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Instructional insights for using single Water Circuit Analogies for Learning introductory circuits

Water Circuit Analogy

Kevin M. Gee

PHY 690

Buffalo State University

Abstract:

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Abstract

Electric circuits ~~may be~~ more difficult for students to understand than mechanics in introductory physics due to the fact that the movement of charges in electric circuits is invisible. A water circuit analogy may be useful in building student understanding and addressing common misperceptions about electric circuits. The applicability and limitations of the water circuit analogy are discussed. Recommendations for the economical sourcing of parts are offered.

Keywords: water circuit, simple circuits, misconceptions

Introduction

This paper explores the use of water circuits as analogies for helping students in introductory physics classes understand electrical circuits. Analogies can be useful in building understanding by mapping a more-familiar source concept to a less-familiar target concept.

Apparatus

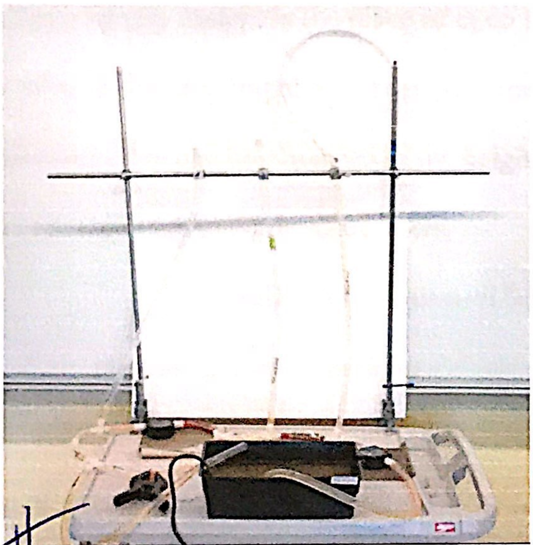

Figure 1: Water Circuit Apparatus

~~The experimental~~ apparatus consists of an open reservoir, a submersible aquarium pump, clear, flexible PVC tubing, mechanical flow meters, as well as straight and "T" barb connectors for tubing. The "resistors" are constructed from different lengths of plastic tubing packed with sponges. The sponges used should be of the open-celled scrubber-type, rather than the closed-cell type used for absorbent sponges. In addition, ring stands and clamps were used to support the tubing. A fluorescent dye was added to the water to improve the visibility of water levels.

The submersible pump, in this analogy, acts as the battery in an electric circuit. The plastic tubing plays the role of wires. Impeller-type visual flow meters act as ammeters in a circuit. Open-ended vertical tubes show the potential. The water rises to different heights above the reservoir to show the pressure at various points in the circuit. Switches can be replicated by folding over the tubing and holding it in place with clamps or using more sophisticated in-line valves.

Create an explicit table of your analogies please

This water circuit is different from other designs (Pfister, 2004) in that there is an open reservoir and open tubes to show potential. The Pfister design is completely enclosed and uses mechanical pressure meters in the place of open tubes. The flow of water through the circuit is evident from the turning impellers of the flow meters, rather than the flow of glitter. Also, the hydrostatic pressure can be observed in the height of the water in each open tube, rather than from the analog gauges of pressure meters.

Addressing Common Students Misconceptions

Many students maintain models of electricity where closed circuits are not necessary in order for electrical devices to operate. It is very straightforward for students to see that the water circuit will only function if a loop is formed with the plastic tubing and that water will only flow through each element if it is correctly placed in the loop.

One of the most common misconceptions held by students is that batteries function as sources of constant current rather than constant voltage (Engelhardt & Beichner, 2004). It should be intuitive to most students that the flow produced by the pump is not constant but depends on the load of resistors in the circuit. Even if this idea is not intuitive, the change in flow through the water circuit can easily be observed by watching the flow meters.

See also added cites.

A related misconception is the idea that batteries act as a pure source of electrons or that the batteries are "filled up" with current that is released as the batteries operate (Korganci, Miron, Dafinei, & Antohe, 2015; Pfister, 2004). It should be clear to students that water is not stored in the pump, but that the pump serves to circulate the water through the circuit. Care should be taken to explain that the reservoir is not a part of the battery in the analogy but functions like electrical ground.

The water circuit can also help address the misconception that current is somehow "used up" by loads in an electrical circuit (Korganci et al., 2015). The water circuit allows students to see that the flow of water into circuit elements must equal the flow of water out of the elements in the steady state. Running the water circuit without refilling the reservoir also makes it clear that the amount of water/charge is conserved.

Suggested Student Learning Activities

Series Water Circuit

Figure 2 depicts a water circuit in a series configuration and its analogous electrical circuit. Building and observing these circuits addresses the misconception that current is consumed by devices in the circuit. Students should observe that the flows through both flow meters are roughly the same. It also makes it clear that the potential is increased by the pump and becomes lower with each successive device in the circuit. The sponge resistors can be replaced by ones of different lengths. Students should observe that P_2 and P_3 are affected by this change, but P_1 and P_4 are not.

Parallel Water Circuit

Figure 3 depicts a water circuit in a parallel configuration and its analogous electrical circuit. Students can experiment with using different resistances for the sponge resistors to see their effect on the potentials and flows. Students should observe that increasing the length of the sponge resistors reduces the flow in each branch. They should connect this conceptually with the reduction in current caused by increasing the resistance in each branch of the equivalent electrical circuit.

Switched Water Circuit expand or eliminate

Figure 4 shows a water and electrical circuit that can be switched from a series configuration to a mixed series and parallel configuration. In this activity, students could predict the change in the flow meters and in the potential P_2. Students can see the increase in cross-sectional area of the parallel portion of the circuit when the switch is closed. Observing macroscopic flows may be easier than imagining the flows of charge carriers in the electrical circuit that cannot be directly observed.

Using fans in the place of resistors or light bulbs in the electrical circuits (Ekey, Edwards, McCullough, Reitz, & Mitchell, 2017) may help students to draw parallels between the two circuits. Both the fans and water flow meters have impellers and should behave in a similar matter for the two circuits.

What about the act of switching and disrupting "steady state" circuits or "steady equilibrium" circuits.

You must address this earlier. (see later comment.)

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Fig 2: Series Circuit Analogy

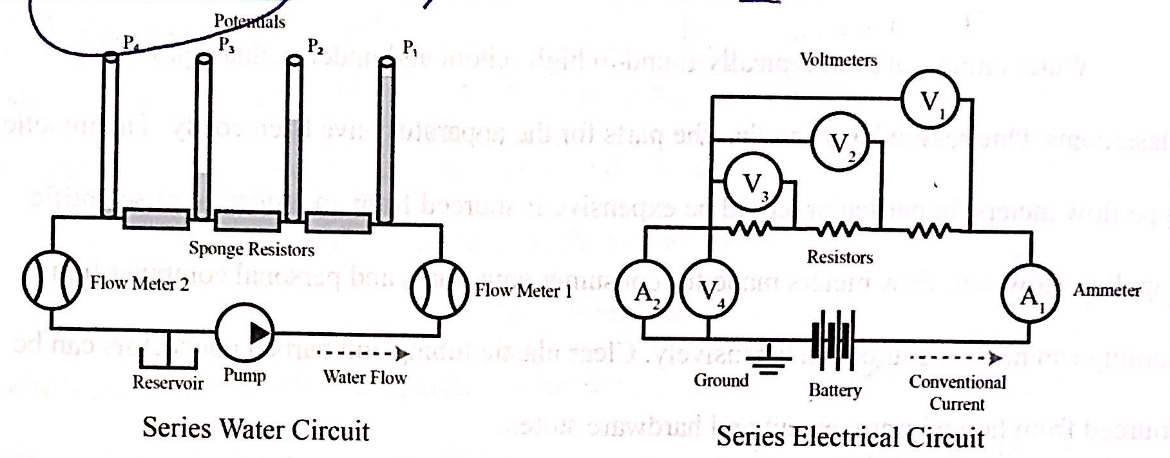

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Fig. 3: Parallel Circuit Analogy

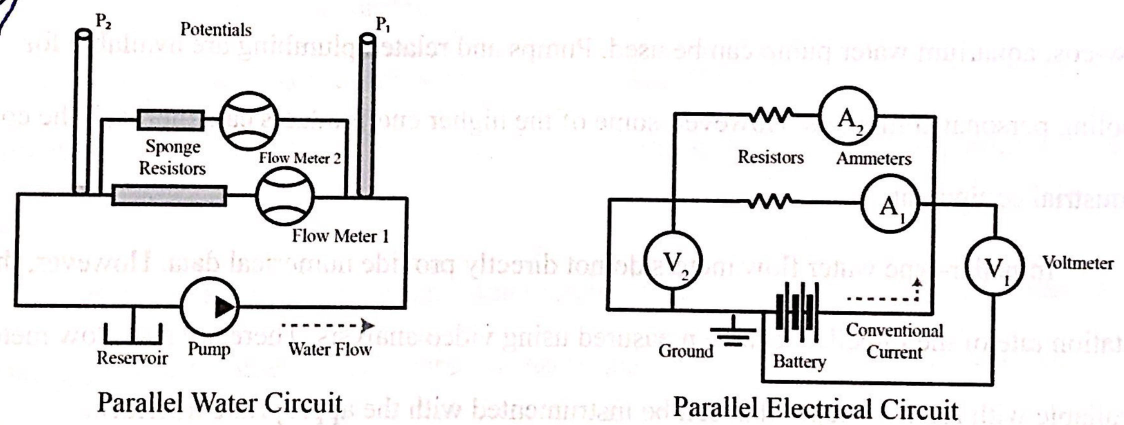

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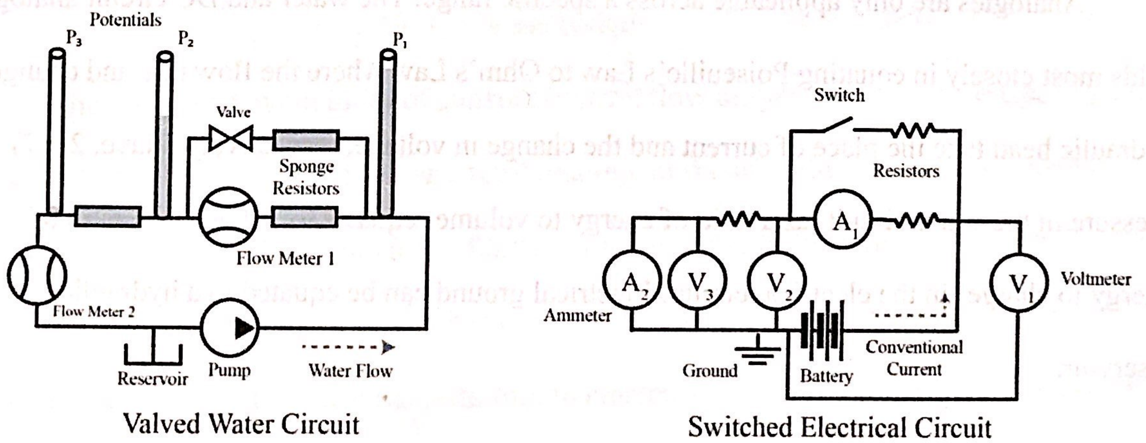
Fig. 4: Switched Circuit Analogy



Construction and Sourcing of Apparatus

Water circuits are not typically found in high school and undergraduate physics classrooms. One reason has been that the parts for the apparatus have been costly. The impeller-type flow meters, in particular, could be expensive if sourced from an industrial or scientific supplier. However, flow meters made for consumer aquariums and personal computer liquid cooling can now be sourced inexpensively. Clear plastic tubing and barbed connectors can be sourced from home improvement and hardware stores.

The glitter water circuit described in Pfister (2004) used a slightly exotic salvaged slush pump that is resistant to clogging by the glitter. If glitter is not used in the water circuit, then any low-cost aquarium water pump can be used. Pumps and related plumbing are available for cooling personal computers. However, some of the higher end products can approach the cost of industrial equipment.

Impeller-type water flow meters do not directly provide numerical data. However, the rotation rate of the impellers can be measured using video analysis. There are also flow meters available with Reed switches that can be instrumented with the appropriate interface.

Domain and Range of Analogy

Analogies are only applicable across a specific range. The water and DC circuit analogy holds most closely in equating Poiseuille's Law to Ohm's Law where the flow rate and change in hydraulic head take the place of current and the change in voltage, respectively (Nave, 2017). Pressure in the water circuit (as a ratio of energy to volume) equates to voltage (the ratio of energy to charge) in the electrical circuit. Electrical ground can be equated to a hydraulic reservoir.

While the water circuit analogy can help students understand the behavior of electrical circuits, the analogy should not be extended to where it does not apply. For instance, the working fluid in the water circuit occupies the entire volume of the tubing, while the excess charge carriers in an electrical circuit exist primarily on the surface of conductors.

Students may observe a small time-delay from when the pump is turned on until water flows back into the reservoir after completing the circuit. However, charge carriers begin to circulate almost instantaneously when the battery is connected in an equivalent electric circuit. This delay could be considered outside the range of the analogy or it could be modeled as a small parasitic capacitance in the water circuit.

The analogy also breaks down in that there is no equivalent to positive and negative charge in the water circuit. However, the potentials can have an arbitrary zero reference point in both cases.

Students will notice when building water circuits that the water can be casually shaken out of the apparatus. Charge carriers cannot be easily shaken out of conductors in electrical circuits. However, the Tolman-Stewart Effect (Arons, 1997) shows that accelerating conductors can result in displacement of the mobile charge carriers within the conductors.

Conclusions

The increased availability of consumer-level flow meters and water pumps makes it more cost-effective to use the water circuit analogy in the introductory physics classroom. Water circuits link visible behavior of fluids to the behavior of invisible charge carriers in an electrical circuit. Using vertical tubes to measure potential in the water circuit links students' intuition of gravitational potential to electrical potential. Several water circuits can be built along with their equivalent electrical circuits as part of a sequence of learning activities to address common misconceptions relating to passive circuits.

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ALSO Cite ① Sadli & MacIsaac (2007) TPT and ② McIsaac Ward & Wilson (2009) STANYS Bulletin (esp last 2 pages) also the ③ Modeling Curriculum Teachers' Guide for E?

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