Teaching High School Physics With a Story-Line

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ABSTRACT: High school physics curricula are designed to meet a number of goals, all of which compete for classroom and homework time. The process-oriented goals include the development of skills in problem solving, measurement, analyzing data, and research, particularly in this world of internet based, unfiltered information. Content goals, on the other hand, insist on mastery or, at least, exposure to kinematics, dynamics, geometrical and physical optics, fluid dynamics, electric and magnetic fields, circuits, electromagnetism, nuclear physics, relativity, and quantum mechanics. Infusing history and nature of science topics into this already packed agenda is a challenge for even the most gifted of teachers.

KEYWORDS: High school physics, storyline, history and nature of science.

Integrating stories into my teaching of high school physics is not only a common occurrence, but fundamental to the design of my curriculum. Thirty-five years of experience in the classroom has given me some insight as to which stories to include in my course. I look for stories with roots, stories with social and economic consequences that are essential to helping students understand the scientific principles behind our technological world. I use what I call my history-of-science filter to decide which content topics to include and which to omit. I select stories that can build skills and yet maintain the interest of students and keep them focused on the broader picture of science as a dynamic, creative, and engaging field of human endeavor. I string these stories together to construct a *big* story with a beginning, a middle, and an end. The big story is that physics is one strand in the tapestry of human intellectual development. In this paper, I share my story of how stories from history have enriched my teaching experience and given me a different perspective on my role as a science educator.

Ever since I was introduced to *Project Physics* during my second year of teaching in 1972, I have continued to believe that the ideas of science deserve to be taught as an intellectual achievement and not as a set of

Interchange, Vol. 41/4, 335–345, 2010

DOI: 10.1007/s10780-010-9134-z

principles that we teach students to apply mechanically in order to develop their problem solving skills. With each passing year, I have set aside more of the traditional curriculum, and my course has become more and more of a cohesive unit modified by ideas and concepts from the history and philosophy of science. In this paper, I explain my curriculum and provide the rationale for including these ideas in a high school physics course.

Like most physics teachers, my graduate and undergraduate work prepared me to understand physics and showed me some important applications of physics, but it did not prepare me to present physics with a *storyline*. Luckily, I had attended an eight-week NSF-funded institute that exposed me to the knowledge I needed to teach *Project Physics* effectively. More recently, I have been fortunate to have attended two (1998 and 2000) International Seminars in Munich, Germany, on the history of science in science education organized by Art Stinner of the University of Manitoba and Juergen Teichmann of the Deutsches Museum in Munich. With this newfound knowledge and my old, now of out-of-print, *Project Physics* textbook, I have set to work on the task of infusing the history and philosophy of physics into my traditional college prep high school physics course.

My task, though difficult, has not been without support. Both the American Association for the Advancement of Science (AAAS) report, *Benchmarks for Science Literacy,* and the National Academy of Sciences report, known as the *Standards*, (1996) have provided solid backing to my intuition for how science should be taught. The suggested standards for science content for Kindergarten through Grade 12, published by the National Academy in 1996, for example state clearly:

> In learning science, students need to understand that science reflects its history and is an ongoing, changing enterprise. The standards for the history and nature of science recommend the use of history of science in school science programs, to clarify different aspects of scientific inquiry, the human aspects of science, and the role science has played in the development of various cultures. (p. 107)

The *Standards* offer more details with the specification that:

> As a result of activities in Grades 9-12, all students should develop an understanding of:
>
> - Science as a human endeavor,
> - Nature of scientific knowledge,
> - Historical perspectives. (p. 200)

Prominent scientists, like Brian Greene, professor of physics at Columbia University and author of *The Elegant Universe*, have voiced the need for a different approach in the teaching of science.

> Science is the greatest of all adventure stories, one that's been unfolding for thousands of years as we have sought to understand ourselves and our surroundings. Science needs to be taught to the young and communicated to the mature in a manner that captures this drama. We must embark on a cultural shift that places science in its rightful place alongside music, art and literature as an indispensable part of what makes life worth living. (2008)

The task of translating these goals into successful classroom activities has been the focus of my energies.

To bring Greene's sense of adventure to my classroom, I need to tell stories that capture the curiosity and wonder of my students. Have you ever talked to fourth graders about the Big Bang? They have no understanding of the isotropic nature of the background radiation or of mathematical singularities, but they have no problem latching onto the big idea and responding with the wonder and amazement that it deserves. Can I help students think of science as inspiring as opposed to thinking of it as cold, distant, and intimidating? Instead of presenting all the tedious details and then climbing up the ladder to the big picture, can I do it backwards?

This leads me to my first dilemma: Which stripped-down stories to choose? Using what I call my history-of-science filter, I have established three criteria:

- concepts with roots,
- concepts that are essential to appreciate contemporary developments in science and technology, and
- concepts with social and economic consequences.

My current course reflects this thinking. It is divided into three, roughly equal parts: the first part includes motion, force, energy, and the Newtonian world view (concepts with roots); the second part covers waves, sound, physical optics, and light, but focuses on the wave-particle duality (concepts that are essential to appreciate contemporary developments in science and technology); the third part is an introduction to electricity and magnetism in the context of social and economic consequences. I painfully exclude some of my favorite topics: rotational dynamics, fluid dynamics, heat and thermodynamics, geometrical optics, nuclear physics, most of atomic physics, and relativity. I must swallow hard when students tell me they knew only one-half of the questions on their SATII test. I continue to fight off all pressure to align my course with the syllabus prescribed by the College Board for their Advanced Placement Physics B course and stick to my historical storyline, trusting that it provides me with a defensible way to define for myself what is relevant and what is not. I include only those topics that fit into my overall themes.

Likewise, my history-of-science filter helps me achieve a suitable balance between process and content. I translate the recommendations in the *Standards* into a very broad and generalized set of goals. Students should

- appreciate the beauty of science,
- view science as dynamic,
- understand the role of experiments and data,
- understand criteria for evaluating theories,
- see connections among disciplines,
- understand the work of a scientist within society, and
- view physics as one strand in mankind's intellectual tapestry.

Classroom Implementation of Goals

My stories on classical mechanics have four lead characters: Archimedes, Aristotle, Galileo, and Newton. The story of Archimedes provides an example of an engineer, as well as a philosopher. Born in Syracuse, Sicily, in 287 BC, educated in Alexandria, Egypt, his work comes closest to what we would label as true science. The crux of modern science is corroborating theory with measurement. In the "eureka" story, Archimedes compares his measurement of the volume of the king's crown (as obtained by water displacement) to the volume of an equal mass of pure gold. When the crown's mass does not match the theory, the goldsmith is executed. Despite the limitations of ancient Greek philosophy, formal science was born in ancient Greece, and Archimedes was its prophet. "Give me a lever and a place to stand on," he said, "and I can move the earth."

Archimedes is an indispensable figure in my story because of his inventiveness. He should be remembered for applying this knowledge to create the fields of statics and hydrostatics, discover the laws of the lever, buoyancy, fluid equilibriums, density, the center of gravity, and so on. He invented or improved war machines, compound pulley systems, planetarium, water screw, water organ, and burning mirrors. Archimedes was a man of his times and, true to Greek thinking, these achievements in applied science and manual activity were considered much less important to him than intellectual activity. He is a fine example of someone who experienced the excitement of mathematical science. Legend has it that he often spent days working on a problem, forgetting to eat or bathe. He would write his problem solutions in the sand. He figured how to determine the area of a circle, the quadrature of a parabola, described the first infinite geometric progression, and the surface area and volume of a sphere. I tell my students the story of Cicero finding his tomb – a tomb that was adorned with a cylinder and a sphere to highlight his analysis that the ratio of the volume of a sphere to a cylinder was 2:3. The story of Archimedes gives students an understanding of the differences among engineers, artisans, and scientists. My students understand from the very first that physics is a creative process. Unfortunately, the creativity of modern scientists is hidden from the layman in the complex language of mathematics.

My second chapter outlines the beginnings of modern science. Once again, a Greek takes center stage, but the focus here is to compare Greek philosophy with Renaissance philosophy in order to understand the underpinnings of the modern scientific method. The Greek philosopher is, of course, Aristotle (384 BC-322 BC). His incredible achievements in areas that range from astronomy to biology made him an authority figure of legendary proportions. As such, he championed views of moderation and acceptance of life as one finds it – an ethical standard that appealed to the Church of the Middle Ages.

Aristotle developed a model that divided motion into two types. Natural motion is not caused by force but arises from the intrinsic nature of objects; objects *strive* to reach their natural state. Rocks fall naturally until they reach the ground, their natural place.

Violent motion is motion that disrupts the natural order of things. It is caused by forces. Lifting a rock above its natural location (ground) is an example of violent motion.

The framework for Aristotle's concepts was the hierarchy of the four elements: earth, water, air, and fire. We spend much time talking about the intuitive, common-sense appeal of this theory. We use it to explain the motion of smoke through air, the motion of steam through air, the floating of Styrofoam on water, and the position of clouds. I emphasize the intellectual achievement that this model represents; it was a satisfactory framework for viewing the world. It was intuitive and self-consistent; there was no need for an experimental basis since the senses are an imperfect means of obtaining truth.

By contrast, Galileo devised an experiment to prove that heavy objects do not strive to reach their natural place more than a light object and, therefore, do not fall faster than lighter objects. In fact, he claimed that all objects, regardless of mass, will fall with the same acceleration.

We recreate a version of Galileo's lab to learn about his views and methods:

- Galileo used an indirect method to prove his hypothesis. Since measuring instantaneous speed was difficult, he used algebra to connect variables that could be measured (distance and time);
- Galileo used the ramp to *dilute* gravity – to slow down the fall so that accurate time measurements could be made with crude timing devices such as metronomes or water clocks;
- Galileo understood the importance of experimental precision. He stated that his measurements were "accurate to within a heartbeat."
- Galileo extrapolated his data to increasing angles of inclination to arrive at his conclusion at 90 degrees (freefall);
- Galileo made a leap towards idealization by eliminating considerations of friction as a "first approximation."

We spend much time discussing in class why Galileo can be considered the "father of modern science," and we talk about how scientists today follow a version of these investigative steps: construct a model, predict results, design an experiment to test predictions, interpret observations, compare to prediction, and revise the model as needed. Even though every scientist works in his own way, this sequence of steps embodies the spirit of how scientists work.

To complete the classical mechanics chapter, there needs to be a scene dominated by Isaac Newton, with Galileo, Copernicus, Brahe, and Kepler playing important supporting roles. I cast Newton as the man who provides the world-view that is lacking in Galileo's work. We learn about the role of theories in science by considering the history of astronomy as demonstrated by the indicated scientists:

- Copernicus, in removing complicated equants and epicycles, is a good illustration of how scientists value simplicity and beauty;
- Brahe's work allows me to emphasize the importance of data in formulating theories;
- Kepler is a fine example of how mathematics is useful in science; his work exemplifies the need for data and also the need for knowledge of the precision of the data. Kepler tried to fit circles for the orbit of Mars to Brahe's data but found that they were always at least eight minutes of arc off, an eight minutes that is more than the precision claimed by Brahe;
- It is also easy for students to see how Kepler's work led to Newton's gravitational force law'

- Galileo met considerable resistance; people rightly will not give up familiar and successful ideas without good reason;
- Competing theories are common in science. It is important to recognize that theories that are judged to be less useful in modern terms served an important purpose in pointing the path to later research.

The other aspect of Newton's work is what I call the Newtonian synthesis. I outline the view of the Greeks: perfection in the heavens, natural circular motions of the heavenly bodies, and their belief in the *specialness* of the heavens where earthly laws did not apply. Then we discuss the implications of Galileo's telescopic observations of sunspots, moons around other planets, comets, variable stars, and the imperfections on the surface of the moon. With this background in mind, we discuss the reasons why the application of Newton's laws can be labeled with the word "synthesis," namely,

- it attributes the same cause, gravity, for many diverse phenomena: tides, value of the acceleration due to gravity on any planet's surface, the motion of the moon, the motion of the planet, the wobble of the sun, and so forth;
- it brings together the work of all the scientists before him, and
- it unites *earth* physics with *universe* physics and sets aside the old Greek idea that the laws of physics do not apply in the heavens.

I view my course as telling a story with a beginning, a middle, and an end. The middle follows the same plot as our work on classical mechanics. The section on the wave-particle duality features theories from Newton, Hooke, Young, Huygens, Kelvin, Planck, Einstein, and Feynman. We focus heavily on the particle-wave debate that occurred during the 19th century. The work of Feynman (1985) on quantum electrodynamics allows students to see how theories progress. The ending of my physics story covers electromagnetism and features the work of Faraday and Maxwell. Here the emphasis is on the interplay among science, technology, and society. The engineering achievements demonstrated in the development of the motor, the transformer, the speaker, and the generator are considered.

The Role of Theories in Science: The BIG Story

The story of how science progresses must be told in a unified way if students are to understand its relevance to their lives and their futures. The defining activity of science is the formation of theories, and it is only fitting that it be the glue that binds the stories together, forming the *big* story. We spend time talking about why theories are *useful* or *not useful*. I make sure that I present some theories that have not stood the test of time so that students can understand the process by which theories come to dominance. I discuss in detail, early in the course, a set of criteria by which theories can be evaluated. After we conclude each portion of the course, students are asked to give examples of how scientists constructed useful theories. Below are the criteria and some examples.

Criteria for Evaluating a Theory

Examples From My Course

Criteria	Example
A good theory should agree and not conflict with a body of tested observations.	Ptolemy was trying to predict successfully eclipses and motions of the planets when he proposed epicycles and equants.
There is nothing more practical than a good theory.	Archimedes' work on hydrostatics enabled him to propose changes in ship building.
A good theory should permit predictions that, sooner or later, can be tested.	•Galileo predicted that objects would fall at precisely the same rate in a vacuum, a space devoid of air and, therefore, free of air resistance. It was many years later that Hooke built a vacuum pump that could be used to support Galileo's assertion. •Newton predicted from his particle theory that the speed of light in water would, eventually, be measured and found to be faster than in air (he was wrong).
A good new theory should give almost the same predictions as older theories for the range of phenomena where they worked well.	•Equations from Einstein's relativity are consistent with those from classical mechanics for speeds that are not close to the speed of light. •Quantum Electrodynamics had to predict the same results as Young's experiment and Huygens's work on diffraction, etc..
Every theory involves assumptions. Some also involve the esthetic preferences of the scientist.	•Copernicus felt that the sun should have a more special place in the universe than the earth. •Wave theory assumed that there was a medium through which light travels.

A new theory relates some previously unrelated observations.	Newton's gravitational force law connects the "wobble" of the sun to the motion of the planets to the tides, etc.
Theories often involve abstract concepts derived from observation.	Kepler's idea of an attractive, non-contact force between the sun and the planets is abstract.
Empirical laws or "rules" organize many observations and reveal how changes in one quantity vary with changes in another, but such laws provide no explanation for the causes or mechanisms.	•Kepler's law of periods is simply a relationship between orbital radius and period. It offers no information about the causes. •The wave equation implies that the wavelength of a wave is inversely proportional to its frequency.
Theories that permit quantitative predictions are preferred to qualitative theories.	•Galileo's work on free fall depended on his use of algebra to justify his indirect test (replacing the measurement of fast speeds with measurable variables of distance and time). •Young applied the formula of interference to predict the wavelength of various colors of light.
Communication among scientists is an essential part of the way science grows.	•The Greeks were hampered by the artificial division between philosopher and artisan. •The availability of books in the Renaissance was one reason for the successes in science during that era. •The founding of institutions, like the Royal Society of London helped science to flourish during the age of the Enlightenment.

Predictions from theories may lead to the observation of new effects.	•Proponents of the heliocentric theory predicted that parallax of the stars would be observed. •Newton predicted that the pull of the planets on the sun would cause the sun to travel in small ellipses. This should be observable as a "wobble" in the sun's position. Astronomers did, eventually, detect such a "wobble". •Proponents of the wave theory predicted that light would interfere as it diffracts around a circular barrier to produce a bright spot at the center.
Theories that later had to be discarded may have been useful because they encouraged new observations.	•Aristotle's theory on motion allowed for advances in warfare technology and Roman engineering success. •Wave and particle theories have been incorporated into our modern view of light.
An "unwritten text" lies behind the statement of every law of nature.	Newton assumed a knowable universe where cause and effect can be linked and where properties of matter were the same in the terrestrial and celestial realms.
Some theories seem initially so strange that they are rejected completely or accepted only very slowly.	The geocentric theory seem to conflict with the common sense notion that the ground we stand on could not be moving through space.
Models are often used in the making of a theory or in describing a theory to people.	The behavior of light is more easily understood by referencing a model of a particle or a wave.
The power of theories comes from their generality.	The wave theory helped to understand interference and diffraction of sound and light. Relativity came to replace classical mechanics because it applies to very large masses and very large speeds.

Criteria adapted from Rutherford, Holton, & Fletcher (1981, p. 240).

The creativity involved in constructing theories encourages students to think carefully about what they know and how they can make sense of it. The geocentric theory, for example, becomes a set of ideas that can be evaluated with a yardstick other than truth or fact. Science becomes dynamic, and even adolescents must adjust to the uncomfortable presence of uncertainty and begin to sort out the *shades of gray*.

Conclusion

There is no prescription that will make all my students treat physics in the same way as a fourth grader listening to the story of the Big Bang. I can say that I enjoy answering questions about how Galileo made the connection between free fall and an inclined plane much more than questions about which formula to use on problem #11. It has encouraged me to use some of my classroom time in ways that are less mundane, and I know that some of my students find physics to be less intimidating and tedious. I still teach students how to construct and use a spreadsheet in analyzing their lab data, and I still teach them how to use units effectively in problem solving, but I also share with them why science is an adventure and a tribute to the spirit and wisdom of the whole of the human race.

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