Scientific Inquiry

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Overview

Proposed here in is a complimentary theoretical/hands-on inquiry based laboratory series to accompany a high school physics I course. The series' main objective is to introduce first year high school physics students to scientific inquiry. The process of exactly how scientific inquiry is actually done varies from researcher to researcher however in general the steps are similar. First a testable theory is developed. This theory is then subjected to rigorous testing and analysis. The testable theory must stand the scrutiny of others in the field in order to become widely accepted as standard models for a given phenomena.

Most traditional physics classes include laboratory exercises. In these laboratory experiments certain physical phenomena are investigated. The students follow a set of instructions and perform a "canned experiment" meant to reinforce a concept. Common investigations include; physical properties of mater, motion, forces, energy, momentum, electrical charge, magnetism, waves, light, sound, radio activity, etc… While these traditional labs certainly demonstrate key concepts and make "concrete and tangible" the concept, they do not always help a student to understand how "real investigation" happens for theoretical and experimental scientists. The main focus of this series of laboratory exercises is to develop in the student an appreciation of that process.

Rationale

Watch a baby in a crib before he can walk or talk. On his back he lies stretching his arms and legs in seemingly random directions. A search without purpose, or is it? His eyes dart around his local area: the crib, the bars, his blanket, the pillow, a toy, a mobile... Babies don't see very far and tend to focus on close things. This is the extent of his universe.

If you continue to watch his development over the course of his first year you begin to understand that the motions are not without purpose but are actually experimentation. The baby instinctively knows to experiment test. He uses experiments to learn about the physical laws that operates in his environment. For example, gravity which pulls everything down, his hand, a toy and a bowl of Cheerios. Babies don't just study mechanics but also sound, light, thermal physics and many other disciplines. "To engineer is Human" is a book title from a few years back of some fame. "To experiment is Human" would be another good book title. The main argument is this; *experimentation is as natural to humans as drinking and walking*. If we can help students tap into that innate ability their enthusiasm and understanding can be increased.

Scientific inquiry depends on curiosity. A natural part of human behavior, most children explore and experiment from their earliest years and into elementary school. Unfortunately this innate sense of curiosity often dissipates in time. Many students (even many academically successful students) appear to get a message from school that they should read what they are told to read, calculate as shown in examples and memorize the facts they are presented. If they do these things, they will be successful. By and large the message is clear: curiosity, imagination and experimentation aren't a requirement of the academic world. This was made clear recently when a highly successful student (top 5 in her class and in all accelerated classes) responded quickly to "cut-off" a question I had posed about an interesting and seemingly paradoxical phenomena. I began to ask the class "Have you ever wondered …" she cut me off and said " no, Mr. Iasella, I don't". I wondered how could a bright, driven, hardworking, successful individual achieve so much and yet not have that internal drive to know why. I know from experience that there are many such learners. This proposed laboratory series seeks to enlighten that type of learner.

Science is taught in schools as a very formal course in study. In grade school a way of thinking is taught called the "scientific method". The "scientific method" is a logical progression from 1) observation of at phenomenon 2) formation of a hypothesis 3) use of the hypothesis to make a quantitative prediction 4) design and perform an experiment designed to isolate variables. The method is often taught as a ridged set of rules that must be followed exactly in order for legitimate science to take place. But is it the only way? Did Archimedes, Galileo, Newton, Maxwell, Bohr, Einstein, Fermi, Feynman and other great scientists all proceed according to exactly the same method? As part of the series the students will research some of the most important discoveries ever made and exactly how the scientists arrived at the "eureka moment".

In general, first year physics students appreciate and can get excited about several of the topics included in a first year physics course. Lab experiments can help to solidify concepts but exploration can also be used to excite and engage. The planned physics laboratory series is to be implemented at a high school level. It will begin in the first weeks of school and continue throughout the year. A traditional high school physics curriculum covers the following topics generally in this order; 1) displacement/velocity/acceleration, 2) motion in one dimension, 3) projectile motion, 4) forces, 5) momentum, 6) work / energy, 7) planetary motion / universal law of gravitation / rotational motion, 8) static electricity/electric force / electric fields 9) capacitance / resistance 10)current 11) parallel/series circuits 12) Magnetic Fields / EMF 13) sound waves 14) electromagnetic waves 15) optics 16) relativity.

According to a recent study only thirty percent of American students graduate high school having taken physics. Out of those going to college many do not take physics unless they are going into engineering, science or technical fields. Therefore the percentage of the general population that has any formal training in physics is small.

This fact is amazing when one considers the nature of the world we live in. Technology is everywhere and has become indispensable for modern life. From the internal combustion engine, to the computer on your desk, to the florescent tube for lighting, the majority of people in the United States have no idea how the technology upon which they depend actually works. Furthermore there is one thing essential to the modern world that it cannot do without, energy.

Quality scientific exploration can dramatically increase student interest. If a student starts asking "why" he has then become a self actuated learner. Is this not the true goal of every educator? This series of laboratories is intended to foster that curiosity.

“Critical thinking” is a hot button word in education. Many disciplines strain to develop these skills in students. In physics there is no need to “stretch” in order to obtain critical thinking exercises. In fact, it is in the very nature of physics itself to promote this higher level thinking. The combination of conceptual understanding and the mathematics which allow prediction and analysis demands this type of thinking.

This laboratory series will help to develop exploration techniques. For students the hardest part of a scientific exploration is the development of the hypothesis. It often appears that the students have a mental block which must be overcome. A certain amount of experience is needed before one can develop this ability. The next hardest problem is in developing procedures that allow clear observation of the phenomena being tested. To rid the experiment of variables which impact the results but that are not the ones being tested is a difficult skill to develop.

As Leonard Susskind put it "the process of discovery has always fascinated me. I'm referring to the mental process; what was the line of reasoning - the insight - that led to the eureka moment". These "mental processes" are critical for theoretical physicist and good scientists in all disciplines. Other non-scientific disciplines would do well to develop such thinking skills.

Around 250 B.C. Archimedes gave us the first Eureka moment using logical reasoning methods to develop a way of telling the purity of the gold in a crown. Since that time many have had similar moments. But how do they occur? Can ingenuity and creative thinking be learned? Years of research has shown this to be very difficult to do. (See the article “Critical Thinking, Why Is It So Hard to Teach?” By Daniel T. Willingham)

However at the very least, an appreciation of this process can be learned by students but I believe more than that is possible. The typical high school student has been exposed to far more knowledge than was available to Archimedes. Yet there are many concepts in physics that they do not understand and in fact have never even considered. Therefore explorations can be undertaken which can result in the same “Ah-ha” moments experienced by those great physicists who first perceived the truth. The effect on students of this type of self-directed exercise can become self-fulfilling and inspire the student to strive for more such experiences. These proposed laboratory explorations aspire to that lofty goal.

Objective

Laboratory experimentation has long been incorporated into high school physics. Many physics instructors perform numerous demonstrations in class to illustrate a particular phenomina. The teacher is directing the thought process and with a bit of showmanship he leaves his class wondering how something occurred. However in most cases the students leave it in the classroom. Much like a television show, such demonstrations can be a passinve curiosity.

Actual hands on activities can give a very concrete experience to the student. Traditionally there are student laboratories in a high school physics course. Many “cookbook labs” are done to give the student a taste of hands-on applications. The students simply follow detailed instructions but don’t always become engaged in the questioning. These traditional labs have their place in the classroom as they are very time efficient. They clearly identify and isolate the phenomena being studied. Students can build connections to the theory they are learning and legitimately belong in a physics course. However this paper advocates at least 5 student directed inquiry based laboratories throughout the year.

The laboratories presented here will try to develop the student’s innate curiosity while developing prerequisite skills for logical scientific study. Different aspects of scientific inquiry are identified and laboratories developed to help students gain skill in those areas. Those aspects are: the thought experiment, developing a theory, observation, experimentation and reproducibility.

The thought experiment

An apple falls from a tree. Whether it hits Newton on the head or he just sees it. the important thing comes next. Newton is able to extrapolate and imagine an apple falling on the moon or anywhere else.

Albert Einstein asked a question similar to this one:
Can a person distinguish between the following situations?
1) A person is in an elevator that is standing still at the surface of the earth.
2) A person in an elevator far away from earth and the influence of gravitational fields is accelerates at a rate of $9.8 m/s^2$.

Can the person tell the difference? No. The reference frame is important. One event can be seen from two different vantage points and look like different things. This eventually led to the understanding that we live in something called space-time and the understanding that it curves and changes due to the influence of mass in an area.

Einstein later was able to work out the mathematics for this curvature which predicted just how much space-time would bend due to a certain mass. Realizing that light travels through space and must follow the curvature he was able to make a prediction. That prediction was tested in 1919 by Eddington and thus Einstein's theory was justified by experimentation.

In one way a traditional high school physics class can be seen as a capstone course for a student's compulsory education. First year physics students must apply the many skills they have learned in isolation in a seamless complimentary fashion. The study of physics is an amalgamation of reading comprehension, spatial understanding, tactal exploration, observations, logic and mathematical abilities. In short the "critical thinking" is the educational buzz.

Breaking a physical phenomena down in one's mind's eye is an innate skill to some but one that must be taught and practiced in others if any proficiency is to be developed. Newton and Einstein both had this innate ability but how is this skill developed in others? And further more can the process be made interesting? The answer to both of these questions is "yes".

One teaching strategy called the "discrepant event" is a most effective means to get student's using their mind's eye and can be very engaging. For example the

M.C. Escher drawing) “Waterfall” depicts a scene in which a water wheel is being turned by falling water from a sluiceway (channel). The water then takes a “zigzag” path as it travels “down” a channel back to the top of the waterfall. Of course this can not be true in the “real world”. Most students know this but still have a very difficult time analyzing the drawing. Gravity pulls the water “down” the waterfall but gravity also appears to move the water “down” channels to the top of the water fall.

Students can be guided through the process of logically breaking down this drawing in their minds. They must establish some idea as “true” and then proceed to apply this idea to all cases within the drawing. In this case the “true” idea or principle is that “water flows down, from a high point to a low point”. Once that is established this principle must be used to analyze the water fall. The high point and low point are easily established and the water can be said to be behaving in accordance with our guiding principle.

Now analyze the channel carrying the water away from the bottom of the water fall. It appears to flow “down” but ends up at the top of the waterfall. This can’t be if the “top” of the water fall is higher than the bottom. At this point the students start to realize the “devices” which Escher employs to create the illusion, such as the block work which is stepped in such a way to let the mind interpret the water as going down. Another illusion is the tower columns supporting the unlikely channel structure. Although the columns appear to support the channel in the 2 dimensional drawing they cannot possibly work in the 3 dimensional spaces we live in.

The students can learn to breakdown a problem into parts, apply physics principles and logic. In this case an artistic device can be employed to create a 3 dimensional illusion in 2 dimensions that is not possible in the real world.
This thought experiment did not need to be tested since an adequate explanation was arrived at without the need for experimentation. However some thought experiments can benefit greatly by seeing the actual phenomena. (See Appendix A: Thought Experiment: Analyzing M.C.Echers’s “Waterfall”.)

Centrifugal force causes things to fly out on any spinning object, right? As children this is explained to us and it becomes an axiom. Why shouldn’t we believe in it? After all it is a very old idea and well accepted for thousands of years. Of course since Newton’s time it has been proven wrong. Yet even today most people believe it to be true.

Memories of a playground merry-go-round or a swivel chair on wheels and a rope tied to the stem are all that is required to stir the thoughts of first year students concerning circular motion. Ask the students “where do you sit on the merry-go-round and why? Invariably the students say “the center, because if you are near the outside you will be thrown off by centrifugal force. When a student is placed on a chair and pushed in an arc he will point to the outside of the curve to indicate the direction of force acting on him.

For this experiment to be productive some of Newton’s First Law, *the Law of Inertia* must be well established. It is from this point that the students begin their investigation of the observed phenomena. Newton’s first law is a very powerful idea. It opposes directly any notion of an object going in a circular path, just because. Another force must be acting on the body and it most definitely does not point out. (See Appendix B Centrifugal force? A thought experiment.)

The Rise of a Theory

For a first year physics student the hardest portion of a self directed inquiry laboratory is defining a hypothesis. It’s easy to see the problem when you look at how the lab exercise is typically presented to the class. Students typically start a lab after only a few days of studying particular phenomena. Typically the student has read or learned in lecture about the concepts governing the phenomena and been introduced to algebraic formulations for solving for some desired quantity.

However this is not how theories are developed in the real world. Typically a scientist spends years observing, thinking, scribbling and contemplating connections to other known phenomena. Michael Faraday spent years observing and testing various conditions before formalizing a prediction for the electric field. There is a need for adequate time to allow students to experiment with different manifestations of phenomena. Only with adequate time spent in exploration can patterns be seen and then further developed into a hypothesis.

Sound and ripples in water both have wave properties and both easy to investigate. (See Appendix C: The Making of a Hypothesis)

Observation

Edwin Hubble explored the cosmos using a telescope. He was interested in the stuff of stars. He knew of the science of spectroscopy and employed it to find out what elements were in stars. His diligent observation led to the collection of data with a curious pattern. Absorbsion patterns appeared to be the same in many galaxies but the patterns appeared to be shifted. In fact, the further away the galaxy the more its absorption pattern was shifted towards the lower “red” frequencies. He saw the pattern and this lead him to theorize the expansion of the universe and even predicted a value for that number. It was an empirical number based on his observations and it has been revised over the years but the basic theory has held up.

Copernicus first deduced that the earth and planets revolved around the Sun. So objectionable was this theory that he published his assertion in a pamphlet called "Little Commentary", anonymously. What was at stake was the destruction of the Aristotelian model of how the known universe operated and tied up with that model the power of the Church. The story of Copernicus, Tyco Brache, Galileo and Kepler is one of the most captivating to students. Spanning over 2 millennia this tale has human intrigue, subterfuge, drama, death and triumph. However none of it was possible without observation. The critical data providing proof for Kepler's Laws to be formulated came from the precision observations made by Tyco Brahe.

The students could be brought into this story by having them participate in a detailed long term star observation. From the beginning of the year they could collect data on the moon, visible planets and major stars. At first they will not understand fully why this is being done but as the year advances this data can be used for comparison purposes to accepted values. A few rudimentary paper instruments could be made by the students for this application.

From these observations students can develop predictions about distance, angular speed, orbital periods etc… These concepts aren't familiar to the students in the physics sense at the beginning of the year but are learned gradually. When appropriate and with some teacher facilitation the students can share in the 2 millennium quest started by Aristotle and completed by Kepler and Galileo. (See Appendix D: Distance to stars)

Experimentation

Michaela Faraday's electrical and magnetic fields were at first glance not accepted by many until he could demonstrate its effect. In fact the deflection of the compass needle in the presence of a conductor carrying current was known to everyone. Only Faraday's mind could see the 3 dimensional fields emanating from the wire. His was not purely a theoretical pursuit but rather the combination between observable phenomena and abstract thought. He could however make leaps of understanding. The needle could be moved. He realized that he could move an object with this force which eventually led to the electric motor and later electrical generator. The relationship between the magnetic and electric field was a type of symmetry. Theoretical physicists are always looking for symmetry when they explore phenomena. The experimentation process by which Faraday discovered the electric and magnetic fields can be duplicated by the students. (See Appendix E: The Magnetic Field and the Motor)

Enrico Fermi a physicist who excelled at both the experimental and theoretical physics. He was on the leading edge of quantum and particle physics through the 1930's and 1940's.

Reproducibility

The independent verification of a hypothesis is the cornerstone upon which all scientific thought rests. So important is this concept that any other line of reasoning is deemed to be "Unscientific". The world was "flat" until it was proven through multiple tests and "Magellan's crew" laid it to rest once and for all.

An object traveling through space under a constant acceleration in one direction will travel in a parabola. Since Newton this has been tested and verified by every first year physics students and several moon shots.

Due to time constraints in a typical classroom often labs are not repeated even when the results don't match with the predicted results. This means one of three things. 1) The lab was poorly executed or designed. 2) The hypothesis is wrong. 3) The lab was poor and the hypothesis was wrong.

Many times the student can not tell which of the three possibilities is correct. Time must be dedicated to analyzing the results with respect to the expected outcome. Certain labs are more prone to large variability than others. Many quality experiments fail because of inaccurate readings, additional variables that spoil the result or insufficient resolution of measurements.

Early in a course a series of labs designed to demonstrate to the student the need for accurate measurements and separating of variables should be performed. These skills become the fundamental basis for all subsequent investigations.

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Appendices:

Appendix A: Thought Experiment: Analyzing M.C.Echers's "Waterfall"

Purpose: To exercise the student's imagination and logical reasoning ability.

Background: Many scientists use the thought experiment to use reason to explain a phenomenon even before actual experimentation. In this exercise the students are shown M.C. Echer's "Waterfall". The students' prior knowledge must be engaged to explain the sketch.

Process:
Step1: Have students describe in detail the basic operation of the flowing water.
Step 2: The students should identify the "phenomena" that does not "make sense".
Step 3: Identify the basic physics principles that lead the student to the paradox.
Step 4: Break the problem into parts and apply the basic principles.
Step 5: Evaluate why or why not certain part breaks or complies with the principle.
Step 6: Look for the artistic devices which are employed by the artist to "Fool the eye"

Appendix B: Centrifugal force? A thought experiment

Purpose: To exercise the student's imagination and logical reasoning ability.

Background: We all develop an understanding of physics from first hand experimentation. Whether it is watching a baseball take a curved path or noticing the angle at which rocks skip across a pond. These observations normally lead to an understanding of circular motion which thanks to popular conventional thought utilizes "centrifugal force". This miss-conception is common through out our population. The interesting thing is that most people have enough basic principles already developed to prove this notion is incorrect.

Process:
Step 1: Have students describe in detail how children ride on a playground merry-go-round.

Step 2: Ask what is the “trick” to riding on a fast moving merry-go-round? Where do all the “new kids” get placed?
Step 3: How does the rider get thrown off? (Centrifugal force is usual reply)
Step 4: Next start asking to visualize a car trying to round a bend on an icy road. What happens and why?
Step 5: Identify basic principles evolved in the linear motion of the car. (Newton’s First Law)
Step 6: More examples of things in circular motion. A student on vinyl seats in a school bus or a ball on a flat board moving forward and then swung in a circle. What happens to the ball?

Appendix C: Making a Hypothesis

Purpose: To develop the ability to make predictions about a phenomenon. In other words to predict the relationship between two variables.

Background: One of a child’s first fascinations is playing with water. A child will move his hand through water to make a toy “bob” up and down or toss rocks into a puddle to see its splash. All this “play” is actually experimentation with a purpose. How does this substance differ from the floor, wall, etc..? Why does it flow down? Why is it that a rock will produce a splash and ripples that seem to bounce off a nearby curb? Why do the ripples become smaller as they spread out?

Sound is equally fascinating. Why can a yell produce an echo only in certain rooms? Children must test this out and do much to the chagrin of their parents. Why does the echo fade away with time?

Process: In this exercise the student is to develop an hypothesis. To focus the students they are told to concentrate on the intensity (loudness) of sound.

Step 1: Have students describe in detail what things affect sound loudness.
Step 2: Relate sound waves and sound waves and have the students experiment with a wave tank with a single oscillating point.
Step 3: What represents loudness in the tank and observe the effect of distance from the source has on the ripple.

Step 4: Activate prior knowledge by talking about the energy of the initial rock and how that relates to the size of the ripples created.

Step 5: Once the students relate energy to amplitude of the waves it is a short leap to understanding how the energy is dissipated.

Step 6: The students should be guided to use mathematics to describe what they see. The easiest relationship between intensity and distance is that it inversely proportional. However with a bit more prodding the students will see that as the ripple circle increase the energy becomes spread out and the may bring in the circumference and radius of the circle.

Step 7: Next the students should be asked to consider the intensity of a sound. They should see the analogy clearly and then make the crucial leap that it is a three dimensional problem and therefore it deals with the area of a sphere and its radius.

Step 8: Test hypothesis with decibel meter.

Appendix D: Distance to stars

Distance and displacement are the first topics in physic I. In the classroom we use a ruler or tape measure. But what allows you to take a measurement? First you have an instrument of known length and secondly you can physically touch both points.

But what if you can't physically get to the second point? A modern survey crew uses a laser. Using a mirror at one point a laser beam is sent out of a transit and reflected back. The time delay is measured and using the speed of light the distance determined.

When distances are very far away "standard candles" are used. Light spreads out as it travels further in a very predictable rate. If you know an object's absolute brightness then by measuring the brightness at any location you can calculate the distance. In space we use Cepheid Variables. Due to the specific nuclear reaction going on inside this star its output can be determined no matter where it occurs.

To see this principle in action use a bright projector bulb and a light intensity meter. In a dark room have the students graph light intensity versus distance. The graph should be done on logarithmic paper. The students should recognize a relationship.

Appendix E: The Magnetic Field and the Motor

Purpose: To create an environment of discovery in which experimentation is promoted.

Background: Michael Faraday was a great experimenter. He is remembered to day for his "magnetic field" but he was also the first to put this theoretical idea to a more practical use. He was able to take the notion that a magnetic field interacts with flowing charge and develop a motor. His main inspiration was his imagination and his reason for success was patience. The students will first experiment with the magnetic field around a wire. Next they will identify the nature of the interaction between the magnetic field in a wire and a field created by a permanent magnet. Finally with a little initial help the students make a loop of wire and then test its field. From this loop they develop an actual running motor.

Experiments: Several stations are preset for the students:

Station 1: Draw the Field lines around Permanent magnets using iron filings.

Station 2: Draw Field lines around a wire with current running through it.

Station 3: draw field lines around a wire supported in a magnetic field and perform an experiment to see how the forces act on the suspended wires.

Station 4: Create a multi-loop coil and draw the field lines around the loop using iron filings

Station 5: Make a multi-loop coil attach to a D-Cell Battery with Paper clips and make a motor.