Instructional Insights for Using Water Circuit Analogies for Learning Introductory Circuits

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Abstract

Electric circuits is 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 (Saeli and Macisaac, 2007). 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.

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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 (J. Clement, 1993). Observing macroscopic flows can be an initial step towards imagining the flows of charge carriers in the electrical circuit that cannot be directly observed (Saeli and Macisaac, 2007).

Addressing Common Student Misconceptions

Analogies can form an important bridge from students' prior knowledge and pre-conceptions to expert models of physics, even compared to formal proofs and empirical investigations. Prior knowledge is best invoked early in the curriculum to create more coherent lessons. Analogous phenomena can form inspiration for students to explore both the domain and range of their models and test previously developed conceptions in a more concrete fashion.

Many students maintain models of electricity for which 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 and 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.

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 et al., 2015; Shaffer and McDermott, 1992). 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; Shaffer and McDermott, 1992). 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.

Apparatus

Figure 1 shows the completed water circuit apparatus. Table 2 and Figure 2 lists the parts and sources needed to build the apparatus for the learning activities described later. The submersible pump, in this analogy, acts as the battery in an electric circuit. The plastic tubing plays the role of wires. Tubes packed with scouring pads act analogously to resistors. 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.

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.

Suggested Student Learning Activities

Table 3 lists the applicable NYS Science Learning Standards (NYSED, 2018). Note that the K-12 Framework (National Research Council, 2012) does not explicitly address circuits aside from being in a general category of energy conversion devices. However, the NYSSLS directly calls for instruction in Ohm's Law. Students will benefit from hands-on experimentation with the water circuit side-by-side with the equivalent electrical circuit over perhaps a three lesson period. Students should be encouraged to map analogous elements and observations from the two circuits. However, explicitly tabulating analogous elements as in Table 1 should be delayed until sufficient student discourse and experimentation has taken place. Guided worksheets could provide scaffolding to encourage students to identify both the domain over which the analogies are applicable and the cases where the analogies do not apply. Particular care should be taken to discuss the domain (applicable areas) and range (non-applicable or inconsistent areas) of any analogies identified by students.

Series Water Circuit

Figure 3 shows a hydraulic schematic for a water circuit in a series configuration and its analogous electrical circuit schematic. 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 and the flows in and out of the entire circuit are roughly the same, reflecting the conservation of moving charge carriers within the electrical circuit (AMTA, 2017). 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 4 depicts a water circuit in a parallel configuration and its analogous electrical circuit. Students can experiment with using different resistances for the scrub pad resistors to see their effect on the potentials and flows. Students should observe that increasing the length of the scouring pad 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, according to Ohm's Law.

The parallel water circuit is also a good opportunity to look for equivalence to Kirchhoff's Laws: Students should observe that the net change in potential along any loop is zero and that the net flow of water into any junction always equals the net flow out of that same junction.

Switched Water Circuit

Figure 5 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. Predicting the behavior of this hybrid series/parallel circuit requires more mastery of the series and parallel circuit models than the simpler activities described earlier (Chabay and Sherwood, 2002, p. 779). However, starting and stopping the flow may cause non-equilibrium behavior in the water circuit that is similar to that seen in RC circuits (MacIsaac et al., 2019).

Construction and Sourcing of Apparatus

Water circuits are not typically found in high school and undergraduate physics classrooms. Water circuit classroom demonstration kits were available from a limited number of vendors. The individual components have been difficult to source after the kits were no longer offered. The impeller-type flow meters, in particular, were only available from a limited number of suppliers that stopped carrying the products. However, flow meters made for lab use, consumer aquariums and personal computer liquid cooling applications 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 slow-motion video analysis, or by counting revolutions while timing with a stopwatch. There are also flow meters available with reed switches that can be instrumented with the appropriate interface.

Domain and Range of Analogy

Table 1 summarizes analogous attributes of the water and electrical circuit. 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). Poiseuille's Law relates the resistance to flow and flow rate of fluids in laminar flow conditions. 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 (Saeli and Macisaac, 2007).

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 (J. Clement, 1993). Students refine their understanding both where analogies are valid and where they do not apply (J. J. Clement, 2013). 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 low-cost flow meters and water pumps makes it more cost-effective to use the water circuit analogy in the introductory physics classroom. Water circuits link the 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.

The author has used the water circuit analogy in two settings, so far: First during a teacher professional development workshop (as a teacher-student), and second as a review while teaching Regents Physics. The Regents Physics class used it as part of a mini-lab over a video conferencing link during a school building closure. In both cases, students were exposed to the idea of *liftage* as gravitational potential prior to the circuits unit. Students were able to use this to bridge from their prior knowledge to a model of circuits. A video conference is certainly less than ideal for this type of lab exploration. Students were able to interact with the circuit with the instructor as proxy through the video link and complete the lab successfully.

In the future, the author would use the water circuit analogy either as an extension to an initial treatment of circuits, or as an end-of-year review. The water circuit can be introduced during the initial treatment if students are struggling with particular ideas within circuits. Students can explore the water circuit in more depth until the ideas are solidified. The water circuit makes an ideal end-of-year review because it refreshes student understanding of both gravitational and electrical potential.

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About the Author

Kevin Gee currently teaches Regents Physics, Physical Science, and Computer Science at WNY Maritime Charter School, in Buffalo, NY. He began teaching one year ago after transitioning from an 18 year career as a high-tech product manager in Silicon Valley. He earned a BSc Physics from SUNY Binghamton, a MSc Electrical and Computer Engineering from UC Santa Barbara, and is completing his MS Ed Physics (7-12) with Alternative Certification Pathway at SUNY Buffalo State (December 2020, expected).

Table 1

Analogies between water circuit and electrical circuit

Water Circuit	::	Electrical Circuit	Limitations
water	::	charge carriers	water pressure does not have polarity
water pump	::	battery	energy consumption of battery goes to zero as resistance goes to infinity while energy consumption of pump does not
tubes	::	wires	water flows through entire area of tube, while excess charge flows on surface of wire
reservoir	::	electrical ground	
scouring pad packed tube	::	resistor	
water flow rate	::	current	no analogy to magnetic fields with water flow
hydrostatic head	::	voltage	head can only be positive, while voltage has polarity
vertical open tube	::	voltmeter	open tube holds water, while voltmeter does not store charge
water flow meter	::	ammeter	water flow meter has non-negligible resistance, while ammeter does not
clamp	::	switch	

Table 2

Sourcing for water circuit components

Component	Cost	Part Num.	Manufacturer	Vendor URL
Submersible fountain pump	$26.00	WT125P	FountainPro	fountainpro.com
Visual flow meter	$15.00	8720-1002	Burkle	thomassci.com
0.5 in. ID x 10 ft. clear vinyl tubing	$5.20	T10006010	UDP	homedepot.com
3/8 in. ID x 10 ft clear vinyl tubing	$4.30	T10006008	UDP	homedepot.com
4X 0.5" x 3/8" reducing coupler	$4.00	C8-6NK	Eldon James	grainger.com
0.5 in. T connector	$4.00	800389	Everbilt	homedepot.com
0.5 in. Y connector	$3.30	Y0-8HDPE	Eldon James	grainger.com
Scouring pads	$4.00	88HD-CC	Scotch-Brite	lowes.com
2X Table clamps	$160.00	H-8265	Humboldt	thomassci.com
Ring stand support rods	$22.00	H-21470	Humboldt	thomassci.com
5X Perpendicular clamp holders	$40.00	RCLBH1	United Scientific Supplies	thomassci.com
Food coloring	$4.00	52100071077	McCormick	target.com

Table 3

NYS Science Learning Standards (2016) and A Framework for K-12 Science Education relevant to the water circuit analogy

Standard	**Explanation**
HS-PS3-1	Create a computational model to calculate the change in the energy of one component in a system when the change in energy of the other component(s) and energy flows in and out of the system are known.
HS-PS3-2	Develop and use models to illustrate that energy at the macroscopic scale can be accounted for as a combination of energy associated with the motions of particles (objects) and energy associated with the relative position of particles(objects).
HS-PS3-3	Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.
HS-PS3-5	Develop and use a model of two objects interacting through electric or magnetic fields to illustrate the forces between objects and the changes in energy of the objects due to the interaction.
HS-PS3-6	Analyze data to support the claim that Ohm's Law describes the mathematical relationship among the potential difference, current, and resistance of an electric circuit.

Figure 1

(a) Front and (b) top view of completed water circuit.

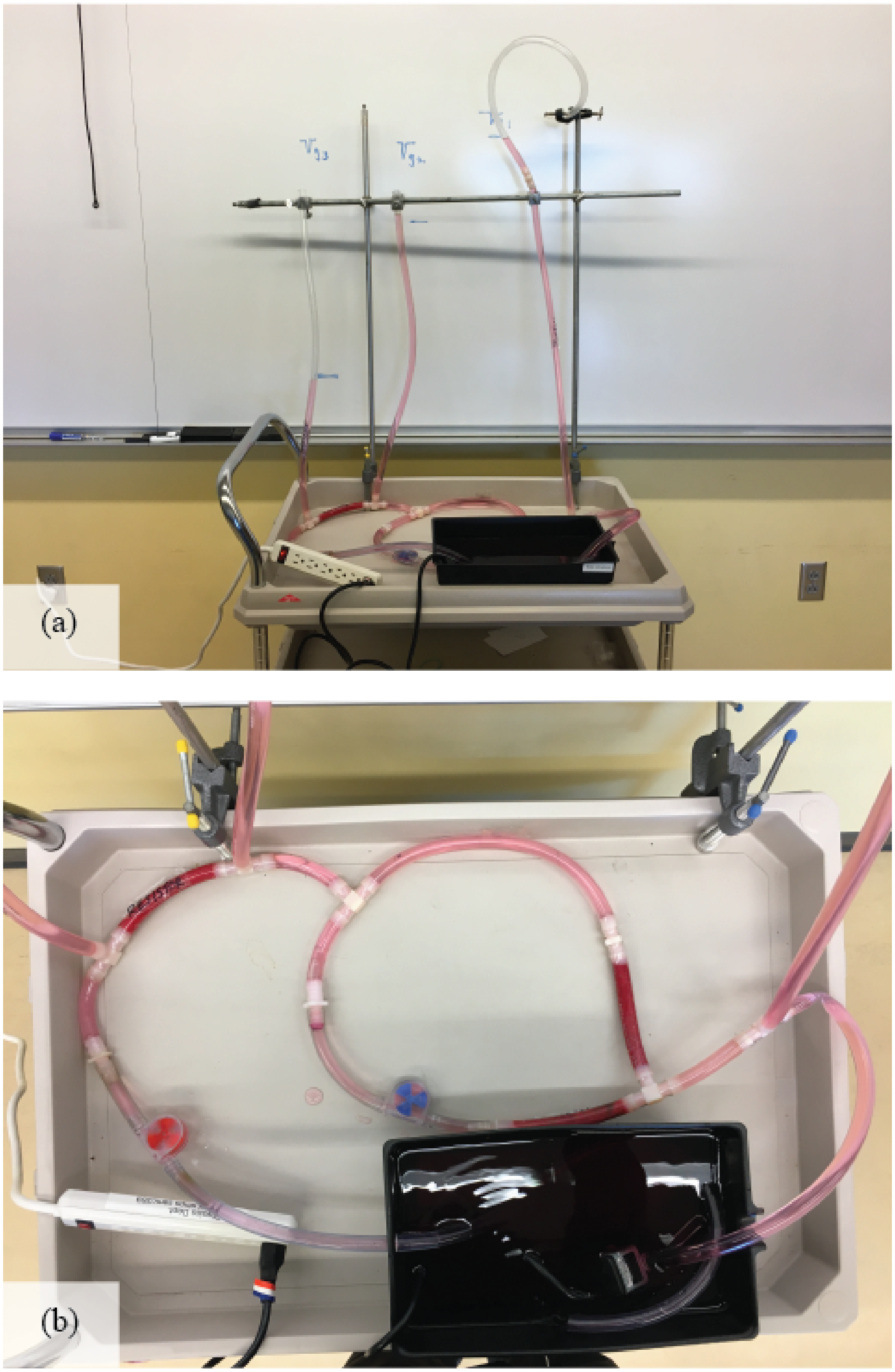


Figure 2

Photos of select components: (a) water pump, (b) plastic tubing, (c) barb connectors and adapters, (d) scrub pad "resistors", (e) visual flow meter, (f) reservoir.

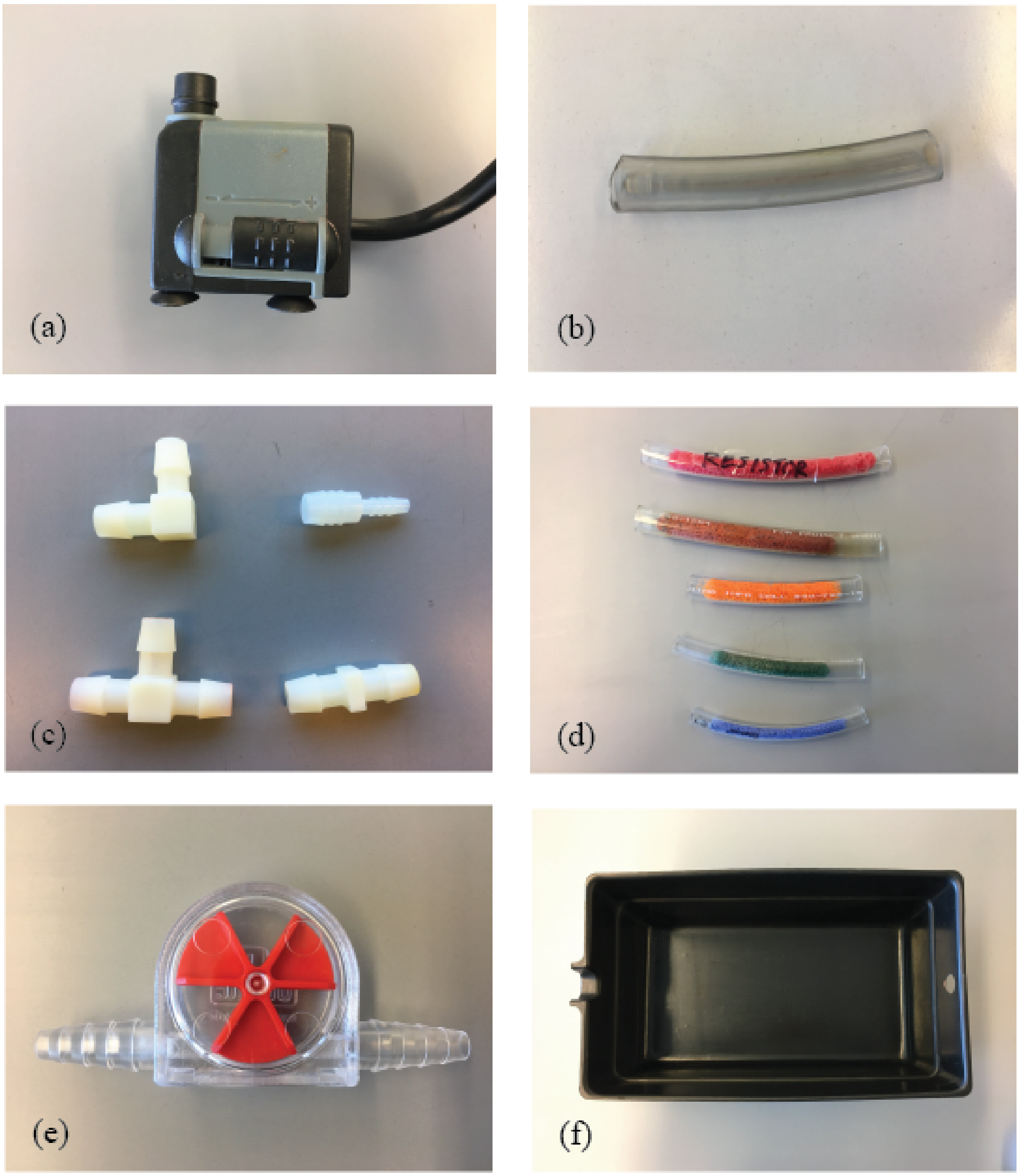
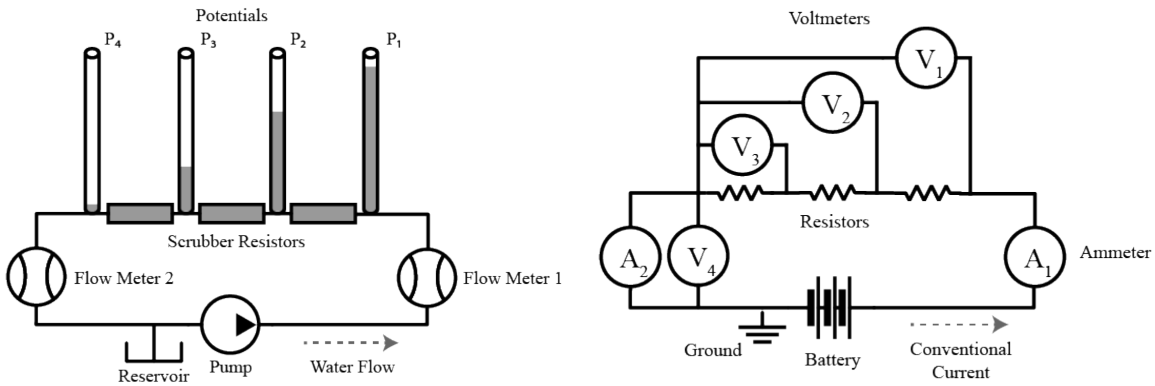


Figure 3

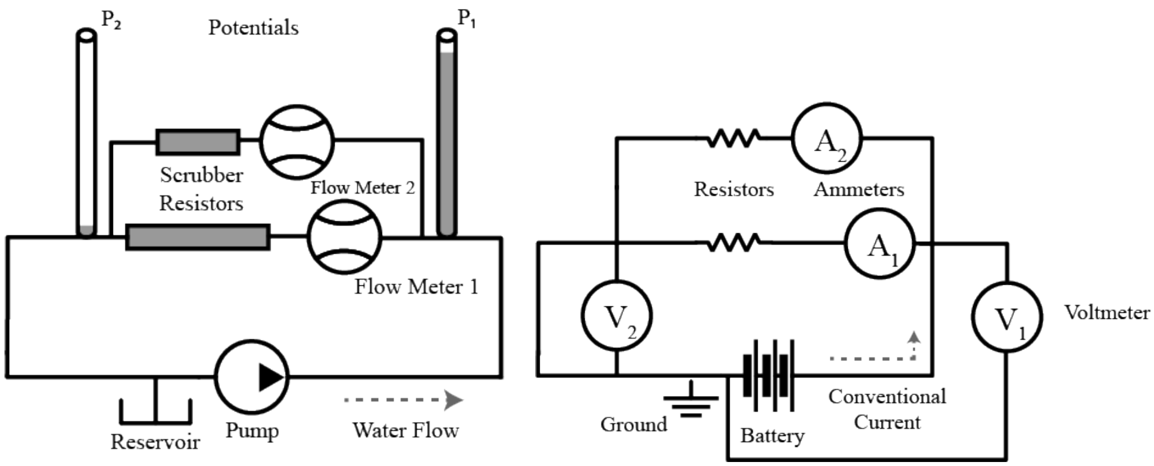
Schematic of series (a) water circuit and (b) electrical circuit.



(a) (b)

Figure 4

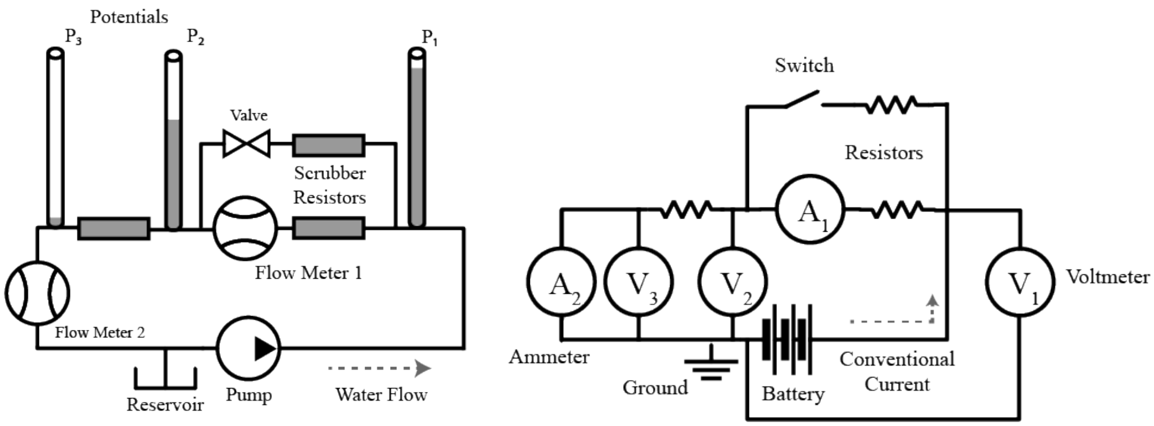
Schematic of parallel (a) water circuit and (b) electrical circuit.



(a) (b)

Figure 5

Schematic of switched (a) water circuit and (b) electrical circuit.



(a) (b)

Name: ___________________________ Per: ___________________ Date:___________________

Water Circuit Analogy

Learning Objectives

- Model Ohm's Law describing relationship between resistance, potential drop, and current for any circuit element.
- Model Kirchhoff's Laws for total potential change around loop, and flows in and out of junctions.
- Understand energy changes in electrical and mechanical systems

Before the Water Circuit is Powered-On

1. Take some time to inspect the different parts of the water circuit. Identify the water pump, plastic tubing, "resistors", flow meters, vertical tubes, and reservoir.

2. Make a diagram of a "resistor" used in the water circuit.

3. Predict what will happen to the water in the circuit when the pump is powered-on.

4. Do you think water will fill the vertical tubes? How high do you think the water will go in each tube? Why?

5. How fast do you think each of the flow meters will spin? Will they spin the same or different speeds? Why?

Once the Water Circuit is Running

6. Observe what happens once the water circuit is running. Do your observations match your predictions?

7. Write the terms for electrical circuits that are analogous to each water circuit term and your reasoning.

Water Circuit	Electrical Circuit	Reasoning
water		
water pump		
tubes		
reservoir		
scrubber-filled tube		
water flow rate		
water pressure		
vertical open tube		
water flow meter		
clamp		

Electrical Circuit Terms: wires, switch, voltmeter, ammeter, voltage, resistor, battery, electrical ground, charge carriers, electrical current

Name: ________________________ Per: _________________ Date: _________________

Water Circuit Analogy Questions

Directions

- Divide into groups to discuss two to three problems per group
- Each group will present answers to class

1. If voltage is in units of energy per unit charge, what is the equation for the potential energy per unit mass in gravitational fields (or *liftage*)? (Hint: PE= m g Δh)
2. How would you compare the role of the pump in the water circuit with a battery in an electrical circuit? Should you include the reservoir as part of the battery, or not?
3. What do the "resistors" do to the flow of water in the water circuit? How does this compare to what a resistor does in an electrical circuit?
4. Do any parts of the water circuit "use up" water (cause it to be permantly consumed)? What does this mean for charge carriers in an electrical circuit?
5. What happens to the water in the water circuit right after the pump is turned on or off? Do you think something similar happens in electrical circuits?
6. Where does the energy for the water circuit come from? Where does it go as the circuit is running? Could you design a water circuit that uses a different source of energy?
7. How is energy converted in the water circuit? Is there anything that uses water to transport energy in your own life?
8. A water circuit is formed by connecting a high "resistance" tube in series with a low "resistance" tube. How would you compare the flow rates through each tube? What if the tubes were connected in parallel? How would the flow rates change?
9. If the flow of water through the water circuit is closed off (by squeezing it shut or closing a valve), does water keep coming out of the vertical tube while the pump is operating, or does it stop? Why? How does this compare to opening a switch in a DC electrical circuit?
10. What would happen to the water in the vertical tubes of the water circuit if there were no "resistors" in the circuit? Does something analogous happen to a DC circuit with no resistors in it?
11. [**CHALLENGE QUESTION**] What moves faster, the water in the water circuit, or the charge in an electrical circuit?

Name: _________________________ Per: __________________ Date: __________________

Water Circuit Analogy Question Key

1. If voltage is in units of energy per unit charge, what is the equation for the potential energy per unit mass in gravitational fields (or *liftage*)? (Hint: PE= m g Δh)
   Full credit: Liftage =Σ PE / m = g Δh
   this is analogous to
   V = Σ PE / q = E Δh
   for an electric circuit.
   Partial credit: Liftage =Σ PE / m

2. How would you compare the role of the pump in the water circuit with a battery in an electrical circuit?
   Full credit: The pump and battery both provide energy to the water and electrical circuits, respectively.
   Partial credit: The pump pushes the water and the pump pushes the electrons in the circuit.

3. What do the "resistors" do to the flow of water in the water circuit? How does this compare to what a resistor does in an electrical circuit? *Full credit: The resistors impede the flow of water in the water circuit. Resistors in an electrical circuit impede the flow of charged electrons.*
   Partial credit: Answers with the terms "slow down", "get in the way of", or similar.

4. Do any parts of the water circuit "use up" water (cause it to be permantly consumed)? What does this mean for charge carriers in an electrical circuit?
   Full credit: The elements of the water circuit and electrical circuit do not consume water or charge, respectively. Circuit elements such as reservoirs in the water circuit or capacitors in an electrical circuit may temporarily store water or charge, but they do not consume it. Water from the water circuit may leak or spill out of the circuit, but this does not happen with electrical circuits.
   Partial credit: Answers using the terms "conservation" or "conserved".

5. What happens to the water in the water circuit right after the pump is turned on or off? Do you think something similar happens in electrical circuits?
   Full credit: It will fluctuate up and down. Something similar happens in electrical circuits in the form of stray capacitance. This is caused by electric fields that can cause charge to build up in certain parts of the circuit. These charges can move when the circuit is not in steady state equilibrium.
   Partial credit: Answers suggesting that the charge carriers will fluctuate in some way.

6. Where does the energy for the water circuit come from? Where does it go as the circuit is running?
   Full credit: The energy for the water circuit comes from the wall outlet in the form of electrical energy for the water pump. The energy primarily becomes thermal energy of the water in the circuit.
   Partial credit: Answers suggesting electricity as an energy source.

7. How is energy transformed in the water circuit? Is there anything that uses water to transform energy in your own life?
   Full credit: Electrical energy from the wall outlet becomes: kinetic energy of the moving water, gravitational potential energy of the water-earth system, elastic potential energy of the tubes stretching, and thermal energy of the water in the circuit. The geological water cycle, hydroelectric power plants, and the electrical appliances in the home are examples of systems that transform energy using water.
   Partial credit: Answers involving the terms "kinetic energy" or "potential energy".

8. A water circuit is formed by connecting a high "resistance" tube in series with a low "resistance" tube.

a) How would you compare the flow rates through each tube? b) How would the flow rates change if you connected the tubes in parallel?
Full credit: The flow rates through each tube connected in series must be the same due to conservation of current (Kirchhoff's Laws). If the same tubes are connected in parallel the total flow rate through the circuit will increase. $I = V/R$, $R_{EQ1}=R_1+R_2 > R_{EQ2}=R_1R_2 / (R_1+R_2)$, *so* $I_1<I_2$
Partial credit: Answers suggesting the flow will be greater in the parallel case and that provide some reasoning.

9. If the flow of water through the water circuit is closed off (by squeezing it shut or closing a valve), does water keep coming out of the vertical tube while the pump is operating, or does it stop? Why? How does this compare to opening a switch in a DC electrical circuit?
Full credit: The water will rise in the vertical tubes until the hydrostatic head at the base of the tubes equals the pressure caused by the water in the vertical tubes. The height of the water in the vertical tubes will fluctuate until the circuit reaches equilibrium. This is analogous to charge being stored in an electrical circuit by stray capacitance. When an electrical switch is first opened the circuit is not at equilibrium. The charges in the circuit will oscillate in a similar manner (see RC circuits for more information).
Partial credit: Answers that recognize that the water "sloshes" or fluctuates, and that similar behavior might happen with the charge carriers in an electrical circuit.

10. What would happen to the water in the vertical tubes of the water circuit if there were no "resistors" in the circuit? Does something analogous happen to a DC circuit with no resistors in it?
Full credit: If there were no resistors in the water circuit the water would not rise in the vertical tubes because the pressure change would be too small. If there were no resistors in an electrical circuit the circuit would be in a short-circuit condition. The current in the short-circuit would be limited only by the internal resistance of the battery.
Partial credit: Answers that suggest that the water or electrons will flow more quickly.

11. [CHALLENGE QUESTION] What moves faster, the water in the water circuit, or the charge in an electrical circuit?
(Young and Freedman, 2014, University Physics, p. 822) if the cross-sectional area of a typical electrical wire is $A = \pi d^2/4$, *the current density* $J = I/A$, *gives a drift velocity of:*

$$v_d = \frac{J}{n|q|} = \frac{2.04 \times 10^6 A/m^2}{(8.5 \times 10^{28} m^{-3})(-1.60 \times 10^{-19} C)}$$
$$= 0.15\ mm/s$$

The velocity of water is about 5×10^{-2} *m/s in the water circuit. Therefore the water flows through the water circuit is about 30X faster than the excess charge carriers (electrons) flow through a typical electrical circuit.*