

Creating Wind Chimes, Toy Train Simultaneous Equation Collisions and  
Applying Physics to Energy-Cost Analysis of a Shower

by

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A Master's Paper

Submitted to the Graduate Faculty

in partial fulfillment of the requirements for the Degree of

Master of Science in Education - Physics

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Advisor's Signature

University of Wisconsin – River Falls  
October 26, 2012

## Abstract

I have compiled 3 original activities I created to enhance the physics education my students receive via the use of data collection and analysis hardware and software, project-based applications of physics, and discussions focused on increasing students' understanding of the world around them through physics.

The first activity is "The Shower Lab" in which students experiment with their home shower-calculating flow, cost, and comparisons to low-flow shower head data. They extrapolate data to see energy savings for the state and the country. Students are engaged and excited by this real world physics example.

The second original activity is "The Train Lab" in which students design a set of measurements to calculate the constant velocities of two toy trains. The students then use these velocities and a known separation distance to calculate the location where the two trains will meet. Students place a domino at the location and attempt to have the two trains hit the domino simultaneously thus holding the domino upright between them. Students are challenged by and enthusiastic about keeping the domino upright by making careful measurements and calculations.

The third is "The Wind Chime Lab." Students collect data for various lengths of pipe and their resonant frequencies. Students then graph the data and obtain a frequency-length relationship which is used to calculate the pipe lengths needed for specific frequencies students have chosen that sound good together. This activity takes students from theory to production, and shows students how physics can be applied to something as artistic as a wind chime. Students enjoy constructing the wind chimes and are proud to explain how the wind chime was designed to produce the exact sound they wanted.

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# Shower Lab

## Description

The goal of this lab was to have students connect areas of physics (fluids and thermodynamics), extrapolate numbers, estimate, and relate physics to taking a real-world activity, in this case, a shower. I am also able to intersperse some key discussions during this lab about energy production and distribution, governmental policy and estimations. This lab is done in two parts, the first part of the fluids chapter and the second is in the thermodynamics chapter.



*Figure 1: Shower head with a indicated flow rate of 2.5 GPM*

The first part involves each student measuring the flow rate of their shower head at home and how much water they use during a typical shower, both in gallons and kilograms. This part has students take a measurement of a volume of water over a given period of time at home, with materials they already have. To determine the volume students choose a method to follow, ranging from using a known density value and the weight of the water to using a bucket and a measuring cup. Many shower heads are stamped with their flowrate as seen in Figure 1.

The second part is done as a thermodynamics problem where students calculate the amount of energy required to heat the water they used for their shower from 55°F to 110°F. Next, students calculate the energy input of the water heater using given efficiencies of both electric (99%) and gas (70%) water heaters. I will most likely have to expand this to include the categories of high efficiency and on-demand water heaters. I give them the temperature range and the heater efficiencies. Students calculate the cost using both types, not just the type they use at their own home. Then they calculate the cost for each heating type using numbers from the local power and water utilities which I supply. The students then approximate the water used and cost of a shower for themselves, their family, the state, and the country in a given year. The assumption that everyone's shower is similar to each student's is made.

Finally, the students are asked to see how much water and money would be saved if they and everyone else switched to a low flow shower head.

Objective 1: Students will be able to experimentally find flow rate. I originally thought about using a mini-lab to find the flow rate of the faucets in the room, but decided to ask students how they might find the flow rate of their shower head and let the students share ideas. In the future I will try this as a small group discussion and sharing.

Objective 2: Students will be able to calculate mass and volume of water for their shower. This ensures students can use the flow rate and density equations as well as convert between various units. This is needed to produce values for later calculations.

Objective 3: Students will be able to solve a  $Q=mc\Delta T$  problem to calculate the energy needed to heat the water for their shower. This objective provides an opportunity for students to apply knowledge learned in class to calculate the value of an event in their lives. Again, this tests students' abilities to solve equations and convert units.

Objective 4: Students will be able to use efficiencies to calculate the energy required by a water heater. We have not covered an equation for efficiency in class, so this is a good practical problem for students to work through. I usually answer a few questions on this before word spreads about how to calculate the energy input for the heater. One student showing another student of how to solve this problem is an excellent example of peer teaching.

Objective 5: Students will be able to calculate the cost of energy, both electric and gas. This is useful in two ways. First, students get a chance to do a cost-of-energy calculation and, second, they get to see how much their showers actually cost. Many are surprised by the fact that a shower costs less than 1 dollar, and often less than 50 cents. Another interesting surprise is that the gas water heater, which is far less efficient than the electric, actually costs less to heat the water. This causes a bit of dissonance in the students' minds that higher efficiency costs more. Dissonance often leads to teachable moments, in this case, how we get our different forms of energy. For example we typically go through the following process to get most of our electricity in our geographic area: Coal is mined,

hauled to the surface, transported by train, burned to boil water to steam which turns a turbine which turns a generator, which produces electricity that is finally transmitted via power lines to our houses. On the other hand, gas is drilled for, pressurized and driven to the surface, refined, and then piped to our houses. It is not long after or during this discussion, which is often led by me questioning the students, that the student gets that “eureka” moment and understands. Of course we also talk about the other types of energy production like wind and solar. This nicely foreshadows a project we do later in the year where students research and present one of the many types of power production and energy conversion methods.

Objective 6: Students will understand the extrapolation of small changes when applied to large populations or time frames. This is a common area with which students, and people in general even, have a hard time. It is often referred to as “number sense.” When students calculate the cost of a shower, the common first response is, “Wow, that's cheap.” If you ask them to extrapolate and think of how much it costs their family to shower during a year, or how much the US spends on showers in a year, the numbers vary considerably between students. Furthermore, when asking a student how much would they save if they switch to a low flow shower head, say from 2.5 gpm (gallons per minute) to 1.5 gpm, the response from students is, “Not much.” After they calculate these values, we have lively discussions about being a conscious consumer, water shortages in the southwest, pollution sources associated with energy production, and even what role the government does/should play in these types of choices. I have always thought this lab would fit wonderfully in a cross-curricular lesson with social studies, but so far the opportunity has not arisen.

I chose the format of this lab to be outside of class, or a homework lab. This format is needed for data collection, but furthermore, it brings physics into their daily life. Hopefully they will be interacting with parents when they fill a bucket of water in the shower and measure it. This not only looks good from a school-parent relationship, but also it helps involve them in the discussion about cost, efficiency, types of water heaters, governmental roles, and as much discourse as I can hope parents and 17-year-olds can have. I also think that home measurements are fine since this is an

estimation exercise. Because of the format of the lab, students have been more likely to discuss the lab with me with a curiosity to explain, not just a “tell me the answer so I can put it down.”

## **Results**

By far the largest positive from this lab is relating student life experiences to basic physics, energy production, and consumer choice. It is often hard to find a lab that can relate all of this and still be at a level at which students are excited and curious about the results.

The negatives come from the students all having individual numbers to work from, so checking for errors and grading for correct calculations is difficult. Especially disappointing is a student who has done a lot of work only for me to tell them that a flow rate of 0.5 gpm or 8.5 gpm is rather unrealistic and probably erroneous. The discussions and “ah ha” moments for students about the numbers they calculate are worth these negatives. Since I implemented this lab I would say more than 600 students have experienced it. I have also shared this lab with a local physics teacher as part of the Central Wisconsin Physics Share Session.

An interesting study that I might add is to compare the maximum flow rate as stamped on a shower head versus the measured flow rate by the students. For example, the max flow rate stamped on the faucet pictured in Figure 1 is 2.5 gpm, which is probably based on a government standard of 2.5 gpm at 80 PSI (pounds per square inch). The well pump on my house does not reach 80 PSI and is variable cycling between 40 and 60 PSI. We can tie flow rate and pressure together with Bernoulli's equation and expand the discussion of the definition of flow rate used by shower head manufacturers. I have discussed this with a few students and more generally as a class on how water pressure can vary with height and how tall buildings deal with this issue.

## **Reflection**

After taking a geology course on rivers and streams I was trying to get water issues into my curriculum. River flow rate curves, water rights, and stream data were rather obscure and did not fit easily. Then I bought a low flow shower head in response to these water issues and the questions I had led to this lab.

This lab has worked well for me, however grading it is very difficult even with a Microsoft Excel® spreadsheet for calculating the correct numbers based on students' initial values. I am considering switching to more of an in-class "ballpark-type" answers format, tallying up categories of cost and volume of different showers, and small group discussions about some of the findings and relationships. Our school is also shifting to more of a summative-only grading practice, so if I wanted to continue grading this, a more formal lab write-up would be needed. I am not sure how long I can do the low flow comparison part of this as more and more of my students already have low flow shower heads.

This lab follows several levels of Bloom's Taxonomy. Students string multiple pieces of knowledge together from different chapters to arrive at values such as shower's water volume, water mass, energy usage and cost. Students then use this information to compare and contrast different energy types for heating and compare different shower heads as applied to both personal and global scales. Finally, students analyze the results and produce viewpoints on what choices they and others should make based on their calculations. The synthesis of social ideals, environmental issues and personal practices all can be brought together and some estimated values integrated to help analyze the relationships. Because of the personal nature of this activity students have more incentive to understand the relationship between their practices and the larger effects of those choices and the choices of others.

This lab has encouraged me to think more globally about the labs we do, and how we can use the knowledge we gain from the labs to make predictions or derive insight about current issues facing humanity.

I was recently visited by a hopeful candidate for my region's state assembly seat who thinks that global warming has nothing to do with human activity and that tax payer money is being wasted on environmental education curriculum that teaches environmental extremism. After a half hour of talking with him, I thought about this lab and the goals, discussions, and opinions I bring to this lab. Both of us agreed that these issues should be discussed; however, we differed on the best means of generating

these discussions. This encounter confirmed for me how important and pertinent science education can be and how controversial it can be, and how, as an educator, I need to be mindful of how these discussions contribute to students becoming thoughtful citizens.

**Sources** (MLA 7<sup>th</sup>, Format):

"ACEEE | Water Heating." *aceee.org*. American Council for an Energy-Efficient Economy, 22 Jan 2013. Web. 2010. <<http://aceee.org/node/3068>>.

Water heater efficiencies source.

"EcoFlow Low Flow Shower heads." *waterpik.com*. waterpik, 22 Jan 2013. Web. 2010. <<http://www.waterpik.com/shower-head/products/fixed-mount/ecoflow/ECO-533>>.

Shower Head box (ECO-533) that inspired me to verify the numbers advertised:

*“Save up to 1 gallon of water per minute and up to \$100 annually<sup>1</sup> with the EcoFlow® shower head. This innovative shower head was engineered for maximum performance with less water. It features five powerful spray settings plus an exclusive water-saving trickle setting that reduces flow to a trickle when shampooing, conditioning or shaving. Equipped with OptiFLOW® technology, which improves water force by up to 30%, the EcoFlow® conserves water without sacrificing a refreshing and invigorating shower experience.*

*1. Based on two 10-minute showers per day. Water, gas and sewer costs based on national average and U.S. Department of Energy estimates. Water costs:*

*\$2.67/1,000 gal.; sewer costs: \$2.67/1,000 gal.; gas costs: \$16.00/1,000 cf.”*

“Electricity and Gas Bill.” *wisconsinpublicservice.com*. Wisconsin Public Service 22 Jan 2013. Web. 2010. <<http://www.wisconsinpublicservice.com/>>.

Used to get the local electricity and gas costs to tailor the calculations to myself and students.

Keen, Dr. Kerry. "Geology 700." Field Hydrology and Geomorphology. University of Wisconsin - River Falls. Wisconsin, River Falls. 2009. Lecture.

Geology 700 at UWRF – Pushed me to involve water resource issues in my classroom

“Public works\Utilities:Rates.” westonwisconsin.org. Village of Weston 22 Jan 2013. Web. 2010.

<<http://www.westonwisconsin.org/utilities/>>.

Originally I called, but I can now access the water/sewer rates for my students online.

"Various titles." *American Whitewater*. 2009-2013: Print. <americanwhitewater.org>.

American Whitewater Magazine – Western US water resource articles, a bias source.

## Shower Lab

## WHAT THE STUDENT HAS

Show your calculations on a separate sheet of paper

### Part 1: Finding your shower head's flow rate

- Turn your shower on (use cold water so you don't waste hot water)
- Place a large container under the head to collect the water for 30 seconds?.
- Use a measuring device (measuring cup) to find the volume of water.
- Convert your volume of water to gallons.
- Calculate your shower's flow rate in gallons per minute.
- Find the average length of your shower in minutes. Not sure? Time it.
- Calculate the number of gallons you use per shower.
- Find the mass of water used per shower (3.7854 kg per gallon)

Number of people

in your family \_\_\_\_\_ people  
Volume per 30s \_\_\_\_\_ gallons  
Flow rate \_\_\_\_\_ gal/min (gpm) - between 0 and 10  
Avg. shower length \_\_\_\_\_ min  
Volume per shower \_\_\_\_\_ gal/shower  
Water per shower \_\_\_\_\_ kg/shower

### Part 2: Finding the cost of your shower (Remember to store your numbers)

-Calculate the heat needed to heat your mass of water per shower from 55°F (approximate temperature of ground water/city water) to 110°F (approximate temperature of your shower).

-For an electric water heater, which is about 99% efficient, find the amount of energy used

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- Convert J to kW-hr (1 kW-hr =  $3.6 \times 10^6$  J)
- Find the cost for you to heat the water at \$0.12 per kW-hr from WPS
- Find the cost for the water at \$0.00505 per gallon from Weston water department.
- Find the cost per shower with an electric heater.

-For a gas water heater, which is about 70% efficient, find the amount of energy used

- Convert J to therms of gas (1 therm = 105,506,000 J)
- Find the cost to heat the water at \$0.955 per therm from WPS
- Find the cost for the water at \$0.00505 per gallon from Weston water department.
- Find the cost per shower with a gas heater.

#### Electric Heater

Q to heat water \_\_\_\_\_ J  
Energy for 99% \_\_\_\_\_ J (should be more than Q)  
Energy needed \_\_\_\_\_ kW-hr  
Cost to heat \_\_\_\_\_ dollars  
Cost of water \_\_\_\_\_ dollars  
Total cost per shower \_\_\_\_\_ dollars (should be less than \$2)

#### Gas Heater

Q to heat water \_\_\_\_\_ J  
Energy for 70% \_\_\_\_\_ J (should be more than Q)  
Gas needed \_\_\_\_\_ therms  
Cost to heat \_\_\_\_\_ dollars  
Cost of water \_\_\_\_\_ dollars  
Total cost per shower \_\_\_\_\_ dollars (should be less than \$2)

**Questions:**

---For questions 1-4 assume 1 shower per day that is the same as yours. Use both electric and gas prices for each problem---

1. What is the cost per year for your showers? How many gallons of water would you use?

Electric \_\_\_\_\_ Gas \_\_\_\_\_ Gallons \_\_\_\_\_

2. What is the cost per year for your family? How many gallons of water would your family use?

Electric \_\_\_\_\_ Gas \_\_\_\_\_ Gallons \_\_\_\_\_

3. What is the cost per year for all of Wisconsin? How many gallons of water would WI use?

(WI pop. = 5,627,967)

Electric \_\_\_\_\_ Gas \_\_\_\_\_ Gallons \_\_\_\_\_

4. What is the cost per year for all of the USA? How many gallons of water would the USA use?

(USA pop. = 304,059,724)

Electric \_\_\_\_\_ Gas \_\_\_\_\_ Gallons \_\_\_\_\_

5. What is the cost per year if you used a low flow (1.5 gpm) shower head? How many gallons of water would you use?

Electric \_\_\_\_\_ Gas \_\_\_\_\_ Gallons \_\_\_\_\_

6. What is the cost per year for all of the USA if they used a low flow (1.5 gpm) shower heads instead? How many gallons of water would the USA use?

Electric \_\_\_\_\_ Gas \_\_\_\_\_ Gallons \_\_\_\_\_

## Shower Lab Sample Data

	A	B	C	D	E	F	G	H
1	volume for 30 sec	2.1 gal			Q to heat water	20,335,324.56 J		
2	flow rate	4.2 gal/min			Energy for 99%	20,540,731.88 J		
3	avg shower length	10 min			Energy needed	5.7058 kW-hr		
4	volume per shower	42 gal/shower			Cost to heat	\$0.6847 dollars		
5	water per shower	158.99 kg/shower			Cost of water	\$0.2121 dollars		
6					Total cost per shower	\$0.8968 dollars		
7								
8	<b>Input Data</b>	<b>here!!!</b>			Q to heat water	20,335,324.56 J		
9	volume for 30 sec	2.1			Energy for 70%	29,050,463.66 J		
10	avg shower length	10			Gas needed	0.28 therms		
11	number of people in family	4			Cost to heat	\$0.2630 dollars		
12					Cost of water	\$0.2121 dollars		
13					Total cost per shower	\$0.4751 dollars		
14								
15		<u>Q's</u>	<u>Gallons</u>		<u>Electric</u>	<u>Gas</u>		
16		1	15,330.00		\$327.3320	\$173.3959		
17		2	61,320.00		\$1,309.33	\$693.58		
18		3	86,276,734,110.00		\$1,842,213,747.03	\$975,866,155.31		
19		4	4,661,235,568,920.00		\$99,528,480,439.13	\$52,722,696,107.40		
20		5	5,475.00		\$116.9043	\$61.9271		
21		6	1,664,726,988,900.00		\$35,545,885,871.12	\$18,829,534,324.07		
22								
23					<b>Constants</b>			
24					cost per kW-hr	\$0.120		
25					cost per therm	\$0.955		
26					cost per gallon	\$0.00505		
27					Efficiency of electric water heater (%)	99		
28					Efficiency of gas water heater (%)	70		
29					WI population	5,627,967.00		
30					US population	304,059,724.00		

This is a spreadsheet calculator that provides the correct numbers students should get given the three input values highlighted in yellow. I have used this to check each student's lab for correct values in the past.

# Train Lab

## Description

The goal of this lab activity was to include solving simultaneous equations in an actual application, particularly the question of where and when two objects will be when they pass one another. The idea of trains came from the classic question of, “a train leaves New York at 9:55 am headed West at 45mph and another train etc. ...” So I found motorized toy trains, Thomas and



Figure 2: The scale of the trains.

Friends® to be specific. These different trains all had different velocities, so in setting up the application similar to the math question, the trains won't simply meet half way. I chose to have the students start the trains at the same time and calculate the collision *location*. Of course this can be modified with other variables instead. This method seemed the easiest to test with consistency and has worked well as a capstone activity for studying linear motion. Figure 2 shows the scale of the 2 trains and the ½ inch electrical conduit I used to guide the trains.

Students choose two trains per group. There are two pieces of ½ - inch diameter electrical conduit placed on the floor to guide the trains. Students are told they will have to let the trains go at the same time and predict the location of the collision. A domino is placed at that location, and if the students' calculations are correct the domino should be pinned between the two trains as they collide. Students are then told to go to work and ask for any tools they need to complete the measurements. We have solved textbook problems similar to this and have measured velocity in a previous lab, thus students are given limited instructions and increased autonomy in collecting information. Groups are able to collect data, calculate the location, and test their prediction within a one hour class period.

Students measure the constant velocity of both motorized trains, measure the distance between starting locations, identify a common coordinate system, remember the use of vector direction and

signs, and solve simultaneous equations. (Example of solving on page 19) There is a tangible game-like goal of keeping the domino upright that adds to the motivation.

Objective 1: Students will be able to determine methods for collecting data such as distances and velocities to use for calculating an impact location. This lab is designed as a capstone lab for students to exercise the knowledge and skills they have acquired throughout the linear motion chapter.

Objective 2: Students will be able to measure the required values and calculate the constant velocity of a motorized toy train. Students have found the velocity of a ball rolling across a flat table in an earlier lab. In the previous lab students had used a photogate setup. The speed of the ball in the earlier lab was much greater, but for this lab a stopwatch is sufficient. Many students feel more comfortable with the stopwatch and don't even bother to ask for the photogate setup. This gives students an opportunity to apply previous knowledge and skills to a problem even with a change of equipment.

Objective 3: Students will be able to set up and solve a system of equations for the position of two objects on the same coordinate plane with respect to time and solve for the location of impact. Students have performed this calculation in the homework and seen it as an in-class example. This also serves as a nice refresher and review at the end of the chapter.

## **Results**

The biggest positive of this lab is that it is student-driven. With only a few parameters and an obvious visible measure of success, students must choose the methods and perform the calculations from prior knowledge and skills to complete the task. There are a number of skills that students must perform to find the location at the end, making this a multistage and complex problem, which encourages collaboration, debate, and resolution amongst group members.

There are some negatives. For example, the battery power source for the trains changes over time as the batteries drain, thus calculations taken today may not be valid tomorrow after other groups have used the trains. Each group could be given their own set of batteries if the lab needed to be spread over multiple days. I also find it hard to grade the upright domino as a definitive marker of success, as

error is located in the simultaneous release of the trains from exact locations, friction with the side rails, and energy loss in the battery source. Thus, grading is not as simple as I had hoped. I am considering other methods of grading, for example based on how close they come to the predicted position. This lab has affected more than 100 students.

## **Reflection**

The mechanics and calculus in physics courses in the MSE program at UWRF provided further ground-work for helping me teach students to understand and perform this type of problem. The lab activities associated with my MSE physics coursework pushed me to implement more student-driven activities, with my role more as resource than leader.

Simultaneous equation solving is a skill some students struggle greatly with. This lab tends to be good at highlighting the different math capabilities of my traditional students. So for some this is a good challenge with successful results and increased self-confidence; however, others struggle though with help and perpetuate the idea that “physics is too hard for me.” I will continue to use this in the future with the Honors class and take it year by year as I estimate their confidence with the traditional group to perhaps make it less rigorous.

This lab fits well into the Learner Autonomy Theory (Dam, 1995), where students should have activities in which they are in charge. This lab, being a capstone activity, provides the opportunity for the students to take ownership of the knowledge and skills needed to solve the problem presented by the lab. Taking ownership of knowledge and skills is believed to be a key part of student learning. This theory has parallels to inquiry in that it is student-driven, but does not need to form new knowledge.

This lab also follows several levels of Bloom's Taxonomy. Students create a method for collecting data based on prior experience and knowledge. This experience of creating a lab design is an important skill for students to be able to do, and not just in physics. Students need to collect the data such that it can be analyzed and the desired value of velocity can be calculated. This involves thinking several steps ahead in the lab procedure. Finally, students compile their data along with prior

knowledge to construct a solution that is tested with the toy trains.

I have grown in my ability to judge students' abilities and emotions with this lab. This has made me better at walking the fine line between "What do you think? Keep thinking! Have you thought about...?" and providing concrete directed help. I would also like to continue to incorporate autonomy carefully into activities in my classroom to help improve both my teaching and student learning.

**Sources:**

Serway, R. A., and J. S. Faughn. *Holt Physics*. Austin, TX: Holt Rinehart & Winston, 2002. Print.

Chapter 2, Question #15 from Holt Physics Book – My book only had one

problem, and students needed more practice, which inspired me to create this lab.

Blodgett, Dr. Earl. "Physics 700." Mechanics. University of Wisconsin - River Falls. Wisconsin, River Falls. 2011. Lecture.

MSE physics coursework, which further inspired me to create a lab with simultaneous equations.

Dam, Leni. *Learner Autonomy: From Theory to Classroom Practice 3*. Dublin: Authentik. 1995. Print.

## ***WHAT THE STUDENT HAS***

### **Thomas the Train and the Gauntlet of Carnage**

**Objective:** Calculate the location the 2 train engines will collide. Furthermore, place a domino at that location so when the trains collide they sandwich the domino causing it to remain upright.

**Procedure:**

-Select 2 trains you will need to share with a group

-Individually collect data to calculate the velocity of each engine  
(use a meter stick and stopwatch)

-Use the gauntlet distance and the velocities of the 2 trains to calculate the location where the trains will collide. Be sure to identify which train is on the side from which you are calculating your distance.

**Conclusion:**

Place a domino at your calculated location on the gauntlet, place the 2 trains on their respective sides and release simultaneously.

**Lab Report** - On Printer paper, 1 per person

2 pts Data

4 pts Calculation

2 pts Domino position (2 = upright, 1 = fell to side, 0 = fell flat)

Materials:

**Example Solution: (Students do not have this)**

Find the average velocity of the train:

- Measure the time ( $t$ ) for the train to travel a set distance ( $x$ ), usually 1 meter.
- Average the times from multiple trials ( $t_{avg}$ )
- Find average speed ( $v_{avg}$ ) call ( $v_1$  and  $v_2$ ) for each train.

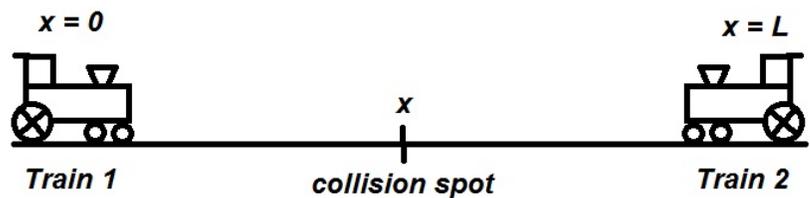
$$v_{avg} = \frac{x}{t_{avg}}$$

Setting up and solving the problem:

$$x_1 = 0 + v_1 t$$

$$x_2 = L + (\square v_2) t$$

- The trains' initial positions are placed on the same coordinate system. Where  $L$  is the length of the track.



- Equations for each train's positions are generated using the average speeds for each train ( $v_1$  and  $v_2$ ).

$$x = 0 + v_1 t$$

$$x = L + (\square v_2) t$$

Note: train 2 has a negative velocity because it is traveling in the negative direction per the coordinate system. And the  $x$  is the distance measured from train 1's location.

$$\frac{x}{v_1} = t$$

$$x = L + \square v_2 \frac{\square x}{\square v_1}$$

- The equations are then solved using a common final location ( $x$ ) reached in a common amount of time ( $t$ ). I used the solve, substitute and solve method here.

$$x + x \frac{v_2}{v_1} = L$$

$$x \left[ 1 + \frac{v_2}{v_1} \right] = L$$

Alternatively, you can solve this by graphing the 2 equations and finding the intersection point, subtract the equations and solve for  $t$ , then substitute back in to find  $x$ , or use rref (reduced row echelon form) to solve the systems of equations in matrix form.

$$x = \frac{L}{1 + \frac{v_2}{v_1}}$$

# Wind Chime Lab

## Description

My original goals in creating this lab were to increase the number of labs in which students collected and interpreted data and then used that interpretation to generate equations and make predictions. I was also hoping to come up with a long term project that would generate a strong positive memory of physics for my students. It also brings physics back from cutting edge particle accelerators and string theory to actually doing something hands-on and tangible, in this case: designing and building a wind chime. Figure 3 shows a student with his completed wind chime.



*Figure 3: Student with his assembled wind*

This lab is based on determining the frequency of a resonating pipe. When the pipes of the wind chime are struck they vibrate and produce sound by creating periodic changes in the pressure of the air around the pipe as it moves back and forth. The frequency of this sound can be influenced by the length of the pipe, the location of support strings, and where the pipe is struck. As the vibrations, or waves, travel along the pipe they reach the end and reflect back. The reflected waves then interfere with other waves. When the interfering waves are in phase the amplitude increases and when the waves are  $180^\circ$  out of phase the waves completely cancel each other out. Each length of pipe has a series of frequencies, known as harmonics, which set up interference patterns that produce areas of large amplitude, antinodes, and areas of very little amplitude, nodes. This is known as resonance. The lab isolates one of the resonant frequencies, the fundamental frequency, which is the lowest frequency. In order to accomplish this, the three factors that influence the frequency need to be addressed: the length of the pipe, the location of support strings, and where the pipe is struck.

In the wind chime lab students experimentally determine the relationship between length and frequency produced by a resonating pipe. The general relationship (Equation 1) was obtained from an

article in *The Physics Teacher* and *The American Journal of Physics*, Where  $v$ ,  $K$ ,  $m$  are parameters of the harmonic and the pipe.

Equation 1: 
$$f_n = \frac{\rho v K m^2}{8L^2}$$

This relationship is different than the one discussed traditionally which focuses on the resonance of the air inside the tube. This equation looks at the resonance of the pipe itself and therefore was obtained from an outside source.

The articles further states that node locations along the pipe for the fundamental frequency are at 22.4% the length of the pipe from each end. The pipes in the lab are hung from locations 22.4% the length of the pipe from each end; this dampens other harmonic frequencies whose nodes are not at these locations and the fundamental frequency is dominant and observable.

The relationship of concern for this lab, a pipe's fundamental frequency is proportional to the inverse of the length of the pipe squared (Equation 2), would be used to calculate pipe lengths for certain fundamental frequencies.

Equation 2: 
$$f \propto \frac{1}{L^2}$$

This relationship was not enough; a full equation is need (Equation 3). The other variables in the general equations were parameters of the pipe and the harmonic number and were lumped into a single “Constant” that could be found experimentally for the pipes used in the lab.

Equation 3: 
$$f_1 = \frac{\text{Constant}}{L^2}$$

In this lab, rather than graph frequency vs. length and find the “Constant”, the equation is manipulated to form a linear equation and frequency is graphed versus  $1/L^2$ . In this case the slope is then the “Constant.”

This is done by the students using LabPros, LoggerPro (made by Vernier®), and a microphone to determine the 1<sup>st</sup> harmonic of different lengths of pipe. The pipes range in length from 35cm to 60 cm and are suspended from the node locations with the microphone placed below the center of the pipe, where the pipe is sounded/struck. Figure 4 shows 2 students using the setup to find the fundamental frequency of the pipe. This forces the 1<sup>st</sup> harmonic to dominate. Students create a graph of frequency versus  $1/\text{length}^2$  to find the linear relationship. The slope of this graph corresponds to the “Constant” for the pipes used in the lab. Students then choose six musical notes for their wind chime, which hopefully sound good together. This is done by either choosing on their own or using notes chosen by the music department. The students can then use their

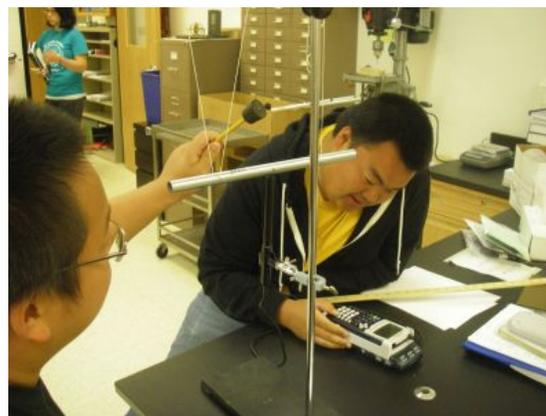


Figure 4: Measuring the fundamental frequency of the pipe.

experimental equation from the graph to calculate the lengths of pipe which resonate at the frequencies they chose. Students then cut the pipe to these lengths as seen in Figure 5, drill a hole at node locations to force the 1<sup>st</sup> harmonic as seen in Figures 6 and 7, file the pipe edges smooth, string the wind chime pipes up and hang the whole structure. Of course many of the choices and results are based on getting the first harmonic to



Figure 5: Cutting the pipe to the calculated lengths.

resonate. So students hang all of the centers at the same height and place the “donger” or striker at that same height. The technical and problem-solving skills students use in completing these building tasks make this a lab unique in combining theory with technical skills.

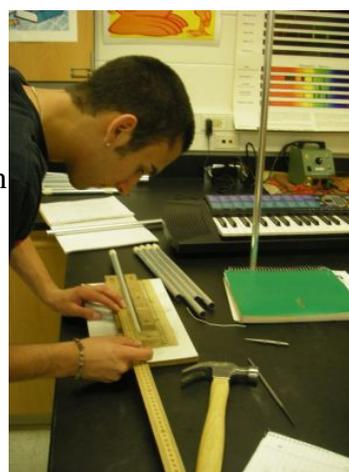


Figure 6: Locating and center punching the node locations.



Figure 7: Drilling the node locations.

Objective 1: Students will be able to accurately and independently determine frequency from an Amplitude vs. Time graph. The independent part of this comes from the expectation that students retained skills from the two simple harmonic motion labs. This is also an objective for students being able to collect data using the LabPro and LoggerPro interfaces, a skill used throughout the year.

Objective 2: Students will be able to input, manipulate, graph and analyze data. This is part of my continued effort to find labs that require data collection, manipulation, graphing, analysis and application. My choice at the moment is using Microsoft Excel®, since it is the program students have the most familiarity with among data programs. This objective gets at one of the core pillars of science and other methodical processes, which is using data to produce a product or results. This skill is applicable across many careers these students may choose.

Objective 3: Students will be able to calculate pipe length and node position using experimental *and* theoretical equations. At this point in the lab students use a spreadsheet checker (a Microsoft Excel® file students access on the school intranet which, when provided numbers from students graphs, will calculate and compare with the numbers students calculated – example seen below) to verify correct values based on numbers they obtained from their graphs. After this point students begin construction and the checker makes sure the students are building the wind chime they want.

Objective 4: Students will be able to critically think to solve problems involved in construction of the wind chime. For many students in my physics classes this is the first time they will have used a pipe cutter, drill press, file, center punch and/or other tools used in construction. This objective gives students a chance to increase their confidence with these tools.

The format of actually building these wind chimes is to take theory and transform it into reality. This gives students a tangible example of how physics helps design and manufacture products. A lot of practical questions come up in this lab that lend themselves well to discussing other physics concepts such as friction, sound, resonance and harmonics. I also like the idea of labs that produce a take-home product for students to talk about and that can act as a physical anchor of knowledge.

## Results

I have had positive responses from students about labs with either a “create and test” or a “test and create” design and this lab is no exception. This lab encourages students to engage in conversation with parents, mainly because it is nearly impossible for a 17-year-old to walk into a house with a wind chime and not have to explain what it is for, so once again, a good school-parent relationship builder. Furthermore, this lab provides an excellent opportunity to collect, graph, analyze data, and finally produce a product from the results.

Getting material for this lab was difficult - including purchasing and transporting 200 10-foot-long ½- inch diameter steel conduit and 200 square feet of Plexiglas®, and coordinating with students in the technical education class who cut out all of the 600 pieces (tops, “dongers” and “wind catchers”) of Plexiglas® with some degree of quality. Grading is also not as clear cut in terms of setting standards and assigning value for the end product. This lab also takes about 5 days from start to finish – a rather large piece of curriculum time. However, the experience and application involved in this lab are worth these inconveniences.

More than 200 students have built wind chimes.

## Reflection

The touting of *The Physics Teacher* in the UWRF MSE mechanics course pushed me to resubscribe and dig through past issues to help improve my understanding and to implement new teaching ideas. This entire lab would not have been possible without the articles from *The Physics Teacher* defining the relationship between pipe length and resonant frequency.

I am still going through a bit of fine tuning and equipment consolidation with the wind chime lab so that it runs more smoothly. We have a better and faster way of handling the Plexiglas piece cutting on the CNC machine (a large computer operated two-dimensional router) in the tech ed area, so we should get our pieces with a higher quality and faster turn-around in the future. I would like to incorporate more discussion about choices the students make while constructing the wind chimes. This would help students to practice verbalizing critical thinking processes they are using. This type of

metacognition has been shown to improve student learning.(Domoinowski,1998) This is similar to the requirement of explaining the *process* used in solving homework problems and the explanation of choices and procedures used in lab notebooks in physics coursework in the MSE program.

This lab also follows the ideas of Bloom's taxonomy. Students move from a theoretical relationship to an actual product with the creation, synthesis, analysis and application of data. This lab also takes hold of the Dewey philosophy of project-based learning (Dewey, 1897). I have been looking to incorporate purpose and practicality to the theory in labs, and the Dewey approach works well for this. Dewey was a strong supporter that learning is facilitated by the piquing of a student's interest by applications involving hands-on learning. This lab takes an object, a wind chime, that students may not associate with physics and links the two in such a way that the student learns the physics to explain and have a deeper understanding of the wind chime's function.

The success I have had with this project-based lab has encouraged me to look into other project-based labs. We have made racquet ball poppers, built small DC motors and done bungee jump calculations for a weighted Winnie the Pooh stuffed animal. We also plan to build speakers next year. (I use "we", because the other physics teacher and I collaborate a lot and do these labs together.) My focus for improving my teaching through the Master in Secondary Education program is to develop relevant activities and increase the use of computer-aided data collection and analysis. I have sought out activities that are enhanced by either an understanding or application of physics. It is through this exploration and development process that I have gained valuable experience and an increased repertoire of activities.

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*The Physics Teacher*. Vol. 36, April 1998. pp. 204-208. PRINT.

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Providing the CNC Machine for cutting out the Plexiglas® pieces

D.C. Everest Senior High School music dept. Personal Interview. 2010.

Providing sets of 6 notes that sound good together

Dewey, John. *The School Journal*, Vol. LIV, No. 3 January 16, 1897, pp. 77-80. PRINT.

Domoinowski, R.L. (1998). Verbalization and Problem Solving. In D.J. Hacker, J. Dunlosky, and A.C.

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Foster, Tim. Personal Interview. 2010.

Junior achievement Leader – What materials work well for homemade wind chimes

Frinash, K.; Richie, Jr., J.P.; Jones, T. “Wind chime physics.” *American Journal of Physics*. 58 (1), Jan.

1990, pp. 82-83. PRINT.

**Schematic:**

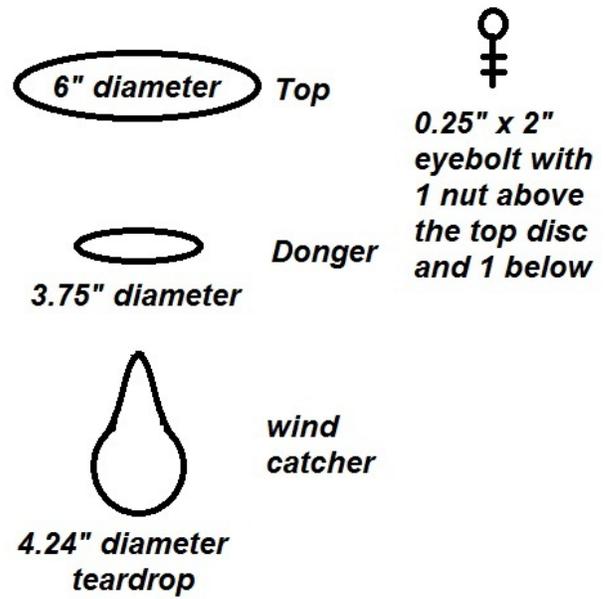
A hole is drilled in the center of the top disc to accommodate the eye bolt. Six string holes are drilled at the outside edge of the top disc to attach the pipes.

A hole is drilled through the eye bolt to allow the string to be tied on.

A center hole is drilled through the “donger” to allow for the string to pass to the “wind catcher”.

We have used both glue and a small hole and concrete anchors and a large hole. The most difficult part is getting the “donger” to hang level.

0.9mm braided nylon rope is used to connect all of the parts.



## WHAT THE STUDENT HAS

### Wind chime Lab

A simple wind chime is a great example of how complex engineering can come from even the most basic piece of equipment.

#### Goal for the lab:

Experimentally determine the relationship between length and frequency produced. Then choose musical notes that sound well together and using your experimental data to calculate the correct length of pipe needed to make the desired note. You will be piggy backing on some physics research to help you as well.

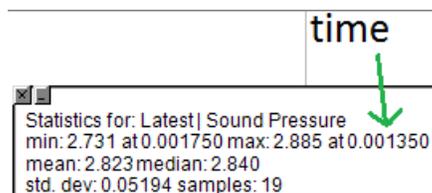
#### Procedure:

##### First, choose 6 musical notes.

- Choose notes that sound good together from the allowable scale.
- Not sure what sounds good together? Try the tuning forks or use one of the combinations on the frequency sheet.

##### Second, gather frequency and length data.

- Create a data table with columns pipe length, time 1, time 2, # of waves, period, frequency.
- Using the wooden mallet, gently sound the pipe by striking it in the center. Try this a few times until you get a consistent sound.
- Make sure everything is plugged in and open Logger Pro on the netbook
- “sound pressure” should be displayed in the lower left corner along with a numerical reading (this means the microphone is connected properly. If not, recheck the first 3 steps
- Using the mallet, gently sound the pipe by striking it in the center. You do not want the pipe to sway under the microphone.
- Click the “collect” button. 
- A waveform should appear graphed on the screen. Silence the pipe so it does not interfere with others data
- Click the “autoscale” button to zoom in on the wave form. 
- Highlight the first peak
- Click on the “stat” button 
- Record the time of the first peak
- Highlight the last peak, click the stat button, and record the time.
- Find the difference between the time of the first peak and the last peak
- Count the number of periods/full waves between the peaks
- Find the average frequency by dividing the number of periods by the time difference.
- Do 3 trials for each pipe length.



##### Third, analyze your data.

- There is an inverse squared relationship between frequency and length, so you will have to graph frequency ( $y$ ) and  $1/\text{length}^2$  ( $x$ ).
- Add a linear trend line; be sure to display the equation on the graph.
- You now have an equation for the relationship between length and frequency.

$$f = \frac{m}{L^2} + b$$

From the graph  $y = m x + b$ , after substitution

- Use the equation to calculate the pipe lengths that correspond to the frequencies you chose in part 1.
- Calculate the locations of nodes,  $0.224L$ . This will be the location of your holes.
- Cross check your answers with the excel sheet >outbox>physics 426>windchime\_data\_xcheck.xls

##### Forth, building your wind chime

- Obtain a piece of conduit
- Measure one of your pipe lengths, mark it and use the pipe cutter to cut it. Choose lengths that will allow you to cut pipes but leave the UPC sticker on a short section of pipe, this way you won't have to clean it off.

- Use the files to clean off the sharp ends.
- Measure from the end of each pipe to your node location, and then drill a string hole.
- Repeat this for each length of pipe
- Figure out how to hang all of the pipes so all of the centers are at the same height, this is where the “donger” will be hung to sound the chimes.
- See demonstration wind chime for putting it together.

**Note to frequency conversions.**

These frequencies keep your wind chime pipes a reasonable length.

“Middle C” is C<sub>4</sub>

Note	Frequency (Hz)
A <sub>4</sub>	440.00
A <sup>#</sup> <sub>4</sub> /B <sup>b</sup> <sub>4</sub>	466.16
B <sub>4</sub>	493.88
C <sub>5</sub>	523.25
C <sup>#</sup> <sub>5</sub> /D <sup>b</sup> <sub>5</sub>	554.37
D <sub>5</sub>	587.33
D <sup>#</sup> <sub>5</sub> /E <sup>b</sup> <sub>5</sub>	622.25
E <sub>5</sub>	659.26
F <sub>5</sub>	698.46
F <sup>#</sup> <sub>5</sub> /G <sup>b</sup> <sub>5</sub>	739.99
G <sub>5</sub>	783.99
G <sup>#</sup> <sub>5</sub> /A <sup>b</sup> <sub>5</sub>	830.61
A <sub>5</sub>	880.00
A <sup>#</sup> <sub>5</sub> /B <sup>b</sup> <sub>5</sub>	932.33
B <sub>5</sub>	987.77
C <sub>6</sub>	1046.50
C <sup>#</sup> <sub>6</sub> /D <sup>b</sup> <sub>6</sub>	1108.73
D <sub>6</sub>	1174.66
D <sup>#</sup> <sub>6</sub> /E <sup>b</sup> <sub>6</sub>	1244.51
E <sub>6</sub>	1318.51
F <sub>6</sub>	1396.91
F <sup>#</sup> <sub>6</sub> /G <sup>b</sup> <sub>6</sub>	1479.98
G <sub>6</sub>	1567.98
G <sup>#</sup> <sub>6</sub> /A <sup>b</sup> <sub>6</sub>	1661.22
A <sub>6</sub>	1760.00

Patterns for possible use

$A_4 - C_5 - D_5^{\#} - F_5 - A_5 - C_6$   
 $A_4^{\#} - C_5^{\#} - E_5 - G_5 - A_5^{\#} - C_6^{\#}$   
 $E_5 - G_5 - B_5 - D_6 - E_6 - G_6$   
 $G_5 - A_5 - C_6 - E_6 - G_6 - A_6$   
 $F_5 - A_5 - C_6 - D_6^{\#} - F_6 - A_6$   
 $C_5 - E_5 - G_5 - A_5 - C_6 - E_6$

Wind Chime Lab Checker with sample data

	A	B	C	D	E
1	<b>Fill in the yellow boxes</b>				
2					
3	107.45	Slope from graph			
4	8.4	Y-intercept from graph			
5					
6			Pipe lenth difference (cm)		
7	Frequency (Hz)	Your length (m)	0-2	2-4	more than 4
8	440	0.499	good	0	0
9	523	0.485	0	close	0
10	622	0.418	good	0	0
11	698	0.654	0	0	recalculate
12	880	0.351	good	0	0
13	1046	0.322	good	0	0
14					
15					
16			Node difference (cm)		
17	Frequency (Hz)	Your length	0-1	1-3	more than 3
18	440	0.112	good	0	0
19	523	0.102	good	0	0
20	622	0.910	0	0	recalculate
21	698	0.088	good	0	0
22	880	0.094	0	close	0
23	1046	0.072	good	0	0

Students input their values from the best fit line on their graph, the frequencies they chose, the lengths and node locations they calculated. The spreadsheet then determines if the number is “good”, “close” or needs to be “recalculated”. This file is on the server for students to access and insures the correct lengths of pipe are cut and node location holes are drilled in the proper spots. The spreadsheet uses a combination of calculations, if-then statements and conditional formatting to produce the results section.