim* of another component failure, and not the *cause* of the system fault. For instance, shorted wiring located far from the equipment enclosure may have caused the components to destruct. This is a common assumption made by beginning troubleshooters: that the most obvious failure is the only failure, or that it must be the primary failure.



Question 91

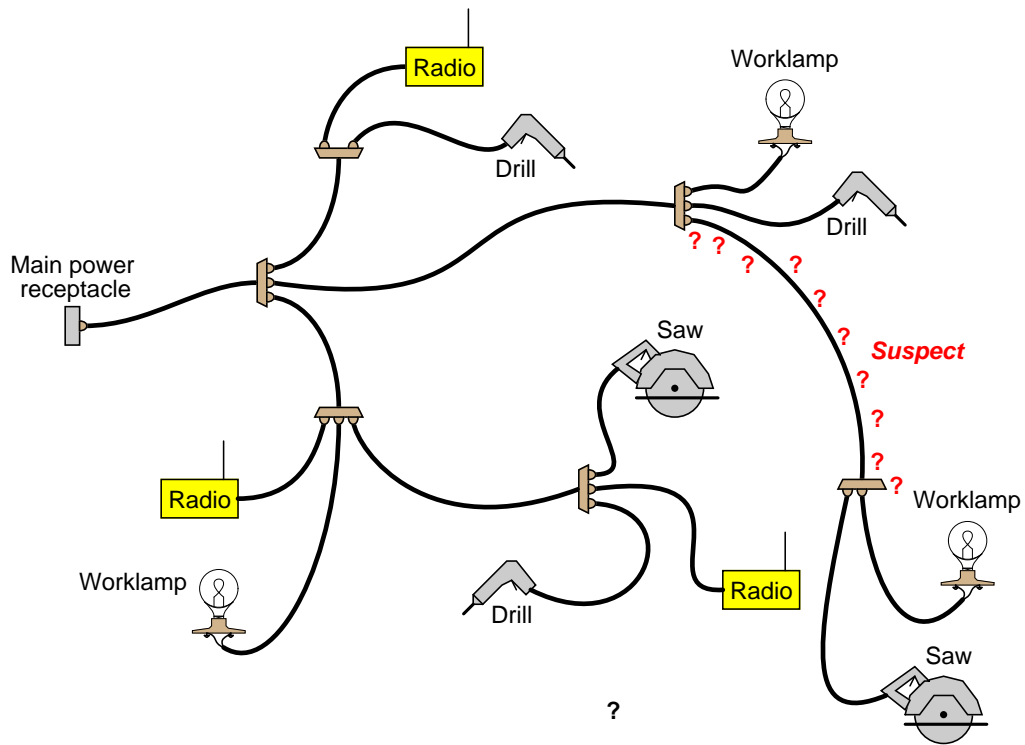
At a construction site, workers have used power extension cords to create a "network" of power cabling for their various electric tools. Each cord has one (male) plug and a receptacle (female) end that accepts up to three plugs:



Despite this dangerous wiring, all tools have functioned so far without trouble. Then suddenly both the worklight and the circular saw in the lower-right corner of the illustration stop working. All the other tools continue to function properly (including all the radios, which is very fortunate because the workers become irritable without their music).

From this information alone, determine what sections of this "network" are good, and what sections are suspect.

[file 01575](#)



Follow-up question: describe the general principle you used to locate the suspect area of this power network.

Notes 91

Now, of course, it is possible that both the worklight and the saw suffered independent, simultaneous failures, and all the extension cords are good, but this is not very likely. Be sure to discuss this possibility with your students, and the reasoning why the one extension cord would be more likely to be faulted than two separate devices.

---

### Question 92

Two computer technicians are called to troubleshoot malfunctioning computer systems. Although the symptoms in each system are very similar, the histories of the two systems are not. The first computer is a unit that has been in operation for over two years, while the second system is a brand-new prototype, still in the developmental stages.

Without knowing any more details on these two computer systems, what recommendations can you give to the two technicians about to troubleshoot them? If you were asked to troubleshoot each system, how would you approach the two systems differently? What ranges of problems might you expect from each system?

[file 01580](#)

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### Answer 92

I'll let you determine the answers to this question! I do not expect that you will provide specific, technical answers, because I have given very little information about the malfunctioning systems. What I want is for you to think in general terms: how might the scope of possible problems differ between *any* two similar systems, one of which is proven while the other is untried?

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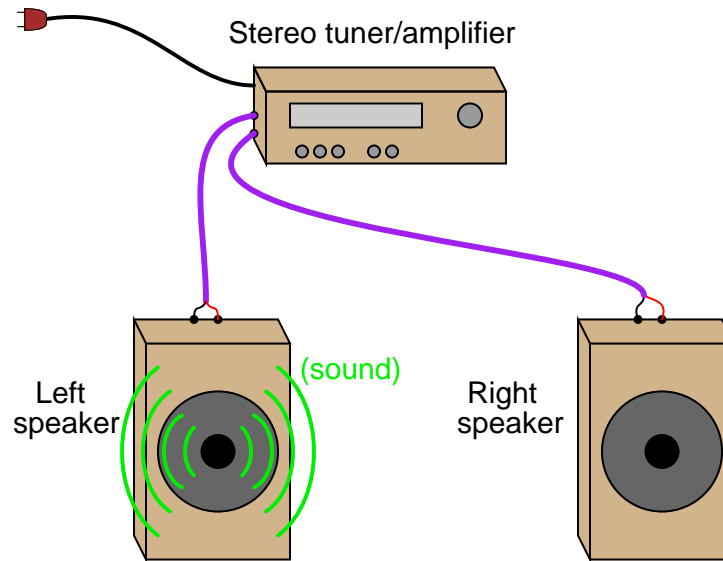
### Notes 92

As an illustration of this principle, you might want to elaborate on your own experiences as an electronics instructor. When assisting students with lab projects, what typical problems do you encounter with the circuits they build, and how do these problems typically differ from problems you've seen in real-life electronic equipment?

---

### Question 93

This stereo system has a problem: only one of the two speakers is emitting sound. While the left speaker seems to be working just fine, the right speaker is silent regardless of where any of the stereo's controls are set:



Identify three possible faults that could cause this problem to occur, and identify what components of the stereo system are known to be okay (be sure to count each cable as a separate component of the system!).

**Possible faults in the system:**

- Fault #1:
- Fault #2:
- Fault #3:

**Components known to be okay in the system:**

- Component #1:
- Component #2:
- Component #3:

Explain how you might go about troubleshooting this problem, using no test equipment whatsoever. Remember that the speaker cables detach easily from the speakers and from the amplifier.

file 01570

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### Answer 93

Components known to be okay include the left speaker, left speaker cable, and power cord for the amplifier. There are, of course, more known "good" components in this system than the three mentioned here, especially if you count discrete electronic components inside the amplifier itself.

Possible faults include the right speaker, the right speaker cable, and the right output channel of the amplifier. A very good way to determine which of these components is faulted is to swap cables and speakers between sides, but I'll let you determine which component swaps test which components.

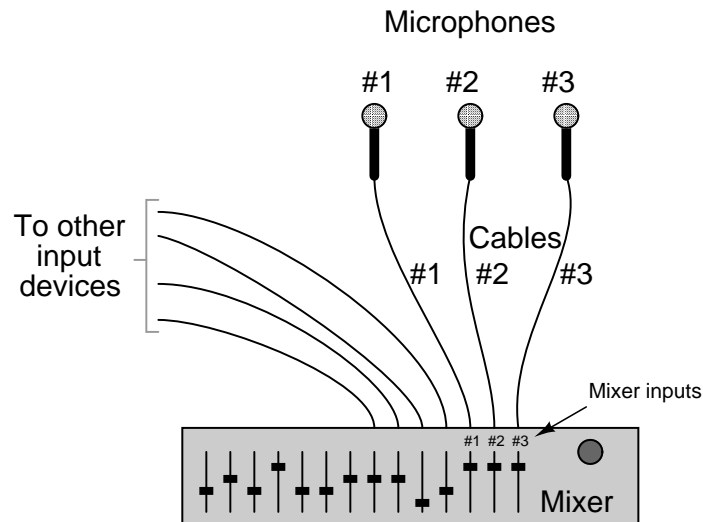
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### Notes 93

Swapping components can be a very powerful means of troubleshooting system problems where interchangeable components exist.

Question 94

A music recording studio is equipped with three microphones, each of which connect to the "mixer" panel by means of shielded cables:



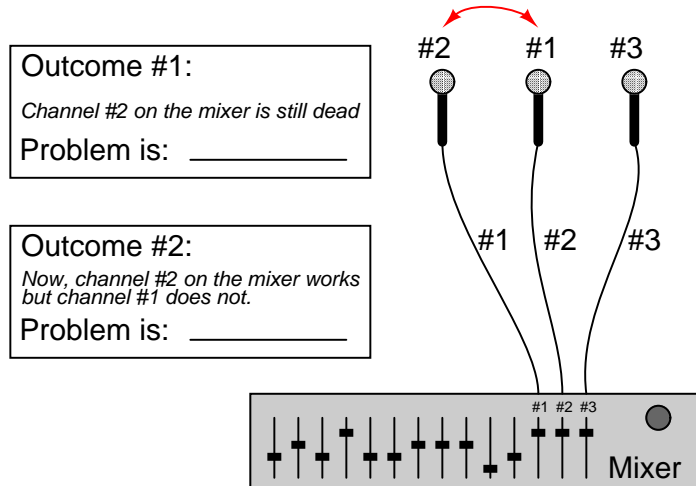
The purpose of the mixer is to function as a multi-channel audio signal amplifier, to control the volume of each sound channel so that a good "mix" is obtained for recording. The studio engineer will use the individual controls on the mixer to "blend" the inputs for the best recording tone and quality.

This system has a problem, though. Microphone #2 seems to be "dead," meaning that channel #2 on the mixer does not register any signal when the singer sings into that microphone. All the other channels are working just fine, though.

Being the studio technician, your job is to troubleshoot this problem in the shortest time possible. Unfortunately, in your rush to get to the job site you forgot to bring your test equipment. That isn't a problem, however, because you know how to troubleshoot systems by swapping interchangeable components.

I will present four different "swap" scenarios to you, with two different outcomes for each. Your task is to declare what is known about the location of the fault based on these scenarios and outcomes.

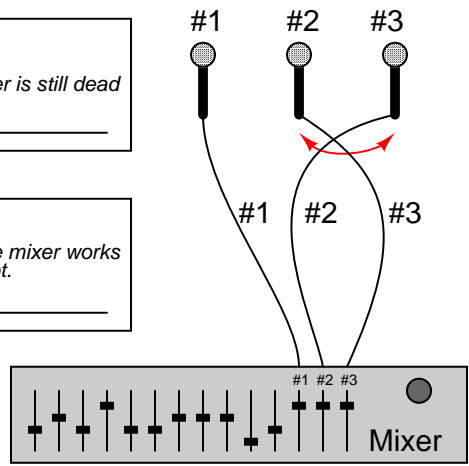
**Scenario #1: Swap microphones 1 and 2**



**Scenario #2:** Swap cables 2 and 3 at microphones

**Outcome #1:**  
*Channel #2 on the mixer is still dead*  
Problem is: \_\_\_\_\_

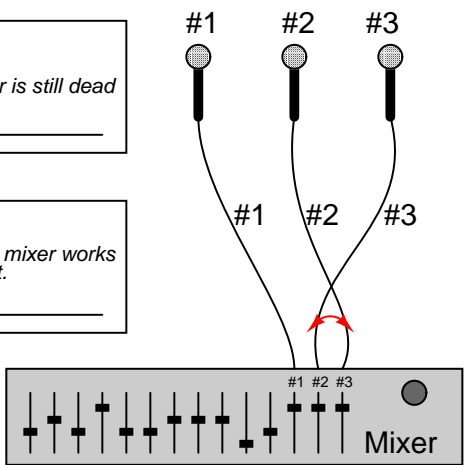
**Outcome #2:**  
*Now, channel #2 on the mixer works but channel #3 does not.*  
Problem is: \_\_\_\_\_



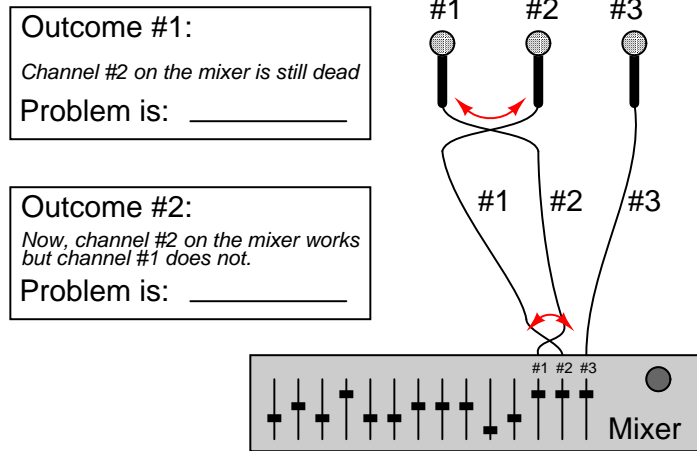
**Scenario #3:** Swap cables 2 and 3 at mixer

**Outcome #1:**  
*Channel #2 on the mixer is still dead*  
Problem is: \_\_\_\_\_

**Outcome #2:**  
*Now, channel #2 on the mixer works but channel #3 does not.*  
Problem is: \_\_\_\_\_



### Scenario #4: Swap cables 1 and 2 at both ends



[file 01571](#)

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#### Answer 94

Scenario #1, outcome #1: problem is *not* in the microphone.

Scenario #2, outcome #2: microphone #2 is faulty.

Scenario #2, outcome #1: problem is *not* in the microphone.

Scenario #2, outcome #2: microphone #2 is faulty.

Scenario #3, outcome #1: mixer input #2 is faulty.

Scenario #3, outcome #2: the problem is *not* in the mixer.

Scenario #4, outcome #1: the problem is *not* in the cable.

Scenario #4, outcome #2: cable #2 is faulty.

---

#### Notes 94

Your more adept students will immediately recognize that scenarios 1 and 2 are really quite the same. The logical thinking behind this troubleshooting strategy may confound some of your students, so be prepared to spend adequate time covering and re-covering (if necessary) this question. By the way, this type of question is excellent for a written test!

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### Question 95

A friend of yours brings you their damaged stereo amplifier, hoping that perhaps you would be able to repair it cheaper than the local electronics repair shop. The amplifier was damaged at a recent party, when one of your friend's guests turned up the volume to full and left it there until smoke billowed out of the power amplifier chassis.

Your friend has already done some troubleshooting of his own: after turning off the amplifier and letting the smoke clear, he turned it back on at low volume to find that the left channel is dead, but the right channel is still working. He then swapped speakers and speaker wires, and consistently found that whatever speaker was plugged into the left channel did not make sound, but the speaker plugged into the right channel always did.

You remove the chassis cover on the amplifier and look inside. There, the damage is visually apparent: both of the power transistors for the left channel output are burnt beyond recognition. You unsolder the transistors from the circuit board and unscrew them from the heat sink, but you cannot read the part numbers on their cases due to the thermal damage. This is not good, because without knowing the proper part numbers, your friend cannot order the proper replacement transistors to repair the amplifier.

As usual, there is no schematic diagram supplied with this amplifier that would indicate the proper part numbers. What do you do?

[file 01589](#)

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### Answer 95

Read the part numbers off the power transistors for the right channel output!

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### Notes 95

Some students may question this logic, believing that the left and right channels of a stereo amplifier would be mirror-symmetric rather than identical, and thus possibly contain different components. You may answer this objection by appealing to the indistinguishable sound of the two channels, when listened to separately (mono). There is nothing "right-handed" or "left-handed" about the two channels. Each one is identical to the other at the circuit level, because each channel is expected to perform exactly the same.



---

### Question 96

A very powerful method for discerning cause-and-effect relationships is *scientific method*. One commonly accepted algorithm (series of steps) for scientific method is the following:

1. Observation
2. Formulate an hypothesis (an educated guess)
3. Predict a unique consequence of that hypothesis
4. Test the prediction by experiment
5. If test fails, go back to step #2. If test passes, hypothesis is provisionally confirmed.

This methodology is also very useful in technical troubleshooting, since troubleshooting is fundamentally a determination of cause for an observed effect. Read the following description of an experienced troubleshooter diagnosing an mechanical noise problem in a bicycle, and match the troubleshooter's steps to those five steps previously described for scientific method:

One day a bicyclist called a mechanic friend of his over the telephone, and describes a problem with his bicycle. The bicycle is making a rhythmic "clicking" sound as it is pedaled, but the bicyclist is not very mechanically inclined, and cannot determine the cause of the noise.

The mechanic considered some of the options. Being a rhythmic noise, it was probably being caused by one of the bicycle's rotating objects. This includes the wheels, crank, and chain, which all rotate at different speeds. After a bit of thought, the mechanic asked his bicyclist friend a question.

"Does the pace of the clicking increase as you ride faster?" The bicyclist answered, "Yes, it does."

"If you shift into a higher gear so that your crank is turning slower for the same road speed, does the pace of the clicking change?" asked the mechanic. The bicyclist admitted he didn't know the answer to this question, as he hadn't thought to pay attention to this detail. After riding the bike once again to test the mechanic's idea, the bicyclist reported back. "No, the pace of the clicking does not change when I shift gears. It only changes with changes in road speed."

Upon hearing this, the mechanic knew the general location of the problem, and continued his troubleshooting over the telephone with further questions for the bicyclist.

Where is the clicking sound coming from on this bicycle, based on the information presented here? How do you (and the mechanic) know?

[file 01596](#)

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### Answer 96

The clicking noise has something to do with one of the wheels, and not the chain or crank.

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### Notes 96

Discuss with your students the relationship between the mechanic's steps and the steps given for scientific method. Have them locate the observation, hypothesis, prediction, and test.

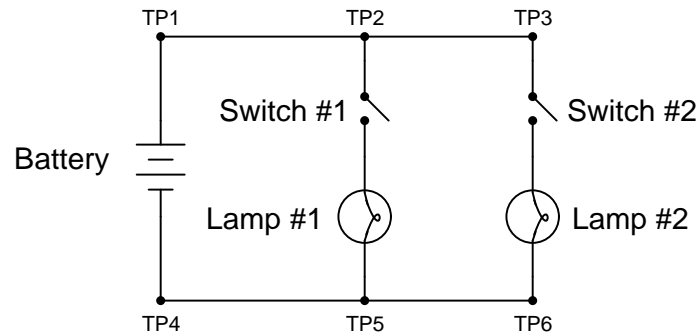
Once students have successfully identified the mechanic's reasoning, ask them to explain how the prediction of noise rhythm distinguishes which part of the bicycle is making the noise.

Also, discuss whether this concludes the diagnostic procedures, or if there is more troubleshooting left to do. What steps are recommended to take next, if any?

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Question 97

The following circuit has a problem. Switch #2 is able to control lamp #2, but lamp #1 never comes on no matter what is done with switch #1:



Identify which of these hypothetical faults could account for this problem, and which could not account for the problem. In other words, which of these faults are possible, and which are not possible, given the symptoms exhibited by the circuit? Consider each of these hypothetical faults one at a time (no multiple, simultaneous faults):

- Battery is dead
- Lamp #1 filament failed open
- Lamp #2 filament failed open
- Switch #2 failed open
- Switch #2 failed shorted
- Switch #1 failed open
- Switch #1 failed shorted
- Open wire between test points 1 and 2 (between TP1 and TP2)
- Open wire between test points 4 and 5 (between TP4 and TP5)
- Open wire between test points 5 and 6 (between TP5 and TP6)

[file 03299](#)

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Answer 97

- Battery is dead: *Not possible*
- Lamp #1 filament failed open: *Possible*
- Lamp #2 filament failed open: *Not possible*
- Switch #2 failed open: *Not possible*
- Switch #2 failed shorted: *Not possible*
- Switch #1 failed open: *Possible*
- Switch #1 failed shorted: *Not possible*
- Open wire between test points 1 and 2 (between TP1 and TP2): *Not possible*
- Open wire between test points 4 and 5 (between TP4 and TP5): *Not possible*
- Open wire between test points 5 and 6 (between TP5 and TP6): *Not possible*

Follow-up question: if we allow ourselves to consider more than one fault occurring at the same time, which of these scenarios becomes possible? Explain why.

This question helps students build the skill of eliminating unlikely fault possibilities, allowing them to concentrate instead on what is more likely. An important skill in system troubleshooting is the ability to formulate probabilities for various fault scenarios. Without this skill, you will waste a lot of time looking for unlikely faults, thereby wasting time.

For each fault scenario it is important to ask your students *why* they think it is possible or not possible. It might be that some students get the right answer(s) for the wrong reasons, so it is good to explore the reasoning for each answer.

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Question 98

There is a fundamental Law in physics known as the Law of Energy Conservation. This law states that energy can neither be created nor destroyed, merely transformed from one form to another.

In regard to this Law, is it possible to make an electrical battery that lasts forever, and never becomes exhausted? Explain why or why not.

[file 00224](#)

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Answer 98

According to the Law of Energy Conservation, it is not possible to make a battery that lasts forever.

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Notes 98

This question may lead into a discussion on perpetual motion machines, a subject that seems to be perpetual itself in the popular interest.

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Question 99

Where does the energy come from that causes a battery to be a source of electricity for powering electrical devices? Ultimately, what is the energy *source* of a battery?

[file 00225](#)

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Answer 99

Electrical batteries derive their energy from chemical compounds stored within.

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Notes 99

Battery electrochemistry is quite complex, and not easily addressed in a class environment unless all students have a good background knowledge of chemistry. It is not the point of this question to address issues of electrochemistry, but merely to point out the nature of a battery's energy source.

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Question 100

Describe what a *fuel cell* is, and what the practical importance of such a device might be.

file 00226

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Answer 100

"Fuel cells" are essentially batteries *externally* supplied with chemicals for their source of energy.

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Notes 100

Much attention has been directed toward fuel cells as energy conversion devices, for their high efficiency and environmentally "clean" operation. Your students should have no trouble finding current information on fuel cell technology.

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Question 101

What does it mean if a battery, or a bank of batteries, receives a *floating* charge? What does it mean if a battery, or a bank of batteries, receives an *equalizing* charge?

[file 00515](#)

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Answer 101

A "floating" charge is a very low charge rate, just enough to maintain a state of full charge despite normal load fluctuations on the power bus. An "equalizing" charge is a state of overcharging, done to equalize the chemistry in all cells of a battery.

Follow-up question: qualitatively speaking, at what voltage should the power supply be set to in order to "float" a battery bank, versus in order to "equalize" a battery bank?

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Notes 101

Being able to identify these types of charge strategies is important, because many battery-powered systems with automatic chargers are either designed to charge in a particular way, or have the ability to switch between different charging modes. Failure to properly charge a battery, or a battery bank, will lead to decreased performance and/or decreased life.

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Question 102

It is a common phenomenon for the electrical resistance of a substance to change with changes in temperature. Explain how you would experimentally demonstrate this effect.

[file 00506](#)

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Answer 102

It is a simple thing to demonstrate a substance's change in resistance with temperature. I'm interested in finding out how you might discern a *quantitative* measurement of this change. That is, how would you design an experiment so as to "attach a number" to the effect of resistance changing with temperature?

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Notes 102

This question is an excellent starting point for an in-class experiment. There are several ways in which this effect could be demonstrated.



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### Question 103

A length of copper wire ( $\alpha = 0.004041$  at  $20^\circ\text{C}$ ) has a resistance of 5 ohms at 20 degrees Celsius. Calculate its resistance if the temperature were to increase to 50 degrees Celsius.

Now, take that calculated resistance, and that new temperature of  $50^\circ\text{C}$ , and calculate what the resistance of the wire should go to if it cools back down to  $20^\circ\text{C}$ . Treat this as a separate problem, working through all the calculations, and don't just say "5 ohms" because you know the original conditions!

file 01484

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### Answer 103

$$R_{50^\circ\text{C}} = 5.606\ \Omega$$

If you got an answer of  $R_{20^\circ\text{C}} = 4.927\ \Omega$  for the second calculation, you made a common mistake that is not always warned against in textbooks! Try the math again. If you got the proper answer of  $5\ \Omega$  upon doing the second calculation, try to figure out why someone may have calculated  $4.927\ \Omega$  taking the temperature from  $50^\circ\text{C}$  down to  $20^\circ\text{C}$ .

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### Notes 103

One thing students need to learn is they can't simply use the resistance-temperature formula as it is normally given if the "reference" (starting) temperature is not the same as the temperature at which  $\alpha$  is specified at!

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Question 104

The resistance of a piece of copper wire at temperature  $T$  (in degrees Celsius) is given by the following formula:

$$R_T = R_o [1 + 0.004041(T - 20)]$$

Suppose you wished to alter this formula so it could accept values for  $T$  in units of degrees Fahrenheit instead of degrees Celsius. Suppose also that the only formula you are able to find for converting between Fahrenheit ( $T_F$ ) and Celsius ( $T_C$ ) is this one:

$$T_F = T_C \left( \frac{9}{5} \right) + 32$$

Combined these two formulae into one solving for the resistance of a copper wire sample ( $R_T$ ) at a specific temperature in degrees Celsius ( $T_C$ ), given the specimen's "reference" resistance ( $R_o$ ) at 20° Celsius (room temperature).

[file 03068](#)

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Answer 104

$$R_T = R_o \left[ 1 + 0.004041 \left( \frac{5}{9} T_F - 37.\overline{77} \right) \right]$$

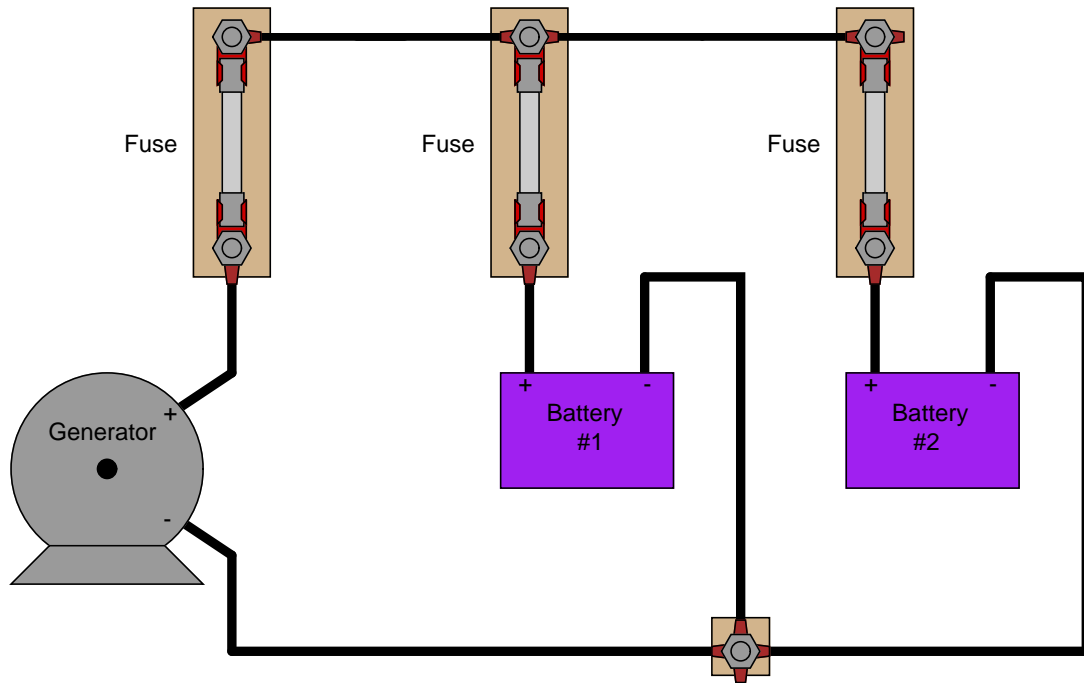
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Notes 104

Solving this algebraic problem requires both manipulation of the temperature equation *and* substitution of variables. One important detail I incorporated into this question is the lack of a subscript for  $T$  in the original resistance formula. In the first sentence I identify that temperature as being in degrees Celsius, but since there is no other  $T$  variables in the equation, I did not have to include a "C" subscript. When students look to the Celsius-Fahrenheit conversion formula to substitute into the resistance formula, they must decide which  $T$  in the conversion formula to use,  $T_F$  or  $T_C$ . Here, I purposely wrote the conversion formula in terms of  $T_F$  to see how many students would blindly substitute  $T_F$  for  $T$  in the resistance formula instead of properly identifying  $T_C$  as the variable to substitute and doing the work of manipulation.

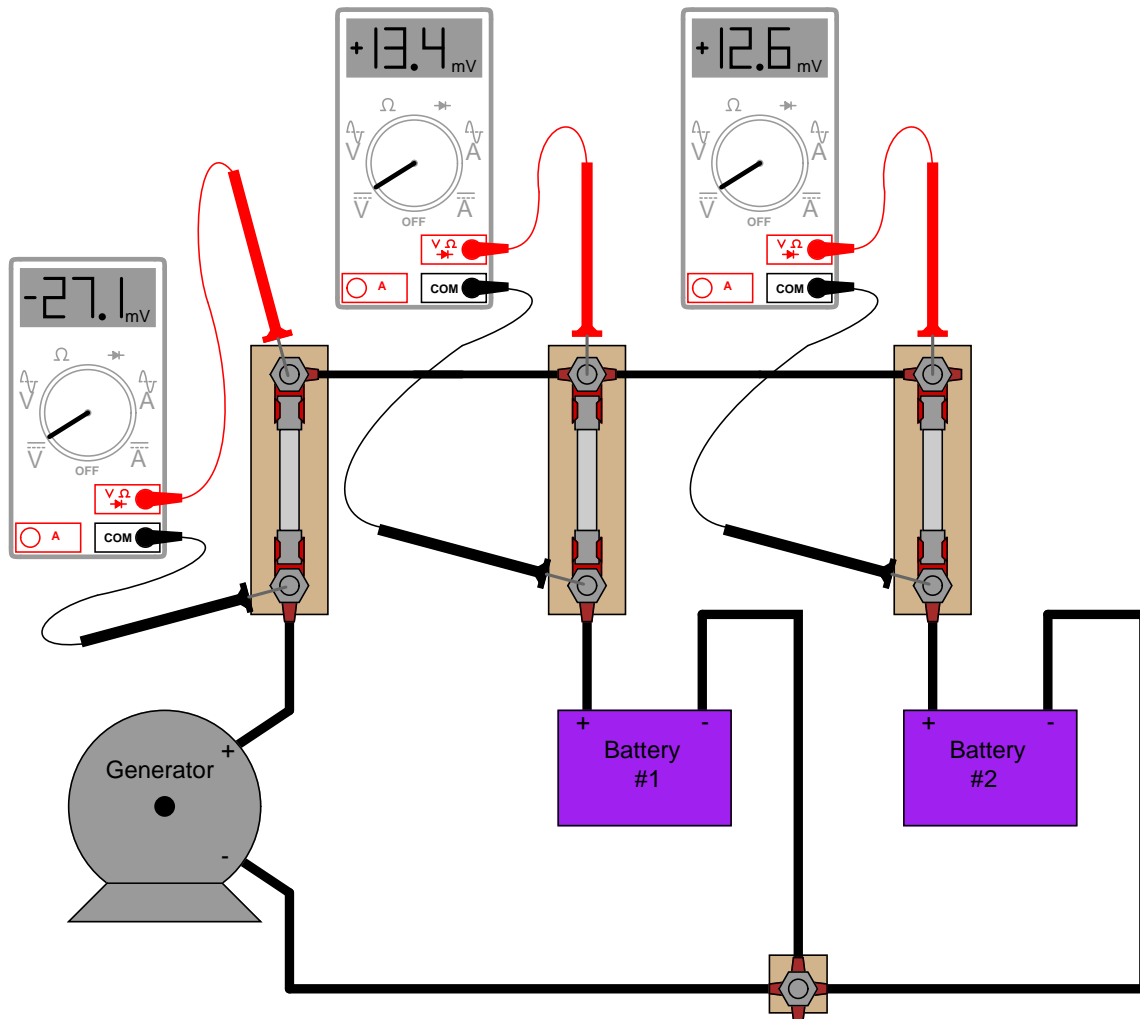
Far from being a "trick" question, this scenario is very realistic. Formulae found in reference manuals do not necessarily use standardized variables, but rather cast their variables according to context. Multiple formulae will most likely not be written with *identical* subscripted variables just waiting to be substituted. It is the domain of the intelligent technician, engineer, or scientist to figure out what variables are appropriate to substitute based on context!

Suppose you are asked to determine whether or not each battery in this circuit is charging or discharging:



To do so, of course, you need to determine the direction of current through each battery. Unfortunately, your multimeter does not have the current rating necessary to directly measure such large currents, and you do not have access to a clamp-on (magnetic) ammeter capable of measuring DC current.

You are about to give up when a master technician comes along and uses her multimeter (set to measure *millivolts*) to take these three voltage measurements:



"There," she says, "it's easy!" With that, she walks away, leaving you to figure out what those measurements mean. Determine the following:

- How these DC millivoltage measurements indicate direction of current.
- Whether or not each battery is charging or discharging.
- Whether or not these millivoltage measurements can tell you *how much* current is going through each battery.
- How this general principle of measurement may be extended to other practical applications.

file 03403

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Answer 105

The master technician exploited the inherent resistance of each fuse as a current-indicating *shunt resistor*. The measurements indicate both batteries are *charging*.

This is a very practical (and handy!) method of qualitative current measurement I've used many times on the job. Fuses, as well as other current-handling components, always have some non-zero amount of electrical resistance between their terminals, which means they are usable as crude shunt resistors. Their actual resistance will most likely be unknown to you, which is why they are useful in this capacity as *qualitative* measurement devices only, not quantitative.

Some students may point out that the measurement taken across the generator's fuse is not necessary to determine battery charging status. Technically, this is true, but doing so helps to confirm the validity of this technique. The polarity of that measurement does indeed show (conventional flow) current to be going upward through the generator fuse, versus downward through the battery fuses.

Students may also point out that the battery fuse millivoltage measurements do not add up to equal the generator fuse millivoltage measurement, as Kirchhoff's Current Law (KCL) would suggest. This is one example showing how the technique is strictly qualitative, not quantitative. We have no idea how much resistance lies within each fuse, and so we cannot rely on the millivoltage measurements as being proportional to current. This is especially true if the fuses are not identical!

Other circuit elements lending themselves to this same sort of application include overload "heater" elements for motor control circuits, long lengths of wire (provided you can stretch your millivolt-meter leads to reach both ends), circuit breakers, (closed) switches, and wire connections (particularly if the connection is old and possibly corroded).