Circuit happenings

Paul G. Hewitt
City College of San Francisco, San Francisco, CA 94112, USA.

E-mail: PGHewitt@aol.com

(Received 6 August 2007; accepted 23 August 2007)

Abstract
Much of the confusion in electricity is a failure to correctly distinguish between the concepts of voltage, current, energy, power, or a combination of these concepts. By carefully examining what happens in simple circuits, perhaps confusion can be minimized.

Key words: Physics Education, electric circuits.

Resumen
Mucha de la confusión en electricidad es debida a la mala distinción entre los conceptos de voltaje, corriente, energía, potencia, o una combinación de estos conceptos. Mediante una revisión cuidadosa sobre qué sucede en circuitos sencillos, la confusión quizás pueda ser minimizada.

Palabras clave: Física educativa, circuitos eléctricos.

PACS: 01.40.–d, 01.40.Fk, 01.40.Gm, 01.40.Jp.

I. INTRODUCCIÓN

Figure 1 shows a very simple circuit consisting of a battery and a bulb. The battery is analogous to a water pump that produces sustained water pressure in a pipe or system of pipes. The battery produces an *electric pressure* called *voltage*, that energizes the bulb. The energy is supplied through an *electric field* that permeates the circuit at nearly the speed of light. So for practical purposes, when a switch completing a circuit is closed, voltage across the circuit occurs instantaneously. Similar to a bridge across a river that connects opposite shores, voltage is established *across* the opposite terminals of the battery and *across* the circuit [1].

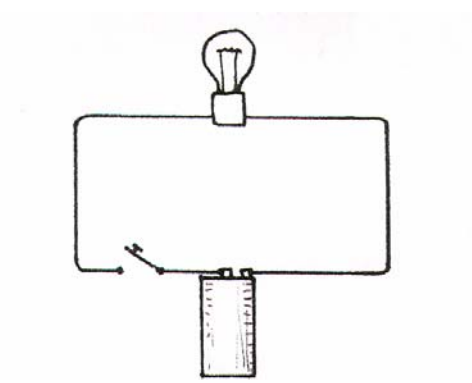

FIGURE 1. Simple electric circuit, a battery and a bulb.

It is important to note that charge flows though *all* parts of the circuit, including the battery itself. Like voltage, current is established in the circuit at nearly the speed of light—practically instantaneous. Loose electrons in the conducting material are immediately set into motion when voltage is sensed. Although electrons flow in the battery and through the circuit and then through the battery again where they are re-energized, it is a mistake to think they originate in the battery. Free charged particles such as electrons are in every part of any conducting material, and all move at the instant the electric switch is closed. They move in unison, all at once, similar to how the command "forward march" makes each member of a marching band step at the same time. Water provides another analogy: when you turn on your kitchen faucet, water flows through the connecting pipe. The water that fills your glass was already in the pipe, under pressure, and may have left the reservoir weeks ago! Likewise, the electrons that flow in the current through the light bulb are already present in the filament before and during turning on the switch. (When current is alternating, ac, the electrons do not flow through the filament, but are centered in one place as they vibrate to and for 60 times each second. Most of the electrons in the filament of an old light bulb were there when the bulb was first manufactured. In fact, they were in the material making up the filament *before* the bulb was manufactured!) Unlike water pipes that require you to supply water, electric wires are "pipes" that contain their own "water." Electrons are already in the wires of an electric circuit. A battery supplies them with energy.
The life of a battery depends on the length of time it shares its chemical energy with bulbs or other circuit devices. Like water pipes that become clogged with overuse and time, batteries build up resistance that further shortens their useful lives.

II. CIRCUITS CONSIDERATIONS

Let's assume the battery supplies 6 volts to the circuit. A 6-volt pressure means that during each second 6 joules of energy from the battery is delivered to each coulomb of charge comprising the current. If the resistance of the bulb is 1 ohm, then in accord with Ohm's law, the flow of charge—the *current*—is 6 amperes (V/R = 6 V/1 Ω = 6 amps). Six coulombs of charge flow through the circuit each second. The more current in a bulb, the brighter it glows. Remember that whereas voltage is established *across* a circuit, charge flows *through* a circuit.

Energy is delivered to and dissipated at locations of circuit *resistance*. In the single-bulb circuit, most all the resistance is in the filament of the bulb, where energy is converted to heat and light. The resistance offered by the connecting wires and the battery interior are small enough to neglect compared with the bulb's resistance. For simplicity, we therefore ignore all resistance in the circuit except that of the bulb.

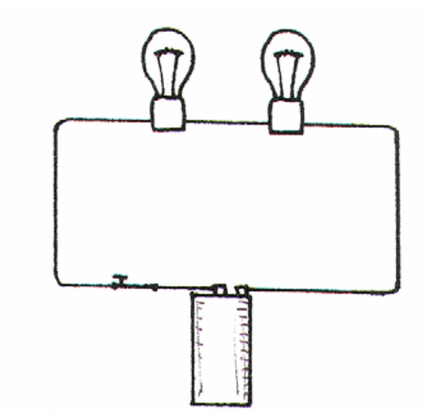

FIGURE 2. Simple series electric circuit, a battery and two bulbs.

What happens in the circuit when we add another identical bulb in series, as shown in Figure 2? Now the circuit has twice as much resistance. The voltage is the same because the battery is the same, and in accord with Ohm's law, twice the resistance for the same voltage means half as much current. So 3 amps flow in each bulb (and in every part of the circuit). In which bulb does the charge first flow? The answer is, both at once. It makes no difference as to which bulb is closer to whatever terminal of the battery. Current is established in all parts of the circuit instantaneously [2].

The 6 volts across the circuit divides among the two bulbs. Since the bulb resistances are the same, 3 volts are impressed across each bulb. This checks with Ohm's law: (3 V/1 Ω) = 3 amps. Or, for the overall circuit, (6 V/2 Ω) = 3 amps. So we see that current in the circuit is less and the bulbs are dimmer than the single bulb of the circuit in Figure 1.

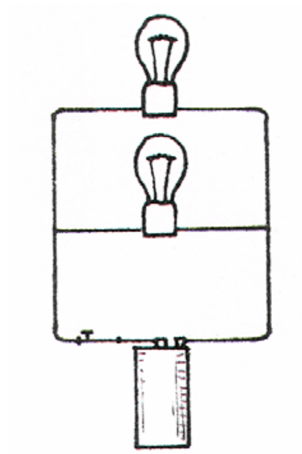

FIGURE 3. Simple parallel electric circuit, a battery and two bulbs.

When the two identical bulbs are connected in parallel, Figure 3, voltage does not divide among them. Think of the two branches as two parallel bridges across the same river. Each bulb is still energized with the full 6 volts, the current in each is still 6 amps, and each bulb glows with the same brightness of the lone bulb in Figure 1. A little thought will show that if the current in each bulb is 6 amps, the current in the battery must be 12 amps. In accord with Ohm's law, the battery supplies twice the current to the circuit because the *equivalent resistance* of the circuit is half that of Figure 1. Similar to an increased number of lanes for toll booths on a highway, more branches in a parallel circuit reduce resistance and allow a greater flow.

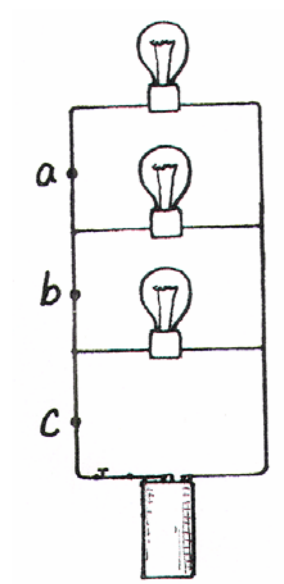

FIGURE 4. Simple parallel electric circuit, a battery and three bulbs.

Adding still another identical bulb in parallel, Figure 4, further reduces the overall circuit resistance, resulting in increased total current. Each bulb draws 6 amps, so the current supplied by the battery (and the current *in* the battery) is 18 amps. This is consistent with Ohm's law; for the same voltage, one-third the resistance results in three times the current. Consider points *a*, *b*, and *c*, in Figure 4.

A little thought will show that 6 amps flows through point *a*, 12 amps through point *b*, and 18 amps through point *c*. It's like buses leaving a terminal that branch into 3 streets. If 18 buses leave the terminal and branch equally along 3 streets, then 6 buses occupy a street. How many return to the terminal? All 18. Likewise with electric current—6 amps in three bulbs means 18 amps in the battery. Can we continue adding bulbs in parallel indefinitely? The answer is no, because the current in the battery increases with each addition, eventually producing an internal-heating problem. Then the internal resistance of the battery is no longer small enough to be negligible.

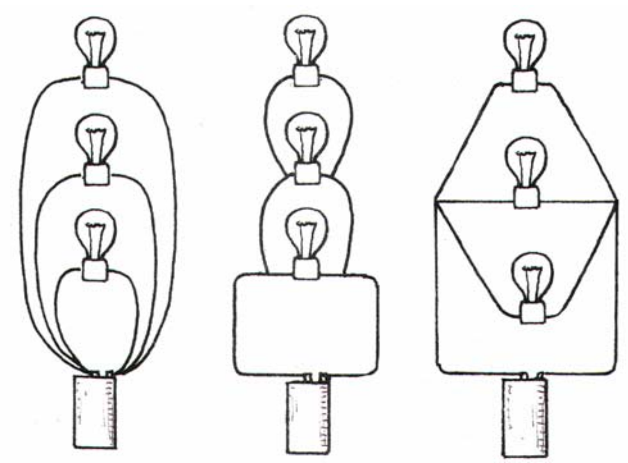

FIGURE 5. Same arrangement of a simple parallel electric circuit, a battery and three bulbs.

Notice that the three circuits in Figure 5 are all the same. Whatever the orientation of the wires, each bulb is connected across the full 6 volts of the battery. The battery "senses" the three circuits as the same [3].

III. ELECTRIC POWER

Consider power in the foregoing circuits. Power is energy dissipated per time. Which circuit dissipates the most energy per second? One way to look at it is to ask which circuit runs the battery down fastest? Another way is to ask which circuit is brightest when viewed from afar, so only the combined amount of light is seen [4]. The brightest light indicates the circuit with the greatest dissipation of power.

First consider the series circuits of Figures 1 and 2. Will light emitted by the two dim bulbs of Figure 2 combine to be as bright as the single bulb of Figure 1? We can let the equation for electrical power guide our thinking: Power = current x voltage ($P = i \times V$). The voltage source for both circuits is the same, but the current is less in the two-bulb circuit. So the power of the two-bulb circuit of Figure 2 is less—the combined brightness of the two bulbs is less than the brightness of the single bulb of Figure 1.

Let's ask the same question for the parallel circuits of Figures 3 and 4. The voltage for these circuits is the same, but again, the current is different. Current is greater in the battery when it lights three bulbs than two bulbs, so power dissipated by the battery is greater when lighting three bulbs. Brightness of the three lit bulbs is greater than the brightness of the two bulbs. Correspondingly, a battery that lights three bulbs in parallel will sooner exhaust its supply of chemical energy and go dead faster than when lighting fewer bulbs of the same resistance.

It is erroneous to say that current is "used up" in an electrical circuit. The quantity that is used up (consumed) in a circuit is not current, but *energy*. If current diminishes, it is because the energy per unit of charge (voltage) supplied by chemical action in the battery decreases. Energy is usually dissipated as heat.

IV CONCLUSIONS

In summary, we distinguish between *voltage* and *current*. A battery imparts a voltage across a circuit, producing a current that depends on battery voltage and on the resistance of the circuit. Total current in the circuit is also the current in the battery. In a series circuit, current in every part of the circuit is the same. In a parallel circuit, the sum of the currents in the parallel branches equals the current in the battery. We also distinguish between *energy* and *power*. Electric energy in the bulbs or other devices is energy transformed from chemical energy in the battery. When the supply of energy runs its course, the battery must be recharged or it goes flat—dead. The rate at which electric energy dissipates is power. A powerful battery transforms chemical energy faster than a weak battery.

REFERENCES

[1] Grayson, D. J., *Concept substitution: A teaching strategy for helping students disentangle related physics concepts*. Am. J. Phys. **72**, 1126 - 1133 (2004).

[2] Fredette, N. and Lochhead, J., *Student conceptions of simple electric circuits*, Phys. Teach. **19**, 194-198 (1980).

[3] Fredette, N., Clement, J. and Coll, J., *Student misconceptions of an electric circuit: What do they mean?*, Sci. Teach. **10**, 280-285 (1981).

[4] Livelybrooks, D., *"Feel" the Difference Between Series and Parallel Circuits*, Phys. Teach. **41**, 102 (2003).