

AC 2007-452: A HYDRAULIC CIRCUITS LABORATORY – TO IMPROVE STUDENT UNDERSTANDING OF BASIC ELECTRICITY

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A Hydraulic Circuits Laboratory – To Improve Student Understanding of Basic Electricity

Abstract

Concepts of voltage and current have often seemed foreign to students since they are measurable but not directly visible. For nearly forty years the author has introduced basic circuit concepts using a fluid analogy and has seen similar explanations in various textbooks. This year a true “wet lab” has been implemented to illustrate the concepts of voltage and current as well as Kirchhoff’s current law and the transient behavior of RC circuits. The hydraulic lab takes place as a portion of a supplementary lab for Circuits I which includes hands-on experiments with circuit components, timers, LED’s, and op amps. Student response to the hydraulic circuit lab will be discussed. This project was supported in part by a grant from the Keck Foundation with a purpose of updating laboratories and developing interdisciplinary laboratory experiments.

Introduction

The circuit concepts of voltage and current have often seemed foreign to students since they are measurable but not directly visible. Many students dread taking a circuits course because they have no “feeling” for voltage, current, resistance, capacitance, or inductance. It might be akin to never having used a prybar, rolled an object on wheels, or used a screwdriver or pulley. Some students have never even siphoned water from one container to another.

(The primary author (RWG) admits to having a hard time during his sophomore and junior years trying to understand these basic concepts,¹ they were simply mathematical equations. He had, when younger, thought that there was something magical about working with mathematics. It took a very long time for him to regard electrical problems as physical systems to be modeled by mathematical concepts rather than a set of equations to be manipulated to obtain an answer.)

All engineering students at LeTourneau University take the same Circuits I course, whether their specialty is electrical, mechanical, biomedical, materials joining, or computers. Students in the mechanical concentration must learn the basic circuit concepts as well as those in the electrical concentration. Often the students in the mechanical option are more tactile learners and have difficulty grasping electrical concepts.

The first author has been trying to give students a bridge to communicate the basic concepts of electricity, and has found that an analogy to fluid flow can be very helpful. For nearly forty years he has introduced basic circuit concepts using a hydraulic analogy and has seen similar explanations in various textbooks. The water analogy has been used as an explanation on the blackboards (and whiteboards) for several years,^{2,3} but the goal has been to have a more tactile method of communication. This year a true “wet lab” has been implemented to illustrate the concepts of voltage and current, as well as Kirchhoff’s current law and the transient behavior of RC circuits.

The hydraulic lab experiment takes place as a portion of a supplementary lab for Circuits I which includes hands-on experiments with circuit components, timers, LED’s, and op amps. This

project was supported in part by a grant from the Keck Foundation with a purpose of updating laboratories and developing interdisciplinary laboratory experiments. Keck funds were used to purchase materials and to hire student workers to make the exercise practical.

The lab sessions

This circuits lab session is, in essence, a no-credit addition to the Circuits I course, since it counts as only 7.7% of the final grade. The lab meets in a standard 40-seat classroom for approximately two hours per week, and the students are given their own breadboard, VOM, 9-volt battery, and a set of resistors, capacitors, wires, and electronic components. (This may be the first incidence the authors have seen of the students actually receiving something physical for their laboratory fee.)

The basic agenda for this lab is to enable the instructor and student helpers to interact with the students on a one-to-one basis and help them through misunderstandings they might have concerning the material. (Some students seem to be to be ill-prepared due to overdependence on calculators.) This set of labs is, virtually, “no credit”, because, in order to produce graduates with the same expertise as those produced 30 years ago, extra instruction is needed in the course. This extra lab time is in essence a “tutorial study hall”, which serves to add the necessary input.

The overall format of the lab involves giving the students a brief handout of the experiment to be performed, a short explanation, and a problem to be worked. The students usually work in pairs, and the faculty member, along with two or more student helpers, circulates around the room to help. When a student shows that he or she has completed the experiment and has done the problem, that student can leave, or may stay to help others with their problems. No partial credit is given, and virtually all students complete the tasks. These are called “fun labs”; there are twelve to fourteen experiments and as many problems done in each semester.

A list of the previous experiments is as follows:

1. Resistor combinations and breadboard tutoring
2. Building an astable timer, using a 555 timer
3. Utilization of a 741 op-amp to build an amplifier
4. Building a sine wave amplifier using an npn transistor
5. Voltmeter and capacitor lab
6. Simple inductors
7. The 555-band (a team project to present a tune to the rest of the class)
8. An R-C transient and op-amp
9. Investigation of a NAND gate
10. Use of a transistor
11. Building a thermometer using a transistor

Within this context, the Hydro-circuits lab was introduced this year.

A typical laboratory session is illustrated in Figure 1.



Figure 1: Typical “fun lab” in session

This year the plan was to introduce the hydro-circuits lab at the third session. Delays in the acquisition of parts delayed it to the sixth session. Two sections of Circuits I were taught this semester, so that there were two lab sessions per week. Since not all students in the course came to the lab, although there were about 40 in each section, only 25 were present in the first lab session, with 35 in the second. A lab of this magnitude cannot be done without student help.

Preparation and description

Twenty-five kits were prepared for this lab, so that there were some spares in case of unforeseen problems (which did occur.) Two students were to use each kit, and the kit was to be returned intact at the end of the experiment.

The following parts were in each kit:

1. Plastic box, 23 in. x 16 in. x 5 in., plastic, with lid, to hold materials
2. Three yardsticks, with base and three plastic ties per yardstick, holding a 24 in. piece of plastic tubing, $\frac{1}{4}$ in. I.D., onto each yardstick
3. Three flow indicators, Roto-Flo© VWR catalog # 47727-232
4. Two valves
5. Three “waresistors” (“water Resistors”), small, medium, and large, built with pieces of large, medium and small I.D. tubing, respectively
6. Four “T” connectors
7. Two straight connectors
8. Ten pieces of $\frac{1}{4}$ in. I.D. tubing, 3 in. long
9. Two pieces of $\frac{1}{4}$ in. I.D. tubing, 12 in. long
10. Ten pieces of $\frac{1}{4}$ in. I.D. tubing, 36 in. long
11. Six balloons
- 12 One 1000ml. beaker
13. One “wacapacitor” (“water capacitor”), as described below
14. One catsup or mustard container for filling the apparatus with water.

The wacapacitor was constructed by using successively larger neoprene tubing which was hot-glued together to a maximum of 1- $\frac{1}{4}$ in. O.D.. A very thin rubber membrane was then used to

cover this opening, and a 1 – ¼ in. I.D. piece was slipped on so that it fit tightly, and successively smaller pieces were then glued together to reduce this to the standard 1/4 in. I.D. tubing.

The flow indicators were the most expensive items in the kit, at \$15.85 each. The total price per kit was about \$100. All of the materials necessary for this experiment are available at Lowe's or Wal-Mart, except for the flow indicators, available from VWR.com as Roto-Flo© Flow Indicators.

First part: calibration

The experiment has three basic parts; in the first part, the student calibrates the water resistors (waresistors), one of which is seen in Figure 1.



Figure 1: Waresistor

The calibration is accomplished by siphoning water from a beaker and timing the rate of water flow with a stopwatch. Current is measured as milliliters of water per second, and voltage as centimeters of water, which gives the water head. Figure 2 shows the experimental setup. The water resistance is then the ratio of water head to water current flow.



Figure 1: Procedure for waresistor measurement

There are three water resistors provided in the kit, and this measurement shows the student that resistance is roughly dependent upon the diameters of the constricting piece between the two ¼ in. I.D. tubes, the narrower constrictions producing the larger resistances. There are small, medium, and large values of water resistors provided in the kit.

Second part: KCL demonstration

The second part of the experiment serves to demonstrate Kirchhoff's current law (KCL). The student connects two branches of tubing, each with a flow indicator and water resistor in series, so that those two branches are in parallel. This pair is then connected in series with another piece of tubing, which has another flow indicator in series, and which is also in series with a water-filled balloon. This system is illustrated in Figures 3 and 4. When the balloon is squeezed, Kirchhoff's current law can be visually displayed, as the flow indicator represents an ammeter.

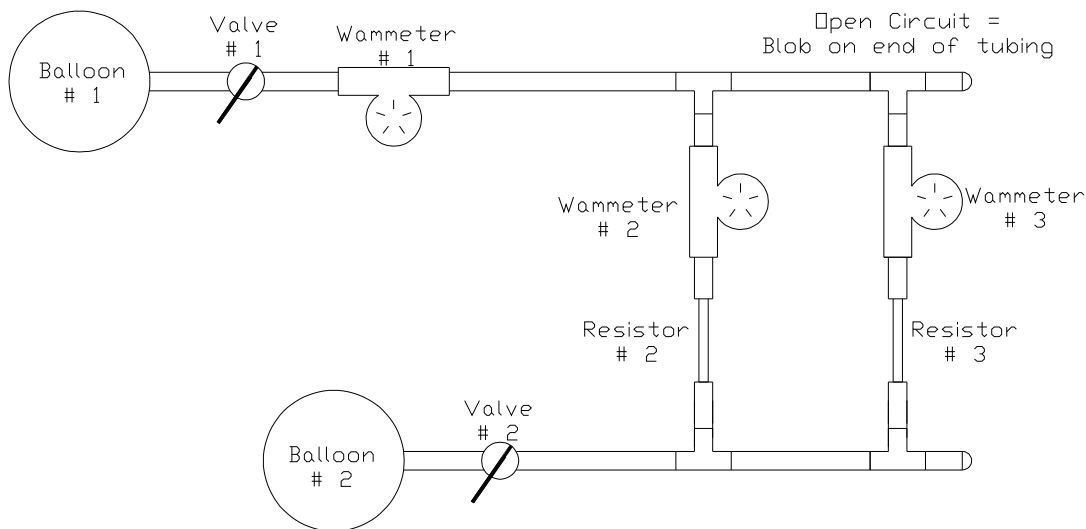


Figure 3: KCL demonstration diagram

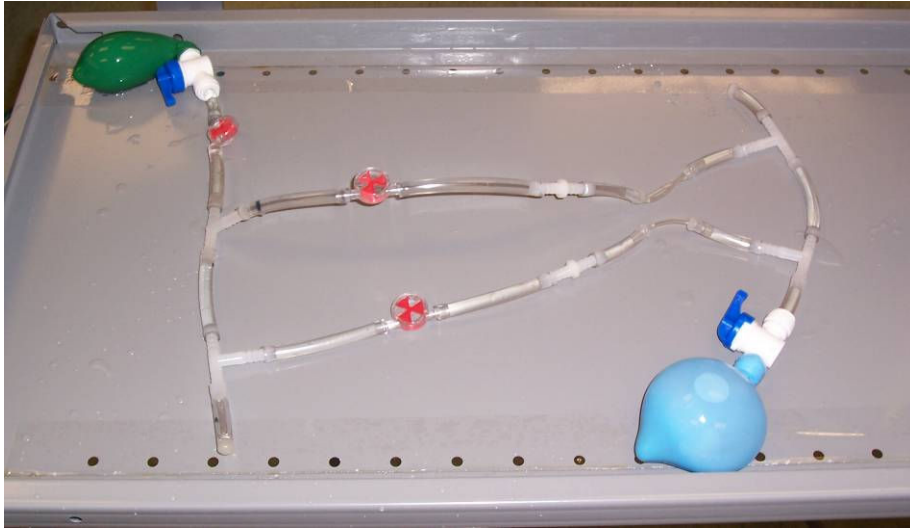


Figure 4: KCL actual demonstration

The third part of the experiment illustrates the transient behavior of a series RC circuit. This setup is illustrated in Figures 5, 6, and 7. In this case, the voltage at three points is given by the height of the water levels in the tubes. Since voltage is, in reality, a voltage difference, a concept not easily understood at first by some students at this point, it can be mentioned that all these levels represent the differences between the pressures at those points in the circuit and atmospheric pressure. A sudden squeeze of one of the balloons shows that one cannot suddenly change the voltage across a capacitor. There is also a time constant involved, as pressure differences equalize by means of flow through the circuit resistor (which is the largest resistor in the kit, for this circuit). Realization of these concepts is illustrated by the response of the happy student in Figure 8.

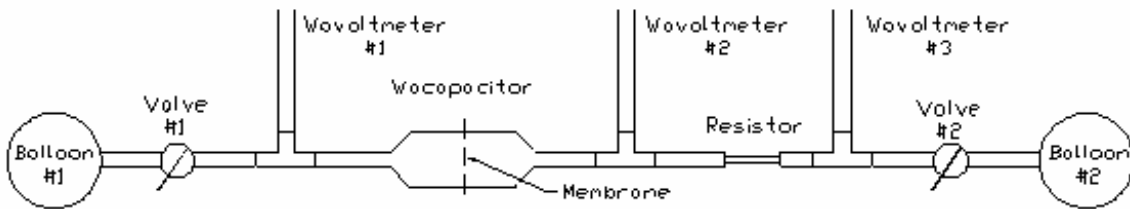


Figure 5: Transient measurement diagram

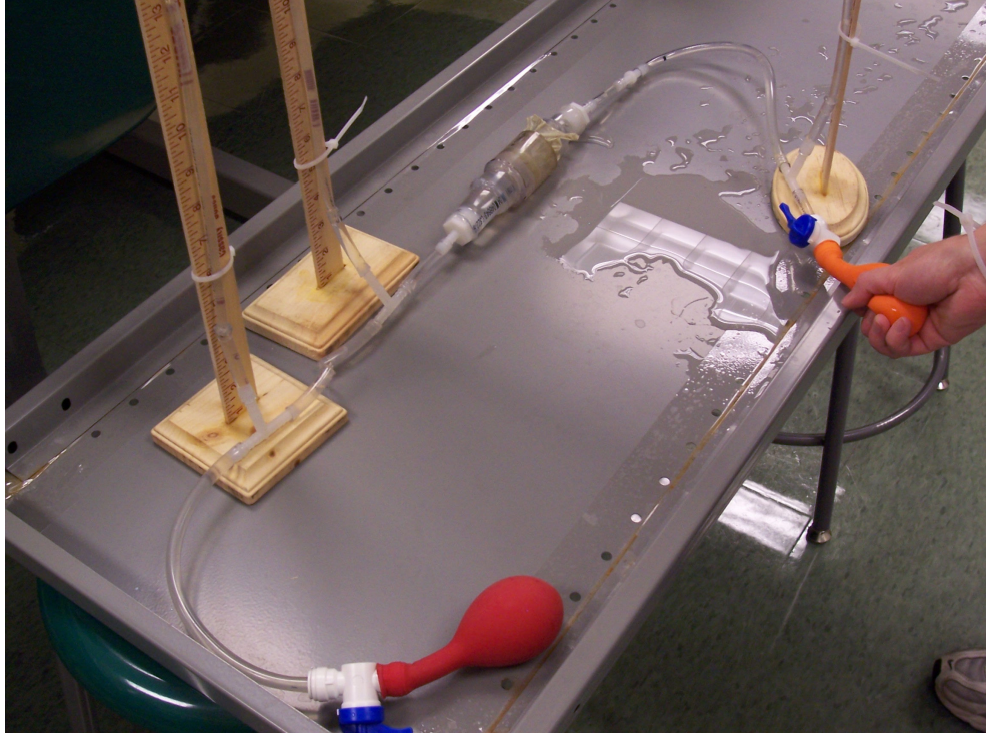


Figure 6: Actual transient measurement setup



Figure 7: Charged wacapacitor



Figure 8: Happy student

Student responses

Soon after the experiments were performed, an anonymous survey was taken to find the student responses to the lab. The first section consisted of 25 students, with 35 in the second section. The actual performances of the two labs were five days apart. The following survey was given:

Survey for students who have performed L-195, The Hydraulic Circuits Laboratory:

Participation in this survey is voluntary. The results of the survey will be accumulated and shared with anybody who wants to read the resultant paper only. No individual results will be reported on or connected to any faculty, staff or student respondent. Do not sign your name.

1. Has this experiment improved your understanding of circuit theory in any way? If so, please describe how:
2. Do you think this experiment is worth repeating for future circuits students? On a scale of 1 – 10, how would you rate it? (1 = “it was a waste of time”; 10 = “it was an excellent addition to the course”).
3. Any other comments? Do you think anything should be omitted, added, or changed in some way?

The numerical average for the response to question number two was 8.417 for the first group (for which there were 25 students), and 7.257 for the second group (of 35). In general, the lower ratings were by students who said they had already figured out these concepts.

Interesting written comments to questions one and three were:

“I’m an ME and have a hard time grasping concepts that I can’t observe. This lab helped me ‘see’ what was going on and I really liked that. It probably would have been better earlier on in the semester.”

“...balloons are quite messy”

“...you could actually see what went on in the circuit!”

“...it gave me a visual knowledge of the water example and allowed me to ‘see’ movement..”

“It was very wet and might consider taking the tables outside so there is less of a mess to clean up”

This student’s advice was followed, and we allowed students in the second section to take tables outside. Some further comments, paraphrased, were:

Bubbles in the tubing were problematic

Wires should be provided to poke bubbles out of the tubing

Clarify the setup instructions

Do it earlier in the course (this comment was repeated several times)

Water capacitors break easily and often leak

Current makes you wet

Should have a water balloon fight to conclude the event (three made this comment)

Divide the experiment into two, with KCL earlier

Graphical part almost impossible for the given time with the given equipment

Easier way to fill capacitors needed

Can you make a water inductor?

Future plans, modifications

The student responses, together with the practical experience gained by this first laboratory experience, gave the following guidance for subsequent use of this lab:

More practical instruction needs to be given concerning how to fill the wacapacitors with water and to seal them more carefully. (On the first run, 8 out of 20 had slight –to –serious leaks.)

In order to produce a “voltage difference” (or water pressure difference), an attempt was made to incorporate aquarium pumps, which resulted in a mess and extra complication. Gravity flow did not produce enough pressure. A closed system, using balloons, produced just the right result.

It should not take much more effort to implement an experiment to illustrate Kirchoff’s voltage law. This lab will be broken into two experiments, so that KCL and KVL are illustrated by the first one, given in the third laboratory session, and the transient part will be reserved for a later lab, when more appropriate to the course material.

Summary and conclusion

This experiment was a great success, in that it did produce the desired understanding in the students. It had the flavor of a 1960’s “happening”. The present plan is to continue using it, with some of the modifications suggested. We are presently considering an addition to illustrate

Kirchhoff's voltage law, which we plan to combine with the current law part of the present experiment. The RC transient part will then be done in a later session, when transients are covered in class. An inexpensive way to hydraulically model an inductor is also being sought. Additionally, in the course for which this lab was a part, a problem was given in which the students were to design (on paper) a sprinkler system for a lawn. They were given the water pressure with all taps turned off, the maximum water flow rate at the tap to be used, and the flow rate for a given sprinkler. The problem was to find the number of sprinklers needed to give maximum lawn coverage using these sprinklers. This problem gave good reinforcement of the principles shown in the hydro-circuits lab.

Appendix

LeTourneau University Hydraulic Circuits Lab

Introduction

The purpose of this lab is to be able to model the loss and energy storage of a resistor and a capacitor in an electrical circuit, using fluids. This will be demonstrated in a three part lab: Measuring the resistance produced by the fluid resistors, looking at current division, and the transient in an RC circuit.

Objective

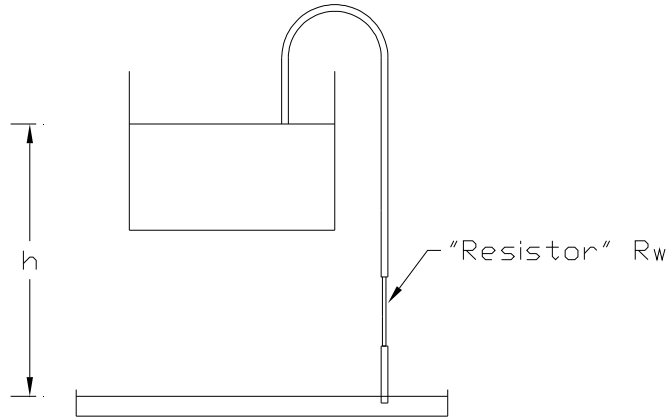
Build the fluid models necessary to demonstrate current division and the RC circuit transient. Measure the resistance of a fluid resistor and experiment with a water voltmeter.

Equipment

- Hydraulic Circuits Kit

Procedure

1. Find the hydraulic resistance in "wohms" of the 2 resistors provided. Record values in the table on the next page.
 - To do this, siphon water through a resistor and measure the time it takes to siphon 200ml. See picture for example:



Useful Equations:

$$R_w = \frac{V_w}{I_w}$$

Where: $V_w = cm$ of water, h $I_w = \frac{cc \text{ of } H_2O}{s}$

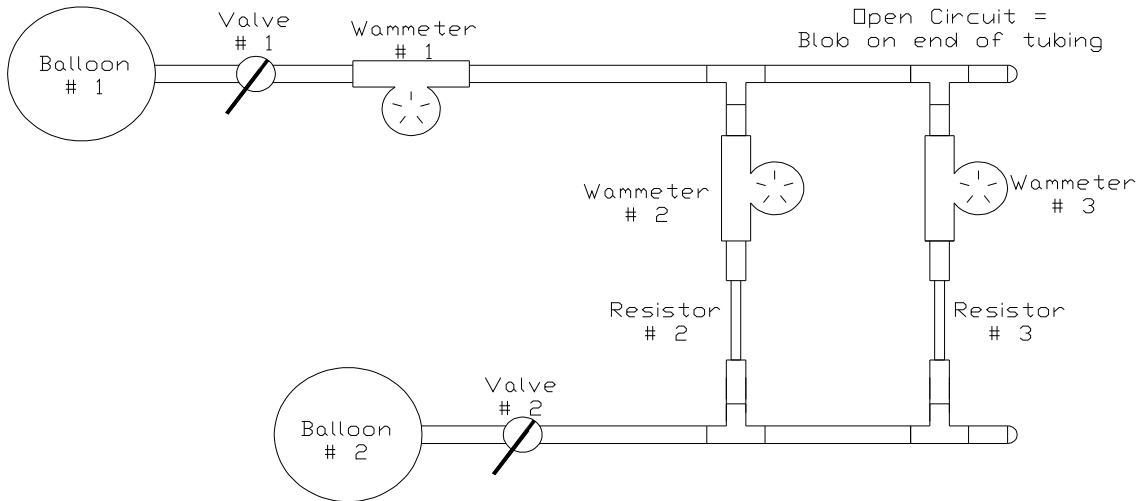
Example:

Say it takes 30 seconds to siphon out 200 ml of water and the difference in height of the water levels, h , is 40". What resistance in "Wohms" is being used?

$$R_w = \frac{V_w}{I_w} = \frac{(40in)(2.54cm)}{200cc/30s} = 15.24 \text{ Wohms}$$

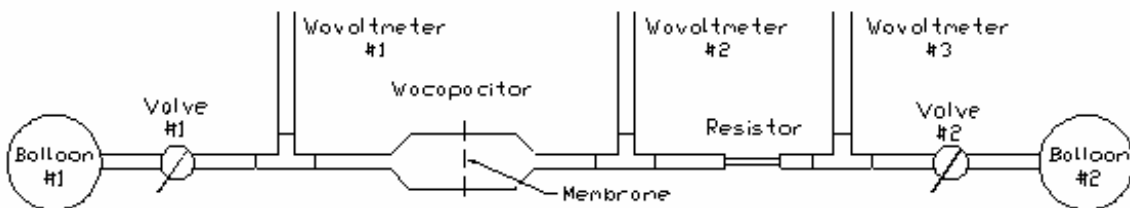
	Volume Water (mL = cc)	Time (s)	Resistance (Wohms)
R1			
R1			
R2			
R2			
R1ave		R2ave	

2. Show KCL by building the following circuit:



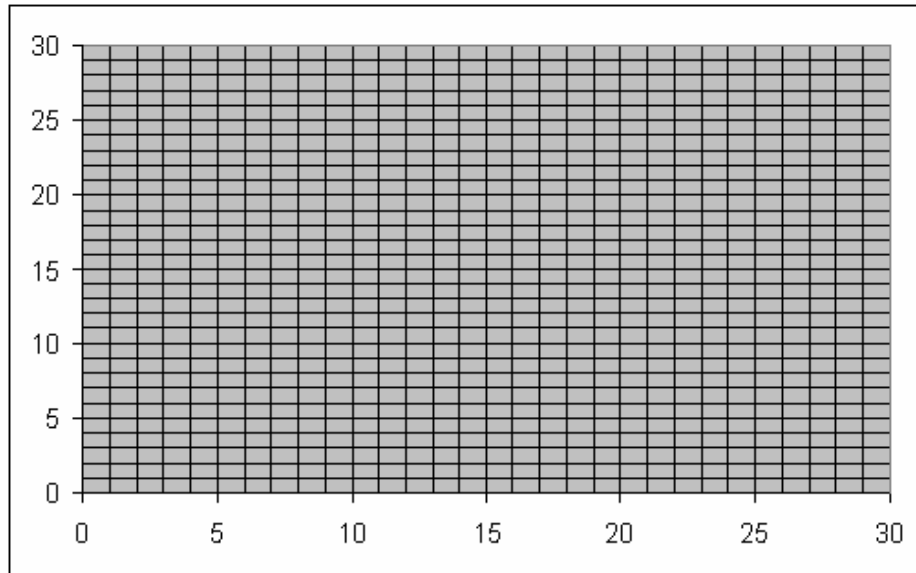
- The “wammeters” (water ammeters) are VWR International Roto-Flo flow indicators.
- Show a working model of the above circuit to your instructor and explain to him the relationships between large and small resistors and the currents in the different branches of the fluid model.

3. The following circuit should demonstrate transient behavior in an RC circuit.

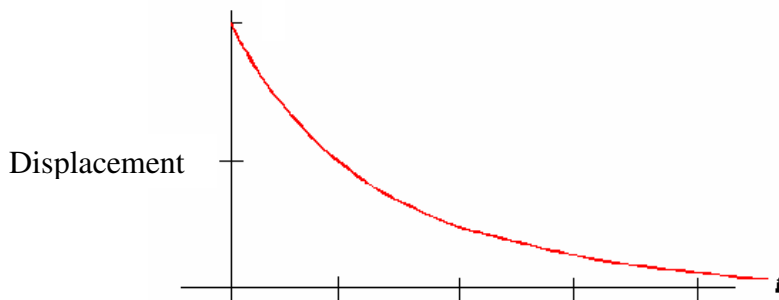


- Fill both sides of the “wacapacitor” (water capacitor) and all associated tubing completely full of water as well as the connections for the “wavoltmeters”. (Make sure that the pressures on either side of the membrane are approximately equal, when entire set-up is lying flat on the table, once full of water. Adjust if necessary.)
- Adjust resting pressure in the circuit to read 10 in. on all three “wavoltmeters”.
- If you open valves #1 and #2, and suddenly squeeze balloon #1, the pressure in “wavoltmeter #1” will rise instantly. This is illustrated by the change in the height of the water in “wavoltmeter #1”. The same will be seen in “wavoltmeter #2”. Why?
- The pressure (voltage) in “wavoltmeter #3” will rise more slowly, however, as water runs through the resistor and the membrane bubbles to the right.

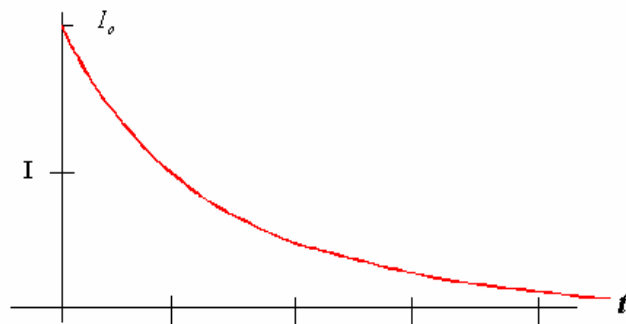
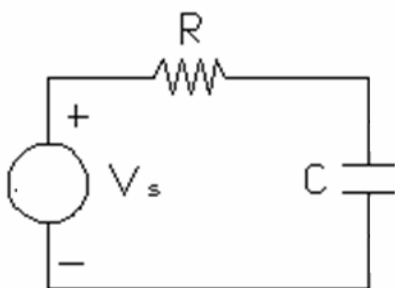
- Record data to show the rate at which the pressure in the two “wavoimeters” equalize. Squeeze (or raise) balloon #2 until “wavoimeter #3” reads 24 in. Hold it steady until “wavoimeter #2” equalizes with “wavoimeter #3”. Suddenly release pressure on (or lower) balloon #2 and record the displacement of “wavoimeter #2”. Draw a graph of the displacement with respect to time in the space provided below. Be sure to label the axes.



Your data should look like this:



- This is analogous to a current in an RC circuit:



- How are these things related? Explain to your instructor.

Bibliography

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