Recommended schedule

<u>Day 1</u>

Topics: *Series-parallel circuit analysis*
Questions: *1 through 15*
Lab Exercise: *Kirchhoff's Voltage Law (question 61)*

<u>Day 2</u>

Topics: *Series-parallel circuits and Wheatstone bridges*
Questions: *16 through 30*
Lab Exercise: *Wheatstone bridge (question 62)*

<u>Day 3</u>

Topics: *Series-parallel circuits, safety grounding, and troubleshooting*
Questions: *31 through 45*
Lab Exercise: *Series-parallel DC resistor circuit (question 63)*

<u>Day 4</u>

Topics: *Loaded voltage dividers*
Questions: *46 through 60*
Lab Exercise: *Loaded voltage divider (question 64)*

<u>Day 5</u>

Exam 1: *includes Series-parallel DC resistor circuit performance assessment*
Lab Exercise: *Troubleshooting practice (loaded voltage divider circuit – question 64)*

<u>Practice and challenge problems</u>

Questions: *67 through the end of the worksheet*

<u>Impending deadlines</u>

Troubleshooting assessment (voltage divider) due at end of ELTR105, Section 3
Question 65: Troubleshooting log
Question 66: Sample troubleshooting assessment grading criteria

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.
B.14 Understand the principles and operations of DC series-parallel and bridge circuits.
B.15 Fabricate and demonstrate DC series-parallel and bridge circuits.
B.16 Troubleshoot and repair series-parallel and bridge circuits.
B.17 Understand the principles and operations of the Wheatstone bridge.
B.18 Understand principles and operations of DC voltage divider circuits (loaded and unloaded).
B.19 Fabricate and demonstrate DC voltage divider circuits (loaded and unloaded).
B.20 Troubleshoot and repair DC voltage divider circuits (loaded and unloaded).
C Technical Skills – AC circuits
C.07 Demonstrate an understanding of the principle and operation of safety grounding systems: (lightning arrestors, ground fault interrupters, etc.).

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: *Respective rules for series versus parallel circuits.*

By themselves, series circuits should be fairly easy for you to analyze at this point. The same may be said for parallel circuits by themselves. The respective rules for each (voltages same across parallel components; currents same through series components; parallel currents add; series voltages add; etc.) are not that difficult to remember, especially if you understand *why* each one is true. Things become much trickier, though, when we begin to mix series networks of resistors with parallel networks of resistors, as we jump from one rule set to the other in our analysis. My best advice here is to avoid trying to memorize the rules by rote, and rather work on comprehending why each rule is as it is for each type of circuit. And of course, practice, practice, practice!

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

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

Common mistake: *Carelessness when analyzing series-parallel networks.*

When analyzing a series-parallel circuit to determine component voltages and currents, one must be very careful to reduce the circuit step-by-step, section-by-section, into equivalent resistances. Students new to this process typically see all the work that is involved and try to save effort by taking shortcuts, which paradoxically causes *more* work and *more* confusion for them later on. Use lots of paper to document your work when you reduce series-parallel resistor networks to equivalent resistances, re-drawing the circuit for each reduction. This helps reduce the number of mistakes, and also makes it easier to transfer calculated values of voltage and current to the correct components (see the difficult concept shown above: using Ohm's Law in context).

Difficult concept: *Qualitative analysis of circuits.*

Most students find that qualitative analysis of electric circuits is much more difficult than quantitative analysis. In other words, it is easier to use a calculator to compute how much current goes through a particular resistor in a circuit than it is to figure out if that current will increase, decrease, or remain the same given a certain change in the circuit. What this requires is a "feel" for how variables in Ohm's Law and Kirchhoff's Laws relate to each other, which is a very different skill than numerical calculation. A good way to build this skill is to practice qualitative analysis on every quantitative circuit question you encounter. Even though the question only asks for a numerical answer, you can challenge yourself by asking whether or not a particular variable will change (and which direction that change will be in) given any particular change in the circuit (more or less supply voltage, a wire breaking open, a resistor failing open, or a resistor failing shorted). Then, you may re-calculate the numerical answers to see if your qualitative predictions are correct. Computer-based circuit simulation programs are excellent for this, as they allow one to skip the steps of numerical calculation to rapidly see the effects of certain circuit faults.

Question 1

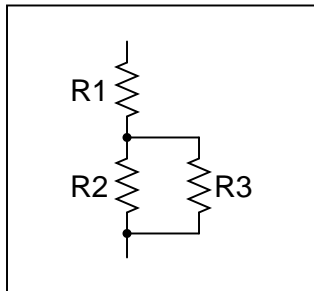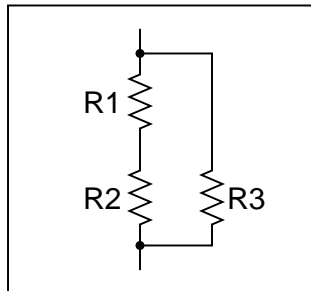Identify which of these components are connected directly in series with each other, and which are connected directly in parallel with each other:

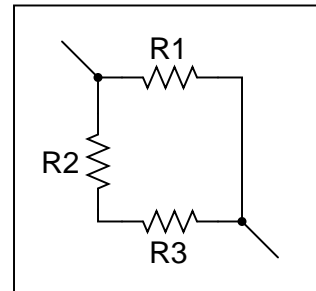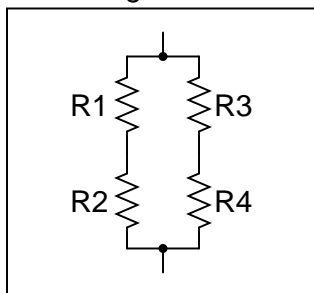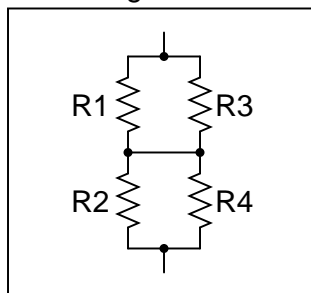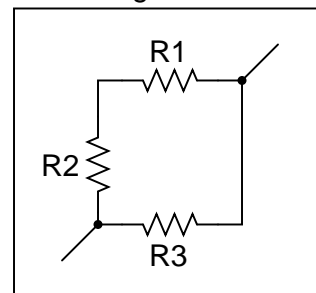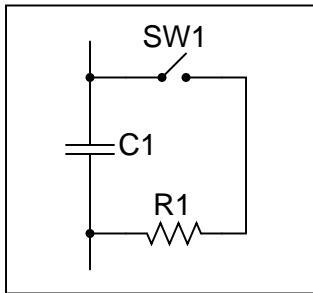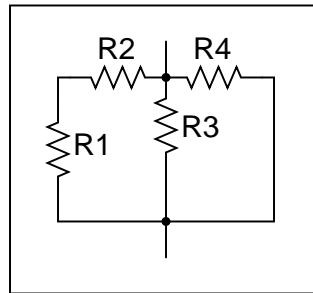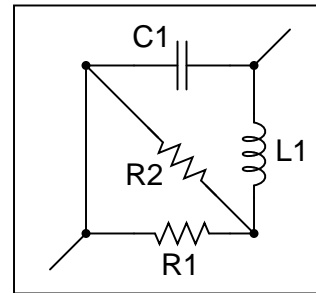Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Assume that the open wire ends are connection points to a power source.
file 01752

Answer 1

Figure 1:

R2 in parallel with R3.

Figure 2:

R1 in series with R2.

Figure 3:

R2 in series with R3.

Figure 4:

R1 in series with R2; R3 in series with R4.

Figure 5:

R1 in parallel with R3; R2 in parallel with R4.

Figure 6:

R1 in series with R2.

Notes 1

   Work with your students to clearly identify rules by which series and parallel connections may be identified. This is extremely important for students to grasp if they are to be successful analyzing series-parallel networks of any kind. The most common problems I encounter as an electronics instructor with reference to series-parallel are invariably related to students' lack of ability to consistently distinguish series sub-networks and parallel sub-networks in series-parallel combination circuits.

Identify which of these components are connected directly in series with each other, and which are connected directly in parallel with each other:
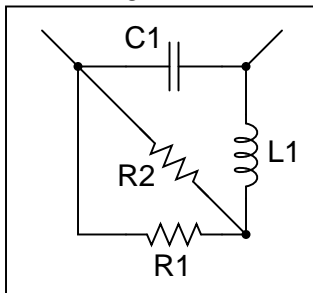
Figure 1

Figure 2
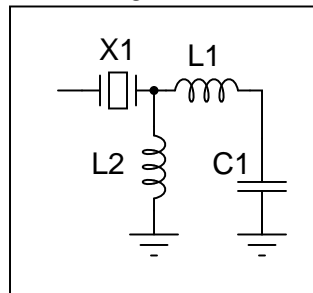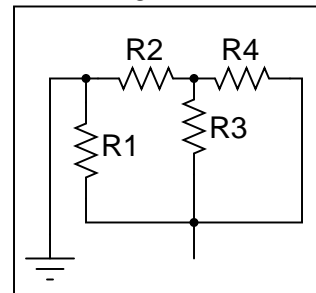
Figure 3

Figure 4

Figure 5

Figure 6

Assume that the open wire ends are connection points to a power source. In circuits where ground symbols appear, consider ground as the other side of the power source.

file 01753

Answer 2

Figure 1:
   R1 in series with SW1.

Figure 2:
   R1 in series with R2; R3 in parallel with R4.

Figure 3:
   R1 parallel with R2.

Figure 4:
   R1 parallel with R2.

Figure 5:
   L1 in series with C1.

Figure 6:
   R3 in parallel with R4.

   Challenge question: if you compare figures 2 and 6, you see how merely changing the location(s) where the power supply connects to the network can alter the series/parallel relationships of the components. But, exactly what is it that is altered? If two components are in series with each other in one power source configuration, can that series relationship change by moving the power supply connection points? How about parallel connections? If two components are in parallel with each other, can that parallel relationship become altered merely by moving the points where the power source connects to the network? Explain.

Notes 2

   Work with your students to clearly identify rules by which series and parallel connections may be identified. This is extremely important for students to grasp if they are to be successful analyzing series-parallel networks of any kind. The most common problems I encounter as an electronics instructor with reference to series-parallel are invariably related to students' lack of ability to consistently distinguish series sub-networks and parallel sub-networks in series-parallel combination circuits.
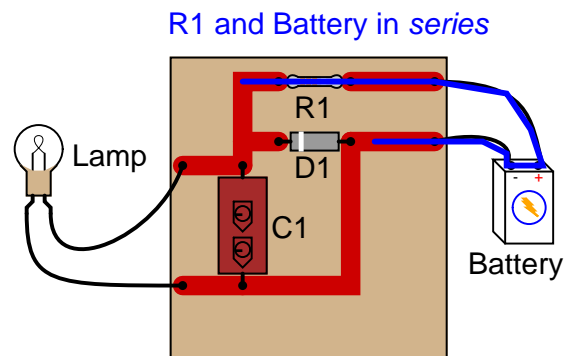
Question 3

Identify which of these components are connected directly in series with each other, and which are connected directly in parallel with each other:
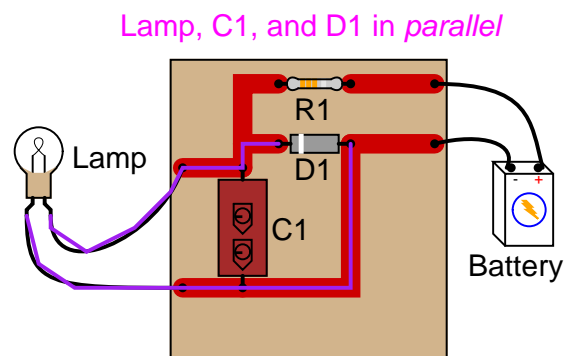

Printed circuit board
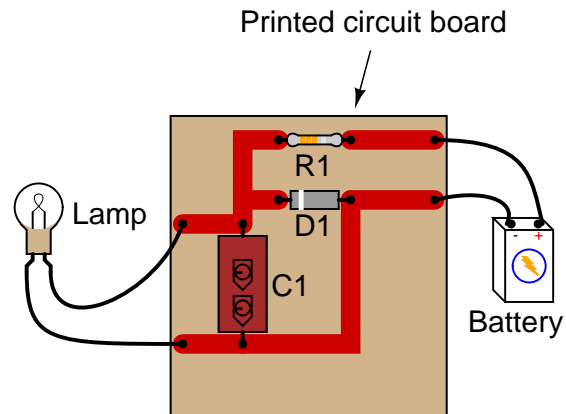
Answer 3

Connected directly in series: *Battery and R1.*

R1 and Battery in *series*

Connected directly in parallel: *Lamp, C1, and D1*

Lamp, C1, and D1 in *parallel*

Notes 3

Students must have a firm understanding of what constitutes "series" versus "parallel" in real circuits. Here is a place where some students will feel uncomfortable because the textbook definitions they memorized are easier said than applied. It is imperative that students have a strong working knowledge of terms, and do not simply memorize definitions.

Question 4

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 4

"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, resistance*s add to equal the total*."

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

Notes 4

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 5

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

"In a parallel circuit, voltage . . ."

"In a parallel circuit, current . . ."

"In a parallel circuit, resistance . . ."

"In a parallel circuit, power . . ."

For each of these rules, explain *why* it is true.
file 00292

Answer 5

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

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

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

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

Notes 5

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.

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Question 6

Rank these three light bulb assemblies according to their *total* electrical resistance (in order of least to greatest), assuming that each of the bulbs is the same type and rating:
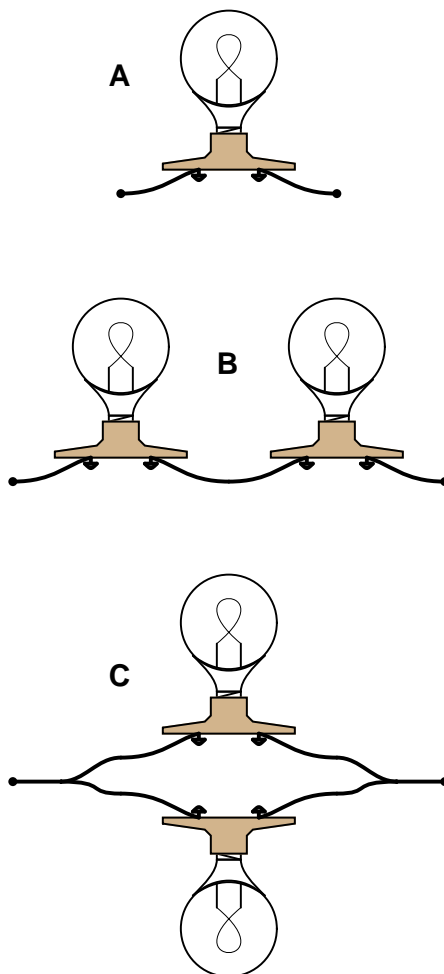
Explain how you determined the relative resistances of these light bulb networks.
<u>file 00030</u>

Answer 6

- C (least total resistance)
- A
- B (greatest total resistance)

Notes 6

I prefer to enter discussion on series and parallel circuits prior to introducing Ohm's Law. Conceptual analysis tends to be more difficult than numerical analysis in electric circuits, but is a skill worthwhile to build, especially for the sake of effective troubleshooting.

It is effective *after* conceptual (qualitative) analysis, though, to go through a numerical (quantitative) analysis of a circuit like this to prove that the concepts are correct, if the students are advanced enough at this point to do series-parallel resistance calculations.

Question 7

Which components are guaranteed to share the exact same *voltage* by virtue of their connections with each other? Which components are guaranteed to share the exact same *current* by virtue of their connections with each other?

Printed circuit board
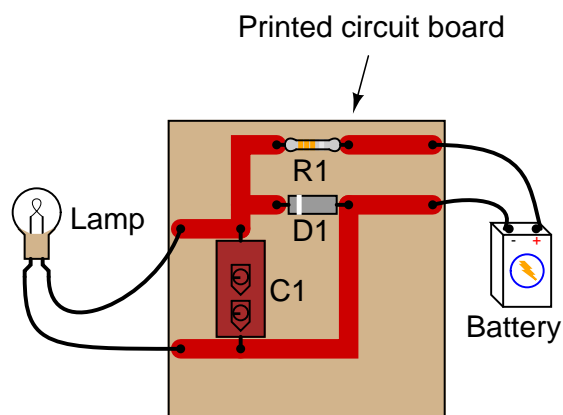
Answer 7

The lamp, C1, and D1 are all guaranteed to share the exact same voltage. The battery and R1 are both guaranteed to share the exact same current.

Notes 7

Here, the important relations between voltage, current, and component connection patterns are explored. This serves to further define, in practical ways, what the terms "series" and "parallel" really mean.

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Question 8

Which components in this partial automobile schematic diagram are guaranteed to share the exact same *voltage* by virtue of their connections with each other? Which components are guaranteed to share the exact same *current* by virtue of their connections with each other?
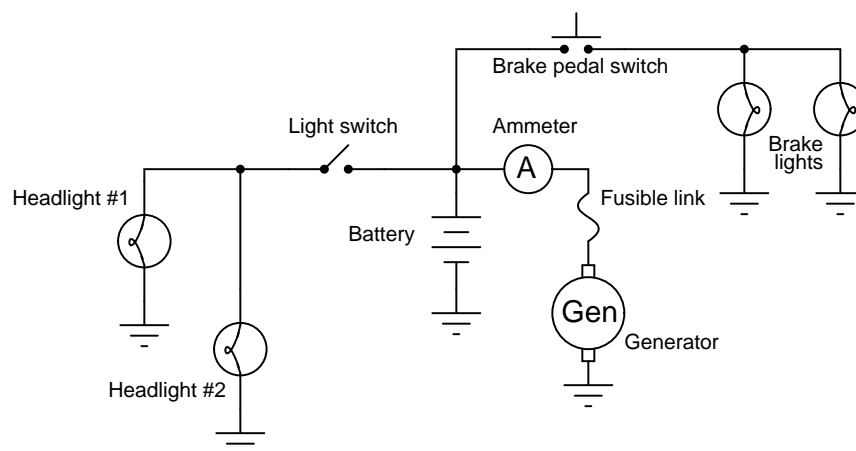
file 00034

Answer 8

The two headlights are guaranteed to share the same voltage. So are the two brake lights. However, the voltage across the brake lights may not be the same as the voltage across the headlights at any given time!

So long as the fusible link is not "blown," the generator and battery will share approximately the same voltage.

The ammeter, fusible link, and generator are all guaranteed to share the same current.

Notes 8

Here, the important relations between voltage, current, and component connection patterns are explored. This serves to further define, in practical ways, what the terms "series" and "parallel" really mean.

This question also affords the opportunity of discussing what a "fusible link" is, and how it compares to fuses and circuit breakers as an overcurrent protection device.

In this series-parallel circuit, resistors R1 and R2 are in series with each other, but resistor R3 is neither in series nor in parallel with either R1 or R2:
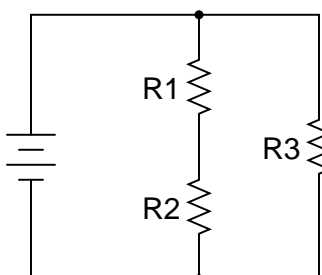
Normally, the first step in mathematically analyzing a circuit such as this is to determine the total circuit resistance. In other words, we need to calculate how much resistance the voltage source "sees" in the network formed by R1, R2, and R3. If the circuit were a simple series configuration, our task would be easy:
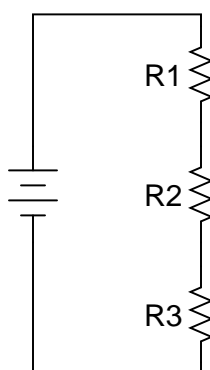
Likewise, if the circuit were a simple parallel configuration, we would have no difficulty at all calculating total resistance:
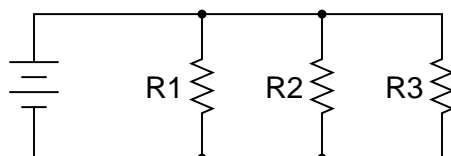
Due to the fact that our given circuit is neither purely series nor purely parallel, though, calculation of total resistance is not a simple one-step operation. However, there is a way we could simplify the circuit to something that *is* either simple series or simple parallel. Describe how that might be done, and demonstrate using numerical values for resistors R1, R2, and R3.

file 01755

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Answer 9

Suppose we had these resistor values:

- R1 = 3000 Ω
- R2 = 2000 Ω
- R3 = 5000 Ω

The total resistance in this case would be 2500 Ω. I'll let you figure out how to do this!

Hint: 2.5k is exactly one-half of 5k

Notes 9

Figuring out how to calculate total resistance in a series-parallel network is an exercise in problem-solving. Students must determine how to convert a complex problem into multiple, simpler problems which they can then solve with the tools they have.

This sort of exercise is also helpful in getting students to think in terms of *incremental* problem-solving. Being able to take sections of a circuit and reduce them to equivalent component values so that the circuit becomes simpler and simpler to analyze is a very important skill in electronics.

Question 10

Rank these five light bulb assemblies according to their *total* electrical resistance (in order of least to greatest), assuming that each of the bulbs is the same type and rating:
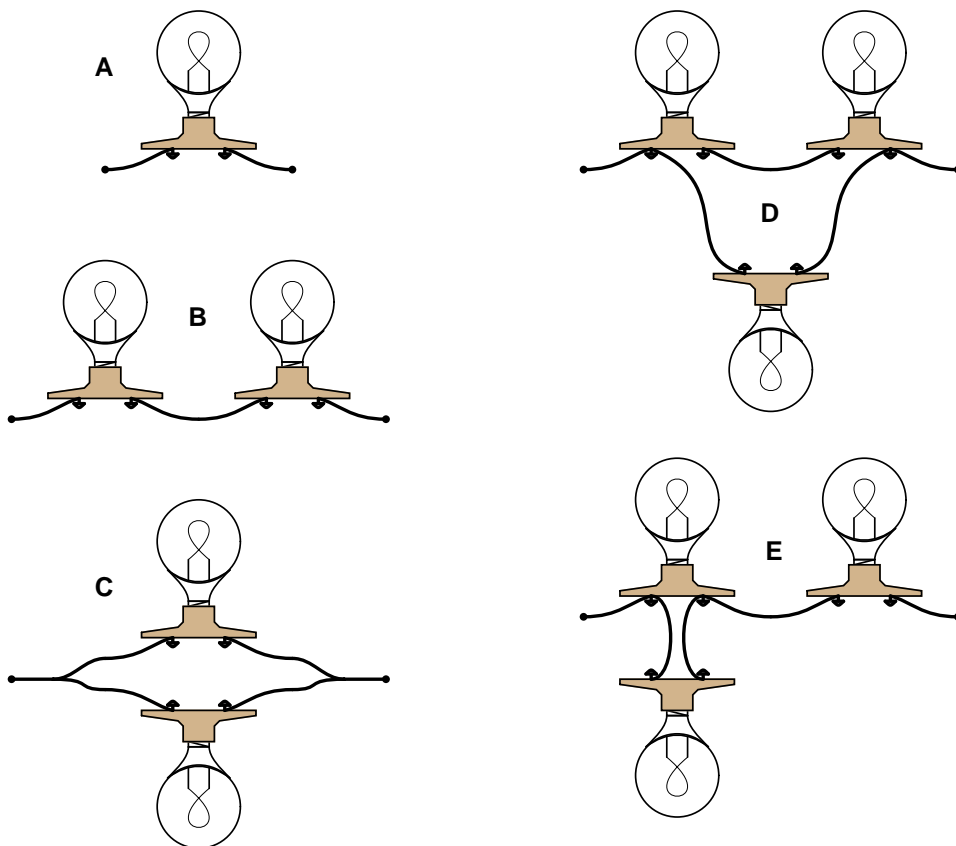
Explain how you determined the relative resistances of these light bulb networks.

file 00039

Answer 10

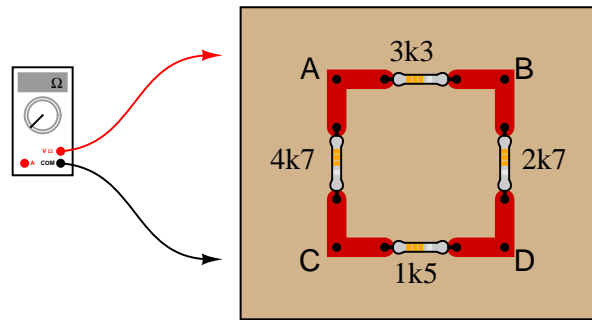- C (least total resistance)
- D
- A
- E
- B (greatest total resistance)

Notes 10

I prefer to enter discussion on series and parallel circuits prior to introducing Ohm's Law. Conceptual analysis tends to be more difficult than numerical analysis in electric circuits, but is a skill worthwhile to build, especially for the sake of effective troubleshooting.

It is effective *after* conceptual (qualitative) analysis, though, to go through a numerical (quantitative) analysis of a circuit like this to prove that the concepts are correct, if the students are advanced enough at this point to do series-parallel resistance calculations.

Question 11

Determine the amount of electrical resistance indicated by an ohmmeter connected between the following points in this circuit:

- Between points A and B =
- Between points A and C =
- Between points C and D =
- Between points D and B =
- Between points B and C =

Explain whether or not it makes any sense to speak of a "total" resistance for this network.
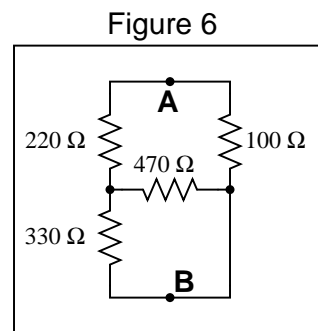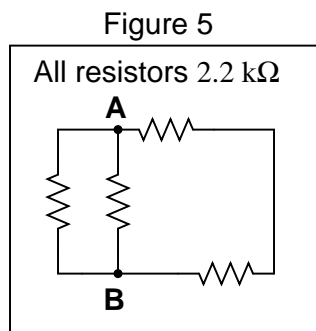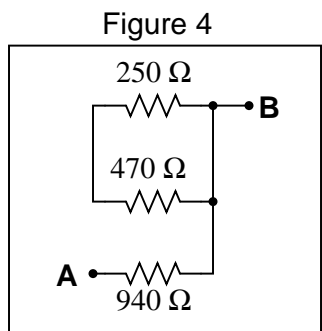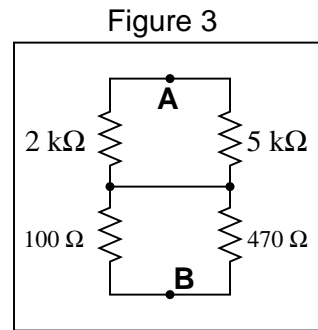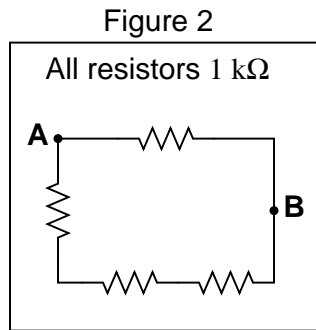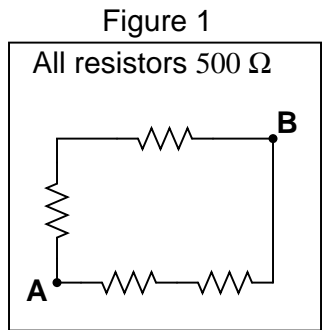<u>file 01601</u>

Answer 11

- Between points A and B = 2.41 kΩ
- Between points A and C = 2.89 kΩ
- Between points C and D = 1.32 kΩ
- Between points D and B = 2.10 kΩ
- Between points B and C = 2.75 kΩ

Notes 11

The purpose of this question is to get students to realize that the resistance "looking into" different areas of a resistive network depends on what those areas are.

Question 12

Calculate the resistance between points **A** and **B** (R_{AB}) for the following resistor networks:

Figure 1
All resistors 500 Ω

Figure 2
All resistors 1 kΩ

Figure 3

Figure 4

Figure 5
All resistors 2.2 kΩ

Figure 6

file 01757

Answer 12

Figure 1:
   $R_{AB} = 500 \ \Omega$

Figure 2:
   $R_{AB} = 750 \ \Omega$

Figure 3:
   $R_{AB} = 1.511 \ \text{k}\Omega$

Figure 4:
   $R_{AB} = 940 \ \Omega$

**Figure 5:**
   $R_{AB} = 880 \ \Omega$

Figure 6:
   $R_{AB} = 80.54 \ \Omega$

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Note that the circuit in figure 4 is a "trick:" two of the resistors contribute absolutely nothing to R_{AB}! Be sure to discuss why this is with your students.

Discuss with your students how they approached each of these problems, and let the entire class participate in the reasoning process. The point of this question, like most of the questions in the Socratic Electronics project, is not merely to obtain the correct answers, but to stimulate understanding of *how* to solve problems such as these.

Question 13

Calculate the amount of voltage dropped across resistor R_2:
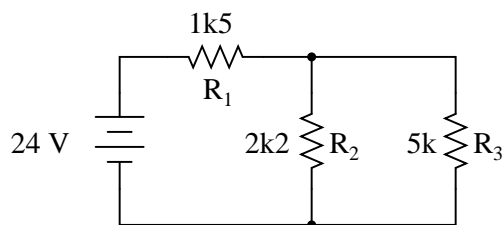
Also, note the direction of current through it and the polarity of the voltage drop across it.

file 01759

Answer 13

$V_{R2} = 12.11$ volts, positive on top and negative on bottom. If you follow conventional flow notation, this means current goes down through resistor R_2. The actual flow of electrons through R_2, however, is up.

Notes 13

Discuss with your students how they obtained their answers for this question. The reasoning and procedures are far more important than the actual answer itself.

Students often have difficulty formulating a method of solution: determining what steps to take to get from the given conditions to a final answer. While it is helpful at first for you (the instructor) to show them, it is bad for you to show them too often, lest they stop thinking for themselves and merely follow your lead. A teaching technique I have found very helpful is to have students come up to the board (alone or in teams) in front of class to write their problem-solving strategies for all the others to see. They don't have to actually do the math, but rather outline the steps they would take, in the order they would take them.

By having students outline their problem-solving strategies, everyone gets an opportunity to see multiple methods of solution, and you (the instructor) get to see how (and if!) your students are thinking. An especially good point to emphasize in these "open thinking" activities is how to check your work to see if any mistakes were made.

Question 14

Complete the table of values for this circuit:
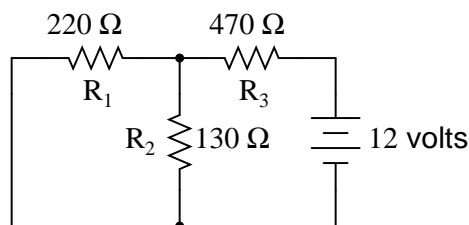
	R$_1$	R$_2$	R$_3$	Total
V				
I				
R	220 Ω	130 Ω	470 Ω	
P				

file 01758

Answer 14

	R$_1$	R$_2$	R$_3$	Total
V	1.778 V	1.778 V	10.22 V	12 V
I	8.079 mA	13.67 mA	21.75 mA	21.75 mA
R	220 Ω	130 Ω	470 Ω	551.7 Ω
P	14.36 mW	24.30 mW	222.3 mW	261.0 mW

Notes 14

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

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Question 15

Antique American automobiles often used 6 volt electrical systems instead of the 12 volt components found in more modern cars and trucks. People who restore these old vehicles may have difficulty finding old 6-volt generators and batteries to replace the defective, original units. An easy solution is to update the vehicle's generator and battery with modern (12 volt) components, but then another problem arises.

A 12 volt generator and 12 volt battery will overpower the old 6 volt headlights, brake lights, and other electrical "loads" in the vehicle. A solution used by antique automobile restorers is to connect resistors between the 12-volt generator system and the 6-volt loads, like this:
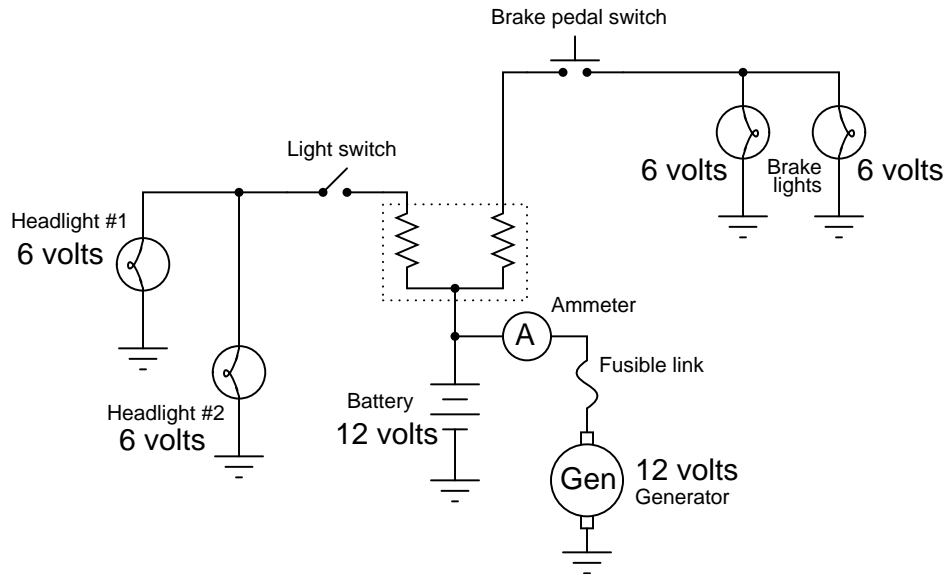
Explain why this solution works, and also discuss some of the disadvantages of using resistors to adapt the new (12 volt) to the old (6 volt) components.

file 00062

Answer 15

The purpose of the resistors is to "drop" half the voltage supplied by the generator and battery, so that the loads (light bulbs, in this case) receive only 6 volts instead of 12 volts. A disadvantage of using resistors to do this is that the resistors waste a lot of electrical power in the form of heat.

Notes 15

Make sure your students understand the concept of a "load:" any electrical or electronic component that uses power from an electrical source. Usually, "loads" are the end-use components of a circuit: light bulbs, motors, solenoids, speakers, etc. In this case, the resistors could be considered loads as well as the light bulbs, but since the light bulbs are the only components performing useful work from the power source, it is customary to think of them when the word "load" is used, rather than the resistors.
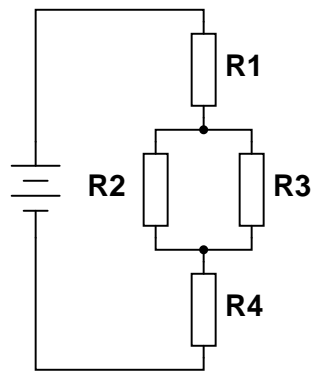
Question 16

Draw a schematic diagram of this "breadboarded" circuit:
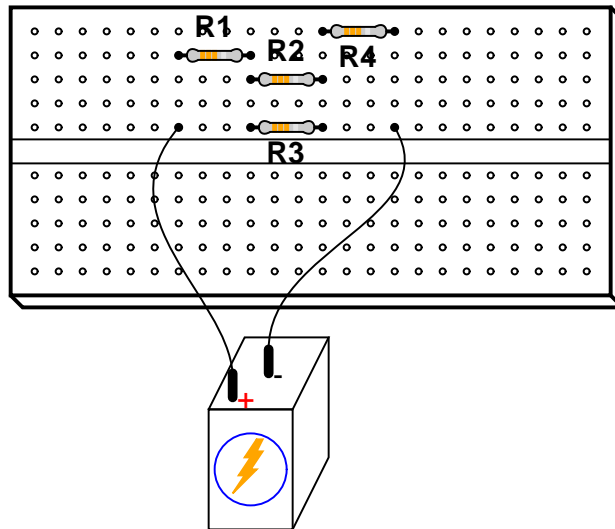
Answer 16

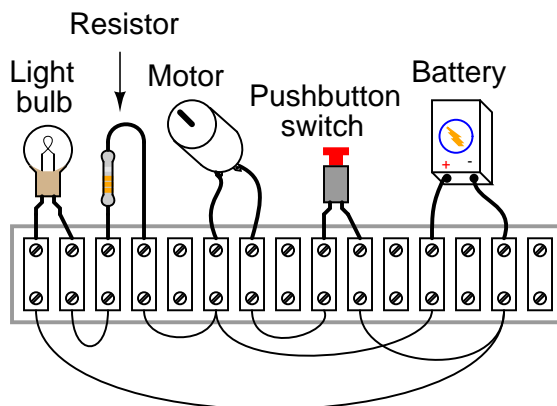## Notes 16

If your students are not yet aware of how solderless breadboard holes are connected together, this is a good time to introduce them!
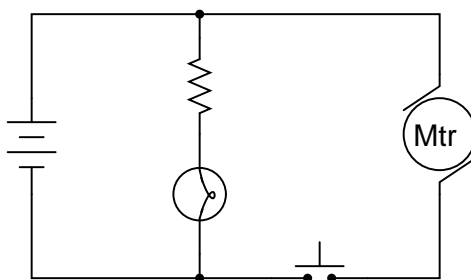
From observation of this circuit (with components attached to a "terminal strip"), draw an appropriate schematic diagram:


<u>file 00115</u>

Answer 17

Notes 17

This type of question is one that lends itself well to students drawing their answers on the board in front of class. The skill of transferring a real circuit into a cleanly-drawn schematic is one that some students struggle mightily with, but it is important. Those students will want to know what technique(s) may be used to make the transfer. Students who are more spatially adept will probably have a couple of different ways to approach a problem such as this. Allow them to explain to the rest of the class their technique(s) for tracing the real circuit's wiring into a schematic diagram.

Giving students the opportunity to teach their peers is a powerful instructional method, and should be encouraged at all times!

Question 18

Think of a way to re-wire the electrical system of this old automobile (with 6-volt light bulbs) so as to not require resistors between the loads and the generator/battery portion of the circuit (operating at 12 volts each).
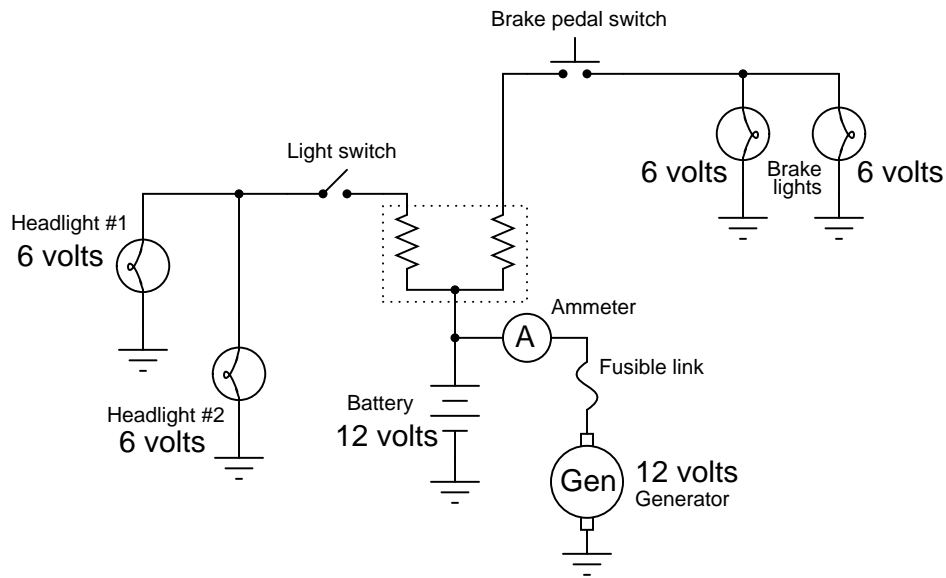
Answer 18

Connect the light bulb pairs in series instead of parallel. This way, each light bulb will receive 6 volts, with a total system voltage of 12 volts.

Follow-up question: there is a disadvantage of this strategy, though, and it concerns the safety of operating the automobile. Explain what this disadvantage is.

Notes 18

This solution works only because the load sets are in pairs, and because 6 + 6 = 12. One benefit of this solution is greater efficiency, as there are no resistors in the circuit to "waste" power by dissipating it in the form of heat. However, there is a disadvantage to doing things this way, as indicated by the follow-up question. Discuss this disadvantage with your students, reinforcing the idea that the most efficient engineering solutions may not be the best when assessed from other perspectives, such as safety!

Question 19

Calculate the voltage drops V_{AB}, V_{BC}, and V_{CD} in the following circuit:
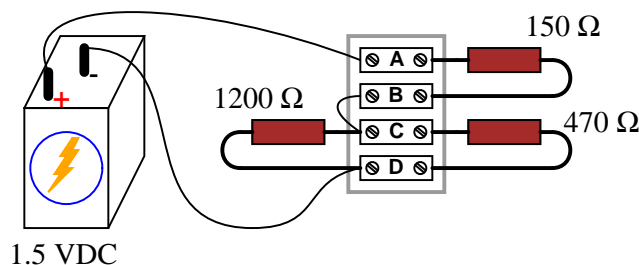
file 01764

Answer 19

$V_{AB} = 461$ mV
$V_{BC} = 0$ V
$V_{CD} = 1.039$ V

Follow-up question: explain why the voltage between points A and B (V_{AB}) would *increase* if the 1200 Ω resistor were to fail shorted. Hint: imagine a "jumper" wire connected across that resistor to simulate a shorted failure.

Challenge question: explain how you can calculate these same answers without ever having to calculate total circuit current.

Notes 19

Ask your students how they could tell V_{BC} must be zero, just by examining the circuit (without doing any math). If some students experience difficulty answering this question on their own, have them translate the drawing into a proper schematic diagram.

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Question 20

Calculate the voltage magnitude and polarity between points **A** and **D** in this circuit, assuming a power supply output voltage of 10.5 volts:
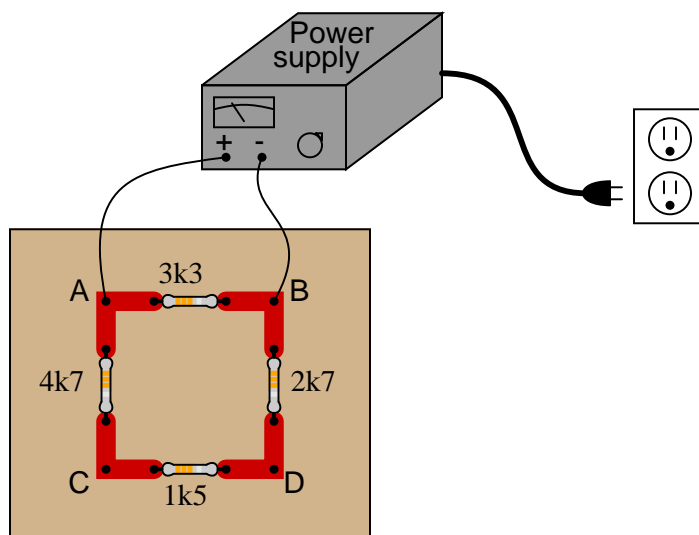
Also, calculate the total current output by the power supply as it energizes this resistor network.

file 01765

Answer 20

$V_{AD} = 7.31$ volts, **A** positive and **D** negative. The total power supply current is 4.36 mA.

Follow-up question: explain why the voltage across the 4.7 kΩ resistor would go to zero if the 1.5 kΩ resistor were to fail open.

Notes 20

Though some students might not realize it at first, there is no series-parallel analysis necessary to obtain the voltage drop V_{AD}.

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As a follow-up to the follow-up question, ask your students what *other* resistor in this circuit would completely lose voltage given an open failure of the 1.5 kΩ resistor.

Question 21

Calculate the power supply's output (total) current:
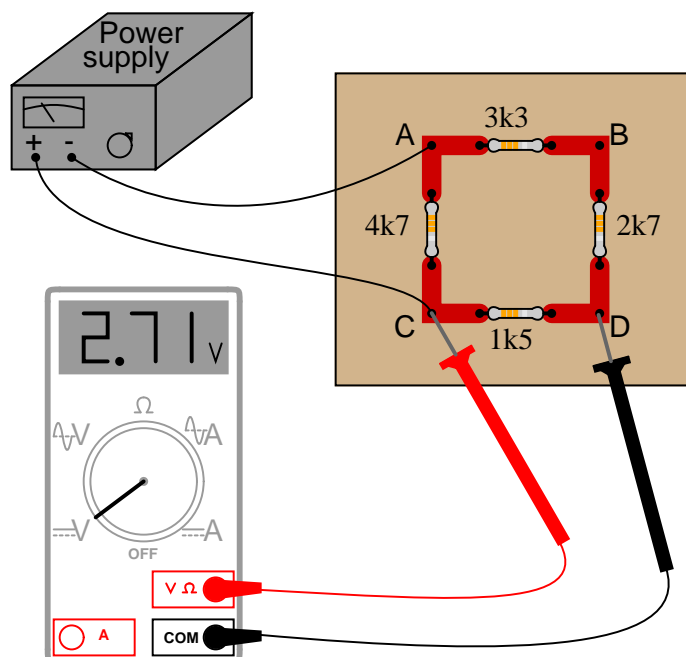
Answer 21

$I_{total} = 4.69$ mA

Follow-up question: explain why the voltage across the 1500 Ω resistor would remain unchanged if the 4700 Ω resistor were to fail open.

Challenge question: what crucial assumptions underlie the calculated figure for current shown here? In other words, what unknown quantities can affect the accuracy of our predicted current value?

Notes 21

This is an interesting series-parallel circuit problem to solve, and it shows once again how a good understanding of circuit theory enables unmeasured variables to be inferred.

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Question 22

How much voltage needs to be dropped across resistor R_1 in order to make voltage V_{AB} equal to zero?
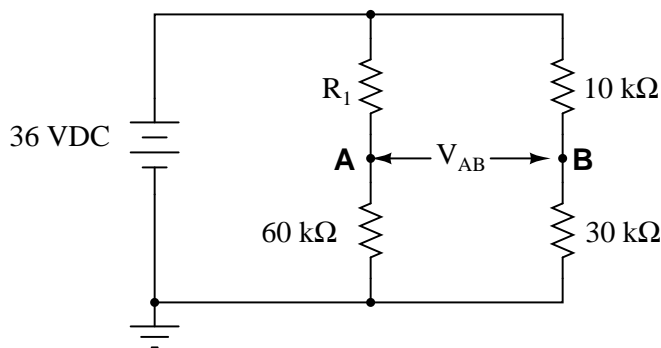
How much resistance must R_1 possess in order to drop that amount of voltage?

file 00543

Answer 22

$V_{R1} = 9$ V

$R_1 = 20$ kΩ

Follow-up question: what do you notice about the four resistors' values in this condition where $V_{AB} = 0$? Pair up these four resistors into two sets of two pairs, and calculate the ratios of those pairs. What do you notice about these ratios?

Notes 22

The follow-up question regarding ratios is a good introduction to the fundamental principle of balanced bridge circuits. Having students work through the calculations together is a good way for them to see the principle for themselves.

It is also important to note in this circuit which ratios are *not* in agreement with each other. You can't just divide these four resistors into any set of two pairs and expect the ratios to equal each other! It is very important for students to see this, as well.

Question 23

In general terms, describe what must be done to *balance* this bridge circuit. What, exactly, does the term "balance" mean in this context?
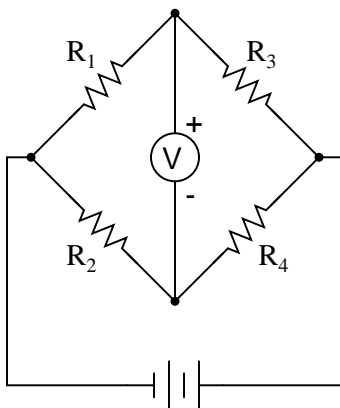
Also, write an equation containing only the four resistor values (R_1, R_2, R_3, and R_4) showing their relationship to one another in a balanced condition.

file 00544

Answer 23

For a bridge circuit to be "balanced" means that there is zero voltage between the two opposite corners of the circuit (where the battery does *not*) connect. Achieving a condition of "balance" in a bridge circuit requires that the resistance ratios of the four "arms" of the circuit be in proportion:

$$\frac{R_1}{R_3} = \frac{R_2}{R_4}$$

Follow-up question: the bridge-balance equation shown above may also be written in a slightly different form:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

Show algebraically how the first equation may be manipulated to take the form of the second equation, thus demonstrating these two equations' equivalence.

Notes 23

Challenge your students to write a "balance equation" describing how the ratios must relate to each other in order to achieve balance.

Question 24

Identify the most important qualification for the "null" meter used to balance a bridge circuit. In other words, describe what type of meter we would be looking for if we were to select one for use as a "null" meter. Describe why this particular quality is important.

file 00545

Answer 24

Above all, a null meter must be *sensitive*.

Notes 24

Discuss with your students the definition of "sensitivity" with regard to meter movements, and why null meters have to be sensitive in order for the bridge circuit to be accurately balanced. If your students have studied meter movement design, you may wish to challenge them with a question on exactly how a null meter movement might be constructed (i.e. what would have to be done to maximize its sensitivity?).

Question 25

What will happen to the voltage between points **A** and **B** if the power supply voltage increases?
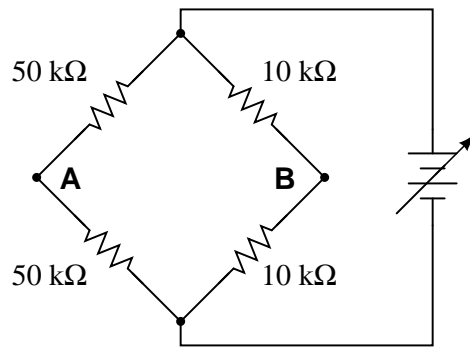
file 00546

Answer 25

V_{AB} will remain the same as V_{supply} increases.

Notes 25

This question highlights another important concept of bridge circuits, namely that balance is irrespective of supply voltage.

Question 26

Explain how this bridge circuit is capable of being "balanced" for *any* values of R_1 and R_2:
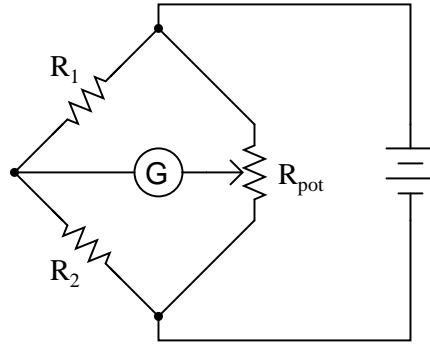
Answer 26

The potentiometer acts as a complementary pair of resistors: moving the wiper one direction increases the value of one while decrease the value of the other. Thus, it forms a voltage divider with an infinitely adjustable division ratio of 0% to 100%, inclusive.

Notes 26

This question showcases one more use of the potentiometer: as a voltage divider used specifically to balance a bridge circuit for any arbitrary values of fixed resistances. If students have difficulty seeing how this is possible, you might want to try representing the pot as a pair of fixed resistors (R_3 and R_4), the wiper position determining the balance of those two resistance values ($R_{pot} = R_1 + R_2$).

Question 27

A *strain gauge* is a device used to measure the strain (compression or expansion) of a solid object by producing a resistance change proportional to the amount of strain. As the gauge is strained, its electrical resistance alters slightly due to changes in wire cross-section and length.

The following strain gauge is shown connected in a "quarter-bridge" circuit (meaning only one-quarter of the bridge actively senses strain, while the other three-quarters of the bridge are fixed in resistance):
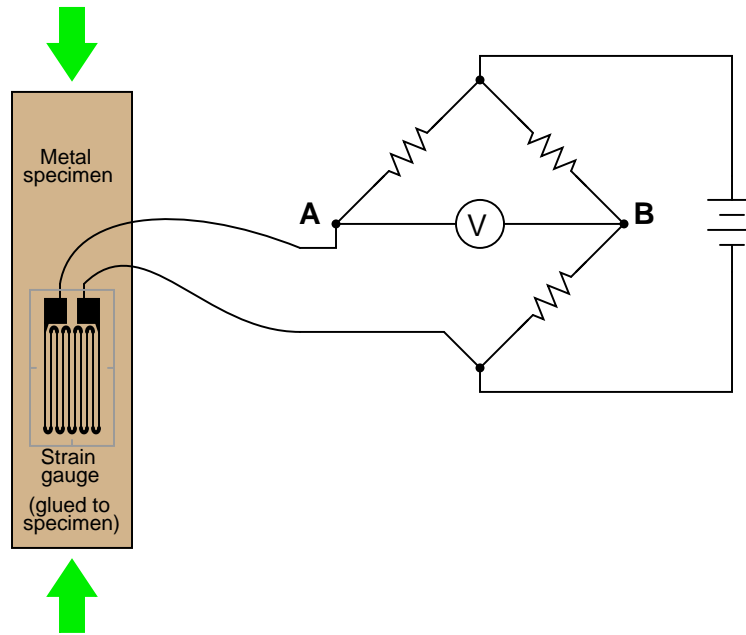
Explain what would happen to the voltage measured across this bridge circuit (V_{AB}) if the strain gauge were to be *compressed*, assuming that the bridge begins in a balanced condition with no strain on the gauge.
file 00547

Answer 27

The bridge circuit will become more unbalanced, with more strain experienced by the strain gauge. I will not tell you what the voltmeter's *polarity* will be, however!

Notes 27

Be sure to have your students explain how they arrived at their answers for polarity across the voltmeter terminals. This is the most important part of the question!

35

A *strain gauge* is a device used to measure the strain (compression or expansion) of a solid object by producing a resistance change proportional to the amount of strain:
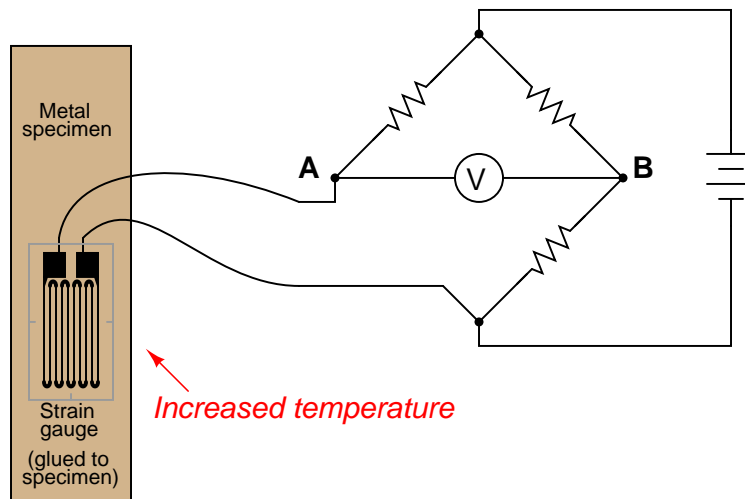
The bridge circuit is supposed to respond to changes in specimen strain, but explain what will happen to the voltage measured across this bridge circuit (V_{AB}) if the specimen's temperature increases (with no stress applied), assuming that the bridge begins in a balanced condition with no strain on the gauge, at room temperature. Assume a positive α value for the strain gauge conductors.

What does this indicate about the effectiveness of this device as a strain-measuring instrument?

file 00548

Answer 28

If the specimen heats up, a voltage will develop between points **A** and **B**, with **A** being positive and **B** being negative.

Notes 28

Be sure to have your students explain how they arrived at their answers for polarity across the voltmeter terminals.

Ask your students whether or not the fact of the circuit's sensitivity to temperature invalidates its use as a strain-measuring system. Is it impossible to obtain a reliable measurement of strain, if we know temperature also affects the circuit output voltage? How could we compensate for the effects of temperature on the system?

Explain how this strain gauge circuit exploits a property of bridge circuits to provide automatic temperature compensation (so that changes in specimen temperature do not compromise strain measurement accuracy):
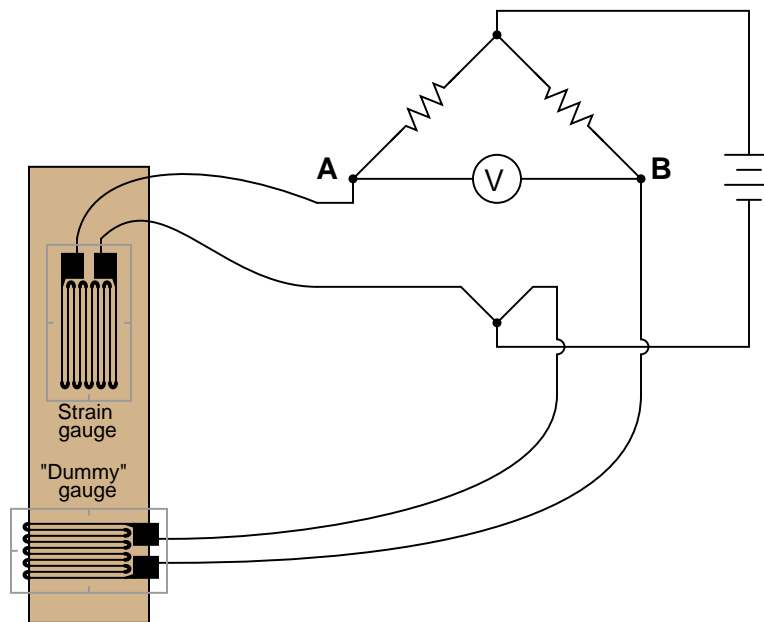
file 00550

Answer 29

The "dummy" gauge is attached to the specimen in such a way that it is not subjected to strain like the "working" gauge is. It it merely exposed to the same specimen temperature. The action of this circuit is easiest to comprehend in a scenario where there is no stress applied to the specimen, but its temperature changes.

Follow-up question: suppose the "dummy" strain gauge develops an open failure, so no current may pass through it. Identify the polarity of the voltage drop that will develop across the voltmeter as a result of this fault.

Notes 29

Because bridge circuits are inherently *differential* circuits, it is possible to perform neat "tricks" such as this where the effects of the undesired influence (temperature) become canceled. Incidentally, the principle of cancellation by differential measurement is one that is very common in electronic systems, especially instrumentation systems.

Question 30

This bridge circuit is suppose to generate an output voltage proportional to the *difference* between light exposure on the two photocells:
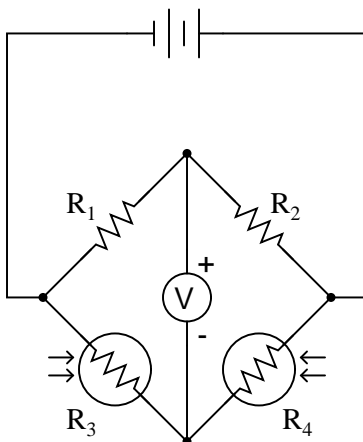
However something has failed in this circuit, because the voltmeter is "pegged" fully negative and will not change with varying light exposures on the two cells. Identify at least two possible failures that could cause the voltmeter to over-range in the negative direction.

file 00504

Answer 30

Here are two failures, although they are not the only possibilities:

- R_1 could have failed shorted.
- Photocell R_3 could have failed open.

Notes 30

Be sure to ask your students to describe failures *other* than the two mentioned in the answer. And, for all answers given, be sure to ask students how they determined those faults would cause the observed "negative pegging" of the voltmeter. As usual, the method of solution is much more important than the actual answer in this question.

Question 31

Complete the table of values for this circuit:

2.2 kΩ   6.8 kΩ
R₂   R₄
1 kΩ R₁   R₃ 470 Ω
6 volts
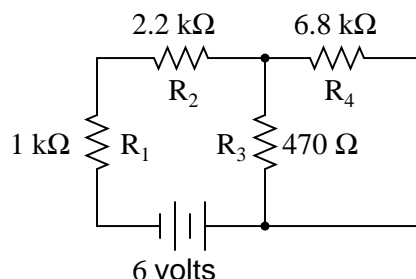
	R₁	R₂	R₃	R₄	Total
V					
I					
R	1 kΩ	2.2 kΩ	470 Ω	6.8 kΩ	
P					

file 01756

Answer 31

	R₁	R₂	R₃	R₄	Total
V	1.649 V	3.627 V	725 mV	725 mV	6 V
I	1.649 mA	1.649 mA	1.542 mA	107 μA	1.649 mA
R	1 kΩ	2.2 kΩ	470 Ω	6.8 kΩ	3.64 kΩ
P	2.718 mW	5.979 mW	1.117 mW	77.24 μW	9.891 mW

Notes 31

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

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39

Question 32

Complete the table of values for this circuit:
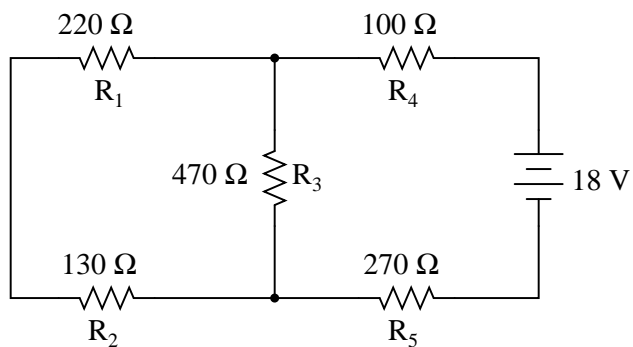
	R_1	R_2	R_3	R_4	R_5	Total
V						
I						
R	220 Ω	130 Ω	470 Ω	100 Ω	270 Ω	
P						

<u>file 01767</u>

Answer 32

	R_1	R_2	R_3	R_4	R_5	Total
V	3.978 V	2.351 V	6.328 V	3.155 V	8.517 V	18 V
I	18.08 mA	18.08 mA	13.46 mA	31.55 mA	31.55 mA	31.55 mA
R	220 Ω	130 Ω	470 Ω	100 Ω	270 Ω	570.6 Ω
P	71.92 mW	42.50 mW	85.21 mW	99.51 mW	268.7 mW	567.8 mW

Notes 32

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.

Complete the table of values for this circuit:

	R₁	R₂	R₃	R₄	R₅	Total
V						
I						
R	790 Ω	1 kΩ	8.6 kΩ	2.2 kΩ	630 Ω	
P						

file 01768

Answer 33

	R₁	R₂	R₃	R₄	R₅	Total
V	13.43 V	18.57 V	13.43 V	32 V	0 V	32 V
I	17.00 mA	18.57 mA	1.562 mA	14.55 mA	0 mA	33.11 mA
R	790 Ω	1 kΩ	8.6 kΩ	2.2 kΩ	630 Ω	966.4 Ω
P	228.4 mW	344.7 mW	20.98 mW	465.5 mW	0 mW	1.06 W

Challenge question: what circuit parameters will change if the diagonal wire in the right-hand side of the circuit is cut?
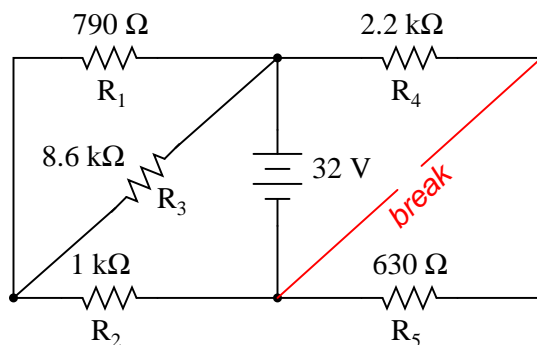
Notes 33

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 34

Complete the table of values for this circuit:

	R₁	R₂	R₃	R₄	R₅	Total
V						
I						
R	2 kΩ	1 kΩ	3.3 kΩ	4.7 kΩ	4.7 kΩ	
P						
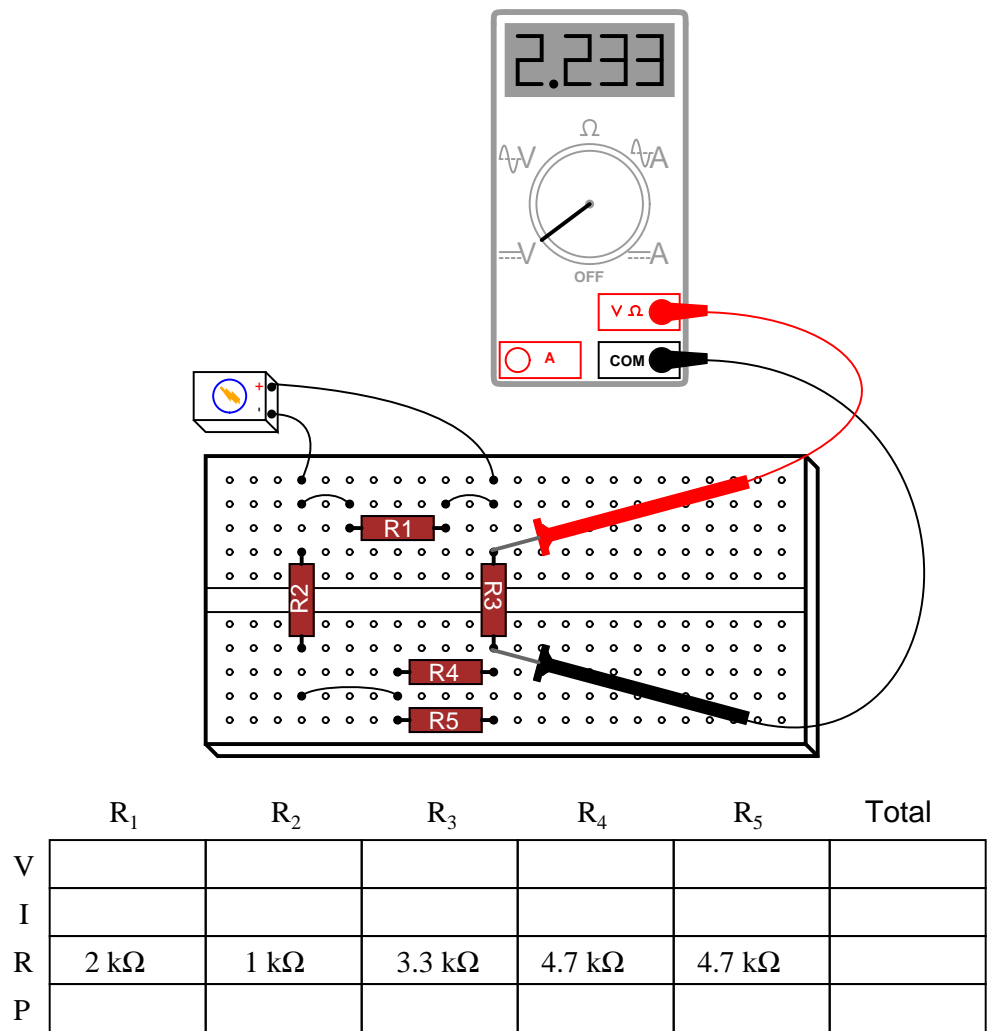
file 01769

Answer 34

	R₁	R₂	R₃	R₄	R₅	Total
V	4.500 V	676.6 mV	2.233 V	1.590 V	1.590 V	4.500 V
I	2.250 mA	676.7 µA	676.7 µA	338.3 µA	338.3 µA	2.927 mA
R	2 kΩ	1 kΩ	3.3 kΩ	4.7 kΩ	4.7 kΩ	1.538 kΩ
P	10.12 mW	457.9 µW	1.511 mW	538.0 µW	538.0 µW	13.17 mW

43

Ask your students to identify components in this series-parallel circuit that are guaranteed to share the same voltage, and components that are guaranteed to share the same current, without reference to any calculations. This is a good exercise in identifying parallel and series interconnections, respectively.

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In simple AC power systems, one of the two conductors is typically called the *hot*, while the other conductor is typically called the *neutral*. What distinguishes the "hot" conductor from the "neutral" conductor in such a system? In other words, what exactly determines whether a conductor will be called either "hot" or "neutral"?
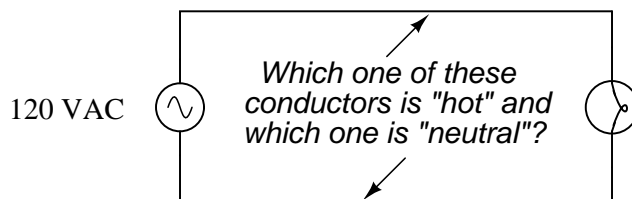
file 00312

Answer 35

The "neutral" conductor in an AC power system is always made electrically common with the earth, while the non-grounded conductor in an AC power system is called the "hot" conductor:
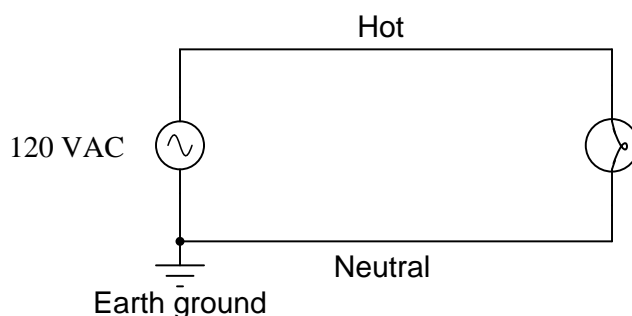
Follow-up question #1: in a power circuit such as this, there is typically a single fuse or circuit breaker for overcurrent protection. Identify the *best* location to place this fuse or circuit breaker in the circuit.

Follow-up question #2: explain how to use a multimeter to identify the "hot" and "neutral" conductors of a power system such as this.

Notes 35

Ask your students what safety issues surround the "hot" and "neutral" conductors, respectively. What do the names imply about relative hazard, and why is this? Ask them to explain how these safety considerations impact the placement of the overcurrent protection device.

Question 36

Is there any shock hazard posed to a person touching the metal case of this appliance? Explain your answer.

Wire "shorted" to metal case
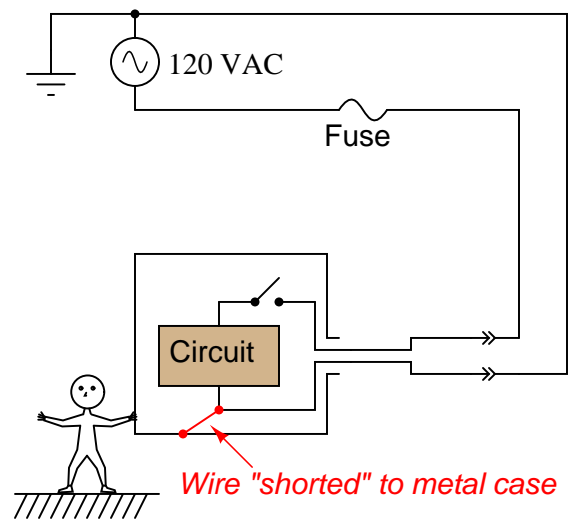
file 00313

Answer 36

No.

Follow-up question: what do the double-chevron symbols represent in a schematic diagram?

???

—»—

Notes 36

Even though no shock hazard presently exists in the circuit, ask your students to identify a condition where the "shorted" wire inside the appliance *would* pose a shock hazard. What would have to change in order for this wiring fault to pose a hazard?

Question 37

Is there any shock hazard posed to a person touching the metal case of this appliance? Explain your answer.
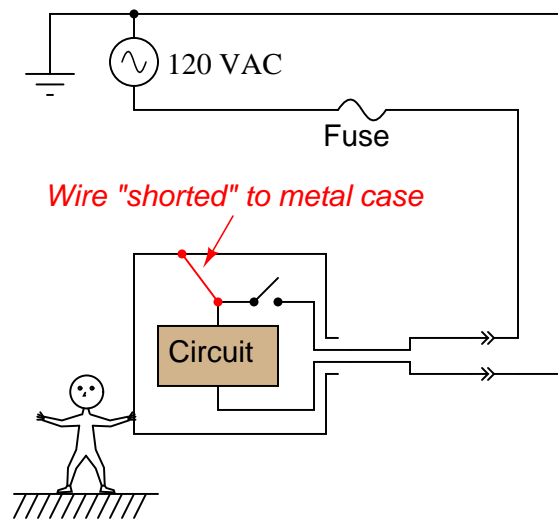
Answer 37

Yes, if the power switch is turned "on".

Notes 37

Aside from removing the "short" connecting the power conductor to the metal case of the appliance, what else could be done to eliminate the shock hazard in this scenario? Discuss this with your students.

Question 38

The metal case of this appliance is *grounded* by means of a third conductor:
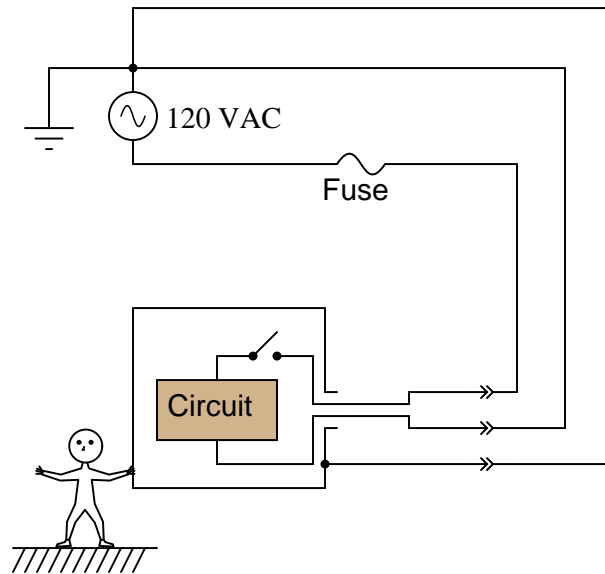
Explain how this grounding connection makes the appliance safer for anyone touching its metal case.

file 00315

Answer 38

The ground wire connection makes the metal case of the appliance electrically common with earth ground.

Notes 38

Ask your students to explain why the case's electrical commonality with earth makes it safer to touch. What do they know about "electrically common points" in a circuit, and voltage between those points?

Question 39

Special safety devices called *Ground Fault Current Interrupters*, or *GFCI's*, reduce the risk of shock hazard in electrical systems even where there is no ground conductor. Explain the operating principle of a GFCI. How are they able to sense a "ground fault" condition, so as to automatically turn off power to a receptacle?

file 00319

Answer 39

"GFCI" devices work on the principle of *differential current measurement* as a means to sense ground faults.

Notes 39

Be sure to discuss with your students what "differential current measurement" means, rather than assume they all researched the answer in greater detail than what is provided here. This really is a clever way to detect the presence of a ground fault!

You should point out to your students that GFCI power receptacles are commonly installed in "wet" areas of residences, such as in the bathroom and outside, where the hazard of ground-fault electric shock is maximized by the presence of water.

This question also provides an opportunity to discuss why the presence of water at a point of bodily contact increases the severity of electric shock.

Question 40

What would happen to the voltage drops across each resistor in this circuit if resistor R1 were to fail open?
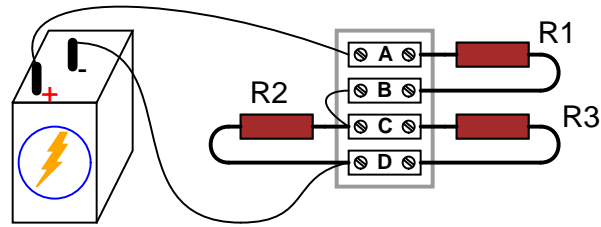
<u>file 01771</u>

Answer 40

If resistor R1 were to fail open (internally), it would drop the full battery voltage across its terminals, leaving no voltage for R2 or R3.

Notes 40

In most DC circuit failure scenarios, the effects of open or short faults may be estimated or even precisely predicted without having to perform any mathematical calculations. Of course, you could calculate the effects by using extremely large values for open resistors and 0 for shorted resistors, but that would be an inefficient use of time!

Question 41

What would happen to the voltage drops across each resistor in this circuit if either resistor R2 or R3 were to fail open?
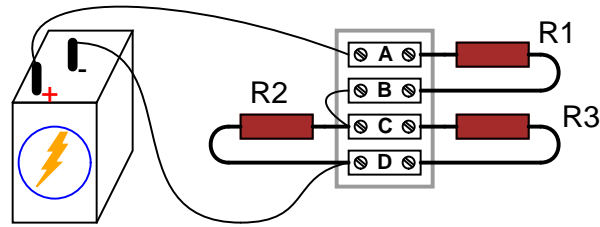
file 01772

Answer 41

If either resistor R2 or R3 were to fail open (internally), the voltage across both R2 *and* R3 would increase (but not to full battery voltage), leaving less voltage dropped across R1.

Follow-up question: explain why it doesn't matter which resistor (R2 or R3) fails open – the *qualitative* results for voltage (voltage increasing or decreasing, but not by any specific amount) will be the same.

Notes 41

I have found in teaching that many students loathe qualitative analysis, because they cannot let their calculators do the thinking for them. However, being able to judge whether a circuit parameter will increase, decrease, or remain the same after a component fault is an *essential* skill for proficient troubleshooting.

Question 42

What will happen to each resistor's voltage and current in this circuit if resistor R1 fails open? Provide individual answers for each resistor, please.
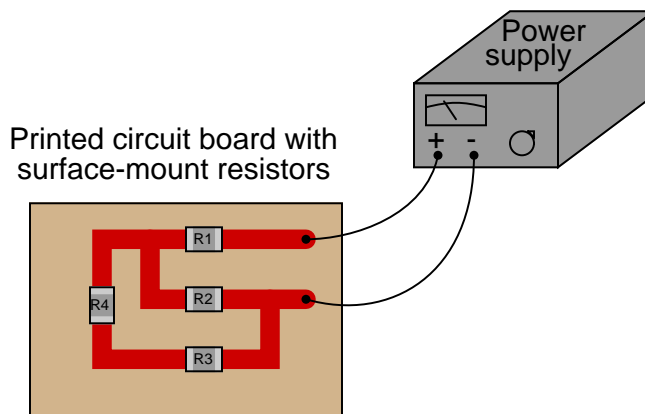
file 01775

Answer 42

If resistor R1 fails open . . .

- V_{R1} will increase to full supply voltage, I_{R1} will decrease to zero
- V_{R2} will decrease to zero, I_{R2} will decrease to zero
- V_{R3} will decrease to zero, I_{R3} will decrease to zero
- V_{R4} will decrease to zero, I_{R4} will decrease to zero

Follow-up question: note the order in which I list the qualitative effects of R2's shorted failure. Reading from the top of the list to the bottom reveals the sequence of my reasoning. Explain why I would come to the conclusions I did, in the order I did.

Notes 42

I have found in teaching that many students loathe qualitative analysis, because they cannot let their calculators do the thinking for them. However, being able to judge whether a circuit parameter will increase, decrease, or remain the same after a component fault is an *essential* skill for proficient troubleshooting.

Question 43

What will happen to each resistor's voltage and current in this circuit if resistor R2 fails shorted? Provide individual answers for each resistor, please.
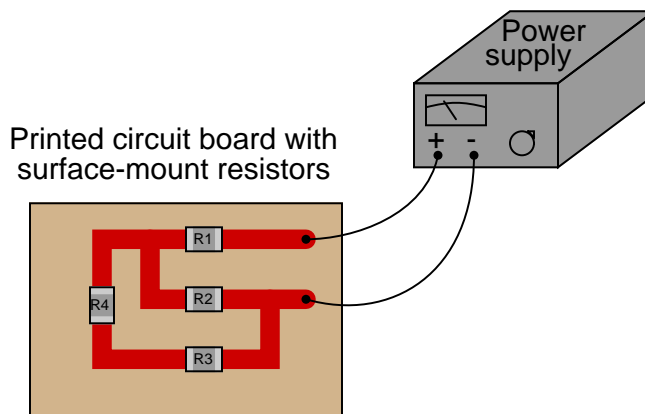
Answer 43

If resistor R2 fails shorted . . .

- V_{R2} will decrease to zero, I_{R2} will increase
- V_{R1} will increase to full supply voltage, I_{R1} will increase
- V_{R3} will decrease to zero, I_{R3} will decrease to zero
- V_{R4} will decrease to zero, I_{R4} will decrease to zero

Follow-up question: note the order in which I list the qualitative effects of R2's shorted failure. Reading from the top of the list to the bottom reveals the sequence of my reasoning. Explain why I would come to the conclusions I did, in the order I did.

Notes 43

I have found in teaching that many students loathe qualitative analysis, because they cannot let their calculators do the thinking for them. However, being able to judge whether a circuit parameter will increase, decrease, or remain the same after a component fault is an *essential* skill for proficient troubleshooting.

What will happen to each resistor's voltage in this circuit if resistor R4 fails shorted? Provide individual answers for each resistor, please.

Printed circuit board with
surface-mount resistors

Power
supply
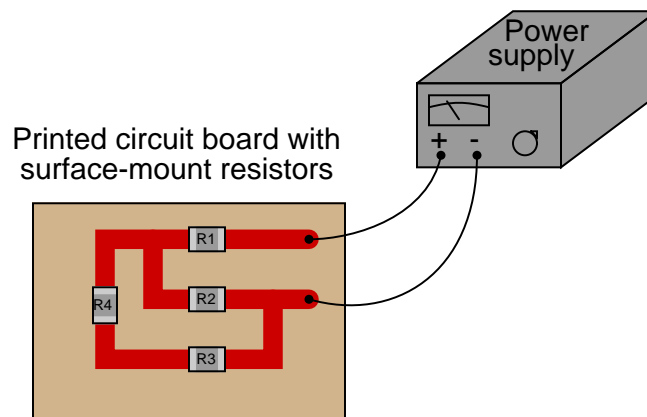
Also, comment on the practical likelihood of a resistor failing shorted, as opposed to failing open.
file 01773

Answer 44

If resistor R4 fails shorted . . .

- V_{R4} will decrease to zero
- V_{R1} will increase
- V_{R2} will decrease
- V_{R3} will increase

Follow-up question: resistors are actually far less likely to fail shorted as they are to fail *open*. However, this does not mean something else on a circuit board cannot go wrong to make it appear as though a resistor failed shorted! One example of such a fault is called a *solder bridge*. Explain what this is, any why it could produce the same effect as a resistor failing shorted.

Notes 44

I have found in teaching that many students loathe qualitative analysis, because they cannot let their calculators do the thinking for them. However, being able to judge whether a circuit parameter will increase, decrease, or remain the same after a component fault is an *essential* skill for proficient troubleshooting.

A student built this resistor circuit on a solderless breadboard, but made a mistake positioning resistor R3. It should be located one hole to the left instead of where it is right now:
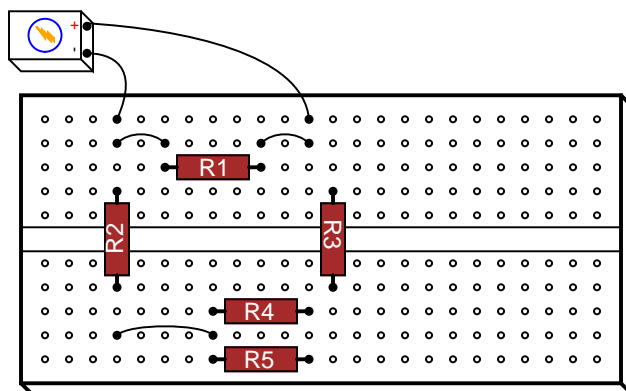
Determine what the voltage drop will be across each resistor, in this faulty configuration, assuming that the battery outputs 9 volts.

- $R_1 = 2$ kΩ $V_{R1} =$
- $R_2 = 1$ kΩ $V_{R2} =$
- $R_3 = 3.3$ kΩ $V_{R3} =$
- $R_4 = 4.7$ kΩ $V_{R4} =$
- $R_5 = 4.7$ kΩ $V_{R5} =$

file 01770

Answer 45

Rather than tell you each voltage drop, I'll give you this one hint: there is only *one* resistor in this breadboard circuit that has voltage across it! All the other resistors in this circuit are de-energized, thanks to the misplacement of resistor R3.

Notes 45

Tell your students that the fault shown in this question is quite typical. The hole spacings on solderless breadboards are small enough that it is surprisingly easy to mis-locate a component in the manner shown.

Point out to your students (if they haven't already noticed) that no calculations are necessary to answer this question! It may be answered through simple, qualitative analysis alone.

Question 46

Suppose you were designing a circuit that required two LEDs for "power on" indication. The power supply voltage is 15 volts, and each LED is rated at 1.6 volts and 20 mA. Calculate the dropping resistor sizes and power ratings:
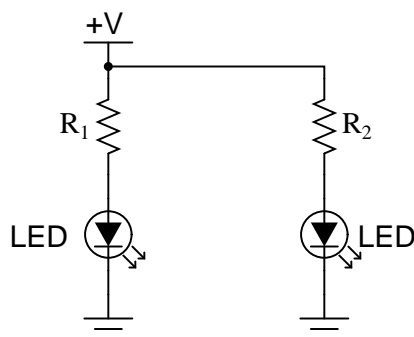
After doing this, a co-worker looks at your circuit and suggests a modification. Why not use a single dropping resistor for both LEDs, economizing the number of components necessary?
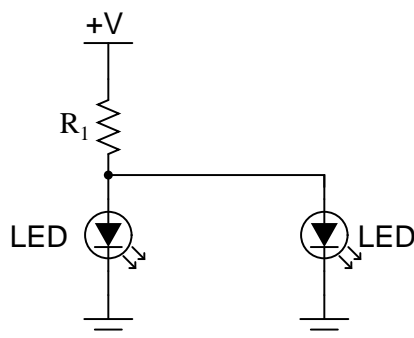
Re-calculate the dropping resistor ratings (resistance *and* power) for the new design.
file 01777

Answer 46

With two resistors: $R_1 = R_2 = 670\ \Omega$, rated for at least 0.268 watts (1/2 watt would be a practical rating).

With one resistor: $R_1 = 335\ \Omega$, rated for at least 0.536 watts (1 watt would be a practical rating).

Follow-up question: if there were no perfectly sized resistors sized 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 these applications? For example, if you needed 670 Ω but the closest options on hand were 680 Ω and 500 Ω, which resistance value would you select? Explain your answer.

Notes 46

If students are not yet familiar with the "+V" symbol used to denote the positive power supply connection in this schematic, let them know that this is a very common practice in electronic notation, just as it is common to use the ground symbol as a power supply connection symbol.

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 47

What will happen to the voltages across resistors R1 and R2 when the load is connected to the divider circuit?
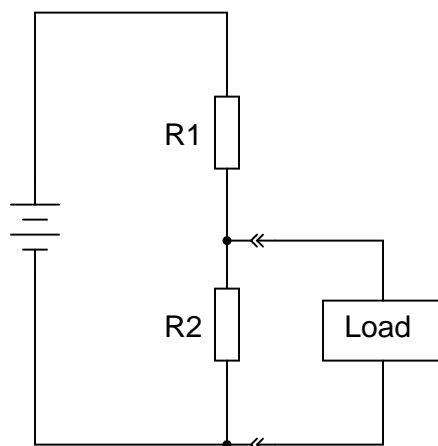
file 00358

Answer 47

When the load is connected across R2, R2's voltage will "sag" (decrease) while R1's voltage will rise (increase).

Notes 47

This is a very important concept to be learned about voltage divider circuits: how they respond to applications of load. Not a single calculation need be done to arrive at the answer for this question, so encourage your students to think *qualitatively* rather than *quantitatively*. Too many students have the habit of reaching for their calculators when faced with a problem like this, when they really just need to apply more thought.

Question 48

Calculate the voltmeter voltage in each of these circuits, assuming the wiper position is 25% up from the bottom:
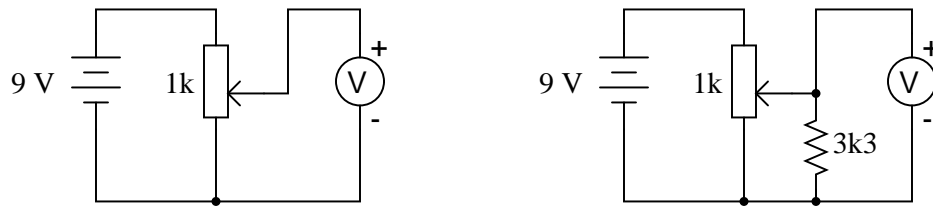
file 00342

Answer 48

Voltmeter in left-hand circuit = 2.25 volts
Voltmeter in right-hand circuit = 2.13 volts

Notes 48

Challenge your students to explain the significance of the reduced voltage from the potentiometer in the presence of a load (the 3.3 kΩ resistor). What impact could this effect have on a circuit we might build, where we expect the potentiometer to output a certain voltage corresponding to a specific wiper position?

Question 49

Which voltage divider circuit will be *least* affected by the connection of identical loads? Explain your answer.
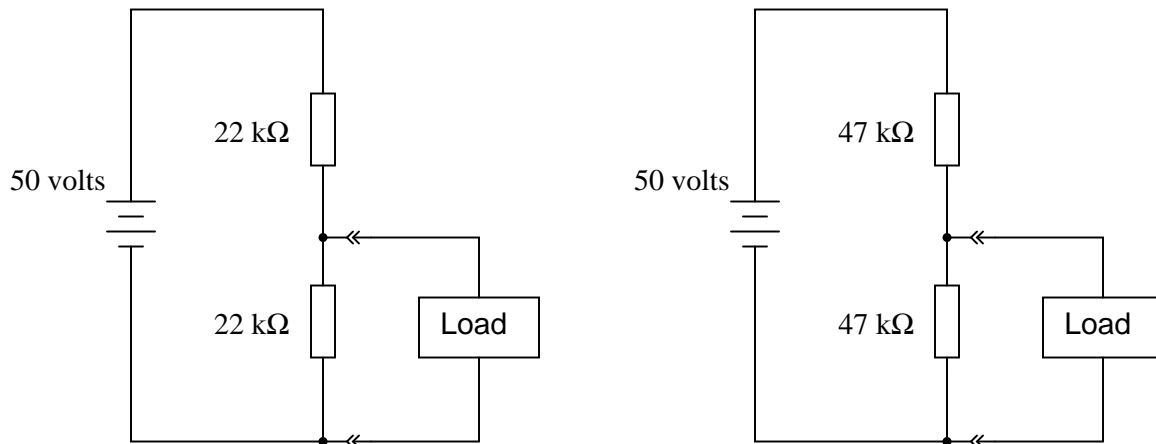
What advantage does the other voltage divider have over the circuit that is least affected by the connection of a load?

file 00359

Answer 49

The divider circuit with proportionately lower-value resistors will be affected least by the application of a load. The other divider circuit has the advantage of wasting less energy.

Notes 49

Some students may be confused by the lack of a resistance value given for the load. Without a given value, how can they proceed with any calculations? Ask the other students how they solved this problem: how did they overcome the problem of not having a load resistance value to work with?

Question 50

Size the resistor in this voltage divider circuit to provide 3.2 volts to the load, assuming that the load will draw 10 mA of current at this voltage:
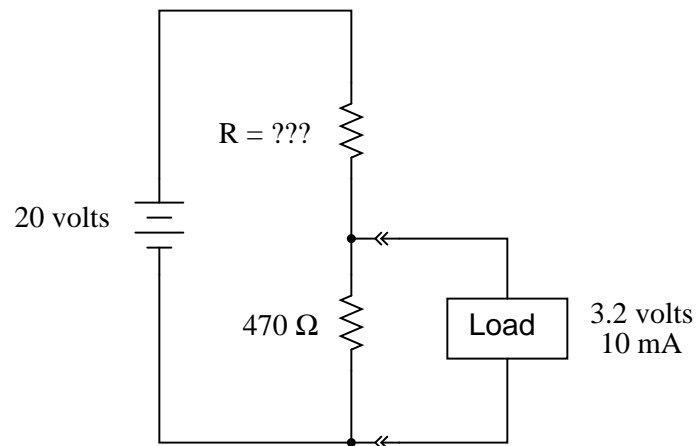
As part of your design, include the power dissipation ratings of both resistors.

file 01778

Answer 50

R = 1 kΩ. The 470 Ω resistor will fare well even with a (low) power dissipation rating of $\frac{1}{8}$ watt, though the 1 kΩ resistor will need to be rated in excess of 1/4 watt.

Notes 50

Ask your students what would change in this divider circuit if the load were to suddenly draw more, or less, current.

Question 51

Size the resistor in this voltage divider circuit to provide 5 volts to the load, assuming that the load will draw 75 mA of current at this voltage:
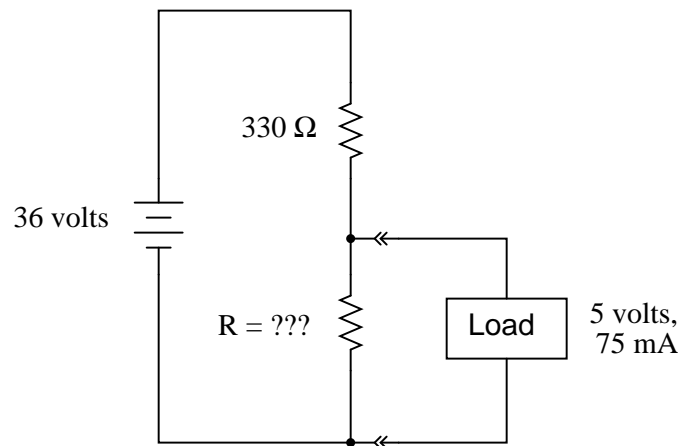
As part of your design, include the power dissipation ratings of both resistors.

<u>file 00363</u>

Answer 51

R = 264 Ω. The 330 Ω resistor must have a power dissipation rating of at least 3 watts, while the 264 Ω resistor will fare well even with a (low) power dissipation rating of $\frac{1}{8}$ watt.

Notes 51

Ask your students what would change in this divider circuit if the load were to suddenly draw more, or less, current.

Question 52

Size both resistors in this voltage divider circuit to provide 6 volts to the load, assuming that the load will draw 7 mA of current at this voltage, and to have a "bleeder" current of 1 mA going through R_2:
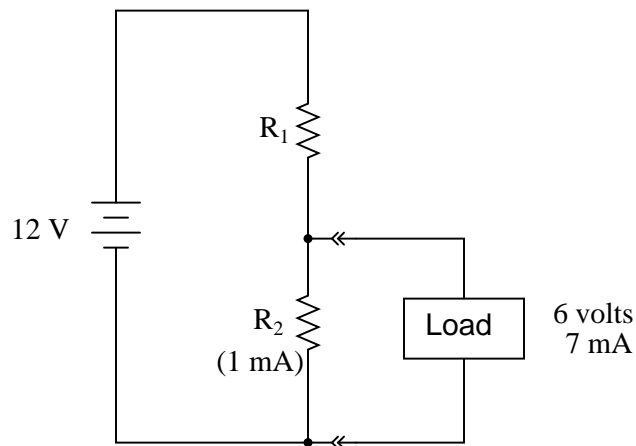
As part of your design, include the power dissipation ratings of both resistors.

file 01780

Answer 52

$R_1 = 750\ \Omega$ and $R_2 = 6\ \text{k}\Omega$. $\frac{1}{8}$ watt resistors are perfectly adequate to handle the dissipations in this circuit.

Notes 52

This may seem like a tricky problem to some students, as though it is lacking in information. All the necessary information is there, however. Students just need to think through all the laws of series-parallel circuits to piece together the necessary resistor values from the given specifications.

Question 53

Explain what will happen to the first load's voltage and current in this voltage divider circuit, as a second load is connected as shown:
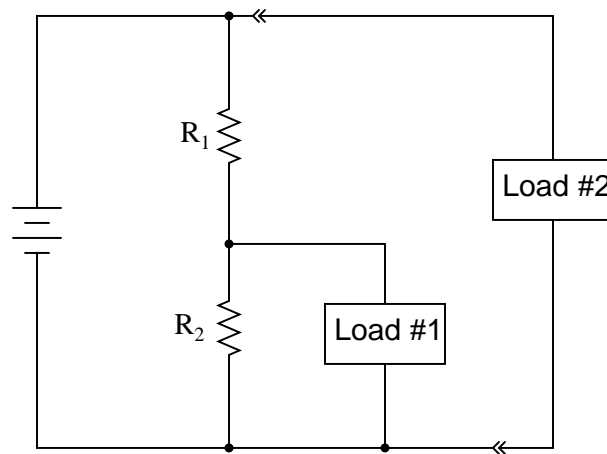
Answer 53

Ideally, the first load's voltage and current will remain unaffected by the connection of load #2 to the circuit. In reality, there will inevitably be a slight sag in the load voltage though, because the voltage source is bound to have *some* internal resistance.

Notes 53

It is important for students to realize that the second load constitutes a separate parallel branch in the circuit, which (ideally) has no effect on the rest of the circuit.

Question 54

Explain what will happen to the first load's voltage and current in this voltage divider circuit if the second load develops a short-circuit fault:
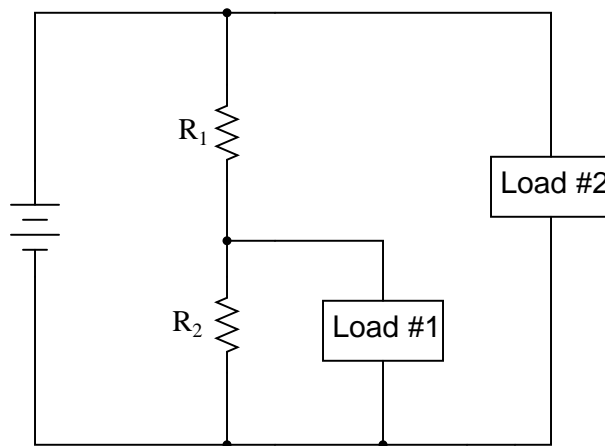
<u>file 01782</u>

Answer 54

Ideally, the first load's voltage and current will remain unaffected by any fault within load #2. However, in the event of a short-circuit in load #2, the source voltage will almost surely decrease due to its own internal resistance. In fact, it would not be surprising if the circuit voltage decreased almost to zero volts, if it is a "hard" short in load #2!

Notes 54

While it is important for students to realize that the second load constitutes a separate parallel branch in the circuit and therefore (ideally) has no effect on the rest of the circuit, it is crucial for them to understand that such an ideal condition is rare in the real world. When "hard" short-circuits are involved, even small internal source resistances become extremely significant.

Question 55

Size all three resistors in this voltage divider circuit to provide the necessary voltages to the loads, given the load voltage and current specifications shown:
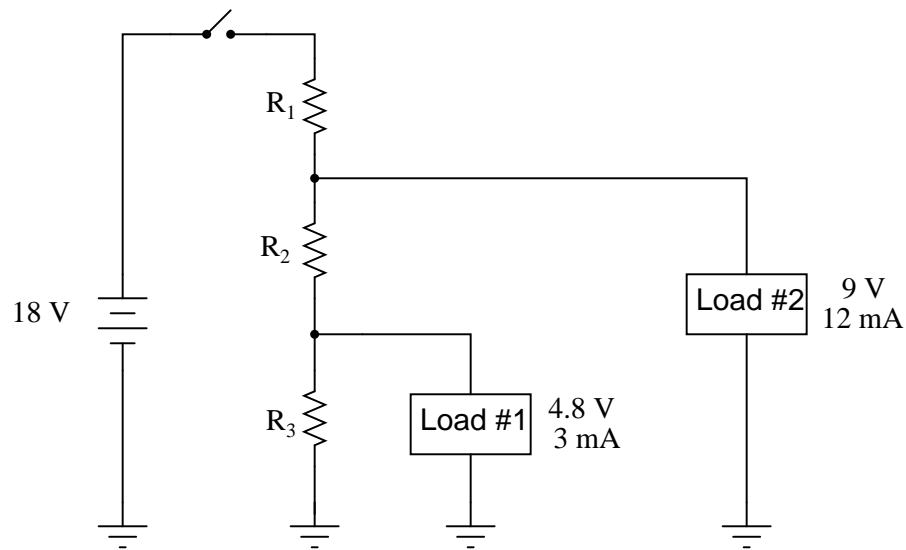
Assume a bleed current of 1.5 mA. As part of your design, include the power dissipation ratings of all resistors.

file 01783

Answer 55

$R_1 = 545.5\ \Omega$, rated for at least 148.5 mW dissipation ($\frac{1}{4}$ watt recommended).
$R_2 = 933.3\ \Omega$, $\frac{1}{8}$ watt power dissipation is more than adequate.
$R_3 = 3.2\ k\Omega$, $\frac{1}{8}$ watt power dissipation is more than adequate.

Notes 55

Nothing special to comment on here, just a straightforward voltage divider design problem.

Question 56

Old vacuum-tube based electronic circuits often required several different voltage levels for proper operation. An easy way to obtain these different power supply voltages was to take a single, high-voltage power supply circuit and "divide" the total voltage into smaller divisions.

These voltage divider circuits also made provision for a small amount of "wasted" current through the divider called a *bleeder* current, designed to discharge the high voltage output of the power supply quickly when it was turned off.

Design a high-voltage divider to provide the following loads with their necessary voltages, plus a "bleeder" current of 5 mA (the amount of current going through resistor R4):
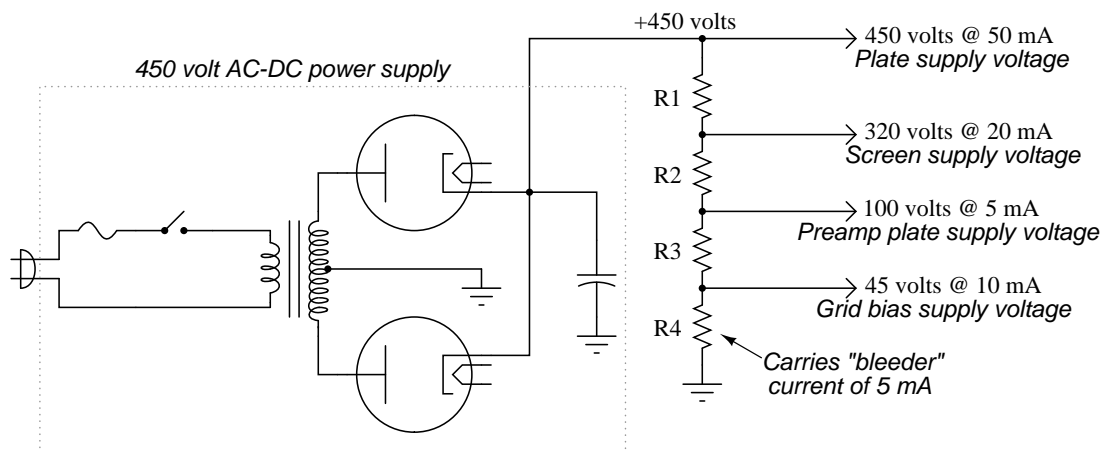
file 00364

Answer 56

$R_1 = 3.25$ kΩ

$R_2 = 11$ kΩ

$R_3 = 3.67$ kΩ

$R_4 = 9$ kΩ

Follow-up question: how would the various output voltages (plate, screen, preamp, etc.) be affected if the bleeder resistor were to fail open? You don't need to calculate anything, but just give a qualitative answer.

Notes 56

Be sure to ask your students *how* they obtained the solution to this problem. If no one was able to arrive at a solution, then present the following technique: simplify the problem (fewer resistors, perhaps) until the solution is obvious, then apply the same strategy you used to solve the obvious problem to the more complex versions of the problem, until you have solved the original problem in all its complexity.

Question 57

One of the resistors in this voltage divider circuit is failed open. Based on the voltage readings shown at each load, determine which one it is:
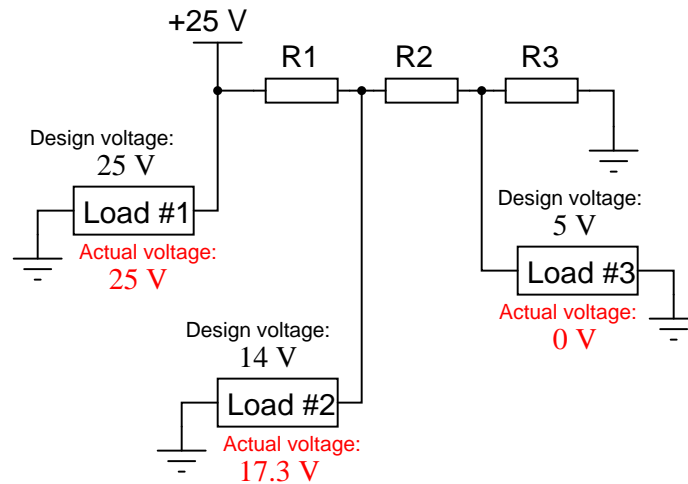
file 01784

Answer 57

Resistor R2 has failed open.

Notes 57

Discuss with your students how they were able to predict R2 was the faulty resistor. Is there any particular clue in the diagram indicating R2 as the obvious problem?

Question 58

One of the resistors in this voltage divider circuit is failed (either open or shorted). Based on the voltage readings shown at each load, determine which one and what type of failure it is:
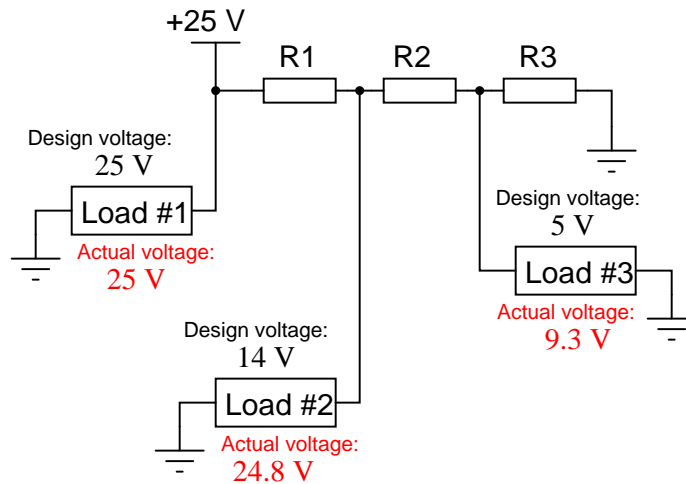
file 01785

Answer 58

Resistor R1 has failed shorted.

Follow-up question: note that the voltage at load #2 is not fully 25 volts. What does this indicate about the nature of R1's failure? Be as specific as you can in your answer.

Notes 58

Discuss with your students how they were able to predict R1 was the faulty resistor. Is there any particular clue in the diagram indicating R1 as the obvious problem? Some students may suspect an open failure in resistor R3 could cause the same effects, but there is a definite way to tell that the problem can *only* come from a short in R1 (hint: analyze resistor R2).

Explain that not all "shorted" failures are "hard" in the sense of being direct metal-to-metal wire connections. Quite often, components will fail shorted in a "softer" sense, meaning they still have some non-trivial amount of electrical resistance.

Question 59

Draw an equivalent schematic diagram for this circuit, then 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
R_5 = Brn, Blk, Org, Gld
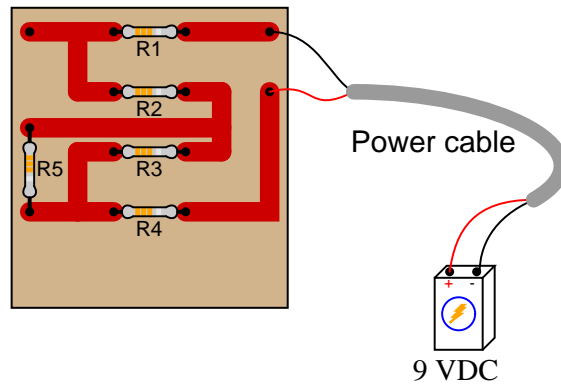
Compare the voltage dropped across R1, R2, R3, and R4, with and without R5 in the circuit. What general conclusions may be drawn from these voltage figures?

file 00356
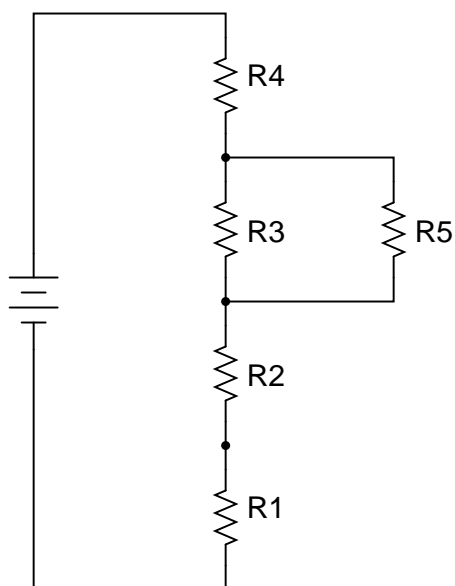
With R5 in the circuit:
$E_{R1} = 0.226$ volts
$E_{R2} = 7.109$ volts
$E_{R3} = 0.303$ volts
$E_{R4} = 1.36$ volts

Without R5 in the circuit:
$E_{R1} = 0.225$ volts
$E_{R2} = 7.05$ volts
$E_{R3} = 0.375$ volts
$E_{R4} = 1.35$ volts

Notes 59

Ask your students to describe the "with R5 / without R5" voltage values in terms of either *increase* or *decrease*. A general pattern should be immediately evident when this is done.

Question 60

Calculate all voltages and currents in this circuit:
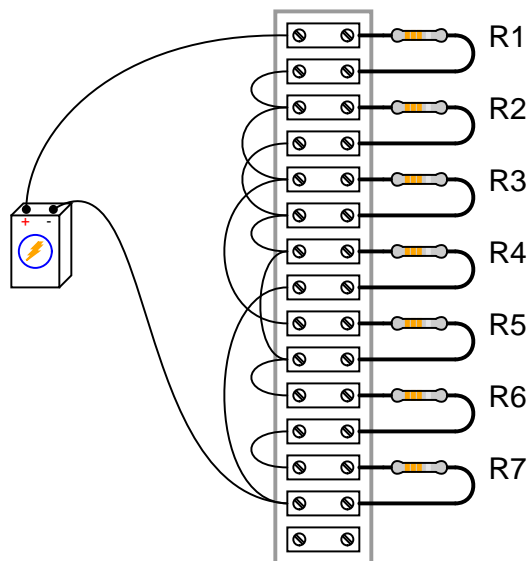
The battery voltage is 15 volts, and the resistor values are as follows:

R1 = 1 kΩ
R2 = 3.3 kΩ
R3 = 4.7 kΩ
R4 = 2.5 kΩ
R5 = 10 kΩ
R6 = 1.5 kΩ
R7 = 500 Ω

file 00406

Answer 60

R1 = 1 kΩ	E_{R1} = 4.016 V	I_{R1} = 4.016 mA
R2 = 3.3 kΩ	E_{R2} = 6.522 V	I_{R2} = 1.976 mA
R3 = 4.7 kΩ	E_{R3} = 6.522 V	I_{R3} = 1.388 mA
R4 = 2.5 kΩ	E_{R4} = 4.462 V	I_{R4} = 1.785 mA
R5 = 10 kΩ	E_{R5} = 6.522 V	I_{R5} = 652 μA
R6 = 1.5 kΩ	E_{R6} = 3.347 V	I_{R6} = 2.231 mA
R7 = 500 Ω	E_{R7} = 1.116 V	I_{R7} = 2.231 mA

Your students will benefit greatly from having a clean schematic diagram to work off of. However, do not supply this for them! Let them figure out how to derive a schematic diagram from the illustrated circuit.

Students often have difficulty formulating a method of solution: determining what steps to take to get from the given conditions to a final answer. While it is helpful at first for you (the instructor) to show them, it is bad for you to show them too often, lest they stop thinking for themselves and merely follow your lead. A teaching technique I have found very helpful is to have students come up to the board (alone or in teams) in front of class to write their problem-solving strategies for all the others to see. They don't have to actually do the math, but rather outline the steps they would take, in the order they would take them.

By having students <u>outline their problem-solving strategies</u>, everyone gets an opportunity to see multiple methods of solution, and you (the instructor) get to see how (and if!) your students are thinking. An especially good point to emphasize in these "open thinking" activities is how to check your work to see if any mistakes were made.

Competency: **Kirchhoff's Voltage Law**   Version:

Schematic

Given conditions

V_{supply} = Any whole-number value evenly divisible by 4

$R_1 = R_2 = R_3 = R_4 =$

Parameters

	Predicted	Measured			Predicted	Measured
V_{R1}				V_{R3}		
V_{R2}				V_{R4}		
V_{BD}				V_{DA}		
V_{BE}				V_{DC}		
V_{AC}				V_{CE}		

Note: "V_{BD}" means voltage measured with the red
lead touching **B** and the black lead touching **D**.

Answer 61

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

Notes 61

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: **Wheatstone bridge**   Version:

Schematic

Given conditions

$V_{supply} =$ $R_1 =$ $R_2 =$ $R_3 =$

Parameters

                Predicted   Measured

R_{pot} (balance)

I_{supply}

Fault analysis

Suppose component ☐ fails   ☐ open   ☐ other _____
                            ☐ shorted

What will happen in the circuit?

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 kΩ and 100 kΩ (1k5, 2k2, 2k7, 3k3, 4k7, 5k1, 6k8, 10k, 22k, 33k, 39k 47k, 68k, etc.), and be sure to specify a potentiometer value in excess of the amount required to balance the bridge.

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-parallel DC resistor circuit**   Version:

Schematic

Given conditions

$V_{supply} =$ $R_1 =$ $R_2 =$ $R_3 =$ $R_4 =$

Parameters

	Predicted	Measured		Predicted	Measured
I_{supply}			I_{R1}		
V_{R1}			I_{R2}		
V_{R2}			I_{R3}		
V_{R3}			I_{R4}		
V_{R4}					

Fault analysis

Suppose component [   ] fails   ☐ open   ☐ other _____
                                      ☐ shorted

What will happen in the circuit?

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 kΩ and 100 kΩ (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.

Competency: **Loaded voltage divider**   Version:

Schematic

Given conditions

$V_{supply} =$ $R_1 =$ $R_2 =$ $R_3 =$ $R_{load1} =$ $R_{load2} =$

Parameters

	Predicted	Measured			Predicted	Measured
I_{supply}				I_{load1}		
V_A				I_{load2}		
V_B				I_{bleed}		

Fault analysis

Suppose component [   ] fails   ☐ open   ☐ other _____

                                 ☐ shorted

What will happen in the circuit?

file 01609

Answer 64

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

Notes 64

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

I have used this circuit as both a "quick" lab exercise and a troubleshooting exercise, using values of 10 kΩ for R1, R2, and R3; 15 kΩ for R(load1); 22 kΩ for R(load2); and 6 volts for the power supply. Of course, these component values are not critical, but they do provide easy-to measure voltages and currents without incurring excessive impedances that would cause significant voltmeter loading problems.

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. *What I did and/or noticed . . .*)	Conclusions (i.e. *What this tells me . . .*)

file 03933

Answer 65

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

Notes 65

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 66

NAME: _____ **Troubleshooting Grading Criteria**

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

<u>100 %</u> *(Must meet or exceed all criteria listed)*
  A. Absolutely flawless procedure
  B. No unnecessary actions or measurements taken

<u>90 %</u> *(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

<u>80 %</u> *(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)

<u>70 %</u> *(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)

<u>65 %</u> *(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

<u>60 %</u> *(Must meet or exceed these criteria)*
  A. Fault accurately identified
  B. Safe procedures used at all times

<u>50 %</u> *(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

<u>0 %</u> *(If <u>any</u> of the following conditions are true)*
  A. Unsafe procedure(s) used at any point

  <u>file 03932</u>

Answer 66

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

Notes 66

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 67

Examine these two variable-resistance (*rheostat*) networks, each one with a large-range potentiometer and a small-range potentiometer:
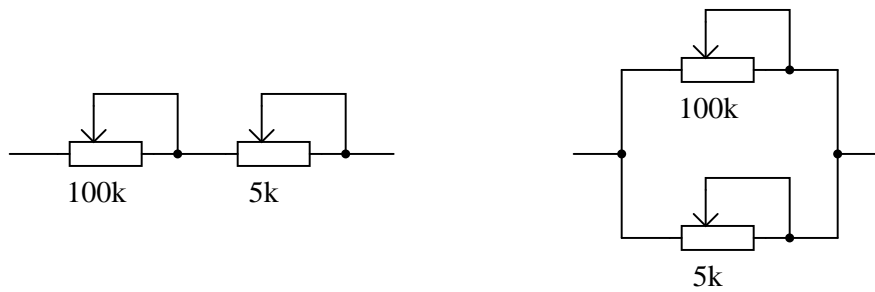
For each network, determine which pot is the *coarse* adjustment and which pot is the *fine* adjustment for total resistance.

file 03454

Answer 67

Series network

100k = Coarse adjustment ; 5k = Fine adjustment

Parallel network

5k = Coarse adjustment ; 100k = Fine adjustment

Notes 67

The purpose of this question is for students to identify the dominant resistance values in series versus parallel circuits. Remind your students if necessary that $R_{total} > R_n$ for series and $R_{total} < R_n$ for parallel (where R_n represents any particular resistor in the network).

Question 68

Identify which of these components are connected directly in series with each other, and which are connected directly in parallel with each other:
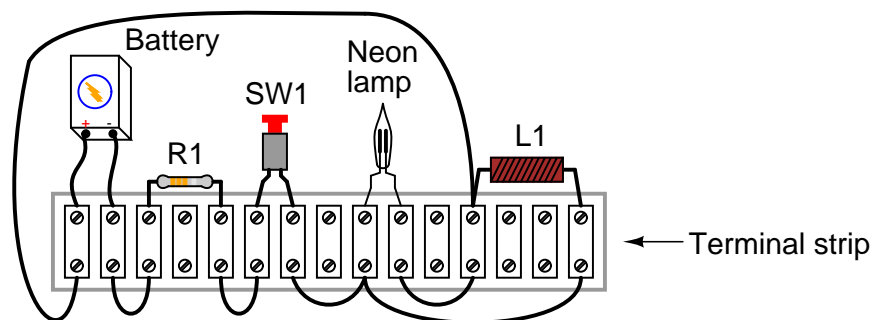
file 00032

Answer 68

Connected directly in series: *Battery, R1, and SW1.* Connected directly in parallel: *Neon lamp and L1.*

Notes 68

Students must have a firm understanding of what constitutes "series" versus "parallel" in real circuits. Here is a place where some students will feel uncomfortable because the textbook definitions they memorized are easier said than applied. It is imperative that students have a strong working knowledge of terms, and do not simply memorize definitions.

Question 69

Complete the table of values for this circuit:
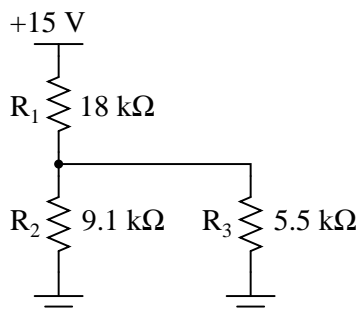
	R₁	R₂	R₃	Total
V				
I				
R	18 kΩ	9.1 kΩ	5.5 kΩ	
P				

file 03268

Answer 69

	R₁	R₂	R₃	Total
V	12.6 V	2.4 V	2.4 V	15 V
I	700 µA	263.7 µA	436.3 µA	700 µA
R	18 kΩ	9.1 kΩ	5.5 kΩ	21.43 kΩ
P	8.82 mW	632.8 µW	1.05 mW	10.5 mW

Follow-up question: how much voltage is present at the node (junction point) where R_1, R_2, and R_3 all connect together, measured with reference to ground?

86
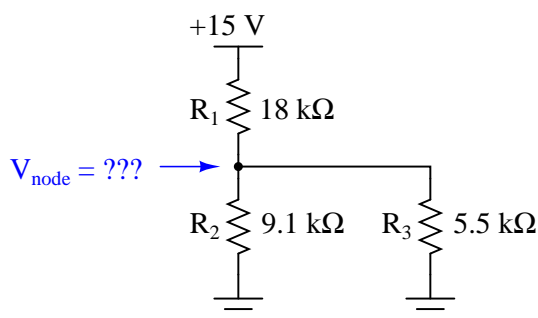
A noteworthy feature of this circuit's schematic is how the power supply connections are shown. Unlike many of my schematic diagrams, I do not show a "battery" symbol here for a voltage source. Instead, I show power supply "rail" symbols (flat line and a ground symbol). Let your students know that this is very common symbolism in modern schematics, and that is merely saves having to draw lines to a voltage source symbol (as well as the source symbol itself).

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.

Students often have difficulty formulating a method of solution: determining what steps to take to get from the given conditions to a final answer. While it is helpful at first for you (the instructor) to show them, it is bad for you to show them too often, lest they stop thinking for themselves and merely follow your lead. A teaching technique I have found very helpful is to have students come up to the board (alone or in teams) in front of class to write their problem-solving strategies for all the others to see. They don't have to actually do the math, but rather outline the steps they would take, in the order they would take them.

By having students outline their problem-solving strategies, everyone gets an opportunity to see multiple methods of solution, and you (the instructor) get to see how (and if!) your students are thinking. An especially good point to emphasize in these "open thinking" activities is how to check your work to see if any mistakes were made.

Question 70

Complete the table of values for this circuit:

	R_1	R_2	R_3	Total
V				
I				
R	180 Ω	100 Ω	250 Ω	
P				

file 03259

Answer 70

	R_1	R_2	R_3	Total
V	5.01 V	1.99 V	1.99 V	7 V
I	27.84 mA	19.89 mA	7.95 mA	27.84 mA
R	180 Ω	100 Ω	250 Ω	251.4 Ω
P	139.5 mW	39.55 mW	15.82 mW	194.9 mW

Notes 70

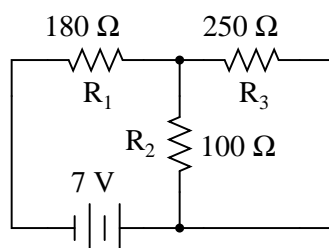Discuss with your students what a good procedure might be for calculating the unknown values in this problem, and also how they might check their work.

Students often have difficulty formulating a method of solution: determining what steps to take to get from the given conditions to a final answer. While it is helpful at first for you (the instructor) to show them, it is bad for you to show them too often, lest they stop thinking for themselves and merely follow your lead. A teaching technique I have found very helpful is to have students come up to the board (alone or in teams) in front of class to write their problem-solving strategies for all the others to see. They don't have to actually do the math, but rather outline the steps they would take, in the order they would take them.

By having students outline their problem-solving strategies, everyone gets an opportunity to see multiple methods of solution, and you (the instructor) get to see how (and if!) your students are thinking. An especially good point to emphasize in these "open thinking" activities is how to check your work to see if any mistakes were made.

Question 71

Complete the table of values for this circuit:

	R₁	R₂	R₃	R₄	Total
V					11 V
I					
R	1 kΩ	500 Ω	150 Ω	450 Ω	
P					

file 03257

Answer 71

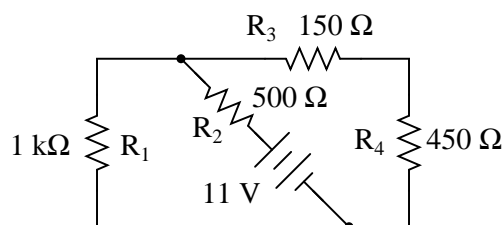|	R₁	R₂	R₃	R₄	Total
V	4.714 V	6.286 V	1.179 V	3.536 V	11 V
I	4.714 mA	12.57 mA	7.857 mA	7.857 mA	12.57 mA
R	1 kΩ	500 Ω	150 Ω	450 Ω	875 Ω
P	22.22 mW	79.02 mW	9.26 mW	27.78 mW	138.3 mW

Notes 71

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.

Students often have difficulty formulating a method of solution: determining what steps to take to get from the given conditions to a final answer. While it is helpful at first for you (the instructor) to show them, it is bad for you to show them too often, lest they stop thinking for themselves and merely follow your lead. A teaching technique I have found very helpful is to have students come up to the board (alone or in teams) in front of class to write their problem-solving strategies for all the others to see. They don't have to actually do the math, but rather outline the steps they would take, in the order they would take them.

By having students outline their problem-solving strategies, everyone gets an opportunity to see multiple methods of solution, and you (the instructor) get to see how (and if!) your students are thinking. An especially good point to emphasize in these "open thinking" activities is how to check your work to see if any mistakes were made.

Question 72

Complete the table of values for this circuit:

	R₁	R₂	R₃	Total
V				
I				10 mA
R	4.7 kΩ	2.7 kΩ	3.9 kΩ	
P				

file 03256

Answer 72

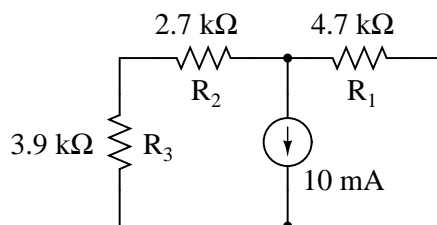|	R₁	R₂	R₃	Total
V	27.45 V	11.23 V	16.22 V	27.45 V
I	5.841 mA	4.159 mA	4.159 mA	10 mA
R	4.7 kΩ	2.7 kΩ	3.9 kΩ	2.745 kΩ
P	160.3 mW	46.71 mW	67.47 mW	274.5 mW

Notes 72

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.

Students often have difficulty formulating a method of solution: determining what steps to take to get from the given conditions to a final answer. While it is helpful at first for you (the instructor) to show them, it is bad for you to show them too often, lest they stop thinking for themselves and merely follow your lead. A teaching technique I have found very helpful is to have students come up to the board (alone or in teams) in front of class to write their problem-solving strategies for all the others to see. They don't have to actually do the math, but rather outline the steps they would take, in the order they would take them.

By having students outline their problem-solving strategies, everyone gets an opportunity to see multiple methods of solution, and you (the instructor) get to see how (and if!) your students are thinking. An especially good point to emphasize in these "open thinking" activities is how to check your work to see if any mistakes were made.

Determine which light bulb(s) will glow brightly, and which light bulb(s) will glow dimly (assuming all light bulbs are identical).

Solar panel
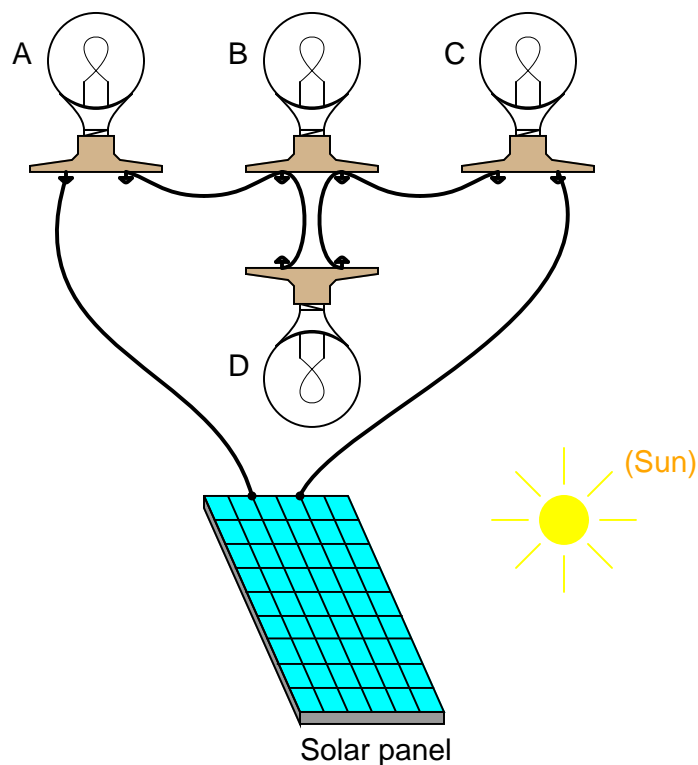
<u>file 00040</u>

Answer 73

Bulbs "A" and "C" will glow brightly, while bulbs "B" and "D" will glow dimly.

Follow-up question: explain why bulbs "A" and "C" will become dimmer (less bright) if the filament in bulb "D" fails open.

Notes 73

This question provides an opportunity to discuss current in series- versus parallel-connected components. The follow-up question challenges students to qualitatively analyze the circuit.

Question 74

Calculate the output voltages of these two voltage divider circuits (from point **A** to ground, and from point **B** to ground:
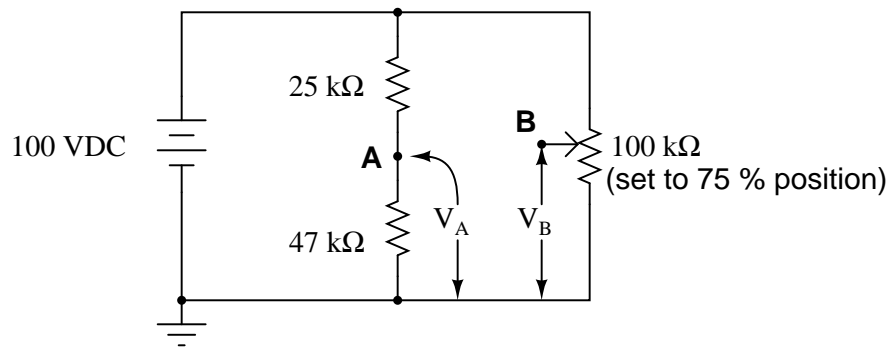
Now, calculate the voltage between points **A** (red lead) and **B** (black lead).

file 00542

Answer 74

$V_A = + 65.28$ V

$V_B = + 75.0$ V

$V_{AB} = - 9.72$ V

Notes 74

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).

Question 75

What is a *polarized* power plug, and what does this have to do with electrical safety?

file 00321

Answer 75

A "polarized" power plug is one that is designed to plug into a power receptacle one way only (i.e. it cannot be reversed). Usually this is accomplished by the use of one "prong" on the plug being wider than the other, with matching-width holes in the receptacle.

Notes 75

Discuss with your students the relative merits of polarized plugs versus three-wire plugs that provide a hard ground connection with the frame of the electrical device. Which plug type provides a greater level of safety? Why?

The presence of a "ground" wire increases the degree of electrical safety for anyone using an electrical appliance. It entails having a third "prong" on the power plug, connecting with a third hole on the power receptacle, which connects to a separate wire running all the way back to the power system's grounding point:
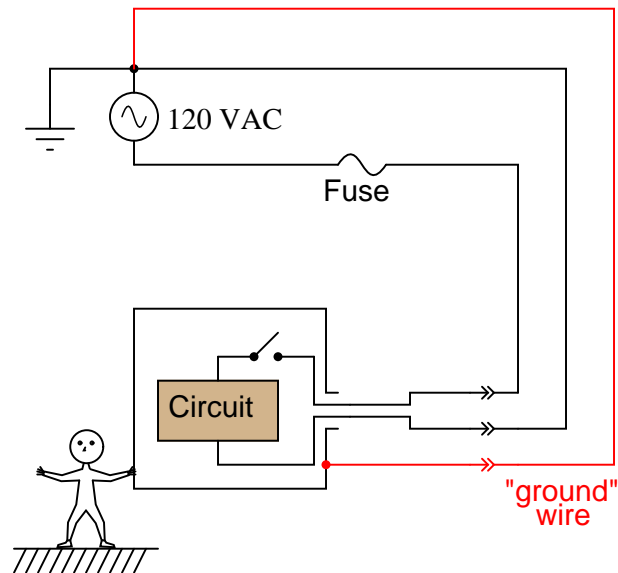
But why not eliminate all that extra wiring, and simply connect the third hole on the power receptacle to the "neutral" wire?
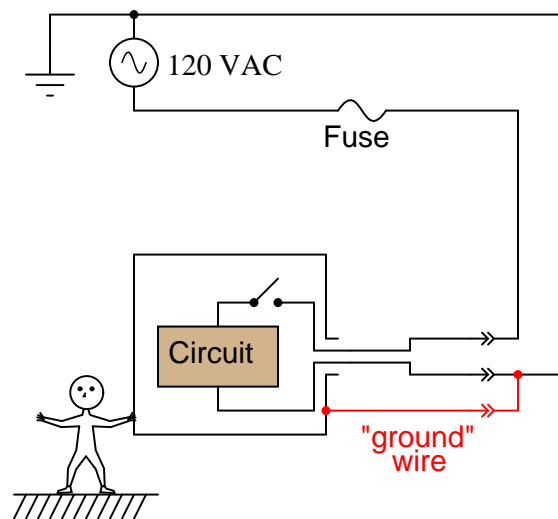
Why would this idea be unwise?

file 00317

Answer 76

Using the neutral conductor as a safety ground is a bad idea, in the event the neutral wire were to ever fail "open" between the receptacle and the system ground point.

Discuss this particular failure scenario with your students, drawing a schematic diagram if necessary. Not only does this illustrate the importance of having a separate ground conductor, but it also shows how the neutral wire can potentially be unsafe to touch!

Question 77

Determine whether or not a shock hazard exists for a person standing on the ground, by touching any one of the points labeled in this circuit:
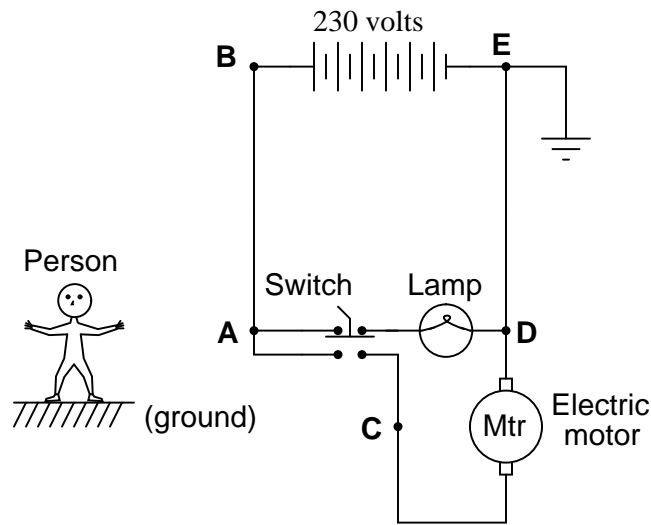
- Point "A"
- Point "B"
- Point "C"
- Point "D"
- Point "E"

file 00303

Answer 77

- Point "A" *dangerous to touch*
- Point "B" *dangerous to touch*
- Point "C" *dangerous to touch when motor is turned on*
- Point "D" *safe to touch*
- Point "E" *safe to touch*

Notes 77

One suggestion for approaching this question is to ask your students to identify which of the power source conductors is "hot" and which one is "neutral," then identify which points in the circuit are electrically common to either one or the other source conductors.

Question 78

Determine whether or not a shock hazard exists for a person standing on the ground, by touching any one of the points labeled in this faulted circuit:

- Point "A"
- Point "B"
- Point "C"
- Point "D"
- Point "E"

file 00304

Answer 78

- Point "A" *dangerous to touch*
- Point "B" *dangerous to touch*
- Point "C" *dangerous to touch*
- Point "D" *dangerous to touch*
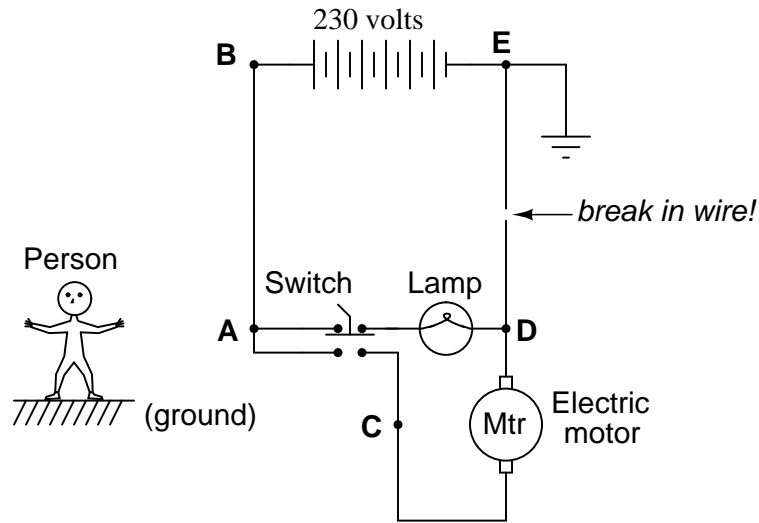- Point "E" *safe to touch*

Notes 78

The purpose of this question is to get students to realize that safe conditions may turn into unsafe conditions in a circuit, given certain wiring failures!

97

Question 79

Suppose a GFCI is rated to "trip" with a ground fault current of 5 mA. Given a source voltage of 115 volts, calculate the ground fault resistance range required to trip.

file 00337

Answer 79

Any resistance value between 0 Ω to 23 kΩ

Notes 79

This question requires the use of Ohm's Law, but to calculate a *range* of resistance values and not just a singular value. All students should be able to obtain the figure of 23 kΩ, but some may be confused as to whether this is a minimum or a maximum resistance value needed to trip the GFCI. Discuss this with your students, asking them to explain how we know 23 kΩ is a maximum figure and not a minimum figure.

Question 80

One of the resistors in this voltage divider circuit is failed open. Based on the voltage readings shown at each load, determine which one it is:
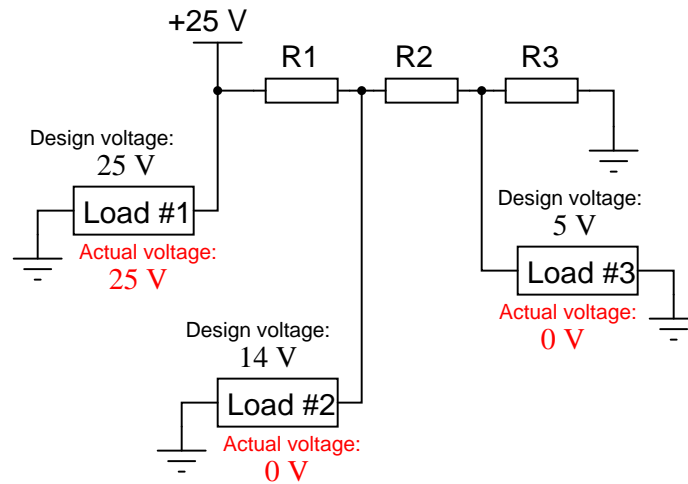
file 03262

Answer 80

Resistor R1 has failed open.

Notes 80

Discuss with your students how they were able to predict R1 was the faulty resistor. Is there any particular clue in the diagram indicating R1 as the obvious problem?

Question 81

Determine the voltages (with respect to ground) at points **A** and **B** in this circuit under four different conditions: both loads off, load 1 on (only), load 2 on (only), and both loads on:

Voltage	Both loads off	Load 1 on (only)	Load 2 on (only)	Both loads on
V_A				
V_B				

file 03260

Answer 81

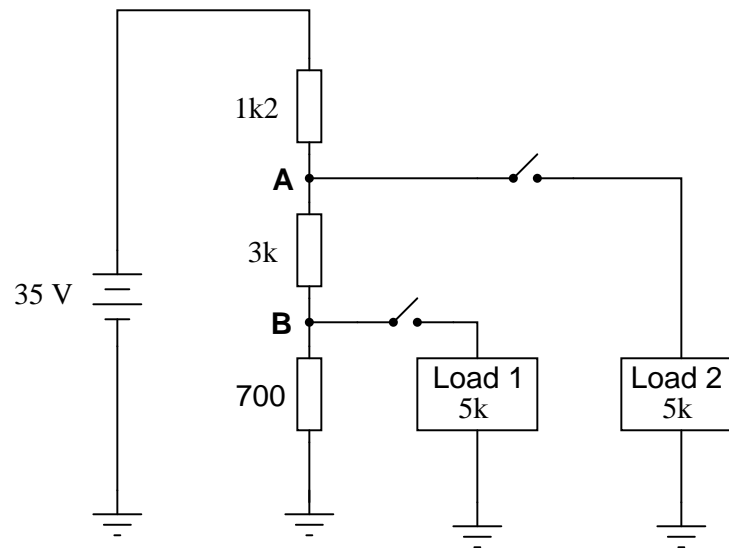| Voltage	Both loads off	Load 1 on (only)	Load 2 on (only)	Both loads on
V_A	26.4 volts	26.3 volts	22.4 volts	22.3 volts
V_B	5 volts	4.46 volts	4.23 volts	3.78 volts

Notes 81

Students will have to re-consider (and possible re-draw) the circuit for each loading condition, which is one of the major points of this question. The fact that a circuit can "change" just by throwing a switch is an important concept for electronics students to grasp.

Another concept employed in this question is that of voltages specified at single points with an implied reference of ground. Note to students how each voltage was simply referenced by a single letter, either **A** or **B**. Of course there is no such thing as voltage at a single point in any circuit, so we need another point to reference, and that point is ground. This is *very* commonly seen in electronic circuits of all types, and is a good thing to be exposed to early on in one's electronics education.

A much less obvious point of this question is to subtly introduce the concept of discrete states (loading conditions) available with a given number of boolean elements (switches). Given two load switches, there are four possible states of circuit loading, previewing binary states in digital circuits.

When the 5 kΩ potentiometer in this circuit is set to its 0%, 25%, 50%, 75%, and 100% positions, the following output voltages are obtained (measured with respect to ground, of course):
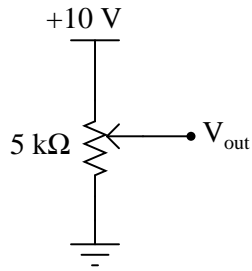
- At 0% setting, $V_{out} = 0$ V
- At 25% setting, $V_{out} = 2.5$ V
- At 50% setting, $V_{out} = 5$ V
- At 75% setting, $V_{out} = 7.5$ V
- At 100% setting, $V_{out} = 10$ V

Calculate what the output voltages will be if a 1 kΩ load resistor is connected between the "V_{out}" terminal and ground:
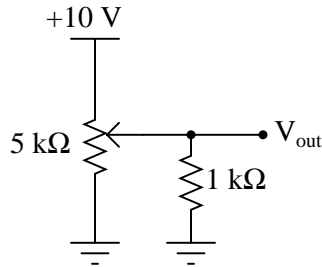
- At 0% setting, $V_{out} =$
- At 25% setting, $V_{out} =$
- At 50% setting, $V_{out} =$
- At 75% setting, $V_{out} =$
- At 100% setting, $V_{out} =$

file 01779

Answer 82

- At 0% setting, $V_{out} = 0$ V
- At 25% setting, $V_{out} = 1.29$ V
- At 50% setting, $V_{out} = 2.22$ V
- At 75% setting, $V_{out} = 3.87$ V
- At 100% setting, $V_{out} = 10$ V

Notes 82

This question is really nothing more than five loaded voltage divider problems packed into one! It is a very practical question, as potentiometers are very often used as variable voltage dividers, and students must realize the effects a load resistance will have on the characteristics of such dividers. Point out to them the extreme nonlinearity created by the inclusion of the load resistance.

Question 83

As adjustable devices, potentiometers may be set at a number of different positions. It is often helpful to express the position of a potentiometer's wiper as a *fraction* of full travel: a number between 0 and 1, inclusive. Here are several pictorial examples of this, with the variable m designating this travel value (the choice of which alphabetical character to use for this variable is arbitrary):

$$m = 0 \qquad m = 0.25 \qquad m = 0.5 \qquad m = 0.75 \qquad m = 1$$
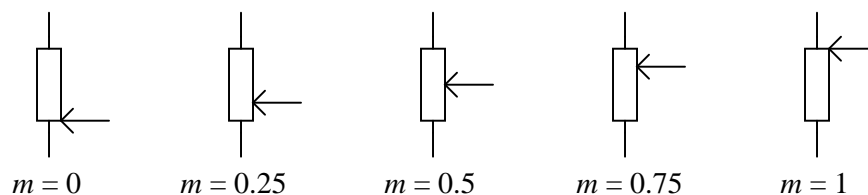
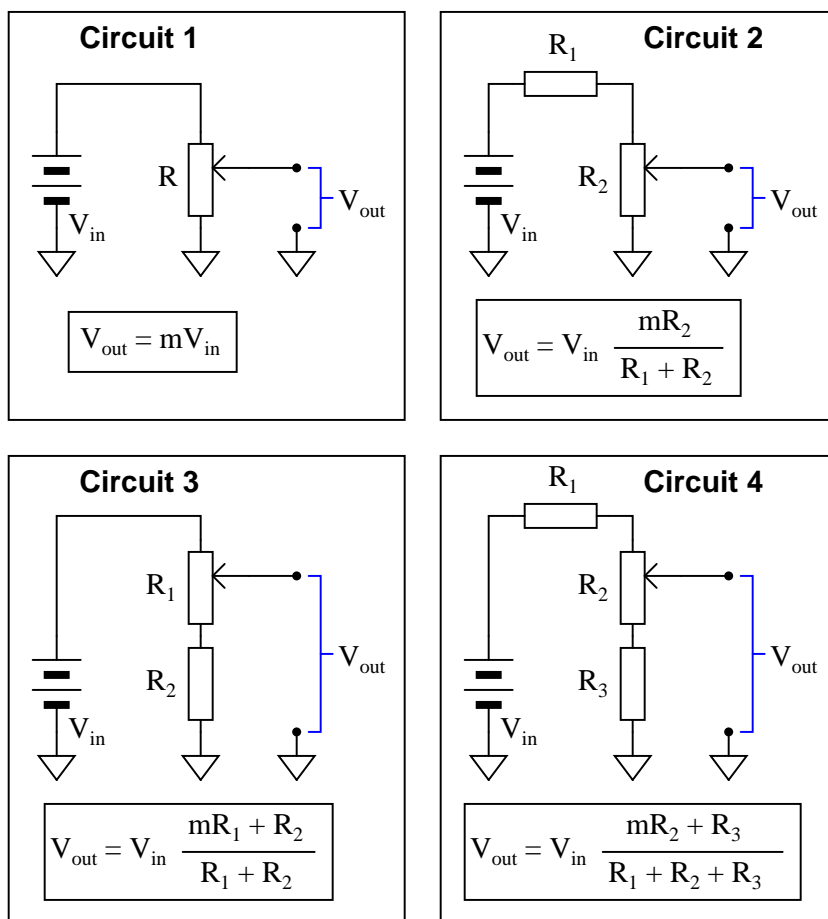Using an algebraic variable to represent potentiometer position allows us to write equations describing the outputs of voltage divider circuits employing potentiometers. Note the following examples:

Circuit 1

$$V_{out} = mV_{in}$$

Circuit 2

$$V_{out} = V_{in} \frac{mR_2}{R_1 + R_2}$$

Circuit 3

$$V_{out} = V_{in} \frac{mR_1 + R_2}{R_1 + R_2}$$

Circuit 4

$$V_{out} = V_{in} \frac{mR_2 + R_3}{R_1 + R_2 + R_3}$$

Algebraically manipulate these four equations so as to solve for m in each case. This will yield equations telling you where to set each potentiometer to obtain a desired output voltage given the input voltage and all resistance values ($m = \cdots$).

file 03267

Answer 83

$$\text{Circuit 1:} \qquad m = \frac{V_{out}}{V_{in}}$$

$$\text{Circuit 2:} \qquad m = \frac{V_{out}(R_1 + R_2)}{V_{in}R_2}$$

$$\text{Circuit 3:} \qquad m = \frac{V_{out}(R_1 + R_2) - V_{in}R_2}{V_{in}R_1}$$

$$\text{Circuit 4:} \qquad m = \frac{V_{out}(R_1 + R_2 + R_3) - V_{in}R_3}{V_{in}R_2}$$

Hint: in order to avoid confusion with all the subscripted R variables (R_1, R_2, and R_3) in your work, you may wish to substitute simpler variables such as a for R_1, b for R_2, etc. Similarly, you may wish to substitute x for V_{in} and y for V_{out}. Using shorter variable names makes the equations easier to manipulate. See how this simplifies the equation for circuit 2:

$$\text{Circuit 2 (original equation):} \qquad y = x\left(\frac{mb}{a+b}\right)$$

$$\text{Circuit 2 (manipulated equation):} \qquad m = \frac{y(a+b)}{bx}$$

Notes 83

The main purpose of this question is to provide algebraic manipulation practice for students, as well as shown them a practical application for algebraic substitution. The circuits are almost incidental to the math.

Question 84

Calculate both the total resistance of this voltage divider circuit (as "seen" from the perspective of the 25 volt source) and its output voltage (as measured from the V_{out} terminal to ground):
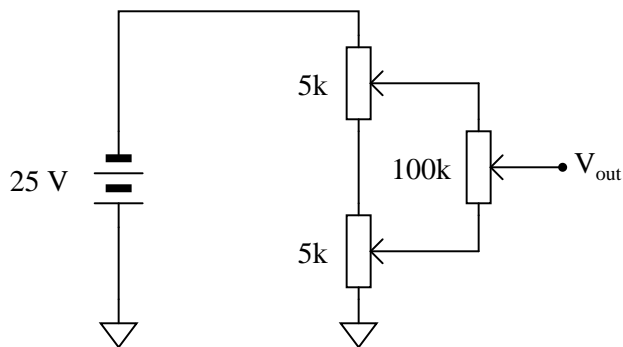
Note that all potentiometers in this circuit are set exactly to mid-position (50%, or $m = 0.5$).
file 03269

Answer 84

$R_{total} = 9.762$ kΩ

$V_{out} = $ -12.5 V

Notes 84

Ask your students to explain why the output voltage is expressed as a negative quantity. Is this important, or is it an inconsequential detail that may be omitted if desired?

Also, it might be good to ask your students to show the equivalent circuit (made up entirely of fixed resistors) that they drew in route to solving for total resistance and output voltage. Encourage them to take this step if they have not already, for although it does involve "extra" work, it helps greatly in keeping track of the series-parallel relationships and all calculated circuit values.

Question 85

Calculate both the total resistance of this voltage divider circuit (as "seen" from the perspective of the 25 volt source) and its output voltage (as measured from the V_{out} terminal to ground):

Note that the two 5 kΩ potentiometers are set to their 80% positions ($m = 0.8$), while the 100 kΩ potentiometer is set exactly to mid-position (50%, or $m = 0.5$).

file 03270

Answer 85

$R_{total} = 9.762$ kΩ
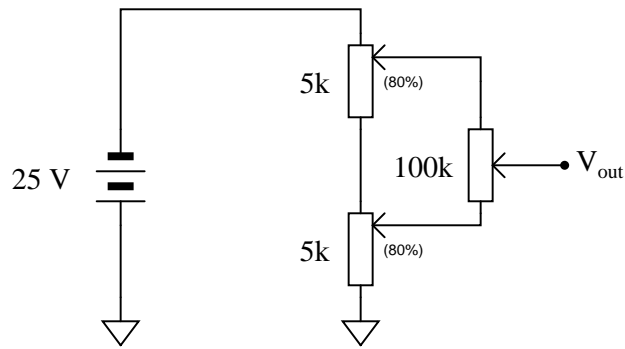
$V_{out} =$ -16.341 V

Notes 85

Ask your students to explain why the output voltage is expressed as a negative quantity. Is this important, or is it an inconsequential detail that may be omitted if desired?

Also, it might be good to ask your students to show the equivalent circuit (made up entirely of fixed resistors) that they drew in route to solving for total resistance and output voltage. Encourage them to take this step if they have not already, for although it does involve "extra" work, it helps greatly in keeping track of the series-parallel relationships and all calculated circuit values.

Question 86

Calculate both the total resistance of this voltage divider circuit (as "seen" from the perspective of the 25 volt source) and its output voltage (as measured from the V_{out} terminal to ground):
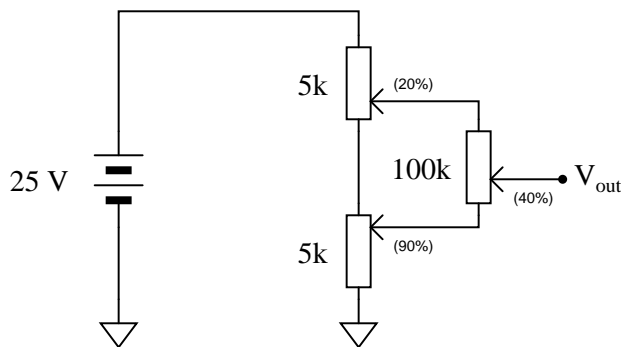
Note that the upper 5 kΩ potentiometer is set to its 20% position ($m = 0.2$), while the lower 5 kΩ potentiometer is set to its 90% position ($m = 0.9$), and the 100 kΩ potentiometer is set to its 40% position ($m = 0.4$).

file 03271

Answer 86

$R_{total} = 9.978$ kΩ

$V_{out} = 12.756$ V

Notes 86

Ask your students to explain why the output voltage is expressed as a positive quantity. Is this significant, or could it be properly expressed as a negative quantity as well? In other words, is this an *absolute value* of a voltage which may be negative, or is it definitely a positive voltage? How may we tell?

Also, it might be good to ask your students to show the equivalent circuit (made up entirely of fixed resistors) that they drew in route to solving for total resistance and output voltage. Encourage them to take this step if they have not already, for although it does involve "extra" work, it helps greatly in keeping track of the series-parallel relationships and all calculated circuit values.

Question 87

A student builds the following voltage divider circuit so she can power a 6-volt lamp from a 15-volt power supply:
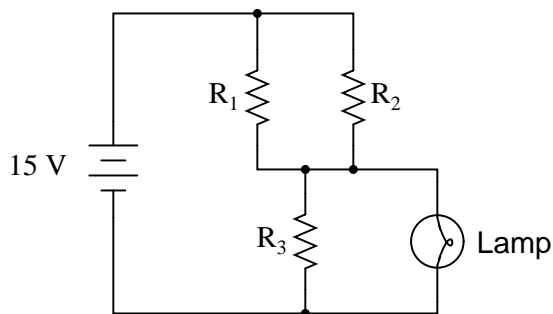
When built, the circuit works just as it should. However, after operating successfully for hours, the lamp suddenly goes dark. Identify all the possible faults you can think of in this circuit which could account for the lamp not glowing anymore.

file 03332

Answer 87

Here are a few possibilities (by no means exhaustive):

- Lamp burned out
- 15-volt power supply failed
- Resistors R_1 *and* R_2 simultaneously failed open

Follow-up question: although the third possibility mentioned here is certainly valid, it is less likely than any *single* failure. Explain why, and how this general principle of considering single faults first is a good rule to follow when troubleshooting systems.
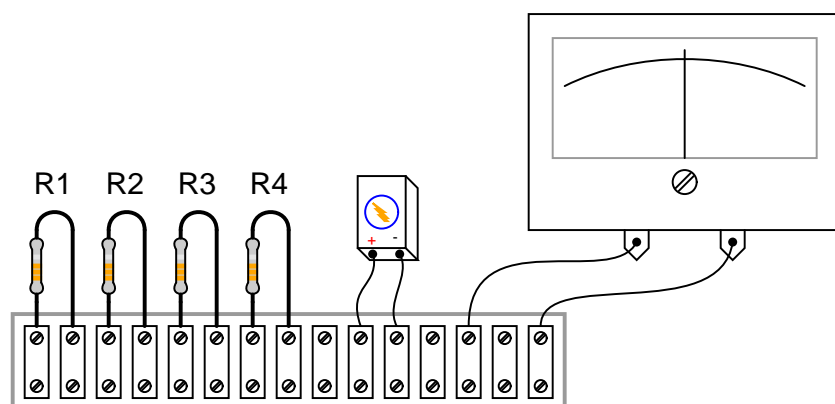
Notes 87

Have fun with your students figuring out all the possible faults which could account for the lamp going dark! Be sure to include wires and wire connections in your list.

The follow-up question is intended to get students to come up with their own version of Occam's Razor: the principle that the simplest explanation for an observed phenomenon is probably the correct one.
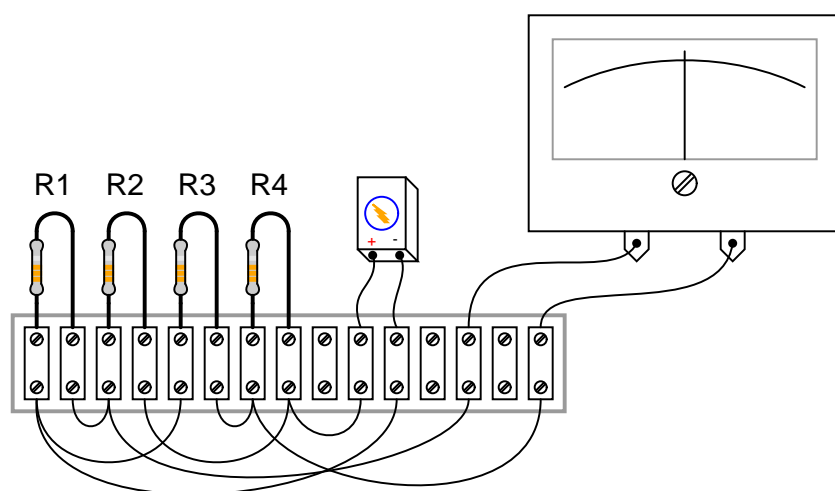
Question 88

Complete the wire connections necessary to make this a bridge circuit, where $\frac{R_1}{R_2} = \frac{R_3}{R_4}$ at balance:

Answer 88

This, of course, is not the only way to connect the components to make a bridge circuit!

Notes 88

Challenge your students to connect the resistors in a manner different from the diagram shown in the answer, to make a bridge circuit. A good way to do this is to project an image of the original components (with no interconnections drawn) on a whiteboard with a video projector, then have students use dry-erase markers to draw the connecting wires in place. If any errors are made, they can be very easily erased without erasing any components themselves.

The following bridge circuit uses two strain gauges (one to measure strain, the other to compensate for temperature changes), the amount of strain indicated by the voltmeter in the center of the bridge. Unfortunately, though, it has a problem. Instead of registering a very small voltage as it normally does, the voltmeter shows a large voltage difference, with point **A** positive and point **B** negative:

Something is wrong in the bridge circuit, because this voltage is present even when there is no physical stress on the specimen. Identify which of the following faults could cause the excessive voltage to appear across the voltmeter, and which could not. Consider only one of these faults at a time (no multiple, simultaneous faults):

- Resistor R_1 failed open
- Resistor R_1 failed shorted
- Resistor R_2 failed open
- Resistor R_2 failed shorted
- Strain gauge (measurement) failed open
- Strain gauge (measurement) failed shorted
- "Dummy" gauge (temperature compensation) failed open
- "Dummy" gauge (temperature compensation) failed shorted
- Voltage source is dead (no voltage output at all)

file 03331

Answer 89

- Resistor R_1 failed open *Not possible*
- Resistor R_1 failed shorted *Possible*
- Resistor R_2 failed open *Possible*
- Resistor R_2 failed shorted *Not possible*
- Strain gauge (measurement) failed open *Possible*
- Strain gauge (measurement) failed shorted *Not possible*
- "Dummy" gauge (temperature compensation) failed open *Not possible*
- "Dummy" gauge (temperature compensation) failed shorted *Possible*
- Voltage source is dead (no voltage output at all) *Not possible*

Follow-up question: identify possible *wire* or *connection* failures in this circuit which could cause the same symptom to manifest.
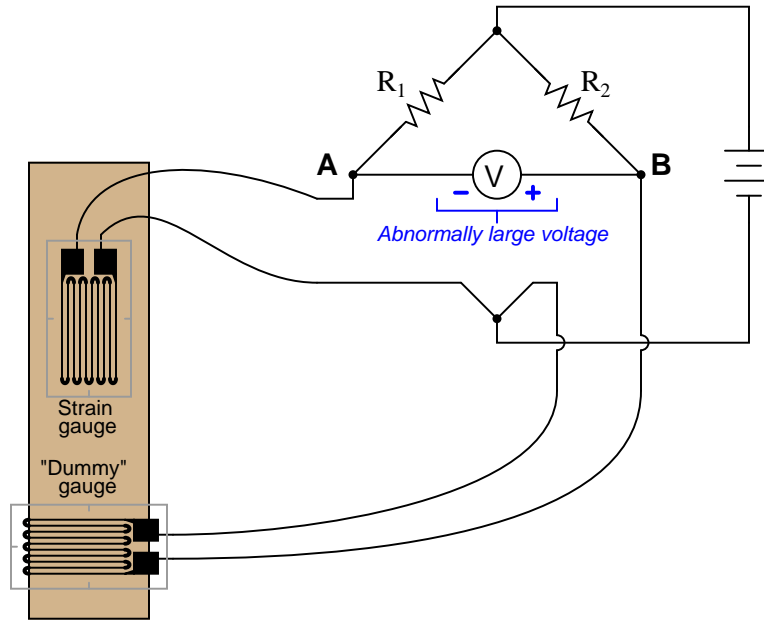
Notes 89

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

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

The following bridge circuit uses two strain gauges (one to measure strain, the other to compensate for temperature changes), the amount of strain indicated by the voltmeter in the center of the bridge. Unfortunately, though, it has a problem. Instead of registering a very small voltage as it normally does, the voltmeter shows a large voltage difference, with point **B** positive and point **A** negative:

Something is wrong in the bridge circuit, because this voltage is present even when there is no physical stress on the specimen. Identify which of the following faults could cause the excessive voltage to appear across the voltmeter, and which could not. Consider only one of these faults at a time (no multiple, simultaneous faults):

- Resistor R_1 failed open
- Resistor R_1 failed shorted
- Resistor R_2 failed open
- Resistor R_2 failed shorted
- Strain gauge (measurement) failed open
- Strain gauge (measurement) failed shorted
- "Dummy" gauge (temperature compensation) failed open
- "Dummy" gauge (temperature compensation) failed shorted
- Voltage source is dead (no voltage output at all)

file 03330

Answer 90

- Resistor R_1 failed open *Possible*
- Resistor R_1 failed shorted *Not possible*
- Resistor R_2 failed open *Not possible*
- Resistor R_2 failed shorted *Possible*
- Strain gauge (measurement) failed open *Not possible*
- Strain gauge (measurement) failed shorted *Possible*
- "Dummy" gauge (temperature compensation) failed open *Possible*
- "Dummy" gauge (temperature compensation) failed shorted *Not possible*
- Voltage source is dead (no voltage output at all) *Not possible*

Follow-up question: identify possible *wire* or *connection* failures in this circuit which could cause the same symptom to manifest.

Notes 90

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

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

Question 91

Suppose we were building a circuit that required an adjustable resistance with a range of 1500 Ω to 4500 Ω. The only potentiometer we have on hand is a 10 kΩ unit. Of course, we could simply connect the potentiometer as-is and have an adjustable range of 0 Ω to 10,000 Ω, but that would be too "coarse" of an adjustment for our application.

Explain how we could connect other resistors to this 10 kΩ potentiometer in order to achieve the desired adjustable resistance range.

file 00470

Answer 91

I'll give you a hint:
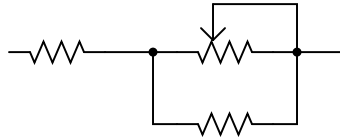
Notes 91

Knowing how to limit the adjustable range of a potentiometer is a very useful skill when designing and building circuits where precision of adjustment is important. The only drawback to building such a sub-circuit is that the adjustment becomes nonlinear (i.e., setting the potentiometer to the half-way position does not result in the total resistance being 50% of the way between the lower and upper range values).