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Incorporating Scientific Methodology Into Introductory Science Courses

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Abstract

In thinking about how humankind might do better in the 21st century than it has in the 20th, we might ponder science's most basic value: *All ideas are subject to testing by experience and to challenge by critical rational thought.* This value might itself be science's most important benefit. This article describes how to incorporate lessons about scientific methodology into existing science courses. Historical examples, such as the history of astronomy from Pythagoras to Galileo, are useful. "How do we know" is always a valid question: How do we know that things are made of atoms? That the universe is billions of years old? That Earth is a sphere? And so forth. "Models" can be illustrated by three common atomic models: Greek, planetary, and quantum. The limitations of a theory can be illustrated by the special relativistic, general relativistic, and quantum limitations of Newtonian physics. Galileo contributed experimental testing, idealizations of real-world conditions, limiting the scope of the inquiry, and quantitative methods. Scientific unification can be illustrated by historical examples. The core of science's method is the use of experience and reason, rather than emotion and prior beliefs, as the guide to knowledge. Science does not seek absolute truth.

David Keeports and Dean Morier have described an interesting course about the scientific method (Keeports and Morier 1994), and have argued convincingly that every college student, especially nonscience students, should gain an understanding of how science works. Other recent *JCST* articles have made a similar point (Ganem 1993; Bates and Culpepper 1991), as has the American Association for the Advancement of Science's educational reform project (Rutherford and Ahlgren 1990).

This article describes ways in which teachers can incorporate lessons about scientific methodology into any existing introductory science course.

The Importance of Teaching the Methods of Science

Scientific methodology is a topic of much more than merely academic interest. The basic contradiction of our time is the one between the scientific knowledge that makes this the "scientific age," and the irrational ways in which that knowledge is used. The twentieth century has been torn by rigidly held political, religious, ethnic, national, and economic ideologies, all of them held with complete conviction and yet most of them in contradiction with each other. As a result, the potentially helpful power and insight of science has been often overlooked or misused, and scourges such as war, prejudice, fanaticism, needless disease, overpopulation, and pollution, have flourished. The danger in these ideologies lies not so much in the beliefs themselves as in their absolute nature. Even wrong or harmful beliefs can be corrected if one is willing to trust experience and to be intellectually honest, while correct and healthy beliefs can become dangerous if accepted uncritically or absolutely.

Thus, in thinking about how we might do better in the twenty-first century than we have in the twentieth, we should perhaps ponder science's most basic value: *All ideas are subject to testing by experience and to challenge by critical rational thought.* It is a practical, simple, but painful and demanding code: be open-minded, observe the real world, and think hard. It is a code that has worked surprisingly well for science. This code, the scientific way, might itself be science's most important benefit. Perhaps I am naively optimistic about the possibility of popular cultures adopting some modicum of rationality, but it seems to me that a consistent emphasis on scientific methodology in all science classes at all levels could help pull the world through its present crisis of emotionally-held belief systems.

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Because it is hard to look honestly at the real world, scientific methodology needs to be emphasized again and again in all introductory science courses. In addition to specialized courses in scientific methodology, such as the one that Keeports and Morier describe, science teachers can incorporate these ideas into every science course, whether for scientists or for nonscientists.

This article is directed to teachers of introductory science courses, in order to facilitate the incorporation of scientific methodology as an ongoing theme in those courses. It is based on my 20 years of teaching a large (220 students every semester) liberal-arts physics course at the University of Arkansas. Perhaps other instructors who feel as I do about the importance of scientific methodology will benefit from these suggestions. None of these teaching ideas are new, but the idea of incorporating many of them into a "standard" introductory science course, and thus making scientific methodology one of the ongoing themes of the course, deserves wider attention.

Use Historical Examples to Teach the Methods of Science

The methods that scientists have actually used are so varied and subtle that it might be a mistake to try to boil scientific methodology down to a single "Scientific Method." Thus, rather than discussing scientific methodology in isolation, I prefer to present examples of the methods of science in action and then draw lessons from those examples. At Arkansas, these examples occur throughout the semester, and form one of the themes of the course.

You might start the semester with two or three lectures about history's most famous example of scientific methodology: the transition from an Earth-centered to a sun-centered theory during the early history of astronomy. Begin by describing the night sky, the nightly rotation, and the wandering of the moon and planets, as they appear to the unaided eye. Students can see these phenomena themselves, by following the stars as they rise and set during a single night, observing the position of the moon every night at sunset or moonrise for a month, and following the nightly motion of Venus for a few weeks.

During one or two lectures, outline the main theories and observations from the early Greeks through Ptolemy, Copenicus and Kepler. Any number of history books and textbooks tell this story (Koestler 1959; Berry 1961; Casper and Noer 1972; Holton and Brush 1973; Cohen 1985; Spielberg and Anderson 1985; Hobson 1995). Emphasize the connections between the observations and the theories, but don't be too specific yet about the meaning of "theory." As you proceed, record a running summary on the overhead projector, along lines of Figure 1.

Point out that the ancient Greeks knew Earth was a sphere, and ask the class how they might have known this (ships sank below the horizon, travelers reported that the noon sun was lower when viewed from more northern lands, and the shadow cast by Earth during lunar eclipses was that of a sphere). Today, the evidence is even more direct, as you can demonstrate with a transparency showing Earth as photographed from space.

Now lead your class in a discussion of scientific methodology, as revealed by the foregoing history. Use your summary of this history to demonstrate the interplay between theory and observation that is the essence of science. Rather than lecturing, lead your class to discover scientific methodology for themselves. Guide them by asking such questions as: What is the justification for scientific theories? Can evidence ever prove, for certain, a scientific theory? Can evidence ever disprove a scientific theory? What does it mean, then, to say that a theory is "true?" Can two different theories be simultaneously "true"? Would another word, such as "useful" or "fruitful," be better than "true"? What role, if any, do aesthetics play in science? Ask the class to cite historical examples to demonstrate their answers.

Summarize the discussion with some simple informal descriptions of the essence of the methods of science. Don't leave students with the feeling that scientific methodology is dependent on some complicated or difficult program of action called "The Scientific Method." Basically, science operates by careful observation and careful thought, combining evidence with intellectual creativity to try to understand nature. For class discussion, ask your students "to what extent is scientific thinking a model for the way we should all try to think, about most things?"

You could quote any number of experts (Mackay 1991). Here are a few. Einstein: "The whole of science is nothing more than a refinement of everyday thinking." Richard Feynman: "Science is the belief in the ignorance of the experts." Henri Poincare: "Science is built up with facts, as a house is with stones. But a collection of facts is no more a science than a heap of stones is a house." Max Born: "For the belief in a single truth and in being the possessor thereof is the root cause of all evil in the world."

Ask Frequently: "How Do We Know?"

Give observational or theoretical (based on theories that have in turn been justified by evidence) support for your course's main scientific principles. Encourage students to adopt the sceptical "show me" attitude of science. How do we know that things are made of atoms? That light moves at 3 x 10^8 m/s? That the universe is some 15 billion years old, and Earth is about 5 billion years old? That Earth is a sphere? That life evolves? That continents drift? And so forth. Although time limitations preclude justifying everything, do cite evidence for the most important assertions and be prepared to justify all of them just in case a student asks--and they should be encouraged to ask.

By constantly asking how we know, you can emphasize scientific methodology throughout your entire course. The answers can take many forms, such as: everyday observations, logical deductions from everyday observations, classroom demonstrations and experiments, reference to experiments carried out in an associated laboratory, descriptions of historical experiments, and deductions from previously-established general principles and theories.

For example, it is not obvious from casual observation that a heavy object falling through a short distance accelerates all the way down. How might we know this? Drop a book to the table from a short height above the table. Now drop it from about twice that height, and compare the loudness of the impacts. Books fall faster when they fall farther.

For another example, it is commonly observed that, when a cool object is put into contact with a hot object, the cool object warms while the hot object cools. It never goes the other way, unless there is outside assistance. Thus thermal energy flows spontaneously from a higher-temperature object to a lower-temperature object, and not the other way. This commonplace observation, the "law of heat flow," is one form of the second law of thermodynamics. A second form of this law, the "law of heat engines," states that any cyclic process that uses thermal energy to do work must be less than 100% efficient (i.e. must have an exhaust). You can easily prove this statement from the law of heat flow, by showing that a violation of the law of heat engines would imply a violation of the law of heating. This proof by contradiction is an interesting example of the use of logic in science.

How do we know that things are made of atoms? The question is relevant to every scientific field, and its history holds many lessons about the workings of science. About 2500 years ago, Greek materialists such as Democritus were the first to hypothesize the existence of atoms. Although their evidence was indirect, the Greeks had reasons for this hypothesis, namely odors. For example, how can we smell a loaf of bread from a distance? Being a materialist, Democritus believed that an unseen (because of its small size) material particle must break off of the bread, move through the air, and enter our noses. Since bread always smells like bread and never like roses, such particles are characteristic of the substance from which they come. It is natural to conclude that substances are made of tiny unseen particles that are characteristic of that substance. A substantial improvement of this argument occurred about 1800 A.D., when John Dalton discovered that substances combining chemically to form other substances always combine in simple ratios by weight. The simple ratios are easy to understand if matter is made of atoms that themselves have simple weight ratios. This evidence is persuasive but still indirect. Later in the nineteenth century, Robert Browning provided fairly direct evidence by his observation of Brownian motion. However, this evidence was still only qualitative and so many scientists remained unconvinced. Einstein's 1905 prediction of the diffusion speeds of Brownian particles convinced all scientists, because of the detailed quantitative nature of his predictions. It was difficult to believe that some other explanation, other than atoms, lay behind Brownian motion, when the atomic hypothesis (which by then surely warranted a promotion to "atomic principle" or "atomic theory") led to such detailed quantitative predictions that were then confirmed by experiment. Today the electron microscopy evidence for atoms is very direct. It is worth noting that, despite such evidence, nobody ever has or ever will *see* an atom, because if "seeing" means anything it surely means "detection with visible radiation," and visible wavelengths are far too long to detect individual atoms (Hobson 1992). Instead, electron microscopes should be said to "detect" atoms.

Other Observations About Scientific Methodology

There are many other opportunities to provide perspectives on the methods of science. For example, you can note the fact that there are at least three distinctly different scientific models of the atom: the Greek model according to which an atom really is, as its name implies, "without parts;" the planetary model, according to which atoms are made of subatomic parts called protons, neutrons, and electrons; and the quantum "model" according to which atoms cannot be visualized at all so that the title "model" might be inappropriate. Each model has its virtues. The first two models are known to be of limited validity, but are widely used because they are useful within their limited ranges. As of today, there are no known limitations on the third model. This all makes a nice example of models in science, and teaches students that a theory or model is not so much true as it is useful, and that in fact scientists often use models that are known to be incorrect in some respects, because those models give sufficiently accurate predictions for the purposes at hand.

Pursuing the theme of the range of validity of scientific theories, I use Figure 2, which was inspired by a similar diagram in Edwin R. Jones and Richard L. Childers' *Contemporary College Physics* (Second Edition 1993, Reading, MA: Addison-Wesley), to discuss the limitations of Newtonian physics. Despite Newtonian physics' great practical usefulness, its range of validity is quite small in the overall scheme of things. Despite the fact that Newtonian physics ruled supreme and had no known exceptions for more than two centuries, it appears today that the universe is described by relativity and quantum theory, not Newtonian physics.

A survey of Galileo's contributions is one way of introducing many of the methods of science. These contributions include:

- *Experiments*, designed to test specific hypotheses. Although careful observation goes back at least to Aristotle, Galileo was the first to refine this process with controlled experiments to test specific hypotheses.
- *Idealizations* of real-world conditions, or the consideration of limiting cases (such as zero air resistance), to eliminate (at least in one's mind) side-effects that obscure the main effects.
- *Limiting the scope of the inquiry* by considering only one question at a time. For example, Galileo did not make Aristotle's mistake of trying to understand both *why* horizontal projectile motion occurs and also *how* it occurs. Aristotle believed that horizontal motion occurs because of external assistance, so that an unassisted horizontally-moving object should slow down and stop (that is how it occurs, says Aristotle). But Galileo looked more carefully at only the question of *how* horizontal occurs, and found that in the absence of friction an object would not slow down.
- *Quantitative methods.* For example, Galileo went to great lengths to *measure* the motion of bodies. He understood that a theory capable of making quantitative predictions is more powerful then one that only makes qualitative, descriptive predictions.

Unification in science is another theme worth pursuing. There are many examples: the Newtonian synthesis, the unification of the electric and magnetic forces, unification of all forces into four fundamental ones, unification of the electromagnetic and weak nuclear forces, the possible grand unification, the possible "theory of everything," and so forth (Figure 3).

Conclusion

The core of scientific methodology is the use of experience and reason, rather than emotion and prior beliefs, as the guide to knowledge. Underlying this is an even more important lesson: Science does not seek absolute truth, for no matter what general scientific principle one considers, that principle is always in danger of disproof by some new observation. You can never be certain. Although absolute truth might (or might not) exist in some sense, scientists (when acting as scientists) cannot ever be sure of having discovered it.

In a time wracked by the ideologies of people who *feel* or *believe* that they have discovered an absolute truth of one sort or another, and who are willing to hold grimly to their beliefs through all manner of contrary evidence and human suffering, this fundamental and humbling lesson of science might provide some of the fresh air that the world surely needs now.

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Figure 1. A summary of the early history of astronomy

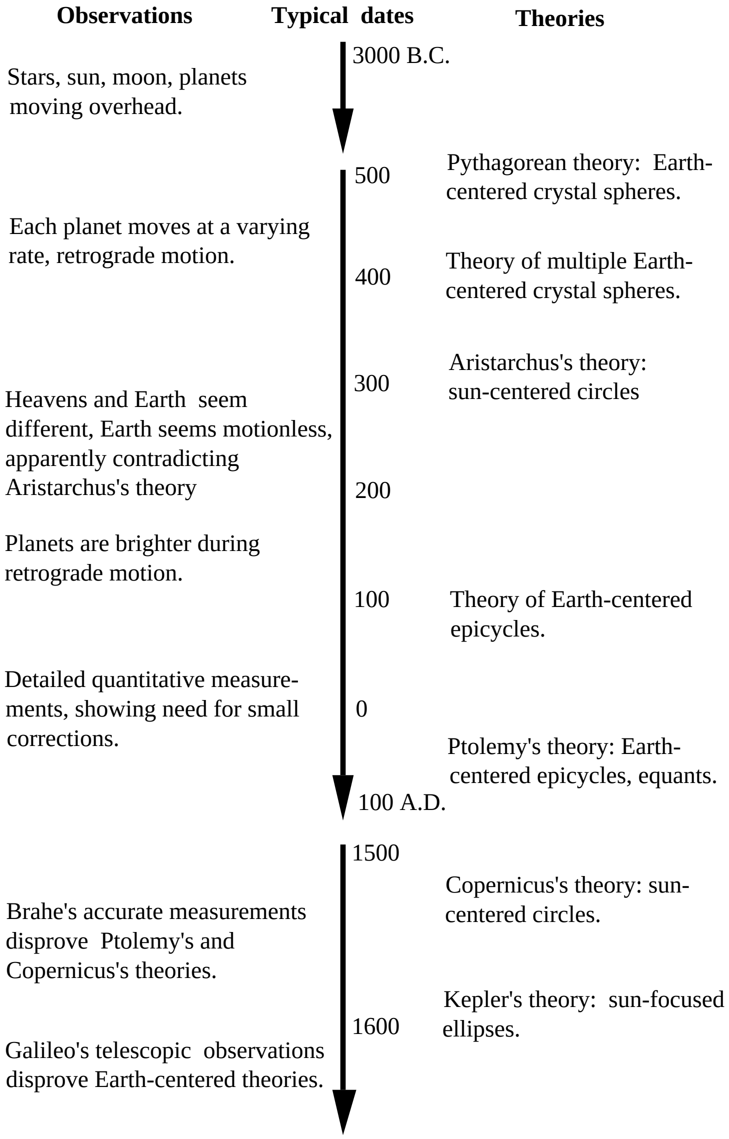
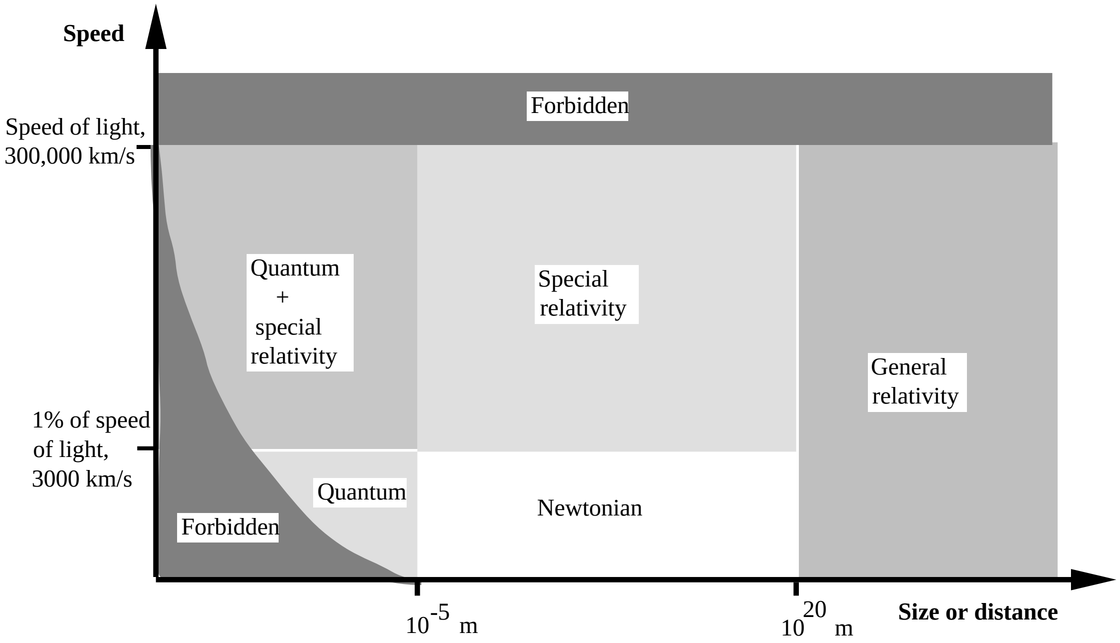


Figure 2. Newtonian physics breaks down for very small objects, very large objects, and very fast objects. Newtonian physics also breaks down for strong gravitational forces, such as those near a star, although this limitation is not pictured on this diagram.



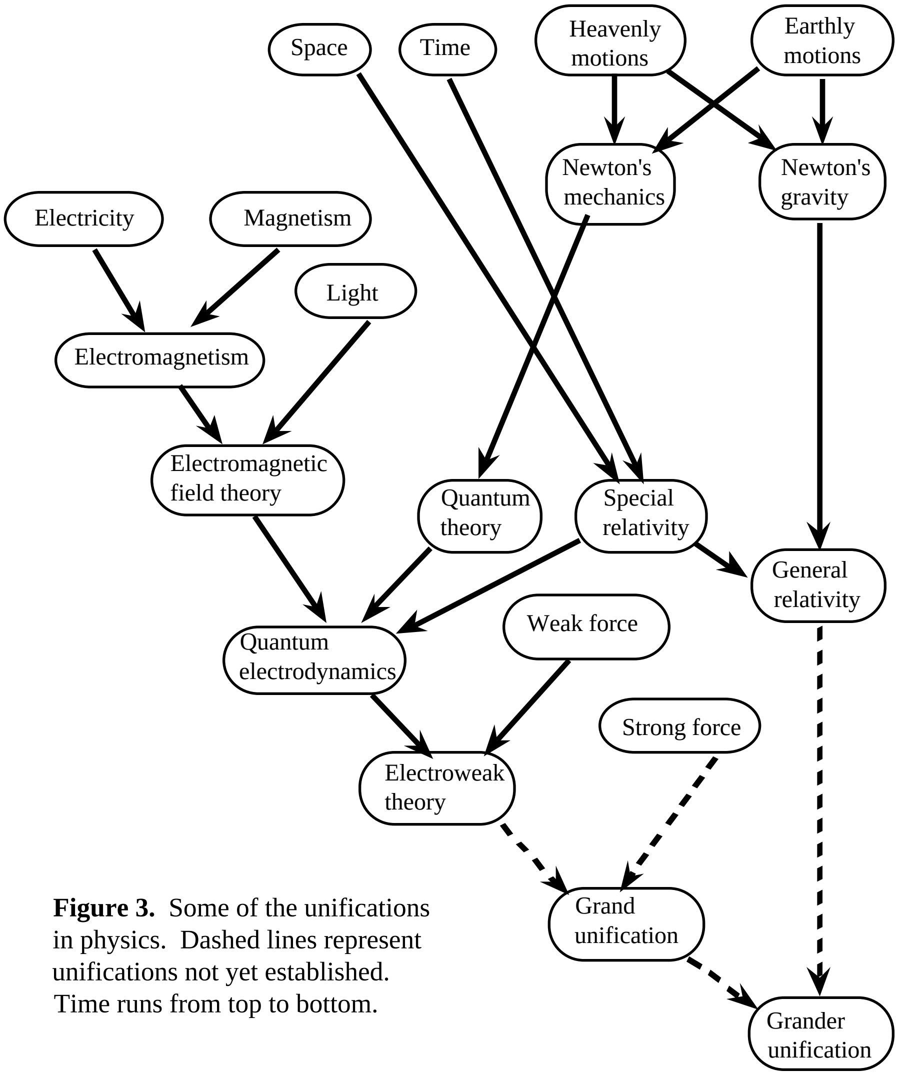


Figure 3. Some of the unifications in physics. Dashed lines represent unifications not yet established. Time runs from top to bottom.