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Demonstration of Electrical Principles in the Classroom by Hydraulic Analogues

Dr. R. William Graff, LeTourneau University

R.Willliam Graff is a professor emeritus, retired but teaching half time in the school of Engineering and Engineering Technology at LeTournrau University, where he has taught since 1975. He received his B.S., M.S., and Ph..D. degrees from Purdue University in electrical engineering. Prior to joining the faculty at LeTourneau, he was assistant professor of electrical engineering at Drexel University for six years, and at Wilkes College for two years. His professional interests include antennas, microwaves, plasmas, teaching, and ethics.

Dr. Paul R. Leiffer, LeTourneau University

Paul R. Leiffer, Ph.D., P.E., is a professor in the School of Engineering and Engineering Technology and Chairman of the Engineering Department at LeTourneau University, where he has taught since 1979. He is the co-developer of LeTourneau's program in Biomedical Engineering. He received his B.S.E.E. from the State University of New York at Buffalo, and his M.S. and Ph.D. degrees from Drexel University. His professional interests include biomedical signal processing, engineering design, and engineering ethics.

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Introduction

Hydraulic analogies for the basic three circuit elements (resistor, capacitor, and inductor) have been known for many years, and some practical and inexpensive physical examples have recently been built and used in basic circuit laboratories. Since non-engineering majors, as well as non-electrical engineering majors, are typically mystified by electricity, these basic three hydraulic models are effective in breaking down the "mystification factor" concerning basic electricity. The author's Interaction at a recent workshop on the assessment of "Technological Literacy" and "How Things Work" courses, funded by the National Science Foundation, indicated that the hydraulic analogy to circuit theory would be helpful in educating non-STEM students.

Students generally learn new concepts by comparing them to things with which they are already familiar. One of our problems with the present generation is that students tend not to be as physically active as they were in previous generations. We have fewer "farm boys" and "shade tree mechanics" coming in as freshmen. They may never have siphoned water, played with "friction motor" cars, or gyroscopes. They may have no idea that flowing water has inertia, that water pressure in your house is due to the water tower in your town, and that water pressure can be used to cut metal. A hydraulic circuit lab can help them understand both hydraulic and circuits concepts.

In the summer of 2012 the first author attended an NSF workshop on the topic of Technological Literacy. One of the goals of the workshop was to develop a series of questions which could be posed to a person not familiar with technical subjects to determine their level of technological literacy. Attendees at the workshop were very interested in the possibility of using a hydraulic circuits model to improve technical literacy. Parts of those discussions appear in this paper.

Electricity cannot be seen (except as lightning, or other high-voltage or high-current phenomena). Some students decide to study engineering because they have had mechanical experiences, such as fixing cars or tractors at home. The "feel" for mechanical things is already there; you push it, and it moves. This is not always so with electrical things.

In order to present electrical concepts to students unfamiliar with electricity, analogies are helpful. Some thought experiments and analogies are presented to help communicate electrical concepts to lay people, and have recently been used to successfully explain basic electrical concepts to children 10 to 14 years of age. Actual laboratory experiments, using water resistors, water capacitors, water ammeters, water voltmeters, and balloons, have been used in laboratory experiments in our curriculum for several years, and these experiments have become eagerly anticipated in the basic engineering circuits class at LeTourneau University.

Teaching electrical concepts by analogies

Energy is running down – that's based on the engineering concept that "entropy is always increasing in a closed system." Thus, engineering simply consists of transferring energy from one place to another efficiently. So, what is energy? How is it stored and transferred? Many students, whether they are potential liberal education or science majors, are already familiar with the use of energy of some form – some have worked on car engines, ridden bicycles, siphoned water out of aquaria, spoken to one another over telephones or personally – all these involve use of or transfer of energy. If we can relate a familiar energy transfer to a new, relatively unfamiliar one, we increase the "tool kit" which a student can use in future activities, whether those are in the areas of engineering or elsewhere. If he or she is not going to major in engineering, the student will be still able to understand some basic engineering principles.

One of the most difficult concepts to master in the area of engineering is that of electricity. A few analogies have been found which help to familiarize students with electricity. One of the authors has taught circuits for around 50 years now, and has found that water flow gets the point across most effectively. That author now teaches students who are majoring in civil, mechanical, bio-medical, materials joining and computer engineering, as well as electrical engineering.

Based on the experience gleaned throughout one instructor's teaching experience, the format for the circuits class has been slowly modified. A two-hour per week laboratory has been added, in which students are given their own breadboard, DMM, and electrical components. Note: this may be a first: Students actually being allowed to keep something for which they paid lab fees! In each of these lab sessions the students are given a simple circuit to wire up and build, and also a problem to work. Student workers, who have previously taken the course, are hired to help the circuit students along. When each student finishes demonstrating his circuit, and then works his problem successfully, he leaves. From this interaction, the instructor is able to find concepts which need to be emphasized, and identify students that need extra help.

One of these sessions is the hydro-circuits lab, described in a previous paper,[1] designed to give students a "feel" for the hydraulic analogies for the resistor, capacitor, voltage and current. Real water, balloons, plastic tubing, and fluid flow meters are used to show Kirchhoff's current law and an R-C transient. It gets pretty messy. One of the civil engineering majors, who had questions about fluid flow, became excited during this lab as he realized that the basis for ram pumps (inertia pumps) is the same as that for current flow in an inductor. The following treatise is the explanation of various illustrations which have been found effective in explaining electrical principles by commonly understood phenomena[2,3,4]

The water resistor, voltage, and current

A water "resistor" is constructed from a pinched piece of plastic tubing. If the student has ever siphoned water (or gasoline) from a container, he can relate to the concept that "current is through, and voltage is across." Early in the course, this is emphasized on the board with an illustration of an aquarium, showing that water head determines the flow rate of water through a tube, and water seeks its own level outside the aquarium. Pinching the tube is essentially adding a resistor in series. Parallel pipes show that a pair of resistors in parallel provide lower overall resistance, while in series the resistance increases.

The instructor also indicates that water towers are often used to produce the pressure (equivalent to voltage) for the water supply of small towns. This leads to the illustration, later on, that the height of the water tower gives the very high pressure of water obtained straight fromthe faucet – it cannot even be stopped manually, usually, so it’s like a current source.

The electrical concept that a power source may be represented by either a Thevenin equivalent circuit (a voltage source in series with a resistor), or a Norton equivalent circuit (a current source in parallel with the same resistor) can be coupled to the explanation of the principles of the implementation of a sprinkler system for one’s lawn. The instructor has also given students a design problem, involving sprinkler system design, based on this concept – it was realized that this would be a good design problem when he asked what data was needed for his own design of a sprinkler system for his own home – he was told to record the water flow rate, in gallons per minute for his outdoor faucet with all other home faucets turned off; and then to measure the pressure in pounds per square inch at that faucet. Thus, they had asked for the short circuit current and open circuit voltage, which is all the information one needs in order to specify a Norton or Thevenin equivalent circuit.)

The water capacitor

When explaining capacitance, the instructor begins with the statement “the current through a capacitor equals that capacitance multiplied by the time derivative of voltage across it”, and converts it to the following statement: “One can’t change the voltage on a capacitor in zero time”. He then “builds a water capacitor” on the board by explaining to them as follows: “punch a hole in the closed end of an empty soup can and insert a tube. Do the same with another soup can, put a rubber membrane between the two; clamp the two cans together somehow, and we now have a water capacitor, or ‘wacapacitor’”. The essential elements of the wacapacitor are that it consists of two chambers, with an elastic membrane between them, and separate entrance tubes to each chamber.

On the whiteboard, the following “trick” is then performed: add a funnel to the input tube of the left hand soup can, and fill one side of the water capacitor with red water and the other with blue – Then, if you pour more red water into a funnel leading to the red side, blue water runs out the other.” (Taa Daa). This illustrates what happens in a real electrical circuit, in that positive charges go in one side, expelling positive charges out the other, off the other plate, so that the same amount of charge flows out of the second side as had flowed in the first side, except they are not the same charges – If we had somehow tagged the charges into the first plate, different charges would be coming out of the second plate – as the water comes into the first side of the water capacitor, the rubber membrane stretches, producing a back pressure (analogous to voltage) which is equivalent to the increase of voltage in a charged circuit. The energy is stored in the electric field. The analogy is that water pressure is the analog to voltage, and water current flow is the analog to electrical current.

The water inductor

The inductor is the dual of a capacitor, so that the basic rule in this case is: "One can't change the current through an inductor in zero time". Again, the statement is tied up with the differential equation, which states that "the voltage across an inductor is equal to the inductance times the time derivative of the current through the inductance." This time, the energy is stored in the magnetic field. The mechanical analogy in this case is a "friction car", in which a toy car has a flywheel attached so that one can push it across the floor very quickly and then just set it down and it will speed away – probably most students have seen such a toy at some time. The physical model used for this is a closed circular chamber with an input and output, with a paddle wheel inside, so that by turning the shaft to which the paddle wheel is attached, water is pumped from the input to the output. A flywheel is attached to the axle, so that, when water flows through the input to the output, the paddle wheel is rotated, making the flywheel spin. This is difficult to make. One attempt was made with bearings that had a bit of play in them, so that when fluid flowed under the paddles the paddle moved down and stuck. The model is now being remade.

The favorite illustration, used by one of the authors for the principle of inductance, comes from an experience which had occurred at the home of an uncle, who raised chickens and beheaded them with an axe, which he sharpened with a huge (or, at least it seemed huge to the author at the time) sharpening stone with a crank at the axis. One would turn the crank to get the stone, probably three or four inches thick and a foot or two in diameter, to spin rapidly, but the crank would also be spinning (there was no clutch to the system; the crank was simply imbedded in the stone). The inertia would cause it to spin for several minutes, unless the handle was grabbed. This had to be done carefully, to avoid getting one's knuckles "rapped". The analogy is that turning the crank is like applying current through an inductor, and the energy of the spinning wheel represents the energy in the magnetic field of the inductor, proportional to the current squared. One could slow down the spin, by exerting pressure to the handle, but it could not be stopped instantly. One cannot change the current through an inductor in zero time. It takes time to move energy from one place to another.

The ammeter and voltmeter

A device which is similar to the proposed hydraulic inductor, but without the flywheel for amplifying the inertial properties, is the "Roto-Flo Indicator, manufactured by Bel-Art Products. It is used as a water ammeter in the hydraulic circuit laboratory; in fact, there was an attempt to modify one to build a water inductor by adding a small flywheel to it, but the inductive effect was too small for our purposes.

The device used in the hydraulic circuit laboratory as a voltmeter is simply a long piece of open-ended transparent tubing, fastened to a wooden yardstick, with a T-connector at the bottom. Balloons with weights can also be used to vary water pressure.

Oscillation

In theory, (which works well as a picture on the board) one could attach the water inductor to a water capacitor, charge up the capacitor, and let it go in a closed circuit. As water begins to flow through the water inductor, the flywheel will speed up, so that, when the wacapacitor has discharged completely (the rubber membrane has reached a flat condition), the water inductor's flywheel is spinning, so that the paddles continue to force water into the other side of the capacitor, charging it up in reverse. Since a frictionless system can be produced on the board, students soon visualize the sinusoidal oscillation which is illustrated by the system. At this point, the whole process can be related to two other physical properties the students are or may be familiar with – the pendulum, and the "water hammer" effect in the plumbing of some old houses.

The water-hammer effect" comes from having an air bubble in the water system of a house – if a water faucet is turned off suddenly, one can hear a repeated "thump" somewhere else in the house – this is due to the effect of the flowing water suddenly stopping, compressing a bubble, and the bubble re-expanding to send the water in the opposite direction. In large old houses, one can sometimes hear several thumps as the water bounces back and forth in the pipes, since the moving water has inertia, whether or not a flywheel is involved, and the compression of an air bubble in the line gives "capacitance" to the system.

Inductance is associated with inertia, or kinetic energy in the system. In the flywheel model, this is augmented by the flywheel, much as current through an inductor produces a magnetic field, which cannot collapse instantly due to the fact that $E=mc^2$. More about that will be noted later.

Water capacitance is associated with potential energy, produced by the rubber membrane in the model, but also by a compressed bubble somewhere in the house's water pipes. This can also be seen when one waters a lawn using a rubber hose. If the hose has an adjustable nozzle, and the nozzle is shut off while the house faucet feeding the hose is left on, and subsequently the house faucet is turned off and then the nozzle is turned back on, some water will squirt out. This results because the hose, being elastic, has expanded due to the house water pressure, and squirts the extra water out when the nozzle is opened. Thus, the water hose has water capacitance, as well.

Energy considerations

A pendulum is a very straightforward illustration of energy that moves from potential to kinetic and back again. When the pendulum is at its lowest point, with its maximum kinetic energy, the analogy would be the inertial energy of the spinning flywheel in the water inductor. When the pendulum is at its highest point, the potential energy of the stretched membrane is the analogy. In a capacitor, the energy is stored in the electric field between the capacitor plates; in the pendulum, the energy is stored in the gravitational field. The reason why one can't change the current through an inductor in zero time is that the energy in both cases is in the field, and one can't move a field from one place to another instantly – because energy is equivalent to mass ($E=mc^2$, Einstein's revelation to us), and since nothing can move faster than light, energy takes time to move from one place to another, just as one cannot move a physical thing, a mass, from one place to another instantly.

The battery

The hydraulic analogues help to explain the difference between a capacitor and a battery. Each can be used as a power source in a system, so how are they different? One could charge an electric capacitor by placing opposite charges on the two plates, and set it on a table. If the voltage is large enough, and the capacitance big enough, it can be demonstrated that it is, indeed, full of energy, by shorting it, producing a student-awakening explosion. The same can be done with a "wacapacitor" by filling one chamber with more water than the other, and pinching either of the entrance tubes. When the tube is un-pinched, water squirts out, but only until the rubber membrane no longer has any pressure across itself.

This emphasizes that voltage in the electrical case is similar to pressure difference in the hydraulic case. The energy is stored in the voltage in the capacitor, whereas the energy is stored in the stretched membrane in the hydraulic capacitor's case.

The energy in a battery is due to chemical reactions which continually produce the charges as they are removed by the current, so the basic energy storage is chemical. Thus, the current flow depends on how fast the chemical reaction can proceed. If a capacitor is used instead of a battery, one can obtain higher currents from it than from the battery, but there is no chemical source to produce additional current, so that the capacitor would have to be recharged once the potential energy is used.

Three phase systems

Three phase motors and sources almost always elicit the question "why?" Three arguments help to explain; the first uses water, the second, experience with cars and motor bikes, and the third, mathematics. The water explanation involves trying to get energy from a waterfall to spin a water wheel. Suppose your water wheel had only two blades, each at 180 degrees from the other. There would be times when the water would be flowing without touching either blade; this would be wasting the kinetic energy of the flowing water. If one used six blades, all equally spaced around the wheel, it would be equivalent to a three-phase generator. The motor bike explanation will probably help students who are familiar with single cylinder machines, but an explanation will help the rest of the class to imagine how a single cylinder car would jerk ahead at intervals, so that a six cylinder car would give a much smoother ride. The mathematical explanation can be shown by simply drawing three sine waves on the board 120 degrees apart, and drawing vertical lines at intervals, pointing out that the sum is always zero, but sum of the squares is a constant. So the power flow is a constant, all the time.

Summary: The wife test

The first author asked his wife to read this paper, and she told him she didn't understand it. He went over it with her to find the problems, which were found to be typical of those of many students without a science background. She understood that a wire is like a tube (she had seen him siphon water from an aquarium, so she has that experience; It has been found that many engineering students have never siphoned water out of a container). As the author explained that water current is like electric current, she could see that a pinched tube would resist the flow of water current. "But, what is an electric resistor?" she asked. He told her that it was a little cylinder with a piece of wire sticking out of each end, with colored bands that tell you how much resistance, in ohms, it has to current flow. The more ohms, the more it resists the flow of charges through the wire. One puts it in series with the wire from the battery.

"What is 'series'?" she asked. He returned to the water analogy. If you had just one tube running from the aquarium to a lower spot, and pinched it, the pinch, which is the resistor, is in series. If you had two separate tubes coming from the same aquarium, they would be in parallel. The next question was "what is a battery?" The explanation was that a water battery would be like the city water tower, which, because it is so high, produces a high water pressure in our water faucet; in fact, the faucet is a variable resistor, to control the flow rate (current) of water. But the water tower doesn't have a pipe running up to refill it when we turn on the faucet, and neither does the aquarium; so, why does a battery have two terminals, so that you have to connect both ends to get current out of it?

He found that the analogy of an aquarium was not complete. In order to have a hydro-battery, one must have a water pump in order to put the water, which was siphoned out, back into the tank. It is important to refer often to energy balances: where energy comes from, where it goes, how it is stored, and that it can't be created or destroyed. In this case, energy is supplied by the pump to keep the water level constant in the tank, even though water is being siphoned out through the tube, but as the water runs out through a pinched tube (a "waresistor"), it heats up the pinch, so that the added energy is used up (energy has to be conserved). Why, then, in the electrical example, doesn't the electricity just run out of the battery and make a puddle on the floor? Because, unlike water, electricity comes in two opposite kinds: positive and negative. If you try to pull the positive stuff out, the negative stuff tries to pull it back. We think of current as a positive fluid that flows through a fixed negative web of molecules which constitutes the wire (actually, it's the other way around, but it works either way; you can blame Ben Franklin for the way the charges were chosen).

Conclusion

The hydraulic analogy for electrical elements and circuits does help to explain a lot of the basic problems involved in communicating and teaching students who are unfamiliar with basic electricity. The analogies presented herein have been found to be worthwhile. As teachers who delight in seeing the "Aha!" moments, these explanations have produced many of them.

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