35 Electric Circuits

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 electrical devices, as compared to mechanical gadgets, you are encouraged to put extra effort into the laboratory part of this course. This is because an understanding of electric circuits is helped by hands-on experience. This experience can be fun.

35.1 A Battery and a Bulb

Take apart a flashlight, the ordinary kind 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 with a single battery* and a couple of pieces of wire or foil.

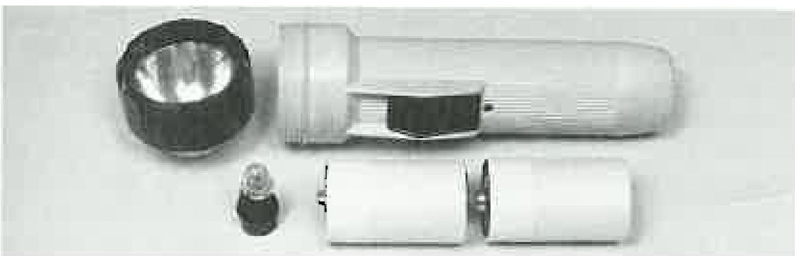


Fig. 35-1 A flashlight taken apart.

* Strictly speaking, a battery consists of two or more cells. What most people call a flashlight battery is more properly called a flashlight dry cell. To conform with popular usage, this chapter uses the term *battery* to mean either a single cell or series of cells.

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**, 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 bottom (or side) of the bulb, through the filament inside the bulb, and out the side (or bottom) 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.

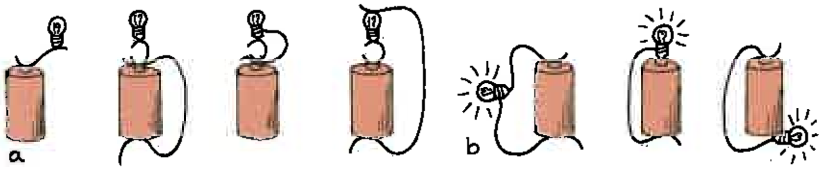


Fig. 35-2 (a) Unsuccessful ways to light a bulb. (b) Successful ways to light a bulb.

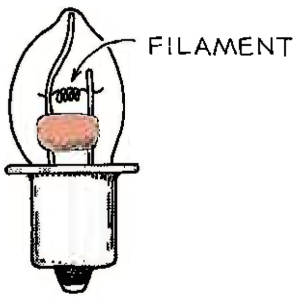


Fig. 35-3 Electrons do not pile up inside a bulb, but instead flow through its filament.

It is a bit misleading to say that electrons flow "out of" the battery, or "into" the bulb; a better description is to say they flow *through* these devices. The flow of charge in a circuit is analogous to the flow of water in a closed system of pipes. The battery is analogous to a pump, the wires to the pipes, and the bulb to any device that operates when the water is flowing. The water flows through both the pump itself and the circuit it connects. It doesn't "squash up" and concentrate in certain regions, but flows continuously. Electric current behaves the same way.

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. Except for these and some other differences, thinking of electric current in terms of water current is a useful 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 two ways, *series* or *parallel*. When connected **in series**, they 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**, they 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.

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**. 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 that make up this current leave the negative terminal of the battery, pass through each of the resistive filaments in the lamps in turn, and then return to the positive terminal of the battery (the same amount of current passes through the battery). This is the only path of the electrons through 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.

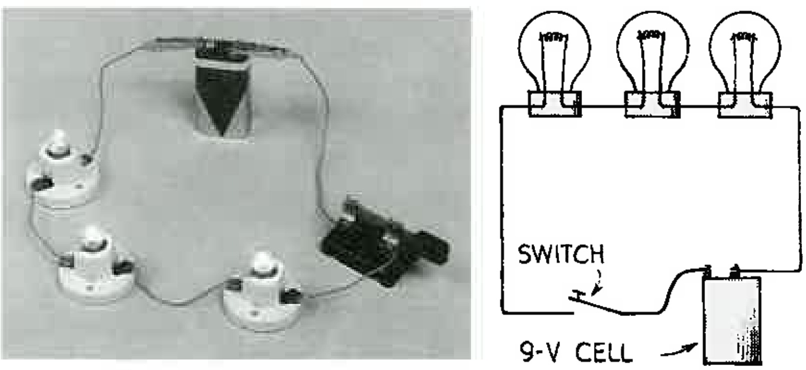


Fig. 35-4 A simple series circuit. The 9-volt battery provides 3 volts across each lamp.

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 the resistance of each electrical 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 follows Ohm's law.
4. The *voltage drop*, or potential difference, across each device is proportional to 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 electrical devices in the circuit so that the sum of the voltage drops across each individual device 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 electrical device in turn.

► **Questions**

1. What happens to current in other lamps if one lamp in a series circuit burns out?
2. What happens to the light intensity of each lamp in a series circuit when more lamps are added to the circuit?

It is easy to see the main disadvantage of a series circuit: if one device fails, current in the whole circuit ceases. Some cheap Christmas tree lights are connected in series. When one lamp burns out, it's "fun and games" (or frustration) trying to find which bulb to replace.

► **Answers**

1. If one of the lamp filaments burns out, the path connecting the terminals of the voltage source will break and current will cease. All lamps will go out.
2. The addition of more lamps in a series circuit results in a greater circuit resistance. This decreases the current in the circuit and therefore in each lamp, which causes dimming of the lamps. Energy is divided among more lamps so the voltage drop across each lamp will be less.

Most circuits are wired so that it is possible to operate electrical 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 electrical devices. This is because these devices are connected not in series but in parallel to one another.

35.4 Parallel Circuits

Figure 35-5 shows three lamps connected to the same two points A and B. This is an example of a simple **parallel circuit**. Electrical devices connected in parallel are connected to the same two points of an electric circuit. Electrons leaving the negative terminal of the battery need travel through only *one* lamp filament before returning to the positive terminal of the battery. In this case, current branches into three separate pathways from A to B. A break in any one path does not interrupt the flow of charge in the other paths. Each device operates independently of the other devices.

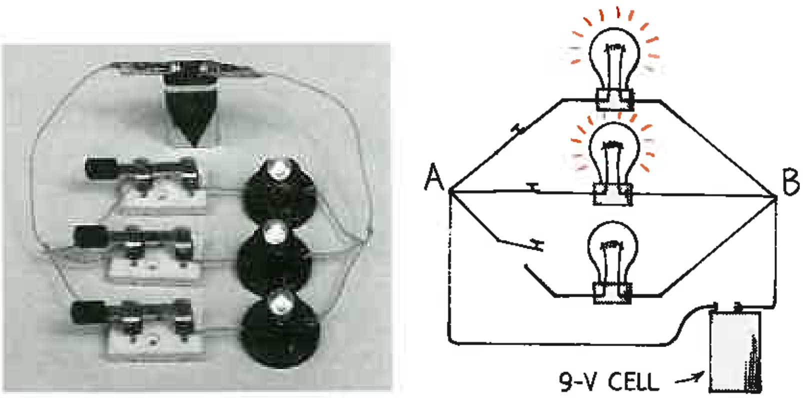
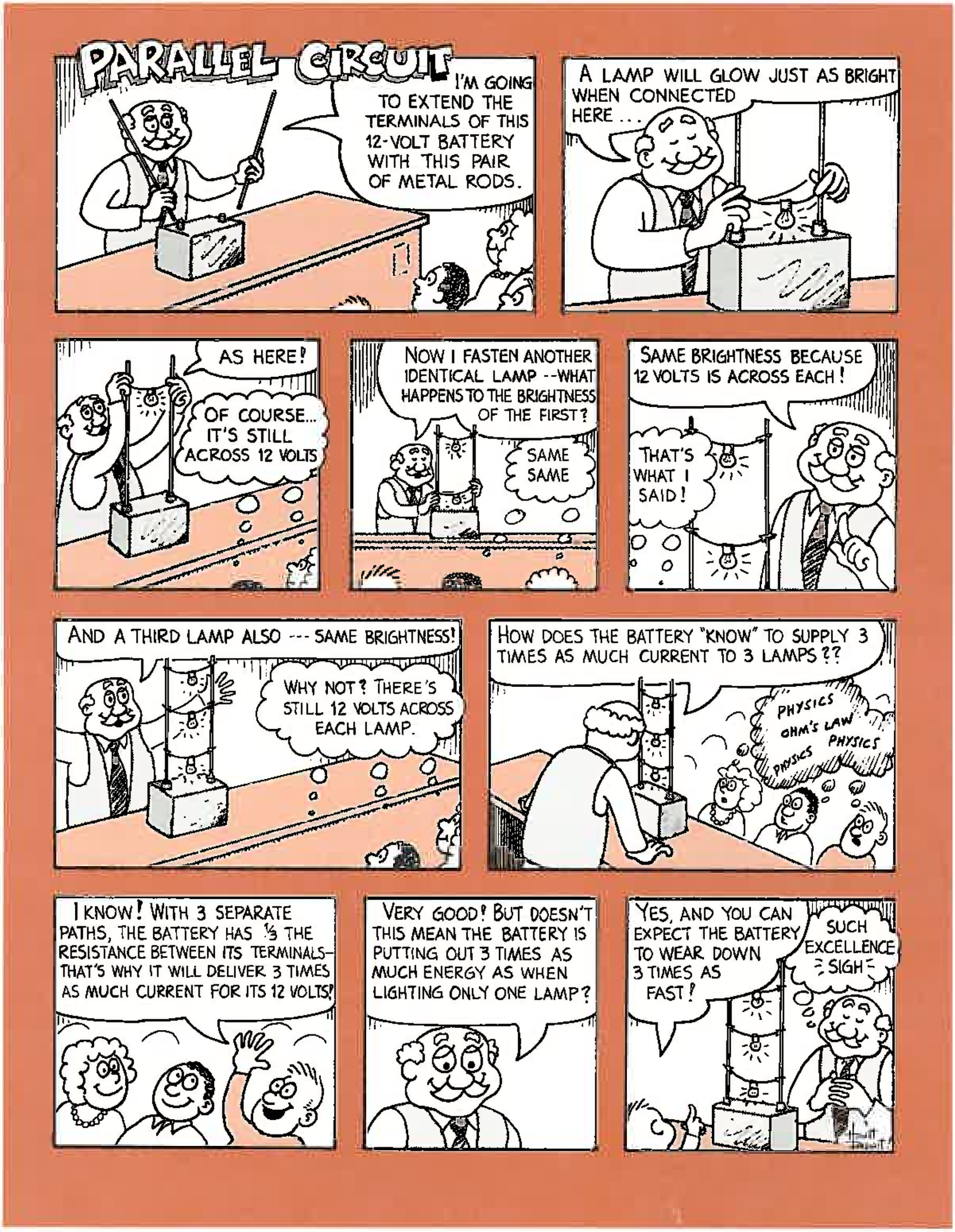


Fig. 35-5 A simple parallel circuit. A 9-volt battery provides 9 volts across each lamp.

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 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. This follows Ohm's law.


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 ⅓ 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 ≈

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 overall resistance of the circuit is *decreased*. Overall resistance is lowered with each added path between any two points of the circuit. This means the overall resistance of the circuit is less than the resistance of any one of the branches.

▸ **Questions**

1. What happens to the current in other lamps if one of the lamps in a parallel circuit burns out?
2. What happens to the light intensity of each lamp in a parallel circuit when more lamps are added in parallel to the circuit?

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. Resistance is shown by a zigzag line, and ideal resistanceless wires are shown with solid straight lines. A single cell battery is represented with a set of short and long parallel lines. The convention is to represent the

▸ **Answers**

1. If one lamp burns out, the other lamps will be unaffected. The current in each branch, according to Ohm's law, is equal to (voltage)/(resistance), and since neither voltage nor resistance is affected in the branches, the current in those branches is unaffected. The total current in the overall circuit (the current through the battery) however, is decreased by an amount equal to the current drawn by the lamp in question before it burned out. But the current in any other single branch is unchanged.
2. The light intensity for each lamp is unchanged as other lamps are introduced (or removed). Only the total resistance and total current in the total circuit changes, which is to say, the current in the battery changes. (There is resistance in a battery also, which we assume is negligible here.) As lamps are introduced, more paths are available between the battery terminals, which effectively decreases total circuit resistance. This decreased resistance is accompanied by an increased current, the same increase that feeds energy to the lamps as they are introduced. Although changes of resistance and current occur for the circuit as a whole, no changes occur in any individual branch in the circuit.

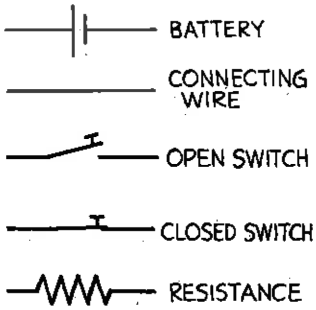


Fig. 35-6 Symbols of some common circuit devices.

positive terminal of the battery with a long line and the negative terminal with a short line. A two-cell battery is represented with a pair of such lines, a three-cell with three, and so on. Figure 35-7 shows schematic diagrams for the circuits of Figures 35-4 and 35-5.

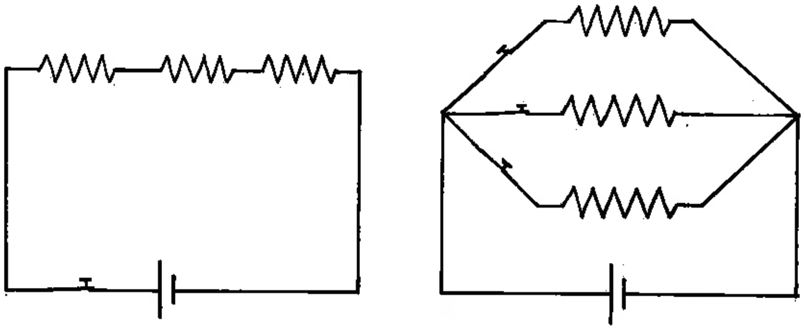


Fig. 35-7 Schematic diagrams. (Left) The circuit of Figure 35-4, with three lamps in series. (Right) The circuit of Figure 35-5, with three lamps in parallel.

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 can be found by the rules for adding resistors in series and parallel. 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 of people trying to exit, the *less* will be the resistance to migration.) The equivalent resistance for a pair of equal resistors in parallel is half the value of either resistor.

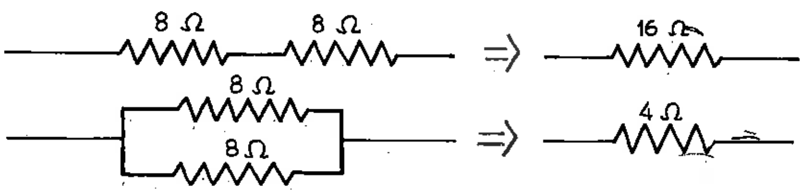


Fig. 35-8 (a) The equivalent resistance of two 8-ohm resistors in series is 16 ohms. (b) The equivalent resistance of two 8-ohm resistors in parallel is 4 ohms.

Figure 35-9 shows a combination of three 8-ohm resistors. The two in parallel are equivalent to a single 4-ohm resistor, which is in series to the 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 *internal resistance*.)

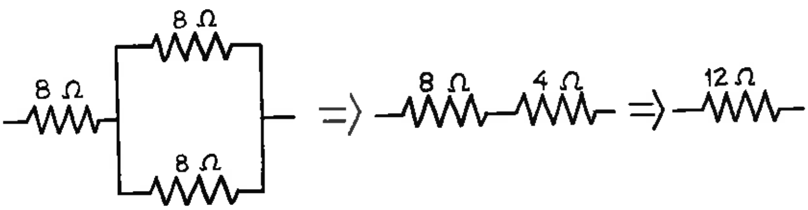


Fig. 35-9 The equivalent resistance of the circuit is found by combining resistors in successive steps.

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.* The value of the single resistor left is the equivalent resistance of the combination.

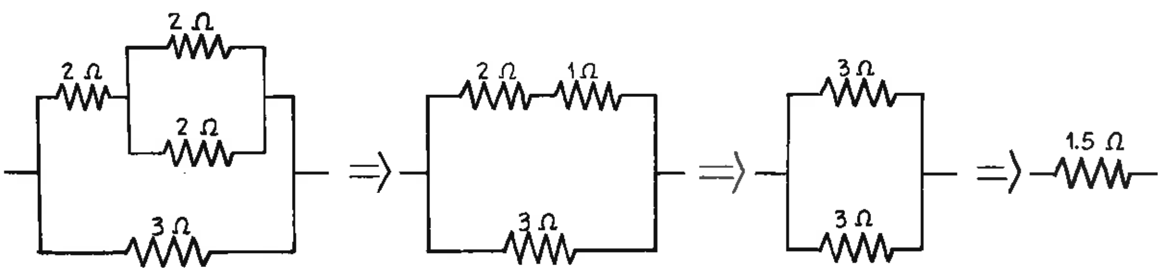


Fig. 35-10 The equivalent resistance of the top branch is 3 ohms, which is in parallel with the 3-ohm resistance of the lower branch. The overall equivalent resistance is 1.5 ohms.

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* For a pair of non-equal resistors in parallel, the equivalent resistance is found by taking the product of the pair and dividing by the sum of the pair. That is:

$$R_{\text{equivalent}} = \frac{R_1 R_2}{R_1 + R_2}$$

This rule of "product divided by sum" holds only for two resistors in parallel. For three or more parallel resistors, you can do a pair at a time (as is done in Figures 35-10 and 35-11), or use the more general formula:

$$1/R_{\text{equivalent}} = 1/R_1 + 1/R_2 + 1/R_3 \text{ and so on}$$

Details can be found in other physics textbooks.

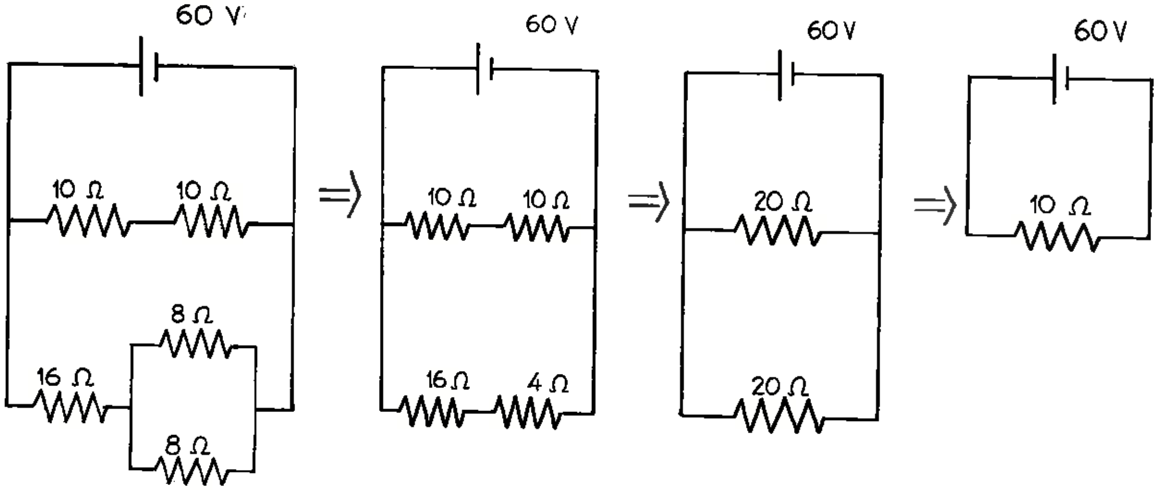

Fig 35-11 Schematic diagrams for an arrangement of various electric devices. The equivalent resistance of the circuit is 10 ohms.

▶ **Questions**

The following questions are based on the schematic diagrams in Figure 35-11.

1. What is the current in amperes through the battery? (Neglect the internal resistance of the battery.)
2. What is the current in amperes through the pair of 10-ohm resistors?
3. What is the current in amperes through each of the 8-ohm resistors?
4. How much power is provided by the battery?

▶ **Answers**

1. The current in the battery (or total current in the circuit) is 6 A. You can get this from Ohm's law: current = (voltage)/(resistance) = (60 V)/(10 ohms) = 6 A. You know that the equivalent resistance of the circuit is 10 ohms from step (d) in the figure.
2. Half the total circuit current, 3 A, will flow through the pair of 10-ohm resistors. You know this because you can see in step (c) of the figure that both branches have equal resistances. This means that the total circuit current will divide equally between the upper and lower branches.
3. The current through the pair of 8-ohm resistors is 3 A, and the current through each is therefore 1.5 A. This is because the 3-A current divides equally through these equal resistances.
4. The battery supplies 360 watts. This is from the relationship

$$\text{power} = \text{current} \times \text{voltage} = (6\ \text{A}) \times (60\ \text{V}) = 360\ \text{watts}$$

This power will be dissipated among all the resistors in the circuit.

35.7 Parallel Circuits and Overloading

Electricity 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 generators at the power utility. 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.

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.

To prevent overloading in circuits, *fuses* are connected in series along the supply line. In this way the entire line current must pass through the fuse. The 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.

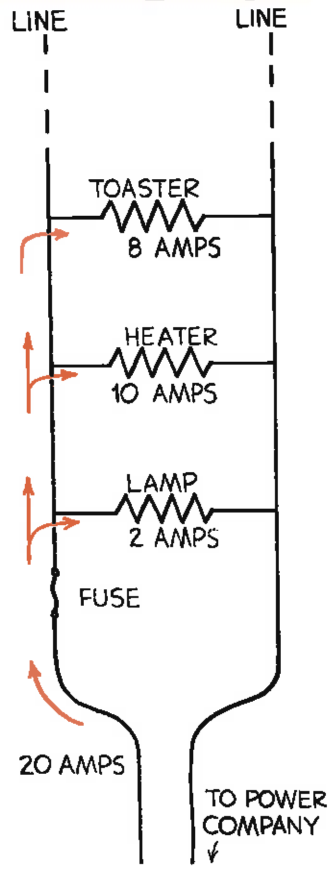

Fig. 35-12 Circuit diagram for appliances connected to a household supply line.

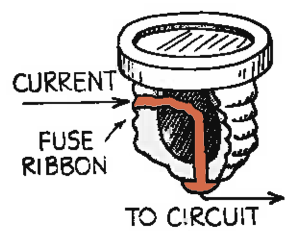

Fig. 35-13 A safety fuse.

35 Chapter Review

Concept Summary

Any path along which electrons can flow is a circuit.

- A complete circuit is needed to maintain a continuous electron flow.

In a series circuit, electrical devices form a single pathway for electron flow.

- A break anywhere in the path stops the electron flow in the entire circuit.
- The total resistance is equal to the sum of individual resistances along the current path.
- The current is equal to the voltage divided by the total resistance.
- The voltage drop across each device is proportional to its resistance.
- The sum of voltage drops across the resistance of each individual device is equal to the total voltage.

In a parallel circuit, electrical devices form branches, each of which provides a separate path for the flow of electrons.

- Each device connects the same two points of the circuit; the voltage is the same across each device.
- The amount of current in each branch is inversely porportional to the resistance of the branch.
- The total current is equal to the sum of the currents in each branch.

Electric circuits are often described by schematic diagrams, in which each element of the circuit is represented by a symbol.

In a circuit with several resistors, the equivalent resistance is the value of the single resistor that would comprise the same load to the battery or power source.

- For resistors in series, the equivalent resistance is the sum of their values.
- For resistors in parallel, the equivalent resistance is less than the value of any individual resistor.

Lines carrying an unsafe amount of current are overloaded.

- To prevent overloading, fuses are connected in series. Any current above the rating of the fuse will "blow out" the fuse and break the circuit.
- A short circuit is often caused by faulty wire insulation.

Important Terms

circuit (35.1)
in parallel (35.2)
in series (35.2)
parallel circuit (35.4)
schematic diagram (35.5)
series circuit (35.3)

Review Questions

1. Do electrons flow from a battery into a circuit or through both the battery and the circuit it connects? (35.1)

2. Why must there be no gaps in an electric circuit? (35.1)

3. Distinguish between a series circuit and a parallel circuit. (35.2)

4. If three lamps are connected in series to a 6-volt battery, how many volts are impressed across each lamp? (35.3)

5. If one of three lamps blows out when connected in series, what happens to the current in the other two? (35.3)

6. If three lamps are connected in parallel to a 6-volt battery, how many volts are impressed across each lamp? (35.4)

7. If one of three lamps blows out when connected in parallel, what happens to the current in the other two? (35.4)

8. a. In which case will there be more current in each of three lamps—if they are connected to the same battery in series or in parallel?
   b. In which case will there be more voltage across each lamp? (35.4)

9. What happens to the total circuit resistance when more devices are added to a series circuit? To a parallel circuit? (35.6)

10. What is the equivalent resistance of a pair of 8-ohm resistors in series? In parallel? (35.6)

11. Why does the total circuit resistance decrease when more devices are added to a parallel circuit? (35.6)

12. What does it mean to say that lines in a home are overloaded? (35.7)

13. What is the function of fuses in a circuit? (35.7)

14. Why will too many electrical devices operating at one time often blow a fuse? (35.7)

15. What is meant by a short circuit? (35.7)

Think and Explain

1. Sometimes you hear someone say that a particular appliance "uses up" electricity. What is it that the appliance actually "uses up," and what becomes of it?

2. Why are household appliances almost never connected in series?

3. As more and more lamps are connected in series to a flashlight battery, what happens to the brightness of the lamps?

4. As more and more lamps are connected in parallel to a battery, and if the current does not produce heating inside the battery, what happens to the brightness of the lamps?

5. When excessive charge flows in a battery, battery resistance increases. This lowers the voltage that is supplied to the external circuit. If too many lamps are connected in parallel across a battery, will their brightness diminish? Explain.

6. Consider the combination series and parallel circuit shown in Figure A.
   a. Identify the parallel part of the circuit. What is the equivalent resistance of this part? In other words, what single resistance could take their place and not change the total current from the battery?
   b. What is the equivalent resistance of all the resistors? In other words, what single resistance could take their place without changing the current from the battery?

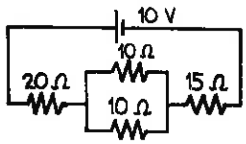

Fig. A

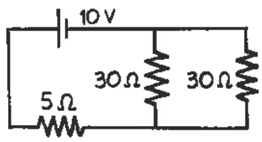

Fig. B

7. What is the current in the battery of the circuit shown in Figure B? (What must you find before you can calculate the current?)

8. The rear window defrosters on automobiles are made up of several strips of heater wire connected in parallel. Consider the case of four wires, each of 6 ohms resistance, connected to 12 volts.
   a. What is the equivalent resistance of the four wires? (Consider the wires to be two groups of two.)
   b. What is the total current drawn?

9. How does the line current compare to the total currents of all devices connected in parallel?
   Line current = sum of currents in branches.

10. Why should you not use a copper penny in place of a safety fuse that blows out?