

Recommended schedule

Day 1

Topics: *Series circuits and troubleshooting*

Questions: *1 through 20*

Lab Exercises: *Series resistances (question 61)*

Demo: Set up and use battery/lamp troubleshooting board in front of class

Day 2

Topics: *Series circuits, wire resistance, and overcurrent protection*

Questions: *21 through 40*

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

Demo: Show wire pieces of several different gauge

Day 3

Topics: *Series circuits, voltage divider circuits, and Kirchhoff's Voltage Law*

Questions: *41 through 60*

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

MIT 6.002 video clip: Disk 1, Lecture 2; Kirchhoff's Voltage Law 8:02 to 10:36

Demo: Set up battery/resistors circuit to validate KVL around any arbitrary path

MIT 8.02 video clip: Disk 3, Lecture 19; Electrocardiogram demo 15:55 to 20:25

Day 4

Exam 2: *includes Series DC resistor circuit performance assessment*

Lab Exercise: *Troubleshooting practice (simple light bulb circuit)*

Practice and challenge problems

Questions: *66 through the end of the worksheet*

Impending deadlines

Troubleshooting assessment (simple lamp circuit) due at end of ELTR100, Section 3

Question 64: Troubleshooting log

Question 65: Sample troubleshooting assessment grading criteria

Solder-together kit due at end of ELTR100, Section 3

Skill standards addressed by this course section

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

B Technical Skills – DC circuits

- 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 – series circuits only.*
- B.08** Understand principles and operations of DC series circuits.
- B.09** Fabricate and demonstrate DC series circuits.
- B.10** Troubleshoot and repair DC series 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

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 voltage drop across resistor R_2 , you must be sure that the values for current and resistance are appropriate for that resistor and not some other resistor in the circuit. If you are calculating E_{R_2} using the Ohm's Law equation $E = IR$, then you must use the value of *that resistor's* current (I_{R_2}) and *that resistor's* resistance (R_2), not some other current 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.

Very difficult concept: *Voltage is a relative quantity – it only exists between two points.*

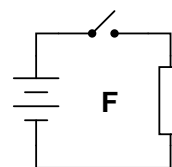
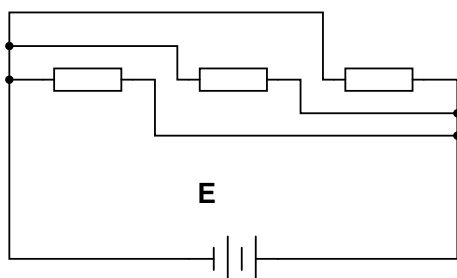
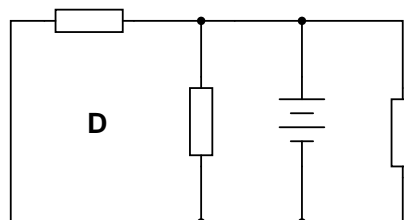
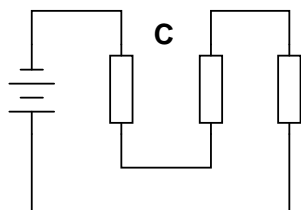
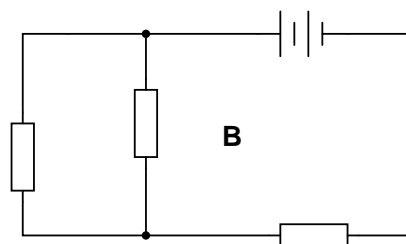
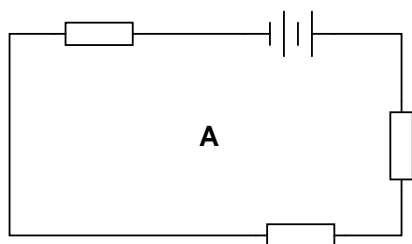
Unlike current, which may be measured at a single point in a circuit, voltage is fundamentally relative: it only exists as a *difference* between two points. In other words, there is no such thing as voltage existing at a single location. Therefore, while we speak of current going *through* a component in a circuit, we speak of voltage being *across* a component, measured between two different points on that component. So confusing is this concept that a significant number of students continue to harbor conceptual errors about the nature of voltage for several months after having first learned about it. A good way to understand voltage is to experiment with a voltmeter, measuring voltage between different pairs of points in safe, low-voltage circuits. Another good way to gain proficiency is to practice on conceptual problems relating to the measurement of voltage in circuits.

Difficult concept: *Kirchhoff's Voltage Law.*

The reason this concept is difficult to grasp is because it directly builds on the concept of voltage as a quantity relative between two points, which itself is a difficult concept to grasp. Many students find the "altitude change" analogy helpful in understanding how voltage exists between pairs of points, and the practice problems using that analogy to be helpful in developing confidence with this concept.

Question 1

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



file 01717

Answer 1

Circuits **A**, **C**, and **F** are *series* circuits.

Notes 1

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

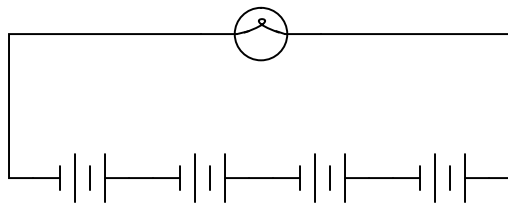
Circuit **F** is thrown in the mix just to show students that the non-battery components don't have to all be the same (resistors) in order for a circuit to qualify as "series."

Question 2

Most flashlights use multiple 1.5 volt batteries to power a light bulb with a voltage rating of several volts. Draw a schematic diagram of showing how multiple batteries may be connected to achieve a total voltage greater than any one of the batteries' individual voltages.

file 00038

Answer 2



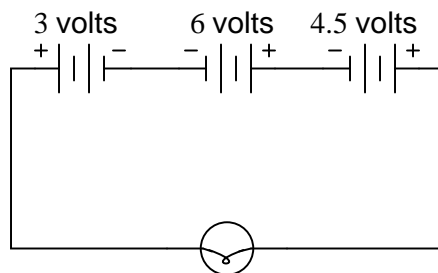
Follow-up question: if each of these batteries outputs a voltage of 1.5 volts, how much voltage does the light bulb experience?

Notes 2

Ask the students where they would place a switch to control the light bulb in the circuit shown in the answer.

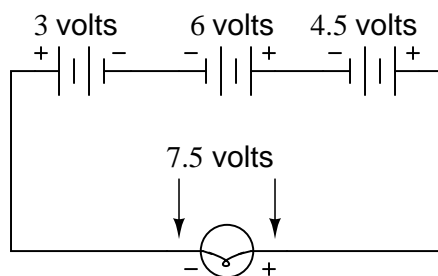
Question 3

How much voltage does the light bulb receive in this circuit? Explain your answer.



Also, identify the polarity of the voltage across the light bulb (mark with "+" and "-" signs).
[file 01719](#)

Answer 3



Follow-up question: draw the direction of current in this circuit.

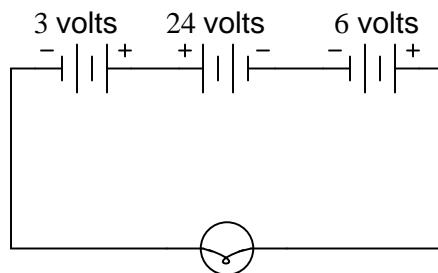
Notes 3

This is a very fundamental concept that students must learn: how to determine the total voltage in a series circuit where opposing voltage sources exist. One thing mistake students sometimes make is to try to discern polarity by looking at the polarity signs at the end terminals of the end battery; i.e. at the 3-volt battery's left-hand terminal, and the 4.5-volt battery's right-hand terminal, then try to transfer those signs down to the load terminals. This is *not* an accurate way to tell polarity, but it seems to "work" for them in some situations. This problem is one example of a situation where this faulty technique most definitely does not work!

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.

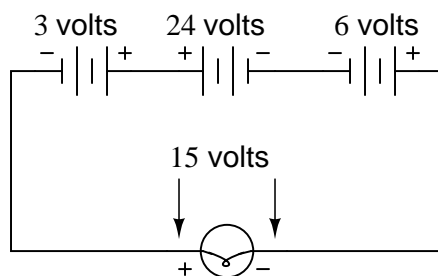
Question 4

How much voltage does the light bulb receive in this circuit? Explain your answer.



Also, identify the polarity of the voltage across the light bulb (mark with "+" and "-" signs).
[file 01720](#)

Answer 4



Follow-up question: being that 30 volts is the commonly accepted "danger" threshold voltage for electric shock, determine whether or not this particular circuit poses a shock hazard.

Notes 4

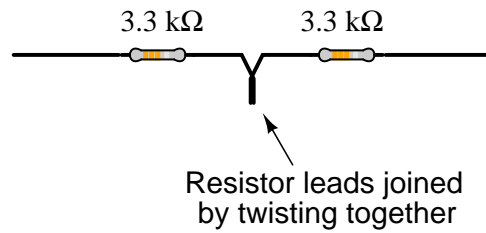
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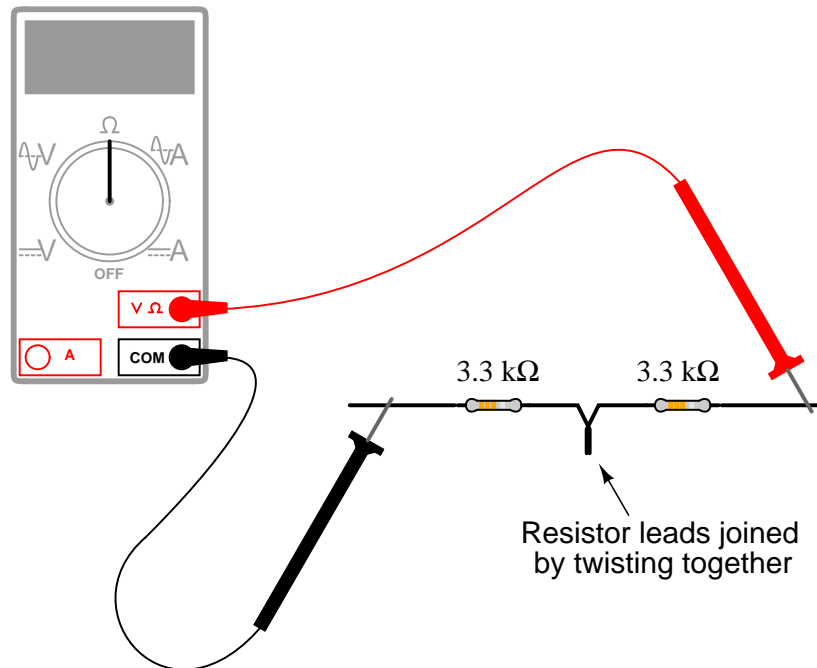
With regard to the safety question, there is more to determining risk of shock than a simple voltage check. It is important for your students to realize this, despite "accepted" thresholds for hazardous voltage and such.

Question 5

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

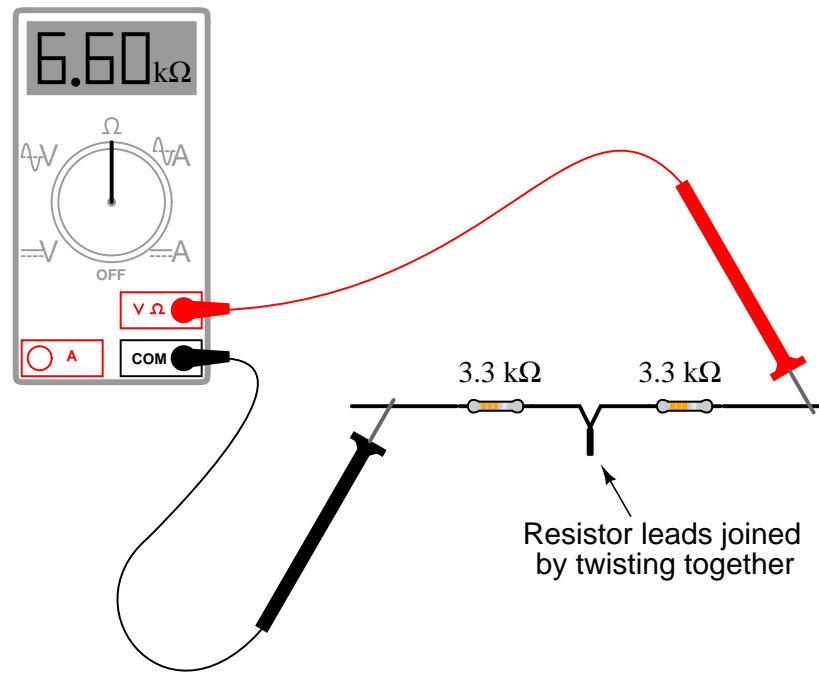


How much electrical resistance would you expect an ohmmeter to indicate if it were connected across the combination of these two series-connected resistors?



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

file 01721



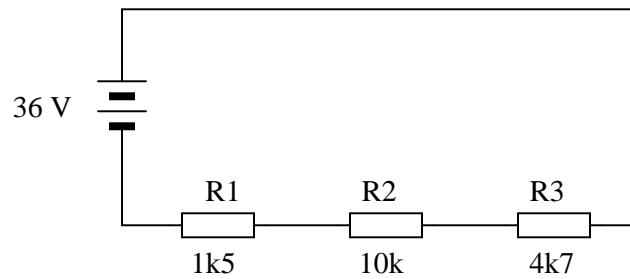
Follow-up question: how much resistance would you expect the ohmmeter to register if there were *three* similarly-sized resistors connected in series instead of two? What if there were *four* resistors?

Notes 5

The concept of series (total) resistance, in relation to individual resistances, usually does not present any difficulties to new students. Parallel resistances are a bit trickier, though . . .

Question 6

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



[file 01549](#)

Answer 6

$$I_{R1} = 2.22 \text{ mA} ; V_{R1} = 3.33 \text{ V}$$

$$I_{R2} = 2.22 \text{ mA} ; V_{R2} = 22.2 \text{ V}$$

$$I_{R3} = 2.22 \text{ mA} ; V_{R3} = 10.4 \text{ V}$$

Notes 6

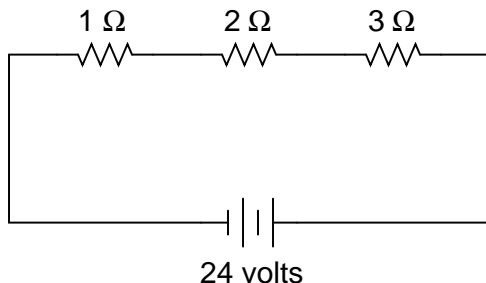
Students often just want to memorize a procedure for determining answers to questions like these. Challenge your students to not only understand the procedure, but to also explain *why* it must be followed.

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.

Note to your students that European symbols are used throughout this schematic diagram.

Question 7

In this circuit, three resistors receive the same amount of current (4 amps) from a single source. Calculate the amount of voltage "dropped" by each resistor, as well as the amount of power dissipated by each resistor:



file 00090

Answer 7

$$\begin{aligned}E_{1\Omega} &= 4 \text{ volts} \\E_{2\Omega} &= 8 \text{ volts} \\E_{3\Omega} &= 12 \text{ volts}\end{aligned}$$

$$\begin{aligned}P_{1\Omega} &= 16 \text{ watts} \\P_{2\Omega} &= 32 \text{ watts} \\P_{3\Omega} &= 48 \text{ watts}\end{aligned}$$

Follow-up question: Compare the direction of current through all components in this circuit with the polarities of their respective voltage drops. What do you notice about the relationship between current direction and voltage polarity for the battery, versus for all the resistors? How does this relate to the identification of these components as either *sources* or *loads*?

Notes 7

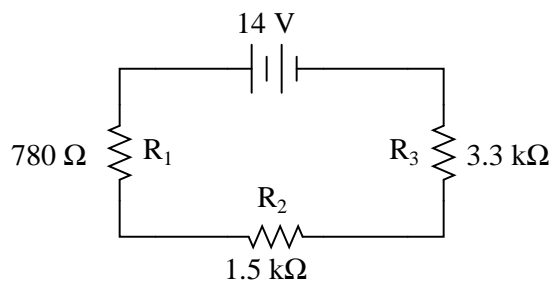
The answers to this question should not create any surprises, especially when students understand electrical resistance in terms of *friction*: resistors with greater resistance (more friction to electron motion) require greater voltage (push) to get the same amount of current through them. Resistors with greater resistance (friction) will also dissipate more power in the form of heat, given the same amount of current.

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

Challenge your students to recognize any mathematical patterns in the respective voltage drops and power dissipations. What can be said, mathematically, about the voltage drop across the 2 Ω resistor versus the 1 Ω resistor, for example?

Question 8

Complete the table of values for this circuit:



	R_1	R_2	R_3	Total
V				
I				
R	$780\ \Omega$	$1.5\ \text{k}\Omega$	$3.3\ \text{k}\Omega$	
P				

file 01957

Answer 8

	R_1	R_2	R_3	Total
V	1.957 V	3.763 V	8.280 V	14 V
I	2.509 mA	2.509 mA	2.509 mA	2.509 mA
R	$780\ \Omega$	$1.5\ \text{k}\Omega$	$3.3\ \text{k}\Omega$	$5.58\ \text{k}\Omega$
P	4.910 mW	9.442 mW	20.77 mW	35.13 mW

Follow-up question #1: without performing any mathematical calculations, determine the effects on all the component voltage drops and currents if resistor R_1 were to fail *open*.

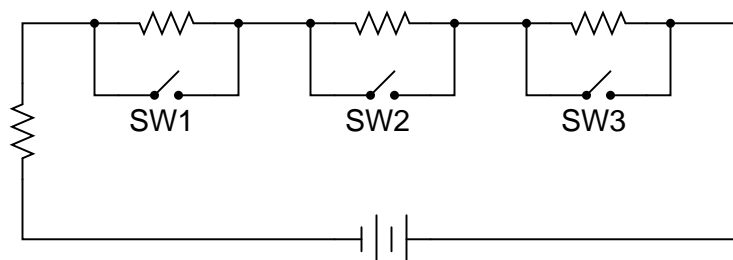
Follow-up question #2: without performing any mathematical calculations, determine the effects on all the component voltage drops and currents if resistor R_1 were to fail *shorted*.

Notes 8

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 9

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

Also, provide a safety-related reason for the existence of the fourth resistor in this circuit, on the left-hand side of the circuit (not bypassed by any switch).

[file 00295](#)

Answer 9

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 decrease to zero, while the voltages across the remaining resistors will increase. The current through resistor R1 will also decrease to zero, and the current through the remaining resistors will also increase. Each of the resistors will experience the same amount of current as the others, and this amount of current will also be experienced by the battery. Overall, the battery "sees" less total resistance than before.

The fourth resistor is there to prevent a short-circuit from developing if all switches are simultaneously closed.

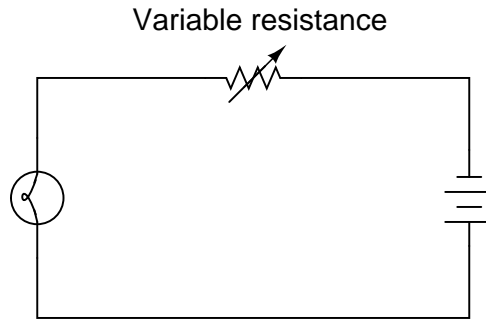
Notes 9

One problem I've encountered while teaching the "laws" of series circuits is that some students mistakenly think the rule of "all currents in a series circuit being the same" means that the amount of current in a series circuit is fixed over time and cannot change. The root of this misunderstanding is memorization rather than comprehension: students memorize the rule "*all currents are the same*" and think this means the currents 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 currents are *the same* in a series 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 series circuit behavior by asking what happens after a change is made to the circuit. The purpose of the switches is to "remove" resistors from the circuit, one at a time, without actually having to remove components.

Question 10

The brightness of a light bulb – or the power dissipated by any electrical load, for that matter – may be varied by inserting a variable resistance in the circuit, like this:



This method of electrical power control is not without its disadvantages, though. Consider an example where the circuit current is 5 amps, the variable resistance is $2\ \Omega$, and the lamp drops 20 volts of voltage across its terminals. Calculate the power dissipated by the lamp, the power dissipated by the variable resistance, and the total power provided by the voltage source. Then, explain why this method of power control is not ideal.

file 00104

Answer 10

$$P_{lamp} = 100 \text{ watts}$$

$$P_{resistance} = 50 \text{ watts}$$

$$P_{total} = 150 \text{ watts}$$

Follow-up question: note how in the original question I offered a set of hypothetical values to use in figuring out why a series rheostat (variable resistance) is not an efficient means to control lamp power. Explain how the assumption of certain values is a useful problem-solving technique in cases where no values are given to you.

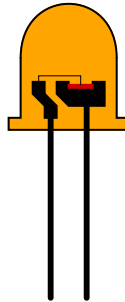
Notes 10

Discuss the concept of energy conservation: that energy can neither be created nor destroyed, but merely changed between different forms. Based on this principle, the sum of all power dissipations in a circuit must equal the total amount of power supplied by the energy source, regardless of how the components are connected together.

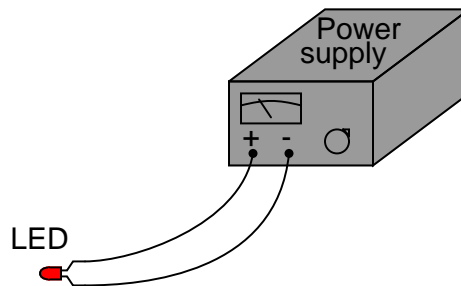
Question 11

Light-emitting diodes, or *LEDs*, are rugged and highly efficient sources of light. They are far more rugged and efficient than incandescent lamps, and they also have the ability to switch on and off much faster because there is no filament inside needing to heat or cool:

Close-up view of a light-emitting diode

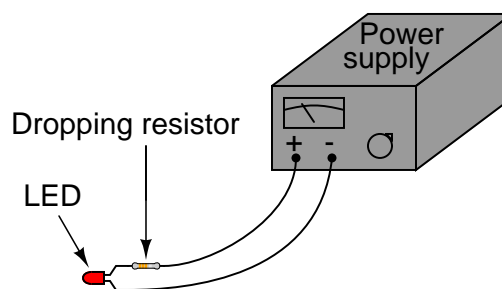


LEDs are low voltage devices, typically rated in the range of 1.5 to 2 volts DC maximum. Single diodes generally draw low currents as well, about 20 milliamps each. The problem is, how do you operate an LED from a typical electronic power source, which may output 24 volts DC or more?



The LED will become damaged if overpowered!

The answer is to use a *series dropping resistor*:



Calculate the necessary resistance value and minimum power rating of a series dropping resistor for an LED rated at 1.7 volts and 20 mA, and a power supply voltage of 24 volts.

[file 01776](#)

Answer 11

$R_{dropping} = 1115\ \Omega$, with a power rating of at least 0.446 watts (1/2 watt would be ideal).

Follow-up question: if there were no 1115 Ω resistors to choose from (which there most likely will not be!), would it be safer to choose a higher-value resistor or a lower-value resistor for this application? For example, if your only choices in 1/2 watt resistors were a 1 k Ω and a 1.2 k Ω , which one would you choose? Explain your answer.

Notes 11

The follow-up question is a very practical one, for it is seldom that you have the exact components on-hand to match the requirements of a circuit you are building. It is important to understand which way is safer to err (too large or too small) when doing "as-built" design work.

Question 12

In a series 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 series circuit, voltage . . ."

"In a series circuit, current . . ."

"In a series circuit, resistance . . ."

"In a series circuit, power . . ."

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

file 00291

Answer 12

"In a series circuit, voltage *drops add to equal the total.*"

"In a series circuit, current *is equal through all components.*"

"In a series circuit, resistances *add to equal the total.*"

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

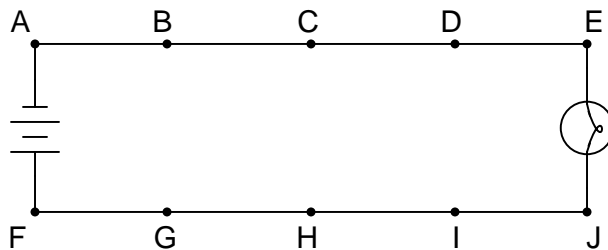
Notes 12

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.

Question 13

In this circuit, where would you expect to measure full battery voltage (between what pairs of test points)?



file 00119

Answer 13

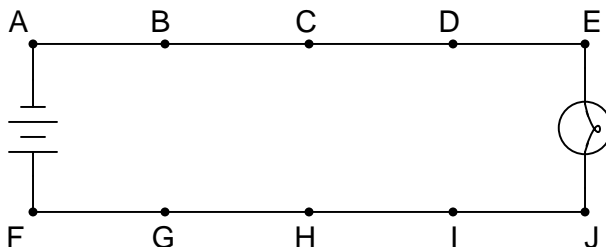
You should expect to measure full battery voltage with one test lead of your voltmeter touching any of the points along the top wire of the circuit (points A through E), and with the other test lead touching any of the points along the bottom wire of the circuit (points F through J).

Notes 13

This circuit provides an excellent opportunity to discuss the concept of "electrically common" points. Any points in a circuit directly connected together with wire are considered "electrically common" to each other: a voltage measurement referenced at any one of those points should be identical if referenced any of the other points as well.

Question 14

In this circuit, where would you *not* expect to measure significant voltage (between what pairs of test points)?



file 00120

Answer 14

You should not measure any significant voltage between any of the test points along the upper wire (A to B, A to C, A to D, etc.), nor between any of the test points along the lower wire (F to G, F to H, F to I, etc.). As a general rule, points in a circuit that are *electrically common* to each other should never have voltage between them.

Notes 14

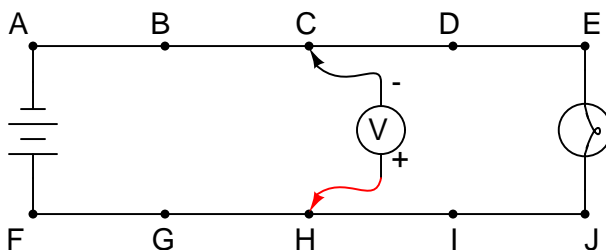
The answer uses a concept which I've found to be very helpful in understanding electrical circuits: the idea of points in a circuit being *electrically common* to each other. Simply put, this means the points are connected together by conductors of negligible resistance. Having nearly 0 ohms of resistance between points assures insignificant voltage drop, even for large currents.

Conversely, if significant voltage is measured between points in a circuit, you can be assured that those points are *not* electrically common to each other. Engage your students in a discussion of electrical commonality and expected voltage drops:

- If voltage is measured between two points in a circuit, are those two points electrically common to each other? Why or why not?
- If no voltage is measured between two points in a circuit, are those two points electrically common to each other? Why or why not?

Question 15

Suppose this battery and light bulb circuit failed to work:



Using a voltmeter, a technician measures full battery voltage between the points C and H. What does this single measurement indicate about the condition of the circuit? Be as specific as you can.

file 00122

Answer 15

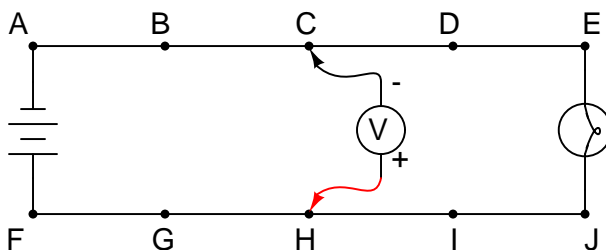
Based on this one measurement, we are able to determine that the battery is outputting full voltage, and that the circuit wiring is continuous from the negative battery terminal to point C, and from the positive battery terminal to point H. The fault is an "open" somewhere to the right of points C and H – possibly more than one.

Notes 15

Some measurements given definite answers, while others only indefinite answers. In this particular question, the single voltage measurement tells us definite things about the left-hand side of the circuit, but little about the right-hand side. It is very important for students to develop the logical skill of distinguishing *necessary* conclusions from *possible* conclusions in troubleshooting scenarios. A skill like this takes time and practice to develop, so be sure to spend adequate time throughout the course with your students honing it!

Question 16

Suppose this battery and light bulb circuit failed to work:



Using a voltmeter, a technician measures full battery voltage between the points C and H. The result of this single measurement indicates which half of the circuit there is a definite problem in. What would you recommend as the *next* voltmeter measurement to take in troubleshooting the circuit, following the same "divide in half" strategy?

[file 00124](#)

Answer 16

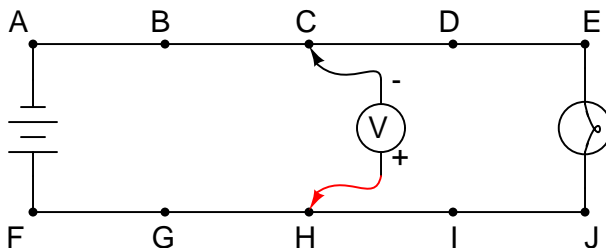
To "divide the circuit in half" again, measure voltage between points D and I.

Notes 16

Some troubleshooters refer to this strategy as "divide and conquer," because it divides the possibilities of fault location by a factor of 2 with each step. Make sure your students understand that being able to immediately determine which part of a system is *not* faulted is a valuable time-saver.

Question 17

Suppose this battery and light bulb circuit failed to work:



Using a voltmeter, a technician measures 0 volts between the points C and H. What does this single measurement indicate about the condition of the circuit? Be as specific as you can.

file 00123

Answer 17

Based on this one measurement, we are able to determine that there is definitely a problem in the circuit somewhere on the left-hand side (from points C and H, left). The exact nature of the problem is unknown, but there is definitely a problem of some nature in that half of the circuit.

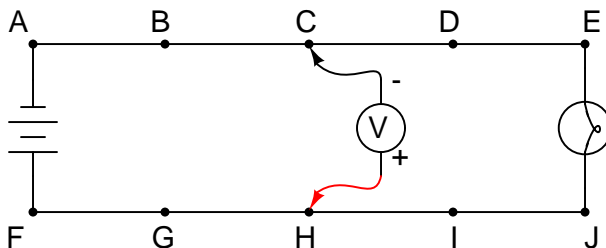
There may or may not be a problem on the right-hand side of the circuit, as well. Given this single voltage measurement, we simply cannot tell.

Notes 17

There are times when a voltmeter indication of 0 volts is just as informative concerning a circuit fault as a non-zero measurement. In this case, the measurement tells us that a definite problem exists in one half of the circuit.

Question 18

Suppose this battery and light bulb circuit failed to work:



Using a voltmeter, a technician measures 0 volts between the points C and H. The result of this single measurement indicates which half of the circuit there is a definite problem in. What would you recommend as the *next* voltmeter measurement to take in troubleshooting the circuit, following the same "divide in half" strategy?

[file 00125](#)

Answer 18

To "divide the circuit in half" again, measure voltage between points B and G.

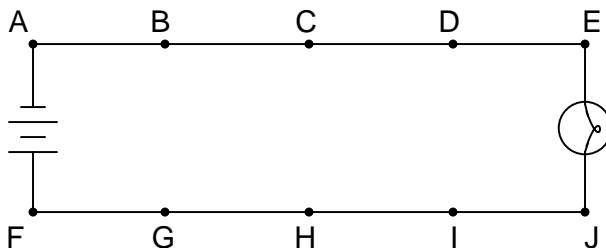
Notes 18

Some troubleshooters refer to this strategy as "divide and conquer," because it divides the possibilities of fault location by a factor of 2 with each step.

It is important to realize in situations such as this that no determination of faultlessness in the circuit has been made yet. By measuring 0 volts between points C and H, we know there is a definite problem in the left half of the circuit, but we have by no means "cleared" the right half of any fault. For all we know, there may be faults in *both* halves of the circuit! Only further investigation will reveal the truth.

Question 19

Suppose this battery and light bulb circuit failed to work:



Using nothing but a voltmeter, a technician measures voltage between the following sets of points:

- Between A and C: 0 volts
- Between D and G: 12 volts
- Between E and J: 0 volts
- Between B and E: 12 volts

From these voltage measurements, what can you tell about the condition of the battery, wiring, and light bulb? Be as specific as you can.

Challenge question: identify which of the four measurements are unnecessary in determining the precise location of the fault in this circuit.

file 00121

Answer 19

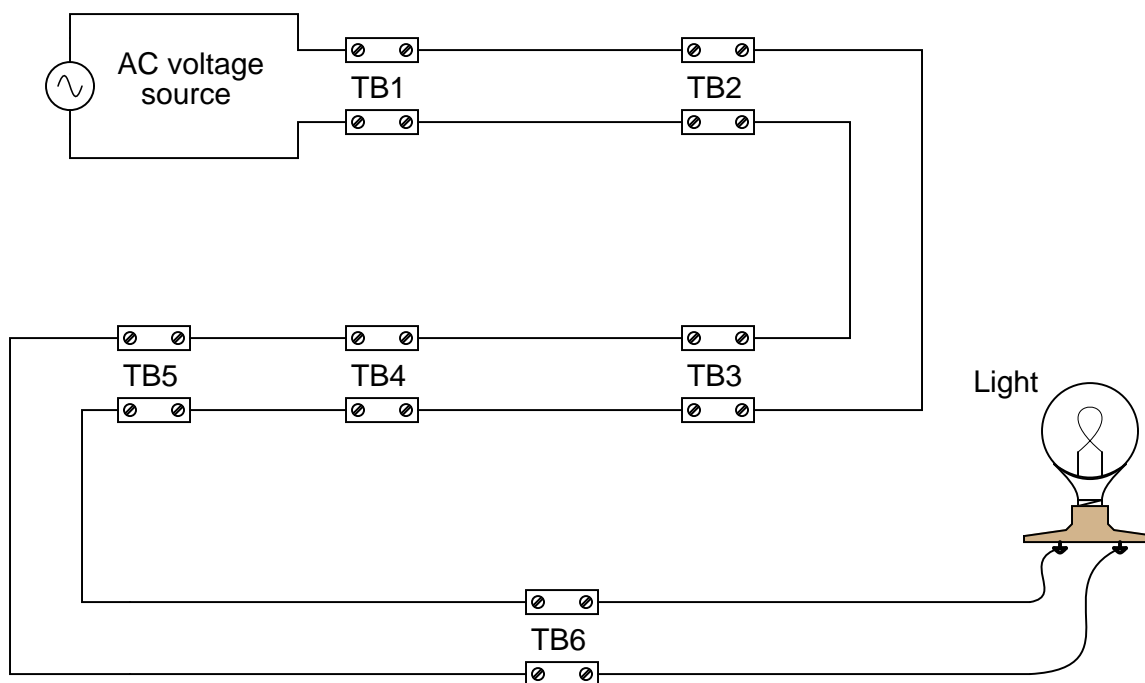
Based on these measurements, we are able to determine that the battery's voltage is 12 volts, that the light bulb has good continuity, and that there is a single break in the circuit between points D and E.

Challenge answer: the two "0 volt" measurements are unnecessary in determining the location of the fault in this circuit.

Notes 19

Scenarios such as this are excellent for group discussion, encouraging students to think critically about the data and to apply their practical knowledge of electricity to a realistic problem.

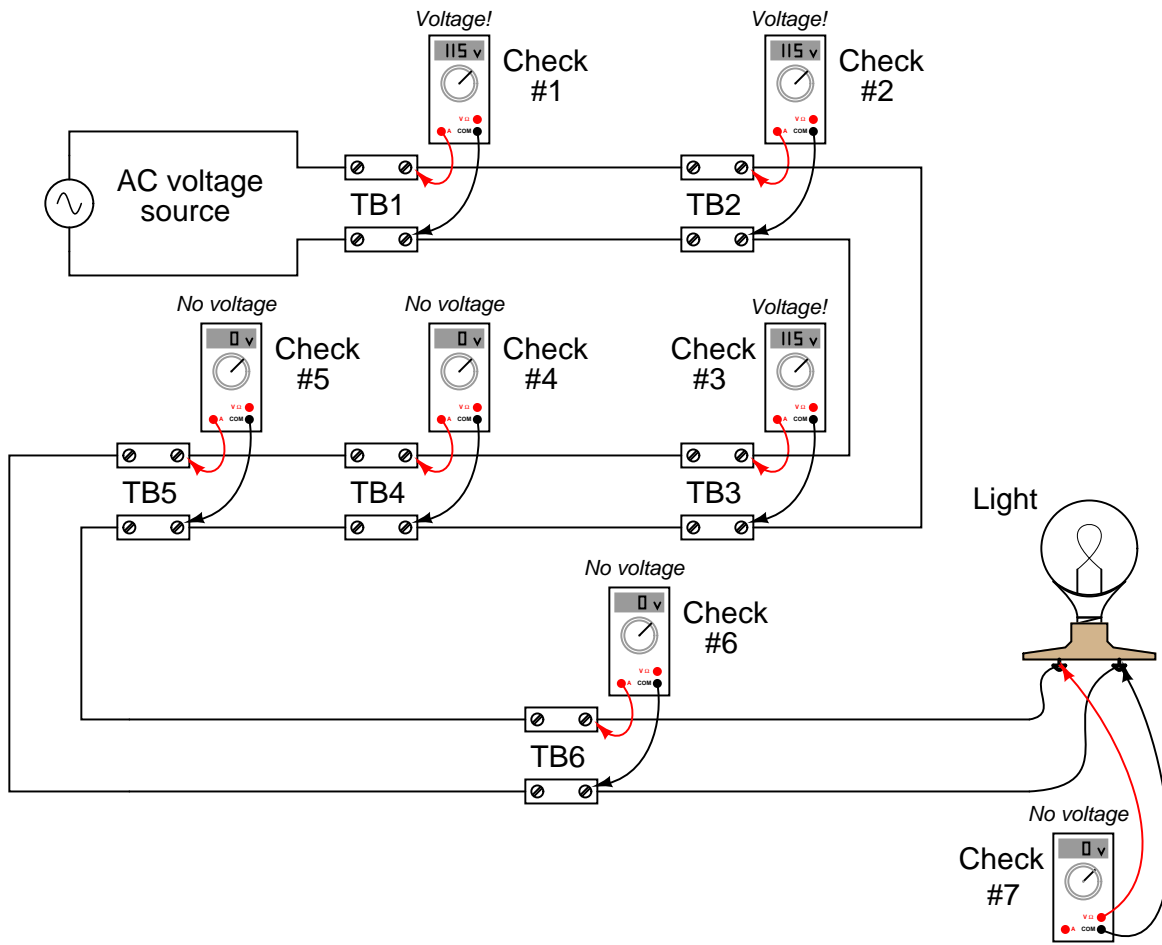
An electrician is troubleshooting a faulty light circuit, where the power source and light bulb are far removed from one another:



As you can see in the diagram, there are several terminal blocks ("TB") through which electrical power is routed to the light bulb. These terminal blocks provide convenient connection points to join wires together, enabling sections of wire to be removed and replaced if necessary, without removing and replacing *all* the wiring.

The electrician is using a voltmeter to check for the presence of voltage between pairs of terminals in the circuit. The terminal blocks are located too far apart to allow for voltage checks between blocks (say, between one connection in TB2 and another connection in TB3). The voltmeter's test leads are only long enough to check for voltage between pairs of connections at each terminal block.

In the next diagram, you can see the electrician's voltage checks, in the sequence that they were taken:



Based on the voltage indications shown, can you determine the location of the circuit fault? What about the electrician's choice of steps – do you think the voltage measurements taken were performed in the most efficient sequence, or would you recommend a different order to save time?

[file 01578](#)

Answer 20

The fault is located somewhere between TB3 and TB4. Whether or not the electrician's sequence was the most efficient depends on two factors not given in the problem:

- The distance between terminal blocks.
- The time required to gain access for a voltage check, upon reaching the terminal block location.

Follow-up question: describe a scenario where the given sequence of voltage readings would be the most efficient. Describe another scenario where a different sequence of voltage readings could have saved time in locating the problem.

Notes 20

One of the most common troubleshooting techniques taught to technicians is the so-called "divide and conquer" method, whereby the system or signal path is divided into halves with each measurement, until the location of the fault is pinpointed. However, there are some situations where it might actually save time to perform measurements in a linear progression (from one end to the other, until the power or signal is lost). Efficient troubleshooters never limit themselves to a rigid methodology if other methods are more efficient.

Question 21

If an electric drill is plugged into a very long extension cord instead of being plugged directly into a power receptacle, what will happen to the drill's performance? Explain your answer, with reference to Ohm's Law.

[file 00386](#)

Answer 21

The drill will not perform with as much power as it would if directly plugged into a power receptacle.

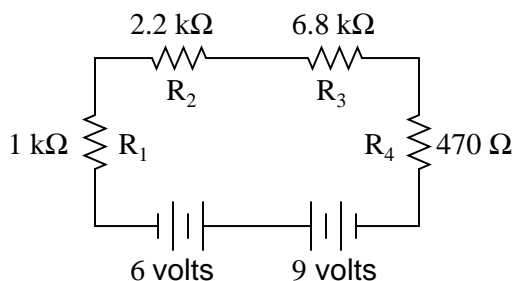
Challenge question: draw an equivalent schematic diagram showing the resistance of the extension cord conductors as resistors with the labels R_{wire1} and R_{wire2} .

Notes 21

Students who have worked with power tools, especially on construction sites where long extension cords are commonly used, will be familiar with this phenomenon. Ask your students what effect different gauges of wire in the extension cord would have on this degradation of drill motor performance. Also, ask about different lengths of extension cord. What, exactly, is the electrical quantity that varies with these dimensional changes, that causes the drill motor performance to vary?

Question 22

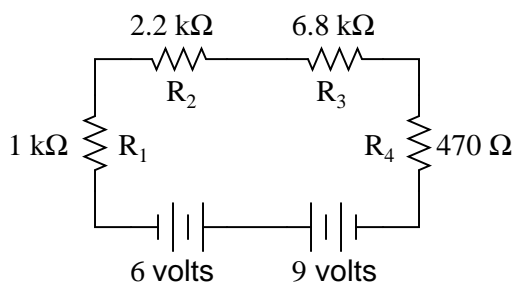
Complete the table of values for this circuit:



	R_1	R_2	R_3	R_4	Total
V					
I					
R	1 kΩ	2.2 kΩ	6.8 kΩ	470 Ω	
P					

[file 01722](#)

Answer 22



	R_1	R_2	R_3	R_4	Total
V	286.5 mV	630.4 mV	1.948 V	134.7 mV	3 V
I	286.5 μA	286.5 μA	286.5 μA	286.5 μA	286.5 μA
R	1 kΩ	2.2 kΩ	6.8 kΩ	470 Ω	10.47 kΩ
P	82.10 μW	180.6 μW	558.3 μW	38.59 μW	859.6 μW

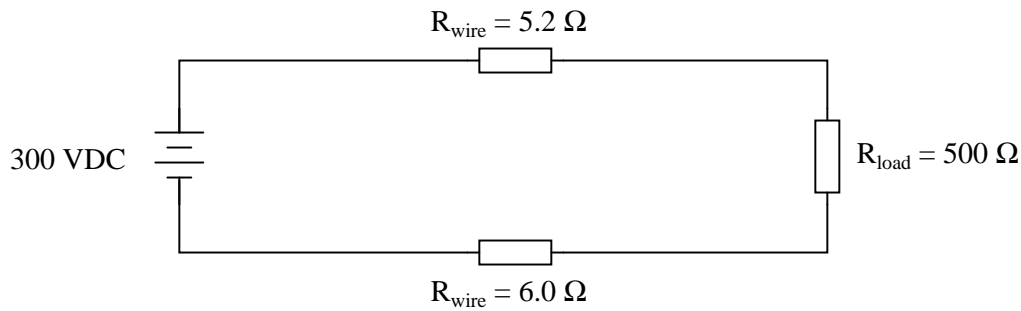
Follow-up question #1: without performing any mathematical calculations, determine the effects on all the component voltage drops and currents if resistor R_2 were to fail *open*.

Follow-up question #2: without performing any mathematical calculations, determine the effects on all the component voltage drops and currents if resistor R_2 were to fail *shorted*.

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 23

Calculate the amount of power delivered to the load resistor in this circuit:



Also, calculate the amount of power that would be delivered to the load resistor if the wires were superconducting ($R_{\text{wire}} = 0.0 \, \Omega$).

file 01724

Answer 23

$P_{\text{load}} \approx 170$ Watts (with resistive wire)

$P_{\text{load}} = 180$ Watts (with superconducting wire)

Follow-up question: Compare the direction of current through all components in this circuit with the polarities of their respective voltage drops. What do you notice about the relationship between current direction and voltage polarity for the battery, versus for all the resistors? How does this relate to the identification of these components as either *sources* or *loads*?

Notes 23

Not only is this question good practice for series circuit calculations (Ohm's and Joule's Laws), but it also introduces superconductors in a practical context.

Question 24

Given two lengths of metal wire, which one will have the least electrical resistance: one that is short, or one that is long? Assume all other factors are equal (same metal type, same wire diameter, etc.).

file 00157

Answer 24

The short wire will have less electrical resistance than the long wire.

Notes 24

Many analogies exist to express this concept: water through a pipe, compressed air through a hose, etc. Which pipe or hose is less restrictive: the short one or the long one?

Question 25

Given two lengths of solid metal wire with round cross-sections, which one will have the least electrical resistance: one that is small-diameter, or one that is large-diameter? Assume all other factors are equal (same metal type, same wire length, etc.).

file 00158

Answer 25

The large-diameter wire will have less electrical resistance than the small-diameter wire.

Notes 25

Many analogies exist to express this concept: water through a pipe, compressed air through a hose, etc. Which pipe or hose is less restrictive: the skinny one or the fat one?

Question 26

Electrical wire is often rated according to its cross-sectional diameter by a *gauge* scale. Which is the larger-diameter wire size, 14 gauge or 8 gauge?

[file 00164](#)

Answer 26

8 gauge is the larger diameter.

Notes 26

For students familiar with shotguns, the methodology of the wire gauge scale makes sense. For just about everyone else, the gauge scale seems "backward."

Question 27

The cross-sectional area of wires is often measured in units of *circular mils* rather than square inches or other common area units. Explain how the "circular mil" is defined, and how it is calculated for round wires.

[file 01954](#)

Answer 27

The "circular mil" is defined as the area of a circle with a diameter of $\frac{1}{1000}$ inch (a diameter of one *mil*).

Notes 27

Explain how this is analogous to the "square inch" being defined as the area of a square measuring one inch on a side. If you need to approach the definition in smaller conceptual steps, you might want to first define what a "circular inch" is before you define what a "circular mil" is.

Question 28

What is *specific resistance*, symbolized by the Greek letter "rho" (ρ)?

file 00156

Answer 28

Specific resistance is a measure of how resistive any particular substance is, relative to its length and cross-sectional area.

Notes 28

Ask your students, "Why is it important to have a quantity called *specific* resistance? Why don't we just compare the "resistivity" of different substances in regular units of ohms?"

Question 29

Write a single equation relating the resistance, specific resistance, length, and cross-sectional area of an electrical conductor together.

file 00159

Answer 29

$$R = \rho \frac{l}{A}$$

Where,

R = Resistance, measured along the conductor's length

ρ = Specific resistance of the substance

l = Length of the conductor

A = Cross-sectional area of the conductor

Follow-up question: algebraically manipulate this equation to solve for length (l) instead of solving for resistance (R) as shown.

Notes 29

A beneficial exercise to do with your students is to analyze this equation (and in fact, any equation) *qualitatively* instead of just *quantitatively*. Ask students what will happen to R if ρ increases, or if l decreases, or if A decreases. Many students find this a more challenging problem than working with real numbers, because they cannot use their calculators to give them qualitative answers (unless they enter random numbers into the equation, then change one of those numbers and re-calculate – but that is twice the work of solving the equation with one set of numbers, once!).

Question 30

Small electrical wires are almost always sized by *gauge* rather than by *circular mils* (cmils). So, if you had to calculate the resistance of a length of 22-gauge copper wire and did not have the proper tools to measure the wire's diameter, how could you find the equivalent cross-sectional area in circular mils so as to use the equation $R = \frac{\rho l}{A}$?

file 01955

Answer 30

This information may be found in a *wire gauge table*, where gauge numbers and circular mil values are cross-referenced.

Notes 30

Show your students a wire gauge table, if their textbooks do not already contain one.

Question 31

What is the electrical resistance of a 12-gauge copper wire, 500 feet long, at room temperature?
file 00165

Answer 31

Wire resistance = $0.7726 \, \Omega$

Notes 31

Ask your students to share their sources for data: values of ρ , cross-sectional area, etc.

Question 32

A spool holds an unknown length of aluminum wire. The size of the wire is 4 AWG. Fortunately, both ends of the wire are available for contact with an ohmmeter, to measure the resistance of the entire spool. When measured, the wire's total resistance is $0.135\ \Omega$. How much wire is on the spool (assuming the spool is at room temperature)?

file 00485

Answer 32

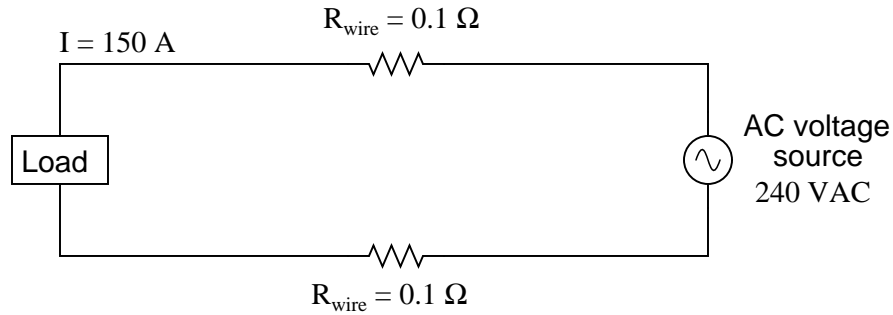
353.51 feet

Notes 32

This question illustrates another practical application of specific resistance calculations: how to determine the length of wire on a spool. The amount of resistance in this example is quite low, being a mere fraction of an ohm. Ask your students what kinds of problems they might encounter trying to measure such a low resistance with accuracy. Would the typical errors incurred in such a low-resistance measurement tend to make their calculation of length be excessive, or too low? Why?

Question 33

Suppose a power system were delivering AC power to a resistive load drawing 150 amps:



Calculate the load voltage, load power dissipation, the power dissipated by the wire resistance (R_{wire}), and the overall power efficiency, indicated by the Greek letter "eta" ($\eta = \frac{P_{load}}{P_{source}}$).

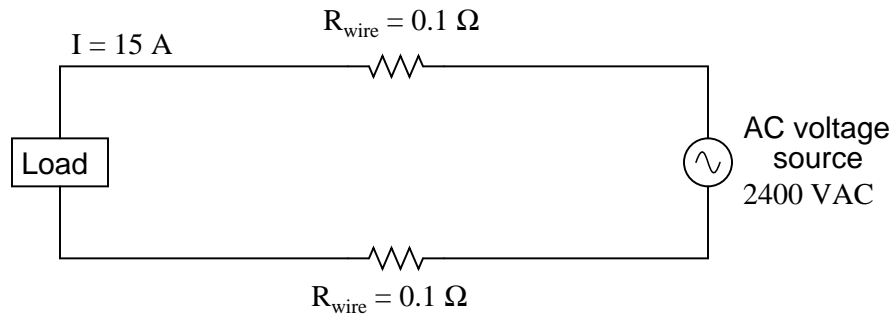
$$E_{load} =$$

$$P_{load} =$$

$$P_{lines} =$$

$$\eta =$$

Now, suppose we were to re-design both the generator and the load to operate at 2400 volts instead of 240 volts. This ten-fold increase in voltage allows just one-tenth the current to convey the same amount of power. Rather than replace all the wire with different wire, we decide to use the exact same wire as before, having the exact same resistance (0.1Ω per length) as before. Re-calculate load voltage, load power, wasted power, and overall efficiency of this (higher voltage) system:



$$E_{load} =$$

$$P_{load} =$$

$$P_{lines} =$$

$$\eta =$$

file 01723

Answer 33

240 volt system:

$$E_{load} = 210 \text{ volts}$$

$$P_{load} = 31.5 \text{ kW}$$

$$P_{lines} = 4.5 \text{ kW}$$

$$\eta = 87.5\%$$

2400 volt system:

$$E_{load} = 2397 \text{ volts}$$

$$P_{load} = 35.96 \text{ kW}$$

$$P_{lines} = 45 \text{ W}$$

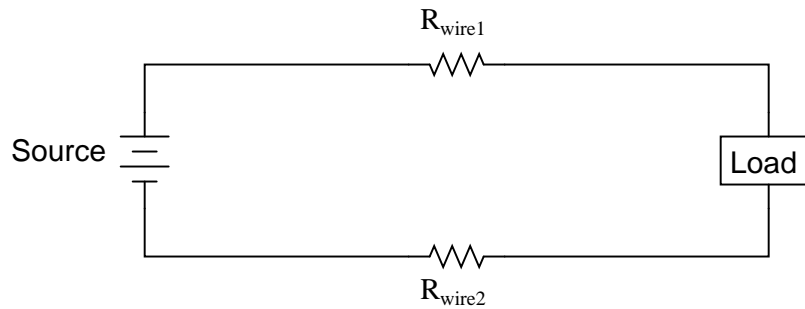
$$\eta = 99.88\%$$

Notes 33

An example like this usually does a good job clarifying the benefits of using high voltage over low voltage for transmission of large amounts of electrical power over substantial distances.

Question 34

The efficiency (η) of a simple power system with losses occurring over the wires is a function of circuit current, wire resistance, and total source power:



A simple formula for calculating efficiency is given here:

$$\eta = \frac{P_{\text{source}} - I^2 R}{P_{\text{source}}}$$

Where,

P_{source} = the power output by the voltage source, in watts (W)

I = the circuit current, in amperes (A)

R = the *total* wire resistance ($R_{\text{wire1}} + R_{\text{wire2}}$), in ohms (Ω)

Algebraically manipulate this equation to solve for wire resistance (R) in terms of all the other variables, and then calculate the maximum amount of allowable wire resistance for a power system where a source outputting 200 kW operates at a circuit current of 48 amps, at a minimum efficiency of 90%.

[file 03255](#)

Answer 34

$$R = \frac{P_{\text{source}} - \eta P_{\text{source}}}{I^2}$$

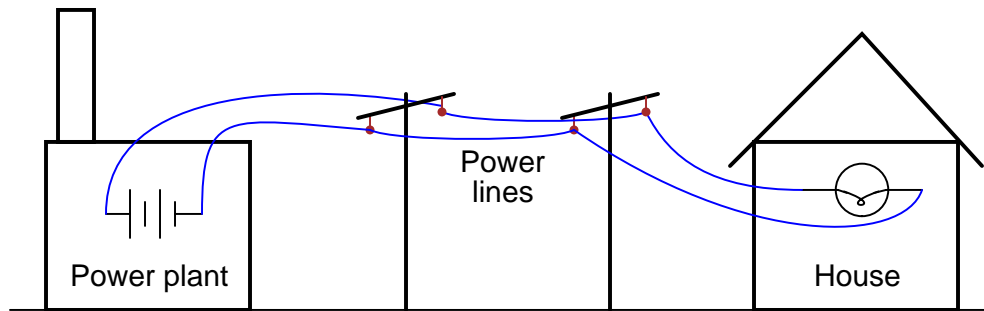
The maximum allowable (total) wire resistance is 8.681 Ω .

Notes 34

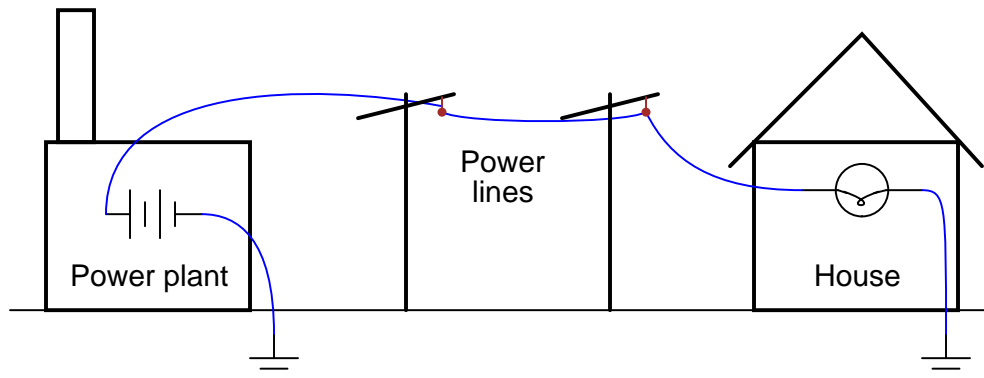
A common mistake for students to make here is entering 90% as "90" rather than as "0.9" in their calculators.

Question 35

Shown here is a simplified representation of an electrical power plant and a house, with the source of electricity shown as a battery, and the only electrical "load" in the house being a single light bulb:



Why would anyone use two wires to conduct electricity from a power plant to a house, as shown, when they could simply use one wire and a pair of *ground* connections, like this?



file 00075

Answer 35

This is not a practical solution, even though it would only require half the number of wires to distribute electrical power from the power plant to each house! The reason this is not practical is because the earth (dirt) is not a good enough conductor of electricity. Wires made of metal conduct electricity far more efficiently, which results in more electrical power delivered to the end user.

Notes 35

Discuss the fact that although the earth (dirt) is a poor conductor of electricity, it may still be able to conduct levels of current lethal to the human body! The amount of current necessary to light up a household light bulb is typically far in excess of values lethal for the human body.

Question 36

What hazards might be posed by a circuit with excessive current going through its conductors (excessive as defined by the conductors' ampacity)? In other words, what would be bad about a wire carrying too much current?

Also determine which type of component fault, an *open* or a *short*, would most likely be the cause of excessive current in a circuit.

file 00325

Answer 36

Overloaded wiring gets hot – perhaps enough to start a fire.

A *shorted* component could cause excessive current in a circuit, but an *open* fault will result in less (or no) current.

Notes 36

Even if an overloaded wire does not get hot enough to ignite nearby combustible material, there are other ill effects of conductor overloading. Challenge your students to think of some other, negative consequences which may result from conductor overloading.

One of the goals of this question is for students to be able to distinguish between *open* and *short* component faults.

Question 37

What is the difference between a *fuse* and a *circuit breaker*?

file 00327

Answer 37

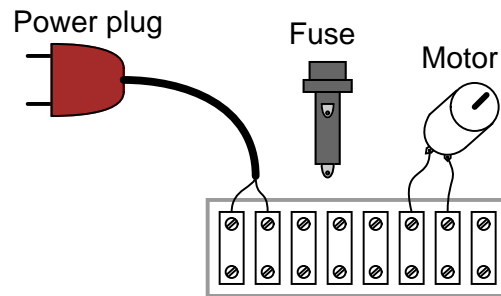
A fuse is for one-time use, while a circuit breaker may be re-set and used repeatedly.

Notes 37

There used to be a time when overcurrent protection for household circuits was primarily provided by fuses. In modern times, however, fuses are obsolete for household wiring – circuit breakers have completely taken their place. Discuss the relative advantages and disadvantages of these two overcurrent protection technologies.

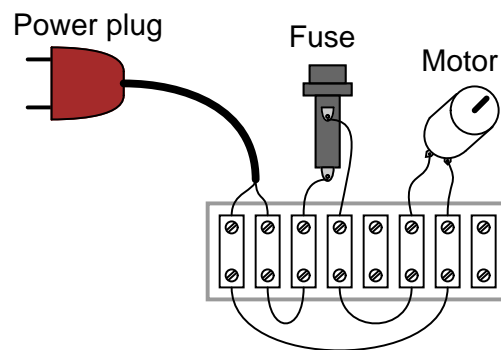
Question 38

Show the proper placement of the fuse in this circuit, where an electric motor will be powered by utility (120 volt AC) power:



file 00328

Answer 38



Notes 38

You can redirect this question into one more general: should fuses be connected in series with the load, or in parallel with the load? Have your students explain their choices, based on their knowledge of series and parallel circuits.

Question 39

Are fuses and circuit breakers located at a power distribution panel rated to protect the wiring from overcurrent, or to protect the load devices from overcurrent? Explain your answer.

file 00329

Answer 39

Generally speaking, distribution panel overcurrent protection devices are rated in such a way as to protect the wiring, not the load devices.

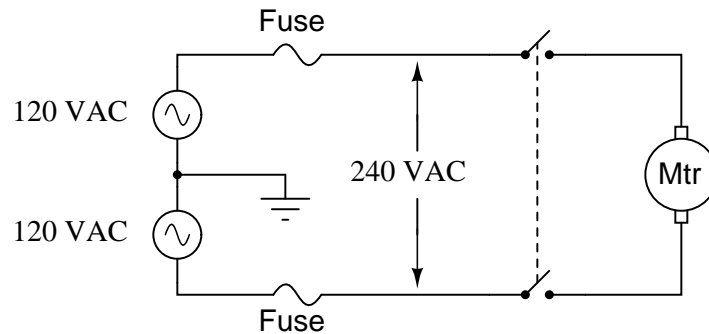
Follow-up question: suppose a computer with a 300 watt power supply is plugged into a receptacle, which is serviced by a circuit breaker rated at 15 amps. Where in the circuit would it be best to install an overcurrent protection device for protecting the computer from burning itself up in the event of an internal failure?

Notes 39

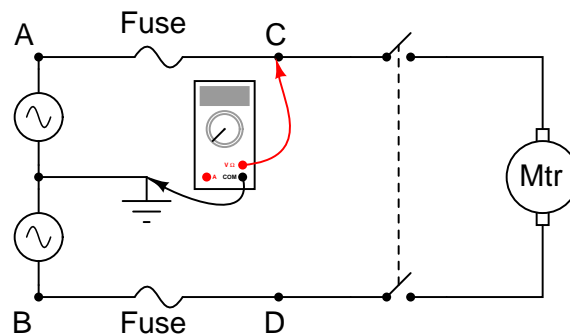
This lesson is very important for students to learn: that panel-mounted overcurrent protection devices are rated to protect the wiring they supply power to, and nothing else. Of course, there are exceptions to this rule in large industrial power systems.

Question 40

A large industrial electric motor is supplied power through a pair of fuses:



One day the motor suddenly stops running, even though the switch is still in the "on" position. An electrician is summoned to troubleshoot the failed motor, and this person decides to perform some voltage measurements to determine whether or not one of the fuses has "blown" open before doing anything else. The measurements taken by the electrician are as such (with the switch in the "on" position):



- Between A and ground = 120 volts AC
- Between B and ground = 120 volts AC
- Between C and ground = 120 volts AC
- Between D and ground = 120 volts AC

Based on these measurements, the electrician decides that both fuses are still in good condition, and that the problem lies elsewhere in the circuit. Do you agree with this assessment? Why or why not?

[file 00330](#)

Answer 40

So long as the switch is still in the "on" position when these measurements were taken, one of the fuses could still be blown!

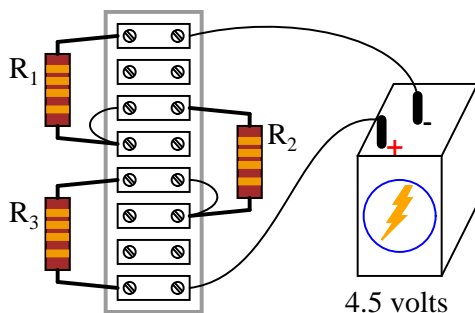
Follow-up question: what voltage measurement(s) would conclusively test the condition of both fuses?

Notes 40

I have actually seen an experienced electrician make this mistake on the job! Ask your students to explain how full voltage could be measured at points C and D, with respect to ground, even with one of the fuses blown.

Question 41

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



Also, determine the following information about this circuit:

- Current through each resistor
- Power dissipated by each resistor
- Ratio of each resistor's voltage drop to battery voltage ($\frac{E_R}{E_{bat}}$)
- Ratio of each resistor's resistance to the total circuit resistance ($\frac{R}{R_{total}}$)

file 00354

Answer 41

Voltage across each resistor = 1.5 V

Current through each resistor = 1.5 mA

Power dissipated by each resistor = 2.25 mW

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

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

Follow-up question: are the two ratios' equality a coincidence? Explain your answer.

Notes 41

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 (voltage 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 42

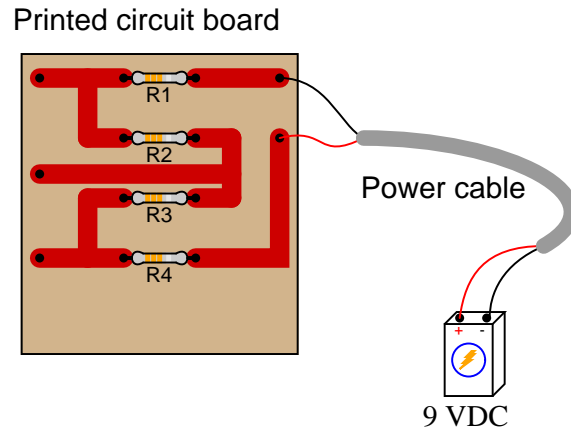
Calculate the voltage dropped by each of these resistors, given a battery voltage of 9 volts. The resistor color codes are as follows (assume 0% error on all resistor values):

R_1 = Brn, Grn, Red, Gld

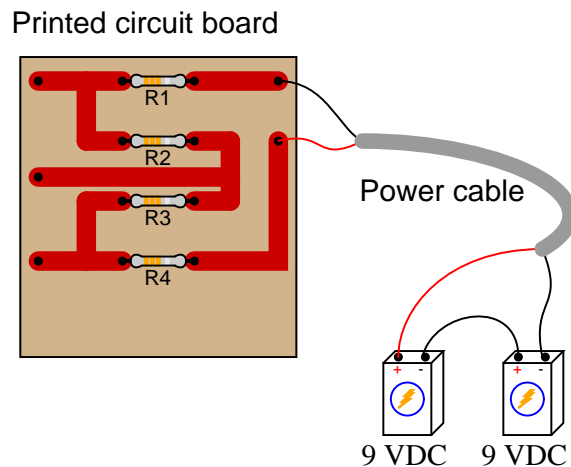
R_2 = Yel, Vio, Org, Gld

R_3 = Red, Grn, Red, Gld

R_4 = Wht, Blk, Red, Gld



Now, re-calculate all resistor voltage drops for a scenario where the total voltage is different:



[file 00355](#)

Answer 42

First scenario:

$$E_{R1} = 0.225 \text{ volts}$$

$$E_{R2} = 7.05 \text{ volts}$$

$$E_{R3} = 0.375 \text{ volts}$$

$$E_{R4} = 1.35 \text{ volts}$$

Second scenario:

$$E_{R1} = 0.45 \text{ volts}$$

$$E_{R2} = 14.1 \text{ volts}$$

$$E_{R3} = 0.75 \text{ volts}$$

$$E_{R4} = 2.7 \text{ volts}$$

Follow-up question: what do you notice about the *ratios* of the voltages between the two scenarios?

Ask your students if they notice any pattern between the voltage drops of the first scenario and the voltage drops of the second scenario. What does this pattern tell us about the nature of voltage divider circuits?

Question 43

We know that the current in a series circuit may be calculated with this formula:

$$I = \frac{E_{total}}{R_{total}}$$

We also know that the voltage dropped across any single resistor in a series circuit may be calculated with this formula:

$$E_R = IR$$

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

file 00360

Answer 43

$$E_R = E_{total} \left(\frac{R}{R_{total}} \right)$$

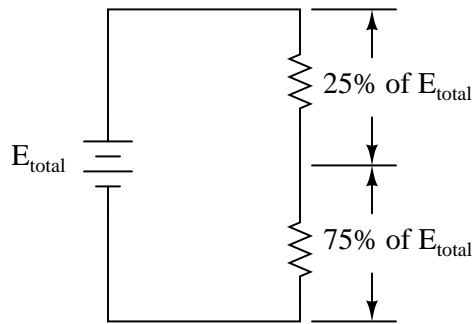
Follow-up question: algebraically manipulate this equation to solve for E_{total} in terms of all the other variables. In other words, show how you could calculate for the amount of total voltage necessary to produce a specified voltage drop (E_R) across a specified resistor (R), given the total circuit resistance (R_{total}).

Notes 43

Though this "voltage 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.

Question 44

Design a voltage divider circuit that splits the power supply voltage into the following percentages:



[file 01429](#)

Answer 44

There are many different sets of resistor values that will achieve this design goal, but here is one pair of resistance values that will suffice:

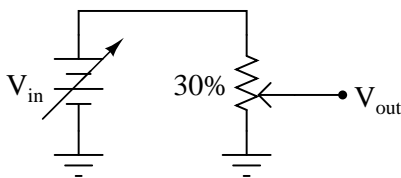
$250\ \Omega$ and $750\ \Omega$

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

Suppose I set a potentiometer to the 30% position, so that the wiper is 30% of the way up from the bottom:



Describe the mathematical relationship between V_{in} and V_{out} with the potentiometer in this position. What does this suggest about the usefulness of a potentiometer as an analog computational element?

file 03501

Answer 45

$V_{out} = (0.3)V_{in}$, for any value of V_{in} which does not overpower the potentiometer. In essence, the potentiometer is capable of functioning as an *analog computer* in that it outputs a signal that is a precise, controllable ratio of the input signal.

Notes 45

The important idea in this question is for students to view a potentiometer as an *adjustable divider* which may be used to provide a *ratio* function in an analog circuit. This may be your students' first step into the world of analog computational circuitry (using voltage and current values to represent numerical quantities), so be sure to emphasize the significance of this lowly potentiometer's function. The very idea that such a simple device can actually be used to *perform a mathematical operation* is profound.

Question 46

The formula for calculating voltage across a resistor in a series circuit is as follows:

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

In a simple-series circuit with one voltage source and three resistors, we may re-write this formula to be more specific:

$$V_{R1} = V_{source} \left(\frac{R_1}{R_1 + R_2 + R_3} \right)$$

Suppose we have such a series circuit with a source voltage of 15 volts, and resistor values of $R_1 = 1 \text{ k}\Omega$ and $R_2 = 8.1 \text{ k}\Omega$. Algebraically manipulate this formula to solve for R_3 in terms of all the other variables, then determine the necessary resistance value of R_3 to obtain a 0.2 volt drop across resistor R_1 .

file 03254

Answer 46

$$R_3 = V_{source} \left(\frac{R_1}{V_{R1}} \right) - (R_1 + R_2)$$

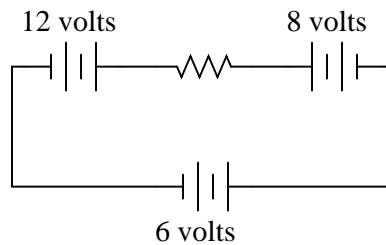
$$R_3 = 65.9 \text{ k}\Omega$$

Notes 46

This question provides students with another practical application of algebraic manipulation. Ask individual students to show their steps in manipulating the voltage divider formula to solve for R_3 , so that all may see and learn.

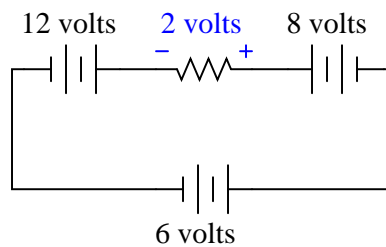
Question 47

Determine both the polarity of voltage across the resistor in this circuit, and how much voltage will be dropped across the resistor:



Explain the procedure(s) you used to answer both these questions.
[file 01548](#)

Answer 47



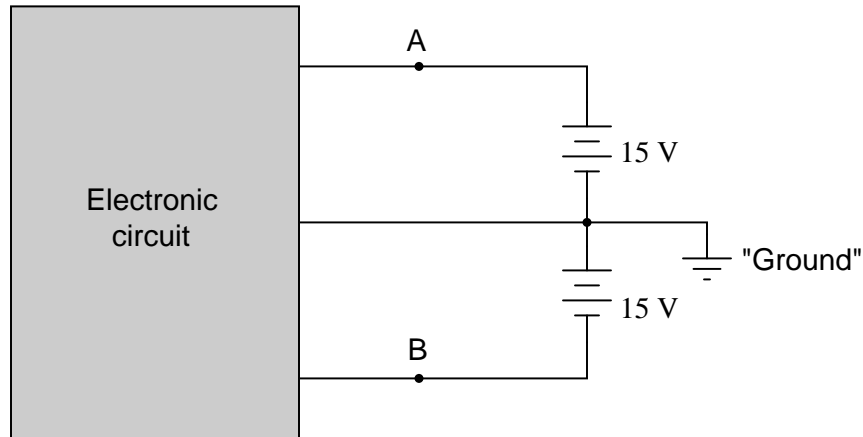
Notes 47

The answer to this question is fairly simple, but the real point of it is to get students thinking about how and why it is the way it is. One thing I've noticed as an instructor of electronics is that most students tend to follow the rule of proximity: the resistor's voltage drop polarity is determined by proximity to poles of the battery. The resistor terminal closest to the battery's negative terminal must be negative as well, or so the thinking goes.

In this particular circuit, though, the rule of proximity does not hold very well, and a different rule is necessary.

Question 48

Many electronic circuits use what is called a *split* or a *dual* power supply:



Determine what a digital voltmeter would indicate if connected between the following points:

- Red lead on "A", black lead on ground
- Red lead on "B", black lead on ground
- Red lead on "A", black lead on "B"
- Red lead on "B", black lead on "A"

NOTE: in electronic systems, "ground" is often not associated with an actual earth-soil contact. It usually only refers to a common point of reference somewhere in the circuit used to take voltage measurements. This allows us to specify voltages at single points in the circuit, with the implication that "ground" is the other point for the voltmeter to connect to.

file 00267

Answer 48

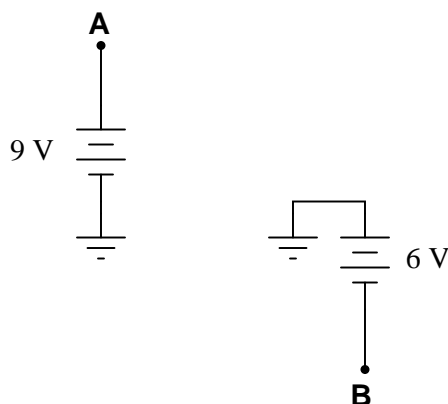
- Red lead on "A", black lead on ground (*Digital voltmeter reads +15 volts*)
- Red lead on "B", black lead on ground (*Digital voltmeter reads -15 volts*)
- Red lead on "A", black lead on "B" (*Digital voltmeter reads +30 volts*)
- Red lead on "B", black lead on "A" (*Digital voltmeter reads -30 volts*)

Notes 48

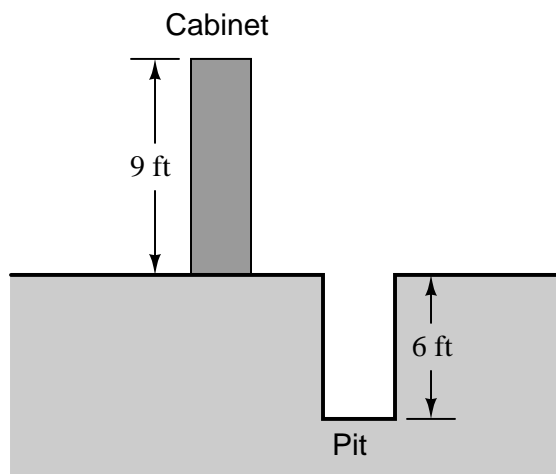
This question may be easily answered with only a voltmeter, two batteries, and a single "jumper" wire to connect the two batteries in series. It does not matter if the batteries are 15 volts each! The fundamental principle may still be investigated with batteries of any voltage, so this is a very easy demonstration to set up during discussion time.

Question 49

A student is puzzled by a problem given by her instructor. The task is to determine the voltage V_{AB} (defined by the instructor as the voltage indicated by a voltmeter with the red test lead touching point **A** and the black test lead touching point **B**) in this circuit:



The student has already figured out that $V_A = +9\text{ V}$ and $V_B = -6\text{ V}$, but does not know for certain how to calculate the voltage between points **A** and **B**. Asking her instructor for an explanation, the instructor begins to draw this illustration:



Before the instructor begins to explain what the illustration means, however, he receives a call on his telephone and must leave the student momentarily. The student then asks you to help explain what the instructor's illustration might mean, and how it applies to the problem of determining voltage V_{AB} in the original circuit.

What would your explanation be? Where do you think the instructor was going with this illustration, and how it might relate to voltages in a circuit?

file 01959

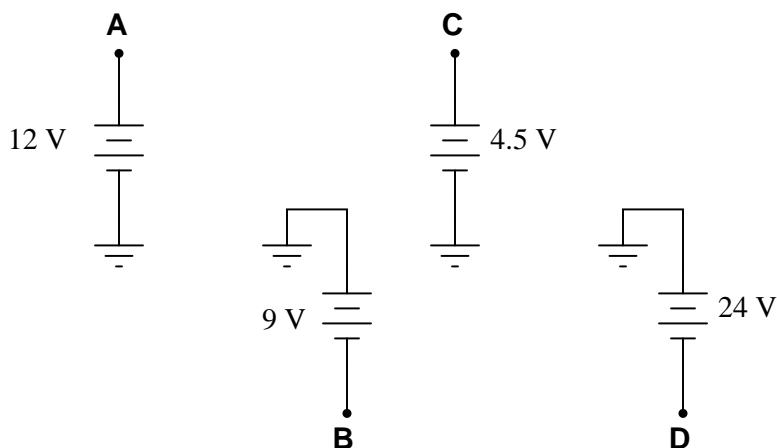
Answer 49

The height of the cabinet (*above* ground) represents the *positive* voltage at point **A**, while the depth of the pit (*below* ground) represents the *negative* voltage at point **B**. The *difference* in altitude between the cabinet's height and the pit's depth represents the voltage V_{AB} in the circuit.

It may be good to remind your students that voltage is and forever will be a quantity *between two points* and never defined at a single point. The only reason we can say $V_A = +9$ volts and $V_B = -6$ volts is because there is a *ground point* in the circuit, which by convention is the point of reference for any voltages defined at other, single points in the circuit.

Question 50

Determine the voltages registered by a voltmeter between the following points in this circuit:



$V_A = \underline{\hspace{1cm}}$ (red lead on **A**, black lead on ground)

$V_B = \underline{\hspace{1cm}}$ (red lead on **B**, black lead on ground)

$V_C = \underline{\hspace{1cm}}$ (red lead on **C**, black lead on ground)

$V_D = \underline{\hspace{1cm}}$ (red lead on **D**, black lead on ground)

$V_{AC} = \underline{\hspace{1cm}}$ (red lead on **A**, black lead on **C**)

$V_{DB} = \underline{\hspace{1cm}}$ (red lead on **D**, black lead on **B**)

$V_{BA} = \underline{\hspace{1cm}}$ (red lead on **B**, black lead on **A**)

$V_{BC} = \underline{\hspace{1cm}}$ (red lead on **B**, black lead on **C**)

$V_{CD} = \underline{\hspace{1cm}}$ (red lead on **C**, black lead on **D**)

[file 01961](#)

Answer 50

$V_A = \underline{+12 \text{ volts}}$ (red lead on **A**, black lead on ground)

$V_B = \underline{-9 \text{ volts}}$ (red lead on **B**, black lead on ground)

$V_C = \underline{+4.5 \text{ volts}}$ (red lead on **C**, black lead on ground)

$V_D = \underline{-24 \text{ volts}}$ (red lead on **D**, black lead on ground)

$V_{AC} = \underline{+7.5 \text{ volts}}$ (red lead on **A**, black lead on **C**)

$V_{DB} = \underline{-15 \text{ volts}}$ (red lead on **D**, black lead on **B**)

$V_{BA} = \underline{-21 \text{ volts}}$ (red lead on **B**, black lead on **A**)

$V_{BC} = \underline{-13.5 \text{ volts}}$ (red lead on **B**, black lead on **C**)

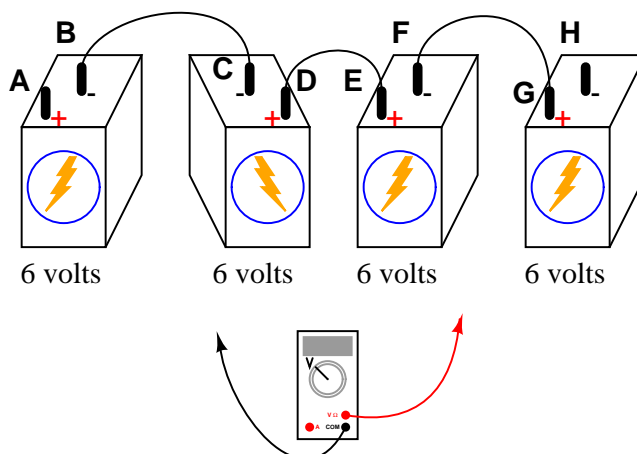
$V_{CD} = \underline{+28.5 \text{ volts}}$ (red lead on **C**, black lead on **D**)

Notes 50

Discuss with your students multiple techniques of solving for these voltages, asking them first for their solution strategies.

Question 51

Determine what a digital voltmeter (DVM) would indicate if connected between the following points in this circuit:

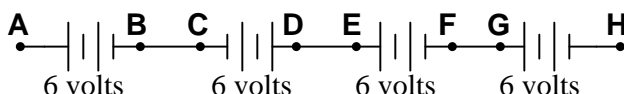


- Red lead on A, black lead on H
- Red lead on C, black lead on G
- Red lead on F, black lead on B
- Red lead on F, black lead on A

[file 00347](#)

Answer 51

Here is a schematic diagram to help you:



- Red lead on A, black lead on H = +12 volts
- Red lead on C, black lead on G = 0 volts
- Red lead on F, black lead on B = 0 volts
- Red lead on F, black lead on A = -6 volts

Notes 51

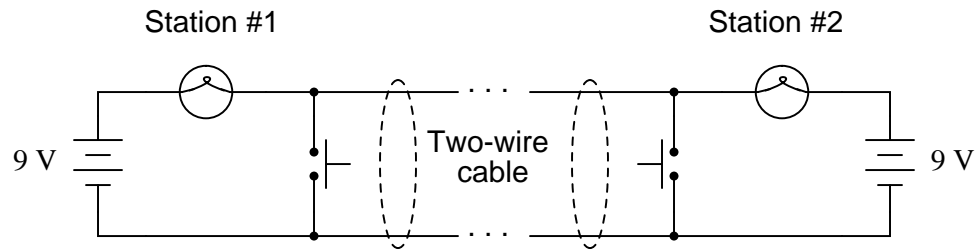
Kirchhoff's Voltage Law (KVL) is very easily explored in real life with a set of batteries and "jumper wire" connections. Encourage your students to build battery circuits like the one shown in this question, to be able to see the results for themselves!

One really nice feature of digital multimeters (DMMs) is the ability to register negative as well as positive quantities. This feature is very useful when teaching Kirchhoff's Laws, with the *algebraic* (sign-dependent) summation of voltages and currents.

Students may arrive at more than one method for determining voltmeter indications in problems like these. Encourage this type of creativity during discussion time, as it both helps students gain confidence in being able to approach problems on their own terms, as well as educates those students who might be confused with the concept. Quite often the explanation of a peer is more valuable than the explanation of an instructor. When students are given the freedom to explore problem-solving methods, and then share those methods with their classmates, substantial learning always results.

Question 52

Shown here is a simple telegraph circuit:



Explain why the lamps energize when either pushbutton is actuated, and why they de-energize when both pushbuttons are open (despite there being an unbroken circuit connecting both lamps and both batteries).
[file 00920](#)

Answer 52

The key to understanding this circuit is that both batteries are equal in voltage and opposed in polarity to one another.

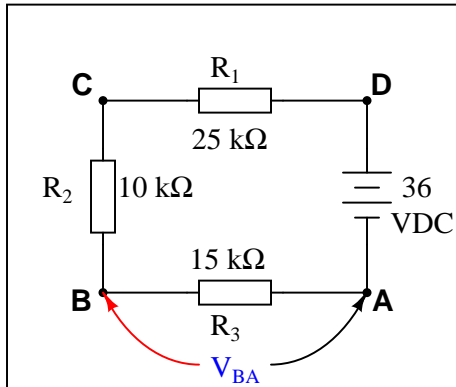
Notes 52

This is a simple circuit, yet practical in its function as a telegraph and as an example of KVL in action.

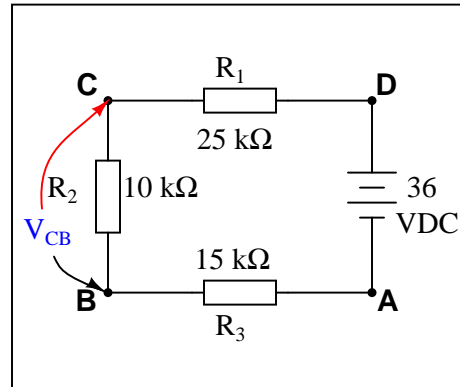
Question 53

Imagine you are using a digital voltmeter to measure voltages between pairs of points in a circuit, following the sequence of steps shown in these diagrams:

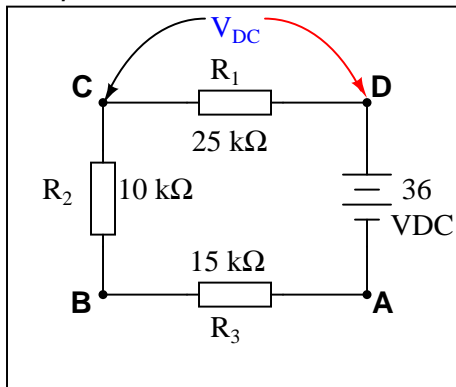
Step 1



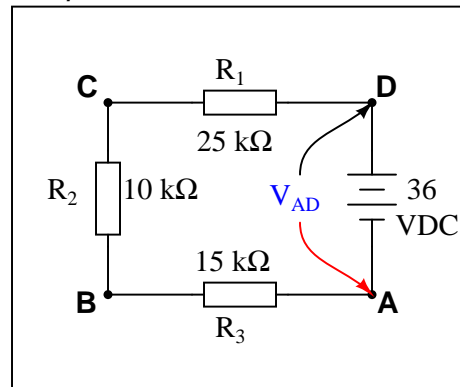
Step 2



Step 3



Step 4



How much voltage would be registered by the voltmeter in each of the steps? Be sure to include the sign of the DC voltage measured (note the coloring of the voltmeter leads, with the red lead always on the first point denoted in the subscript: V_{BA} = red lead on "B" and black lead on "A"):

- $V_{BA} =$
- $V_{CB} =$
- $V_{DC} =$
- $V_{AD} =$

What is the algebraic sum of these voltages?

file 00345

Answer 53

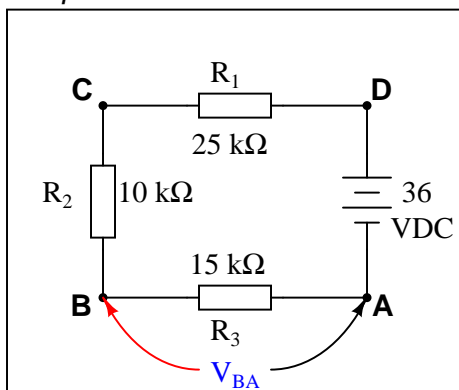
- $V_{BA} = +10.8$ volts
- $V_{CB} = +7.2$ volts
- $V_{DC} = +18$ volts
- $V_{AD} = -36$ volts

Ask your students this question: "Will the algebraic sum of voltage measurements ever be other than zero in a loop?" Ask them to explain *why* this is, as best they can.

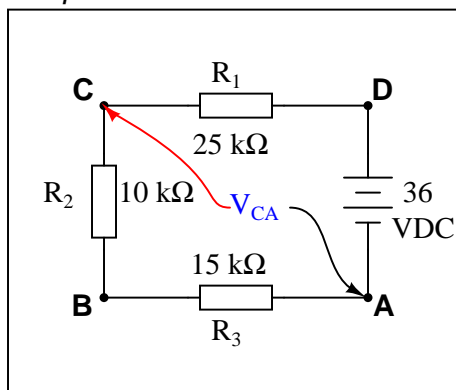
Question 54

Imagine you are using a digital voltmeter to measure voltages between pairs of points in a circuit, following the sequence of steps shown in these diagrams:

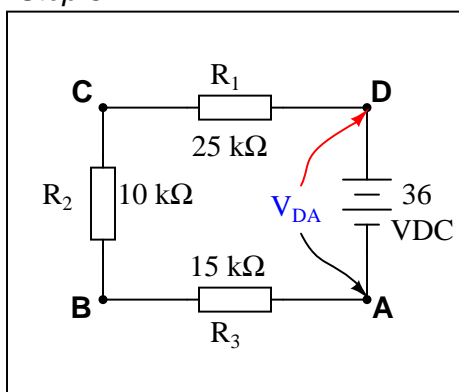
Step 1



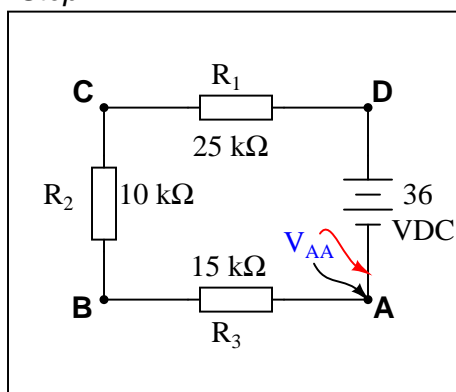
Step 2



Step 3



Step 4



How much voltage would be registered by the voltmeter in each of the steps? Be sure to include the sign of the DC voltage measured (note the coloring of the voltmeter leads, with the red lead always on the first point denoted in the subscript: V_{BA} = red lead on "B" and black lead on "A"):

- $V_{BA} =$
- $V_{CA} =$
- $V_{DA} =$
- $V_{AA} =$

Challenge question: how do these voltage measurements *prove* Kirchhoff's Voltage Law, where the algebraic sum of all voltages in a loop equals 0 volts?

file 00348

Answer 54

- $V_{BA} = +10.8$ volts
- $V_{CA} = +18.0$ volts
- $V_{DA} = +36.0$ volts
- $V_{AA} = 0$ volts

With each successive step, one more voltage is being added to the previously measured voltage(s), as the meter measures across a larger series chain of resistors. Ultimately,

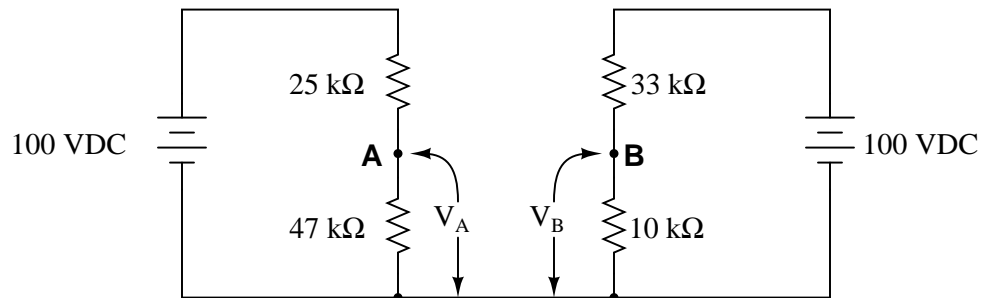
$$V_{AA} = V_{AD} + V_{DC} + V_{CB} + V_{BA} = 0 \text{ volts}$$

Notes 54

Building on the knowledge of series voltages being additive, this example serves as a simple proof of Kirchhoff's Voltage Law. At the final step of the sequence, the voltage indicated by the meter *must* be zero volts because the two test leads are now electrically common to each other.

Question 55

Calculate the output voltages of these two voltage divider circuits (V_A and V_B):



Now, calculate the voltage between points **A** (red lead) and **B** (black lead) (V_{AB}).

[file 01725](#)

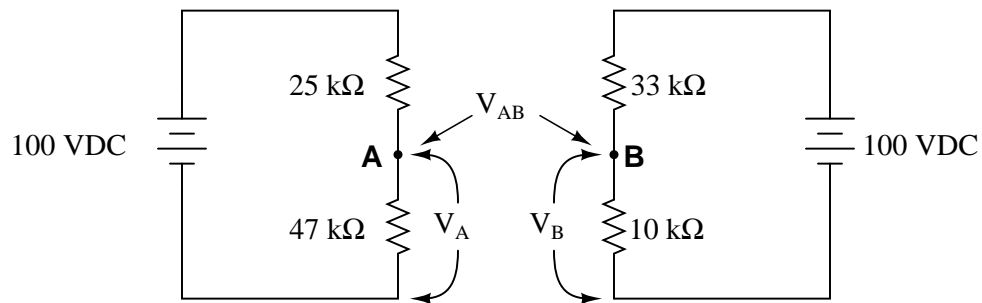
Answer 55

$$V_A = + 65.28 \text{ V}$$

$$V_B = + 23.26 \text{ V}$$

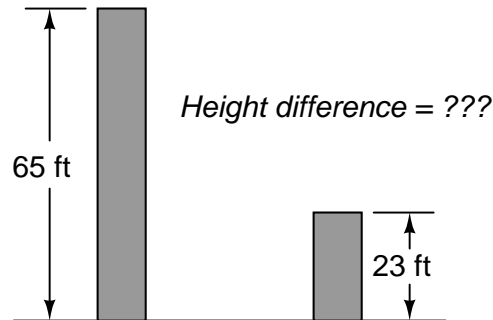
$$V_{AB} = + 42.02 \text{ V (point A being positive relative to point B)}$$

Challenge question: what would change if the wire connecting the two voltage divider circuits together were removed?



In this question, I want students to see how the voltage between the two dividers' output terminals is the difference between their individual output voltages. I also want students to see the notation used to denote the voltages (use of subscripts, with an applied reference point of ground). Although voltage is *always and forever* a quantity between two points, it is appropriate to speak of voltage being "at" a single point in a circuit if there is an implied point of reference (ground).

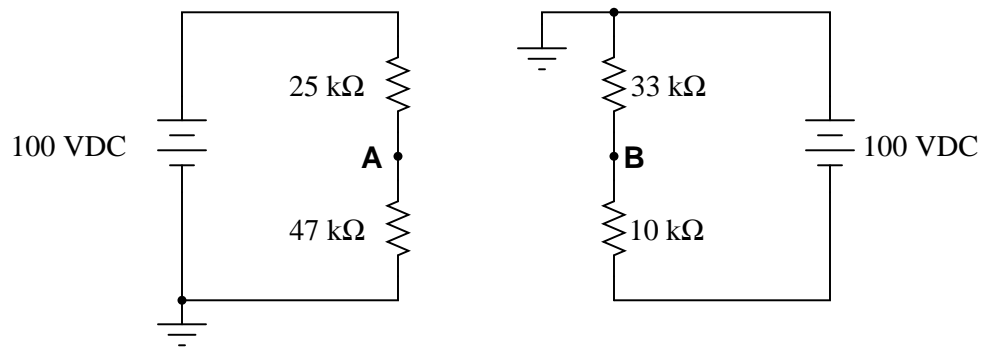
It is possible to solve for V_{AB} without formally appealing to Kirchhoff's Voltage Law. One way I've found helpful to students is to envision the two voltages (V_A and V_B) as heights of objects, asking the question of "How much height *difference* is there between the two objects?"



The height of each object is analogous to the voltage dropped across each of the lower resistors in the voltage divider circuits. Like voltage, height is a quantity measured *between two points* (the top of the object and ground level). Also like the voltage V_{AB} , the difference in height between the two objects is a measurement taken between two points, and it is also found by subtraction.

Question 56

Calculate V_A (voltage at point **A** with respect to ground) and V_B (voltage at point **B** with respect to ground) in the following circuit:



Now, calculate the voltage between points **A** and **B** (V_{AB}).

file 01727

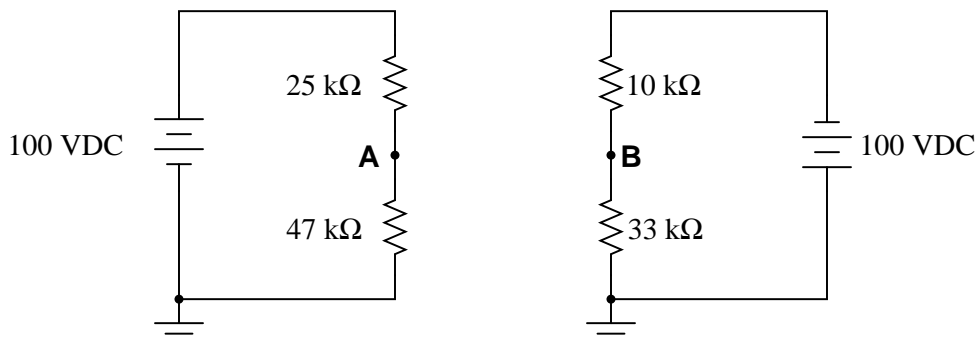
Answer 56

$$V_A = 65.28 \text{ V}$$

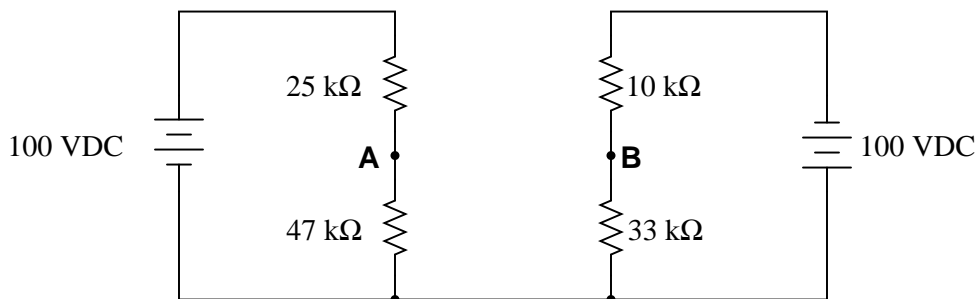
$$V_B = -76.74 \text{ V}$$

$$V_{AB} = 142.02 \text{ V (point A being positive relative to point B)}$$

If you are experiencing difficulty in your analysis of this circuit, you might want to refer to this re-drawing:



To make it even easier to visualize, remove the ground symbols and insert a wire connecting the lower wires of each circuit together:



It's all the same circuit, just different ways of drawing it!

Follow-up question: identify, for a person standing on the ground (with feet electrically common to the ground symbols in the circuits), all the points on the circuits which would be safe to touch without risk of electric shock.

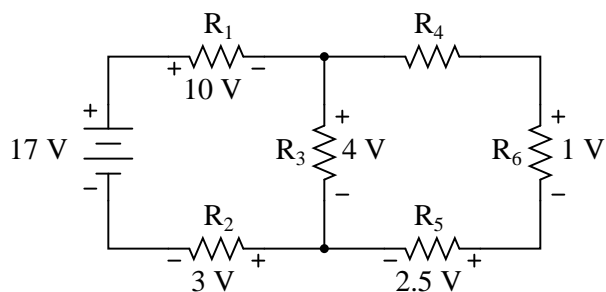
Notes 56

New students often experience difficulty with problems such as this, where ground connections are located in "strange" places. The alternate diagram may be helpful in this case.

The follow-up question challenges students to apply the practical rule-of-thumb (30 volts or more is considered potentially a source of electric shock) to a circuit that is otherwise quite abstract.

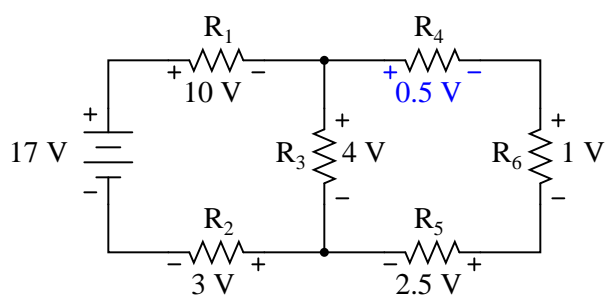
Question 57

Use Kirchhoff's Voltage Law to calculate the magnitude and polarity of the voltage across resistor R_4 in this resistor network:



file 01728

Answer 57



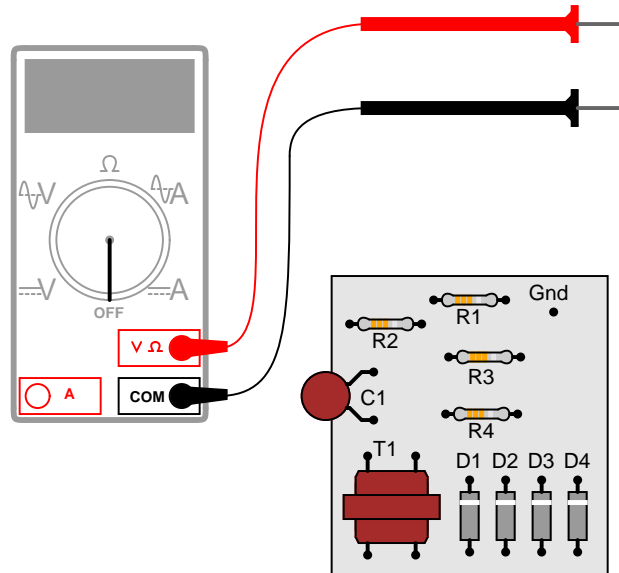
Notes 57

In your discussion, be sure to explore more than one "loop" when using KVL. Not only does this demonstrate the arbitrary nature of your loop choice, but it also serves as a double-check for your work!

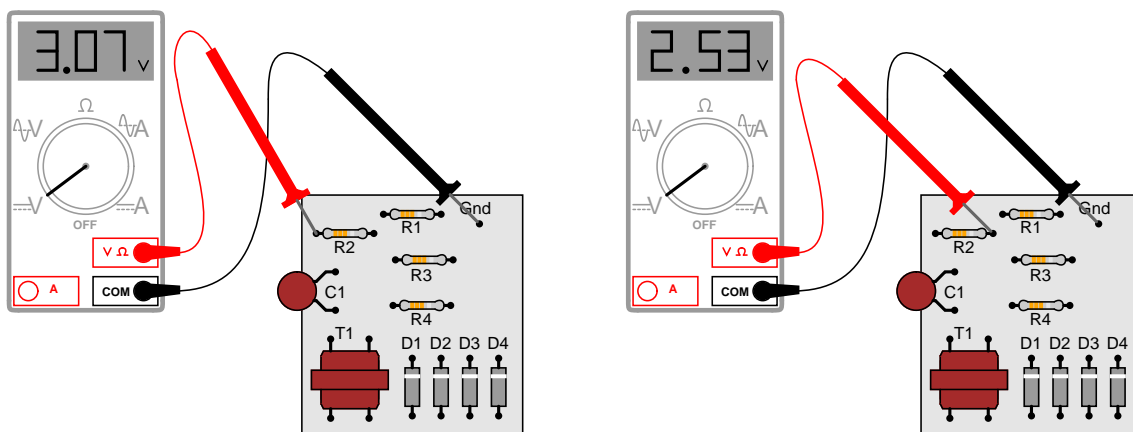
It is not necessary to know anything about series-parallel or even parallel circuits in order to solve the R_4 's voltage – all one needs to know is how to use Kirchhoff's Voltage Law.

Question 58

Suppose you wanted to measure the amount of current going through resistor R2 on this printed circuit board, but did not have the luxury of breaking the circuit to do so (unsoldering one end of the resistor, detaching it from the PCB, and connecting an ammeter in series). All you can do while the circuit is powered is measure voltage with a voltmeter:



So, you decide to touch the black probe of the voltmeter to the circuit's "Gnd" (ground) test point, and measure the voltage with reference to ground on both sides of R2. The results are shown here:



R2's color code is Orange, Orange, Red, Gold. Based on this information, determine both the direction and the magnitude of DC current through resistor R2, and explain how you did so.

[file 01729](#)

Answer 58

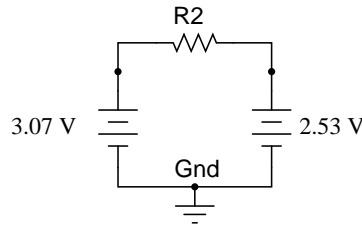
$I_{R2} \approx 160 \mu\text{A}$, conventional flow from left to right (electron flow from right to left).

Follow-up question: this technique for estimating resistor current depends on one important assumption. Describe what this assumption is, and how the accuracy of your current calculation may be affected if the assumption is invalid.

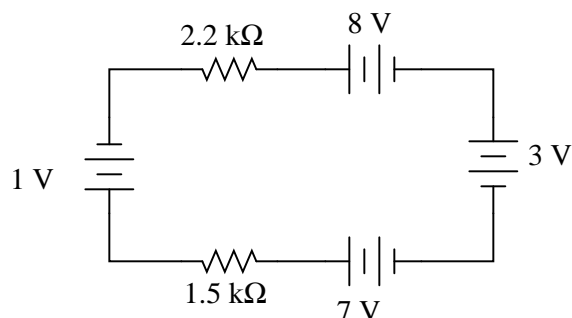
Notes 58

This is a good example of how Kirchhoff's Voltage Law is more than just an abstract tool for mathematical analysis – it is also a powerful technique for practical circuit diagnosis. Students must apply KVL to determine the voltage drop across R2, and then use Ohm's Law to calculate its current.

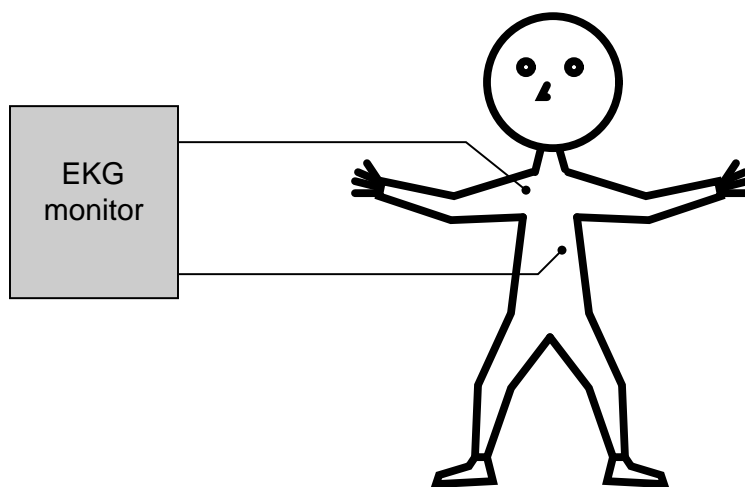
If students experience difficulty visualizing how KVL plays a part in the solution of this problem, show them this illustration:



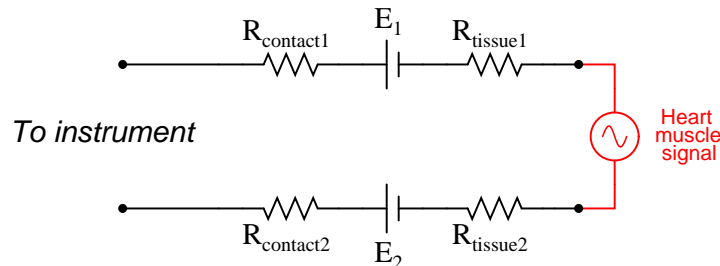
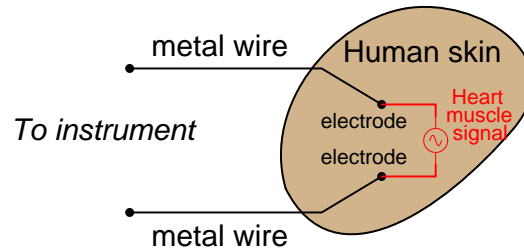
When electricity and electronics students begin learning about series circuits and Kirchhoff's Voltage Law, they are often mercilessly subjected to circuits such as this:



A common (and legitimate!) question asked by students is, "Where would we ever encounter a circuit such as this, with batteries *opposing* each other?" In practice, it is rare to find electrochemical batteries intentionally connected in such a manner, with some aiding and some opposing. However, there are many practical applications where the voltages involved are not intentional, but rather are unavoidable potentials created by junctions of dissimilar materials. Take for instance the application of EKG (electrocardiogram) measurements, where metal electrodes must be placed in contact with a human body to intercept tiny voltage signals from the contracting heart muscles:



A junction of metal wire to human skin is surprisingly complex from an electrical perspective, and may be approximately modeled by the following collection of idealized components:



Resistors R_{contact1} and R_{contact2} represent electrical resistance between the metal electrodes and skin at the point of contact. Resistors R_{tissue1} and R_{tissue2} represent electrical resistance of human tissue between the points of electrode contact and the actual heart muscle. The two series-opposing potentials (E_1 and E_2) are not intentional, but rather the result of electrochemical action between the metal electrode surfaces and human skin. They cannot be eliminated, but their combined effect is minimal because they are approximately equal in magnitude. Explain how Kirchhoff's Voltage Law applies to this equivalent circuit, especially how the biomedical instrument "sees" only the heart muscle voltage signal and neither of the skin-contact potentials.

[file 03007](#)

Answer 59

Applying KVL to the circuit loop, we find that equal contact potentials E_1 and E_2 cancel each other out, leaving only the heart muscle voltage to be present at the instrument terminals.

Follow-up question: why is the heart muscle represented in the equivalent circuit by an AC voltage source symbol rather than by a DC voltage source symbol (battery)? Does this matter when we apply KVL to the loop? Why or why not?

Notes 59

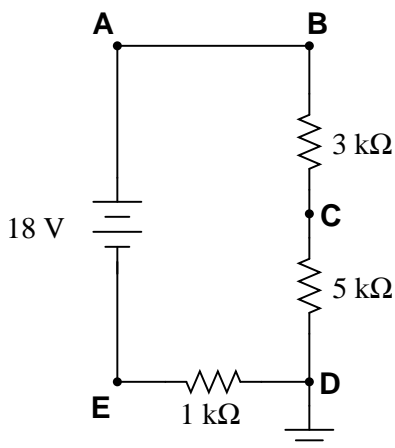
The question of "where will we ever see this?" is too often ignored by teachers, who forget the lack of context present in their new students' understanding. Remember that this is all **new** to most of your students, so they lack the years of experience you have working with circuits in practical scenarios. A question like this deserves to be answered, and answered well.

Truth be known, the equivalent circuit for electrode-to-skin contact is far more complex than what is shown here (impedances everywhere!), but the point here is to simplify it enough so that students studying DC circuits and KVL would be able to grasp it.

Electrode half-cell potentials (E_1 and E_2 in the equivalent schematic diagram) caused by electrochemical action are not the only source of stray potentials in measurement circuits by any means! Noise voltage is a consideration in many circumstances (whether induced by outside sources or generated by physical action such as Johnson noise), thermal voltages caused by junctions of dissimilar metals, and others. If all we are doing is making crude measurements, these stray voltages will be of little concern. If precision is necessary, which is often the case in medical and scientific measurements, these spurious voltages can be devastating.

Question 60

Identify each of the specified voltages in the following circuit. The subscripts refer to the specific test points (where the red test lead of the voltmeter touches the circuit), while ground is the point where the voltmeter's black lead is assumed to be attached:



For example, V_B means the voltage indicated by a voltmeter with the red test lead touching point B and the black test lead touching ground.

- $V_A =$
- $V_B =$
- $V_C =$
- $V_D =$
- $V_E =$

file 03250

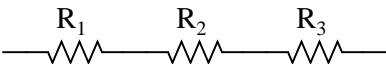
Answer 60

- $V_A = +16$ volts
- $V_B = +16$ volts
- $V_C = +10$ volts
- $V_D = 0$ volts
- $V_E = -2$ volts

Follow-up question: explain how it is possible to determine that V_A and V_B will be exactly the same value, prior to performing any mathematical calculations.

Notes 60

This question helps to familiarize students with the concept of "ground" as the default reference point for taking voltage measurements, as well as being an application of Kirchhoff's Voltage Law.

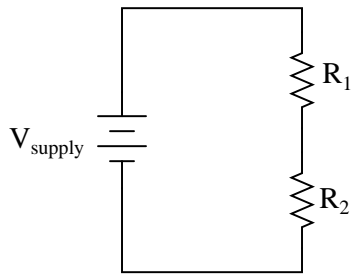
Competency: Series resistances		Version:
Schematic		
		
Given conditions		
$R_1 =$	$R_2 =$	$R_3 =$
Parameters		
R_{total}	Predicted <input style="width: 80px; height: 25px;" type="text"/>	Measured <input style="width: 80px; height: 25px;" type="text"/>
Analysis		
Equation used to calculate R_{total} :		

Answer 61

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

Notes 61

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

Competency: Series DC resistor circuit	Version:																								
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Schematic</div> <div style="text-align: center; margin-top: 20px;">  </div>																									
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Given conditions</div> <div style="margin-top: 10px;"> $V_{\text{supply}} =$ $R_1 =$ $R_2 =$ </div>																									
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Parameters</div> <table style="width: 100%; border-collapse: collapse; margin-top: 10px;"> <thead> <tr> <th style="width: 15%;"></th> <th style="width: 15%; text-align: center;">Predicted</th> <th style="width: 15%; text-align: center;">Measured</th> <th style="width: 15%;"></th> <th style="width: 15%; text-align: center;">Predicted</th> <th style="width: 15%; text-align: center;">Measured</th> </tr> </thead> <tbody> <tr> <td>I_{supply}</td> <td><div style="border: 1px solid black; width: 80px; height: 25px;"></div></td> <td><div style="border: 1px solid black; width: 80px; height: 25px;"></div></td> <td>I_{R1}</td> <td><div style="border: 1px solid black; width: 80px; height: 25px;"></div></td> <td><div style="border: 1px solid black; width: 80px; height: 25px;"></div></td> </tr> <tr> <td>V_{R1}</td> <td><div style="border: 1px solid black; width: 80px; height: 25px;"></div></td> <td><div style="border: 1px solid black; width: 80px; height: 25px;"></div></td> <td>I_{R2}</td> <td><div style="border: 1px solid black; width: 80px; height: 25px;"></div></td> <td><div style="border: 1px solid black; width: 80px; height: 25px;"></div></td> </tr> <tr> <td>V_{R2}</td> <td><div style="border: 1px solid black; width: 80px; height: 25px;"></div></td> <td><div style="border: 1px solid black; width: 80px; height: 25px;"></div></td> <td></td> <td></td> <td></td> </tr> </tbody> </table>			Predicted	Measured		Predicted	Measured	I_{supply}	<div style="border: 1px solid black; width: 80px; height: 25px;"></div>	<div style="border: 1px solid black; width: 80px; height: 25px;"></div>	I_{R1}	<div style="border: 1px solid black; width: 80px; height: 25px;"></div>	<div style="border: 1px solid black; width: 80px; height: 25px;"></div>	V_{R1}	<div style="border: 1px solid black; width: 80px; height: 25px;"></div>	<div style="border: 1px solid black; width: 80px; height: 25px;"></div>	I_{R2}	<div style="border: 1px solid black; width: 80px; height: 25px;"></div>	<div style="border: 1px solid black; width: 80px; height: 25px;"></div>	V_{R2}	<div style="border: 1px solid black; width: 80px; height: 25px;"></div>	<div style="border: 1px solid black; width: 80px; height: 25px;"></div>			
	Predicted	Measured		Predicted	Measured																				
I_{supply}	<div style="border: 1px solid black; width: 80px; height: 25px;"></div>	<div style="border: 1px solid black; width: 80px; height: 25px;"></div>	I_{R1}	<div style="border: 1px solid black; width: 80px; height: 25px;"></div>	<div style="border: 1px solid black; width: 80px; height: 25px;"></div>																				
V_{R1}	<div style="border: 1px solid black; width: 80px; height: 25px;"></div>	<div style="border: 1px solid black; width: 80px; height: 25px;"></div>	I_{R2}	<div style="border: 1px solid black; width: 80px; height: 25px;"></div>	<div style="border: 1px solid black; width: 80px; height: 25px;"></div>																				
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<div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Analysis</div> <div style="margin-top: 10px; text-align: center;"> Relationship between resistor voltage drops and total voltage: </div>																									
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px; margin-bottom: 5px;">Fault analysis</div> <div style="margin-top: 10px;"> Suppose component <div style="border: 1px solid black; width: 50px; height: 25px; display: inline-block;"></div> fails <div style="display: inline-block; vertical-align: middle; margin-left: 10px;"> <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted </div> </div> <div style="margin-top: 10px;"> <i>What will happen in the circuit?</i> </div>																									

file 01627

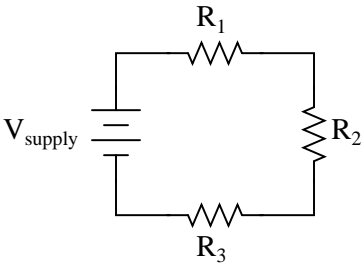
Answer 62

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 Ω and 100 k Ω (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.

Competency: Series DC resistor circuit		Version:	
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px;">Schematic</div>			
			
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px;">Given conditions</div>			
$V_{\text{supply}} =$	$R_1 =$	$R_2 =$	$R_3 =$
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px;">Parameters</div>			
	Predicted	Measured	
I_{supply}			I_{R1}
V_{R1}			I_{R2}
V_{R2}			I_{R3}
V_{R3}			
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px;">Analysis</div>			
Relationship between resistor voltage drops and total voltage:			
<div style="border: 1px solid black; display: inline-block; padding: 2px 5px;">Fault analysis</div>			
Suppose component fails <div style="display: inline-block; vertical-align: middle; margin-left: 10px;"> <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted </div>			
<i>What will happen in the circuit?</i>			

file 01604

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 Ω and 100 k Ω (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.

Troubleshooting log

Actions / Measurements / Observations (i.e. <i>What I did and/or noticed . . .</i>)	Conclusions (i.e. <i>What this tells me . . .</i>)

file 03933

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

Answer 65

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

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

A chandelier has five light bulbs in it, and one of them is not working. The problem could be in the chandelier's wiring (open wire connection, open connection in socket), or in the bulb itself (burned-out filament). Describe a procedure for determining the location of the problem (chandelier vs. bulb), without using any electrical test instruments.

file 01190

Answer 66

Swap the non-working bulb for one of the other four working bulbs, and see if the problem moves with the bulb.

Challenge question: can you think of a scenario where this troubleshooting procedure could *cause* additional failures in a system?

Notes 66

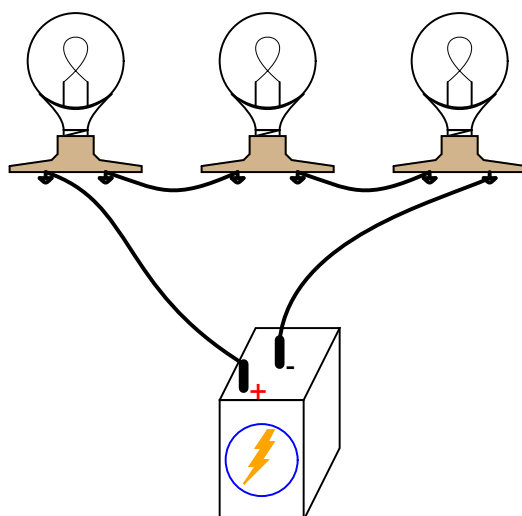
This simple troubleshooting technique is applicable to a wide variety of electrical, electronic, and other types of systems: swap the suspect component with an identical component known to be functional, and see observe whether or not the problem changes location.

There is, however, a potential hazard to doing this. If the swapped component is indeed faulty, but in such a way that it *causes* a different part of the system to fail with connected to it, this technique will cause a failure in the system where the faulty component is moved to.

A similar hazard occurs if the swapped component was damaged because of other components in the system that it's connected to. In this case, the good component it it swapped with will be damaged in the swap, and the bad component will not work where it is moved to.

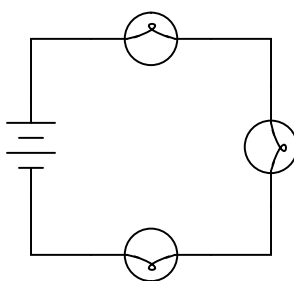
Question 67

Re-draw this circuit in the form of a schematic diagram:



file 00068

Answer 67



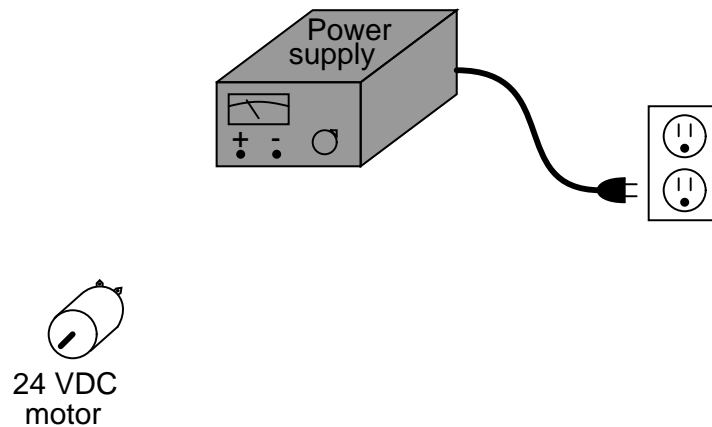
Notes 67

One of the more difficult skills for students to develop is the ability to translate the layout of a real-world circuit into a neat schematic diagram. Developing this skill requires lots of practice.

It is very worthwhile for students to discuss how they solve problems such as these with each other. For those students who have trouble visualizing shapes, a simple hint or "trick" to use when translating schematics to illustrations or visa-versa may be invaluable.

Question 68

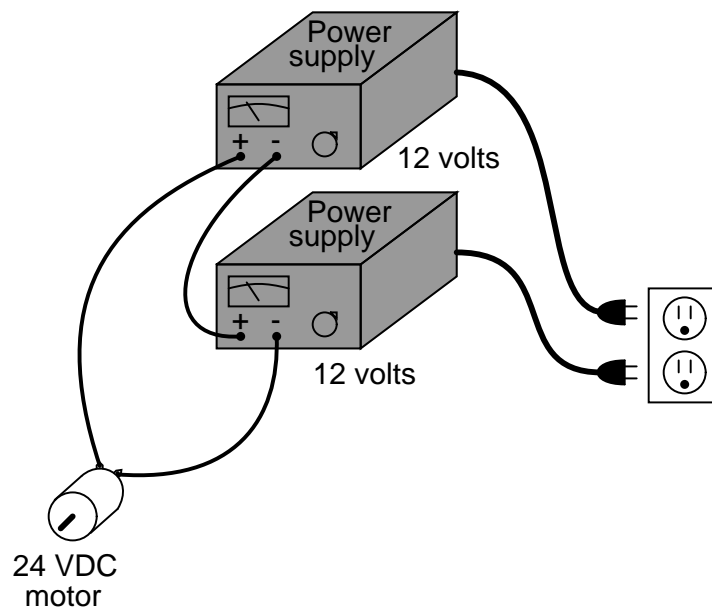
A technician wants to energize a 24 volt motor, but lacks a 24 volt battery to do it with. Instead, she has access to several "power supply" units which convert 120 volt AC power from a power receptacle into low-voltage DC power that is adjustable over a range of 0 to 15 volts. Each of these power supplies is a box with a power cord, voltage adjustment knob, and two output terminals for connection with the DC voltage it produces:



Draw a picture of how this technician might use power supplies to energize the 24 volt motor.
[file 00042](#)

Answer 68

This is perhaps the most direct solution (setting each power supply to output 12 volts):

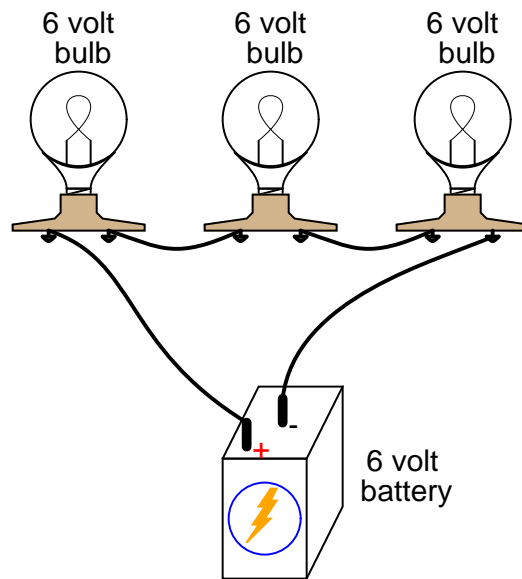


Notes 68

Although this is a very simple and direct solution, it is not the only possible one. Incidentally, this scenario is very common in electronics work: having to couple multiple power supplies together to achieve a desired total voltage or total current.

Question 69

What would happen if three 6-volt light bulbs were connected as shown to a 6-volt battery? How would their brightnesses compare to just having a single 6-volt light bulb connected to a 6-volt battery?



file 00035

Answer 69

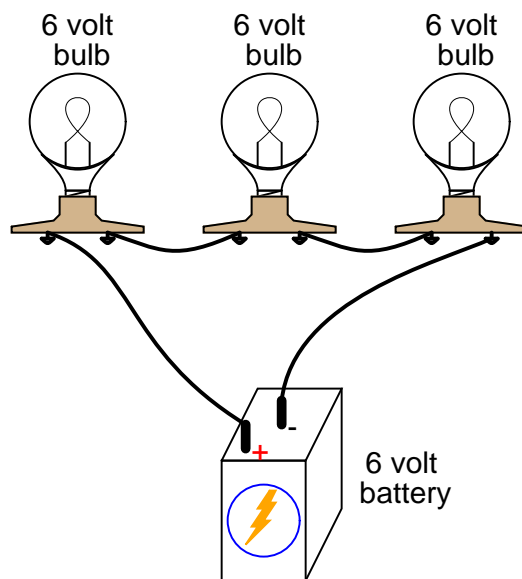
The three light bulbs would glow dimly.

Notes 69

Here, the important principle of voltage "drops" in a series circuit is highlighted. This question serves to further define, in practical ways, what the term "series" really means.

Question 70

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 00036

Answer 70

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

Notes 70

Here, the important principles of voltage and current in a series circuit are highlighted. This question serves to further define, in practical ways, what the term "series" 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 71

Calculate the necessary series "dropping" resistor value to operate a 1.6 volt, 20 mA LED from a 15 volt DC power source. Also, calculate the power dissipated by the resistor while operating.

$$R = \quad \quad P_R =$$

file 02304

Answer 71

$$R = 670 \, \Omega \quad \quad P_R = 0.268 \, \text{W}$$

Notes 71

Ask your students to explain how they calculated the correct answer for this question.

Question 72

Calculate the necessary series "dropping" resistor value to operate a 1.8 volt, 20 mA LED from a 34 volt DC power source. Also, calculate the power dissipated by the resistor while operating.

$$R = \quad \quad P_R =$$

file 02305

Answer 72

$$R = 1.61 \text{ k}\Omega \quad \quad P_R = 0.644 \text{ W}$$

Notes 72

Ask your students to explain how they calculated the correct answer for this question.

Question 73

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

$$R = R_1 + R_2 + R_3$$

Algebraically manipulate this equation to solve for one of the series resistances (R_1) in terms of the other two series 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 03066](#)

Answer 73

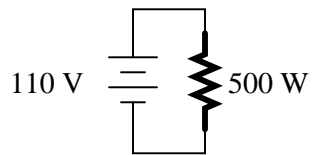
$$R_1 = R - (R_2 + R_3) \quad \text{or} \quad R_1 = R - R_2 - R_3$$

Notes 73

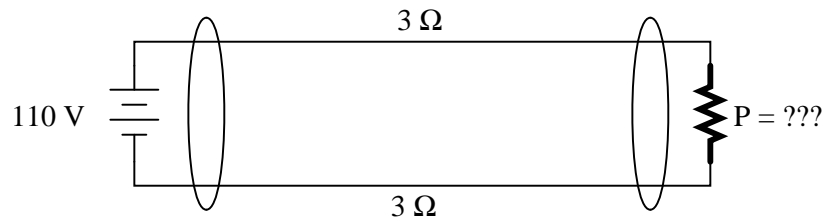
This question is nothing more than practice algebraically manipulating equations. Ask your students to show you how they solved it, and how the two given answers are equivalent.

Question 74

Suppose that an electric heater, which is nothing more than a large resistor, dissipates 500 watts of power when directly connected to a 110 volt source:



Now suppose that exact same heater is connected to one end of a long two-wire cable, which is then connected to the same 110 volt source. Assuming that each conductor within the cable has an end-to-end resistance of 3 ohms, how much power will the heater dissipate?



file 03252

Answer 74

$$P = 321.1 \text{ watts}$$

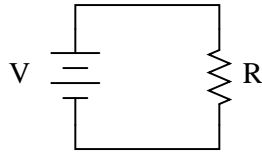
Notes 74

The purpose of this question, besides providing a good problem-solving exercise for students, is to get them to realize one of the practical implications of power-line resistance.

Question 75

Substitution is the term we give to the mathematical equivalence of one variable to one or more other variables in an expression. It is a fundamental principle used to combine two or more equations into a single equation (among other things).

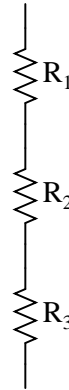
For example, we know that the formula for calculating current in a simple one-resistor circuit is as follows:



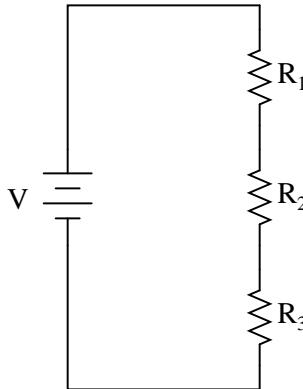
$$I = V / R$$

We also know that the total resistance (R) of a three-resistor series circuit is as follows:

$$R = R_1 + R_2 + R_3$$



Combine these two equations together using substitution so that we have a single equation for calculating current I in a three-resistor series circuit given the source voltage V and each resistance value R_1 , R_2 , and R_3 :



$$I = f(V, R_1, R_2, R_3)$$

"I is some function of V, R₁, R₂, and R₃"

In other words, you need to have as your answer a single equation that begins with " $I =$ " and has all the variables V , R_1 , R_2 , and R_3 on the other side of the "equal" sign.

Answer 75

$$I = \frac{V}{R_1 + R_2 + R_3}$$

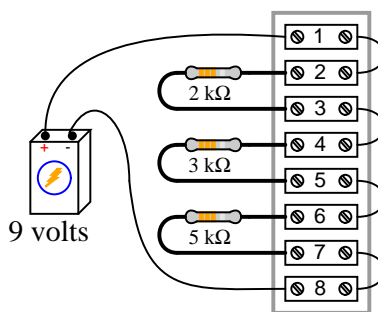
Notes 75

I like to speak of the process of substitution in terms of *definitions* for variables. In this particular case, $R_1 + R_2 + R_3$ is a *definition* for R that we put in R 's place in the first equation ($I = \frac{V}{R}$).

The notation shown in the third schematic, $I = f(V, R_1, R_2, R_3)$, is known as *function notation*. It merely means that the value of I is determined by the values of all those variables within the parentheses, rather than just one.

Question 76

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



- Voltage between terminals 2 and 3 =
- Voltage between terminals 4 and 5 =
- Voltage between terminals 6 and 7 =
- Voltage between terminals 6 and 8 =
- Voltage between terminals 4 and 8 =
- Voltage between terminals 2 and 8 =
- Current through each resistor =
- R_{total} =

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

[file 00293](#)

Answer 76

- Voltage between terminals 2 and 3 = 1.8 volts
- Voltage between terminals 4 and 5 = 2.7 volts
- Voltage between terminals 6 and 7 = 4.5 volts
- Voltage between terminals 6 and 8 = 4.5 volts
- Voltage between terminals 4 and 8 = 7.2 volts
- Voltage between terminals 2 and 8 = 9 volts
- Current through each resistor = 0.9 mA
- R_{total} = 10 kΩ

Note how all the voltage drops are a certain *proportion* of the total voltage. What do you think would happen to these voltage drops if the source voltage (9 volts from the battery) were doubled?

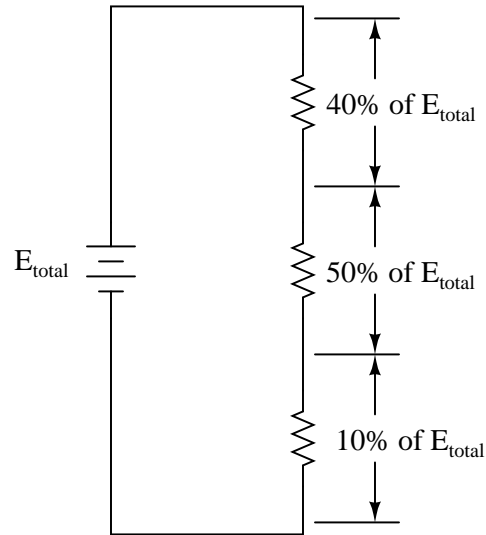
Notes 76

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 *voltage divider*?"

Question 77

Design a voltage divider circuit that splits the power supply voltage into the following percentages:



file 00357

Answer 77

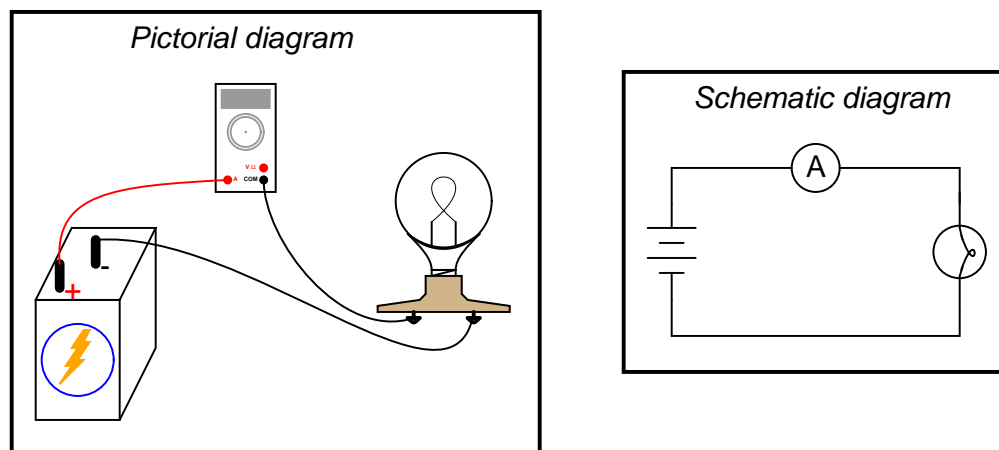
There are many different sets of resistor values that will achieve this design goal!

Notes 77

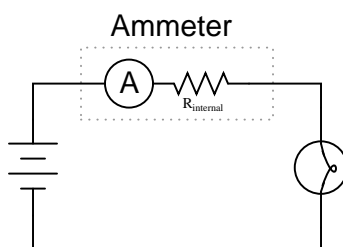
Different students will likely arrive at different solutions for this design task. Have your students share their differing solutions, emphasizing that there is often more than one acceptable solution to a problem!

Question 78

Ammeters must be connected in *series* with the current to be measured, to ensure that all the current moves through the meter:



In order to practically function, an ammeter must have some internal resistance. It is usually a very small amount, but it does exist. It should be apparent to you that the presence of this resistance will have some effect on the circuit current, when compared to the amount of current in the circuit without any meter connected:



Explain why it is usually safe to ignore the internal resistance of an ammeter, 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 ammeter."

[file 03638](#)

Answer 78

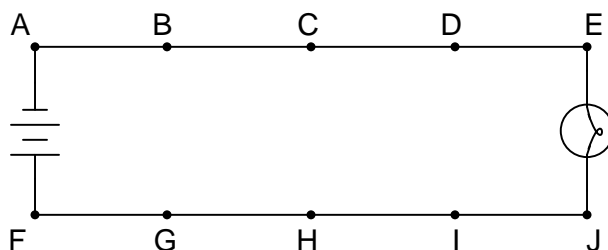
When one quantity "swamps" another, we mean that its effect is huge compared to the effect of the other, so much so that we may safely ignore it in our calculations and still arrive at a reasonably accurate result.

Notes 78

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 79

Suppose this battery and light bulb circuit failed to work. Using nothing but a voltmeter, how would you check the circuit to determine where the problem is located? Note: the letters indicate "test points" along the wiring where you may probe with the circuit with your voltmeter.



file 00118

Answer 79

There are several strategies which may be employed to find the location of the problem in this circuit. One popular technique is to "divide the circuit in half" by testing for voltage between points C and H first. The presence or absence of voltage between these two points will indicate whether the problem lies between those points and the battery, or between those points and the light bulb (assuming there is but a *single* problem in the circuit – a large assumption!).

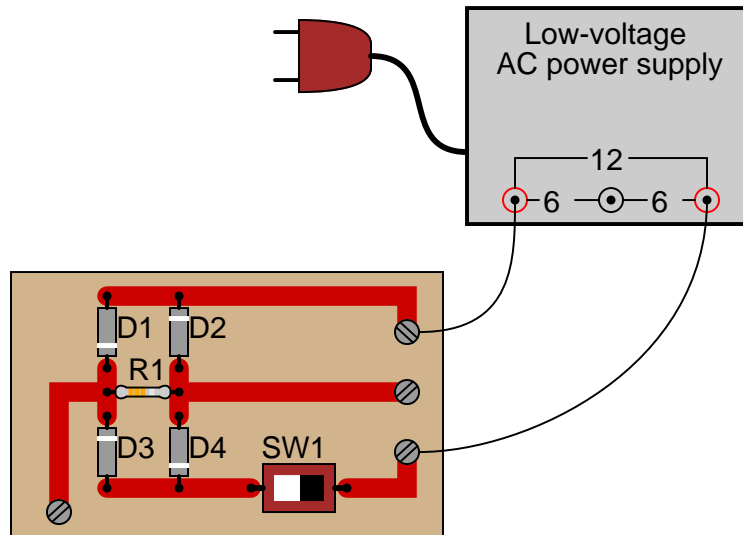
Notes 79

A circuit like this is very easy to construct, and makes for an excellent classroom demonstration piece. I've used such a circuit, constructed on a piece of pegboard 2 feet by 4 feet, with metal screws acting as test points, for students to develop their troubleshooting skills in front of the class where everyone may observe and learn together.

It has been my experience that students who experience difficulty troubleshooting circuits in general usually experience difficulty troubleshooting this simple circuit in particular. Although the circuit itself couldn't be simpler, the fundamental concept of *voltage* as a quantity measurable only between 2 points is confusing for many. Spending lots of time learning to troubleshoot a circuit such as this will be greatly beneficial in the future!

Question 80

The circuit shown here is called a "bridge rectifier," and its purpose is to convert alternating current (from the "power-supply" unit) into direct current. Suppose you were instructed to check the continuity of the switch (SW1) mounted on the printed circuit board. What would be a fast and effective way of testing this switch's continuity (ideally, without removing the switch from the circuit board)?



file 00100

Answer 80

Disconnect the power supply from the circuit board (only one wire need be disconnected), and then use an ohmmeter to measure continuity across the switch terminals when in the "ON" position and when in the "OFF" position. Incidentally, this is not the only way to check the switch's continuity, but it is the most direct.

Notes 80

Challenge your students to think of other methods which could be used to check the switch's continuity. There is often more than one way to perform a certain check of component function, if you are knowledgeable in electrical theory and creative in your use of test equipment!

Question 81

Identify which of these are true statements:

1. Between two points that are electrically common to each other, there is guaranteed to be zero voltage.
2. If zero voltage is measured between two points, those points must be electrically common to each other.
3. Between two points that are not electrically common to each other, there is guaranteed to be voltage.
4. If voltage is measured between two points, those points must not be electrically common to each other.

[file 00184](#)

Answer 81

Only two out of the four given statements are true:

1. Between two points that are electrically common to each other, there is guaranteed to be zero voltage.
4. If voltage is measured between two points, those points must not be electrically common to each other.

For those having difficulty understanding this, test the following statements for truth. Each of these statements follows the same logical pattern of electrical statements given at the beginning of this question:

1. All rabbits are mammals.
2. All mammals are rabbits.
3. All non-rabbits are non-mammals.
4. All non-mammals are non-rabbits.

Notes 81

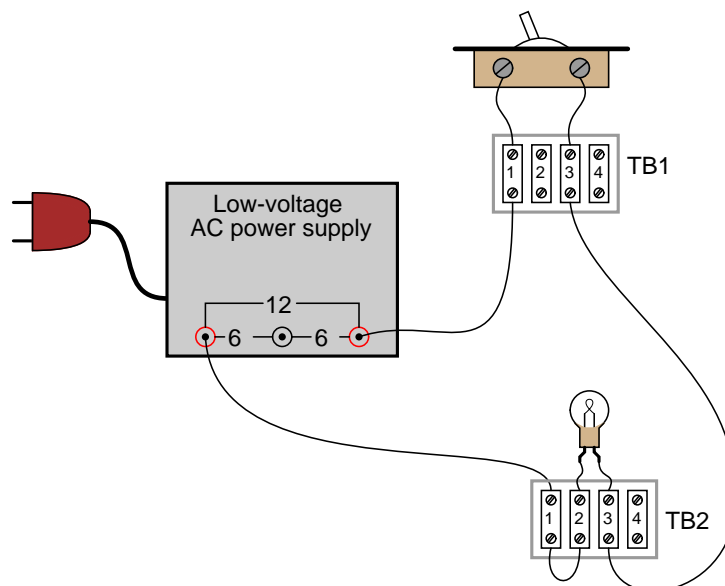
What we have here is an exercise in Aristotelian logic. In either scenario (points in a circuit, or animals), statement 2 is the *converse* of statement 1, while statement 3 is the *inverse* and statement 4 is the *contrapositive*. Only the contrapositive of a statement is guaranteed to share the same truth value as the original statement.

This is no esoteric exercise. Rather, it is a hard-learned fact: many students mistakenly think that because there is guaranteed to be no voltage between electrically common points in a circuit, then the absence of voltage between two points must mean those two points are electrically common to each other! This is not necessarily true, because situations exist where two points may not be electrically common, yet still have no voltage between them. Electrical commonality is just *one way* that two points can have zero voltage between them, not the only way!

The contrapositive of this rule, however, is a valuable troubleshooting tool: if there is substantial voltage measured between two points in a circuit, then we know without a doubt that those two points are *not* electrically common to each other!

Question 82

Suppose a technician were troubleshooting the following circuit, whose light bulb refused to light up:



The technician records their steps on a piece of paper divided into two columns: **Observations**, and **Conclusions**, drawing a horizontal line underneath each conclusion after it is made:

Observations (What I measured, sensed, or did)	Conclusions (What I <i>think</i>)
Turned switch ON -- no light.	Definitely a problem in this circuit!
Measured 12 volts AC between terminals TB1-1 and TB2-1	Power supply is functioning properly.
Measured no voltage across the light bulb (between TB2-2 and TB2-3)	Light bulb is good, but just not receiving any power
Measured no voltage across switch (between TB1-1 and TB1-3)	Switch is good
Measured 12 volts AC between terminals TB2-1 and TB2-3	Wire between TB1-3 and TB2-3 is good
Measured 12 volts AC between terminals TB1-3 and TB2-1	
Measured 12 volts AC between terminals TB2-1 and TB2-2	Bad connection between those two terminals. Possibly an open wire or dirty connection between wire and the terminal block.
Replaced wire between TB2-1 and TB2-2, and the light bulb now lights up!	<i>Problem solved.</i>

Critique this technician's troubleshooting job, noting any errors or unnecessary steps.
[file 00185](#)

The first step and conclusion, while seemingly unnecessary, are actually good to check. Just because someone tells you there is a problem with a circuit does not necessarily mean there is a problem with it. People can make mistakes, and it is usually a good idea to verify the nature of the problem with a system before troubleshooting.

The second conclusion ("Power supply is functioning properly") is understated. In actuality, the presence of voltage between these two points proves that not only is the power supply functioning properly, but both wires between the power supply and terminals TB1-1 and TB2-1 have good continuity, and the connections between the wires and their respective terminals are good as well. This eliminates several portions of the circuit as being problematic.

Checking for voltage across the light bulb terminals is a good step, but the lack of voltage does not prove the light bulb is not failed! All it means is that there is some other problem between the light bulb and the last two connections where voltage was measured (between TB1-1 and TB2-1). For all we know at this point, the light bulb could be failed *as well* as there being a failure somewhere else in the circuit.

Checking for voltage across the switch is another good step, but the lack of voltage there does not prove that the switch has good continuity, any more than a lack of voltage proved the light bulb's filament had good continuity either. There still could be multiple "opens" in this circuit.

The presence of voltage between TB2-1 and TB2-3 narrows the possibility of failure in the circuit quite a bit. Knowing that there is voltage between these two terminals proves there is good continuity from TB2-3 to TB1-3, through the switch, and all the way back to the power supply. From step 2 we already know there is good continuity from TB2-1 back to the power supply as well. This conclusively tells us that the problem(s) must lie between TB2-1 and TB2-3.

It is a wasted step to check for voltage between TB1-3 and TB2-1.

The measurement of voltage between TB2-1 and TB2-2 proves the location of the failure: an "open" between those two points. It also proves that there are no other "open" failures in the circuit.

The final step documenting replacement of the wire between TB2-1 and TB2-2, while not essential, is not really wasted, either. Troubleshooting journals such as this are helpful when searching for complex problems in large systems, where more than one person may have to work on finding the problem(s). If there is more than one failure in a system, it is helpful to document the repair for the benefit of anyone else working on solving the problem later!

Notes 82

Circuit troubleshooting is the highest level of thinking required of many electrical and electronics professionals: to identify faults efficiently based on a knowledge of fundamental principles and test equipment usage. Good troubleshooters are rare, and in my opinion that has more to do with the lack of effective technical education than it does a lack of natural ability.

It is not enough to merely tell students what they should do in troubleshooting, or to give them easy-to-follow steps. Students must be placed in scenarios where they are required to *think* their way through to a solution. Fortunately, electrical circuit troubleshooting is an activity that works well for small groups of students to engage in as well as individual students. A "virtual" troubleshooting exercise such as this one is a good way to start students thinking in the right ways to becoming effective troubleshooters.

Question 83

Troubleshooting a system of any kind requires scientific thinking: sound deductive reasoning from effect to cause, and cause to effect. One of the principles frequently applied in science is *Ockham's Razor*, named after Sir William of Ockham (1284-1350). In Ockham's own words, the principle is as follows:

"A plurality is not to be posited without necessity"

Applied to troubleshooting electric circuits, one could re-phrase Ockham's Razor as such:

"Look for single faults before considering multiple, simultaneous faults."

Justify the use of Ockham's Razor in troubleshooting circuits. Why should we first consider single faults to account for the problems the circuit is having rather than considering interesting combinations of faults which would account for the same problems?

[file 02893](#)

Answer 83

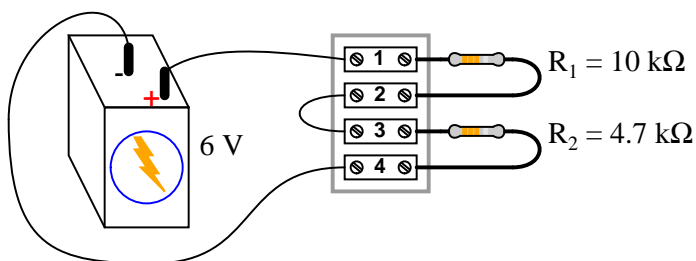
Because it is simply more likely that one thing has failed, than that multiple (unrelated) things have failed in just the right way to cause the problem to occur.

Notes 83

A mistake common to new students is to consider wild combinations of faults in a broken system before thoroughly considering all the simpler possibilities. This seems especially true when students answer troubleshooting questions on written exams. When actually working on real circuits, students seem more likely to first look for simple causes.

Question 84

A student is troubleshooting a two-resistor voltage divider circuit, using a table to keep track of his test measurements and conclusions. The table lists all components and wires in the circuit so that the student may document their known status with each successive measurement:



Measurement taken	Battery	Wire +/1	R_1	Wire 2/3	R_2	Wire 4/-

Prior to beginning troubleshooting, the student is told there is no voltage across R_2 . Thus, the very first entry into the table looks like this:

Measurement taken	Battery	Wire +/1	R_1	Wire 2/3	R_2	Wire 4/-
$V_{R2} = 0 \text{ V}$						

Based on this data, the student then determines possible faults which could cause this to happen, marking each possibility in the table using letters as symbols. The assumption here is that there is only one fault in the circuit, and that it is either a complete break (open) or a direct short:

Measurement taken	Battery	Wire +/1	R_1	Wire 2/3	R_2	Wire 4/-
$V_{R2} = 0 \text{ V}$	O	O	O	O	S	O

"O" symbolizes a possible "open" fault, while "S" symbolizes a possible "shorted" fault.

Next, the student measures between terminals 1 and 4, obtaining a full 6 volt reading. This is documented on the table as well, along with some updated conclusions regarding the status of all wires and components:

Measurement taken	Battery	Wire +/1	R_1	Wire 2/3	R_2	Wire 4/-
$V_{R2} = 0 \text{ V}$	O	O	O	O	S	O
$V_{1-4} = 6 \text{ V}$	OK	OK	O	O	S	OK

After this, the student measures between terminals 1 and 2 (across resistor R_1), and gets a reading of 0 volts. Complete the table based on this last piece of data:

Measurement taken	Battery	Wire +/1	R_1	Wire 2/3	R_2	Wire 4/-
$V_{R2} = 0 \text{ V}$	O	O	O	O	S	O
$V_{1-4} = 6 \text{ V}$	OK	OK	O	O	S	OK
$V_{R1} = 0 \text{ V}$						

file 03585

Answer 84

Measurement taken	Battery	Wire +/1	R_1	Wire 2/3	R_2	Wire 4/-
$V_{R2} = 0 \text{ V}$	O	O	O	O	S	O
$V_{1-4} = 6 \text{ V}$	OK	OK	O	O	S	OK
$V_{R1} = 0 \text{ V}$	OK	OK	OK	O	OK	OK

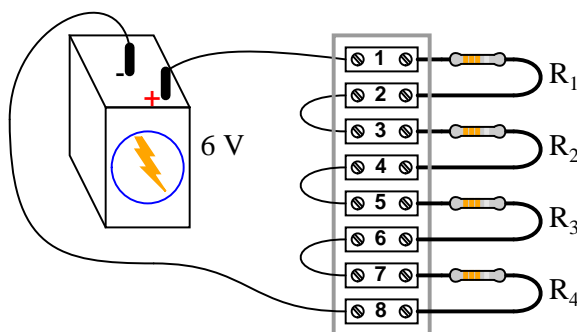
Conclusion: there is an open fault (break) between terminals 2 and 3. This is the only *single* fault which will account for all the data.

Notes 84

The main purpose of this question is to introduce students to this style of documentation and strategy for use in troubleshooting a circuit. For each successive reading, the student is required to re-assess the status of each component, figuring out what single failure could account for all data up to that point.

Question 85

This voltage divider circuit has a problem: there is no voltage output between terminals 7 and 8.



A technician has taken several measurements with a voltmeter, documenting them chronologically from top to bottom in the far-left column:

Measurement	Batt	(+)/1	R_1	2/3	R_2	4/5	R_3	6/7	R_4	8/(-)
$V_{1-8} = 6\text{ V}$										
$V_{1-5} = 0\text{ V}$										
$V_{5-7} = 6\text{ V}$										

Fill in all cells of this table with one of three different symbols, representing the status of each component or wire (numbers separated by a slash indicate the wire connecting those terminals):

- **O** for an "open" fault
- **S** for an "short" fault
- **OK** for no fault

You are to assume that there is only one fault in this circuit, and that it is either a complete break (open) or a direct short (zero resistance). After completing the table, assess whether or not the exact fault may be known from the data recorded thus far. If not, suggest the next logical voltage measurement to take.

[file 03586](#)

Answer 85

Measurement	Batt	(+)/1	R_1	2/3	R_2	4/5	R_3	6/7	R_4	8/(-)
$V_{1-8} = 6\text{ V}$	OK	OK	O	O	O	O	O	O	S	OK
$V_{1-5} = 0\text{ V}$	OK	OK	OK	OK	OK	OK	O	O	S	OK
$V_{5-7} = 6\text{ V}$	OK	OK	OK	OK	OK	OK	O	O	OK	OK

We do not yet have enough information to determine whether resistor R_3 or wire 6/7 is failed open. A good voltage measurement to take now would be across the resistor (terminals 5 and 6), or between terminals 6 and 7.

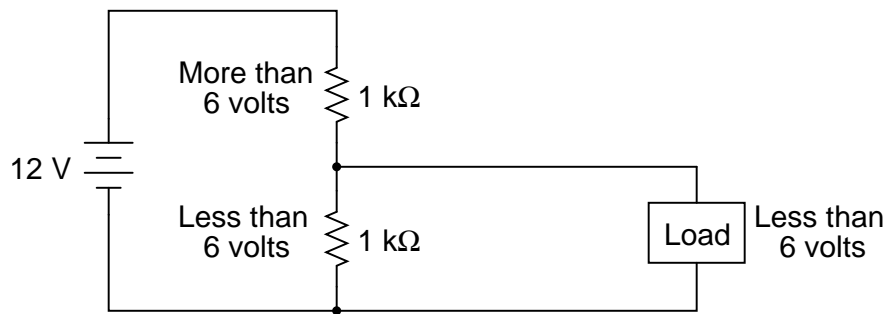
Follow-up question: describe how much voltage you would expect to find between either of these terminal pairs, given an open fault with either suspected component.

Notes 85

Ask your students to defend their answers for each component status, for each of the successive measurements. What you will find is that this forces students to rigorously analyze the possibilities of a fault in each portion of the circuit. Not only is this beneficial for reinforcing basic circuit principles, but it also teaches students to consider all possibilities when troubleshooting a circuit.

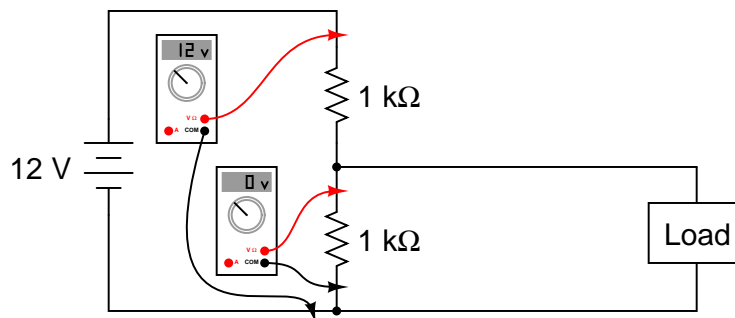
Question 86

This circuit is called a *voltage divider*, because it presents a fractional portion of the total voltage to the load:



(Of course, with no load connected, the voltage across the lower resistor would be precisely 6 volts. With the load connected, the parallel combination of load and $1\text{ k}\Omega$ resistor results in an effective resistance of less than $1\text{ k}\Omega$ on the lower half of the divider, resulting in a voltage of less than half the total supply voltage.)

Suppose that something goes wrong in this voltage divider circuit, and the load voltage suddenly falls to zero. A technician following the "divide-and-conquer" troubleshooting strategy begins by measuring voltage across the lower resistor (finding 0 volts), then measuring voltage across both resistors (finding 12 volts):



Based on these measurements, the technician concludes that the upper resistor must be failed open. Upon disassembling the divider circuit and checking resistance with an ohmmeter, though, both resistors are revealed to be in perfect operating condition.

What error did the technician make in concluding the upper resistor must have been failed open? Where do you think the problem is in this circuit?

[file 01579](#)

Answer 86

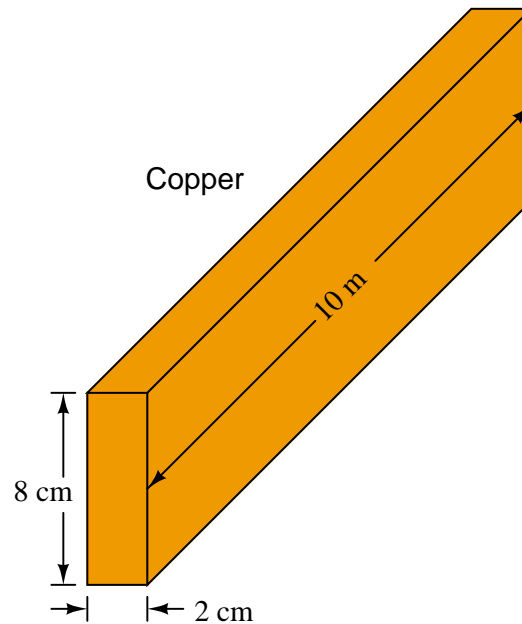
The technician wrongly assumed that an open (upper) resistor was the only possible fault that could have caused the observed voltage readings.

Notes 86

This is a common mistake students make when applying the "divide-and-conquer" method of troubleshooting: that whatever component(s) located between the point of good measurement and the point of bad measurement must be the source of the problem. While this simple reasoning may apply in finding "open" faults in long lengths of wire, it does not necessarily hold true for more complex circuits, as other faults may result in similar effects.

Question 87

The cross-sectional dimensions of a copper "busbar" measure 8 cm by 2.5 cm. How much resistance would this busbar have, measured end-to-end, if its length is 10 meters? Assume a temperature of 20° Celsius.



file 00486

Answer 87

83.9 $\mu\Omega$

Notes 87

This question is a good review of the metric system, relating centimeters to meters, and such. It may also be a good review of unit conversions, if students choose to do their resistance calculations using English units (cmils, or square inches) rather than metric.

Students may be surprised at the low resistance figure, but remind them that they are dealing with a solid bar of copper, over 3 square inches in cross-sectional area. *This is one big conductor!*

Question 88

Calculate the end-to-end resistance of a 20 meter length of copper wire with a diameter of 0.05 cm. Use $1.678 \times 10^{-6} \Omega \cdot \text{cm}$ for the specific resistance of copper.

file 01483

Answer 88

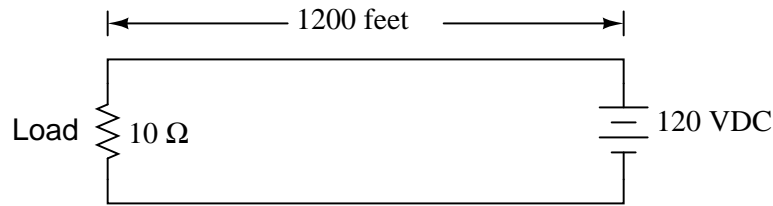
1.709 Ω

Notes 88

Nothing to comment on here – just a straight-forward calculation of resistance. Students need to be careful of the *centimeter* dimension, though!

Question 89

What size (gauge) of copper wire is needed in this circuit to ensure the load receives at least 110 volts?



file 00166

Answer 89

#6 gauge copper wire comes close, but is not quite large enough. #5 gauge or larger will suffice.

Notes 89

Several steps are necessary to solve this problem: Ohm's Law, algebraic manipulation of the specific resistance equation, and research into wire sizes. Be sure to spend adequate time discussing this problem with your students!

The concept of a generic "load" is any component or device that dissipates electrical power in a circuit. Often, generic loads are symbolized by a resistor symbol (a zig-zag line), even though they might not really be a resistor.

Question 90

How does the *conductance* (G) of a conductor relate to its length? In other words, the longer the conductor, the (fill-in-the-blank) its conductance is, all other factors being equal.
file 00487

Answer 90

Conductance decreases as length increases, all other factors being equal.

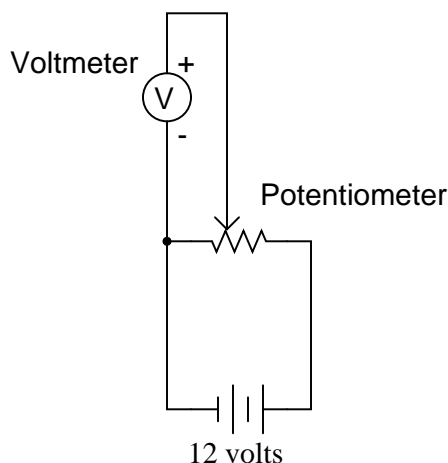
Follow-up question: how does "conductance" (G) mathematically relate to resistance (R), and what is the unit of measurement for conductance?

Notes 90

There are two units of measurement for conductance: the old unit (which makes perfect sense, even though your students may laugh at it, at first), and the new unit (named after a famous electrical researcher). Make sure your students are familiar with both.

Question 91

What would you expect the voltmeter in the following circuit to do when the potentiometer wiper is moved to the right?



What would you expect the voltmeter to register if the wiper were set precisely at the 50% (half-way) position?

[file 00339](#)

Answer 91

As the wiper is moved to the right, we should expect to see the voltmeter register an increasing voltage, ranging between 0 and 12 volts DC.

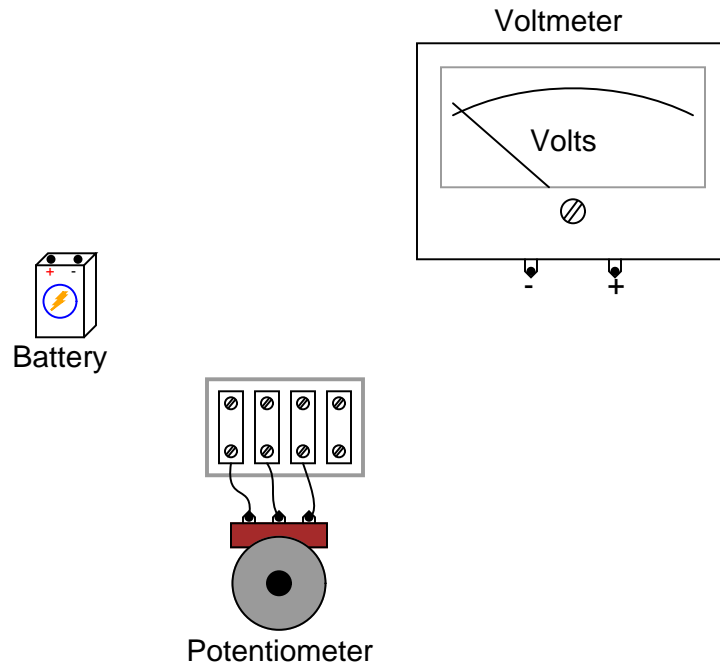
Follow-up question: a useful problem-solving method is to imagine multiple "test case" scenarios, sometimes referred to as *thought experiments*, for the purpose of identifying a trend. For instance, in this circuit you might imagine what the voltmeter would register with the wiper moved all the way to the left, and then with the wiper moved all the way to the right. Identify the voltmeter's readings in these two scenarios, and then explain why the analysis of "test cases" like these are useful in problem-solving.

Notes 91

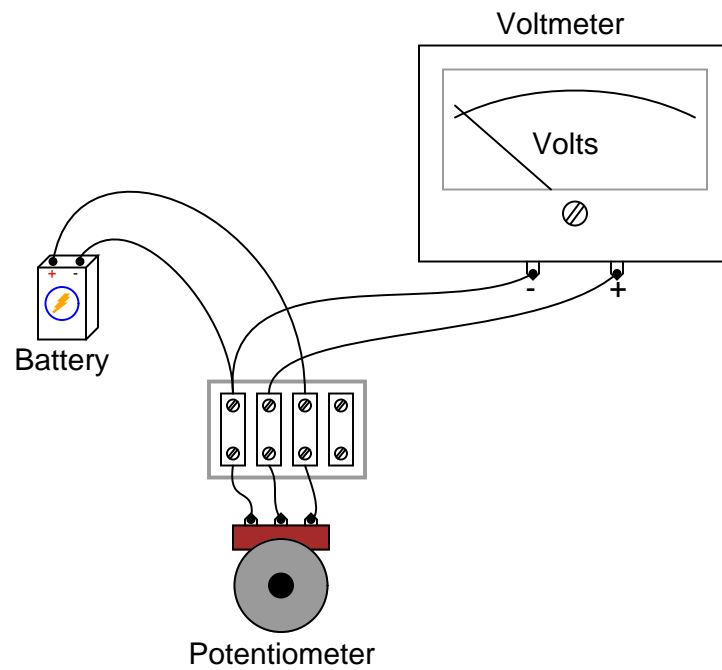
Ask your students to describe possible applications for a circuit like this. Where might we wish to utilize a potentiometer in such a way that it outputs a variable voltage, from a constant voltage source?

Question 92

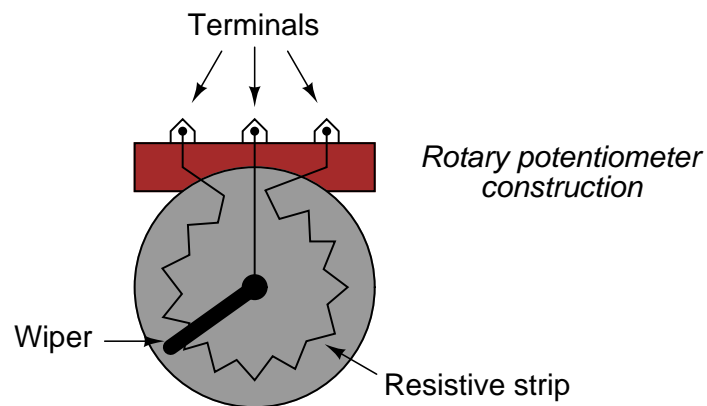
Connect the necessary wires in this illustration to make the potentiometer act as a variable voltage divider, providing a variable voltage to the voltmeter:



file 00322



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

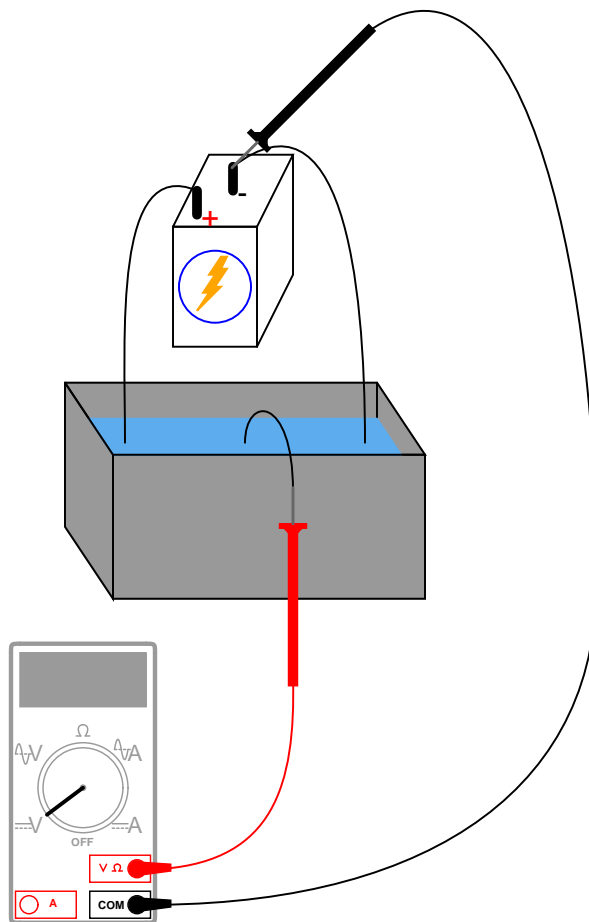


Notes 92

A good follow-up question to this would be to ask your students which way the potentiometer knob needs to be turned in order to *increase* the voltage applied to the meter.

Question 93

With a trough of water and three pieces of wire, you could make a *liquid potentiometer*:



Which way would you have to move the middle wire (the one touching the voltmeter's red test lead) in order to increase the voltmeter's reading?

file 03300

Answer 93

Move the wire to the left in order to make the voltmeter register a greater voltage.

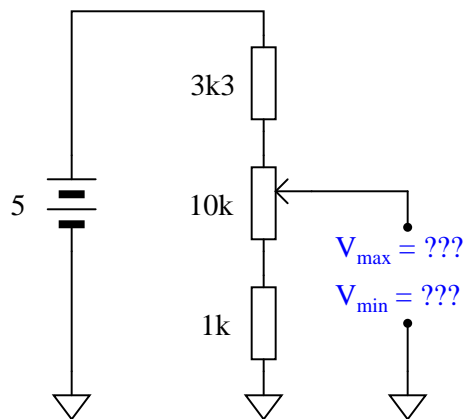
Follow-up question: identify any advantages and disadvantages of such a "liquid pot" over standard potentiometers using solid pieces. Are there any potential safety hazards that occur to you as you look at the illustration of this liquid potentiometer?

Notes 93

Believe it or not, I have actually seen an application in industry where a "liquid rheostat" (not a potentiometer, but close) was used rather than a device made from solid parts. Very interesting. Very dangerous as well, since it was being used as part of a large motor speed control circuit, handling many amps of current at potentially deadly voltages! I do not know what maniac thought of building this contraption, but it was built and had been working for a number of years.

Question 94

Calculate both the maximum and the minimum amount of voltage obtainable from this potentiometer circuit (as measured between the wiper and ground):



file 03248

Answer 94

$$V_{\max} = 3.85 \text{ volts}$$

$$V_{\min} = 0.35 \text{ volts}$$

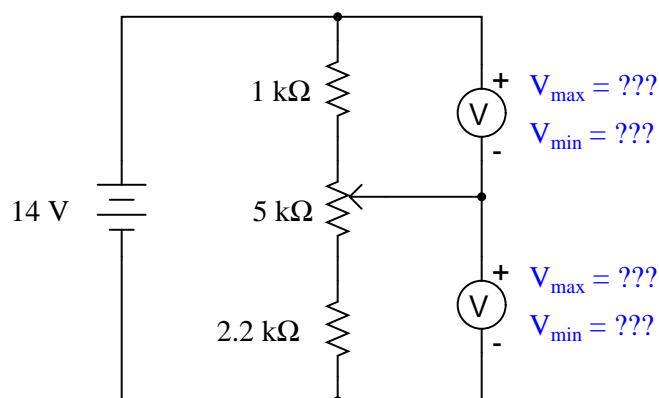
Notes 94

Be sure to ask your students how they obtained their answers, not just what the answers are. There is more than one correct way to analyze this circuit!

Incidentally, there is nothing significant about the use of European schematic symbols in this question. I did this simply to provide students with more exposure to this schematic convention.

Question 95

Calculate both the maximum and the minimum amount of voltage that each of the voltmeters will register, at each of the potentiometer's extreme positions:



file 03249

Answer 95

For upper voltmeter:

$$V_{\max} = 10.24 \text{ volts} \quad V_{\min} = 1.71 \text{ volts}$$

For lower voltmeter:

$$V_{\max} = 12.29 \text{ volts} \quad V_{\min} = 3.76 \text{ volts}$$

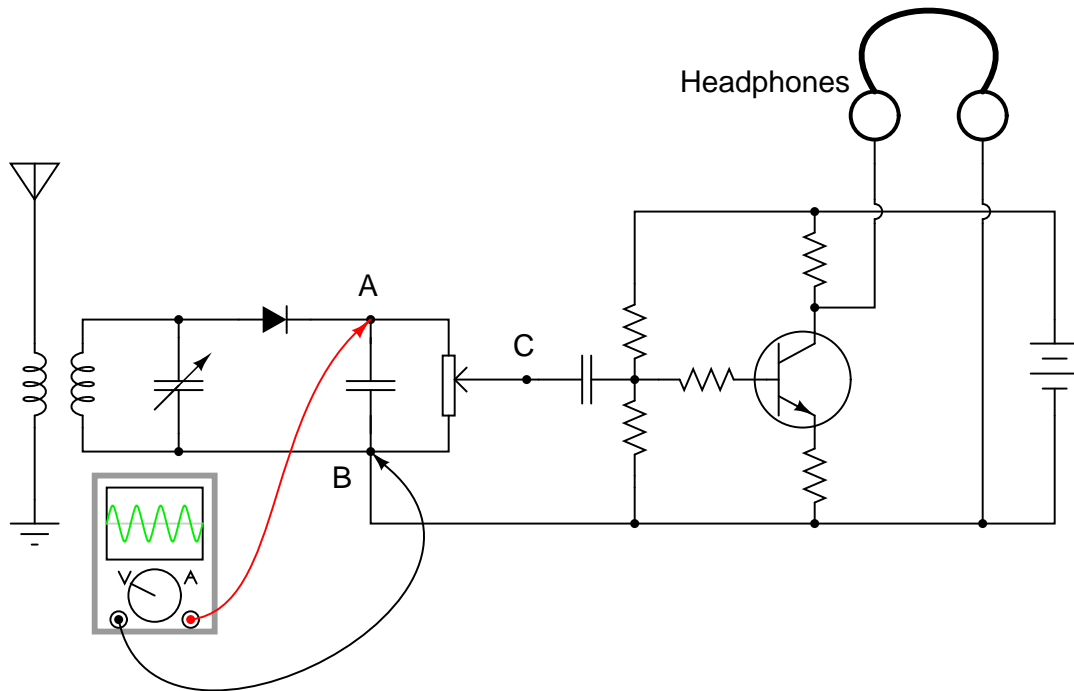
Follow-up question: identify the positions in which the potentiometer wiper must be set in order to obtain all four of the voltage readings shown above.

Notes 95

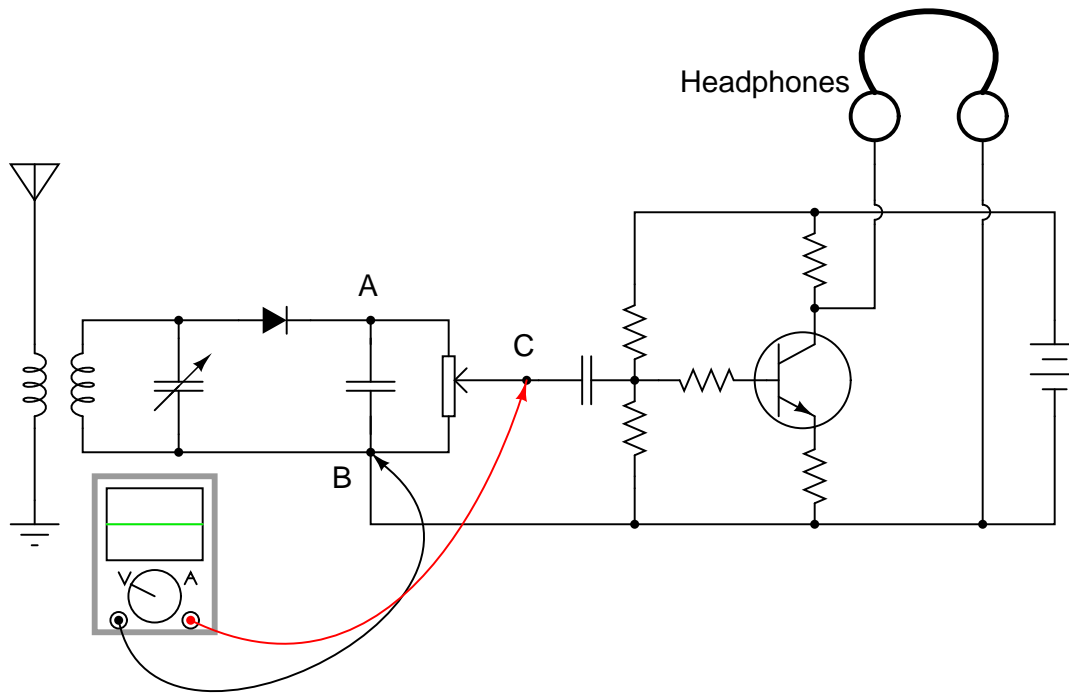
Be sure to ask your students how they obtained their answers, not just what the answers are. There is more than one correct way to analyze this circuit!

A radio technician is troubleshooting a problem in a simple AM receiver, using a voltage-measuring device called an *oscilloscope*. An oscilloscope is nothing more than a graphical voltmeter, indicating the "wave shape" of voltages that change rapidly over time. The problem with this radio is that no sound at all is heard in the headphones.

When checking for a voltage signal between points A and B in the circuit, a strong signal is obtained:



However, when checking between points C and B in the circuit, no signal is measured:



What do these voltage measurements indicate about the nature of the problem in the receiver circuit?
 Is there a general troubleshooting rule that may be drawn from this example? If so, what is it?
 If possible, identify the precise nature of the failure.
[file 00341](#)

Answer 96

The fact that there is good signal before the potentiometer, and no signal afterward, indicates that the problem is somewhere between those two sets of signal measurement points (i.e. the potentiometer itself).

Notes 96

Do not worry if your students have not studied inductors, capacitors, diodes, transistors, amplifiers, or radio theory yet. This problem focuses on the potentiometer's function, and that is all your students have to understand in order to determine an answer.

It is very important for electronics technicians to be able to isolate portions of circuits they do understand from portions they do not, and perform as much diagnostic work as they can based on what they know. For this reason, I believe it is a good practice to show beginning students problems such as this, where they are challenged to see beyond the complexity of the circuit, to focus only on those portions that matter. On the job, I was frequently challenged with troubleshooting large, complex systems that I had no hope of understanding the entirety of, but which I knew enough about to isolate the problem to sections I could repair proficiently.

Ask your students to identify where, exactly, they think the potentiometer could have failed in order to cause this particular problem. Not just any fault within the potentiometer will result in the same loss of signal!

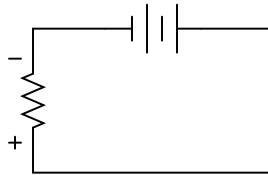
Question 97

Determine the polarity of voltage across the resistor in this simple circuit, and be prepared to explain *how* you did so:



[file 01546](#)

Answer 97

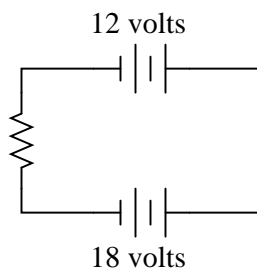


Notes 97

The answer to this question is fairly trivial, but the real point of it is to get students thinking about how and why it is the way it is. One thing I've noticed as an instructor of electronics is that most students tend to follow the rule of proximity: the resistor's voltage drop polarity is determined by proximity to poles of the battery. The resistor terminal closest to the battery's negative terminal must be negative as well, or so the thinking goes. While this is sound reasoning in a simple circuit such as this, it can lead to confusion in circuits where there is more than one power source at work!

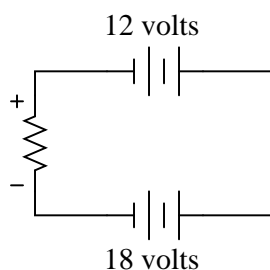
Question 98

Determine the polarity of voltage across the resistor in this simple circuit, and be prepared to explain *how* you did so:



file 01547

Answer 98



Follow-up question: are the battery voltage values important to the answer? Explain why or why not.

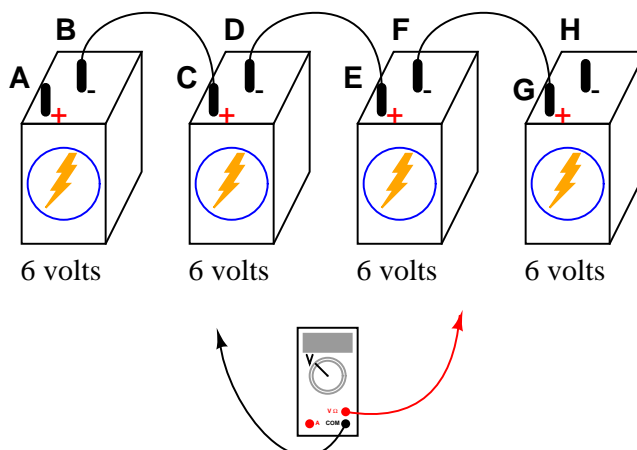
Notes 98

The answer to this question is fairly simple, but the real point of it is to get students thinking about how and why it is the way it is. One thing I've noticed as an instructor of electronics is that most students tend to follow the rule of proximity: the resistor's voltage drop polarity is determined by proximity to poles of the battery. The resistor terminal closest to the battery's negative terminal must be negative as well, or so the thinking goes.

In this particular circuit, though, the rule of proximity does not hold very well, and a different rule is necessary.

Question 99

Determine what a digital voltmeter (DVM) would indicate if connected between the following points in this circuit:

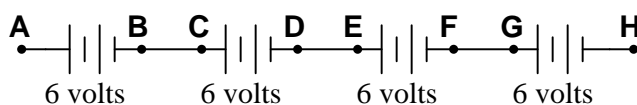


- Red lead on A, black lead on H
- Red lead on C, black lead on G
- Red lead on F, black lead on B
- Red lead on F, black lead on A

[file 00344](#)

Answer 99

Here is a schematic diagram to help you:



- Red lead on A, black lead on H = +24 volts
- Red lead on C, black lead on G = +12 volts
- Red lead on F, black lead on B = -12 volts
- Red lead on F, black lead on A = -18 volts

Notes 99

Kirchhoff's Voltage Law (KVL) is very easily explored in real life with a set of batteries and "jumper wire" connections. Encourage your students to build battery circuits like the one shown in this question, to be able to see the results for themselves!

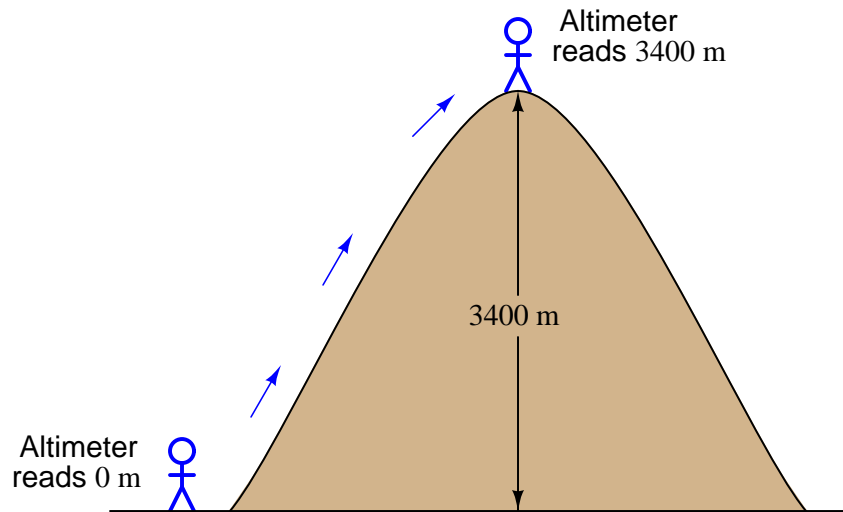
One really nice feature of digital multimeters (DMMs) is the ability to register negative as well as positive quantities. This feature is very useful when teaching Kirchhoff's Laws, with the *algebraic* (sign-dependent) summation of voltages and currents.

Question 100

A *barometric altimeter* is a device used to measure altitude (height) by means of atmospheric pressure. The higher you go up from sea level, the less air pressure you encounter. This decrease in air pressure is closely correlated with height, and thus can be used to infer altitude.

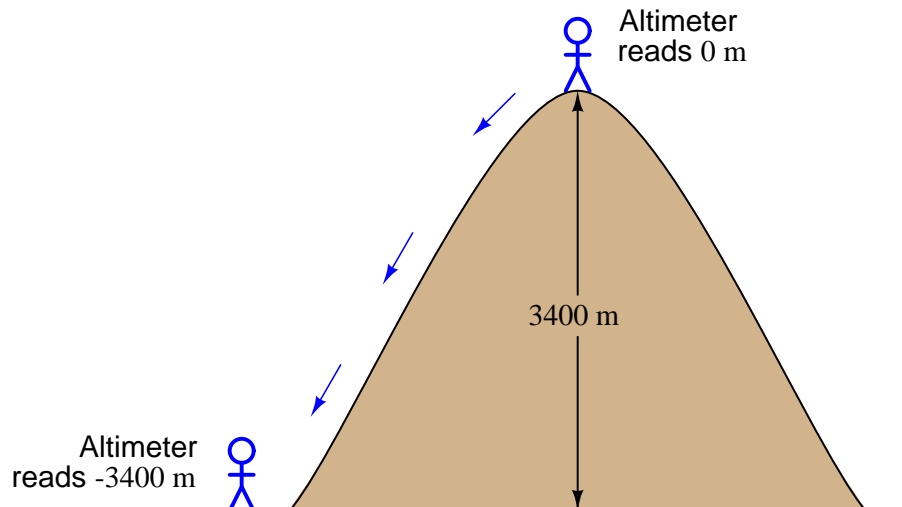
This type of altimeter usually comes equipped with a "zero" adjustment, so that the instrument's indication may be offset to compensate for changes in air pressure resulting from different weather conditions. This same "zero" adjustment may also be used to establish the altimeter's zero indication at any arbitrary height.

For example, if a mountain climber sets her barometric altimeter to zero meters at the base of a mountain, then climbs to the summit of that mountain (3400 meters higher than the base), the altimeter should register 3400 meters at the summit:

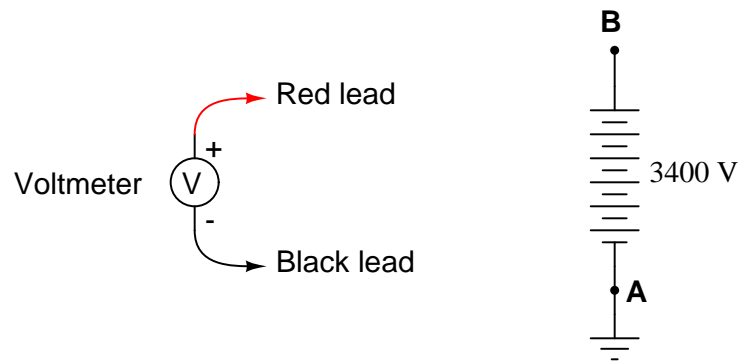


While at the summit, the climber may re-set the altimeter's "zero" adjustment to register 0 meters once again. If the climber then descends to the base of the mountain, the altimeter will register -3400 meters:

*Altimeter re-set to zero
while at the summit*



Explain how this scenario of mountain climbing and altimeter calibration relates to the measurement of voltage between points **A** and **B** in the following circuit:



file 01960

Answer 100

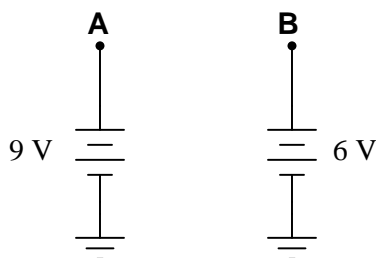
The voltmeter's black lead is analogous to the "zero reference" level in the mountain-climbing altimeter scenario: the point at which the altimeter is calibrated to register 0 meters height.

Notes 100

Physical height (and depth) is a very useful analogy for electrical potential, helping students relate this abstract thing called "voltage" to more common differential measurements.

Question 101

Determine the amount of voltage measured at points **A** and **B** with reference to ground, and also determine voltage V_{AB} (defined here as the voltage indicated by a voltmeter with the red test lead touching point **A** and the black test lead touching point **B**):



[file 01958](#)

Answer 101

$$V_A = +9 \text{ volts}$$

$$V_B = +6 \text{ volts}$$

$$V_{AB} = +3 \text{ volts}$$

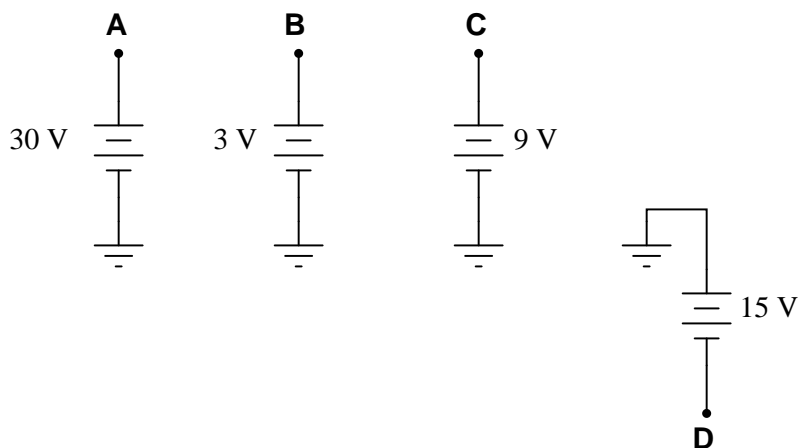
Follow-up question: explain why the mathematical signs ("+") are important in these answers.

Notes 101

Determining differential voltages is a skill that many students find frustrating to attain. There is more than one way to explain how to arrive at +3 volts as the answer for V_{AB} , and it is good for students to see more than one way presented.

Question 102

Determine the voltages registered by a voltmeter between the following points in this circuit:



$V_A = \underline{\hspace{1cm}}$ (red lead on **A**, black lead on ground)

$V_B = \underline{\hspace{1cm}}$ (red lead on **B**, black lead on ground)

$V_C = \underline{\hspace{1cm}}$ (red lead on **C**, black lead on ground)

$V_D = \underline{\hspace{1cm}}$ (red lead on **D**, black lead on ground)

$V_{AC} = \underline{\hspace{1cm}}$ (red lead on **A**, black lead on **C**)

$V_{DB} = \underline{\hspace{1cm}}$ (red lead on **D**, black lead on **B**)

$V_{BA} = \underline{\hspace{1cm}}$ (red lead on **B**, black lead on **A**)

$V_{BC} = \underline{\hspace{1cm}}$ (red lead on **B**, black lead on **C**)

$V_{CD} = \underline{\hspace{1cm}}$ (red lead on **C**, black lead on **D**)

[file 02750](#)

Answer 102

$V_A = \underline{+30 \text{ volts}}$ (red lead on **A**, black lead on ground)

$V_B = \underline{+3 \text{ volts}}$ (red lead on **B**, black lead on ground)

$V_C = \underline{+9 \text{ volts}}$ (red lead on **C**, black lead on ground)

$V_D = \underline{-15 \text{ volts}}$ (red lead on **D**, black lead on ground)

$V_{AC} = \underline{+21 \text{ volts}}$ (red lead on **A**, black lead on **C**)

$V_{DB} = \underline{-18 \text{ volts}}$ (red lead on **D**, black lead on **B**)

$V_{BA} = \underline{-27 \text{ volts}}$ (red lead on **B**, black lead on **A**)

$V_{BC} = \underline{-6 \text{ volts}}$ (red lead on **B**, black lead on **C**)

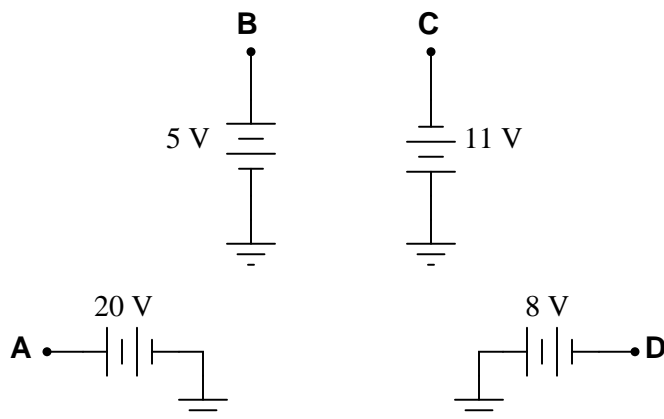
$V_{CD} = \underline{+24 \text{ volts}}$ (red lead on **C**, black lead on **D**)

Notes 102

Discuss with your students multiple techniques of solving for these voltages, asking them first for their solution strategies.

Question 103

Determine the voltages registered by a voltmeter between the following points in this circuit:



$V_A = \underline{\hspace{1cm}}$ (red lead on **A**, black lead on ground)

$V_B = \underline{\hspace{1cm}}$ (red lead on **B**, black lead on ground)

$V_C = \underline{\hspace{1cm}}$ (red lead on **C**, black lead on ground)

$V_D = \underline{\hspace{1cm}}$ (red lead on **D**, black lead on ground)

$V_{AC} = \underline{\hspace{1cm}}$ (red lead on **A**, black lead on **C**)

$V_{DB} = \underline{\hspace{1cm}}$ (red lead on **D**, black lead on **B**)

$V_{BA} = \underline{\hspace{1cm}}$ (red lead on **B**, black lead on **A**)

$V_{BC} = \underline{\hspace{1cm}}$ (red lead on **B**, black lead on **C**)

$V_{CD} = \underline{\hspace{1cm}}$ (red lead on **C**, black lead on **D**)

[file 02751](#)

Answer 103

$V_A = \underline{+20 \text{ volts}}$ (red lead on **A**, black lead on ground)

$V_B = \underline{+5 \text{ volts}}$ (red lead on **B**, black lead on ground)

$V_C = \underline{-11 \text{ volts}}$ (red lead on **C**, black lead on ground)

$V_D = \underline{-8 \text{ volts}}$ (red lead on **D**, black lead on ground)

$V_{AC} = \underline{+31 \text{ volts}}$ (red lead on **A**, black lead on **C**)

$V_{DB} = \underline{-13 \text{ volts}}$ (red lead on **D**, black lead on **B**)

$V_{BA} = \underline{-15 \text{ volts}}$ (red lead on **B**, black lead on **A**)

$V_{BC} = \underline{+16 \text{ volts}}$ (red lead on **B**, black lead on **C**)

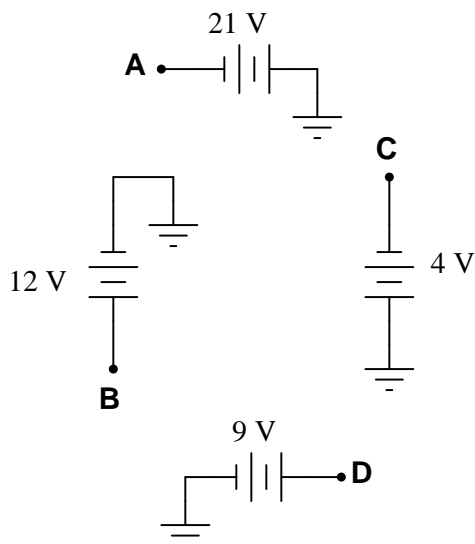
$V_{CD} = \underline{-3 \text{ volts}}$ (red lead on **C**, black lead on **D**)

Notes 103

Discuss with your students multiple techniques of solving for these voltages, asking them first for their solution strategies.

Question 104

Determine the voltages registered by a voltmeter between the following points in this circuit:



$V_A = \underline{\hspace{1cm}}$ (red lead on **A**, black lead on ground)

$V_B = \underline{\hspace{1cm}}$ (red lead on **B**, black lead on ground)

$V_C = \underline{\hspace{1cm}}$ (red lead on **C**, black lead on ground)

$V_D = \underline{\hspace{1cm}}$ (red lead on **D**, black lead on ground)

$V_{AC} = \underline{\hspace{1cm}}$ (red lead on **A**, black lead on **C**)

$V_{DB} = \underline{\hspace{1cm}}$ (red lead on **D**, black lead on **B**)

$V_{BA} = \underline{\hspace{1cm}}$ (red lead on **B**, black lead on **A**)

$V_{BC} = \underline{\hspace{1cm}}$ (red lead on **B**, black lead on **C**)

$V_{CD} = \underline{\hspace{1cm}}$ (red lead on **C**, black lead on **D**)

file 02752

Answer 104

$V_A = \underline{-21 \text{ volts}}$ (red lead on **A**, black lead on ground)

$V_B = \underline{+12 \text{ volts}}$ (red lead on **B**, black lead on ground)

$V_C = \underline{-4 \text{ volts}}$ (red lead on **C**, black lead on ground)

$V_D = \underline{+9 \text{ volts}}$ (red lead on **D**, black lead on ground)

$V_{AC} = \underline{-17 \text{ volts}}$ (red lead on **A**, black lead on **C**)

$V_{DB} = \underline{-3 \text{ volts}}$ (red lead on **D**, black lead on **B**)

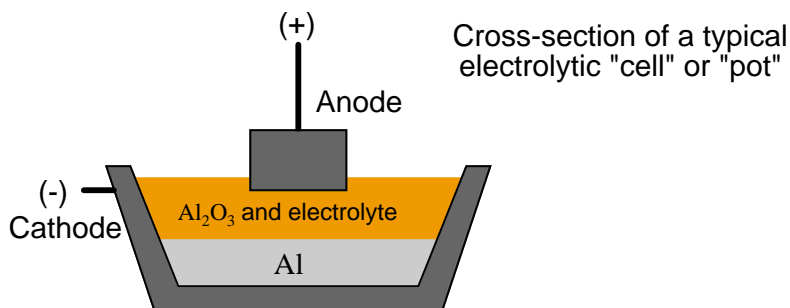
$V_{BA} = \underline{+33 \text{ volts}}$ (red lead on **B**, black lead on **A**)

$V_{BC} = \underline{+16 \text{ volts}}$ (red lead on **B**, black lead on **C**)

$V_{CD} = \underline{-13 \text{ volts}}$ (red lead on **C**, black lead on **D**)

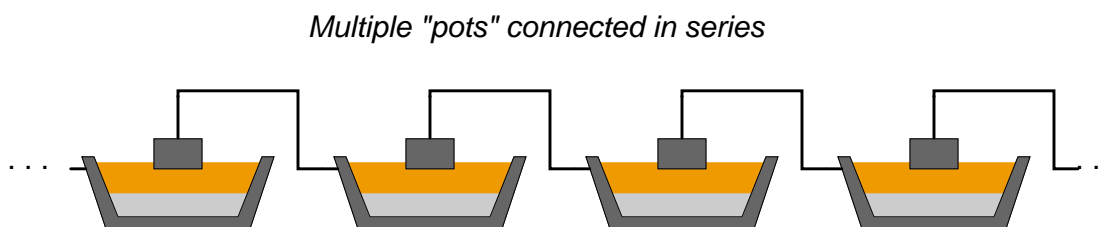
Discuss with your students multiple techniques of solving for these voltages, asking them first for their solution strategies.

Many manufacturing processes are *electrochemical* in nature, meaning that electricity is used to promote or force chemical reactions to occur. One such industry is aluminum smelting, where large amounts of DC current (typically several *hundred thousand* amperes!) is used to turn alumina (Al_2O_3) into pure metallic aluminum (Al):

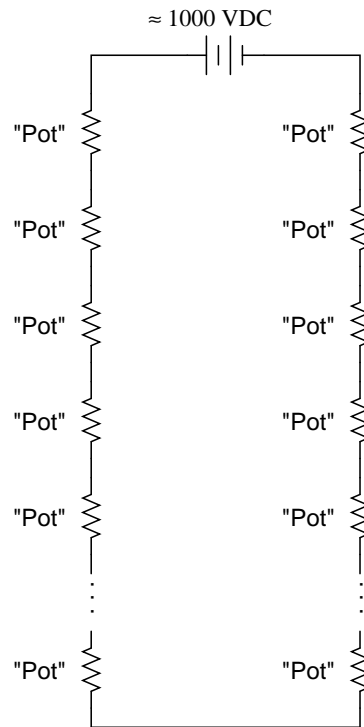


The alumina/electrolyte mixture is a molten bath of chemicals, lighter than pure aluminum itself. Molecules of pure aluminum precipitate out of this mix and settle at the bottom of the "pot" where the molten metal is periodically pumped out for further refining and processing. Fresh alumina powder is periodically dropped into the top of the pot to replenish what is converted into aluminum metal.

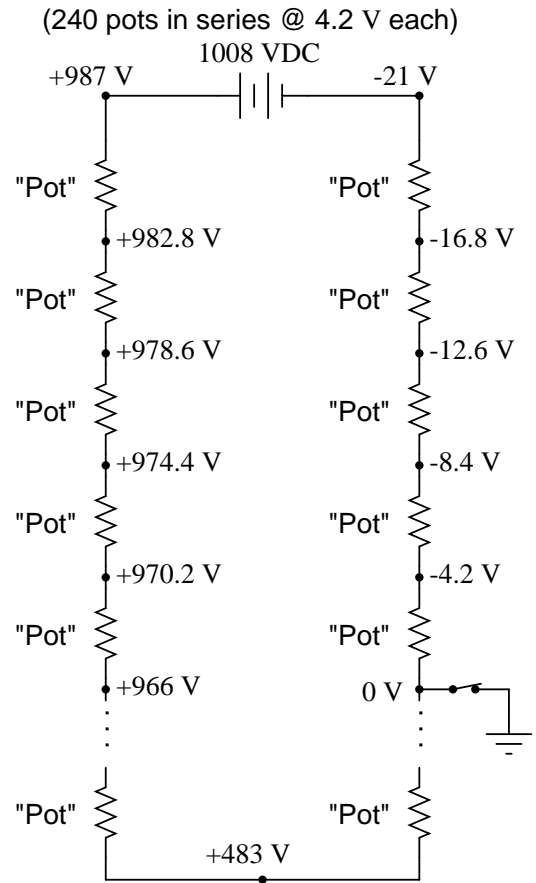
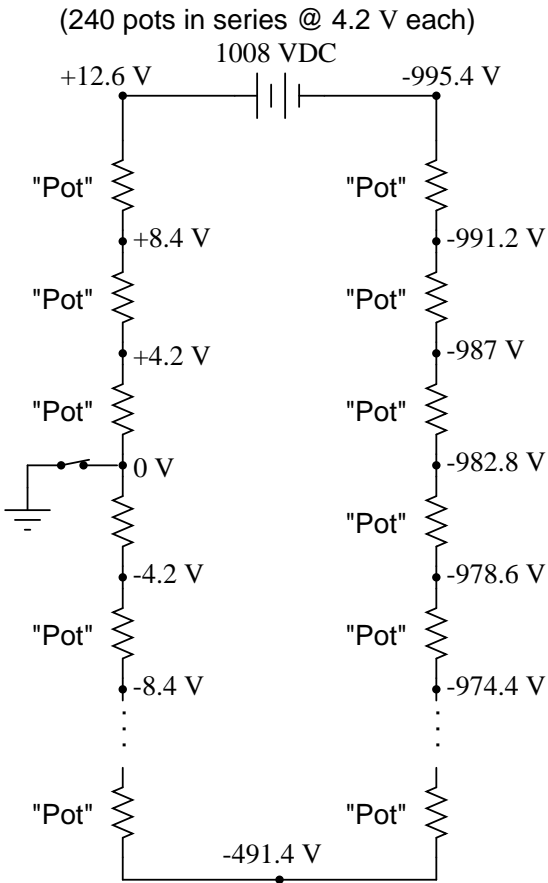
Although the amount of current necessary to smelt aluminum in this manner is huge, the voltage drop across each pot is only about 4 volts. In order to keep the voltage and current levels reasonable in a large smelting facility, many of these pots are connected in series, where they act somewhat like resistors (being energy *loads* rather than energy *sources*):



A typical "pot-line" might have 240 pots connected in series. With a voltage drop of just over 4 volts apiece, the total voltage powering this huge series circuit averages around 1000 volts DC:



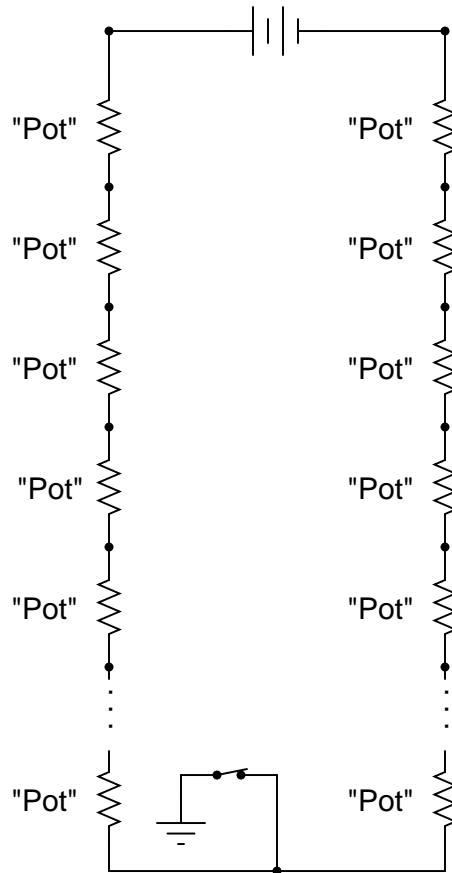
With this level of voltage in use, electrical safety is a serious consideration! To ensure the safety of personnel if they must perform work around a pot, the system is equipped with a "movable ground," consisting of a large switch on wheels that may be connected to the steel frame of the shelter (with concrete pilings penetrating deep into the soil) and to the desired pot. Assuming a voltage drop of exactly 4.2 volts across each pot, note what effect the ground's position has on the voltages around the circuit measured with respect to ground:



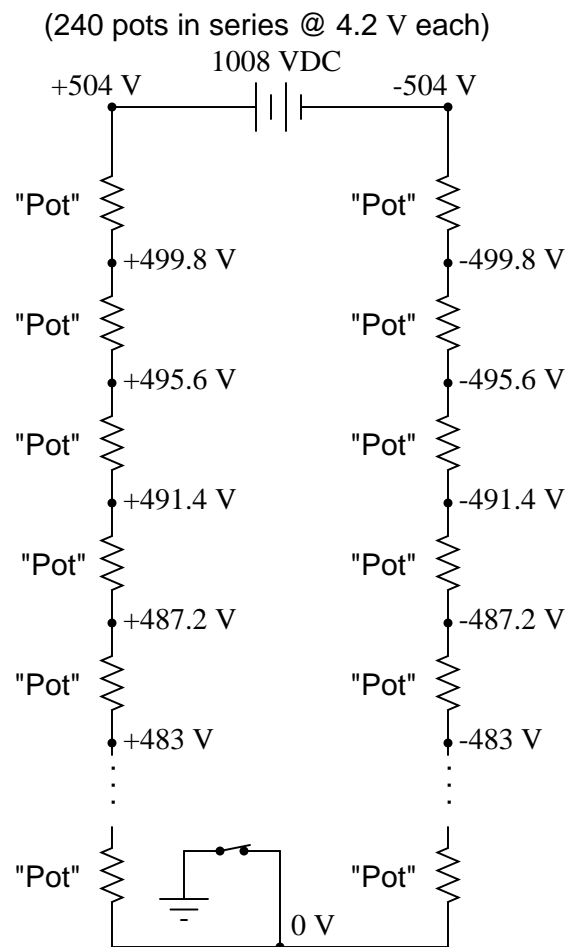
Determine the voltages (with respect to earth ground) for each of the points (dots) in the following schematic diagram, for the ground location shown:

(240 pots in series @ 4.2 V each)

1008 VDC



file 01726



Follow-up question: assuming each of the pots acts exactly like a large resistor (which is not entirely true, incidentally), what is the resistance of each pot if the total "potline" current is 150 kA at 4.2 volts drop per pot?

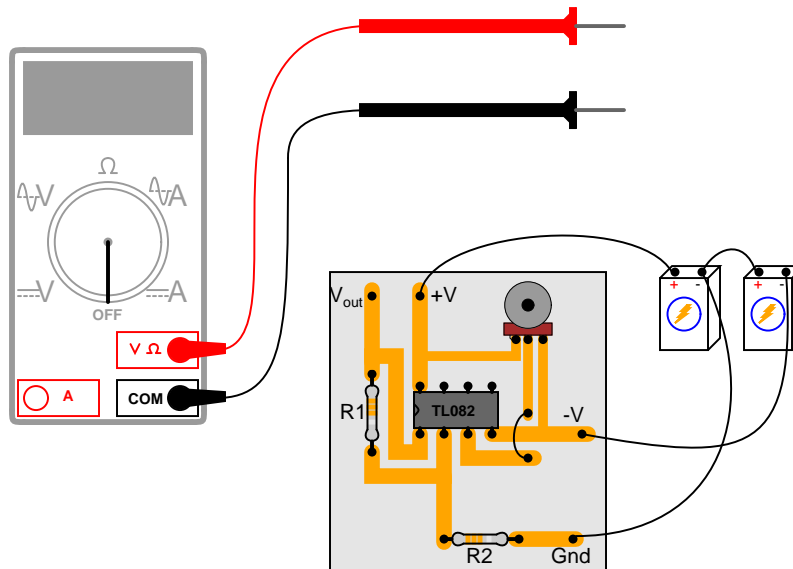
I (Tony Kuphaldt) worked for over six years at an aluminum smelter in northwest Washington state (United States of America), where part of my job as an electronics technician was to maintain the measurement and control instrumentation for three such "potlines." Very interesting work. The magnetic field emanating from the busbars conducting the 150 kA of current was strong enough to hold a screwdriver vertical, if you let it stand on the palm of your hand, assuming your hand was just a few feet away from the horizontal bus and even with its centerline!

Discuss with your students how voltage measured with respect to ground is an important factor in determining personnel safety. Being that your feet constitute an electrical contact point with the earth (albeit a fairly high-resistance contact), it becomes possible to be shocked by touching only one point in a grounded circuit.

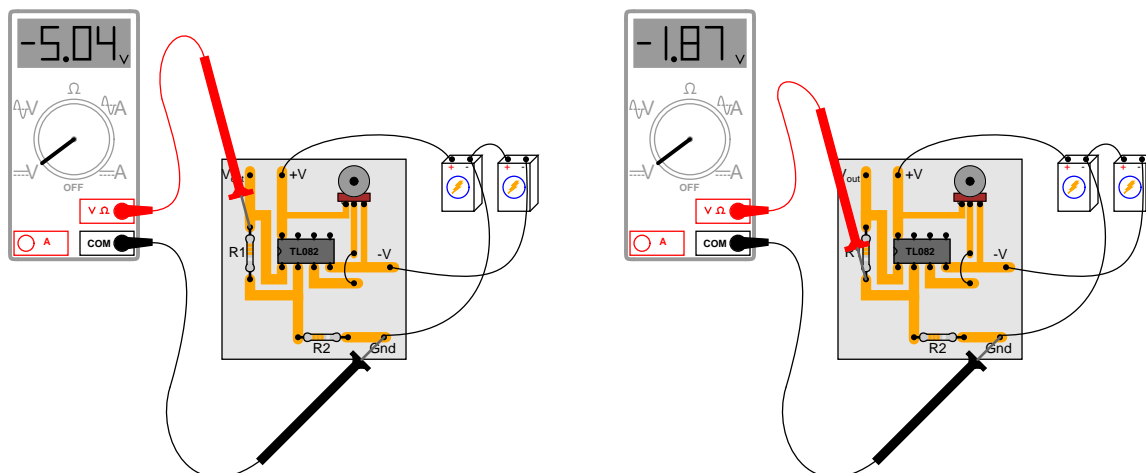
In your discussion, it is quite possible that someone will ask, "Why not eliminate the ground entirely, and leave the whole potline floating? Then there would be no shock hazard from a single-point contact, would there?" The answer to this (very good) question is that accidental groundings are impossible to prevent, and so by *not* having a firm (galvanic) ground connection in the circuit, no point in that circuit will have a *predictable* voltage with respect to earth ground. This lack of predictability is a worse situation than having *known* dangerous voltages at certain points in a grounded system.

Question 106

Suppose a technician is checking the operation of the following electronic circuit:



She decides to measure the voltage on either side of resistor R1 with reference to ground, and obtains these readings:



On the top side of R1, the voltage with reference to ground is -5.04 volts. On the bottom side of R1, the voltage with reference to ground is -1.87 volts. The color code of resistor R1 is Yellow, Violet, Orange, Gold. From this information, determine the following:

- Voltage across R1 (between top to bottom):
- Polarity (+ and -) of voltage across R1:
- Current (magnitude) through R1:
- Direction of current through R1:

Additionally, explain how this technician would make each one of these determinations. What rules or laws of electric circuits would she apply?

file 02733

- Voltage across R1 (between top to bottom): **3.17 volts**
- Polarity (+ and -) of voltage across R1: **(-) on top, (+) on bottom**
- Current (magnitude) through R1: **67.45 μA**
- Direction of current through R1: **upward, following conventional flow**

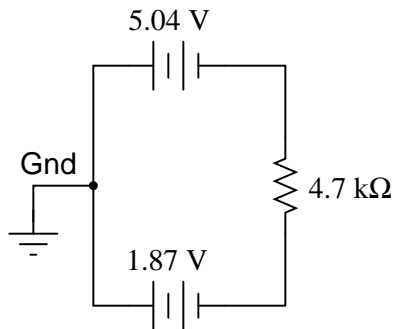
Follow-up question: calculate the range of possible currents, given the specified tolerance of resistor R1 (67.45 μA assumes 0% error).

Challenge question: if you recognize the type of circuit this is (by the part number of the IC "chip": TL082), identify the voltage between pin 3 and ground.

Notes 106

This is a good example of how Kirchhoff's Voltage Law is more than just an abstract tool for mathematical analysis – it is also a powerful technique for practical circuit diagnosis. Students must apply KVL to determine the voltage drop across R1, and then use Ohm's Law to calculate its current.

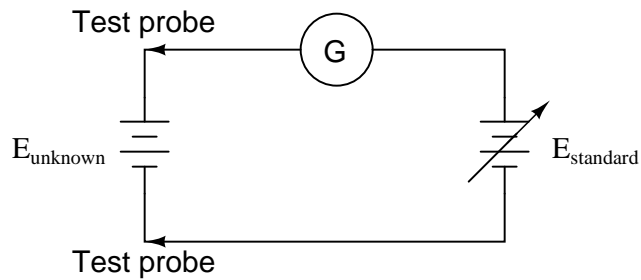
If students experience difficulty visualizing how KVL plays a part in the solution of this problem, show them this illustration:



By the way, the answer to the challenge question may only be realized if students recognize this circuit as a noninverting opamp voltage amplifier. The voltage at pin 3 (noninverting input) will be the same as the voltage at pin 2 (inverting input): -1.87 volts.

Question 107

A very old but highly accurate technique for measuring voltage is to use a sensitive meter (a *galvanometer*) as a "balance" indicator between two voltage sources: the unknown source and a calibrated, adjustable source called the *standard*:



The technique is to adjust the standard voltage source until the galvanometer registers exactly zero. When this condition is met, the system is said to be "balanced," indicating that the two voltage sources are equal in magnitude to each other. This voltage magnitude is then read from the calibrated adjustment dial on the standard source.

Explain how this voltage measurement technique exploits Kirchhoff's Voltage Law, which states that the algebraic sum of all voltages in a loop must equal zero:

$$E_{\Sigma(loop)} = 0$$

[file 01730](#)

Answer 107

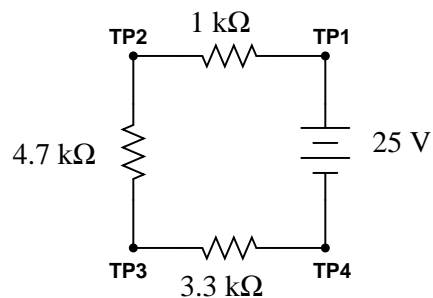
I'll leave the answer for you to demonstrate!

Notes 107

Potentiometric voltage measurement is not only practical, but for quite a while in the early field of electrical measurements it was the *only* way to accurately measure voltage from "weak" (high-impedance) sources. It is still used today in electrical metrology, and serves as a simple application of KVL for students to examine.

Question 108

Calculate the amount of voltage between test points TP1 and TP3, and also the amount of voltage between test points TP2 and TP4:



$$V_{TP1-TP3} = \quad \quad V_{TP2-TP4} =$$

file 03251

Answer 108

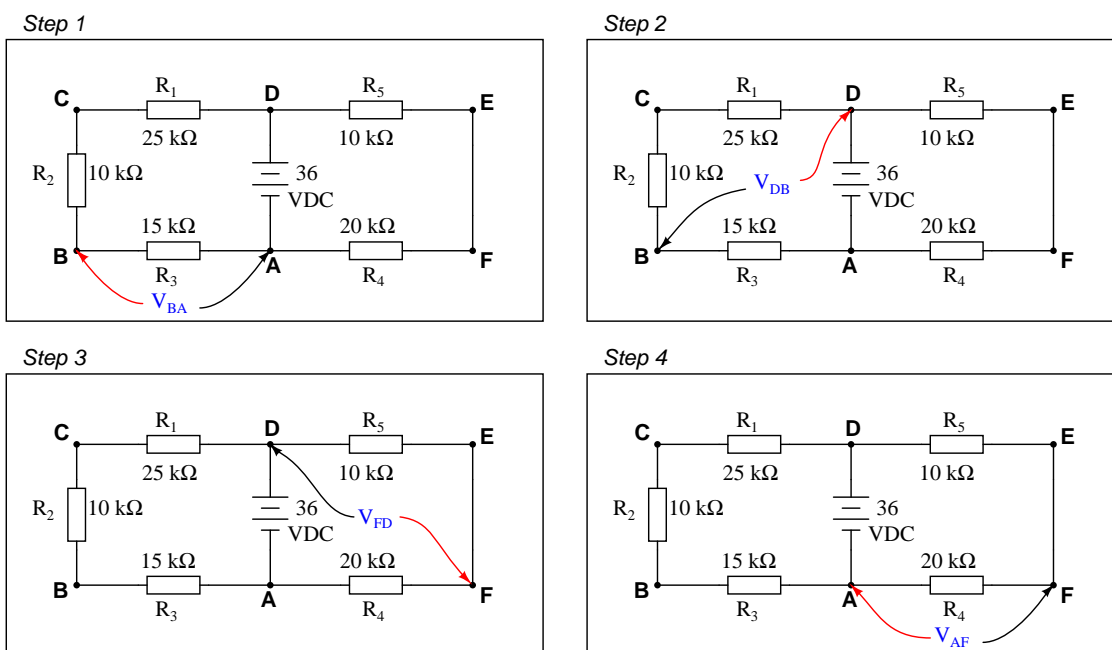
$$V_{TP1-TP3} = 15.83 \text{ volts} \quad \quad V_{TP2-TP4} = 22.22 \text{ volts}$$

Notes 108

Ask your students to explain how they obtained their answers. There is more than one correct way to answer this question!

Question 109

Imagine you are using a digital voltmeter to measure voltages between pairs of points in a circuit, following the sequence of steps shown in the following diagrams:



How much voltage would be registered by the voltmeter in each of the steps? Be sure to include the sign of the DC voltage measured (note the coloring of the voltmeter leads, with the red lead always on the first point denoted in the subscript: V_{BA} = red lead on "B" and black lead on "A"):

- $V_{BA} =$
- $V_{DB} =$
- $V_{FD} =$
- $V_{AF} =$

What is the algebraic sum of these voltages?

file 00346

Answer 109

- $V_{BA} = +10.8$ volts
- $V_{DB} = +25.2$ volts
- $V_{FD} = -12.0$ volts
- $V_{AF} = -24.0$ volts

Notes 109

Ask your students this question: "Will the algebraic sum of voltage measurements ever be other than zero in a loop?" Ask them to explain *why* this is, as best they can.