

Recommended schedule

Day 1

Topics: *Introduction to trades and programs*
Questions: *(none)*
Lab Exercises: *Gather books, tools, and parts*

Day 2

Topics: *Basic concepts of electricity, simple circuits, and voltmeter/ammeter usage*
Questions: *1 through 20*
Lab Exercises: *Voltmeter usage (question 101) and Ammeter usage (question 102)*
MIT 8.02 video clip: Disk 1, Lecture 1; Van De Graff 25:45 to 29:30
MIT 8.02 video clip: Disk 1, Lecture 1; Electroscopes 42:08 to end
Socratic Electronics animation: Simple switch circuit

Day 3

Topics: *Ohm's Law and electrical safety*
Questions: *21 through 40*
Lab Exercise: *Circuit with switch (question 103)*
MIT 8.02 video clip: Disk 1, Lecture 5; Faraday cage 45:40 to end
MIT 6.002 video clip: Disk 1, Lecture 1; V/I plots 29:20 to 35:12
MIT 6.002 video clip: Disk 1, Lecture 1; Burning pickle 35:35 to 37:28

Day 4

Topics: *Ohm's Law, Joule's Law, scientific notation, and metric prefixes*
Questions: *41 through 60*
Lab Exercise: *Ohm's Law (question 104)*

Day 5

Topics: *Resistors, precision, the standard color code, and ohmmeter usage*
Questions: *61 through 80*
Lab Exercise: *Ohmmeter usage (question 105)*
Demo: Show dissected potentiometer to students

Day 6

Topics: *Circuit connections, soldering technique, and solderless breadboards*
Questions: *81 through 100*
Lab Exercise: *Ohm's Law (question 106)*
Demo: Show a breadboard next to a terminal block and a printed circuit board
Socratic Electronics animation: Soldering a wire to a lug

Day 7

Exam 1: *includes Ohm's Law performance assessment*
Lab Exercises: *PCB soldering (question 107) and exploring solder-together kit*

Practice and challenge problems

Questions: *110 through the end of the worksheet*

Impending deadlines

Troubleshooting assessment (simple lamp circuit) due at end of ELTR100, Section 3
Question 108: Troubleshooting log

Question 109: Sample troubleshooting assessment grading criteria
Solder-together kit due at end of ELTR100, Section 3

Skill standards addressed by this course section

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

A Technical Skills – General

- A.05** Demonstrate an understanding of acceptable soldering/desoldering techniques, including through-hole and surface-mount devices. *Partially met – no SMD soldering/desoldering techniques.*
- A.06** Demonstrate an understanding of proper solderless connections.
- A.10** Demonstrate an understanding of color codes and other component descriptors.

B Technical Skills – DC circuits

- B.01** Demonstrate an understanding of sources of electricity in 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.04** Demonstrate an understanding of measurement of resistance of conductors and insulators and the computation of conductance.
- B.24** Demonstrate an understanding of measurement of power in DC circuits.

B Basic and Practical Skills – Communicating on the Job

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

C Basic and Practical Skills – Solving Problems and Critical Thinking

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

D Basic and Practical Skills – Reading

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

E Basic and Practical Skills – Proficiency in Mathematics

- E.01** Determine if a solution is reasonable.
- E.02** Demonstrate ability to use a simple electronic calculator.
- E.05** Solve problems and [sic] make applications involving integers, fractions, decimals, percentages, and ratios using order of operations.
- E.06** Translate written and/or verbal statements into mathematical expressions.
- E.09** Read scale on measurement device(s) and make interpolations where appropriate. *Met by analog multimeter usage.*
- 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.

F Basic and Practical Skills – Proficiency in Physics

F.04 Understand principles of electricity including its relationship to the nature of matter.

Common areas of confusion for students

Difficult concept: *An interruption anywhere in a simple circuit stops current everywhere.*

A common misunderstanding is that the location of a break (interruption) in a simple circuit matters to the electrons moving around in it. To the contrary, *any* break in a simple circuit halts the flow of electrons *everywhere* in it. A good way to grasp this concept is by experimenting with a simple one-battery, one-lamp circuit, seeing the effect that breaks in the circuit have on the lamp's illumination.

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

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

Difficult concept: *Algebraically manipulating Ohm's Law equations.*

It is common for students uncomfortable with algebra to resort to "cheat" techniques to figure out how to write the various equations for Ohm's and Joule's Law (e.g. drawing the letters in a pyramid shape and then covering up the one you want to solve for to see where the others are in relation to each other; or using a "cheat sheet" showing all algebraic combinations of V, I, R, and P). The real problem is lack of math skill, and the only solution is to gain proficiency by *using* algebra to transpose variables in these equations. Ohm's Law is the easiest equation you will see in electronics for practicing your algebra skills, so use this as an opportunity to learn!

Question 1

Early scientific researchers hypothesized that electricity was an invisible *fluid* that could move through certain substances. Those substances "porous" to this "fluid" were called *conductors*, while substances impervious to this "fluid" were called *insulators*.

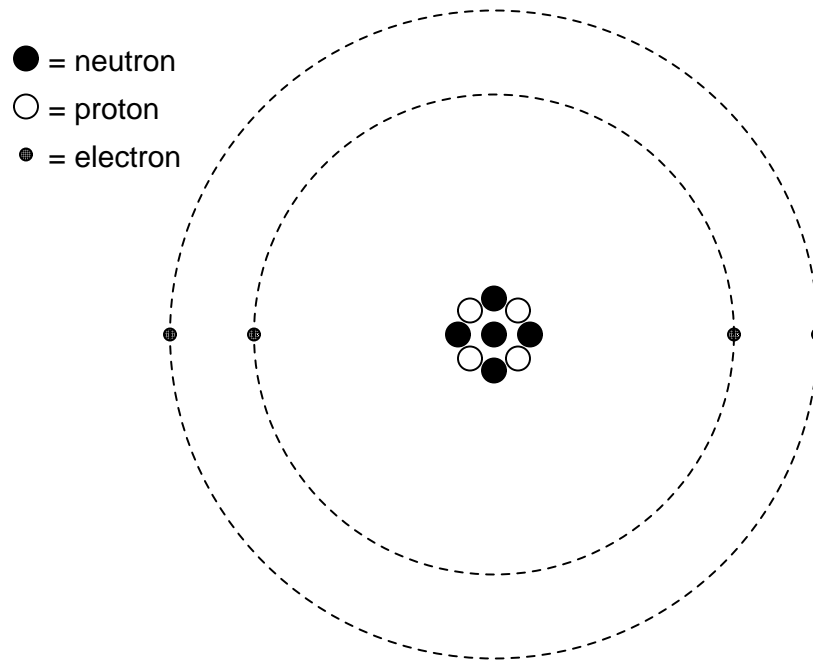
We now know what electricity is composed of: tiny bits of matter, smaller than atoms. What name do we give these tiny bits of matter? How do these particles of matter relate to whole atoms?

In terms of these tiny particles, what is the difference between the atoms of conductive substances versus the atoms of insulating substances?

[file 01698](#)

Answer 1

The tiny bits of matter that move through electrically conductive substances, comprising electricity, are called *electrons*. Electrons are the outermost components of atoms:



Although electrons are present in all atoms, and therefore in all normal substances, the outer electrons in conductive substances are freer to leave the parent atoms than the electrons of insulating substances. Such "free" electrons wander throughout the bulk of the substance randomly. If directed by a force to drift in a consistent direction, this motion of free electrons becomes what we call *electricity*.

Notes 1

It is worthy to note to your students that metallic substances – the best naturally-occurring conductors – are characterized by extremely mobile electrons. In fact, solid-state physicists often refer to the free electrons in metals as a "gas" or a "sea," ironically paying homage to the "fluid" hypothesis of those early experimenters.

The specific details of why some atoms have freer electrons than others are extremely complex. Suffice it to say, a knowledge of quantum physics is necessary to really grasp this basic phenomenon we call "electricity." The subject becomes even more complex when we turn to superconductivity and semiconducting substances.

Question 2

Some of the particles comprising atoms react to each other in a way that scientists categorize as *electric charge*. There are two fundamental types of electric charge: *positive* and *negative*. Identify the respective charges of the following particles:

- Electrons
- Protons
- Neutrons

What would happen if you placed two electrons near each other in free space? Would they repel each other or attract each other? How about two protons? How about an electron and a proton? How about a neutron and a proton?

[file 00137](#)

Answer 2

I'll let you research which charge type (positive or negative) is characteristic of electrons, protons, and neutrons!

As for their respective physical reactions, particles of differing charge are physically attracted to each other while particles of identical charge repel each other.

Notes 2

Many students will want to know "why?" in response to electrical charges. The technical answer has to do with electric fields extending through space, but this may be a philosophically impossible question to answer. The concept of charge was invented to explain the physical behavior of electrical attraction and repulsion, but coining a term to explain a phenomenon does nothing to explain *why* that phenomenon occurs.

Still, this is a worthwhile subject for discussion, especially if students have done their research well and know something about the history of electricity.

Question 3

What does it mean for an object to have an electric *charge*? Give an example of an object receiving an electric charge, and describe how that charged object might behave.

file 00044

Answer 3

For an object to be electrically *charged*, it must have either a surplus or a deficit of electrons among its atoms.

A common example of electrically charging objects is rubbing latex balloons against wool clothing, or brushing your hair with a plastic comb. The consequences of these electric charges are very easy to perceive!

Notes 3

This question naturally leads to a discussion on atomic theory. Encourage your students to discuss and explore simple models of the atom, and how they serve to explain electricity in terms of electron placement and motion.

Question 4

How many electrons are contained in one *coulomb* of charge?

file 00010

Answer 4

There are 6.25×10^{18} electrons in one *coulomb* of charge. What would this appear as without the use of scientific notation? Write this same figure using the most appropriate metric prefix.

Notes 4

A little math review here: using scientific notation to denote very large (or very small) numbers.

Question 5

What is the difference between *DC* and *AC* electricity? Identify some common sources of each type of electricity.

[file 00028](#)

Answer 5

DC is an acronym meaning *Direct Current*: that is, electrical current that moves in one direction only. *AC* is an acronym meaning *Alternating Current*: that is, electrical current that periodically reverses direction ("alternates").

Electrochemical batteries generate DC, as do solar cells. Microphones generate AC when sensing sound waves (vibrations of air molecules). There are many, many other sources of DC and AC electricity than what I have mentioned here!

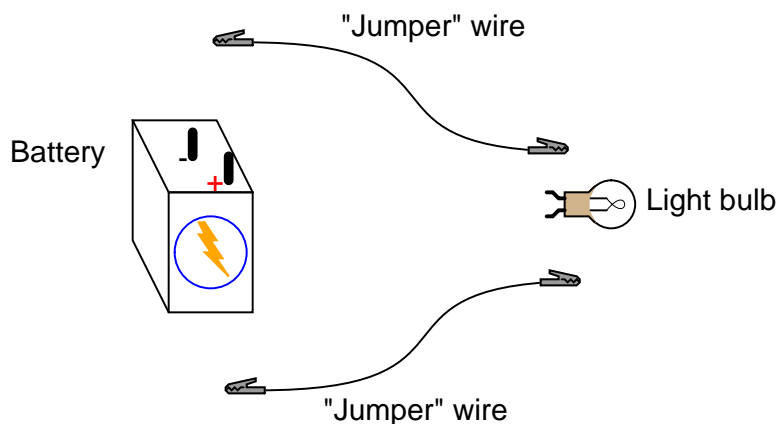
Notes 5

Discuss a bit of the history of AC versus DC in early power systems. In the early days of electric power in the United States of America, there was a heated debate between the use of DC versus AC. Thomas Edison championed DC, while George Westinghouse and Nikola Tesla advocated AC.

It might be worthwhile to mention that almost all the electric power in the world is generated and distributed as AC (Alternating Current), and not as DC (in other words, Thomas Edison lost the AC/DC battle!). Depending on the level of the class you are teaching, this may or may not be a good time to explain *why* most power systems use AC. Either way, your students will probably ask why, so you should be prepared to address this question in some way (or have them report any findings of their own!).

Question 6

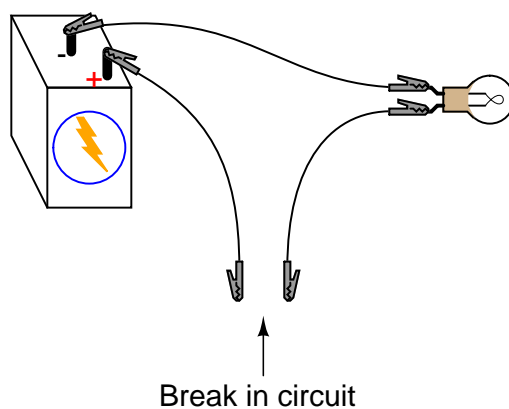
Build a simple electric circuit using a battery as the electrical energy *source*, and a small light bulb as the electrical *load* (I suggest using a 6-volt "lantern" battery and a miniature incandescent light bulb rated for either 6 or 12 volts). Use "jumper" wires with metal clips at the ends to join these two electrical devices together:



After connecting the components together properly so the light bulb lights up, answer the following questions:

- What conditions must be met for the light bulb to light up?
- What happens if the circuit is "broken"?
- Does it matter where the circuit is "broken"?

Then, add a third jumper wire to the circuit so you have a ready "break" to experiment with:



Try bridging this "break" with various materials, and note whether or not the light bulb lights up:

- Paper
- Steel paper clip
- Gold ring
- Rubber eraser
- Pencil lead (graphite)

Also, try touching the jumper wire ends together along their plastic exteriors, rather than at the metal "clip" ends. Does the light bulb light up when you do this?

Explain what this experiment demonstrates about the electrical *conductivity* of the various substances listed as well as the plastic coating of the jumper wires. Also explain why electrical wires are provided with that plastic coating, instead of being bare metal. Finally, explain what this experiment has taught you about electric circuits in general.

file 01697

Answer 6

Let the electrons show you the answers to these questions!

Notes 6

I find that 6-volt "lantern" batteries work well for an experiment such as this, along with either 6 or 12 volt miniature light bulbs. Sometimes the over-rated light bulbs (12 volt rated lamp powered by a 6 volt battery) work better for showing students the glowing filament. The filament of an incandescent light bulb at full brightness is difficult to distinguish.

Please avoid using LED's or any polarity-sensitive devices until your students are ready to explore polarity!

Question 7

What, exactly, is necessary to establish electrical *continuity* between two wires? If I want to have an electric current flow out of one wire and into another, what must be done with those two wires to make that flow path complete?

Conversely, what things might prevent continuity from being established between two wires when they are supposed to electrically connect with one another?

file 00231

Answer 7

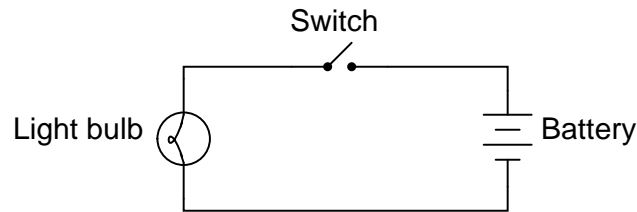
There must be metal-to-metal contact between the two wires in order to establish electrical continuity between the two. Anything preventing this clean contact between metal surfaces will inhibit continuity. This includes dirt, dust, oil, corrosion, misplaced insulation, and the like.

Notes 7

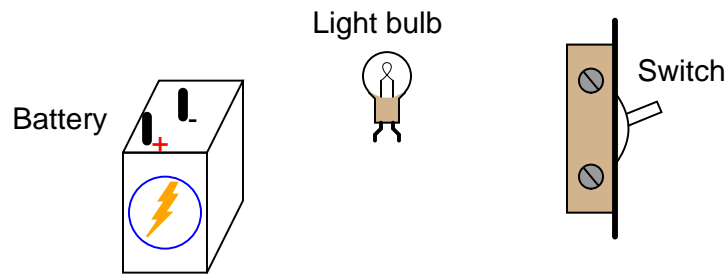
It might be helpful to show students what real pieces of wire look like, in order for them to better understand the nature of the problem. Most electrical wire is *insulated* in one form or another, and this insulation must not be removed (or "stripped") in order to establish bare metal-to-metal contact.

Question 8

Examine this schematic diagram:

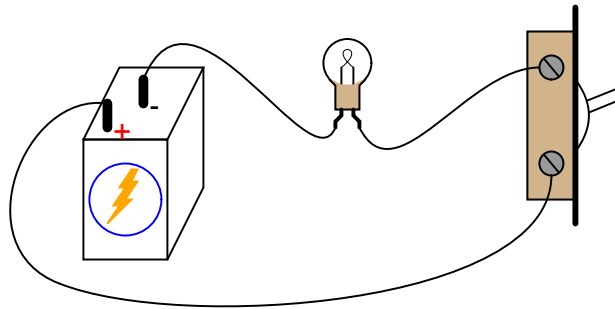


Now, without moving the following components, show how they may be connected together with wires to form the same circuit depicted in the schematic diagram above:



file 00069

Answer 8



Follow-up question: suppose the circuit were built like this but the light bulb did not turn on when the switch was closed. Identify at least five specific things that could be wrong with the circuit to cause the light not to turn on when it should.

Notes 8

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

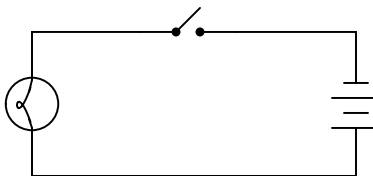
In case students have not learned battery symbol convention yet, please point out to them the "+" and "-" polarity marks, and note which side of the battery is which.

One analogy to use for the switch's function that makes sense with the schematic is a drawbridge: when the bridge is down (closed), cars may cross; when the bridge is up (open), cars cannot.

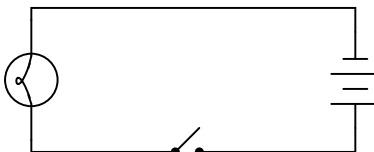
Question 9

What difference will it make if the switch is located in either of these two alternate locations in the circuit?

Switch on negative side of circuit



Switch on positive side of circuit



file 00014

Answer 9

The choice of switch locations shown in the two alternate diagrams makes no difference at all. In either case, the switch exerts the same control over the light bulb.

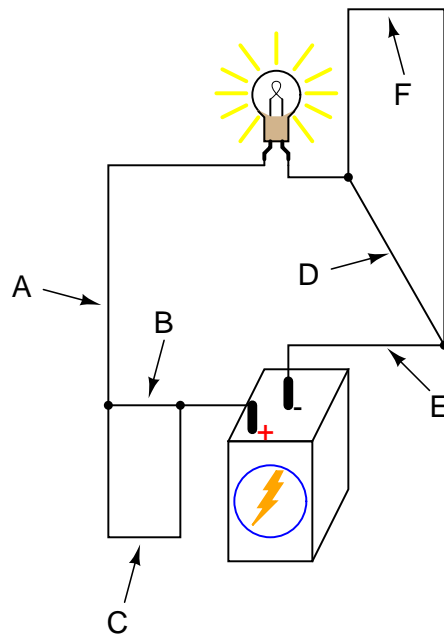
Notes 9

This is a difficult concept for some students to master. Make sure they all understand the nature of electrical current and the importance of continuity *throughout* the entire circuit. Perhaps the best way for students to master this concept is to actually build working battery-switch-lamp circuits. Remind them that their "research" of these worksheet questions is not limited to book reading. It is not only valid, but *preferable* for them to experiment on their own, so long as the voltages are low enough that no shock hazard exists.

One analogy to use for the switch's function that makes sense with the schematic is a drawbridge: when the bridge is down (closed), cars may cross; when the bridge is up (open), cars cannot.

Question 10

Determine if the light bulb will de-energize for each of the following breaks in the circuit. Consider just one break at a time:



• **Choose one option for each point:**

- A: de-energize / no effect
- B: de-energize / no effect
- C: de-energize / no effect
- D: de-energize / no effect
- E: de-energize / no effect
- F: de-energize / no effect

file 00002

Answer 10

- A: de-energize
- B: no effect
- C: no effect
- D: no effect
- E: de-energize
- F: no effect

Notes 10

This question is an important one in the students' process of learning troubleshooting. Emphasize the importance of inductive thinking: deriving general principles from specific instances. What does the behavior of this circuit tell us about *electrical continuity*?

Question 11

Explain what the electrical terms *voltage*, *current*, and *resistance* mean, using your own words.
file 00008

Answer 11

Voltage: electrical "pressure" between two different points or locations.

Current: the flow of electrons.

Resistance: opposition, or "friction," to the flow of electrons.

Notes 11

While it is easy enough for students to look up definitions for these words from any number of references, it is important that they be able to cast them into their own words. Remembering a definition is not the same as really understanding it, and if a student is unable to describe the meaning of a term using their own words then they definitely do not understand it! It is also helpful to encourage students to give real-life examples of these terms.

Question 12

What units of measurement are used to express quantities of *voltage*, *current*, and *resistance*?
[file 00181](#)

Answer 12

- Voltage is measured in the unit of the *volt* (V).
 - Current is measured in the unit of the *ampere*, or *amp* (A).
 - Resistance is measured in the unit of the *ohm* (Ω).
-

Notes 12

Like all other physical quantities, there are units of measurement appropriate for specifying electrical quantities. In this sense, the "volt," "amp," or "ohm" are no different from "gram," "yard," or "bushel."

Question 13

Electric current is measured in the unit of the *ampere*, or *amp*. What is the physical definition for this unit? What fundamental quantities constitute 1 ampere of electric current?

[file 00109](#)

Answer 13

1 ampere of electric current is the rate of electron motion equal to 1 coulomb per second:

$$I = \frac{Q}{t}$$

Where,

I = Electric current (amperes)

Q = Charge in motion (coulombs)

t = Time (seconds)

Notes 13

It may be helpful at this point to review the number of electrons constituting one coulomb of charge: 6.25×10^{18} electrons.

Technically, current's mathematical definition involves calculus:

$$I = \frac{dQ}{dt}$$

However, students at this stage may not be ready to explore derivatives yet, and so the equation given in the answer for (average) current will suffice.

Question 14

What, exactly, is a *short circuit*? What does it mean if a circuit becomes *shorted*? How does this differ from an *open* circuit?

file 00026

Answer 14

A *short circuit* is a circuit having very little resistance, permitting large amounts of current. If a circuit becomes *shorted*, it means that a path for current formerly possessing substantial resistance has been bypassed by a path having negligible (almost zero) resistance.

Conversely, an *open circuit* is one where there is a break preventing any current from going through at all.

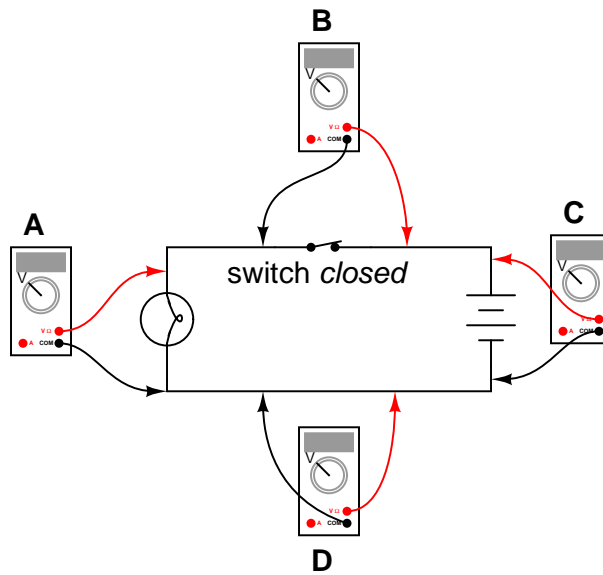
Notes 14

Discuss with your students some of the potential hazards of short circuits. It will then be apparent why a "short circuit" is a bad thing. Ask students if they can think of any realistic circumstance that could lead to a short-circuit developing.

I have noticed over several years of teaching electronics that the terms "short" or "short-circuit" are often used by new students as generic labels for *any* type of circuit fault, rather than the specific condition just described. This is a habit that must be corrected, if students are to communicate intelligently with others in the profession. To say that a component "is shorted" means a very definite thing: it is not a generic term for any type of circuit fault.

Question 15

Determine what these four voltmeters (A, B, C, D) will register when connected to this circuit in the following positions (assume a battery voltage of 6 volts):



- Voltmeter A =
- Voltmeter B =
- Voltmeter C =
- Voltmeter D =

file 00016

Answer 15

- Voltmeter A = 6 volts
- Voltmeter B = 0 volts
- Voltmeter C = 6 volts
- Voltmeter D = 0 volts

Notes 15

Students often find the terms "open" and "closed" to be confusing with reference to electrical switches, because they sound opposite to the function of a door (i.e. you can only go through an open door, but electricity can only go through a closed switch!). The words actually make sense, though, if you look at the schematic symbol for an electrical switch as a door mounted "sideways" in the circuit. At least visually, then, "open" and "closed" will have common references.

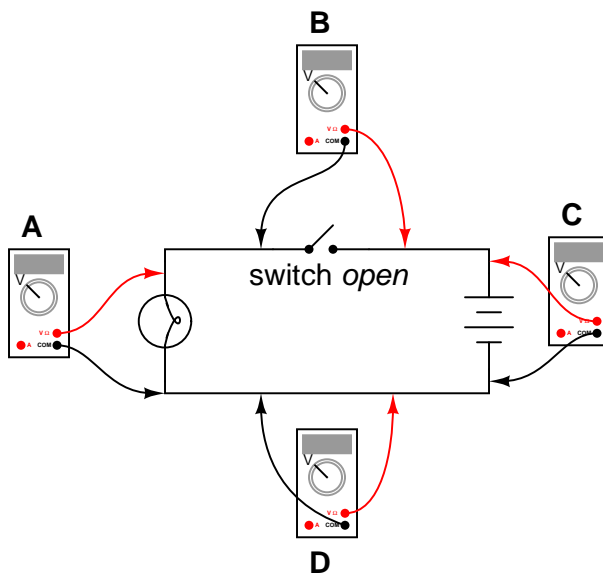
One analogy to use for the switch's function that makes sense with the schematic is a drawbridge: when the bridge is down (closed), cars may cross; when the bridge is up (open), cars cannot.

I have found that the concept of *electrically common points* is most helpful when students first learn to relate voltage drop with continuity (breaks or non-breaks) in a circuit.

To be able to immediately relate the expected voltage drop between two points with the electrical continuity between those points is a very important foundational skill in electrical troubleshooting. Without mastery of this skill, students will have great difficulty detecting and correcting faults in circuits caused by poor connections and broken wires, which constitute a fair portion of realistic circuit failures.

Question 16

Determine what these four voltmeters (A, B, C, D) will register when connected to this circuit in the following positions (assume a battery voltage of 6 volts):



- Voltmeter A =
- Voltmeter B =
- Voltmeter C =
- Voltmeter D =

file 00015

Answer 16

- Voltmeter A = 0 volts
- Voltmeter B = 6 volts
- Voltmeter C = 6 volts
- Voltmeter D = 0 volts

Notes 16

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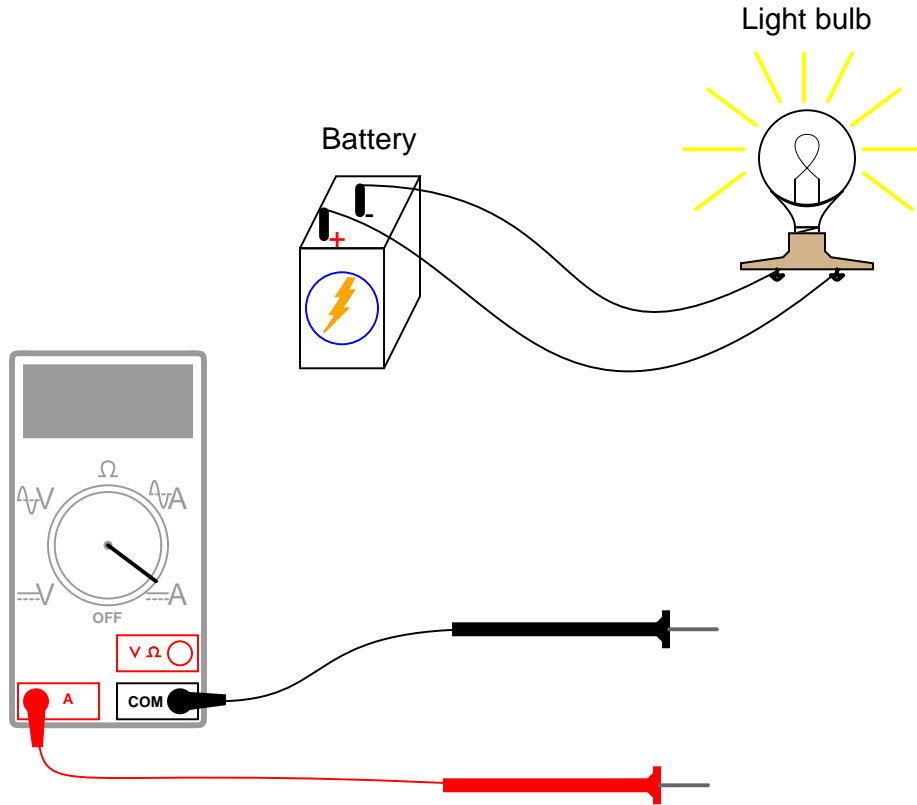
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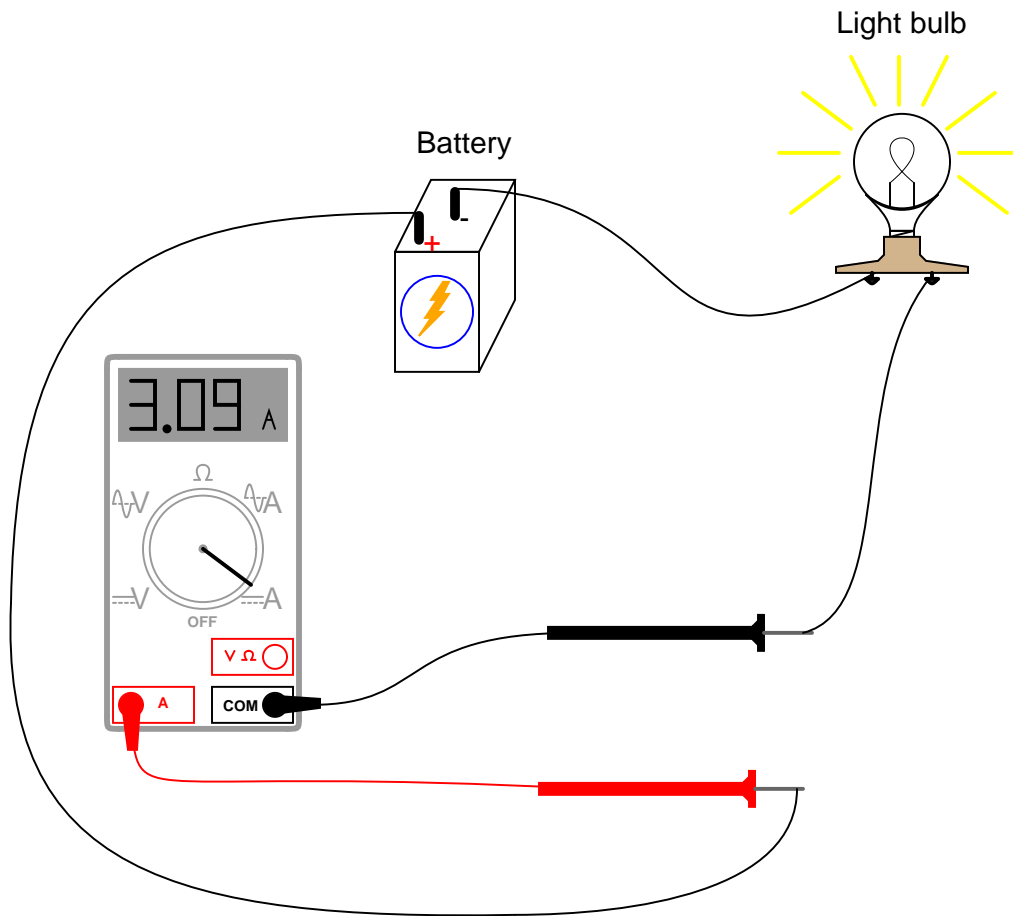
To be able to immediately relate the expected voltage drop between two points with the electrical continuity between those points is a very important foundational skill in electrical troubleshooting. Without mastery of this skill, students will have great difficulty detecting and correcting faults in circuits caused by poor connections and broken wires, which constitute a fair portion of realistic circuit failures.

Question 17

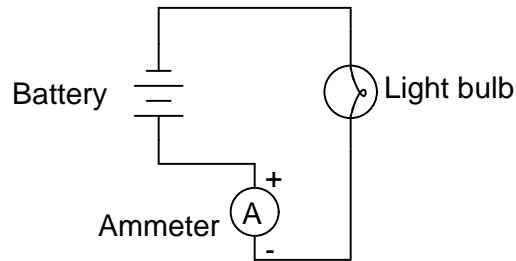
Show how this ammeter would be connected to the light bulb circuit to measure the circuit's electric current:



Also, draw a schematic diagram of this same circuit (with the ammeter connected).
[file 01699](#)



(Note: the meter's indication of 3.09 amps is arbitrary, and not important to the question).

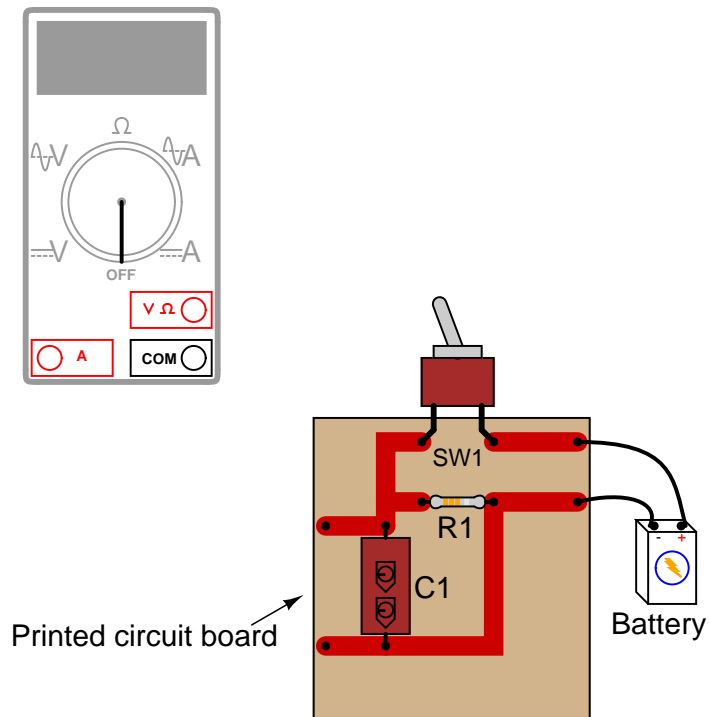


Notes 17

The important thing for students to understand in this question is that the ammeter must become part of the path that the electric current flows through. Explain how this fact contains an element of danger, as contrasted against the relatively "non-invasive" connection of a voltmeter to a circuit.

Question 18

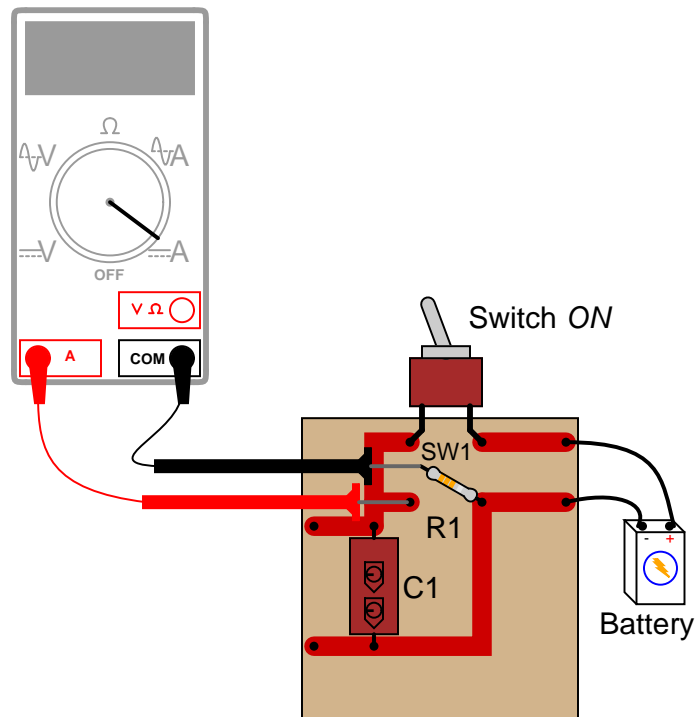
Shown here is a circuit constructed on a PCB (a "Printed Circuit Board"), with copper "traces" serving as wires to connect the components together:



How would the multimeter be used to measure the current through the component labeled "R1" when energized? Include these important points in your answer:

- The configuration of the multimeter (selector switch position, test lead jacks)
- The connections of the meter test leads to the circuit
- The state of the switch on the PCB (open or closed)

file 00097



In order to measure current through resistor R1, one of its leads must be de-soldered from the circuit board so that the meter may be connected directly in-line (in *series*) with it.

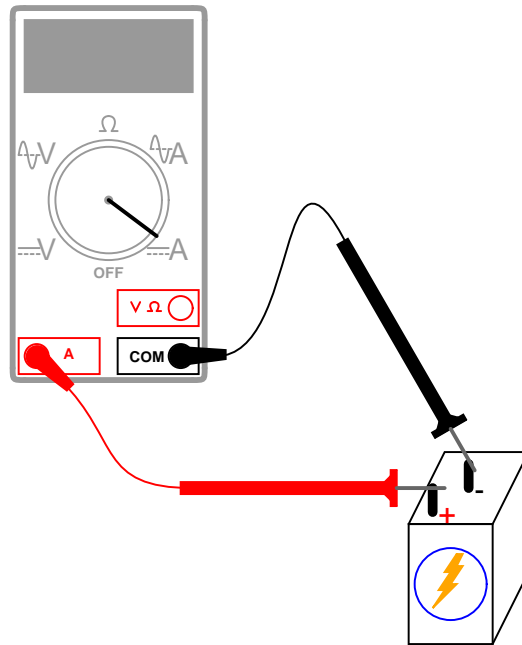
Notes 18

Many multimeters use "international" symbols to label DC and AC selector switch positions. It is important for students to understand what these symbols mean.

As you can see in this answer, measuring current through components is generally more difficult than measuring voltage across components, and involves greater risk because the meter must conduct the component's full current (which in some cases may be significant). For this reason, technicians need to learn troubleshooting techniques prioritizing voltage measurements over current measurements.

Question 19

Why is it a very bad idea to connect an ammeter directly across a voltage source, like this?



[file 00070](#)

Answer 19

Due to the ammeter's very low resistance, it will "draw" a lot of current from the voltage source. In effect, the ammeter will form a short circuit with the voltage source, potentially damaging the meter and/or the source.

In applications where the voltage source possesses very little internal resistance of its own, the current surge resulting from such a short-circuit may be huge. Very large surges of electric current are capable of heating wires to the point where their insulation bursts into flames, as well as causing super-heated blasts of *plasma* (electrically ionized gas) to form at any point of electrical contact where there is a spark. Either of these high-temperature conditions are hazardous to the person holding the meter and test leads!

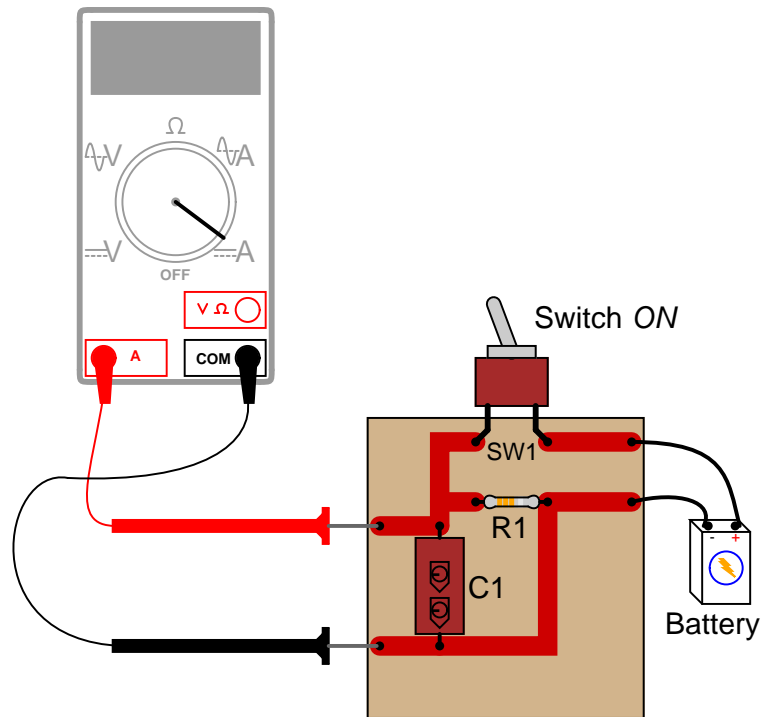
Notes 19

An important point to discuss is how electrical safety encompasses more than just shock hazard. In particular, *arc blasts* caused by high-current "faults" such as this may be just as dangerous as electric shock. At the very least, placing an ammeter directly across the terminals of a voltage source will likely result in the ammeter's fuse being blown.

In some cases, ammeter fuses are more expensive than one might think. Safety-rated ammeters often use expensive fast-action fuses with significant current interruption ratings. In the case of the Fluke 187 and 189 multimeters, these fuses cost around \$8 each (American dollars, 2004)!

Question 20

What would happen if a multimeter were connected across the component labeled "C1" on this printed circuit board, as shown?



file 00098

Answer 20

The meter would create a short-circuit with the battery. Determine what damage this short-circuit might cause, to all components involved.

Notes 20

Even though it might not appear that the meter is "shorting" the battery in this example, it most certainly is. In asking students to determine the resulting damage from such an action, it is important for them to trace the path of "fault current" through the circuit. Those components within the path of fault current are in risk of damage, while those components not within the path of fault current are not at risk.

Question 21

Shown here is the schematic symbol for a *resistor*:



What is the purpose of a resistor? What function does it perform? Also, draw an illustration of what a real resistor looks like.

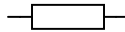
[file 00059](#)

Answer 21

The purpose of a *resistor* is to provide a precise amount of electrical resistance in a circuit. Here is an illustration of a small (1/8 or 1/4 watt) resistor:



It is also good to know that the zig-zag symbol shown in the question is not the only symbol used to represent resistors. Another common resistor symbol is shown here:



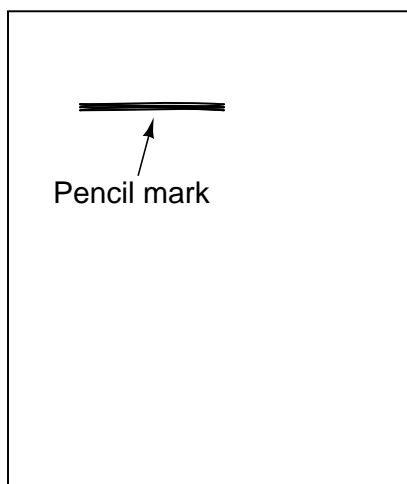
Notes 21

Students may (properly) ask, "Why is there such a thing as a component whose sole purpose is to *impede* the flow of electrons?" While resistors may seem rather pointless at first, they end up being extremely valuable electrical/electronic components. If asked, you may cite several uses of resistors in circuits:

- To limit maximum circuit current to a safe value.
- To "split" a voltage into proportions.
- To "scale" meter movements, for precise measurement of current and voltage.
- To provide a non-shorting path to discharge static electricity.

Question 22

A primitive resistor may be formed by sketching a thick line on a piece of paper, using a pencil (not an ink pen!):



How may the end-to-end electrical resistance of this pencil mark be increased? How may it be decreased? Explain your answers.

file 00212

Answer 22

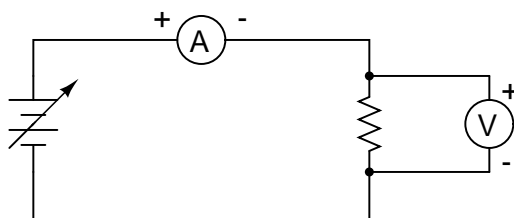
The electrical resistance of a pencil mark may be increased by increasing its length. It may be decreased by increasing its width.

Notes 22

Creating a resistor on paper using a pencil is a very easy experiment to perform, the resistance of which may be measured with an ohmmeter. I strongly recommend this as a classroom exercise!

Question 23

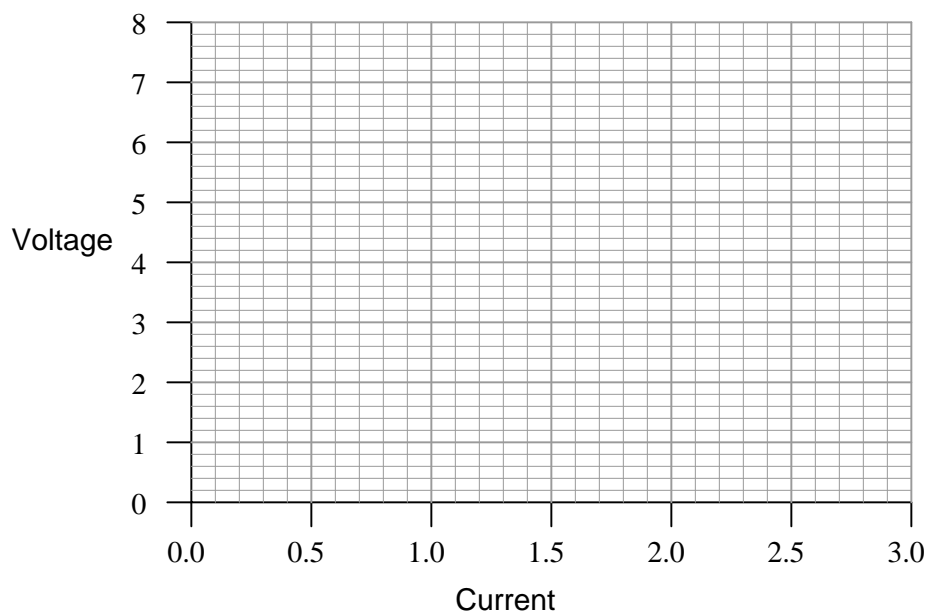
Suppose you were to build this circuit and take measurements of current through the resistor and voltage across the resistor:



Recording these numerical values in a table, the results look something like this:

Current	Voltage
0.22 A	0.66 V
0.47 A	1.42 V
0.85 A	2.54 V
1.05 A	3.16 V
1.50 A	4.51 V
1.80 A	5.41 V
2.00 A	5.99 V
2.51 A	7.49 V

Plot these figures on the following graph:



What mathematical relationship do you see between voltage and current in this simple circuit?
[file 00057](#)

Answer 23

This is an example of a *linear* function: where the plot describing the data set traces a straight line on a graph. From this line, and also from the numerical figures, you should be able to discern a constant ratio between voltage and current.

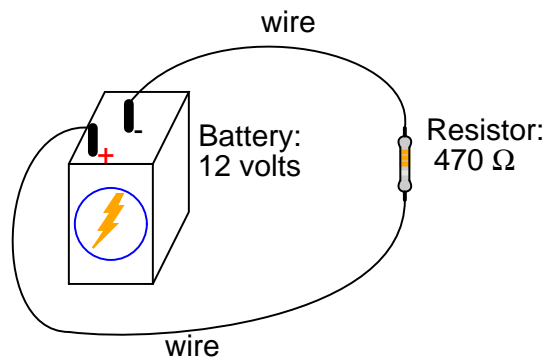
Notes 23

The raw data figures were made intentionally "noisy" in this problem to simulate the types of measurement errors encountered in real life. One tool which helps overcome interpretational problems resulting from noise like this is graphing. Even with noise present, the linearity of the function is quite clearly revealed.

Your students should learn to make graphs as tools for their own understanding of data. When relationships between numbers are represented in graphical form, it lends another mode of expression to the data, helping people to apprehend patterns easier than by reviewing rows and columns of numbers.

Question 24

Explain, step by step, how to calculate the amount of current (I) that will go through the resistor in this circuit:



file 00081

Answer 24

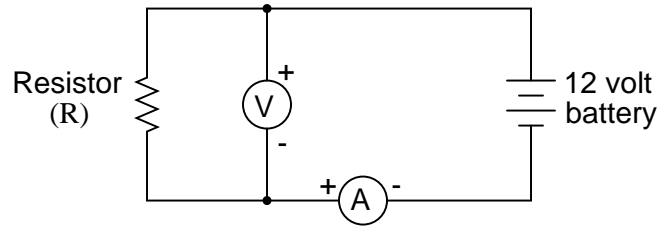
Resistor current = 0.02553 amps, or 25.53 milliamps (mA).

Notes 24

Just a simple Ohm's Law calculation here – no tricks! The point of this question, however, is to get students to think about the steps they follow in doing the calculation. Many students simply wish to memorize procedures rather than learn *why* to do what they need to do to answer such questions. It is your task as the instructor to challenge them beyond memorization, and through to understanding.

Question 25

What is the value of this resistor, in *ohms* (Ω)?



Voltmeter indication = 12.3 volts
Ammeter indication = 4.556 milliamps

[file 00064](#)

Answer 25

Resistor value = 2700 Ω , or 2.7 k Ω .

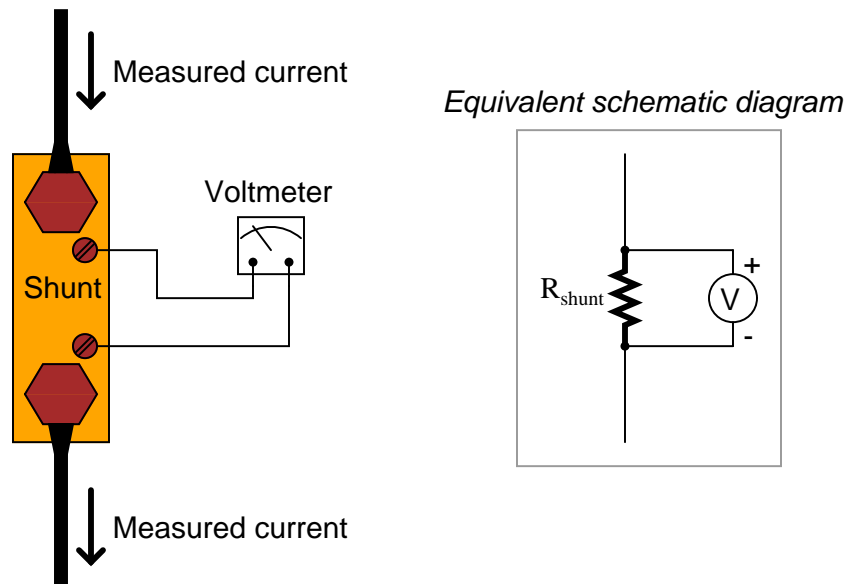
One format of component value expression popular in Europe is to replace the decimal point with the metric prefix, so 2.7 k Ω would be represented as 2k7 Ω . Not only is this notation simpler, but it also transcends the interpretational difficulties experienced between Europeans and Americans with their opposite usages of commas and decimal points.

Notes 25

Some students might not realize that in Europe, commas are used as decimal points and visa-versa. Thus, two thousand seven hundred would be written as 2,700 in America and 2.700 in Europe. Conversely, the number π would be written as 3.141593 in America but 3,141593 in Europe. Confusing? Yes!!

Question 26

Shunt resistors are often used as current-measuring devices, in that they are designed to drop very precise amounts of voltage as large electric currents pass through them. By measuring the amount of voltage dropped by a shunt resistor, you will be able to determine the amount of current going through it:



Suppose that a shunt resistance is labeled with the following rating: **150 A , 50 mV**. What is the resistance of this shunt, in ohms? Express your answer in metric notation, scientific notation, and plain decimal notation.

file 00371

Answer 26

Metric notation: $333.3 \mu\Omega$

Scientific notation: $3.333 \times 10^{-4} \Omega$

Plain decimal notation: 0.0003333Ω

Notes 26

Ask your students how they think a resistor could be made with such a low resistance (a tiny fraction of an ohm!). What do they think a shunt resistor would look like in real life? If you happen to have a shunt resistor available in your classroom, show it to your students *after* they express their opinions on its construction.

Question 27

It is sometimes said regarding electrical safety that, "It's not the *voltage* that will hurt you, it's the *current*." Why then are there signs reading **Danger: High Voltage** near electrical substations and on large pieces of electrical equipment, rather than signs reading **Danger: High Current**?

file 00004

Answer 27

Yes, it is electric *current* that does the damage when enough of it passes through a body, but current exists only when there is sufficient *voltage* to push it through that body's *resistance*. Thus, there is no shock hazard when there is too little voltage present to force dangerous levels of current through a human body.

Notes 27

Ask students how this question relates to *Ohm's Law*. If they don't know what Ohm's Law is yet, this is a really good place to begin exploring!

Question 28

Why is this sign a joke?



file 00066

Answer 28

Electrical *resistance* is not hazardous in the least. In fact, the more resistance there is, the less chance there is for electrons to flow, thus minimizing shock hazard.

Notes 28

A joke it may be, but still a fun one to play. Hang a large sign saying "Danger: high resistance" over the entrance to the electrical lab and watch the responses of the uninitiated!

Question 29

Using Ohm's Law, explain why personal protective equipment such as insulating gloves and boots help reduce the risk of electric shock.

file 00302

Answer 29

Such personal protective equipment serves the purpose of increasing electrical resistance in the shock path.

Notes 29

Ohm's Law has many applications, and electrical safety is just one of them. I have found that the topic of safety is an excellent venue for highlighting certain (otherwise abstract) physical principles. Not only is the topic interesting, but it is of great personal importance, and so student attention is very easy to attain and hold in discussion.

Question 30

In the late 1700's, an Italian professor of anatomy, Luigi Galvani, discovered that the leg muscles of a recently deceased frog could be made to twitch when subjected to an electric current. What phenomenon is suggested by Galvani's discovery? In other words, what does this tell us about the operation of muscle fibers in living creatures? More importantly, what practical importance does this have for people working near electric circuits?

[file 00223](#)

Answer 30

Essentially, muscle fibers are "activated" by electrical signals. I'll let you figure out what practical importance this effect has for you!

Notes 30

This question presents an excellent opportunity to discuss one of the important aspects of electrical safety: involuntary muscle contraction.

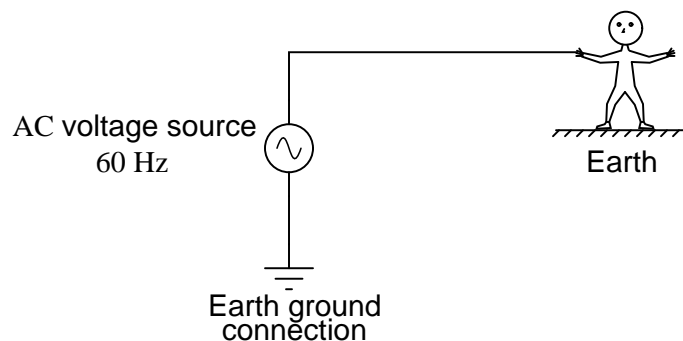
Question 31

An American researcher named Charles Dalziel performed experiments with both human and animal subjects to determine the effects of electric currents on the body. A table showing his research data is presented here:

<i>Bodily effect</i>	<i>Gender</i>	<i>DC</i>	<i>60 Hz AC</i>	<i>10 kHz AC</i>
Slight sensation at point(s) of contact	Men	1 mA	0.4 mA	7 mA
	Women	0.6 mA	0.3 mA	5 mA
Threshold of bodily perception	Men	5.2 mA	1.1 mA	12 mA
	Women	3.5 mA	0.7 mA	8 mA
Pain, with voluntary muscle control maintained	Men	62 mA	9 mA	55 mA
	Women	41 mA	6 mA	37 mA
Pain, with loss of voluntary muscle control	Men	76 mA	16 mA	75 mA
	Women	51 mA	10.5 mA	50 mA
Severe pain, difficulty breathing	Men	90 mA	23 mA	94 mA
	Women	60 mA	15 mA	63 mA
Possible heart fibrillation after three seconds	Men	500 mA	100 mA	X
	Women	500 mA	100 mA	X

Important Note: *Dalziel's human test subjects were men and women in good health, with no known heart conditions or any other abnormalities that would have compromised their safety. In other words, these data points represent best-case scenarios, and do not necessarily reflect the risk to persons in poorer states of health.*

Assuming a skin contact resistance of 600Ω for a sweaty hand, 1000Ω of resistance for foot-to-ground contact, 50Ω internal body resistance, 70Ω of resistance through the soil from the person's location to the earth ground point, and a male victim, calculate the amount of voltage necessary to achieve each of the listed shock conditions (threshold of perception, pain, etc.) for the following circuit:



file 01703

- Slight sensation at point(s) of contact: **0.69 volts**
- Threshold of bodily perception: **1.9 volts**
- Pain, with voluntary muscle control maintained: **15.5 volts**
- Pain, with loss of voluntary muscle control: **27.5 volts**
- Severe pain and difficulty breathing: **39.6 volts**
- Possible heart fibrillation after three seconds: **172 volts**

Notes 31

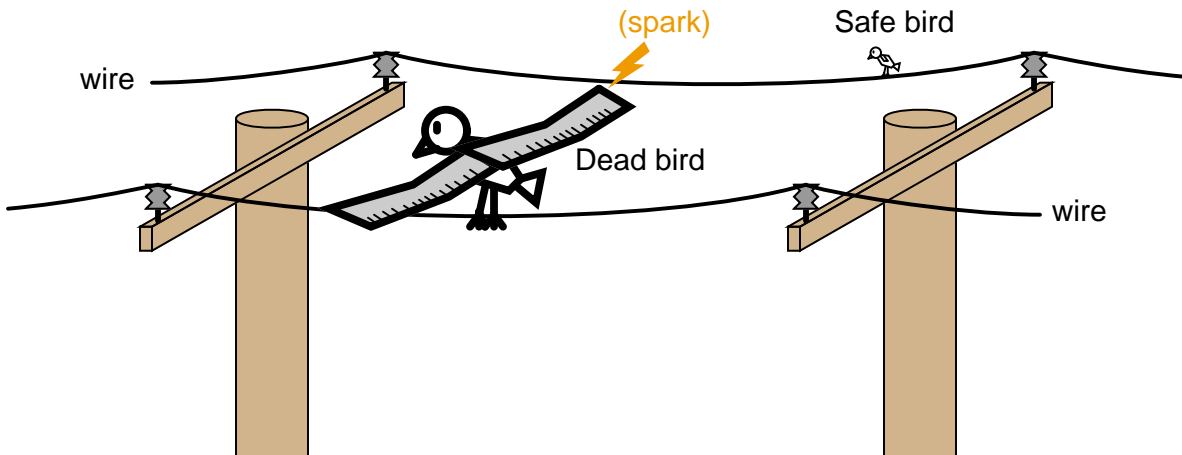
Not only does this question introduce students to the various levels of shock current necessary to induce deleterious effects in the (healthy) human body, but it also serves as a good exercise for Ohm's Law, and for introducing (or reviewing) the concept of series resistances.

For the morbidly curious, Charles Dalziel's experimentation conducted at the University of California (Berkeley) began with a state grant to investigate the bodily effects of sub-lethal electric current. His testing method was as follows: healthy male and female volunteer subjects were asked to hold a copper wire in one hand and place their other hand on a round, brass plate. A voltage was then applied between the wire and the plate, causing electrons to flow through the subject's arms and chest. The current was stopped, then resumed at a higher level. The goal here was to see how much current the subject could tolerate and still keep their hand pressed against the brass plate. When this threshold was reached, laboratory assistants forcefully held the subject's hand in contact with the plate and the current was again increased. The subject was asked to release the wire they were holding, to see at what current level involuntary muscle contraction (tetanus) prevented them from doing so. For each subject the experiment was conducted using DC and also AC at various frequencies. Over two dozen human volunteers were tested, and later studies on heart fibrillation were conducted using animal subjects.

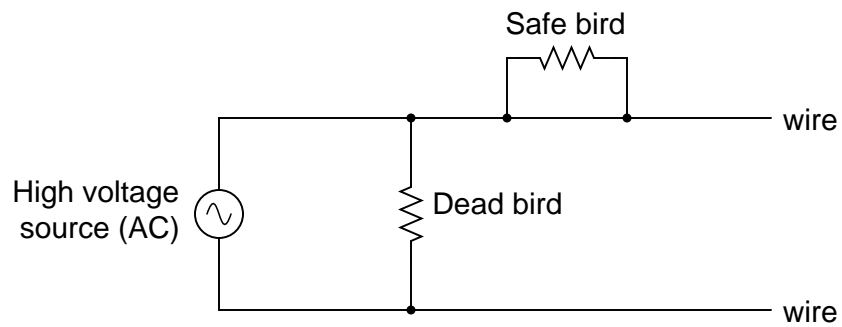
Given that Dalziel tested subjects for the effects of a hand-to-hand shock current path, his data does not precisely match the scenario I show in the schematic diagram (hand-to-foot). Therefore, the calculated voltages for various hand-to-foot shock conditions are *approximate only*.

Question 32

Explain why birds do not get shocked when they perch on a power line, even if both of their feet touch the wire. Explain why birds become electrocuted if their wings bridge between two different power conductors:



For a schematic view of both scenarios, see this diagram:



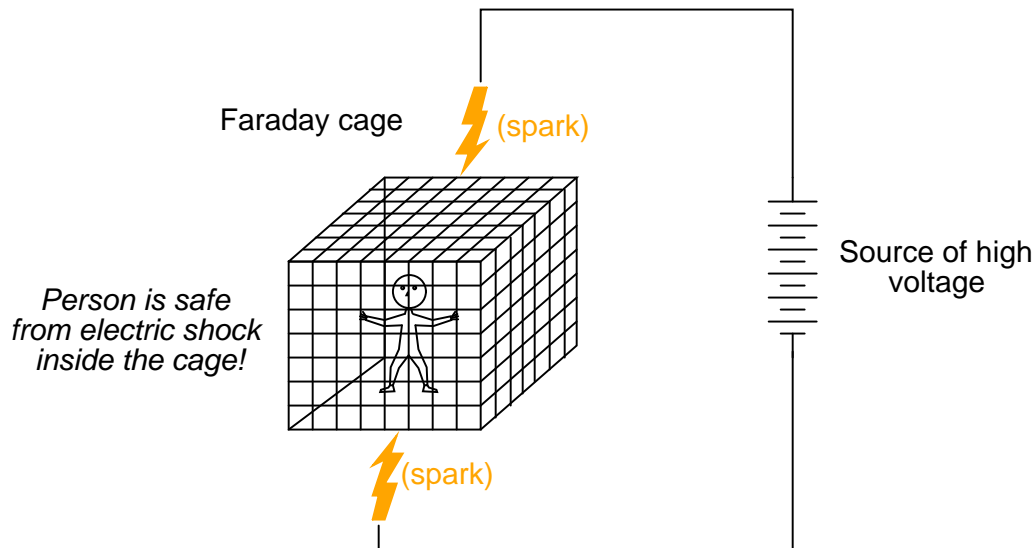
[file 01704](#)

Answer 32

Perhaps the easiest way to explain the relative danger of these two scenarios is by way of voltage. The "safe" bird will not be shocked because there is negligible voltage between its feet (both feet resting on the same wire). Points connected directly together with low-resistance (conductive) wire are said to be *electrically common*, and should never have appreciable voltage between them.

The dead bird got that way because there is full source voltage between the two points of contact (each wing-tip touching a different wire).

Follow-up question: a safety device called a *Faraday cage* protects anyone inside from electrical shock. A Faraday cage is nothing more than a cage made of closely-spaced metal bars (or alternatively, made of metal wire mesh):



Explain how the principle of electrically common points protects the person inside the Faraday cage from being shocked by the outside source of high voltage. Discuss how this principle might apply to metal-frame automobiles and aircraft.

Notes 32

Very vivid demonstrations have been performed with Van de Graaff generators and Tesla coils showing the protective nature of a Faraday cage. When students understand that substantial voltage cannot exist between electrically common points (at least at frequencies below RF!), not only are they prepared to understand the purpose of safety grounding in electrical systems, but they are also equipped with an extremely important concept for use in electrical troubleshooting.

Question 33

Briefly answer the following safety questions:

- What does electric current do to muscle tissue?
- What can electric current do to motor muscles (fingers, arms, legs)?
- What can electric current do to heart and lungs?
- Why should you use one hand while working on live power circuits? Which hand?
- Why is water dangerous when working around electric power?
- Why is metal jewelry dangerous to wear when working on electric circuits?
- What kinds of tools are best for working on live power circuits?
- What kind of immediate medical attention does an electric shock victim require?
- What footwear is appropriate when working around electric power?
- What footwear is **not** appropriate when working around electric power?

[file 01702](#)

Answer 33

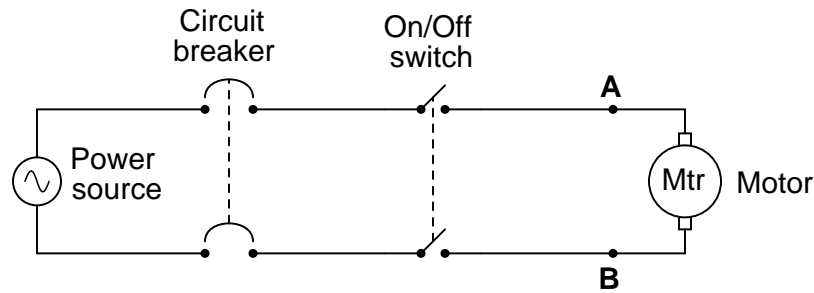
- What does electric current do to muscle tissue? *Electric current causes muscles to contract.*
- What can electric current do to motor muscles (fingers, arms, legs)? *It may cause them to involuntarily contract.*
- What can electric current do to heart and lungs? *Paralyze them.*
- Why should you use one hand while working on live power circuits? *To minimize the danger of an across-the-chest path for electric current. Which hand? The right, because the heart is more vulnerable to shock current going through the left-hand side of the chest.*
- Why is water dangerous when working around electric power? *It lowers the resistance of porous substances, including human skin.*
- Why is metal jewelry dangerous to wear when working on electric circuits? *Because the metal pieces optimize contact between your skin and an exposed power conductor, or between two power conductors.*
- What kinds of tools are best for working on live power circuits? *Tools with electrically-insulated handles.*
- What kind of immediate medical attention does an electric shock victim require? *CPR if they are not breathing or their heart is not beating.*
- What footwear is appropriate when working around electric power? *Closed-toed work boots or shoes with good, thick, insulating soles.*
- What footwear is **not** appropriate when working around electric power? *Sandals, flip-flops, or other shoes exposing the skin.*

Notes 33

The safety concern of jewelry worn around electric circuits is not limited to high voltages where shock is possible. It is also a concern around low-voltage circuits where high current through a ring or bracelet (caused by bridging two conductors with the jewelry) can cause the jewelry to heat up and burn the skin.

Question 34

In this motor control circuit, how would you ensure that there is no danger of electric shock prior to touching either of the motor terminals (shown as points **A** and **B** in the schematic diagram)? Describe both the action required to secure the power, and the means by which you would check for the presence of hazardous voltage at the motor:



[file 00566](#)

Answer 34

Follow these steps:

1. Open the circuit breaker.
2. Lock the circuit breaker in its "open" position so no one can close it.
3. Try to start the motor by turning the On/Off switch "on".
4. Leave the On/Off switch in the "off" position.
5. Test for hazardous voltage (both AC and DC) between A and B, between A and ground, and between B and ground.

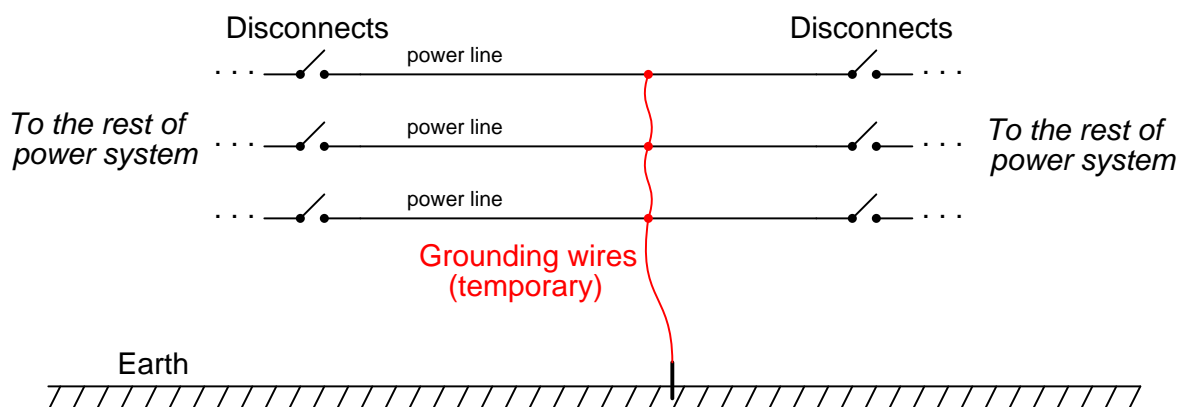
Notes 34

For each of the steps given in the answer, discuss the rationale with your students. *Why* is it important we do each one of those steps, in the order shown? How many voltage checks must we do with the voltmeter, total?

Also, be sure to ask your students how they would know whether or not their voltmeter was functioning properly prior to using it to check for the presence of hazardous voltage. What types of faults in the meter could cause it to not indicate voltage when there really was voltage?

Question 35

Linemen working on high-voltage conductors do not simply rely on open disconnect switches to isolate sections of power lines from sources of electricity during maintenance. They also attach "grounding" cables from line to line, and then to earth ground like this:



Explain why this decreases the risk of electric shock for the linemen, based on what you know about *electrically common points* in a circuit.

[file 03333](#)

Answer 35

By connecting the three wires together, you make them electrically common to each other. This prevents any substantial voltage (potential difference) developing between them. Likewise, connecting the three wires to the earth makes them electrically common to the earth, preventing any substantial voltage from developing between any of the wires and ground.

Follow-up question: after the linemen are done with their work, they remove the grounding wires from the power lines before they close the disconnect switches. Explain why this is done, by describing the catastrophic consequences of closing the disconnect switches with the grounding wires still in place.

Notes 35

A physicist would describe such a "grounded" system as being one large *equipotential surface*. This is an important concept for students to grasp, not only for safety but also for the purpose of better understanding where voltage drops should and *should not* be in working circuits.

Some students may (wisely) ask how any voltage at all could be developed between the isolated conductors in the absence of grounding wires, since the disconnect switches are open at all points. Although it may be premature to discuss with your students how capacitive coupling with nearby (energized) conductors could cause voltages to appear between non-grounded conductors and ground (depending on their level of electrical understanding), you can still answer the question by appealing to a general sense of safety conservatism. With the wires all made electrically common to each other and to earth ground, there is still some measure of protection even in the event of one or more of the disconnect switches accidentally closing, a lightning strike, or a bird landing between the open poles of a disconnect switch.

If your students have not yet studied three-phase AC systems, they may (wisely) ask why three power line conductors are necessary instead of two. You may tell them that this is irrelevant to the safety question: that all they need to know is that there will be high voltage present between each wire pair (A and B, B and C, A and C) and between each wire and ground, when the power lines are in operation.

Question 36

Describe what the phrase *zero energy state* means for a system, in terms of safety for those performing maintenance work on it.

file 00572

Answer 36

"Zero energy state" means that all sources of energy, either conducted from an outside source or stored within components of the system, have been secured so as to pose no danger to the people working on the system.

Identify some sources of energy in a system that could pose a safety hazard to people working on it.

Notes 36

When discussing this with your students, be sure to emphasize that "zero energy" is not just limited to electrical energy, but to all forms of energy that could cause harm. This includes mechanical and thermal energy as well.

Question 37

When using a padlock to secure a disconnect device in the "open" (off) state, who should be able to open that lock? In other words, how many other people should share a key to the lock you use to secure a breaker or switch in the safe position, if you are the one working on the system?

file 00571

Answer 37

You and you alone should be able to open that lock. It needs to be a *personal* lock, not a lock whose key is shared by other people.

Notes 37

Discuss with your students why a personal lock is preferred over a "group" lock for locking out circuit disconnect devices.

Question 38

When securing equipment for safe maintenance, special *tags* are attached with the lock(s) used to keep circuit breakers and other disconnect devices in the open (off) state. A typical "lockout" tag looks something like this:



What is the purpose of attaching such a tag to an electrical disconnect device in addition to locking it in the open position? Why is a lock, by itself, not sufficient from a safety perspective?

[file 00573](#)

Answer 38

A tag informs anyone wishing to turn the disconnect device "on" as to *when* it was turned off, and *who* placed the lock(s) on it. Many lockout tags have space on for a written description so that the reason for the lockout may be explained.

Notes 38

Discuss with your students the need for good communication between all people performing maintenance work on large and (potentially) dangerous systems. Tags are an integral part of this communication.

Question 39

What step(s) must be taken after locking and tagging an electrical disconnect device for a circuit to be worked on, and prior to actually proceeding with the work? What step(s) come between the lock-out and the work itself?

file 00574

Answer 39

Check for the presence of voltage on the conductors of the circuit to be worked on.

Notes 39

There is more to this answer than simply "check for voltage." Ask your students to explain what types of voltage they need to check for, and how they can ensure their voltmeters are properly functioning, so as not to "miss" detecting a dangerous condition.

Question 40

Suppose you are finishing a maintenance project where an electric motor was locked out and tagged, and now the work is complete. Your lock is the last one to be removed from the circuit breaker, everyone else already having taken their locks and tags off. What should you do before removing your lock and turning the circuit breaker back on?

[file 00575](#)

Answer 40

You should check the equipment site to be sure no one is still working on it, unaware of the impending startup.

Notes 40

Real-life story here: I was once asked to place an electric motor back in service after it had been locked out for a few days, for routine maintenance. I removed my lock and tag, and was just about to turn the breaker back on, when better judgment prevailed and I decided to first check the job site. Lo and behold, there, still working on the motor coupling, were two contract employees completely oblivious to the situation. They had not been told there was a circuit breaker to secure power to that electric motor, nor were they aware that they needed to lock it out in addition to everyone else on the project! Had I turned that circuit breaker back on, the motor could have started up and severely injured at least one of them!

Lesson to be learned: if you are performing work on a piece of equipment, *you* need to have *your* lock and *your* tag securing energy to that equipment. Never, ever trust someone else to lock-out and tag-out a circuit breaker for you!

Question 41

How many physical points must be referenced when speaking of the following electrical quantities?

- Voltage
- Current
- Resistance

In other words, does it make sense to speak of voltage at a single point, or between two points, or between three points, etc.? Does it make sense to speak of current at a single point, between two points, between three points, etc.?

[file 00147](#)

Answer 41

- Voltage is always measured *between two points*.
- Current may be measured at a single point (at a cross-section of a conductive path).
- Resistance is always measured *between two points*.

Follow-up question: explain, if you can, the relevance of these facts to electrical safety. For example, why is it important to know that voltage is always a quantity existing *between* two points (rather than existing *at* a single point) when considering your personal safety?

Notes 41

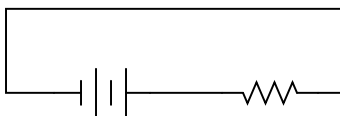
One of the more confusing aspects of electrical theory is that both voltage and resistance are quantities relative between two points. It is meaningless to speak of the amount of voltage "at this point" in a circuit, at least without implying a reference point such as ground. The same goes for resistance: it makes no sense to speak of how much electrical resistance there is "at this point" in a circuit either.

Conversely, it makes perfect sense to speak of either voltage or resistance lying "between *this* point and *that* point," because both these quantities are relative between exactly two points.

Current, on the other hand, is the coordinated motion of electric charge through a conductor. As such, it may be measured at any single point in a circuit, like measuring the flow of water in a river at any one particular cross-sectional sample.

Question 42

Draw the direction of current in this circuit, and also identify the polarity of the voltage across the battery and across the resistor. Then, compare the battery's polarity with the direction of current through it, and the resistor's polarity with the direction of current through it.

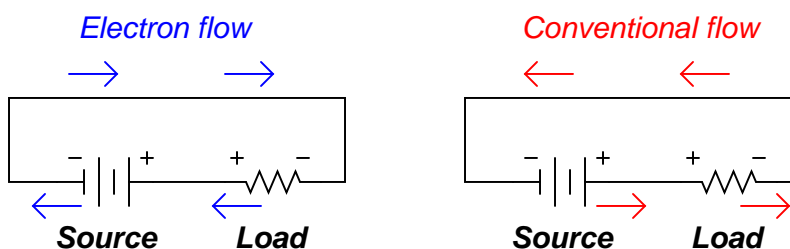


What do you notice about the relationship between voltage polarity and current direction for these two different types of components? Identify the fundamental distinction between these two components that causes them to behave differently.

[file 01555](#)

Answer 42

Here I show the answer in two different forms: current shown as *electron flow* (left) and current shown as *conventional flow* (right).



Whichever notation you choose to follow in your analysis of circuits, the understanding should be the same: the reason voltage polarities across the resistor and battery differ despite the same direction of current through both is the flow of power. The battery acts as a *source*, while the resistor acts as a *load*.

Notes 42

This type of distinction is very important in the study of physics as well, where one must determine whether a mechanical system is *doing work* or whether *work is being done on it*. A clear understanding of the relationship between voltage polarity and current direction for sources and loads is very important for students to have before they study reactive devices such as inductors and capacitors!

Question 43

Define the following terms: *energy*, *work*, and *power*.
file 00107

Answer 43

Work is the exertion of a force over a distance. *Energy* is the capacity to perform work. *Power* is the rate of work performed per unit time.

Notes 43

Students may find a basic physics text helpful in obtaining these definitions. "Work" is a difficult concept to precisely define, especially for students unfamiliar with basic physics. Technically, it is the vector dot-product of force and displacement, meaning that work equals force times distance *only* if the force and distance vectors are precisely parallel to each other. In other words, if I carry a 10 kg mass (lifting *up* against the tug of gravity) while walking parallel to the ground (not going up or down), the force and displacement vectors are perpendicular to each other, and the work I do in carrying the mass is *zero*. It is only if my force is directed precisely the same direction as my motion that all of my effort is translated into work.

Question 44

When an electric current travels through an electrical resistance, not only will there be a voltage "drop" across that resistance ($V = IR$), but there will also be energy dissipated by that resistance. We describe the rate of energy dissipation over time as *power* (P), and we express power in the unit of the *watt* (W).

Write the equation relating power to voltage and current, for an electrical resistance. Also, describe what physical form this dissipated energy usually takes.

file 01713

Answer 44

$$P = IV$$

Energy dissipated by an electrical resistance is usually manifest as *heat*, although sometimes it is also in the form of *light*.

Notes 44

Most people, even if they have no prior experience with electric circuit analysis, have some sense of what a "Watt" is, because so many consumer-grade appliances are rated in watts (light bulbs, heaters, blow driers, etc.). Use these examples as context for your discussion on electric power.

Question 45

For a given amount of electric current, which resistor will dissipate the greatest amount of power: a small value (low-resistance) resistor, or a high value (high-resistance) resistor? Explain your answer.

file 00082

Answer 45

A resistor with a high resistance rating (many "ohms" of resistance) will dissipate more heat power than a lower-valued resistor, given the same amount of electric current through it.

Notes 45

This question is designed to make students think *qualitatively* about the relationship between current, resistance, and power. I have found that qualitative (non-numeric) analysis is often more challenging than asking students to calculate answers quantitatively (with numbers). Often, simple math is a kind of barrier behind which students seek refuge from true understanding of a topic. In other words, it is easier to punch keys on a calculator (or even perform calculations with paper and pencil) than to really *think* about the inter-relationships of variables in a physical problem. Yet, a qualitative understanding of electrical systems is vital to fast and efficient troubleshooting.

Question 46

There are two basic Ohm's Law equations: one relating voltage, current, and resistance; and the other relating voltage, current, and power (the latter equation is sometimes known as *Joule's Law* rather than Ohm's Law):

$$E = IR$$

$$P = IE$$

In electronics textbooks and reference books, you will find twelve different variations of these two equations, one solving for each variable in terms of a unique pair of two other variables. However, you need not memorize all twelve equations if you have the ability to algebraically manipulate the two simple equations shown above.

Demonstrate how algebra is used to derive the ten "other" forms of the two Ohm's Law / Joule's Law equations shown here.

[file 00088](#)

I won't show you how to do the algebraic manipulations, but I will show you the ten other equations. First, those equations that may be derived strictly from $E = IR$:

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

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

Next, those equations that may be derived strictly from $P = IE$:

$$I = \frac{P}{E}$$

$$E = \frac{P}{I}$$

Next, those equations that may be derived by using algebraic *substitution* between the original two equations given in the question:

$$P = I^2 R$$

$$P = \frac{E^2}{R}$$

And finally, those equations which may be derived from manipulating the last two power equations:

$$R = \frac{P}{I^2}$$

$$I = \sqrt{\frac{P}{R}}$$

$$E = \sqrt{PR}$$

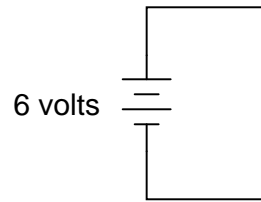
$$R = \frac{E^2}{P}$$

Algebra is an extremely important tool in many technical fields. One nice thing about the study of electronics is that it provides a relatively simple context in which fundamental algebraic principles may be learned (or at least illuminated).

The same may be said for calculus concepts as well: basic principles of derivative and integral (with respect to time) may be easily applied to capacitor and inductor circuits, providing students with an accessible context in which these otherwise abstract concepts may be grasped. But calculus is a topic for later worksheet questions . . .

Question 47

What would happen if a wire having no resistance at all (0Ω) were connected directly across the terminals of a 6-volt battery? How much power would be dissipated, according to Joule's Law?



Suppose I short-circuited a 6-volt battery in the manner just described and found that the wire used to make the short-circuit gets warm after just a few seconds of carrying this current. Does this data agree or disagree with your predictions?

file 00180

Answer 47

Calculations based on power equations would suggest either zero watts of power dissipated or infinite power dissipation, depending on which equation you chose to calculate power with. Yet, the experiment described yields a power dissipation that is neither zero nor infinite.

If you think that the wire used in the experiment is not resistance-less (i.e. it *does* have resistance), and that this accounts for the disparity between the predicted and measured amounts of current, you are partially correct. Realistically, a small piece of wire such as that used in the experiment will have a few tenths of an ohm of resistance. However, if you re-calculate power with a wire resistance of 0.1Ω , you will still find a large disparity between your prediction and the actual measured power in this short-circuit.

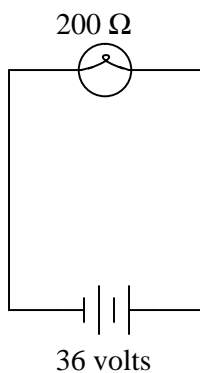
What is going on here?

Notes 47

Remind students that short-circuit testing of electrical power sources can be dangerous. A student of mine once stuffed a 6-volt "lantern" battery in his tool pouch, only to have it discharge smoke an hour later, after the battery terminals had been shorted together by the metal handle of a wrench!

Question 48

How much electrical power is being dissipated by the light bulb in this circuit?



In this circuit, identify which component is the *source* and which is the *load*.
[file 00178](#)

Answer 48

6.48 watts

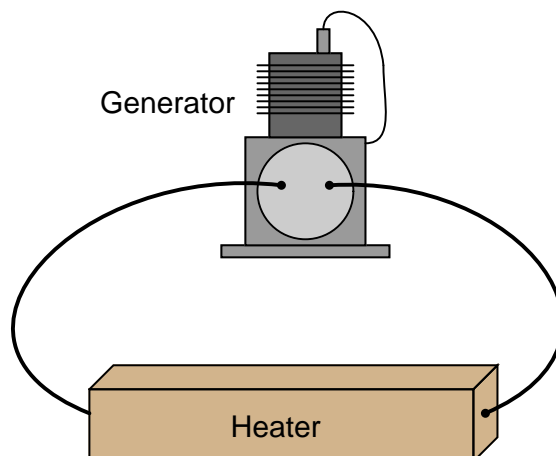
Here, the battery is the source and the light bulb is the load.

Notes 48

The solution to this problem simply requires the application of Ohm's Law. As for the question of source versus load, ask your students to define each of these words in terms of energy transfer.

Question 49

Calculate the amount of power dissipated by this electric heating element, if the generator's output voltage is 110 volts and the heater's resistance is 2.5 ohms:



Now, calculate the power dissipated by the same heater if the generator's output voltage is doubled.
[file 00179](#)

Answer 49

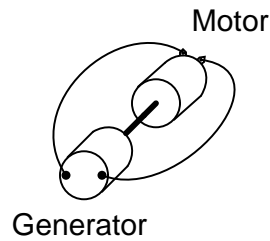
4,840 watts at 110 volts; 19,360 watts at 220 volts.

Notes 49

Many students will mistakenly calculate 9,680 watts as the power dissipation at 220 volts. However, power dissipation does not increase linearly with increases in voltage!

Question 50

Suppose someone mechanically couples an electric motor to an electric generator, then electrically couples the two devices together in an effort to make a perpetual-motion machine:



Why won't this assembly spin forever, once started?
[file 00041](#)

Answer 50

This will not work because neither the motor nor the generator is 100% efficient.

Notes 50

The easy answer to this question is "the Law of Conservation of Energy (or the Second Law of Thermodynamics) forbids it," but citing such a "Law" really doesn't explain *why* perpetual motion machines are doomed to failure. It is important for students to realize that reality is not *bound* to the physical "Laws" scientists set; rather, what we call "Laws" are actually just *descriptions* of regularities seen in nature. It is important to emphasize critical thinking in a question like this, for it is no more intellectually mature to deny the possibility of an event based on dogmatic adherence to a Law than it is to naively believe that anything is possible.

Question 51

A DC electric motor transforms 1.75 kW of electrical power into mechanical form. If the motor's operating voltage is 300 volts, how much current does it "draw" when operating at full load (full power output)?

Also calculate the motor's output power in units of *horsepower*, assuming 100% efficiency.

file 00183

Answer 51

Motor current = 5.833 amps. Motor power = 2.346 horsepower.

Notes 51

To answer both parts of this question, students will have to apply Ohm's (Joule's) Law to calculate power from figures of voltage and current, and they will also have to research the conversion factor between watts and horsepower.

Question 52

Write the following exponential expressions in expanded form:

$$10^1 =$$

$$10^2 =$$

$$10^3 =$$

$$10^4 =$$

$$10^{-1} =$$

$$10^{-2} =$$

$$10^{-3} =$$

$$10^{-4} =$$

file 01706

Answer 52

$$10^1 = 10$$

$$10^2 = 100$$

$$10^3 = 1000$$

$$10^4 = 10000$$

$$10^{-1} = \frac{1}{10}$$

$$10^{-2} = \frac{1}{100}$$

$$10^{-3} = \frac{1}{1000}$$

$$10^{-4} = \frac{1}{10000}$$

Notes 52

I have found that many students entering college (at least those entering a technical college in the United States) have a very limited understanding of exponents, especially *negative* exponents. You may find it necessary to review this concept, explaining what a negative exponent is and how it is defined.

Question 53

Evaluate the following arithmetic expressions, expressing the answers in expanded form:

$$3.6 \times 10^2 =$$

$$1.53 \times 10^{-4} =$$

$$8.2 \times 10^1 =$$

$$6 \times 10^{-3} =$$

Comment on the effect multiplication by a power of ten has on how a number is written.

file 01707

Answer 53

$$3.6 \times 10^2 = 360$$

$$1.53 \times 10^{-4} = 0.000153$$

$$8.2 \times 10^1 = 82$$

$$6 \times 10^{-3} = 0.006$$

The effect that multiplication by a power of ten has on a number's written expression should be obvious: the decimal point gets shifted.

Notes 53

The fact that multiplication by powers of ten simply shifts the decimal point is not a coincidence. Rather, it is a logical consequence of using a *base-10* numeration system. If we all used binary for our daily enumeration, we would be using "powers of two" for scientific notation!

Question 54

Express the following numbers in scientific notation:

$$0.00045 =$$

$$23,000,000 =$$

$$700,000,000,000 =$$

$$0.00000000000000000001 =$$

$$0.000098 =$$

file 01708

Answer 54

$$0.00045 = 4.5 \times 10^{-4}$$

$$23,000,000 = 2.3 \times 10^7$$

$$700,000,000,000 = 7 \times 10^{11}$$

$$0.00000000000000000001 = 1 \times 10^{-20}$$

$$0.000098 = 9.8 \times 10^{-5}$$

Follow-up question: explain why scientific notation is used so frequently by scientists and engineers.

Notes 54

The convenience in which scientific notation allows us to express and manipulate extremely large and small quantities is perhaps the most important reason why it is used by scientists and engineers.

Your students will be pleased to discover that their calculators can be used to easily convert between "expanded" (sometimes called *fixed-point*) and scientific notations.

Question 55

Metric prefixes are nothing more than "shorthand" representations for certain powers of ten. Express the following quantities of mass (in units of grams) using metric prefixes rather than scientific notation, and complete the "index" of metric prefixes shown below:

$$8.3 \times 10^{18} \text{ g} =$$

$$3.91 \times 10^{15} \text{ g} =$$

$$5.2 \times 10^{12} \text{ g} =$$

$$9.3 \times 10^9 \text{ g} =$$

$$6.7 \times 10^6 \text{ g} =$$

$$6.8 \times 10^3 \text{ g} =$$

$$4.5 \times 10^2 \text{ g} =$$

$$8.11 \times 10^1 \text{ g} =$$

$$2.1 \times 10^{-1} \text{ g} =$$

$$1.9 \times 10^{-2} \text{ g} =$$

$$9.32 \times 10^{-3} \text{ g} =$$

$$1.58 \times 10^{-6} \text{ g} =$$

$$8.80 \times 10^{-9} \text{ g} =$$

$$6.9 \times 10^{-12} \text{ g} =$$

$$7.2 \times 10^{-15} \text{ g} =$$

$$4.1 \times 10^{-18} \text{ g} =$$

10^{18}	10^{15}	10^{12}	10^9	10^6	10^3	10^2	10^1	(units)	10^{-1}	10^{-2}	10^{-3}	10^{-6}	10^{-9}	10^{-12}	10^{-15}	10^{-18}
	peta		giga		kilo						milli		nano			
E					k				d		m					a

file 01709

$$8.3 \times 10^{18} \text{ g} = 8.3 \text{ Eg}$$

$$3.91 \times 10^{15} \text{ g} = 3.91 \text{ Pg}$$

$$5.2 \times 10^{12} \text{ g} = 5.2 \text{ Tg}$$

$$9.3 \times 10^9 \text{ g} = 9.3 \text{ Gg}$$

$$6.7 \times 10^6 \text{ g} = 6.7 \text{ Mg}$$

$$6.8 \times 10^3 \text{ g} = 6.8 \text{ kg}$$

$$4.5 \times 10^2 \text{ g} = 4.5 \text{ hg}$$

$$8.11 \times 10^1 \text{ g} = 8.11 \text{ dag}$$

$$2.1 \times 10^{-1} \text{ g} = 2.1 \text{ dg}$$

$$1.9 \times 10^{-2} \text{ g} = 1.9 \text{ cg}$$

$$9.32 \times 10^{-3} \text{ g} = 9.32 \text{ mg}$$

$$1.58 \times 10^{-6} \text{ g} = 1.58 \mu\text{g}$$

$$8.80 \times 10^{-9} \text{ g} = 8.80 \text{ ng}$$

$$6.9 \times 10^{-12} \text{ g} = 6.9 \text{ pg}$$

$$7.2 \times 10^{-15} \text{ g} = 7.2 \text{ fg}$$

$$4.1 \times 10^{-18} \text{ g} = 4.1 \text{ ag}$$

10^{18}	10^{15}	10^{12}	10^9	10^6	10^3	10^2	10^1	(units)	10^{-1}	10^{-2}	10^{-3}	10^{-6}	10^{-9}	10^{-12}	10^{-15}	10^{-18}
exa	peta	tera	giga	mega	kilo	hecto	deka		deci	centi	milli	micro	nano	pico	femto	atto
E	P	T	G	M	k	h	da		d	c	m	μ	n	p	f	a

Notes 55

Once students realize metric prefixes are nothing more than shorthand for certain powers of ten, they see that scientific and metric notations are really one and the same. The only difficult part of this is committing to memory all the different metric prefixes and their respective powers of ten. Be sure to mention that the power of ten that are multiples of three (10^3 , 10^6 , 10^{-12} , etc.) are more commonly used than the other powers (h, da, d, and c).

In case anyone asks, the metric prefix for 10^1 (deka) is sometimes spelled *deca*. There seems to be no "standard" way to spell the name of this prefix.

Question 56

One of the fundamental equations used in electricity and electronics is *Ohm's Law*: the relationship between voltage (E or V , measured in units of *volts*), current (I , measured in units of *amperes*), and resistance (R , measured in units of *ohms*):

$$E = IR \quad I = \frac{E}{R} \quad R = \frac{E}{I}$$

Where,

E = Voltage in units of volts (V)

I = Current in units of amps (A)

R = Resistance in units of ohms (Ω)

Solve for the unknown quantity (E , I , or R) given the other two, and express your answer in both scientific and metric notations:

$$I = 20 \text{ mA}, R = 5 \text{ k}\Omega; \quad E =$$

$$I = 150 \text{ }\mu\text{A}, R = 47 \text{ k}\Omega; \quad E =$$

$$E = 24 \text{ V}, R = 3.3 \text{ M}\Omega; \quad I =$$

$$E = 7.2 \text{ kV}, R = 900 \text{ }\Omega; \quad I =$$

$$E = 1.02 \text{ mV}, I = 40 \text{ }\mu\text{A}; \quad R =$$

$$E = 3.5 \text{ GV}, I = 0.76 \text{ kA}; \quad R =$$

$$I = 0.00035 \text{ A}, R = 5350 \text{ }\Omega; \quad E =$$

$$I = 1,710,000 \text{ A}, R = 0.002 \text{ }\Omega; \quad E =$$

$$E = 477 \text{ V}, R = 0.00500 \text{ }\Omega; \quad I =$$

$$E = 0.02 \text{ V}, R = 992,000 \text{ }\Omega; \quad I =$$

$$E = 150,000 \text{ V}, I = 233 \text{ A}; \quad R =$$

$$E = 0.0000084 \text{ V}, I = 0.011 \text{ A}; \quad R =$$

[file 01710](#)

Answer 56

$$I = 20 \text{ mA}, R = 5 \text{ k}\Omega; \quad E = 100 \text{ V} = 1 \times 10^2 \text{ V}$$

$$I = 150 \text{ }\mu\text{A}, R = 47 \text{ k}\Omega; \quad E = 7.1 \text{ V} = 7.1 \times 10^0 \text{ V}$$

$$E = 24 \text{ V}, R = 3.3 \text{ M}\Omega; \quad I = 7.3 \text{ }\mu\text{A} = 7.3 \times 10^{-6} \text{ A}$$

$$E = 7.2 \text{ kV}, R = 900 \text{ }\Omega; \quad I = 8.0 \text{ A} = 8.0 \times 10^0 \text{ A}$$

$$E = 1.02 \text{ mV}, I = 40 \text{ }\mu\text{A}; \quad R = 26 \text{ }\Omega = 2.6 \times 10^1 \text{ }\Omega$$

$$E = 3.5 \text{ GV}, I = 0.76 \text{ kA}; \quad R = 4.6 \text{ M}\Omega = 4.6 \times 10^6 \text{ }\Omega$$

$$I = 0.00035 \text{ A}, R = 5350 \text{ }\Omega; \quad E = 1.9 \text{ V} = 1.9 \times 10^0 \text{ V}$$

$$I = 1,710,000 \text{ A}, R = 0.002 \text{ }\Omega; \quad E = 3.42 \text{ kV} = 3.42 \times 10^3 \text{ V}$$

$$E = 477 \text{ V}, R = 0.00500 \text{ }\Omega; \quad I = 95.4 \text{ kA} = 9.54 \times 10^4 \text{ A}$$

$$E = 0.02 \text{ V}, R = 992,000 \text{ }\Omega; \quad I = 20 \text{ nA} = 2 \times 10^{-8} \text{ A}$$

$$E = 150,000 \text{ V}, I = 233 \text{ A}; \quad R = 640 \text{ }\Omega = 6.4 \times 10^2 \text{ }\Omega$$

$$E = 0.0000084 \text{ V}, I = 0.011 \text{ A}; \quad R = 760 \text{ }\mu\Omega = 7.6 \times 10^{-4} \text{ }\Omega$$

Notes 56

In calculating the answers, I held to proper numbers of significant digits. This question is little more than drill for students learning how to express quantities in scientific and metric notations.

Question 57

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

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

The unit of conductance is the *siemens*, symbolized by the capital letter "S". Convert the following resistance values into conductance values, expressing your answers in both scientific and metric notations:

$$R = 5 \text{ k}\Omega ; G =$$

$$R = 47 \text{ }\Omega ; G =$$

$$R = 500 \text{ M}\Omega ; G =$$

$$R = 18.2 \text{ }\mu\Omega ; G =$$

Now, algebraically manipulate the given equation to solve for R in terms of G , then use this new equation to work "backwards" through above calculations to see if you arrive at the original values of R starting with your previously calculated values of G .

file 01712

Answer 57

$$R = 5 \text{ k}\Omega ; G = 200 \text{ }\mu\text{S} = 2 \times 10^{-4} \text{ S}$$

$$R = 47 \text{ }\Omega ; G = 21 \text{ mS} = 2.1 \times 10^{-2} \text{ S}$$

$$R = 500 \text{ M}\Omega ; G = 2 \text{ nS} = 2 \times 10^{-9} \text{ S}$$

$$R = 18.2 \text{ }\mu\Omega ; G = 55 \text{ kS} = 5.5 \times 10^4 \text{ S}$$

Solving for R in terms of G :

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

Notes 57

Ask your students to show you exactly how they manipulated the equation to solve for R . The last instruction given in the question – working backwards through the five calculations to see if you get the original (given) figures in degrees Celsius – is actually a very useful way for students to check their algebraic work. Be sure to make note of this in class!

Question 58

What is the difference between the following three values of mass (in kilograms)?

$$4 \times 10^2 \text{ kg}$$

$$4.5 \times 10^2 \text{ kg}$$

$$4.500 \times 10^2 \text{ kg}$$

file 01711

Answer 58

The difference between these figures is *precision*: the degree of uncertainty in the value expressed.

Notes 58

It is important for students to understand that although a computer may see these three quantities as precisely equivalent, they are actually not. Human beings do not write extra zeros if they do not have to, and so these zeros serve to indicate extra certainty in the figure.

Question 59

Suppose an electric current of 1.5 microamps ($1.5 \mu\text{A}$) were to go through a resistance of 2.3 mega-ohms ($2.3 \text{ M}\Omega$). How much voltage would be "dropped" across this resistance? Show your work in calculating the answer.

file 00182

Answer 59

1.5×10^{-6} amps of current through a resistance of $2.3 \times 10^6 \Omega$ will produce a voltage "drop" equal to 3.45 volts.

Notes 59

It is important for students to understand that metric prefixes are nothing more than "shorthand" forms of scientific notation, with each prefix corresponding to a specific power-of-ten.

Question 60

How many electrons are there in 2×10^{-5} coulombs of charge? Determine the answer without using a calculator, and express the answer in scientific notation!

file 00142

Answer 60

There are approximately 1.25×10^{14} electrons in this quantity of charge.

Notes 60

One of the benefits of using scientific notation is that it allows us to easily perform multiplication and division using very large and very small numbers.

Question 61

When a resistor conducts electric current, its temperature increases. Explain how this phenomenon is significant to the application of resistors in electric circuits. In other words, why would we care about a resistor's temperature increasing?

Also, what does this indicate about the technical ratings of resistors? Aside from having a specific resistance rating (i.e. a certain number of *ohms*), what other rating is important for proper selection of resistors in electric circuits?

file 00214

Answer 61

The heating effect of electricity through a resistance is significant because that resistance may be damaged by excessive temperature. To avoid damage, resistors must be selected to be able to withstand a certain amount of heating.

Notes 61

Students need to understand that resistance alone does not fully dictate the selection of a resistor for electrical service. Failure to heed the dissipation ratings of a resistor can result in catastrophic failure!

A good follow-up question to this is to ask what the *unit of measurement* is for this kind of thermal rating.

Question 62

Many resistors have their electrical resistance shown by a set of color codes, or "bands," imprinted around their circumference. A standard color code associates each color with a specific decimal digit (0 through 9). Associate each of the following digits with its respective color:

0 =

1 =

2 =

3 =

4 =

5 =

6 =

7 =

8 =

9 =

file 00215

Answer 62

0 = Black

1 = Brown

2 = Red

3 = Orange

4 = Yellow

5 = Green

6 = Blue

7 = Violet

8 = Grey

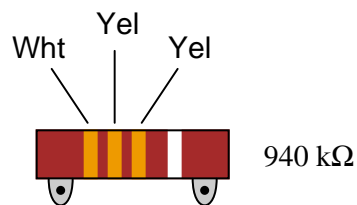
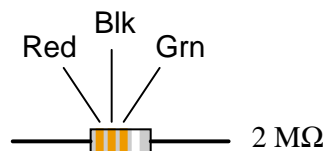
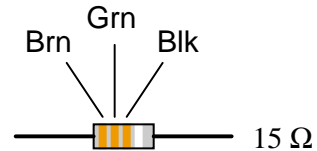
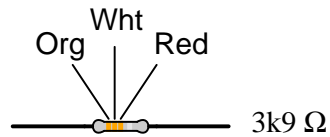
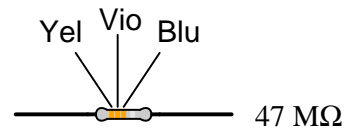
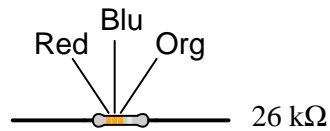
9 = White

Notes 62

Several limericks have been invented to remember this color code, most of them "politically incorrect." I often challenge students to invent their own limericks for remembering this color code, and screen the inappropriate creations from general class discussion.

Question 63

Observe the following "4-band" resistors, their color codes, and corresponding resistance values (note that the last color band is omitted, since it deals with precision and not nominal value):



What patterns do you notice between the color codes (given as three-letter abbreviations, so as to avoid interpretational errors resulting from variations in print quality), the resistance values, and the physical sizes of the resistors?

[file 00216](#)

Answer 63

The first three color "bands" for all these four-band resistors denote two digits and a "multiplier" value, respectively. Physical size has no relation to resistance.

Follow-up question: what does the physical size of a resistor represent, if not resistance?

Notes 63

The normal way to teach students the resistor color code is to show them the code first, then show them some resistors. Here, the sequence is reversed: show the students some resistors, and have them figure out the code. An important cognitive skill is the ability to detect and apply patterns in sets of data. Exercises such as this help build that skill.

Question 64

What does the *last* color band represent on a color-coded resistor?
[file 00217](#)

Answer 64

There is more than one answer to this question! On some resistors, the last band represents the *tolerance* (also known as *precision*) for that resistor, expressed as a percentage. On other resistors, the last band represents a *reliability* rating for that resistor.

Notes 64

This question is worded simply and directly enough that students might think there is only one right answer. However, upon doing some research they should find that there is more involved than one simple answer can encompass! Discuss with your students the different color code types, and what applications one might find resistors with "reliability" color codes in.

Regarding precision, nothing in life is perfectly accurate. However, the absence of perfect accuracy does not necessarily imply total uncertainty. In science, especially, it is important that all data be qualified by a statement of precision (or tolerance). Your students may be familiar with "margins of error" stated for public opinion polls. With resistors, this "margin of error" (expression of uncertainty) is explicitly given in the form of a separate color band.

Question 65

Determine the nominal resistance values of these resistors, given their band colors, and also express the allowable tolerance in ohms.

For example, a 25 k Ω resistor with a 10% tolerance rating would have an allowable tolerance of ± 2.5 k Ω .

- Red, Org, Blu, Gld =
- Brn, Blk, Grn, Sil =
- Blu, Blk, Brn, Gld =
- Yel, Vio, Red, Sil =
- Grn, Brn, Yel =
- Wht, Blu, Blk, Sil =
- Gry, Grn, Org, Gld =
- Org, Org, Gld =
- Vio, Red, Sil, Gld =
- Brn, Red, Blk, Sil =

[file 00264](#)

Answer 65

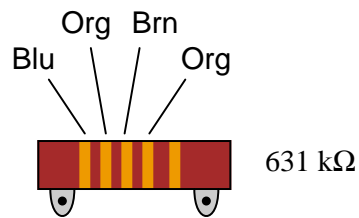
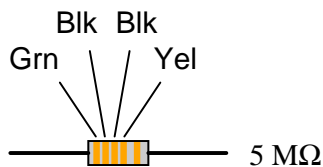
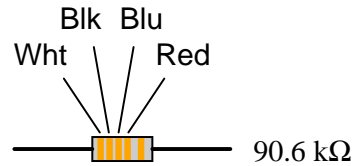
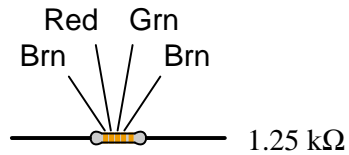
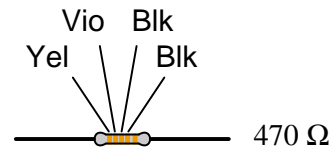
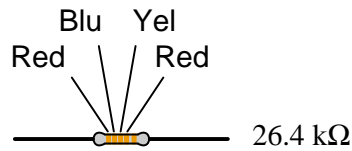
- Red, Org, Blu, Gld = 23 M Ω , ± 1.15 M Ω
- Brn, Blk, Grn, Sil = 1 M Ω , ± 100 k Ω
- Blu, Blk, Brn, Gld = 600 Ω , ± 30 Ω
- Yel, Vio, Red, Sil = 4.7 k Ω , ± 470 Ω
- Grn, Brn, Yel = 510 k Ω , ± 102 k Ω
- Wht, Blu, Blk, Sil = 96 Ω , ± 9.6 Ω
- Gry, Grn, Org, Gld = 85 k Ω , ± 4.25 k Ω
- Org, Org, Gld = 3.3 Ω , ± 0.66 Ω
- Vio, Red, Sil, Gld = 0.72 Ω , ± 0.036 Ω
- Brn, Red, Blk, Sil = 12 Ω , ± 1.2 Ω

Notes 65

This question serves as a great review for the mathematical concepts of scientific notation and percentages. Challenge your students to perform all the math without using a calculator, and without writing anything!

Question 66

Observe the following "5-band" precision resistors, their color codes, and corresponding resistance values (note that the last color band is omitted, since it deals with precision and not nominal value):



What patterns do you notice between the color codes (given as three-letter abbreviations, so as to avoid interpretational errors resulting from variations in print quality) and the resistance values of each resistor? Why do precision resistors use a "5-band" color code instead of a "4-band" color code?

[file 00265](#)

Answer 66

The first three color "bands" for precision five-band resistors denote three digits and a "multiplier" value, respectively. A five-band color code is necessary to express resistance with a greater number of significant digits than a four-band code.

Notes 66

The normal way to teach students the resistor color code is to show them the code first, then show them some resistors. Here, the sequence is reversed: show the students some resistors, and have them figure out the code. An important cognitive skill is the ability to detect and apply patterns in sets of data. Exercises such as this help build that skill.

It should be noted that there is a 5-band color code for *non-precision* resistors as well, with the first four bands serving the same purpose as in a 4-band code, the extra band indicating resistor *reliability*. This scheme was developed for military purposes and is seldom seen in civilian circuitry.

Question 67

Determine whether or not the following resistors measure within the resistance range specified by their color codes:

- (Org, Org, Red, Blk, Blu) Measured resistance = 332.5Ω
- (Brn, Blk, Blk, Gld, Red) Measured resistance = 9.7Ω
- (Blu, Vio, Brn, Red, Grn) Measured resistance = $67.43 \text{ k}\Omega$
- (Red, Wht, Grn, Yel, Vio) Measured resistance = $2.949 \text{ M}\Omega$
- (Yel, Vio, Org, Gld) Measured resistance = $44.68 \text{ k}\Omega$
- (Gry, Red, Brn, Sil) Measured resistance = 905Ω
- (Grn, Blu, Gld) Measured resistance = 6.73Ω
- (Vio, Brn, Red, Gld, Brn) Measured resistance = 70.82Ω
- (Wht, Org, Blu, Brn, Grn) Measured resistance = $9.38 \text{ k}\Omega$
- (Red, Blk, Wht, Grn, Vio) Measured resistance = $20.86 \text{ M}\Omega$

Assume that all five-band resistors listed here use the *precision* color code as opposed to the military 5-band code where the fifth band indicates resistor reliability.

[file 00266](#)

Answer 67

- (Org, Org, Red, Blk, Blu) Measured resistance = 332.5Ω *Within tolerance*
- (Brn, Blk, Blk, Gld, Red) Measured resistance = 9.7Ω **Out of tolerance!**
- (Blu, Vio, Brn, Red, Grn) Measured resistance = $67.43 \text{ k}\Omega$ *Within tolerance*
- (Red, Wht, Grn, Yel, Vio) Measured resistance = $2.949 \text{ M}\Omega$ *Within tolerance*
- (Yel, Vio, Org, Gld) Measured resistance = $44.68 \text{ k}\Omega$ *Within tolerance*
- (Gry, Red, Brn, Sil) Measured resistance = 905Ω **Out of tolerance!**
- (Grn, Blu, Gld) Measured resistance = 6.73Ω **Out of tolerance!**
- (Vio, Brn, Red, Gld, Brn) Measured resistance = 70.82Ω *Within tolerance*
- (Wht, Org, Blu, Brn, Grn) Measured resistance = $9.38 \text{ k}\Omega$ *Within tolerance*
- (Red, Blk, Wht, Grn, Vio) Measured resistance = $20.86 \text{ M}\Omega$ **Out of tolerance!**

Notes 67

This question serves as a great review for the mathematical concepts of scientific notation and percentages. They will have to calculate the allowable range of resistance values for each resistor in order to determine whether or not the measured value falls within that range.

Question 68

Find one or two real resistors and bring them with you to class for discussion. Identify as much information as you can about your resistors prior to discussion:

- Resistance (ideal)
- Resistance (actual)
- Power rating
- Type (carbon composition, metal film, wire-wound, etc.)

[file 01150](#)

Answer 68

If possible, find a manufacturer's datasheet for your components (or at least a datasheet for a similar component) to discuss with your classmates.

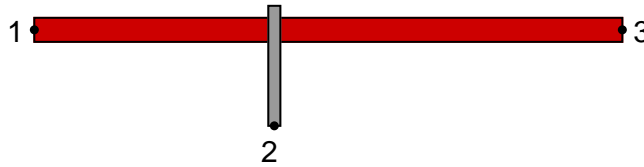
Be prepared to *prove* the actual resistance of your resistors in class, by using a multimeter!

Notes 68

The purpose of this question is to get students to kinesthetically interact with the subject matter. It may seem silly to have students engage in a "show and tell" exercise, but I have found that activities such as this greatly help some students. For those learners who are kinesthetic in nature, it is a great help to actually *touch* real components while they're learning about their function. Of course, this question also provides an excellent opportunity for them to practice interpreting color codes and/or component markings, use a multimeter, access datasheets, etc.

Question 69

Suppose a length of resistive material (such as *nichrome* wire) had three points of electrical contact: one at each end (points 1 and 3), plus a movable metal "wiper" making contact at some point between the two ends (point 2):



Describe what happens to the amount of electrical resistance between the following points, as the wiper is moved toward the left end of the resistive element (toward point 1)? State your answers in terms of "increase," "decrease," or "remains the same," and explain why each answer is so.

Wiper moved toward point 1



- Between points 1 and 2, resistance . . .
- Between points 2 and 3, resistance . . .
- Between points 1 and 3, resistance . . .

[file 00213](#)

Answer 69

As the wiper moves to the left (toward point 1):

- Between points 1 and 2, resistance *decreases*
- Between points 2 and 3, resistance *increases*
- Between points 1 and 3, resistance remains the same

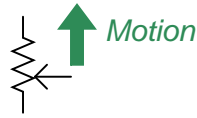
Notes 69

The purpose of this question is to get students to comprehend the function of a *potentiometer*, before they have ever seen one.

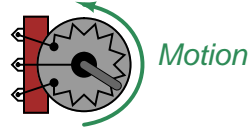
Question 70

A very common misconception students have about potentiometers is the relationship between resistance and direction of wiper motion. For instance, it is common to hear a student say something like this, "Turning the potentiometer so the wiper moves *up* will increase the resistance of the potentiometer."

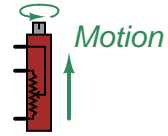
Schematic symbol



Internal view



Internal view



Explain why it does not really make sense to say something like this.
[file 03673](#)

Answer 70

Moving a potentiometer wiper changes *two* resistances in complementary directions: one resistance will increase as the other will decrease.

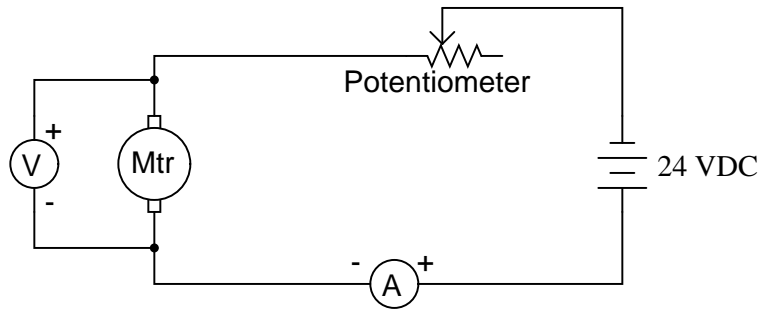
Notes 70

Ask your students to identify which resistance (which two connection points on the potentiometer) increases and which decreases, and how they know this from the "internal views" of the potentiometers. This is a very important thing for your students to learn.

Year after year of teaching has revealed that a great many students have difficulty grasping this concept. This is especially true when they become accustomed to using a potentiometer as a rheostat and not as a voltage divider. The more you can make them think carefully about the operation of a potentiometer, the better!

Question 71

A technician decides to use a potentiometer as a speed control for an electric motor. The potentiometer has a resistance rating of $10\ \Omega$ and a power rating of 25 watts:



When operating the motor at a voltage of 16 volts and a current of 2 amps, though, smoke begins to pour out of the potentiometer, indicating that its power rating is being exceeded.

The technician is perplexed! According to his calculations, the potentiometer should be dissipating less than 25 watts of power. Why, then, is a potentiometer rated for 25 watts burning up under this condition?
[file 00340](#)

Answer 71

The power rating of a potentiometer is based on the heat dispersing ability of the *entire* resistive element. The actual power dissipation rating of a potentiometer must be "de-rated" for wiper positions not utilizing the whole length of the resistive element.

Challenge question: based on the voltage and current values measured in this circuit (16 volts across the motor, 24 volts from the source, and 2 amps of current through it all), determine how badly the potentiometer is being overpowered. In other words, calculate the de-rated power rating of the potentiometer and compare that against the amount of power it is actually dissipating in this condition.

Notes 71

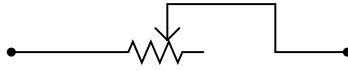
A very practical and important lesson, learned after watching students send many potentiometers to an early demise.

In order to answer the challenge question, students must determine the pot's setting as a percentage between 0% ($0\ \Omega$) and 100% ($10\ \Omega$), and use that setting to estimate power de-rating. It is safe to assume a linear power derating proportional to wiper position.

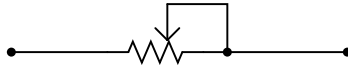
Question 72

When potentiometers are used as variable resistors (*rheostats*), the unused terminal is often connected to the wiper terminal:

Potentiometer as rheostat
(minimum necessary connections)



Potentiometer as rheostat
(typical connection)



Explain what advantage is gained by connecting the wiper to the unused terminal. Why is the lower potentiometer connection scheme more commonly used than the upper?

[file 00343](#)

Answer 72

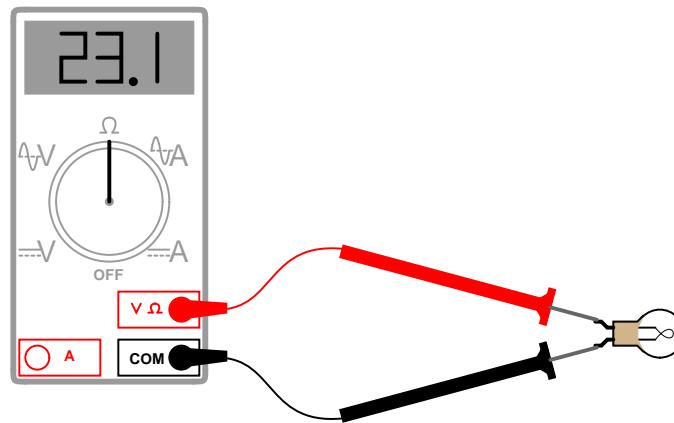
Here is a hint: suppose the potentiometer becomes worn with use, to the point where the wiper occasionally loses electrical contact with the resistive element. How would these two connection schemes compare, then?

Notes 72

This is an example of "defensive engineering": designing something with eventual failure in mind, with the goal of minimizing the consequences of that inevitable failure. Whether your students go on to become engineers, or simply technicians, it is important for them to think past the immediate application and design issues, to consider what may happen as their system ages.

Question 73

Explain how an ohmmeter is able to measure the resistance of a component (in this case, a light bulb) when there is no battery or other source of power connected to it:



Also, identify the reading you would expect the ohmmeter to indicate if the light bulb were burnt out (failed "open").

[file 00101](#)

Answer 73

Ohmmeters always contain a battery or some other internal source of electrical power so that the component under test may be supplied with a small amount of current, in order to measure how hard it is for current to go through.

If the light bulb were burnt open, the ohmmeter would register an extremely large (infinite) amount of resistance.

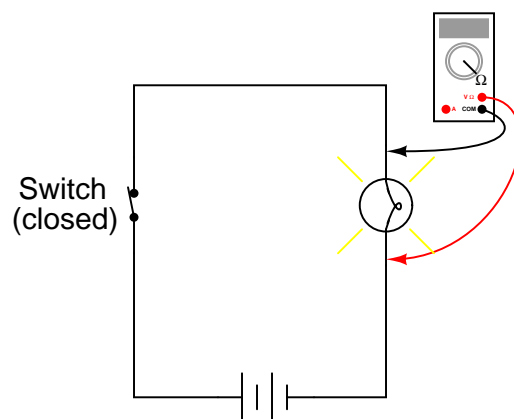
Notes 73

Unlike voltmeters or ammeters, ohmmeters *must* contain their own power sources. An implication of this fact is that ohmmeters must never be used to measure the resistance of an energized component. Discuss this important caveat with your students, being sure to ask them to explain why connecting an ohmmeter to an energized component might give erroneous measurements (if it doesn't destroy the meter first!).

In regard to the ohmmeter reading for an open bulb, I have found that many math-weak students have a difficult time grasping the differentiating zero from infinity. They recognize both as being extreme conditions (nothing versus everything), but many make the mistake of regarding "infinity" as identical to zero. Quite to the contrary, "infinity" means *bigger than big, and huger than huge*. Do not be surprised if one or more of your students harbor this same misconception, and be ready to address it!

Question 74

What would be wrong about measuring the resistance of a light bulb while it is being powered by a battery?



file 00306

Answer 74

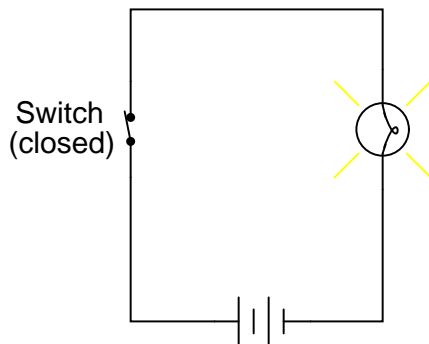
The voltage impressed across the light bulb by the battery will interfere with the ohmmeter's measurement.

Notes 74

This principle is very easy to illustrate, simply by building a "live" circuit and trying to measure the resistance of a known component in that circuit, while energized. Different ohmmeters will, of course, respond differently to this abuse, but none will yield the proper value for that component's resistance.

Question 75

Suppose we needed to determine the resistance of the light bulb in this circuit, while energized:



Now, we know we cannot simply connect an ohmmeter to an energized circuit, so how is it possible to obtain the resistance measurement we desire?

[file 00307](#)

Answer 75

Measure voltage across the light bulb, and current through the light bulb, and then use Ohm's Law to calculate filament resistance from these measurements.

Challenge question: explain how it would be possible to make these measurements without de-energizing the light bulb (not even once!).

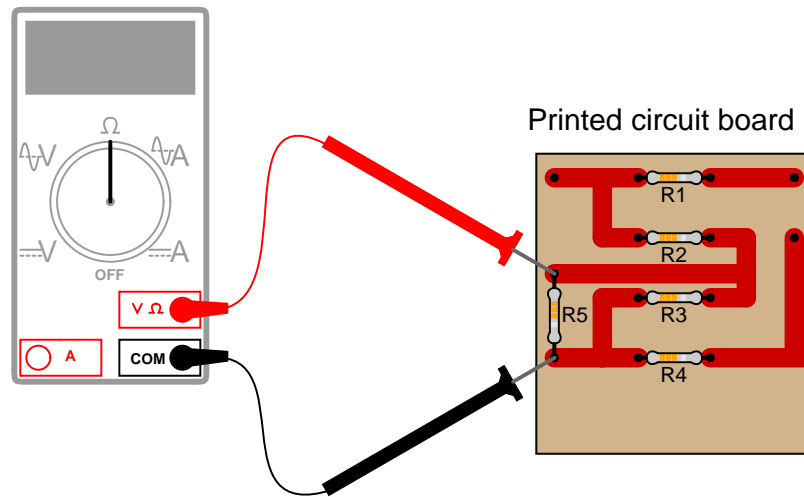
Notes 75

Quite often, resistance measurements on a component are not practical because the component cannot be "powered down," or perhaps because the component's resistance is different when energized versus when de-energized (incandescent light bulbs being an excellent example of this). Knowing how to derive a resistance measurement from voltage and current measurements is a valuable skill.

The "challenge" question, to measure light bulb voltage and current without breaking the circuit, is also very practical. Once students figure out how to do this (no, using an inductive ammeter is *not* an acceptable answer!), it would be a great classroom activity to actually build such a circuit and have students practice the technique on it.

Question 76

Suppose a technician attempted to measure the resistance of resistor R5 on this printed circuit board:



What is wrong with doing this?
[file 00362](#)

Answer 76

R5 is not the only component whose resistance is being measured!

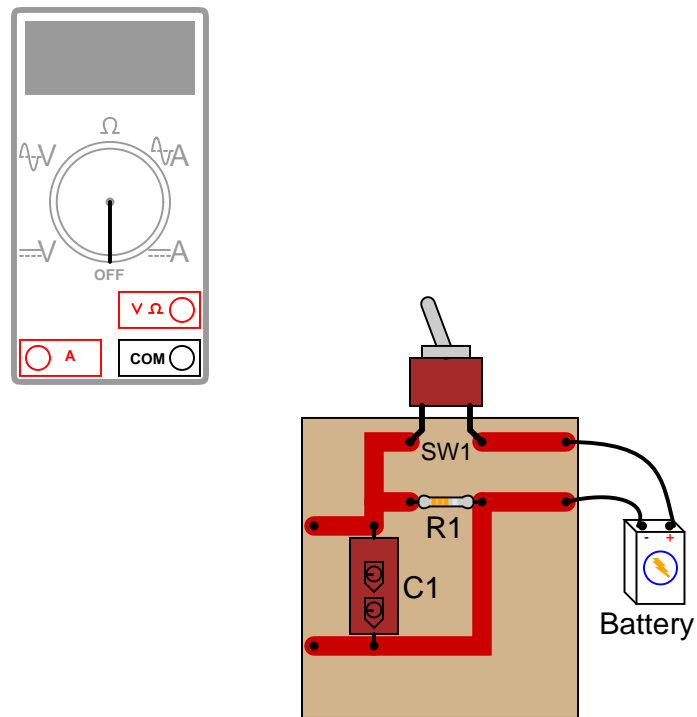
Follow-up question: what components on this printed circuit board *may* be measured with the ohmmeter without error?

Notes 76

This is very important for students to understand: the fact that the resistance of an individual component cannot be measured in a circuit, unless it is guaranteed that the ohmmeter's measuring current passes through that component only.

Question 77

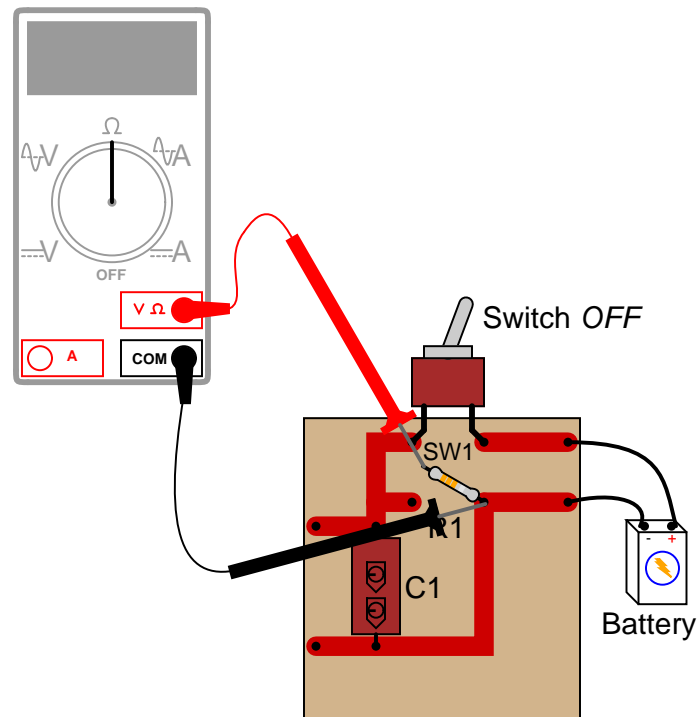
Shown here is a circuit constructed on a PCB (a "Printed Circuit Board"), with copper "traces" serving as wires to connect the components together:



How would the multimeter be used to measure the resistance of the component labeled "R1"? Include these important points in your answer:

- The configuration of the multimeter (selector switch position, test lead jacks)
- The connections of the meter test leads to the circuit
- The state of the switch on the PCB (open or closed)

[file 00099](#)



Notes 77

It is very important that students understand component resistance cannot be measured when the component is energized! In cases such as this, it is necessary to disconnect the component from the rest of the circuit so that only *its* resistance (and not any other components' resistance) is measured. In other cases, though, it may be acceptable to leave the component in place to take a resistance measurement.

Question 78

A technician picks up a resistor with the following color bands:

Color code: **Brn, Blk, Sil, Gld**

Having forgotten the resistor color code, and being too lazy to research the color code in a book, the technician decides to simply measure its resistance with an ohmmeter. The value this technician obtains is 0.6Ω .

What is wrong with the technician's measurement?

[file 00308](#)

Answer 78

The resistance measurement is too high (it should be closer to 0.1Ω) because the ohmmeter was not properly set up to compensate for test lead resistance.

Notes 78

Analog ohmmeters had to be "zeroed" prior to almost every measurement out of necessity, to give accurate measurements despite changes in internal battery voltage. Modern digital ohmmeters do not have this problem, but the lack of a "zeroing" procedure can lead to errors due to uncompensated test lead resistance. Your students should research the proper use of their own digital meters in this regard.

Question 79

A technician picks up a resistor with the following color bands:

Color code: **Org, Wht, Blu, Gld**

Having forgotten the resistor color code, and being too lazy to research the color code in a book, the technician decides to simply measure its resistance with an ohmmeter. Holding one lead of the resistor and one test lead of the ohmmeter between the thumb and index finger of the left hand, and the other resistor lead and meter test lead between the thumb and index finger of the right hand (to keep each test lead of the meter in firm contact with the respective leads of the resistor), the technician obtains a resistance measurement of 1.5 M Ω .

What is wrong with the technician's measurement?

[file 00309](#)

Answer 79

The resistance measurement is much too low (it should be closer to 39 M Ω) because the technician's body resistance is in parallel with the resistor.

Notes 79

This is a very common mistake made by beginning students of electronics: holding resistors improperly when measuring their resistance values. Discuss with your students some alternative methods of maintaining resistor lead contact with the meter probes so that the person's body does not become part of the resistance being measured.

Question 80

What is a *megger*, and what type of resistance measurements would it typically be used for? Explain how the design of a "megger" differs from that of a normal ohmmeter.

Also, explain how improper use of a "megger" may actually be hazardous, either to the operator of the meter or to the circuit under test.

[file 00311](#)

Answer 80

A "megger" is a high-range ohmmeter, typically used to measure the resistance of wire insulation. They utilize relatively high voltage (upwards of 1000 VDC) to measure resistance.

Follow-up question: what is a *hi-pot* meter, and what function is it typically used for?

Challenge question: why are special, high-voltage ohmmeters even needed? What's wrong with using a regular ohmmeter that outputs just a few volts to measure resistance? What does the existence of these specialized ohmmeter types tell us about the nature of electrical resistance?

Notes 80

"Meggers" are very useful tools, but they can cause damage as well. Your students need to be aware of proper and improper uses of "meggers" before they are entrusted with the use of one.

The challenge question is worth exploring if time permits! In real life, the simplicity of Ohm's Law is deceptive . . .

Question 81

What type of electrical test would be the most direct means of checking the integrity of an electrical connection between two conductors? Explain your answer.

file 00237

Answer 81

An electrical *resistance* test.

Notes 81

Discuss with your students the ideal resistance of an electrical connection, regardless of type (soldered, terminal strip, wire wrap, wire nut, crimp connector, etc.), and under what conditions you would test the resistance of an electrical connection.

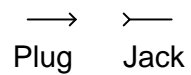
Question 82

What is the difference between a *plug* and a *jack*? What are these two devices used for? Draw the schematic diagram symbols for single-conductor plugs and jacks.

file 00232

Answer 82

A "plug" is the male half of a temporary electrical connector, while the "jack" is the female half. Electrical connectors are used to make convenient connections between individual wires or sets of wires.



Notes 82

Be sure to inform your students that poor electrical connections, often with regard to plug-and-jack assemblies, are a *very* common source of failure in electrical and electronic systems.

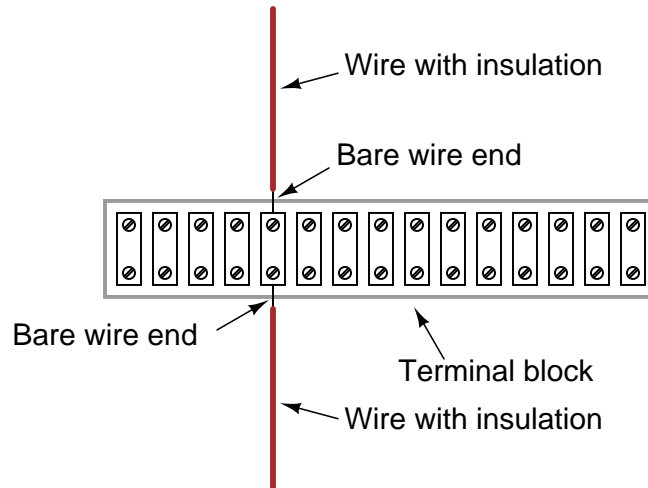
Question 83

What is a *terminal block*, or *terminal strip*? How are these devices used to make electrical connections between different conductors?

[file 00234](#)

Answer 83

Terminal "blocks" or "strips" are rows of short, metal blocks with screws or other fastener devices used to make firm mechanical bonds to conductors:



Sometimes, terminal blocks also go by the name of "barrier strips."

Notes 83

Be sure to have a variety of terminal blocks available for your students to see and touch during discussion time. Terminal blocks are widely used in industrial applications, for making permanent and semi-permanent connections.

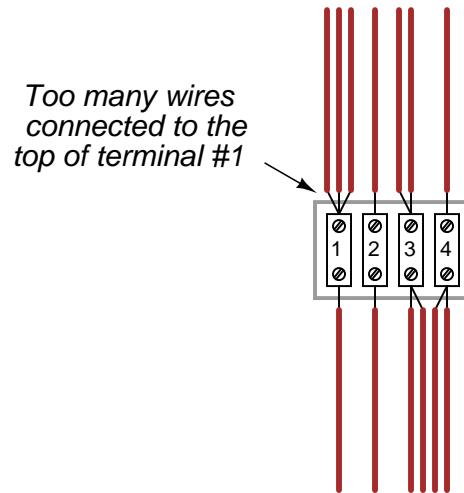
Question 84

What is generally considered to be the maximum number of individual wires that may be attached to a single terminal on a terminal block?

file 00238

Answer 84

Two wires per fastener, maximum:



Notes 84

I'm not sure if there is a specific code or regulation governing the number of terminals connected to a terminal block, but the "no more than two wires per lug" rule makes good sense. That is, of course, unless two conductors stuffed in the same hole would exceed the maximum cross-sectional area limit of the block, then "no more than one wire" is the rule.

I have had the misfortune of seeing egregious violations of both rules in my work experience!

Question 85

Wire nuts are special electrical connection devices commonly used in residential power wiring. Describe what a "wire nut" is and how they are used to make connections between wires.

file 00239

Answer 85

"Wire nuts" are electrical fasteners which use a coiled spring to clasp bare metal wire ends together. The "nut" is screwed on to the ends of two or more wires to be joined, as though it were a nut being threaded onto a bolt. The coils of the spring inside the nut function as threads, which grip the wire ends tighter as the nut is turned clockwise over them.

Notes 85

It would be good to have several sizes of wire nuts available in the classroom for your students to see and touch during discussion.

Question 86

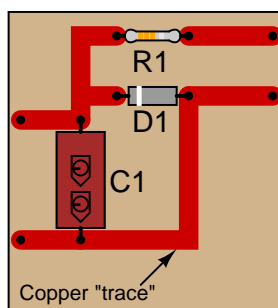
How are connections made between the various wire ends of components inserted into *printed circuit boards* ("PCBs")?

[file 00235](#)

Answer 86

Component wire ends are typically soldered onto strips of copper metal (called "traces") affixed on the surface of the printed circuit board material, which itself is electrically insulating.

Printed circuit board

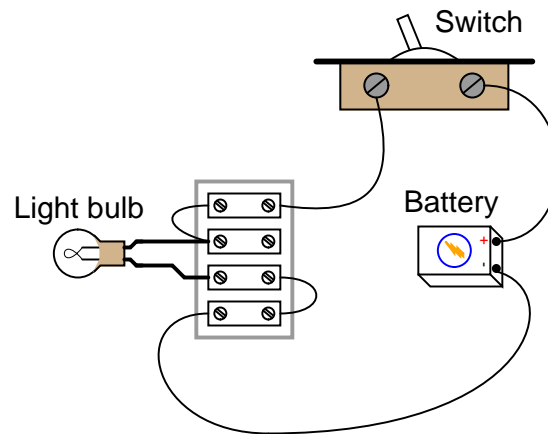


Notes 86

Be sure to have a variety of printed circuit boards available for your students to see and touch during discussion time. PCBs are widely used in all varieties of electronic applications, and are well suited for mass production manufacturing techniques.

Question 87

Suppose this circuit has a problem: the light bulb does not light up when the switch is turned "ON". You suspect that a "bad" connection may exist in the circuit which is preventing current. How would you test the integrity of each connection using a voltmeter only?



file 00240

Answer 87

If voltage is measured across any connection of two wires, that connection is definitely faulty.

Notes 87

It may be more difficult than it first appears to test for voltage across any single connection, if the wires are covered with insulation! Ask your students this question: if you test for voltage between two screws on a terminal strip, how many electrical connections are you actually measuring voltage across?

Question 88

Both soldering *irons* and soldering *guns* are tools used in the process of electrical soldering. Describe what each of these tools looks like, and how they function.

[file 00595](#)

Answer 88

A modern soldering "iron" is a pencil-shaped device with an electrical heating element in its end. Soldering "guns" have a pistol-shaped body, with a loop of thick copper wire at the end acting directly as a heating element. Soldering irons have no on/off switch, while soldering guns do, which should tell you something about the speed at which they heat.

Notes 88

Antique soldering irons were really nothing more than iron wedges with wooden handles, which were set directly in a fire for heat, much like clothes irons used to be nothing more than an anvil-shaped mass of iron that was set on top of a hot stove for heat. I've used one of these old soldering irons to solder sheet metal pieces together, and the technique of use was exactly the same as it is for a modern (electric) soldering iron.

If you have soldering irons and guns available in your classroom, show them to your students during discussion.

Question 89

What does it mean to *tin* a piece of wire prior to making a soldered connection with it?
[file 00557](#)

Answer 89

"Tinning" is the act of pre-soldering the bare wire end, so that its appearance is like solder instead of copper.

Notes 89

Some wire may be purchase "pre-tinned" to save you this step, but most electrical wire is not. Here is a helpful hint: tinning the ends of a piece of stranded copper wire really helps to prevent individual strands from bending and breaking away when the wire end is clamped in a terminal strip!

Question 90

All electrical soldering, and most other forms of soldering as well, requires the addition of a substance known as *flux*. What is the purpose of adding "flux" to the soldering process, and what type of flux is typically used for electrical soldering?

[file 00555](#)

Answer 90

"Flux" is a substance that chemically cleans the metal surfaces prior to soldering. For electrical work, the preferred flux is "rosin".

Notes 90

This question, and the corresponding answer, point to one of the fundamental requirements for a good solder joint: clean metal surfaces. Flux is designed to chemically clean the joint prior to and during the soldering process, but it is no substitute for proper preparatory cleaning beforehand.

Discuss this point with your students. If possible, set up some wire connections to be soldered, and show the effects of a small amount of oil or grease on a solder joint (even when using flux).

Question 91

As in all technician tasks, safety must be your first priority. Soldering harbors specific dangers of its own that you need to be aware of. Explain what precautions you need to take with regard to the following aspects of soldering:

- Safe handling of soldering iron/gun
- Safe handling of solder and flux
- Personal protective equipment
- What to do (and not do) after soldering

file 01705

Answer 91

Safe handling of soldering iron/gun

- Never hold it by the metal end – always by the handle!
- Place iron on a stand when idle, and be careful that no flammable materials contact it.
- Never leave the iron on, unattended.

Safe handling of solder and flux

- Never hold solder in your mouth, as it contains heavy metals that are not healthy for your body.
- Avoid breathing fumes – use a ventilation hood if available.
- Do not eat food while soldering.
- Wash your hands after soldering.

Personal protective equipment

- Safety glasses or goggles – an absolute *must!*
- If soldering large wires, use heat-resistant gloves.

What to do (and not do) after soldering

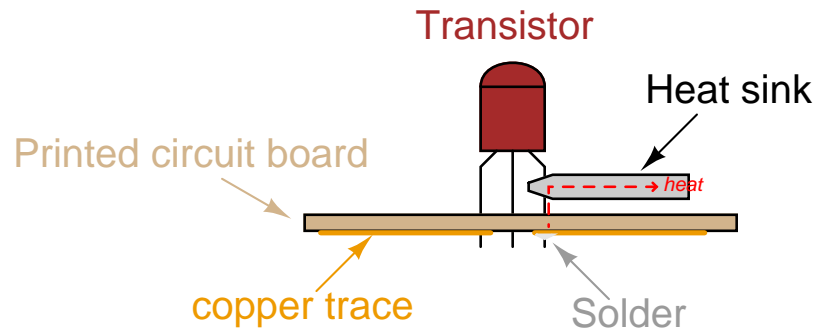
- Clean up worksite.
 - Give the soldering iron enough time to cool down before putting it away.
 - Put soldering equipment away where it belongs, and where others can find it.
 - Never leave the iron on, unattended.
-

Notes 91

Much of this is common sense, but some of it is not. Students must realize that even though soldering is a relatively low-temperature process, it is still hot enough to start fires and burn skin. Also, molten droplets of solder can cause major damage to the eyes, so safety glasses/goggles are imperative.

Question 92

Semiconductor components such as diodes and transistors are easily damaged by the high temperatures of soldering, so care must be taken to protect these components during the soldering process. One way to do this is to use a *heat sink* to draw heat away from the component without cooling the connection point too much. Heat sinks made out of sheet metal may be temporarily clipped to the component leads, one at a time, to prevent the solder's high temperature from thermally conducting all the way to the component body:



In the absence of a formal heat sink, can you think of any ways to fashion your own "impromptu" heat sinks out of commonly available tools and/or objects?

[file 00556](#)

Answer 92

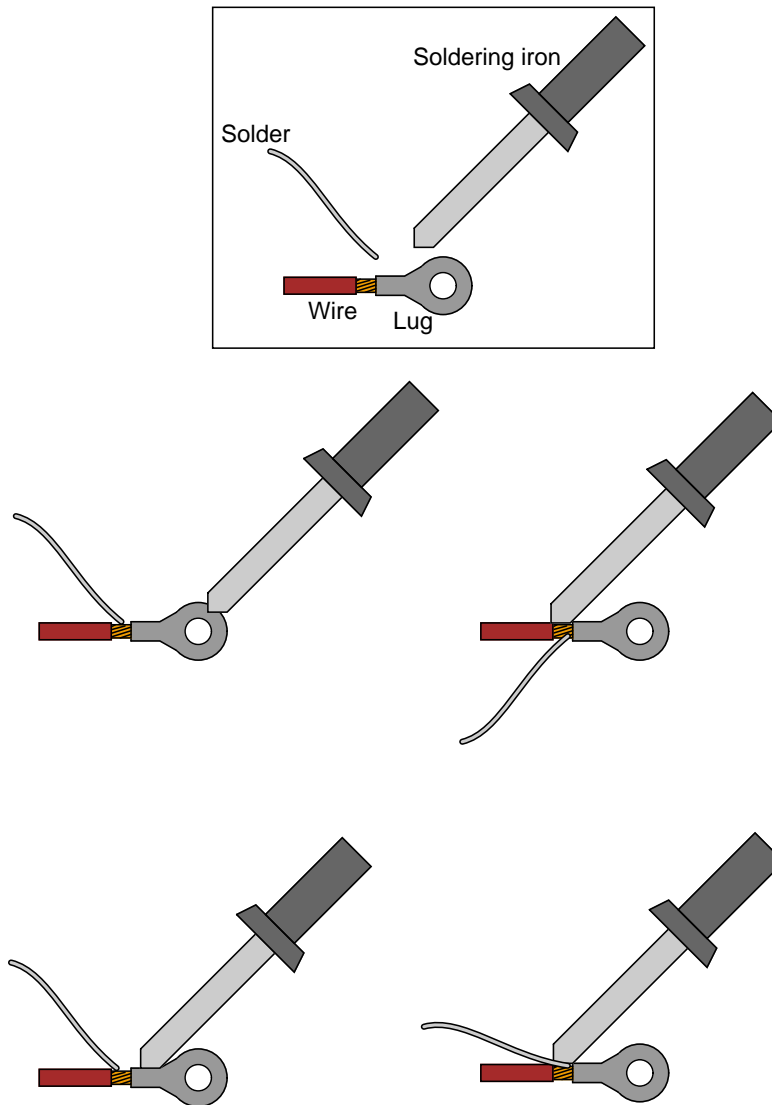
One trick that works well is to wrap a rubber band around the handles of a pair of needle-nose pliers, so the jaws clamp together on their own, then clip the jaws on to the component lead being soldered.

Notes 92

This is an exercise in creative thinking, as well as an introduction to one of the practical concerns of soldering. Even some passive components (electrolytic capacitors, for example) do not handle high temperatures well, and so learning to manage temperatures is an important skill when performing maintenance or prototype soldering. See if you and your students can invent any other simple "heat sinks" for use when a formal heat sink is not available.

Question 93

When soldering a wire into a metal lug, which of these positions would be considered best for soldering iron and solder?

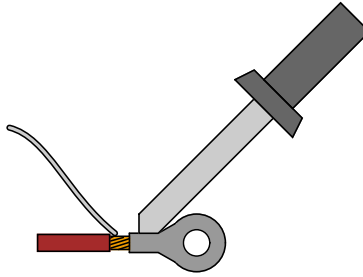


Explain why you think one of these positions is better than the others for producing a sound solder connection between the lug and the wire.

[file 00558](#)

Answer 93

The following illustration shows the best positions for iron and solder, when soldering a wire into a lug:



Notes 93

Discuss with your students why the positions shown in the answer would be superior to the others shown in the question. Keep in mind principles of heat conduction and the necessity for all parts of the connection to be at sufficient temperature as to melt the solder. What, precisely, would be wrong with trying to solder this connection in any of the other ways shown?

Question 94

What is a *cold solder joint*? Identify its causes, its appearance, and the means of correction.
[file 00597](#)

Answer 94

A "cold solder joint" is a poor solder connection resulting from motion of the pieces during the cooling process or insufficient temperature.

Notes 94

Ask your students where they obtained their information regarding the causes, appearance, and remedy for cold solder joints. There is a lot of information available on soldering, and it is always interesting and informative to discover new sources of information for future reference.

Question 95

After a period of use, the tip of a soldering iron (or a soldering gun) becomes dark and "encrusted" with oxidation and flux residue. Describe why this accumulation impedes the soldering process, and how it may be removed.

[file 00596](#)

Answer 95

Any oxidation or foreign material on the soldering tool tip will impede heat flow to the item being soldered. Routine cleaning is easy: just touch the hot tip to a water-soaked sponge or rag.

Notes 95

Discuss with your students why a wet sponge or rag works to clean the end of a heated soldering tool. Also, discuss what to do to the tip of a soldering tool that has been abused by lack of periodic cleaning.

Question 96

What may be done if you solder a component into a circuit board and then realize you soldered it in the wrong place? What, exactly, must you do to move this component to a different location on the board?
[file 00598](#)

Answer 96

You must *desolder* the component from the board, using any number of desoldering tools:

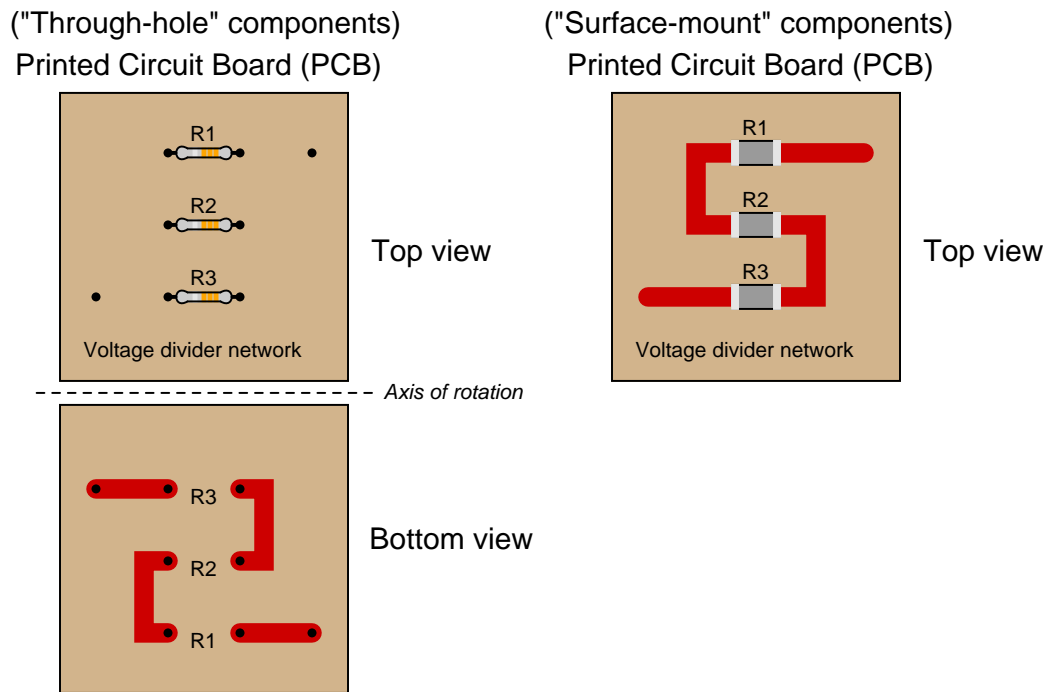
- De-soldering "wick"
 - De-soldering bulb
 - De-soldering "pump"
 - Vacuum station
-

Notes 96

Ask your students to describe how some common desoldering tools (wick, bulb, plunger, vacuum system) work, and also ask them where they obtained their information.

Question 97

Explain what *surface-mount devices* are, and how the soldering and desoldering processes for them differ from the processes used to solder and de-solder "through-hole" components on printed circuit boards. The following illustration contrasts "through-hole" component construction versus surface-mount construction for a voltage divider circuit (three resistors connected in series):



[file 00599](#)

Answer 97

"Surface-mount" components solder to the surface of a printed circuit board, and have no mechanical means of attachment, unlike "through-hole" components. Because of their small size and lack of attachment prior to soldering, special soldering equipment must be used.

Notes 97

Ask your students to describe some of the special soldering equipment that must be used for surface-mount devices? How does it differ in terms of power from regular soldering irons and guns? Why are surface-mount soldering tools rated at a different power level?

Ask your students to describe how surface-mount components may be held to the board during the soldering process. Are all surface-mount components identical, or are there different types? What special soldering tool attachments are available for working with surface-mount devices?

Question 98

The equation for converting degrees Celsius ($^{\circ}C$) to degrees Fahrenheit ($^{\circ}F$) is as follows:

$$T_F = \frac{9}{5}T_C + 32$$

Use this equation to convert the following temperatures from Celsius to Fahrenheit:

- $0^{\circ}C =$
- $100^{\circ}C =$
- $-40^{\circ}C =$
- $250^{\circ}C =$
- $310^{\circ}C =$

Now, algebraically manipulate the equation so that you may solve for degrees Celsius from a given figure in degrees Fahrenheit. Show all your work, then check your results by working backward through the five calculations above to arrive at the original figures in degrees Celsius.

file 03253

Answer 98

- $0^{\circ}C = 32^{\circ}F$
- $100^{\circ}C = 212^{\circ}F$
- $-40^{\circ}C = -40^{\circ}F$
- $250^{\circ}C = 482^{\circ}F$
- $310^{\circ}C = 590^{\circ}F$

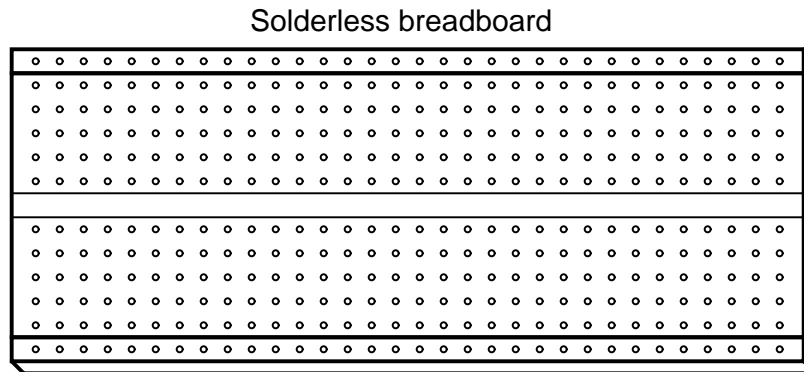
$$T_C = \frac{5}{9}(T_F - 32)$$

Notes 98

The last instruction given in the question – working backwards through the five calculations to see if you get the original (given) figures in degrees Celsius – is actually a very useful way for students to check their algebraic work. Be sure to make note of this in class!

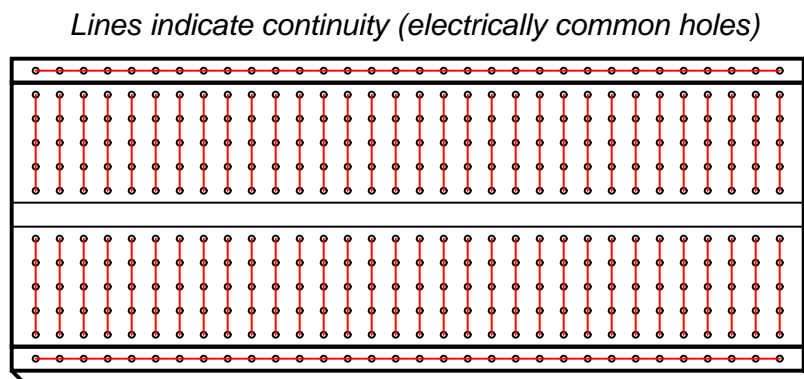
Question 99

Map the interconnections between holes in a typical *solderless breadboard*, also commonly known as a *proto-board*:



[file 01762](#)

Answer 99

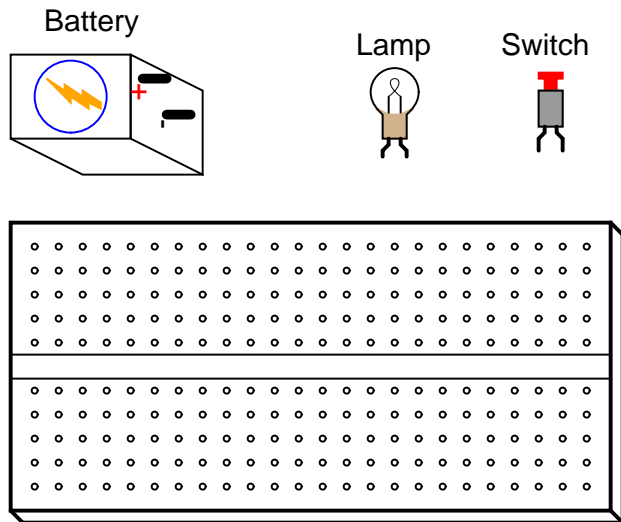


Notes 99

”Mapping” the holes on a solderless breadboard is a fun exercise to do in class with ohmmeters (or any other form of continuity indicator).

Question 100

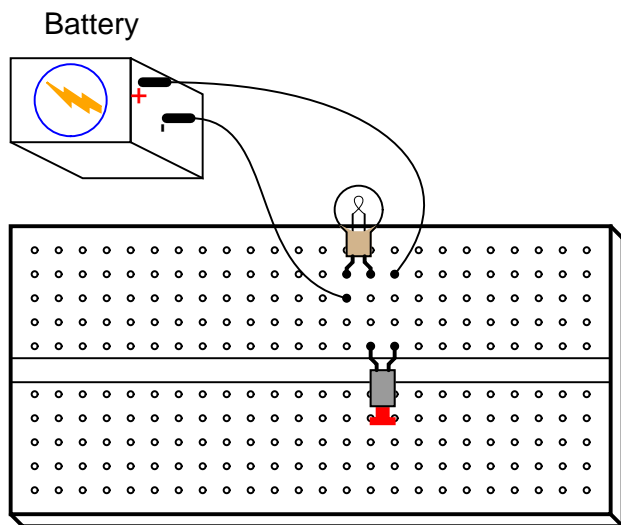
Show how to build a simple circuit consisting of a battery, a lamp, and a switch, mounting the lamp and switch on a *solderless breadboard* (also known as a *proto-board*):



[file 01763](#)

Answer 100

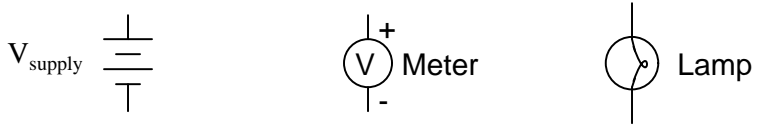
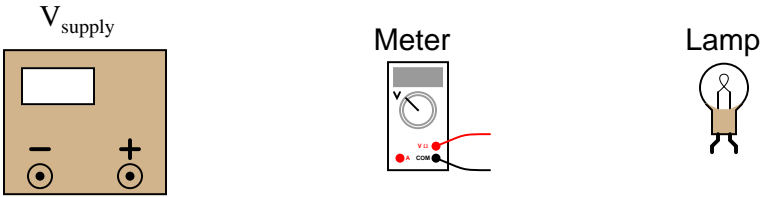
This is just one possibility – there are many others!



Notes 100

Solderless breadboards are extremely useful tools for prototyping circuits in a classroom/lab environment. Familiarity with their use is a virtual necessity for any modern electronics curriculum. That being said, it is important not to over-emphasize breadboards, though. I have seen some electronics courses where breadboards are the only form of circuit construction students ever use! This does not prepare them for challenges of the job, where breadboards are (rightfully) used only for prototyping.

In summary, use breadboards in your students' labwork, *but not all the time*, or even most of the time!

Competency: Voltmeter usage	Version:
<div data-bbox="310 216 472 258" style="border: 1px solid black; padding: 2px;">Description</div> <p data-bbox="483 289 1144 363" style="text-align: center;">Build a simple one-source, one-lamp circuit and use two multimeters to measure the lamp voltage.</p>	
<div data-bbox="310 426 586 468" style="border: 1px solid black; padding: 2px;">Schematic diagram</div> <div style="text-align: center; margin-top: 20px;">  </div>	
<div data-bbox="310 758 586 800" style="border: 1px solid black; padding: 2px;">Pictorial diagram</div> <div style="text-align: center; margin-top: 20px;">  </div>	
<div data-bbox="310 1066 500 1108" style="border: 1px solid black; padding: 2px;">Parameters</div> <div style="display: flex; justify-content: space-around; margin-top: 20px;"> <div style="text-align: center;"> <p data-bbox="532 1115 667 1146">Measured</p> <p data-bbox="446 1171 511 1203">V_{lamp}</p> <div data-bbox="521 1150 691 1213" style="border: 1px solid black; width: 100px; height: 30px; margin: 0 auto;"></div> <p data-bbox="472 1220 732 1251">(with analog meter)</p> </div> <div style="text-align: center;"> <p data-bbox="938 1115 1073 1146">Measured</p> <p data-bbox="852 1171 917 1203">V_{lamp}</p> <div data-bbox="927 1150 1097 1213" style="border: 1px solid black; width: 100px; height: 30px; margin: 0 auto;"></div> <p data-bbox="885 1220 1144 1251">(with digital meter)</p> </div> </div>	
<div data-bbox="310 1283 500 1325" style="border: 1px solid black; padding: 2px;">Explanation</div> <p data-bbox="427 1339 1185 1413" style="text-align: center;">Should the voltmeter be connected in <i>series</i> or in <i>parallel</i> with the lamp in order to measure voltage?</p> <p data-bbox="427 1444 1193 1518" style="text-align: center;">What will happen if the meter is connected the wrong way (series vs. parallel)?</p>	

file 01715

Answer 101

Connect the voltmeter in *parallel* with the component whose voltage is to be measured.

Notes 101

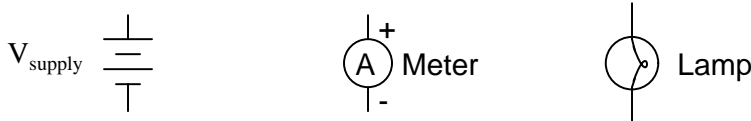
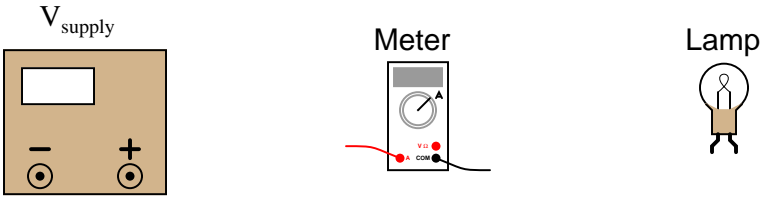
The purpose of this exercise is to make absolutely sure students can safely measure voltage with a multimeter.

General concepts and principles to emphasize

- Voltage is a *differential* quantity: always measured between two points
- The relationship between the mathematical sign of the measured voltage (on the DMM display) versus the orientation of the red and black test leads
- The relationship between the needle movement (on the analog meter's display) versus the orientation of the red and black test leads

Suggestions for Socratic discussion and experimentation

- Try setting the voltmeter to a different *range* and re-measuring the same voltage sources. What practical purpose does the range of a meter serve?
- Can a metal frame (e.g. the steel frame of a lab workbench) be used as an electrical conductor to allow powering of the lamp with just one copper wire between the lamp and battery?

Competency: Ammeter usage	Version:
<div data-bbox="310 212 472 254" style="border: 1px solid black; padding: 2px;">Description</div> <p data-bbox="483 289 1138 359" style="text-align: center;">Build a simple one-source, one-lamp circuit and use two multimeters to measure the lamp current.</p>	
<div data-bbox="310 422 586 464" style="border: 1px solid black; padding: 2px;">Schematic diagram</div> <div style="text-align: center; margin-top: 20px;">  </div>	
<div data-bbox="310 758 586 800" style="border: 1px solid black; padding: 2px;">Pictorial diagram</div> <div style="text-align: center; margin-top: 20px;">  </div>	
<div data-bbox="310 1066 500 1108" style="border: 1px solid black; padding: 2px;">Parameters</div> <div style="display: flex; justify-content: space-around; margin-top: 20px;"> <div style="text-align: center;"> <p>Measured</p> <p>I_{lamp} <input style="width: 60px; height: 20px;" type="text"/></p> <p>(with analog meter)</p> </div> <div style="text-align: center;"> <p>Measured</p> <p>I_{lamp} <input style="width: 60px; height: 20px;" type="text"/></p> <p>(with digital meter)</p> </div> </div>	
<div data-bbox="310 1283 500 1325" style="border: 1px solid black; padding: 2px;">Explanation</div> <p data-bbox="423 1339 1179 1409" style="text-align: center;">Should the ammeter be connected in <i>series</i> or in <i>parallel</i> with the lamp in order to measure current?</p> <p data-bbox="423 1444 1190 1514" style="text-align: center;">What will happen if the meter is connected the wrong way (series vs. parallel)?</p>	

IMPORTANT NOTE: do not actually try to connect the ammeter improperly in the circuit, as the meter may be damaged in the process!

[file 01714](#)

Answer 102

Connect the ammeter in *series* with the component whose current is to be measured.

Notes 102

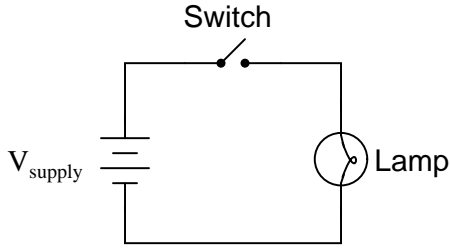
The purpose of this exercise is to make absolutely sure students can safely measure current with a multimeter.

General concepts and principles to emphasize

- The relationship between the mathematical sign of the measured current (on the DMM display) versus the orientation of the red and black test leads
- The relationship between the needle movement (on the analog meter's display) versus the orientation of the red and black test leads

Suggestions for Socratic discussion and experimentation

- Try setting the ammeter to a different *range* and re-measuring the same current. What practical purpose does the range of a meter serve?
- Can a metal frame (e.g. the steel frame of a lab workbench) be used as an electrical conductor to allow powering of the lamp with just one copper wire between the lamp and battery?

Competency: Circuit with switch	Version:																
Schematic																	
																	
Given conditions																	
$V_{\text{supply}} =$	$I_{\text{lamp}} \text{ (nominal)} =$																
Parameters																	
<table style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 15%;"></th> <th style="width: 30%; text-align: center;">Predicted</th> <th style="width: 30%; text-align: center;">Measured</th> <th style="width: 25%;"></th> </tr> </thead> <tbody> <tr> <td style="vertical-align: middle;">V_{lamp}</td> <td style="border: 1px solid black; height: 20px;"></td> <td style="border: 1px solid black; height: 20px;"></td> <td rowspan="3" style="vertical-align: middle; padding-left: 10px;">} <i>With switch closed (on)</i></td> </tr> <tr> <td style="vertical-align: middle;">I_{lamp}</td> <td style="border: 1px solid black; height: 20px;"></td> <td style="border: 1px solid black; height: 20px;"></td> </tr> <tr> <td style="vertical-align: middle;">V_{switch}</td> <td style="border: 1px solid black; height: 20px;"></td> <td style="border: 1px solid black; height: 20px;"></td> </tr> </tbody> </table>		Predicted	Measured		V_{lamp}			} <i>With switch closed (on)</i>	I_{lamp}			V_{switch}					
	Predicted	Measured															
V_{lamp}			} <i>With switch closed (on)</i>														
I_{lamp}																	
V_{switch}																	
<table style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 15%;"></th> <th style="width: 30%; text-align: center;">Predicted</th> <th style="width: 30%; text-align: center;">Measured</th> <th style="width: 25%;"></th> </tr> </thead> <tbody> <tr> <td style="vertical-align: middle;">V_{lamp}</td> <td style="border: 1px solid black; height: 20px;"></td> <td style="border: 1px solid black; height: 20px;"></td> <td rowspan="3" style="vertical-align: middle; padding-left: 10px;">} <i>With switch open (off)</i></td> </tr> <tr> <td style="vertical-align: middle;">I_{lamp}</td> <td style="border: 1px solid black; height: 20px;"></td> <td style="border: 1px solid black; height: 20px;"></td> </tr> <tr> <td style="vertical-align: middle;">V_{switch}</td> <td style="border: 1px solid black; height: 20px;"></td> <td style="border: 1px solid black; height: 20px;"></td> </tr> </tbody> </table>		Predicted	Measured		V_{lamp}			} <i>With switch open (off)</i>	I_{lamp}			V_{switch}					
	Predicted	Measured															
V_{lamp}			} <i>With switch open (off)</i>														
I_{lamp}																	
V_{switch}																	

file 01640

Answer 103

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

Notes 103

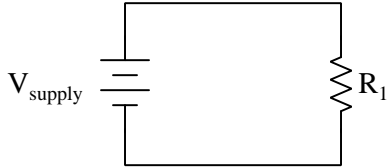
Use a variable-voltage, regulated power supply to supply a suitable DC voltage for the incandescent lamp.

General concepts and principles to emphasize

- Electricity can only travel continuously when there is a *complete circuit* (i.e. a conductive “loop”)
- Any break in a circuit, anywhere in that circuit, prevents the continuous flow of electricity everywhere in that circuit
- The distinction between electrical *sources* and electrical *loads*

Suggestions for Socratic discussion and experimentation

- Try relocating the switch to some other point in the circuit. Does it still perform the same function? Are any of the voltage or current readings affected by this alteration?
- Identify some of the various switch types available in your parts kit. How do their functions differ from one another?
- Explain how you can use a multimeter to test the function of a switch before it is connected to a circuit with a power supply and load.
- Sketch the direction of current in this simple circuit when the switch is closed (“on”). Also sketch the + and – symbols marking voltage polarity across each component in the circuit when the switch is closed. Explain why the relationship between the power supply’s voltage polarity and current direction is different than the relationship between the lamp’s voltage polarity and current direction. Which of these components is an electrical *source* and which of these is an electrical *load*?
- Sketch the + and – symbols marking voltage polarity across the switch when it is open (“off”). Does the switch’s polarity of voltage match the power supply’s polarity or not?
- Demonstrate how you can measure current in this circuit without ever disconnecting a single wire (i.e. “breaking” the circuit), just by connecting the ammeter across the switch terminals.

Competency: Ohm's Law	Version:									
Schematic										
										
Given conditions										
$V_{\text{supply}} =$ $R_1 =$										
Parameters										
<table style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 10%;"></th> <th style="width: 20%; text-align: center;">Predicted</th> <th style="width: 20%; text-align: center;">Measured</th> </tr> </thead> <tbody> <tr> <td style="padding-right: 10px;">I_{total}</td> <td style="border: 1px solid black; width: 80px; height: 25px;"></td> <td style="border: 1px solid black; width: 80px; height: 25px;"></td> </tr> <tr> <td style="padding-right: 10px;">V_R</td> <td style="border: 1px solid black; width: 80px; height: 25px;"></td> <td style="border: 1px solid black; width: 80px; height: 25px;"></td> </tr> </tbody> </table>			Predicted	Measured	I_{total}			V_R		
	Predicted	Measured								
I_{total}										
V_R										
Fault analysis										
<p>Suppose component R_1 fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted</p> <p><i>What will happen in the circuit?</i> <small>Write "increase", "decrease", or "no change" for each parameter.</small></p> <p>I_{total} </p> <p>V_R </p> <p>V_{supply} </p>										

Answer 104

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

Notes 104

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

If using this question as a lab exercise rather than an assessment, I recommend specifying a voltage that is standard for batteries, so students don't necessarily have to have an adjustable power supply available to do this lab.


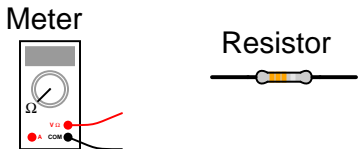
For example, specify V_{supply} as 6 volts and R_1 as 33 k Ω . The resulting current is sufficient to provide a nice, strong needle deflection on most cheap analog ammeters, too!

General concepts and principles to emphasize

- Resistor color codes
- Multimeter usage: measuring voltage, current, and resistance
- Electricity can only travel continuously when there is a *complete circuit* (i.e. a conductive “loop”)
- Any break in a circuit, anywhere in that circuit, prevents the continuous flow of electricity everywhere in that circuit
- The distinction between electrical *sources* and electrical *loads*
- Qualitative analysis using Ohm's Law (i.e. how to analyze *increases* and *decreases* without the use of numerical quantities)

Suggestions for Socratic discussion and experimentation

- Sketch the direction of current in this simple circuit. Also sketch the + and – symbols marking voltage polarity across each component in the circuit. Explain why the relationship between the power supply's voltage polarity and current direction is different than the relationship between the resistor's voltage polarity and current direction. Which of these components is an electrical *source* and which of these is an electrical *load*?
- If voltage increases while resistance remains constant in a simple circuit, what happens to current?
- If current increases while resistance remains constant in a simple circuit, what happens to voltage?
- If resistance increases while voltage remains constant in a simple circuit, what happens to current?
- If resistance increases while current remains constant in a simple circuit, what happens to voltage?

Competency: Ohmmeter usage	Version:	
Description		
Interpret the color codes for several resistors, and then compare their rated resistances with the indication given by an ohmmeter.		
Schematic diagram		
		
Pictorial diagram		
		
Given conditions and parameters		
Resistor colors: _____	Predicted	Measured
Resistor colors: _____	<input style="width: 100px; height: 20px;" type="text"/>	<input style="width: 100px; height: 20px;" type="text"/>
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Resistor colors: _____	<input style="width: 100px; height: 20px;" type="text"/>	<input style="width: 100px; height: 20px;" type="text"/>

file 01639

Answer 105

The ohmmeter's indication is the "final word" on resistance.

Notes 105

The purpose of this exercise is to make absolutely sure students can accurately measure resistance with a multimeter, and also that they can interpret resistor color codes. Select resistors that span a wide range, from less than 10 ohms to millions of ohms.

I recommend the following resistor color codes for students to try (all 5% tolerance):

- Blk, Brn, Grn, Gld
- Brn, Red, Brn, Gld
- Blu, Gry, Blk, Gld
- Red, Red, Org, Gld
- Brn, Grn, Yel, Gld
- Org, Org, Red, Gld

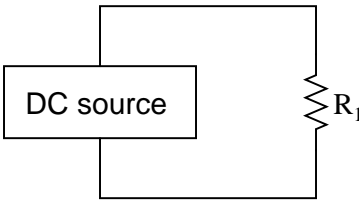
A good extension of this assessment is to have students demonstrate competency using both digital and analog multimeters!

General concepts and principles to emphasize

- Resistance, like voltage, is a *differential* quantity: always measured two points
- Meter test lead wire resistance, and its effects on resistance measurement

Suggestions for Socratic discussion and experimentation

- Suppose one of your ohmmeter's test leads were to fail open. How would that affect your meter's ability to measure resistance?
- Demonstrate how to measure your ohmmeter's test lead resistance so that you have an exact quantity to use when compensating for this lead resistance.
- Once you know how many ohms of resistance are in your ohmmeter's test leads, what can you do with this number to derive a more accurate measurement of any component's resistance?

Competency: Ohm's Law	Version:																				
Schematic																					
																					
Given conditions																					
$V_{\text{supply}} =$ (see multiple values given below) $I_{\text{supply}} =$ (see multiple values given below) $R_1 =$																					
Parameters																					
<table style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 30%;"></th> <th style="width: 30%; text-align: center;">Given</th> <th style="width: 20%; text-align: center;">Predicted</th> <th style="width: 20%; text-align: center;">Measured</th> </tr> </thead> <tbody> <tr> <td>$V_{\text{supply}} =$</td> <td style="text-align: center;"><input style="width: 100%;" type="text"/></td> <td style="text-align: center;">I_{R1} <input style="width: 100%;" type="text"/></td> <td style="text-align: center;"><input style="width: 100%;" type="text"/></td> </tr> <tr> <td>$V_{\text{supply}} =$</td> <td style="text-align: center;"><input style="width: 100%;" type="text"/></td> <td style="text-align: center;">I_{R1} <input style="width: 100%;" type="text"/></td> <td style="text-align: center;"><input style="width: 100%;" type="text"/></td> </tr> <tr> <td>$I_{\text{supply}} =$</td> <td style="text-align: center;"><input style="width: 100%;" type="text"/></td> <td style="text-align: center;">V_{R1} <input style="width: 100%;" type="text"/></td> <td style="text-align: center;"><input style="width: 100%;" type="text"/></td> </tr> <tr> <td>$I_{\text{supply}} =$</td> <td style="text-align: center;"><input style="width: 100%;" type="text"/></td> <td style="text-align: center;">V_{R1} <input style="width: 100%;" type="text"/></td> <td style="text-align: center;"><input style="width: 100%;" type="text"/></td> </tr> </tbody> </table>		Given	Predicted	Measured	$V_{\text{supply}} =$	<input style="width: 100%;" type="text"/>	I_{R1} <input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	$V_{\text{supply}} =$	<input style="width: 100%;" type="text"/>	I_{R1} <input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	$I_{\text{supply}} =$	<input style="width: 100%;" type="text"/>	V_{R1} <input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	$I_{\text{supply}} =$	<input style="width: 100%;" type="text"/>	V_{R1} <input style="width: 100%;" type="text"/>	<input style="width: 100%;" type="text"/>	
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Fault analysis																					
Suppose component <input style="width: 50px;" type="text"/> fails <input type="checkbox"/> open <input type="checkbox"/> other _____ <input type="checkbox"/> shorted <i>What will happen in the circuit?</i>																					

Answer 106

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

Notes 106

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

An interesting "twist" on this exercise is to specify the value of resistor R_1 in colors. For example: Red, Vio, Red, Gld instead of 2.7 k Ω .

When students set their power supplies for a certain amount of current, it is often helpful to have them do so while it is powering the resistor (rather than connecting their ammeter directly across the power supply to set its current output). This helps avoid the possibility of blowing the fuse in their ammeter!

General concepts and principles to emphasize

- Resistor color codes
- Multimeter usage: measuring voltage, current, and resistance
- Electricity can only travel continuously when there is a *complete circuit* (i.e. a conductive "loop")
- Any break in a circuit, anywhere in that circuit, prevents the continuous flow of electricity everywhere in that circuit
- The distinction between electrical *sources* and electrical *loads*
- Qualitative analysis using Ohm's Law (i.e. how to analyze *increases* and *decreases* without the use of numerical quantities)

Suggestions for Socratic discussion and experimentation

- Sketch the direction of current in this simple circuit. Also sketch the + and - symbols marking voltage polarity across each component in the circuit. Explain why the relationship between the power supply's voltage polarity and current direction is different than the relationship between the resistor's voltage polarity and current direction. Which of these components is an electrical *source* and which of these is an electrical *load*?
- If voltage increases while resistance remains constant in a simple circuit, what happens to current?
- If current increases while resistance remains constant in a simple circuit, what happens to voltage?
- If resistance increases while voltage remains constant in a simple circuit, what happens to current?
- If resistance increases while current remains constant in a simple circuit, what happens to voltage?
- Demonstrate how to measure voltage across different pairs of points in the circuit. Do you get different measured values, or the same value? Explain the results.

Competency: PCB soldering	Version:
Description	
Solder at least five resistors into a printed circuit board, being careful not to apply excess heat or excess solder. The resistors should lay flat on the board, with the soldered wire ends neatly trimmed.	
Given conditions	
Five resistors, 1/4 watt each Printed circuit board with copper pads 25 watt soldering iron Electrical solder, small-diameter Needle-nose pliers Miniature diagonal cutting pliers	
Parameters	(Check)
Five resistors soldered in place (flat on board)	<input type="checkbox"/>
Even solder coverage of all pads and leads	<input type="checkbox"/>
No excess solder on pads (<i>solder has concave profile</i>)	<input type="checkbox"/>
No cold solder joints	<input type="checkbox"/>
All soldering flux cleaned off	<input type="checkbox"/>
All leads neatly trimmed	<input type="checkbox"/>
No overheated or lifted pads	<input type="checkbox"/>
Good "wetting" of solder on all pads	<input type="checkbox"/>

file 01971

Answer 107

Instructor will certify quality of solder joints.

Notes 107

The purpose of this exercise is to ensure students can make good solder joints on a printed circuit board.

General concepts and principles to emphasize

- Heat transfer
- Craftsmanship
- Proper use of hand tools
- Safety (protective eyewear, handling hot soldering iron, chemical exposure to solder and flux and fumes)

Suggestions for Socratic discussion and experimentation

- Identify ways to *destructively* test the solder joint.
- Identify ways to *non-destructively* test the solder joint.:w

Troubleshooting log

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

file 03933

Answer 108

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

Notes 108

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 109

NAME: _____ **Troubleshooting Grading Criteria**

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

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

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

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

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

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

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

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

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

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

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

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

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

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

- A. Working prototype circuit built and demonstrated

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

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

file 03932

Answer 109

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

Notes 109

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 110

Suppose you are building a cabin far away from electric power service, but you desire to have electricity available to energize light bulbs, a radio, a computer, and other useful devices. Determine at least three different ways you could generate electrical power to supply the electric power needs at this cabin.

file 00003

Answer 110

There are several different devices capable of producing electrical power for this cabin of yours:

- Engine-driven generator
- Solar cell
- Thermopile
- Windmill

For each of these devices, what is its operating principle, and where does it obtain its energy from?

Notes 110

For each of these electric power "sources," there is a more fundamental source of energy. People often mistakenly think of generator devices as magic sources of energy, where they are really nothing more than energy *converters*: transforming energy from one form to another.

Question 111

Where does the electricity come from that powers your home, or your school, or the streetlights along roads, or the many business establishments in your city? You will find that there are many different sources and types of sources of electrical power. In each case, try to determine where the *ultimate* source of that energy is.

For example, in a hydroelectric dam, the electricity is generated when falling water spins a turbine, which turns an electromechanical generator. But what continually drives the water to its "uphill" location so that the process is continuous? What is the *ultimate* source of energy that is being harnessed by the dam?
[file 00024](#)

Answer 111

Some sources of electrical power:

- Hydroelectric dams
- Nuclear power plants
- Coal and oil fired power plants
- Natural gas fired power plants
- Wood fired power plants
- Geothermal power plants
- Solar power plants
- Tidal/wave power plants
- Windmills

Notes 111

A great point of conversation here is that almost all "sources" of energy have a common origin. The different "sources" are merely variant expressions of the same true source (with exceptions, of course!).

Question 112

Lightning is a natural, electrical phenomenon. It is caused by the accumulation of a large electrical charge over time resulting from air, dust, and water droplets transporting small electrical charges.

Explain how the terms *voltage*, *current*, and *resistance* relate to the process of lightning. In other words, use these three terms to explain the cycle of charge accumulation and lightning discharge.

[file 00146](#)

Answer 112

As electric charges accumulate between clouds and earth, the **voltage** between these points increase. Air under normal conditions is a good insulator of electricity: that is, it possesses very high electrical **resistance**. So, at first there is no **current** resulting from the rise in voltage between clouds and earth. However, when the **voltage** exceeds the air's "ionization" potential, the air becomes a good conductor of electricity (its electrical **resistance** decreases dramatically), resulting in a transient **current** as the accumulated electric charge dissipates in the form of a lightning bolt.

Notes 112

I usually avoid spending a lot of time on technical definitions, because undue emphasis on the definitions of words tends to reinforce rote memorization rather than true comprehension. If students must master certain definitions, though, it is best to develop that mastery in the context of application: ask the students to *use* their new vocabulary, not just recite it.

Question 113

Is it possible to have a condition where an electrical voltage exists, but no electric current exists? Conversely, is it possible to have a condition where an electric current exists without an accompanying voltage? Explain your answers, and give practical examples where the stated conditions are indeed possible.
[file 00151](#)

Answer 113

It is not only possible, but quite common in fact, to have a condition of voltage with no current. However, the existence of an electric current must normally be accompanied by a voltage. Only in very unique conditions (in "superconducting" circuits) may an electric current exist in the absence of a voltage.

Notes 113

This question challenges students' comprehension of voltage and current by asking them to explain the relationship between the two quantities in practical contexts. Do not allow students to simply give a "yes" or a "no" answer to either of the stated conditions. Encourage them to think of examples illustrating a possible condition.

The term "superconducting" may spur some additional questions. As usual, do not simply tell students what superconductivity is, but let them research this on their own. Your more inquisitive students will probably have already researched this topic in response to the answer!

Question 114

Voltage is also known by another name: *electromotive force*, or *EMF*. Explain what this other name for voltage means.

file 00148

Answer 114

Electromotive force literally means, "a force that motivates electrons."

Notes 114

This sheds some light on why the letter "E" is often used to symbolize voltage in mathematical equations. Some of your students may wonder later why the letter "I" is used to represent current. Let them research this on their own!

Question 115

Voltage is commonly defined as "electrical pressure." The unit of the *volt*, however, may be defined in terms of more fundamental physical units. What are these units, and how do they relate to the unit of the volt?

[file 00108](#)

Answer 115

1 volt is equal to 1 joule of energy imparted to 1 coulomb of charge (6.25×10^{18} electrons):

$$V = \frac{W}{Q}$$

Where,

V = Voltage (volts)

W = Work, or potential energy (joules)

Q = Charge (coulombs)

Notes 115

Note that I use the letter "V" to denote voltage rather than "E" as I usually do. This is because in general physics work, "E" usually stands for either "Energy" or "Electric field". Some electronics reference books use the letter "E" for voltage, while others use the letter "V", or even use the two letters interchangeably.

Question 116

What naturally occurring substance is the *best* conductor of electricity?
[file 00155](#)

Answer 116

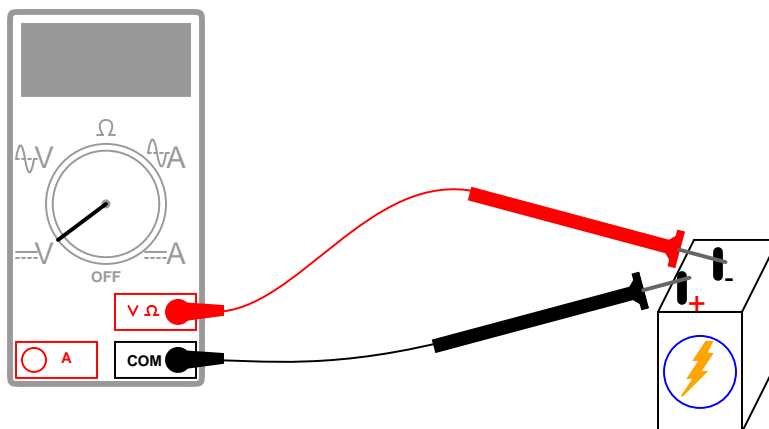
Most people think the answer to this question is *gold*. However, there is another type of metal that conducts electricity better than any other type of metal, including gold! Document where you found your answer to this question.

Notes 116

A few of your students may come across *superconductors* in their research, which of course conduct electricity perfectly (with no resistance to electric current whatsoever). However, the answer I'm looking for here is the non-superconducting metal with the lowest electrical resistance of all.

Question 117

What will this voltmeter register when connected to a battery as shown (assume a battery voltage of 6 volts)? Explain your answer.



file 00021

Answer 117

The voltmeter will register -6 volts.

What do you suppose will happen if the voltmeter is of the *analog* style (with a moving "needle" rather than a numerical display)?

Notes 117

Ask the students how an analog (moving pointer) style of voltmeter would respond in this situation. This question lends itself very well to simple experimentation in the classroom, even during discussion time.

Question 118

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

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

[file 00224](#)

Answer 118

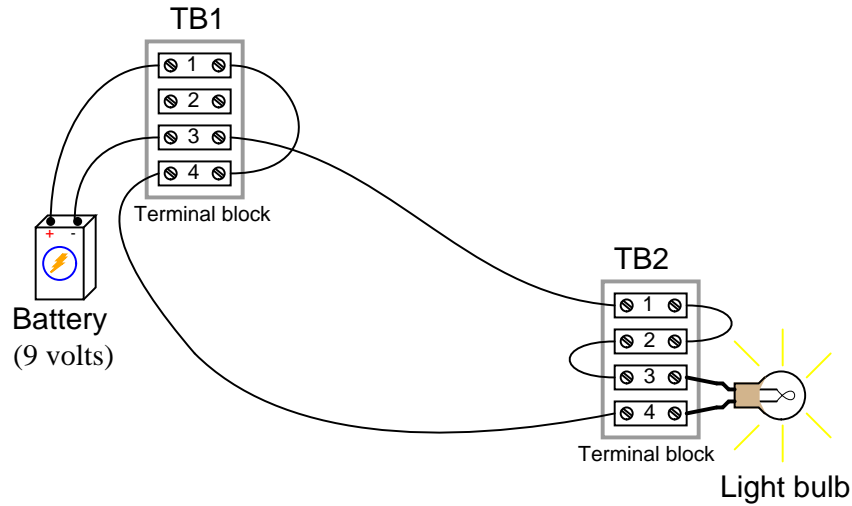
According to the Law of Energy Conservation, it is not possible to make a battery that lasts forever.

Notes 118

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

Question 119

Determine how much voltage a voltmeter would indicate when connected between the following points in this circuit:



- Between TB1-1 and TB1-3
- Between TB1-4 and TB2-4
- Between TB2-3 and TB2-1
- Between TB1-1 and TB2-1

Hint: it might help to draw a neat schematic diagram of this circuit first, with all connection points labeled!

[file 00268](#)

Answer 119

- Between TB1-1 and TB1-3 (*Voltmeter measures 9 volts*)
- Between TB1-4 and TB2-4 (*Voltmeter measures 0 volts*)
- Between TB2-3 and TB2-1 (*Voltmeter measures 0 volts*)
- Between TB1-1 and TB2-1 (*Voltmeter measures 9 volts*)

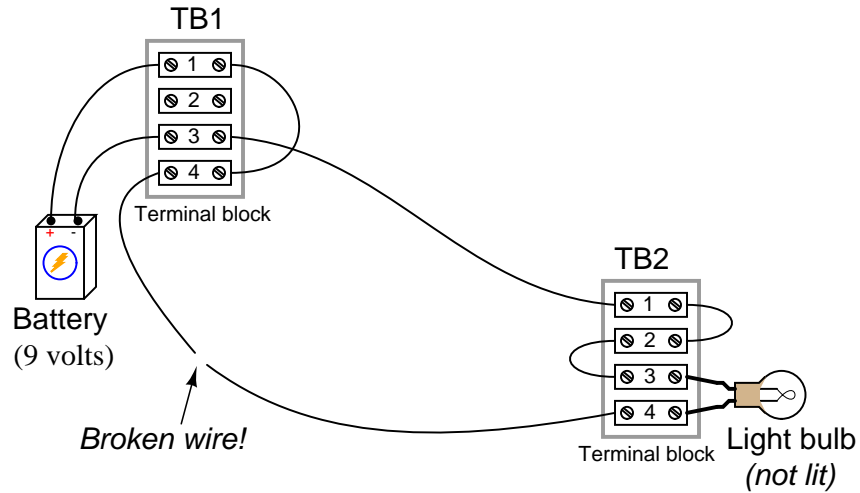
Notes 119

This question provides an opportunity to discuss the concept of *electrically common points*: namely, that there can be no substantial voltage built up between points that are made "electrically common" by means of low-resistance connections between them.

This is also an opportunity to develop the skill of drawing a schematic diagram for a real-life circuit. Schematic diagrams, of course, are very helpful in that they provide a nice, neat layout of all circuit components, making visualization of voltage drops and other quantities easier.

Question 120

Determine how much voltage a voltmeter would indicate when connected between the following points in this faulted circuit:



- Between TB1-1 and TB1-3
- Between TB1-4 and TB2-4
- Between TB2-3 and TB2-1
- Between TB1-1 and TB2-1

Hint: it might help to draw a neat schematic diagram of this circuit first, with all connection points labeled!

[file 00269](#)

Answer 120

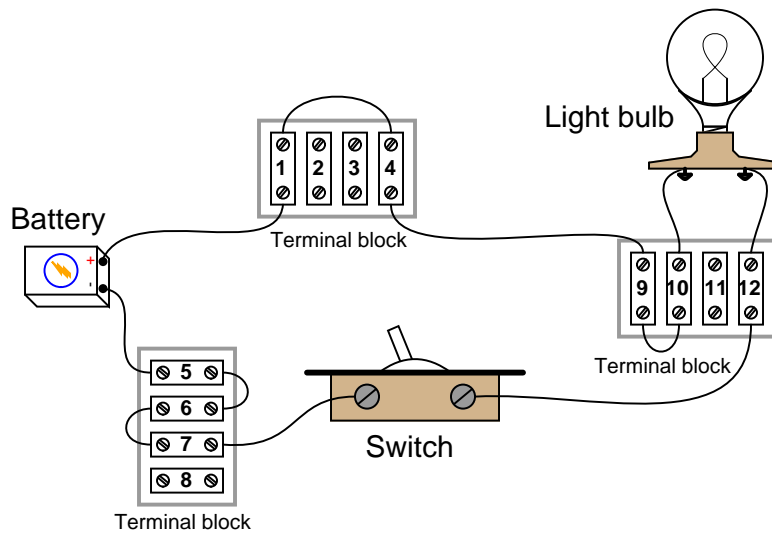
- Between TB1-1 and TB1-3 (*Voltmeter measures 9 volts*)
- Between TB1-4 and TB2-4 (*Voltmeter measures 9 volts*)
- Between TB2-3 and TB2-1 (*Voltmeter measures 0 volts*)
- Between TB1-1 and TB2-1 (*Voltmeter measures 9 volts*)

Notes 120

Ask your students this question: how does the break in the wire affect electrical "commonality" between TB1-4 and TB2-4?

Question 121

Examine the following illustration of a simple battery-switch-lamp circuit, connected together using screw-terminal blocks, each connection point on each terminal block identified by a unique number:



Determine whether or not voltage should be present between the following pairs of terminal block points with the switch in the ON position:

- Points 1 and 5:
- Points 6 and 7:
- Points 4 and 10:
- Points 9 and 12:
- Points 6 and 12:
- Points 9 and 10:
- Points 4 and 7:

Now, determine whether or not voltage should be present between the following pairs of terminal block points with the switch in the OFF position:

- Points 1 and 5:
- Points 6 and 7:
- Points 4 and 10:
- Points 9 and 12:
- Points 6 and 12:
- Points 9 and 10:
- Points 4 and 7:

[file 03302](#)

Answer 121

Switch ON:

- Points 1 and 5: **Voltage!**
- Points 6 and 7: *No voltage*
- Points 4 and 10: *No voltage*
- Points 9 and 12: **Voltage!**
- Points 6 and 12: *No voltage*
- Points 9 and 10: *No voltage*
- Points 4 and 7: **Voltage!**

Switch OFF:

- Points 1 and 5: **Voltage!**
- Points 6 and 7: *No voltage*
- Points 4 and 10: *No voltage*
- Points 9 and 12: *No voltage*
- Points 6 and 12: **Voltage!**
- Points 9 and 10: *No voltage*
- Points 4 and 7: **Voltage!**

Follow-up question: explain *why* there will be voltage or no voltage between each of these pairs of points for the two circuit conditions (switch on and switch off).

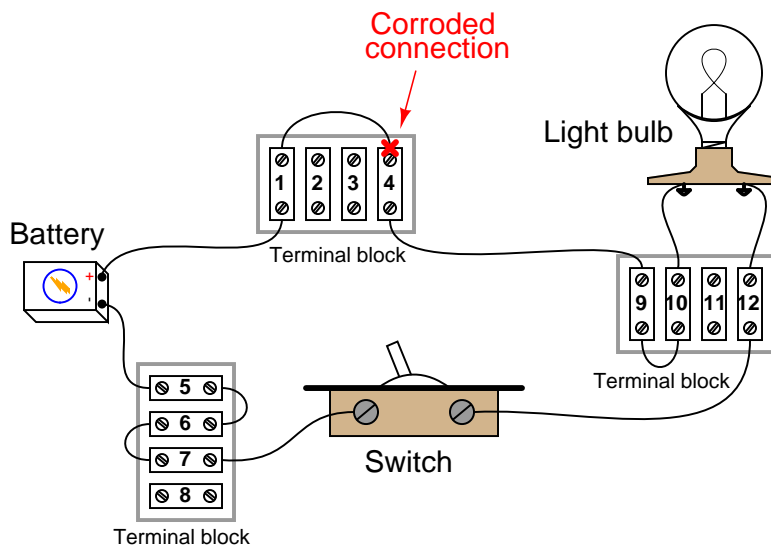
Notes 121

This question is not really a troubleshooting question per se, but the principles involved in successfully determining the presence or absence of voltage are critically important to being able to troubleshoot simple circuits using a voltmeter.

I have found that the concept of *electrically common points* is most helpful when students first learn to relate voltage drop with continuity (breaks or non-breaks) in a circuit. You might want them to identify which points in this circuit are electrically common to one another (in either or both switch positions).

Question 122

The following battery-switch-lamp circuit has a problem. Over time, corrosion has developed between the wire end and the screw terminal labeled "4" on the upper side of the top terminal block. This corroded connection now has a high resistance instead of a low resistance as it should. As a result, the light bulb does not energize when the switch is turned ON:



Taking voltage measurements with a voltmeter, how do you think this corrosion problem will reveal itself with the switch on the ON position? In other words, which voltage measurement in this circuit (i.e. between which pair or pairs of terminal block points) will be unusual as a result of the bad connection at point #4, and approximately how much voltage should that measurement be?

[file 03303](#)

Answer 122

With the corroded connection at terminal #4, the following voltage measurements should read abnormally high (almost full battery voltage, whereas they *should* register zero volts if all connections in the circuit are good):

- Points 1 and 4
- Points 1 and 9
- Points 1 and 10

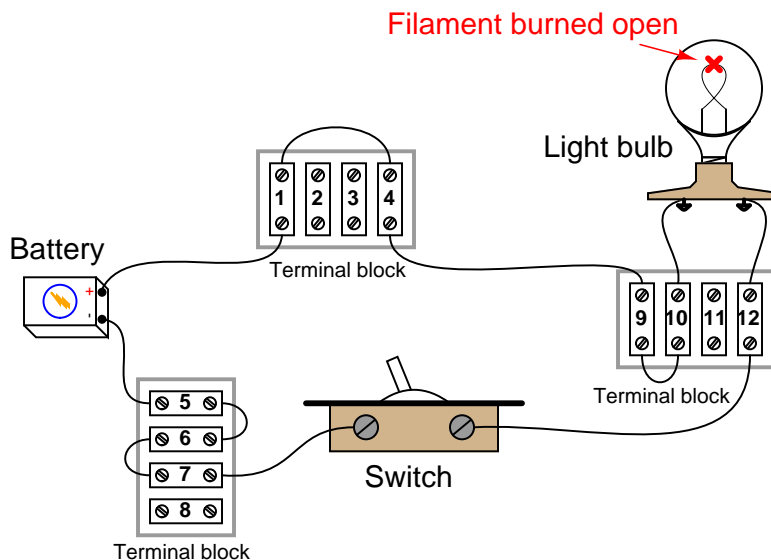
Follow-up question: there are also several voltage measurements in this faulty circuit that will read abnormally *low* as a result of the corroded connection at point #4. Identify which pairs of points the abnormally low voltage will be measured between.

Notes 122

Explain to your students what environmental factors contribute to corrosion (water, acids, caustics, etc.) and how a corroded electrical connection is usually not equivalent to a complete "open" break in a circuit. Quite often a corroded connection is a substantial resistance of unstable value, leading to intermittent problems in the circuit.

Question 123

In this battery-switch-lamp circuit, the metal filament wire inside the lamp has burned up, so that it no longer forms an electrically continuous connection. In other words, the filament has failed "open."



Of course, this means the lamp will not turn on, no matter what is done with the switch. It also means that most of the voltage measurements taken in the circuit will be the same as with a properly operating circuit. There is, however, *one* voltage measurement which will be different in the circuit with the burned-out filament than in a properly working circuit. Identify what pair or pairs of terminal block points this different voltage will be measured between, what switch state (ON or OFF) it will appear in, and what this different voltage measurement will actually be relative to the battery voltage.

[file 03304](#)

Answer 123

With the filament burned open, the only voltage measurement that will change in the circuit is the voltage across the switch when it is in the OFF state. Normally, the voltage across the switch in the OFF state will be full battery voltage, but now (with the open filament) it will be zero. I will let you determine which points in the circuit you may measure switch voltage between.

Notes 123

Be sure to ask your students why they think there will be no voltage dropped across the switch when it is OFF, now that the filament has burned open. It may be helpful to draw a schematic diagram (without all the terminal block points shown) as you discuss the reasoning with your students.

Question 124

Paramedics and other emergency medical personnel sometimes use a machine called a *defibrillator* to re-start the regular heart-beat of a person whose heart has stopped or is spastically convulsing (fibrillating). Explain what this machine does to "restart" a person's heart.

[file 03245](#)

Answer 124

A defibrillator machine sends a powerful surge of electric current through the victim's chest to force his or her heart muscles to contract.

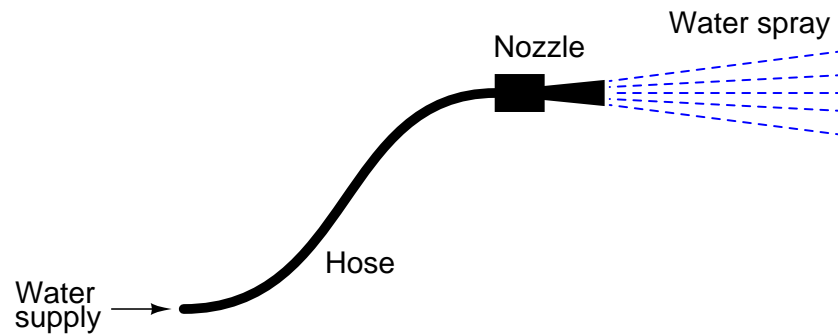
Follow-up question: explain how this principle is similar to that of an electric stun-gun ("TASER") or other high-voltage, non-lethal weapon to immobilize a person. How does a defibrillator's function differ from that of a stun-gun?

Notes 124

This question is intended to start a lively and active discussion on the effects of electric current on human muscle and nerve tissue. Students are likely to come up with all sorts of interesting questions about defibrillators and stun-guns, so be sure to do your own research in preparation for posing this question to them?

Question 125

For a given amount of water pressure, which will flow a greater rate of water: a small (restrictive) nozzle or a large (unrestrictive) nozzle? Explain how this relates to the study of voltage, current, and resistance in a simple electric circuit.



file 00083

Answer 125

Obviously, an unrestrictive nozzle will pass a greater flow rate of water through it, all other factors being equal. In an electric circuit, less resistance will pass a greater flow rate of electrons (current) for a given amount of "pressure" (voltage).

Notes 125

Water flow is not a perfect analogy for electricity, but is close enough to be useful in basic electricity education. Be prepared to discuss the inadequacies of water as an analogy with your students (i.e. "How come electrons don't spill out the end of an open wire like water spills out the end of an open hose or pipe?").

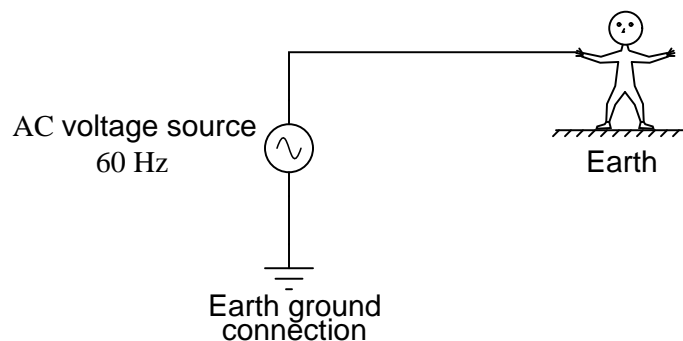
Question 126

An American researcher named Charles Dalziel performed experiments with both human and animal subjects to determine the effects of electric currents on the body. A table showing his research data is presented here:

<i>Bodily effect</i>	<i>Gender</i>	<i>DC</i>	<i>60 Hz AC</i>	<i>10 kHz AC</i>
Slight sensation at point(s) of contact	Men	1 mA	0.4 mA	7 mA
	Women	0.6 mA	0.3 mA	5 mA
Threshold of bodily perception	Men	5.2 mA	1.1 mA	12 mA
	Women	3.5 mA	0.7 mA	8 mA
Pain, with voluntary muscle control maintained	Men	62 mA	9 mA	55 mA
	Women	41 mA	6 mA	37 mA
Pain, with loss of voluntary muscle control	Men	76 mA	16 mA	75 mA
	Women	51 mA	10.5 mA	50 mA
Severe pain, difficulty breathing	Men	90 mA	23 mA	94 mA
	Women	60 mA	15 mA	63 mA
Possible heart fibrillation after three seconds	Men	500 mA	100 mA	X
	Women	500 mA	100 mA	X

Important Note: *Dalziel's human test subjects were men and women in good health, with no known heart conditions or any other abnormalities that would have compromised their safety. In other words, these data points represent best-case scenarios, and do not necessarily reflect the risk to persons in poorer states of health.*

Assuming a wire-to-hand contact resistance of 1500 Ω , 4400 Ω of resistance for foot-to-ground contact, 50 Ω internal body resistance, 200 Ω of resistance through the soil from the person's location to the earth ground point, and a female victim, calculate the amount of voltage necessary to achieve each of the listed shock conditions (threshold of perception, pain, etc.) for the following circuit:



file 03246

- Slight sensation at point(s) of contact: **1.85 volts**
- Threshold of bodily perception: **4.3 volts**
- Pain, with voluntary muscle control maintained: **36.9 volts**
- Pain, with loss of voluntary muscle control: **64.6 volts**
- Severe pain and difficulty breathing: **92.3 volts**
- Possible heart fibrillation after three seconds: **615 volts**

Notes 126

Not only does this question introduce students to the various levels of shock current necessary to induce deleterious effects in the (healthy) human body, but it also serves as a good exercise for Ohm's Law, and for introducing (or reviewing) the concept of series resistances.

For the morbidly curious, Charles Dalziel's experimentation conducted at the University of California (Berkeley) began with a state grant to investigate the bodily effects of sub-lethal electric current. His testing method was as follows: healthy male and female volunteer subjects were asked to hold a copper wire in one hand and place their other hand on a round, brass plate. A voltage was then applied between the wire and the plate, causing electrons to flow through the subject's arms and chest. The current was stopped, then resumed at a higher level. The goal here was to see how much current the subject could tolerate and still keep their hand pressed against the brass plate. When this threshold was reached, laboratory assistants forcefully held the subject's hand in contact with the plate and the current was again increased. The subject was asked to release the wire they were holding, to see at what current level involuntary muscle contraction (tetanus) prevented them from doing so. For each subject the experiment was conducted using DC and also AC at various frequencies. Over two dozen human volunteers were tested, and later studies on heart fibrillation were conducted using animal subjects.

Given that Dalziel tested subjects for the effects of a hand-to-hand shock current path, his data does not precisely match the scenario I show in the schematic diagram (hand-to-foot). Therefore, the calculated voltages for various hand-to-foot shock conditions are *approximate only*.

Question 127

One of the fundamental equations used in electricity and electronics is *Ohm's Law*: the relationship between voltage (E or V , measured in units of *volts*), current (I , measured in units of *amperes*), and resistance (R , measured in units of *ohms*):

$$E = IR \quad I = \frac{E}{R} \quad R = \frac{E}{I}$$

Where,

E = Voltage in units of volts (V)

I = Current in units of amps (A)

R = Resistance in units of ohms (Ω)

Solve for the unknown quantity (E , I , or R) given the other two, and express your answer in both scientific and metric notations:

$I = 45 \text{ mA}, R = 3.0 \text{ k}\Omega; \quad E =$

$I = 10 \text{ kA}, R = 0.5 \text{ m}\Omega; \quad E =$

$E = 45 \text{ V}, R = 4.7 \text{ k}\Omega; \quad I =$

$E = 13.8 \text{ kV}, R = 8.1 \text{ k}\Omega; \quad I =$

$E = 500 \text{ }\mu\text{V}, I = 36 \text{ nA}; \quad R =$

$E = 14 \text{ V}, I = 110 \text{ A}; \quad R =$

$I = 0.001 \text{ A}, R = 922 \text{ }\Omega; \quad E =$

$I = 825 \text{ A}, R = 15.0 \text{ m}\Omega; \quad E =$

$E = 1.2 \text{ kV}, R = 30 \text{ M}\Omega; \quad I =$

$E = 750 \text{ mV}, R = 86 \text{ }\Omega; \quad I =$

$E = 30.0 \text{ V}, I = 0.0025 \text{ A}; \quad R =$

$E = 0.00071 \text{ V}, I = 3389 \text{ A}; \quad R =$

[file 03247](#)

Answer 127

$$I = 45 \text{ mA}, R = 3.0 \text{ k}\Omega; \quad E = 140 \text{ V} = 1.4 \times 10^2 \text{ V}$$

$$I = 10 \text{ kA}, R = 0.5 \text{ m}\Omega; \quad E = 5 \text{ V} = 5 \times 10^0 \text{ V}$$

$$E = 45 \text{ V}, R = 4.7 \text{ k}\Omega; \quad I = 9.6 \text{ mA} = 9.6 \times 10^{-3} \text{ A}$$

$$E = 13.8 \text{ kV}, R = 8.1 \text{ k}\Omega; \quad I = 1.7 \text{ A} = 1.7 \times 10^0 \text{ A}$$

$$E = 500.0 \text{ }\mu\text{V}, I = 36 \text{ nA}; \quad R = 14 \text{ k}\Omega = 1.4 \times 10^4 \text{ }\Omega$$

$$E = 14 \text{ V}, I = 110 \text{ A}; \quad R = 130 \text{ m}\Omega = 1.3 \times 10^{-1} \text{ }\Omega$$

$$I = 0.001 \text{ A}, R = 922 \text{ }\Omega; \quad E = 900 \text{ mV} = 9 \times 10^{-1} \text{ V}$$

$$I = 825 \text{ A}, R = 15.0 \text{ m}\Omega; \quad E = 12.4 \text{ V} = 1.24 \times 10^1 \text{ V}$$

$$E = 1.2 \text{ kV}, R = 30 \text{ M}\Omega; \quad I = 40 \text{ }\mu\text{A} = 4 \times 10^{-5} \text{ A}$$

$$E = 750 \text{ mV}, R = 86 \text{ }\Omega; \quad I = 8.7 \text{ mA} = 8.7 \times 10^{-3} \text{ A}$$

$$E = 30.0 \text{ V}, I = 0.0025 \text{ A}; \quad R = 12 \text{ k}\Omega = 1.2 \times 10^4 \text{ }\Omega$$

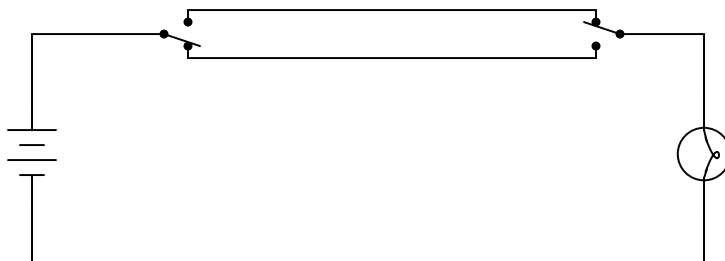
$$E = 0.00071 \text{ V}, I = 3389 \text{ A}; \quad R = 210 \text{ n}\Omega = 2.1 \times 10^{-7} \text{ }\Omega$$

Notes 127

In calculating the answers, I held to proper numbers of significant digits. This question is little more than drill for students learning how to express quantities in scientific and metric notations.

Question 128

What positions do the switches have to be in for the light bulb to receive power?



file 00045

Answer 128

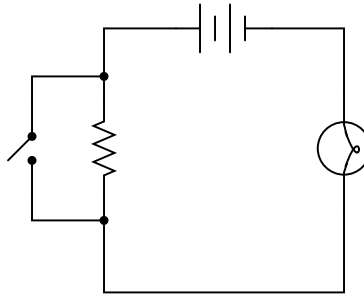
For the light bulb to be energized, both switches must either be in the "up" position, or in the "down" position.

Notes 128

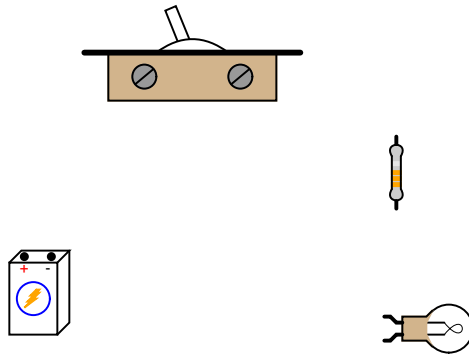
This wiring arrangement ("three-way" switches) is commonly used in residential lighting, for controlling a light bulb in a hallway with switches at either end. Once students relate this circuit to personal experience, it usually makes a lot more sense to them.

Question 129

Examine this schematic diagram:

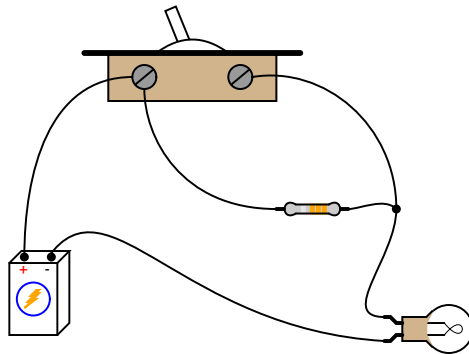


Now, without moving the following components, show how they may be connected together with wires to form the same circuit depicted in the schematic diagram above:



file 00067

Answer 129



Notes 129

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

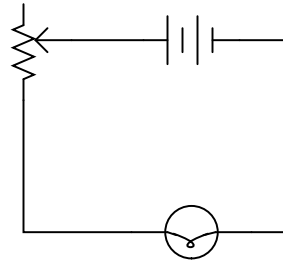
It is very worthwhile for students to discuss how they solve problems such as these with each other. For those students who have trouble visualizing shapes, a simple hint or "trick" to use when translating schematics to illustrations or visa-versa may be invaluable.

Question 130

Draw a schematic diagram showing a potentiometer being used as a simple variable resistor for varying current to a light bulb. Also, designate which way the "wiper" should be moved to make the bulb glow brighter.

file 00324

Answer 130



Notes 130

Make note of the fact that only two of the potentiometer's three terminals need be used if a simple variable resistor is desired.

Question 131

Suppose a battery outputs a voltage of 9 volts. Using algebra, calculate how many joules of energy are imparted to every individual electron moving through this battery.

file 00150

Answer 131

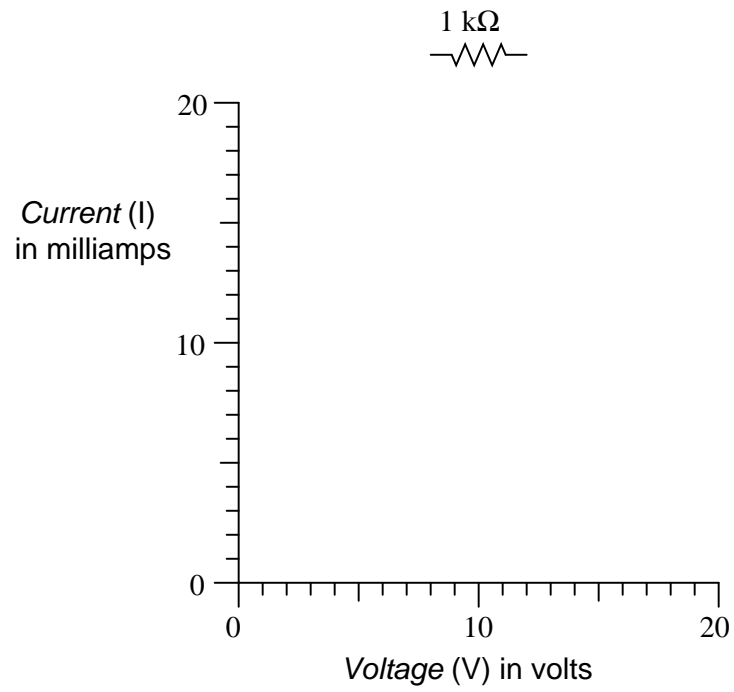
For a 9 volt battery, there will be 1.44×10^{-18} joules of energy imparted to each electron moving through it.

Notes 131

This problem is another exercise in using scientific notation, and requires that students put concepts together that were learned previously.

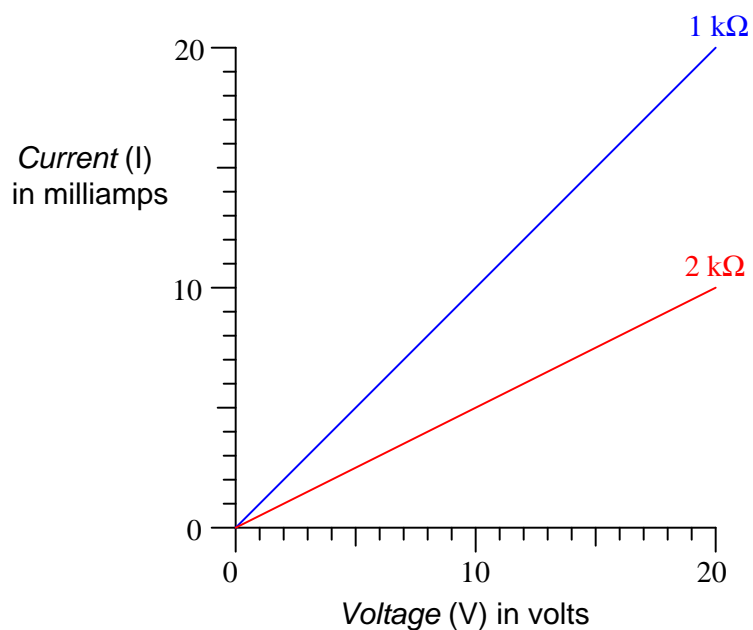
Question 132

Many different equations used in the analysis of electric circuits may be graphed. Take for instance Ohm's Law for a $1\text{ k}\Omega$ resistor:



Plot this graph, following Ohm's Law. Then, plot another graph representing the voltage/current relationship of a $2\text{ k}\Omega$ resistor.

[file 03059](#)

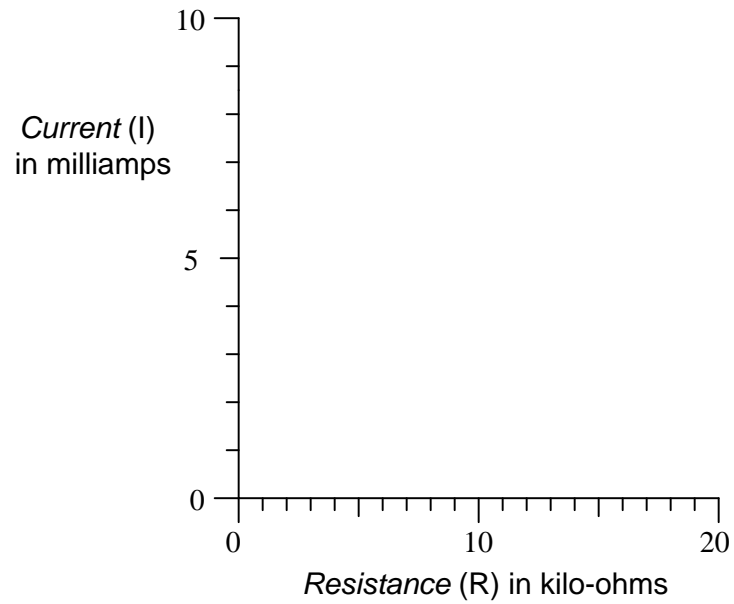


Notes 132

Ask your students to explain how they plotted the two functions. Did they make a table of values first? Did they draw dots on the paper and then connect those dots with a line? Did anyone plot dots for the endpoints and then draw a straight line in between because they knew this was a linear function?

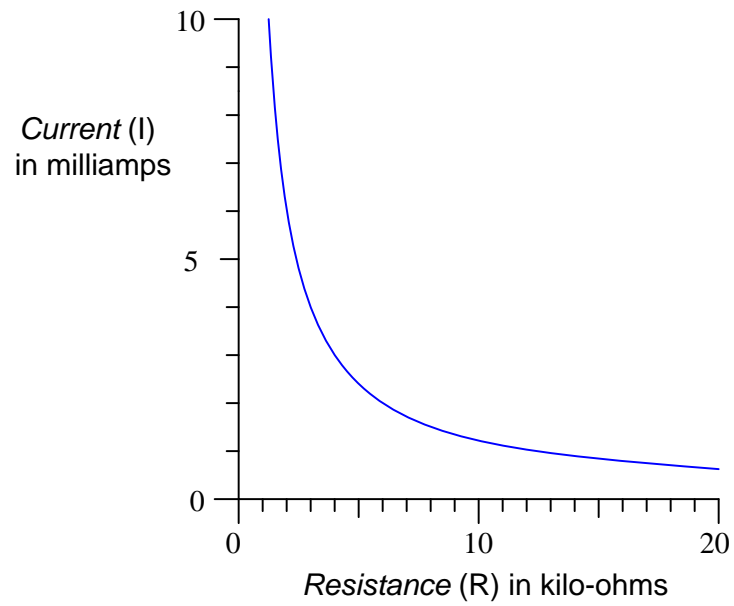
Question 133

Many different equations used in the analysis of electric circuits may be graphed. Take for instance Ohm's Law for a variable resistor connected to a 12 volt source:



Plot this graph, following Ohm's Law.
[file 03060](#)

Answer 133



Ask your students to explain how they plotted the two functions. Did they make a table of values first? Did they draw dots on the paper and then connect those dots with a line? Did anyone plot dots for the endpoints and then draw a straight line in between because they knew this was a linear function?

Many students are surprised that the plot is nonlinear, being that resistors are considered linear devices!

Question 134

Observe the following equivalence:

$$4^3 \times 4^2 = (4 \times 4 \times 4) \times (4 \times 4)$$

Since all operations are the same (multiplication) and reversible, the parentheses are not needed. Therefore, we may write the expression like this:

$$4 \times 4 \times 4 \times 4 \times 4$$

Of course, the simplest way to write this is 4^5 , since there are five 4's multiplied together.

Expand each of these expressions so that there are no exponents either:

- $3^5 \times 3^2 =$
- $10^4 \times 10^3 =$
- $8^2 \times 8^3 =$
- $20^1 \times 20^2 =$

After expanding each of these expressions, re-write each one in simplest form: one number to a power, just like the final form of the example given (4^5). From these examples, what pattern do you see with exponents of products. In other words, what is the general solution to the following expression?

$$a^m \times a^n =$$

[file 03054](#)

Answer 134

$$a^m \times a^n = a^{m+n}$$

Notes 134

I have found that students who cannot fathom the general rule ($a^m \times a^n = a^{m+n}$) often understand for the first time when they see concrete examples.

Question 135

Observe the following equivalence:

$$\frac{4^3}{4^2} = \frac{4 \times 4 \times 4}{4 \times 4}$$

It should be readily apparent that we may cancel out two quantities from both top and bottom of the fraction, so in the end we are left with this:

$$\frac{4}{1}$$

Re-writing this using exponents, we get 4^1 .

Expand each of these expressions so that there are no exponents either:

- $\frac{3^5}{3^2} =$
- $\frac{10^6}{10^4} =$
- $\frac{8^7}{8^3} =$
- $\frac{20^5}{20^4} =$

After expanding each of these expressions, re-write each one in simplest form: one number to a power, just like the final form of the example given (4^1). From these examples, what pattern do you see with exponents of products. In other words, what is the general solution to the following expression?

$$\frac{a^m}{a^n} =$$

[file 03055](#)

Answer 135

$$\frac{a^m}{a^n} = a^{m-n}$$

Notes 135

I have found that students who cannot fathom the general rule ($\frac{a^m}{a^n} = a^{m-n}$) often understand for the first time when they see concrete examples.

Question 136

Observe the following equivalence:

$$\frac{4^2}{4^3} = \frac{4 \times 4}{4 \times 4 \times 4}$$

It should be readily apparent that we may cancel out two quantities from both top and bottom of the fraction, so in the end we are left with this:

$$\frac{1}{4}$$

Following the rule of $\frac{a^m}{a^n} = a^{m-n}$, the reduction of $\frac{4^2}{4^3}$ should be 4^{-1} . Many students find this confusing, as the intuitive concept of exponents (how many times a number is to be multiplied by itself) fails here. How in the world do we multiply 4 by itself -1 times?!

Expand each of these expressions so that there are no exponents either:

- $\frac{3^2}{3^5} =$
- $\frac{10^4}{10^6} =$
- $\frac{8^3}{8^7} =$
- $\frac{20^4}{20^5} =$

After expanding each of these expressions, re-write each one in simplest form: one number to a power, just like the final form of the example given (4^{-1}), following the rule $\frac{a^m}{a^n} = a^{m-n}$. From these examples, what easy-to-understand definition can you think of to describe negative exponents?

Also, expand the following expression so there are no exponents, then re-write the result in exponent form following the rule $\frac{a^m}{a^n} = a^{m-n}$:

$$\frac{5^3}{5^3}$$

What does this tell you about exponents of zero?

[file 03056](#)

Answer 136

A negative exponent is simply the reciprocal ($1/x$) of its positive counterpart. A zero exponent is always equal to 1.

Notes 136

I have found that students who cannot fathom the meaning of negative or zero exponents often understand immediately when they construct their own definition based on the general rule ($\frac{a^m}{a^n} = a^{m-n}$).

Question 137

A 22-gauge metal wire three feet in length contains approximately 28.96×10^{21} "free" electrons within its volume. Suppose this wire is placed in an electric circuit conducting a current equal to 6.25×10^{18} electrons per second. That is, if you were able to choose a spot along the length of this wire and were able to count electrons as they drifted by that spot, you would tally 6,250,000,000,000,000 electrons passing by each second. (This is a reasonable rate for electric current in a wire of this size.)

Calculate the average velocity of electrons through this wire.

[file 00117](#)

Answer 137

Average electron velocity = 0.000647 feet per second, or 6.47×10^{-4} ft/s. This is very slow: only 0.00777 inches per second, or 0.197 millimeters per second!

Notes 137

Despite the rapid progression of the *effects* of electron motion throughout a circuit (i.e. approximately the speed of light), the actual electron velocity is extremely slow by comparison.

Base figures used in this calculation are as follows:

- Number of free electrons per cubic meter of metal (an example taken from [Encyclopedia Britannica](#) 15th edition, 1983, volume 6, page 551) = 10^{29} electrons per m^3 . The metal type was not specified.
- 22 gauge wire has a diameter of 0.025 inches.

Questions like this may be challenging to students without a strong math or science background. One problem-solving strategy I have found very useful is to simplify the terms of a problem until a solution becomes obvious, then use that simplified example to establish a pattern (equation) for obtaining a solution given *any* initial parameters. For instance, what would be the average electron velocity if the current were 28.96×10^{21} electrons per second, the same figure as the number of free electrons residing in the wire? Obviously, the flow velocity would be one wire length per second, or 3 feet per second. Now, alter the current rate so that it is something closer to the one given in the problem (6.25×10^{18}), but yet still simple enough to calculate mentally. Say, half the first rate: 14.48×10^{21} electrons per second. Obviously, with a flow rate half as much, the velocity will be half as well: 1.5 feet per second instead of 3 feet per second. A few iterations of this technique should reveal a pattern for solution:

$$v = 3 \frac{I}{Q}$$

Where,

v = Average electron velocity (feet per second)

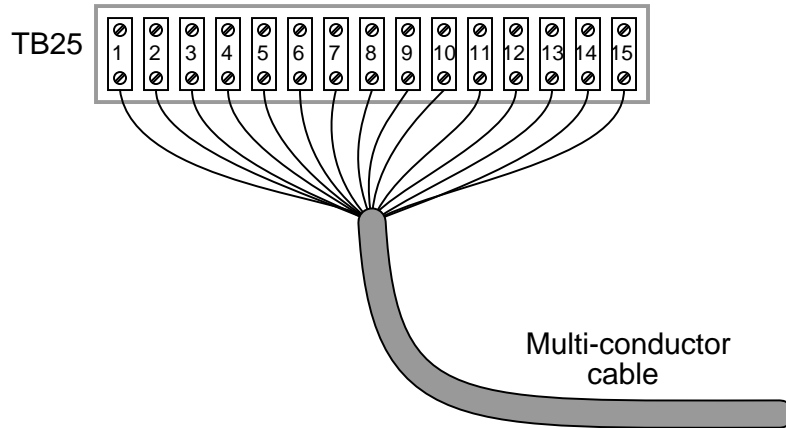
I = Electric current (electrons per second)

Q = Number of electrons contained in wire

It is also very helpful to have knowledgeable students demonstrate their solution techniques in front of the class so that others may learn novel methods of problem-solving.

Question 138

Suppose I needed to test for the presence of DC voltage between all wires connected to this terminal block. What is the fewest number of individual measurements I would have to perform with with a voltmeter in order to test for voltage between all possible wire pair combinations (remember that voltage is *always* measured between two points!)?



[file 00271](#)

Answer 138

105 voltage measurements are necessary (minimum) to test for voltage between every possible combination of two wires out of 15 wires. Mathematically, the number of two-wire test combinations is specified by the equation:

$$\sum_{i=1}^n (i - 1)$$

Where,

n = The number of wires

Challenge question: there is a way to mathematically reduce the expression shown above so that it only contains the variable n , and not i or the "summation" symbol (Σ).

Notes 138

This is an interesting mathematical exercise, to determine the total number of 2-wire combinations resulting from 15 wires. If your students have difficulty determining this number, suggest they try to figure out the total number of 2-wire combinations with a smaller quantity of wires, say four instead of fifteen.

Incidentally, this is a powerful problem-solving technique: simplify the problem into one with smaller quantities, until the solution becomes intuitively obvious, then determine the precise steps needed to arrive at that obvious solution. After that, apply those same steps to the original problem.

The challenge question is actually pre-calculus or calculus level.

Question 139

Suppose I were about to measure an unknown voltage with a manual-range voltmeter. This particular voltmeter has several different voltage measurement ranges to choose from:

- 500 volts
- 250 volts
- 100 volts
- 50 volts
- 25 volts
- 10 volts
- 5 volts

What range would be best to begin with, when first measuring this unknown voltage with the meter? Explain your answer.

[file 00270](#)

Answer 139

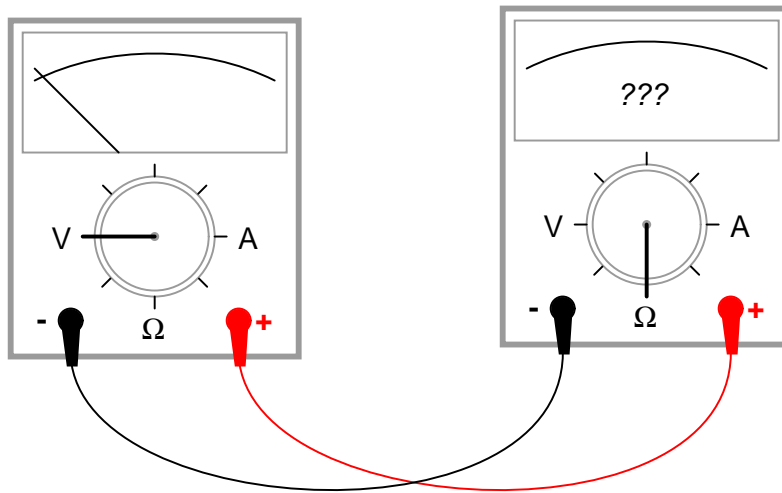
Begin by setting the voltmeter to its highest range: 500 volts. Then, see if the movement needle registers anything with the meter leads connected to the circuit. Decide to change the meter's range based on this first indication.

Notes 139

I always like to have my students begin their test equipment familiarity by using old-fashioned analog multimeters. Only after they have learned to be proficient with an inexpensive meter do I allow them to use anything better (digital, auto-ranging) in their work. This forces students to appreciate what a "fancy" meter does for them, as well as teach them basic principles of instrument ranging and measurement precision.

Question 140

If we were to connect a voltmeter directly to an ohmmeter, what would you expect to see the ohmmeter register, for resistance between its test leads?



file 01696

Answer 140

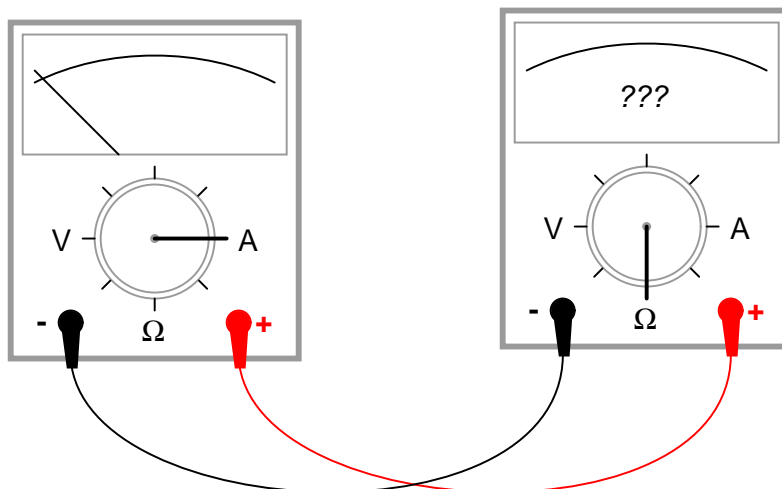
The ohmmeter should register a very high resistance.

Notes 140

Ask your students *why* a voltmeter should have a very high resistance (many thousands or millions of ohms) between its test leads. How does this property of all voltmeters relate to how they are used to measured current in real circuits?

Question 141

If we were to connect an ammeter directly to an ohmmeter, what would you expect to see the ohmmeter register, for resistance between its test leads?



file 00272

Answer 141

The ohmmeter should register a very low resistance.

Notes 141

Ask your students *why* an ammeter should have a very low resistance (fractions of an ohm) between its test leads. How does this property of all ammeters relate to how they are used to measure current in real circuits?

Question 142

Most ammeters contain *fuses* inside to provide protection for the person using the ammeter, as well as for the ammeter mechanism itself. Voltmeters generally do *not* contain fuses inside, because they are unnecessary.

Explain why ammeters use fuses and voltmeters do not? What is it about the nature of an ammeter and how it is used that makes fuse-protection necessary?

[file 00274](#)

Answer 142

The purpose of the fuse inside the ammeter is to "blow" (open-circuit) in the event of excessive current through the meter.

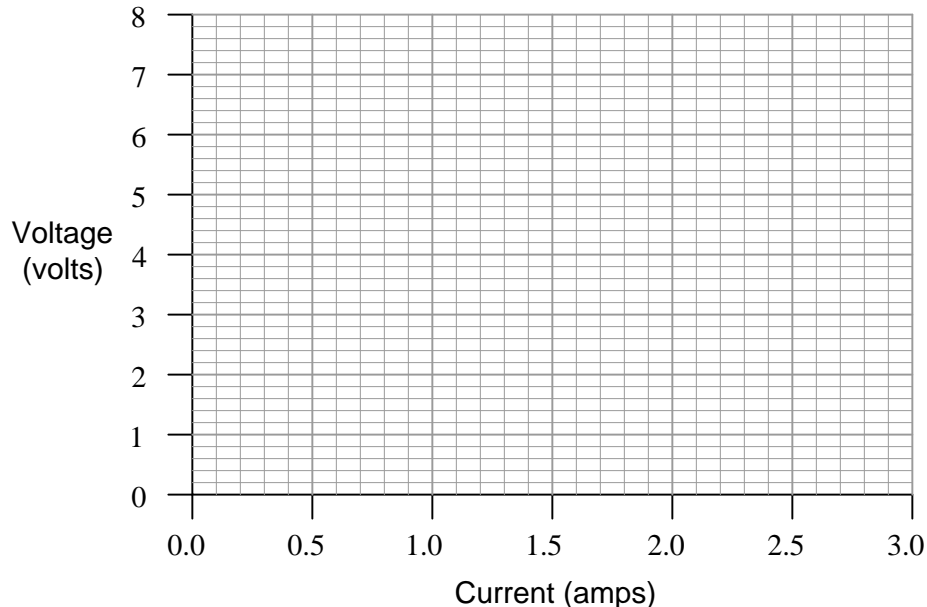
Notes 142

This is a very important question for several reasons. First, it alerts students that ammeters are generally fuse-protected, and therefore they must be aware that this fuse could "blow" and render the ammeter inoperative. Secondly, it highlights one of the major differences between voltmeters and ammeters, and that is the amount of current typically handled by the respective meter types.

Question 143

$\int f(x) dx$ Calculus alert!

Plot the relationships between voltage and current for resistors of three different values (1Ω , 2Ω , and 3Ω), all on the same graph:



What pattern do you see represented by your three plots? What relationship is there between the amount of resistance and the nature of the voltage/current function as it appears on the graph?

Advanced question: in calculus, the instantaneous rate-of-change of an (x, y) function is expressed through the use of the *derivative* notation: $\frac{dy}{dx}$. How would the derivative for each of these three plots be properly expressed using calculus notation? Explain how the derivatives of these functions relate to real electrical quantities.

[file 00086](#)

Answer 143

The greater the resistance, the steeper the slope of the plotted line.

Advanced answer: the proper way to express the derivative of each of these plots is $\frac{dv}{di}$. The derivative of a linear function is a constant, and in each of these three cases that constant equals the resistor resistance in ohms. So, we could say that for simple resistor circuits, the instantaneous rate-of-change for a voltage/current function *is* the resistance of the circuit.

Students need to become comfortable with graphs, and creating their own simple graphs is an excellent way to develop this understanding. A graphical representation of the Ohm's Law function allows students another "view" of the concept, allowing them to more easily understand more advanced concepts such as *negative* resistance.

If students have access to either a graphing calculator or computer software capable of drawing 2-dimensional graphs, encourage them to plot the functions using these technological resources.

I have found it a good habit to "sneak" mathematical concepts into physical science courses whenever possible. For so many people, math is an abstract and confusing subject, which may be understood only in the context of real-life application. The studies of electricity and electronics are rich in mathematical context, so exploit it whenever possible! Your students will greatly benefit.

Question 144

The mathematical equivalence between *watts* and *horsepower* is approximately 746:1. Given this equivalency, how many watts of electrical energy may theoretically be produced by a generator, if turned by an engine rated at 50 horsepower?

[file 00228](#)

Answer 144

37.3 kW of electrical power.

Notes 144

Unit conversion problems are handled most easily by using "unity fractions" comprised of a quotient of two different numerical quantities having the same physical value. For instance:

746 watts = 1 horsepower

$$\boxed{\frac{746 \text{ W}}{1 \text{ HP}} = 1 \text{ (unity)}}$$

$$\frac{50 \cancel{\text{ HP}}}{1} \frac{746 \text{ W}}{1 \cancel{\text{ HP}}} = 37,300 \text{ W}$$

Units of "HP" cancel, leaving units of "W"

Question 145

Suppose a person decides to attach an electrical generator to their exercise bicycle, so as to do something useful with their "pedal power" while they exercise. The first time this person uses their bicycle generator, the electricity is used to power a single 60-watt light bulb. However, the next time this person uses their bicycle generator, a second 60-watt light bulb is connected to the generator, for a total load of 120 watts.

When pedaling with the additional load, the person notices the bicycle is much more difficult to pedal than before. It takes greater force on the pedals to maintain the same speed as before, when there was only a single 60-watt light bulb to power. What would you say to this person if they asked you, the electricity expert, to explain why the bicycle is more difficult to pedal with the additional light bulb connected?

[file 00230](#)

Answer 145

I won't give you the answer directly, but here is a hint: the Law of Energy Conservation.

Notes 145

This phenomenon is more easily understood when experienced directly. If you happen to have a hand-powered generator available for a classroom demonstration, help your students set it up to demonstrate this principle.

An excellent topic of discussion related to this question is the effect that using more electrical power has on the generators at power plants (hydroelectric, nuclear, coal-fired, etc.). What would happen at the power plants supplying electricity to the nation's electrical "grid" if everyone simultaneously turned on all their electrical loads at home?