23 Electric Current

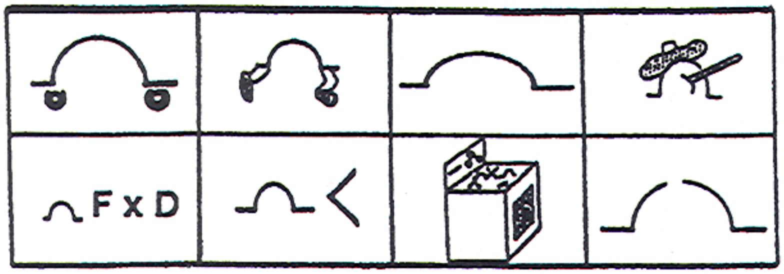
Four dear physics friends are in the photos that open this chapter: New Zealand David Housden, Southern California Juliet Layugan, San Franciscans Will Maynez, and Jill Johnsen.

Georg Simon Ohm provides the personal profile.

This chapter seeks to build a "basic understanding" of current electricity, and to dispel some of the popular misconceptions about electricity. The treatment of series and parallel circuits avoids the calculation of equivalent circuit resistances, multiple emfs, and the like. This chapter may be skipped, as a knowledge of elementary circuits is not needed elsewhere in the text.

The analogy of water pumped in a pipe is useful for understanding electric current in a circuit. When you buy a water pipe in a hardware store, the pipe comes with no water. You supply the water. When you buy an electron pipe (a wire), it comes *with* electrons—quite different than a water pipe.

If you're into puns in your lectures on rainy days, Marshall Ellenstein and coworkers Connie Bownell and Nancy McClure have a few pictorial Ohmwork puns on the symbol for resistance:



Answers in order are: Mobile Ohm; Ohm Run; Ohm Stretch; Ohm Sick; Ohmwork; Ohmless; Ohm on the Range; Broken Ohm.

The problems with power blackouts have more to do with overloading power grids than faulty generators. Triggering of outages often begins with overheated lines on hot days and when loads are high. Lines expand and sag, touching trees that short them out. We're very dependent upon electric power. To smooth the power needs of New York City, banks of lithium-ion batteries, the same kind that power cell phones but enormously bigger, are charged up at nighttime when demand for power is low, and discharged during the day when power demand is high.

How batteries work is not treated in the chapter. In short: A battery is a collection of cells, each of which balances the charges within its innards by moving positively charged ions from the anode to the cathode through an electrolyte, which can be solid, liquid, or gelatinous. In the electrolyte, ions rather than electrons flow. So ions flow inside the battery and electrons flow in the external circuit. In this chapter we stress that the current in a battery is the same amount of current that powers the circuit. But the chapter overlooks the detail that an ion flowing in the electrolyte is in effect an electron flowing in the opposite direction.

Inside a lithium-ion battery is a graphite anode stuffed with lithium atoms and a cathode made of some lithium-based substance. When operating, the anode's lithium atoms release electrons into the external circuit, where they flow and then reach the electron-thirsty cathode. Flow continues until the anode runs out of lithium. That's where recharging comes in to reverse the process. Voltage applied between the two electrodes moves electrons and ions to the graphite side, which stores energy in the battery.

Volta invented the first battery by trial and error using metal electrodes and wet cardboard. At the time nobody knew about atoms, ions, or electrons. Only a century later did investigators understand how a battery works.

Interestingly but sadly, Andre Ampere was forced to witness the guillotine death of his father during the French Revolution.

Arbor Scientific supplies lots of E&M demos, one of which is a Series/Parallel Bulb Board (P6-1120).

Practicing Physics Book:
- Flow of Charge
- Parallel Circuits
- Ohm's Law
- Circuit Resistance
- Electric Power
- Electric Power in Circuits
- Series Circuits

Problem Solving Book:
An excellent overview of the terms of this chapter is presented in Practice Problem 1. And others also.

Laboratory Manual:
- The Lemon Electric Battery *Basics and a Basic Battery Puzzle* (Activity)
- Ohm, Ohm, on the Range *Connect Meters, Determine Resistance* (Experiment)
- Batteries and Bulbs *Electric Circuits* (Activity)
- An Open and Shut Case *Defective Circuits* (Activity)
- Be the Battery *Powering Circuits by Hand* (Activity)

Next-Time Questions:
- 3-Bulb Circuit
- Circuit Current
- 40- and 100-Watt Bulbs
- Glowing Tube
- Battery Demo
- Clay Resistance
- Power Lines
- Direct Current
- How Can Can Roll
- New Wire Resistance
- Battery Current
- The 3 Rs
- Equivalent Resistance

Hewitt-Drew-It! Screencasts: •*Ohm's Law* •*Voltage Drop* •*Water and Electron Circuits*
•*Bulbs in Parallel* •*Electric Power* •*Equivalent Resistance* •*Circuit Resistances* •*Battery Demo*
•*Battery Power* •*Circuit Medley*

SUGGESTED LECTURE PRESENTATION

Flow of Charge; Electric Current

Define electric current and relate it to the lighting of the lamp via the Van de Graaff generator at the end of your last lecture. Explain this in terms of current being directly proportional to a difference in voltage. That is, one end of the lamp was in a stronger part of the energy field than the other—more energy per charge on one end than the other—more voltage at one end than the other. Write on the board *Current-voltage difference*. (You're on your way to Ohm's law. Strictly speaking, the voltage term in Ohm's law implies the difference in potential, so voltage difference is redundant. Nevertheless, it underscores a point that may be missed, so go for it.)

Voltage Sources

Relate voltage to the idea of electrical pressure. Emphasize that a *difference* in electric potential must exist—or as above, a voltage difference. Cite how a battery provides this difference in a sustained way compared to suddenly discharging a Van de Graaff generator. Generators at power plants also provide a voltage difference across wires that carry this difference to consumers (more detail is in Chapter 25). Cite examples of voltage differences with birds sitting on bare high-voltage wires, walking unharmed on the third rail of electric-powered train tracks, and the inadvisability of using electric appliances in the bathtub.

Dimmed Headlights

An auto battery, like all batteries, has internal resistance. When charge flows in battery, there is a voltage drop across this resistance, and some heating occurs. This makes the voltage across the terminals drop as the current increases. When the car's starter is activated, considerable current is delivered by the battery, lowering the voltage output of the battery. This is evident in the dimmed headlights.

Discuss the function of the **third prong on electric plugs** (that it provides a ground wire between the appliance and the ground, Figure 23.8). The ground prong is longer than the pair of flat prongs. Why? (So it will be first to be connected when plugging it into a socket, establishing a ground connection slightly before the appliance is electrically connected. This path to ground prevents harm to the user if there is a short circuit in the appliance that would otherwise include the user as a path to ground.)

When a power line falls near you, don't walk from it—hop with both feet together. Why? Because there may be a voltage difference across the ground. If one foot is anchored to a voltage much different than where your other foot is, you could be electrocuted.

Discuss **electric shock** and why electricians put one hand behind their back when probing questionable circuits, which is to prevent a muscular contraction that keeps their hands gripping a wire, and to also prevent a difference in potential across the heart of the body. Discuss how being electrified produces muscle contractions that account for such instances as "not being able to let go" of hot wires, and "being thrown" by electric shock.

Electrical Resistance

Introduce the idea of electrical resistance, and complete Ohm's law. Compare the resistances of various materials, and the resistances of various thickness of wires of the same metal. Call attention to the glass supports on the wires that make up high-voltage power lines; the rubber insulation that separates the pair of wires in a common lamp cord.

Ohm's Law

Complete your chalkboard equation by introducing resistance and you have Ohm's law. Many instructors write Ohm's law in the form, $V = IR$. Ouch! It is conceptually easier to understand as $I = V/R$, just as Newton's second law is more conceptual as $a = F/m$ than $F = ma$.

> DEMONSTRATION: Connect two or three lamps to a battery and relate the current, as viewed by the emitted light, to the voltage of the battery and the resistance of the lamps. (Be sure the lamps are not bright enough to make viewing uncomfortable.) Interchange lamps of low and high resistance, relating this to the brightness of the lamps.

DC and AC

Discuss the differences between dc and ac. Compare the dc current that flows in a circuit powered with a battery to the ac current that flows in a household circuit (powered by a generator). A hydrodynamic analogy for ac is useful: imagine powering a washing-machine agitator with water power. Verbally describe with gestures a pair of clear plastic pipes connected to a paddle wheel at the bottom of the agitator, fashioned so water that sloshes to-and-fro in the pipes causes the agitator to rotate to-and-fro. Suppose the free ends of the plastic pipe are connected to a special socket in the wall. The socket is powered by the power utility. It supplies no water, but consists of a couple of pistons that exert a pumping action, one out and the other in, then vice versa, in rapid alternation. When the ends of the pipe containing water are connected to the pistons, the water in the pipes is made to slosh back-and-forth: Power is delivered to the washing machine. There is an important point to note here: The **source** of flowing substance, water or electrons, is supplied by you. The power company supplies no water, just as the power utilities supply no electrons! The greater the load on the agitator, the more energy the power company must deliver to the action of the alternating pistons. This analogy affords a visual model for household current—especially with the transparent plastic pipes where your students can "see" the sloshing water!

The water analogy also serves to show the function of a **capacitor** in smoothing the conversion of ac to dc, Figure 23.12.

Speed of Electrons in a Circuit

To impart the idea of how dc current travels in a circuit, use the following analogy. Ask the class to suppose that there is a long column of marchers at the front of the room, everyone standing at rest close together. Walk to the end of this imaginary column and give a shove to the "last person." Ask the class to imagine the resulting impulse traveling along the line until the first marcher is jostled against the wall. (Or use the analogy of loosely coupled railroad cars.) Then ask if this is a good analogy for how electricity travels in a wire. The answer is no. Such is a good analogy for how *sound* travels, but not electric current. Cite how slowly the disturbance travels, and how slowly sound travels compared to light or electricity. Again call attention to the column of marchers and walk to the far end and call out, "Forward march!" As soon as the command reaches each individual, each steps forward. The marcher at the beginning of the column, except for the slight time required for the sound to get to her, steps immediately. State that this is an analogy for electric current. Except for the brief time it takes for the electric *field* set up at the power source to travel through the wire, nearly the speed of light, electrons at the far end of the circuit respond immediately. State that the speed at which the command "forward march" travels is altogether different from how fast each marcher moved upon receiving that command—and that the velocity of the electric signal (nearly the speed of light) is very much different than the drift velocity of electrons (typically 0.01 cm/s) in a circuit.

> CHECK QUESTIONS: When you turn on your key to start your car, electrons migrate from the negative battery terminal through the electric network to the starter motor and back to the positive battery terminal. About how long is required for electrons to leave the negative terminal and go through the circuit and back again? Less than a millisecond? Less than a second? About a second or two? Or about a day? (Class interest should be high when you announce the latter answer!)

Ask for an estimate of the number of electrons pumped by the local power plant into the homes and industries locally in the past year. Then stress the idea that power plants do not sell electrons—that they sell *energy*. Discuss the origin of electrons in electric current flow.

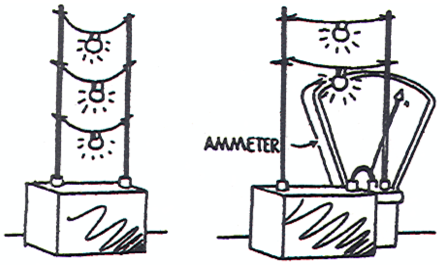
Electric Power

Distinguish between energy and power. Electric power is usually expressed in kilowatts, and electric energy in kilowatt-hours. It is effective if you use an actual electric bill to make your point. Note that a kilowatt-hour is 1000 joules per second times 3600 seconds or 3600 kJ.

> CHECK QUESTION: Does a 40-W lightbulb *have* 40 watts, or does it use 40 watts when lit? [It uses (consumes) 40 W only when lit.]

Light Bulbs
Compact fluorescent light (CFL) bulbs are much more efficient than the incandescent bulbs invented by Edison. A downside is the CFLs contain mercury. Light-emitting diodes (LEDs) are hazard free and provide the color in many TV monitors. White-light LEDs are already in screw-socket form for home lighting (more on this in Chapter 30).

Electrical Circuits
You simply must use an automobile storage battery with extended terminals as shown here. The extended terminals are simply a pair of rigid rods, welding rods or simply pieces of thick wire. They are easily inserted and removed if female connectors are permanently fastened into the battery terminals. Also fasten alligator clips to the ends of short lengths of wire fastened to about three or so lamps of equal resistance. If you use a 6-volt battery and lamps designed for 12 volts, they'll glow at a brightness just right for viewing. Brighter lamps are too much for your students' eyes.



> DEMONSTRATION: Connect the ends of one of the lamps directly to the battery terminals. It glows, evidence of current flow. Then insert the rods and repeat. It glows as before. Slide the lamp farther up the rods and its glow is the same. It is easily accepted that the 6-volt potential difference between the terminals is also established along and across the full length of the rods. State how the rods could extend across campus and someone far away could similarly light up a lamp. State how the resistance of the rods is very small compared to the resistance of the lamp filament. Compare the rods to a long lamp cord. Then to power lines from power plants to consumers. Take your time with these ideas, for they are central! (I show this in the screencast Battery Demo, a favorite!)_

Series Circuits

> DEMONSTRATION CONTINUED: Attach two lamps in series via alligator clips. Before connecting the double lamp circuit to the rods, ask for a neighbor check about the relative brightness of light. [Since the resistance is doubled, the current is halved and the brightness diminished—brightness is "less than half" because most of the energy is going to heat and not light. The effects of heat can be discerned for low currents when no light is seen.] Point out that the voltage across each lamp is half the voltage across the battery terminals when connected in series. Repeat the process for three lamps in series, where three lamps share the 6 volts, and describe the reduced current in terms of Ohm's law. This is even more effective if you connect a lecture-size ammeter to your circuit.

Parallel Circuits

> DEMONSTRATION CONTINUED: Now connect a pair of lamps in series. Before making the second connection, ask for a neighbor check about the relative brightnesses. It's easy to see that the voltage across each lamp is not reduced as with the series connection, but each is impressed with a full 6 volts. [Nearly a full 6 volts; line voltage diminishes with increased current through the battery—perhaps information overload at this stage of learning.] Repeat with three lamps after a neighbor check. Ask about the "equivalent resistance" of the circuit as more lamps are attached in parallel (or the equivalent resistance to people flow if more doors are introduced to the classroom). The lesser resistance is consistent with Ohm's law. An ammeter between one of the rods and the terminal shows line current, which is seen to increase as lamps are added. This is the simplest and most visually comprehensible demo of parallel circuits I have devised.
>
> CHECK QUESTION: Consider two resistors to be connected in a circuit. Which will have more resistance, if they are connected in series or in parallel? [A series connection will have more resistance, regardless of the values of resistance; the equivalent resistance of a parallel connection will always be less than that of the smaller resistor.]

Home Circuits and Fuses

Discuss home lighting circuits. Draw a simple parallel circuit of lamps and appliances on the board. Estimate the current flowing through each device, and point out that it makes no difference how many of the other devices are turned on. Show on your diagram the currents in the branches and in the lead wires. Show where the fuse goes and describe its function. Then short your circuit and blow the fuse.

Overloading

Discuss the consequences of too many appliances operating on the same line, and why different sets of lines are directed to various parts of the home. Most home wiring is rated at 30 amperes maximum. A common air conditioner uses about 2400 watts, so if operating on 120 volts the current would be 20 amps. To start, the current is more. (Why the starting current is larger would be premature to explain here—if it comes up you can explain that every motor is also a generator, and the input electricity is met with a generated output that reduces the net current flow.) If other devices are drawing current on the same line, the fuse will blow when the air conditioner is turned on, so a 220-volt line is usually used for such heavy appliances. Point out that most of the world operates normally at 220-240 volts.

Answers and Solutions for Chapter 23

Reading Check Questions

1. Heat must have a difference in temperature. Flow of charge must have a difference in electrical potential.
2. Sustained flow of water in a pipe needs a difference in water pressure. Sustained flow of charge needs a difference in electric potential.
3. Electrons in metals are free to wander, whereas protons are imbedded in atomic nuclei, not free to roam.
4. An ampere is a unit of electric current, a flow of 1 coulomb per second.
5. One kind is a battery; another is a generator.
6. 12 joules of energy are supplied to each coulomb of charge that flows through a 12-volt battery.
7. Electric charge flows through a circuit. Voltage doesn’t flow at all, but is impressed across a circuit.
8. Water flows more easily through a wide pipe, and similarly charge flows more easily through a thick wire.
9. Heating a metal wire increases molecular motion and therefore its electrical resistance.
10. The unit of electrical resistance is the ohm, symbol Ω.
11. When resistance doubles, current is halved.
12. When voltage is halved, current is halved.
13. Wetness lowers the body’s electrical resistance.
14. The third prong is connected to the “ground,” providing a route for unwanted charge. It prevents charge buildup on the appliance.
15. A battery produces dc. A generator normally produces ac.
16. Current oscillates 60 times per second at 60 hertz.
17. A diode passes current in one direction only.
18. A capacitor smoothes the pulses when a diode converts ac to dc.
19. The error is that no particle can travel at the speed of light.
20. Electrons collide with atoms transferring some of their energy to the atoms as increased vibrations, making the wire hotter.
21. Drift velocity is the net velocity of electrons that make up an electric current.
22. No. Electrons move with the electric field, which is established at about the speed of light in conductors. The domino analogy does fit sound, for their motion is due to molecules hitting molecules.
23. The error is that the source is the conducting wires themselves, not the power source.
24. You are billed for the energy consumed.
25. When you are shocked, your own body is the source of electrons, but not the source of energy imparted to them.
26. The relationship is given by the formula, power = current × voltage.
27. A watt and a kilowatt are units of power. A kilowatt-hour is a unit of energy.
28. Energy that goes to heat instead of light is wasted, so efficiency is less.
29. Current is 1 A everywhere in two lamps connected in series.
30. Voltages add, so if voltage in one lamp is 2 V, voltage in the other is 4 V to account for the 6 V impressed across both in series.
31. Both lamps have 6 volts across them when connected in parallel.
32. The sum of the currents in the branches add to the current in the voltage source.
33. The function of a fuse or a circuit breaker is to prevent overloading that may lead to fire.

Think and Do

34. This is a worthwhile activity.
35. A close-to-home activity!
36. This letter may dispel a widely-held misconception.

Plug and Chug

37. $I = \frac{V}{R} = \frac{120\ \text{V}}{15\ \Omega} = 8\ \text{A}$.

38. $I = \frac{V}{R} = \frac{6\ \text{V}}{1000\ \Omega} = 0.006\ \text{A}$.

39. $I = \frac{V}{R} = \frac{120\ \text{V}}{240\ \Omega} = 0.5\ \text{A}$.

40. $P = IV$ = (0.5 A)(120 V) = 60 W.

41. $P = IV$ = (10 A)(120 V) = 1200 W.

Think and Solve

42. From $I = V/R$, if both voltage and resistance are doubled, current remains unchanged. Likewise if both voltage and resistance are halved.

43. From “Power = current × voltage,” 60 watts = current × 120 volts, current = $\frac{60\text{W}}{120\text{V}}$ = 0.5 A.

44. From current = $\frac{\text{voltage}}{\text{resistance}}$, resistance = $\frac{\text{voltage}}{\text{current}} = \frac{120\text{V}}{20\text{A}} = 6\ \Omega$.

45. From power = current ´ voltage, current = $\frac{\text{power}}{\text{voltage}} = \frac{1200\text{W}}{120\text{V}}$ = 10 A.
From the formula derived above, resistance = $\frac{\text{voltage}}{\text{current}} = \frac{120\text{V}}{10\text{A}} = 12\ \Omega$.

46. Two headlights draw 6 amps, so the 60 ampere-hour battery will last for about 10 hours.

47. $2.52. First, 100 watts = 0.1 kilowatt. Second, there are 168 hours in one week (7 days × 24 hours/day = 168 hours). So 168 hours × 0.1 kilowatt = 16.8 kilowatt-hours, which at 15 cents per kWh comes to $2.52.

48. (a) From power = current × voltage, current = power/voltage = 4W/120V = **1/30 A**.
(b) From current = voltage/resistance (Ohm’s law), resistance = voltage/current = 120 V/(1/30 A) = 3600 W.
(c) First, 4 watts = 0.004 kilowatt. Second, there are 8760 hours in a year (24 hours/day × 365 days = 8760 hours). So 8760 hours × 0.004 kilowatt = 35.0 kWh.
(d) At the rate of 15 cents per kWh, the annual cost is 35.0 kWh × $0.15/kWh = $5.25.

49. The iron’s power is $P = IV$ = (110 V)(9 A) = 990 W = 990 J/s. The heat energy generated in 1 minute is E = power × time = (990 J/s)(60 s) = 59,400 J.

50. Since current is charge per unit time, charge is current × time: $q = It$ = (9 A)(60 s) = (9 C/s)(60 s) = 540 C. (Charges of this magnitude on the move are commonplace, but this quantity of charge accumulated in one place would be incredibly large.)

51. The resistance of the toaster is $R = V/I$ = (120 V)/(10 A) = 12 Ω. So when 108 V is applied, the current is $I = V/R$ = (108 V)/(12 Ω) = 9.0 A and the power is $P = IV$ = (9.0 A)(108V) = 972 W, only 81 percent of the normal power. (Can you see the reason for 81 percent? Current and voltage are both decreased by 10 percent, and 0.9 × 0.9 = 0.81.)

Think and Rank

52. A = B = C
53. A = B = C
54. C, B, A
55. A, B, C
56. a. C, B, A b. A= B = C

Think and Explain

57. A sustained flow needs a sustained difference in potential across a conducting medium, due to a battery or generator.

58. Make the pipe wider and apply more pressure. Make the conducting wire thicker and apply more voltage (also you could use material with less resistance).

59. Six gallons per minute (10 – 4 = 6).

60. Six amperes (10 – 4 = 6).

61. The cooling system of an automobile is a better analogy to an electric circuit because like an electric circuit it is a closed system, and it contains a pump, analogous to the battery or other voltage source in a circuit. The water hose does not re-circulate the water as the auto cooling system does.

62. As the current in the filament of a lightbulb increases, the bulb glows brighter.

63. The circuit in the center is a complete circuit and will light the lamp.

64. Disagree, for the battery supplies the electric field in the circuit. The electrons already exist in the circuit.

65. Six joules of energy is given to each coulomb passing through a 6-volt battery.

66. Normally a current-carrying wire is not electrically charged because for every electron in the wire there is a proton.

67. Your tutor is wrong. An ampere measures current, and a volt measures electric potential (electric “pressure”). They are entirely different concepts; voltage produces amperes in a conductor.

68. Only circuit 5 is complete and will light the bulb. (Circuits 1 and 2 are “short circuits” and will quickly drain the cell of its energy. In circuit 3 both ends of the lamp filament are connected to the same terminal and are therefore at the same potential. Only one end of the lamp filament is connected to the cell in circuit 4.)

69. Current flows *through* electrical devices, just as water flows through a plumbing circuit of pipes. If a water pump produces water pressure, water flows through both the pump and the circuit. Likewise with electric current in an electric circuit. For example, in a simple circuit consisting of a battery and a lamp, the electric current produced in the lamp is the same electric current in the wires that connect the lamp and the same electric current flowing through the battery. Electric charge flows through these devices (the flow of charge being current).

70. Agree with the friend who says energy, not current, is used up.

71. Your friend is sharing voltage from his battery by connecting the two batteries in parallel.

72. Agree, for then the same appropriate voltage will power the circuit.

73. All other things being equal, a material with a short mean-free path offers more resistance to electron flow and has a higher electrical resistance. For all materials, the application of heat imposes more molecular chaos and shortens the path even more, increasing resistance in most materials. So to lengthen the path, simply cool the material. Conductivities are greatly increased in most materials when they are cooled to low temperatures.

74. Before it heats up, the filament is cooler and has less resistance.

75. Most of the energy, more than 90%, of the electrical energy in an incandescent lamp goes directly to heat. Thermal energy is the graveyard of electrical energy.

76. CFLs are more efficient because, relative to incandescents, more of the energy they transfer is light and less is heat.

77. Thick wires have less resistance and will more effectively carry currents without excessive heating.

78. Glow occurs where resistance is higher and therefore where most energy is being dissipated, in the filament.

79. The thick filament has less resistance and will draw (carry) more current than a thin wire connected across the same potential difference.

80. Electric shock *occurs* when current is produced in the body, which is *caused* by an impressed voltage. So the initial *cause* is the voltage, but it is the current that does the damage.

81. In the first case the current passes through your chest; in the second case current passes only through your arm. You can cut off your arm and survive, but you cannot survive without your heart.

82. Electric power in your home is likely supplied at 60 hertz and 110-120 volts via electrical outlets. This is ac. Battery terminals don't alternate, and current provided by them flows in one direction and is dc.

83. Auto headlights are wired in parallel. Then when one burns out, the other remains lit. If you've ever seen an automobile with one burned out headlight, you have evidence they're wired in parallel.

84. The more branches in both cases, the less the overall resistance.

85. (a) volt, (b) ampere, (c) joule.

86. Current remains the same in all the resistors in a series circuit.

87. Voltage across parallel branches, whatever the resistance, remains the same.

88. The amount of current through any conductor depends upon the voltage of the conducting device and its resistance. Also important is the amount of charge the device can deliver; a relatively large amount of charge at high voltage represents high energy (like that from a power line) while a small amount of charge at high voltage represents low energy (like discharging a balloon rubbed on your hair). The device being warned about is likely highly energized to a high voltage, and should be respected. It possesses no current to be warned about, but because of its high energy and high voltage, may produce a lethal current in anyone offering a conducting path from it to the ground.

89. The sign is a joke. High voltage may be dangerous, but high resistance is a property of all nonconductors.

90. No cause for concern. The label is intended as humor. It describes electrons, which are in all matter.

91. Damage generally occurs by excess heating when too much current is driven through an appliance. For the hairdryers, less damage is done plugging the 220-V one into 110 volts.

92. If the parallel wires are closer than the wing span of birds, a bird could short circuit the wires by contact with its wings, be killed in the process, and possibly interrupt the delivery of power.

93. Zero. Power companies do not sell electrons; they sell energy. Whatever number of electrons flow into a home, the same number flows out.

94. How quickly a lamp glows after an electrical switch is closed does not depend on the drift velocity of the conduction electrons, but depends on the speed at which the electric field propagates through the circuit—about the speed of light.

95. Electric energy is propagated through a circuit by electric fields moving at close to the speed of light, not by electron collisions. Sound, on the other hand, travels by molecular or atomic collisions—a much slower process.

96. Bulbs will glow brighter when connected in parallel, for the voltage of the battery is impressed across each bulb. When two identical bulbs are connected in series, half the voltage of the battery is impressed across each bulb. The battery will run down faster when the bulbs are in parallel.

97. Brightness remains the same.

98. Most of the electric energy in a lamp filament is transformed to heat. For low currents in the bulb, the heat that is produced may be enough to feel but not enough to make the filament glow white or even red hot.

99. Bulb C is the brightest because the voltage across it equals that of the battery. Bulbs A and B share the voltage of the parallel branch of the circuit and have half the current of bulb C (assuming

resistances are independent of voltages). If bulb A is unscrewed, the top branch is no longer part of the circuit and current ceases in both bulbs A and B. They no longer give light, while bulb C glows as before. If bulb C is instead unscrewed, then it goes out and bulbs A and B glow as before.

100. More bulbs in series means more resistance and less current. Bulbs glow dimmer. But when more bulbs are connected to the battery in parallel, the brightness of the bulbs doesn't change, for each bulb is connected directly to the battery. Each bulb has its own current path.

101. Line current decreases as more devices are connected in series. But line current increases as more devices are connected in parallel. This is because the circuit resistance is increased when devices are added in series, but decreased (more pathways) when devices are added in parallel.

102. What affects the other branches is the voltage impressed across them, and their own resistance—period. Opening or closing a branch doesn't alter either of these.

103. All are the same for identical resistors in series. If the resistors are not the same, the one of greater resistance will have less voltage across it and less power dissipated in it. Regardless of the resistances, however, the current through both will be the same.

104. All are the same for identical resistors in parallel. If the resistors are not the same, the one of greater resistance will have less current through it and less power dissipation in it. Regardless of the resistances, the voltage across both will be identical.

105. Yes, there will be a decrease in brightness if too many lamps are connected in parallel because of the increased current that flows through the battery. Internal voltage drop increases with current in the battery, which means reduced voltage supplied at its terminals to the circuit it powers. (If the parallel circuit is powered by a stronger source such as the power utility provides via common wall sockets, no dimming of bulbs will be seen as more and more parallel paths are added.)

106. All three are equivalent parallel circuits. Each branch is individually connected to the battery.

107. A fuse in series with any one of the appliances could be useful, for it would melt only if something went wrong with that particular appliance.

Think and Discuss

108. A lie detector circuit relies on the likelihood that the resistivity of your body changes when you tell a lie. Nervousness promotes perspiration, which lowers the body's electrical resistance, and increases whatever current flows. If a person is able to lie with no emotional change and no change in perspiration, then such a lie detector will not be effective. (Better lying indicators focus on the eyes.)

109. A resistor doesn't "attract" or "draw" current, just as a pipe in a plumbing circuit doesn't "draw" water; it instead "allows" or "provides for" the passage of current when an electrical pressure is established across it.

110. There is less resistance in the higher wattage lamp. Since power = current × voltage, more power for the same voltage means more current. And by Ohm's law, more current for the same voltage means less resistance. (Algebraic manipulation of the equations $P = IV$ and $I = V/R$ leads to $P = V^2/R$.)

111. The equivalent resistance of resistors in series is their sum, so connect a pair of resistors in series for more resistance.

112. The equivalent resistance of resistors in parallel is less than the smaller resistance of the two. So connect a pair of resistors in parallel for less resistance. (Interestingly, when in parallel more current also means more filament resistance, which doesn't change this answer.)

113. A lightbulb burns out when a break occurs in the filament or when the filament disintegrates or falls apart.

114. Agree, for resistances in series add.

115. Agree, because even for the smallest resistor, current has an alternative path(s), making for an overall smaller resistance.

116. Connect a pair of 40-ohm resistors in parallel.

117. Connect four 40-ohm resistors in parallel.

118. More current flows in the 100-watt bulb. We see this from the relationship “power = current × voltage.” More current for the same voltage means less resistance. So a 100-watt bulb has less resistance than a 60-watt bulb. Less resistance for the same length of the same material means a thicker filament. The filaments of high wattage bulbs are thicker than those of lower-wattage bulbs. (It is important to note that both watts and volts are marked on a light bulb. A bulb that is labeled 100 W, 120 V, is 100 W *only* if there are 120 volts across it. If there are only 110 volts across it, and the resistance remains unchanged, then the power output would be only 84 watts!)

119. The 100-watt bulb has the thicker filament and lower resistance (as discussed in the previous answer) so in series where the current is the same in each bulb, less energy is dissipated in going through the lower resistance. This corresponds to lower voltage across the resistance—a lower voltage drop. So the greater voltage drop is across the 60-watt bulb in series. Interestingly, in series the 60-watt bulb is brighter than the 100-watt bulb! When connected in parallel, the voltage across each bulb is the same, and the current is greater in the lower resistance 100-watt bulb, which glows brighter than the 60-watt bulb.

120. (a) Equivalent resistance is 4 ohms. (b) $I = V/R$ = 24V/4ohm = 6 A. (c) $I = V/R$ =24V/12ohm = 2 A. So 2A flows through each branch.

121. (a) By Ohm’s law, current in the 6-ohm resistor is V/R = 12 V/6 ohm = 2 A.
(b) The other two resistors, in series, add to 12 ohms, so the current in them is
12 V/12 ohm = 1 A.
(c) Current in the voltage source is the total current; 2A + 1A = 3 A.
(d) Two ways to find R_{eq}. (1) From $I_{total} = V/R_{eq}$, $R_{eq} = V/I_{total}$ = 12 V/3 A = 4 ohms.
(2) Since the circuit has 6 ohms in parallel with 12 ohms, the "product-over-sum rule" can be used to find the combined resistance:
$R = (R_1 \times R_2)/(R_1 + R_2) = (6 \times 12)/(6 + 12) = 4$ ohms.