Illustrating Electric Circuit Concepts with the Glitter Circuit

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Many beginning physics students have a harder time understanding basic concepts of electric circuits than understanding basic mechanics concepts. This is likely due to the fact that we cannot see electric charge carriers (electrons) move through an electric wire. It is thus the responsibility of the physics instructor to introduce his/her students to a variety of electric circuit models that will enable those students encountering circuits for the first time to come up with their own coherent mental picture of current flow in an electric circuit. Electric circuit analogs might prove helpful in this endeavor.

Some of the most common misconceptions pertaining to simple electric circuits containing batteries and bulbs are, for example, the notion that a light bulb "uses up" current, or that a battery "produces" current. The prevalence of these misconceptions is evidenced by assessment tools such as the Electric Circuits Concepts Evaluation (ECCE), a well-accepted diagnostic tool developed by David Sokoloff.[1]

We present here a fairly simple, new apparatus—the Glitter Electric Circuit Analog (GECA)—that illustrates several fundamental electric circuit properties to beginning physics students. It can eliminate and possibly even preempt some of the battery and light bulb misconceptions. While numerous instructors employ water circuit analogs in their teaching, circuits that we find in the literature depend in part on concepts of fluid dynamics.[2] In contrast, the introduction of a few hundred discernable, discrete glitter pieces allows students to identify the glitter pieces suspended within the fluid with the electrons in the electric wire.

Fig. 1. Photograph of the Glitter Electric Circuit Analog (GECA) showing the pump (battery), the valve (switch), the thin tube (light bulb), a flow meter (ammeter), and two pressure sensors that indicate the pressure difference across the thin tube. Not shown is the valve that shuts off the filler/drain tube at the bottom right of the circuit. ***Photo by Pierce Bounds***

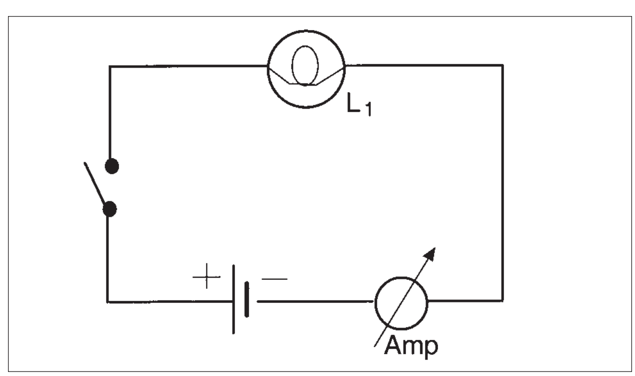

Fig. 2. Schematic of a simple electric circuit containing a battery, a switch, a light bulb, and an ammeter.

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The glitter circuit analog no longer requires knowledge of fluid dynamics but merely the counting of glitter pieces.

Description of the Apparatus

The Glitter Electric Circuit Analog shown in Fig. 1 is a water circuit analog using parts that are readily available from plumbing suppliers.[3] We use ¾-in clear plastic tubing (e.g., Tygon tubing) and matching clear plastic elbows, not so much as to reveal the fluid within the tubing but rather the many pieces of glitter suspended within this fluid. The fluid may be either simply water or a mixture of glycerin and water. The glitter pieces represent the electrons that move through the electric wire. The mechanical pump, the equivalent of the battery, is a rugged rotary pump, typically used to remove sludge from old tanks. This ruggedness reduces the likelihood of glitter pieces clogging the pump. We represent the equivalent of the light bulb in the water circuit with a piece of thin (¼-in) Tygon tubing that is looped once, resembling the shape of the light bulb filament in the light bulb symbol (cf. Fig. 2). The counterpart to the electric switch is represented by a quarter-turn ball valve.

A small paddle wheel (flow meter) inserted in the circuit serves as the equivalent of a current meter. Two pressure meters, installed right before and after the "light bulb" section, allow the students to see that there is a pressure drop across this part of the circuit, paralleling the potential drop across the light bulb in the electric circuit.

Arranging the glitter circuit in rectangular fashion and placing the various elements of the water circuit as shown in Fig. 1 helps to visually underline the parallels between the electric circuit (cf. Fig. 2) and the water circuit.

Finally, the GECA has a filler/drain tube at its bottom right-hand corner, facilitating the initial filling of the circuit and the removal of possible air bubbles. This, of course, has no equivalent in the electric circuit.[4]

Pedagogic Benefits of the GECA in Conveying Basic Electric Circuit Concepts

» ***Current conservation.*** The number of glitter pieces traversing any cross section of the tube per unit time is the same no matter where the cross-sectional area is chosen. We can readily see that the glitter pieces do not accumulate at any part of the circuit;[5] we also do not find a location anywhere in the circuit that gets successively more devoid of glitter pieces.

» ***The light bulb does not use up current.*** If 27 glitter pieces enter the thin tube representing the light bulb per unit time, then 27 glitter pieces leave the thin tube during the same time interval. In particular, the students comprehend that a light bulb does not destroy the charge carriers just as the "light bulb tube" does not destroy glitter. (Electrons simply cannot be destroyed in an electric circuit!)[5]

» ***The battery does not create electrons.*** It is immediately evident that the pump in the GECA does not create any glitter pieces but rather only pumps them through the circuit. In the time it takes for 53 glitter pieces to emerge from the pump, about 53 other glitter pieces have entered the inlet of the pump.

» ***The battery does not have a surplus of electrons.*** Students also notice that the pump does not have a surplus of glitter pieces stored inside of it. There is a student conception that attributes this property to a battery. They see a battery as a reservoir of electric charges. "Whenever the switch is closed some of these surplus charges flow to the light bulb to light it." In everyday language we speak of a "charged" battery, a "fully charged" battery, or simply a "full" battery. This linguistic habit reflects the notion that a fully charged battery has "a lot of charges" in it (see also below the notion regarding an "empty" battery).

» ***The electric circuit needs to be a complete loop.*** The electric wire must go from one terminal of the battery to the light bulb, and then from the other side of the light bulb back to the battery. The water circuit needs to be a complete one in order to see glitter pieces move continually through the tube representing the light bulb filament. The ECCE pretest shows that introductory physics students who never had to deal with electric circuits are not necessarily familiar with the fact that electric circuits have to be a closed loop.

Furthermore, the GECA can be used to illustrate the following facts:

1. *The flow of electrons may not be interrupted.* Closing of the valve in the water circuit analog stops the flow of glitter pieces. It not only stops the flow of glitter pieces at the location of the valve but everywhere in the water circuit. Interruption of the flow of electrons anywhere in the circuit stops the flow of electrons everywhere in the circuit.
2. *The flow starts instantaneously.* At essentially the same time when we flip a light switch, the light comes on. Similarly, at the same time we open the valve in the GECA, glitter pieces start to flow everywhere in the circuit, including the "light bulb tube."
3. *The battery maintains its potential difference even when the switch is opened.* In the same way, the impeller of the pump keeps rotating and maintains the higher pressure at its outlet. However, glitter pieces do not move through the circuit; no glitter pieces emerge from the pump and no glitter pieces enter the pump's inlet.
4. *The "dead" or "empty" battery.* Turning off the pump, i.e., stopping the impeller, corresponds to an "empty" battery. Our linguistic use of the term "empty" battery reflects the notion that the battery is thought to be "devoid of charges." The GECA eliminates this notion very nicely: the nonpumping pump is still full of fluid and glitter pieces. Students readily agree that there are about the same number of glitter pieces in the turned off pump as in the rotating pump.
5. The thin section of Tygon tubing that the GECA employs to symbolize the light bulb begs the comparison to the fact that the light bulb filament is a very thin piece of wire.
6. The *opening* of the valve in the glitter circuit corresponds to the *closing* of the switch in the electric circuit. At first glance it appears that the valve in the GECA and the switch in the electric circuit function in an opposite manner. However, closer inspection shows that the opening of the valve and the closing of the switch both attain the same goal: in either case we enable a flow. Turning the ball valve establishes a connection between one tube and another tube. Closing the switch establishes an electric connection between one wire and another wire.

Fig. 3. To illustrate concepts of current conservation in circuits involving resistors in parallel, the light bulb tubing is replaced by two small Tygon tubes. *Photo by Pierce Bounds*

7. To measure electric current with an ammeter, the circuit needs to be interrupted and the ammeter needs to be inserted into the circuit. To measure the flow of glitter fluid through the tubes of the GECA, the tube needs to be interrupted at some point and the flow meter needs to be inserted.[7]
8. At a later time in the semester when the students encounter resistors in series and parallel, the GECA again conveniently serves to point out current conservation. For this purpose we exchange the Tygon tube section representing the light bulb with either two thin tubing sections connected in series, or with two thin tubing sections connected in parallel as shown in Fig. 3. Here the students can readily recognize that the number of glitter pieces arriving from the left at the first T-section is the same as the number of glitter pieces moving through the upper tube plus the number of glitter pieces moving through the lower tube. At the second T-section both streams join and we are back to the original number of glitter pieces moving through the large Tygon tube. I typically let my students express in their own words what they observe regarding the number of glitter pieces at the T-section. Once I get an answer like, "The number of glitter pieces coming into the T-section is the same as the number of glitter pieces leaving the T-section," I declare proudly that this student just rediscovered Kirchhoff's node rule!

Recognizing the Limitations of Analogs

While our electric circuit analog is rich in parallels, we must not lose sight of the fact that the GECA is only an analog, and therefore, necessarily contains properties and features that are distinctly different from an electric circuit. For example, in the GECA the fluid and the glitter pieces move together through the tube while in the copper wire only the electrons move. In addition, electric potential differences are measured between two points of the circuit whereas the GECA's pressure gauges indicate the hydrostatic pressure at a single point.[8]

Boo and Toh[9] point out that analogies are valuable tools in conceptual change learning as they provide visualization and understanding of the abstract by pointing to similarities in the real world. Nevertheless, students need to be made aware of the fact that an analog is nothing more than just that: an analog—a fairly familiar concept or phenomenon that serves to illustrate a less familiar concept, sometimes called the "target concept." Ideally, certain features of the analog nicely mimic features of the new or less familiar situation they are supposed to elucidate. Since the new concept and the analog are certainly two different things, we are bound to find differences between the two. It is important to discuss with the students which features parallel each other and which features are distinctively different. Comparisons should no longer be made when they stretch the analog too far. If the analog is stretched too far, it no longer serves its purpose and can actually lead to new misconceptions.[10] With these warnings and provisions in place, analogs prove to be beneficial.

Acknowledgment

I would like to thank Rick Lindsey for his careful assembly of the circuit and his idea to employ a slush pump.

References

1. David Sokoloff, "The Electric Circuit Concept Evaluation" (ECCE). The ECCE is available (with password) from the Workshop Physics webpage at Dickinson College at http://physics.dickinson.edu/~wp_web/wp_resources/wp_assessment.html#ECCE .
2. (a) C.R. Nave from the Dept. of Physics & Astronomy at Georgia State University has, as part of his online HyperPhysics website, an interactive DC Circuit Water Analogy display at http://hyperphysics.phy-astr.gsu.edu/hbase/electric/watcir.html#c1 .

   (b) Shawn Glynn, Alan Russell, and David Noah from the College of Education at the University of Georgia discuss in detail the benefits of using analogs in teaching new concepts. Their website, http://www.coe.uga.edu/edpsych/faculty/glynn/twa.html, lists, among many other analogs, the use of a water circuit as an analog for an electric circuit.

   (c) Members of the Windows Team at the University Corporation for Atmospheric Research (UCAR) use in their website "Windows to the Universe" (http://www.windows.ucar.edu/) water circuit analog seashells that plug up the pipe and constrict the flow of the water as their counterpart to the resistance in the electric circuit; http://www.windows.ucar.edu/spaceweather/how_circuit_works.html .

   (d) Members of the faculty of education of the University of Central England (UCE) at Birmingham display on their website an animated water circuit right next to an electric circuit. Dark blue dots are shown to move around the water circuit. These correspond to the electrons (again blue dots) that move through the copper lattice of the wire in the electric circuit; http://www.uce.ac.uk/education/research/cript/electricity%20book/compare%20animate.htm.
3. The pump is a Grainger part #1p579 ($75); the flow meter is a McMaster/Carr part #80135k12 ($45); the gauges are McMaster/Carr part #3846k311 ($10 ea.); the 1-in o.d. and 3/4-in i.d. tubing is a McMaster/Carr part #5233k71 ($0.71/linear ft).
4. We have tried carefully to assemble the circuit without the use of a filler tube. However, it turned out that it was too hard to fill the GECA with the glitter fluid while avoiding air bubbles. Circulating air bubbles are a distraction. We would welcome your comments if you can come up with a design that avoids the filler tube.
5. For very small flow velocities and with water as the carrier fluid, it is possible that a few glitter pieces simply stay in the corner of an elbow. Glitter pieces might also be stuck to the inside wall of the Tygon tubing if the GECA was not in use for an extended period of time. In this case it helps to run the pump briefly at its maximum rpm.
6. Priscilla W. Laws, *Workshop Physics Activity Guide,* Module 4, Activity 22.9 asks students in essence the question, "Is current 'used up' in a light bulb?" Students are directed to measure the current directly before and directly after the light bulb. The currents turn out to be the same—current is not used up in the light bulb. I ask

students to imagine two identical flow meters inserted immediately before and immediately after the tube representing the light bulb in the GECA. Which flow meter would spin more rapidly?

7. At the time we discuss these basic circuit properties in the course, we do not mention yet that it is possible to measure a current with only a fraction of the current flowing through the ampere meter and the majority of the current flowing through a shunt resistor of known value. However, we stress the fact that an ampere meter has to be inserted in the circuit such that the current to be measured flows through it. In contrast, a potential difference is measured between two points of the circuit and an interruption of the circuit for the sake of the insertion of the voltmeter is not necessary.
8. While there are numerous things that can be illustrated with the GECA, it would be nice if the glitter circuit would allow differential pressure measurements. It might be possible to add valves similar to the ones used in car tires or inner tubes at several strategically placed points along the Tygon tubing that allow access to the hydrostatic pressure at those points. Using a pressure gauge that reads the pressure difference between the hydrostatic pressure present at two different valves would then directly correspond to the differential potential measurement in the electric circuit. Ideas are welcome!
9. H.K. Boo and K.A. Toh, "Use of analogy in teaching the particulate theory of matter," *Teach. Learn*. **17**(2), 79–85 (1997).
10. S.M. Glynn "Conceptual bridges: Using analogies to explain scientific concepts," *Sci. Teach*. **62**(9), 25–27 (1995), and S.M. Glynn and T. Takahashi, "Learning from analogy-enhanced science text," *J. Res. Sci. Teach*. **35**, 1129–1149 (1998).

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