An Introduction to Modern Topics in Physics

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Overview

A three week unit of study for high school physics students is proposed herein. This unit's main objective is to introduce the most current scientific theories concerning relativity, quantum mechanics, and the search for a unifying theory in a first year high school physics course. To many people this may appear to be an ambitious and even an unrealistic challenge for first year physics students. In fact, it is traditional not to discuss any of these topics except in upper-level college courses. The following rationale sets the stage for what is intended to be an enjoyable unit for first year physics students and sets reasonable expectations of achievement for the students. Exploring the deepest mysteries of the universe can be fun for anyone who has ever contemplated how the universe began and what is "behind it all." Aristotle knew much less about the physics behind the world he saw than present day high school students. Yet, many of the questions he contemplated are the same as those physicists are still asking today.

Rationale

Why teach nuclear physics, quantum particles, cosmology and string theory to first year physics students? What sense does it make to discuss these topics of modern physics to students whose understanding is so basic? How can they comprehend that "far out stuff" when they can barely grasp the concepts of projectile motion and the equilibrium of forces? These questions are not uncommon criticisms. However, before I develop the rational for why they can be expected to understand (in a conceptual way) modern physics, I would like to explain the reason why the subject should be attempted at all. First I will describe the practical considerations of the subject and then I will appeal to that innate natural yearning for reason and purpose that most human beings have.

Out of a typical graduating class of high school seniors approximately one-third to one-half take 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. Additionally, the vast majority of those people with some physics education never had any lessons on the topics of modern physics.

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.

Today we are embroiled once again in a dispute in the Middle East evolving our military. Why have we been involved in this area and why is it deemed to be of strategic importance to all the presidents no matter what party for the past 60 years? Simple, that three letter word, "oil."

While the politicians argue over the merits of drilling in Anwar, the environmental impacts of fossil fuels or the possibility of the general use of solar cells, the electorate knows very little about the underling technology. In order to talk substantively about the alternatives, some knowledge of the underlying fundamentals is essential to understanding the pros and cons. Traditional physics courses discuss the basics of force, energy, electricity, magnetism and waves, but don't usually get into nuclear physics. This topic is essential if an informed discussion on the subject of energy is to take place.

We have already seen that the majority of the adult population has not had any formalized exposure to the concepts involved in nuclear energy, therefore what is known about it must have been learned through mass media which tends to emphasize those sensational aspects dealing with disasters and fear. This does not lead to a "well informed" electorate.

My second argument for the inclusion of this topic in a first year physics course is that every human being has asked the questions "Where did we come from" and "why are we here?" Cosmology picks up these ancient philosopher's questions and seeks out scientific explanations.

While the actual question of where the universe came from before the "Big Bang" is not known, modern physics has provided sound experimentally verified explanations for many of the things we see in our universe for the past 13 billion years. Much of this evidence has come in the last 30 years and can be shown dramatically using modern instruments like the Hubble Space Telescope.

The stars, galaxies, nebulae, black holes etc… are fascinating to the majority of people even if they don't have a technical understanding of them. The questions that arise from exploring their existence are far reaching and wide ranging. The topics are exciting to students and are for that reason engaging. The study of cosmology requires an understanding of basic physics to appreciate the evidence. It is these connections to classical Newtonian physics, electromagnetism, nuclear physics and relativity that make it the perfect ending topic that ties the whole course together.

Can first year physics students appreciate and understand the wide ranging topics included in modern physics? The answer is yes. It can be very engaging for the students. The planned physics unit is to be implemented at a high school level. It will be inserted towards the end of the second semester. 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.

This new unit will be inserted after electromagnetic waves and replace the relativity unit. As a review of the aforementioned topics shows, the students by this point in time should have been introduced to all the major forces except strong and week nuclear forces. They also have knowledge of waves, light's speed limit, movement in Newtonian reference frames and the motion of planets. As a necessary building block for understanding this proposed unit, the topics of nuclear fusion, fission and radiation will make up the first week of the proposed unit. Basic quantum particles will also be introduced at this time.
With all prerequisites in place, the next two weeks are dedicated to exploring relativity, the relationships between forces and string theory.

It is useful at this point to explore the abilities, pre-existing knowledge, and general interests of typical high school physics students. They often enter physics without any idea as to what they will be learning. Unlike biology and chemistry the study of physics (a subject which attempts to explore the fundamental workings of everything they see) is just too expansive to be tangible. It takes almost 5 months to build up a core of working knowledge that allows the students to investigate new topics with educated scientific exploration. The first step is to understand technical definitions like displacement, acceleration, reference frames, trajectory, inertia, forces, momentum and energy. Along the way the students learn problem solving strategies and develop critical thinking skills. For many students physics is the first and last time in their educational experience they will have to apply the mathematics they have learned in disperse courses to newly learned concepts in order to make useful and accurate predictions.

By the time we start to explore satellite motion and the Universal Law of Gravitation the students are able to use their working knowledge of Newtonian physics to ask informed questions about topics they have heard about but have no real knowledge (stars, black holes, time dialation, speed of light travel, extraterrestrial life, etc.). With the help of concrete experimentation the students develop a trust in the link between the concepts and mathematics. This transformation from the completely guided learner to a scientific explorer is exciting to see. It also leads naturally to exploring the "big questions" in physics like nuclear reactions, relativity and cosmology.

Although these topics could be explored after studying planetary motion, there are bits of physics yet to learn that would help them greatly. In months 6 and 7 electromagnetism and wave properties are covered. With this greater understanding and application experience the students are better prepared to deal with the more abstract and less tangible topics in physics.

The enthusiasm many students show for the "big topics" in physics is heartening to observe. It is also interesting to see their natural skepticism emerge when discussing the possibility of "squashing all of earth's mass down to the size of an orange" or when discussing the "twin paradox" of speed of light travel. Great discussions always arise and with their background in the fundamental ideas of physics these discussions can be termed a "wonderful exploration."

Objectives

This project seeks to develop a three week long unit to explore the following three topics; 1) nuclear physics 2) cosmology 3) string theory. To this point the argument has been made that the necessary knowledge and analytical thinking skills have been acquired by physics students to support a meaningful exploration of these topics. However, while this is true it does not mean that a detailed grasp of quantum phenomenon or the application of Einstein's equations should be expected of high school students.

With the topics selected, what must now be determined is to what depth the topics should be explored. The topics will be introduced in the sequence outlined above. Since "Earth-Space Science" is not a required course in the Pittsburgh Public School system, students often have limited knowledge of space phenomenon. For example, they often do not know the differences between planets and stars, what a nebula is or even why the seasons change on earth. Many of their misconceptions are addressed when planetary motion is covered in month 6 but the explanation of the nuclear reactions in stars cannot be fully explored. The first topic "Nuclear Reactions" will proceed as an extension of earlier class discussions on stars.

Nuclear Reactions

In this section the distinctions between the familiar "chemical reactions" experienced in a burning log and the "nuclear reactions" occurring in the sun will be discussed. By qualitatively comparing the mass to energy output ratio, discussions on energy sources can develop. Basic fission and fusion reactions will be identified. Out of this inquiry some of the basic quantum particles will be introduced. The basic ideas behind quantum mechanics will be discussed.

Cosmology

The distinctions between Special Relativity, General Relativities and all the later "tweeks," although of important to physicists, will not be delineated at this level. However, the concepts of space-time, warpage of time / space, reference frames, gravity's effect on light and the mass-energy relationship will be explored. The class can be expected to be very skeptical of this material and video of real experiments carried out supporting these theories will be very helpful to the students.

String Theory

In the last 3 days of the unit it will be time to start pondering all the aspects of physic covered in the year. "How do they relate?" Throughout the course, time and again old formulas "pop-up" (only with new variables) to describe completely unrelated phenomenon (i.e. Newton's Universal Law of Gravitation and Coulomb's Law). This similarity is not lost on the students. The exploration of string theory and multiple dimensions as a possible solution to what underlies everything is an enticing subject. Certainly showing the Nova special "The Elegant Universe" at this point will draw a lot of lose ends together.

Strategy (Implementation)

The following topics will be introduced to a first year physics class over a 3 week period. The variety of topics have been chosen as to help build for the first year student a common base to explore the many facets of modern physics. Overhead graphics, labs, demonstrations and hands-on activities will be included at various points to help students grasp the topics.

NUCLEAR PHYSICS

500 B.C - Four Types of Matter Earth, Water, Fire, Wind

1800 A.D. – Atom, A fundamental building block of matter that cannot be broken down further.

First year physics students have had Chemistry and all know about the basic structure of the atom. Few however know that matter can be broken down even further. Describing just a few of the particles (quarks, leptons, photons etc…) opens up a whole new world for them to think about. Use of the available internet resources can be a tremendous help to understand the standard model.

The CPEP (Contemporary Physics Education Project) web site and charts were made to be interactive educational resources exploring subatomic particles, nuclear reactions and cosmology. The students are able to explore these resources online. The students are very excited to use these web based educational resources. The self-directed activities have met with very positive responses.

An appreciation of the small particles observed in stars or in high energy particle experiments is essential to understanding the evidence supporting the current theories of an accelerating expanding homogenous and isotropic universe.

Fission and Fusion

The first thing that comes to mind concerning nuclear physics is the atomic bomb. Although it conjures up horrorific thoughts, it and the hydrogen bomb are natural segways into the actual reactions going on. Most students don't know the type of reactions going on in the sun. A comparison of the chemical bonds releasing energy in a burning piece of wood to the nuclear bonds in fission and fusion reactions generates a good discussion.

Radioactive decay can be discussed as a way to introduce subatomic particles. Using the Nuclides chart the students can see how the large isotopes break apart and learn about half-lives and decay rates. The development of this subject is necessary later on to enable the student to understand the cosmic background radiation evidence pointing to an isotropic universe. (See Appendix A)

Discussing the constituent particles involved in radioactive decay is an excellent way to introduce the CPEP chart "The Standard Model of Fundamental Particles and Interactions." The students are able to explore the interactive CPEP website on-line and learn about the all the subatomic particles.

COSMOLOGY

In the past 30 years scientists have been rewriting our understanding of the history and future of the universe. Current understanding is that the "Big Bang" wasn't so explosive and that we don't need to fear the collapse of the universe. These big ideas will be explored with the students along with some historical background. The nature of light, measuring distances in space, the Doppler shift, gravity lenses, and modeling the shape of the universe will all be discussed in turn.

The speed of light is constant, IN A VACUUM. This caveat is often forgotten. Einstein first imposed his universal speed limit in the early 1900's and it has withstood much scrutiny since. With this understanding the famous relationship between Mass and Energy, (E=mc^2) could be developed.

The speed of light does vary as it passes through different medium. This can be demonstrated using a water tank and rod. (See Appendix B)

This speed limit and associated mathematics also has the consequence of disgurgeing anything from being accelerated to the speed of light (300,000,000 m/s), since mass increases as an object approaches light speed and therefore it takes ever more energy to push.

Relativistic Effects and Frames of Reference

As first year physics students the topic of defining a reference frame is not new. However, near speed of light travel and its effects will take some time to get a handle on. The twin paradox will be introduced to show the effects of an accelerated frame of reference.

Graphics on overheads will show how the length of objects change as they are accelerated. The perspective from two different observers helps to illustrate that if velocity is constant, length must change. As proof of this the experiment with fast airplanes and atomic clocks will be discussed.

Distance of Celestial Objects

How are the distances to objects we can't travel to determined? This is a very important ability. The methods have to be believable in order for the student to accept the concepts of billions of lightyears and the expanding universe.

The concept of "triangulation" as a tool to determine distance and location on earth in surveying or search and rescue will be discussed. A hands-on exercise using triangulation to determine location will help cement the idea and lead to understanding the parallax. (See Appendix C)

Wave Nature of Light
(Red *Shift and the Expanding Universe and 12 Billion Years at Least*)

Light has properties of particles and waves. Waves like water or sound have frequencies which can be altered by the medium that the waves pass through (slowing down or speeding up). When a train whistle changes pitch as the train passes us it is due to the relative motion of the train compared to the observer and the fact that the waves are being emitted at a different frequency. The Doppler Effect happens because the speed of the observer affects the sound wave in the medium (air).

However light is fundamentally different from sound and ocean waves in that it does not need a medium in order to propagate. Light can travel through interstellar space, sound cannot.

With that background we can look at the amazing findings of Edwin Hubble. Light can also shift frequency (Change color) if the object is moving away or towards an object (More precisely the space in between them is expanding or contracting) Astronomers knew that the light from distant galaxies was shifted to red. (ROYGBIV)

Shape of the Universe

Current theory says that the universe is much like a flat sheet extending out infinitely in all directions. This is a 2 dimensional analogy to the actual universe. All experimental data points to this kind of universe. Until recently there were three competing models; open, closed, flat. The evidence has thus far pointed to “flat” being the correct interpretation. (See Appendix D)

Gravity Lenses

Sir Isaac Newton proposed that light could be deflected by a massive object (of course in 1687 he did not know that photons of light were massless). Einstein predicted that space could be warped by gravity and therefore changes the path of a photon of light traveling nearby. Since the actual space is curved the light must travel in a curved path around it. At this point a demonstration (See Appendix E) would be used to illustrate the warpage of space.

An English physicist Arthur Eddington tested this theory in the South Atlantic during an eclipse noting the apparent difference in the position of a star which was behind the sun. This difference indicated that the light was “bent” like light going through a lense. To demonstrate the effect of light bending through a magnifying glass (see Appendix F).

Even more fantastic images have been captured by telescopes from light coming from stars and even galaxies very far away. The Hubble Telescope has given us fantastic pictures of the lense effect. (Pictures can be downloaded from the internet and projected on a overhead)

STRING THEORY

How can we tie it all together? (Maybe we need a String)

$F = G\, m_1\, m_2 / d^2$

$F = K\, q_1\, q_1 / d^2$

Every first year physics student learns these equations. For many it is an epiphany moment. The mathematical description for the force of gravity and the electrostatic force have the same form. To see two completely different phenomena expressed in the same way leads directly to the conclusion that they are somehow fundamentally linked.

However for the past half century a link could not be found. Some physicists believe they now know where to look for that connection. “String Theory” holds the promise of explaining all the manifestations of force in nature.

At our current level of technology we can only see structure on the atomic level (individual atoms). Proponents of this theory envision extremely small bundles of energy in a string like form which vibrate. Depending upon how they vibrate different types of matter or energy can be formed.

Brian Green’s “Elegant Universe” is a beautiful way to tie all the concepts from this unit and the entire year together and the PBS Series would be a culminating event.

Appendices:

Appendix A: Hands-on Activity: Measuring Radiation with a *Geiger counter*

It is often very difficult for students to conceptualize small particles that they can't see. To help them believe in things they can't see a few radioactive sources can be used in conjunction with a Geiger counter. Those with speakers are the best for mass demonstrations.

Turn the Geiger counter on and measure the background radiation. Compare this reading with that of a gas light mantle (thorium) or a piece of uranium ore. The students can then explore shielding using paper and metal. How does thickness and density affect the shielding?

Next you can show the effect of how distance can reduce the radiation reaching the Geiger tube. The students can be questioned about why this happens.

Appendix B: Hands-on Activity: *Bending Light*

1) Set out a beaker of water. And lay a pencil beside it. Ask the students to drop it in and observe what happens. (The pencil appears larger)

2) Place a penny in a shallow empty cup. Ask the students to lower their heads until the rim of the cup just keeps them from seeing the penny. Now add water to the cup.
(Eventually the water fills to a point at which you can see the penny)

The speed of light is a constant $c = 3x\ 10^8$ m/s. What is often left out is IN A VACUUM. As light travels through substances it speed can decrease. The effect is that light can be bent if it goes from one substance into another. Both phenomenon depicted above illustrates light can indeed be bent.

Appendix C: Hands-on Activity: *Determining Distances in Space*

Distance and displacement are the first topics in Physics 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 D: Hands-on Activity:

The Shape of Space

What does our universe look like?

Many people have heard of the Big Bang Theory and can picture a 3-D universe that has started at a center point and that in any direction mater has been pushed outwards. This model of the universe would look like a fire cracker exploding.

If this is the case then there aught to be a way of observing the stars to find patterns in them that support this idea.

What would the distribution of stars (as seen from earth) look like?

It depends on where we are within the universe. If one was expanding outward with the explosion you would expect to discern the direction of the center of the universe. The distribution of matter, stars and energy would point this out, right?

Demonstration: Blow up 3 balloons. Put a 1 cm grid on each and place star pasties on each then blow each up to different sizes.

Like these models, no matter in which direction we look we see approximately the same density of stars! Most of these galaxies are moving away from ours. In fact their movement is accelerating! We know this from the "Red Shift" (Doppler Effect) when we look at the light coming from distant galaxies. Note the wave drawn on the balloon is elongating.

Appendix E: Hands on Activity: Warpage of the Fabric of Space due to Gravity

Einstein's notion of space depends not on gravity being an actual force caused by some "invisible string" but rather the natural consequence of the inertia of an object always wanting to travel in a straight line or more to the point the shortest distance. Depending upon the surface one travels a "straight line" may not be the "shortest distance."

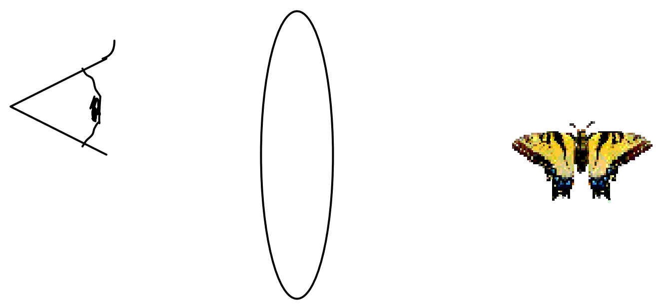
For example traveling around the earth it is often shorter to travel in great arcs rather than trace a straight line. (Demonstrate this with a globe tracing 2 different paths to the same location. Using a string show how the "straight line" can be longer.)

According to Einstein's theory mass (great or small) bends space. The greater the mass the more space is bent. Around an object with mass space is warped into an invited curved cone. This "gravity well" can cause objects with mass or energy to "fall in." If an object has sufficient speed when it encounters this "well" it may orbit the object, like our sun and the planets. A black hole is so massive that even photons of light cannot escape once past the "event horizon." Scientists call this a singularity. In fact, current equations breakdown at this point. Physicists don't know what happens inside a black hole.

Demonstration: Take a very elastic black sheet and anchor on four sides. Tie a small weight on its bottom side to create a divot. Role balls across to simulate the effect of warped space. Note that this is only a 2d model of what is really a 4d phenomenon. It does not wholly represent the complexities of the real world situation.

Appendix F: Hands-on Activity: *Bending of Light through a Magnifying Glass*
Evidence for Dark Matter

Mass has the effect of bending light. In these experiments a magnifying glass will be used to bend an image. Similar effects can be caused by gravity.



Vary the distance to the lens of both the object and the eye. Also change the position of the eye and object. Note the different distorted images you see through the lens. Can you get a position where multiple images form in circle around the object?

(Show images of the lens effect on galaxies from Hubble)

Appendix G: Content Standards

Science and Technology

1. All students explain how scientific principles of chemical, physical and biological phenomenon have developed and relate them to the real-world.

2. All students demonstrate knowledge of basic concepts and principles of physical, chemical, biological and earth sciences.

4. All students explain the relationship among science technology and society.

5. All students construct and evaluate scientific and technological systems using models to explain or predict results.

7. All students evaluate advantages, disadvantages and ethical implications associated with the impact of science and technology.

9. All students demonstrate basic computer literacy, including word processing, software applications and the ability to access the global information infrastructure, using current technology.

Math

1. All students use numbers, number systems and equivalent forms (including numbers, words, objects and graphics) to represent theoretical and practical situation.

2. All students compute measure and estimate to solve theoretical and practical problems using appropriate tools, including modern technology such as calculators and computers.

3. All students evaluate, infer and draw appropriate conclusions from charts, table and graphs, showing relations, showing relationships between data and real-world situations.

4. All students formulate and solve problems and communicate the mathematical processes used and the reasons for using them.

5. All students understand and apply basic concepts of concepts of algebra, geometry, probability and statistics to solve theoretical and practical problems.

6. All students evaluate, infer and draw appropriate conclusions from charts tables and graphs, showing the relationships between data and real-world situations.

Reading

2. All students read and use a variety of methods to make sense of complex texts.

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