Teaching Critical Thinking and Problem Solving Skills in a Global Environment

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This curriculum unit is recommended for: High School Physics, all grade levels

Keywords: Physics, Critical Thinking, Problem Solving, Simple Pendulum, Photoelectric Effect, STEM education

Teaching Standards: See Appendix 1 for teaching standards addressed in this unit.

Synopsis: I always think of science as being universal for all people. It does not have a political or cultural bias. The law of gravity is the same for all objects, not just people. It does not discriminate; when we trip, we all fall to the ground at the same speed. Is the teaching of science across all cultural boundaries also the same? Will strategies that we routinely use in the US to teach science work in other countries? After spending three weeks in Rwanda sharing science at two different girls schools, I think the teaching of science is the same; we are teaching the same concepts the same formula and use many of the same sources. What needs to change in developing nations and in the US is an increase of the inclusion of technology as a tool to give instruction and analysis. Good use of technology promotes discussion of experimental data to develop students' critical thinking skills as opposed to memorization of facts or cookbook lab activates that many classroom now use in all countries. This curriculum unit describes how to move from a lecture based classroom instruction to more discussion and analysis of data based science classroom.

I plan to teach this unit during the coming year in to 100 students in Physics grades 10,11,12 at East Mecklenburg High School and 150 Rwandan students at Groupe Scolaire Notre Dame de Lourde Byimana, Gitarama, Rwanda.

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Debra Blake Semmler

> *"I try to show the public that chemistry, biology, physics, astrophysics is life. It is not some separate subject that you have to be pulled into a corner to be taught about."* Neil deGrasse Tyson[i]

Introduction

I always think of science as being universal for all people. It does not have a political or cultural bias. The law of gravity is the same for all objects, not just people. It does not discriminate; when we trip, we all fall to the ground at the same speed. Is the teaching of science across all cultural boundaries also the same? Will strategies that we routinely use in the US to teach science work in other countries? After spending three weeks in Rwanda sharing science at two different girls schools, I think the teaching of science is the same; we are teaching the same concepts the same formula and use many of the same sources. What needs to change in developing nations and in the US is an increase of the inclusion of technology as a tool to give instruction and analysis. Good use of technology promotes discussion of experimental data to develop students' critical thinking skills as opposed to memorization of facts or cookbook lab activates that many classroom now use in all countries. This curriculum unit describes how to move from a lecture based classroom instruction to more discussion and analysis of data based science classroom. The change in instruction will reduce the need for expensive lab equipment because the learning of critical thinking skills is in the analysis of data and the discussion of the results and improvements, not in the collection of data.

Classroom and School Environment

I teach at an urban, partial magnet high school with a total population of roughly 2,000 students, with approximately 900 students who are part of the International Baccalaureate (IB) magnet. The school is comprised of approximately 52 % Africans American, 25 % white, 16% Hispanics and 6 % Asian. More than 60% of the student population is on free or reduced lunch. I will be using the curriculum unit in all my physics class and as part of international STEM academy, called Pivot Academy, teaching critical thinking skill in developing nations. A 2016 pilot of Pivot Academy will take place in June-July 2016 with S5 (11th grade) students at Groupe Scolaire Notre Dame de Lourde Byimana, an all-girls Catholic boarding school in Gitarama, Rwanda.

Background Information

The definition of Science is the intellectual and practical activity encompassing the systematic study of the structure and behavior of the physical and natural world through observation and experiment.[ii] How do we go about teaching the structure and behavior of the natural world? It would be impossible for a single person to learn all we know today about the natural world. How many facts do we really need to memorize considering the vast amount of information available in an instant on the Internet? What we need to teach students are the big ideas or major concepts in science and how to do the processes of science. We also want students to understand the ethical, legal and social implication of science. Appendix one contains a listing of the big ideas in science.

There is a strong research base on effective teaching approaches to science and universally they include a strong hands-on, engaging activity approach. So why do most introductory science courses in many high schools, colleges and universities still rely primarily on lectures and recipe-based experiments where students memorize facts and concepts and little opportunity for reflection, discussion or student designed experiment are given? Why do people in developing countries think if you build a science lab and do recipe based experiments, students will be able to apply this new science knowledge to solve problems? To solve problems, students must learn to think systematically. They have to weigh all the options and test their solutions and reflect on the results and redesign, which is applying the scientific method to solve problems.

What is Critical Thinking and why is it important?

A 2014 Wall Street Journal article titled “Bosses Seek ‘Critical Thinking,’ but What Is That?” states that the mention of critical thinking in a job posting has doubled since 2009 to the point that 38,000 management and healthcare posting contained some reference to critical thinking skills.[iii] One of the most used terms use in education today, we want students to be critical thinkers but what does it mean to be a critical thinker? The follow are some of the definitions for Critical thinking.

> *“Critical thinking is disciplined thinking that is clear, rational, open minded and informed by evidence or the mental process of actively and skillfully reaching answer or conclusion”. - dictionary.com*[iv]

> *The ability to cross-examine evidence and logical argument. To sift through all the noise.” -Richard Arum, New York University sociology professor*[v]

"Thinking about your thinking, while you're thinking, in order to improve your thinking."-Linda Elder, educational psychologist; president, Foundation for Critical Thinking[vi]

How can educators teach a student critical thinking? How do we teach students to think?

Critical thinking is often compared to using the scientific method and its procedural approach to the process of answering questions.[vii] It involves practicing problem solving by using the scientific method or the design cycle. Using these procedural methods, students work on the skills involved in applying, analyzing and synthesizing information, and when reevaluating their results. As stated above, it is a method to sift through all the noise to reach a conclusion. Critical thinking skills are about making connections between what students learn, in class or on the Internet, and what is needed to solve real world problems. When comparing the scientific method and the design cycle, the steps are very similar as illustrated in the diagram below

The steps of the scientific method:

1. Ask a Question
2. Do background research
3. Construct a Hypothesis
4. Test your Hypothesis by doing an experiment and repeat the experiment
5. Analyze your results and draw a conclusion
6. Communicate your results

Steps in the design process:

1. Identify the need or problem
2. Research the problem or need
3. Develop possible solutions and select the best possible solution
4. Test and evaluative the solutions
5. Communicate the solutions
6. Redesign

There are a few reasons that teaching critical thinking skills are difficult to include in class instruction. The first is the lack of training and/or lack of information on what is critical thinking and how is it taught within your subject area. The methodology of how to teach critical thinking skills is often lacking in educational courses, in addition to the lack of instructional material involving critical thinking resources. Second, both teachers and students have preconceptions about a subject that restricts their ability to think critically about that subject. The third is the objection by teachers; "I did not learn it this way, so why should I teach it differently than how I learned the material?" How we learned in the past has been changed forever by the easy access to information and to the vast amount of information available instantly. We do not have to teach students to memorize the parts of a cell, they can look it up on their smart phones. What is important to teach students is how to connect the form and function of the cell or to ask why do we have cells at all? The most difficult barrier to adding critical thinking skills in a classroom is time. Teachers are focused on covering an ever-expanding content rather than teaching thinking skills. In addition, a teacher's effectiveness is often based on teaching prescribed non-integrated objectives, measuring student's growth in knowing these objectives with multiple choice test questions. Lecturing is faster and easier than integrating projects and in many cases lecturing is how we were taught. Objective tests are faster to take and grade than subjective assessment. However, research indicates that lecturing and note taking is not the best method of instruction.[viii]

Critical Thinking skills require personal discovery of information, teaching methods to encourage students to learn, discover understand or solve problem on their own. Students are able to evaluate possible answers or solutions by trial and error. Critical thinking requires active learning were students learn teamwork, creative discussion, integration and synthesis of a variety of knowledge.

The following is an example of how a critical thinking activity is different than a just teaching content and would be part of a group of project based learning activities used in a week long academy of thinking and learning.

Teaching Critical Thinking

Surface area verses Volume critical thinking activity

Using 3 half-sheets of 8 ½ x 11 paper and some masking tape, fold two pages into fourths, length-wise and width-wise to form a rectangular volume one tall and one wide the third sheet make the short circular column.

Now ask students to predict which structure will hold more (could be anything popcorn, polystyrene peanuts) or will they hold the same volume because they are all made with the same size paper. Have students record their predictions. Students will now fill the volumes with popcorn to test their predictions. Self-discovery will occur. The circular volume will hold the most, 455 cm^3 compared to the tall rectangular column at 263 cm^3.

Compared to just teaching the formula for calculating surface area and volume of objects, and practicing problem solving from a prescribe book or worksheet, this method of self-discovery will make a lasting memory for most students, but do not stop at just this discovery. Have a discussion of the realization that for the same surface area (the same size page). There are different volumes that can be constructed. Ask students to brainstorm in small groups or individually where this may be important in design of a product, in biology, in engineering, or anything. Ask questions. Why are some cells round? Are all cells spherical? If not why? Why are skyscrapers tall narrow building but most single family home generally shaped like cubes? What about the shape of bags, grain silos, water bottles? This list could be endless. For example, How do you design a water bottle for more water and less bottle, or a house for more interior space less material for walls? When a company wants to sell you less product (e.g. shampoo) but make the container look as big as the previous container? If you have an expensive content in a container, maybe you want more surface area for advertisement and less volume to make the customer feel like they are getting more for their money.

The next step is to have students group together and use what they have learned about surface area and volume to solve a real world problem using the design cycle. It can be anything they brainstormed, from building affordable housing to the design a better water bottle. Learning the concept is quick and easy. The applying the new knowledge to solve a problem takes more time but that is when student learn how to critically think, how to use information to form a conclusion or make decisions, how to apply the design cycle to solve a problem. A YouTube video of this lesson can be found at the following link. [https://www.youtube.com/watch?v=zwBsM92c3h8]

To teach students to think critically, we must have them practice the application of knowledge to solve problems. Take a concept from your curriculum and have students self-discover the concept and then apply that knowledge to real world problems which means the possibilities are limitless and do not have to involve building or designing.

Using Case Studies to teach Science Concepts

Case Study: The Simple Pendulum for Introductory Physics

Another method to teach critical thinking skills, especially in science, involves students looking at the scientific data for a particular concept. For example, any physics lab will include a simple pendulum experiment. The taking of the data for the simple pendulum lab is useful in learning lab technique of using a stop watch, and following directions. The analysis is where the critical thinking skills are learned. Let's look at how to learn to critically think from a case study data analysis. First, start with the following questions for students.

Simple Pendulum
Today we are going to explore how a simple pendulum works. A simple pendulum is a mass or weight at the end of a string allowed to swing back and forth. The period is the time for one complete swing out and back (time for the mass to return to the starting point).

Data for Simple Pendulum

Description of experiment

Students performed an experiment where they hung a 250-gram mass from a string and measured the time for 30 swings for different lengths of string. Student data are shown in the table, and a graph of period and string length follows the table. For a student handout, place the data and graph on the back of the student questions and ask students to answer the questions before looking at the data and graph on the back of the page.

Student Questions:
Prior to reviewing the data

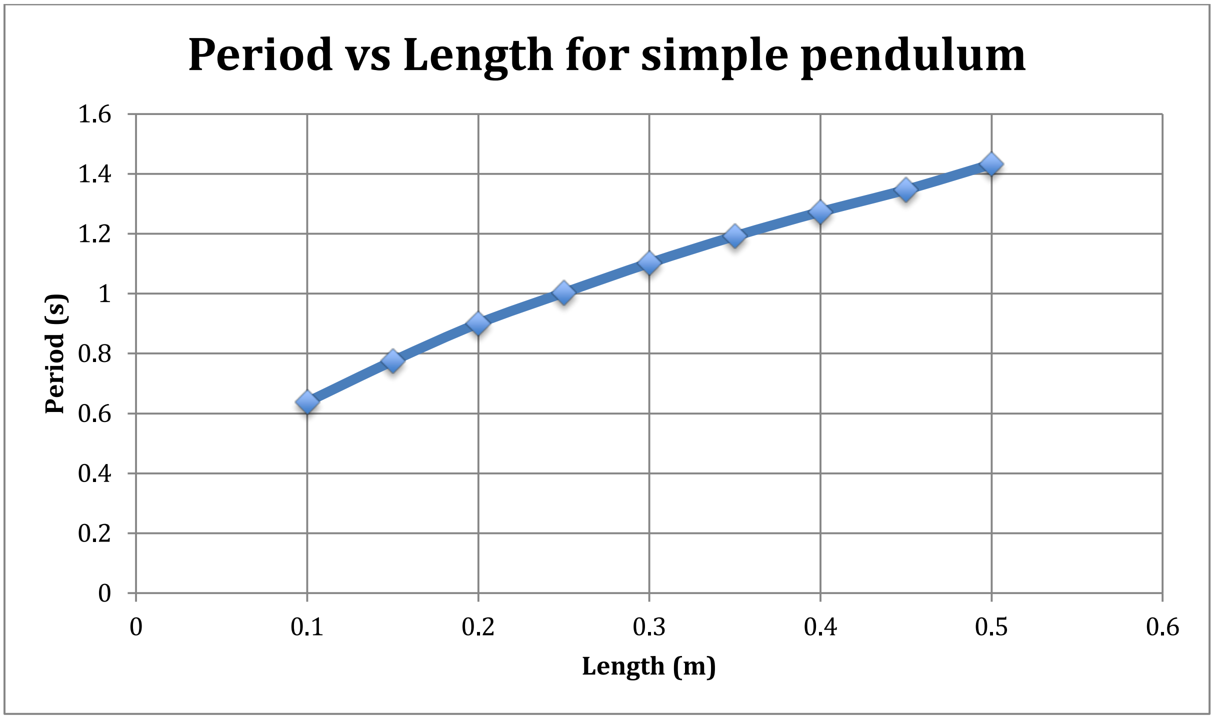
1. Do you think there is a relationship between the length of string for a simple pendulum and the period? If so, what is it?
2. Complete the following statement: As the length of the pendulum increases the period will _________.

Turn the page over and examine the data and graph:

3. Why did the experimenter time the pendulum for 30 individual swings?
4. Why they repeated the timing three times for an average?
5. What are the independent and dependent variables in this experiment?
6. Draw a pictograph of how you would perform the experiment.
7. Study the data and the graph of the results.
8. What is the relationship between the period and the length of a pendulum?
9. How do you know?
10. What would the uncertainty be in the measurement of period based on the data?
11. What would the uncertainty be in the measurement of the length based on the data?
12. Name one example (other than a swing set) where a simple pendulum is used?

Data for simple pendulum, period as length varied

t_1(s)	t_2(s)	t_3(s)	t_{avg}(s)	T_{avg}	L(m)
19.12	19.17	19.17	19.15	.6383	0.10
23.19	23.30	23.27	23.25	.7751	0.15
26.97	27.04	27.04	27.02	.9006	0.20
30.09	30.04	30.16	30.10	1.003	0.25
33.01	33.06	33.09	33.05	1.102	0.30
35.73	35.78	35.79	35.77	1.192	0.35
38.18	38.21	38.16	38.18	1.273	0.40
40.48	40.34	40.45	40.42	1.347	0.45
43.06	42.98	42.78	42.96	1.432	0.50



Graph 1. Period vs. string length for a simple pendulum

Prior to the students viewing the second set of data:

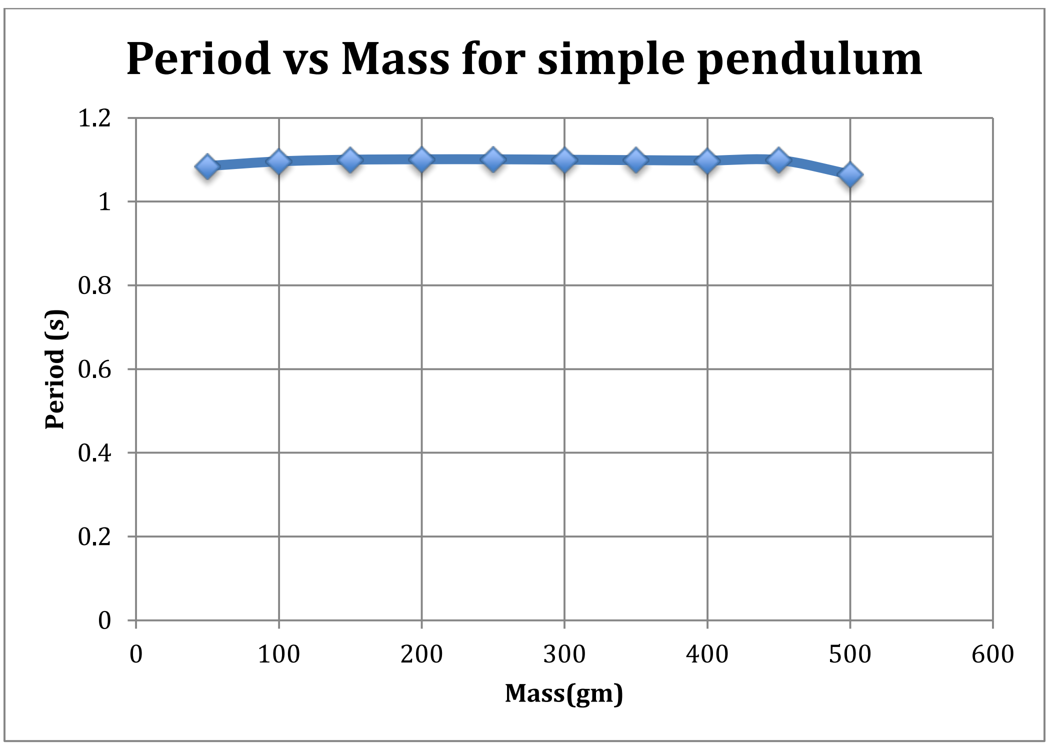
1. What is the relationship between the period of a pendulum and the mass? Complete the following statement:
2. As mass increases, the period would__________.

Now, exam the data for mass and period on the back of your paper:

3. Draw a pictograph of how you would perform that experiment.
4. How does the graph compare to your prediction?
5. What does this mean as applied to the first experiment, how is this result applied in the world?

Data for simple pendulum, period as massed varied

t_1(s)(+/-0.005)	T_t(s)	t_3(s)	t_{avg}(s)	T_{avg}	Mass (gm)
32.57	32.51	32.53	32.54	1.085	50
32.85	32.90	32.88	32.88	1.096	100
33.01	33.01	33.00	33.01	1.100	150
33.06	33.01	33.06	33.04	1.101	200
32.96	33.11	33.04	33.04	1.101	250
32.98	32.99	33.00	32.99	1.100	300
32.96	32.96	32.96	32.96	1.099	350
32.96	32.96	32.94	32.95	1.098	400
32.94	32.99	32.99	32.97	1.099	450
32.86	32.83	32.83	32.84	1.065	500



Graph 2 Period vs. mass for a simple pendulum

Case study for Advance physics students: The photoelectric effect

Background information

At the turn of the twenty-century, scientists experimenting with electricity had discovered something unusual about the interaction of light (EM waves) with metals. Scientists observed that when shining light on a piece of metal, current flow was created. Von P. Lenard, a German physicist, describe his experimental results in a 1902 paper. Figure 1, is his actual experimental equipment design and results[ix]

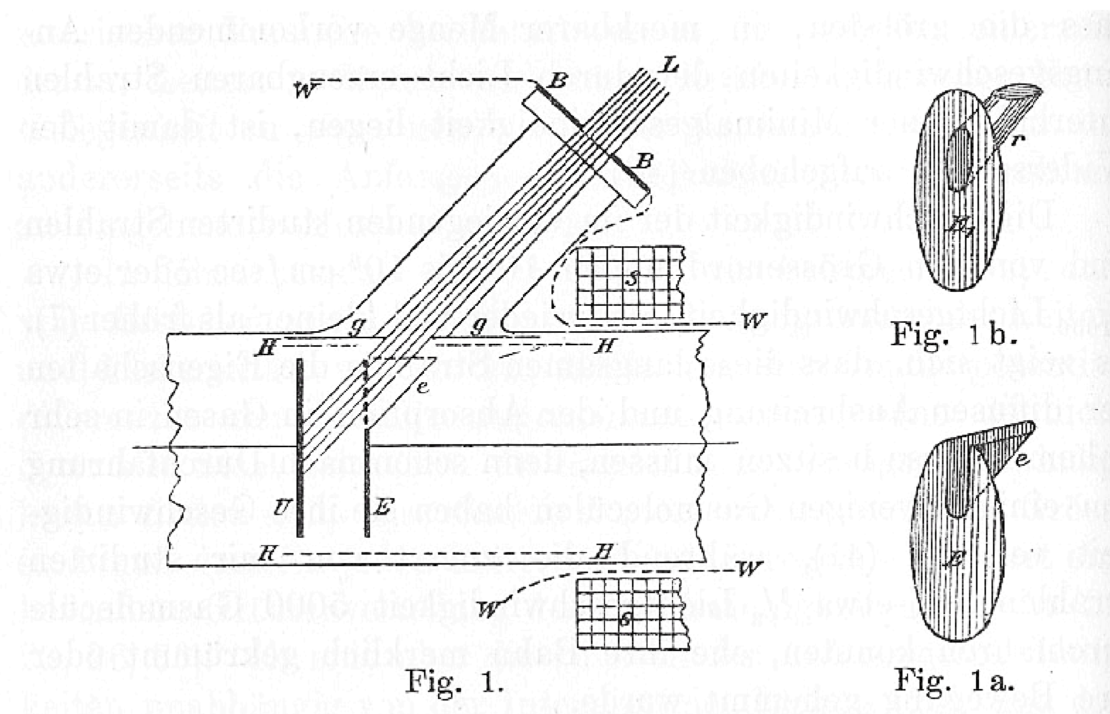


Fig. 1. Fig. 1a. Fig. 1b.

In this figure, a circuit connects metal palates U and E, which are separated in a vacuum by a small gap. One can set a voltage across the plates by modifying the circuit. Light from source L shines onto plate U. The light waves may knock some electrons out of the plate U, causing them to fly across the vacuum to the other plate E, these electrons complete the circuit and current flows. An ammeter is used to measure precisely how many electrons jump from one plate to the other. This current of electrons produced by light is called the photoelectric effect.

In teaching this, I will give students several copies of this experimental design (figure 1 above) and have them annotate the picture and answer the following questions.

1. Where would you place the ammeter? Add it to your diagram.
2. Where is variable voltage source? Add it to your diagram.
3. Show the path of the electrons ejected from the plate on your diagram?
4. Why is this experiment performed in a vacuum?
5. Describe to you partner how this experiment works?

In a new arraignment of the experiment, the voltage between the plates is set such that the source plate U is negative and receptor plate E is positive, the electrons are pushed away from the source and toward the receptor which helps the current to flow. But if the experimenter makes the source positive and the receptor negative, then the voltage across the plates, forces the electrons back to the source. I will ask the student to annotate a second diagram the path of the electrons if the source is positive and the receptor is negative.

In Lenard's second experiment, he started with zero voltage across the plates, and a source current flowed when the light was turned on: electrons were knocked off the source plate with any speed and will eventually reach the target plate. As Lenard gradually increased the voltage difference, fewer and fewer electrons made the journey, and eventually the current disappeared. Figure 2 is the original graph from Lenard's 1902 paper. The potential difference, voltage, is plotted on the horizontal axis, and the current on the vertical axis. There is a small offset from zero current due to Lenard's apparatus.[x] (Note: Kohlebogen mean carbon arc and Zukbogen means arc in English.)

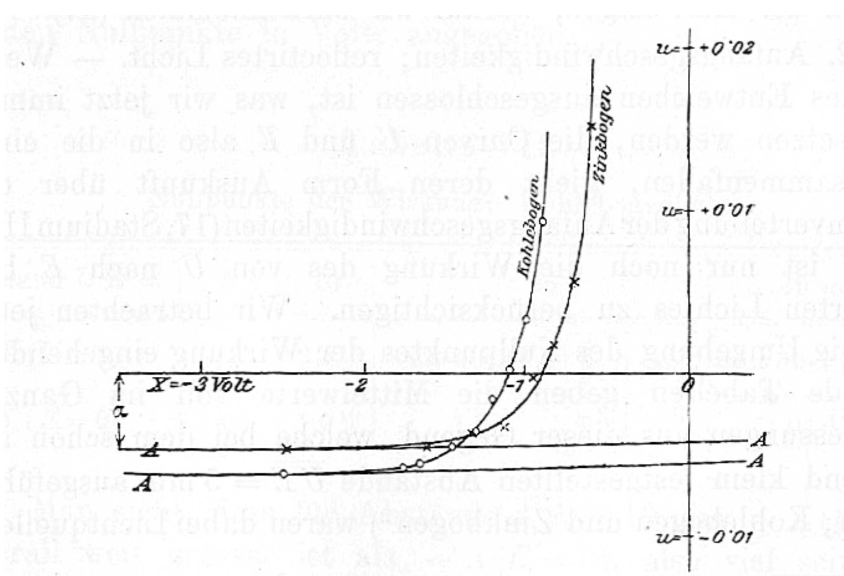


Fig. 2.

I will now have the student discuss the following questions:

1. Describe what is happening to the electron?
2. What is this data telling us about the energy of the electron?
3. Calculate the energy balance.
4. What is an offset?
5. Did Lenard repeat the experiment?

The conclusion I want students to reach though discussion and critical thinking is: As each electron moves from the positive source plate towards the receptor plate, it must do work against the electric field. The electron exchanges kinetic energy for electric potential energy. (Big Idea: conservation on energy) At some point, it loses all its kinetic energy and the electron stops moving forward. When the electrons are knocked free, some have a lot of kinetic energy, others only a little. The ones with the most kinetic energy are the last ones to stop moving towards the receptor as the voltage is increased. The conclusion is the maximum kinetic energy for the photoelectrons is equal to the electric potential energy or

$$KE_{max} = EPE$$
$$\frac{1}{2} mv^2 = q \Delta V$$

From Lenard's data in figure 2, what is the maximum kinetic energy of the photoelectron?

I will ask students to try and explain the photoelectric effect using their knowledge of wave nature of light.

As light waves hit the source plate, the energy of the light waves gives energy to the electrons on the plate. The electrons leave the source plate and move to the receptor plate due to electrostatic force.

Wave theory of light predicts several things:

1. The more intense the light, the more energy the electron will have when they fly off the plate.
2. If the light is very weak and you expose the source plate for long enough time, energy will build up to knock an electrons loose.
3. Wave of any frequency should knock electrons free from the metal given enough time.

Though careful experiment by Lenard, Plank and Maxwell, the above predictions were wrong and experiments showed that

1. The energy of the electron does NOT depend on the intensity of light. Weak light produced electrons with the same kinetic energy as strong light.
2. The electrons always appear AS SOON AS the light reaches the plate even with weak light sources.
3. No electrons are produced if the frequency of light waves is below a critical value.

Einstein suggests a solution

Planck's explanation of blackbody spectrum was published in 1900 and my students have studied Planck's blackbody spectrum prior to this unit. Five years later, Einstein published a paper, in which he used Plank's idea of quanta to explain the photoelectric effect's He wrote:

> "The wave theory of light, which operates with continuous spatial functions, has worked well in the representation of purely optical phenomena and will probably never be replaced by another theory. It should be kept in mind, however, that the optical observation refer to time averages rather than instantaneous values. In spite of the complete experimental confirmation of the theory as applied to diffraction, reflection, refraction, dispersion, etc., it is still conceivable that the theory of light which operates with continuous spatial function may lead to contradictions with experience when it is applied to the phenomena of emission and transformation of light. It seem to me that the observations associated with blackbody radiation, fluorescence, the production of cathode rays by ultraviolet light, and the other related phenomena connected with the emission or transformation of light are more readily understood if one assumes that the energy of light is discontinuously distributed in space. In accordance with the assumption to considered here, the energy of light ray spreading out from a point source in not continuously distributed over an increasing space but consists of a finite number of energy quanta which are localized at points in space, which move without dividing, and which can only be produced and absorbed as complete units."[xi]

Einstein proposed that light behaved not like a wave, but like a particle: the term "photon was not used until 1926 and was proposed by G. N. Lewis.[xii]

Einstein demonstrated through the analysis of thermodynamic and statistical considerations that electromagnetic radiation might be conceived as consisting of finite numbers of discrete corpuscles of energy. His theory is supported by the following facts that lead to this point of view

1. The difficulty with regard to the theory of blackbody radiation

2. The determination of fundamental constants specifically Planck's constant
3. The entropy of radiations found in Wien research
4. The asymptotic form for the entropy of monochromatic radiation at low radiation density
5. The dependence of the entropy of gases and the dilute solution on the volume
6. Stokes' rule
7. The emission of cathode rays through the illumination of solid bodies
8. The ionization of gases by ultraviolet light

His prediction of the linear relation between the stopping potential of photoelectron and the frequency of the light was not supported by experimental data until 1915 when Robert Millikan did an experiment where he measure the photoelectric effect from freshly-scraped surface alkali metals. Figure 3 shows a diagram of Millikan original experimental design. In a vacuum chamber, one of the metal samples was mounted on the wheel W and was rotated 180 degrees to face light shining through aperture O. The frequency of light was change and the resulting stopping potential measured.

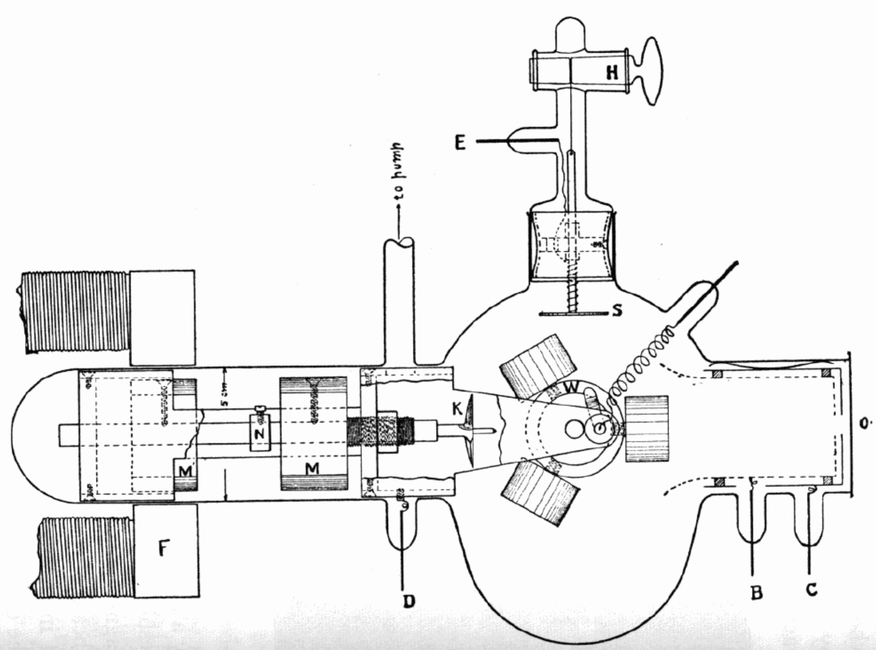


FIG. 28

Figure 3 Millikan's 1915 experimental set-up to measure the stopping potential in the photoelectric effect

In figure 4, Millikan's original data are shown for light of various frequencies on the metal plate and determined the minimum voltage necessary to halt the induced current.

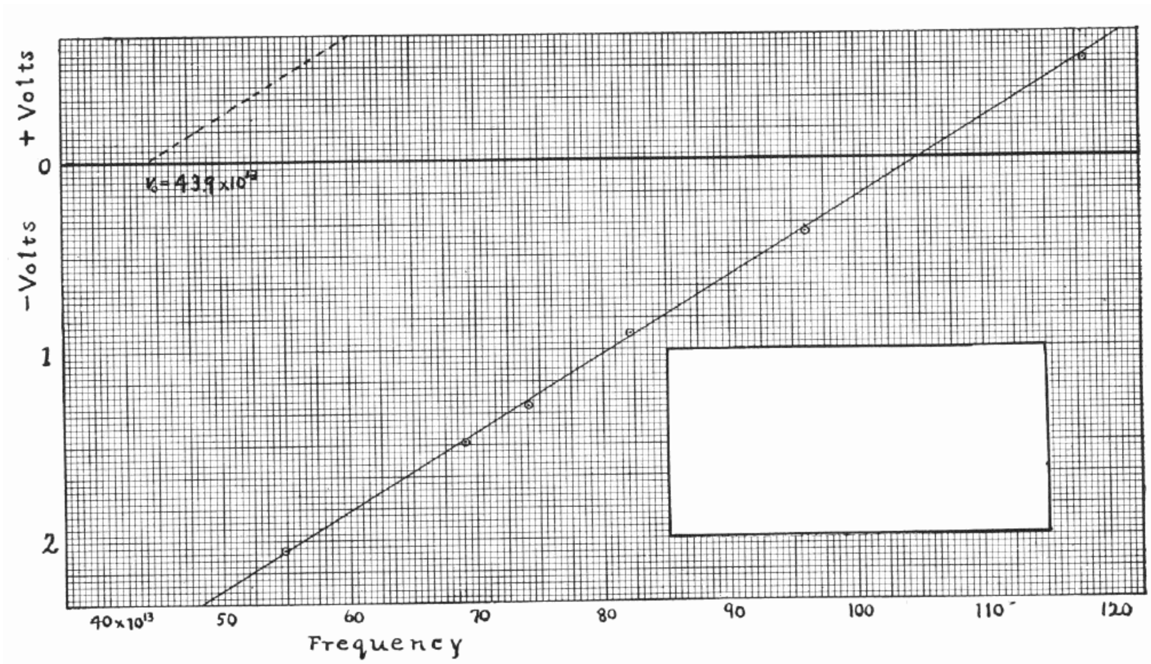


Figure 4 Millikan's 1915 photoelectric effect data. The white box showed Millikan's calculation that I want students to make so it has been removed.

Student questions based on Millikan's original data

1. Does the stopping voltage increase linearly with frequency of the incident light?
2. What is the value of Planck's constant *h* based on these data?
3. How do the data shown in this graph support Einstein's idea of discrete corpuscles of energy or photons?

The answers are that the:

1. The energy of the electrons does NOT depend on the intensity of the light.
2. The electrons always appear AS SOON AS the light reaches the plate.
3. NO electrons are produced if the frequency of the light waves is below a critical value.

I feel this experiment will be much more difficult for students to realize the implications from the data. But having student study the original experimental equipment diagrams and original data, instead of the color coded labeled diagram from textbooks, will make a stronger impression on the difficulty of this experiment. My hope is that students will retain the concepts of photon energy and the experimental support for Einstein’s theory and the processes of science.

Above are two different methods of adding critical thinking skills into a curriculum, experimental case studies and hands on problem based learning. If we work on teaching the big ideas in science using critical thinking skills instead of teaching students lists of facts or objectives on the subject that is growing longer daily, I am confident in the ability of students to learn to be critical thinkers and problem solvers at the same time learn to love science.

Appendix 1

Big Ideas in Biology[xiii]

1. Living systems have multiple mechanism to store, retrieve, and transmit information
2. The process of evolution can explain the diversity and unity of life.
3. Cells are a fundamental structural and functional unit of life.
4. Interdependent relationships characterize biological system and these interactions give rise to emergent properties
5. Biological system maintain homoeostasis

Big Ideas in Physics[xiv]

1. Objects and systems have properties such as mass and charge. Systems may have internal structure.
2. Fields existing in space can be used to explain interactions
3. The interaction of an object with other object can be described by forces
4. Interactions between systems can result in changes in those systems
5. Changes that occur as a result of interactions are constrained by conservation laws
6. Waves can transfer energy and momentum from one location to another without the permanent transfer of mass and serve as a mathematical model for the description of other phenomena
7. The mathematics of probability can be used to describe the behavior of complex systems and to interpret the behavior of quantum mechanical systems.

Big Ideas in Chemistry[xv]

1. The chemical elements are fundamental building material of matter, and all matter can be understood in terms of arrangement of atoms. These atoms retain their identity in chemical reactions.
2. Chemical and physical properties of materials can be explained by the structure and arrangement of atoms, ions, or molecules and the forces between them.
3. Changes in matter involve the rearrangement and or reorganization of atoms and or the transfer of electrons.
4. Rates of chemical reactions are determined by details of the molecular collisions.
5. The laws of thermodynamics describe the essential role of energy and explain and predict the direction of changes in matter.
6. Any bond or intermolecular attraction that can be formed can be broken. These two processes are in dynamic competition, sensitive to initial condition and external perturbations.

Big Ideas in Environmental Science[xvi]

1. Science is a process
2. The earth itself is one interconnected system
3. Humans alter natural systems
4. Environmental problem have a cultural and social context
5. Human survival depend on developing practices that will achieve sustainable systems

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Notes

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[i] Tyson
[ii] Dictionary.com
[iii] Korn 2014
[iv] Dictionay.com
[v] (Korn 2014)
[vi] (Korn 2014) (Korn 2014) (Korn 2014) (Korn 2014) (Korn 2014)
[vii] (Snyder and Snyder 2008)
[viii] (Snyder and Snyder 2008)
[ix] (Richmond, Einstein and the Photoelectic effect 2005)
[x] (Richmond, Einstein and the Photoelectic effect 2005)
[xi] (Peppard 1964) (Peppard 1964)
[xii] (Richmond, Introduction to Modern Physics 2005)
[xiii] (Richmond, Einstein and the Photoelectic effect 2005)
[xiv] (College Board 2015)
[xv] (College Board 2015)
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