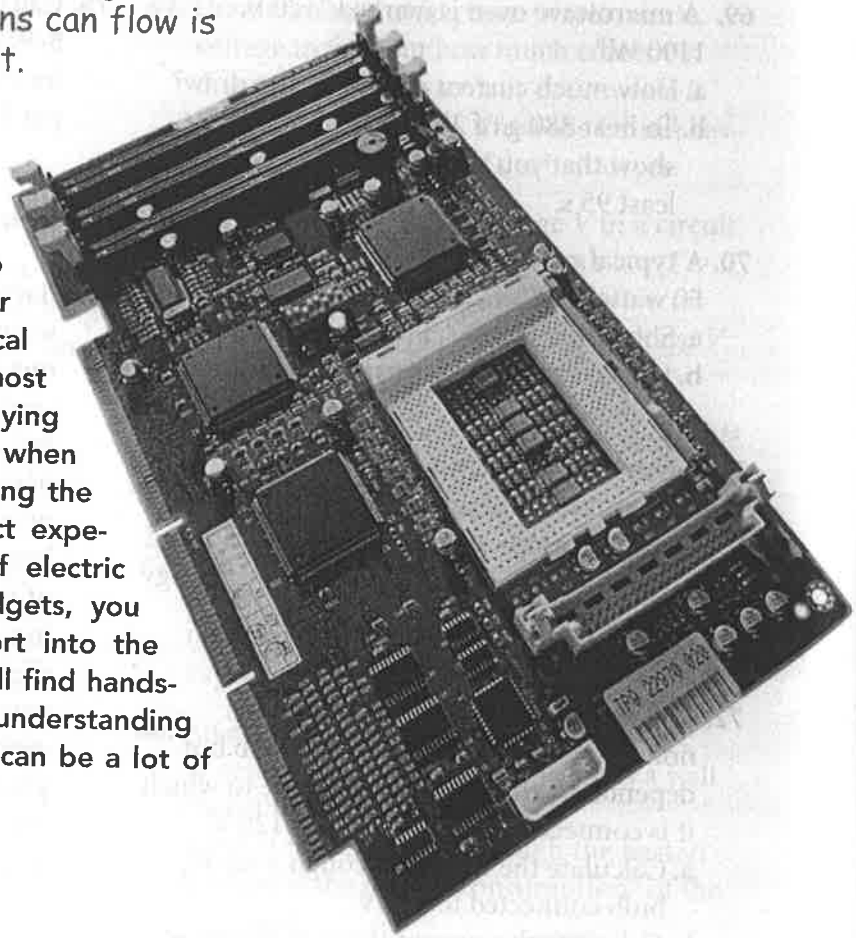
35 ELECTRIC CIRCUITS

THE BIG IDEA *Any path along which electrons can flow is a circuit.*



Mechanical things seem to be easier to figure out for most people than electrical things. Maybe this is because most people have had experience playing with blocks and mechanical toys when they were children. If you are among the many who have had far less direct experience with the inner workings of electric devices than with mechanical gadgets, you are encouraged to put extra effort into the laboratory part of this course. You'll find hands-on laboratory experience aids your understanding of electric circuits. The experience can be a lot of fun, too!

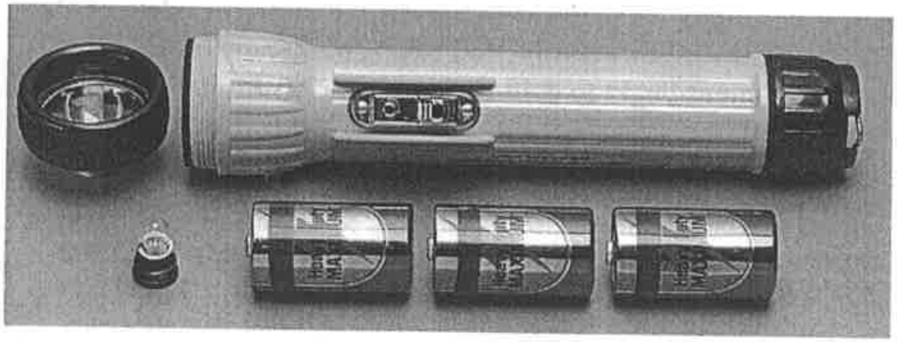
discover!

What Does It Take to Light a Lightbulb?

1. Try to light a lightbulb with just a battery and a single piece of wire.
2. Now try to get the same result with different arrangements of the wire, the battery, and the lightbulb.

Analyze and Conclude

1. **Observing** Describe both successful and unsuccessful attempts to light the lightbulb.
2. **Predicting** How many possible arrangements of the wire, the battery, and the lightbulb will result in the bulb being lit?
3. **Making Generalizations** What conditions are necessary in order for the bulb to light?



◀ FIGURE 35.1
A flashlight consists of a reflector cap, a lightbulb, batteries, and a barrel-shaped housing with a switch.

35.1 A Battery and a Bulb

Take apart an ordinary flashlight like the one shown in Figure 35.1. If you don't have any spare pieces of wire around, cut some strips from some aluminum foil that you probably have in one of your kitchen drawers. Try to light up the bulb using a single battery[35.1] and a couple of pieces of wire or foil.

Some of the ways you *can* light the bulb and some of the ways you *can't* light it are shown in Figure 35.2. The important thing to note is that there must be a complete path, or **circuit,** that includes the bulb filament and that runs from the positive terminal at the top of the battery to the negative terminal, which is the bottom of the battery. Electrons flow from the negative part of the battery through the wire or foil to the side (or bottom) of the bulb, through the filament inside the bulb, and out the bottom (or side) and through the other piece of wire or foil to the positive part of the battery. The current then passes through the interior of the battery to complete the circuit.

The flow of charge in a circuit is very much like the flow of water in a closed system of pipes. In a flashlight, or for the setups shown in Figure 35.2b, the battery is analogous to a pump, the wires are analogous to the pipes, and the bulb is analogous to any device that operates when the water is flowing. When a valve in the line is opened and the pump is operating, water already in the pipes starts to flow.

Filament resistance in a 120-V, 60-W bulb increases about 15 times from room temperature to its nearly 3000-K operating temperature in a time of about 100 milliseconds. The initial 10-A current drawn quickly decreases to a steady 0.7 A.

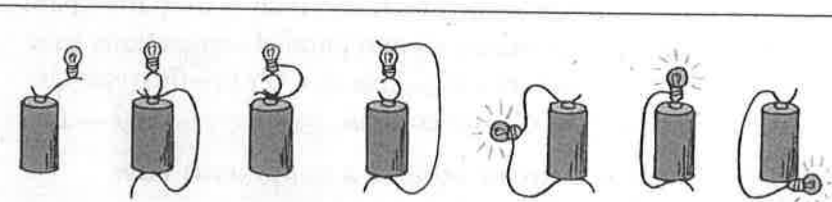
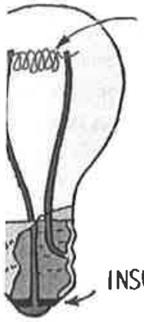


FIGURE 35.2 ▲
a. Unsuccessful ways to light a bulb. **b.** Successful ways to light a bulb.



IRE 35.3 ▲
rons do not pile up
ɘ a bulb, but instead
through its filament.

In a flashlight, when the switch is turned on to complete an electric circuit, the mobile conduction electrons already in the wires and the filament begin to drift through the circuit. The water flows *through* the pump and electrons in effect flow *through* the battery. Neither the water nor the electrons "squash up" and concentrate in certain places; they flow continuously around a loop, or circuit.

CONCEPT CHECK: What happens to the mobile conduction electrons when you turn on a flashlight?

35.2 Electric Circuits

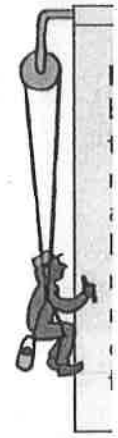
Any path along which electrons can flow is a circuit. **For a continuous flow of electrons, there must be a complete circuit with no gaps.** A gap is usually provided by an electric switch that can be opened or closed to either cut off or allow electron flow.

The water analogy is quite useful for gaining a conceptual understanding of electric circuits, but it does have some limitations. An important one is that a break in a water pipe results in water spilling from the circuit, whereas a break in an electric circuit results in a complete stop in the flow of electricity. Another difference has to do with turning current off and on. When you *close* an electrical switch that connects the circuit, you allow current to flow in much the same way as you allow water to flow by *opening* a faucet. Opening a switch stops the flow of electricity. An electric circuit must be closed for electricity to flow. Opening a water faucet, on the other hand, starts the flow of water. Despite these and some other differences, thinking of electric current in terms of water current is a helpful way to study electric circuits.

Most circuits have more than one device that receives electrical energy. These devices are commonly connected in a circuit in one of two ways, *series* or *parallel*. When connected **in series,** the devices in a circuit form a single pathway for electron flow between the terminals of the battery, generator, or wall socket (which is simply an extension of these terminals). When connected **in parallel,** the devices in a circuit form branches, each of which is a separate path for the flow of electrons. Both series and parallel connections have their own distinctive characteristics. This chapter briefly treats circuits with these two types of connections.

CONCEPT CHECK: How can a circuit achieve a continuous flow of electrons?

ɘr failing more than
0 times before per-
ing the first electric
tbulb, Thomas
ion stated that his
s were not failures,
ause he successfully
overed 6000 ways
don't work.



35.

Figur
is an
are ar
switcl
The c
lamp.
electr
move
ment
the ci
and t
ment

Physics on the Job

Electrician An electrician is called upon whenever a building is being constructed or rewired. Electricians install wiring and connect the circuits to the local power company. The first step an electrician must take is to prepare a wiring diagram that shows how the series and parallel circuits will be arranged and where the switches will be located. The next step is to install the circuits and make sure current flows through the circuits properly and safely. The electrician must also make sure that the wiring meets local codes. Builders and contractors rely on electricians for any structure that uses electricity—from tall skyscrapers to backyard lighting systems.

35.3 Series Circuits

Figure 35.4 shows three lamps connected in series with a battery. This is an example of a simple **series circuit,** or a circuit in which devices are arranged so that charge flows through each in turn. When the switch is closed, a current exists almost immediately in all three lamps. The current does not "pile up" in any lamp but flows *through* each lamp. Electrons in all parts of the circuit begin to move at once. Some electrons move away from the negative terminal of the battery, some move toward the positive terminal, and some move through the filament of each lamp. Eventually the electrons move all the way around the circuit. A break anywhere in the path results in an open circuit, and the flow of electrons ceases. Burning out of one of the lamp filaments or simply opening the switch could cause such a break.

think!

What happens to the light intensity of each lamp in a series circuit when more lamps are added to the circuit?
Answer: 35.3.1

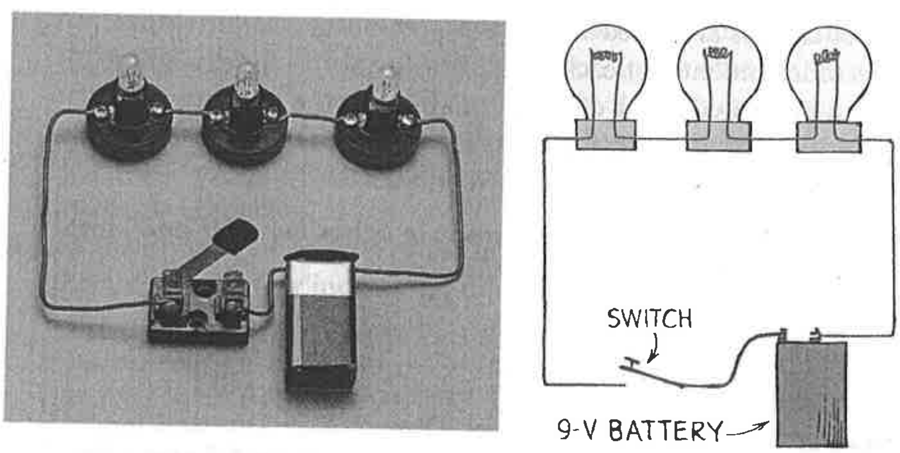


FIGURE 35.4 ▲
In this simple series circuit, a 9-volt battery provides 3 volts across each lamp.

Go Online active art
For: Series Circuit activity
Visit: PHSchool.com
Web Code: csp – 3503

The circuit shown in Figure 35.4 illustrates the following important characteristics of series connections:

1. Electric current has but a single pathway through the circuit. This means that the current passing through each electric device is the same.
2. This current is resisted by the resistance of the first device, the resistance of the second, and the third also, so that the total resistance to current in the circuit is the sum of the individual resistances along the circuit path.
3. The current in the circuit is numerically equal to the voltage supplied by the source divided by the total resistance of the circuit. This is Ohm's law.
4. Ohm's law also applies separately to each device. The *voltage drop*, or potential difference, across each device depends directly on its resistance. This follows from the fact that more energy is used to move a unit of charge through a large resistance than through a small resistance.
5. The total voltage impressed across a series circuit divides among the individual electric devices in the circuit so that the sum of the voltage drops across the individual devices is equal to the total voltage supplied by the source. This follows from the fact that the amount of energy used to move each unit of charge through the entire circuit equals the sum of the energies used to move that unit of charge through each of the electric devices in the circuit.

It is easy to see the main disadvantage of a series circuit. ✓ **If one device fails in a series circuit, current in the whole circuit ceases and none of the devices will work.** Some cheap party lights are connected in series. When one lamp burns out, it's "fun and games" (or frustration) trying to find which bulb to replace.

Most circuits are wired so that it is possible to operate electric devices independently of each other. In your home, for example, a lamp can be turned on or off without affecting the operation of other lamps or electric devices. This is because these devices are connected not in series but in parallel to one another.

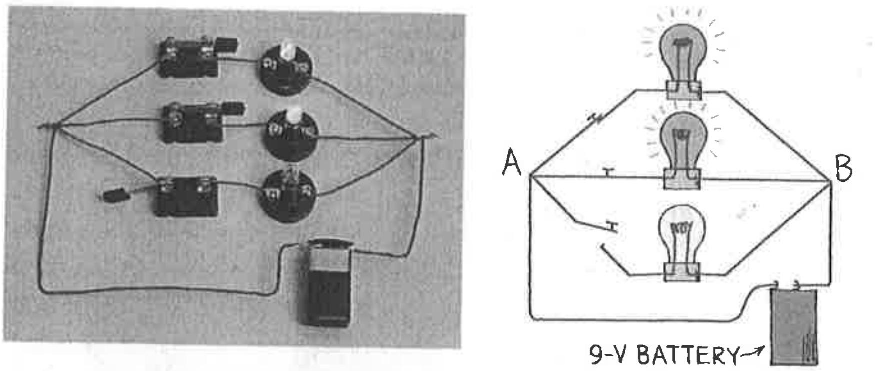
A series circuit is like a single-lane road with no alternate path. If there is a roadblock or a cave-in, traffic will stop.

CONCEPT CHECK What happens to current in other lamps if one lamp in a series circuit burns out?

think!

Look at the circuit shown in Figure 35.4. If the current through one of the bulbs is 1 A, can you tell what the current is through each of the other two bulbs? If the voltage across bulb 1 is 2 V, and across bulb 2 is 4 V, what is the voltage across bulb 3?

Answer: 35.3.2



◀ **FIGURE 35.5**
In this simple parallel circuit, a 9-volt battery provides 9 volts across each activated lamp.

Go Online
active art
For: Parallel Circuits activity
Visit: PHSchool.com
Web Code: csp - 3504

35.4 Parallel Circuits

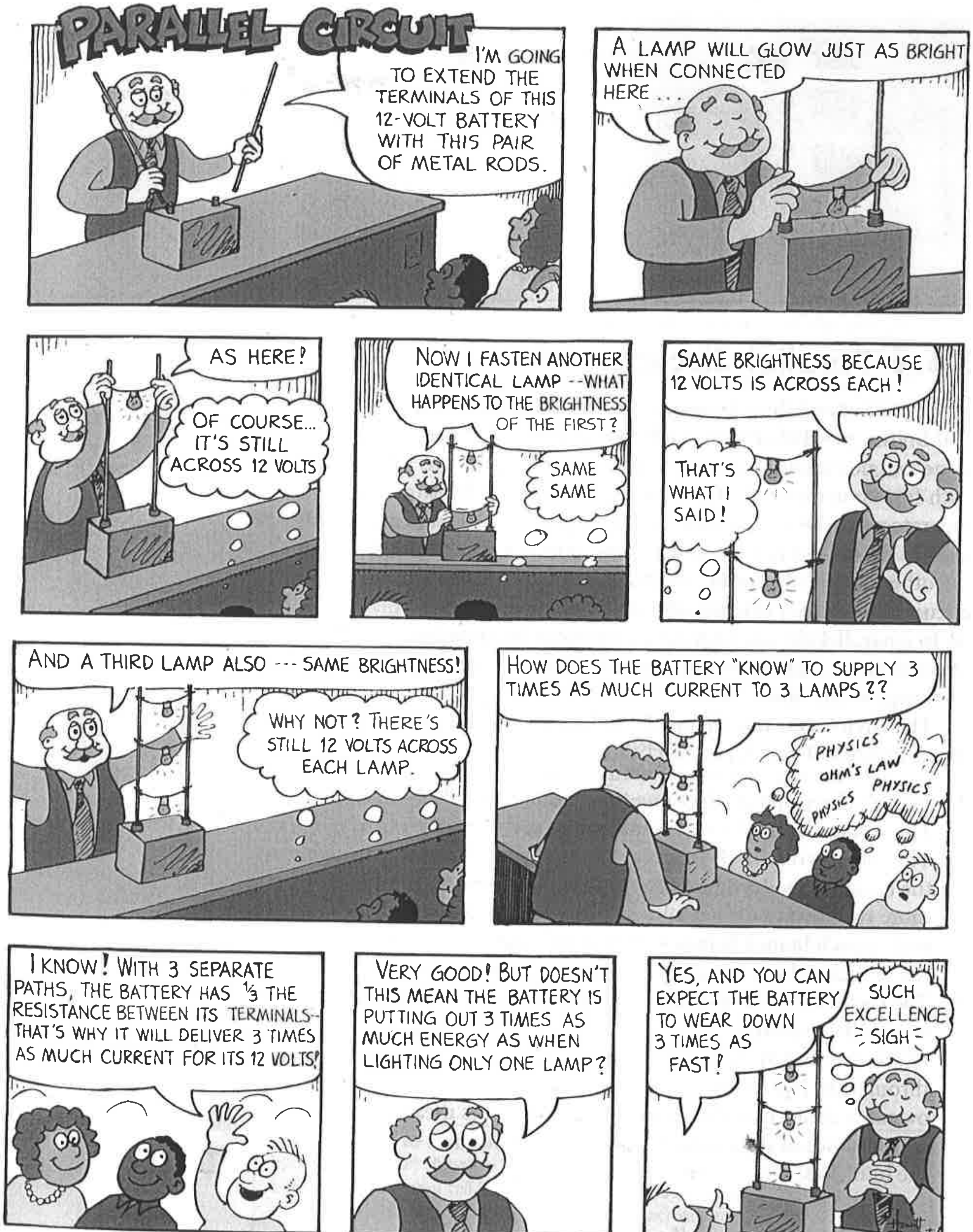
Figure 35.5 shows three lamps connected to the same two points A and B. In a **parallel circuit,** each electric device is connected to the same two points of the circuit. Notice that each lamp has its own path from one terminal of the battery to the other. There are three separate pathways for current, one through each lamp. In contrast to a series circuit, the current in one lamp does not pass through the other lamps. Also, unlike lamps connected in series, the parallel circuit is completed whether all, two, or only one lamp is lit. **In a parallel circuit, each device operates independent of the other devices. A break in any one path does not interrupt the flow of charge in the other paths.**

The circuit shown in Figure 35.5 illustrates the following major characteristics of parallel connections:

1. Each device connects the same two points A and B of the circuit. The voltage is therefore the same across each device.
2. The total current in the circuit (that is, the total current through the battery) divides among the parallel branches. Current passes more readily into devices of low resistance, so the amount of current in each branch is inversely proportional to the resistance of the branch. Ohm's law applies separately to each branch.
3. The total current in the circuit equals the sum of the currents in its parallel branches.
4. As the number of parallel branches is increased, the total current through the battery increases. From the battery's perspective, the overall resistance of the circuit is *decreased.* This means the overall resistance of the circuit is less than the resistance of any one of the branches.

think!
What happens to the light intensity of each lamp in a parallel circuit when more lamps are added in parallel to the circuit?
Answer: 35.4

CONCEPT CHECK What happens if one device in a parallel circuit fails?


PARALLEL CIRCUIT
I'M GOING TO EXTEND THE TERMINALS OF THIS 12-VOLT BATTERY WITH THIS PAIR OF METAL RODS.
A LAMP WILL GLOW JUST AS BRIGHT WHEN CONNECTED HERE . . .
AS HERE?
OF COURSE... IT'S STILL ACROSS 12 VOLTS
NOW I FASTEN ANOTHER IDENTICAL LAMP --WHAT HAPPENS TO THE BRIGHTNESS OF THE FIRST?
SAME SAME
SAME BRIGHTNESS BECAUSE 12 VOLTS IS ACROSS EACH!
THAT'S WHAT I SAID!
AND A THIRD LAMP ALSO --- SAME BRIGHTNESS!
WHY NOT? THERE'S STILL 12 VOLTS ACROSS EACH LAMP.
HOW DOES THE BATTERY "KNOW" TO SUPPLY 3 TIMES AS MUCH CURRENT TO 3 LAMPS??
PHYSICS
OHM'S LAW
PHYSICS
PHYSICS
I KNOW! WITH 3 SEPARATE PATHS, THE BATTERY HAS 1/3 THE RESISTANCE BETWEEN ITS TERMINALS-- THAT'S WHY IT WILL DELIVER 3 TIMES AS MUCH CURRENT FOR ITS 12 VOLTS!
VERY GOOD! BUT DOESN'T THIS MEAN THE BATTERY IS PUTTING OUT 3 TIMES AS MUCH ENERGY AS WHEN LIGHTING ONLY ONE LAMP?
YES, AND YOU CAN EXPECT THE BATTERY TO WEAR DOWN 3 TIMES AS FAST!
SUCH EXCELLENCE = SIGH =

35.5 Schematic Diagrams

Electric circuits are frequently described by simple diagrams, called **schematic diagrams,** that are similar to those of the last two figures. Some of the symbols used to represent certain circuit elements are shown in Figure 35.6. **In a schematic diagram, resistance is shown by a zigzag line, and ideal resistance-free wires are shown with solid straight lines. A battery is represented with a set of short and long parallel lines.** The convention is to represent the positive terminal of the battery with a long line and the negative terminal with a short line. Sometimes a two-cell battery is represented with a pair of such lines, a three-cell with three, and so on. Figures 35.7a and 35.7b show schematic diagrams for the circuits of Figures 35.4 and 35.5.

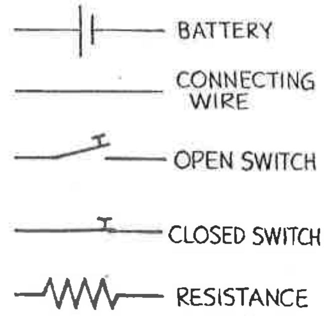
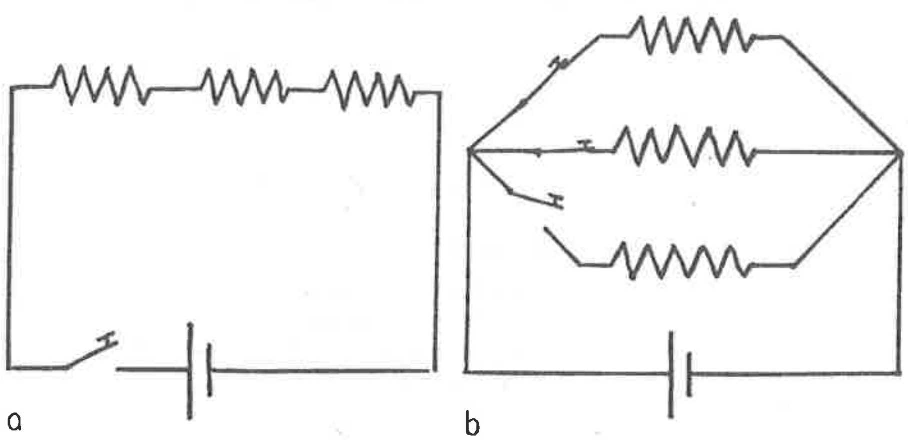


FIGURE 35.6 ▲
Symbols of some common circuit devices.

CONCEPT CHECK: What symbols are used to represent resistance, wires, and batteries in schematic diagrams?



◀ FIGURE 35.7
These schematic diagrams represent **a.** the circuit of Figure 35.4, with three lamps in series; and **b.** the circuit of Figure 35.5, with three lamps in parallel.

Link to TECHNOLOGY

Measuring with Current A fuel gauge in an automobile uses variable resistance to measure the level in the gasoline tank. A float in the tank adjusts the resistance of a variable electric resistor. Maximum resistance occurs when the float bottoms out in the tank. Maximum resistance produces the minimum current, which barely deflects the pointer on the fuel gauge. When the tank is full, the variable resistor has its lowest resistance and the maximum current flows through the fuel gauge. For this current, the gauge is calibrated to read a full tank. Between empty and full, corresponding values of current produce appropriate deflections of the fuel gauge pointer.

The resistance in the filament of a lightbulb varies with temperature. When cold (at room temperature) it may be only 16 Ω in a 120-V, 60-W bulb, while 100 ms later when it reaches its operating temperature, filament resistance increases to a steady 240 Ω.

35.6 Combining Resistors in a Compound Circuit

Sometimes it is useful to know the *equivalent resistance* of a circuit that has several resistors in its network. The equivalent resistance is the value of the single resistor that would comprise the same load to the battery or power source. **The equivalent resistance of resistors connected in series is the sum of their values.** For example, the equivalent resistance for a pair of 1-ohm resistors in series is simply 2 ohms.

The equivalent resistance for a pair of 1-ohm resistors in parallel is 0.5 ohm. (The equivalent resistance is *less* because the current has "twice the path width" when it takes the parallel path. In a similar way, the more doors that are open in an auditorium full of people trying to exit, the *less* will be the resistance to their departure.) **The equivalent resistance for a pair of equal resistors in parallel is half the value of either resistor.** Figure 35.8 shows how you can simplify schematic diagrams by using equivalent resistances.

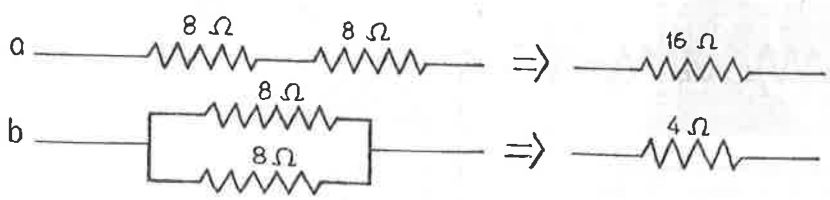


FIGURE 35.8 ▲
a. The equivalent resistance of two 8-ohm resistors in series is 16 ohms. **b.** The equivalent resistance of two 8-ohm resistors in parallel is 4 ohms.

Figure 35.9 shows a combination of three 8-ohm resistors. The two resistors in parallel are equivalent to a single 4-ohm resistor, which is in series with an 8-ohm resistor and adds to produce an equivalent resistance of 12 ohms. If a 12-volt battery were connected to these resistors, can you see from Ohm's law that the current through the battery would be 1 ampere? (In practice it would be less, for there is resistance inside the battery as well, called the battery's *internal resistance.*)

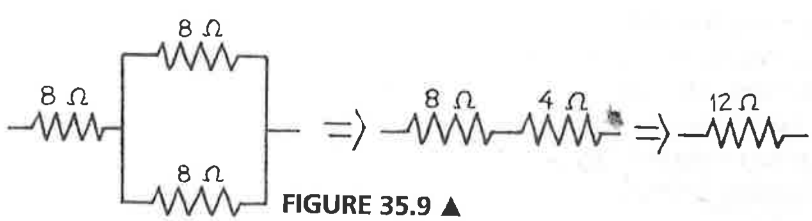
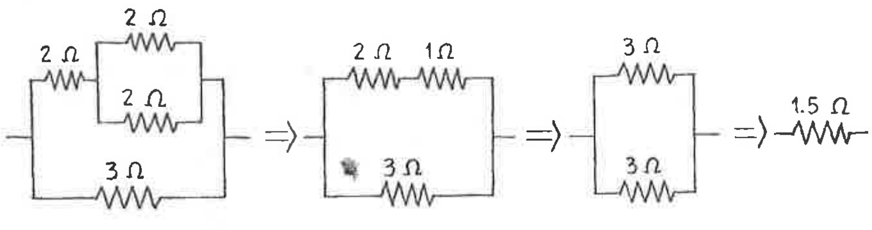
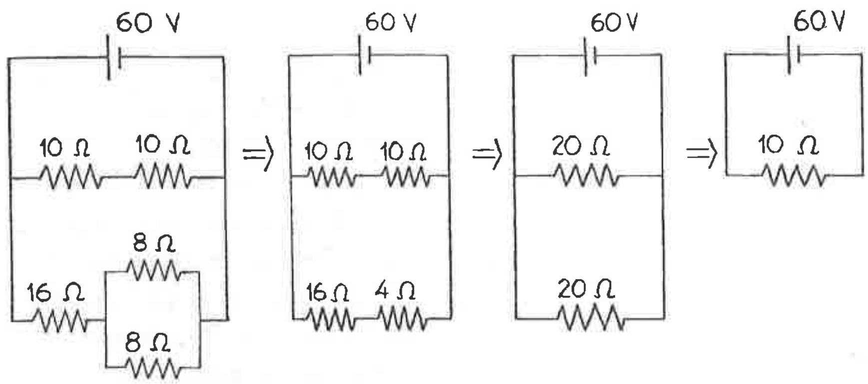


FIGURE 35.9 ▲
The equivalent resistance of the circuit is found by combining resistors in successive steps.



◀ FIGURE 35.10
The equivalent resistance of the top branch is 3 ohms, which is in parallel with the 3-ohm resistance of the lower branch. The overall equivalent resistance is 1.5 ohms.



◀ FIGURE 35.11
Schematic diagrams for an arrangement of various electric devices. The equivalent resistance of the circuit is 10 ohms. (The 60-V battery is for numerical convenience—most batteries are less than 60 V.)

Two more complex combinations are broken down in successive equivalent combinations in Figures 35.10 and 35.11. It's like a game: Combine resistors in series by adding; combine a pair of equal resistors in parallel by halving.[35.6] The value of the single resistor left is the equivalent resistance of the combination.

See Note 35.6 on page 908 for more on equivalent resistances.

CONCEPT CHECK: **What is the equivalent resistance of resistors in series? Of a pair of equal resistors in parallel?**

35.7 Parallel Circuits and Overloading

Electric current is usually fed into a home by way of two lead wires called *lines.* These lines are very low in resistance and are connected to wall outlets in each room. About 110 to 120 volts are impressed on these lines by the power company. This voltage is applied to appliances and other devices that are connected in parallel by plugs to these lines.

As more devices are connected to the lines, more pathways are provided for current. What effect do the additional pathways produce? The answer is, a lowering of the combined resistance of the circuit. Therefore, a greater amount of current occurs in the lines. Lines that carry more than a safe amount of current are said to be *overloaded.* The resulting heat may be sufficient to melt the insulation and start a fire.

think!

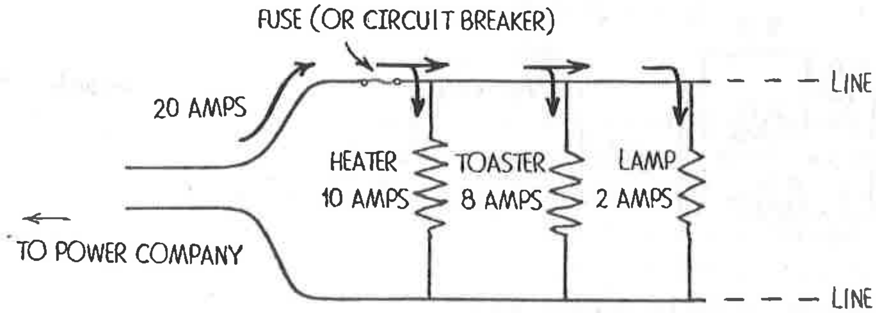
Use Figure 35.11 to answer the following questions.

What is the current in amperes through the battery? (Neglect the internal resistance of the battery.)
Answer: 35.6.1

What is the current in amperes through the pair of 10-ohm resistors? Through *each* of the 8-ohm resistors?
Answers: 35.6.2

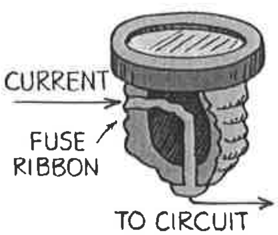
How much power is provided by the battery?
Answer: 35.6.3

FIGURE 35.12 ▶
The more devices you connect to your household supply line, the more you increase the total line current.



You can see how overloading occurs by considering the circuit in Figure 35.12. The supply line is connected to an electric toaster that draws 8 amperes, to an electric heater that draws 10 amperes, and to an electric lamp that draws 2 amperes. When only the toaster is operating and drawing 8 amperes, the total line current is 8 amperes. When the heater is also operating, the total line current increases to 18 amperes (8 amperes to the toaster and 10 amperes to the heater). If you turn on the lamp, the line current increases to 20 amperes. Connecting any more devices increases the current still more.

FIGURE 35.13 ▼
Above a specified current, the metal ribbon in a safety fuse melts and breaks the circuit.



✓ **To prevent overloading in circuits, fuses or circuit breakers are connected in series along the supply line.** In this way the entire line current must pass through the fuse. The safety fuse shown in Figure 35.13 is constructed with a wire ribbon that will heat up and melt at a given current. If the fuse is rated at 20 amperes, it will pass 20 amperes, but no more. A current above 20 amperes will melt the fuse, which "blows out" and breaks the circuit. Before a blown fuse is replaced, the cause of overloading should be determined and remedied. Often, insulation that separates the wires in a circuit wears away and allows the wires to touch. This effectively shortens the path of the circuit, and is called a *short circuit.* A short circuit draws a dangerously large current because it bypasses the normal circuit resistance.

Circuits may also be protected by *circuit breakers,* which use magnets or bimetallic strips to open the switch. Utility companies use circuit breakers to protect their lines all the way back to the generators. Circuit breakers are used instead of fuses in modern buildings because they do not have to be replaced each time the circuit is opened. Instead, the switch can simply be moved back to the "on" position after the problem has been corrected.

In practice, the lines in your home are not perfect conductors. With the large current used to operate a vacuum cleaner, the connecting wires do warm up. But for most cases, the resistance of the lines can be neglected.

CONCEPT CHECK **How can you prevent overloading in circuits?**